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Review of the EP Activities of US Academia

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Review of the EP Activities of US Academia

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Abstract

A review of electric propulsion (EP) research activities at academic institutions throughout the United States is presented. The research presented here encompasses experimental, computational, and theoretical investigations of a wide variety of electric propulsion devices as well as the development of new electric propulsion systems. This work is both broad in its scope and deep in its quest for knowledge. Academic research in electric propulsion contributes not only by being an educational tool to train graduate and undergraduate students, but also by being an important fundamental research component that complements government and industrial efforts. This article reviews electric propulsion research activities at Colorado State University, Massachusetts Institute of Technology, Princeton University, Stanford University, Texas Tech University, University of Illinois at Urbana-Champaign, University of Michigan, and Worcester Polytechnic Institute.

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There is an interest in probing interstellar space as part of the NASA Origins Program. The Ion Propulsion Interstellar Precursor Mission, which is an example of such a probe, would have 100 kW of power available for travel to 250 AU in 10 years. With an optimum specific impulse of ~14,000 sec. and krypton as the proposed propellant, a net accelerating voltage of 13 kV is required. This is an attractive operating regime for ion propulsion, but it is one that has not received much research attention.

In order to assure proper operation over the long operating lifetime required, a study of ion thruster grids in the required operating regime has been initiated. After completing preliminary numerical modeling of the grids, nineteen-hole grid-segment arrays that model proposed grid designs are being subjected to experimental study. The effects of screen and accel grid geometrical factors (hole diameter, thickness and spacing), grid voltages and beam currents on ion beamlet focussing, non-charge-exchange ion impingement current and electron backstreaming phenomena are being measured. One interesting result is that the magnitude of the accel voltage required to prevent electron backstreaming is about the same for conventional, low-specific-impulse ion thrusters and the high-specific-impulse ones under investigation.

Results are showing that the OPT code used to establish a preliminary grid design does not adequately describe phenomena that are being observed experimentally. A new code written by Yoshinori Nakayama appears to be more accurate. A paper that describes the code[1] will be presented at this conference.

As mission requirements on ion thruster lifetime increase, concern about grid sputter erosion damage also increases. One way of improving grid lifetime would

Associate Professor, Associate Fellow AIAA.

involve ion implantation as a final step of grid fabrication. Molybdenum and titanium grid materials are being implanted using nitrogen and carbon as the implant elements. In order to achieve the needed treatment depth at a reasonable cost, the implantation is being done at a high current density and at an elevated temperature where implanted species diffuse substantially beyond their ballistic implantation depths.

The processing is most cost effective at the highest possible implantation temperature where diffusion rates are greatest, and for both Mo and Ti this is about 850 °C. Beyond this temperature an α-β phase change induces unacceptable warpage in Ti and recrystallization induces unacceptable brittleness in Mo. In order to effect treatment of most of the grid thickness and also to prevent grid warpage it appears that both sides of a grid would have to be implanted simultaneously. Results suggest that a 50% reduction in the sputter yield of Ti can be accomplished by implanting it with C. A lesser reduction in yield (~30%) is observed when N is implanted into Ti and when C is implanted into Mo. The smallest reduction is observed when N is implanted into Mo (~15%).

Reference

1. Nakayama, Y. and P. J. Wilbur, "Numerical Simulation of Ion Beam Optics for Many-Grid Systems" Paper AIAA-2001-3782.

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During the past year, our group has been active in Hall thruster theory, colloid propulsion, electro-dynamic tethers, and preparation of a Shuttle-based interactions test. We have also completed theoretical work on a seeded arcjet. A few highlights follow:

J. Szabo completed his Doctoral work in which he developed an advanced PIC code that treats electrons as particles and allows calculation of their distribution function. Several special numerical procedures were introduced to handle the wide disparity of time scales present. The electron distribution is seen to be fairly anisotropic, but close to Maxwellian if the directions along and across **B** are examined separately.

In preparation for time-of-flight studies of colloid sources, P. Lozano demonstrated the electrostatic refocusing of an electrosprayed beam with an initial divergence angle of 17 degrees. A novel apparatus combining ToF and energy analysis capabilities for the study of mixed ion/droplet beams has been designed and built.

L. F. Velasquez completed the design and first build of a novel micro-fabricated colloid engine with 121 emitters, each 8 microns in diameter. The emitters are linearly arranged at the interface of two Silicon wafers, and occupy a linear dimension under 1.5 cm.

A study by J. Reichbach compared several micro-propulsion options for a number of active or planned missions. Colloid, FEEP and PPT all were found to be optimal depending on the specifics of the mission.

D. Robertson completed his Doctoral study of the physics and applicability of a Cesium-seeded Hydrogen arcjet. A wide stable range is predicted, in which Cesium is fully ionized, but Hydrogen remains diatomic and neutral, thus ensuring a high efficiency. A mission study indicates that this propulsion option would outperform all others for time-limited missions, such as LEO-GEO transfer of communications satellites.

New programs have been started on Hall thruster engine and plume modeling. The former is focused on high specific impulse regimes, and will use a combination of our new PIC code and a new plasma and gyro-averaged code being developed by Dr. O. Batischev. The plume effort aims at examining complex geometries, such as whole spacecraft with EP thrusters or multiple spacecraft, and also at improving the physical description of both, plasma and surface-plasma interactions.

