The Compatibility of Electric Propulsion and Field Emission Cathode Technologies

Ph.D THESIS DEFENSE

for

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MAY 14, 1999

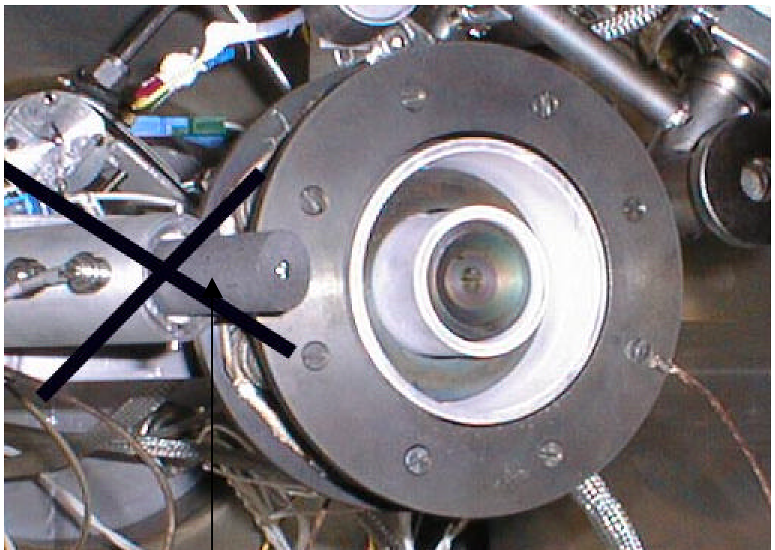
Aerospace Engineering Dept.

Plasmadynamics and Electric Propulsion Lab.

Research Objective-

To replace hollow cathodes used in EP systems with cold cathodes.

Hall Thruster with Hollow Cathode



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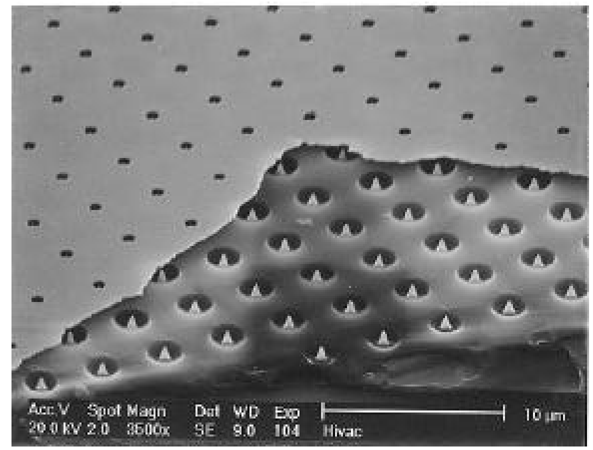
Field Emission Array Cathode



Hollow cathode

- Heater required
- Propellant required
- 1/4” cathode: 25-40 W, 0.5 mg/s, 4.5 A
- 1/8” cathode: 7 W, 0.1 mg/s, 100 mA

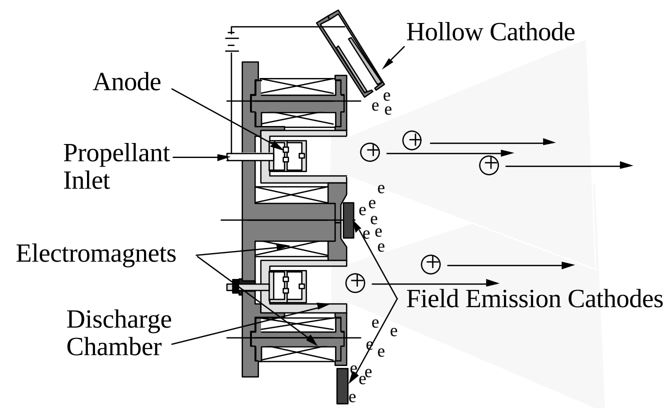
Field emission array cathode

- **NO propellant required**
- **NO heater required**
- **1 mW, 0 mg/s, 100 mA**
- **Easily scalable in size and power to be used with micropropulsion systems**

Electric Propulsion Systems Requiring Cold Cathode Technology

Small/Mesoscale Thrusters

1. Mesoscale Hall thruster developed by MIT
   ~300 mA, ~50 W, ~3 mN,
2. Mesoscale ion thruster
   ~100-200 mA, ~50 W, ~5 mN

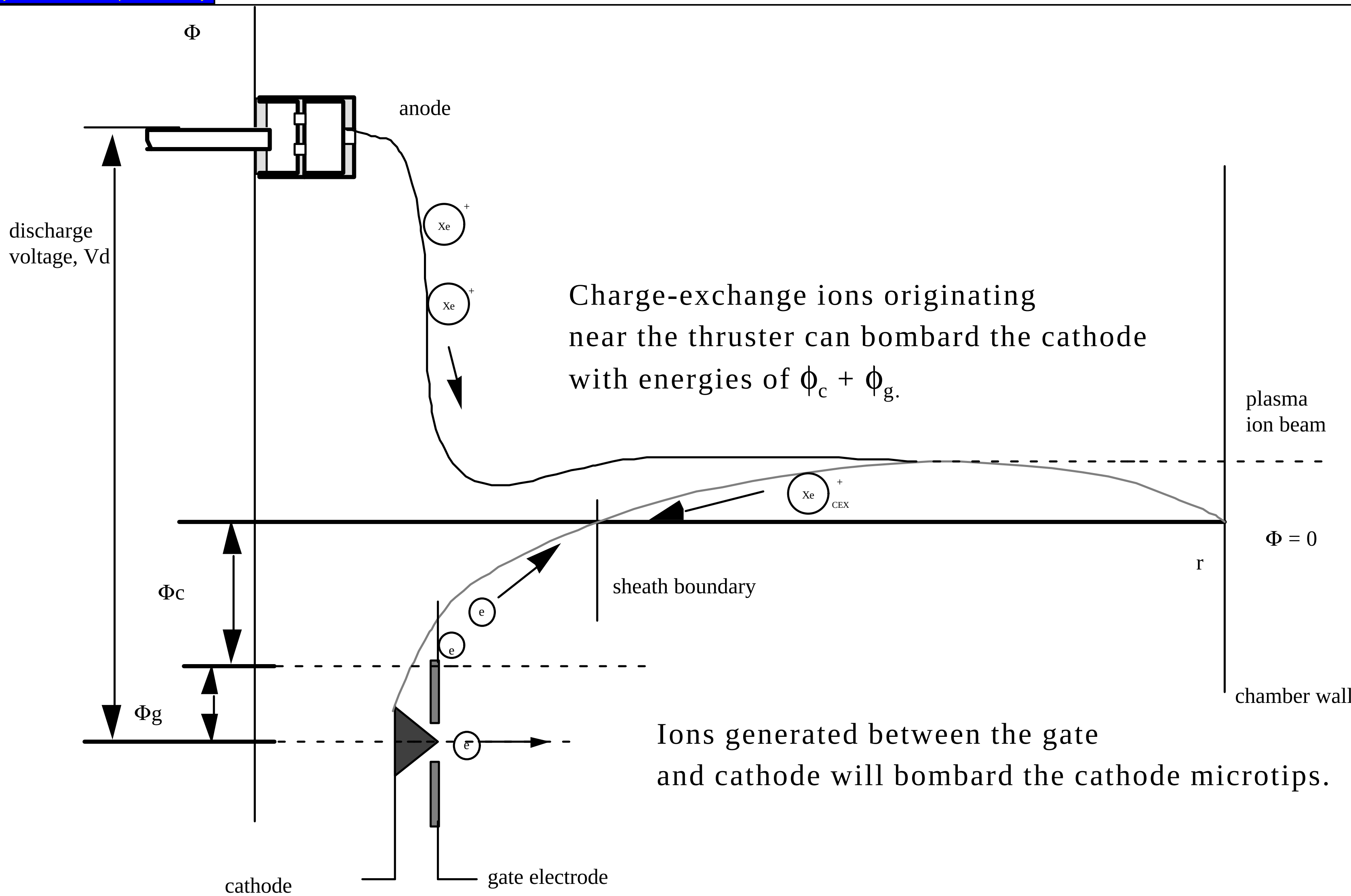


Small Hall thruster

Microscale Propulsion Systems

1. Microcolloidal thruster ~10 uN, 10-100 uA
2. Field emission electric propulsion(FEEP) system
   ~1 mA, 100 uN, 6 kV

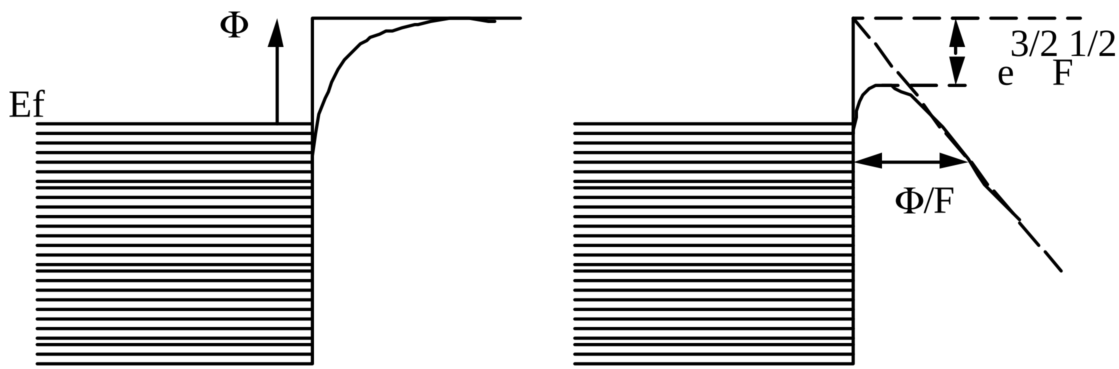
Potential Diagram



Charge-exchange ions originating near the thruster can bombard the cathode with energies of $\phi_c + \phi_g$.

Ions generated between the gate and cathode will bombard the cathode microtips.

FIELD EMISSION



Potential well diagram

Potential barrier at the cathode surface is lowered by the electric **field** so that electrons can tunnel out of the material.

Fowler-Nordheim eqn. for field emission current density:

$$J_{FN}(F) = a_{fn} F^2 \exp(-b_{fn} / F)$$

$$b_{fn} = \frac{2}{\hbar F}\sqrt{2 m f_w}\, t(y) \qquad a_{fn} = \frac{1}{16 p \hbar t(y) f_w} \exp\left(\frac{4}{3\hbar}\sqrt{2 m f_w^3}\, u_o\right)$$

F (V/cm): surface electric field

Φ_w (eV): work function of the material

E_f(eV): Fermi energy

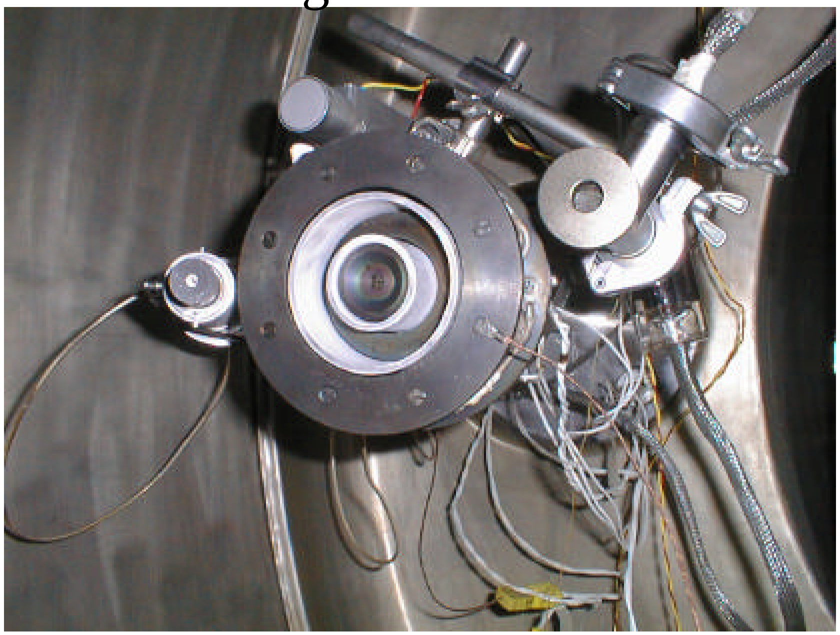
e= electron charge

Role of this Thesis and Structure of the Defense

1. Cathode environment characterization.
2. FE cathode testing in simulated thruster environment.
   - –Can cathodes operate in thruster environment?
   - –How does the environment affect the cathode performance?
   - –What are the limitations in cathode operation?
3. Develop a performance degradation model.
   - –Predict effect of CEX ions on lifetime
   - –Accelerated testing
   - –Reduced development costs
4. Develop a sheath model to predict space-charge current limits.
   - –Thruster
   - –Tether
5. Use models to design cathodes for Hall thruster and tether environments.
   - –Tolerable operating voltages
   - –Size of cathodes
   - –I/cathode
   - –# of cathodes required to do the job

