PLASMA PHYSICS SUMMER SCHOOL

P-24
Plasma Physics
Los Alamos
NATIONAL LABORATORY

# INTRODUCTION TO SPACE PLASMA PROPULSION


## *by Leonid Dorf*



***Special thanks to***: *Hall Thruster eXperiment at PPPL (go to URL: htx.pppl.gov), and Jahn, R. G. and Choueiri, E. Y. (2002). Electric Propulsion. In Encyclopedia of Physical Science and Technology, 3rd Edition (Academic Press, San Diego), Vol. 5, p. 125.*

Presented at Plasma Physics Summer School
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# Abstract

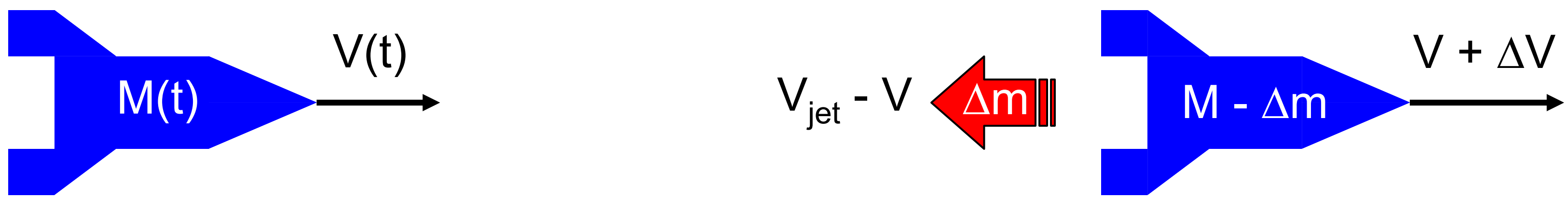
Electric propulsion (EP) devices utilize a constantly renewable on-orbit resource (electric power from solar arrays or a nuclear source) to minimize the consumption of non-renewable on-board propellant. The EP techniques group broadly into three categories: electrothermal propulsion, wherein the propellant is electrically heated, then expanded thermodynamically through a nozzle; electrostatic propulsion, wherein ionized propellant particles are accelerated through an electric field; and electromagnetic propulsion, wherein current driven through a propellant plasma interacts with an internal or external magnetic field to provide thrust. Such systems can produce a range of exhaust velocities and payload mass fractions an order of magnitude higher than that of the most advanced chemical rockets, which can thereby enable or substantially enhance many attractive space missions. The attainable thrust densities (thrust per unit exhaust area) of these systems are much lower, however, which predicates longer flight times. This talk will focus mainly on the electrostatic and electromagnetic propulsion techniques, also called plasma propulsion, due to the nature of the propellant. Principles of operation, key issues, and commonly used diagnostics are discussed in detail for such complex devices as magnetoplasmadynamic thruster (MPDT), pulsed plasma thruster (PPT), ion thruster (IT), Hall thruster (HT), cylindrical Hall thruster (CHT), VASIMR, and others. Key physical questions specific to Hall thrusters are also elucidated.

# Outline

- Basic Concepts and Equations of Propulsion
- Types of Plasma Propulsion
- Electrothermal propulsion
- Electrostatic Propulsion: Ion Thrusters
- Electromagnetic Propulsion: MPD, PPT, TAL, VASIMR, HT, CHT
- Hall Thruster Diagnostics: plume divergence, electron temperature, etc
- Anode Sheath in Hall Thrusters

# Rocket Equation

Time = t $\longrightarrow x$ Time = t + $\Delta t$




<u>Momentum Conservation:</u> P (t) = Const

$P_x(t) = M\,V$

$P_x(t + \Delta t) = (M - \Delta m)\,(V + \Delta V) - \Delta m\,(V_{jet} - V) = M\,V + M\,\Delta V - \Delta m\,V_{jet}$

