The Use of Electrostatic Probes to Characterize the Discharge Plasma Structure and Identify Discharge Cathode Erosion Mechanisms in Ring-Cusp Ion Thrusters

by

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DEDICATION

To my parents who have offered their encouragement throughout my entire life by their example and with their unconditional love and support.

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PREFACE

This dissertation presents research aimed at extending ion engine lifetime by increasing the life of the discharge cathode assembly (DCA) inside ring-cusp ion engines. Ion engines have been developed for more than 40 years spanning a wide range of propellants and configurations. The scope of this investigation focuses on xenon-propellant electron-bombardment ion thruster development in the United States. The two thrusters in this investigation contain: permanent magnet ring-cusp magnetic fields, partial-conic non-ferrous discharge chambers, hollow cathodes for propellant ionization and beam neutralization, discharge and neutralizer keeper electrodes, two-grid dished ion optics, and are operated with a reduced beam density, *i.e.* "derated," to extend life. Several wear tests have been conducted on ion engines of equivalent configuration to determine component and thruster lifetime, which will be reviewed. These preliminary wear tests, specifically those related to the 30-cm engine development, diagnosed the erosion of the ion optic grids and discharge cathode as the primary failure mechanisms in long-term ion engine operation.

To address these two lifetime limiters, two different approaches were employed. To mitigate discharge erosion a sacrificial keeper electrode was added effectively shielding the discharge cathode and was thought to be an engineering solution to the problem. The use of a keeper shifted the observed erosion from the cathode to the keeper (be it at a reduced rate), but this may not extend the cathode assembly lifetime enough to meet future ion propulsion missions' requirements. Extensive resources have been dedicated to model grid erosion resulting in improved discharge chamber and ion optics design.

Ion engines have been successfully flown in space for North-South station keeping (NSSK), attitude control, orbit-transfer from low Earth orbit (LEO) to geosynchronous Earth orbit (GEO), orbital maintenance, and have been used as primary propulsion for the Deep Space 1 (DS1) mission. The 30-cm <u>N</u>ASA <u>Solar</u> Electric Propulsion <u>T</u>echnology <u>Applications R</u>eadiness (NSTAR) ion engine used on DS1 demonstrated superior performance as it completed its comet and asteroid rendezvous, exceeding its design life (demonstrating 16,265 hours of in-space operation with a thruster design life of 8,000 hours). As a follow on to this successful in-flight test, the flight spare from the DS1 mission was put through an Extended Life Test (ELT) at the Jet Propulsion Laboratory (JPL) in which severe erosion of the DCA was observed. To date this anomalous erosion has yet to be fully explained and is a motivating factor for this research endeavor.

To determine the cause of the DCA erosion, Laser-Induced Fluorescence (LIF) measurements were made at the University of Michigan by Williams on a modified 30cm NSTAR Functional Model Thruster (FMT). These near-DCA LIF measurements discovered the existence of high-energy ions with appreciable axial velocities flowing

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back towards the DCA. While the LIF measurements prove the existence of the highenergy ions long thought responsible for the DCA erosion, they do not offer a clear explanation about the formation of these ions. To this extent, the cause of the DCA erosion is still a mystery. To this end the Plasmadynamics and Electric Propulsion Laboratory (PEPL) has developed a diagnostic to interrogate the near-DCA regions of the NSTAR and NASA Evolutionary Xenon Thruster (NEXT) ion engines.

An extensive array of high-resolution discharge chamber data was obtained using a variety of electrostatic probes in the near-DCA regions for both engines and, for the NEXT engine, in the near-optics region. Measurements were taken in three configurations: 1) the nominal configuration with beam extraction, 2) without beam extraction, and 3) with the discharge cathode keeper shorted to discharge cathode common.

The first two configurations will isolate the variations in plasma structure due to beam extraction, which will be useful when apply the results of discharge-only operation in ground based testing to flight operation, if possible. The third configuration will investigate the effects that a shorting event between discharge cathode keeper and common would have on the near-DCA plasma structure. This configuration is of particular interest because the onset of increased DCA erosion rate in the ELT coincided with an intermittent short of the cathode keeper to cathode common.

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For each configuration, data were taken over the permissible range of engine operating conditions. While operating the NEXT engine, the power supply console limited operation to the low and mid-power ranges of the NEXT set points. For each operating condition single Langmuir probe and/or double Langmuir probe, emissive probe, and electron energy distribution function (EEDF) measurements were taken. Further adding to the test matrix, the near-optic region of the NEXT engine was probed. To make the data collection and analysis tractable, test matrices (*i.e.* operating conditions) were chosen to minimize time, but maximize results over a variety of throttling conditions.

The characterization on both engines indicates very similar plasma parameters. Experimental results indicate that number densities are highest along cathode centerline as the axial magnetic field near the DCA effectively confines electrons to a narrow plume. Number densities as high as 3×10^{13} have been measured directly downstream of the DCA. Electron temperatures range from 2 - 7 eV throughout this investigation. The off-axis maximum in electron temperature contours results from the acceleration of the electrons across a free standing potential structure that forms the transition between the low-potential cathode plume and the high-potential bulk discharge plasma. This type of structure is termed a double layer. In the bulk discharge plasma, the accelerated electrons are thermalized, leading to a reduction in the electron temperature. An analysis of the electron energy distributions utilizing two different methods with comparable results supports the double layer acceleration as a means of increasing the electron temperature. A single bump distribution is observed throughout the discharge cathode plume and in

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the bulk discharge plasma. Across the double layer, a two-hump distribution is evident due to the additional accelerated electron species. The accelerated electrons become thermalized in the bulk discharge, though their effect can be seen as a high energy tail in the distributions.

Plasma potentials mappings of the 30-cm and 40-cm ion thrusters rule out the existence of a potential-hill structure as the cause of the DCA erosion. The formation of a potential-hill has been proposed as a cause of the DCA erosion, yet the axial magnetic field near the DCA not only serve to reduce the radial diffusion of electrons, but also enhances the axial conductivity of electrons. This tends to smooth out potential structures in the axial direction preventing the formation of a potential-hill. The existence of a double layer formation has been observed. The magnetic field near the DCA establishes this free standing potential structure that transitions between two plasma at different potentials. The field-aligned double layer can accelerate electrons across it towards the bulk discharge plasma affecting the electron temperatures and electron energy distributions. The double layer also accelerates ions from the bulk discharge plasma towards the DCA and may be the dominant mechanism in DCA erosion.

The variation in plasma structure when a beam was not extracted show a change in the potential structures corresponding to the change in the discharge voltage (if the mass flow rates are maintained) or a change in the number densities (if the discharge voltage is maintained). The electron temperature profiles are noticeably altered by the extraction of a beam indicating coupling between the beam and discharge plasmas.

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Though they may serve to assess thruster performance, testing without beam extraction does not simulate the discharge plasma structure of a flight thruster and therefore will not accurately predict erosion phenomena.

Shorting the cathode keeper to cathode common was used to simulate the operating condition of the ELT at which accelerated erosion was observed. The shorting event had a negligible effect on the measured cathode plume and bulk discharge plasma parameters. It appears as though the changes are confined to the keeper sheath and do not permeate into the surrounding plasma. The shorting event does increase the ion acceleration through the sheath structure by a value equal to the discharge cathode keeper to common voltage.

From the measured plasma parameters in this investigation and from ion velocimetry of Williams LIF investigations, an erosion rate is calculated from low-energy sputtering yield formulae. The contribution due to singly ionized xenon alone was not enough to account for the erosion rates observed in the NSTAR wear testing. Incorporation of the effect of doubles, from measured double-to-single current measurements in the plume of 30-cm and 40-cm thrusters, significantly increases the calculated erosion rates to the values obtained in the NSTAR wear tests.

The same erosion rate calculation is applied to estimate the erosion rate that is expected in the NEXT wear test. Owing primarily to the slightly lower double-to-singe current ratio in the NEXT plume, it is expected that the NEXT DCA will experience

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slightly less erosion than the NSTAR thrusters. Recent results from a NEXT 2000-hr wear test indicate an erosion rate moderately increased compared to the NSTAR 1000-hr and 8200-hr rates. It is clear that this erosion calculation does not encompass all the features of the DCA erosion. The calculated erosion rate does not account for the more axially-aligned magnetic field of the NEXT engine which would tend to accelerate ions across the double layer towards DCA centerline. A Monte Carlo simulation will provide more accurate erosion calculations.

The effect of shorting the keeper to common has been duplicated in the erosion rate calculation leading to an accelerated rate strikingly similar to the estimated rate in the ELT. The additional acceleration of both doubly and singly ionized xenon through the keeper sheath significantly affects the erosion rate by increasing the incident ion energy. It appears as though the main cause of the DCA erosion is acceleration of both doubly and singly ionized xenon across the double layer towards the DCA.

The errors in the erosion rate calculation are mainly due to the error in the sputtering yield theory for near-threshold energies. The calculated erosion rate is highly sensitive to the number density input – affecting the directed flux, to the plasma potential – affecting incident ion energy, the angle of incidence – affecting the angular dependent sputtering threshold energy, and the double-to-single ion current ratio. Additional experimental data on near-threshold erosion would enhance the erosion rate calculation. Measurement of the double-to-single ion current ratio near the DCA would provide a better estimate than the plume value.

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Some methods of reducing the DCA erosion are discussed including: alternative keeper materials, biasing the keeper, reducing the incident ion energy, reducing the double-to-single ion current ratio, and possibly the manipulation of the double layer through alteration of the magnetic field near the DCA.

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NOMENCLATURE

Variables

А	collection area, m ²
a	Thomas-Fermi screening radius, Å
A _p	probe surface area, m ²
A _s	ion collection area, m ²
В	Magnetic field vector, G
В	Scalar magnetic field, G
B 1	primary electron current intercept, A
B ₂	primary electron current slope, A/V
B ₃	$I_{e,sat}exp(\textbf{-}\phi_{p}/T_{eV})$, A
B ₄	$1/T_{eV}$, A
c	Effective exhaust velocity, m/s
d	emitting filament wire diameter, mm
E	energy, eV
<e></e>	average electron energy, eV
Ei,a	discharge loss, W/A
E _{TF}	Thomas-Fermi energy unit
E _{th}	sputtering threshold energy, eV

\mathbf{f}_{E}	distribution function, m ⁻³ ·eV ⁻¹
Ι	probe collected current, mA
Ie	electron current, A
Ii	ion current, A
I _{e, sat}	electron saturation current, A
$I_{sat} \text{ or } I_{ion, sat}$	ion saturation current, A
i _p	primary electron current at ϕ_p , mA
I _{sp}	specific Impulse, s
j	current density, A/m2
J _a	acceleration grid current, mA
J _b	beam current, A
J _{dc} or J _d	discharge current, A
J _{nk}	neutralizer keeper current, A
JxB	Lorentz force
k _e	Lindhard electronic stopping coefficient
Kn	Knudsen number
1	probe length, m
М	vehicle mass, kg
M ₁	particle atomic mass, amu
M ₂	target atomic mass, amu
Mi	ion mass, kg
'n	propellant mass flow rate, kg/s
N or n	number density, cm ⁻³

n _i	ion number density, cm ⁻³
n _e	electron number density, cm ⁻³
n _{e,m}	Maxwellian electron number density, cm ⁻³
n _p or n _{e,p}	primary electron number density, cm ⁻³
P _b	base pressure (air), Torr
P _i	indicated pressure (xenon), Torr
P _{in}	thruster input power, W
P _c	corrected pressure (xenon), Torr
$Q(Z_2)$	sputter yield best-fit parameter
R ₀	average lattice constant, m
R _p or r	probe radius, m
R_p/R_a	ratio of projected range to average path length
S _n	elastic nuclear stopping cross section, eV $Å^2$ atom ⁻¹
$s_n(\epsilon)$	elastic reduced nuclear stopping power
Т	thrust, N
T_e or T_{eV}	Maxwellian electron temperature, eV
T _i	ion temperature, K
T _w	filament wall temperature, K
Us	sublimation energy, eV
Ub	surface binding energy, eV
V	velocity, m/s
Va	acceleration grid voltage, V
V _{bias}	probe bias referenced to discharge cathode common, V

V _{ck-cc}	keeper to cathode common voltage, V
$V_{dc} \text{ or } V_d$	discharge voltage, V
V_{f}	floating potential, V
V_{g}	neutralizer to ground coupling voltage, V
V_{nk}	neutralizer keeper voltage, V
V_s or V_b	screen grid voltage, V
$W(Z_2)$	sputter yield best-fit parameter
Y	sputter yield, atoms/ion
Z_1	particle atomic number
Z_2	target atomic number
α	energy-independent function of mass ratios
α*	universal energy-independent function of mass ratios
γ	energy transfer factor
Γ	sputter yield mechanism contribution factor
δ	sheath thickness, cm
3	reduced energy
ζp	primary electron energy, eV
η	thruster efficiency, %
θ	angle, degrees
λ	mean free path, m
λ_{D}	Debye length, cm or mm
φ or V	voltage or potential, V
$\phi_p \text{ or } V_p$	plasma potential, V

ω	frequency,	Hz
---	------------	----

 Δv mission velocity increment, m/s

Constants

g ₀	gravitational acceleration, 9.80665 m/s2
e or q	electron charge, 1.6022x10 ⁻¹⁹ C
k	Boltzmann's constant, 1.3807x10 ⁻²³ J/K
m or m _e	electron mass, 9.1094x10 ⁻³¹ kg
M or M_{Xe}	mass of a xenon atom, 2.18x10 ⁻²⁵ kg

Subscripts

0	initial
a	accelerator grid
b	beam
d or dc	discharge
e	electron
f	final
g	ground
i	ion
р	plasma
pr	probe
S	screen grid
Xe	xenon

٢	1 st derivative
ډ ۲	2 nd derivative
، ، ،	3 rd derivative
()))	4 th derivative
+	singly-ionized
++	doubly-ionized

Acronyms

AIAA	American Institute of Aeronautics and Astronautics
AD	Analog Devices
AFRL	Air Force Research Laboratory
BBPPU	Bread Board Power Processing Unit
BOL	Beginning Of Life
СК	Cathode Keeper (Discharge)
CC	Cathode Common (Discharge)
DCA	Discharge Cathode Assembly
DCIU	Digital Control and Interface Unit
DEEDF	Druyvesteyn (Second Derivative) Electron Energy Distribution Function
DL	Discharge Level
DP	Double Langmuir Probe
DS1	Deep Space One
ECR	Electron Cyclotron Resonance
EEDF	Electron Energy Distribution Function

ELT	Extended Life Test
EM or EMT	Engineering Model Thruster
EOL	End Of Life
EP	Electric Propulsion
FEEP	Field Emission Electric Propulsion
FEP	Floating Emissive Probe
FMT	Functional Model Thruster (NSTAR)
FT	Flight Thruster
GEO	Geosynchronous Earth Orbit
GFE	Government Furnished Equipment
GRC	Glenn Research Center, Cleveland, OH
HARP	High-speed Axial Reciprocating Probe positioning system
HEEDF	Harmonic (AC Method) Electron Energy Distribution Function
HET	Hall Effect Thruster
HiPEP	High-Power Electric Propulsion
HLP	Harmonic Langmuir Probe
IPD	Inspection and Process Document
JIMO	Jupiter Icy Moons Orbiter
JPL	Jet Propulsion Laboratory
LDT	Long Duration Test
LEO	Low Earth Orbit
LIF	Laser-Induced Fluorescence
LM	Laboratory Model thruster

- LVTF Large Vacuum Test Facility
- MCDC Multiple-Cathode Discharge Chamber
- MPD MagnetoPlasmaDynamic thruster
- NASA National Aeronautics and Space Administration
- NEAT New England Affiliated Technologies
- NEP Nuclear-Electric Propulsion
- NEXIS Nuclear Electric Xenon Ion System
- NEXT NASA Evolutionary Xenon ion Thruster
- NGEP Next Generation Electric Propulsion project
- NK Neutralizer Keeper
- NSSK North-South Station-Keeping
- NSTAR NASA Solar electric propulsion Technology Applications Readiness
- OML Orbital Motion Limited
- PEPL Plasmadynamics and Electric Propulsion Laboratory
- PIT Pulsed Inductive Thruster
- PPT Pulsed Plasma Thruster
- PPU Power Processing Unit
- RF Radio Frequency
- RPA Retarding Potential Analyzer
- SCCM Standard Cubic Centimeter per Minute
- SDLP Second Derivative Langmuir Probe
- SEPS Solar Electric Propulsion System
- SERT Space Electric Rocket Test

SLP	Single Langmuir Probe
SKIT-Pac	Station-Keeping Ion Thruster Package
STS	Space Shuttle
TAG	Thick Accelerator Grid
TH	THrottling Level
TOC	Thruster Operating Condition
UM	University of Michigan
WT	Wear Test
XIPS	Xenon Ion Propulsion System

CHAPTER 1

INTRODUCTION

1.1 Rocket Propulsion Basics

In its most basic definition, a rocket is a vehicle that propels itself forward by emitting a jet of stored matter at high velocity. The force acting on the vehicle is the reaction, owing to momentum exchange, of the vehicle structure due to the ejection of matter. Applying Newton's third law, "for each action there is an equal and opposite reaction," to the exhaust gases; an accelerating force acts on the vehicle. The force produced, referred to as thrust, is the product of the effective exhaust velocity of propellant and the propellant mass flow rate, which is given by:

$$T = c m$$
. Eqn. 1-1

The effective exhaust velocity, c, is the average equivalent exhaust velocity for a given period of operation of the rocket engine, which combines the true exhaust velocity with the effects of pressure differentials between the exhaust stream and ambient. The mass of the rocket, or spacecraft, is changing with respect to time as matter is ejected in

the exhaust. The change in the mass of the vehicle is equal to the mass flow of propellant. Applying Newton's third law again to the rocket gives:

$$T = M \frac{dv}{dt}$$
 Eqn. 1-2

where v is the velocity of the vehicle and M is the vehicle mass. Equating the right hand side of both equations, neglecting gravity, and some minor manipulation yields the following relation for the vehicle velocity, vehicle mass, and propellant exhaust velocity,

$$dv = c \frac{dM}{M}$$
. Eqn. 1-3

For constant effective exhaust velocity, for a specified "burn", this equation may be integrated over the limits of initial-to-final velocity and initial-to-final mass:

$$\int_{v_0}^{v_f} dv = c \int_{M_0}^{M_f} \frac{dM}{M}$$
 Eqn. 1-4

The solution of the integral above gives an expression for the maximum velocity increment that a rocket can attain by expending all its propellant:

$$v_f - v_0 = c \ln \left(\frac{M_0}{M_f} \right).$$
 Eqn. 1-5

Eqn. 1-5 is referred to as the Rocket Equation or Tsiolkovsky's Equation. Named after famous mathematics teacher Konstantin Tsiolkovsky, who in 1903 first published its derivation, the Rocket Equation identifies exhaust velocity as the important performance parameter in rocket propulsion.¹ If all of the propellant is exhausted, this equation gives the maximum theoretical velocity increment obtainable from a single stage. The Rocket Equation can be rearranged, illustrating that the fraction of the original vehicle mass that can be accelerated through a given Δv is a negative exponential in the ratio of that velocity increment to the effective exhaust velocity:

$$\frac{M_f}{M_0} = e^{-\left(\frac{\Delta v}{c}\right)}$$
. Eqn. 1-6

Eqn. 1-6 establishes the need for an effective exhaust velocity that is comparable with the mission Δv if a significant fraction of the original mass is to be brought to the final velocity. For missions with high Δv requirements, the higher exhaust velocity benefits may be any of the following: (1) make the mission feasible, (2) increase the deliverable payload (revenue-producing or scientific instrument payload), (3) extend satellite lifetime, or (4) reduce cost by reducing propellant requirements and/or launch vehicle needs. Deep space missions are prime examples of the need for high exhaust velocity, but this can also be true for North-South station-keeping (NSSK) requirements in which long satellite lifetimes may require substantial Δv 's to overcome the solar radiation pressure drag and gravity gradients to maintain their orbit. Similar definitions and derivations of Tsiolkovsky's equation can be found in References 2-5. Having established the need for high effective exhaust velocity, it is important to introduce a related operating parameter, specific impulse, which is typically used instead of exhaust velocity as a performance measure of propulsion systems. Specific impulse, I_{sp} , is defined as the total impulse per unit weight of propellant. For constant propellant mass flow, constant thrust, and negligible transients; specific impulse can be calculated by Eqn. 1-7 where g_0 is the standard acceleration of gravity at sea level (9.8066 m/sec²):

$$I_{sp} \equiv \frac{T}{\dot{m}g_0} = \frac{c}{g_0}$$
 Eqn. 1-7

Specific impulse is directly related to the effective exhaust velocity, c, and is one of the main performance parameters that will be used when comparing electric propulsion technologies amongst themselves and with chemical systems.

A chemical rocket engine consists of a combustion chamber into which fuel and oxidant are mixed and ignited. The high-pressure hot gas produced is expanded through a nozzle generating a high-velocity exhaust stream. The maximum attainable exhaust velocity of conventional chemical rockets is limited by the stored energy in the bonds of the propellant that is released during combustion and converted to enthalpy of the gas. No more energy can be put into the rocket than is contained in the propellant flowing through the engine. Thus, the power of the rocket is constrained by the chemical energy of the fuel/oxidant combination, and their flow rate. For reference, the specific impulse of the Space Shuttle chemical rockets, solid rocket motors and liquid oxygen and liquid

hydrogen main engines, are 268.2 sec and 452.5 sec, respectively.² In the 1960's, as the space age progressed, chemical rockets were stretched to their limit through novel concepts such as multi-staging and maximizing both chemical reaction and rocket nozzle performance to approach their theoretical maximum. The chemical rocket has approached the highest exhaust velocity possible, equivalently I_{sp}, without a leap forward in material science engineering and chemistry. One approach to increasing the space vehicle I_{sp}, which is the fundamental idea behind electric propulsion (EP), is to separate the energy input from the propellant flow and represents a significant departure from classical chemical rockets. In this way, EP devices can achieve exhaust velocities, or equivalently specific impulses, that far exceed those of chemical rockets.

1.2 Electric Propulsion Overview

The idea of electric propulsion (EP) can be traced back to rocket pioneer Robert H. Goddard who experimented with an electric gas discharge tube in 1906.⁴ He noted that high velocity streams of negative and positive particles could be used as a second stage to accelerate and decelerate a spacecraft on its trajectory to other planets. Electric propulsion devices utilize energy, drawn in one form or another from electricity, which is independent of the propellant itself.

Electric propulsion has three subsets identifying the mechanism through which electric energy is added and converted to kinetic energy of the particles accelerated. These categories are electrothermal, electromagnetic, and electrostatic propulsion systems. Additional information on the various EP categories, historical perspectives of these systems, and more comprehensive discussion of the various EP technologies can be found in References 6-9.

1.2.1 Electrothermal Propulsion

Electrothermal propulsion systems are the most similar to chemical rocket systems and are more easily understood than the other two EP systems in terms of operating fundamentals. Electrothermal systems heat the propellant gas electrically in one of two ways. In a resistojet, the propellant gas is heated by passing it over an electrically heated surface, while an arcjet heats propellant by passing it through an arc discharge. The high-temperature gas then flows through the throat and expansion nozzle producing thrust by thermodynamic forces. The benefit of electrical heating over chemical propulsion is that the gas temperatures of the electrothermal system are not limited by the enthalpies of the fuel-oxidizer reactions of chemical systems. The amount of energy added, and hence the maximum exhaust velocity, is instead limited by the maximum temperature the nozzle and combustion chamber can sustain and the molecular weight of the exhaust species.

In arcjets, the high energy density arc partially ionizes the propellant that reaches thermodynamic equilibrium temperatures of several thousand degrees when the ions mix with the gas in the chamber. The higher gas temperature obtained by arc heating is also advantageous because the arc heating is directly applied to the gas and not through or

near the chamber walls. If properly cooled, this process keeps wall and nozzle temperatures lower, which is desirable from a thruster life standpoint. Arcjets and resistojets have been used since the late 1950s in space for station-keeping, attitude control, and orbital maneuvers. These devices found early application owing to 1) their compatibility with existing space-qualified hydrazine propellant feed systems, 2) the low system mass of the thrusters and power processing units, and 3) acceptable cost and schedule for space qualification. More information can be found on resistojet and arcjets in References 10-19.

1.2.2 Electromagnetic Propulsion

Electromagnetic propulsion systems use electrical power to ionize propellant that is then acted upon by a combination of electric and magnetic forces produce thrust. In electromagnetic devices, the combination of perpendicular electric and magnetic fields leads to a force that acts on the charged particles. The magnetic field may be externally applied field, self-generated, or a combination of the two. Examples of electromagnetic devices include magnetoplasmadynamic (MPD) thrusters, pulsed-plasma thrusters (PPT), pulsed inductive thrusters (PIT), and the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) thruster. Hall thrusters are included in this category because of the importance of the magnetic field topology in this device, though electrostatic forces (set up by the magnetic field impedance to electron flow) are responsible for beam acceleration. It is common for Hall thrusters to be included in either electromagnetic or electrostatic devices.

A close competitor to the ion engine (see \$1.2.3) is the Hall Effect Thruster (HET). Unlike the ion engine, the Hall thruster is not space-charge limited and has a relatively high thrust density, which is typically 10 to 100 times that of ion engines. The acceleration mechanism responsible for this desirable Hall thruster performance, however, results in I_{sp} values and efficiencies that are typically below those of ion engines. An explanation for these characteristics can be found by briefly discussing the operating theory behind Hall thrusters.

A schematic of the operation of a Hall thruster is shown in Figure 1-1. Typically a cylindrical geometry is chosen, however, racetrack and linear geometries have been investigated.²⁰⁻²² In a cylindrical Hall thruster, the applied magnetic field is in the radial direction and the applied electric field is in the axial direction. Electrons, emitted by a cathode, move towards the anode in the rear of the discharge channel. The electron motion is impeded by the applied radial magnetic field, which traps the electrons in cyclotron motion. The magnetic field is typically produced by electromagnets so that the magnetic field can be optimized for a given operating condition. The trapped electrons produce a spiraling closed-drift Hall current in the azimuthal direction. Although the axial motion of electrons is impeded, they drift towards the anode primarily due to collisions with the discharge chamber wall and other particles.



Figure 1-1: Components of a typical Hall thruster (isometric view).

Electron collisions with neutral xenon particles, injected through the segmented anode, are responsible for the ionization. Collisions with the discharge channel wall create more electrons as the channel walls of many Hall thrusters are lined with a high secondary electron coefficient dielectric material. Once ionized, the heavier ions, which are relatively unaffected by the magnetic field, are accelerated by the axial electric field away from the engine. The Hall thruster acceleration mechanism can also be explained in terms of the **JxB** force acting on ions due to the azimuthal Hall current and the radial magnetic field (hence the dual electromagnetic/electrostatic category). The two different views of Hall thruster acceleration are in fact equivalent.²³

The space charge in the ion acceleration region is neutralized by the electron current moving towards the anode in the transverse direction (see Figure 1-1 with the electron cyclotron motion and center of mass shown in white). The presence of the trapped electrons within the accelerator neutralizes the ionic space charge. The end result is a higher beam current (higher thrust density) compared with ion thrusters. Ions are formed at various locations in the discharge channel and, based upon the electrostatic conditions of this location, are accelerated by varying electric field strengths.

An example state-of-the-art Hall thruster is the NASA-173Mv1 Hall thruster, shown in Figure 1-2. Though higher-power Hall thrusters have been developed, the NASA-173Mv1 is a 5 kW Hall thruster that is able to achieve high specific impulse (up to 3300 sec on xenon and 4300 sec on krypton) with total efficiencies in the 50-60% range through the use of a tailored magnetic field topology.²⁴ In addition to the traditional electromagnet coils, located outside the outer wall of the discharge channel, an auxiliary trim coil located in the rear of the thruster allows additional modification of the magnetic field topology to improve thruster performance.



Figure 1-2: NASA-173Mv1 Hall thruster.

High-power Hall thrusters, like the NASA-457, have been developed demonstrating operation up to 100 kW, producing several Newtons of thrust at specific impulses up to 3050 seconds and thrust efficiencies between 40% and 57% on xenon. The NASA-457 has also achieved an I_{sp} of 4500 seconds on krypton.²⁵⁻²⁸ While the use of krypton increases the specific impulse of Hall thrusters, at the expense of thrust and efficiency; ion engines, in general, continue to have superior efficiency at specific impulses above 4000 seconds. The interested reader can find more details about Hall thruster technology and development in References 23, and 27-39.

1.2.3 Electrostatic Propulsion

In the electrostatic EP system, the propellant particles are directly accelerated by applied electrostatic fields. The electrostatic category consists of gridded ion engines, Hall thrusters, field emission electric propulsion thrusters (FEEPs), and colloid thrusters. Oberth was perhaps the first to dream of the primitive ion engine. In 1957, he wrote of porous plates that when combined with dispersed propellant flow and high applied voltage, could produce a spray of charged particles leaving the vehicle with very high velocity.⁸

In ion engines, the propellant must be at least partially ionized and have an average time between collisions less than the residence time in the acceleration zone. Very high specific impulses, 3,000 – 20,000 seconds, are achievable without excessive heat flux to the walls of the engine. As early as 1952, Lyman Spitzer pointed out that the flow of ions from the source will be space-charge limited, implying that an upper limit on the thrust density of gridded ion systems is inherent.^{1,8} This fact is illustrated by the application of the Child-Langmuir Law, which determines the change in electrostatic field between charged plates as charged particles fill the space between them shielding the applied electric field. A beam of high-velocity, positively-charged particles streaming from the spacecraft will charge the spacecraft negatively setting up an electrostatic field to inhibit the flow of further ions away. This charge buildup is prevented by neutralizing the ion beam (after acceleration) through an external electron source. Before discussing in detail the operation of gridded ion engines, it is useful to connect the operating parameters of the various propulsion systems introduced. Table 1-1 illustrates how the

various EP technologies introduced compare to conventional chemical rocket performance.

Engine	Propulsion Type	Max specific impulse [sec]	Maximum thrust [N]	Efficiency	Reference
STS Solid					
Rocket Motor	Chemical solid	268.2	1.36×10^7	N/A	2
STS Main Engines	Chemical liquid bipropellant	452.5	2.18x10 ⁶	N/A	2
Resistoiet	Electrothermal	700	0.8	80%	2640
Arcjet	Electrothermal	1970	1	28%	<i>2</i> ,0,40
NSTAR (2.3 kW)	Electrostatic	3189	0.093	63%	42
NEXT (6.9 kW)	Electrostatic	4090	0.237	69%	43
UofM/AFRL P5 (5 kW)	Electromagnetic	2326	0.246	57%	44
NASA-457M (50 kW)	Electromagnetic	3050	2.9	57%	25
РРТ	Electromagnetic	1500	0.005	7%	6,7,40
MPD	Electromagnetic	5000	200	50%	2,6

 Table 1-1: Sample performance of various propulsion systems including chemical and electric propulsion systems.

These numbers are meant to give an order of magnitude comparison of the various propulsion technologies. The main points to draw from Table 1-1 are: electric propulsion systems can achieve higher exhaust velocities (*i.e.*, higher I_{sp}) compared to their chemical counterparts, electric propulsion devices are low-thrust systems, and finally that gridded ion thrusters are on the higher end, in terms of I_{sp} , of the electric propulsion devices.

1.3 Ring-Cusp Ion Engine Overview



Figure 1-3: 3D gridded ion engine diagram indicating the discharge cathode, discharge plasma, ion beam, and external neutralizer cathode (used with NASA GRC permission).

1.3.1 Theory of Operation

Gridded ion thrusters are electrostatic, in-space propulsion devices in which the ionization and acceleration regions are separate and can be optimized individually resulting in highly efficient thrusters. The ionization takes place in a discharge chamber, typically from bombardment by electrons emitted from a hollow cathode, though radio-frequency waves (RF) and microwaves have also been employed.^{9,45-47} Neutral Xe is fed into the discharge chamber, mainly through the main plenum line, to maintain a pressure $\sim 10^{-4}$ Torr. The ionization is enhanced by the presence of a magnetic field that prolongs the residence time of electrons in the engine, thereby increasing the probability of an ionization collision with neutral propellant molecules injected into the main discharge chamber. Roughly 10 percent of the gas in the discharge chamber is ionized by electrons

from the discharge cathode.⁴⁸ After colliding with the neutral gas, the electrons become thermalized and are collected by the anode.

The ions in the discharge chamber migrate towards the first of two grids, the screen grid, which is electrically connected to cathode common. The set of multi-aperture grids (typically two or three) make up the ion optics that accelerate the ions to high velocities by the applied electric field. The ion optics are composed of charged multiple-aperture grids; the screen grid at high positive potential (a few thousand volts above spacecraft common), an acceleration grid at negative potential (a few hundred volts below spacecraft common), and an optional deceleration grid. The primary function of the acceleration grid is to prevent electron backstreaming from the neutralizer to the DCA. The ion extraction rate is space-charge limited. The ion extraction rate, and hence thrust, is limited by the open area fractions of the ion optics, the inter-grid gap, and the uniformity of the discharge plasma density near the screen grid surface. An external neutralizer, typically a hollow cathode, emits electrons to neutralize the accelerated ions to prevent spacecraft charge buildup. Schematics visualizing the ion engine operation are shown in Figure 1-3 and Figure 1-4.



Figure 1-4: Ion engine schematic showing gridded ion engine operating principles (NASA GRC schematic used with permission).

Ion thrusters are characterized as possessing high specific impulse and high thrust efficiency as was illustrated in Table 1-1. Ion thrusters are inherently low thrust devices (hundreds of mN), resulting in extended operation (months to years) to build up the required Δv 's for interplanetary missions. The ion thruster flown on DS1 has a design operational life of approximately one year, though it demonstrated almost two years of in-space operation before the xenon propellant was exhausted and over three years of continuous operation in the Extended Life Test (ELT) before it was voluntarily terminated. Future missions may require ion engine lifetimes of several years.

1.3.2 History and Development of Ion Thrusters

The idea of electrical propulsion has been around for over 100 years, yet actual electric propulsion experiments did not begin until the late 1950s. Dr. Harold Kaufman built the first ion engine in 1959.^{49,50} From the early years of electric propulsion experimentation, ion propulsion systems have been considered because of their combination of high specific impulse and high efficiencies. This combination makes them ideal for missions requiring high Δv . The early years of ion engine technology utilized mercury and cesium propellants, wire-mesh or flat multi-aperture optics grids, axial magnetic fields, filament cathodes, and discharge cathode baffles.⁴⁹ The first successful space test of an ion thruster, the Space Electric Rocket Test I (SERT I), occurred on July 20, 1964.^{9,51} Early ion thrusters, including SERT I and SERT II, were intended for use on Earth-orbiting spacecraft and for station keeping. A gradual progression from those infant days saw the advent of new ion thruster ideas and technologies such as: transitioning to the less contaminating inert gas propellant; hollow cathodes extending engine lifetime; dished, multi-aperture grids; incorporation of lowsputtering yield materials; ring-cusp magnetic fields; and semi-conical discharge chambers. The evolution of these changes and milestones marking their introduction and demonstration is beyond the scope of this work. For a more comprehensive discussion on the history of electrostatic ion engine operation see References 51 and 52.

It is pertinent to discuss the evolution of ion engines developed in the United States as the two engines in this investigation stem from this development. The

discussion is limited to ion engines with the following characteristics: xenon propellant; ring-cusp magnetic field; hollow cathode electron sources; and electron-bombardment ionization. It should be noted that over the last three decades, ion propulsion research and development programs have also been conducted in Japan and Europe.⁵³⁻⁵⁵

The operational flight era of ion propulsion began in the late 1980's. The Xenon Ion Propulsion System (XIPS) Program, from 1985 – 1988, employed solely xenon propellant and serves as a logical starting point for this investigation. The transition from mercury propellant to xenon was implemented to reduce contamination of spacecraft and ground testing surfaces. The XIPS-25 program developed a 25-cm diameter ion engine with: three-dished-grid optics; ring-cusp magnetic field; and keepered hollow cathodes as well as the bread board power processing units (BBPPUs) and a xenon pressure regulator for NSSK of 2500-kg class geosynchronous communication satellites.⁵⁶ Initially, the 1.3 kW, 2800s thruster successfully completed 4350 hours of testing, which is equivalent to 10 years of NSSK. After the first few hundred hours of this early wear-mechanism test, the primary thruster-life-limiting wear mechanisms identified were cathode orifice erosion and decelerator, third-grid aperture enlargement. Minor configuration changes were made eliminating those wear mechanisms throughout the duration of testing. The only remaining long-term performance degradation resulted from erosion of the acceleration grid.

The operation of the XIPS-25 was rescoped for combined orbit insertion and NSSK with a maximum input power of 4.2 kW and an I_{sp} of 3800 seconds. Hughes Space

and Communications Company developed the XIPS-13 thruster specifically for NSSK. The XIPS-13 has a maximum input power of 0.44 kW and a specific impulse of 2560 seconds.⁵⁷

While the early operational ion thruster flights focused on auxiliary propulsion for Earth-orbiting communication satellites, the first deep-space mission to use ion thrusters for primary propulsion was the Deep Space One (DS1) mission, which was funded by NASA's New Millennium Program. Propelled by the <u>NASA Solar Electric Propulsion</u> <u>Technology Application Readiness (NSTAR) ion propulsion system, the DS1 spacecraft successfully performed a flyby of the asteroid Braille and the comet Borrelly.⁵⁸⁻⁶¹</u>

1.3.2.1 30-cm NSTAR Development

The 30-cm <u>NASA Solar Electric Propulsion Technology Application R</u>eadiness (NSTAR) ion engine can be traced back to the 30-cm mercury ion thruster developed for the Solar Electric Propulsion System (SEPS) program, which was intended for deep space and geosynchronous missions. To meet the mission analysis performance goals of 2.75 kW input power, 135 mN thrust, and 3000 sec I_{sp}, the 30-cm 700/800 series engines incorporated significant improvements to existing mercury ion thruster designs, most notably the introduction of hollow cathodes and dished, high-perveance grids.⁶² Perveance relates the effectiveness of a given gridlet geometry at maintaining a focused beamlet. By altering the electrostatic field between the ion optic grids, the beamlet can either be overfocused or defocused resulting in direct ion impingement on the accelerator

grid. Typically, the perveance limit is determined by the amount that the beam can be defocused before direct ion impingement on the accelerator grid occurs. The overfocusing of a beamlet requires high-voltage application which can have deleterious effects on the thruster and therefore is typically not measured. The perveance limit, for a given thruster operating condition, is found by decreasing the beam voltage (keeping the accelerator voltage constant to prevent electron backstreaming damage) while monitoring the accelerator current. The perveance limit is defined as the reduced screen grid voltage where a 10 volt reduction in the screen grid voltage results in a 0.2 mA increase in accelerator grid impingement current.^{43,63} High-perveance indicates an ion optics configuration that has a large margin in the operating voltages before direct impingement occurs.

The J-series 30-cm diameter, divergent-field ion thruster was developed to a state of technology readiness for operation up to 3 kW with mercury. The decision to investigate inert gases on the J-series was predicated by the need to reduce contamination issues for spacecraft and ground testing facilities as well as quenching ecological concerns. The use of an inert gas also reduced the complexity of the propellant feed system by eliminating mercury vaporizers and, with the absence of propellant condensation, resulted in more reliable, simpler, and cooler propellant isolators. Performance of the J-series discharge chamber operating with xenon was nearly identical to its performance with mercury, as the performance degradation due to the lighter atomic mass was offset by the larger values of electron impact ionization cross sections.⁶⁴ To obtain equivalent values of thrust, input power values increased by roughly the inverse of

the ratio of the propellant atomic masses: mercury (200.59 amu) and xenon (131.29 amu). The small payload fraction penalty incurred with xenon was offset by its benefits enabling xenon to be the primary propellant for ion thruster technology. With the advent of large solar power systems, nuclear reactor systems, and advanced photovoltaic solar arrays, the space power restrictions (near 5 kW) were lifted. Testing with xenon at increased power levels demonstrated more than four times the thrust of the mercury thruster (0.52 N instead of 0.13 N) at increased power levels up to a factor of six (20 kW instead of 3 kW).⁶⁵

Orbit transfer mission analyses and thruster life assessments from the initial highpower xenon testing identified the 10 kW xenon ion thruster as optimum for a number of space missions and in terms of increased reliability and decreased system complexity.^{65,66} While krypton and argon propellants were also investigated, the increased discharge voltages needed for these propellants would decrease discharge component lifetimes. Furthermore, their higher payload fraction penalties made these lighter propellants less attractive than xenon.⁶⁷

At an input level of 10 kW, erosion of the discharge baffle downstream of the discharge cathode was so severe, that research on 30-cm divergent field thrusters was terminated. Simply eliminating the discharge baffle in divergent field ion thrusters resulted in significant degradation in performance.^{68,69} The early axial, divergent, and line-cusp magnetic field discharge designs were replaced by multipole ring-cusp magnetic fields using permanent samarium-cobalt magnets of alternating polarity. The

result was a significant increase in discharge chamber performance in the 10-kW 30-cm xenon thruster and the elimination of the discharge baffle.⁷⁰⁻⁷² Significant improvements in discharge chamber performance were realized by the ring-cusp topology, which features a diverging field in the cathode region and a nearly field-free volume upstream of the ion extraction system. The ring-cusp design reduced ion-wall losses between cusps by a factor of two, resulting in improved ion-beam production costs (90 to 120 W/A at 90% propellant efficiency).^{70,73} Thrusters incorporating ring-cusp magnetic field designs became the baseline geometry.

Gridded, high-power ring-cusp ion thrusters are limited by the maximum beam current density and the maximum thruster component temperatures (particularly the permanent magnets). Large area thrusters (\geq 50-cm diameter) were investigated to supply high values of thrust at relevant specific impulse values with increased thermal margins. Decreased erosion of the ion optics in the 50-cm diameter testing, at comparable 30-cm diameter power levels, resulted from reduced average current densities by nearly a factor of three.^{66,74}

The performance of the large diameter thrusters operating at "derated" conditions maintained modest discharge chamber component temperatures and offered prospects for improved lifetime. The "derated" philosophy was applied to the 30-cm ion engine development for NSSK applications. The performance testing of the 30-cm xenon thruster, over a throttling range of 0.6 to 2.0 kW, illustrated enhanced thruster life and reliability. Subsequent performance testing motivated the transition from magnetic steel,

cylindrical discharge chambers to non-ferrous, semi-conical discharge chambers to reduce weight and enhance structural stability.⁷⁵ These preliminary performance tests also attempted to address lifetime issues with lifetime calculations identifying the erosion of the molybdenum accelerator grid as the dominant wear mechanism, with screen grid and discharge cathode assembly erosion a distance second.^{76,77} Wear testing was used to characterize the erosion of critical components in 30-cm xenon ring-cusp ion thrusters.

The series of test programs previously described established a solid database for the development of an engineering model 30-cm ion thruster for both auxiliary and primary propulsion functions over an input power envelope of 0.5 to 5.0 kW with a 10,000 hour lifetime.⁶³ The engineering model thruster development also benefited from the hollow cathode component test program for the space station plasma contactor program precluding extensive life and performance testing of hollow cathodes.⁷⁸⁻⁸¹

The 30-cm xenon ion engine was identified as a primary candidate for orbit transfer and planetary missions. It was the focus of the NSTAR program to validate ion propulsion for space flight applications. The 30-cm NSTAR ion engine evolved from existing xenon 30-cm programs to an industrial production capable 30-cm ion thruster to demonstrate the technical maturity of xenon ion thrusters. The NSTAR development spanned several years bringing the 30-cm thruster from a functional model thruster, to an engineering model thruster, and eventually to a flight model thruster. Detailed mission analyses, conducted at the Jet Propulsion Laboratory, identified a required NSTAR thrust power throttling range of 0.5 to 2.3 kW for planetary missions of interest.⁸² The

development of the power processing unit (PPU), xenon feed and propellant isolators, and digital control and interface unit (DCIU) as well as the evolution of the functional model thruster (FMT), engineering model thruster (EMT), and flight qualified thrusters can be found in References 82-86.

During development of the EMT's, several design changes were made as a consequence of performance and wear testing, which will be discussed later. A summary of the major changes include: the addition of a discharge cathode keeper to mitigate cathode orifice plate erosion; referencing the screen grid to cathode common; and the treatment of discharge chamber surfaces to retain sputtered material and control the size of spalled flakes.⁸⁴

In the NSTAR development, four engineering model thrusters (EMT), and two flight thrusters were built. The final NSTAR flight engine design, shown (along with an EMT) in Figure 1-5, processes a maximum thruster input power of 2.3 kW, provides 92 mN of thrust, a maximum specific impulse of 3300 sec, and thruster efficiency of 0.62.⁸⁵ The 30-cm beam diameter thruster is throttleable over a range of 0.5 to 2.3 kW, consistent with the calculated power available from the NSTAR solar array as the solar intensity diminishes with increasing distance from the sun through the duration of the mission. The size of the NSTAR ion thruster is approximately 41 cm in diameter (including plasma screen), 33 cm long, with a mass of 8.2 kg.⁸⁶



Figure 1-5: NSTAR ion engine, engineering model (EM) on left, and flight thruster on the DS1 spacecraft on the right (photos reproduced with NASA GRC and JPL permission).

1.3.2.2 NSTAR on Deep Space One

Deep Space 1 (DS1) was the first mission of NASA's New Millennium program, whose purpose was to test high-risk, advanced technologies. The 30-cm NSTAR ion thruster was just one of 12 technologies evaluated. In summary, the NSTAR engine design follows the derated operation philosophy to extend lifetime and utilizes a non-magnetic anode, a ring-cusp magnetic field, a keeper electrode on both discharge and neutralizer cathodes, and low sputter-yield materials such as molybdenum for the ion optics and keeper faceplate. Two flight thrusters were fabricated and tested to Protoflight Qualification levels. After similar performance and vibration testing, one thruster was installed on the DS1 spacecraft while the other was set aside as the flight spare.⁸⁵ The overall NSTAR subsystem dry mass, including thruster, PPU, DCIU, cables, and the xenon storage/feed system is 48 kg. The ion engine design life is 8,000 hours at the full-power operating point, which is equivalent to a total propellant throughput capability of 83 kg (NSTAR thruster design throughput).⁴²

The flight engine, shown in Figure 1-6, was launched onboard the DS1 spacecraft on October 28, 1998 and has since fulfilled all of its performance objectives. The DS1 spacecraft demonstrates the first use of an ion engine as the primary propulsion system. The spacecraft propulsion system consists of a single xenon, NSTAR ion engine designed to deliver a total Δv of 4.5 km/s while using only 81 kg of xenon (NSTAR propulsion system design throughput).⁵⁸ The NSTAR 30-cm engine successfully provided the Δv required for the July 29, 1999 flyby of the asteroid Braille after 1800 hours of operation (11.8 kg of xenon processed).⁵⁹ Following the successful completion of the primary mission, DS1 spacecraft flawlessly completed a high-risk encounter with comet Borrelly as an extended mission (closest approach on September 22, 2001).^{60,61} With the faultless conclusion of the extended mission, DS1 undertook a hyperextended mission to collect data on the effects of long-term operation in space, with a focus on the ion propulsion system and its effects on various spacecraft hardware. Following the completion of the hyperextended mission, the DS1 mission was voluntarily terminated on December 18, 2001. The DS1 NSTAR ion thruster accumulated 16,265 hours of operation in space and processed 73.4 kg of xenon propellant (actual NSTAR mission throughput).^{42,58}


Figure 1-6: Photographs of the NSTAR Flight Thruster installed on the DS1 Spacecraft (reproduced with JPL permission).

The NSTAR engine operation on DS1 was operated successfully without detectable contamination of spacecraft surfaces or impacts on communication and scientific instruments.^{58,87} The DS1 mission success has stimulated future interest in ion thruster missions. Future planned NASA science missions, utilizing solar electric propulsion, require more demanding lifetimes and higher throughput.

NASA's Dawn mission, the first full-up NASA science mission to use ion propulsion, will be propelled by three 30-cm NSTAR ion thrusters and is expected to launch in the summer of 2006. Dawn will rendezvous with two minor planets, Ceres and Vesta, which reside in the asteroid belt between Mars and Jupiter. Dawn will build upon the established performance of the NSTAR DS1 thruster that has been subjected to 16,265 hours of in-space testing on DS1 and 30,352 hours of operation in the Extended Life Test (ELT) at the Jet Propulsion Laboratory (JPL).⁸⁸ Each of the three NSTAR ion thrusters are required to process 150 kg of xenon and operate for up to 24,000 hours.⁸⁹

The ion propulsion system must process 450 kg of xenon over a 10-year period for a total Δv of 11 km/s.⁹⁰

1.3.2.3 40-cm NEXT

The successful demonstration of the NSTAR ion engine provides an off-the-shelf 2.5 kW ion engine suitable for discovery-class NASA missions. Many missions have been identified as being either enabled or strongly enhanced by the use of solar electric propulsion. Several missions under consideration for the exploration of the solar system have identified higher-power, higher-throughput 5-10 kW ion propulsion systems as a requirement for feasible missions. These missions based on NSTAR (or NSTAR derivative) ion engine technology include: Comet Nucleus Sample Return; Mars Sample Return; Mercury Orbiter; Neptune Orbiter; Titan Explorer; Saturn Ring Observer; Europa Lander; and Venus Sample Return missions.^{58,91} Studies for comet and Mars sample return missions as well as outer planet orbiters such as a Titan Explorer or a Neptune Orbiter have shown the need for higher-power, higher total impulse capability thrusters than NSTAR to minimize the propulsion system size, mass, and complexity.^{52,92} Based on thermal, current density, and electric field strength limitations; significant increases in 30-cm thruster input power beyond 3.5 kW appear impractical without high risk to thruster lifetime.⁹³

For these larger flagship-type missions, specifically robotic exploration of the outer planets using 25 kW-class solar-powered electric propulsion, NASA GRC has led a

team to develop the next generation ion thruster. The 40-cm xenon ion engine, termed <u>NASA's Evolutionary Xenon Ion Thruster (NEXT)</u> was selected in 2002 for technology development as part of the Next Generation Electric Propulsion Project (NGEP). The project includes the development of a lightweight, modular PPU and a proportional-valve xenon feed system. However, only thruster development will be discussed here. The reader interested in NEXT subsystem development should refer to References 94-96. Originally designed as a 1-10 kW thruster, the NEXT power range was re-scoped to 1-6 kW in response to design requirements provided by the project.⁹⁷ See Figure 1-7 for a picture of the 40-cm NEXT Engineering Model One (EM1) ion thruster.



Figure 1-7: NEXT Engineering Model One (EM1) ion engine (reproduced with NASA GRC permission).

The NEXT ion engine follows the "derated" approach of the NSTAR program to preserve the NSTAR design heritage. This design approach maintains low beam current densities, low component operating temperatures (most importantly the permanent magnets), and reduces operating voltages to inhibit wear mechanisms. To maintain low beam current densities while increasing throughput, an engine twice the beam area of the NSTAR thruster was designed. Increasing the engine beam diameter from 28 cm (NSTAR) to 40-cm doubles the beam extraction area. The higher beam area provides higher-power capability while maintaining comparable current densities, temperatures, and operating voltages. An input power of 4.7 kW on the NEXT engine operates at the same voltages and beam current density as 2.3 kW on the NSTAR engine. The NEXT engine can therefore be expected to yield the same operating life time while producing twice the thrust. A greater than two times increase in throughput capability for the NEXT engine is anticipated, based on the increased beam area and improved beam flatness, which preserve grid life. The throughput capability requirement of the NEXT engine is 405 kg of xenon and is attainable with the use of a thick accelerator grid (TAG) ion optics.⁹⁸⁻¹⁰² The NEXT ion optics are shown in Figure 1-8 with one of the NSTAR grids.



Figure 1-8: Photograph of the NSTAR 30-cm ion optics size compared to the NEXT 40-cm diameter ion optics (used with permission from NASA GRC).

The major components of the NEXT engine are designed based upon NSTAR heritage, and include: a non-ferrous spun-form discharge chamber; comparable discharge and neutralizer hollow cathode designs; similar electrical isolation techniques; analogous flake retention mesh; and a dished, two-grid optics system. Improvements beyond NSTAR include: improved beam flatness via magnetic field design; a compact propellant isolator; increased beam voltage (up to 1800 V vs. 1100 V for NSTAR); and advanced ion optics design. The discharge and neutralizer cathodes feature increased dimensions to accommodate the elevated current as well as some other minor modifications. Performance testing of two engineering model thrusters and a laboratory model thruster exhibit peak specific impulse and thrust efficiency ranges of 4060 – 4090 seconds and 0.68 - 0.69, respectively, at the 6.1 kW power point.⁴³ A 2000 hour wear test has been conducted on EMT1 at a thruster input power of 6.9 kW demonstrating specific impulse, thrust efficiency, and calculated thrust of 4110 s, 0.694, and 237 mN respectively.¹⁰³

The NEXT program includes development activities such as PPU, DCIU, PMS, and gimbal development in addition to the electric propulsion thruster.^{52,93,94,104-106} The NEXT program is currently in the process of qualifying each of these components as well as conduction component integration testing.⁹⁵ The program is currently in Phase 2, development of flight-like engineering model components with life analysis and testing.¹⁰⁶ At the time of this publication, the construction of a prototype model thruster, detailed in Reference 107, is ongoing.

The qualification process of an ion engine from the development laboratory model thruster to a flight-qualified thruster involves many steps. This process for NSTAR utilized a series of ground-based wear tests to access thruster capabilities and lifetime. The NEXT engine has successfully completed a 2000-hour wear test and is in an ongoing long duration test.^{103,108,109} The NEXT EM3 thruster is currently in a long duration test (LDT) and has accumulated ~2000 hours at an input power of 6.9 kW (full-power point) at the time of this publication.^{108,110} The NEXT wear tests are discussed in §1.3.3.2.

1.3.3 Wear Testing and DCA Erosion

Ion thrusters are designed for an operating lifetime of several years in order to make up for their low thrust levels. For a significant Δv , the decreased thrust can be offset by the higher exhaust velocity of the ion engine. As a result, a key component of the NSTAR program is ground-testing of engineering model thrusters (EMT's) for extended periods of time. The NEXT program follows a similar qualification process of extended wear testing of engineering model thrusters.