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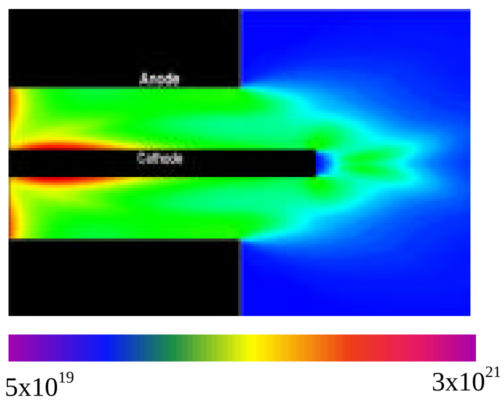
Measurements of the current sheet canting angle in electromagnetic PPTs for eight different propellants (including methane) are presented in Ref. [1] using optical, interferometric diagnostics and magnetic probes and showed an inverse dependence on the atomic mass implicating a possible role for Hall and ion conduction behind canting. The concept of using UV light to initiate uniform current sheets in PPTs is studied in Ref. [2] using a YAG laser and a potassium photocathode. A miniaturized ablative Z-pinch PPT was developed based on the performance improvements prescriptions developed in Ref. [3] that allow scaling of performance to thrust/power ratios as high as 30 μN/s by increasing the propellant height-to-inner diameter ratio.

A study of energy partitioning in the lithium Lorentz Force accelerator (Li-LFA) is being conducted using a

30-kWe thruster developed at the Moscow Aviation Institute. In Ref. [4] the focus is on performance characterization using an inverted pendulum thrust stand. The details of the development, calibration and integration of a high-accuracy lithium mass feeding system is discussed in Ref. [5].

A two-temperature fluid code[6], with a real equation of state and anomalous transport for simulating plasma thrusters has successfully predicted many salient features (see Fig. 1). This code is now being adapted for parallel computers.

Numerical Simulation



Observed Ion Emission

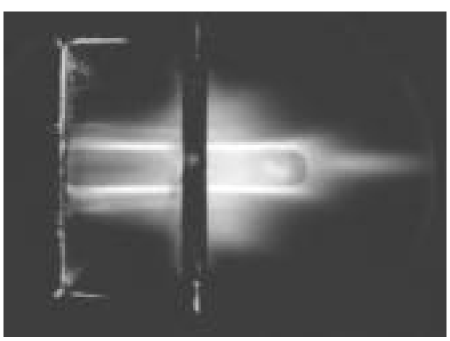


Fig. 1 Results (top) of the new numerical simulation code at Princeton showing the calculated charged particle density pattern in an MPDT compared to observed ion emission (bottom).

A systems level trade-off study has been performed [7] for the Terrestrial Planet Finder (TPF) mission for three architectures (free-flyer, monolithic and tethered) using one of 5 types of thrusters (Hall, APPT, AZPPT, GFPPT and FEEP). Using a low-power Hall thruster with a tethered configuration was found to yield the most competitive option (initial mass below 3200 kg).

A newly discovered ion acceleration mechanism that occurs naturally in the ionosphere has been studied theoretically using a Hamiltonian representation of the interaction between two beating electrostatic waves and a magnetized ion. The study (to be presented at the 2001 IEPC) is guiding the design of an experiment that evaluates the merit of this mechanism for propulsion.

A numerical investigation [8] of supersonic radiative energy addition in a two-stage microwave electrothermal thruster showed that a toroidal plasma forms in the supersonic section and can lead to a 55% increase in the thermal efficiency. The code is being used to build an experimental thruster.

The final results [9] from neutral gas injection in the ionosphere from a spacecraft using a Hall thruster in a no-discharge mode show that lower hybrid waves can explain much of the wave and particle activity observed during the releases.

The fundamental difference between the SPT and TAL variants of the Hall thruster is shown [10] analytically to be related to the secondary electron emission coefficient of the walls which controls the electron energy flux to the walls and affects the spatial extent of the accelerating potential.

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Fundamental issues of Hall thrusters are explored at PPPL, including the control of the accelerating electric field, plasma instabilities in the acceleration region, and scaling limitations for low-power applications. As a part of these efforts, we proposed, developed, and studied a number of non-conventional Hall thruster configurations including a segmented electrode Hall thruster and a cylindrical Hall thruster.

The segmented electrode Hall thruster uses emissive or low-emissive electrodes to localize the electric field in the region of the focusing concave magnetic field. Such a localization of the acceleration region with an increased axial electric field should reduce both plume divergence and power losses, thereby increasing the lifetime of Hall thrusters. We have reported a reduction in plume divergence through the use of low-emissive segmented electrodes.