Cathode Environment Characterization- Hall Thruster

Fig. PEPL-70



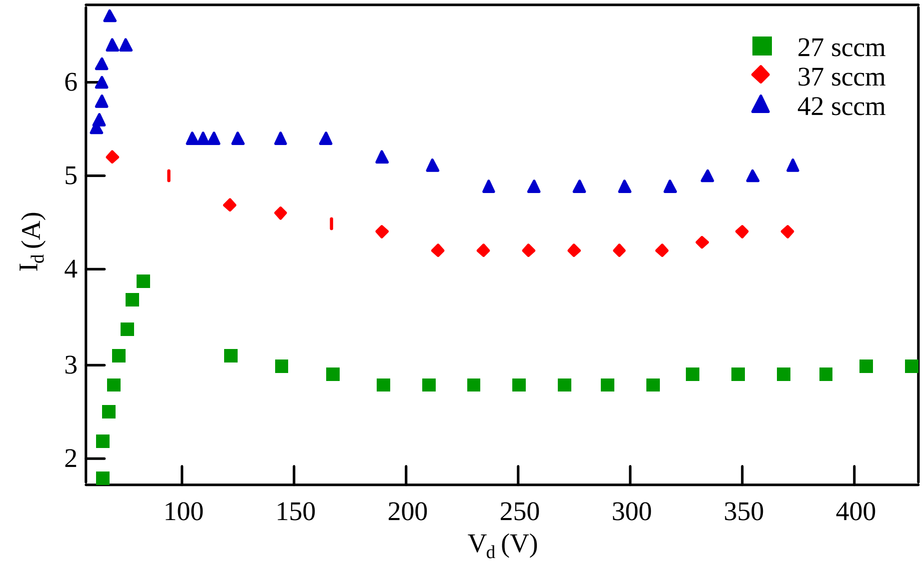


Fig. Thruster I-V characteristics.zz

Table-Thruster performance

V_d (V)	$\dot{V}$ (sccm)	I_d (A)	T (mN)	η_{eff}(%)
300	23.4	1.8	26.1	27
300	27.4	2.4	33.8	29
300	34.0	3.2	45.4	32
300	38.6	3.8	55.3	35
300	43.0	4.6	65.4	36

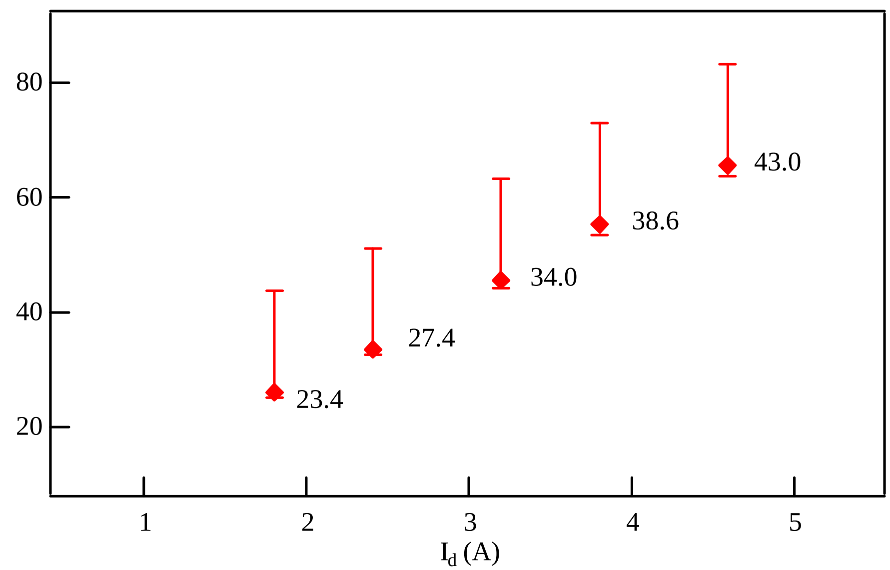


Fig. Thrust vs. discharge current

Cathode Environment Characterization-
NPF and Faraday Probe Measurements

Ion current density

$\dot{V}$ (sccm)	I_d (A)	V_d (V)	I_{MI}(A)	I_{MO}(A)	P_{tank} (Torr)	**J (mA/cm^2)**
23.8	1.9	259	19	8	$1.1x10^{-5}$	**0.010**
23.8	1.9	300	19	8	$1.1x10^{-5}$	**0.010**
28.6	2.7	298	18	5	$1.3x10^{-5}$	**0.013**
33.5	3.5	298	18	5	$1.5x10^{-5}$	**0.018**
38.0	3.5	300	28	15	$1.7x10^{-5}$	**0.014**
42.7	4.5	300	26	7	$1.9x10^{-5}$	**0.019**
43.1	4.9	300	27	0	$1.9x10^{-5}$	**0.020**

Neutral xenon pressure and ion current density

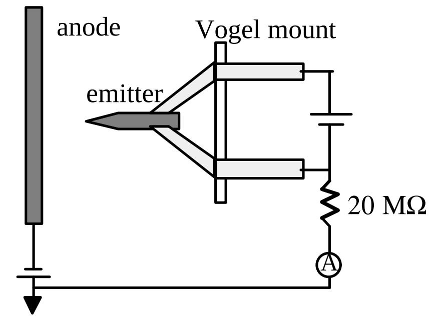
$\dot{V}$ (sccm)	I_d (A)	V_d (V)	I_{MI}(A)	I_{MO}(A)	P_{tank} (Torr)	**P_{NPF} (Torr)**	**J (mA/cm^2)**
18.7	1.3	260	25	12	$8.0x10^{-6}$	**$2.1x10^{-5}$**	**0.001**
19.1	1.3	280	25	12	$8.3x10^{-6}$	**$2.1x10^{-5}$**	**0.001**
19.4	1.3	302	25	12	$8.3x10^{-6}$	**$2.1x10^{-5}$**	**0.001**
23.5	2.0	200	27	7	$9.8x10^{-6}$	**$8.9x10^{-6}$**	**0.003**
23.4	1.8	300	27	7	$1.0x10^{-5}$	**$9.1x10^{-6}$**	**0.002**
27.4	2.4	300	27	7	$1.2x10^{-5}$	**$9.1x10^{-6}$**	**0.003**
34.0	3.1	300	27	8	$1.4x10^{-5}$	**$1.3x10^{-5}$**	**0.005**
38.6	3.8	300	27	8	$1.9x10^{-5}$	**$1.7x10^{-5}$**	**0.006**
43.0	4.6	300	26	8	$1.9x10^{-5}$	**$1.6x10^{-5}$**	**0.008**

Cathode Test Configuration at LRI- Cold Cathode Technology 1- HfC and ZrC Single Tip Cathodes

Objectives

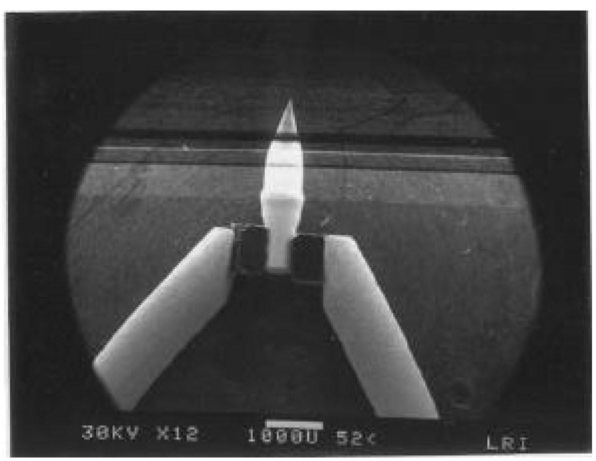
Can FE cathodes operate in O_2 and Ar environments?

What happens to the cathode surface during the exposures?

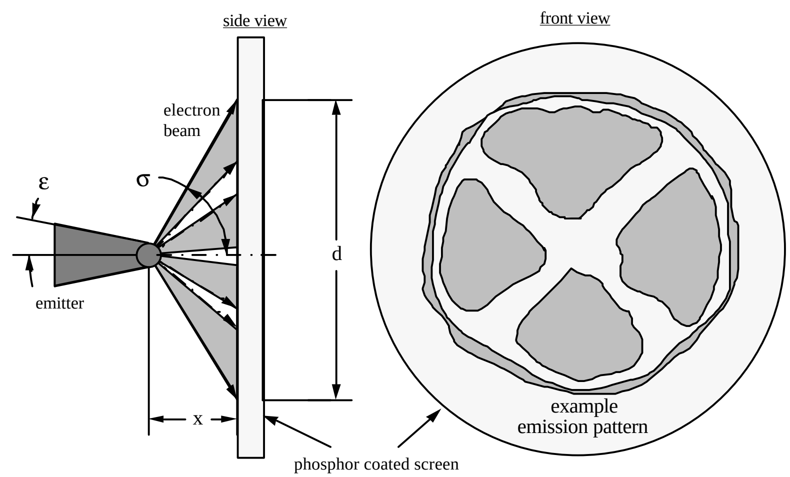


FEM Electrical Schematic

Vogel cathode mount



Field Emission Microscope (FEM)



Field Emission Microscope Images

Fig. Dirty cathode tip or nanoscale protrusions

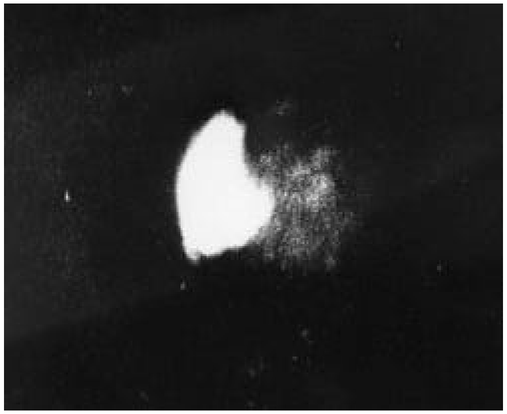
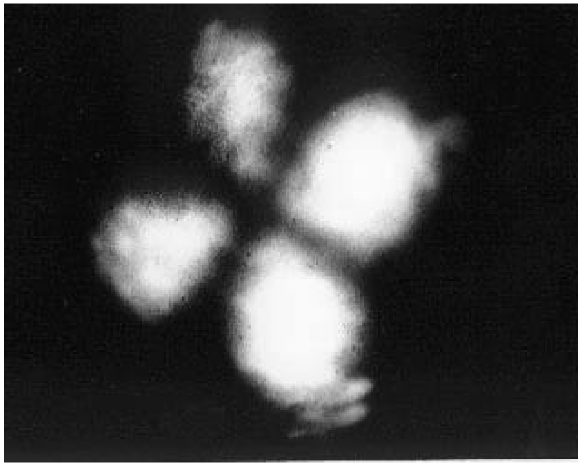
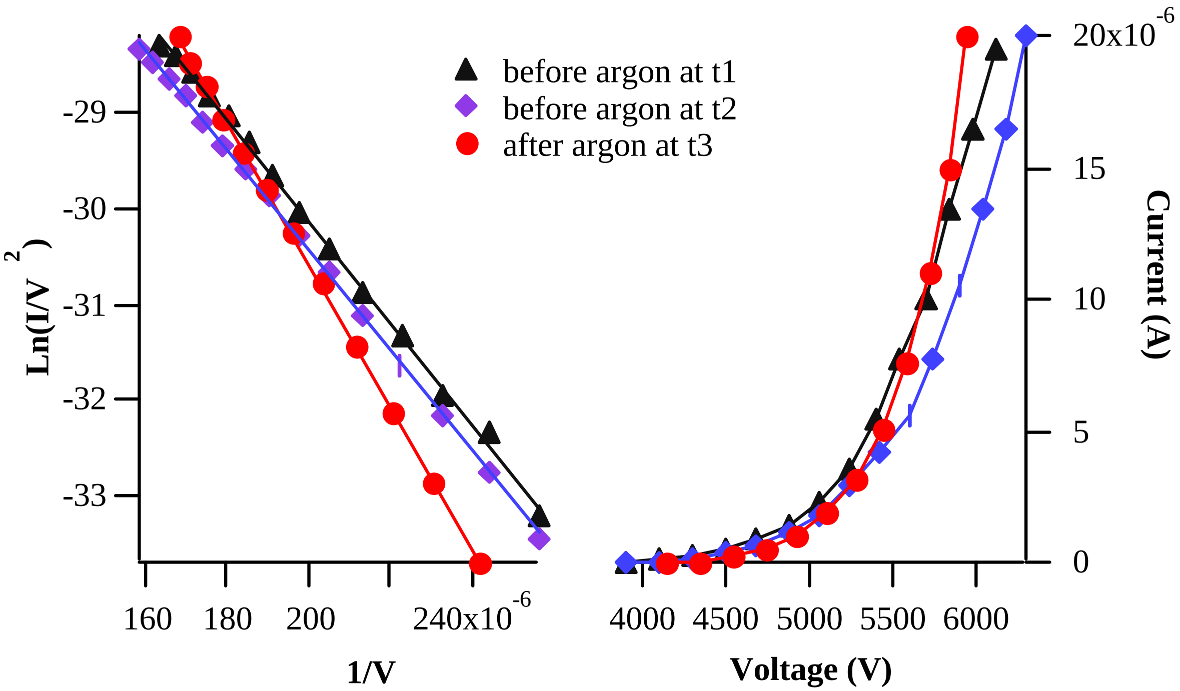