1.3.3.1 NSTAR Wear Testing

The first wear test of a xenon, ring-cusp ion engine was the 4350 hour wearmechanism test of the XIPS-25 (25-cm diameter) ion thruster by Hughes Research Laboratories. During the first few hundred hours of the test, the erosion of the discharge cathode orifice (with a keeper electrode) and decelerator grid (3 grid optics set) elongation were considered thruster life-limitting.⁵⁶ It should be noted that the cathode design, discharge chamber design, and operating parameters vary significantly from NSTAR as this test predates the advances made in the NSTAR development. Minor changes were made to the XIPS-25 thruster to address the observed early erosion, and completion of the test occurred without significant erosion of these components. The only long-term performance degradation identified was the life limiting wear mechanism of the accelerator grid.

Still prior to the NSTAR development, a 5 kW xenon thruster lifetest was performed at the NASA GRC for a ring-cusp magnetic field. Though the discharge cathode was unkeepered, this test marks the first wear test of a cusp-magnetic field 30-cm xenon thruster. The 900 hour wear test diagnosed component wear issues and experienced thruster efficiency decay of roughly 5.6%. The discharge and neutralizer orifices decreased, due to sputtered deposits attached to them, without noticeable performance decay. The discharge insert, orifice plate, and upstream heater coils exhibited wear from ion bombardment. The starting electrode, slightly downstream of discharge cathode, experienced excessive erosion and was later found unnecessary for cathode ignition. Again the accelerator grid erosion, due to charge exchange, was identified as the primary life limiter. Erosion of the screen grid was not detectable. The complete results of the test are outlined in Reference 111. Design modifications were made and transferred to the NSTAR engine, which include the removal of the starting electrode for the discharge cathode.

To support the ground-testing effort of the NSTAR program, four engineering model thrusters (EMT's) were developed based on the design of the functional model thruster (FMT). Two flight thrusters (FT's) were fabricated at Hughes Electron Dynamics Division; FT1 was installed and flew on the DS1 spacecraft.

Concurrent with ion thruster development was the initiation of a hollow cathode test program supporting the International Space Station plasma contactor requirements (Figure 1-9).¹¹² This dual-use technology development benefited both programs and demonstrated xenon hollow cathode lifetimes up to 27,800 hours of operation and the ability to undergo more than 32,000 cycles before ignition failure.^{113,114} The main benefit of the plasma contactor hollow cathode development to the NSTAR program was the investigations for improving the hollow cathode design (*i.e.*, the dimensions and materials) as well as providing established protocols to address contamination issues. The primary cause of early hollow cathode testing performance degradation was oxygen contamination of the electron emitter surfaces.^{78,79} Control protocols and improved gas feed system fidelity resulted in improved hollow cathode performance and reduced degradation of the emitter surfaces. The wear testing of hollow cathodes for plasma contactor development indicated both cathode orifice diameter increase (erosion) and decrease (deposition), texturing of the downstream orifice plate, erosion of the radiation shielding, and texturing of the cathode exterior and heater surfaces.^{80,113} The applicability

of these results to the observed erosion of the discharge cathode in ion thrusters depends mostly upon the experimental apparatus used; *i.e.*, does the test configuration replicate the environment that the discharge cathode operates in?



Figure 1-9: Schematic of the space station plasma contactor advancing hollow cathode design and operational understanding (NASA GRC schematic used with permission).

The first wear test of an engineering model 30-cm NSTAR thruster was the fullpower (2.3 kW) 2000-hour wear test conducted as NASA GRC (formerly NASA Lewis) using EMT1. The discharge cathode did not employ a keeper and the screen grid was electrically isolated, in the expectation that it would float positive of cathode potential. The test setup and results are detailed in Reference 115. After 867 hours of operation, a propellant isolator failure, due to a power console logic failure, forced the vacuum chamber to be vented. During repair, erosion of the downstream face of the discharge cathode heater coil surrounding the cathode orifice plate was evident. The cathode was replaced with an identical unit and testing continued. Following completion of the test, severe erosion of the downstream surface of the second discharge cathode orifice plate and heater was documented. While the orifice and chamfer on both discharge cathode assemblies appeared to be undamaged, the outer radius of the orifice plates, in the region of the plate electron beam weld, and downstream face of the cathode heater coil experienced severe erosion. It should be noted that an unexpectedly high ratio of doublyto-singly charged ion current (0.30 compared to the nominal 0.13 at centerline) was measured at the end of the wear test possibly due to an error in the main plenum flow controller. The upstream surface of the screen grid also experienced unexpectedly high erosion resulting in a decrease in thickness. Post test performance testing found that when electrically isolated, the screen grid actually floats several volts below cathode potential, thus increasing the energy of impinging ions and resulting in the increased erosion observed. Interestingly, accelerator grid erosion did not appear to be a factor in the lifetime assessment. Finally, minor erosion of the neutralizer keeper tube, likely due to its placement in the beam, as well as spalling of deposited films on discharge surfaces near the screen grid were detected.

The following design changes were made as a result of the 2000-hr wear test: 1) the electron-beam weld of the discharge cathode was moved from the orifice plate to the side of the cathode tube; 2) the discharge heater was moved 1.7 mm upstream of the plane of the cathode tip; 3) the screen grid was electrically connected to discharge cathode common; and 4) a sputter containment system was implemented.

A subsequent 1000-hr. wear test was conducted at JPL using the modified EM1 thruster that incorporated the design changes from the 2000-hr wear test as well as a cylindrical keeper electrode (at an intermediate potential between the cathode and anode potentials) around the cathode to reduce the discharge cathode erosion. The sacrificial keeper was tied to the anode with a 1 k Ω resistor to facilitate ignition without drawing significant keeper current during normal operation. The 1000-hr. wear test was conducted at the full power (2.3 kW) condition, with the expectation that this would be the highest wear condition.

The detailed test results on thruster hardware, testing facility, operating parameters, and thruster performance throughout the test can be found in Reference 116. Post-test inspection of the DCA revealed minimal change in the keeper orifice plate thickness and only superficial texturing of the cathode orifice plate. The addition of the keeper, minor design changes to the DCA, and higher flow rates were believed responsible for the elimination of the DCA erosion; although, these combined effects (and possibly other factors) could not be separated to specifically identify why the DCA erosion was so dramatically reduced. The additional design changes to the EMT, following the 2000-hr. test, appeared to improve thruster life by greatly reducing the screen grid erosion from 46 μ m/khr to 6 μ m/khr, which represent the maximum eroded depth per unit time. The measured double-to-single ion current ratio measured downstream on centerline of the thruster was reduced from 0.30 to approximately 0.15. Flake formation was significantly decreased and the new position of the neutralizer demonstrated slight sputter-cleaning and depositions of downstream surfaces. While the

accelerator grid failure by charge exchange ion erosion was not identified as a lifelimiting problem, it may be so for more demanding missions.

While the DCA erosion and other thruster failure modes observed in the 2000hour wear test were essentially eliminated in the 1000-hr. wear test, there was no understanding of why the DCA erosion occurred and how the design changes affected this erosion process. The addition of the cathode keeper appears to be an "engineering solution" to mitigate discharge cathode erosion. The keeper acts to shield the cathode, but in the process exposes itself to the bombarding ions. The keeper does erode at a lower rate than the discharge cathode would alone, due to floating at a potential closer towards the plasma potential reducing the ion acceleration through the sheath. However, there is no guarantee that this solution will work over the full 0.5 to 2.3 kW operating range of this thruster or for higher-power levels beyond this range. The erosion pattern observed following the 1000-hr. wear test is illustrated in Figure 1-10.^{116,117}



Figure 1-10: Downstream erosion of the discharge cathode keeper for the 1,000 hour wear test across several different angles relative to an arbitrary zero degree diameter. A schematic of a DCA indicating the location of the erosion pattern is included for reference.

Prior to the DS1 flight, an 8200 hour Long Duration Test (LDT) was conducted at the full power point (2.3 kW) on EMT2. During the LDT, a total of 88 kg of xenon was processed over the course of 8192 hours until the test was voluntarily terminated. Having processed more propellant than the planned DS1 engine, the performance of the thruster towards the end of the LDT provided mission designers with more accurate end of life (EOL) performance values than those extrapolated from previous shorter duration tests. Negligible performance changes were observed at the full power point. A 4% decrease in efficiency at the low-power condition was observed resulting from an increased neutralizer flow to maintain efficient spot mode operation. The full details of the LDT can be found in References 91 and 118.

No discharge cathode performance degradation was evident from the LDT. The only significant DCA erosion occurred on the downstream surface of the molybdenum keeper orifice plate. The keeper electrode acted in effect to shadow-shield the cathode as the erosion of the cathode orifice plate was minimal. The keeper electrode did erode at a rate less than the cathode in the 2000-hr. wear test, likely due to the keeper potential being a few volts above cathode potential. Ions falling through the keeper sheath would be accelerated by less of a potential field due to this higher floating potential. The data from the test on DCA erosion is consistent with a source of high-energy ions located just downstream of the keeper orifice. A new failure mode of the DCA was diagnosed. Thick films on the upstream surface of the keeper could short the keeper to the cathode increasing wear and/or adding difficulty to cathode ignition. It was recommended that subsequent designs include a chamfered keeper and grit-blasted interior keeper surfaces to retain films.

The dominant LDT wear processes causing performance degradation were those on the optics. Erosion of the accelerator grid aperture walls and deposition of this material on the screen grid increases the neutral loss rates and reduces ion transparency. Erosion of the neutralizer and spalling of material inside the discharge chamber was minimal.

Just prior to launch of the DS1 spacecraft, the DS1 flight spare, flight thruster two (FT2), began an extended lift test (ELT) at the Jet Propulsion Laboratory. The initial objectives of the ELT were to: demonstrate 150% (125 kg xenon processed) of the DS1 mission throughput capability; identify unknown failure modes; characterize known failure modes; determine how engine performance changes with operating time; and help troubleshoot any problems with the DS1 mission. On December of 2000, the ELT successfully accomplished 125 kg of xenon with no signs of performance degradation. The test was continued to demonstrate throughput capability in excess of 200 kg. The ELT was voluntarily terminated on June 26, 2003 after processing 235 kg of xenon and accumulating a total of 30,352 hours of operation. Information on the thruster, experimental setup, and more detailed discussion can be found in References 59, 88, and 119-122.

Significant observations from the ELT include: **severe discharge cathode keeper erosion**; accelerator grid aperture and web erosion; deposition of material in the neutralizer orifice; and degradation in electrical isolation between several thruster components. Accelerator grid erosion was enough to prevent operation at the full power point towards the end of the ELT. Although accelerator grid erosion, resulting in the inability to prevent electron backstreaming, was the first failure mode exhibited by FT2, anomalous erosion of the DCA was observed in the ELT such that the front face of the keeper was completely eroded away exposing the discharge cathode and heater wire. In addition to the removal of the keeper plate; the cathode orifice plate, cathode heater, radiation shield, and cathode keeper tube all experienced measurable sputter erosion. Although the engine continued to operate throughout the ELT, there exists a clear need to understand the cause of DCA erosion, characterize the parameters that affect DCA erosion, and develop methods to reduce DCA erosion, thereby extending engine lifetime.

The erosion of the DCA observed in the ELT is broken into different segments, listed in Table 1-2. The operating conditions are referred to as throttling (TH) levels, in which higher TH levels correspond to higher input power. The NSTAR thruster operating voltages and currents that correspond to the different TH levels are listed in Table 2-1.^{120,123,124} The ELT was the first wear test to operate at various throttling points. Previous wear tests were conducted at the full power setting, which was thought to be the highest wear condition. The only DCA erosion data taken are visual photographs of the discharge keeper and discharge cathode faces. The throttled operation, lack of detailed

profilometry data, and the complete erosion of the keeper face (preventing post-test erosion rate analysis) make the estimation of the erosion rate during the ELT difficult.

ELT Throttling Point	Start Time [hrs.]	Stop Time [hrs.]
TH12	0	448
TH15	448	4937
TH8	4937	10451
TH15	10451	15617
THO	15617	21306
TH15	21306	25700
TH5	25700	30352

Table 1-2: Thruster operating points during the Extended Life Test (ELT).

The first segment of the ELT encompasses the first 4,693 hours of operation. The thruster was operated for the first 448 hours at TH12 (1.94 kW) and afterwards was exclusively operated at TH15 level (2.29 kW) for this testing segment. Minimal erosion was observed as evident in Figure 1-11.^{88,117,120} Texturing of the downstream surface of the keeper and a small chamfer on the keeper orifice is evident with negligible change in the cathode orifice. The estimated erosion rate is ~64-77 μ m/khr and is consistent with 1,000 hr. and 8200 hr wear tests.



Figure 1-11: Discharge cathode keeper faceplate during the Extended Life Testing (ELT) (used with permission by JPL). The photographs are prior to the ELT (left), after 447 hours (middle), and after 4,693 hours (right).

The second segment of the ELT operation illustrates the onset of increased erosion. After 4,937 hours of operation, the engine was throttled to TH8 (1.44 kW). After 5,850 hours of operation, a short between the discharge keeper and discharge common began (possibly caused by spalled material), reducing the keeper voltage from 3.5 volts to ~ 0.4 volts. The photographs that bracket the keeper short (taken at 4,693 hours at 6,408 hours) indicate that the erosion rate had accelerated and a noticeable chamfer in the keeper orifice diameter is evident. The shorted keeper condition persisted until 7,604 hours of operation (apparently when the keeper orifice eroded sufficiently), afterwards intermittent shorting continued. After 8,873 hours, the intermittent short from keeper to common was cleared. However, the discharge keeper orifice diameter continued to increase at an accelerated rate than previous wear tests. The accelerated cathode keeper erosion is observed in Figure 1-12.^{88,117,120} By 10,000 hours, the keeper plate eroded significantly, partially exposing the cathode orifice plate. After 10,451 hours, the thruster was throttled up to TH15. The accelerated erosion rate appeared to be approximately constant through 12,342 hours.



Figure 1-12: Discharge cathode keeper faceplate during the Extended Life Testing (ELT) (used with permission by JPL). The photographs are after 6,408 hours (left), after 10,451 hours (middle), and after 12,342 hours (right).

The final segment concludes the ELT testing. The enlargement of the keeper orifice diameter continued during the second TH15 throttling segment at the accelerated rate. By 15,000 hours the keeper orifice plate had eroded to fully expose the cathode orifice plate and heater. The thruster was throttled down to TH0 (0.47 kW) between 15,617 and 21,306 hours. At TH0 the keeper erosion rate was significantly reduced. After 21,306 hours of operation, the FT2 was throttled back up to TH15 when the accelerated erosion rate returned. After roughly 25,000 hours of operation, the keeper plate was completely eroded. Subsequent thruster operation at TH5 (1.09 kW), from approximately 25,700 hours until test completion, did not reveal extensive erosion as the keeper plate had been completely eroded already. The photographs from the final test segment are illustrated in Figure 1-13.^{88,117,120}



Figure 1-13: Discharge cathode keeper faceplate during the Extended Life Testing (ELT) (used with permission by JPL). The photographs are after 21,306 hours (left), after 28,726 hours (middle), and post-test after 30,352 hours (right).

From the photographs of the DCA, the keeper orifice diameter as a function of time can be calculated. The calculation, performed at JPL, illustrated in Figure 1-14, ^{88,120,123,124} is the best measure of the keeper erosion rate. Domonkos, *et al.* used assumed erosion geometries to estimate the volume of material eroded based upon the ELT photographic data.¹¹⁷ The volumetric erosion rate, calculated by a chamfered (45°) and inner diameter enlargement assumption, are then converted to an equivalent erosion depth. The erosion rate from previous wear testing is calculated from the maximum eroded depth at any location across the keeper face (typically near mid-radius). The depth is calculated after completion of the test giving the erosion rate as a depth eroded (µm) per unit time (khr).



Figure 1-14: ELT keeper orifice diameter as a function of thruster run time (JPL figure used with permission).

It is important to note that keeper erosion of this severity was not observed during the first full power segment or during the previous 8200-hr. LDT, which was operated exclusively at TH15 (2.3 kW). The understanding of the circumstances that led to the DCA erosion in the ELT is ongoing and has taken several different approaches. The onset of the severe erosion concurrent with operation at the TH8 throttling point and shorting event make both events suspect. The effects of these operating changes will be discussed throughout this thesis. The erosion rates of the DCA downstream surface for the various wear tests are given in Table 1-3. The erosion rates for the ELT testing are broken into pre-short and post-short regimes since this coincided with the increased erosion rate. The estimated values are calculated from the volumetric erosion rates calculated by Domonkos, *et al.*¹¹⁷ An equilateral triangle cross-section of removed keeper material

(across the entire keeper face centered at mid-radius) is assumed to give an equivalent indication of the eroded depth that can be easily compared to the previous wear test erosion rates. The observed erosion occurred from the orifice enlargement thus this estimated erosion rate is meant only for erosion rate comparisons with the previous wear tests. It is of interest that the pre-short equivalent erosion depth is similar to the 8200 hour wear test and the 1000 hour wear test.

Wear Test	DCA Configuration	Throttle Condition	Erosion rate [microns/khr]
2000 hr	cathode only	~TH15	145
1000 hr	keepered	~TH15	70
8200 hr LDT	keepered	~TH15	63 maximum
0 - 5,850 hrs of			
30,352 hr ELT	keepered	predominantly TH15	77 estimated
5,850 -12,342 hrs			
of 30,352 hr ELT	keepered	~TH8 and TH15	173 estimated

Table 1-3: Summary of DCA downstream surface erosion rates.

1.3.3.2 NEXT Wear Testing

The first wear test of a NEXT ion engine was performed at an input power level of 6.9 kW (NEXT full-power operating point) on EM1 to characterize thruster operation and performance, to identify thruster life-limiting phenomena, and to measure critical thruster component wear rates. The discharge cathode keeper plate on EM1 was molybdenum. The full results and description of this test can be found in References 103, 109, and 125. The 40-cm ion engine accumulated 2038 hours of operation exhibiting steady overall performance throughout the wear. Both the cathode and keeper orifice diameters decreased due to deposition of sputtered material. Post-test inspection found the discharge keeper orifice plate and part of the orifice channel were sputter-eroded, similar to the NSTAR 8200 hour wear test engine. The deepest erosion occurred at a radius of about 40% of the total keeper radius.¹⁰³ Assuming a linear eroded depth with time, the wear-through of the keeper orifice plate would be expected to occur after processing 281 kg of xenon (prior to the 405 kg propellant throughput requirement). The peak erosion location indicates an erosion rate of 114 µm/khr, which is considerably higher than the NSTAR 1000-hr wear test and 8200-hr LDT.^{103,109} Images of the discharge cathode assembly pre- and post-test are illustrated in Figure 1-15.¹⁰⁹ Laser profilometer mapping of the molybdenum discharge cathode keeper plate (downstream surface) after completion of the test is shown in Figure 1-16.¹⁰⁹ Both the images and profilometer data indicate an erosion pattern that is asymmetric, possibly due to magnetic field non-uniformities.



Figure 1-15: Discharge cathode and keeper images before and after the NEXT 2000-hr wear test (used with NASA GRC permission). Photograph s a) and b) correspond to 0 hours and 2038 hours of operation, respectively.



Figure 1-16: Percentage change in the discharge cathode keeper plate thickness that was sputter eroded away (used with NASA GRC permission). At the keeper orifice and outer diameter, the profilometer measurements are inaccurate due to surface edge effects.

While the keeper orifice wear-through is not necessarily a thruster failure mode mechanism, the use of carbon-based material (with a sputter yield that is significantly lower than molybdenum) is being investigated. At the time of this publication, a NEXT long duration test (LDT) is underway (completed ~2000-hrs of full-power operation) utilizing a graphite discharge cathode keeper whose sputter yield is significantly lower than the sputter yield of molybdenum.^{108,110} Without a detailed understanding of the erosion processes at play, there is no guarantee that different materials or a biased keeper would reduce or eliminate the sputter erosion. Clearly a comprehensive investigation of the process is needed.

1.3.4 Williams' LIF and Probe Experiments

The large fluctuations in DCA erosion from each of the wear tests illustrate a lack of understanding of the processes responsible for the formation of the high-energy ions that sputter erode the DCA. Without a firm understanding, design modifications will have to be wear tested significantly, increasing development cost and time. The investigation of the DCA failure mechanism has been ongoing at the Plasmadynamics and Electric Propulsion Laboratory (PEPL) at the University of Michigan. Williams conducted a set of Laser-induced Fluorescence (LIF) measurements at PEPL near the DCA of a NSTAR engine, shown in Figure 1-17. The objectives of the investigations conducted by Williams were to identify the physical origins of anomalous DCA erosion phenomena and to provide a correlation between the operating condition (*e.g.*, voltage and flow rates) of the thruster and the rate of erosion. These goals were accomplished by observing the density of high-energy ions and metallic neutrals in the vicinity of the keepered and unkeepered DCA using LIF and emission spectroscopy.⁴⁸



Figure 1-17: Schematic of the LIF multiplex method utilized by Williams on the FMT2 thruster.

While his work provided definitive evidence for the existence of these highenergy ions streaming back towards the DCA, it did not identify the mechanism that creates them. Ray-tracing after the 2000-hr NSTAR wear test indicated the source of the ions was located between 1 and 11 mm downstream of the orifice plate. Williams also speculated on the existence of a "potential-hill" as the primary mechanism responsible for high-energy ion formation. His LIF results indicate that a potential-hill would reside a few mm downstream of the DCA if one exists.

Several theories have been speculated on the cause of DCA erosion including: a potential-hill near the exit of the cathode; plasma oscillations yielding high-energy ions; multiply-charged xenon ions; sheath effects; and charge-exchange collisions. The "potential-hill" model considers a concentrated ion production region resulting from electron impact ionization immediately downstream of the DCA. The more mobile electrons exit the ionization region leaving behind a region of high ion density. In order to maintain quasineutrality, a potential-hill develops to retard the electron mobility, illustrated in Figure 1-18.¹²⁶ Williams, while at PEPL, measured ion velocities directed back towards the DCA as well as an increased plasma potential (above anode potential) a few centimeters downstream of the DCA. His LIF velocimetry measurements support the potential-hill model.



Figure 1-18: Potential-Hill schematics illustrating the formation of high-energy ions proposed as a cause of DCA erosion (NASA GRC schematic used with permission).

LIF measurements were made with and without a keeper electrode, illustrating that the keeper modifies the structure of the plasma downstream of the DCA producing a more collimated region of ions downstream of the DCA that influences ion paths and reduces the number of backflowing ions near the DCA surfaces. Williams' peak LIF signals for the unkeepered case agree with the observed erosion of the 2000-hr wear test. Erosion rates were determined to depend largely on discharge voltage, but also a linear rise is evident with increasing discharge current. Williams also noted that, in the keepered configuration, a significant fraction of ions impacting the DCA surface are moving towards the cathode centerline with measurable radial velocity, suggesting that a different or additional mechanism of ion acceleration than the potential-hill is responsible for the erosion.¹²⁷

Because of the angle dependence on sputtering, Williams has shown that a portion of Xe II ions have sufficient energies to contribute to the DCA erosion. The complete analysis and details of Williams' investigation can be found in References 48, and 127-132. Williams' LIF data, combined with direct measurement of plasma properties in the vicinity of the DCA will improve our knowledge of the near-DCA plasma, permitting evaluation of the sensitivity of discharge parameters on operating condition.

It is the intent of this investigation to build upon the insight gained by the LIF measurements and investigate several of Williams' conclusions. In particular, the existence of a potential-hill can be verified through plasma potential measurements near the DCA as well as verifying the collimated plasma structure suggested. Identifying the mechanism of DCA erosion—and how thruster operating conditions influences it—will be one of the principal goals of this dissertation.

1.3.5 Summary of Internal Measurements

Supported by NASA GRC through grant NAG3-2216, PEPL has developed a system by which probe measurements can be made inside the discharge plasma during normal operation of the ion engine with beam extraction. This proved a challenging task as performing such a measurement with beam extraction near the DCA presents a harsh environment for probe materials, small tolerances on critical discharge plasma containment components, and the need for robust electronic probe circuit components. Lack of a detailed understanding of the discharge plasma precludes an encompassing explanation of the discharge cathode erosion. Severe difficulty is encountered when attempting to measure internal discharge plasma parameters during engine operation. The high-voltage, high-density discharge cathode plume is a hostile environment for probes, ablating material if kept in the plume for an appreciable amount of time. In addition, with

any enclosed, high-voltage plasma environment, containment of the discharge plasma is critical to ensuring that the interrogation method prevents plasma leakage. Given the geometries of ion thrusters, the beam plasmas are expected to be closely coupled to the cathode plasma, and the expansion of the cathode plasma cannot be treated without considering the beam. As will be shown, data without beam extraction may not be representative of flight conditions.

The major drawback of previous probe measurements has been the limited number of locations interrogated. Stationary probes, typically wall mounted, have been used yielding limited data that are far from the discharge cathode region of interest. Limited data are available near the DCA orifice and determination of discharge plasma structure is not possible by a few measurements made along the cathode axis. The experimental setup selected by PEPL, allows unprecedented spatial resolution of electrostatic probe interrogation points with negligible modification of the magnetic field topology. Furthermore, measurements have been made <u>with beam extraction</u> on the 30 and 40-cm ion thrusters.

It would be impossible to list all of the probe measurements made on hollow cathodes and in hollow cathode discharges. Instead a brief summary of the measurements made in NSTAR-like environments will be attempted. This review is in no way exhaustive, but serves as samples of prior research.

If the operation of the hollow cathode inside the discharge environment of the NSTAR ion engine is to be investigated, the primary components of the discharge must be duplicated for the test to be representative of actual flight conditions. The most important components of the discharge chamber are the magnetic circuit, physical geometry of the discharge chamber, and the representative internal discharge pressure (or flow rate of the main plenum and discharge cathode). In order to match all of these parameters, the measurements should ideally be made in an operational (*i.e.*, with beam extraction) NSTAR ion engine. This proves to be difficult and, as a result, limited data are available. Early internal probe measurements with mercury ion engines, including the definitive probe study of a mercury hollow cathode by Siegfried and Wilbur,¹³³ are not representative of an NSTAR environment owing to the different propellant, operating voltages, discharge configurations (e.g., the use of baffles), and magnetic fields.¹³⁴⁻¹³⁶ The early studies of Siegfried and Wilbur did demonstrate the existence of very energetic ions originating at the discharge hollow cathode. Hayakawa published probe data downstream of a hollow cathode in a 14 cm ring-cusp ion thruster that found evidence of primary electrons in the electron energy distribution function.¹³⁷ Internal probe measurements of low-power, small-diameter ion thrusters are also not easily extrapolated to an NSTAR-like environment.^{137,138}

Several researchers have taken measurements of hollow cathodes and hollow cathodes supplemented with a magnetic field and/or representative anode. Williams completed RPA and Langmuir probe measurements in the near-field plume of a hollow cathode assembly with and without a stainless steel anode electrode (*i.e.* in diode or

triode configurations).^{128,129} His data with discharge current flowing to either anode, keeper, or both over discharge currents of 4 to 6 A, and discharge voltage up to 28 volts show electron temperatures ranging from 2 - 6 eV and increasing with axial distance, and number densities with a maximum of 5×10^{12} cm⁻³ and decreasing with axial distance from the keeper (axial locations from the DCA exit plane to 6 cm downstream). Williams measured plasma potentials, on centerline, of 11 - 19 volts (in general increasing with axial distance), but did not detect a potential-hill structure. In Williams' experiment, the lack of a magnetic field, the close proximity of the anode, and the elevated operating pressures of the small vacuum facility (10^{-3}) prevent the results from representing NSTAR discharge conditions. Friedly and Wilbur conducted a similar hollow cathode test with a cylindrical anode and a simulated thruster magnetic field. Their test gave similar performance to the measurements made by Williams.¹³⁹ Again, the high elevated pressures and close proximity of the anode preclude application of these results to an actual NSTAR thruster discharge.

Foster and Patterson have taken measurements internal to an NSTAR-type ion thruster using both wall mounted probes, and radial profiles at discrete axial locations.^{140,141} Though they lack beam extraction, their data represent the closest near-NSTAR environment, barring full out operation, and will allow comparison to results presented in this thesis. A NEXT-type discharge cathode was installed in a three-magnet ring, 30-cm discharge chamber similar to that of the NSTAR engine. The magnetic field magnitude and topology accurately match the NSTAR engine. The bell jar chamber pressure was maintained to approximately 10⁻⁴ Torr, similar to those in ion thruster

discharge chambers with similar discharge voltages to NSTAR (~26 V). A perforated aluminum termination plate at cathode potential simulated the screen grid.

Foster and Patterson found that the axial magnetic field near the cathode tends to confine the hollow cathode external positive column. This field significantly reduces radial electron diffusion and plays a role in determining discharge impedance and stability. The enhanced axial electrical conductivity tends to smooth out potential structures on axis, particularly close to the DCA where the magnetic field is strongest. Local to the DCA, no appreciable axial potential gradient was detected. A significant radial gradient existed, associated with the transition from the hollow cathode column to the main discharge plasma, indicative of a double layer. Their radial profiles of plasma parameters located 3 mm downstream of the keeper plane illustrate a sharp decrease in number density from $\sim 5 \times 10^{12}$ cm⁻³ on centerline in the cathode plume to $\sim 5 \times 10^9$ cm⁻³ in the bulk discharge. Radial plasma potential profiles illustrate a sharp increase in plasma potential from ~ 12 volts to 18-22 volts across the double layer with a discharge voltage of ~ 26 V. These results are intuitive, as the cathode plume represents a high-density core emitting excessive electrons, thus maintaining a lower potential than the main discharge.

During the course of this thesis research, parallel measurements were made at the Jet Propulsion Laboratory (JPL) in several regions of ring-cusp ion thrusters. Single Langmuir probe measurements were made by Sengupta, *et al.*, in a 30-cm diameter NSTAR laboratory model ion engine throughout the discharge.¹⁴² Radial profiles from the anode wall to thruster centerline were performed over a coarse grid from 1 cm to 14 cm downstream of the DCA in roughly 1 or 2 cm increments. The coarse grid and large probe electrodes (1-1.5 mm diameter and ~6 mm long) cannot resolve the millimetersized possible potential-hill structure. The JPL investigation was meant to supplement the data obtained for this thesis by focusing on extending plasma measurements throughout the discharge chamber to axial locations closer to the ion optics. Data were collected for NSTAR throttling points TH8 and TH15, both of which were throttling points of interest in the ELT. Radial profiles confirm a distinct cathode plume. Number densities decreased from the ~10¹² cm⁻³ maximum sharply in the radial direction. A more gradual dropoff, combined with a spread in the number density profile, was exhibited with increasing axial distance. Electron temperatures ranged from 2 - 8 eV following similar trends to number density. Plasma potentials from the Langmuir probe traces overpredicted the true plasma potential by virtue of the first derivative method chosen to analyze the I-V traces.

A second investigation conducted at JPL by Goebel, *et al.* used miniature probes to interrogate the discharge cathode orifice region, from two different directions, with a position resolution of ~0.5 mm.¹⁴³ Again, this investigation was concurrent with this research and serves as an augmentation of ion thruster discharge plasma measurements. The measurements were made on a cathode tube with a conventional barium impregnated tungsten insert enclosed in a keeper electrode. A segmented conical anode was used, similar to NSTAR-type thrusters, to raise the discharge voltage in the neighborhood of 25 V. A solenoid was used to apply an axial magnetic field characteristic of the cathode region of ring-cusp ion thrusters. The probe is swept from inside the discharge cathode

through the cathode-keeper region and extends out past the keeper exit plane. A highfrequency sawtooth voltage waveform is used to obtain Langmuir probe current-voltage characteristics that yield the various plasma parameters.

The investigation by Goebel, *et al.* echoed the measurement of double layers downstream of the cathode, but for certain flow conditions the double layers reside in the orifice region.¹⁴³ The movement of the double layer was found to coincide with changes in discharge current and mass flow (consistent with the observation of two modes of cathode operation, *i.e.* "spot" mode and "plume" mode discussed in §2.4). Centerline plasma potentials illustrated an increase from ~15 volts at the keeper exit plane to a few volts above discharge voltage over a distance of a few centimeters. Electron temperatures ranged from 2 - 5 eV increasing slightly with increasing distance downstream from the DCA. Plasma number density decreased from ~5x10¹³ cm⁻³ to ~5x10¹¹ cm⁻³ along centerline as the axial distance from the DCA increased from zero to 6 cm.¹⁴³ A "potential-hill" was not observed in this JPL investigation that could account for the observed DCA erosion rates. The Goebel, *et al.* measured parameters are consistent with the data presented in this dissertation.

The JPL probe measurements combine with the data presented in this dissertation to give a comprehensive set of discharge plasma data for flight-like ion thruster operation with beam extraction by covering the major areas of the ion thruster discharge plasma: the internal discharge cathode plasma (Goebel, *et al.*); the discharge cathode to very nearfield keeper region (Goebel, *et al.*); the near-DCA region (presented in this dissertation); the DCA plume to bulk discharge plasma transition region (presented in this dissertation); the bulk discharge and near ion optics region (Sengupta, *et al.*). This comprehensive characterization is being used to develop and verify several plasma models that encompass each region and more complex models that can bridge the transition regions and hopefully lead to a comprehensive discharge plasma model spanning the electron emission inside the discharge cathode to the extraction of discharge plasma ions. The details of the various ion thruster discharge region models and full discharge plasma models can be found in References 144-154.

1.3.6 State-of-the-art and Future Ion Thrusters

The <u>NASA Solar Electric Propulsion Technology Applications R</u>eadiness (NSTAR) 30-cm ion thruster was the first ion engine to be used for primary spacecraft propulsion, validating ion thruster technology for use in space. Efforts to increase engine lifetime continue and present a formidable challenge to ion engine designs and operation as the transition from small discovery-class missions to future large flag-ship NASA missions takes place.

Under the Nuclear Systems Program, NASA's Project Prometheus has begun to develop technologies for nuclear systems for space use. The first mission identified to use these technologies is the Jupiter Icy Moons Orbiter (JIMO) mission. The first objective of the JIMO mission is to characterize the three moons of Jupiter: Callisto, Ganymede, and Europa (each of which has been identified as capable of harboring life). The second objective is to demonstrate nuclear propulsion flight system technology. JIMO enabling technologies include: high-power and high-I_{sp} gridded ion propulsion, long life components, high-voltage isolators, high-power PPU options, and radiation-hardened components.

Top level needs for the JIMO propulsion system have been identified and, under Project Prometheus, activities were initiated to demonstrate an EP system that meets the following objectives:¹⁵⁵

- High-power: 20 50 kW per thruster
- High I_{sp} : 6000 9000 seconds
- Efficiencies (thruster and PPU) > 65% over full operating range
- Long Life: 5 10 years burn time
- Radiation Tolerant (> 8 Mrads)

Detailed description of the design improvements needed to increase the JIMO electric propulsion system over the existing state-of-the-art NSTAR system is given in Reference 156.

Two successful proposals were accepted: a NASA GRC-led team for its High-Power Electric Propulsion (HiPEP) System and a JPL-led team with its Nuclear Electric Xenon Ion System (NEXIS) thruster. The higher-power ion thrusters will require higher beam current and require engine lifetimes from 44,000 to 88,000 hours. Research on high-power ion thrusters suggests that discharge cathode keeper wear rates are expected to scale with beam current density, discharge voltage, and discharge current. Enlargement of the thruster, effectively increasing the engine throughput at a fixed beam current density, is not enough to handle the propellant throughput requirement of JIMO-type applications. The increased beam current will combine with the increased discharge power, required to maintain the beam current, resulting in accelerated wear of the DCA. Thus, discharge cathode erosion becomes an increasingly important factor in lifetime of gridded ion thrusters at the higher-power levels of future large-flagship deep space missions.

The approach to increase thruster lifetime includes, but is not limited to, extending the life of two of the engines critical components, namely the DCA and ion optics. Carbon-based (pyrolytic graphite and carbon-carbon) and titanium grid materials are currently being investigated because these materials are more resistant to sputter erosion than molybdenum. Extending electron source lifetimes are being approached in multiple ways: 1) a graphite keeper electrode to protect ion bombardment of the cathode; 2) multiple cathode approach (operated sequentially) to meet lifetime requirements; 3) reservoir cathode use; and 4) an electrodeless microwave electron source.
The rectangular <u>High-power Electric P</u>ropulsion (HiPEP) thruster, shown in Figure 1-19, is currently being developed for nuclear-electric propulsion (NEP) missions such as JIMO. The rectangular geometry allows for ease of scaling to higher-power levels simply by stretching of the lateral dimension with minor modifications to the magnetic circuit. To extend lifetime, the design approach by NASA GRC to reduce DCA erosion is two fold. The first is to use electron cyclotron resonance (ECR) microwaves to sustain the discharge plasma. While this approach does not place an electrode in the discharge plasma, the departure from a hollow cathode reduces confidence levels, creating additional technical issues that cannot easily be anticipated. In fact, due to schedule constraints and technical difficulties encountered with the ECR approach, the DC approach has become the baseline.¹⁵⁷ Preliminary performance values of the HiPEP thruster are illustrated in Table 1-4, which is from References 157 and 158. At the time of this publication, the HiPEP thruster is in the process of completing a 2000-hour wear test.¹⁵⁹



Figure 1-19: High-power Electric Propulsion (HiPEP) thruster operating at NASA GRC (used with NASA GRC permission).

Power	Efficiency	Thrust	Specific Impulse			
[kW]		[mN]	[seconds]			
9.7	72%	240	5970			
15.9	74%	340	7020			
20.2	75%	410	7500			
24.4	76%	460	8270			
29.6	80%	540	8900			
34.6	77%	600	9150			
39.3	80%	670	9620			

 Table 1-4: HiPEP preliminary thruster performance using a single hollow cathode for the DC discharge plasma.

A parallel investigation to extend discharge cathode lifetime is underway at PEPL, improving the HiPEP thruster risk management. The DCA region of a laboratorymodel, multiple-cathode HiPEP-class ion thruster is shown in Figure 1-20. This approach is to use multiple cathodes, operated sequentially, to provide the necessary engine lifetime. Three existing cathode designs, and their heritage, would be used to provide the ionization of the discharge. The extensive testing of the NSTAR and NEXT hollow cathode designs, in performance testing, wear testing, on the space plasma contactor, on the DS1 flight, and in life testing can accurately determine their life. The number of hours of engine operation would then dictate the number of hollow cathodes needed. The placement of these multiple cathodes, the best magnetic field to minimize erosion of the active and dormant cathodes, and engine performance are being investigated to troubleshoot problems and ensure adequate engine lifetime.



Figure 1-20: Photograph of the multiple-cathode discharge chamber (MCDC) HiPEP thruster (with ion optics removed) being developed by PEPL and NASA GRC. The middle cathode is the active cathode with the side "dummy" cathodes outfitted with plasma diagnostics.

The JPL NEXIS thruster design is a 65-cm diameter discharge chamber with a ring-cusp magnetic configuration (Figure 1-21).¹⁶⁰ Advanced carbon-carbon grids are masked down to produce a 57-cm diameter beam to improve plasma uniformity (beam flatness parameter of 0.82), which reduces the peak beam current density. The decreased peak beam current and low sputtering yield carbon-carbon material are expected to extend the NEXIS ion optics lifetime considerably over that of DS1. The use of a reservoir cathode, a carbon keeper electrode, and biasing the carbon keeper should increase discharge cathode life considerably as well. The departure from hollow cathode NSTAR-like designs will require extensive testing to ascertain additional failure modes and sufficient life. The NEXIS design selection and overview can be found in References 160-163. The NEXIS thruster has demonstrated performance of 78% thruster efficiency with beam extraction at an I_{sp} of 7500 s for 25 kW of power.¹⁶⁴ At the time of this publication, the NEXIS thruster is in the process of completing a 2000-hour wear test.¹⁶⁵



Figure 1-21: Nuclear Electric Xenon Ion System (NEXIS) thruster operating at JPL (used with JPL permission).

As higher-power, higher-throughput ion thrusters are designed to meet the demands of outer planet missions, the ability to design around discharge cathode erosion through the use of low sputter yield materials or biasing the keeper electrode, may not be enough to achieve the required component life. It is clear from the results of the ELT that DCA erosion is not well understood and the approach of full-power wear testing may not accurately predict the life of actual flight engines, especially those that are throttled in flight.

1.4 Problem Statement and Research Aim

The need to characterize plasma parameters inside the discharge chamber of ringcusp gridded ion engines, specifically near the DCA, has become apparent as engine wear tests indicate that discharge cathode life may limit thruster lifetime. Mapping the internal plasma structure of the 30-cm ion engine, downstream of the DCA, as a function of engine operating condition is essential to understanding the cause of DCA erosion. Determination of the mechanism by which energetic ions are created and accelerated towards the DCA would be invaluable to increasing discharge cathode life. Knowledge of the plasma structure, as a function of operating condition, will permit a detailed analysis of the erosion mechanisms at play and lead to better predictions of component wear not only of the DCA, but also of the screen grid. The fundamental plasma measurements will also serve to improve the accuracy of discharge chamber and DCA models, discharge design, and ion optics models.

The purpose of this research conducted at the PEPL is to use the High-speed Axial Reciprocating Probe (HARP) system to characterize the discharge chambers of the NSTAR-type FMT-2 and NEXT-type LM4 ion thrusters. Langmuir and emissive probes will be used to measure electron temperature, number density, Electron Energy Distribution Function (EEDF), and plasma potential within the discharge chambers. A complete mapping of the near-DCA region plasma will supplement the recent NASAsupported investigation of DCA erosion. The technique developed at PEPL allows unprecedented spatial resolution of plasma parameters in the discharge plasma. Highresolution plasma parameter measurements will provide invaluable information about the DCA erosion mechanism(s) and how thruster operating conditions affect those processes. High spatial resolution discharge plasma parameters can be used further as inputs to developing discharge plasma models, and the knowledge gained can lead to improved ion production costs, decreased discharge losses, and an increase in overall thruster performance. Multiple engine characterization will help NASA develop a methodology

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for designing future ion thrusters by generating unprecedented information on ion thruster discharge plasmas and validating ion thruster codes and design tools.

The need for data collection with beam extraction will be demonstrated by taking data without beam extraction for comparison. The effects of the shorting event in the ELT will also be investigated by simulating such an event and its effect on the discharge plasma structure.

CHAPTER 2 ION THRUSTER HARDWARE

The Plasmadynamics and Electric Propulsion Laboratory currently has two fully operational ion engines (30-cm NSTAR and 40-cm NEXT ion engines) that were donated by and/or fabricated in conjunction with NASA GRC. Figure 2-1 is a picture of the two engines used for this investigation. To review, the DS1 engine performance is >3000 sec specific impulse and >60% thrust efficiency, while the NEXT engine has demonstrated >4000 sec specific impulse and 70% thrust efficiency. A third engine, a rectangular multi-cathode-variation of the HiPEP thruster, has been built to investigate that approach to extending ion engine lifetime.



Figure 2-1: LM4 40-cm NEXT ion thruster in (left) and FMT2 NSTAR ion thruster (right).

2.1 NSTAR 30-cm Functional Model Thruster (FMT2)

The Functional Model Thruster (FMT) preceded the NSTAR Engineering Model Thruster (EMT) and the NSTAR flight thruster, all of which are based on the 30-cm diameter ion engine development. The FMT was fabricated to verify the physical design and manufacturing processes. The principal difference in the construction between the FMT and the EMT is the anode material. The anode makes up the major structural component of the ion thruster to which all components are mounted. The FMT anode material is a soft aluminum used due to ease of the spun-forming manufacturing process in the 30-cm development. The EMT anodes, however, are spun from higher-strength aluminum and titanium.⁸³ The stronger material selection of the EMT design allows reduced wall thickness resulting in a decrease in the thruster mass from 6.9 kg (FMT) to 6.4 kg (EMT).⁸³ The FMT design does not utilize the wire-mesh flake containment discharge chamber surface or grit blasting of components for emissivity control like the later generation EMT's employ.

The FMT2 thruster, shown in Figure 2-2, was built at NASA GRC and is at PEPL on a Government Furnished Equipment (GFE) loan. All components for the FMT2 and its associated systems (flow control, voltage and current control, SKIT-Pac power processing unit, etc.) were provided by NASA GRC under this agreement. In addition to the FMT2 and LM4 ion engines, NASA GRC provided a soft-walled down-flow clean room to enable ion thruster operation and maintenance at PEPL. The thruster and its associated support equipment were successfully integrated with PEPL's primary vacuum

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chamber by Williams.⁴⁸ This collaborative effort between PEPL and NASA GRC was facilitated by the fact that Williams, the graduate student performing the tests, was intimately involved in the design and construction of the first FMT's



Figure 2-2: FMT2 30-cm ion thruster on the left. For comparison, one of the EM NSTAR thrusters is shown on the right (courtesy of NASA GRC and used with permission).

The FMT2 was configured to resemble the thruster used in the 2000 hour test and was operated at PEPL over various throttle points throughout Williams' investigation. The DCA used in the second half of the 2000 hr. wear test, with a new heater coil and insert, was installed on FMT2.¹³² High priority was given to insure the similarity of the discharge chamber physical dimensions and magnetic field of the FMT2 to those of the EMT1. Measurement of the assembled FMT2 to EMT1 discharge chambers confirmed accurate reproduction of the physical dimensions. Magnetic field mapping of both thrusters demonstrated nearly identical magnetic field topologies. The FMT2 performance, essentially the same at PEPL and GRC, was almost identical to that of the flight engine. More detailed information on the FMT2 thruster, shown in Figure 2-3 can be found in Reference 48.



Figure 2-3: Photograph of FMT2 30-cm ion engine following the LIF and electrostatic probe testing. Visual sputter deposit films from the graphite beam dump on the outer edges of the accelerator grid and erosion of the accelerator grid are evident.

The ion thruster is composed of four major components: the discharge cathode assembly (discussed in §2.4); the discharge chamber; the ion optics; and the neutralizer assembly. As illustrated in the synopsis of the evolution of the 30-cm ion engine development, the FMT2 and EMT thrusters utilize the following concepts:

- Keepered discharge hollow cathode (post 8200 hr wear test)
- Keepered neutralizer hollow cathode
- Ring-cusp magnetic field
- High-perveance molybdenum dished two-grid ion optics
- Low-pressure high-voltage propellant isolators
- Shadow-shielded alumina isolators for mounts
- Plasma shield enclosure

With the development of the FMT's, several design improvements were made that are incorporated into the FMT and EMT designs. Non-ferrous structural components

(primarily the anode) were used to reduce weight and reduced the difficulty in the spinforming manufacturing process.⁸³ The discharge chamber design was modified from a cylindrical anode to a partial-conic design adding structural stability and taking up less volume while maintaining good performance and beam flatness. The large near-cathode wall of the purely cylindrical anode was found to be an inefficient stress bearer and vulnerable to vibration testing.⁶³ A distributed plenum propellant manifold was used to supply the discharge chamber main propellant, resulting in improved propellant efficiency.⁸³ High-field strength, high-temperature (temperature stabilized to 350 °C) samarium-cobalt permanent magnet rings of alternating polarity were used to create the ring-cusp magnetic field.⁸⁶ Three magnetic cusps are located in the discharge chamber, one in each of the following regions: near the DCA; on the sidewall (at the conic-cylinder intersection); and near the ion optics.

The ion optics assembly utilizes high-perveance grids that are dished outward for improved thermal loading. The grids are hydroformed molybdenum sheets that are coated with the desired photoresist pattern and are then photoetched. The grid mounting flange is set to a fixed cold grid gap.^{63,83} The grid geometries are discussed in References 48, 63, 82, 83, and 86. A 34% increase in acceleration grid thickness from previous FMT's and early EMT's acceleration thicknesses was to increase acceleration grid life.

A stainless steel plasma screen is used to shield the thruster to prevent electrons from entering the thruster or reaching high-voltage surfaces. The plasma shield is chemically etched producing holes with an open-area-fraction of 50% to allow radiative heat transfer out of the thruster.⁸³ The hole diameters are such that electron gyroradii are larger than the hole diameters denying electron entry. Though the EMT and FT plasma screens are conformal, the FMT2 plasma screen is cylindrical, facilitating window placement and LIF window replacement after sputter coating during testing.

Under the NASA Research and Technology Program, protocols for cathode flight hardware were developed, based mostly on the Plasma Contactor Development Program for the International Space Station (ISS).⁸⁴ NASA Inspection and Process Documents (IPD's) that were developed for the ISS Plasma Contactor flight program were incorporated in the assembly and operation of the FMT neutralizer cathode.⁸⁶ This procedure takes advantage of the development heritage and reliability testing done previously by NASA on cathode assemblies. A laboratory-model plasma contactor (NSTAR-type keepered hollow cathode) was used as the FMT2 neutralizer.^{112,113} The neutralizer was mounted at 45 degrees on the plasma screen to facilitate LIF optical access instead of the nominal twelve o'clock position. The dimensions of the neutralizer cathode orifice and details of the chamfering are not provided here, per agreement with NASA GRC.

2.1.1 Williams' Thruster Modifications for LIF Experiments

Under research grants from NASA GRC, the FMT2 thruster was modified considerably by Williams at NASA GRC to permit LIF interrogation of the discharge plasma. The principal modifications include:⁴⁸

- Slots cut and covered with quartz windows in the discharge chamber (3 total)
- Slots cut and covered with quartz windows in the plasma screen (3 total)
- Modification of the high-voltage propellant isolator design
- Modified gimbal and neutralizer mounting to permit optical diagnostics
- Modification of the EMT DCA design and mounting components

Three quartz windows covered the rectangular slots cut into the FMT2 anode wall during LIF measurements, shown in Figure 2-4. These three slots, each 10.2 cm by 3.2 cm, replaced roughly twenty percent of the anode surface. The magnetic field, DCA, and geometry of the discharge chamber are identical to those of the EMT1. Williams has shown that these modifications have not altered the discharge chamber magnetic field, the ion production efficiency, or the overall thruster performance.⁴⁸ The thruster has been operated over the entire NSTAR power throttling range at NASA GRC and at PEPL, illustrating comparable performance to the EMT's and flight thrusters.^{48,131,132,166}



Figure 2-4: FMT2 LIF modifications at NASA GRC illustrating the anode optical access slots (left) and schematic of the 30-cm FMT-2 ion engine indicating the location of the anode and plasma screen side and top quartz windows. The windows are located on the discharge chamber and on the plasma screen at 0, 90, and 180 degrees.

2.1.2 Additional Modifications and Discharge Plasma Containment

Transitioning from the Williams' LIF experimental setup to allow electrostatic probing, the side anode quartz window is replaced by a discharge plasma containment mechanism permitting probe access inside the anode over a two-dimensional grid of spatial locations. The starting point of the mechanism design began with the LIF modifications. The flanges used to mount the quartz windows, shown in Figure 2-5, were removed.



Figure 2-5: FMT2 photograph illustrating plasma shield slots and side anode slot access to DCA.

The design, shown in Figure 2-6, consists of a series of overlapping 38-AWG slotted stainless steel sheets that slide along stainless guide tracks. A guiding alumina tube extends from the discharge chamber through the slotted sheets and holes in the plasma shield to isolate the engine components it contacts and to ensure accurate radial location sweeps of the probe at the various axial locations. Repeatable axial movement of the probe is possible without the formation of holes or tears in the sheets. Discharge plasma containment is maintained and visually monitored during thruster operation via an adjacent vacuum-rated camera. Hole or tear formation, while extracting a beam, leads to a surge of discharge plasma towards the hole as the high-voltage plasma escapes to ground. Repeated "recycles" of the engine would ensue.



Figure 2-6: Schematics of the discharge containment mechanism from a cross section (top) including the plasma screen cover and side view (bottom) of the discharge chamber only.

The placement of the DCA exit plane in the FMT is such that the axial location of the DCA keeper face lies along the conical section of the discharge chamber. This has direct implications on the design of the containment mechanism because the movement of the probe downstream of the DCA has to take into account the angled wall of the mechanism with respect to the probe sweep axis. Thus, the guiding alumina tube is mounted onto a New England Affiliated Technologies (NEAT) RMS-800 single axis ball screw table controlled via computer. The table has a lead screw accuracy of 80 µm and a range of motion of 20 cm. The ability to retract and extend the translating alumina tube at various axial locations minimizes protrusion of material into the discharge chamber and prevents binding of the slotted stainless sheets as the coordinated movement between the translation tables relieves the buildup of stress loads on the sheets during movement. A curled sheet guide was used to ensure isolation of the plasma containment mechanism and the plasma shield, shown in Figure 2-7. The guiding alumina tube extends approximately one centimeter inside of the discharge chamber wall at all axial locations. A spring-loaded guard ring, covering the outside of the alumina tube, ensures a pressure fit preventing plasma leakage.

To minimize the likelihood of probe contamination by plasma deposition and perturbing the discharge plasma, the probe is recessed in the low-density interior of the guiding alumina tube when not in use. A rectangular aluminum plate covers the slot in the plasma shield eliminating the line of sight of background particles to the anode.



Figure 2-7: Photograph of the discharge plasma containment mechanism installed on the FMT2 30cm NSTAR engine. A curl on the end of the aluminum guide prevented the stainless sheets contacting the plasma screen. Note that the discharge cathode assembly can be seen through the hole.

2.1.3 Throttling Procedure

Throughout this investigation, the operation of the FMT2 thruster was performed accordingly:

- Conditioning of both neutralizer and discharge cathodes
- Neutralizer cathode ignition
- Discharge cathode ignition
- Minimum wait of ¹/₂ an hour prior to beam extraction allowing ion optics grid gap and discharge chamber temperatures to stabilize
- Beam extraction
- FMT throttled to desired setting
- Minimum ¹/₂ hour wait prior to data collection to allow the thruster time to reach thermal equilibrium

For near-DCA plasma phenomena, the primary thruster operating parameters are the discharge current and voltage. The FMT2 was manually operated at PEPL throughout this investigation. The procedure for operating the FMT2 thruster with beam extraction is to set the mass flow rates of the throttling point of interest equal to those on the NASA throttling table (Table 2-1). The beam and accelerator voltages were then set to their respective values. The discharge current was slowly increased to match the desired NASA Throttling table value (TH Level). The main and discharge flow rates are adjusted until both the discharge voltage and beam current match those recorded in the NASA throttling table. The data taken with beam extraction are referred to as Thruster Operating Conditions (TOC Levels). Referring to them as Throttling Levels (TH) would be erroneous because not all of the thruster operating parameters are matched. This mismatch is likely a result of several factors, including the degradation of the discharge cathode as a result of extended use with repeated exposures to atmospheric pressure, and the slight warping of critical components over time such as the soft aluminum anode and ion optics assembly mounts. The thruster was given at least a half an hour to reach steady operation at each operating condition prior to data collection.