To understand better this effect, a series of comprehensive probe measurements of plasma potential and electron temperature inside the thruster channel was conducted during the last year. These studies were facilitated by the successful development of a high-speed probe actuation system and low-sputtering segmented electrodes, which gave reliable and reproducible thruster operation and measurements. Recent results demonstrated that a single low-emissive segmented electrode, which is placed on the inner channel wall near the channel exit, shifts most of the voltage drop to upstream of the channel exit. The plume divergence reduction in this thruster configuration is most likely associated with the concave focusing magnetic field distribution in the discharge chamber compared to conventional thrusters that have a significant portion of the voltage drop outside the thruster channel. We believe this promising design methodology can be implemented on commercial Hall thrusters readily.

Our interest in the cylindrical Hall thruster stems from the fact that this configuration has a larger channel volume-to-surface ratio than conventional coaxial thrusters. As such, the cylindrical Hall thruster should have lower wall losses and, as a result, reduced erosion of the channel and decreased heating of the magnetic circuit. These issues are, in particular, critical for micro-Hall thrusters. A set of experiments with a 9-cm-diameter laboratory-model cylindrical Hall thruster illustrated the importance of having a cusp magnetic field distribution in order to obtain performance comparable with coaxial Hall thrusters at sub-kilowatt power levels. The important feature of this thruster is its quiescent operation over a broad range of input parameters and the absence of low-frequency discharge oscillations. A scaled-down 3-cm-diameter cylindrical Hall thruster has been recently operated successfully at the power range of 50-300 W. This engine was observed to bifurcate into two operating regimes, with an abrupt transition from quiet and stable operation to unsteady operation.

Recent Publications

1. Y. Raitses, L. A. Dorf, A. A. Litvak and N. J. Fisch, *Plume reduction in segmented electrode Hall thruster*, Journal of Applied Physics **88** (3), 1263--1270 (August, 2000).
2. N. J. Fisch, Y. Raitses, L. A. Dorf and A. A. Litvak, *Variable Operation of Hall thruster with Multiple Segmented Electrodes*, Journal of Applied Physics **89** No. 4, 2040--2046 (February, 2001).
3. Fruchtman and N.J. Fisch, Variational Principle for Optimal Accelerated Neutralized Flow, Physics of Plasma **8**, 56--58 (January, 2001).
4. Fruchtman, N.J. Fisch, and Y. Raitses, *Control of the Electric Field Profile in the Hall Thruster*, Physics of Plasma **8**, 1048--1056 (March, 2001).
5. Litvak and N. J. Fisch, *Resistive Instabilities in Hall Current Plasma Discharge*, Physics of Plasma **8**, 648--651 (February, 2001).

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Research at Stanford University is aimed at developing an understanding of crossed-field electron migration in Hall thrusters [1]. Using extensive measurements of the time-averaged plasma properties in the discharge channel, including laser-induced fluorescence measurements of neutral and ionized xenon velocities and various electrostatic probe diagnostics, the Stanford team is able to determine the effective Hall parameter, $(\omega\tau)_{eff}$, the inverse of which is a measure of the crossed-field electron mobility. These values are then compared to the classical (collision-driven) Hall parameters expected for a quiescent, magnetized plasma. The results indicate that in the vicinity of the anode, where there are fewer plasma instabilities, the electron transport mechanism is found to be in agreement with a "classical" model based on elastic electron collisions with the background neutral xenon. However, they find that in the vicinity of the discharge channel exit, where the magnetic field is the strongest and where there are intense fluctuations in the plasma properties, the inferred Hall parameter departs from the classical value. While it is found to be closer to the Bohm value of $(\omega\tau)_{eff} = 16$, the results are also found to be strongly dependent on the electron shear rate, α, as shown in Fig. 2. These results provide support for a simple model for the Hall parameter (and hence electron mobility or conductivity) that is based on the scalar logarithmic addition of the fluctuation (Bohm) – induced electron mobility and its reduction due to shear, and this model is now being integrated into Hall thruster simulations. While the exact mechanism for this shear-flow induced reduction in the mobility is not yet well understood, the results draw attention to the possible role that shear flow has on reducing turbulent fluctuations in plasma density in the near exit region of the discharge.

Researchers at Stanford University are also continuing their investigation of a linear-geometry Hall thruster with an open electron-drift [2]. The performance of the original linear-thruster prototype has been verified by direct thrust measurements and by laser-induced fluorescence velocimetry. The thruster produced 3 mN of thrust at 14% efficiency, at non-optimum operating conditions. A second linear-thruster, incorporating design improvements to the gas-injection system, anode, and magnetic circuit, can operate at high specific-power and higher efficiencies for longer periods of time. A time-resolved ion-plume study of this thruster shows propellant-utilization over 80% and "breathing" oscillations identical to those of co-axial Hall thrusters.

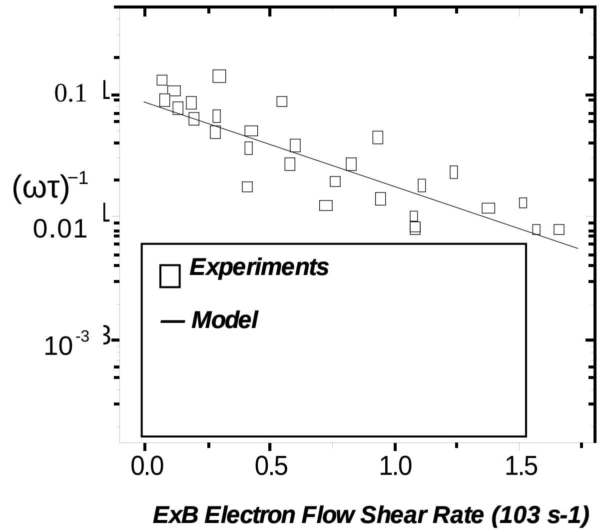

Fig. 2 Comparison of additive collision frequency model to experimental and classical inverse Hall parameter profiles at various axial locations within the discharge channel. The exit plane is at an axial location of x = 0 mm, and the anode is at x = -80 mm.