Fig. Clean cathode tip with stable emission



Carbide Cathode Experimental Results

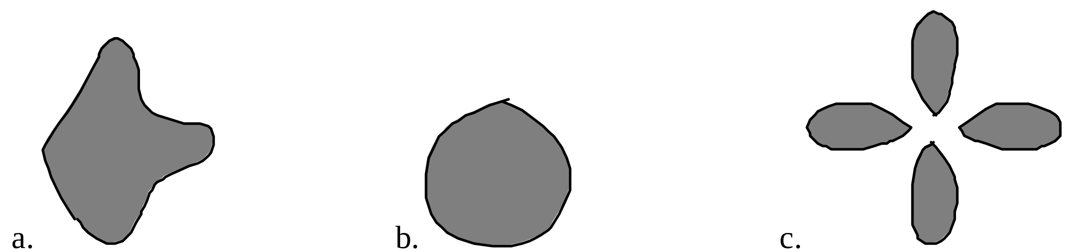


Oxygen (0.5 hr.)

- Emission pattern improved.

Argon-Exposure (0.5 hr.)

- 10^{-10} Torr-no pattern
- **6kV**, 3×10^{-5} Torr, 20 μA
- 10-9 Torr-great pattern
- SEM showed no tip damage from exposure.



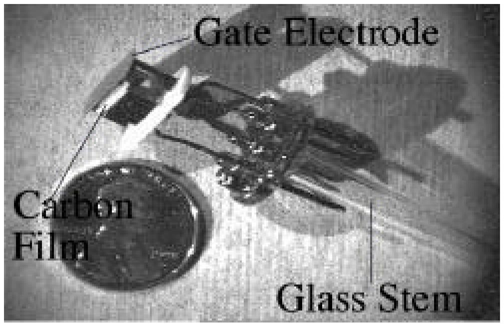
a) during Ar exposure I, b) during exposure II, c) after exposure

Carbide Cathode Experimental Results

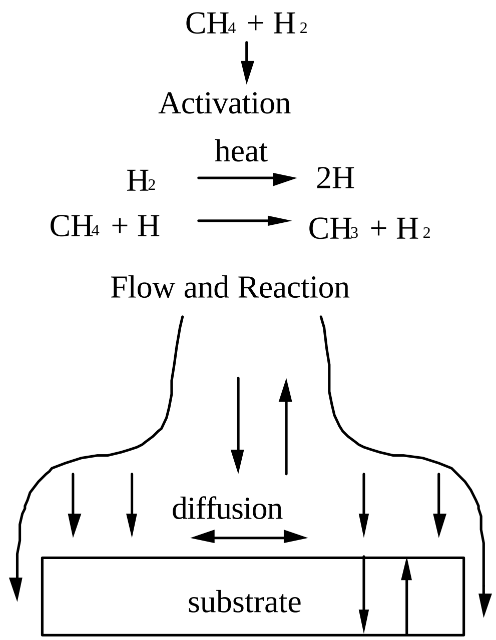
- Exposure to oxygen improved emission pattern.
  - Resistance to oxygen poisoning is valuable for successful ground testing.
- Emission half-angle average was 28°.
- Argon exposure cleaned cathode!
  - Could be true for any inert gas environment?
- Carbide cathodes were incredibly robust, operating at several kV without failure!

Cold Cathode Technology-2: Thin Film Field Emission Sources

Carbon Films from FEPET (Field Emission Picture Element Technology)



Carbon film cathode fabrication



Fabrication

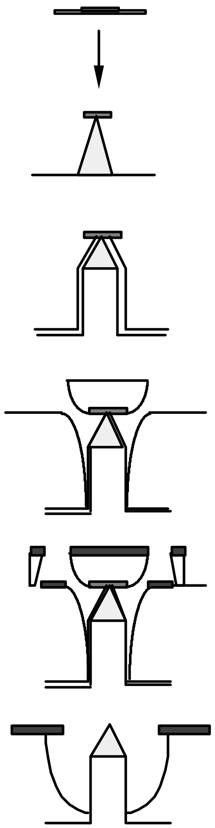
- -process: HFCVD (Hot Filament Chemical Vaporization)
- -thickness: ~ nm

Performance

- -J_{emax}= 100 mA/cm^2 at 10 V/um observed at FEPET
- -start-up in UHV and 10^{-6} Torr xenon no differently!
- -Very robust!
- -High voltages required (800 V)
- -10^5 V/cm required for field emission

Cold Cathode Technology 3-
Si Field Emission Array(FEA) Cathodes

Si cathode fabrication process



a) Deposit insulator
(SiO2 and Si3N4) & pattern

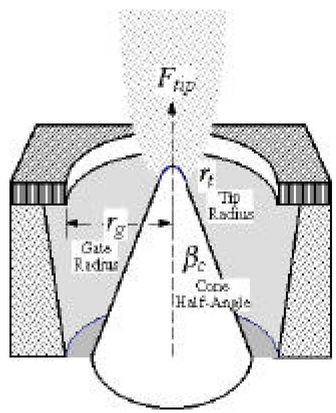
b) Anisotropic etch
to form pyramids

c) Etch columns and
sharpen tips (oxidation)

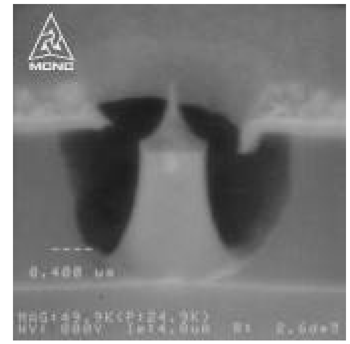
d) Evaporate SiO2

e) Pattern photoresist
& deposit metal

d) Lift metal and etch
insulator



Microtip configuration (courtesy of Dr. Kevin Jensen-NRL)



MCNC Si single FEA cathode tip with 16,000 tips and r_g=1 um

Si characteristics

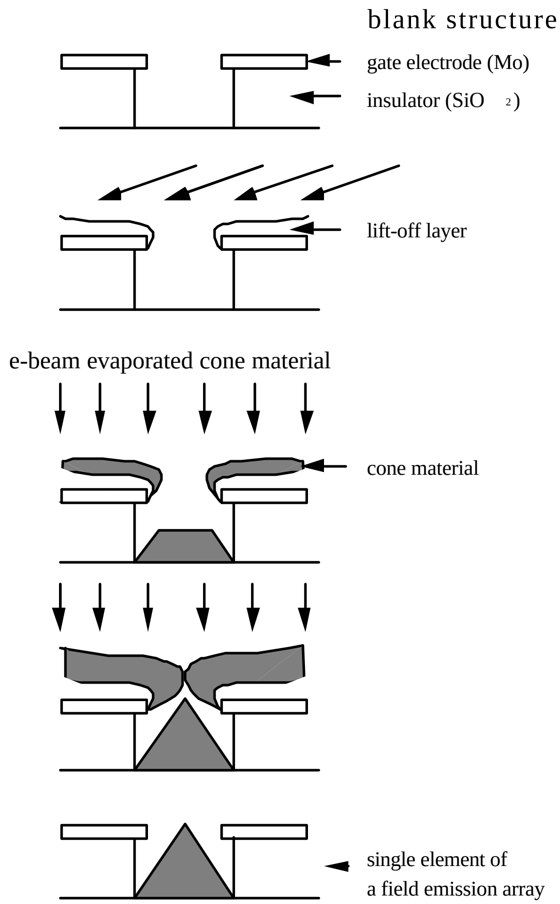
- Work function 4.0 eV
- E_{th} ~ 45 eV (xenon ions)

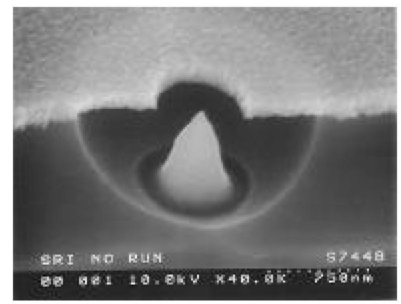
State-of-the-art

- 2.5 uA at 25 V from 1 tip (not at MCNC)
- 3 mA at 85 V from 100 tips (MCNC)
- 7.2×10^6 tips/cm^2 (MCNC)
- 1,021,710 tips in array for sale

Cold Cathode Technology 3- Spindt-type Field Emission Array(FEA) Cathodes

Fabrication of Spindt-type FEA cathodes





SRI Int. Spindt-type Mo single cathode tip in FEA with 50,000 tips

r_g= 0.45 um

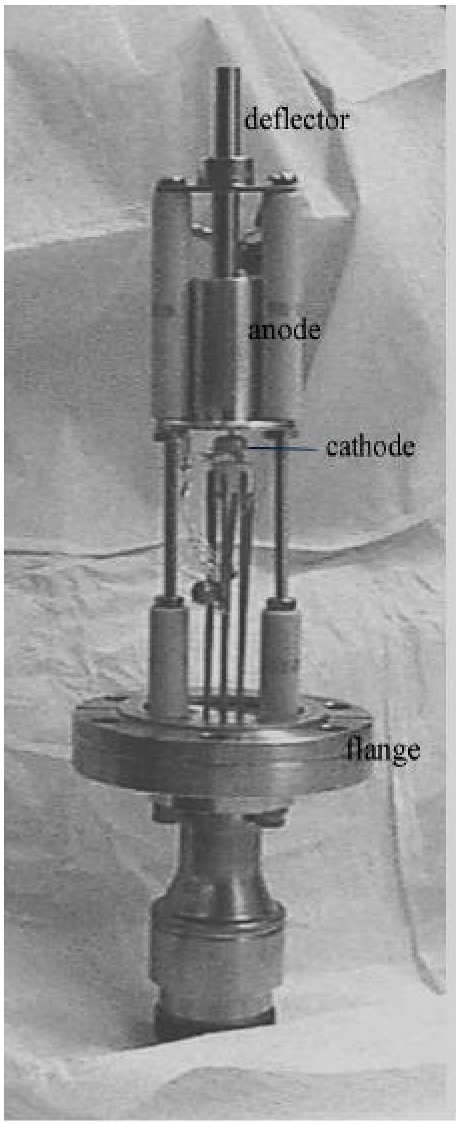
Mo characteristics

- Work function= 4.35 eV
- E_{th} ~ 39 eV (xenon ions)