The FMT2 was also operated *without beam extraction* to illustrate differences in the plasma structure. For the same flow rates, removal of an extracted beam significantly lowers the discharge voltage. Brophy developed a model¹⁶⁷ to simulate beam extraction operating conditions in an ion thruster discharge chamber operating without beam extraction by matching the average neutral atom density while keeping the product of the

average ion density and the square root of the average electron temperature constant. While Brophy's simulated beam extraction gives agreement for performance curves, it was determined that it was not possible to match the neutral atom density and the electron temperature simultaneously.¹⁶⁷ The significantly reduced propellant flow rates and the higher-temperature profiles observed for Brophy's simulated beam extraction indicate that a different discharge plasma environment was present. The beam plasma is coupled to the discharge plasma, affecting the discharge plasma structure and DCA erosion. In order to accurately capture all of the factors in the erosion of the DCA, the thruster is operated with beam extraction in this investigation.

The procedure for operating the FMT-2 *without beam extraction* is, for each throttling point, to set the mass flow rates equal to the NASA throttling table (TH Level). The discharge current is set to the corresponding value. The main anode flow rate and discharge cathode flow rate are adjusted until the discharge voltage matches that of the desired NASA TH Level. While operating *without beam extraction* it is possible to match discharge voltage with a variety of combinations of discharge and main flow. The no-beam data were collected with two separate methods for setting the flow rates. The first was to keep the discharge cathode flow rate as close to the NASA TH level and adjust the main flow only (not always possible). The second was to adjust the flow rates so that they were proportional to the TH level values. The discharge-only operating conditions of the FMT2 are referred to as Discharge Levels (DL). The beam and accelerator voltages were then set to their respective values.

2.1.4 Operating Parameters

The NSTAR 16 point throttle table contains the set points required to operate the thruster over the required throttling range, listed in Table 2-1.⁴² Power throttling is accomplished by varying the beam voltage and current. The NSTAR throttle table was designed to maximize the specific impulse, so the power is varied with beam current throttling over most of the range. However, for the lowest power levels, the minimum beam current is maintained and the beam voltage is throttled. The discharge chamber flow rate was selected to give propellant efficiency of 0.9 at high-power levels as a compromise between maximizing total engine efficiency and minimizing double ion production.

For the DS1 mission, a 112 point throttle table was developed to more closely track the solar array peak power. Throttling between the 16 NSTAR set points is accomplished by varying the beam voltage to give steps approximately 20 W apart.⁴²

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NSTAR	Input	Thrust	Total	Specific									Main	cathode	Neutralizer
TH	Power	(calculated)	Efficiency	Impulse	Vb	Jb	Va	Ja	Vd	Jd	Vnk	Jnk	flow	flow	cathode flow
Level	kW	mN		S	V	Α	V	mA	V	Α	V	Α	sccm	sccm	sccm
TH 15	2.29	92.4	0.618	3120	1100	1.76	-180	5.993	25.14	13.13	14.02	1.5	23.43	3.70	3.60
TH 14	2.17	87.6	0.624	3157	1100	1.67	-180	5.544	25.40	12.35	14.18	1.5	22.19	3.35	3.26
TH 13	2.06	82.9	0.630	3185	1100	1.58	-180	5.115	25.40	11.60	14.35	1.5	20.95	3.06	2.98
TH 12	1.94	78.2	0.628	3174	1100	1.49	-180	4.704	25.40	10.87	14.52	1.5	19.86	2.89	2.81
TH 11	1.82	73.4	0.631	3189	1100	1.40	-180	4.312	25.40	10.17	14.71	1.5	18.51	2.72	2.65
TH 10	1.70	68.2	0.626	3177	1100	1.30	-180	3.898	25.83	9.50	14.90	1.5	17.22	2.56	2.49
TH 9	1.57	63.0	0.618	3136	1100	1.20	-180	3.507	25.40	8.86	15.11	1.5	15.98	2.47	2.40
TH 8	1.44	57.8	0.611	3109	1100	1.10	-180	3.139	25.10	8.24	15.32	1.5	14.41	2.47	2.40
TH 7	1.33	52.5	0.596	3067	1100	1.00	-150	2.795	25.40	7.65	15.54	2.0	12.90	2.47	2.40
TH 6	1.21	47.7	0.590	3058	1100	0.91	-150	2.505	25.40	7.09	15.77	2.0	11.33	2.47	2.40
TH 5	1.09	42.5	0.574	3002	1100	0.81	-150	2.204	25.40	6.56	16.01	2.0	9.82	2.47	2.40
TH 4	0.97	37.2	0.554	2935	1100	0.71	-150	1.927	25.61	6.05	16.26	2.0	8.30	2.47	2.40
TH 3	0.85	32.0	0.527	2836	1100	0.61	-150	1.673	25.40	5.57	16.52	2.0	6.85	2.47	2.40
TH 2	0.74	27.4	0.487	2671	1100	0.52	-150	1.463	25.40	5.12	16.79	2.0	5.77	2.47	2.40
TH 1	0.60	24.5	0.472	2376	850	0.53	-150	1.486	25.40	4.69	17.07	2.0	5.82	2.47	2.40
TH 0	0.47	20.6	0.420	1972	650	0.51	-150	1.443	25.20	4.29	17.36	2.0	5.98	2.47	2.40

 Table 2-1: NSTAR throttle table.

Figure 2-8 illustrates an elementary schematic of the 30-cm FMT2 ion engine indicating the maximum operating voltages for the highest-power condition.



Figure 2-8: Schematic of the FMT2 30-cm ion thruster with component and maximum voltages labeled from largest positive potential (red) to largest negative potential (blue).

2.2 NEXT 40-cm Laboratory Model Thruster (LM4)

The fourth-built, 40-cm Laboratory Model NASA Evolutionary Xenon Thruster (NEXT) ion engine, referred to as LM4, was designed, fabricated, and assembled at NASA GRC. The engine design was modified with the intention of taking electrostatic probe measurements initially and LIF measurements later inside the discharge chamber during normal engine operation with beam extraction. NASA GRC supplied funding for the engine components, generously donated technician time, and provided many of the critical components such as the cathode assemblies and the extraction grids. The variant on the NASA NEXT EM design incorporated features that would facilitate integration with the internal probe system and future LIF characterization. Incorporating LM4 into the existing setup used for FMT2 has been facilitated with the near-DCA measurements in mind from the very beginning of the engine buildup. Figure 2-9 illustrates the LM4 40cm NEXT ion thruster during assembly at NASA GRC.



Figure 2-9: 40-cm LM4 NEXT ion thruster (neutralizer cathode not shown).

2.2.1 Fabrication and Assembly

The LM4 engine is functionally equivalent to the NASA NEXT EM thrusters with several minor differences in its fabrication. The differences have not significantly altered the engine performance and a magnetic field mapping illustrates negligible differences between the LM4 engine and the NEXT EM thrusters. At the time of this publication, five NEXT engineering model (EM) thrusters have been developed based on the design of the LM thrusters. The principal modifications between the LM4 and the EM thrusters include:

- Modification of the gimbal mounting and ion optics mounting (rotated 45 degrees) to permit probe access through the side.
- Fabrication of a purely cylindrical plasma shield to facilitate access to the discharge chamber and minimize complexity of the discharge plasma containment design.
- Fabrication of the LM4 anode from welded stainless steel sheet opposed to the NEXT EM thrusters spun stainless steel anode (resulting in slight dimensional differences).
- Incorporation of cathodes employing machined ceramic to isolate the cathode common, cathode heater, and cathode keeper for the LM4 as opposed to the brazed cathode assemblies of the NEXT EM thrusters.
- Selection of a machined stainless steel optics mounting ring assembly instead of the expensive ion optics stiffener ring mounting assembly of the EM's.
- Ceramic optics spacers and tabs used to hold the grids in place and set the grid gap.
- Modification of the high-voltage propellant isolator design.
- Modification of the neutralizer mounting (at 45 degrees).

These design changes have a negligible effect on the operation of LM4 when compared to the 40-cm Engineering Model thrusters (EM's), as will be verified by magnetic field mapping and engine performance testing. The completed LM4 engine and the NEXT EM1 thruster are shown in Figure 2-10.



Figure 2-10: LM4 40-cm NEXT ion thruster (left) and the EM1 NEXT ion thruster (right). EM1 photograph used with NASA GRC permission.

The LM4 grids were mounted on a stainless steel mounting, separated by insulating spacers, and held in place with 12 equally spaced ceramic tabs. The LM4 coldgrid gap was measured to be 7% less than the EMT nominal cold grid gap specification at the center aperture, increasing to 7% greater than the EMT nominal cold grid gap specification at the outer perimeter. The average cold-grid gap (over a majority of the beam extraction area) is equivalent to the cold-grid gap of the NSTAR 30-cm engine. The LM4 ion optics grids have the same geometry as the NSTAR ion optics. The NEXT program developed two sets of ion optics; one with the same geometry as NSTAR and another with a thick-accelerator grid (TAG) whose thickness has been increased to extend accelerator grid life.⁹⁸⁻¹⁰⁰ TAG optics were not used for this investigation. The screen and accelerator grids were mounted on the stainless steel mounting ring and visually aligned using an optical system. Photographs of the aligned apertures can be seen in Figure 2-11. During alignment, the grids are inverted such that the camera is viewing through the screen grid (larger apertures) to the accelerator grid. The alignment camera is normal to the mounting ring and not the dished surface of the grids. Thus, when alignment of the outer holes is checked, the apertures appear to become misaligned as the outer edge of the grids is approached. The grid apertures are in fact aligned when viewed normal to the dished surface. The optical alignment setup also introduces slight shadowing at the outer radius apertures apparent when comparing the pictures in Figure 2-11.



Figure 2-11: Photographs taken (under magnification) of the ion optics alignment light from the top. The pictures are taken with the screen grid on top (larger apertures) so that the smaller accelerator apertures can be aligned with them. The photographs extend from the center aperture (left) to mid radius (middle) and finally at the outer radius (right). The shift in apertures towards the outer radius is a facet of the optical alignment setup (*i.e.* the camera is not normal to the dished grid surface).

2.2.2 Magnetic Field

The same number and orientation of magnet rings (sequential rings of opposite polarity) in the NEXT EM thrusters has been installed in the LM4 thruster. In each ring, the same number of high-temperature samarium-cobalt permanent magnets has been used on the LM4 thruster as the EM thrusters. The only appreciable difference in the magnetic topology between the LM4 and EM thrusters results from the slight differences in the laboratory- and engineering-model cathodes. In the laboratory-model cathode, the insulation of components is maintained by a machined ceramic piece held in place via stainless steel screws and an iron-nickel-cobalt alloy mounting cup. The EM thruster ceramic components are mounted via brazing of iron-nickel-cobalt alloy ring that forms the bond between the ceramic and a stainless steel mounting cup. The resulting difference in quantity and location of the magnetic iron-nickel-cobalt alloy material leads to slight variations in the magnetic topologies of the engines. The deviation of magnetic field structure between the two engine types is confined to the back face of the anode where the discharge cathode is mounted. The difference in magnetic fields is mostly evident upstream of the discharge cathode keeper exit plane. The minor differences in magnetic field, and confinement of the variations to upstream of the DCA exit plane, are expected to have a negligible effect on the performance of the engine, the discharge plasma, and the discharge cathode erosion mechanisms.

A commercially available three-axis Hall probe and Gaussmeter were used to measure the magnetic field of the LM4 and EM thrusters after fabrication at NASA GRC. The Hall probe and Gaussmeter are positioned relative to the thruster using linear translation stages. Before data collection, the Hall probe and Gaussmeter were zeroed using a zero-Gauss chamber. A two-dimensional mapping of the discharge chamber from the DCA region past the ion optics was performed in 5 mm steps. The uncertainty of the Hall probe position, due mostly to the initial alignment, was estimated as ±1 mm.

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The magnetic field mapping of LM4 exhibited an equivalent magnetic field topology downstream of the DCA exit plane compared to the NEXT Engineering Model thrusters (EM's). Minor differences in magnetic field structure are evident upstream of the DCA and has had a negligible effect on engine performance. The cause of the magnetic field disparity is the slight variations in components between the EM and LM4 cathodes. Figure 2-12 and Figure 2-13 are the non-dimensional magnetic field mappings of the LM4 and EM1 thrusters, respectively, and allow easy comparison between the two.⁴³ The contour plots have been non-dimensionalized in both spatial dimensions by the discharge cathode keeper diameter. All magnetic field magnitudes have been non-dimensionalized by the magnetic field strength on centerline of the LM4 DCA exit plane.



Figure 2-12: The LM4 thruster measured magnetic field map.



Figure 2-13: NASA NEXT EM1 thruster magnetic field map measured at NASA.

The magnetic field plays an important role in the discharge plasma structure. This is no surprise as the cusped magnetic field prolongs electron collection, enhancing the discharge performance. It will be evident, from the electrostatic probe measurements, that the magnetic field is responsible for the measured discharge plasma structures. For clarity, the magnetic field streamlines are illustrated in Figure 2-14 along with the two probe interrogation regions.



Figure 2-14: LM4 magnetic field streamlines and the two probe interrogation regions.

Closer inspection of the near-DCA region of the magnetic fields illustrates that discrepancies between the topologies are contained in the region upstream of the DCA and thus will not impact the erosion mechanisms at play. Figures 2-15 and 2-16 are contour plots of the measured near-DCA magnetic fields of the LM4 and EM1 thrusters, respectively.⁴³



Figure 2-15: Near-DCA view of the LM4 magnetic field topology.



Figure 2-16: Near-DCA magnetic field topology of the NEXT EM1 thruster.

Examination of the magnetic field structures, specifically along the centerline axis, shows more clearly the slight difference in magnetic field upstream of the DCA. Figure 2-17 exhibits the comparable magnitude of the magnetic fields on centerline of the two thrusters downstream of the DCA exit plane. Negligible variations are observed near the DCA exit plane.



Figure 2-17: Axial magnetic field profiles of the EM1 and LM4 thrusters indicating magnetic field variation between engines. The dotted grey line indicates the approximate location of the discharge cathode keeper exit plane.

2.2.3 Throttling Procedures

Throughout this investigation, the operation of the LM4 thruster was performed accordingly:

- Conditioning of both neutralizer and discharge cathodes
- Neutralizer cathode ignition
- Discharge cathode ignition
- Minimum wait of ¹/₂ an hour prior to beam extraction allowing ion optics and discharge chamber temperatures to stabilize
- Beam extraction
- LM4 throttled to desired setting

• Minimum ¹/₂ hour wait prior to data collection to allow the thruster to reach thermal equilibrium

Throttling the LM4 engine is accomplished by fixing the flow rates to the cathodes and discharge plenum corresponding to the desired NASA throttle table values. Two throttling tables were supplied by NASA GRC: a preliminary table, and a post-performance testing table. The beam and accelerator voltages are subsequently set. The discharge current is then adjusted to achieve the desired beam current at a given beam extraction voltage. If the discharge voltage settled in the range of 23.5 - 27 volts and the discharge current was within ± 1 A of the NASA supplied table, the mass flow rates were maintained. If the discharge voltage is outside the desired range, the flow rates and/or discharge current were adjusted slightly to bring the discharge voltage into the range of 23.5 - 27 volts. While taking data, the discharge current was occasionally adjusted to maintain constant beam current.

2.2.4 Operating Parameters

The NASA GRC supplied post-performance testing 40-point throttle table contains the set points required to operate the NEXT thruster over the required throttling range, listed in Table 2-2.⁴³ Power throttling is accomplished by varying the beam voltage and current. The NEXT throttling table used for probe measurements followed the initial characterization (pre-wear test) of the EM thrusters.^{43,95} This updated throttling table is different than the initial throttling table supplied by NASA GRC during the initial

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characterization test of the LM4 thruster at GRC.⁴³ The throttling changes were made following pre-wear testing performance characterization of the NEXT EM thruster. More low-power set points were added and minor adjustments were made to improve engine performance and reduce wear. The NASA GRC supplied preliminary 35-point throttle table is discussed in §2.2.5.1. For ease of reference, throttling levels (TH Levels) have been assigned to each of the throttling points. These do not conform to any NASA numbering system. Figure 2-18 illustrates an elementary schematic of the 40-cm LM4 ion engine indicating the maximum operating voltages for the highest power condition achievable for this investigation (limited by power supply constraints).



Figure 2-18: Schematic of the LM4 40-cm ion thruster with component and maximum voltages (permissible with NSTAR-design SKIT-Pac power console) labeled.

	тн	Pin	Fia	len	Overall	Thrust	Idc	lh	Ve	la	Va	Ink	Main Flow	D.C. Flow	Neut Flow
		r\w/1		[6]	Efficiency	[mN]	ΓΔ1	[Δ]	rv3	[mΔ]	VU [\/]	ΓΔ1	[sccm]	[sccm]	[sccm]
	Level	[00]		[3]			[^]								
00 seconds	39	0080	129.1	4188	0.708	236.4	18.94	3.52	1800	12.0	-210	3.0	49.64	4.87	4.01
	35	6057	132.6	4149	0.699	208.2	17.13	3.10	1800	10.5	-210	3.0	43.47	4.54	4.01
	31	5290	135.9	4148	0.697	181.4	15.28	2.70	1800	9.2	-210	3.0	37.55	4.26	3.50
	26	4618	139.2	4101	0.687	157.8	13.63	2.35	1800	8.0	-210	3.0	32.35	4.05	3.50
	21	4006	173.5	4310	0.705	133.7	13.88	2.00	1800	6.8	-210	3.0	25.79	3.87	2.50
40	16	3247	194.6	4187	0.676	106.9	12.45	1.60	1800	5.4	-210	3.0	20.03	3.70	2.75
, c	11	2439	188.1	3999	0.645	80.2	8.36	1.20	1800	4.1	-210	3.0	14.23	3.57	3.00
	38	6052	133.4	3910	0.699	220.7	19.57	3.52	1567	12.0	-210	3.0	49.64	4.87	4.01
pc	34	5346	136.9	3874	0.691	194.4	17.68	3.10	1567	10.5	-210	3.0	43.47	4.54	4.01
Ŋ	30	4671	140.2	3873	0.688	169.3	15.77	2.70	1567	9.2	-210	3.0	37.55	4.26	3.50
se	25	4079	143.5	3829	0.678	147.4	14.05	2.35	1567	8.0	-210	3.0	32.35	4.05	3.50
8	20	3544	176.5	4024	0.695	124.8	14 12	2 00	1567	6.8	-210	3.0	25 79	3.87	2 50
38(15	2878	197.6	3910	0.665	99.9	12.65	1.60	1567	5.4	-210	3.0	20.03	3 70	2.55
Ŷ	10	2162	101.0	3733	0.634	74.9	8.50	1.00	1567	4.1	-210	3.0	14.23	3.57	3.00
	10	2102	101.2	0100	0.004	74.5	0.00	1.20	1007	- -	-210	0.0	14.20	0.07	0.00
	27	5450	126.6	2602	0.601	209.4	20.03	3 5 2	1206	12.0	210	2.0	40.64	1 97	4.01
ş	37	4004	140.0	2650	0.091	102.6	20.03	2.02	1206	10.5	-210	3.0	49.04	4.07	4.01
ŭ	33	4024	140.0	3030	0.003	103.0	10.09	3.10	1390	10.5	-210	3.0	43.47	4.54	4.01
Ö	29	4210	143.3	3057	0.680	159.9	10.12	2.70	1390	9.2	-210	3.0	37.55	4.20	3.50
~3600 s	24	3683	146.7	3616	0.670	139.2	14.36	2.35	1396	8.0	-210	3.0	32.35	4.05	3.50
	19	3207	179.4	3799	0.685	117.9	14.35	2.00	1396	6.8	-210	3.0	25.79	3.87	2.50
	14	2608	200.5	3692	0.654	94.3	12.83	1.60	1396	5.4	-210	3.0	20.03	3.70	2.75
	9	1960	194.1	3525	0.624	70.7	8.62	1.20	1396	4.1	-210	3.0	14.23	3.57	3.00
seconds	36	4707	140.7	3393	0.677	191.6	20.64	3.52	1179	12.0	-200	3.0	49.64	4.87	4.01
	32	4161	144.2	3362	0.668	168.7	18.63	3.10	1179	10.5	-200	3.0	43.47	4.54	4.01
	28	3639	147.5	3361	0.665	146.9	16.59	2.70	1179	9.2	-200	3.0	37.55	4.26	3.50
	23	3181	150.9	3323	0.655	127.9	14.77	2.35	1179	8.0	-200	3.0	32.35	4.05	3.50
8	18	2780	184.0	3492	0.667	108.3	14.72	2.00	1179	6.8	-200	3.0	25.79	3.87	2.50
33	13	2267	205.1	3393	0.636	86.7	13.13	1.60	1179	5.4	-200	3.0	20.03	3.70	2.75
2	8	1704	198.6	3240	0.606	65.0	8.83	1.20	1179	4.1	-200	3.0	14.23	3.57	3.00
					•								•		
	27	3220	150.9	3126	0.650	136.7	16.97	2.70	1021	9.2	-175	3.0	37.55	4.26	3.50
s الا	22	2816	154.2	3090	0.640	118.9	15.10	2.35	1021	8.0	-175	3.0	32.35	4.05	3.50
)01 20	17	2472	188.3	3247	0.649	100.7	15.07	2.00	1021	6.8	-175	3.0	25 79	3.87	2.50
ec ~3	12	2020	209.4	3155	0.617	80.6	13.40	1.60	1021	5.4	-175	3.0	20.03	3.70	2.00
° v	7	1510	203.4	3013	0.588	60.4	0.02	1.00	1021	4.1	-175	3.0	14.23	3.57	3.00
<u> </u>	1	1019	203.0	3013	0.000	00.4	9.02	1.20	1021	4.1	-175	5.0	14.25	5.57	5.00
<u> </u>		1420	205.0	2002	0.576	570	0.15	1.20	0.26	4.1	150	2.0	14.00	2 57	2.00
er	6	1420	205.9	2003	0.570	57.8	9.15	1.20	930	4.1	-150	3.0	14.23	3.57	3.00
	5	1320	209.0	2745	0.561	55.1	9.29	1.20	850	4.1	-125	3.0	14.23	3.57	3.00
ð	4	1121	214.6	2451	0.527	49.2	9.54	1.20	679	4.1	-115	3.0	14.23	3.57	3.00
۲, D	3	1086	214.6	2399	0.522	48.1	9.54	1.20	650	4.1	-144	3.0	14.23	3.57	3.00
Ň	2	786	214.6	1854	0.430	37.2	9.54	1.20	400	4.1	-394	3.0	14.23	3.57	3.00
	1	665	213.6	1585	0.372	31.8	9.49	1.20	300	4.1	-525	3.0	14.23	3.57	3.00
	0	538	215.8	1401	0.325	25.5	7.99	1.00	275	3.4	-500	3.0	12.32	3.52	3.00

 Table 2-2: Updated NASA GRC supplied NEXT throttling set points with assigned throttle levels based upon input power.

2.2.5 LM4 Initial Characterization

LM4 was transported to PEPL following a complete hardware and electrical

checkout at NASA GRC. During transport both of the cathodes were sealed in doubled-

up nitrogen filled bags where they remained for the approximate three hour trip. Once at

PEPL, the cathodes were placed on nitrogen purges located inside the downdraft cleanroom where they are stored.

The goal of the initial characterization test of LM4 was to validate equivalent engine performance of LM4 compared to the beginning of life (BOL) operation of the NEXT EM thrusters prior to the probe mechanism modifications. LM4 was installed inside the PEPL Large Vacuum Test Facility (LVTF) and electrically connected to the NASA GRC supplied Station-Keeping Ion Thruster Package (SKIT-Pac) power console used to run the FMT2 thruster. Following the NASA IPD's, an electrical checkout was performed prior to chamber pumpdown and again at vacuum, prior to engine ignition. A high-voltage AVO BM25 Megger was used to measure impedance between each of the thruster components to each other and to facility ground. Typical resistance values between the various engine components, including facility ground, for the LM4 were tens of giga-ohms.

The cathodes were conditioned according to NASA IPD prior to operation. The cathodes were allowed to heat the engine to steady state temperature prior to beam extraction (for 30 minutes). Once a beam was extracted, the engine was adjusted to the low-power level of the NEXT throttling table where it was allowed to continue to warm up for an additional half an hour. The engine was then throttled up in power as desired. At each throttling condition, the engine was allowed ¹/₂ an hour to reach steady state before the performance data were taken.
The successful characterization of the LM4 engine confirmed equivalent operation compared with the baseline Beginning Of Life (BOL) operation of the NASA 40-cm EM thrusters shown in Table 2-3.^{43,103} Again, note that this table is slightly different than the "updated" throttling table given in §2.2.4 as input operating parameters were adjusted following the initial EM characterization tests.

	тн	Pin	Fia	Isn	Overall	Thrust	.ldc	Jh	Vs	Ja	Va	Ink	Main Flow	D.C. Flow	Neut Flow
		rw1	ΓW/A1	[9]	Efficiency	[mN]	[A]	[A]	[V]	[mA]	[V]	[A]	[sccm]	[sccm]	[sccm]
	30	6852	120.3	4117	0.698	237.0	18.97	3.52	1800	12.0	-250	30	49.64	4.87	5 16
ds	35	6055	134.7	4086	0.691	208.7	17.39	3 10	1800	10.5	-250	3.0	43.47	4 54	4 95
~4000 secon	31	5295	140.7	4047	0.681	181.8	15.83	2 70	1800	9.2	-250	3.0	37.55	4 26	4 75
	26	4628	147 1	4003	0.671	158.2	14 40	2.35	1800	8.0	-250	3.0	32.35	4 05	4.58
	21	3960	154.8	3946	0.658	134.7	12.90	2.00	1800	6.8	-250	3.0	27.11	3.87	4.41
	16	3193	166.2	3853	0.637	107.7	11.08	1.60	1800	5.4	-250	3.0	21.08	3.70	4.21
	11	2423	182.2	3601	0.589	80.8	8.41	1.20	1800	4.1	-250	3.0	15.68	3.57	4.01
	38	6029	129.3	3841	0.691	221.1	18.97	3.52	1567	12.0	-235	3.0	49.64	4.87	5.16
spr	34	5330	134.7	3811	0.683	194.7	17.39	3.10	1567	10.5	-235	3.0	43.47	4.54	4.95
S	30	4663	140.7	3775	0.673	169.6	15.83	2.70	1567	9.2	-235	3.0	37.55	4.26	4.75
se	25	4078	147.1	3734	0.663	147.6	14.40	2.35	1567	8.0	-235	3.0	32.35	4.05	4.58
8	20	3492	154.8	3681	0.649	125.6	12.90	2.00	1567	6.8	-235	3.0	27.11	3.87	4.41
38	15	2819	166.2	3594	0.628	100.5	11.08	1.60	1567	5.4	-235	3.0	21.08	3.70	4.21
ć	10	2142	182.2	3360	0.580	75.4	8.41	1.20	1567	4.1	-235	3.0	15.68	3.57	4.01
Ś	37	5424	129.3	3624	0.683	208.6	18.97	3.52	1396	12.0	-220	3.0	49.64	4.87	5.16
pu	33	4798	134.7	3596	0.675	183.7	17.39	3.10	1396	10.5	-220	3.0	43.47	4.54	4.95
8	29	4200	140.7	3562	0.665	160.0	15.83	2.70	1396	9.2	-220	3.0	37.55	4.26	4.75
) Se	24	3675	147.1	3524	0.655	139.3	14.40	2.35	1396	8.0	-220	3.0	32.35	4.05	4.58
200	19	3149	154.8	3473	0.641	118.5	12.90	2.00	1396	6.8	-220	3.0	27.11	3.87	4.41
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	14	2544	166.2	3391	0.620	94.8	11.08	1.60	1396	5.4	-220	3.0	21.08	3.70	4.21
	9	1936	182.2	3170	0.571	71.1	8.41	1.20	1396	4.1	-220	3.0	15.68	3.57	4.01
s	36	4658	129.3	3328	0.671	191.6	18.97	3.52	1179	12.0	-200	3.0	49.64	4.87	5.16
pu	32	4123	134.7	3302	0.663	168.7	17.39	3.10	1179	10.5	-200	3.0	43.47	4.54	4.95
20	28	3612	140.7	3271	0.653	147.0	15.83	2.70	1179	9.2	-200	3.0	37.55	4.26	4.75
) S(	23	3163	147.1	3236	0.642	127.9	14.40	2.35	1179	8.0	-200	3.0	32.35	4.05	4.58
300	18	2713	154.8	3189	0.627	108.9	12.90	2.00	1179	6.8	-200	3.0	27.11	3.87	4.41
<u>~</u>	13	2196	166.2	3114	0.606	87.1	11.08	1.60	1179	5.4	-200	3.0	21.08	3.70	4.21
	8	1675	182.2	2911	0.557	65.3	8.41	1.20	1179	4.1	-200	3.0	15.68	3.57	4.01
		0404	4 4 9 7	0011	0.040	100.0	45.00	0.70	1001		475		07.55	1.00	4.75
Ś	27	3184	140.7	3041	0.640	136.6	15.83	2.70	1021	9.2	-175	3.0	37.55	4.26	4.75
8 p	22	2791	147.1	3008	0.628	118.9	14.40	2.35	1021	8.0	-175	3.0	32.35	4.05	4.58
503	17	2396	154.8	2965	0.614	101.2	12.90	2.00	1021	6.8	-175	3.0	27.11	3.87	4.41
۶° ک	12	1942	166.2	2895	0.592	81.0	11.08	1.60	1021	5.4	-175	3.0	21.08	3.70	4.21
<u> </u>	/	1485	182.2	2706	0.543	60.7	8.41	1.20	1021	4.1	-1/5	3.0	15.68	3.57	4.01
			_					1							
ve ve	5	1279	182.2	2464	0.522	55.3	8.41	1.20	850	4.1	-125	3.0	15.68	3.57	4.01
<u>م</u> ۲	3	1073	182.2	2198	0.495	49.3	8.41	1.20	679	4.1	-115	3.0	15.68	3.57	4.01

 Table 2-3: NASA GRC supplied NEXT BOL (pre-characterization test) initial characterization throttle table.

### 2.2.5.1 LM4 Telemetry and Performance

The LM4 engine is shown in Figure 2-19 operating during the initial characterization testing inside the PEPL LVTF. The LM4 telemetry and performance data taken during the LM4 initial characterization test are listed in Table 2-4.⁴³ The data allow easy comparison between BOL EM thrusters and the LM4. The data show excellent agreement confirming the minor differences in engine construction have a negligible effect on engine performance and operation.



Figure 2-19: LM4 thruster operating with beam extraction in PEPL LVTF with chamber lights on (left) and without lighting (right).

<b>—</b>	r 1	r	Deem			r	1		Vol				r	r		Main	DC	Nout	r	Topk
		<b>D</b> .	Deam						VCK-				.,			Iviairi	D.C.	Neut	.,	Tarik
spu	IH	Pin	Power	Isp	Overall	Thrust	Vdc	Jdc	CC	Jb	Vs	Ja	Va	Vnk	Jnk	Flow	Flow	Flow	Vg	Pressure
	Level	[W]	[W]	[S]	Eff.	[mN]	[V]	[A]	[V]	[A]	[V]	[mA]	[V]	[V]	[A]	[sccm]	[sccm]	[sccm]	[V]	[Torr]
	30	4663	-	3775	0.673	169.6	-	15.83	-	2.70	1567	9.20	-235.0	-	3.00	37.55	4.26	4.75	-	-
	30A'	4416	4035	3884	0.714	165.6	24.40	15.11	2.98	2.70	1482	10.63	-228.2	13.35	3.00	35.3	4.26	4.75	-11.82	2.7E-06
	30'	4392	4032	3715	0.691	166.6	23 27	14 76	3.88	2 70	1482	11 54	-227.6	13 41	3 00	37.6	4 26	4 75	-11 85	2.9E-06
	25	4079	1002	2724	0.662	147.6	20.21	14 40	0.00	2.75	1567	0 00	225.0	10.11	2 00	22.25	4.05	4 59	11.00	2.02 00
	20	4076	-	3734	0.003	147.0	-	14.40	-	2.35	1007	0.00	-235.0	-	3.00	32.35	4.05	4.00	-	-
	25A	3899	3546	3887	0.708	144.9	24.31	13.91	2.48	2.36	1490	8.83	-228.2	13.28	3.00	30.1	4.05	4.58	-11.65	2.4E-06
ő	25'	3878	3544	3698	0.682	146.0	23.14	13.66	3.57	2.36	1490	9.57	-228.2	13.24	3.00	32.4	4.05	4.58	-11.62	2.6E-06
se	20	3492	-	3681	0.649	125.6	-	12.90		2.00	1567	6.80	-235.0	-	3.00	27.11	3.87	4.41	-	-
8	20A'	3320	3002	3783	0.687	123.0	24.47	12.28	2.45	2.00	1488	7.11	-228.3	13.22	3.00	25.5	3.87	4.41	-11.43	2.1E-06
80	20'	3327	3002	3625	0.661	123.8	23.26	13.00	3 54	2.00	1480	7 4 4	-228.0	13 24	3.00	27.2	3.87	4 4 1	-11 42	2.2E-06
ž	20	0040	3002	0020	0.001	120.0	20.20	13.03	0.04	2.00	4507	7.44	-220.0	13.24	0.00	21.2	3.07	4.94	-11.42	2.22-00
	CI	2019	-	3594	0.020	100.5	-	11.00	-	1.00	1007	5.40	-235.0	-	3.00	21.00	3.70	4.21	-	-
	15'	2677	2412	3554	0.646	99.2	24.56	9.84	3.71	1.60	1494	5.57	-228.2	13.29	3.00	21.1	3.70	4.21	-11.12	1.9E-06
	10	2142	-	3360	0.580	75.4	-	8.41	-	1.20	1567	4.10	-235.0	-	3.00	15.68	3.57	4.01	-	-
	10'	2033	1805	3327	0.598	74.5	25.31	7.84	4.53	1.20	1490	3.92	-228.2	13.60	3.00	15.7	3.57	4.01	-10.89	1.5E-06
						•								•						
	20	4200		3562	0.665	160.0	L _	15.83	_	2 70	1306	9.20	-220.0	_	3.00	37 55	4 26	4 75		_
	204	4100	2000	2770	0.710	160.0	24 44	15 1 4	2 04	2.70	1200	10.90	220.0	12 20	2.00	25.0	4.00	4.75	11.07	275.00
	ZYA	4190	3009	3113	0.710	100.9	24.41	15.14	3.04	2.70	1098	10.00	-220.1	13.39	3.00	30.3	4.20	4.75	-11.00	2.1 E-00
	-29	4165	3801	3607	0.687	161.8	23.48	14.89	3.85	2.70	1396	11.50	-220.0	13.37	3.00	37.6	4.26	4.75	-11.80	2.8E-06
6	24	3675	-	3524	0.655	139.3	-	14.40	-	2.35	1396	8.00	-220.0	-	3.00	32.35	4.05	4.58	-	-
ğ	24A	3681	3325	3764	0.703	140.3	24.45	13.98	2.52	2.36	1396	8.98	-220.1	13.27	3.00	30.1	4.05	4.58	-11.64	2.4E-06
Ņ	24	3660	3322	3580	0.678	141.4	23.26	13.75	3,59	2.36	1396	9,46	-220.1	13.24	3.00	32.4	4.05	4,58	-11.59	2.5E-06
ĕ	10	3140		3472	0.641	119.5		12 00		2.00	1306	6.80	-220.0		3 00	27.11	3.97	4 11		
ő	104	3149	-	3473	0.041	110.0	-	12.90	-	2.00	1000	7.00	-220.0	-	3.00	27.11	3.07	4.41	-	-
80	19A	3140	2818	3000	0.682	119.1	24.53	12.39	2.48	2.00	1390	7.09	-220.0	13.22	3.00	25.5	3.87	4.41	-11.41	2.1E-06
ŝ	19	3120	2814	3510	0.661	119.8	23.34	12.21	3.54	2.00	1395	7.42	-220.0	13.29	3.00	27.2	3.87	4.41	-11.47	2.2E-06
	14	2544	-	3391	0.620	94.8	-	11.08		1.60	1396	5.40	-220.0	-	3.00	21.08	3.70	4.21	-	-
	14	2522	2257	3438	0.641	96.0	24.57	9.87	3.82	1.60	1397	5.44	-220.3	13.25	3.00	21.1	3.70	4.21	-11.10	1.9E-06
	9	1936	-	3170	0.571	711	_	841	-	1 20	1396	4 10	-220.0	-	3.00	15.68	3 57	4 01	-	_
	o o	1010	1601	3220	0.504	72.1	25 25	7.85	1 58	1.20	1305	3.86	210.0	13.68	3.00	15.7	3.57	4.01	-10.03	1 5E-06
	3	1919	1031	5220	0.554	12.1	20.20	1.05	4.50	1.20	1000	5.00	-213.3	13.00	5.00	15.7	5.57	4.01	-10.35	1.3 <b>Ľ</b> -00
														-					-	
	28	3612	-	3271	0.653	147.0	-	15.83	-	2.70	1179	9.20	-200.0	-	3.00	37.55	4.26	4.75	-	-
	28A	3608	3218	3468	0.698	147.9	24.64	15.40	3.11	2.70	1179	11.18	-200.2	13.30	3.00	35.3	4.26	4.75	-11.77	2.7E-06
	28	3587	3215	3318	0.675	148.8	23.63	15.15	3.90	2.70	1179	11.78	-200.1	13.31	3.00	37.6	4.26	4.75	-11.72	2.8E-06
	23	3163	-	3236	0.642	127.9	-	14.40	-	2.35	1179	8.00	-200.0	-	3.00	32.35	4.05	4.58	-	_
sp	234	3176	2811	3461	0.690	120.0	24 78	14 20	2.63	2 36	1178	0.13	-200.1	13 26	3.00	30.1	4.05	4 58	-11 61	24E-06
5	20/1	2155	2011	2202	0.000	120.0	22.40	12.06	2.00	2.00	1170	0.10	200.1	12.20	2.00	22.4	4.05	4 50	11.01	2.10 00
e e	23	3155	2011	3293	0.000	130.0	23.40	13.90	3.05	2.30	11/9	9.49	-200.2	13.23	3.00	32.4	4.05	4.50	-11.54	2.5E-00
S	18	2713	-	3189	0.627	108.9	-	12.90	-	2.00	1179	6.80	-200.0	-	3.00	27.11	3.87	4.41	-	-
ğ	18A	2718	2387	3373	0.668	109.6	24.72	12.72	2.51	2.00	1180	7.10	-200.0	13.23	3.00	25.5	3.87	4.41	-11.39	2.1E-06
Ř	18	2695	2382	3229	0.648	110.3	23.45	12.45	3.57	2.00	1179	7.36	-200.2	13.19	3.00	27.2	3.87	4.41	-11.32	2.2E-06
`	13	2196	-	3114	0.606	87.1	-	11.08	-	1.60	1179	5.40	-200.0	-	3.00	21.08	3.70	4.21	-	-
	13	2178	1908	3161	0.628	88.2	24.68	10.01	3.84	1.60	1179	5,40	-200.1	13.20	3,00	21.1	3,70	4,21	-11.01	1.8E-06
	8	1675		2011	0.557	65.3		8 4 1		1 20	1170	4 10	-200.0		3.00	15.68	3.57	4 01		
	8	1661	1432	2062	0.591	66.4	25 27	7 02	4 67	1 20	1170	3 70	-200.0	13 50	3.00	15.00	3.57	4.01	-10.85	1.5E-06
-	U	1001	1452	2303	0.001	00.4	20.21	1.33	4.07	1.20	1119	5.13	-200.1	10.00	5.00	15.7	5.57	4.01	-10.00	1.02-00
-									· · · · ·										· · · · ·	
	27	3184	-	3041	0.640	136.6	-	15.83	-	2.70	1021	9.20	-175.0	-	3.00	37.55	4.26	4.75	-	-
	27A	3191	2790	3229	0.684	137.7	24.93	15.72	3.11	2.70	1020	11.68	-175.1	13.30	3.00	35.3	4.26	4.75	-11.72	2.6E-06
	27	3172	2790	3090	0.663	138.6	23.84	15.48	3.90	2.70	1021	12.08	-175.0	13.29	3.00	37.6	4.26	4.75	-11.67	2.8E-06
1	22	2791	-	3008	0.628	118 9	-	14 40	_	2.35	1021	8.00	-175.0	-	3.00	32.35	4 05	4 58	-	_
sp	224	2817	24/1	3225	0.675	120.2	25 12	14 45	2.64	2.36	1021	0.32	-175 1	13 30	3.00	30.1	4.05	4 58	-11.61	24E-06
ñ	22M	2017	2441	2000	0.075	120.2	20.12	14.40	2.04	2.00	1021	0.02	175.0	12.00	3.00	20.1	4.05	4.50	44.47	2.70-00
о С С		2193	Z44	3069	0.003	121.2	23.11	14.19	3.08	2.30	1022	9.00	-1/5.0	13.20	3.00	32.4	4.05	4.58	-11.47	∠.3E-00
s S	17	2396	-	2965	0.614	101.2	-	12.90	-	2.00	1021	6.80	-175.0	-	3.00	27.11	3.87	4.41	-	-
8	17A	2408	2069	3141	0.654	102.1	24.88	12.96	2.56	2.00	1021	7.24	-175.1	1 <u>3.2</u> 5	3.00	25.5	3.87	4.41	-11.38	2.1E-06
Ģ.	17	2388	2067	3008	0.635	102.7	23.67	12.72	3.56	2.00	1021	7.40	-175.1	13.20	3.00	27.2	3.87	4.41	-11.26	2.2E-06
1	12	1942	-	2895	0.592	81.0	-	11 08	_	1.60	1021	5.40	-175.0	-	3.00	21.08	3.70	4,21	-	_
	12	1931	1656	2045	0.615	82.2	24 80	10.18	3 04	1.60	1021	5 30	-175 1	13 20	3.00	21.1	3 70	4 21	-10 96	1 9E-06
1	- 12	1405	1000	2340	0.015	60.7	24.00	0.10	5.54	1.00	1021	1.03	175.0	10.20	2.00	45.00	3.70	4.04	-10.90	1.32-00
		1485	-	2100	0.543	00.7	-	<u>0.41</u>	-	1.20	1021	4.10	-1/5.0	-	3.00	10.68	3.57	4.01	-	-
-	7	1475	1243	2760	0.568	61.8	25.31	8.02	4.76	1.20	1021	3.76	-1/4.9	13.72	3.00	15.7	3.57	4.01	-10.88	1.5E-06
/ei	5	1279	-	2464	0.522	55.3	-	8.41	-	1.20	850	4.10	-125.0	-	3.00	15.68	3.57	4.01	-	-
ð	5	1275	1039	2524	0.548	56.5	25 43	8 20	4 77	1 20	851	3.86	-125 1	13 50	3 00	15.7	3.57	4 01	-10.65	1.5E-06
L L	-	1072	1000	2100	0.405	40.2	_0.70	0 11		1.20	670	4 10	115.0	10.00	2.00	15.69	2 57	4.01	10.00	
ð	3	10/3	-	2198	0.495	49.3	-	8.41	-	1.20	0/9	4.10	-115.0	-	3.00	80.01	3.57	4.01	-	-
1	3	1076	834	2261	0.523	50.6	25.44	8.41	4.75	1.20	680	4.00	-115.2	13.48	3.00	15.7	3.57	4.01	-10.65	1.5E-06

Table 2-4: LM4 thruster telemetry and calculated performance data (black) compared to EM1 BOL telemetry and calculated performance data (blue). A prime marker for the ~3800 sec levels indicated an approximate match (see screen and accelerator grid voltages).

During the characterization testing, the discharge oscillations were recorded for each operating condition to ensure "spot-mode" operation of the discharge cathode. Over all operating conditions investigated, the largest discharge oscillations were  $\pm 1.8$  V and  $\pm 0.2$  A for the discharge voltage and current, respectively. The largest recorded oscillations were 7.2% and 3.3% of the discharge voltage and current, respectively. Defining "plume-mode" as operation of the discharge cathode with discharge voltage oscillations of  $\pm 5$  V or higher, it is clear that the LM4 discharge cathode was operated with margin in "spot-mode." Figure 2-20 illustrates sample discharge oscillation traces taken at the lowest and highest power throttling condition.



Figure 2-20: LM4 discharge oscillation scope traces taken at TH3 and TH30A operating conditions.

#### 2.2.5.2 Thrust Measurement

Thrust measurements were taken during operation of LM4 using a NASA GRC design null-type inverted pendulum thrust stand designed for high-power thrusters/clusters.¹⁶⁸ The thrust stand, shown in Figure 2-21, is a duplicate of the stand used to test the NASA 457 50 kW Hall Thruster and was assembled at PEPL with a designer reported error of  $\pm 1\%$  of the full-scale calibration.¹⁶⁹ In-situ thruster/thrust-stand leveling is performed via a remotely-controlled geared DC motor coupled to a

jackscrew. A remotely-controlled geared DC motor driven pulley system provides in-situ thrust stand calibration by loading and off-loading small calibration weights to simulate thrust. A linear curve-fit of the null-coil voltage versus force applied (*i.e.* the calibration weights applied) is obtained and used for the performance measurements. The thrust stand is enclosed in a copper shroud that is actively cooled with a VWR International 1172 refrigerated recirculating chiller.



Figure 2-21: PEPL null-type inverted pendulum thrust stand.

Figures 2-22 and 2-23 illustrate the LM4 engine mounted on the thrust stand in the LVTF at PEPL during test setup and thruster operation, respectively. The thrust stand was zero flow (complete thruster and flow shutdown) calibrated prior to and following characterization testing. Throughout the performance testing, beam extraction was periodically interrupted to allow recalibration of the thrust stand. The desire to limit the number of discharge on/off cycles resulted in performance testing thrust calibrations with the discharge and neutralizer cathodes ignited. The discharge plasma and neutralizer flow, without a beam, had a negligible effect on the measured thrust.



Figure 2-22: LM4 engine mounted on PEPL thrust stand. A vacuum rated camera mounted on a rotational theta table (shown to the left of the engine) allowed visual monitoring of the discharge cathode during ignition and provided flexibility in diagnosing any operating problems.



Figure 2-23: LM4 operation with beam extraction in PEPL LVTF (chamber lights on). The engine is mounted on the thrust stand. The camera in mounted to an arm (shown in foreground) that is attached to a rotational theta table mounted above the engine.

Figure 2-24 compares the measured and calculated thrust for the LM4 engine as well as comparison to the corresponding GRC EM1 calculated thrust data.⁴³ The EM1 values have been supplied by NASA GRC, while the calculated LM4 values have been

obtained using the NASA supplied Ion Pro (version 3) spreadsheet that uses the performance equations in References 63 and 83. For the calculated thrust, the beam divergence thrust correction factor and the total double-to-single ion current ratio were assumed to be 0.967-0.977 and 0.034-0.044, respectively.⁶³ Ingested mass flow, due to the facility background gas pressure, was included in the total mass flow rate to the engine for determining the thrust efficiency and specific impulse.

Thrust measurements were taken over two days allowing a repeatability check of the thrust stand measurements and LM4 performance. The maximum deviation between thrust stand measurements taken on the two days did not exceed 2 mN which is within the reported error of the thrust stand  $\pm 2$  mN ( $\pm 1\%$  of the 200 mN full scale) by the designer.¹⁶⁸ Typically, the variation of thrust between the two days was less than 1 mN. Examination of the hysteresis and drift of the thrust stand during this experiment indicate an uncertainty of  $\pm 1$  mN. The excellent repeatability speaks to the accuracy of the thrust stand measurement and the quality of the thrust stand hardware.



Figure 2-24: Thrust stand measurements compared to calculated thrust. Left figure illustrates all of the measured LM4 data compared to those values calculated by IonProV3. The right plot illustrates the measured and calculated LM4 thrust compared to corresponding NASA conditions (if any).

The minor differences in measured and calculated thrust can be attributed to a number of factors. The discrepancy is slightly larger than the estimated thrust stand error  $\pm 2$  mN. The subtle differences in discharge chamber fabrication and ion optics mounting design between the EM's and LM4 may affect the beam flatness, the discharge performance, and thrust vector. Though these effects are minor, they may account for the slight differences in performance. The likely cause of the minor differences in the measured thrust versus calculated thrust lies in the accuracy of the alignment of the LM4 thruster centerline with the thrust stand axis and the axis of the calibration pulley system. A tilting of the thruster centerline (both horizontally and vertically) by a few degrees with respect to the center of mass, passing through the plane of motion of the pendulum, would reduce the measured thrust. In addition, any angular shift between the calibration weights and the plane of the pendulum would further add to the possible misalignment and reduction in measured thrust. The thruster alignment was visually performed with an accuracy of a few degrees.