In order to understand transport and ionization mechanisms in Hall thrusters, the Stanford team has also developed a model for the electron energy distribution function (EEDF) in the channel, based on a numerical solution of a zero-dimensional Boltzmann transport equation. This model, which considers elastic and ionizing collisions, and electron loss to the insulator channel, is used to study inelastic processes in the plasma. Secondary electrons from ionizing collisions and wall-loss collisions are also included. The model takes experimentally determined plasma parameters as inputs and returns the EEDF and the wall-sheath potential at each point in the channel. The model examines the impact of the experimentally-determined electron mobility (described above) on the evolving EEDF within the channel. An important finding from these numerical studies is that wall loss collisions are insignificant to cross-field electron transport. The wall-sheath potentials and resultant wall-loss rates, calculated from local electron conservation, generally agree well with simple charge-balance models, except where this model predicts sheath collapse. The EEDF model, in conjunction with new experimental data and/or simulation results, will be used to investigate novel thruster wall materials.

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Electric propulsion research at Texas Tech University has been in two areas. The first is low-cost higher performance power processing and control for electric propulsion devices (both Hall and gridded ion thrusters). This research has been focused on improving PPU topologies by reducing complexity and increasing reliability. Novel operating schemes have also been explored to reduce the number of required supplies and switches.

Another area of research has been the development of a low-power TAL Hall effect thruster. The goal of this research is to determine scaling properties for low-power operation of TAL thrusters and limitations of materials and magnetic circuits required for operation. A laboratory model TAL, shown in Fig. 3, has been built and successfully operated at power levels from 50-1000 W.

During the design process, a full 3-D magnetic field simulation was used to optimize the magnetic field profile and magnetic circuit. The results of these simulations were verified with magnetic field strength recordings within the thruster volume. In addition, thermocouples were placed in the magnetic field coils and on all magnetic field components to obtain temperature profiles at various operating points. These data will be used to more accurately assess the required material properties of the magnetic field coil wire and magnetic circuit components.

The thruster and PPU testing was conducted in TTU's cryo-pumped vacuum facility, shown in Fig. 4. The test chamber (>20 m^3 volume) has a base pressure of $1x10^{-8}$ Torr and can maintain an operating pressure of $5x10^{-6}$ Torr at low to medium thruster power levels (50-500 W).

Fig. 3 Low-power TAL.

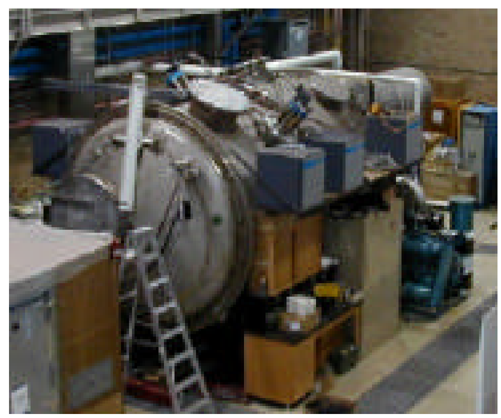

Fig. 4 TTU vacuum facility.

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Research is being performed in several areas concerning pulsed plasma thruster operation and diagnostics. PPT-10 is a coaxial, low mass, electrothermal, breech-fed PPT with a conical Teflon™ fuel cavity and a centrally located Unison spark plug (Fig. 5). Performance characteristics are investigated with diagnostic measurements including thrust, specific impulse, current, capacitor voltage, and mass loss. PPT-10.1 is a coaxial electrothermal breech-fed thruster with an improved geometry, producing a higher electromagnetic thrust fraction, β. It has a high, shot-to-shot repeatability and is currently being developed to produce an impulse bit of 25mN-s/J at a specific impulse of 1000 s.

PPT-7 is a coaxial electrothermal thruster with a cylindrical Teflon™ fuel chamber in a rectangular housing designed to investigate the effects of geometry and energy on performance.[1] Geometric variables include the length of the exposed fuel and diameter of the fuel chamber, the shape of the nozzle and taper angle of the fuel chamber. The capacitor energy is also varied to determine the optimum level. The thruster is fired using a nozzle-mounted, semiconductor spark plug and mica capacitors. Diagnostic measurements including current, capacitor voltage, thrust, mass loss and temperature are used to estimate thruster efficiencies and performance. Thermal modeling as well as thrust measurements away from the baseline were performed. For the baseline design using a 35-mm-long cylindrical chamber with a 14-mm-diameter nozzle fired at 50 J, the average specific thrust is 36 μN-s/J at a specific impulse of 450 s. The measured data agree well with a Two-Stream model of PPT operation.[2]

Fig. 5 PPT-10.