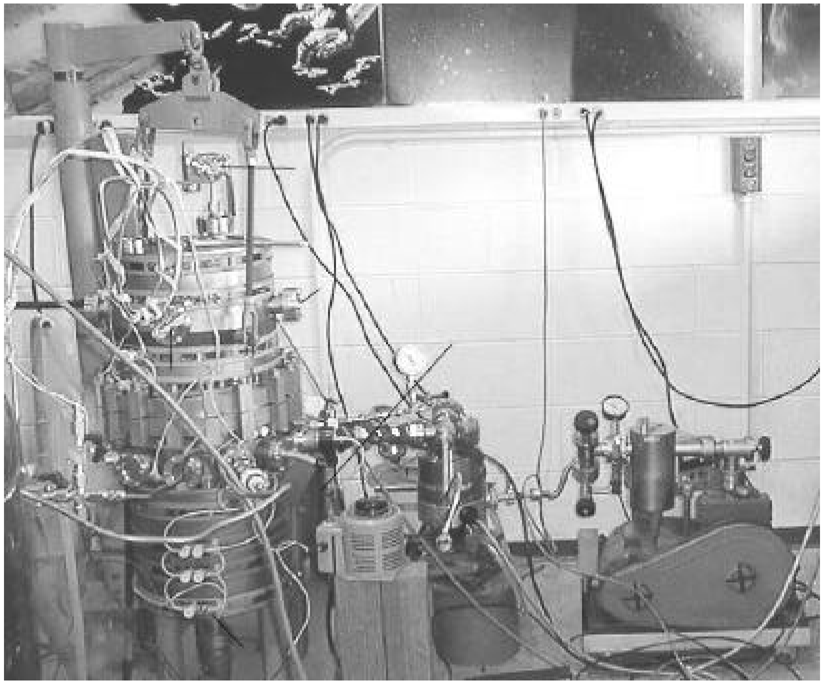
State-of-the-art technology

- 2000 A/cm^2 (SRI)
- 125 uA/tip from 100 tips (SRI)
- 1 uA at 25 V from 900 tips (MIT/LL)
- >10^8 tips/cm^2 (MIT/LL)

Field Emission Cathode Experimental Apparatus and Configuration

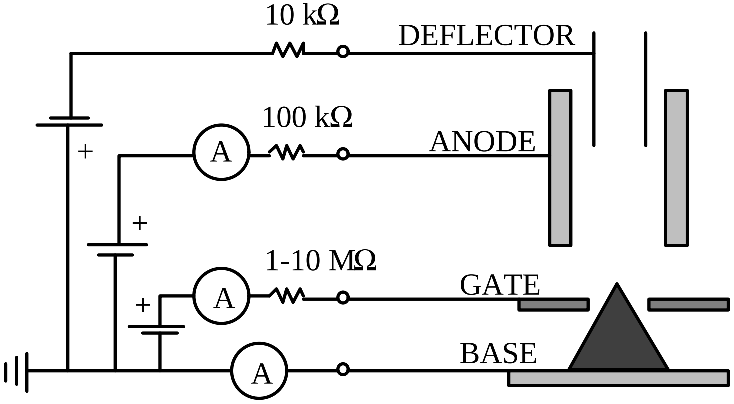


Cathode test flange



Ultra High Vacuum Facility

- Turbomech. pump
- Ionization pump
- Sublimation pump w/liner for LN_2
- GP variable leak valve
- Base pressure ~$7x10^{-11}$ Torr
- 2 cathode test flanges



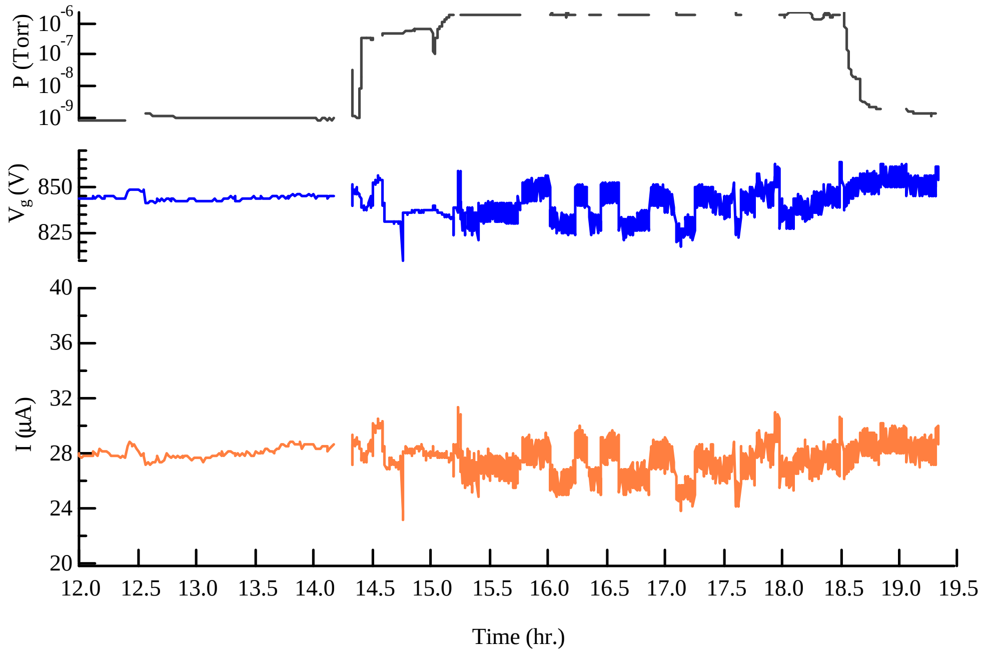
Cathode testing schematic.

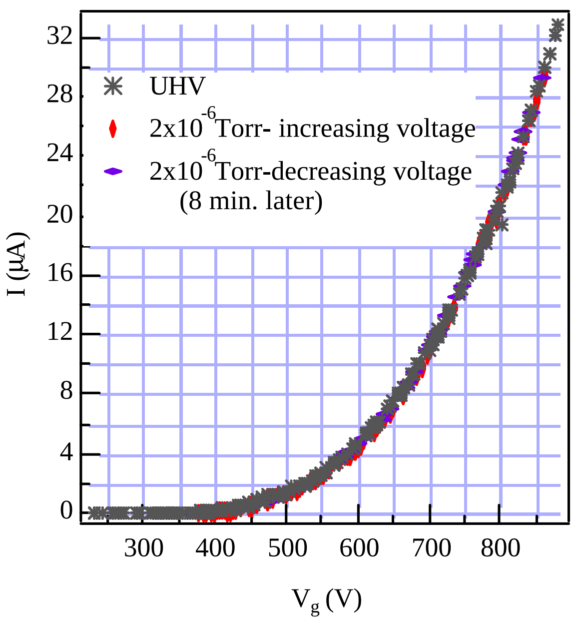
Performance of Carbon Film Field Emission Cathode

Cathode current response to exposure to **$2x10^{-6}$ Torr** of xenon during **4 hours**.

- Anode voltage=900 V
- Gate electrode voltage=845 V
- Cathode current is 28 μA

Fluctuations in I and V_g caused by ionization gauge being turned off and on.





Identical turn-on and turn-off I-V curves in UHV and $2x10^{-6}$ Torr of xenon!!!!!

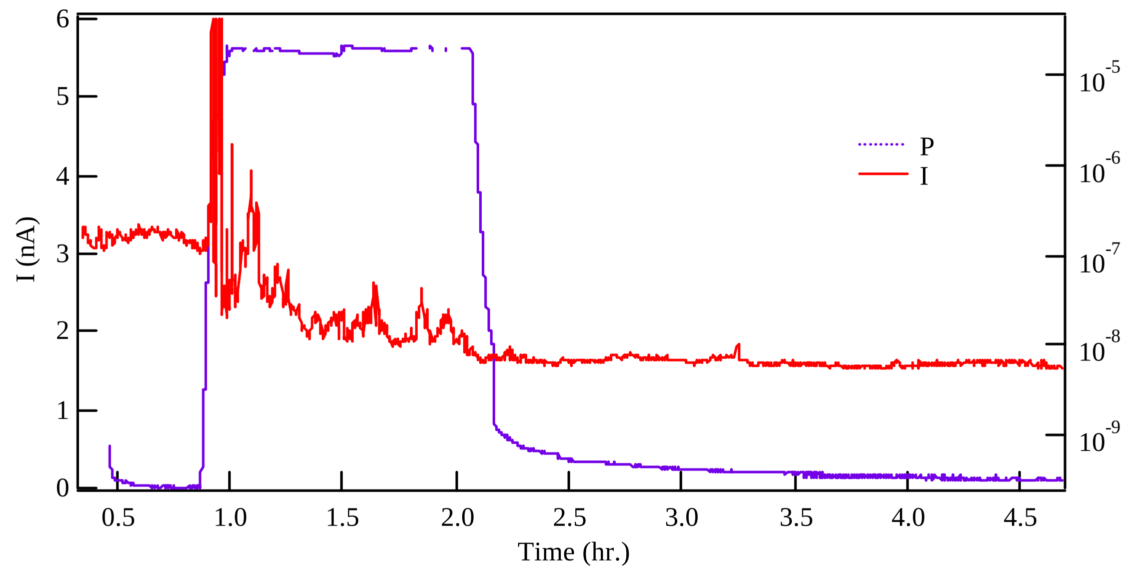
FEA Cathode Experimental Objectives

- Experimental Objectives
  - 1. Can FEA cathodes run in 2×10^{-5} Torr of Xe?
  - 2. How does the performance change in this environment?
    - Efficiency
    - Emission current
      - Temporary ($\Delta\phi_w$)or permanent(Δr_t)?
  - 3. How is the performance affected by operating voltages?
    - Gate electrode
    - Anode
    - Yamamura model
      - E_{th} for Xe ions sputtering Mo is 49 eV.
      - E_{th} for Xe ions sputtering Si is 91 eV.

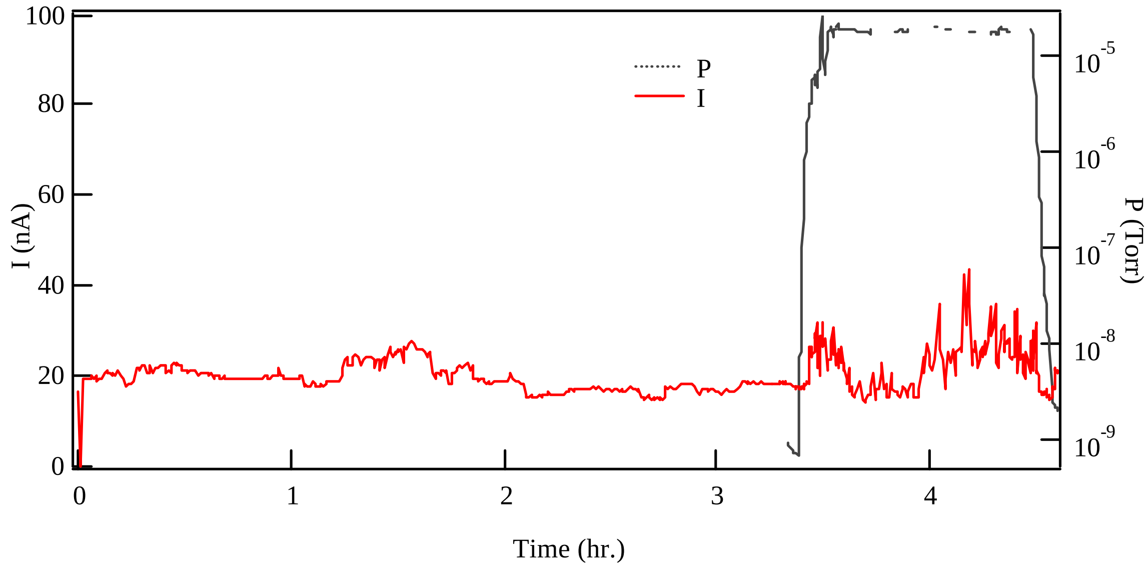
MCNC Si FEA Cathode Experimental Results

Current decreased in xenon environment. Cathode was damaged in this experiment with the gate electrode potential at 70 V and maximum ion energy, E_{imax} at 65 eV.

$V_a = 70$ V
$V_g = 70$ V
$I_o = 3.2$ nA
$E_{imax} = \sim 65$ V



Similar experiment conducted with V_g at 60 V had similar results.



No performance degradation at this operating point!

$V_a = 60$ V
$V_g = 50$ V
$I_o = 20$ nA
$E_{imax} = \sim 45$ V

Can operate Si FEA cathodes in 10^{-5} Torr of xenon if V_g" 50 V.?