The complete listing of thruster telemetry and performance values (with the addition of measured thrust) is tabulated in Table 2-5. The LM4 performance calculations utilize NASA GRC-supplied Ion Pro (version 3) spreadsheet, while the EM1 thruster performance and telemetry values (for reference) are the EM1 pre-wear test values measured at NASA GRC.⁴³

			Boom	I	1	Calc	Moas			Vck							Main	DC	Nout		Tank
			Dealli			Calc.	ivieas.			VCK-							Iviairi	D.C.	Neul		
	TH	Pin	Power	Isp	Overall	Thrust	Thrust	Vdc	Jdc	CC	Jb	Vs	Ja	Va	Vnk	Jnk	Flow	Flow	Flow	Vg	Pressure
	Level	[W]	[W]	[s]	Eff.	[mN]	[mN]	[V]	[A]	[V]	[A]	[v]	[mA]	[M]	[V]	[A]	[sccm]	[sccm]	[sccm]	[V]	[Torr]
	30	4663		3775	0.673	160.6			15.83		2 70	1567	0.20	235.0		3 00	37.55	1 26	4 75		
	30	4005	4005	5775	0.075	105.0	457.7	-	15.05	-	2.70	1307	3.20	-200.0	40.05	0.00	37.33	4.20	4.75	44.00	0.75.00
	30A	4416	4035	3884	0.714	105.0	157.7	24.40	15.11	2.98	2.70	1482	10.63	-228.2	13.35	3.00	35.3	4.20	4.75	-11.82	2.7E-06
	30'	4392	4032	3715	0.691	166.6	159.7	23.27	14.76	3.88	2.70	1482	11.54	-227.6	13.41	3.00	37.6	4.26	4.75	-11.85	2.9E-06
	25	4078	-	3734	0.663	147.6	-	-	14.40	-	2.35	1567	8.00	-235.0	-	3.00	32.35	4.05	4.58		-
sp	25.4'	3800	3546	3997	0 708	1// 0	138 1	2/ 31	13 01	2 / 8	2.36	1/00	8.83	228.2	13 28	3.00	30.1	4.05	1 58	11.65	2 4E 06
č	234	3099	3340	3007	0.700	144.3	130.1	24.31	13.91	2.40	2.30	1430	0.05	=220.2	13.20	5.00	30.1	4.05	4.50	-11.05	2.4L-00
ğ	25'	3878	3544	3698	0.682	146.0	141.7	23.14	13.66	3.57	2.36	1490	9.57	-228.2	13.24	3.00	32.4	4.05	4.58	-11.62	2.6E-06
se	20	3492	-	3681	0.649	125.6	-		12.90	-	2.00	1567	6.80	-235.0	-	3.00	27.11	3.87	4.41	-	-
Q	20A'	3320	3002	3783	0.687	123.0	114 9	24 47	12 28	2 4 5	2 00	1488	7 1 1	-228.3	13 22	3.00	25.5	3.87	4 4 1	-11 43	2 1E-06
8	20/1	0020	20002	0005	0.001	120.0	440.0	21.17	12.20	2.40	2.00	1400	7.44	220.0	40.04	0.00	20.0	0.07	4.44	44.40	2.12 00
Ϋ́	20	3327	3002	3625	0.661	123.8	116.2	23.20	13.09	3.54	2.00	1489	7.44	-228.0	13.24	3.00	21.2	3.87	4.41	-11.42	2.2E-06
¹	15	2819	-	3594	0.628	100.5			11.08	-	1.60	1567	5.40	-235.0		3.00	21.08	3.70	4.21	-	-
	15'	2677	2412	3554	0.646	99.2	95.2	24.56	9.84	3.71	1.60	1494	5.57	-228.2	13.29	3.00	21.1	3.70	4.21	-11.12	1.9E-06
	10	2142		2260	0.590	75.4			0 / 1	-	1 20	1567	4 10	225.0		2.00	15.60	2.57	4.01		
	10	2142		3300	0.300	73.4	-		0.41		1.20	1307	4.10	-233.0	-	5.00	15.00	5.57	4.01	40.00	-
	10'	2033	1805	3327	0.598	74.5	73.9	25.31	7.84	4.53	1.20	1490	3.92	-228.2	13.60	3.00	15.7	3.57	4.01	-10.89	1.5E-06
	29	4200	-	3562	0.665	160.0	-	-	15.83	-	2 70	1396	9 20	-220.0	-	3.00	37 55	4 26	4 75	-	_
	204	4100	2000	2772	0.710	160.0	154 4	24 41	15 14	2.04	2 70	1200	10.96	220.1	12 20	2.00	25.2	4.26	4 75	11 05	2 7E 06
	29A	4190	3609	3113	0.710	100.9	104.4	24.41	15.14	3.04	2.70	1390	10.00	-220.1	15.59	3.00	30.3	4.20	4.75	-11.00	2.7E-00
	29	4165	3801	3607	0.687	161.8	155.9	23.48	14.89	3.85	2.70	1396	11.50	-220.0	13.37	3.00	37.6	4.26	4.75	-11.80	2.8E-06
	24	3675	-	3524	0.655	139.3	-	-	14.40	-	2.35	1396	8.00	-220.0	-	3.00	32.35	4.05	4.58	-	-
sp	24A	3681	3325	3764	0 703	140.3	136.0	24 45	13.98	2 52	2.36	1396	8.98	-220 1	13 27	3.00	30.1	4 05	4 58	-11 64	2 4F-06
Ū.	24	2600	2202	2500	0.070	144 4	120.5	22.40	10.00	2.52	2.00	1200	0.00	200.1	12.27	2.00	20.4	4.05	4.50	11.04	2.72-00
С С	4	3060	3322	3280	0.678	141.4	136.5	23.26	13.75	3.59	2.36	1396	9.46	-220.1	13.24	3.00	32.4	4.05	4.58	-11.59	2.5E-06
š	19	3149	-	3473	0.641	118.5	-	-	12.90	-	2.00	1396	6.80	-220.0	-	3.00	27.11	3.87	4.41	-	-
8	19A	3140	2818	3666	0.682	119.1	112.6	24.53	12.39	2.48	2.00	1396	7.09	-220.0	13.22	3.00	25.5	3.87	4.41	-11.41	2.1E-06
30	10	3120	2814	3510	0.661	110.8	112.0	23 34	12 21	3 54	2 00	1305	7 4 2	-220.0	13 20	3.00	27.2	3.87	4 4 1	-11 47	2 2E-06
ĩ	13	5120	2014	3310	0.001	119.0	112.0	23.34	12.21	3.54	2.00	1000	7.42	-220.0	13.23	3.00	21.2	0.70	4.41	-11.47	2.2L-00
	14	2544	-	3391	0.620	94.8	-	-	11.08	-	1.60	1396	5.40	-220.0	-	3.00	21.08	3.70	4.21	-	-
	14	2522	2257	3438	0.641	96.0	91.8	24.57	9.87	3.82	1.60	1397	5.44	-220.3	13.25	3.00	21.1	3.70	4.21	-11.10	1.9E-06
	9	1936	-	3170	0.571	71.1	-	-	8.41	-	1.20	1396	4.10	-220.0	-	3.00	15.68	3.57	4.01		-
	0	1010	1601	3220	0.504	72.1	70.3	25.25	7.85	4 58	1 20	1305	3.86	210.0	13.68	3.00	15.7	3.57	4.01	10.03	1.5E.06
-	9	1919	1091	5220	0.334	12.1	10.5	23.23	1.05	4.50	1.20	1393	3.00	-219.9	13.00	5.00	13.7	3.57	4.01	-10.95	1.3L-00
	· · · · ·	-		-	-	r		<b>.</b>						-	-		r		r		
	28	3612		3271	0.653	147.0			15.83		2.70	1179	9.20	-200.0	-	3.00	37.55	4.26	4.75	-	-
	28A	3608	3218	3468	0.698	147.9	143.1	24.64	15.40	3.11	2.70	1179	11.18	-200.2	13.30	3.00	35.3	4.26	4.75	-11.77	2.7E-06
	28	3587	3215	3318	0.675	1/18 8	1111	23.63	15 15	3 00	2 70	1170	11 78	200.1	13 31	3.00	37.6	1 26	1 75	11 72	2.85.06
	20	3307	3213	3310	0.075	140.0	144.4	23.03	13.13	3.30	2.70	1173	11.70	-200.1	13.51	3.00	37.0	4.20	4.75	-11.72	2.0L-00
s	23	3163	-	3236	0.642	127.9	-	-	14.40	-	2.35	1179	8.00	-200.0	-	3.00	32.35	4.05	4.58	-	-
5	23A	3176	2811	3461	0.690	129.0	125.7	24.78	14.20	2.63	2.36	1178	9.13	-200.1	13.26	3.00	30.1	4.05	4.58	-11.61	2.4E-06
8	23	3155	2811	3293	0.666	130.0	128.1	23.48	13.96	3.65	2.36	1179	9.49	-200.2	13.23	3.00	32.4	4.05	4.58	-11.54	2.5E-06
ĕ	19	2713	2011	3180	0.627	108.0	120.1	20.10	12.00	0.00	2.00	1170	6.80	200.0	10.20	3.00	27.11	3.87	1.00		2.02 00
ő	10	2713	-	5105	0.027	100.5		-	12.30	-	2.00	1173	0.00	-200.0	40.00	5.00	21.11	5.07	4.41		-
õ	18A	2718	2387	3373	0.668	109.6	103.6	24.72	12.72	2.51	2.00	1180	7.10	-200.0	13.23	3.00	25.5	3.87	4.41	-11.39	2.1E-06
Ϋ́	18	2695	2382	3229	0.648	110.3	104.5	23.45	12.45	3.57	2.00	1179	7.36	-200.2	13.19	3.00	27.2	3.87	4.41	-11.32	2.2E-06
(	13	2196	-	3114	0.606	87.1	-	-	11.08	-	1.60	1179	5.40	-200.0	-	3.00	21.08	3.70	4.21	-	-
	13	2178	1008	3161	0.628	88.2	8/ 0	24 68	10.01	3.84	1.60	1170	5.40	200.1	13 20	3.00	21.1	3 70	1 21	11.01	1.8E.06
	13	2170	1900	3101	0.020	00.2	04.9	24.00	10.01	3.04	1.00	1173	J.40	-200.1	13.20	3.00	21.1	3.70	4.21	-11.01	1.02-00
	8	1675	-	2911	0.557	65.3	-	-	8.41	-	1.20	1179	4.10	-200.0	-	3.00	15.68	3.57	4.01	-	-
	8	1661	1432	2963	0.581	66.4	65.5	25.27	7.93	4.67	1.20	1179	3.79	-200.1	13.58	3.00	15.7	3.57	4.01	-10.85	1.5E-06
	27	3184	-	3041	0.640	136.6	-	_	15.83	_	2 70	1021	9.20	-175.0	-	3.00	37 55	4 26	4 75	_	_
	074	0404	0700	0000	0.001	407.7	405.0	04.00	45.70	0.44	2.70	4000	44.00	475.4	40.00	0.00	05.0	4.00	4.75	44.70	0.05.00
1	2/A	3191	2790	3229	0.684	13/./	135.2	24.93	15.72	3.11	2.70	1020	11.68	-1/5.1	13.30	3.00	35.3	4.26	4./5	-11.72	2.0E-06
	27	3172	2790	3090	0.663	138.6	137.2	23.84	15.48	3.90	2.70	1021	12.08	-175.0	13.29	3.00	37.6	4.26	4.75	-11.67	2.8E-06
	22	2791	-	3008	0.628	118.9	-	-	14.40	-	2.35	1021	8.00	-175.0	-	3.00	32.35	4.05	4.58	-	-
sp	224	2817	2441	3225	0.675	120.2	114 5	25 12	14 45	2.64	2.36	1021	0.32	-175 1	13 30	3.00	30.1	4.05	4 58	-11 61	24E-06
Ū.	227	2700	2441	2000	0.073	101.2	145.0	20.12	14.40	2.04	2.00	1021	0.02	475.0	12.00	2.00	20.1	4.05	4.50	44.47	2.70-00
ŏ	22	2793	2441	3069	0.653	121.2	115.9	23.71	14.19	3.68	2.36	1022	9.66	-1/5.0	13.20	3.00	32.4	4.05	4.58	-11.47	∠.5E-06
ŝ	17	2396	-	2965	0.614	101.2	-	-	12.90	-	2.00	1021	6.80	<u>-175.</u> 0	-	3.00	27.11	3.87	4.41	-	-
8	17A	2408	2069	3141	0.654	102.1	98.6	24.88	12.96	2.56	2.00	1021	7.24	-175.1	13.25	3.00	25.5	3.87	4.41	-11.38	2.1E-06
ž	17	2388	2067	3008	0.635	102.7	98.3	23.67	12 72	3 56	2 00	1021	7 40	-175 1	13 20	3.00	27.2	3.87	4 4 1	-11 26	2 2E-06
ĩ		1040	2007	2000	0.000	04.0	30.3	20.07	14 00	0.00	2.00	1021	F 40	475.0	10.20	2.00	21.2	0.07	4.04	11.20	2.22-00
1	12	1942	-	2095	0.092	01.0	-	-	11.08	-	1.00	1021	5.40	-1/5.0	-	3.00	21.08	3.70	4.21	-	-
1	12	1931	1656	2945	0.615	82.2	80.0	24.80	<u>10.1</u> 8	3.94	1.60	1021	5.39	<u>-175.</u> 1	<u>13.2</u> 0	3.00	21.1	3.70	4.21	-10.96	1.9E-06
	7	1485	-	2706	0.543	60.7	-	-	8.41	-	1.20	1021	4.10	-175.0	-	3.00	15.68	3.57	4.01	-	-
1	7	1475	1243	2760	0.568	61.8	62.2	25 31	8 02	4 76	1 20	1021	3 76	-174 0	13 72	3.00	15.7	3 57	4.01	-10.88	1 5E-06
-	. '	1775	1273	2700	0.000	01.0	02.2	20.01	0.02	- <del>1</del> .70	1.20	1021	0.70	17-3	10.12	0.00	10.7	0.01	1.01	10.00	1.52-50
1																					
Ş	5	1279	-	2464	0.522	55.3	-	-	8.41	-	1.20	850	4.10	-125.0	-	3.00	15.68	3.57	4.01	-	-
õ	5	1275	1039	2524	0.548	56.5	57.5	25.43	8,20	4.77	1.20	851	3,86	-125.1	13.50	3.00	15.7	3.57	4.01	-10.65	1.5E-06
Ц,	-	1070		2100	0.405	40.2	<u> </u>		0 44		1.00	670	4 40	115.0		2.00	15.00	2 57	4.04		
ş		1073	-	2198	0.495	49.3	-	-	0.41	-	1.20	0/9	4.10	-115.0	-	3.00	10.08	3.37	4.01	-	-
1	3	1076	834	2261	0.523	50.6	51.9	25.44	8.41	4.75	1.20	680	4.00	-115.2	13.48	3.00	15.7	3.57	4.01	-10.65	1.5E-06

 Table 2-5:
 LM4 telemetry and performance data (including measured thrust) in black. Also shown are the NASA GRC EM1 telemetry and performance data (shown in blue) for comparison. Prime marker indicates approximate throttling level matching (except for screen and accelerator voltages).

### 2.2.6 LM4 Modifications

Following the initial characterization testing, the LM4 anode was modified by University of Michigan technicians for electrostatic probe access to the discharge chamber via slots in the side of the anode, shown in Figure 2-25. Slots were cut in the anode side and top for probe access and alignment of the probe to the discharge cathode assembly, respectively. Flanges were mounted to the slots permitting axial motion perpendicular to the flange open end and allowing easy transition between probe interrogation hardware and future LIF windows.



Figure 2-25: Schematic illustrating the modifications made to the LM4 discharge chamber (top view) permitting electrostatic probe access to the near-DCA region and the downstream discharge plasma.

The modifications are illustrated in Figure 2-26. The slots were cut into two of the four marked locations (four slots recommended for the LIF measurements) and the mating flanges mounted to the anode. Mating flanges contain external mounting holes to which the discharge plasma containment mechanism is attached.



Figure 2-26: Photographs of the LM4 discharge chamber modifications: mounting flange hardware and slots removed (left) and a side view of the reassembled thruster illustrating the discharge cathode location with discharge plasma containment mechanism removed (right).

# 2.3 SKIT-Pac and Mass Flow

In addition to the FMT2 and LM4 thrusters, NASA GRC provided a stationkeeping ion thruster package (SKIT-Pac) power processing and control rack, shown in Figure 2-27. The SKIT-Pac, located in the PEPL control room, includes control-logic for recovering from a thruster 'recycle' event. A high-voltage thruster 'recycle' is initiated when either a screen or accelerator grid overcurrent is sensed (due to an grid-to-grid arc). Once the recycle is initiated, the power to both the high voltage supplies is interrupted (removing the high voltage on the grids). Concurrently, the discharge current is commanded down to some reduced level (set by the user on the SKIT-Pac panel) to decrease the ion production rate in the discharge chamber. Without this decrease in discharge current a 'recycle' event would cause a momentary buildup of plasma inside the discharge that, upon reactivation of beam extraction, could lead to a surge in current to the grids and thus lead to subsequent repeated recycles. At this point the power is restored to the high-voltage supplies (*i.e.* the voltage is reapplied to the ion optics grids) with the accelerator grid voltage recovery leading the screen supply to prevent electron backstreaming. As the high-voltage is reapplied to the grids, the discharge current is increased back to the original set-point, and a beam is extracted. The total "recycle" time from the detection of the short to the resumption of high voltage is approximately one second.



Figure 2-27: Station-Keeping Ion Thruster Package (SKIT-Pac) power supply console and control logic.

An electrical diagram of the power supply connections to both the FMT2 and LM4 thrusters is shown in Figure 2-28. Not shown are the cathode heater supplies, which are only energized during cathode ignition. The discharge keeper is electrically tied to the anode through a 1-k $\Omega$  resistor that assists in starting of the cathode, while drawing negligible current during thruster operation. The neutralizer to ground coupling voltage is restricted to  $\pm$  30 volts using clamping diodes.



Screen grid electrically connected to discharge cathode common

Figure 2-28: Electrical block diagram of SKIT-Pac / ion thruster power connections (not shown are heater supplies used during cathode ignition only). High-voltage leads and components are in red and orange.

Throughout the ion engine testing program at PEPL, the protocols for cathode hardware, based on the Plasma Contactor Development Program for the International Space Station, were followed.^{79-81,112,113} The cathodes were kept on nitrogen purges in a downdraft cleanroom when not in use. High-purity 99.995% research grade xenon

propellant was used during testing. The propellant feed system consists entirely of welded and metal seal (VCR) gaskets on all exterior tubing. Electropolished stainless steel tubing was baked out and leak checked after exposure to vacuum (*i.e.* xenon bottle change or feed system modifications). The three feed lines to the thruster incorporated individual commercial MKS Model 1159B mass flow controllers to set and measure the propellant mass flow rate. The accuracy of the flow controllers are  $\pm 0.1$  sccm for the cathodes and  $\pm 1$  sccm for the main plenum. The flow controllers are repeatable to  $\pm 0.02$  sccm for the cathodes and  $\pm 0.2$  sccm for the main plenum. Each controller was calibrated using a known volume technique prior to testing. At full power, the NSTAR and NEXT propellant distributions are approximately 80% through the discharge plenum, designated as "main flow," with approximately 10% through each hollow cathode. The SKIT-Pac and flow controllers were manually operated throughout testing and all data were recorded from calibrated digital displays.

Thruster telemetry is measured using twelve Fluke 77 III multi-meters, which measure currents and voltages supplied to the ion engines at the vacuum chamber flange, illustrated in Figure 2-28. A high-voltage AVO BM25 Megger was used to measure thruster component-component and component-ground impedances. Typical resistance values between the various engine components, including facility ground, for the both thrusters were tens of giga-ohms.



Figure 2-29: Electric schematic of the ion thruster telemetry measured with calibrated digital multimeters.

High-voltage, low-pressure propellant isolation is accomplished for both thrusters with the use of cryogenic electrical breaks for the cathodes and viton tubing for the main plenum line. One cryobreak was sufficient for the small voltages between the NSTAR and NEXT neutralizers with respect to facility ground (referred to as the coupling voltage). To maintain isolation of the discharge cathode, a series of cryobreaks were assembled in a twisting configuration to form a tortuous path for electrical breakdown. The viton tubing also follows a zigzag pattern creating a difficult path for electrical breakdown. The NSTAR SKIT-Pac was used to run the 40-cm engine, though it was designed for the NSTAR thruster power levels. This permits LM4 engine operation over approximately half of the design throttling table. The discharge and beam power supplies of the SKIT-Pac are the limiting components in this case. It was not feasible to rebuild the SKIT-Pac or replace the power console with a NEXT EM power console.

## 2.4 Discharge Cathode Assemblies

Concurrent with the development of ion thruster systems was the hollow cathode plasma contactor investigations for space station applications. The desire to eliminate potentially deleterious interactions of the large negative potential surfaces of the space station with the ambient space plasma spurred the plasma contactor development. The plasma contactor controls spacecraft potential by establishing a low-impedance plasma bridge with the local space plasma. Hollow cathode plasma contactors are well suited for this application due to their demonstrated low-impedance, high-current capability and their self-regulating emission control. The dual-use technology of hollow cathodes allowed extensive development and testing efforts benefiting both applications. These investigations led to more efficient hollow cathode designs as well as handling and operating protocols to reduce contamination, thereby extending hollow cathode lifetime.



Figure 2-30: Space station plasma contactor system design (left) and the plasma contactor hollow cathode enclosed in a guard (right). Both photographs are used with permission by NASA GRC.

Design specifications of the hollow cathodes used in this investigation will not be discussed due to an agreement with NASA GRC. Hollow cathodes are thermionic devices used to emit electrons. The hollow cathode designs in this investigation consist of a high-temperature metal (molybdenum-rhenium alloy) tube with a thoriated tungsten orifice (chamfered) plate electron-beam welded to one end. This restricting plate increases the local pressure at the emitter, which serves to lower the voltage requirements for the electrical discharge. The insert, a sintered tungsten cylinder impregnated with a low work function material, is inserted into the tube. A helical-wound sheathed tantalum heater, used to enhance electron emission for cathode activation and ignition, is friction-fitted on the outside of the body tube, over the region occupied by the insert. Layers of Ta foil are tightly wrapped around the heater to reduce radiated power losses and thus enhance heater operation. Once a stable discharge has been established, ion bombardment of the emitter surface sustains the cathode temperature without use of the heater.

The emission of thermionic electrons from the insert creates a negative charge density adjacent to the cathode surface; *i.e.*, a plasma sheath. Ions from the cathode

internal plasma are accelerated radially towards the insert by radial electric field. The collisions of the ions with the insert surface heat it to sustain the discharge. Thermionic electrons are accelerated away from the insert by the negative sheath and comprise a high-energy component within the cathode referred to as primary electrons. The primary electrons are responsible for the bulk of the ionization within the cathode by electron impact ionization and step-wise excitations. The primary electrons become thermalized by these collisions and are accelerated toward the axis and the orifice by the electric field.

A double sheath forms at the boundary of the insert and orifice regions. Electrons are accelerated into the orifice region by this sheath, while ions in the orifice region are accelerated toward the insert region. While most ions recombine at the orifice wall, ions undergo ambipolar diffusion towards the orifice-insert double sheath as well as toward the discharge plasma. As a result some ions are emitted from the cathode. The ions born in the orifice region, due to electron collisions of neutrals, maintain quasineutrality reducing the space-charge effect. Detailed discussions of internal hollow cathode operation is beyond the scope of this investigation and can be found in References 143, 144, 147, and 170-172. Several NSTAR flight cathodes are illustrated in Figure 2-31.



Figure 2-31: NSTAR flight hollow cathode assemblies (used with NASA GRC permission).

The protocols for handling and operation of hollow cathodes, developed from the space station plasma contactor investigations, have been followed throughout this investigation.⁷⁸⁻⁸⁰ When not in use, the hollow cathodes were kept on nitrogen purges. Following exposure to atmosphere of the xenon feed system, typically due to xenon bottle change-out, the entire feed system was exposed to vacuum and completed a 24-hour bake-out procedure. A 24-hour leak-rate test was then performed to verify system integrity. Prior to cathode activation, the hollow cathodes were exposed to high-vacuum (base pressures less than  $5x10^{-6}$  Torr) for at least 12 hours. A multi-step cathode conditioning procedure was used to remove absorbed carbon dioxide and water while preparing the insert surface for electron emission.

The two major electron emission regimes of orificed hollow cathodes are spot and plume modes. Spot-mode emission is characterized by a low coupling voltage to the anode, negligible ac components of discharge voltage and current, and a bright plasma "spot" at the cathode orifice plate. Plume-mode emission is characterized by a slightly increased coupling voltage, large ac components of discharge voltage ( $\pm$  5 V) and current, and a plasma plume downstream of the cathode. The larger coupling voltage and increased ac components of plume-mode operation increase wear on the cathode orifice plate due to energetic ion bombardment. Thus, it is advantageous to maintain operation in spot-mode in order to extend cathode life.

A better understanding of the differences between spot and plume modes of operation can be found when considering the plasma in the cathode-to-keeper region. If the current density of ions emitted from the orifice is sufficient to maintain quasineutrality, then electrons readily stream toward the keeper due to the slight axial electric field. This condition is satisfied during spot-mode operation. As the flow rate is decreased for a given emission current, the ion current density in the insert region is decreased. The sheaths must grow in order to draw the electrons to the keeper resulting in the luminous plume. The phenomena account for the visual differences between spot and plume mode operation.

The FMT2 discharge cathode, NSTAR-design hollow cathode, is enclosed in a concentric cylindrical molybdenum keeper electrode that is electrically isolated from the cathode common. The FMT2 discharge cathode keeper consists of a Mo structure similar to those employed on the EMT's. An additional upstream flange to the keeper assembly was installed to facilitate removal for servicing during William's LIF characterization (Figure 2-32). The keepered FMT2 neutralizer cathode is a laboratory-model plasma contactor.



Figure 2-32: Photograph of the FMT2 DCA keeper assembly with additional flange

The LM4 discharge cathode is a mechanical laboratory design incorporating a cathode tube with twice the diameter of the NSTAR discharge cathode (Figures 2-33 and 2-34).⁵² The discharge cathode is enclosed in a concentric molybdenum cylindrical keeper electrode similar in design to the NSTAR thruster discharge cathode. The LM4 neutralizer is similar to the NSTAR design and has the enclosed-keeper geometry shown in Figure 2-35. The critical dimensions for the LM4 cathode (internal emitter dimensions, cathode and keeper orifice plates, etc...) have been adjusted from the NSTAR design to accommodate the higher emission current requirements for the 40-cm NEXT engine. The NEXT cathode designs satisfy the emission requirements at reduced ratios of propellant flow rate-to-emission current.



Figure 2-33: Schematic of a NEXT DCA (not drawn to scale).



Figure 2-34: 40-cm laboratory-model discharge cathode design (left) and the LM4 discharge cathode assembly (right).



Figure 2-35: LM4 neutralizer cathode design shown with mounting bracket.

# **CHAPTER 3**

# **PROBE THEORY AND ANALYSIS**

Electrostatic probes have been used extensively to measure plasma parameters since their inception. Langmuir probes, named after the pioneering work of Irving Langmuir, are one of the oldest and widely used probes in plasma characterization. The single Langmuir probe consists of a single electrode connected to an external electrical circuit that varies the probe voltage, V, with respect to the local plasma. Appropriate analysis of the resulting "cold" electrostatic probe current-voltage (I-V) characteristic accurately provides multiple plasma parameters. "Hot" electrostatic probes, or emissive probes, are heated filament loops that, when inserted into the plasma at sufficient filament temperature, yield the local plasma potential.

## 3.1 Single Langmuir Probe

The most basic plasma diagnostic tool is the single Langmuir probe, first applied by Irving Langmuir and collaborators.^{173,174} Measurement of the probe bias voltage and collected current are plotted giving the current-voltage characteristic (I-V curve). The ease at which the data are taken, by biasing the probe with respect to another electrode (vacuum chamber, cathode common, anode, secondary electrode, etc...) and measuring the current to the probe, is offset by the difficulty in interpreting the resulting currentvoltage (I-V) characteristic curve. The interpretation of the I-V curves is complicated by multiple regimes of operation, the flowing plasma effects, and large magnetic fields. Probe theory creates a connection between the measured current-voltage characteristic and parameters of the undisturbed plasma. Selection of the most applicable analysis can yield dependable results. Langmuir probe configurations consist of single, double, triple, and even quadruple electrodes. Each configuration has its own benefits and drawbacks. The restriction of independent electrode sheaths of the Langmuir probe designs eliminated triple and quadruple probes as candidates for the near-DCA interrogation where a spatial resolution of 1 mm or smaller is required. As will be illustrated, even the symmetric double probe resolution is insufficient immediately downstream of the DCA.

### 3.1.1 Single Langmuir Probe Theory of Operation

A single Langmuir probe diagnostic was designed to acquire discharge plasma measurements for various operating conditions of both the FMT2 and LM4 ion engines. The single Langmuir probe will allow the highest spatial resolution compared to multiple electrode configurations. The single Langmuir probe theory is widely used and allows calculation of the fundamental local plasma parameters of interest, namely the number density, electron temperature, floating potential, and the plasma potential. Furthermore, the single Langmuir probe has the potential to allow for the extraction of the primary electron number density and energy provided a reliable analysis method can be

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determined. The primary electrons are those that have been accelerated by the electric field between the cathode and the discharge plasma and have not undergone an ionizing impact. The second electron population consists of electrons that result from the ionization events, namely thermalized, Maxwellian electrons.

Langmuir probes measure local plasma parameters and are effectively shielded by the plasma particles when inserted into the plasma. Langmuir probe theory is divided into different probe regimes based upon two non-dimensional parameters: the Knudsen (K_n) number and the Debye length ( $\lambda_D$ ). The first regime distinction is collisionless or continuum and is related to the Knudsen number. The Knudsen number, defined in Eqn. 3-1, relates the mean free path of charged particles to the probe radius. The mean free path of ions and electrons in the discharge chamber of ion engines is on the order of meters, which is larger than the physical dimensions of the discharge chamber and is much larger than the fraction of a millimeter sized probes used for this investigation. For K_n >> 1, a collisionless analysis is appropriate.

$$K_n \equiv \frac{\lambda}{R_p}$$
 Eqn. 3-1

The ratio of the Debye length, given in Eqn. 3-2, to probe radius determines the sheath analysis used. The electrostatic probes traverse two distinctly different plasmas inside the ion thruster discharge chamber resulting in two different sheath regime analysis techniques as discussed in §3.1.5. In both analyses, particles are assumed to be collected without reflection or reaction inside the electrode collection area and cold ions are

assumed with  $T_i \ll T_e$ . The latter assumption is supported by Williams' LIF measurements indicating ion temperatures of 0.4 - 1.3 eV inside the FMT2.^{48,132}

#### **3.1.2 Single Langmuir Probe Tips**

While probes always perturb their surroundings, the extent of the perturbation is minimized by making the electrode as small as possible. The use of miniature probes facilitates the need to maintain adequate spatial resolution while decreasing the probability of probe destruction due to excessive thermal exposure. A balance must be made between minimizing probe size and maintaining measurable ion saturation currents based on predicted plasma parameters. Since the exact plasma parameters were not known a priori, estimated parameters were initially used and the probe designs were iterated once measured values were available.

Based upon the available data inside discharge chambers of ion engines, the expected electron temperatures and number densities range from  $(2 - 11 \text{ eV})^{134,170}$  and  $(10^{10} - 10^{12} \text{ cm}^{-3})$ ,^{134,140} respectively. The electrode of the single Langmuir probe operates in the thin sheath regime near the discharge cathode where the number densities are highest. Inside the ion engine, the number densities are expected to have a maximum on cathode centerline and decrease by over two orders of magnitude with increasing radial distance from centerline, driving an ever-increasing Debye length. The size of the sheath that forms around the probe is proportional to the Debye length and is the reason Debye

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length is important for determining the probe operating regime. The relationship of the Debye length to electron number density and temperature is illustrated in Eqn. 3-2:^{175,176}

$$\lambda_D = 743 \sqrt{\frac{T_{eV}}{n_e}}$$
 Eqn. 3-2

In the thin sheath regime, the flux of particles entering the sheath can be calculated without considering the details about the orbits of these particles in the sheath.^{173,177-179} In this case, the collection area of the electrode is approximated as the area of the electrode, which is justified for a large ratio of probe radius, r, to Debye length,  $\lambda_D$ .^{173,177,179} However, the rapid growth in the Debye length with increasing radial distance from cathode centerline dictates that at some radial location inside the anode, the thin sheath criterion may not strictly apply. The Debye length is expected to grow to the same order of magnitude as the electrode radius near the anode, indicating operation in the transition range between the thin sheath and orbital motion limited (OML) regimes.^{177,180,181} All measured number densities are corrected to account for a growing sheath. In spatial regions near the anode, number densities were low enough for a complete OML analysis to be applicable.

Several Langmuir probes were used due to breakage of probes caused by mechanical malfunction or user input error. All probes were slight variations on the basic probe design, illustrated in Figure 3-1. The basic design consists of either a 0.13 or 0.18mm-diameter cylindrical tungsten electrode, with ~2 mm of exposed length. A large length-to-diameter ratio was selected to minimize end effects. The electrode is held inside a double-bore piece of 99.8% pure alumina epoxied to a larger double-bore piece of 99.8% pure alumina. The ceramic probe material and tungsten filament were necessitated by the high-temperature discharge plasma environment. The total length of the probe is approximately 0.5 m.



Figure 3-1: Schematic illustrating the single Langmuir probe tip design.

After the probes were constructed, each was inspected under magnification to ensure cylindrical geometry. The probe tip electrodes were measured with a digital caliper and double checked under magnification.

### 3.1.3 Single Langmuir Probe Circuit and Electronics

When the probe is swept into the discharge chamber, from the very low-density near-anode plasma to the high-density discharge plasma plume, there is a rapid increase in plasma potential up to 1100 V above ground for the FMT2 and up to 1500 V for the

LM4. Significant errors in the measured current can occur due to any appreciable stray capacitance in the circuit. As such, careful attention is paid to minimizing stray capacitance in the circuit design including the use of batteries to supply the bias voltage. Several different configurations, including different battery types, were used during this investigation. The arrangement, number of batteries, and types of batteries had a negligible effect on the data collection provided they could provide up to 60 volts bias (to ensure ion saturation) and tens of milli-amperes of current (the highest ion saturation current). A potentiometer attached to the battery output sets the electrode bias voltage.

The Langmuir probe circuit employs a modified version of a double probe circuit previously used at PEPL to measure plasma parameters inside a Hall thruster discharge channel.^{23,182} The circuit is built around two Analog Devices AD210 wide-bandwidth isolation amplifiers that are capable of handling up to 2500 volts of common mode voltage, providing an input impedance of  $10^{12} \Omega$ , and a full-power bandwidth of 20 kHz. The low-impedance output (1  $\Omega$  maximum) is connected to a Tektronix TDS 3034B digital oscilloscope that acquires the I-V data. Figure 3-2 illustrates the single Langmuir probe circuit. All connections extending outside the vacuum chamber were made using high-voltage (5 kV) SHV coaxial cables and feedthroughs.



Figure 3-2: Single Langmuir probe circuit design used in LM4 experiments. The FMT2 investigation utilized a 4 k $\Omega$  resistor across the probe bias isolation amplifier.

### 3.1.4 Data Acquisition

Single Langmuir probe measurements are made using a LabVIEW code incorporating the various translating stages, controlled via GPIB connections, and the probe positioning system. For the FMT2 investigation, a NEAT RMS-800 stage was used to prevent the buildup of loads on the discharge plasma containment sheet and to reduce the length of alumina protruding into the discharge. The LabVIEW code steps through the full axial range of motion starting ~1.5 mm downstream of the DCA exit plane. During the FMT2 investigation the axial step size (resolution) is 1.5 mm. This step size is selected to maximize spatial resolution of the discharge plasma structures while maintaining reasonable data collection times. The step size in the axial direction is approximately the same size as the electrostatic probe geometry that determines the radial resolution. The center of the single Langmuir probe electrode is taken as the probe position indicating a position error of  $\pm 1$  mm. The axial step size was reduced during the LM4 data acquisition to resolve the plasma parameters near the DCA better. Electrode bias voltages, referenced to discharge cathode common, are manually set using a potentiometer and the battery supply. The probe is then swept through all spatial locations. The bias voltage setting, which ranges  $\pm 80$  volts if saturation current does not exceed isolation amplifier input, is then manually changed and the process is repeated until the full voltage range from ion saturation to electron saturation is covered. Bias voltage settings were increased approximately 1-2 V in the electron collecting region of the current trace and increased to as much as 10 V in the saturation regions to decrease the data collection time.

Only data taken on the "in sweep" of the probe are analyzed as "out sweep" data are more likely to be affected by probe perturbation. The discharge current perturbation induced by the probe is measured using a Hall probe, in conjunction with the Tektronix TDS 3034B oscilloscope. The maximum discharge current perturbation is approximately 5 - 10% of the nominal value when the probe is positioned directly in front of the DCA plume and is undetectable when the probe is outside of the discharge cathode plume. The highest percentage perturbation occurred at the lowest discharge current setting. The perturbation appeared to be caused by the physical insertion of probe material in front of the narrow plume.

The ion thrusters are allowed a minimum half an hour at the operating condition investigated prior to initiation of data collection. The typical data collection time is one hour for each operating condition. In order to maintain discharge voltage and beam current, the cathode and main flow rates are occasionally adjusted (by a few percent)

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during data collection. The maximum and minimum flow rates during data collection are recorded, with the nominal value reported.

### 3.1.5 Single Langmuir Probe Analysis Techniques

The scientific graphing package Igor is used to analyze the data. The data are read into Igor, which reassembles the data into individual characteristics at discrete spatial locations in the two-dimensional grid, readily giving point-by-point I-V curves illustrated in Figure 3-3. For each operating condition, I-V curves were attained every 1 mm in the radial direction. The axial resolution was increased from 1.5 mm for FMT2 to 1 mm for LM4. The data collected for each thruster resulted in 3,550 I-V traces for the FMT2 thruster and 9,240 I-V traces for the LM4 engine. The data analysis gives plasma parameters for each of these characteristics outputting contour images with a corresponding number of data points.



Figure 3-3: Sample current-voltage characteristic (I-V) curve reconstructed at specific spatial locations in the discharge chamber and serves as the starting point for the Langmuir probe data analysis.

The theoretical probe current voltage characteristic is illustrated in Figure 3-4, and can be explained as follows. The I-V characteristic can be divided into three separate regions, labeled I, II, and III. For large negative bias voltages (I), with respect to the local plasma, essentially all electrons in the vicinity of the probe are repelled. The electric current to the probe consists almost entirely of the ion current, which is on the order of the natural ion diffusion current. Although the ion current will typically increase for larger negative bias voltages due to sheath expansion, this branch is referred to as the "ion saturation" current.

As the probe negative bias voltage is decreased in magnitude, approaching point (a), the most energetic electrons in the plasma are able to overcome the retarding electric field contributing to an electron current component. As the probe bias is further made less negative, a condition is reached where the electron current collected exactly balances the ion current. This point is called the floating potential, designated  $V_f$ . In region (II), the electron repelling region, the probe bias is still negative of the local plasma potential, but the probe increasingly attracts more electrons as the bias is increased. If the electron distribution is Maxwellian, the shape of region (II), after the ion contribution is subtracted, would determine the local plasma electron temperature.

Near the plasma potential,  $V_p$ , the electric field approaches zero and the electron current increases to its natural diffusive value, which is on the order of  $(M_iT_e/m_eT_i)^{1/2}$  times the ion saturation current. For probe bias positive of the local plasma potential, the probe current increases slowly as ions are repelled and electrons are accelerated to the probe. Though the electron current continues to increase past the plasma potential due to sheath expansion, region (III) is often referred to as the "electron saturation" region. Because the electron saturation is much larger than the ion saturation current, which is used to calculate ion number density, the isolation amplifiers limited the I-V curves below electron saturation in the high-density region near the DCA.



Figure 3-4: Typical current vs. voltage (I-V) characteristic for single Langmuir probe operation.

The relative sheath thickness compared to the probe radius is not known a priori; as a result, the data analysis code developed uses a multiple regime approach in the number density calculation. Initially a thin sheath calculation is made with the probe collection area equal to the electrode surface area. The actual sheath size is calculated based upon the measured plasma parameters and the probe collection area is increased, resulting in a new number density. This iterative process continues until convergence. This procedure takes into account moderate departure from the thin sheath assumption. Far from the DCA, a thick sheath exists and an orbital-motion-limited analysis is applicable. Between the two regimes, a transition approximation is used.

Far from the DCA, an orbit-motion-limited (OML) calculation is made to give the ion number density. In the OML regime, ion orbits become important. Not all particles that enter the electrode sheath are collected. Particles can enter trapped orbits or enter and then exit the sheath. Between the two regimes, in the transition regime, a weighted

average (based upon the ratio of Debye length to probe radius) is used to give smooth transition between the two regimes. The details of the data analysis steps will be discussed in the subsequent section. The data analysis techniques used in this investigation can be found in References 175, 177-181, 183, and 184. The large electron saturation currents near the DCA, which were not achievable with the given setup, preclude a plasma potential estimation in the DCA plume. In this case, plasma potential data from the floating emissive probe can be supplied for the near-DCA region and a full plasma potential mapping produced.

#### 3.1.5.1 Single Langmuir Probe Thin Sheath Analysis

For a ratio of probe electrode radius to Debye length of greater than or equal to 10, a thin sheath analysis is applicable. The individual Langmuir probe characteristics are analyzed over the 2-D grid assuming a purely Maxwellian electron population. The inverse slope of the natural log of the electron current versus voltage gives the Maxwellian electron temperature.

The ion saturation current, the electron temperature, and the Bohm condition for ion velocity readily give the ion number density by Eqn. 3-3.^{173,175,176} The Bohm condition establishes that, for ion-attracting probes, electric fields in the quasi-neutral plasma exterior to the sheath (the pre-sheath) accelerate ions such that they enter the sheath with a velocity of  $(kT_e/M_i)^{1/2}$ . The ions must reach the Bohm velocity in order to

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establish a stable sheath.¹⁸⁵ Assuming a quasi-neutral discharge plasma, the ion number density gives the total electron number density

$$n_i = \frac{I_{sat}}{0.61A_s q} \sqrt{\frac{M_{Xe}}{T_{eV}}}$$
. Eqn. 3-3

In Eqn. 3-3, e is electron charge,  $M_{Xe}$  is the mass of the xenon ion, k is Boltzmann's constant, and  $A_s$  is the electrode collection area that is initially considered to be the electrode surface area. The true collection area depends upon the thickness of the sheath surrounding the probe. The electron temperature and the initial value for number density allow the Debye length to be calculated according to Eqn. 3-2. Assuming quasineutrality  $n_e \approx n_i$  (in cm⁻³) gives  $\lambda_D$  (cm). The sheath thickness is calculated according to Eqn. 3-4:^{179,180}

$$\delta = 1.02\lambda_D \left[ \left( -\frac{1}{2} \ln \left( \frac{m}{M_{Xe}} \right) \right)^{\frac{1}{2}} - \frac{1}{\sqrt{2}} \right]^{\frac{1}{2}} \left[ \left( -\frac{1}{2} \ln \left( \frac{m}{M_{Xe}} \right) \right)^{\frac{1}{2}} + \sqrt{2} \right]$$
 Eqn. 3-4

and the sheath area follows from Eqn. 3-5:¹⁷⁸

$$A_s = A_p \left( 1 + \frac{\delta}{r} \right).$$
 Eqn. 3-5

A new ion number density is calculated from the new collection area taking into account the slight departure from the thin sheath regime. The iterative process is repeated until convergence to a final number density that accounts for sheath expansion. The number density calculation based upon ion saturation current is more accurate than the number density based upon electron saturation current as the latter is affected by the presence of a magnetic field. Furthermore, the large electron saturation current can severely perturb the discharge plasma, and this measurement could not be completed in regions where the single Langmuir probe circuit prevented electron saturation. The number densities reported are based upon the ion saturation current unless noted. However, for the bulk discharge plasma where the magnetic fields were weaker, the electron saturation current was reached and an electron number density was calculated according to Eqn. 3-6.

$$n_{e} = \frac{I_{elec,sat}}{q(kT_{e}/2\pi m_{e})^{\frac{1}{2}}A_{p}}$$
 Eqn. 3-6

# 3.1.5.2 Orbital Motion Limited (OML)

For a ratio of probe electrode radius to Debye length of less than or equal to 3, the calculation of electron temperature is identical to the thin sheath regime. However, the number density calculation must be made for an infinitely thick sheath. In the OML regime, the number density for cylindrical probes is calculated from the slope of the ion current squared versus bias voltage according to the following equation:^{175,178,183}

$$n_{OML} = \sqrt{\frac{\left(-\Delta (I_i^2) / \Delta V_p\right) \times M_{Xe}}{0.2 \times e^3 \times A_p^2}}.$$
 Eqn. 3-7

#### 3.1.5.3 Transition Analysis

For Debye ratio in the range  $10 > (R_p / \lambda_D) > 3$ , the probe is not operating in either thin sheath or OML regimes. In this case, a weighted average, based upon the ratio of probe electrode radius to Debye length, is used to blend the two regimes. The final iterated thin sheath calculation is used as the input to the weighted average calculations giving smooth transition between the various regimes. More elaborated parametric fitting algorithms have been developed for the transition region based upon the work done by Laframboise.¹⁸⁶ The algorithms were determined to be overly complicated given the number of I-V curves investigated for each operating condition (approximately 3,550 for the FMT2 and over 9,000 for each probe region of the LM4). The various fitting algorithms are discussed in References 183, 184, and 187-189.

#### 3.1.5.4 Dual Primary and Maxwellian Electron Analysis

Several attempts were made to analyze the centerline I-V traces, on-axis with the discharge cathode orifice, assuming a dual primary and Maxwellian electron distribution to obtain primary electron information.^{135,190} Off-centerline I-V curves in the discharge cathode plume revealed extensive noise that precluded the more detailed dual-population analysis. Outside of the discharge cathode plume, it is unlikely that a significant number

of primary electrons can be detected to obtain accurate results using the dual-population analysis. The main benefit of the dual analysis is that it provides additional information about the primary electron energy and primary electron number density. The primary electrons, those that have not undergone an elastic collision after being emitted by the cathode, are thought to be the electron population responsible for the bulk of the ionization in the discharge chamber. Thus, measurement of the primary electron number densities and energies adds to the understanding of the discharge plasma structure.

The dual-population analysis assumes that the electrons in the discharge chamber consist of two distinct populations: monoenergetic primary electrons and Maxwellian electrons. This assumption is a reasonable one based upon the interaction between the discharge cathode, the discharge plasma, and the magnetic field. Physically, the monoenergetic primary electrons are those electrons emitted from the cathode that are accelerated over the full discharge voltage drop and have not yet undergone a collision. Though these primary electrons will have some spread in energy, for simplicity they are assumed to be monoenergetic.

The Maxwellian, or thermalized, electrons are the electrons that have undergone enough collisions to have a Maxwellian distribution of energies. The dual-population method has been applied to plasmas comparable to the ion thruster discharge plasma, which implies that the dual-population is a reasonable assumption.^{135,190} Several attempts were made to fit I-V characteristics with the theoretical current curve for this dual-

population distribution. The current collected consists of a linear monoenergetic primary electron component and an exponential Maxwellian component shown in Eqn. 3-8:¹⁹⁰

$$I = B_1 + B_2 V_{bias} + B_3 \exp^{(B_4 V_{bias})}.$$
 Eqn. 3-8

The graphing package Igor was used to fit Eqn. 3-8 to the measured currentvoltage traces incorporating the nonlinear Levenberg-Marquardt method yielding the Maxwellian and primary plasma parameters. Difficulty fitting the current-voltage characteristics often resulted in non-physical coefficients, implying negative electron temperatures or negative contributions to the electron current by the primary electrons.

A second attempt was made to analyze the I-V data on centerline using a piecemeal approach. The ion saturation current is first subtracted from the probe collected current leaving only the electron component to the I-V characteristic. The primary component of the characteristic is determined by a fit to the linear region near the floating potential of the electron current as a function of voltage. The primary electron current is zero from the plasma potential illustrated by Eqn. 3-9.¹⁹⁰ Although the plasma potential could not be determined from the Langmuir probe data due to a lack of electron saturation, the plasma potentials on centerline were available from emissive probe measurements in the FMT2.¹⁹¹

$$\zeta_p = \phi_p + \frac{B_1}{B_2}$$
 Eqn. 3-9

The primary electron number densities can be calculated according to:

$$n_p = \left[\frac{8m_e}{q\zeta_p}\right]^{\frac{1}{2}} \frac{i_p}{A_s q}$$
 Eqn. 3-10

where i_p is the primary electron current at plasma potential and is found by extrapolating the linear primary fit to the plasma potential value measured by the emissive probe. The primary electron current is then subtracted from the electron current characteristic resulting in the Maxwellian current. The electron temperature is calculated by plotting the semi-log of the resulting Maxwellian current as a function of voltage. Linear fit to the electron repelling region yields the electron temperature. The ion number density, and thus the total electron number density, is found by using the Bohm approximation for the ion velocity,^{173,175,176} given by Eqn. 3-3.

Implementation of the piecemeal analysis technique proved difficult. Probe I-V characteristics often did not have a well defined linear region, thus the arbitrary selection of a range to fit the primary linear region resulted in a wide range of primary electron plasma parameters. Attempts to fit multiple voltage ranges yielded results with extreme sensitivity to the range selected. Inspection of the natural log of current with respect to voltage indicated that the semi-log plot often became more nonlinear after primaries were subtracted. It is possible that more data pairs on the I-V curve, or multiple traces

averaged, could lead to reliable primary electron information. The dual-population results have been omitted due to difficulty in applying the analysis to the data pairs resulting from this experiment. Attempts to directly measure the electron energy distribution functions (EEDF's) were implemented in §3.4.

# **3.1.6 Magnetic Field Effects**

The magnetic field can affect Langmuir probe results by altering the I-V characteristic. The primary effect of the magnetic field is to confine electrons to spiral along the magnetic field lines reducing the electron saturation current. As a result, sheath structures around probes are no longer symmetric and can become oblong. The presence of a magnetic field has a negligible effect on the single Langmuir probe measurements since the data analysis infers ion number density from the ion saturation current and the magnitude of the magnetic fields in the bulk discharge chamber of ion thrusters is typically not large enough to have an appreciable effect on ion collection. The large magnetic fields that can affect ion motion are confined to the near-cusp regions where the ion number density is low. However, the magnetic field can lead to electron energy distribution function (EEDF) anisotropy. The primary effect of the magnetic field is to confine electrons and depress diffusion across the magnetic field. Passoth determined that EEDF anisotropy depends upon the ratio  $B/p_o$ , where  $p_o$  is the pressure in the containment vessel (in this case the discharge chamber).¹⁹² It has been shown experimentally that EEDF anisotropy is negligible for  $B/p_0 \le 2.5 \times 10^6$  G/Torr.¹⁹³

The magnetic field strengths vary significantly throughout the discharge chamber of an ion thruster and are in excess of several hundreds of gauss near the magnetic cusps. Evaluation of the magnetic field strengths over the domain of probe interrogation in both thrusters is considered here. Over the region of probe interrogation for the FMT2 thruster, the maximum magnetic field (B) occurs on centerline near the DCA and is on the order of 100 G. The LM4 interrogation domain includes the near-DCA region, but also includes near-anode measurements close to the magnet rings. The near-DCA magnetic field strength is less than that of the FMT2, but measurements made near the magnetic cusps on the anode can reach magnetic field magnitudes on the order of two hundred G. The pressures in the discharge chambers of the engines are estimated to be  $\sim 10^{-4}$  Torr.^{48,140} The value of B/p_o near the DCA is  $1 \times 10^6$  G/Torr, and for the worst case near the anode is  $2 \times 10^6$  G/Torr, therefore possible anisotropy in the EEDF to first order is not considered for either thruster.

It has been documented that the presence of the magnetic field results in a reduction of the electron saturation current, thereby affecting the plasma potential calculation from the I-V curves. Typically, the knee of the electron retarding region (or the maximum of the first derivative) is regarded as the local plasma potential. The magnetic field causes a shift in the calculated plasma potential resulting in a decrease in the magnitude calculated compared to the true plasma potential. This shift can be accounted for depending upon the orientation of the probe with the magnetic field, the electron temperature, and the mean free path of an electron.¹⁹⁴ The potential shift due to

the magnetic field was less than the large error evident from calculation of the plasma potential from the single Langmuir probe data.

This analysis is unnecessary as it turns out, since with batteries used to supply the bias voltages, electron saturation was not achievable. The electron saturation current near the DCA was very large; *e.g.*, several amperes. The desire to minimize the discharge plasma perturbation, combined with the limitations of the battery supply and electrical circuit resulted in I-V characteristics that did not always reach electron saturation. As a result, plasma potential could not be calculated from Langmuir probe data except for the case of the EEDF investigations where the circuit was redesigned and a floating bipolar supply was used to capture the full EEDF. Moreover, the emissive probe testing gave a more accurate indication of the true plasma potential. Calculation of the plasma potential from Langmuir probe data is used only as a rough validation.

# 3.1.7 Error Analysis

Traditional estimates of the error in electrostatic probe measurements are 50% for electron number density and 20% for electron temperature.¹⁷⁸ Errors are evident in the electron number density and plasma potential measurements due to the point-by-point I-V data collection technique. While absolute errors may be large, the relative error between two measurements using identical setups is considerably smaller. Foster estimated the overall uncertainties in Langmuir probe measurements made in an NSTAR ion thruster discharge chamber utilizing the same methods described in this dissertation.

The overall uncertainties in the electron temperature and number density measurements were determined to be 15% and 25%, respectively.¹⁹⁵ The density uncertainty is determined by the sum of the fractional uncertainty in the ion current (15%) and the fractional uncertainty in the square root of the electron temperature (7.5%).¹⁹⁵

Noise in measured electron temperatures near the anode is evident as the signalto-noise ratio has been greatly reduced by the reduction in number densities (and hence measured probe currents). Because of small DC offsets in the measured current, the electron temperatures in the near-anode region either increase dramatically in this region or decrease significantly. Therefore, the near-anode electron temperature data are not very accurate. A more detailed investigation of the near anode plasma would permit accurate determination of electron temperature, but this was beyond the scope of this investigation.

Number densities near the anode are relatively unaffected by the electron temperature fluctuations because the OML calculation, applicable in this region, is only a function of the slope of the ion saturation current. Comparisons of the data taken at equivalent thruster operating conditions indicate the excellent repeatability of the engine and electrostatic probe setup. The number density and electron temperature data taken during different facility pump downs illustrate comparable results for the near-DCA and bulk discharge regions from two different probe tips.

# 3.2 Double Langmuir Probe

The double Langmuir probe method utilizes two electrodes, each similar to the single Langmuir probe. The double probe is typically used in applications in which one of the following conditions is satisfied: 1) there is no well-defined ground (rf plasma); 2) large plasma fluctuations make it difficult to obtain the I-V characteristic; or 3) there is a desire to minimize plasma perturbations. The double probe floats as a whole and therefore draws no net current from the plasma. The combination of this feature and the restriction of the electrodes to the lower ion saturation current significantly reduce the double probe's effect on the plasma. The minimal perturbation of the double probe is the motivation for the double probe testing during this investigation, though the spatial resolution suffers. Additionally, the data analysis for the double Langmuir probe is less complicated than for a single Langmuir probe. In terms of analysis, a double Langmuir probe is like a single Langmuir probe except another electrode is inserted into the plasma to provide a reference.

The electrodes are electrically connected as illustrated in Figure 3-5. A relative voltage is applied between the two probes, but the whole system is electrically isolated and allowed to float in potential. As with the single Langmuir probe, the double Langmuir probe analysis is based upon the Bohm condition and the plasma-sheath properties of the discharge. In addition, Kirchhoff's current law is applied indicating that the instantaneous net current flowing to the system from the plasma must be zero.



Figure 3-5: Double Langmuir probe circuit.

# 3.2.1 Theory of Double Langmuir Probe Operation

Unlike the traditional single Langmuir probe, the double probe floats as a whole, which both minimizes discharge plasma perturbations and allows the probe electrodes to follow discharge plasma oscillations.¹⁹⁶ Furthermore, the I-V characteristic curve for a double probe has a well known hyperbolic tangent shape facilitating data analysis.^{175,178,179} The symmetric geometry of the double probe about the discharge cathode orifice facilitate application compared to triple and quadruple probes where spatial resolution in the axial and radial directions suffers severely due to probe operating restrictions; *i.e.* independent electrode sheaths. A symmetric double probe is selected over an asymmetric double probe because the symmetry of the discharge chamber and the simplicity in data analysis outweighs the benefits gained by sampling more of the electron energy distribution (EEDF). The drawbacks of the double probe are the decreased spatial resolution, the lack of distinction between primary and Maxwellian electron populations, lack of plasma potential information, and the sampling of only the fast electrons reducing the accuracy of the  $T_e$  measurements. The latter is a result from the fact that in a double Langmuir probe, the current from one electrode must equal the current to the other since the double probe floats as a whole. Thus, the electron current to an electrode in the double probe is limited in magnitude to the ion saturation current to the other.^{197,198} Though the error in the electron temperature calculation is increased compared to a single Langmuir probe, the double probe has been successfully used to measure a variety of plasmas by other researchers.^{187,197-201} The symmetric double probe accurately measures the bulk discharge plasma parameters where spatial resolution is less critical.

# 3.2.2 Double Langmuir Probe Tips

The symmetric double probe is sized as small as possible in order to allow spatially resolved measurements similar to the single Langmuir probe. The use of ceramic, in this case alumina, is necessitated by the high temperatures in the plasma. The electrodes of the double probe are sized similar to the single Langmuir probe electrode. Because the measured current is fixed at the ion saturation current, the double probe electrodes consist of slightly thicker tungsten wire with longer length in order to increase the measured current and accuracy of the double probe plasma parameters measured.

A large length-to-diameter ratio is chosen to minimize end effects. A conservative gap distance – the distance between the probe electrodes – maintains a minimum factor of three times the sum of the two electrode sheaths (~  $3 \times 2 \times 5\lambda_D$ ) to avoid overlapping. As illustrated in the single Langmuir probe analysis section, §3.1.5, for a floating probe, the sheath size is calculated from Eqn. 3-4. For xenon propellant, this equation is equivalent to a sheath thickness equal to  $5.3\lambda_{\rm D}$ . While the conservative gap prevents sheath interaction over the full range of spatial locations, it greatly reduces the spatial resolution of the near-DCA plasma. Multiple double probes were used during the test due to the breaking of probes. All probes are slight variations on the basic double probe design, shown in Figure 3-6. Two 0.38 mm diameter cylindrical tungsten electrodes, with 4 mm exposed length, are held inside two double-bore pieces of 99.8% pure alumina epoxied to one larger double-bore piece of 99.8% pure alumina. The double probe diameters are larger than the single Langmuir probe to increase the ion saturation current to which the probe is limited. The disadvantage of the larger electrode diameter is a longer electrode length, to reduce end effects, and therefore reduced spatial resolution of plasma structures in the radial direction. The radial location of the double probe is determined by the location of the center of the electrode with an error of  $\pm 2$ mm. The total length of the tungsten and alumina is approximately 46 cm (18 inches). The "double-tier" design reduces the amount of blockage mass that is inserted into the discharge cathode plume, reducing discharge perturbation.



Figure 3-6: Reduced-blockage double probe tip design.