Herriot cell interferometry is being performed in conjunction with the Air Force Research Laboratory (Fig. 6). Introduction of a Herriot cell to a quadrature heterodyne interferometer increases the signal to noise ratio for both electron and neutral density measurements, without sacrificing spatial resolution of the system. System evaluation has been performed on both parallel plate and coaxial PPTs. Currently the system has been upgraded to use two laser frequencies for separation of electron and neutral densities during the thruster pulse. Combining this with the Herriot cell allows measurement of both electron and neutral densities on AFRL microPPTs. Advantages of this non-intrusive technique also include insensitivity to EMI. These data are being used to explore spacecraft contamination issues and validate modeling efforts.

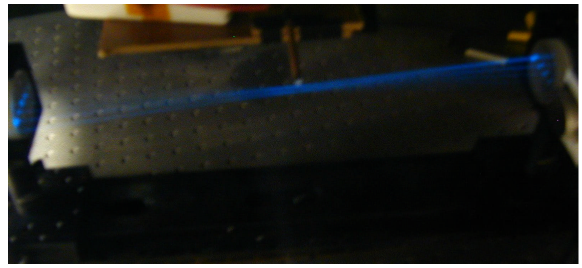

Fig. 6 Herriot cell inteferometry.

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Our research involves the development of advanced computer models for plasma and gas flows of electric propulsion (EP) systems. We are developing models of EP devices to aid in thruster design and to assess lifetime issues. We are also developing models of the plumes from EP devices partly to validate the device models, but also for assessment of spacecraft integration issues. Our research is sponsored by AFOSR, NASA Glenn Research Center, the Air Force Research Laboratory, the TRW Foundation, the Aerospace Corporation, and DOE. A brief summary of our current work is given below.

Pulsed Plasma Thrusters

a) A kinetic model of the Teflon™ ablation process created by a discharge plasma was developed that uses a multi-layer approach. Previous modeling had assumed the ablation occurs into vacuum. See Refs. 1 and 2 for details.
b) The performance of the AZ-PPT developed at Princeton University was modeled by modifying our previous model of an electro-thermal PPT. The model was subsequently used to identify optimized configurations for the AZ-PPT [3].
c) Plasma acceleration in the oscillating electromagnetic field of a micro-PPT developed at AFRL was modeled using a particle approach [4].
d) A model was developed to try to explain charring of the Teflon propellant face observed experimentally on micro-PPT's developed at AFRL [5]. Figure 7 shows a comparison of the model prediction of Teflon ablation rate with a photograph of the charred propellant face.

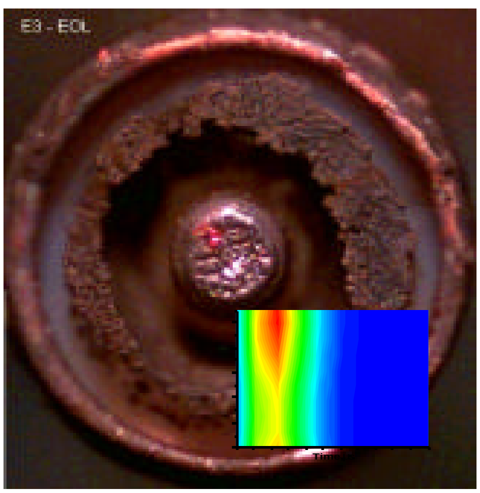

Fig. 7 Charring on the propellant face of a micro-PPT (contours show predicted ablation rate as a function of radius (x) and time (y) with blue being the lowest rate).

Hall Thrusters

a) A 2-D, unsteady model of the acceleration channel and near-field plume is under development [6,7] to simulate the P5 Hall thruster.
b) Effects of new elastic collision cross sections on the plume of the BPT-4000 Hall thruster was studied in collaboration with SAIC and AFRL [8].
c) 2-D presheath structures in the acceleration channel were modeled using a hydrodynamic approach [9].
d) A review of measurements, computational methods, and theory was conducted for sputtering of spacecraft materials by xenon ions [10].

Ion Thrusters

a) Grid optics analysis software is being developed for NASA Glenn Research Center [11].
b) Analysis of the UK-T5 triple-grid optics was completed [12].
c) A preliminary model was developed to describe the plume from a hollow cathode [13].

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Over the past year, the Plasmadynamics and Electric Propulsion Laboratory (PEPL) has conducted a wide array of electric propulsion research activities that were sponsored by the AFOSR, NASA Glenn Research Center, NASA Marshall Space Flight Center, and The Michigan Technic Corporation. Graduate student support was provided by the Air Force Palace Knight Program, the Department of Energy, and the National Science Foundation. PEPL also participated in the qualification processes of commercial Hall thrusters. A summary of our work follows.