SRI Int. Mo FEA Cathode Experimental Results

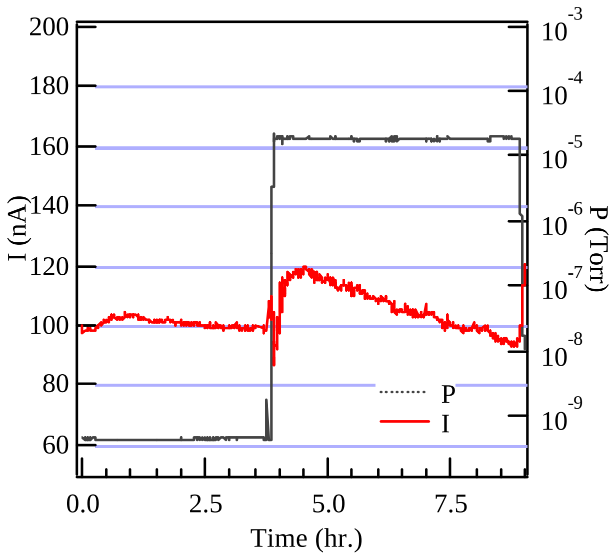


Fig. Cathode current response to increases in xenon pressure to $2x10^{-5}$ Torr with V_g at 50 V and V_a at 60 V during **5 hr**.

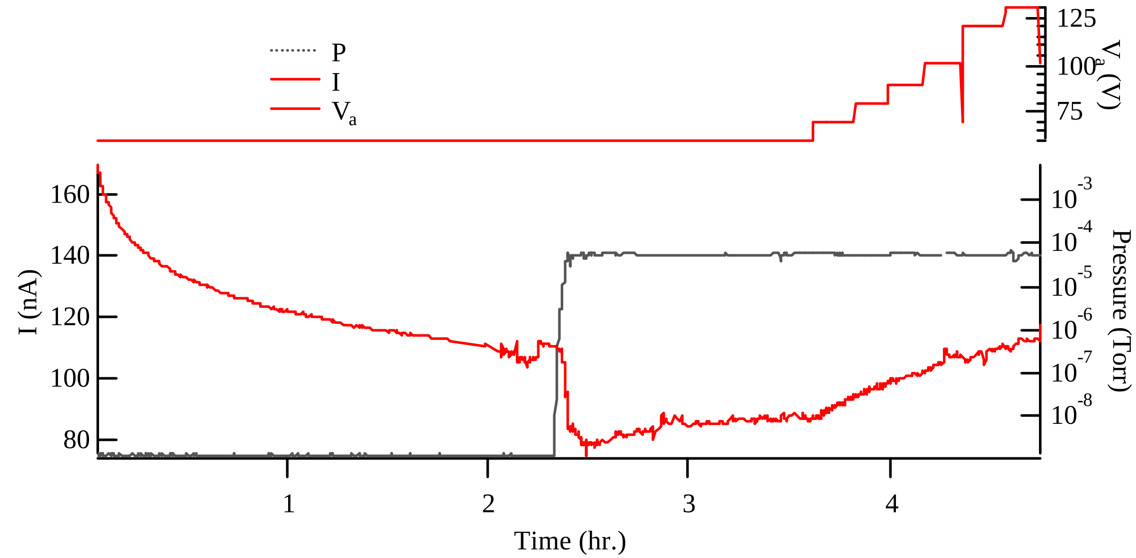


Fig. Cathode current response to xenon exposure and increasing anode voltage with V_g at 50 V and V_a at 60-120 V.

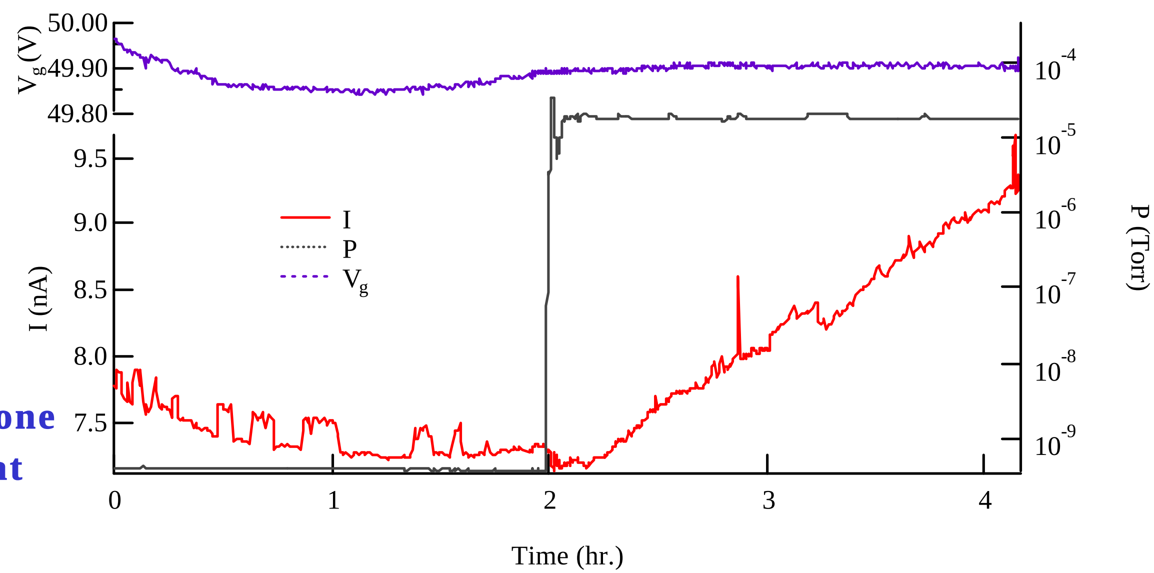


Fig. Cathode current response to xenon exposure with V_g at 50 V and V_a at 100 V.

***Very little if any damage if any was done to the cathode when exposed to xenon at low enough gate electrode potentials (V_g" 50 V).**

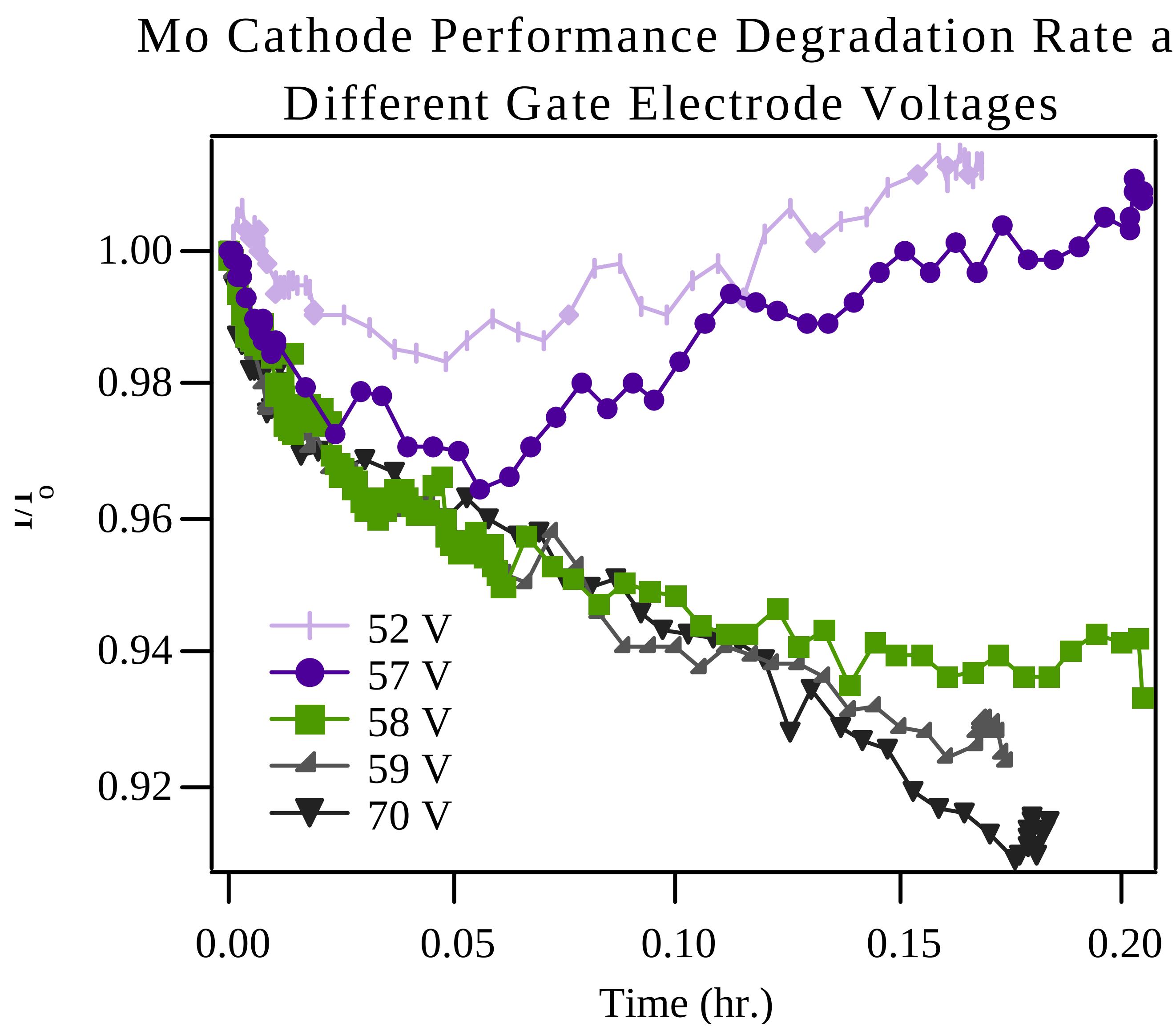
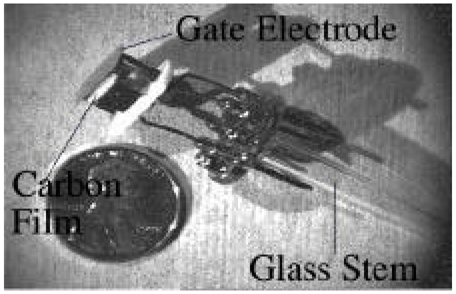
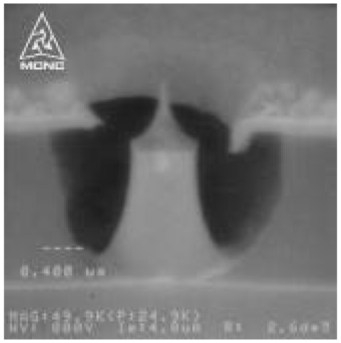


Fig. Cathode current response with V_a at 100 V and a pressure of $2x10^{-5}$ Torr of xenon and V_g increasing in 1 V increments every 10 min.

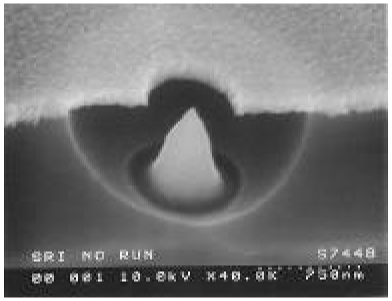
Experimental Results



- **FEPET carbon film cathode**
  - Cathode performance was not affected by xenon environment (10^{-6} Torr) with V_g at 850 V!!
  - Low efficiency-must reduce dimensions to increase efficiency and decrease operating voltages.



- **MCNC Si FEA cathode**
  - Xenon exposure did not change the Si cathode work function!
  - Si FEA cathode can operate in xenon environment (10^{-5} Torr) with very little damage, if any for several hours!
  - Gate electrode voltage limited to below 60 V to avoid tip sputtering.
    - Yamamura model predicted E_{th} is 91 eV.



- **SRI International Mo FEA cathode**
  - Xenon exposure did not change the Mo cathode work function!
  - Mo FEA cathode can operate in xenon environment (10^{-5} Torr) with very little damage, if any for several hours!
  - Gate electrode voltage limited to below 50 V to avoid tip sputtering.
    - Yamamura model predicted E_{th} is 49 eV.

How can the changes in emission current, I(t), be predicted from a FEA cathode in the thruster-like environment?

Current change from cathode array due primarily to changes in tip radius and spread in tip radius in array from ion bombardment.