# **3.2.3 Double Langmuir Probe Circuit and Electronics**

During probe insertion into the discharge plasma, the floating potential of the double Langmuir probe and circuitry rapidly increases to over one thousand volts with respect to ground, which causes considerable difficulty for most electronics. The double probe circuit was designed in a similar fashion to the single Langmuir probe circuit in Figure 3-2. The double probe circuit, previously used to make similar measurements inside the discharge channel of a Hall Thruster,²⁰⁰ is built around two Analog Devices AD210 isolation amplifiers. Batteries are used to supply the bias voltage, minimizing stray capacitance in the circuit. The double probe battery supply consists of two series groups of four 67.5-volt zinc-manganese dioxide batteries connected in parallel. The batteries are capable of outputting 135 V at 100 mA. A potentiometer and polarity switch set the electrode bias voltage with respect to the second electrode. The double probe circuit, illustrated in Figure 3-7, was kept inside the vacuum chamber to reduce the length of wires between the electrodes and the circuit. High-voltage (up to 5 kV) SHV cables

and feedthroughs are used to connect the double probe electrodes to the battery pack outside the vacuum chamber.



Figure 3-7: Double probe circuit electrical diagram.

### **3.2.4 Double Langmuir Probe Data Acquisition**

Bias voltages are set manually using a potentiometer and the battery supply. The probe is then swept through all spatial locations. A LabVIEW code steps through the full axial range of motion in 1.6 mm increments. For each axial step, the program triggers the probe positioning system to sweep the probe radially through the discharge plasma. After all axial locations are interrogated, the computer returns the FMT2 to the zero axial position located 1.5 - 2 mm downstream of the DCA exit plane. The bias voltage is manually changed and the process repeats until the 31 bias voltages are investigated. Though ion saturation is achieved at a bias of approximately 25 volts, the bias voltage was increased up to 80 volts to determine the slope of the ion saturation current used in the orbital-motion-limited (OML) regime.

A Tektronix TDS 3034B oscilloscope triggers off of the HARP position and records all data. The oscilloscope records probe position, probe collected current, probe bias voltage, and the discharge current (from a Hall sensor) as a function of time during probe insertion. From the oscilloscope raw data, the discharge current, probe collected current, and probe bias voltage are calculated as a function of probe position.

Only data taken on the "in sweep" of the probe are analyzed. The measured discharge current perturbation induced by the double probe is approximately 5 - 10% of the nominal value. The similar discharge perturbation of the floating double probe compared to the single Langmuir probe supports the notion that the probe perturbation is predominantly physical in nature; *i.e.*, as opposed to electronic.

# 3.2.5 Double Langmuir Probe Analysis

The current-voltage curves from the double Langmuir probe are analyzed according to the appropriate operating regime. The data are reassembled by an Igor code into current-voltage characteristics (I-V curves) at each spatial location in the twodimensional grid, shown in Figure 3-8. The double probe characteristics are analyzed assuming infinite, quasi-neutral, quiescent, and collisionless plasma.



Figure 3-8: Sample of double Langmuir probe I-V curves (+) and fit curves (lines).

Post test inspection of the I-V data revealed asymmetric I-V curves at locations near the DCA. The asymmetry is most extreme closest to the DCA and decreases monotonically with increasing axial distance from the DCA. The asymmetry is larger than can be accounted for by slightly different electrode lengths. The most probable cause is any electrode-to-orifice misalignment that may have occurred during pumpdown. The probe positioning system is mounted to the wall of the chamber, while the FMT2 engine and positioning system rest on a platform inside the vacuum facility. During pumpdown the walls of the chamber compress resulting in a shift of the probe tip. A vertical shift of one millimeter would result in one electrode lying directly in front of the discharge cathode plume. The disappearance of the asymmetry outside the plume supports the misalignment theory. Mounting both the engine and the probe positioning system on a common structure would eliminate this problem, as was done for subsequent investigations (FMT2 single Langmuir probe and EEDF measurements). The common structure setup was exclusively used for the LM4 investigations. The unexpected misalignment brings to light another more important problem with the double probe measurement. The plasma isolation constraint on the two electrodes requires the electrodes to be placed millimeters apart (Figure 3-9). This, combined with the magnetic confinement of the electrons from the hollow cathode to a distinct narrow plume, results in inadequate characterization of the near-cathode plume, which is of the utmost importance. Thus, the single Langmuir probe characterizes the near-DCA plasma and can be validated using the double probe results outside the DCA plume. To account for the misalignment shift, the electrode collected current and bias voltage data corresponding to the larger collected current (*i.e.*, the electrode more in the discharge cathode plume) is mirrored and the resulting I-V curve is analyzed.



Figure 3-9: Photograph of the double probe located near the DCA indicating the lack of adequate spatial resolution at the discharge cathode orifice.

Similar to the single Langmuir probe, the double probe data are initially analyzed assuming a thin sheath. The initial number density and electron temperature allow an identical iterative solution for the sheath size and final number density. Based upon the

ratio of the Debye length (from the final number density) to probe electrode radius, either the iterative thin sheath result, a weighted average transitional value, or the OML output is recorded.

#### **3.2.5.1** Thin Sheath Analysis

For a ratio of probe electrode radius to Debye length of greater than or equal to 10, each I-V characteristic is fitted with the theoretical hyperbolic tangent curve for a symmetric cylindrical double probe (Eqn. 3-11) incorporating the Levenberg-Marquardt fit method,^{179,180}

$$I = I_{sat} \times \tanh\left(\frac{\phi}{2 \times T_{eV}}\right) + A_1 \times \phi + A_2$$
Eqn. 3-11

In Eqn. 3-11,  $I_{sat}$  is the ion saturation current,  $\varphi$  is the probe bias voltage with respect to discharge cathode common, the parameter A₁ accounts for sheath expansion in the ion saturation region, and A₂ accounts for any offset current due to stray capacitance. Figure 3-8 illustrates representative I-V traces and their corresponding curve fits using the above equation. Electron temperature can be determined immediately from the fit parameters. The ion saturation from the hyperbolic tangent fit is used, along with the electron temperature, to calculate the number density using Eqn. 3-3. An iterative solution, identical to the single Langmuir probe analysis, accounts for growing the sheath thickness as number density decreases.

### 3.2.5.2 Orbital Motion Limited (OML) and Transition Analysis

For a ratio of probe radius to Debye length of less than or equal to 3, the electron temperature calculation remains the same. However, the number density is calculated from the slope of the ion current squared versus bias voltage according to Eqn. 3-7.

When the Debye length calculation, based upon the iterated number density, reveals  $10 > (R_p / \lambda_D) > 3$ , the probe is operating in a transitional regime. In this case, a weighted average, based upon the ratio of probe electrode radius to Debye length, is used to blend the two regimes. This is the same procedure used in the single Langmuir probe measurements.

# **3.2.6 Magnetic Effects**

The presence of a magnetic field has a negligible effect on the probe measurements. The double probe analysis infers number density from the ion saturation current and therefore is unaffected by the reduction in electron saturation current caused by the presence of a magnetic field. The magnetic field does not lead to electron energy distribution function (EEDF) anisotropy as discussed in the single Langmuir probe section.

### **3.2.7 Error Analysis**

The error associated with double Langmuir probe measurements is similar to that of the single Langmuir probe. Additional electron temperature error is introduced by sampling only a small portion of the electron distribution and the differences in plasma sampled by the individual electrodes. Because double probe current is limited to the ion saturation current of a single electrode, only the fast electron portion of the electron retarding region is sampled. This introduces error in the calculated electron temperature that the single Langmuir probe minimizes by sampling more of the EEDF.

Additional spatial resolution error for the double probe results from the independent electrode requirement, illustrated in Figure 3-9. One of the underlying assumptions of the double probe is that each electrode is exposed to the same plasma environment. This is satisfied when the spatial variation of plasma parameters, in the plane of the electrodes, does not vary substantially over distances smaller than or comparable to the gap distance. This is clearly not the case for the near discharge plasma where the discharge plume emanates from the millimeter sized orifice with an electrode gap of 3 mm. Thus substantial error is incurred close to the DCA and the double probe results should be regarded merely as estimates close to the DCA. Assuming a plume divergence angle of 30 degrees in all directions, the resolution error would be eliminated approximately 3 mm downstream of the DCA if the probe were properly aligned.

The discharge perturbations (5-10% nominal) were monitored throughout the double probe testing. Figure 3-10 illustrates a typical probe insertion induced perturbation to the discharge.



Figure 3-10: Sample discharge and bias voltage perturbation (20 V bias, 13.13 A, 25 V shown).

# 3.3 Floating Emissive Probe

Electron emission from "hot" electrostatic probes provides a means to directly measure the local plasma potential. This measurement resolves many problems encountered with interpretation of the "knee" of the I-V potential from single Langmuir probes. Langmuir I-V characteristics are complicated by probe geometry, magnetic fields, presence of a flowing plasma, and ionization near the probe.²⁰² Emitting probes offer an alternative technique to determine the plasma potential that is less sensitive to plasma flow and plasma density. Furthermore, emissive probes provide a means to accurately measure the local plasma potential in fluctuating plasma environments.

# 3.3.1 Floating Emissive Probe Theory of Operation

The floating emissive probe operates under a simple principle yielding direct measurement of the local plasma potential without the need for a bias voltage sweep or extensive data analysis. The theory of the floating emissive probe is well established.^{177,181,196,202,203} Current is applied through a filament that is inserted into the plasma at the point of interest. As the filament heats up, electrons are thermionically emitted from the filament. In theory, when heated sufficiently, the emitted electrons essentially neutralize the sheath around the probe tip allowing the probe (and probe circuitry) to float at the local plasma potential. In reality, for the floating probe in strong emission, the space-charge limit creates a double sheath because of the excess of slow electrons emitted near the probe surface, illustrated in Figure 3-11. The double sheath reflects the thermionically emitted electrons back to the probe surface and some of the Maxwellian plasma electrons back to the plasma. The high-energy Maxwellian tail electrons from the plasma are able to reach the probe. Considering the relative energy ratios of the two different electron populations, the maximum emitted current cannot be sufficient to compensate for the collected current because the plasma electrons have much higher velocities.

The structure surrounding the emissive probe can be broken into pre-sheath and collector sheath regions. The pre-sheath is on the order of the mean free path, while the collector sheath is on the order of the Debye length. The magnitude of the potential barrier to emitted electrons is on the order of  $T_w/e$ , where  $T_w$  is the filament temperature. The potential barrier preventing plasma electrons from reaching the probe is on the order

of  $T_e/e$ . As a result, the emissive probe will float at a potential  $(T_e - T_w)/e$  less than the true plasma potential. Since  $T_e >> T_w$  this is approximated as  $T_e/e$ . The presence of positive ions helps to cancel the space charge reducing the difference between floating probe potential and plasma potential to a fraction of  $T_e$ .



Figure 3-11: Schematic of the potential distribution in a double sheath surrounding an emitting probe.

# 3.3.2 Emissive Probe Filament

The filament of the emissive probe was selected as the smallest diameter tungsten wire that allows manageable construction of the emissive probe and has adequate survivability under the high accelerating forces of the probe positioning system. The emitting portion of the probe, shown in Figure 3-12, consists of 0.13 mm diameter tungsten wire bent to form a closed loop roughly 1.2 mm in diameter.

The filament is held inside two double-bore pieces of 99.8% pure alumina epoxied to one larger double-bore piece of 99.8% pure alumina. Two 18 AWG copper wire leads run the entire length of the 0.5 m probe up to the probe tip to reduce the resistance of the closed path and hence reduce the undesirable voltage drop associated with it. The ends of the tungsten filament are inserted down the small alumina tube along with additional lengths of 0.18 mm and 0.13 mm tungsten wire, creating a snug fit. Additional tungsten wires (and the filament ends) are crimped with the 18-AWG leads to ensure good contact between the tungsten and copper wires. The filament is further held in place by ceramic epoxy.

The "double-tier" design of the emissive probe tip reduces the amount of blockage mass that is inserted into the discharge cathode plume. The probe is oriented such that the plane of the loop of the probe filament is perpendicular to the DCA and thruster axis. This configuration allows the maximum axial resolution and bodes well with the axisymmetric nature of the discharge chamber and discharge cathode plume. Several probe tips were used during testing due to breakage at the high acceleration and filament melting, each requiring a slightly different saturation heater current. For the strong emission necessary to neutralize the probe sheath, the tungsten filament is heated until it is very close to the melting temperature (3695 K), which limits the lifetime of the probe to tens of minutes in the harsh discharge plasma plume environment



Figure 3-12: Floating emissive probe tip design illustrating the components and physical dimensions.

# **3.3.3 Emissive Probe Circuit and Electronics**

The emissive probe circuit, illustrated in Figure 3-13, consists of the emissive probe, a dc power supply capable of supplying enough current to heat the filament, an isolation transformer to isolate the power supply from ground, and two AD210 isolation amplifiers to record both the emitting probe potential and the voltage drop across the filament. The probe is swept in the radial direction at discrete axial locations. For each sweep, the probe position, probe floating potential (plasma potential), and filament voltage drop are recorded.



Figure 3-13: Floating emissive probe circuit and electrical diagram.

All plasma potential measurements are made with respect to the discharge cathode common and not the facility ground. Due to the recession of the probe tip inside the alumina tube when data collection is not taking place, floating potentials negative of discharge cathode common are observed. This expected result indicates the effectiveness of the magnetic field in confining the discharge plasma. The transverse diffusion of charged particles across the magnetic field lines is inhibited resulting in a floating potential somewhere between the bulk discharge plasma potential (in this case approximately up to 1500 V referenced to ground) and facility ground.

Typical floating potentials of the emissive probe in the "stored" location are 700 V with respect to ground (-400 V with respect to discharge cathode common). This

relative voltage, combined with the restriction of the isolation amplifiers maximum allowable differential voltage, dictated the size of the voltage divider resistors and thus the resolution of the circuit. Both the "high" and "low" side floating potentials, of the power supply are recorded to determine the uncertainty of the measurement. However, only the high side potentials are reported. The reason for choosing the high side is because, as indicated in §3.3.1, the probe floating potential will always be a fraction of the electron temperature **less** than the plasma potential. For ion thrusters, the electron temperatures are fairly constant ranging from 2 - 5 eV in the bulk discharge. The electron collection shifts down the floating emissive probe potentials by 1 - 3 volts compared to the true plasma potential. Thus, the high side potential is expected to be closer to the true plasma potential by ~1.5 volts.

# **3.3.4 Floating Emissive Probe Data Acquisition**

The ion engines are throttled to the desired operating condition and allowed sufficient time ( ¹/₂ hour minimum) to reach steady operation . In order for the probe floating potential to approach the true plasma potential, adequate heater current must be applied to the filament to neutralize the probe sheath. The correct heater current is determined by taking several preliminary sweeps at the zero axial position and observing when the probe potential saturates. Figure 3-14 illustrates the difference between sufficient and insufficient heater current. With minimal heater current, the probe potential is well below cathode common potential. When the filament reaches the cathode plume there is a substantial jump in the probe potential. During the time that the probe is

stationary in the discharge cathode plume, the probe floating potential increases as the plasma provides additional filament heating by the flux of high-energy particles in the high-density cathode plume.



Figure 3-14: Graphs of the emissive probe floating potential and position as a function of time made with respect to the discharge cathode common. The emissive probe tip exits the alumina tube into the discharge plasma after 0.15 seconds.

At intermediate heater current, the probe potential continues to exhibit a sharp drop-off in probe potential (a few hundred volts) immediately outside of the cathode plume. Further increasing to sufficient heater current shifts the few hundred volt drop in probe potential to the location at which the probe is recessed inside the outer alumina tube. At this current, the probe potential is approximately at anode potential, outside of the outer alumina tube, and does not exhibit an increase in floating potential while the probe is stationary in the cathode plume. To check for saturation, the heater current is increased slightly and the entire sweep is checked for any increase in floating potential. Once a sufficient heater current is determined, the emissive probe current is held at this value for the entire data collection domain. Problems setting the heater current occur at the higher-power thruster settings. If the user attempts to set the heater current for the bulk plasma region, excessive filament heating will occur in the DCA plume resulting in rapid filament failure. Conversely, if the additional heating by the high-density DCA plume is considered when setting the heater current, the probe will have insufficient heater current in the bulk discharge region. It was determined that the heater current would be set to the value giving accurate measurement of the near-DCA region since this is the primary area of interest. The bulk discharge measurements at high-power are reported, but may be slightly lower than true plasma potential in these locations. A more accurate method of mapping the bulk discharge plasma and near-cusp regions could be performed. However, this activity is beyond the scope of the current investigation.

Once adequate heater current could be determined, the probe was swept through all spatial locations. Both the high and low side of the floating power supply are recorded giving the floating potential of the probe and the voltage drop across the resistor. The probe position and discharge current are also recorded giving plasma potential as a function of position and an indication of the probe-induced perturbation to the discharge plasma. Typical perturbations were 5 - 10% of the nominal discharge current.

# 3.3.5 Emissive Probe Analysis

The floating emissive probe method gives direct indication of the local plasma potential without the need for extensive data analysis. The probe floating voltages are sent through voltage dividers and into the isolation amplifier. Calculation of the output signal is readily converted back to the probe floating voltage. The plasma potential data are reassembled by an IGOR code giving the plasma potentials over the entire 2D spatial domain.

# **3.3.6 Magnetic Field Effects**

The presence of large magnetic fields and large density gradients can increase the problems associated with space-charge limited emission. In magnetized plasmas, the emitted electrons tend to follow the magnetic field rather than expanding away from the probe in all directions, increasing the disparity between the potential of the emitting probe and the actual local plasma potential. Additional space-charge effects due to the magnetic field can be avoided by sizing the probe such that the filament diameter, that is the diameter of the tungsten wire and not the loop diameter, is much less than the electron gyroradius. This condition has been shown by Hershkowitz to be equivalent to the following equation:²⁰²

$$B << \frac{4.8\sqrt{T_{eV}}}{(d_{10})}$$
. Eqn. 3-12

In Eqn. 3-12,  $T_{eV}$  is in eV, d is the emitting filament diameter in mm, and B is the magnetic field in Gauss. For a filament diameter of 0.13 mm and electron temperatures inside the discharge chambers ranging from 2 – 7 eV, over all operating conditions

investigated, the Hershkowitz equation yields the restriction that  $B \ll 650$  G. The maximum magnetic field magnitudes in the discharge chambers of the FMT2 and LM4 engine are on the order of 100 G at the exit plane of the discharge cathode and decreases with increasing axial and radial distances from the centerline DCA exit plane before approaching the anode and the magnet cusps, where the magnet field increases. At the closest proximity of the magnetic field mapping, near the magnetic cusps at the anode, the magnetic field magnitude increases to a few hundred Gauss. Even for the worst case conditions where probe measurements are made, the Hershkowitz criterion is maintained.

# **3.3.7 Floating Emissive Probe Error Analysis**

There are several sources of error in the floating emissive probe diagnostic technique used. Noise is reduced as much as possible by using high-voltage SHV coaxial cables for the entire circuit, both inside and outside of the chamber. Isolated feedthroughs permit a common grounding point for all circuit components, eliminating noise pick-up through ground loops. The non-ideal floating power supply introduces the possibility of leakage current to ground when the probe and dc supply float at high potential. The result of appreciable leakage current is that the probe floats at a value less than the true plasma potential. To determine the effect of the leakage current, the measured plasma potential near the anode is compared to the true anode potential. Examination of the high supplyside plasma potential contours illustrate that near the anode the measured plasma potential is equal to or a few volts above anode potential. This indicates that there is no appreciable leakage current. Plasma potential measurement with heater current through the filament leads to a voltage drop across the filament. This voltage drop adds to the uncertainty in the measured value. The voltage drop is recorded during testing and is approximately 3 V, leading to an uncertainty of  $\pm$  1.5 volts from the averaged floating potential. The effects of the leakage current and voltage drop contribute to an overall shift in absolute magnitude of plasma potential measurement leaving the relative potential measurements unaffected.

Due to space-charge effects, the electron current from the highly emissive probe is limited, and the true plasma potential will be underpredicted. Thus the emissive probe measurement gives rise to an error on the order of a fraction of  $T_e/e$ .^{177,179,204} Given the electron temperatures measured with the Langmuir probes, the floating potentials can be corrected. The electron temperatures vary from roughly 2 – 5 eV in the near-DCA domain indicating that the true local plasma potential would be 1 – 3 V above the saturated floating emissive probe. The space-charge correction was not incorporated in this analysis because the calculation of electron temperature is difficult for the near-DCA non-Maxwellian multi-population electron distribution and the space-charge correction results in an approximately constant shift up in measured plasma potential that is similar to the more simplistic "high" supply side shift. Combining the voltage drop and spacecharge effects, the expected error in the reported high-side plasma potentials is estimated as -0.5/+1.5 volts. The perturbation of the discharge current by the probe insertion was recorded throughout the test. As expected the maximum perturbation occurred at the closest axial position on centerline. The temporary perturbation spike in discharge current is at most 10% of the nominal value. Outside of the discharge cathode plume region, no perturbation is detectable.

# **3.4 EEDF Measurement**

Several attempts were made to analyze the single Langmuir probe results to attain information about the primary and Maxwellian electrons. These attempts were unsuccessful owing mostly to the limited number of data pairs in the I-V curve permissible with the battery bias voltage. Measurement of primary electrons near the DCA would offer additional information about the local plasma environment and would be beneficial for the direct measurement of the electron energy distribution function (EEDF). To measure the complete EEDF, the probe must reach the high electron saturation current. The probe size was minimized as much as possible to reduce the electron saturation current and a redesign of the single Langmuir probe circuit was needed. EEDF measurement was performed using two different techniques: the Druyvesteyn method (or second derivative method) and the harmonic method (or ac method), discussed below. The EEDF measurement was performed on the LM4 engine only.

# 3.4.1 Druyvesteyn Method (Second Derivative Method)

Druyvesteyn was the first to utilize the fact that the second derivative of the electron current with respect to probe potential is proportional to the electron energy distribution function (EEDF) if the velocity distribution is isotropic (Eqn. 3-13):¹⁷⁷

$$f_E(E) = \frac{-4}{A_p e^2} \left(\frac{m_e(V_{plasma} - V)}{2e}\right)^{\frac{1}{2}} \frac{d^2 I_e(V)}{dV^2} \quad V_p < 0$$
 Eqn. 3-13

where E is in eV and the EEDF,  $f_E(E)$  is in m⁻³eV⁻¹. If the EEDF is Maxwellian, Eqn. 3-13 can be integrated twice giving the theoretical electron current as a function of probe voltage below the plasma potential:

$$I_e(V) = \left(eA_p N_v \sqrt{\frac{kT_e}{2\pi m_e}}\right) \exp\left(\frac{-e(V_{plasma} - V)}{kT_e}\right).$$
 Eqn. 3-14

Unfortunately, Eqn. 3-13 is difficult to calculate because of the inaccuracies introduced by taking the second derivative of the experimentally-measured I-V characteristic. Data smoothing and extensive data analysis techniques are needed to reduce the introduced error. To assist, multiple I-V traces were measured and averaged to remove noise in the characteristics.
#### **3.4.1.1 Circuit and Electronics**

The second derivative method circuit is similar to the single Langmuir probe circuit, except with different resistors, shown in Figure 3-15. The resistors were changed so that achieving electron saturation current was possible without overloading the  $\pm$  15 V maximum input of the isolation amplifiers. The probe is connected to a floating Kepco BOP 100-2M programmable bipolar power supply that is driven by a floating signal generator. The bipolar power supply and generator are used to rapidly sweep the bias voltage permitting many more data pairs in the I-V curve, facilitating differentiation. The Langmuir probe is biased with respect to the discharge cathode. The function generator provides a ramping voltage signal at 200 Hz with the resulting bipolar sweep from + 30 to – 40 volts, covering both electron and ion saturation regions. The outputs from the isolation amplifiers are sent to an oscilloscope where they are displayed and stored on a PC via a National Instruments GPIB interface.



Figure 3-15: Electrical diagram of the second derivative method for determination of the near-DCA EEDF.

#### 3.4.1.2 Data Acquisition

The LM4 engine was throttled in similar fashion previously discussed. Once the engine operating condition has reached steady state, the ramping voltage bias is applied to the Langmuir probe. A LabVIEW code triggers the probe positioning system to complete a radial sweep of the probe. Data are recorded at the final position of the probe only to maintain the desired resolution of the I-V curve and maximize spatial resolution. For each sweep, one I-V characteristic is stored. A minimum of 20 sweeps at each spatial location are stored and averaged. Because of the labor intensive and time consuming method associated with this experiment, a relatively coarse grid of spatial locations was chosen.

#### 3.4.1.3 Druyvesteyn (Second Derivative) Method Analysis

The EEDF's are obtained from the averaged I-V characteristics. Druyvesteyn has shown that the EEDF is proportional to the second derivative of the probe current:

$$f_E(E) \propto \sqrt{E} \cdot \frac{d^2 I_p}{dV_p^2}$$
 Eqn. 3-15

where  $E = (V_{plasma} - V)$ . The local plasma potential at the location of the EEDF measurement is determined from the floating emissive probe results. Thus, if it is possible to differentiate the electron current to the probe accurately twice, the EEDF is proportional to this result. The most common problem with application of this method stems from the amplification of noise in the I-V curve when taking derivatives. To minimize this effect multiple ( $\geq 20$ ) I-V characteristics are recorded and averaged at each spatial location interrogated. The resulting averaged I-V curve roughly contains 200 I-V pairs. A 5-point box smoothing algorithm is applied to the I-V curve to further reduce noise. After the numerical first derivative is calculated, an 11-point box smoothing algorithm is applied to the resultant I'-V curve before the second derivative is taken. After the second numerical differentiation is applied, the resultant I''-V curve is again smoothed in the same fashion as the first derivative. The second derivative is multiplied by the square root of the energy with respect to local plasma potential giving the EEDF. Finally, the EEDF is normalized by the area under the curve and multiplied by the local plasma number density measured from the single Langmuir probe giving the electron energy distribution in the plasma.

From the measured EEDF, the type of distribution can now be determined. As described by Druyvesteyn, experimental electron energy distribution functions can be described by the following equation:²⁰⁵

$$f_E(E) = C \cdot \sqrt{E} \cdot \exp(-BE^n)$$
 Eqn. 3-16

where E is the electron energy, C is a normalization factor, and B and n are constants to be fitted to the experimental data. A Maxwellian distribution is a special case where n equals one, while a Druyvesteyn distribution corresponds to an n value of two. A convenient way to fit the second derivative data is the following form:²⁰⁵

$$\ln\left[\frac{f_E(E)}{\sqrt{E}}\right] = \ln[C] - BE^n \propto \ln\left[\frac{d^2 I_e}{dV_p^2}\right].$$
 Eqn. 3-17

The value of n (*i.e.*, the type of distribution) can be determined from a least squares fit to the second derivative of electron current as a function of E. The parameter C is equal to the natural log of the intercept and B is equal to the slope of the least squares fit with the determined value of n. The parameter B relates to the average electron energy,  $\langle E \rangle$ . For a Maxwellian distribution, B equals  $1.5 \langle E \rangle^{-1}$  and n equals 1. For the Druyvesteyn distribution, B equals  $0.54 \langle E \rangle^{-2}$  and n equals 2.205

#### 3.4.1.4 Error

The presence of noise in the measured signal is amplified when taking derivatives. This introduces substantial error to the EEDF calculated using this method even when using advanced smoothing techniques and averaging multiple I-V data sets. The result of over-smoothing the data and derivatives would be to remove small voltage spanning distribution features. The amount of smoothing applied to the current and resultant derivatives was minimized while maintaining decent EEDF's.

#### 3.4.2 Harmonic Method

Calculation of the EEDF utilizing the Druyvesteyn method is difficult owing to the amplification of noise in the original I-V characteristic. Taking the average of multiple I-V curves and using smoothing techniques minimizes the effects of the noise on the resultant EEDF, but a more accurate method is desirable. The harmonic method allows direct electronic determination of the second derivative. In the harmonic method, a small ac signal is superimposed on the dc probe voltage. The dc current rises by a small amount, which is proportional to the second derivative. A Taylor expansion of the modulated electron current reveals that the second derivative term is proportional to the term containing the second harmonic of the small input ac signal ( Eqn. 3-18):^{206,207}

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$$I_{e}(V_{p} + a \cdot \sin(\varpi t)) = \left[I_{e} + \frac{a^{2}}{4}I_{e}'' + \frac{a^{4}}{64}I_{e}''' + \dots\right] \text{ dc component}$$

$$+ \left[aI_{e}' + \frac{a^{3}}{8}I_{e}''' + \dots\right]\sin(\varpi t) \text{ undistorted ac component}$$

$$- \left[\frac{a^{2}}{4}I_{e}'' + \frac{a^{4}}{48}I_{e}''' + \dots\right]\cos(2\varpi t) \text{ second harmonic}$$

$$- \left[\frac{a^{3}}{24}I''' + \dots\right]\sin(3\varpi t) + \left[\frac{a^{4}}{192}I_{e}''' + \dots\right]\cos(4\varpi t) + higher harmonics. \text{ Eqn. 3-18}$$

For sufficiently low amplitude (a $<<V_p$ ), the increase of the dc current can be approximated by Eqn. 3-19. Since  $I_p"\approx I_e"$  for sufficiently negative probe potentials, the second derivative of  $I_e$  can be taken directly from the second harmonic. A lock-in amplifier can be utilized to obtain the second harmonic, which is related to the second derivative of the electron current by:

$$\Delta I_{e} = \frac{1}{4} a^{2} I_{e}'' (V_{p}).$$
 Eqn. 3-19

#### **3.4.2.1** Circuit and Electronics

The harmonic EEDF measurement setup is similar to those for the single Langmuir probe and Druyvesteyn method. The harmonic EEDF measurement utilizes an additional function generator to supply the ac signal, which is superimposed on the dc ramping bias voltage. The Stanford Research Systems SR810 DSP lock-in amplifier has a full scale sensitivity of 2 nV and a frequency range of 1 mHz to 102 kHz. The unit has a relative phase error is  $<0.01^{\circ}$  and time constants are as low as 10 µs. A summing circuit was used to combine the two signals and input into the bipolar supply setting the probe bias voltage. The experimental setup is illustrated in Figure 3-16.



Figure 3-16: Harmonic EEDF circuit and electronics. The high-frequency, small-amplitude ac sine wave signal is superimposed on the low-frequency ramp voltage signal with the probe current signal sent to the lock-in amplifier.

#### 3.4.2.2 Data Acquisition

Due to the number of electronic components involved, it was not possible to float all components with reasonable safety for the equipment and personnel. The harmonic EEDF was applied to the LM4 engine without beam extraction only. Once the engine operating condition has reached steady state, the combined voltage bias is applied to the Langmuir probe. The ac signal has an amplitude of 4 V pk-pk and a frequency of 2 kHz, the dc ramping voltage has a range of -24 V to + 32 V and a frequency of 5 Hz. A LabVIEW code then triggered the probe positioning system to complete a radial sweep of the probe. The probe current is sent as the input of the Stanford Research Systems SR810 DSP lock-in amplifier, which is set to measure the second harmonic. The probe dc bias signal and lock-in second harmonic signals are sent to the TDS 3034B oscilloscope. Data are recorded only at the final position of the probe. For each sweep, one set of second harmonic data as a function of ramp dc voltage is stored. Multiple sweeps at each spatial location are stored and averaged to remove the noise. Because of the labor intensive and time consuming method, a relatively coarse grid of spatial locations for interrogation was chosen.

#### 3.4.2.3 Analysis

The second harmonic of the probe current, measured by the lock-in amplifier, is proportional to I''. Ten measurements are made at each spatial location and the signals later averaged to remove the noise in the measurement. The output of the lock-in amplifier, A(E), is related to the electron energy distribution function by:²⁰⁵

$$f(E) = \sqrt{E}A(E)$$
. Eqn. 3-20

In Eqn. 3-20, E is the voltage with respect to local plasma potential. Similar to the Druyvesteyn method data analysis, the distribution function calculated by Eqn. 3-20 is normalized and the result multiplied by the local plasma number density, giving the electron energy distribution in the plasma.

By using the model for the EEDF (Eqn. 3-16), it is possible to ascertain the nature of the distribution. From a semi-log plot of the lock-in signal versus probe voltage, the value of n can be determined indicating the distribution type (n=1 then Maxwellian, n=2 then Druyvesteyn, etc...). Once n is known, the other fitting parameters can be determined giving the distribution function formula and the average electron energy, <E>.

#### 3.4.2.4 Error

Aside from the typical single Langmuir probe errors previously discussed, most of the uncertainty in the harmonic EEDF measurement is associated with higher order derivatives that contribute to the signal detected by the lock-in amplifier. The small superimposed ac signal may penetrate into the plasma causing oscillations. The estimated error in the harmonic EEDF measurement is approximately 8%.²⁰⁵ The high-frequency amplitude used in the experiments was set to 4 volts pk-pk to achieve a satisfactory signal-to-noise ratio. This amplitude is higher than desired and may smooth out EEDF structures whose voltage width is smaller than this amplitude.

## **CHAPTER 4**

# **EXPERIMENTAL APPARATUS**

## 4.1 Large Vacuum Test Facility (LVTF)

The discharge chamber ion engine investigations are conducted in PEPL's cylindrical 6-m-diameter by 9-m-long stainless steel-clad Large Vacuum Test Facility (LVTF), which has been used extensively for testing a variety of electric propulsion devices (Figure 4-1). The LVTF underwent a major facility upgrade in 1998 wherein four CVI TM-1200 nude re-entrant cryopumps were installed to replace the oil diffusion pumps previously used. Three additional cryopumps were installed in August of 2000. A pair of 900 l/s blowers and four, 200 l/s mechanical pumps are used to evacuate the LVTF to rough vacuum (80 - 100 mTorr). Once the chamber has reached rough vacuum, the blowers and mechanical pumps are shut off and isolated via gate valves, and the cryopumps are activated. The cryopump system can be operated with any number of pumps in use permitting variation in the LVTF pumping speed. The seven cryopumps, surrounded by liquid nitrogen cooled baffles, give the LVTF a maximum pumping speed of the facility of 240,000 l/s on xenon (500,000 l/s on air).



Figure 4-1: Photographs of the Large Vacuum Test Facility (LVTF) at the University of Michigan Plasmadynamics and Electric Propulsion Lab (PEPL). The completed vacuum facility is shown on the left and an aerial view of the facility under construction in August of 1961 is shown on the right.

During testing, chamber pressure is monitored using two hot-cathode ionization gauges. The primary ion gauge used is a Varian model UHV-24 nude gauge with a Varian UHV senTorr vacuum gauge controller. A complete pressure mapping of the LVTF has shown that the nude ion gauge reading is the most accurate measure of the LVTF near-thruster background pressure and will be the facility pressure reported unless otherwise noted.²⁰⁸ An auxiliary Varian model 571 gauge with a HPS model 919 Hot Cathode controller is used for verification and as a backup.

Pressure measurements from both ion gauges are corrected for xenon using the known base pressure on air, the indicated gauge pressure, and a correction factor of 2.87 for xenon according to,²³

$$P_c = \frac{P_i - P_b}{2.87} + P_b$$
. Eqn. 4-1

For the FMT2 and LM4 testing, the LVTF is operated with either four or seven cryopumps depending upon the ion thruster operating condition. With four cryopumps, the facility pumping speed is 140,000 l/s on xenon with a base pressure typically  $4x10^{-7}$  Torr. The LVTF can maintain a pressure in the low  $10^{-6}$  Torr range during operation of the FMT2 at full power (2.3-kW) with the four cryopumps activated. To reduce the ingested flow into the discharge chamber, the LM4 testing was conducted with four cryopumps for low-power and with seven cryopumps for higher-power. With seven cryopumps activated, the LVTF base pressure was typically  $2x10^{-7}$  Torr. At the LM4 highest power condition permissible, the corrected background pressure was typically  $2.8x10^{-6}$  Torr for a total xenon flow rate of 5 mg/s.

Throughout the electrostatic probe testing, the ion engines were mounted on translation tables with the probe positioning system fixed. For the double Langmuir probe investigation of the FMT2, the thruster was mounted on a two-axis NEAT translation system mounted to a platform located in the middle of the LVTF along centerline (referred to as thruster station 2 in Figure 4-2). Subsequent single Langmuir and emissive probe testing on both the FMT2 and LM4 thrusters were conducted with the thrusters mounted on an Aerotech translation table whose structure is fixed directly to the chamber wall along with the probe positioning support. This last configuration was employed to eliminate probe misalignment during and after chamber pumpdown. This setup positions the thruster station 2 as well. During the initial characterization testing of the

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LM4, the ion engine was mounted on the inverted pendulum thrust stand (referred to as thruster station 1 in Figure 4-2). A schematic of the LVTF indicating the two thruster stations and location of the various components is shown in Figure 4-2.



Figure 4-2: Schematic of the Large Vacuum Test Facility (LVTF) at the University of Michigan (not to scale).

A dedicated propellant feed system consisting of three MKS 1159B mass flow controllers independently controls the xenon flow rate to the discharge cathode, neutralizer cathode, and main plenum with accuracies of  $\pm 0.1$  sccm,  $\pm 0.1$  sccm, and  $\pm 1$ sccm, respectively. The flow rates are periodically calibrated using a known control volume technique. A 2 m by 2.5 m louvered graphite panel beam dump is positioned approximately 4 m downstream of the ion thruster station 2 to reduce back sputtering.

## 4.2 High-speed Axial Reciprocating Probe (HARP)

A linear motor assembly provides accurate direct linear motion of the probe with minimal discharge cathode plume residence times. The HARP system, shown in Figure 4-3, is a three-phase Trilogy 210 brushless dc servo motor consisting of a linear "U"-shaped magnet track and a "T"-shaped coil moving on a set of linear tracks. The linear encoder provides positioning resolution to 5  $\mu$ m.¹⁸² A Pacific Scientific SC950 digital, brushless servo drive controls the motor. The HARP is a linear table with a 559 mm stroke length. The HARP is capable of moving small probes at speeds above 250 cm/s with acceleration rates above 7 g's.

Through the course of this investigation it is estimated that the HARP was swept a minimum of 100,000 times and continues to perform flawlessly. The entire HARP table is enclosed in a stainless steel shroud with a graphite outer skin. Residence times of the probe inside the discharge cathode plume are kept under 100 msec to minimize probe heating and discharge plasma perturbation. The HARP system was initially designed for internal discharge channel electrostatic probe measurements for Hall thrusters and additional information of the HARP system can be found in References 34, 130, 132, 166, 182, and 209. The HARP system was minimally modified for the near-DCA discharge plasma characterization.



Figure 4-3: HARP probe positioning system enclosed inside a graphite shell. Top cover is removed in photograph.

### **4.3** Linear Tables and Mechanisms

During the initial discharge plasma characterization testing of the FMT2 thruster utilizing the double probe, the thruster was mounted on a computer controlled two-axis crossed-stage positioning table. The HARP was mounted to the LVTF wall, while the two-axis New England Affiliated Technologies (NEAT) tables were mounted on a moveable platform. Following the double probe testing, data analysis revealed a misalignment of the double probe during pumpdown. To remedy this undesirable effect, a new setup was constructed in which a common mounting structure was used for both the ion engine and the HARP, thereby eliminating pumpdown shifting. For both setups, the HARP is fixed with respect to the tank and the thruster is moved with high precision about the HARP for spatial mapping. This approach is consistent with previous optical measurements and HARP measurements.⁴³

#### **4.3.1 NSTAR**

### 4.3.1.1 Double Probe Experimental Setup

The FMT2 thruster is mounted on a custom built, two-axis positioning system consisting of two NEAT translational stages (Figures 4-4 and 4-5). The custom-build NEAT tables have a range of 1.8 m in the radial direction and 0.9 m in the axial direction. Both stages have an absolute linear accuracy of 0.15 mm. The upper axis maintains a constant radial distance between the thruster and the HARP positioning system. The lower axis controls the engine axial location with respect to the probe to an absolute position accuracy of 0.15 mm.



Figure 4-4: Two-axis NEAT table used for FMT2 double probe testing.



Figure 4-5: Orientation of the FMT2 and positioning hardware used in double probe testing of FMT2, only. Note: the two-axis NEAT table (and hence FMT2) is mounted to a moveable platform, while the HARP is mounted to the LVTF wall leading to pumpdown shifting.

#### 4.3.1.2 Common Mounting Structure Experimental Setup

The floating platform, to which the two-axis NEAT table was mounted, shifted during pumpdown resulting in a misalignment of the double probe affecting the measured I-V curves. Subsequent electrostatic probe testing for the FMT2 engine were performed with a setup in which both the HARP and ion engine are mounted to a common structure affixed to the LVTF wall. A single Aerotech ATS62150 linear ball screw translation table provides axial movement of the thruster relative to the probe. The Aerotech table has a travel length of 1.5 m with an accuracy of  $\pm 2.5 \,\mu$ m. A Renco RCM21 encoder provides precision measurement of the position of the thruster with a resolution of 5  $\mu$ m and a frequency response to 200 kHz. The electrostatic probe is positioned radially inside the discharge chamber using the HARP. When actuated, the probe extends to the thruster centerline then returns to the starting location recessed inside the translation table retracts and extends the alumina tube as the axial location changes to minimize the length of guiding alumina that protrudes into the discharge chamber. The RMS-800 has a travel

distance of 20 cm and a leadscrew accuracy of 80  $\mu$ m, per manufacturer. The experimental setup is illustrated in Figure 4-6.

The FMT2 internal discharge mapping begins  $\sim 1.5 - 2$  mm downstream of the DCA face with an axial resolution of 1.6 mm (1/16 of an inch). The FMT2 discharge plasma containment mechanism has been described in §2.1.2. Figure 4-7 demonstrates the probe insertion into the discharge chamber and is representative of all electrostatic probes though the double probe is in the photographs. An Opticom CC-02 vacuum-rated camera is mounted inside the plasma shield of the FMT2 thruster to monitor the discharge plasma containment mechanism during testing. The camera provides 400 horizontal TV lines.



Figure 4-6: FMT2 orientation with respect to the HARP for probe insertion mounted on Aerotech table. The (0, 0) location is 2 mm from the DCA on thruster and discharge cathode centerline. Note: the Aerotech table (and hence FMT2) is mounted to the same support structure as the HARP eliminating the pumpdown misalignment problem. Interrogation region located in red (radial sweeps).



Figure 4-7: Photographs taken inside the discharge chamber prior to engine testing showing the interior of the Discharge Plasma Containment Mechanism (DPCM): (a) no probe insertion, (b) double probe is roughly halfway to the cathode centerline, and (c) close up with double probe at discharge cathode centerline. The closest axial location to the Discharge Cathode Assembly is 2 mm.

#### 4.3.2 NEXT

The LM4 characterization utilizes the same FMT2 setup in which both the HARP and ion engine are mounted to a common structure affixed to the LVTF wall. The single Aerotech ATS62150 linear ball screw translation table provides axial movement (accuracy of  $\pm 2.5 \,\mu$ m) of the thruster relative to the probe. The axial location is verified by the Renco RCM21 encoder, which has a resolution of 5 µm. The LM4 test configuration features two staggered electrostatic probes that are inserted into the discharge plasma. The upstream probe characterizes the near-DCA region while the downstream probe characterizes the near-grid region. The near-DCA mapping begins  $\sim$ 1.5 mm downstream of the discharge keeper face. The electrostatic probes are positioned radially inside the discharge chamber using the HARP. Each probe is activated individually, with the dormant probe floating. When actuated, the probe extends to the thruster centerline then returns to the starting location recessed inside the translating alumina tube. Because the mounting flange is at 90° with respect to the probe axis, the RMS-800 NEAT table is not needed during data collection, but is used during setup to facilitate alignment. The experimental setup is illustrated in Figures 4-8 and 4-9.

The LM4 internal discharge mapping begins 2 mm downstream of the DCA face with an axial resolution of 1 mm. The LM4 discharge plasma containment mechanism has been described in §2.2.6.



Figure 4-8: The LM4 dual-region (near-DCA and near-grid) interrogation setup. The (0, 0) location is 1.5 mm from the DCA on thruster and discharge cathode centerline. Interrogation regions are indicated in red (radial sweeps).



Figure 4-9: Photograph of the LM4 discharge plasma containment mechanism illustrating the two interrogation regions.

# **CHAPTER 5**

## **FMT2 NSTAR NEAR-DCA MEASUREMENTS**

Electrostatic probe measurements are presented in the FMT2 thruster over a wide variety of operating conditions using a symmetric double Langmuir probe, a single Langmuir probe, and a floating emissive probe. The thruster operating conditions are labeled according to the electrostatic probe used for clarity. The operating condition abbreviations are: symmetric double Langmuir probe (DP), single Langmuir probe (SLP), and floating emissive probe (FEP). NSTAR throttling points or TH levels are included for reference. Multiple characterizations at equivalent operating conditions permit a repeatability check on the methods and are labeled sequentially by lower case letters. The discharge plasma parameters are measured for radial sweeps extending from just inside the anode wall to DCA centerline. The radial sweeps extend downstream of the DCA in the axial directions giving two-dimensional contours of the discharge cathode plume and discharge chamber plasmas. Each of the full interrogation region contour plots contains parameters calculated from over 3,000 I-V characteristics.

## 5.1 Operating Conditions Investigated

Tables 5-1 and 5-2 list the symmetric double Langmuir probe conditions investigated for operation with ion beam extraction and with discharge-only operation, respectively. Operation of the ion thruster with beam extraction is designated as a thruster operating condition (TOC) while thruster operation without a beam is referred to as a discharge level (DL). Several different discharge-only conditions were investigated while troubleshooting problems with the transition to beam extraction. The discharge-only operating conditions span a range of main and discharge cathode flow conditions. Discharge-only operation is conducted with the screen grid electrically connected to discharge cathode common. No attempts were made to bias the screen grid to simulate ion extraction.

										Disch.	Neut.	
									Main	Cath.	Cath.	Vck-
	Vs	Jb	Va	Ja	Vdc	Jdc	Vnk	Jnk	flow	flow	flow	СС
Level	V	A	V	mA	V	A	V	A	sccm	sccm	sccm	V
TH 4	1100	0.71	-150	1.927	25.61	6.05	16.26	2.0	8.30	2.47	2.40	-
DP TOC 4a	1100	0.71	-150.0	2.72	25.65	6.05	19.93	2.0	8.9	4.94	3.47	7.00
DP TOC 4b	1103	0.71	-150.3	2.68	25.60	6.05	17.68	2.00	8.7	5.21	3.47	6.84
TH 8	1100	1.10	-180	3.139	25.10	8.24	15.32	1.5	14.41	2.47	2.40	-
DP TOC 8	1101	1.10	-180.1	4.84	25.10	8.24	17.40	2.00	15.3	4.02	3.68	6.49
TH 12	1100	1.49	-180	4.704	25.40	10.87	14.52	1.5	19.86	2.89	2.81	-
DP TOC 12	1100	1.49	-180.1	6.75	25.40	10.87	18.50	1.50	21.2	3.28	3.89	5.80
TH 15	1100	1.76	-180	5.993	25.14	13.13	14.02	1.5	23.43	3.70	3.60	-
DP TOC 15	1100	1.76	-180.1	8.30	25.14	13.13	-	-	25.1	2.96	3.60	5.53

 Table 5-1: Double Langmuir probe (DP) nominal Thruster Operating Conditions (TOC Levels) and reference NSTAR Throttling Levels (TH Levels).

			Main	Disch. Cath.	Corrected		
	Vdc	Jdc	Flowrate	Flowrate	Pressure		
Level	V	Α	sccm	sccm	Torr		
TH 4	25.61	6.05	8.3	2.47	-		
DP TOC 4a	25.65	6.05	8.9	4.94	2.5E-06		
DP TOC 4b	25.60	6.05	8.7	5.21	2.5E-06		
DP DL 4a	25.61	6.05	12.1	4.07	2.3E-06		
DP DL 4b	25.41	6.05	19.5	2.54	3.1E-06		
DP DL 4c	25.60	6.05	8.1	2.29	1.6E-06		
TH 8	25.10	8.24	14.4	2.47	-		
DP TOC 8	25.10	8.24	15.3	4.02	2.5E-06		
DP DL 8a	25.10	8.24	16.3	3.37	2.7E-06		
DP DL 8b	25.15	8.24	15.8	2.54	2.5E-06		
DP DL 8c	25.15	8.24	21.5	2.78	3.3E-06		
DP DL 8d	25.10	8.24	23.0	3.17	3.5E-06		
TH 12	25.40	10.87	19.9	2.89	-		
DP TOC 12	25.40	10.87	21.2	3.28	3.9E-06		
DP DL 12a	25.40	10.87	16.0	2.22	2.8E-06		
DP DL 12b	25.45	10.87	16.2	2.89	2.5E-06		
TH 15	25.14	13.13	23.4	3.70	-		
DP TOC 15	25.14	13.13	25.1	2.96	4.4E-06		
DP DL 15a	25.15	13.13	11.4	2.17	2.0E-06		
DP DL 15b	25.10	13.13	8.4	3.47	1.7E-06		

 Table 5-2: Double Langmuir probe (DP) discharge levels (DL) operation with thruster operating conditions (TOC) and NSTAR throttle points (TH) for reference.

Table 5-3 lists the single Langmuir probe operating conditions investigated for the FMT2 investigation. The operating conditions focus on the ELT conditions highlighting operation at the equivalent TH 8, TH 15, and a configuration at TH 8 with the discharge cathode keeper voluntarily shorted to cathode common. The shorted configuration is of special interest because the onset of the increased erosion coincided with reduced thruster power from TH 15 to TH 8 operation with an unexpected reduction in the resistance between discharge cathode common and the cathode keeper. The throttled conditions are also characterized for equivalent discharge plasma only operation with similar discharge voltages and currents. Finally, the conditions of the 2000 hr and 8200 hr wear tests were

investigated to give a one-to-one comparison of discharge plasma parameters with the

erosion rates observed in those wear tests.

l evel	Vs V	Jb A	Va V	Ja mA	Vdc V	Jdc A	Vnk V	Jnk A	Main flow sccm	Disch. Cath. flow sccm	Neut. Cath. flow	Vck-cc	Pressure
TH 8	1100	1.10	-180	3.139	25.10	8.24	15.32	1.5	14.41	2.47	2.40	-	-
SLP DL 8	-	-	-	-	25.12	8.24	-	-	15.7	3.85	-	-	1.9E-06
SLP TOC 8a	1100	1.10	-180.0	4.41	25.12	8.24	16.83	1.50	16.0	3.81	4.61	6.70	2.3E-06
SLP TOC 8b	1100	1.10	-180.0	4.47	25.10	8.24	18.06	1.50	15.5	4.87	4.86	6.96	2.3E-06
SLP TOC 8 CK-													
CC shorted	1100	1.10	-180.0	4.40	25.10	8.24	17.63	1.50	15.5	4.92	4.86	0.00	2.4E-06
TH 12	1100	1.49	-180	4.704	25.40	10.87	14.52	1.5	19.86	2.89	2.81	-	-
SLP DL 12	-	-	-	-	25.45	10.87	-	-	15.7	2.94	-	-	1.8E-06
SLP TOC 12	1100	1.49	-180.0	6.56	25.40	10.87	17.50	1.50	21.1	3.30	4.61	6.34	2.7E-06
TH 15	1100	1.76	-180	5.993	25.14	13.13	14.02	1.5	23.43	3.70	3.60	-	-
SLP DL15	-	-	-	-	25.15	13.13	-	-	15.1	2.77	-	-	1.8E-06
SLP TOC 15	1100	1.76	-180.0	8.37	25.10	13.13	16.13	1.50	24.5	3.06	4.61	6.30	2.9E-06
SLP 2000 Hr	1100	1.76	-180.0	7.66	26.80	12.10	16.35	2.00	24.3	3.00	4.86	6.84	2.9E-06
SLP 8200 Hr	1100	1.76	-180.0	8.15	25.10	12.80	15.95	1.50	25.4	3.21	4.86	6.75	3.0E-06

 Table 5-3: Experiment single Langmuir probe (SLP) nominal Thruster Operating Conditions (TOC Levels) and reference NASA Throttling Levels (TH Levels).

Table 5-4 presents the floating emissive probe (FEP) operating conditions investigated. Due to time constraints no data were taken without beam extraction. The ELT TH 8 condition was investigated with the discharge cathode keeper electrically connected to cathode common. Although much less accurate, plasma potentials calculated from single Langmuir probe data are presented for verification of the FEP trends.

	V			N		N				Main	Disch. Cath.	Neut. Cath.	Proseuro
	V _{dc}	J _{dc}	V _{ck-cc}	Vs	J _b	Va	J _a	V _{nk}	J _{nk}	now	now	now	Flessule
Level	V	Α	V	V	Α	V	mA	V	Α	sccm	sccm	sccm	Torr
TH 8	25.10	8.24	-	1100	1.10	-180.0	3.139	15.32	1.50	14.41	2.47	2.40	-
FEP TOC 8a	25.20	8.24	7.70	1100	1.10	-180.0	5.46	-	-	17.0	4.37	4.49	4.1E-06
FEP TOC 8b	25.20	8.24	6.84	1100	1.10	-180.0	5.15	-	-	17.1	4.54	4.49	4.1E-06
FEP TOC 8													
CK-CC short	25.15	8.24	0	1100	1.10	-180.0	5.09	-	-	16.9	4.64	4.49	4.2E-06
TH 12	25.40	10.87	-	1100	1.49	-180.0	4.704	14.52	1.50	19.86	2.89	2.81	-
FEP TOC 12	25.40	10.87	5.86	1100	1.49	-180.0	6.94	-	-	21.6	3.52	4.49	4.4E-06
TH 15	25.14	13.13	-	1100	1.76	-180.0	5.993	14.02	1.50	23.43	3.70	3.60	-
FEP TOC 15	25.15	13.13	5.47	1100	1.76	-180.1	8.46	-	1	24.8	3.13	4.49	4.6E-06
2000 hr WT	26.80	12.10	5.91	1100	1.76	-180.1	8.50	-	-	24.5	2.93	4.49	4.7E-06

 Table 5-4: Experiment floating emissive probe (FEP) nominal Thruster Operating Conditions (TOC Levels) and reference NSTAR Throttling Levels (TH Levels).

## 5.2 Number Density Results

Ion/electron number density data are presented again for various throttled operating conditions both with and without beam extraction. The axial and radial locations of all plasma parameter plots are non-dimensionalized by the FMT2 discharge cathode keeper outer diameter. The number density contours have a similar structure over all operating conditions investigated. The number density contours are shaped by the magnetic field inside the discharge. The magnetic field of FMT2 at the discharge cathode exit plane is primarily in the axial direction. Electrons are confined to orbits about the magnetic field lines thereby inhibiting motion in the transverse direction. Because the electrons are restricted to a narrow region, a majority of the ionization occurs directly downstream of the DCA producing a plume of high number density. The high-density plume is visually observed during testing via vacuum-rated cameras mounted above the FMT2 thruster, illustrated in Figure 5-1.