- Use of a high-speed reciprocating probe system (HARP), with a discharge chamber residence time <100 msec, to measure Te, Ne, vacuum and thruster-on magnetic field, plasma potential, and Hall current within the discharge chamber of the P5 Hall thruster (AIAA-2001-3507). Through the use of HARP we have been able to provide unprecedented insight on the acceleration and ionization mechanisms present in closed-drift Hall thrusters.
- Our P5 Hall thruster was operated at low voltage (100-150 V) to serve as a plasma source for emulating the ionosphere for the evaluation of bare-wire electro-dynamic tether (EDT) configurations (AIAA-2001-3337).* This technique captured many of the voltage-current characteristics observed in space on Shuttle flights.[1]
- We are continuing our work on Field Emitter Array Cathodes (FEACs) for small EP thrusters and EDTs. We tested a 50,000-tip FEAC from SRI, Inc. at $3x10^{-8}$ Torr in preparation for future tests at elevated pressures and in a tenuous plasma.*
- We are initiating a proof-of-concept test of our Two-Wavelength Simultaneous Laser Induced Fluorescence (TWS-LIF) technique for characterizing Hall thruster discharge chamber erosion
- We increased the xenon pumping speed of the 6 m by 9 m Large Vacuum Test Facility (LVT) from 140,000 l/s to 245,000 l/s by installing three internal cryopumps.
- Utilizing a state-of-the-art 3-D magnetic field code, we were able to design and build the two-stage P5-2 Hall thruster and the Linear Gridless Ion Thruster.† The P5-2 (IEPC-01-36) utilizes a LaB_6 emitting electrode while the LGIT (AIAA-2001-3649) uses a hollow-cathode in its ionization stage.
- We studied the effects of chamber pressure on Hall thruster performance and plume measurements with our P5 Hall thruster.
- In collaboration with the Air Force Research Laboratory and Busek, we have initiated a program to investigate issues associated with clustering Hall thrusters.
- We performed near-field and internal laser-induced fluorescence measurements of an NSTAR-derivative ion thruster (see Highlight below).

Research Highlight: LIF Investigation of Ion Thruster Discharge Cathode Assembly Erosion

NASA-supported research at the PEPL has focused on investigating Discharge Cathode Assembly (DCA) erosion using laser-induced fluorescence (LIF). An NSTAR-derivative, 30-cm ion thruster was modified to provide optical access for this investigation. We have performed three-component LIF ion (Xe II) velocimetry and have successfully interrogated Xe, Mo, and W neutral species as well.

Tungsten LIF data taken across the face of the unkeepered discharge cathode corresponded well with erosion patterns observed after the 2000-hr NSTAR wear test. LIF measurements made with Mo also corroborated erosion patterns observed in an 8200-hour test with a keepered DCA. Maps of neutral and singly-ionized xenon particles downstream of the keepered and unkeepered cathode allowed for a physical portrait of the erosion processes to be rendered. Such a portrait is shown as Fig. 8 for a keepered DCA.[2] Here the zones of ion production and convection are illustrated on the basis of LIF measurements.

By combining ion energy distributions measured by LIF, estimated cathode/keeper sheath potentials, and W/Mo sputtering data, one can determine if Xe II impingement alone can account for the W and Mo erosion observed in the 2000-hr and 8200-hr wear tests, respectively. Figure 9 shows the Xe II number densities required to produce the erosion of the Mo keeper observed in the 8200-hr wear test as a function of incident ion energy and angle. The shaded box represents a conservative estimate of the range of number densities and energies expected/measured in the near-DCA region of the ion thruster. While Xe II can account for the observed erosion, tests are planned to conduct LIF sweeps for Xe III near the DCA and just downstream of the ion optics, and to use HARP to

***** *In collaboration with Professor Brian Gilchrist of the Electrical Engineering Department at The University of Michigan*

† ***Patent Pending***

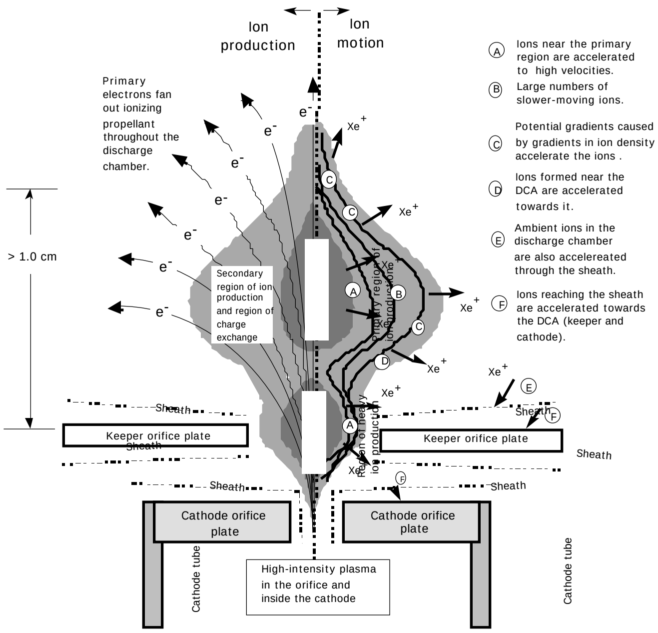

Fig. 8 Schematic of proposed Xe II acceleration mechanisms for keepered operation (from Ref. 2).