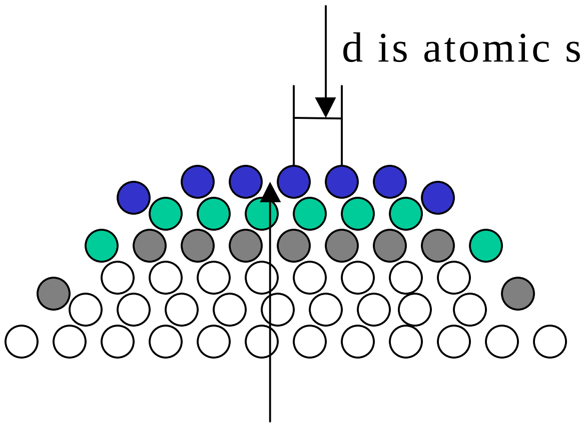
Two populations of ions bombarding the microtip structures

- **CEX population** with uniform flux over the microtip surface
- **Local population** primarily hits emitting area of the tips

1) $I(r_t(t))=?$

2) $$\frac{dr_t}{dt} = \frac{d}{t_e}$$

Tip radius changes by d with each layer removed.

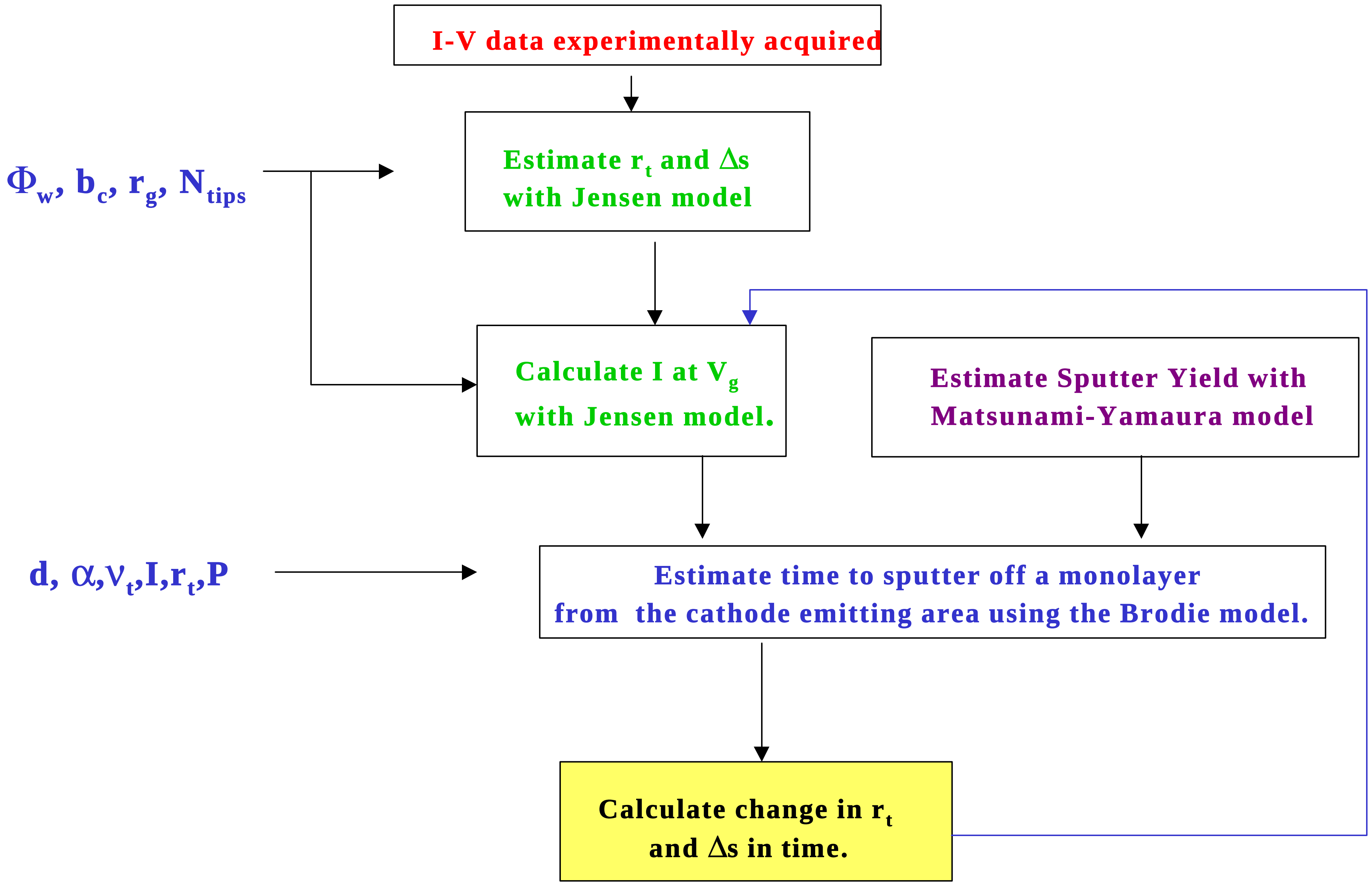


3) $$\Delta s(t) = \frac{r_{t\,\max}}{r_t(t)} - 1$$

nomenclature

- r_t is the minimum tip radius
- r_{tmax} is the maximum tip radius
- d is atomic spacing
- t_e is time to remove a monolayer and increase the tip radius by d.
- Δs is the spread in tip radii across the array

Cathode Performance Degradation Model



Jensen FEA Cathode Performance Model

Statistical approach to modeling FEA cathode performance:

$$I_{array}\left(V_g\right) = N_{tips}\sum\left(\Delta s, V_g\right) b_{area}\left(V_g\right) J_{FN}\left(F_{tip}\left(V_g\right)\right)$$

$$J_{FN}(F) = a_{fn}F^2 \exp(-b_{fn} / F)$$

$$F_{tip} \approx b_g V_g \qquad b_g \approx \left(\frac{p}{\ln\left(kr_g / r_t\right)} - \tan^2 b_c\right)\frac{1}{r_t}$$

r(s)=r_t(1+s), where 0" s" Δs

Tip radius is represented by a distribution of tip radii with the minimum tip radius being r_t and the spread in tip radii Δs.

$$\sum\left(\Delta s, V_g\right) = \frac{\exp(\Delta s b) - 1}{\Delta s b}$$

r_t and Δs can be determined from the following equations and from I-V curve experimentally acquired:

$$B_{FN} = \frac{b_{FN}}{b_g} + \frac{d^2 + 2x_o}{x_o^3}$$

$$A_{FN} = N_{tips} 2p r_t^2 \cos^2\left(b_c\right) a_{fn} \frac{b_g^3}{x_o b_{fn}} \exp\left(2 + \frac{4}{3}\frac{d^2}{x_o^2}\right) \sum\left(\Delta s, x_o^{-1}\right)$$

Brodie Tip Sputtering Model

A tip sputtering model was developed by Brodie to determine the time to remove a monolayer from the emitting area of the microtips:

$$t_e = \frac{2pr_t^2(1-\cos s)}{d^2 n_s}$$

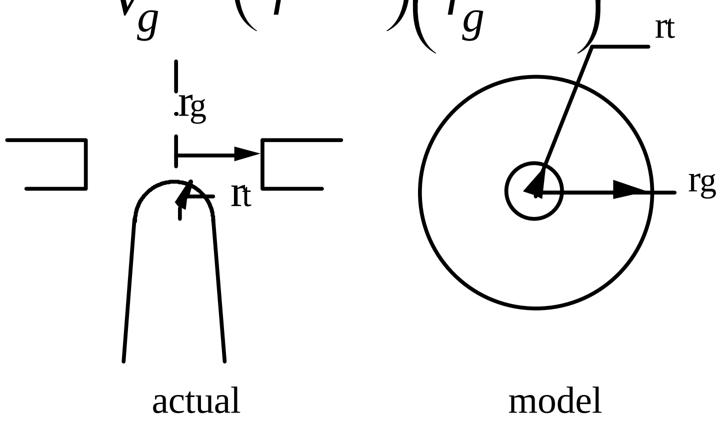
Removal rate of material from the emitting tip area (atoms/sec):

$$n_s = \int_{r_s}^{r_m} \frac{I_e}{e} NQ(V_r)Y(V_r)dr$$

N=3.55x10^{16}P (molec./cm3)

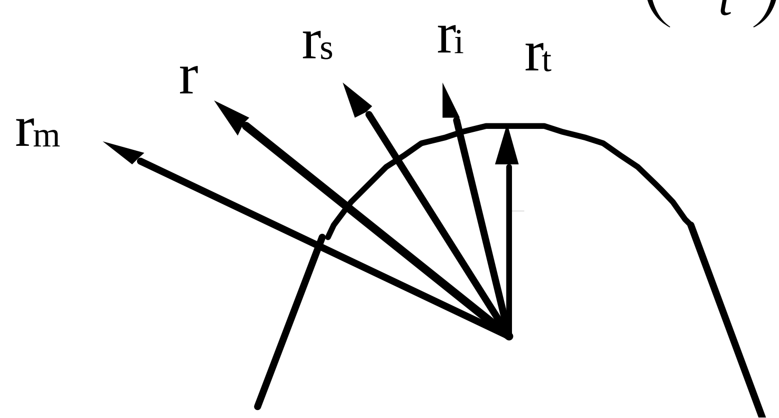
Radial potential distribution used in the model:

$$\frac{V_r}{V_g} = \left(\frac{r_t}{r} - 1\right)\left(\frac{r_t}{r_g} - 1\right)^{-1}$$

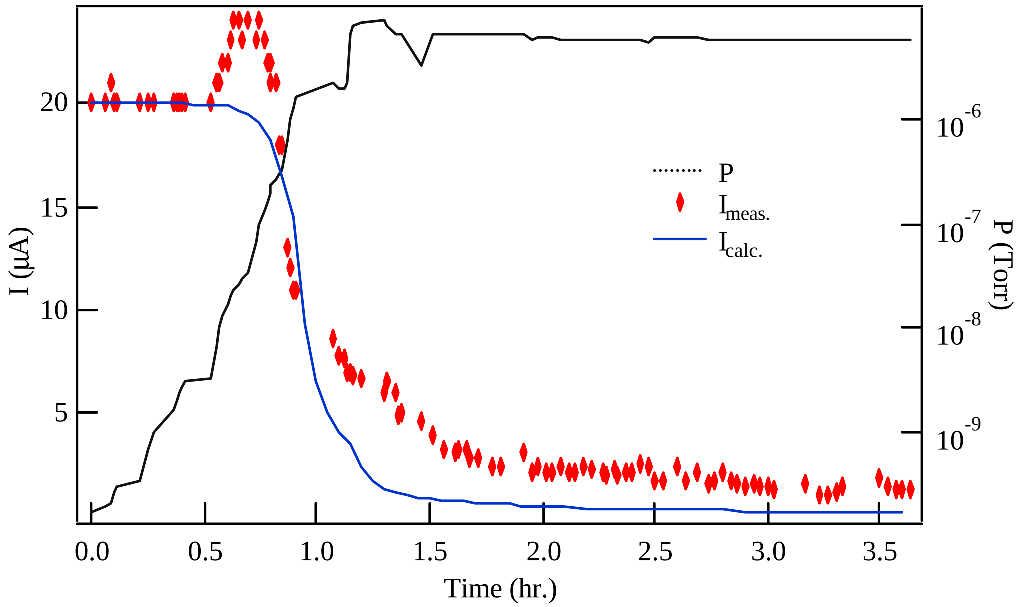


Significant radial positions with r_m being the maximum radial position from which ions generated will hit the emitting area of the tips:

$$r_m = r_t\left(\frac{V_g}{V_t}\right)^{\frac{1}{3}}$$



Performance Degradation Model Results-Si FEA Cathode



Xenon pressure at $7x10^{-6}$ Torr

V_g at 86 V

V_a at 400 V

I=20 μA

2.5 hr. exposure

rt= 45.2 Å

Δs=185

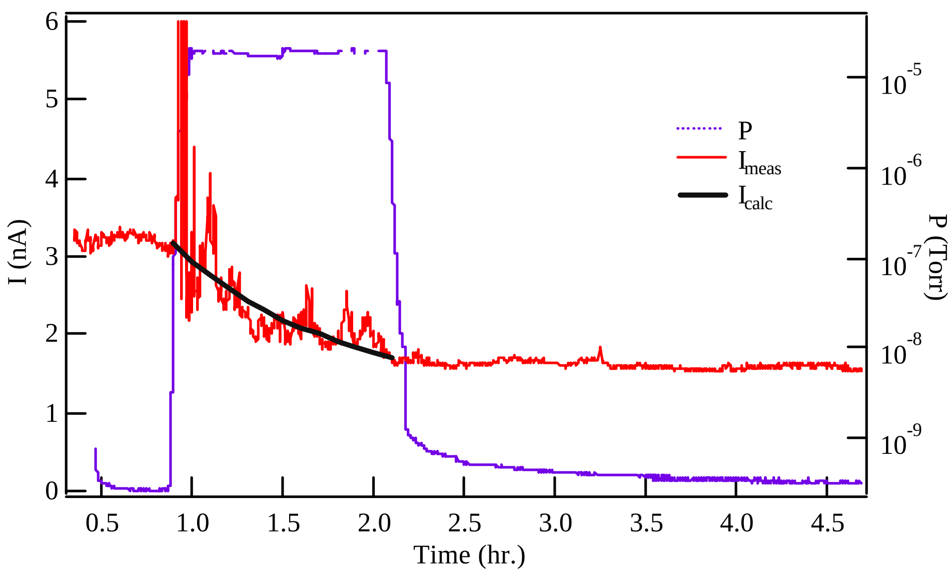
Xenon pressure at $2x10^{-5}$ Torr

V_g at 70 V

V_a at 70 V

I = 3 nA

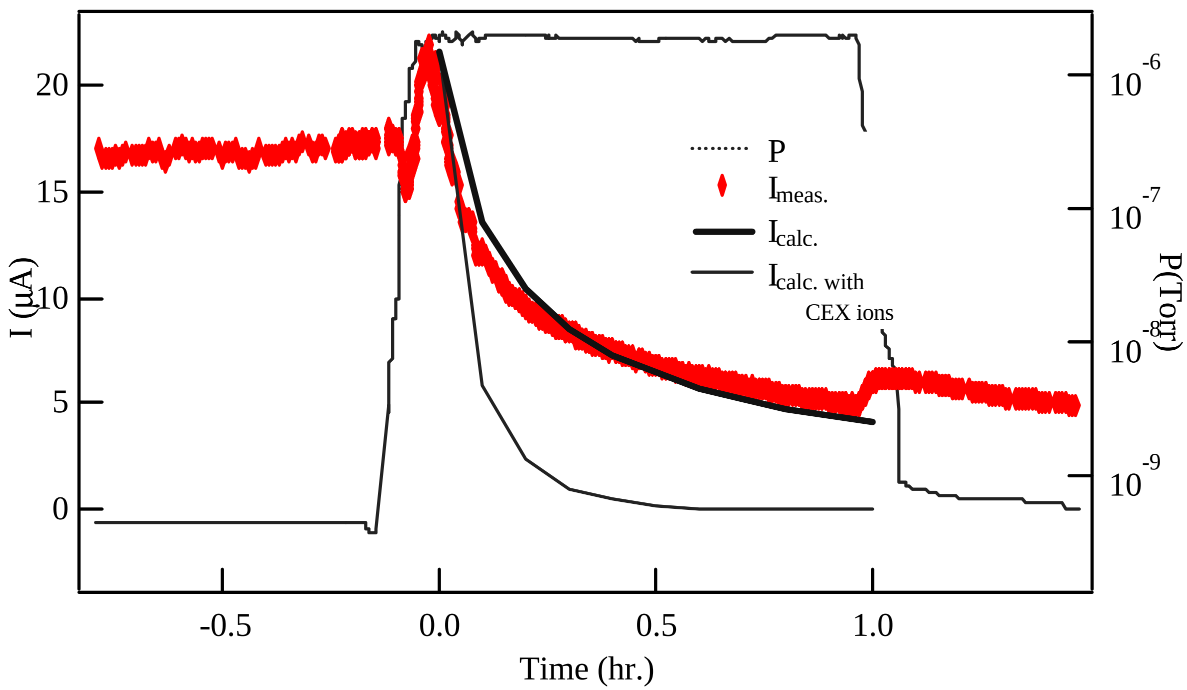
1 hr. exposure



Good correlation between experiment and theory if E_{th} for sputtering Si with xenon ions is 45 eV!

Performance Degradation Model Results-Mo FEA Cathode

	ϕ_w (eV)	β_c (rad.)	r_g (Å)	N_{tips}	A_{FN} (A/V^2)	B_{FN} (V)	r_t (Å)	Δs	
I	4.35	0.26	4500	50000	0.0013	819	43.6	50.0	← Initial parameters calculated from I-V data
II	4.35	0.26	4500	50000	0.0024	952	53.5	42.5	← Final parameters calculated from I-V data
III	4.35	0.26	4500	50000			53.6	40.8	← Final parameters calculated by the performance degradation model showing great agreement between theory and experiment!



P = 2x10^{-6} Torr of xenon

V_g = 65.6 V

V_a = 80 V

E_{th}= 39 eV

Good correlation between experiment and theory if E_{th} for Sputtering Mo with xenon ions is 39 eV!

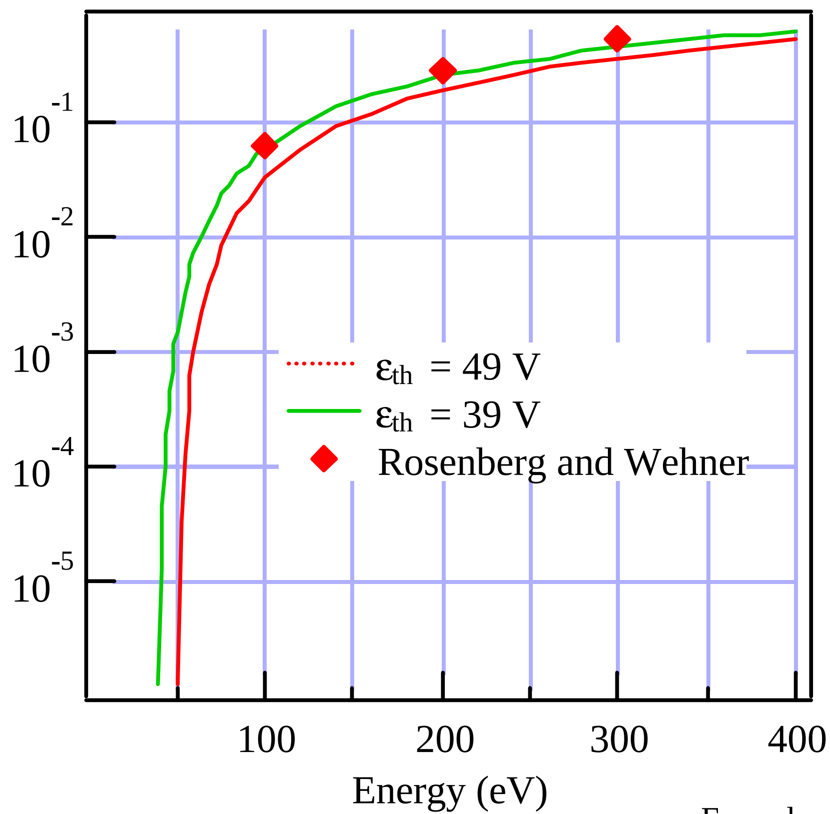
P E P L Michigan
Plasmadynamics and Electric Propulsion Laboratory

Sputter Yields of Mo and Si by Xe Ions

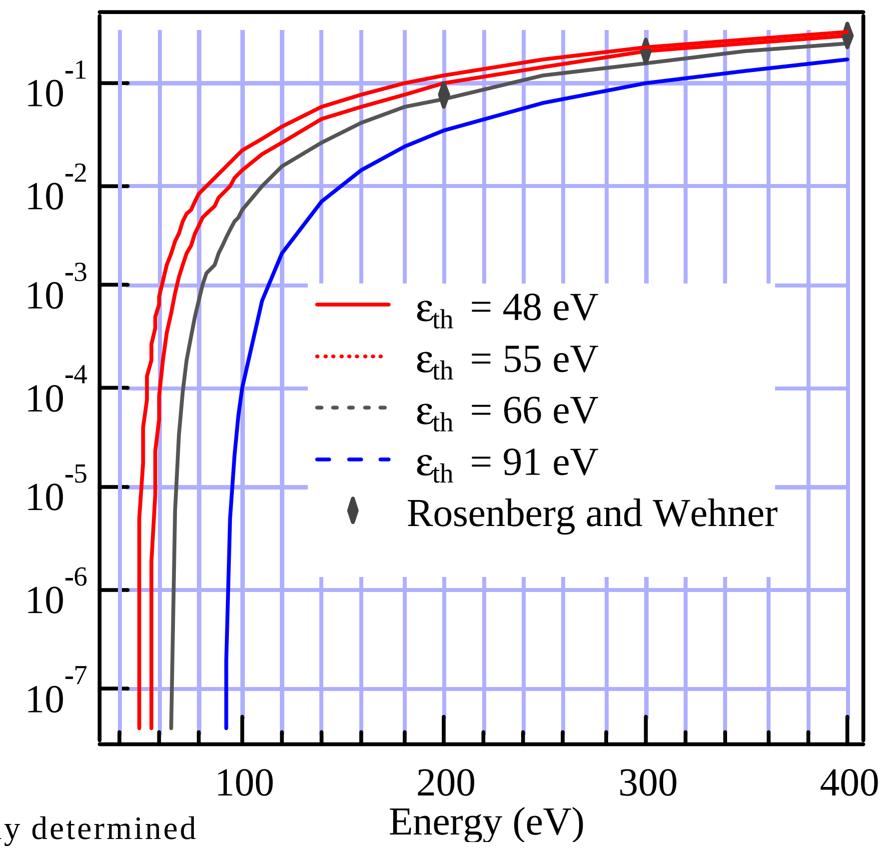
JPL

Comparison between sputter yield values calculated by Yamamura and Matsunami model using various E_{th} values and sputter yield values measured by Rosenberg and Werner.

Molybdenum



Silicon



E_{th} ~39 eV ← E_{th} values indirectly determined from experimental and theoretical results in this study. → E_{th} ~48 eV

Cathode Dimensions Required with and without a CEX ion population to provide 100 mA and 100 hours of life

Maximum operating voltages and corresponding Mo cathode array size required to emit 100 mA for 100 hours ($\Delta I<10\%$), both with and without a CEX ion population. Estimates based on experimental and theoretical results.

	ϕ_w (eV)	β_c (rad).	r_g (Å)	r_t (Å)	Δs	V_g (V)	N_{tips}	I_o (mA)	I_f (mA)	Size (m^2)
Mo	**4.41**	**0.1974**	**2000**	**40.4**	**1.98**	43	1.3×10^{8}	108	107	8.12
Mo	4.41	0.1974	1000	40.4	1.98	42	1.4×10^{7}	105	101	0.88
Mo	4.41	0.1974	1000	30	1.98	42	1.2×10^{6}	108	107	0.075
Mo	4.41	0.1974	2000	40.4	1	43	6.5×10^{7}	107	106	4.06
Mo	4.41	0.1974	2000	30	1.98	43	7×10^{6}	100	95	0.44
Mo_{CEX}	**4.41**	**0.1974**	**2000**	**40.4**	**1.98**	20	4.5×10^{15}	108	101	2.8×10^{8}
Mo_{CEX}	4.41	0.1974	1000	40.4	1.98	20	4×10^{13}	104	98	2.5×10^{6}
Mo_{CEX}	4.41	0.1974	1000	30	1.98	20	3×10^{11}	107	101	1.9×10^{4}

Packing density of this array is **16,000,000 tips/cm²**.

This table shows how the CEX ion population limits the V_g and the necessity of CLAIR to shield the cathode from the CEX ion population if Mo cathode dimensions are to be compatible with EP systems!!

Cathode Dimensions Required with and without a CEX Ion Population to Provide 100 mA and 100 Hours of Life

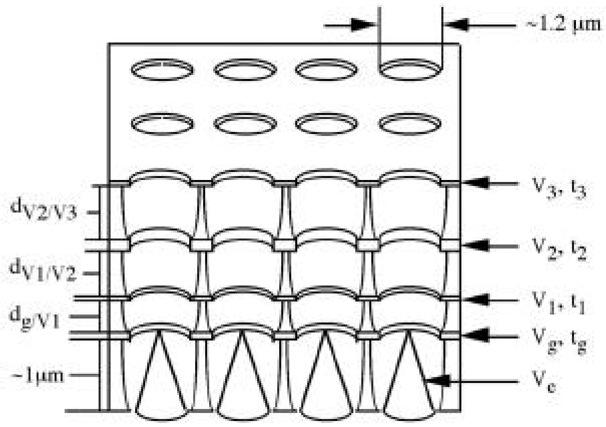
Maximum operating voltages and corresponding Si and HfC cathode array size required to emit 100 mA for 100 hours ($\Delta I<10\%$), both with and without a CEX ion population. Estimates based on experimental and theoretical results.