Figure 5-1: Photograph of the intense high-density discharge cathode plume. The staggered single Langmuir probes are seen during data collection. Here the near-DCA probe is active and collecting data.

The radial sweeps are performed across magnetic field lines in between two of the FMT2 magnetic cusps. The number density decreases rapidly in the radial direction reinforcing the importance of the magnetic field in the discharge plasma structure. Number densities also decrease with increasing axial distance, but with much smaller gradients than in the radial direction.

### 5.2.1 Number Density - Symmetric Double Langmuir Probe

Symmetric double Langmuir probe measurements are presented over a twodimensional spatial array in the discharge chamber of the 30-cm FMT2 ion thruster. The independent sheath constraint of the double probe requires a large gap between the two electrodes, which reduces the spatial resolution. Because neither electrode is sampling the high-density discharge cathode plume, when straddling the cathode orifice at the closest locations near the discharge cathode exit plane, the measured number density near cathode centerline is lower than the actual value. This leads to large errors in the discharge parameters measured in the extreme near-DCA region. Single Langmuir probe measurements do not suffer from this restriction and therefore more accurately measure the near-DCA plasma.

Double Langmuir probe number density contours are illustrated with a maximum of  $8 \times 10^{12}$  cm⁻³ on centerline for the highest power condition (TOC 15). The figures provide detailed number density data that are accurate in the bulk discharge, but offer diminishing information in the near-DCA region. The data support confinement of electrons to a narrow stream along the discharge cathode centerline evident from a highly visible plume extending downstream of the discharge cathode. The number density profiles demonstrate such a narrow plume-like structure consistent with the FMT2 magnetic field. As expected, the number density gradients are largest in the radial direction with the number density decreasing by an order of magnitude from cathode centerline to the cathode keeper outer radius.

Figures 5-2 through 5-5 illustrate the number density structure as a function of FMT2 thruster operation. Because of the importance of the magnetic field, representative magnetic streamlines are indicated for some of the contours. As expected, for the higher flow rates and discharge currents of the higher-power operating conditions, the number

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density increases as the FMT2 is throttled to higher-power. The near-DCA number density ranged from  $4x10^{12}$  to  $8x10^{12}$  cm⁻³ for the lowest and highest power conditions, respectively.



Figure 5-2: DP TOC 4b full interrogation region number density mapping with representative magnetic streamlines.



Figure 5-3: DP TOC 8 full interrogation region number density mapping.



Figure 5-4: DP TOC 12 full interrogation region number density mapping.



Figure 5-5: DP TOC 15 full interrogation region number density mapping with representative magnetic streamlines.

#### 5.2.1.1 Double Probe Discharge-Only Comparison - n_i

When a beam is no longer extracted, the discharge voltage decreases because of the reduced plasma resistivity at constant discharge current. As a result, the dischargeonly conditions require reduced propellant flow rates to achieve equivalent discharge voltages compared to operation with a beam. The flow reduction can be accomplished by reducing the discharge cathode and main plenum flow in a number of ways. For the lowpower conditions, the ratios of total propellant flowrate between the thruster operation with and without beam extraction are close to one. Comparison of the contours for these conditions reveals very little variation in the number density contours when a beam is no longer extracted. For the higher-power operating conditions, the total flow rate ratios of the beam and discharge-only conditions differ by up to a factor of two. The number density contours for these conditions are noticeably different with and without a beam. A slight decrease in the near-DCA centerline value is observed without a beam. The contours without a beam tend to become more stretched in the axial direction revealing diminished axial gradients in number density compared to their beam extracted counterparts.



Figure 5-6: DP DL 4a full interrogation region number density mapping.



Figure 5-7: DP DL 8b full interrogation region number density mapping.



Figure 5-8: DP DL 12b full interrogation region number density mapping with notional magnetic streamlines.



Figure 5-9: DP DL 15a full interrogation region number density mapping.

#### 5.2.2 Number Density - Single Langmuir Probe

Single Langmuir probe number densities are presented, in Figure 5-10 through Figure 5-12, over a range of FMT2 operating conditions similar to the double Langmuir probe results. All discharge plasma locations have been non-dimensionalized based upon the discharge cathode keeper diameter. The single Langmuir probe number density contours are similar in structure to the double Langmuir probe results. The number density contours are shaped by the magnetic field lines creating a high-density cathode plume. As expected, the single Langmuir probe measures higher number densities than the double Langmuir probe near the DCA. The single Langmuir probe number densities are as high as  $3x10^{13}$  cm⁻³ at the discharge cathode keeper exit plane for the highest power condition. The plasma number density monotonically decreases with increasing axial distance from the DCA. A pump down misalignment would eventually position the electrode outside the high-density cathode plume as the DCA exit plane is approached producing a quick drop in number density. Because this is not observed, a pump down misalignment has not occurred and the common mounting structure has eliminated the problem.

Outside of the DCA plume, the bulk discharge plasma number densities are similar to double probe results with a range from  $5 \times 10^{10}$  cm⁻³ to  $5 \times 10^{11}$  cm⁻³. The closeness of the measured number densities for the two Langmuir probe diagnostics indicates the robustness of the Langmuir probe diagnostic. Near the anode, in between magnetic cusps, a magnetic field almost parallel to the anode causes the number density to drop as low as  $1 \times 10^{10}$  cm⁻³.

As the FMT2 is throttled to higher-power, the near-DCA single Langmuir probe number densities show little variation. The single Langmuir probe profiles display slight broadening in the cathode plume as the engine is throttled to higher-power. This broadening may have contributed to the observed increase in the on-axis double Langmuir probe number densities that straddle cathode centerline.



Figure 5-10: SLP TOC 8a full interrogation region number density mapping with representative magnetic field lines.



Figure 5-11: SLP TOC 12 full interrogation region number density mapping.



Figure 5-12: SLP TOC 15 full interrogation region number density mapping.

Data are presented for two of the NSTAR wear test operating conditions. Figure 5-13 and Figure 5-14 indicate the number densities for FMT2 at the 2000 hour and 8200 hour wear tests, respectively. The 2000 hour wear test was roughly operated at the TH 15 level, but with an increased discharge voltage of 26.80 V and decreased discharge current of 12.10 A. The 8200 hour wear test was also conducted roughly at the highest-power TH 15 level, but with a discharge current of 12.80A. The DCA plume structures for the wear tests are identical to all other conditions. However, the bulk discharge number densities are slightly larger than the TOC 15 operating condition, in the range of  $1 \times 10^{11} - 1 \times 10^{12}$  cm⁻³.



Figure 5-13: SLP 2000 hr. wear test full interrogation region number density mapping.



Figure 5-14: SLP 8200 hr. wear test full interrogation region number density mapping with representative magnet streamlines.

#### 5.2.2.1 Single Langmuir Probe Discharge-Only Comparison – n_i

The effects of beam extraction are illustrated by comparing the single Langmuir probe results with beam extraction, Figure 5-10 through Figure 5-12, to the dischargeonly single Langmuir probe results, Figure 5-15 through Figure 5-17. Comparison of the contours with discharge-only operation to their extracted beam operation counterparts reveals a stretching of the DCA plume structure indicating a relaxation of the axial number density gradient. This phenomenon may result from the extraction of ions at the mid- to outer-radius, which adds to the radial diffusion of ions compared to the discharge-only cases. The bulk discharge number densities are unaffected by the extraction of a beam.



Figure 5-15: SLP DL 8a full interrogation region number density mapping with representative magnetic field lines.



Figure 5-16: SLP DL 12 full interrogation region number density mapping.



Figure 5-17: SLP DL 15 full interrogation region number density mapping.
#### 5.2.2.2 Cathode Keeper to Cathode Common Shorting Effect – n_i

The effect of shorting the discharge cathode keeper to the discharge cathode common is illustrated by comparison of Figure 5-18 and Figure 5-19. The short does not have a noticeable effect on the measured number densities. The two contour plots are almost indistinguishable. A closer inspection of the near-DCA plasma is performed in the next section, §5.2.3.







 $n[cm^3]$ 

Figure 5-19: SLP TOC 8 with discharge cathode keeper to cathode common short full interrogation region number density mapping.

### 5.2.3 Near-DCA Parameters

For clarity, the near discharge regions are focused upon in the following figures. Since the near-DCA plasma is most important to discharge cathode erosion, this examination will provide more detailed information related to DCA wear mechanisms. The near-DCA contours consist of data calculated from approximately 1,600 I-V characteristics

### 5.2.3.1 Number Density Beam Extraction Effects – Double Probe

Closer inspection of number density contours, obtained from the double probe and illustrated in Figure 5-20 and Figure 5-21, confirm a stretching of the DCA plume without beam extraction. The extraction of a beam clearly couples to the discharge cathode plume and influences the near-DCA plasma. This result justifies the rigorous investigation of DCA erosion in the presence of a beam. The number densities in the cathode plume of the operation with beam extraction increase as the engine is throttled to higher-power. Though the double probe resolution is reduced near the DCA, the trends observed are similar to the single Langmuir probe results and serve as qualitative verification.



Figure 5-20: DP TOC 4b (left) and DP DL 4a (right) near-DCA region number density mapping.



Figure 5-21: DP TOC 8 (left) and DP DL 8b (right) near-DCA region number density mapping.

Williams' Langmuir probe data⁴⁸ exhibit a drop in number density with increasing axial distance from the DCA along centerline consistent with the current measurements (by an order of magnitude after 4 cm). In addition, his maximum number density, measured at the nearest axial location (5 mm), was  $2x10^{12}$  cm⁻³.

Foster, *et al.* have taken high-current hollow cathode measurements on a 12.7 mm hollow cathode inside an NSTAR type discharge chamber.^{140,141,210} Radial measurements taken 3 mm downstream of the keeper plate report a maximum number density of approximately  $2x10^{12}$  cm⁻³ on-axis with steep radial gradients, similar to the present data. Their results also indicate an increase in number density with increasing discharge current consistent with the current measurements.



Figure 5-22: DP TOC 12 (left) and DP DL 12b (right) near-DCA region number density mapping.



Figure 5-23: DP TOC 15 (left) and DP DL 15a (right) near-DCA region number density mapping.

#### 5.2.3.2 Number Density Beam Extraction Effects – Single Langmuir Probe

The single Langmuir probe offers the most accurate flight-like NSTAR environment measurement of the near-DCA number densities taken to date. The near-DCA number densities show little variation with thruster operating condition. The presence of a beam introduces stronger axial gradients in the number density as the electric field of the ion optics appears to couple to the discharge cathode plume. The steep radial gradients are unaffected by thruster throttling condition and the extraction of a beam. Number densities as high as  $3x10^{13}$  cm⁻³ are measured on centerline at the discharge keeper exit plane. The axially extended plume structures are surprising given that the cathode flowrates with beam extraction are larger than the discharge-only flowrates. The extraction of beam increases ion removal possibly leading the reduction, while discharge-only operation leads to a buildup of ions along the DCA centerline.



Figure 5-24: SLP TOC 8a (left) and SLP DL 8 (right) near-DCA region number density mapping.



Figure 5-25: SLP TOC 12 (left) and SLP DL 12 (right) near-DCA region number density mapping.



Figure 5-26: SLP TOC 15 (left) and SLP DL 15 (right) near-DCA region number density mapping.

### 5.2.3.3 Cathode Keeper to Cathode Common Short Effect - n_i

Reproduction of the thruster conditions at the time of the onset of severe DCA erosion in the ELT indicates an unperceivable change in number density structure with the keeper shorted to discharge cathode common. Figure 5-26 demonstrates the

equivalent near-DCA structures with and without reduced resistance between the keeper and common connections to the discharge cathode.



Figure 5-27: SLP TOC 8b (left) and SLP TOC 8 with discharge cathode keeper to cathode common short (right) near-DCA region number density mapping.

# 5.2.3.4 Wear Test Condition Near-DCA Number Density

The thruster conditions of the 2000 hr. and 8200 hr wear tests have been duplicated offering discharge plasma data for erosion models used to account for the measured erosion rates of these tests. The near-DCA number densities are similar to the TOC 15 operation. The maximum number density is approximately  $3x10^{13}$  cm⁻³ for both operating conditions occurring just downstream of the DCA along centerline. Just outside the high-density plume, the number densities are approximately  $5x10^{11}$  cm⁻³. These values will be important in determining the flux of ions towards the DCA used in the erosion calculation of CHAPTER 9.



Figure 5-28: SLP 2000 hr. wear test (left) and SLP 8200 hr. wear test (right) near-DCA region number density mapping.

# **5.3 Electron Temperatures**

Graphical representations of the measured Maxwellian electron temperatures for varying FMT2 thruster operating conditions both with and without beam extraction are presented. The contour plots of electron temperature have the same general shape. A region of lower electron temperature plasma exists in the discharge cathode plume near the DCA. An off-axis electron temperature maximum is evident for many of the contours. The bulk discharge electron temperatures range from 2 - 5 eV for almost all operating conditions. Near the anode, higher than bulk discharge or lower than bulk discharge electron temperatures are measured depending upon the thruster condition. The electron temperatures near the anode may not be representative of the true electron temperatures in these regions due to the low signal-to-noise ratios.

As the number density mappings indicate, there is a substantial decrease in number density as the anode wall is approached due to the magnetic field. This decrease reduces the currents measured for the Langmuir probe I-V characteristics. As the signalto-noise ratio decreases, the scatter in the electron retarding region increases. Electron temperatures calculated for this condition have large errors associated with them. To further aggravate the problem, a small DC offset in the current measurement can force the calculated electron temperature to become either extremely high or extremely low depending upon the sign of the shift. The sporadic regions of increased electron temperature near the anode are a result of the combination of noise in the I-V characteristics at these locations and the reduction of the number of points in the region from which electron temperature is calculated.

As the floating emissive probe plasma potentials will show, the plasma potential structure produces electric fields between the discharge cathode plume and bulk discharge to enhance diffusion of electrons across the axial magnetic field. As the electrons are accelerated across the radial potential gradient their energy is increased resulting in an increased electron temperature. This effect is further supported by the electron energy distributions measured across the potential gradient. The potential change, 7 - 12 volts across the distance of the discharge keeper plate outer radius from cathode centerline, is on the order of the first ionization potential of xenon (12.13 eV). This finding has also been documented by Foster, *et al.* in an NSTAR discharge chamber.¹⁴⁰

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## 5.3.1 Electron Temperature - Double Langmuir Probe

The maximum ion current from one electrode of the double probe limits the electron current measured by the other since the probe floats as a whole. Thus, only the high-energy electrons are sampled, reducing the accuracy of the double Langmuir probe electron temperature. The double Langmuir probe electron temperature results indicate a low electron temperature plume (2 - 3 eV) extending downstream of the DCA. The bulk discharge plasma electron temperatures are a few eV higher (3 - 5 eV). Near the anode, the reduced signal-to-noise level of the double probe currents precludes accurate electron temperature calculation. The decreased electron temperatures may result from sheath effects on the anode and/or guiding alumina. A slight increase in the electron temperature in the bulk discharge is discernable as the engine is throttled to higher-power levels.



Figure 5-29: DP TOC 4b full interrogation region electron temperature mapping.



Figure 5-30: DP TOC 8 full interrogation region electron temperature mapping with representative magnetic field lines.



Figure 5-31: DP TOC 15 full interrogation region electron temperature mapping.

#### **5.3.1.1** Discharge-Only Te Effects – Double Probe

The effects of beam extraction are also evident in the electron temperatures of the discharge plasma. Without a beam, the discharge cathode plume structure of reduced electron temperature becomes less evident. The bulk discharge electron temperatures are reduced for the discharge-only operation compared to their beam extracted counterparts. Beam extraction, with comparable mass flow rates, would cause a decrease in the pressure inside the discharge chamber as ions (previously atoms) leave the chamber. Fewer neutrals are available to cool the electrons via inelastic collisions resulting in a broadening of the high electron temperature plume. Though the discharge-only mass flow

rates have been reduced to match the discharge voltage, a decreased bulk discharge electron temperature is observed. Discharge voltage oscillations, considerably higher for beam extraction, may also contribute to the higher observed beam extraction electron temperatures. Although less pronounced, the discharge-only data do follow the trend of increasing electron temperature for higher-power operation.



Figure 5-32: DP DL 4a full interrogation region electron temperature mapping.



Figure 5-33: DP DL 8b full interrogation region electron temperature mapping.



Figure 5-34: DP DL 12b full interrogation region electron temperature mapping.



Figure 5-35: DP DL 15a full interrogation region electron temperature mapping.

### **5.3.2 Electron Temperature - Single Langmuir Probe**

Similar to the electron temperature measurements made with the double Langmuir probe, each of the single Langmuir probe contours illustrates an off-axis maximum electron temperature region. Electron temperatures in the DCA plume range from 2 - 4 eV and increase with axial distance from the keeper exit plane. The off-axis maximum coincides with the visual boundary between the discharge cathode plume and the bulk discharge plasma. Over most of the operating conditions investigated, the bulk discharge plasma electron temperatures range from 4 - 7 eV. The electron temperature contours are relatively unaffected as the engine is throttled up to higher-power levels. This finding is different than the double Langmuir probe cases, which indicate a slight increase in electron temperature with increasing thruster power levels.

The larger electron saturation current measured with the single Langmuir probe extends the region of useful electron temperatures, with good current signal-to-noise, compared to the double Langmuir probe. Close to the anode, dc offsets and reduced current resolution may contribute to the high electron temperature regions. High electron temperatures are often observed near the anode in Hall thrusters. However, the near-anode increase in temperature is a sheath effect with a characteristic distance on the order of the Debye Length.²¹¹ Though the Debye length, and hence sheath, can increase substantially in a high-electron temperature, low-density plasma, it does not extend to distances consistent with the observed trends. The high electron temperatures measured with the single Langmuir probe are primarily due to the combined effects of a low signal-to-noise ratio for probe current and the magnetic field reduction of measured electron saturation current in this low-density region.



Figure 5-36: SLP TOC 8a full interrogation region electron temperature mapping with representative magnetic streamlines.



Figure 5-37: SLP TOC 12 full interrogation region electron temperature mapping.



Figure 5-38: SLP TOC 15 full interrogation region electron temperature mapping.



Figure 5-39: SLP 2000 hr. wear test full interrogation region electron temperature mapping.



Figure 5-40: SLP 8200 hr. wear test full interrogation region electron temperature mapping with representative magnetic field lines.

#### 5.3.2.1 Discharge-Only Te Effects – Single Langmuir Probe

The suspension of beam extraction results in a decrease in the discharge plasma electron temperatures similar to the double Langmuir probe results. Furthermore, the high electron temperatures near the anode appear to be confined to a smaller region near the anode. Without a beam, the discharge chamber pressure increases. Due to inelastic collisions with neutrals, the electron temperature is quenched with discharge-only operation. This decrease in electron temperature is enhanced by the reduced discharge voltage oscillations for discharge-only operation.



Figure 5-41: SLP DL 8 full interrogation region electron temperature mapping.



Figure 5-42: SLP DL 12 full interrogation region electron temperature mapping with representative magnetic field lines.



Figure 5-43: SLP DL 15 full interrogation region electron temperature mapping.

# 5.3.2.2 Cathode Keeper to Cathode Common Short Effect - Te

The electron temperature contours in Figure 5-44 and Figure 5-45 indicate a negligible change as the cathode keeper is shorted to discharge cathode common simulating the ELT condition. This finding is not surprising, given that the plasma will act to smooth out discontinuities and shield charges with sheaths. The shorting of the keeper to common is restricted to the keeper sheath and does not have an effect on the electron temperature of the bulk discharge plasma.



Figure 5-44: SLP TOC 8b full interrogation region electron temperature mapping.



Figure 5-45: SLP TOC 8 with discharge cathode keeper shorted to cathode common full interrogation region electron temperature mapping with representative magnetic streamlines.

## **5.3.3 Near-DCA Electron Temperatures**

The electron temperature data near the DCA are highlighted in the following section. This section serves to focus on the plasma parameters that directly impact the discharge cathode plasma and erosion mechanisms.

### 5.3.3.1 Te - Double Probe

The near-DCA double Langmuir probe contours indicate very little variation of the discharge cathode plume electron temperatures. The electron temperatures measured outside of the plume increase in magnitude as the thruster is throttled to higher-power and decrease noticeably when a beam is not extracted. The discharge cathode plume electron temperatures range from 2 - 3 eV. The electrons gain energy as they are accelerated across the transition region between the cathode plume and main discharge plasma, which results in an increase in the electron temperature. The EEDF measurement will offer more insight on this mechanism.



Figure 5-46: DP TOC 4b (left) and DP DL 4a (right) near-DCA region electron temperature mappings.



Figure 5-47: DP TOC 8 (left) and DP DL 8b (right) near-DCA region electron temperature mappings.



Figure 5-48: DP TOC 12 (left) and DP DL 12b (right) near-DCA region electron temperature mappings.



Figure 5-49: DP TOC 15 (left) and DP DL 15a (right) near-DCA region electron temperature mappings.

# 5.3.3.2 Te - Single Langmuir Probe

The near-DCA electron temperatures measured with the more accurate single Langmuir probe indicate a minimum electron temperature immediately downstream of the DCA. This approximately 2 eV value increases up to 5 eV in the axial direction and quickly jumps up to 5 or 6 eV with increasing radial distance from cathode centerline. The increased electron temperatures result from potential features inside the ion thruster discharge. Very little variation in the near-DCA electron temperatures is observed as the engine is throttled to higher-power. However, the decrease in electron temperature without a beam is evident and indicates the coupling of the discharge plasma and the ion beam, further supporting the need for beam extraction when measuring discharge chamber plasma parameters.



Figure 5-50: SLP TOC 8a (left) and SLP DL 8 (right) near-DCA region electron temperature mappings.



Figure 5-51: SLP TOC 12 (left) and SLP DL 12 (right) near-DCA region electron temperature mappings.



Figure 5-52: SLP TOC 15 (left) and SLP DL 15 (right) near-DCA region electron temperature mappings.

## 5.3.3.3 Cathode Keeper to Cathode Common Short Effect - Te

The near-DCA electron temperatures are unaffected by the reduction in resistance between discharge cathode keeper and common. The shorting is expected to impact the discharge plasma potential. However, plasma potential data presented later show the changes in plasma potential due to keeper shorting is restricted to sheath of the keeper.



Figure 5-53: SLP TOC 8b (left) and SLP TOC 8 with discharge cathode keeper shorted to cathode common (right) near-DCA region electron temperature mappings.

# 5.3.3.4 Wear Test Electron Temperature Contours

The wear test conditions were investigated illustrating comparable electron

temperature magnitudes and structures compared to the TOC 15 condition.



Figure 5-54: SLP 2000 hr. wear test (left) and SLP 8200 hr. wear test (right) near-DCA region electron temperature mappings.

# 5.4 Plasma Potential

Plasma potentials have been measured using two methods. The "knee" of the I-V curves from single Langmuir probe data serves as an estimate of the local plasma potential if electron saturation is achieved. For much of the near-DCA region electron saturation was not possible given the electric circuit design and without unduly perturbing the discharge plasma. Over this region a floating emissive probe diagnostic provides accurate measurement of the discharge plasma. The floating emissive probe plasma potentials will determine the local plasma potential more accurately throughout the discharge chamber. The "knee" calculation serves only to roughly corroborate the observed floating emissive probe trends.

#### 5.4.1 Plasma Potential - Single Langmuir Probe

Plasma potentials are estimated from the location of the "knee" in the I-V characteristics for spatial locations in which electron saturation is reached. Electron current saturation is not reached in the high-density cathode plume region due to the limitation of the Langmuir probe circuit and desire to minimize discharge plasma perturbations. Where electron saturation was not achieved, the results from the floating emissive probe have been blended to fill out the contour images. Analyses of the plasma potentials from the single Langmuir probe are very noisy due to the uncertainty in estimating the characteristic "knee" location. The overall magnitude of the main discharge plasma region ranges from 24 to 36 volts and can be seen in Figures 5-55 through 5-62.

Inspection of the plasma potentials yields a distinct discharge cathode plume of low plasma potential (12 - 20 V) with a rapid increase in the radial direction. This trend in plasma potentials follows the trend of the number densities. The discharge chamber magnetic field effectively confines most of the electrons along the magnetic field lines reducing cross-field (radial) conductivity. The result is a region of high electric potential near the anode in between cusps. The bulk discharge structure is relatively unaffected by the thruster operating conditions. A majority of the potential variation is observed near the anode region where Langmuir probe current signal-to-noise ratios are diminished, adding error to the calculation. The plasma potentials from the single Langmuir probe are considerably higher than those measured by other researchers in ion thruster discharge chambers and higher than floating emissive probe results suggesting that the single

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Langmuir probe "knee" estimation from point-by-point I-V curves over-estimates discharge plasma potentials.

The extraction of a beam appears to have a very modest effect of decreasing the near-anode potentials. This trend will be confirmed by the floating emissive probe.



Figure 5-55: SLP TOC 8a full interrogation region plasma potential contour with representative magnetic field streamlines.



Figure 5-56: SLP DL 8 full interrogation region plasma potential contour.



Figure 5-57: SLP TOC 12 full interrogation region plasma potential contour.



Figure 5-58: SLP DL 12 full interrogation region plasma potential contour.



Figure 5-59: SLP TOC 15 full interrogation region plasma potential contour.



Figure 5-60: SLP DL 15 full interrogation region plasma potential contour.



Figure 5-61: SLP 2000 hr. wear test full interrogation region plasma potential contour.



Figure 5-62: SLP 8200 hr. wear test full interrogation region plasma potential contour.

# 5.4.2 Plasma Potential - Floating Emissive Probe

Floating emissive probe plasma potential data are presented over a twodimensional array of locations in the near Discharge Cathode Assembly (DCA) region of a 30-cm diameter ring-cusp ion thruster. Discharge plasma data are presented *with beam extraction* at throttling conditions comparable to the NASA TH Levels 8, 12, 15 and operating conditions of the 2000 hr. wear test. The operating conditions of the Extended Life Test (ELT) of the Deep Space One (DS1) flight spare ion engine, where anomalous discharge keeper erosion occurred, are TH 8 and TH 15; consequently, they are of specific interest in investigating discharge keeper erosion phenomena.

Figures 5-63 through 5-68 illustrate the high-supply side plasma potentials at various thruster operating conditions *with beam extraction*. An average value of the high and low side potential measurements would be shifted down approximately 1.5 V. All potentials are in reference to the discharge cathode common of the FMT2 thruster. All discharge chamber positions have been non-dimensionalized by the discharge cathode keeper diameter. The plasma potential contours demonstrate an on-axis minimum region indicating the plume structure of the discharge cathode. Plasma potentials inside this low potential column are as low as 16 volts near the discharge cathode. The potential drop is highest at the cathode orifice because the axial magnetic field is strongest there and effectively impedes the diffusion of electrons in the radial direction. The potential increase in the radial direction indicates a free-standing potential gradient forming the transition between the discharge cathode plume and main discharge plasma.

Evaluation of the centerline plasma potential values does not support the existence of a potential-hill structure at the operating conditions investigated. Considering the importance of the magnetic field in shaping the discharge environment, it is not surprising that a potential-hill is not present. While the magnetic field reduces radial diffusion, the axial magnetic field enhances axial diffusion of electrons, which would tend to smooth out potential structures on axis. This is particularly true in regions near the discharge cathode where the axial magnetic field is largest.

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Figure 5-63: FEP TOC 8 with discharge cathode keeper shorted to cathode common full interrogation region plasma potential contour.



Figure 5-64: FEP TOC 12 full interrogation region plasma potential contour with representative magnetic field streamlines.



Figure 5-65: FEP TOC 15 full interrogation region plasma potential contour.



Figure 5-66: FEP 2000 hr. wear test full interrogation region plasma potential contour.

The data do not validate the presence of a potential-hill plasma structure downstream of the DCA, which has been proposed as a possible erosion mechanism. The data are comparable in magnitude to data taken by other researchers in ring-cusp electron-bombardment ion thrusters. The plasma potential structures are insensitive to thruster throttling level with a minimum as low as 16 V measured at the DCA exit plane increasing gradually in the axial direction. A potential rise of 10 - 14 V is measured between points on DCA centerline and the off-axis discharge plasma at a radial position equal to the discharge cathode keeper orifice. A sharp increase in plasma potential to the bulk discharge value of 26 - 28 volts, radially past the discharge keeper edge, is observed. Plasma potential measurements indicate a low-potential plume structure emanating from the discharge cathode.

The data indicate that the potential structure inside the discharge chamber is relatively unaffected by thruster input power for comparable discharge voltage. Shorting of the discharge keeper to discharge cathode common, at roughly NASA TH 8, did not have a significant effect on the near-DCA plasma structure outside the keeper sheath, which is made evident by comparing Figure 5-63 to either Figure 5-67 or Figure 5-68.

The emissive probe measurement is repeatable, as a comparison of Figures 5-67 and 5-68 shows. The interrogation of the discharge plasma is performed utilizing two different probes, for comparable engine operating conditions, and during different facility pump downs. The minor differences between the two contours speak to the repeatability of the floating emissive probe method, the ability to accurately determine the saturation heater current, and the repeatability of the FMT2 engine itself.



Figure 5-67: FEP TOC 8a full interrogation region plasma potential contour.



Figure 5-68: FEP TOC 8b full interrogation region plasma potential contour with representative magnetic field streamlines.

Figure 5-69 further supports the repeatability of the emissive probe measurement as the DCA centerline data taken with two different probes on different days of engine operation are comparable. Figure 5-69 clearly illustrates the absence of a potential-hill at this operating condition.



Figure 5-69: Centerline comparison of floating emissive probe results for different probes with similar operating conditions indicating repeatability (within the error) of the measurement.

## 5.4.2.1 Near-DCA Potential Structures

Examination of the near-DCA plasma structure shown in Figures 5-70 through

5-72 illustrates very little variation as the engine is throttled up to higher-power levels.

No potential-hill structures were observed over the throttling conditions investigated. The

existence of a distinct column of low plasma potential is confirmed. Shorting the cathode

keeper does not change the near-DCA plasma structure noticeably. Thus, shorting the keeper has no appreciable effect on the near-DCA plasma potential structure beyond the keeper sheath. Figure 5-72 illustrates a modest change in plasma structure outside of the DCA plume, resulting from the increased discharge voltage at the 2000 hr. wear test operating point.

The near-DCA plasma contours highlight an important finding. The high-density, low plasma potential plume structure is distinctly different than the bulk discharge plasma. Large radial gradients exist resulting from the magnetic field near the discharge cathode. This free-standing gradient structure is indicative of a double layer. Double layers form the transition between two plasmas that are at two different potentials. A double layer forms the boundary between the discharge cathode plume and the bulk discharge plasma. The magnetic field, potential gradients, and double layer are all tied together. The magnetic field reduces radial electron motion, creating the potential gradient in the radial direction and the high density plume along centerline.

Near the cathode keeper, there is a potential difference of approximately 10 volts across the double layer, which roughly spans the length from cathode centerline to the discharge keeper plate radius. The cathode keeper to cathode common potential was 6 - 7 volts for these operating conditions. Combining the potential drop through the discharge plasma with the non-shorted keeper sheath fall yields an accelerating potential of approximately 20 - 21 volts.



Figure 5-70: FEP TOC 8a (left) and FEP TOC 8b (right) near-DCA region plasma potential contours.



Figure 5-71: FEP TOC 12 (left) and FEP TOC 15 (right) near-DCA region plasma potential contours.



Figure 5-72: FEP 2000 hr. wear test near-DCA region plasma potential contour.

Measurements taken by a number of researchers indicate discharge plasma potentials at or a few volts above anode potential. Williams measured plasma potentials on a 6.4-mm-diameter hollow cathode in a cylindrical anode with a xenon cathode flow rate of 4 sccm and cathode emission current of 6 amperes.⁴⁸ The measured plasma potentials were slightly above anode potential and decreased as the cathode was approached. The same trend is evident in the floating emissive probe results for the FMT2. The single Langmuir probe measurements in the FMT2 indicate a bulk discharge plasma potential ranging from 24 to 36 volts away from the discharge cathode plume. The difference (6 – 8 volts) between the bulk discharge potentials is within the error of the single Langmuir probe measurements.

Foster, *et al.* have taken high-current hollow cathode measurements with a Langmuir probe near a 12.7-mm-diameter hollow cathode inside a ring-cusp magnetic field *without beam extraction*.¹⁴¹ A radial profile 3 mm downstream of the DCA exit
plane, at a discharge current of 10.5 A and discharge voltage of 26.5 V, shows a rapid increase in plasma potential from 14 V at cathode centerline to 22 V near the keeper plate orifice outer diameter that was attributed to the existence of a double layer plasma structure formed between the discharge cathode plasma column and the main discharge.

#### 5.4.2.1.1 Cathode Keeper to Cathode Common Short Effect – $\phi_p$

The double layer structure may have played a role in the ELT erosion. With the shorting event of the cathode keeper to cathode common, the reduced resistance would lead to an additional 6 - 7 volts of accelerating potential. The additional accelerating voltage increases the energy at which ions would strike the keeper to 26 - 28 volts, which is on the order of the threshold sputtering value for molybdenum by xenon at normal incidence.^{205,212-216} Figure 5-73 shows that this added potential drop takes place exclusively inside the discharge cathode keeper sheath and does not extend into the discharge plasma. Since the sputtering energy threshold decreases to a minimum value around 50 - 60 degrees, these accelerating voltages may be enough to cause the DCA keeper erosion observed in the ELT.



Figure 5-73: FEP TOC 8b (left) and FEP TOC 8 with discharge cathode keeper shorted to cathode common (right) near-DCA region plasma potential contours.

Discharge cathode centerline data are compared confirming little variation as the engine is throttled up in power. A slightly decreasing magnitude, less than 1 volt, is discernable as the engine is throttled up, but this trend is within the estimated error of the emissive probe measurement. Figure 5-74 illustrates this finding as well as the insensitivity of the DCA centerline potential data to shorting the discharge keeper to discharge cathode common at TOC 8 (roughly NASA TH 8).



Figure 5-74: Centerline comparison of floating emissive probe results indicating the lack of a potential-hill structure.



Figure 5-75: Centerline comparison of the floating emissive probe measured plasma potentials.

#### 5.4.2.1.2 Debye Length

The data analysis used for the single Langmuir probe data begins with the thin sheath assumption and follows through a transition regime onto an OML calculation. It is relevant to illustrate the calculated Debye lengths to give an indication of the spatial domain of each of the three regimes. Figure 5-76 illustrates the two extreme cases for the size of the Debye length, a measure of the sheath size, for all the data analyzed. The probe radius is 0.13 - 0.18 mm and the sheath is expected to be on the order of 5 Debye lengths. In the high-density discharge cathode plume region the Langmuir probe electrode is much larger than the Debye length. As the number density drops off towards the anode, the Debye length quickly grows eventually exceeding the electrode radius. The thin sheath assumption is satisfied for the near-DCA region of interest.



Figure 5-76: Debye Lengths calculated corresponding to TOC 8 (left) and DL 12 (right).

# 5.5 Oscillations

Oscillations in both the discharge voltage and current are recorded prior to data collection to ensure that the discharge cathode is operating in spot mode, which is indicative of low oscillations (peak-to-peak voltage oscillations less than 5 volts). There is typically a slight increase in the discharge voltage oscillations when a beam is extracted, but this effect is unlikely to cause the spread in electron temperatures or contribute significantly to the DCA erosion. Over all operating conditions, the maximum discharge voltage oscillations range from  $\pm 0.7$  to  $\pm 1.4$  volts peak-to-peak. Examples of the increase in discharge voltage oscillations with beam extraction range from the slight increase from  $\pm 0.75$  to  $\pm 1.0$  volts when transitioning from DL 8 to TOC 8a to the largest increase from  $\pm 0.75$  to  $\pm 1.33$  volts when transitioning from DL 12 to TOC 12. The suspicion that an increase in discharge voltage oscillations is causing the electron temperature broadening is further reduced by comparing contours DL 8, TOC 8, and TOC keeper shorted to common, which all have discharge voltage oscillations of  $\pm 0.75$ volts though a significant spread in the electron temperature plume is evident between DL 8 and the other two conditions with beam extraction.

There exists the possibility of high-frequency plasma potential oscillations in the discharge plasma. The limitations of the data collection method prevented measurement of higher-frequency oscillations in plasma potential during a potential mapping. There exists the possibility that high-frequency (hundreds of kHz) plasma potential oscillations exist in the discharge plasma environment and may contribute to the erosion of the DCA. No attempt was made to measure transient high-frequency potential oscillations that would be beyond the scope of this investigation.

# **CHAPTER 6**

# LM4 NEXT DISCHARGE MEASUREMENTS

A series of electrostatic probe measurements are performed in the LM4 NEXT discharge chamber. As discussed in §4.3.2, two staggered probes are inserted into the LM4 discharge chamber of the LM4 offering two regions of interrogation. The regions are distinguished as the near-DCA region and the near screen grid or near ion optics regions. There is moderate distance (~8 cm) between the final position of the screen grid probe and the actual screen grid. This interrogation region is terminated at this axial location because of the location of the main plenum line. A photograph illustrating the staggered probes, during insertion, is shown in Figure 6-1. The staggered probes are operated sequentially. While one probe is in use, the other is allowed to float reducing the effects of the non-active probe.

The effect of shorting the cathode keeper to cathode common was investigated to determine the influence of this event on the plasma environment to simulate thruster operation during the ELT in which anomalous erosion was observed in an NSTAR thruster.

All of the plasma parameter contours have been non-dimensionalized in terms of spatial coordinates with respect to the discharge cathode keeper outer diameter. Because of the importance of the magnetic field in shaping the discharge plasma, the magnetic field contours from the LM4 thruster have been imposed on the contours and will aid in the discussion. Schematic representations of the discharge cathode assembly, discharge chamber wall, approximate alumina guide tube extension, and mechanism flange are included for clarity and orientation.



Figure 6-1: Photograph of the dual staggered probe technique with an active cathode. View through the top alignment window of the thruster.

Electrostatic probe measurements are presented in the LM4 thruster over a wide variety of operating conditions using a single Langmuir probe, a floating emissive probe, a harmonic EEDF Langmuir setup, and a second derivative EEDF Langmuir setup. The thruster operating conditions are labeled according to the electrostatic probe used for clarity. The operating condition abbreviations are: single Langmuir probe (SLP), floating emissive probe (FEP), harmonic EEDF (HEEDF), and Druyvesteyn (second derivative) EEDF (DEEDF). NEXT throttling points with self-assigned TH levels, based on input power, are included for reference. Multiple characterizations at equivalent operating conditions permit a repeatability check on the methods and are labeled sequentially by lower case letters.

## 6.1 Operating Conditions Investigated

Table 6-1 lists the single Langmuir probe investigated LM4 operating conditions. Operation of the ion thruster with beam extraction is designated as a thruster operating condition (TOC) while thruster operation without a beam is referred to as a discharge level (DL). The operating conditions of the floating emissive probe are listed in Table 6-2. The Druyvesteyn (second derivative) method EEDF (DEEDF) operating conditions are listed in Table 6-3. The harmonic (ac) method EEDF (HEEDF) operating conditions are listed in Table 6-4. The second derivative method of measurement of the EEDF from single Langmuir probe data required a redesign of the probe circuit to permit measurement of electron saturation current. The electronics were modified to permit multiple data sweeps in a timely fashion using a bipolar supply.

										Main	D.C.	Neut	Vck-		
	TH	Vs	Jb	Va	Ja	Vdc	Jdc	Vnk	Jnk	Flow	Flow	Flow	СС	Vg	Pressure
	Level	[٧]	[A]	[V]	[mA]	[V]	[A]	[V]	[A]	[sccm]	[sccm]	[sccm]	[V]	[V]	[Torr]
s	TH 34	1567	3.10	-210.0	10.50	-	17.68	-	3.00	43.47	4.54	4.01	-	-	-
pu	SLP TOC 34'	1459	3.10	-210.1	7.90	23.84	16.64	12.85	3.00	42.5	4.54	4.0	3.65	-11.72	2.8E-06
S S	SLP TOC 34'														
ŝ	CK-CC shorted	1455	3.10	-210.1	7.68	23.86	16.63	12.91	3.00	42.5	4.54	4.0	0.00	-11.70	2.8E-06
8	SLP DL 34'	-	-	-	0.08	20.77	16.70	15.47	3.00	42.5	4.54	4.0	5.61	-0.80	2.8E-06
8	TH 20	1567	2.00	-210.0	6.80	-	14.12	-	3.00	25.79	3.87	2.50	-	-	-
(	SLP TOC 20'	1465	2.01	-210.0	9.15	24.87	13.45	13.86	3.00	24.5	3.87	2.5	0.76	-11.23	3.2E-06
	TH 32	1179	3.10	-200.0	10.50	-	18.63	-	3.00	43.47	4.54	4.01	-	-	-
s	SLP TOC 32	1179	3.10	-200.0	7.39	24.15	17.30	12.74	3.00	42.5	4.54	4.0	3.66	-11.51	2.8E-06
pu	TH 18	1179	2.00	-200.0	6.80	-	14.72	-	3.00	25.79	3.87	2.50	-	-	-
S S	SLP TOC 18	1179	2.01	-200.0	10.09	25.07	13.69	13.85	3.00	25.0	3.87	2.5	1.41	-11.45	3.2E-06
ŝ	TH 8	1179	1.20	-200.0	4.10	-	8.83	-	3.00	14.23	3.57	3.00	-	-	-
õ	SLP TOC 8	1179	1.20	-200.0	4.77	25.93	8.67	13.80	3.00	15.4	3.57	3.0	2.87	-10.20	2.4E-06
ŝ	SLP TOC 8														
ſ	CK-CC shorted	1179	1.20	-200.1	4.82	26.09	8.68	14.00	3.00	15.4	3.57	3.0	0.00	-10.50	2.4E-06
	SLP DL 8	-	-	-	3.20	23.26	8.65	19.70	3.00	15.4	3.57	3.0	7.47	-0.85	2.2E-06
۲ ש	TH 3	650	1.20	-144.0	4.10	-	9.54	-	3.00	14.23	3.57	3.00	-	-	-
Š	SLP TOC 3	649	1.20	-144.0	4.69	26.36	9.28	13.78	3.00	15.6	3.69	3.0	3.97	-9.98	2.4E-06
ď	TH 0	275	1.00	-500.0	3.40	-	7.99	-	3.00	12.32	3.52	3.00	-	-	-
Š	SLP TOC 0a	275	1.00	-500.0	3.45	26.15	7.71	14.34	3.00	13.9	3.59	3.0	5.62	-10.28	2.2E-06
	SLP TOC 0b	275	1.00	-500.0	16.82	26.32	7.72	14.85	3.00	13.3	3.59	3.0	3.88	-10.31	1.3E-06

Table 6-1: Experiment LM4 single Langmuir probe (SLP) nominal Thruster Operating Conditions (TOC Levels), Discharge-only Level (DL), and reference NEXT self-assigned Throttling Levels (TH Levels).

										Main	D.C.	Neut	Vck-		
	TH	Vs	Jb	Va	Ja	Vdc	Jdc	Vnk	Jnk	Flow	Flow	Flow	сс	Vg	Pressure
	Level	[v]	[A]	[V]	[mA]	[V]	[A]	[V]	[A]	[sccm]	[sccm]	[sccm]	[V]	[V]	[Torr]
	TH 34	1567	3.10	-210.0	10.50	-	17.68	-	3.00	43.47	4.54	4.01	-	-	-
ŝ	FEP TOC 34a'	1501	3.10	-210.1	14.19	23.71	17.54	12.85	3.00	43.5	4.54	3.99	4.63	-12.31	2.9E-06
ŭ	FEP TOC 34b'	1450	3.00	-210.1	18.04	23.30	17.27	12.20	3.00	40.5	4.41	4.36	4.54	-11.76	4.5E-06
ê	FEP TOC 34'														
0 s	CK-CC shorted	1455	3.00	-210.1	18.05	23.22	17.23	12.32	3.00	40.5	4.41	4.36	-	-11.85	4.5E-06
80	TH 20	1567	2.00	-210.0	6.80	-	14.12	-	3.00	25.79	3.87	2.50	-	-	-
٣	FEP TOC 20a'	1449	2.00	-210.1	8.70	24.30	13.75	12.89	3.00	25.0	3.87	2.46	2.06	-11.47	3.2E-06
	FEP TOC 20b'	1466	2.00	-210.2	8.37	24.57	14.23	13.04	3.00	24.4	3.83	2.46	1.58	-11.84	3.2E-06
	TH 32	1179	3.10	-200.0	10.50	-	18.63	-	3.00	43.47	4.54	4.01	-	-	-
	FEP TOC 32a	1180	3.11	-200.2	14.63	23.97	18.04	12.97	3.00	43.5	4.54	3.99	4.65	-12.38	2.9E-06
s	FEP TOC 32b	1179	3.00	-200.1	18.61	23.37	17.44	11.79	3.00	42.5	4.48	4.36	5.00	-11.61	4.5E-06
P	TH 18	1179	2.00	-200.0	6.80	-	14.72	-	3.00	25.79	3.87	2.50	-	-	-
S	FEP TOC 18	1179	2.00	-200.1	8.80	24.66	13.89	12.74	3.00	25.0	3.87	2.46	2.33	-11.18	3.2E-06
ŝ	TH 8	1179	1.20	-200.0	4.10	-	8.83	-	3.00	14.23	3.57	3.00	-	-	-
õõ	FEP TOC 8a	1179	1.20	-200.2	4.29	26.01	8.75	13.20	3.00	14.6	3.56	3.09	3.30	-11.16	2.4E-06
ŝ	FEP TOC 8b	1179	1.20	-200.2	3.42	27.05	9.12	14.51	3.00	14.7	3.61	3.00	3.26	-10.47	1.6E-06
Ĺ	FEP TOC 8														
	CK-CC shorted	1179	1.20	-200.1	4.38	25.93	8.70	13.14	3.00	14.6	3.51	3.09	-	-10.97	2.4E-06
	FEP DL 8	-	-	-	12.28	23.20	8.70	14.64	3.00	14.6	3.48	3.09	7.07	-1.53	2.4E-06
	TH 3	650	1.20	-144.0	4.10	-	9.54	-	3.00	14.23	3.57	3.00	-	-	-
ver	FEP TOC 3a	650	1.20	-144.1	4.72	26.25	9.77	13.36	3.00	14.6	3.56	3.09	3.18	-11.16	2.4E-06
õ	FEP TOC 3b	650	1.20	-144.0	3.55	27.03	9.58	14.74	3.00	14.6	3.63	3.00	3.93	-10.13	1.5E-06
×	TH 0	275	1.00	-500.0	3.40	-	7.99	-	3.00	12.32	3.52	3.00	-	-	-
Ć	FEP TOC 0a	275	1.00	-500.0	3.53	26.40	7.80	13.72	3.00	12.4	3.49	3.09	4.65	-11.32	2.2E-06
	FEP TOC 0b	275	1.00	-500.0	3.41	27.10	7.95	15.15	3.00	12.3	3.52	3.00	5.32	-9.79	1.4E-06

 Table 6-2: LM4 floating emissive probe (FEP) nominal Thruster Operating Conditions (TOC Levels), Discharge-only Level (DL), and reference NEXT self-assigned Throttling Levels (TH Levels).

										Main	D.C.	Neut	Vck-		
	TH	Vs	Jb	Va	Ja	Vdc	Jdc	Vnk	Jnk	Flow	Flow	Flow	сс	Vg	Pressure
	Level	[v]	[A]	[V]	[mA]	[V]	[A]	[V]	[A]	[sccm]	[sccm]	[sccm]	[V]	[V]	[Torr]
	TH 34	1567	3.10	-210.0	10.50	-	17.68	-	3.00	43.47	4.54	4.01	-	-	-
00 spi	DEEDF TOC 34'	1501	3.10	-210.1	18.47	23.85	17.54	13.29	3.00	43.5	4.48	4.01	4.68	-12.35	3.5E-06
~38( secor	TH 20	1567	2.00	-210.0	6.80	-	14.12	-	3.00	25.79	3.87	2.50	-	-	-
	DEEDF TOC 20'	1500	2.00	-210.1	8.43	24.51	13.95	13.51	3.00	24.9	3.79	2.50	1.94	-12.41	2.6E-06
	TH 32	1179	3.10	-200.0	10.50	-	18.63	-	3.00	43.47	4.54	4.01	-	-	-
	DEEDF TOC 32	1179	3.10	-200.1	18.68	24.20	18.03	13.25	3.00	43.4	4.48	4.01	4.70	-12.59	3.5E-06
	TH 18	1179	2.00	-200.0	6.80	-	14.72	-	3.00	25.79	3.87	2.50	-	-	-
spc	DEEDF TOC 18a	1179	2.00	-200.4	8.36	24.79	14.04	13.99	3.00	25.0	3.85	2.50	2.31	-12.69	2.5E-06
õ	DEEDF TOC 18b	1179	2.00	-200.1	8.43	24.83	14.10	13.63	3.00	24.9	3.79	2.50	2.19	-12.34	2.6E-06
se	TH 8	1179	1.20	-200.0	4.10	-	8.83	-	3.00	14.23	3.57	3.00	-	-	-
00	DEEDF TOC 8a	1180	1.20	-200.0	4.14	25.75	8.85	13.92	3.00	14.6	3.82	3.20	3.41	-12.21	2.0E-06
33	DEEDF TOC 8b	1179	1.20	-200.0	4.77	25.82	8.75	14.76	3.00	15.0	4.39	3.11	3.78	-12.02	2.0E-06
ć	DEEDF TOC 8														
	CK-CC shorted	1179	1.20	-200.1	5.10	25.81	8.72	15.24	3.00	15.0	4.39	3.11	0.00	-11.71	2.0E-06
	DEEDF DL 8	-	-	-	23.00	23.75	8.74	15.90	3.00	14.3	3.63	3.11	7.40	-1.55	2.0E-06
<u>ب</u>	TH 3	650	1.20	-144.0	4.10	-	9.54	-	3.00	14.23	3.57	3.00	-	-	-
N S	DEEDF TOC 3	650	1.20	-144.0	4.52	26.18	9.96	14.42	3.00	14.5	3.63	3.11	2.85	-12.45	2.0E-06
βĽ	TH 0	275	1.00	-500.0	3.40	-	7.99	-	3.00	12.32	3.52	3.00	-	-	-
	DEEDF TOC 0	275	1.01	-500.0	3.58	26.11	7.85	14.70	3.00	12.6	3.90	3.11	4.77	-12.50	1.9E-06

Table 6-3: LM4 Druyvesteyn Electron Energy Distribution Function (DEEDF) nominal Thruster Operating Conditions (TOC Levels), Discharge-only Level (DL), and reference NEXT self-assigned Throttling Levels (TH Levels). Druyvesteyn method is also known as the second derivative method.

	TH	Vs	Jb	Va	Ja	Vdc	Jdc	Vnk	Jnk	Main Flow	D.C. Flow	Neut Flow	Vck- cc	Vg	Pressure
	Level	[v]	[A]	[V]	[mA]	[V]	[A]	[V]	[A]	[sccm]	[sccm]	[sccm]	[V]	[V]	[Torr]
с st	TH 34	1567	3.10	-210.0	10.50	-	17.68	-	3.00	43.47	4.54	4.01	-	-	-
380( Sono	HEEDF DL 34'	-	-	-	38.70	22.44	17.59	16.08	3.00	37.9	4.31	4.01	6.25	-0.68	3.1E-06
° Sec	HEEDF DL 34' CK-CC shorted	-	-	-	42.00	22.35	17.58	15.44	3.00	37.9	4.31	4.01	-	-0.88	3.1E-06
ş	TH 18	1179	2.00	-200.0	6.80	-	14.72	-	3.00	25.79	3.87	2.50	-	-	-
ouo	HEEDF DL 18	-	-	-	29.00	22.80	14.01	18.02	3.00	21.1	3.58	2.50	6.42	-0.88	2.1E-06
sec	TH 8	1179	1.20	-200.0	4.10	-	8.83	-	3.00	14.23	3.57	3.00	-	-	-
300	HEEDF DL 8	-	-	-	21.70	24.02	9.09	16.77	3.00	15.0	4.32	3.11	7.40	-0.34	1.9E-06
°3	HEEDF DL 8 CK-CC shorted	-	-	-	23.62	24.00	9.10	16.71	3.00	15.0	4.32	3.11	-	-0.23	1.9E-06
wer	TH 0	275	1.00	-500.0	3.40	_	7.99	-	3.00	12.32	3.52	3.00	-	-	-
Poy	HEEDF DL 0	-	-	-	41.50	25.00	7.46	16.40	3.00	13.2	4.33	3.11	8.56	-0.83	1.8E-06

 Table 6-4: LM4 Harmonic Electron Energy Distribution Function (HEEDF) nominal Discharge-only

 Levels (DL) and reference NEXT self-assigned Throttling Levels (TH Levels).

# 6.2 Single Langmuir Probe Parameters

Single Langmuir probe data are presented for the staggered probe setup on the LM4 ion engine. The data were analyzed following the procedure outlined in §3.1 separating the probe operation into three regions. Near the DCA, the probe analysis follows a thin-sheath calculation. Near the anode, a thick-sheath analysis (OML) is appropriate. In between the two regimes, a weighted average offers a smooth transition of number densities between the two regions. The thin-sheath number densities are iterated to account for sheath expansion and these iterated number densities are used in the weighted average calculation for the transition regime. Each contour plot represents 9,240 I-V curves for each interrogation region (18,480 for the combined regions).

In an attempt to quantify the alteration of the discharge plasma environment when a beam is not extracted, data were taken for thruster operation with and without beam extraction for two throttled conditions. The difference in thruster operation between the nominal setting and operation without a beam is that the screen and accelerator grid voltages were turned off (*i.e.* the high voltage setting on the SKIT-Pac was switched off). The removal of a beam is accompanied by a decrease in discharge voltage as the ion transparency is reduced. The reduction in plasma resistivity results in a decrease in discharge voltage for a given discharge current. No attempts were made to adjust propellant mass flow rates in order to match the nominal discharge voltage value or to bias the screen grid to simulate ion extraction.