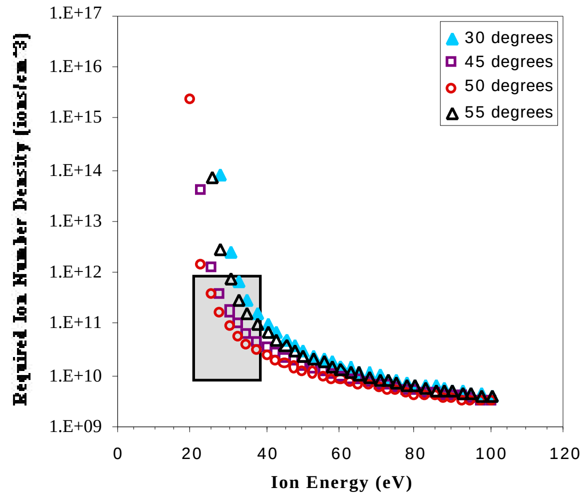

Fig. 9 Xe II number densities required for discharge cathode keeper erosion observed in 8200-hr wear test (Ref. 2).

make internal and near-field plasma density and plasma potential measurements. NASA Glenn Research Center supports this work under grant NAG3-2216 (J. Sovey and M. Patterson monitors).

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2. Williams Jr., G. J., The Use of Laser-Induced Fluorescence to Characterize Discharge Cathode Erosion in a 30 cm Ring-Cusp Ion Thruster, Ph.D. Thesis, Dept. of Aerospace Eng., The University of Michigan, September 2000.

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The University of Southern California nano-Newton, torsional thrust stand has been optimized for operation with several micropropulsion concepts currently being developed. Overall, a design approach was taken that would develop a tool that was simple to construct, operate and maintain. Figure 10 shows a picture of the thrust stand in its current operational configuration. The thrust stand arms shown in Fig. 10 are approximately 25 cm long from the center of rotation, and the stand is symmetric in terms of mass distribution about the pivot point. The present method for detecting angular deflection is to measure a linear displacement at a known radial distance using a linear voltage differential transformer (LVDT). As micro- and nano-Newton thrust levels are approached, the effects of the connections of a thrust stand mounted thruster to its supply infrastructure become increasingly difficult to mitigate. A series of liquid baths are employed to eliminate direct propellant feed and electrical connection to the thruster. In initial tests, a thin walled, 1.0 mm diameter sonic orifice was studied operating in a free molecule regime.[1] Figure 11 shows the thrust stand deflection as a function of the orifice stagnation pressure. The lowest measured thrust value was 103 nano-Newtons with an accuracy of approximately ± 20% based on the repeatability of the measurements. These results were obtained for steady-state operation of the sonic orifice. Over the range of stagnation pressures investigated, free molecule (FM) analytical results were used to determine the thrust. The FM results have been validated using high-fidelity direct simulation Monte Carlo (DSMC) numerical modeling.[2] The results have also been investigated as a function of the facility's background pressure. It has been demonstrated that the details of the facility interaction with the thrust stand are critical in accurately determining extremely low thrust levels.[3]

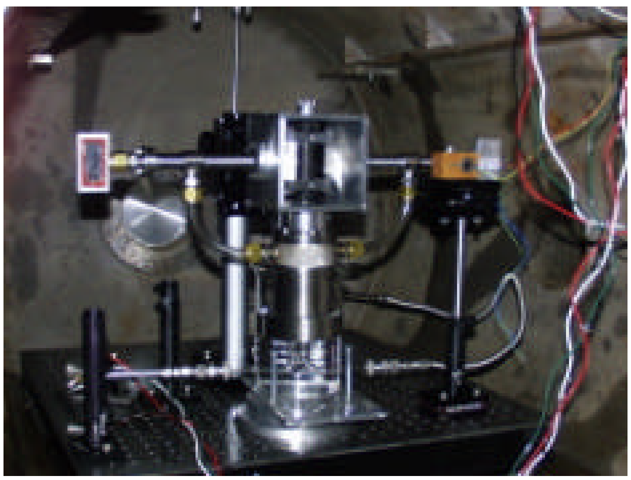

Fig. 10 USC nano-Newton torsional thrust stand.

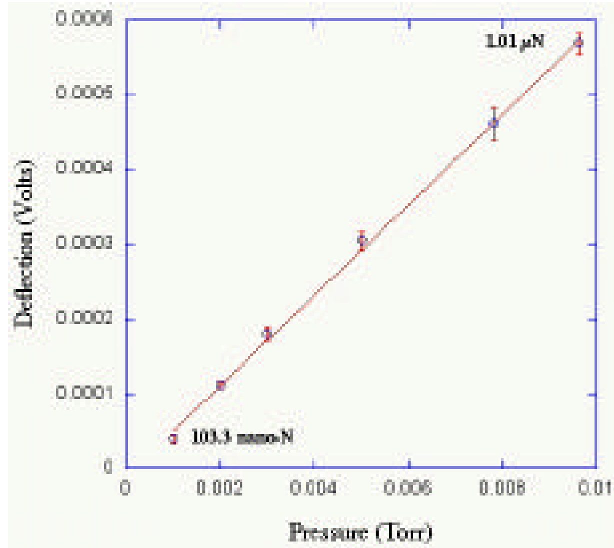

Fig. 11 Thrust stand deflection as a function of orifice stagnation pressure. The minimum thrust measured was 103 nN±20%.