	ϕ_w (eV)	r_g (Å)	r_t (Å)	Δs	V_g (V)	N_{tips}	I_o (mA)	I_f (mA)	Size (cm^2)
Si	4.0	2000	40.4	1	52	$6x10^5$	105	104	0.04
Si	4.0	2000	40.4	2	52	$1.2x10^6$	106	106	0.08
Si_{cex}	4.0	2000	40.4	2	30	$8.3x10^9$	109	101	519
Si_{cex}	4.0	2000	30	2	30	$2.6x10^8$	100	92	16.25
Si_{cex}	4.0	1000	40.4	2	30	$2.9x10^8$	109	102	18.12
HfC_{cex}	3.3	1000	40.4	2	30	$3x10^6$	106	100	0.19
HfC_{cex}	3.3	2000	40.4	2	30	$4.6x10^7$	105	100	2.88

Packing density of this array is 16,000,000 tips/cm^2 and β_c is 0.26

This table shows the danger of the CEX ion population and the necessity of a CEX ion filter (CLAIR) if Si cathodes are to be used in EP systems.
This table also shows that HfC cathodes may not require CLAIR even when a CEX ion population is present!

Cathode Lens and Ion Repeller (**CLAIR**)



CLAIR configuration

Function of CLAIR

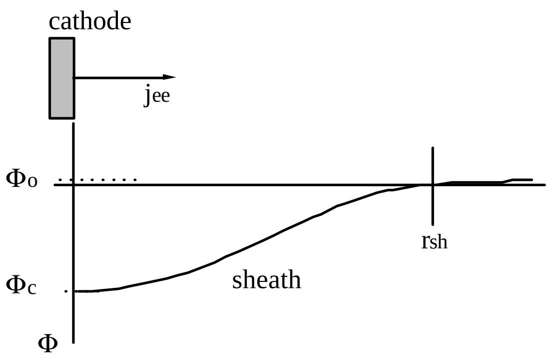
1. To de-couple electron energy from gate electrode potential to increase space-charge current limit without reducing cathode lifetime.
2. To shield the cathode microtips from the CEX ion population so that higher gate electrode voltages are tolerated with the required lifetime and smaller cathode dimensions.

Possible CLAIR parameters to decelerate the electron beam, focus it through the electrodes, and shield 65 eV ions from the cathode microtips.*

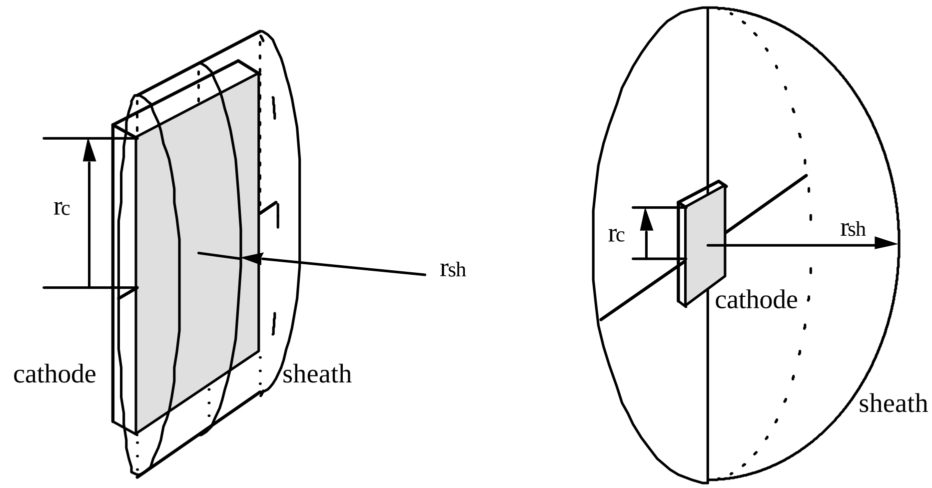
V_c (V)	V_g (V)	V_1 (V)	V_2 (V)	V_3 (V)	dg/v1 (µm)	dv1/v2 (µm)	dv2/v3 (µm)	$t_{1,3}$ (µm)	t_2 (µm)	t_g (µm)
-40	10	-10	100	-20	0.4	0.8	0.8	0.1	0.3	0.25

*CLAIR performance was validated using PIC code MAGIC!

Sheath Model Used to Study Space-Charge Current Limitations



Possible sheath profile.



Possible sheath configurations.

Characteristics of the plasma environments investigated.

	n_{eo} (/cm^3)	T_e (eV)	λ_D (mm)
Hall/Ion thruster side[a]	$8x10^8$	5	0.60
Hall thruster center[a]	$8x10^{10}$	1	0.03
Ion engine discharge chamber	$3x10^{11}$	2 - 3	0.02
Tether at 250 km	$5x10^5$	0.1	3.3

Sheath Model

nomenclature

n_{ee}=electron number density for population emitted from the cathode.
n_e=plasma electron number density
n_i=plasma ion number density
n_{io}=plasma ion number density at the sheath boundary
η=potential
λ_D=Debye length
T_e=electron temperature

Poisson's Eqn. describing potential distribution in the sheath:

$$-\frac{d^2(-f)}{dx^2} = \frac{r}{e_o} = \frac{e}{e_o}\left(n_i - n_{ee} - n_e\right)$$

Charged particle number densities:

$$n_i = n_{io}\left(1 + \frac{f}{f_o}\right)^{-\frac{1}{2}} \qquad n_e = n_{eo}\exp\left(\frac{-ef}{kT_e}\right) \qquad n_{ee} = \frac{j_{ee}}{\left(\frac{2e^3}{m_e}\right)^{1/2}}\left(V_g + f_c - f\right)^{-1/2}$$

Normalized parameters:

$$h = \frac{ef}{kT_e} \qquad x = \frac{x}{l_D} \qquad l_D = \left(\frac{e_o kT_e}{n_{eo}e^2}\right)^{\frac{1}{2}} \qquad j_e = n_{eo}e\left(\frac{2kT_e}{m_e}\right)^{1/2} \qquad J_{ee} = \frac{j_{ee}}{j_e}$$

Normalized form of Poisson's eqn. describing the planar sheath

$$\frac{d^2h}{dx^2} = \left(1 + J_{ee}\left(h_g + h_c\right)^{-\frac{1}{2}}\right)\left(1 + \frac{h}{h_o}\right)^{-\frac{1}{2}} - J_{ee}\left(h_g + h_c - h\right)^{-\frac{1}{2}} - \exp(-h)$$

Sheath Model

Andrews and Allen criterion at the sheath boundary used to determine the accelerating potential of the pre-sheath:

$$\left.\frac{dr}{dh}\right|_{h=0} = 0 \qquad\qquad h_o = \frac{1 + J_{ee}\left(h_g + h_c\right)^{-\frac{1}{2}}}{2 - J_{ee}\left(h_g + h_c\right)^{-\frac{3}{2}}}$$

Boundary conditions in the <u>planar</u> model:

$$1)\ \frac{dh}{dx}\left(h = 0\right) = 0 \qquad 2)\ h\left(x = 0\right) = h_c$$

Poisson’s eqn. for potential distribution in a <u>spherical</u> cathode sheath

$$\frac{d^2h}{dx^2} + \frac{2}{x}\frac{dh}{dx} = \bar{r}$$

$$= \left(1 + J_{ee}\left(h_g + h_c\right)^{-\frac{1}{2}}\left(\frac{x_c^2}{x_{sh}^2}\right)\right)\left(1 + \frac{h}{h_o}\right)^{-\frac{1}{2}}\left(\frac{x_{sh}^2}{x^2}\right) - J_{ee}\left(h_g + h_c - h\right)^{-\frac{1}{2}}\left(\frac{x_c^2}{x^2}\right) - \exp(-h)$$

Boundary conditions in the <u>spherical</u> sheath model:

$$1)\ h\left(x = x_{sh}\right) = 0 \qquad 2)\ \frac{dh}{dx}(x = x_{sh}) = 0$$

Sheath Modeling Results

Space-charge current limits estimated by the planar sheath model for thruster and tether environments.

	n_{eo} (/cm^3)	T_e (eV)	V_g (V)	ϕ_c (V)	j_{eemax} (mA/cm^2)
Hall thruster-side	8x10^8	5	500	20	160
	8x10^8	5	100	20	68
	8x10^8	5	30	20	34
	8x10^8	1	30	20	17
Hall thruster-center	8x10^{10}	1	30	20	1,700
	8x10^{10}	1	100	20	2,884
Ion engine	3x10^{11}	2	30	20	8,800
Tether*	5x10^5	0.1	30	20	0.003
	5x10^5	0.1	100	20	0.005
	5x10^5	0.1	1000	20	0.016
	5x10^5	0.1	30	100	0.002

* sheath near a tether may not be planar

Space-charge limited currents predicted by the planar, cylindrical, and spherical sheath models in non-dimensional units.

geometry	ξ_c	ξ_{sh}	η_c	η_g	η_o	$J_{e\,max}$
planar		20.0	4	6	0.85	2.0
cylindrical	40	54.0	4	6	0.87	2.9
cylindrical	20	32.0	4	6	0.87	3.5
cylindrical	10	19.4	4	6	0.85	4.0
cylindrical	1	9.4	4	6	0.81	17.0
cylindrical	1	18.4	20	6	0.55	9.8
spherical	40	48.6	4	20	1.34	31.0
spherical	40	47.0	4	6	1.34	6.5
spherical	20	27.0	4	6	1.22	7.4
spherical	10	17.0	4	6	1.10	9.9
spherical	1	6.8	4	6	0.76	70.0
spherical	0.4	5.4	4	6	0.65	168.0

Space-Charge Current Limits for Spherical Sheaths in Tether Environments

Model results show effect of cathode parameters on current limits

- Cathode dimensions
- Electron energy
- Cathode potential

ξ_c	ξ_{sh}	η_c	η_g	η_o	J_{eemax}
5	100	200	300	0.52	430
1	97	200	300	0.52	8650
1	104	200	1000	0.52	18400
1	109	200	10000	0.53	63550
1	100	100	300	0.53	4925
1	37	50	300	0.55	2750
1	38	50	1000	0.56	5350
1	38.5	50	10000	0.56	17400

ξ_c	r_c(mm)	V_c (V)	V_g (V)	I_{ee} (mA)
5	16.5	20	30	7.0
1	3.3	20	30	5.6
1	3.3	20	100	12
1	3.3	20	1000	41.4
1	3.3	10	30	3.2
1	3.3	5	30	1.8
1	3.3	5	100	3.5
1	3.3	5	1000	11.4

Research Conclusions

1. FE cathodes can operate in environments similar to Hall and ion thruster environments.
2. Φ_w does not increase from Xe exposure for Mo, Si or C.
3. Carbon film cathodes are incredibly robust, but need to operate at higher efficiency.
4. FEA cathodes are very sensitive to V_g in xenon environments.
5. FEA cathodes can operate below voltage threshold in xenon environments without getting damaged.
6. Performance degradation model results are consistent with experimental results.
7. E_{th} for sputtering Mo is estimated to be ~39 eV and Si is ~45 eV when bombarded by Xe ions!
8. CEX ion population will be incredibly detrimental to FEA cathodes used with thrusters unless operated at ~20 V below E_{th} for sputtering!
9. Sheath and performance degradation models can be used to design Mo and Si cathodes for electric propulsion applications.
10. Compatibility of FEA cathodes could be significantly improved with CLAIR by shielding the cathode from CEX ion bombardment, allowing higher operating voltages to reduce the size of cathode arrays required for the desired current, and to de-couple electron energy from the gate electrode potential to increase space-charge current limits.

Recommended Future Work

- Test HfC, ZrC, Mo, and Si cathodes with current limiting(VECTL) architectures.
- Acquire and test cathodes with >100,000,000 tips and smaller dimensions (r_g~0.2 um)
- Determine E_{th} for sputtering **HfC** and **ZrC** with xenon ions.
- Develop new Hall thruster and start-up sequence.
- **Develop cathode structure with CLAIR.**
- **Get microtips deposited into CLAIR structure.**
- **Help miniaturize the carbon film cathodes to decrease operating voltages to 20-50 V and increase efficiency by microfabricating gate electrode blank structures.**
- Conduct current sharing experiments with a Hall thruster and hollow cathode.
- Study space-charge limited emission experimentally.
- Study the cathode sheath structure experimentally.

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