### 6.2.1 Number Density Measurements

A very distinct plume structure is evident from the number density contours. Inside the discharge cathode plume, number densities near the cathode approach as high as  $2x10^{13}$  cm⁻³ at the DCA. The number densities decrease by an order of magnitude outside of the plume, at a distance on the order of the discharge keeper radius. The bulk discharge plasma density mappings are very similar over the range of operating conditions investigated with values of  $\sim 1x10^{11}$  to  $1x10^{12}$  cm⁻³ in the bulk discharge. The thruster conditions span the low-power (275 V, 1.00 A) settings to medium-power (1500 V, 3.10 A) settings. Just outside of the high-density cathode plume, the number densities are on the order of  $\sim 5 \times 10^{11}$  cm⁻³, which is comparable to the value for the FMT2 thruster and will be important for erosion calculations presented later.

The contour shapes, for the various operating conditions, are all identical and follow the magnetic field structure. Near the DCA, the magnetic field streamlines run almost entirely in the axial direction, which effectively confines the electrons emitted from the DCA to a narrow plume. These electrons spiral around the magnetic field lines and many ions are formed in this narrow plume due to electron bombardment. The number densities near the anode are largest at the magnetic cusps. The near-anode regions in between the magnetic cusps have reduced number densities compared to the magnet locations because the magnetic field reduces the number of electrons that cross the magnetic field lines.

Comparison of Figures 6-2 through 6-8 illustrates the following trends as the engine is throttled to higher-power. In general, there is no discernable change in discharge plasma number density, outside of the DCA plume, as the thruster is operated at higher-power levels. The slight variations evident in the between-cusps, near-anode number densities are difficult to correlate with engine operating condition. If anything, a very modest decrease in the near-anode, between-cusp region number density is evident as the LM4 moves from low-power to medium-power settings. This shift may be due to the preferential drift of the ions towards the screen grid as the screen voltage and accelerator grid voltage are increased in magnitude. Essentially, the engine is more efficient at extraction of ions at the higher-power setting. This hypothesis is consistent

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with the decrease in discharge losses (W/A) measured for the NEXT ion engine with increasing thruster input power. This trend is attributed to the increasing screen grid ion transparency associated with increasing total voltage (*i.e.* more of the discharge chamber ions are extracted by the ion optics).

Where possible, both probe regions are plotted, however, data for the downstream probe were not taken for all operating conditions in which the near-DCA probe was operated. Comparison of the number density mappings from the two regions illustrates some minor discontinuity between the two probes that is attributed to the error in the number density calculation and variation of the thruster in between the subsequent activation of the two probes. The variation of the two regions is at most 40% for the conditions investigated and can be accounted for by the traditional number density error estimate of 50% for Langmuir probes. Furthermore, the lack of an overlap region between the two probes leaves a gap in tying the two regions together.



Figure 6-2: LM4 SLP TOC 0a (V_s=275V and J_b=1.00A) number density staggered probe results.



Figure 6-3: LM4 SLP TOC 3 (V_s=649V and J_b=1.20A ) number density staggered probe results.



Figure 6-4: LM4 SLP TOC 8 (V_s=1179V and J_b=1.20A) number density staggered probe results.



Figure 6-5: LM4 SLP TOC 18 (V_s=1179V and J_b=2.01A) number density staggered probe results.



Figure 6-6: LM4 SLP TOC 32 (V_s=1179V and J_b=3.10A) number density staggered probe results.



Figure 6-7: LM4 SLP TOC 20' (V_s=1465V and J_b=2.01A) number density staggered probe results.



Figure 6-8: LM4 SLP Toc 34' (V_s=1459V and J_b=3.10A) number density staggered probe results.

### 6.2.2 Cathode Keeper to Cathode Common Short Effect – n_i

Figures 6-9 through 6-12 illustrate the effect of shorting the discharge cathode keeper to cathode common. The contour plots indicate nearly identical mappings. For ease of comparison, the downstream region for nominal operation has been duplicated for the shorted keeper to common condition. It is expected that the shorting event will have no effect on the near ion optics plasma. The second probe was not activated for the shorted condition. The lack of change in the near-DCA plasma number density confirms the justification for not acquiring data for the second probe in this condition. Comparison of the near-DCA regions illustrates the repeatability of the two mappings and that shorting the cathode keeper to cathode common does not noticeably alter the bulk plasma number density. A closer examination of the near-DCA region will follow in §7.1.



Figure 6-9: LM4 SLP TOC 8 (V_s=1179V and J_b=1.20A) nominal operating number density staggered probe results.



Figure 6-10: LM4 SLP TOC 8 with cathode keeper to cathode common short ( $V_s$ =1179 and  $J_b$ =1.20A) number density staggered probe results.



Figure 6-11: LM4 SLP TOC 34' (V_s=1459V and J_b=3.10A) nominal operation number density staggered probe results.



Figure 6-12: LM4 SLP TOC 34' ( $V_s$ =1500V and  $J_b$ =3.10A) with cathode keeper to cathode common short number density staggered probe results.

### 6.2.3 Effects of Beam Extraction

Examination of Figures 6-13 through 6-16 indicates a slightly higher number density near the ion extraction grids for nominal operation. This finding is counterintuitive as extraction of a beam should remove some of the ions near the screen grid that would be present without a beam. However, this is accompanied by a broadening of the DCA plume. Examination of the near-DCA structure will follow in the next chapter; however, it appears that the extraction of a beam broadens the discharge plume as ions are pulled toward the mid-radius ion optic apertures compared to discharge-only operation where the plume is not acted upon by the high electric fields of the optics.



Figure 6-13: LM4 SLP TOC 8 (V_s=1179V and J_b=1.20A) nominal operating number density staggered probe results.



Figure 6-14: LM4 DL 8 without beam extraction number density staggered probe results.



Figure 6-15: LM4 SLP TOC 34' (V_s=1459V and J_b=3.10A) nominal operation number density staggered probe results.



Figure 6-16: LM4 SLP DL 34' without beam extraction number density staggered probe results.

#### **6.2.4 Electron Number Density**

The number densities reported have been calculated based upon the ion saturation current and, if a thin-sheath calculation is used, upon the electron temperature. This method yields more accurate results than the number density calculation based upon the electron saturation current due to the ill-defined electron saturation region in the presence of a magnetic field and lack of electron saturation near the discharge cathode. Estimation of the electron saturation yields a method for calculating the electron number density. For cases where electron saturation was not achievable, the highest value of electron current is used for the calculation. This was the case inside the discharge cathode plume and as a result these values will underestimate the true electron number density. The data where electron saturation was achieved, *i.e.* outside of the cathode plume, will be affected by the magnetic field. The electron saturation current is calculated from the knee of the I-V curve. The location of the knee is shifted by the presence of the magnetic field thereby affecting the calculated electron number density. The electron number density contours are given to illustrate similar trends compared to the number density calculation from the ion saturation current

Examination of Figures 6-17 through 6-19 illustrates the same plume structure as the standard number density calculation. As expected, the magnitudes are considerably less than the magnitudes of the ion number densities. Bulk discharge plasma electron number density calculations yield values from  $5 \times 10^{10}$  to  $5 \times 10^{11}$  cm⁻³, an order of magnitude less than the number density calculation from the ion saturation current.



Figure 6-17: Electron number density staggered probe results for  $V_s$ =275V and  $J_b$ =1.00A.



Figure 6-18: LM4 SLP TOC 8 (V_s=1179V and J_b=1.20A) electron number density staggered probe results.



Figure 6-19: LM4 SLP TOC 34' (V_s=1459V and J_b=3.10A) electron number density staggered probe results.

# 6.2.5 Electron Temperature

Analysis of the single Langmuir probe results readily gives the electron temperature from the slope of the natural log of the I-V curve in the electron retarding region. This analysis is independent of whether the thin-sheath, thick-sheath, or transitional probe regime is applicable. The electron temperature contours illustrate a discharge cathode plume where low electron temperatures exist (3-5 eV). Outside of this plume, the electron temperature gradually increases by a few volts to the bulk discharge electron temperatures of 4 to 7 eV. Near the anode, in the inter-cusp regions, the electron temperature reaches much higher values (as high as 13 - 15 eV). The electron temperature analysis assumes a Maxwellian distribution. The near-anode rise in electron temperature may be enhanced by the reduced signal-to-noise ratio in this region. Furthermore, sheath structures near the anode and/or the guiding alumina tube may affect the rising electron temperature measured. The contours in Figures 6-20 through 6-26 illustrate very little variation for the near-DCA probe as the engine is throttled to higher-power. The small electron temperature plume is characteristic of a narrow Maxwellian distribution. As the electrons move downstream of the DCA, they collide with ions and are rapidly thermalized. As the plasma potential measurements will illustrate, the electrons are accelerated across the double layer between the discharge plume and bulk plasma resulting in an increase in the electron temperature. The additional thermalized electron population is broadened in the spread of the distribution resulting in the increased measured electron temperature. It is not clear why the electron temperature rises near the anode, though this behavior has also been measured near the anode in the discharge channel of Hall thrusters.²¹¹



Figure 6-20: LM4 SLP TOC 0a ( $V_s$ =275V and  $J_b$ =1.00A) electron temperature staggered probe results.



Figure 6-21: LM4 SLP TOC 3 (V_s=649V and J_b=1.20A) 3lectron temperature staggered probe results.



Figure 6-22: LM4 SLP TOC 8 (V_s=1179V and J_b=1.20A) electron temperature staggered probe results.



Figure 6-23: LM4 SLP TOC 18 (V_s=1179V and J_b=2.01A) electron temperature staggered probe results.



Figure 6-24: LM4 SLP TOC 32 (V_s=1179V and J_b=3.10A) electron temperature staggered probe results.



Figure 6-25: LM4 SLP TOC 20' (V_s=1465V and J_b=2.01A) electron temperature staggered probe results.



Figure 6-26: LM4 SLP TOC 34' ( $V_s$ =1459V and  $J_b$ =3.10A) electron temperature staggered probe results.

### 6.2.5.1 Cathode Keeper to Cathode Common Short Effect

The bulk discharge plasma electron temperature was unaffected by the shorting of the discharge cathode keeper to the cathode common, evident in Figures 6-27 through 6-30.



Figure 6-27: LM4 SLP TOC 8 nominal operation (V_s=1179V and J_b=1.20A) electron temperature staggered probe results.



Figure 6-28: LM4 SLP TOC 8 with cathode keeper to cathode common short ( $V_s$ =1179V and  $J_b$ =1.20A) electron temperature staggered probe results.



Figure 6-29: LM4 SLP TOC 34' nominal operation ( $V_s$ =1459V and  $J_b$ =3.10A) electron temperature staggered probe results.



Figure 6-30: LM4 SLP TOC 34' with cathode keeper to cathode common short ( $V_s$ =1455V and  $J_b$ =3.10A) electron temperature staggered probe results.

### 6.2.5.2 Effects of Beam Extraction

The effect of extracting a beam on the bulk discharge plasma is evident in Figures 6-31 through 6-34. In general the extraction of a beam results in a slight increase, of one or two eV, compared to data taken without beam extraction. This may be partially due to the increase in discharge voltage associated with beam extraction. The increase in the electron temperatures with beam extraction indicate the coupled nature of the beam and discharge cathodes implying that beam extraction is needed to accurately represent flight-like thruster operating conditions.



Figure 6-31: LM4 SLP TOC 8 nominal operation (V_s=1179V and J_b=1.20A) electron temperature staggered probe results.



Figure 6-32: LM4 SLP DL 8 without beam extraction electron temperature staggered probe results.



Figure 6-33: LM4 SLP TOC 34' nominal operation ( $V_s$ =1459V and  $J_b$ =3.10A) electron temperature staggered probe results.



Figure 6-34: LM4 SLP DL 34' without beam extraction electron temperature staggered probe results.

#### 6.2.6 Single Langmuir Probe Plasma Potential

In the case where electron saturation current is reached, the plasma potential can be estimated from the knee in the I-V characteristic. Similar to the electron number density calculation, this measurement will be affected by the presence of the magnetic field and, in general, be less accurate than the plasma potential measurements taken with the floating emissive probe. This will permit, however, rough verification of the two techniques and is therefore of interest.

For completeness, inside the discharge cathode plume, where the Langmuir probe does not reach electron saturation, the plasma potentials from the emissive probe results on the LM4 are included. As a result, Figures 6-35 through 6-41 are not representative of actual Langmuir probe measurements <u>in the DCA plume</u>. The plots are accurate, within the accuracy of the method of measurement, outside of this plume. The resulting mesh of the two regions sometimes displays a distinct and abrupt transformation evident in the contour plots.

In general, the Langmuir probe plasma potentials are higher than the emissive probe measurements, but follow the same trends. This verification of the emissive probe technique confirms the existence of high plasma potential regions in the inter-cusp nearanode region. Bulk plasma potentials range from 18 to 32 Volts for the operating conditions investigated. The near-DCA probe bulk potentials ranged from 26 to 32 volts, with plasma potentials in the mid-to-upper 30 volt range near the anode. Again there are some artifacts of the data analysis fitting techniques used, which is apparent in the near ion optics mappings. The floating emissive probe will provide more accurate measurement of the plasma potentials.

Shorting of the discharge cathode keeper to cathode common did not have a noticeable effect on the bulk discharge plasma potentials. The effect of extracting a beam was to increase the plasma potential of the near ion optics region by a few volts. This is due to the increase in discharge voltage of a few volts when a beam is extracted.



Figure 6-35: LM4 SLP TOC 0a ( $V_s$ =275V and  $J_b$ =1.00A) plasma potentials from staggered Langmuir probes.



Figure 6-36: LM4 SLP TOC 8 nominal operation (V_s=1179V and J_b=1.20A) plasma potentials from staggered Langmuir probes.



Figure 6-37: LM4 SLP TOC 8 with cathode keeper to common short ( $V_s$ =1179V and  $J_b$ =1.20A) plasma potentials from staggered Langmuir probes.



Figure 6-38: LM4 SLP DL 8 without beam extraction plasma potentials from staggered Langmuir probes.



Figure 6-39: LM4 SLP TOC 34' nominal operation (V_s=1459V and J_b=3.10A) plasma potentials from staggered Langmuir probes.



Figure 6-40: LM4 SLP TOC 34' with discharge cathode keeper to cathode common short ( $V_s$ =1455V and  $J_b$ =3.10A) plasma potentials from staggered Langmuir probes.



Figure 6-41: LM4 SLP DL 34' without beam extraction plasma potentials from staggered Langmuir probes.

## 6.3 Floating Emissive Plasma Potential

Floating emissive probe measurements are more accurate than those estimated by the knee in the Langmuir probe I-V curve applicable to magnetized and flowing plasmas. Detailed plasma potential mappings were conducted over a wide range of operating conditions on the LM4 thruster. 54 two-dimensional mappings were conducted, though only the relevant results will be discussed. For the emissive probe to accurately measure the local plasma potential, sufficient heater current must be applied. This is non-trivial because of the two distinct regions of interrogation. In the DCA plume, the high-density plasma provides additional heating to the probe. Thus if the heater current is set for probe saturation in the bulk discharge, the probe will melt with additional plasma heating in the cathode plume. If the heater current is set for saturation in the cathode plume, then there will be insufficient heater current in the bulk discharge plasma to accurately measure the local plasma potential in this region. Due to the frailty of the emissive probe, it is impractical to map the two regions separately for the near-DCA probe and obtain data for the various thruster operating conditions.

Since this investigation relates to near-DCA erosion mechanisms, the emissive probe heater current was set for this region and the bulk discharge potentials will be underestimated by a few volts. The effects of this routine are not evident at the lowpower settings where the discharge current is low. However, the effects become more pronounced as the engine is throttled up to higher-power and the increased discharge current substantially heats the probe filament. For the high-power thruster conditions considered, the plasma potentials reported outside the cathode plume are shifted up by a few volts to match the plasma potentials measured by the second emissive probe in downstream plasma where heating disparity does not exist. These contours, which are noted in their caption, will be less accurate and may not accurately characterize all of the features of the bulk discharge plasma. Near the anode for the insufficient heater setting, the plasma potential dropped considerably due to the low number densities and therefore that data is omitted.

It is evident that the plasma potential mappings closely follow the magnetic field streamlines as the higher potential regions exist in between cusps near the anode, which electrons have a difficult time reaching. There is a distinct discharge cathode plume rising from 12 volts to 22 volts within a keeper radius in the radial direction. A more gradual increase is observed in the axial direction. This again is a result of the axial magnetic

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field near the DCA confining the electrons to a narrow plume. This free-standing potential profile is characterized as a double layer.

Insufficient heater current at the higher-power settings complicates comparison of the bulk plasma potentials as the engine is throttled. Comparison of Figures 6-42 through 6-46 indicate little change as the engine is throttled up for the low-power operating conditions. It is expected that there would not be a significant shift in bulk plasma potentials without a corresponding change in discharge voltage. The FMT2 investigation confirmed this assumption. The bulk discharge plasma potentials are on the order of the discharge voltage. The plasma potential increases to 3 or 4 volts above the discharge voltage near the anode. A rough inspection of the cathode plume structures illustrates no noticeable change over the operating conditions investigated, though a closer examination of the near-DCA region will follow.



Figure 6-42: LM4 floating emissive probe plasma potential mapping for FEP TOC 0a (275V, 1.00A).



Figure 6-43: LM4 floating emissive probe plasma potential mapping for FEP TOC 0b (275V, 1.00A).



Figure 6-44: LM4 floating emissive probe plasma potential mapping for FEP TOC 3a (650V, 1.20A).



Figure 6-45: LM4 floating emissive probe plasma potential mapping for FEP TOC 3b (650V, 1.20A).



Figure 6-46: LM4 floating emissive probe plasma potential mapping for FEP TOC 8a (1179V, 1.20A).



Figure 6-47: LM4 floating emissive probe plasma potential mapping for FEP TOC 8b (1179, 1.20A). Notice the shift down in Vp right at Axial 3.8! Possible probe deterioration. This mapping is same as P7 near-DCA and has main plasma a few volts higher.



Figure 6-48: LM4 floating emissive probe plasma potential mapping for FEP TOC 18 (1179V, 2.00A).



Figure 6-49: LM4 floating emissive probe plasma potential mapping for FEP TOC 20a' (1449V, 2.00A). Notice the popping in and out of the measurements. This may be indicative of a dying probe. This mapping was done right after P7



Figure 6-50: LM4 floating emissive probe plasma potential mapping for FEP TOC 20b' (1466V, 2.00A) shifted up 3V.



Figure 6-51: LM4 floating emissive probe plasma potential mapping for FEP TOC 32a (1180V, 3.11A). Probe nearly saturated in bulk discharge.



3.11A) shifted.



Figure 6-53: LM4 floating emissive probe plasma potential mapping for FEP TOC 34a' (1501V, 3.10A) shifted.



Figure 6-54: LM4 floating emissive probe plasma potential mapping for FEP TOC 34b' (1450V, 3.00A) shifted.

# 6.3.1 CK-CC Short and Beam Extraction Effect – $\phi_p$

The shorting of the cathode keeper to common had no effect outside of the keeper sheath from the FMT2 results. Therefore, only one such condition was investigated for the floating emissive probe on the LM4. The floating emissive probe is a very delicate diagnostic because of the excessive currents through the filament. Thus, minimal operating times are desired and therefore operating conditions are selected to give the most valuable results. Comparison of Figures 6-55 and 6-56 illustrate negligible differences in the plasma structure when the keeper is shorted to common. The radial streaks of reduced potential are results of ion thruster recycle events and emissive probe transition to insufficient heating after limited operation time.

The lack of beam extraction results in a shift of the bulk discharge plasma equivalent to the shift of the discharge voltage. This shift occurs across the entire interrogation region, including the high-potential inter-cusp regions.



Figure 6-55: LM4 floating emissive probe plasma potential mapping for FEP TOC 8a (1179V, 1.20A) nominal.



Figure 6-56: LM4 floating emissive probe plasma potential mapping for FEP TOC 8 CK-CC short (1179V, 1.20A).



Figure 6-57: LM4 floating emissive probe plasma potential mapping for FEP DL 8 without beam extraction.



Figure 6-58: LM4 floating emissive probe plasma potential mapping for FEP TOC 34b' nominal (1450V, 3.10A).



Figure 6-59: LM4 floating emissive probe plasma potential mapping for FEP DL 34 without beam extraction.

## 6.4 Druyvesteyn (Second-Derivative) Method EEDF's

Electron energy distributions are presented for various operating conditions in the two probe regimes. The EEDF's are generated by first taking multiple ( $\geq$ 20) I-V sweeps using a bipolar power supply, isolated from ground via an isolation transformer, and averaging the resultant characteristics reducing noise in the signal. The resultant average of I-V curves is illustrated in Figure 6-60. Note the significantly reduced noise in the characteristic compared to the I-V characteristics obtained using floating batteries. The larger number of data pairs, faster acquisition times, and reduced noise improve the numeric derivative.



Figure 6-60: Sample averaged I-V characteristic at the closest axial location along centerline location using the floating bipolar supply and function generator (No smoothing applied).

The resultant EEDF's from the Druyvesteyn method are illustrated in the following figures. The EEDF's are plotted as a function of position and are grouped by either constant radial location (indicating the EEDF evolution as progressing downstream in the axial direction) or for constant axial location (indicating the EEDF evolution with increasing distance from DCA centerline). The latter serves as a more interesting representation since the plasma potential gradients exist in the radial direction and therefore will illustrate the EEDF evolution across the double layer.

Near the DCA, inside the cathode plume, the EEDF's are single hump distributions at a peak energy a few volts below the local plasma potential in this region. The EEDF's transition from a single-hump to either a plateau or a double-hump distribution through the double layer. This transition results from the acceleration of electrons across the double layer. Outside the double layer, in the main discharge plasma, the two-hump and plateau distributions quickly become thermalized. The resultant main discharge plasma EEDF is a single hump with a high-energy tail.

For the near-optics probe, almost all of the EEDF's are characterized by a single hump with a gradual drop off towards higher energies. This trend may be due to the evolution of the EEDF from a single hump distribution in which the higher-energy electrons in the main discharge are able to overcome the double layer gradient. As they proceed through the double layer, they lose some of their energy contributing to the large hump near the local plasma potential. In some cases, a double-hump distribution is noticeable, which clearly illustrates this effect (Figure 6-65 is a prime example).

No trends in the EEDF as a function of throttling condition are found. The EEDF's appear to be insensitive to thruster power level. Examination of Figures 6-62 and 6-63 illustrate the effect of beam extraction on the EEDF and therefore will bring to light the changes in electron temperature with/without beam extraction. When a beam is extracted, the high-energy tail of the EEDF's across and outside of the double layer are more broad. This change may result from the higher discharge voltage oscillations with a beam driving a fluctuating double layer (in magnitude and/or position) that in turn leads to broader range of electron energies. The electrons may gain a more distributed range of energies when passing through the double layer (acceleration and deceleration for the corresponding electron species) if it is fluctuating, leading to an effective increase in the measured electron temperature.

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Figure 6-61: EEDF's for various spatial locations as a function of probe bias voltage with respect to cathode common at DEEDF TOC 0.



cathode common at DEEDF TOC 8.



Figure 6-63: EEDF's for various spatial locations as a function of probe bias voltage with respect to cathode common at DEEDF DL 8.



Figure 6-64: EEDF's for various spatial locations as a function of probe bias voltage with respect to cathode common at DEEDF TOC 34'.



Figure 6-65: EEDF's for various spatial locations as a function of probe bias voltage with respect to cathode common at DEEDF TOC 34'.

# **CHAPTER 7**

# LM4 NEXT NEAR-DCA MEASUREMENTS

Examination of the near-DCA plasma structure is most relevant to the discharge cathode erosion phenomena. This will highlight the subtle changes in the discharge cathode plume, the double layer transition, and the overall discharge plasma environment near the DCA. The operating conditions for the near-DCA contours are given in §6.1.

### 7.1 Number Density

The number density contours from the single Langmuir probe are insensitive to the thruster operating condition in LM4. The axial magnetic field near the DCA creates a distinct plume structure in which cross-field diffusion is prevented similar to FMT2. However, there is a notable difference between the FMT2 and LM4 number density plumes. The number density profile for the LM4 exhibits a larger gradient in the axial direction than the FMT2. The decrease in number density in the axial direction for LM4 operation is an order of magnitude at an axial distance of approximately one keeper radius away from the DCA. The axial magnetic field of the LM4 is less than half of the FMT2 thruster at the discharge cathode keeper plate. Therefore, the reduced field of the LM4 does not smooth out the plasma structures in the axial direction the way the FMT2 thruster does. This may significantly affect the DCA erosion mechanisms of the LM4 thruster compared to the FMT2. Number densities at the DCA centerline are as high as  $1 - 2x10^{13}$  cm⁻³. Located just radially outside the discharge cathode plume (outside the double layer), the plasma number density for the LM4 is ~5x10¹¹ cm⁻³ (the same as for FMT2).



Figure 7-1: LM4 near-DCA SLP TOC 0a - 275V, 1.00A (left) and SLP TOC 3 - 649V, 1.20A (right) number density contours.



Figure 7-2: LM4 near-DCA SLP TOC 8 - 1179V, 1.20A (left) and SLP TOC 18 - 1179V, 2.01A (right) number density contours.



Figure 7-3: LM4 near-DCA SLP TOC 20' - 1465V, 2.01A (left) and SLP TOC 32 - 1179V, 3.10A (right) number density contours.



Figure 7-4: LM4 near-DCA SLP TOC 34' - 1500V, 3.10A number density contour.

#### 7.1.1 Keeper to Cathode Common Short and Beam Effects

Shorting of the discharge keeper to cathode common has a negligible effect on the number densities in the DCA plume and the bulk discharge number densities. Number density contours are not significantly altered by beam extraction. This is expected given the comparable mass flow rates and discharge current. In the FMT2 investigation, the flow rates were adjusted to match discharge current, resulting in altered number density mappings. The LM4 investigation allowed the discharge voltage to reach any steady state position for equivalent mass flow rates. The plasma potential structures will be altered by this equivalent mass flow rate approach.







Figure 7-6: LM4 near-DCA SLP TOC 8 - 1179V, 1.20A nominal (left) and SLP DL 8 without beam extraction (right) number density contours.



Figure 7-7: LM4 near-DCA SLP TOC 34' - 1459V, 3.10A nominal (left) and SLP TOC 34' CK-CC short - 1455V, 3.10A (right) number density contours.



Figure 7-8: LM4 near-DCA SLP TOC 34' - 1459V, 3.10A nominal (left) and SLP DL 34' without beam extraction (right) number density contours.

### 7.1.2 Electron Number Density

Electron number densities are an order of magnitude lower than ion number densities in the DCA plume, but are of similar magnitudes outside the plume. This is expected owing to the lack of electron saturation current in the DCA plume leading to an under-prediction of electron number density. If electron saturation was achieved, the magnetic field effects on the I-V curve would have to be accounted for when determining the electron saturation current.



Figure 7-9: LM4 near-DCA SLP TOC 0a - 275V, 1.00A (left) and SLP TOC 3 - 649V, 1.20A (right) electron number density contours.



(right) electron number density contours.



### 7.2 Electron Temperature

Near-DCA electron temperatures illustrate a low electron temperature cathode plume with temperatures from 2 - 4 eV inside. Outside the plasma column, the electron temperatures increase up to 5 - 7 eV. The rise in electron temperature is tied to the

potential gradients across the boundary between the cathode plume and bulk discharge plasma that accelerates electrons across the boundary thereby increasing their energy. The double layer potential profile also decelerates the high-energy electrons that overcome the potential gradient when moving from the high-potential main discharge plasma to the low-potential cathode plume. This effectively replenishes the low-energy electrons in the discharge cathode plume. Very little variation is observed in the near-DCA electron temperatures as the LM4 engine is throttled to higher-power.



Figure 7-12: LM4 near-DCA SLP TOC 0a - 275V, 1.00A (left) and SLP TOC 3 - 649V, 1.20A (right) electron temperature contours.



Figure 7-13: LM4 near-DCA SLP TOC 8 - 1179V, 1.20A (left) and SLP TOC 18 - 1179V, 2.01A (right) electron temperature contours.



Figure 7-14: LM4 near-DCA SLP TOC 20' - 1465V, 2.01A (left) and SLP TOC 32 - 1179V, 3.10A (right) electron temperature contours.



Figure 7-15: LM4 near-DCA SLP TOC 34' - 1459V, 3.10A electron temperature contour.

#### 7.2.1 Keeper to Cathode Common Short and Beam Effects

Consistent with the FMT2 investigation, the shorting of the discharge keeper to common does not alter the electron temperature profiles outside of the keeper sheath. The nominal and shorted profiles are almost indistinguishable. The effect of beam extraction is to increase the bulk discharge plasma by a few eV. This is likely due to the increased discharge voltage oscillations and the coupling of the double layer potential profile and/or position to these fluctuations. There is no variation observed in the DCA plume itself when a beam is extracted.



Figure 7-16: LM4 near-DCA SLP TOC 8 - 1179V, 1.20A nominal (left) and SLP TOC 8 CK-CC short - 1179V, 1.20A (right) electron temperature contours.



Figure 7-17: LM4 near-DCA SLP TOC 8 - 1179V, 1.20A nominal (left) and SLP DL 8 without beam extraction (right) electron temperature contours.



Figure 7-18: LM4 near-DCA SLP TOC 34' - 1459V, 3.10A nominal (left) and SLP TOC 34' CK-CC short - 1455V, 3.10A (right) electron temperature contours.



Figure 7-19: LM4 near-DCA SLP TOC 34' - 1459V, 3.10A nominal (left) and SLP DL 34' without beam extraction (right) electron temperature contours.

### 7.3 Emissive Probe Plasma Potentials

Near-DCA potential structures may be the most important indication of the cause of the DCA erosion. Examination of the plasma potential contours illustrate a cathode plume structure similar to FMT2. A steep increase in potential is observed in the radial direction on the order of 10 volts across the keeper face. A gradual increase in plasma potential is observed in the axial direction. The plasma potential contours of the LM4 thruster are more axially aligned near the DCA than the FMT2. This may affect the angle of incidence of ions towards the DCA and the flux of such ions. The more axially aligned potential gradients in LM4 will tend to accelerate ions in a more radial direction than the curved near-DCA potential profiles of the FMT2. The plasma structures again indicate a free-standing double layer as the boundary between the high-density, low-electron temperature, low-plasma potential DCA plume and the lower-density, higher-electron temperature, higher-plasma potential bulk discharge. The double layer is setup by the axial magnetic field that reduces the cross-field diffusion of electrons in the radial direction.

The plasma potentials inside the DCA plume are all similar regardless of thruster operating power. The plasma potentials are as low as 12 volts at the keeper exit, gradually increasing by 20 volts across the interrogation domain. Outside of the DCA plume, it is difficult to compare the plasma structures because of the insufficient heater currents often observed in these regions. Furthermore, the deterioration of the emissive qualities of the filament, after limited operating time, are observed as streaks or regions of decreased potential. Since the mappings are performed by radial sweeps at increasing axial distance downstream of the DCA, sweeps performed with insufficient heating appears as streaks in the data. The more streaks, the more deteriorated or less sufficient heating and should be considered when viewing the results. Notice, that the streaking regions do not exhibit streaking in the DCA plume confirming adequate heater current and therefore accurate measurement of the DCA plume plasma structures.

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Following the lack of a noticeable change in FMT2 plasma potential contours as the thruster is throttled to higher-power (aside from discharge voltage changes), the LM4 thruster is expected to illustrate the same trend. Thus the plasma potential mapping of the lower-power operation (in which sufficient heater current is applied throughout the interrogation domain in the discharge chamber) is expected to accurately predict the plasma potentials of the mid and high-power thruster operation. This is an important assumption used to determine the plasma potential magnitudes in the NEXT engines for the wear testing (at full throttle point) condition.

Just outside the double layer, the plasma potential is approximately 24-25 volts and the presheath potential (just outside the keeper sheath at mid-radius) is approximately 19 volts, both measured with respect to discharge cathode common.



Figure 7-20: Near-DCA LM4 floating emissive probe potentials for FEP TOC 0a - 275V, 1.00A (left) and FEP TOC 3a – 650V, 1.20A (right).



Figure 7-21: Near-DCA LM4 floating emissive probe potentials for FEP TOC 8a - 1179V, 1.20A (left) and FEP TOC 18 - 1179V, 2.01A (right)



Figure 7-22: Near-DCA LM4 floating emissive probe potentials for FEP TOC 20a' deteriorating - 1449V, 2.00A (left) and FEP TOC 32b - 1179V, 3.00A (right).



Figure 7-23: Near-DCA LM4 floating emissive probe potentials for FEP TOC 32a - 1180V, 3.11A (left) and FEP TOC 34b' - 1450V, 3.00A (right).



Figure 7-24: Near-DCA LM4 floating emissive probe potentials for FEP TOC 34b' - 1450V, 3.00A (left) shifted and FEP TOC 34a' – 1501V, 3.10A (P23) shifted.

#### 7.3.1 Keeper to Cathode Common Short and Beam Effects

Shorting of the discharge keeper to common does not have a noticeable effect on the near-DCA plasma potential structure. The effects of the shorting are confined to the sheath of the discharge keeper. The shorting will increase the incident ion energy by acceleration through the keeper sheath. The magnitude change in erosion by an incident ion energy change of  $\sim$ 5 volts will be examined in CHAPTER 9. Extraction of a beam

results in an increase in the near-DCA plasma structure consistent with the increase in the discharge voltage between the two operating conditions.



Figure 7-25: Near-DCA LM4 floating emissive probe potentials for FEP TOC 8a - 1179V, 1.20A nominal (left) and FEP TOC with cathode keeper to cathode common short - 1179V, 1.20A (right).



Figure 7-26: Near-DCA LM4 floating emissive probe potentials for FEP TOC 8a - 1179V, 1.20A nominal (left) and FEP DL 8 without beam extraction (right).



Figure 7-27: Near-DCA LM4 floating emissive probe potentials for FEP TOC 34b' - 1450V, 3.00A nominal (left) and FEP TOC 34' with cathode keeper to cathode common short - 1455V, 3.00A (right).

## 7.4 Harmonic EEDF

Electron energy distribution functions (EEDF's) are presented near the DCA for a variety of operating conditions. The harmonic method does not rely on a numeric derivative, which can introduce considerable error if not properly analyzed. One of the drawbacks of the harmonic setup used for this investigation is that in order to get a measurable signal, the amplitude of the high-frequency sine wave was increased to 4 V peak-to-peak. This will tend to smooth out the measured distribution, removing features that are smaller, in width, than 2 volts.

Another drawback is that the harmonic method is applied to thruster operation without a beam. The large number of electronics prevented floating all the equipment in a safe manner. As illustrated in §6.4, beam extraction tends to broaden the measured EEDF's towards the higher energies. In spite of this change, the harmonic EEDF's are useful to verify the Druyvesteyn method EEDF's with beam extraction and highlight the near-DCA EEDF evolution.

The harmonic method EEDF's are similar for all operating conditions investigated. A schematic (Figure 7-28) is added to facilitate interpretation of the EEDF results. There is a single-hump distribution inside the discharge cathode plume. Moving in the radial direction, the single hump shifts with the increase of the local plasma potential, but becomes broader and extends to higher energies. In some cases, this broadening creates a high-energy tail. Shorting of the cathode keeper to cathode common did not alter any of the measured EEDF's. Again, this result further supports the conclusion that the effects of the shorting event are contained in the discharge cathode keeper sheath. There is no change in plasma potential, number density, or electron temperature outside the keeper sheath and therefore it is expected that there would not be a change in the EEDF.



Figure 7-28: Electron energy distribution function (EEDF) key. The EEDF is displayed as a function of the probe bias voltage with respect to discharge cathode common, thus the right horizontal-axis crossing of the EEDF corresponds to the local plasma potential at a specific spatial location.



Figure 7-29: LM4 HEEDF DL 0 illustrating the electron energy distributions as a function of bias voltage. Each plot represents various radial spatial locations at the same axial distance from the DCA.



Figure 7-30: LM4 HEEDF DL 0 illustrating the electron energy distributions as a function of bias voltage. Each plot represents various axial spatial locations at the same radial distance from the DCA centerline.


Figure 7-31: LM4 HEEDF DL 8 CK-CC shorted, illustrating the electron energy distributions as a function of bias voltage. Each plot represents various radial spatial locations at the same axial distance from the DCA.



Figure 7-32: LM4 HEEDF DL 34' illustrating the electron energy distributions as a function of bias voltage. Each plot represents various radial spatial locations at the same axial distance from the DCA.



Figure 7-33: LM4 HEEDF DL 34' CK-CC short, illustrating the electron energy distributions as a function of bias voltage. Each plot represents various radial spatial locations at the same axial distance from the DCA.

# 7.5 Druyvesteyn (Second Derivative) Method

The application of the Druyvesteyn method provides a technique to measure EEDF's near the DCA with beam extraction. The results are presented in the subsequent figures. The EEDF plots are of the EEDF versus the probe bias with respect to discharge cathode common. This method is different than displaying the EEDF versus electron kinetic energy and referring to Figure 7-28 will facilitate interpretation of the results. Additional EEDF figures can be found in Appendix B. For equivalent spatial locations inside the discharge chamber, the Druyvesteyn method calculates EEDF's that are comparable to those measured by the harmonic method, verifying both techniques. Again, the EEDF's inside the cathode plume are single-hump distributions with a peak energy of approximately 10 volts with respect to local plasma potential. This corresponds to "primary" electrons of 10 volts. Following the EEDF evolution through the spatial location of the double layer, a more plateau structure and even double hump structure is formed by the acceleration/deceleration of electrons across the double layer. Outside the double layer, in the main discharge plasma, the EEDF returns to a single-hump distribution with a noticeable high-energy tail.

Focusing on Figure 7-35 and Figure 7-36, the repeatability of the EEDF measurement by the Druyvesteyn method is demonstrated. Identical EEDF's are measured for the equivalent thruster operating conditions.



Figure 7-34: EEDF's for various spatial locations as a function of probe bias voltage with respect to cathode common at DEEDF TOC 0.



Figure 7-35: EEDF's for various spatial locations as a function of probe bias voltage with respect to cathode common at DEEDF TOC 8a.



Figure 7-36: EEDF's for various spatial locations as a function of probe bias voltage with respect to cathode common at DEEDF TOC 8b.

Comparison of with Figure 7-35 or Figure 7-36 with Figure 7-37 indicates that shorting of the discharge cathode keeper to common does not alter the EEDF's. As discussed in §6.4, the extraction of a beam tends to broaden the measured EEDF's

(throughout the double layer and outside the double layer) compared to discharge-only operation. This results from coupling of the double layer to the discharge voltage and the increased discharge voltage oscillations with beam extraction.



Figure 7-37: EEDF's for various spatial locations as a function of probe bias voltage with respect to cathode common at DEEDF TOC 8 CK-CC short.



Figure 7-38: EEDF's for various spatial locations as a function of probe bias voltage with respect to cathode common at DEEDF DL 8.



Figure 7-39: EEDF's for various spatial locations as a function of probe bias voltage with respect to cathode common at DEEDF TOC 18a.



Figure 7-40: EEDF's for various spatial locations as a function of probe bias voltage with respect to cathode common at DEEDF TOC 18b.



Figure 7-41: EEDF's for various spatial locations as a function of probe bias voltage with respect to cathode common at DEEDF TOC 34'.



Figure 7-42: EEDF's for various spatial locations as a function of probe bias voltage with respect to cathode common at DEEDF TOC 34'.

# **CHAPTER 8**

# THE ROLE OF THE DOUBLE LAYER

# 8.1 Double Layers: Background and Definition

One unexpected finding in this investigation is the existence of a double layer separating the hollow cathode plasma plume and the bulk discharge plasma. Plasma sheaths are present around bodies immersed in plasma and at the plasma boundary. However, sheath structures can be present free standing in plasmas. One such structure is termed a double layer. Double layers are non-neutral regions located away from the plasma boundary that resemble an ion sheath connected to an electron sheath and are typically several Debye lengths in thickness.²¹⁷ Double layers are special kinds of sheaths used to describe the region of transition between two plasmas at different potentials, far from any boundaries. In this way, the double layer is the region of space charge separation joining two neighboring plasmas that have different potentials. Electric fields produced in the double layers are much stronger than those outside. Plasma double layers were first reported by Langmuir in 1929.²¹⁸ Three-dimensional double layer geometries measured by Coakley and Hershkowitz closely resemble the trough-like double layer

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Double layers have been measured previously for a hollow cathode source interacting with an ambient plasma.²²⁰ Vannaroni, *et al.* found the sharp transition region indicative of a double layer that dominated the current collection process on a hollow cathode source and led to an increased electron temperature where the double layer was located.²²⁰ Concurrent with this investigation, double layers were also measured by Foster and were found to be aligned with the axial magnetic field near the DCA in an ion thruster.¹⁴⁰ Katz, *et al.* indicated the presence (confirmed visually and with probes) of a double layer downstream of the DCA on centerline for high-flow conditions.²¹⁸

Inside the discharge chamber of an ion thruster, a double layer forms between the electron emitting cathode plume and the bulk discharge plasma. A schematic (Figure 8-1) of the double layer offers visual interpretation of this structure.



Figure 8-1: Plasma potential profile associated with the double layer structure transitioning between a low-potential plasma (cathode plume) and a high-potential plasma (bulk discharge plasma).

### 8.2 Double Layer Effects in Ion Thrusters

The presence of a double layer in the ion thruster discharge is supported by the plasma parameter mappings. The most important being the plasma potential mapping. Since the double layer is aligned with the axial magnetic field, examination of a sample radial sweep of the floating emissive probe illustrates the double layer potential geometry illustrated in Figure 8-2. Visual confirmation of the double layer at the boundary between the high-density discharge cathode plume and the bulk discharge plasma is illustrated in Figure 8-3.



Radial Distance from DCA Centerline [ ]

Figure 8-2: Sample radial plasma potential profile illustrating the measured double layer in ion thruster discharge chambers.



Figure 8-3: View of the LM4 DCA during thruster operation confirming the high-density discharge cathode plume and the approximated location of the double layer based on plasma potential measurements.

Ions and electrons can be either reflected by or accelerated through double layers. Free electrons are those electrons entering the double layer from the low potential side and are accelerated by the double layer. Trapped electrons are those electrons entering from the high potential side and are reflected back by the double layer. Similarly, free ions are those entering the double layer from the high potential side that are accelerated through the double layer, while trapped ions are entering from the low potential side and are reflected back by the double layer. The phase space offers visual interpretation of the various species of trapped and free charge particles in Figure 8-4. It is important to emphasize that ions produced in the high potential region (*i.e.*, the bulk discharge plasma) are accelerated towards the low potential region (*i.e.* the cathode plume and the DCA) by the electric field of the double layer.



Figure 8-4: Plasma potential profile (top), ion phase space (middle), and electron phase space (right) associated with a double layer.

Theories of magnetized double layers have been studied in conjunction with the investigation of ionospheric phenomena indicating the formation of a field-aligned double layer.^{221,222} The double layer inside an ion thruster is complicated by the presence of the magnetic field. The phase space diagram indicated in Figure 8-4 is altered because the axial magnetic field near the DCA hampers electron movement across the double layer even though the electric potentials of the double layer would accelerate electrons across it.

The magnetic field profile associated with the ring cusp magnetic circuit directly affects the coupling of the hollow cathode discharge to the main discharge plasma. The axial magnetic field near the DCA confines electrons to a narrow plume significantly reducing radial electron diffusion. Conversely, axial electron conductivity is enhanced. The restricted axial movement of electrons drives the sharp potential transition between the two plasmas. This type of transition is a double layer. It is evident that the magnetic field is responsible for the formation of the double layer and it is not surprising that the double layer is aligned with the axial magnetic field. The voltage gradients are highest at the cathode where the axial magnetic field is strongest, giving rise to a radially directed erosion component.

In addition to contributing to the DCA erosion, the double layer will affect the discharge plasma parameters and will be useful in interpreting the plasma parameter mappings produced by the various electrostatic probes. As previously discussed, the double layer will trap ions created in the discharge cathode plume and therefore contribute to the high number densities measured in the plume. The presence of the axially-aligned double layer will restrict ion diffusion across the double layer further forcing a highly-collimated plume.

The double layer will also affect the electron motion. The double layer will tend to enhance the radial diffusion of electrons that are restricted by the axial magnetic field. Electrons in the bulk discharge plasma will be accelerated across the double layer towards the DCA centerline. All but the high-energy, trapped electrons will be confined to the main discharge region near centerline by the double layer. Thus, the double layer will contribute to the shape of the electron energy distributions. Examination of the EEDF's from both the harmonic and Druyvesteyn methods indicate a single hump distribution in the discharge cathode plume. The EEDF's do not simply shift with plasma

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potential across the double layer. A broader and sometimes double-humped distribution is evident as the plasma transition through the double layer. A clear example of this is in the EEDF's of Figure 7-41 at the further axial locations. The second hump (towards the left away from the local plasma potential) consists of the electrons accelerated across the double layer. These accelerated electrons become thermalized, though the high-energy tail is evident for the EEDF's measured in the bulk discharge plasma outside the double layer. The acceleration of the electrons across the double layer gives rise to the off-axis electron temperature maximum observed. Outside the double layer, the electrons become thermalized and the electron temperature decreases. The two-peaked shape of the EEDF's at specific spatial locations suggests the presence of plasma instabilities. The plasma will tend to smooth out such structures through the bump-in-tail instability.²²⁰ Double layers have been documented to have a similar effect on the electron temperature for the various regions examined.²²³

Double layers have been found to have two distinct frequency spectra: high frequency and low frequency associated with electron and ion plasma frequencies, respectively.²²² In addition to the high- and low-frequency components, the oscillation of the discharge voltage will likely affect both the magnitude and location of the double layer. This may be the reason that examination of the I-V characteristics between the DCA centerline and bulk discharge plasma where the double layer resides exhibited much greater noise. If the double layer position and/or magnitude is shifting between the Langmuir probe sweeps, the collected current for a given spatial location will also shift

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even if the bias voltage is held constant. The noise or "hash" in the point-by-point I-V characteristics is the result of the double layer oscillations.

The coupling of the discharge voltage and double layer, along with the increased discharge voltage oscillations with beam extraction, affect the EEDF's when a beam is extracted. The discharge-only EEDF's are very smooth and more closely follow single-hump distributions. When a beam is extracted, the EEDF's become extended to higher energies and are broader and plateau-shaped, which results in an increase in the electron temperatures when a beam is extracted. This is consistent with the single Langmuir probe measurements.

It is clear that the double layer is an important feature of the discharge chamber. The double layer is closely tied to the magnetic field of the discharge chamber and the analysis in CHAPTER 9 shows it is responsible for some acceleration of ions towards the DCA, and shapes the electron energy distributions throughout the discharge chamber.

# CHAPTER 9 DCA EROSION RATES

The application of the measured parameters to calculate DCA erosion rates is difficult due to the lack of an accurate low-energy, heavy-ion sputter yield description. The sputtering yield, Y, is a statistical variable defined as the mean number of atoms removed from a solid target per incident particle. For application to DCA erosion, the sputtering yield will indicate the mean number of molybdenum atoms removed from the DCA face per incident xenon ion for a given incident energy:

$$Y = \frac{atoms \ removed}{incident \ particle}.$$
 Eqn. 9-1

As the definition implies, the number of atoms removed is proportional to the number of incident particles at a given energy, maintaining all other factors. A detailed description of the physical mechanisms of sputtering is beyond the scope of this investigation. Comprehensive discussion of sputtering yield theories and additional sputtering yield models can be found in References 224-227. Most sputtering yield models rely on a threshold energy input, therefore, the threshold energy calculation will be important to the sputtering yield calculation and will be discussed. A brief description

of the semi-empirical models used to calculate the low-energy, heavy-ion sputtering of ion thruster internal components will be discussed and their results examined. Finally low-energy, heavy-ion recent data will be fit giving a direct measure of the normal incident erosion.

# 9.1 Sputtering Threshold Energy

The sputtering threshold for a given target material,  $E_{th}$ , is defined as the minimum kinetic energy of the bombarding particle for sputtering to occur. The existence of a sputtering threshold energy below which no sputtering occurs is ill defined. The surface binding energy for all atoms on a real surface, with surface defects, has a distribution with a low-energy tail that extends to extremely small values.²¹² Thus, there is a finite statistical probability that a surface atom can acquire sufficient energy to leave the surface from any incident particle energy. It is useful to define the sputtering threshold as the kinetic energy for incident ions below which no observable sputtering occurs. Most analytical formulae that describe the energy dependence of sputtering yield require a sputtering threshold as input. It is traditionally assumed that the sputtering threshold is proportional to the surface binding energy. In most cases the surface binding energy, U_b, and heat of sublimation, U_s, are considered interchangeable. For molybdenum, the heat of sublimation (or surface binding energy) is 6.82 eV.²¹⁶ Several authors have proposed analytical expressions for the threshold energy as a function of the heat of sublimation, Us, and the mass ratio of incident particle to target particle based on fits of experimental and/or calculated data. In all, a total of ten different threshold

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expressions are available for a given mass ratio to estimate the threshold energy at normal incidence, based on different theories or experimental data. The threshold energy calculation of Mantenieks was derived from existing experimental data for mercury and xenon ions and will be used for this investigation:²¹³

$$E_{th} = U_s \left[ 4.4 - 1.3 \log \left( \frac{M_2}{M_1} \right) \right].$$
 Eqn. 9-2

For xenon ions incident upon molybdenum, this results in a value of 31.2 eV. However, the actual data for xenon ion sputtering threshold from Stuart and Wehner, which was used by Mantenieks, indicate that a sputtering threshold of 27 eV is more appropriate for xenon-molybdenum.^{213,228}

In addition to the threshold calculation of Mantenieks, several authors have proposed analytical expressions for the sputtering threshold energy as a function of the target binding energy and relative mass ratios on the basis of experimental data and/or theoretical arguments. Three of the most commonly used are by Bohdansky (for  $M_1/M_2>0.3$ ,^{212,229}

$$E_{th} = 8U_b \left(\frac{M_1}{M_2}\right)^{2/5}$$
, Eqn. 9-3

the expression used in the Third Matsunami formula,²¹⁶

$$E_{th} = \left[1.9 + 3.8 \left(\frac{M_1}{M_2}\right) + 0.134 \left(\frac{M_1}{M_2}\right)^{-1.24}\right],$$
 Eqn. 9-4

and the Yamamura- and Tawara-proposed universal relation for  $M_1 \ge M_2$ :²²⁵

$$E_{th} = U_s \left(\frac{6.7}{\gamma}\right).$$
 Eqn. 9-5

In Eqn. 9-5,  $\gamma$  is the energy transfer factor in the elastic collision given by:^{225,230}

$$\gamma = \frac{4M_1M_2}{(M_1 + M_2)^2}.$$
 Eqn. 9-6

Finally Doerner, *et al.* recently measured molybdenum sputtering yields during xenon ion bombardment in the energy range of 10 and 200 eV. Doerner's results indicate a threshold energy on the order of 15 eV for xenon sputtering of molybdenum.²¹⁵ Therefore, the range of values for the sputtering threshold for the Xe⁺-Mo system for the above equations and reference data is 15-62 eV. This broad range of values confirms the ill-defined nature of the sputtering threshold energy. The near-threshold sputtering yield

calculation is further complicated since the semi-empirical formulae rely on the sputtering threshold energy as a parameter.

Yamamura, *et al.* reported that numerous investigations showed the angular dependence of  $E_{th}$  illustrated in the following equations:

$$E_{th}(\theta) \cong E_{th}(0)\cos^2\theta$$
 Eqn. 9-7

for not-too-oblique angles (low  $\theta$ ), and

$$E_{th}(\theta) \simeq \frac{0.3 \frac{M_2/M_1}{M_2/M_1 + 1} E_{TF} \left(\frac{a}{R_0}\right)^3}{\cos^2 \theta}$$
 Eqn. 9-8

for grazing angles (high  $\theta$ ).^{224,230} E_{th}(0) is the threshold energy for normal incident ions. The definition of the incident ion angle is illustrated graphically in Figure 9-1. Eqn. 9-7 will be used for incident angles less than or equal to 40 degrees with respect to the surface normal. Eqn. 9-8 will be applied for incident angles greater than or equal to 70 degrees. Between the two regimes, a weighted average of the two equations based upon the incident angle will be used. E_{TF} is the Thomas-Fermi energy unit given by:

$$E_{TF} = \frac{M_1 + M_2}{M_2} \frac{Z_1 Z_2 e^2}{a}.$$
 Eqn. 9-9

 $R_0$  is the average lattice constant of the molybdenum target, given by  $R_0=N^{-1/3}$  where N is the number density of the target atom. In Eqn. 9-8 and Eqn. 9-9, a is the Thomas-Fermi screening radius given in Å by:

$$a = 0.4685 \left( Z_1^{\frac{2}{3}} + Z_2^{\frac{2}{3}} \right)^{-\frac{1}{2}}$$
. Eqn. 9-10

The angular dependence of the threshold energy is illustrated in Figure 9-2 for each of the three normal threshold energies used in this investigation. The minimum threshold energies have minimum values in the range of 46 - 57 degrees depending upon the equation or value used. The minimum threshold energies as a function of incident angle are: 8 eV (Doerner value), 12 eV (Stuart and Wehner value), 13 eV (3rd Matsunami Eqn. and Mantenieks Eqn.), 16 eV (Yamamura and Tawara Eqn.), and 18 eV (Bohdansky Eqn.). It should be noted that Yamamura found the minimum threshold for heavy-ion sputtering to be near 60°, which is consistent with the calculation.



Figure 9-1: Schematic illustrating the angle of incidence for an incoming ion referenced to the surface normal.



Figure 9-2: Threshold energy calculations as a function of incident particle (xenon ion) angle with respect to the normal to the molybdenum target surface.

As input to the sputtering yield and erosion rate calculations, the threshold value at normal incidence used in the semi-empirical data will be the value of 27 eV taken directly from Stuart and Wehner.²²⁸ This measured value is specific for xenon ions impacting molybdenum targets at low-energy and therefore serves as the best indication of the normal threshold energy for this investigation.