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2. Alexeenko, A., Levin, D., Gimelshein, S., Ivanov, M., Ketsdever, A., "Numerical and experimental study of orifice flow in the transitional regime," AIAA paper 2001-3072, 35th AIAA Thermophysics Conference, Anaheim, CA, June 2001.
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Research at WPI was sponsored by NASA Glenn Research Center, the Massachusetts Space Grant Consortium, and AFOSR. Research activities encompass experimental investigations, plume and device modeling, design of a Shuttle-based electric propulsion experiment and modeling of space jet experiments. A summary of WPI's research projects follows.

Modeling of Pulsed Plasma Thruster Plumes

WPI has been developing an advanced hybrid (particle/fluid) 3-D computational PPT plume model in order to evaluate potential plume/spacecraft interactions. The code uses unstructured grids and allows spacecraft/thruster geometries to be included. The code uses the Direct Simulation Monte Carlo (DSMC) and a Hybrid-Particle-in-Cell (hybrid-PIC) method. Electric fields are obtained from a Poisson formulation. (IEPC Paper 01-160).

Triple Langmuir Probe Measurements in the Plume of a Teflon Pulsed Plasma Thruster

Along with the computational efforts WPI has been working with NASA GRC on the experimental investigation of PPT plumes. Our recent TLP experiments were conducted in a large vacuum facility. TLP measurements were obtained from the thruster centerline out to the backflow regions on two planes perpendicular and parallel to thruster electrodes. The TLPs were operated using a current-based method (AIAA Paper 2001-3258).

Quadruple Langmuir Probe Measurements in the Plume of a Teflon Pulsed Plasma Thruster
A Quadruple Langmuir probe was designed and used to measure ion axial velocity to thermal speed, electron temperature and density in the plume of a laboratory model PPT. This experiment was performed in a large vacuum facility at NASA GRC. Measurements were taken on planes parallel and perpendicular to the thruster electrodes, from the exit plane to 20 cm downstream, and at angles of 0-180 degrees (IEPC Paper 01-158).

Modeling of Plasma Microthrusters
The research will address fundamental mathematical and computational issues in plasma micro-flows and is aimed at optimizing the performance of micro-PPTs an order of magnitude smaller than current designs. The code under development uses concepts of DSMC, PIC and hybrid methodologies on unstructured grids with adaptation. Code validation results for cold-gas microthrusters and MEMS microthrusters are presented in AIAA Paper 2001-2891. Plasma microthrusters are presented in IEPC Paper 01-229.

Probabilistic Failure Analysis of Ion Thrusters
Determining service life and predicting failure modes using probabilistic methods is important for proper thruster design and integration on the spacecraft, without the need of excessive physical tests. We present results from a code designed to improve the calculation of probabilistic failure analysis of ion thrusters. The code is applied to failure analysis of the accelerator grid due to screen erosion from ion impingement (IEPC-01-78).

Electric Thruster Environmental Effects Verification experiment (ETEEV)
The Electric Thruster Environmental Effects Verification experiment (ETEEV) is designed to obtain in-space measurements in the plume and backflow regions of low-power thrusters. The ETEEV design is lead by MIT, WPI and Draper, and includes other government organizations. The ETEEV payload will be mounted on a Hitchhiker-palette onboard the Shuttle and will use plasma diagnostics mounted on the palette as well as an articulating boom. (IEPC-01-43)

Modeling of Plasma Jet/Ambient Plasma Interactions
Last year WPI completed the modeling of high-speed plasma jets for the APEX plasma jet space experiment. These jets resemble plumes from electric propulsion devices and the results of this effort elucidate plume/ambient plasma and magnetic field interactions. The simulations were based on a 3-D viscous, MHD code. The numerical results show the formation of a diamagnetic cavity that is co-located with the jet and the generation of Alfven and magnetosonic waves.

Acknowledgments

The editor gratefully acknowledges the contributions of the authors reviewed in this article. A list of websites for the various academic research programs reviewed in this paper follows.

Colorado State—Professor P. Wilbur
http://www.engr.colostate.edu/me/

Illinois—Professor R. Burton
http://www.aae.uiuc.edu/labs.html#anchor5648475

MIT—Professor M. Martinez-Sanchez
http://web.mit.edu/aeroastro/www/people/mmart/bio.html

Michigan—Professor I. Boyd
http://hpcc.engin.umich.edu/CFD/research/NGPD/

Michigan—Professor A. Gallimore
http://www.engin.umich.edu/dept/aero/spacelab/

Princeton—Professor E. Choueiri
http://alfven.princeton.edu/

Princeton—Professor N. Fisch
http://pst.pppl.gov/tt/

Stanford—Professor M. Cappelli
http://www.stanford.edu/group/pdl/

Texas Tech—Professor J. Dickens
http://ppl.ee.ttu.edu/

USC—Dr. A. Ketsdever/Professor E. P. Muntz
http://ame-www.usc.edu/rsf/chaff_index.html

WPI—Professor N. Gatsonis
http://www.me.wpi.edu/Gatsonis/