# 9.2 Sputtering Yield Formulae

The interaction between an incident particle and a solid target is primarily dictated by the kinetic energy of the incoming particle. When the kinetic energy of the incoming particle exceeds the lattice displacement energy of the target atoms, the atoms of the target lattice may be pushed to new positions causing surface migrations and damage. When a surface atom is given a surface-normal energy component greater than the surface binding energy, it will be ejected in a process called physical sputtering. It is evident that the sputtering yield is highly dependent on the incident ion kinetic energy. The terms "incident particle" and "ion" are used synonymously throughout this text. Sputtering yield is also a function of the incident particle mass and incoming angle, as well as the target material properties. A large amount of research on sputtering has taken place over the last five decades. However, a majority of this research has been focused on high-energy (greater than a few keV) sputtering yields. The dearth of data for low-energy sputtering by heavy ions restricts the prediction of erosion rates in electron-bombardment ion engines. Currently, low-energy, heavy-ion sputtering yields are predicted from extrapolations from the higher-energy measurements with semi-empirical formulae. These results have a high degree of uncertainty for low-energy (*i.e.*, near-threshold) sputtering, as is evident from the scatter in predicted erosion rates.

#### 9.2.1 Semi-Empirical Sputter Yield Formulae

There is an abundance of analytical approaches to the treatment of the sputtering yield. Perhaps the most authoritative theoretical sputtering study was conducted by Sigmund in 1969.²²⁷ Sigmund assumed an isotropic, homogeneous, semi-infinite, monoatomic, planar target surface so the transport of particles can be described by Boltzmann's equation. Expressions for the cross-sections were obtained by assuming that collisions are binary. Another key assumption that Sigmund used, was that the incident particle energy is well above the effective surface-barrier energy (E > 100-200 eV). At

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energies near threshold, the Sigmund model becomes inaccurate because of a number of assumptions and approximations used in his calculation:²¹²

- The analytical solution to the Boltzmann equation proposed by Sigmund required  $E >> U_b$ .
- The binary collision approximation may break down.
- The velocity distribution of recoils may no longer be isotropic.
- The Thomas-Fermi interaction potential introduces error at low energies.

Though Sigmund's model is not applicable to low, near threshold, energies, it serves as the basis for most of the energy-dependent sputtering yield analytical formulae used to predict sputtering yield at lower energies. Two popular semi-empirical formulae based on Sigmund's model are utilized in this investigation. It should be noted that sputtering yields extrapolated from available higher-energy data ( $E \ge 100 \text{ eV}$ ) and based on formulae derived from Sigmund's model utilizing the assumption of incoming energy much greater than threshold energy are unreliable near the threshold energy.

The Sigmund equation gives the energy dependence of the sputtering yield as a function of the sublimation energy (assumed equivalent to the binding energy) of the target, the elastic (nuclear) stopping cross section  $S_n(E)$ , and the fit parameter  $\alpha(M_2/M_1)$ :²²⁷

$$Y_{Sigmund}(E) = 0.042 \frac{\alpha (M_2/M_1) S_n(E)}{U_s}$$
. Eqn. 9-11

#### 9.2.1.1 Bohdansky Sputter Yield Formula

A semi-empirical relation for the energy dependence of the sputtering yield has been proposed based upon the general Sigmund model to which empirical parameters were added to better fit published experimental data and additional terms incorporated to extend the relation to the threshold regime. The Bohdansky formula has been successively modified to keep the fit parameters updated as additional experimental data became available. The latest revision of the Bohdansky formula, valid for both light and heavy ions, is given by:

$$Y_{Bohdansky}(E) = 0.042 \frac{\alpha S_n(E)}{U_b} \left(\frac{R_p}{R_a}\right) \left[1 - \left(\frac{E_{th}}{E}\right)^{\frac{2}{3}} \right] \left[1 - \left(\frac{E_{th}}{E}\right)\right]^2$$
 Eqn. 9-12

where the numerical constant 0.042 has dimensions of Å⁻².²³¹ The energy-independent function of mass ratios,  $\alpha$ , can be approximated by:²³¹

$$\alpha = 0.3 (M_2/M_1)^{2/3}$$
 Eqn. 9-13

for 0.5<(M₂/M₁)<10. The elastic (nuclear) stopping cross section, S_n(E) can be described by an energy parameter,  $\varepsilon$ , and a function s_n( $\varepsilon$ ) common to all projectile-target combinations²³¹

$$S_n(E) = 4\pi a Z_1 Z_2 e^2 \frac{M_1}{M_1 + M_2} s_n(\varepsilon).$$
 Eqn. 9-14

In Eqn. 9-14,  $Z_1$  and  $Z_2$  are projectile and target atomic numbers, respectively. The Lindhard screening length for interaction potential, a (in Å), is given by:^{225,231}

$$a = 0.4685 (Z_1^{2/3} + Z_2^{2/3})^{-1/2}$$
. Eqn. 9-15

Eqn. 9-14 is given explicitly by Eqn. 9-16 with the constant 84.78 in units of (eV  $Å^2$  atom⁻¹)²²⁵

$$S_n(E) = 84.78 \frac{Z_1 Z_2}{\left(Z_1^{2/3} + Z_2^{2/3}\right)^{1/2}} \frac{M_1}{M_1 + M_2} s_n(\varepsilon).$$
 Eqn. 9-16

The elastic reduced nuclear stopping power,  $s_n(\epsilon)$  is approximated by an analytical expression based on the Thomas-Fermi potential that approximates the  $s_n$  data of Lindhard to within a few percent:^{216,225}

$$s_n(\varepsilon) = \frac{3.441\sqrt{\varepsilon}\ln(\varepsilon + 2.718)}{1 + 6.35\sqrt{\varepsilon} + \varepsilon(6.882\sqrt{\varepsilon} - 1.708)}.$$
 Eqn. 9-17

The reduced energy,  $\varepsilon$ , is given by:^{216,225,231}

$$\varepsilon = \frac{M_2}{M_1 + M_2} \frac{a}{Z_1 Z_2 e^2} E$$
. Eqn. 9-18

Eqn. 9-18 is given explicitly by:²²⁵

$$\varepsilon = \frac{0.03255}{Z_1 Z_2 (Z_1^{2/3} + Z_2^{2/3})^{1/2}} \frac{M_2}{M_1 + M_2} E(eV).$$
 Eqn. 9-19

The average number of surface crossings is proportional to the ratio of the average path length,  $R_a$ , to the projected range,  $R_p$ . An analytic expression for a first order approximation of  $(R_p/R_a)$  in  $M_2/M_1$ , used in Eqn. 9-12, is given if inelastic losses are neglected by:²³¹

$$\left(\frac{R_p}{R_a}\right) = \left(0.4\left(\frac{M_2}{M_1}\right) + 1\right)^{-1}$$
. Eqn. 9-20

#### 9.2.1.2 Third Matsunami Sputter Yield Formula

A series of yield equations based upon Sigmund's equation were adapted by Matsunami and Yamamura. Matsunami, *et al.* improved on Sigmund's equation by taking into account the effect of the threshold energy. Yamamura, *et al.* further refined the equation by making the inelastic stopping explicit and taking into account the effect of the target material on the mass-ratio dependence. The latest version, published in 1996, is known as the third Matsunami formula (or Yamamura Model):²²⁵

$$Y_{3rd Matsunami}(E) = 0.042 \frac{Q\alpha^*}{U_s} \frac{S_n(E)}{1 + \Gamma k_e \varepsilon^{0.3}} \left[ 1 - \sqrt{\frac{E_{th}}{E}} \right]^s.$$
 Eqn. 9-21

Recall that the numerical constant 0.042 has dimensions of Å⁻² and that the target sublimation energy, U_S, and the target surface binding energy, U_b, are assumed equivalent with a value of 6.82 eV for molybdenum. Both heavy ion and light ion sputtering mechanisms are included in the third Matsunami formula permitting application for both light and heavy ions. For heavy ions, the incoming ion deposits its energy near the surface and a collision cascade develops resulting in the ejection of target atoms from the surface (Mechanism A). For light incoming ions a collision cascade is not developed. Instead, the ions are reflected from inside the surface layer, hitting the surface atoms and sputtering those recoil atoms (Mechanism B). The  $\Gamma$  factor, calculated by Eqn. 9-22 with M₁ in amu, describes the contribution of sputtering from Mechanism B. As the mass of the incident ion becomes lighter, the sputtering mechanism gradually shifts from mechanism A to mechanism B and  $\Gamma$  becomes larger.

$$\Gamma = \frac{W(Z_2)}{1 + (M_1/7)^3}$$
 Eqn. 9-22

From existing data for the Mo target, the best-fit values of dimensionless parameters  $W(Z_2)$ ,  $Q(Z_2)$ , and s are: 2.39, 0.85, and 2.8, respectively.²²⁵ The value of  $W(Z_2)$  is indicated as 2.39 for molybdenum in Yamamura's table, however, in the caption of the graph of sputter yield for Xe⁺-Mo the value for  $W(Z_2)$  is indicated as 0.45*Us.²²⁵

As a result there is some uncertainty as to whether the value for  $W(Z_2)$  should be 2.39 or 3.07. The tabulated value of 2.39 will be used. However, no difference in the calculated sputter yields was observed when the value was changed between the two. This result is expected since the incident mass of xenon is large enough such that the light ion sputter by Mechanism B is negligible and thus  $\Gamma$  is very small regardless of the value of  $W(Z_2)$ .

The nuclear stopping cross section,  $S_n(E)$ , the elastic reduced nuclear stopping power,  $s_n(\epsilon)$ , and the reduced energy,  $\epsilon$ , are calculated in the same fashion as for the Bohdansky equation given by Eqn. 9-16, Eqn. 9-17, and Eqn. 9-19, respectively. The best-fit values of  $\alpha^*$  as a function of  $M_2/M_1$  are described by the following manner for  $M_1 \ge M_2$ :²²⁵

$$\alpha^* (M_2/M_1) = 0.0875 (M_2/M_1)^{-0.15} + 0.165 (M_2/M_1).$$
 Eqn. 9-23

Finally, the Lindhard electronic stopping coefficient, ke, is given as:

$$k_{e} = 0.079 \frac{\left(M_{1} + M_{2}\right)^{\frac{3}{2}}}{M_{1}^{\frac{3}{2}} M_{2}^{\frac{1}{2}}} \frac{Z_{1}^{\frac{2}{3}} Z_{2}^{\frac{1}{2}}}{\left(Z_{1}^{\frac{2}{3}} + Z_{2}^{\frac{2}{3}}\right)^{\frac{3}{4}}}$$
 Eqn. 9-24

with M_i in amu.

#### 9.2.2 Wilhelm Sputtering Yield Formula

Wilhelm published the only physical model that does not rely on the binary collision approximation and is specific to low-energy sputtering. The sputtering yield of metals with heavy ions near threshold energies has been determined by Wilhelm based on a quantum-statistical analysis of a three body surface mechanism involving the incoming ion and two target atoms giving the following relationship:^{212,229}

$$Y_{Wilhelm} = K \cdot (E - E_{th})^2$$
 Eqn. 9-25

where the constant K is a function of the ion-atom scattering cross-section and includes the quantum statistical parameters. Mantenieks determined the value of K for 100-eV xenon ions impacting a molybdenum target from available experimental data.²³² The sputtering yield formula for the Xe⁺-Mo system is given by:²¹³

$$Y_{Mantenieks} = 1.3 \times 10^{-5} (E - E_{th})^2$$
. Eqn. 9-26

#### 9.2.3 Doerner Data Fit Sputter Yield

Recently, experimental data taken by Doerner, *et al.* report sputter yield data for  $Xe^+$ -Mo with ion bombardment energies from 10 to 200 eV.²¹⁴ The spectroscopic sputter yields and standard weight loss yields calculated by Doerner compare nicely to each other and to existing low-energy Xe⁺-Mo data taken by other researchers, validating the

results.²¹⁵ As mentioned in the sputtering threshold section, §9.1, based upon data taken by Doerner, the threshold value for xenon sputtering of molybdenum is on the order of 15 eV.²¹⁵ The Doerner sputter yield versus energy data were log-log plotted and a sixthorder polynomial fit was made to the resulting graph. From this fit, a completely experimental determination of the normal incident sputtering yield of the low-energy Xe⁺-Mo system can be determined as a function of energy:

$$Y_{Doerner}(E) = \exp\{-0.372304[\ln(E)]^6 + 9.48041[\ln(E)]^5 - 100.046[\ln(E)]^4 + 560.276[\ln(E)]^3 - 1758.24[\ln(E)]^2 + 2940.48[\ln(E)] - 2064.3\}.$$
 Eqn. 9-27

#### 9.2.4 Sputtering Yield Incident Angle Dependence

Numerous investigations demonstrated a sputtering yield with an angular dependence.^{230,233-237} The incident angular dependence is accounted for in the sputtering calculation in one of two ways. For semi-empirical formulae and the Mantenieks sputter yield analysis where the threshold energy is a parameter, the angle-dependent threshold energy can be used from Eqns. 9-7 and 9-8. Thus, the effect of the angular dependence of the threshold energy adjusts the sputter yield calculations.

Where sputtering yield is calculated directly from the normal energy (*e.g.*, from Doerner's data), this method is not applicable as the threshold energy is not a variable in

the calculation. For Doerner's data, and as a secondary calculation for the other sputtering yields, a second angular dependence correction to the sputter yield calculated at normal incidence is applied directly to the yield. An empirical formula for the angular dependence of the sputtering can be given as:^{224,236}

$$\left(\frac{Y(\theta)}{Y(0)}\right) = \cos^{-19.96} \theta \cdot \exp\left[-13.55\left(\cos^{-1}\theta - 1\right)\right].$$
 Eqn. 9-28

In Eqn. 9-28, the numeric factors are energy-dependent fit parameters determined from 100-eV xenon ions impacting a molybdenum target and Y(0) is the sputtering yield at normal incidence.²²⁴ The exponent fit parameter, 19.96, carries the threshold effect and is a function of the ratio E/E_{th}. Therefore, it is appropriate to apply either the angulardependent threshold energy correction or the angular-dependent sputtering yield correction to account for the near-threshold incident ion angular dependence, but not both as this would account for the angular dependence twice. Figure 9-3 illustrates the angular dependence of the sputtering yield calculated for xenon ions on a molybdenum target calculated from Eqn. 9-28. Here the maximum angular correction factor is approximately 3.7 and corresponds to an angle of 48 degrees. The optimum angle for sputtering from Eqn. 9-28 is slightly less that the optimum angle from the threshold energy calculation of 55 degrees.



Figure 9-3: Angular dependence factor for the sputtering yield utilizing experimental data at 100 eV for the fitting coefficients.

#### 9.3 NSTAR Erosion Rates

The erosion rates for the NSTAR thruster have been estimated based upon the measured plasma parameters at the wear test operating conditions. For semi-empirical sputter yield calculation, the experimental value for the normal incident sputter threshold energy obtained by Stuart and Wehner of 27 eV for the Xe⁺-Mo system was used because it is specific to this system while the universal formula are for heavy ions in general. The erosion rate based on Doerner's data for low-energy Xe on Mo does not rely on a threshold energy and contains normal sputtering yields for multiple energies between the range of 10 - 200 eV and thus will be regarded as the more accurate calculation. Due to the large errors in extrapolating the semi-empirical formulas to near-threshold energies, the calculated values from semi-empirical formulae, which were often either zero or much higher than the Doerner or Mantenieks data, have been omitted. For comparison,

the Mantenieks data, with energy threshold as a parameter, is adjusted for incident angle dependence in two separate fashions. The angular dependence of the threshold is input into Eqn. 9-26 giving the angular dependent yield. For the case of the incident ion energy exceeding the normal threshold energy, the normal threshold energy is used as the input to Mantenieks equation and the normal yield adjusted for angular dependence according to Eqn. 9-28.

The plasma parameters for the NSTAR thruster indicate how erosion mechanisms might occur. The potential drop across the double layer acts to accelerate ions towards the discharge cathode assembly. To illustrate this, the potential contours from floating emissive probe data for the FMT2 is differentiated giving the electric field components corresponding to this potential mapping. The plasma potential mappings for all thruster operating conditions investigated followed the same trends, though the magnitude of the bulk discharge plasma potential shifted slightly with varying discharge voltage. Figure 9-4 illustrates the electric field components responsible for ion impingement on the DCA. For the erosion calculation, two energies corresponding to the plasma potential just outside the double layer serves as inputs to the erosion calculation. A plasma potential of 27 volts is observed outside the double layer in many of the FMT2 potential mappings and serves as an input to the erosion calculation. A slightly higher value of 30 volts will also be used because of the tendency of the emissive probe to float slightly below the true plasma potential indicating the sensitivity of the erosion calculation to an increased energy of a few volts.

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Figure 9-4: Sample electric field vector plot superimposed on the floating emissive probe mapping for FMT2 illustrating the directed electric field towards the DCA.

Given the ion starting potential, 27 or 30 volts, and the presheath potential of the discharge cathode keeper at mid-radius (where the DCA erosion is most severe) of approximately 22 volts (determined from plasma potential mappings) a presheath ion energy is determined. The angular dependence of sputtering yield has been shown to be important and must be accounted for. A range of incident ion angles will be investigated. Based upon the potential mappings and LIF measured velocimetry on FMT2 in the keepered configuration, an incident presheath angle of approximately 60 degrees (with respect to the keeper normal) is expected.^{48,127}

The ion is assumed accelerated through the sheath normal to the surface by the potential between the presheath potential of 22 volts and the discharge keeper floating potential. A through-sheath energy and angle is calculated giving the incident ion energy with angular dependence. The effect of shorting the cathode keeper to cathode common is also investigated. The sputter yields are calculated from the experimental data fits of
Doerner and Mantenieks. The flux of the ions towards the keeper must be determined based upon the directed flux from the higher-potential region by directed acceleration towards the keeper. The location just outside the double layer, where 27 volts potential is measured, corresponds to a non-dimensional radial position of 0.6 and a non-dimensional axial position of 0.4. From Figure 9-5, the ion number density at this location is roughly  $5x10^{11}$  cm⁻³.



Figure 9-5: SLP 2000 hr. wear test (left) and SLP 8200 hr. wear test (right) near-DCA region number density mapping.

The calculated erosion rates as a function of the input variables are listed in Table 9-1 for only singly-ionized xenon. The calculated erosion rates for LIF indicated ion angles and measured plasma parameters are highlighted for clarity. The other calculations illustrate the effect of the variation in incident ion angle on the calculated erosion rate. Doerner's erosion rate serves as the most justified and will be the rate referred to. Mantenieks sputter yield calculations have been included to illustrate the variation in sputter yields near-threshold for the various models.

				Pre-shea	ath	Through-sheath									
												Ave	Doerner	Mantenieks	Mantenieks
Number	Plasma	Potential								Eth	Eth	Erosion	Erosion	Erosion	Erosion
density	potential	at sheath	Vck-cc	Energy	Velocity	Angle	Energy	Velocity	Angle	Normal	(angle)	Rate	Rate	Rate 1 (Eth)	Rate 2 (Y)
												[micron /	[micron /	[micron /	[micron /
[cm^-3]	[V]	[V]	[V]	[eV]	[m/s]	[degrees]	[eV]	[m/s]	[degrees]	[eV]	[eV]	khr]	khr]	khr]	khr]
5.E+11	27	22	5.91	5	2710	0	21	5565	0	27	27	4	4	0	0
5.E+11	27	22	5.91	5	2710	30	21	5565	14	27	25	5	5	0	0
5.E+11	27	22	5.91	5	2710	60	21	5565	25	27	22	8	8	0	0
5.E+11	27	22	5.91	5	2710	75	21	5565	28	27	21	4	9	0	0
5.E+11	30	22	5.91	8	3428	0	24	5948	0	27	27	14	14	0	0
5.E+11	30	22	5.91	8	3428	30	24	5948	17	27	25	18	18	0	0
5.E+11	30	22	5.91	8	3428	60	24	5948	30	27	20	31	30	32	0
5.E+11	30	22	5.91	8	3428	75	24	5948	34	27	19	50	36	65	0
5.E+11	27	22	0	5	2710	0	27	6297	0	27	27	32	32	0	0
5.E+11	27	22	0	5	2710	30	27	6297	12	27	26	20	37	4	0
5.E+11	27	22	0	5	2710	60	27	6297	22	27	23	41	49	32	0
5.E+11	27	22	0	5	2710	75	27	6297	25	27	22	52	55	50	0
5.E+11	30	22	0	8	3428	0	30	6638	0	27	27	35	62	22	22
5.E+11	30	22	0	8	3428	30	30	6638	15	27	25	53	77	56	27
5.E+11	30	22	0	8	3428	60	30	6638	27	27	22	109	116	171	41
5.E+11	30	22	0	8	3428	75	30	6638	30	27	20	137	134	228	47

 Table 9-1: Calculated FMT2 erosion rates based upon measured plasma parameters (plasma potential and number densities) for singly-ionized xenon only.

Recall from Table 1-3 that the measured erosion rates for the 1000 hr. and 8200 hr. wear tests were 70  $\mu$ m/khr and 63  $\mu$ m/khr, respectively. The first 5,850 hrs of the ELT had an estimated erosion rate of 77  $\mu$ m/khr and an accelerated rate of (estimated) 173  $\mu$ m/khr after the shorting event. The erosion rates calculated from the measured plasma parameters assuming only singly-ionized xenon are considerably less than the measured wear test erosion rates. This indicates that the analysis has not accurately accounted for all of the dominant factors in DCA erosion.

The effect of shorting the discharge cathode keeper to cathode common, illustrated in Table 9-1 comparing cases with  $V_{ck-cc} = 5.91$  and  $V_{ck-cc} = 0$ , is shown to have a significant effect on the calculated erosion rates, resulting in an increase of a roughly a factor of 4 for the conditions investigated. It appears as though the shorting event of the ELT did significantly contribute to the increased erosion observed in this wear test.

The aforementioned analysis does not account for the erosion caused by doubleionized xenon. The ratio of the double-to-single ion current ratio near the DCA is unknown. Traditionally, the measured double-to-single ion currents in the plume have been used to estimate the double-to-single current ratio inside the engine. A range of values has been measured in the plume of the NSTAR thrusters for the double-to-single ion current: 0.02-0.34.^{117,166,238} A doubly-charged ion would carry a charge of twice the singly-ionized xenon ion and would therefore be accelerated to twice the energy for a given electric field. The double-to-single current ratio is converted to a number density for each species taking into account that the double ion current accounts for each double ion twice, illustrated by the factor 1/2 in Eqn. 9-31. For a double-to-single current ratio of 0.25, the number densities would be multiplied by 80% and 10% for singly-ionized xenon and doubly-ionized xenon number densities, respectively. This value does not total 100% because the double ions contribute twice the current per particle. The double-tosingle current ratio of 0.25 will be used because it represents measured values in the plume at the high-power range of the NSTAR throttling table.¹⁶⁶ The equations listed below were used to convert the number density measurements to double and single number densities used to calculate flux in the erosion calculation.

$$n_{i,total} = n_{i,single} + n_{i,double}$$
 Eqn. 9-29

$$j_{total} = j^+ + j^{++}$$
 Eqn. 9-30

$$n_{i,double} = \frac{1}{2} \left( \frac{j^{++}}{j_{total}} \right) n_{i,total}$$
 Eqn. 9-31

$$n_{i, \sin gle} = \left(\frac{j^+}{j_{total}}\right) n_{i, total}$$
 Eqn. 9-32

The results of inclusion of doubles has a substantial effect on the calculated erosion rate, illustrated in Table 9-2. These calculated erosion rates are decreased slightly compared to the measured wear test erosion rates ~60-70  $\mu$ m/khr, but are of the same order of magnitude. This is somewhat surprising given the uncertainty of the threshold energy and error in the sputtering yield calculations. Because the number densities only increased slightly as the engine is throttled to higher-power, with the plasma potential mappings dependent on discharge voltage, the erosion rate is expected to increase slightly as the engine is throttled to higher-power, based upon erosion due to singly-ionized xenon alone, that TH8 would result in an increased erosion rate compared to TH15.

When the doubly-charged ions are accounted for, the calculated erosion rate increases. The plasma parameters and LIF data suggest that for a measured number density of  $5 \times 10^{11}$  cm⁻³ and local plasma potential of 27 volts at this location outside the double layer, the calculated erosion rate is expected to be closest to actual measured erosion rates if the incident angle (presheath) is approximately 60 degrees based upon LIF velocimetry.^{48,127} For a double-to-single current ratio of 0.25, the calculated erosion rate from Doerner's data is 54 µm/khr and when the keeper is shorted, jumps to 165 µm/khr. This is strikingly close to the ELT estimated erosion rates indicating that the keeper shorting contributed significantly to the accelerated erosion observed.

			Pre-sheath			Through-sheath									
Number density	Plasma potential	Potential at sheath	Vck-cc	Energy	Velocity	Angle	Energy	Velocity	Angle	Eth Normal	Eth (angle)	Ave Erosion Rate [micron /	Doerner Erosion Rate [micron /	Mantenieks Erosion Rate 1 (Eth) [micron /	Mantenieks Erosion Rate 2 (Y) [micron /
[cm^-3]	[V]	[V]	[V]	[eV]	[m/s]	[degrees]	[eV]	[m/s]	[degrees]	[eV]	[eV]	khr]	khr]	khr]	khr]
5.E+11	27	22	6	5	2710	0	21	5565	0	27	27	31	31	0	0
5.E+11	27	22	6	5	2710	30	21	5565	14	27	25	37	37	0	0
5.E+11	27	22	6	5	2710	60	21	5565	25	27	22	54	54	0	0
5.E+11	27	22	6	5	2710	75	21	5565	28	27	21	76	61	91	0
5.E+11	30	22	6	8	3428	0	24	5948	0	27	27	61	61	0	0
5.E+11	30	22	6	8	3428	30	24	5948	17	27	25	79	79	0	0
5.E+11	30	22	6	8	3428	60	24	5948	30	27	20	163	132	194	0
5.E+11	30	22	6	8	3428	75	24	5948	34	27	19	199	156	241	0
5.E+11	27	22	0	5	2710	0	27	6297	0	27	27	106	106	0	0
5.E+11	27	22	0	5	2710	30	27	6297	12	27	26	155	123	186	0
5.E+11	27	22	0	5	2710	60	27	6297	22	27	23	204	165	243	0
5.E+11	27	22	0	5	2710	75	27	6297	25	27	22	227	183	270	0
5.E+11	30	22	0	8	3428	0	30	6638	0	27	27	226	171	281	281
5.E+11	30	22	0	8	3428	30	30	6638	15	27	25	299	212	338	348
5.E+11	30	22	0	8	3428	60	30	6638	27	27	22	447	321	493	526
5.E+11	30	22	0	8	3428	75	30	6638	30	27	20	514	370	565	608

Table 9-2: NSTAR calculated erosion rates based on a double-to-single current ratio of 0.25.

The oscillations of the discharge voltage may also contribute to the erosion rate. The fluctuating discharge voltage would force an oscillating plasma potential structure. Oscillations of  $\pm$  several volts have been observed in ion thrusters demonstrating dependence upon the cathode flow rate. The discharge oscillations will contribute to the DCA erosion as the transient plasma potential shifts above the keeper potential. This would have the same effect as a decrease in the keeper floating potential by an amount equal to the amplitude of the discharge voltage oscillation (1/2 of the peak-to-peak value).

### 9.4 NEXT DCA Erosion Prediction

The analysis of the NSTAR thruster serves as a verification of the DCA erosion calculation. The sputtering yield was found to be very sensitive to incident ion energies at these high number densities. The plasma potential mappings indicated very little change in the plasma potential contours between operating conditions and that the effect of shorting the discharge keeper to cathode is confined in the sheath. A very slight increase in number density with higher-power operation will result in a slight increase in the calculated erosion rate, assuming equivalent discharge voltages.

These results can be applied to the NEXT engine and a predicted erosion rate can be calculated. Because the LM4 engine was restricted to the low to mid-power throttling, number densities and plasma potentials will have to be estimated for the wear test conditions. The plasma potentials for the FMT2 and LM4 thruster demonstrated very little variation in the near-DCA structure. The plasma potentials found outside the double layer were approximately two volts above the discharge voltage. The decrease in the bulk discharge plasma potentials, measured by the floating emissive probe, with increasing input thruster power have been explained by insufficient heater current in this region. To simulate the operating condition of the NEXT wear test, operated at a discharge voltage of 23.5 volts, a plasma potential outside the double layer of 25.5 volts will also be used.¹²⁵ Analysis of the LM4 near-DCA potentials also indicates a double layer parallel to the DCA centerline where the FMT2 near-DCA potentials exhibited curved profiles that would focus ions on the keeper face. This is not accounted for in the present analysis.

Number densities for the FMT2 thruster were found to increase slightly with thruster throttling. However, for first approximation they are constant. The number density just outside the double layer for the highest throttling condition investigated, TOC 34', indicates a value of 5x10¹¹ cm⁻³. Finally the double-to-single current ratio is needed. Williams measured the double-to-single current ratio for both 30-cm and 40-cm engines finding that the ratio increased with discharge voltage for constant discharge current and with discharge current for constant discharge voltage.¹⁶⁶ For a beam current of 3.52 A, and discharge voltage of 24 volts, Williams measured a double-to-single current ratio of 0.18, less than the input value of 0.25 used in the NSTAR erosion calculation.¹⁶⁶ The presheath potential and discharge keeper-to-cathode potential are determined from the LM4 plasma potential contours indicating values of approximately 19 volts and 4.5 volts, respectively.

The calculation of the erosion rate expected in the NEXT wear test is illustrated in Figure 9-6. The expected erosion rate for the wear test condition is approximately the same as for the NSTAR wear tests, assuming that the keeper does not short to common. Doerner's curve-fit indicates an erosion rate of 49  $\mu$ m/khr. The NEXT wear test erosion calculation differs from the NSTAR calculation in two respects. First, the double-to-single current ratio is expected to be slightly smaller. Second, the presheath acceleration is slightly larger leading to larger incident angles. These two factors compete against each other, but the final result is a slightly decreased erosion rate. A similar increase in the keeper erosion is evident for the case of the keeper shorting to cathode common.

However, due to the lower double-to-single current ratio, this increase in erosion rate due to shorting is expected to be less compared to the NSTAR ELT erosion values.

				Pre-sheath			Through-sheath								
Number	Plasma	Potential								Eth	Eth	Ave Erosion	Doerner Erosion	Mantenieks Erosion	Mantenieks Erosion
density	potential	at sheath	Vck-cc	Energy	Velocity	Angle	Energy	Velocity	Angle	Normal	(angle)	Rate	Rate	Rate 1 (Eth)	Rate 2 (Y)
Fame A 21	D.A	D.A.	D.d.	[a]/[	[m/a]	[doorooo]	[0]/]	[ma/a]	[domooo]	[e]/[]	[a]/[	[micron /	[micron /	[micron /	[micron /
[cm^-3]	[V]	[v]	[V]	[ev]	[m/s]	[degrees]	[ev]	[m/s]	[degrees]	[ev]	levj	ĸnrj	ĸnrj	ĸnrj	ĸnrj
5.E+11	25.5	19	4.5	7	3090	0	21	5553	0	27	27	24	24	0	0
5.E+11	25.5	19	4.5	7	3090	30	21	5553	16	27	25	30	30	0	0
5.E+11	25.5	19	4.5	7	3090	60	21	5553	29	27	21	59	49	70	0
5.E+11	25.5	19	4.5	7	3090	75	21	5553	33	27	19	72	58	86	0
5.E+11	28.5	19	4.5	10	3735	0	24	5937	0	27	27	49	49	0	0
5.E+11	28.5	19	4.5	10	3735	30	24	5937	18	27	24	67	67	0	0
5.E+11	28.5	19	4.5	10	3735	60	24	5937	33	27	19	153	121	185	0
5.E+11	28.5	19	4.5	10	3735	75	24	5937	37	27	17	196	145	248	0
5.E+11	25.5	19	0.0	7	3090	0	25	6120	0	27	27	67	67	0	0
5.E+11	25.5	19	0.0	7	3090	30	25	6120	15	27	25	97	82	113	0
5.E+11	25.5	19	0.0	7	3090	60	25	6120	26	27	22	146	122	170	0
5.E+11	25.5	19	0.0	7	3090	75	25	6120	29	27	21	171	140	203	0
5.E+11	28.5	19	0.0	10	3735	0	28	6469	0	27	27	140	115	166	166
5.E+11	28.5	19	0.0	10	3735	30	28	6469	17	27	25	194	149	215	217
5.E+11	28.5	19	0.0	10	3735	60	28	6469	30	27	20	330	249	379	361
5 E+11	28.5	19	0.0	10	3735	75	28	6469	34	27	19	394	294	461	428

Figure 9-6: NEXT calculated wear rated for the wear test condition and assuming a double-to-single ratio of 0.18.

The estimated NEXT keeper erosion rates are considerably less than the observed erosion rate following the NEXT 2000-hr lifetest (114 $\mu$ m/khr). It should be pointed out that there are large uncertainties associated with the calculated erosion rates. The erosion models used are specific to the Xe⁺-Mo system for low energies and serve as the most accurate yield calculations to date. However, yields calculated between the two vary significantly for the same input conditions. In calculating the erosion rates, the formulas used illustrate a severe sensitivity to the number density and modest changes in the plasma potential (of a few volts). The resulting error in the plasma parameter measurements lead to associated errors in the erosion rate calculations.

Even with if accurate near-threshold sputter yields can be determined as a function of the ion angle of incidence, the erosion calculation in this dissertation is

limited by the number of assumptions made. An assumed erosion geometry has been used to calculate the eroded depth of the keeper face. The flux of incident ions has been determined from a number density measurement at a single spatial location. It is likely that the erosion analysis in this dissertation is overly simplistic and a full Monte Carlo simulation or DCA erosion model based on first principles will be required to accurately encompass all the suttleties of the DCA erosion problem.

### 9.5 DCA Erosion Mitigation

With a detailed picture of the discharge plasma structure, it appears as though the DCA erosion is a result of ions (doubles and singles) accelerated across the double layer imparting energies on the order of the drop across the double layer itself plus the fall voltage through the keeper sheath. There are several ways to reduce the DCA erosion. These will be discussed and the feasibility assessed.

Owing to the sensitivity of the potential between the plasma outside the double layer and the keeper (illustrated by shorting the keeper to common), the erosion may be significantly reduced by decreasing the bulk discharge potential (*i.e.*, discharge voltage) or increasing the keeper voltage. The biasing of the discharge keeper will involve a separate power supply complicating the electronics, adding weight, and serving as thruster performance loss. The discharge voltage may not be decreased indefinitely as the voltage must be high enough to efficiently ionize the xenon propellant. The first ionization potential of xenon is 12.13 eV and the second ionization potential is 33.3 eV for reference.²¹⁵ It seems unreasonable to reduce the discharge voltage below the 23.5 volts of the NEXT wear test. It may be possible to change the 3-dimensional double layer geometry such that the axial gradient of potential is further reduced and only a drop in the radial direction (similar to the NEXT potential profiles) exists, which would reduce the flux of ions to the DCA.

DCA erosion may be reduced by selection of a keeper material whose sputtering threshold energy exceeds that of molybdenum. Some potential substitute materials include carbon, beryllium, and titanium. Doerner, *et al.* investigated erosion of molybdenum, titanium, carbon, and beryllium for near-threshold energies. Their results indicate that carbon is measured to erode at a rate of 20 times slower than molybdenum at 50 eV incident ion energy.²¹⁵ Carbon materials, however, introduce another erosion mechanism besides sputter erosion. The chemical erosion yield of carbon due to the formation of volatile CO molecules is approximately 0.4 for the temperature regime in ion thrusters.²¹⁵ The volatile behavior of carbon when exposed to small amounts of oxygen indicates that it may not be a suitable material for the DCA, given the impurities of the xenon propellant and oxides present in the cathode insert itself.

The sputter yields of titanium and beryllium indicate that the larger mass difference for these two materials compared to molybdenum reduces the yields accordingly. For 50-eV ions, titanium sputters about 1.5 times slower than molybdenum, and beryllium sputters about 4.3 times slower.²¹⁵ The selection of titanium or beryllium

as the keeper material would decrease the NEXT erosion rate from roughly 49  $\mu$ m/khr to 32  $\mu$ m/khr (titanium) and 11.4  $\mu$ m/khr (beryllium).

The role of the relatively small current ratio of double-to-single ions (0.25) is illustrated. It is desirable to reduce this ratio as much as possible. The nature of the discharge voltage dependence indicates that doubly-charged ions result from sequential ionization.¹⁶⁶ Decreased discharge voltage and discharge voltage oscillations will reduce the number of doubly-charged ions.

It seems the best way to reduce DCA erosion is to select a keeper material whose sputtering threshold energy is large, but whose chemical yield is small. Titanium and beryllium are two such materials. Maintaining a moderate discharge voltage (as low as possible without sacrificing performance) and reducing discharge voltage oscillations have a double effect of decreasing the potential fields responsible for ion acceleration and reducing the number of doubly-charged xenon ions. Extreme care should therefore be taken to minimize the discharge voltage and discharge voltage oscillations while maintaining adequate performance. Some adjustment to the magnetic field topology of the ion engine will shape the double layer and can reduce the flux of ions to the keeper face. The magnetic field changes between the NSTAR and NEXT thrusters have modified the double layer geometry, which is expected to reduce the NEXT DCA erosion rate.

## **CHAPTER 10**

## CONCLUSIONS

## **10.1FMT2 NSTAR Results**

Symmetric double Langmuir probe, single Langmuir probe, and floating emissive probes measurements were detailed over a two-dimensional spatial domain encompassing the DCA exit plane.

#### **10.1.1 Method Demonstration**

An ion engine internal discharge chamber diagnostic technique has been demonstrated. A series of overlapping stainless steel sheets contained the discharge plasma while permitting two-dimensional movement of the electrostatic probes. The movement was performed by coordination of several different translation tables and a high-speed probe positioning system.

#### 10.1.2 Data Results

Electron temperature magnitudes, 2 - 7 eV, were comparable to those measured by other researchers in electron bombardment discharge plasmas. The bulk discharge electron temperatures (away from the anode wall) ranged from 2-5 eV. Number density contours, with a maximum of approximately  $8 \times 10^{12}$  cm⁻³ on centerline, showed very little variation over the range of operating conditions investigated. Number densities agree with data taken by other researchers. Double probe spatial resolution was shown to be insufficient very close to the DCA forcing the transition to a single Langmuir probe.

The single Langmuir probe results agreed with the double probe, though slightly larger number densities were measured in the DCA plume. This is consistent with the misalignment of the double probe and insufficient resolution near the DCA. The number densities reach magnitudes of  $1 \times 10^{13}$  cm⁻³ inside the plume decreasing dramatically in the radial direction. The axial magnetic field at the DCA greatly reduces the radial electron diffusion creating a high-density, low-plasma potential column emanating downstream of the discharge cathode. The magnetic field establishes a free-standing double layer structure that serves as the boundary between the DCA plume and the bulk discharge plasma. Significant plasma potential gradients were observed in the radial direction. The increase in potential (~10 volts) is on the order of the ionization energy of xenon and may play an important role in the discharge plasma production. The double layer potential may be responsible for the accelerating potential for both single and double ions towards the DCA.

Electron temperatures range from 2 - 4 eV inside the discharge cathode plume and increase a few eV across the double layer. The increase in electron temperature is a result of the acceleration of electrons across the double layer from the low potential

cathode plume region to the high potential bulk discharge plasma. Electron temperatures are highest in the near-anode region, where the accuracy of the electron temperature calculation is reduced due to the low signal-to-noise measured current ratio and the magnetic field further reduces the measured electron saturation current.

Plasma potential measurements inside the discharge chamber of a 30-cm ringcusp ion thruster were presented for several operating conditions *with beam extraction*. The thruster operating conditions investigated correspond to the operating conditions of the JPL Extended Life Test (ELT) in which anomalous discharge keeper erosion was observed. Plasma potential magnitudes are comparable to those measured by other researchers in electron bombardment discharge plasmas and are on the order of a few volts above anode potential away from the cathode plume. The discharge plasma contours are relatively insensitive to the throttling of the engine to higher-power. The plasma potential contours illustrated a clearly defined region of lower potential where the discharge cathode plume resided indicative of a double layer. A minimum potential of approximately 14 V occurs on centerline at the closest axial position to the discharge cathode assembly. The plasma potential abruptly increases with increasing radial distance from the discharge cathode orifice, but increases more gradually in the axial direction.

No potential-hill structures were measured for the operating conditions investigated. The potential increases to 26 - 28 volts relative to cathode common near the anode. The anode was ~ 25 V relative to cathode common during all tests. Unsuccessful attempts were made to analyze the on-axis Langmuir probe data assuming both

Maxwellian and primary electrons, yielding inaccurate results that were extremely sensitive to initial estimate of the fit parameters in the iterative analysis.

As the discharge current and flow rates are increased, the magnitude of the number density plume tends to increase slightly. All number densities measured in the 2D domain fall within the range with values from  $1 \times 10^{10} - 8 \times 10^{12}$  cm⁻³.

#### **10.1.3 Beam/No Beam Comparison**

Discharge plasma data taken *with beam extraction* exhibited a broadening of the higher electron temperature plume boundary compared to similar discharge conditions *without beam extraction*. The change in electron temperature without a beam alters the discharge plasma environment affecting the erosion processes.

#### **10.1.4Cathode Keeper to Cathode Common Short Effects**

Shorting the discharge cathode keeper to common had no noticeable effect on the discharge plasma parameters outside the keeper sheath. Shorting the keeper to common increases the incident energy of ions towards the keeper which may significantly affect the DCA erosion rate. There appears to be no effect on electron temperature of shorting the cathode keeper to the discharge cathode common at the TOC 8 level. The increased acceleration of 4 - 6 volts may be enough (or 8 - 12 volts for Xe III) to account for the

increased erosion in the ELT of the DS1 flight spare without the requirement of a change in the number density and electron temperature.

#### **10.1.5Impact on DCA Erosion**

The plasma potential mappings refute the existence of a potential-hill as the dominant factor in DCA erosion. No potential-hill structures were measured for the operating conditions investigated. The existence of a double layer, formed due to the axial magnetic field near the DCA, may contribute to the DCA erosion. The double layer potential increase is on the order of several volts from the DCA plume to the bulk plasma accelerating electrons to the ionization energy of xenon. The double layer imparts a directed energy to both single and double ionized xenon at moderately large angles of incidence. Combining this acceleration with the acceleration (and angle change) through the keeper sheath the incident ion can obtain energies in excess of the angular dependent sputter threshold of molybdenum.

Given the number densities, electron temperatures, and plasma potentials measured for the FMT2 thruster, the flux and energies of ions accelerated through the DCA were calculated assuming only singly charged ions and for the case of a double-tosingle current ratio of 0.25. The presheath ion angle of 60 degrees was used based upon the plasma potential mappings near the DCA and from the Williams' LIF data. With these inputs, and a normal sputtering threshold energy of 27 eV, the calculated erosion rate from Doerner's Xe⁺-Mo data is 54  $\mu$ m/khr which is similar to the erosion rates

measured in the NSTAR wear tests of  $63 - 77 \mu m/khr$ . Additionally, with the cathode keeper shorted to common, the additional energy resulted in an increase of the calculated erosion rate to 165  $\mu$ m/khr, which is very close to the estimated accelerated erosion rate in the ELT when the keeper shorted to common of 173  $\mu$ m/khr.

The calculated erosion rates are sensitive to the number density, incident ion energy (a function of plasma potentials), the incident ion angle, and the double-to-single current ratio.

## **10.2LM4 NEXT Results**

Two staggered electrostatic probes were used to interrogate both the near-DCA region of the LM4 thruster and a region near the ion optics. Single Langmuir probe, floating emissive probe, and two methods for EEDF measurement have been applied over a wide range of thruster operating conditions. Additionally, the effects of beam extraction and shorting of the discharge keeper to common have been investigated.

#### **10.2.1 Method Improvements**

The discharge plasma is contained by a sheet of stainless steel extending across both regions. The stainless steel sheet is held between two stainless guides mounted to flanges on the discharge chamber wall. The complicated movement at an angle to the radial sweeps has been eliminated by the incorporation of the flanges in the mechanism design.

#### 10.2.2 Data Results

Number densities were presented for the low to mid-power operation of the LM4 thruster illustrating comparable results to the NSTAR thruster. The number densities illustrate a clear plume structure peaked along centerline (up to  $2x10^{13}$  cm⁻³). The near-DCA centerline value was fairly constant at a value of  $1x10^{13}$  cm⁻³ over the operating conditions investigated. Number densities illustrate no dependence upon thruster power level.

Electron temperatures were similar to those measured in the NSTAR thruster. The electron temperatures in the discharge cathode plume are typically 2-4 eV and increase slightly off-axis to 5-7 eV. This increase is caused by the acceleration of electrons across the double layer formed at this location and is confirmed by the electron energy distribution measurements. Outside the off-axis maximum, the electron temperature decreases as the accelerated ions are thermalized. Near the anode wall very high electron temperatures were measured. This may be a real increase due to the sheath formation or double sheath formation on the anode and/or the alumina guiding tube end. This apparent increase in electron temperature near the anode may simply be a result of the decreased signal-to-noise ratio at this location and a small dc offset in the measured probe current.

Plasma potential mappings confirmed the existence of a double layer structure between the discharge cathode plume and the bulk discharge plasma. The double layer structure of the LM4 is more closely aligned in the axial direction near the DCA resulting in a more narrow discharge cathode plume. The axially-aligned double layer may serve to reduce the ion flux on the DCA thereby reducing the DCA erosion rate.

Electron energy distribution functions were measured utilizing two different methods which gave comparable results. The harmonic method was used very close to the DCA, while the Druyvesteyn method (second derivative method) was employed over a much larger spatial domain. Both methods indicated electron energy distributions that are a single hump inside the discharge cathode plume. Across the double layer, the EEDF's become stretched and for some cases a second hump appears due to the accelerated electron population. The two-hump distribution and stretched distributions are thermalized outside of the double layer in the bulk discharge. The resultant bulk discharge distributions become a single hump, but with a high energy tail.

#### **10.2.3 Beam/No Beam Comparison**

Throughout the LM4 investigation, the effects of beam extraction were investigated by simply turning off the high-voltage power supplies. The equivalent mass flow rates and discharge currents maintained equivalent number density profiles with and without a beam. The reduction in discharge voltage without a beam decreased the measured plasma potentials inside the discharge chamber. The electron temperatures with beam extraction were slightly higher in magnitude than the discharge-only values. Examination of the EEDF's highlights more broad distributions as the reason for this electron temperature increase. From the LM4 equivalent mass flow approach and the FMT2 equivalent discharge voltage approach, it is evident that the thruster must be operated at high voltage to encompass equivalent electron temperatures, number densities, and plasma potentials to flight conditions. All of the discharge plasma parameters are important in describing the discharge plasma environment and therefore the DCA erosion mechanisms.

#### **10.2.4Cathode Keeper to Cathode Common Short Effects**

Consistent with the FMT2 investigation, the bulk discharge plasma environment and near-DCA plasma plume are not affected by the shorting of the keeper to common. The effects of this event are contained inside the sheath of the keeper which was not interrogated. This indicates that the major change when the keeper is shorted to cathode common is a slight increase in the acceleration through the keeper sheath, equivalent to the cathode keeper to cathode common voltage without the short. The additional acceleration, of several volts, is significant enough to enhance the DCA erosion.

#### **10.3 Role of Double Layer**

The double layer forms as a free-standing boundary between the discharge cathode plume and the bulk discharge plasma. The double layer is established by the axial magnetic field near the DCA, which reduces radial diffusion across the magnetic field lines and enhances the axial diffusion of electrons. The enhanced axial diffusion serves to smooth out axial structures evident from the distinct discharge cathode column. The double layer potential gradient in the radial direction is approximately 10 volts. This radial gradient is responsible for the acceleration of electrons through the double layer contributing to an effective rise in the electron temperatures off-axis. The double layer potential structure is also responsible for accelerating ions across the double layer with radial velocities towards the DCA causing erosion of the DCA.

#### **10.3.1 Prediction of NEXT DCA Erosion**

The erosion calculation gave no indication that the NEXT DCA erosion would be significantly changed compared to the NSTAR thruster. The measured plasma parameters for the LM4 thruster over the permissible operating conditions indicated very little change in number densities and plasma potentials near the DCA. The number densities are comparable to those measured in the FMT2 and the plasma potentials in the bulk discharge were found to be a function primarily of the discharge voltage. The measured double-to-single current ratio in the NEXT engines for the high-power wear test operating condition (0.18) is less than the ratio for high-power operation of the NSTAR thruster (0.25) further reducing the erosion rate.

The expected keeper erosion rate for the NEXT wear test was calculated based upon the discharge voltage of the wear test, plasma parameters measured on the LM4, the double-to-single current ratio measured by Williams in the NEXT plumes, and a 60 degree presheath angle of incidence. This value was found to be 49  $\mu$ m/khr, slightly less than the calculated NSTAR erosion rate. The measured NEXT keeper erosion rate (114  $\mu$ m/khr) exceeds the observed NSTAR 1000-hr and 8200-hr wear test rates. The fact that the NEXT erosion calculation has missed the increase in erosion rate highlights the overly simplistic nature of the calculation. An erosion model or Monte Carlo simulation may be required.

### **10.4Oscillations**

The discharge plasma oscillations were monitored throughout the FMT2 and LM4 investigations. The engines were operated in spot mode yielding minimal discharge oscillations in voltage and current (maximum of ~10% of nominal value, <5% typical). The magnitudes of the oscillations are small, though oscillations of a few volts may cause an increase in the DCA erosion as the ac component increases the incident ion energy. No attempt was made to measure discharge plasma oscillations.

#### **10.5Future Work**

The mapping of the discharge plasmas of the FMT2 and LM4 thrusters complements the LIF measurements conducted by Williams. It appears as though the potential-hill structure postulated as the cause of DCA erosion does not exist in ion thrusters. Its existence is prevented by the axial smoothing of the magnetic structure near the DCA. The existence of a double layer that supplies directed energies back towards the DCA has been confirmed.

The erosion rate calculations performed in this investigation are based upon very little low-energy sputtering yield experimental data. Furthermore, the universal angular dependence corrections may differ significantly for low-energy erosion. More experimental data on heavy-particle, low-energy erosion as a function of angle of incidence would be invaluable to calculated erosion rates. This added data would offer more accurate sputter yield calculations and therefore more accurate erosion rates. A large variation in threshold energies and sputter yields are available based upon the semiempirical formulae and experimental data fitting of higher energy sputtering.

The erosion rate calculation used in this investigation is based upon the measured plasma parameters for each thruster and upon the LIF measurements of Williams. From the number density just outside the double layer, a flux was calculated and an assumed presheath angle assigned to give an approximation of the sputtering yield. The presheath energy is added to the voltage fall through the keeper sheath (normal to the surface)

giving a new incident ion energy and angle. A more accurate calculation would involve a Monte Carlo simulation utilizing the measured plasma parameters.

The calculated erosion rate was found to be sensitive to the ratio of double-tosingle current. The ratios used to calculate the NSTAR and NEXT erosion rates were taken from data measured in the plume of the corresponding thrusters. Measurements made downstream of the engine may not be representative of the internal discharge plasma. An accurate measurement of the ratio of double-to-single charged ions made inside the discharge chamber would offer an accurate input to the erosion rate calculation and determine the effect of the doubles on the erosion of the DCA.

The only regions of high plasma (several volts above the discharge voltage) potentials occur in between the cusps near the anode. The emissive probe measurements were set to accurately measure the near-DCA plasma where plasma heating of the probe can be significant. Near the anode, and often in parts of the bulk discharge plasma, the emissive probe heater current is insufficient and the probe floats at a diminished potential. A separate emissive probe mapping of the bulk discharge plasma potential and the inter-cusp region would offer a complete description of the discharge chamber structures in ion thrusters. It is possible that if a significant number of ions are created in these inter-cusp regions of high potential, they may gain enough energy to sputter erode the molybdenum keeper face. A simple modification of the single Langmuir probe circuit would also permit a better examination of the near anode region to confirm or refute the excessive electron temperatures measured at these locations.

It would also be of interest to probe the cusp region of the thrusters. Due to the importance of the magnetic field in shaping the discharge plasma, it is logical that the cusp regions, where electron mirroring occurs, would be important to discharge performance and DCA erosion. The current setup is restricted to regions in between cusps, but modification of the existing method could permit cusp region interrogation.

Finally, the transient components of the discharge plasma have not been investigated in this work. High-frequency, high-amplitude oscillations in plasma potential may exist and should be investigated.

# **Appendix A: Additional FMT2 Plasma Parameter**

## Contours



Figure A-1: DP DL 4b full interrogation region number density mapping.



Figure A-2: DP DL 4c full interrogation region number density mapping.



Figure A-3: DP DL 8a full interrogation region number density mapping.



Figure A-4: DP DL 8c full interrogation region number density mapping.



Figure A-5: DP DL 8d full interrogation region number density mapping.



Figure A-6: DP DL 12a full interrogation region number density mapping.



Figure A-7: DP DL 15b full interrogation region number density mapping.



Figure A-8: SLP TOC 8a full interrogation region electron number density (from electron saturation current) mapping.



Figure A-9: SLP TOC 12 full interrogation region electron number density (from electron saturation current) mapping.



Figure A-10: SLP TOC 15 full interrogation region electron number density (from electron saturation current) mapping.



Figure A-11: DP DL 4c full interrogation region number density mapping.



Figure A-12: DP DL 4b full interrogation region number density mapping.



Figure A-13: DP DL 8a full interrogation region electron temperature mapping.



Figure A-14: DP DL 12a full interrogation region electron temperature mapping.



Figure A-15: DP TOC 12 full interrogation region electron temperature mapping.



Figure A-16: DP SL 15b full interrogation region electron temperature mapping.



Figure A-17: SLP TOC 8b full interrogation region plasma potential contour.



Figure A-18: SLP TOC 8 with discharge cathode keeper shorted to cathode common full interrogation region plasma potential contour.

# **Appendix B: LM4 Additional Contours**



Figure B-1: LM4 HEEDF DL 8 illustrating the electron energy distributions as a function of bias voltage. Each plot represents various radial spatial locations at the same axial distance from the DCA.



Figure B-2: LM4 HEEDF DL 18 illustrating the electron energy distributions as a function of bias voltage. Each plot represents various radial spatial locations at the same axial distance from the DCA.



Figure B-3: EEDF's for various spatial locations as a function of probe bias voltage with respect to cathode common at DEEDF TOC 3.



Figure B-4: EEDF's for various spatial locations as a function of probe bias voltage with respect to cathode common at DEEDF TOC 32.



Figure B-5: EEDF's for various spatial locations as a function of probe bias voltage with respect to cathode common at DEEDF TOC 20'.
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