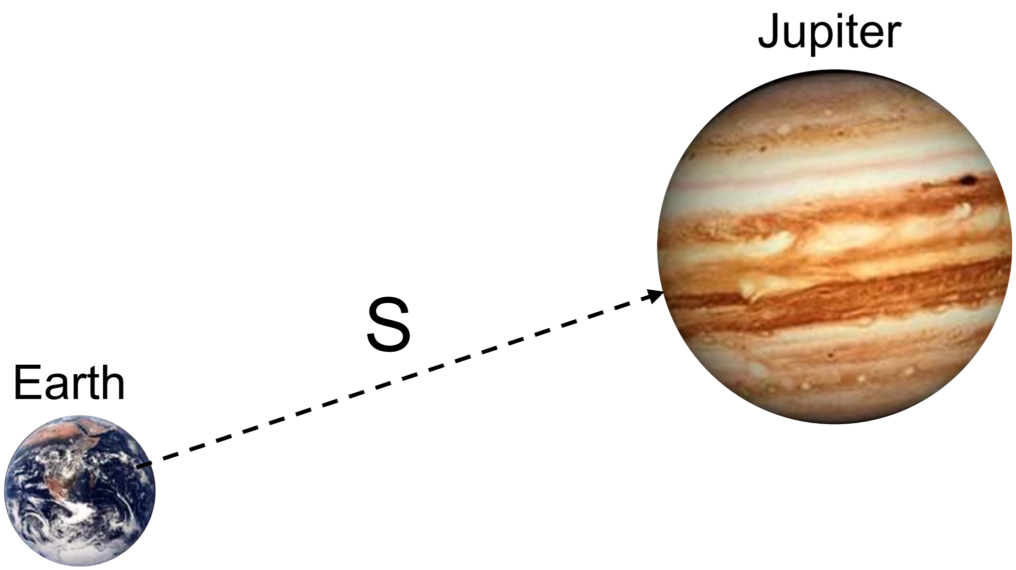
$\Delta m = \mu\,\Delta t$

$$\mathbf{M\,dV/dt = \mu\,V_{jet}}$$ – Rocket (Mescherskii's) Equation

$$\mathbf{V(t) = V_{jet}\,\ln[M_0 / M(t)]}$$ – Tziolkovskii's Formula

# Electric Propulsion = Large Exhaust Velocity

**$V_{jet}$ (plasma) ~ 10 – 100 km/s >> $V_{jet}$ (chemical) ~ 3 km/s**



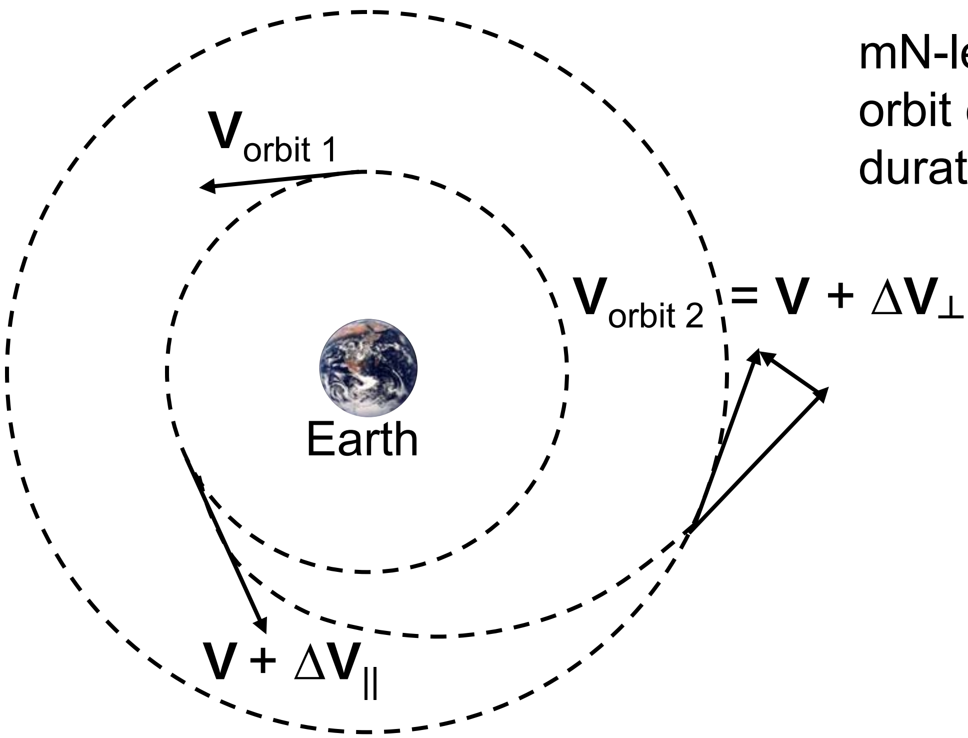

Interplanetary Missions:

$$M_{fuel} \approx \sqrt{2 M_{sat} \eta P S / V_{jet}^3}$$

$$t_{flight} \approx \sqrt{2 V_{jet} M_{sat} S / \eta P}$$

**Higher $V_{jet}$ → LESS FUEL (but longer time)**

# Limit on Exhaust Velocity




## On-Orbit Station Keeping

mN-level plasma thrusters are perfect for orbit correction tasks (precise, short-duration kicks)

$$\Delta V = T\ \Delta t / M_{sat}$$

$$T = 2\eta\ P / V_{jet}$$

**Limit on $V_{jet}$ is set by mission time requirements**

# Types of Electric Propulsion

1. ***Electrothermal propulsion***, wherein the propellant is heated by some electrical process, then expanded through a suitable nozzle

    a. *Resistojets*
    b. *Arcjets*
    c. *Inductively and radiatively heated devices*

2. ***Electrostatic propulsion***, wherein the propellant is accelerated by direct application of electrostatic forces to ionized particles

    a. *Ion Thrusters (IT)*
    b. *Field Emission Electric Propulsion (FEEP)*
    c. *Colloidal Thrusters*

3. ***Electromagnetic propulsion***, wherein the propellant is accelerated under the combined action of electric and magnetic fields

    a. *MagnetoPlasmaDynamic (MPD) Thrusters*
    b. *Hall Thrusters (HT)*
    c. *Pulsed Plasma Thrusters (PPT)*
    d. *Inductive Thrusters*

# Electric Propulsion in US and USSR

Ernst Stuhlinger's book
*"Ion Propulsion for Space Flight"*

Hall thrusters have been used on Soviet and
Russian spacecraft since the mid-1970s

Resistojets became common options
for station keeping and attitude control

Electrothermal arcjets were adopted for NSSK
of many communication satellites in GEO

1st use of ion thrusters for NSSK

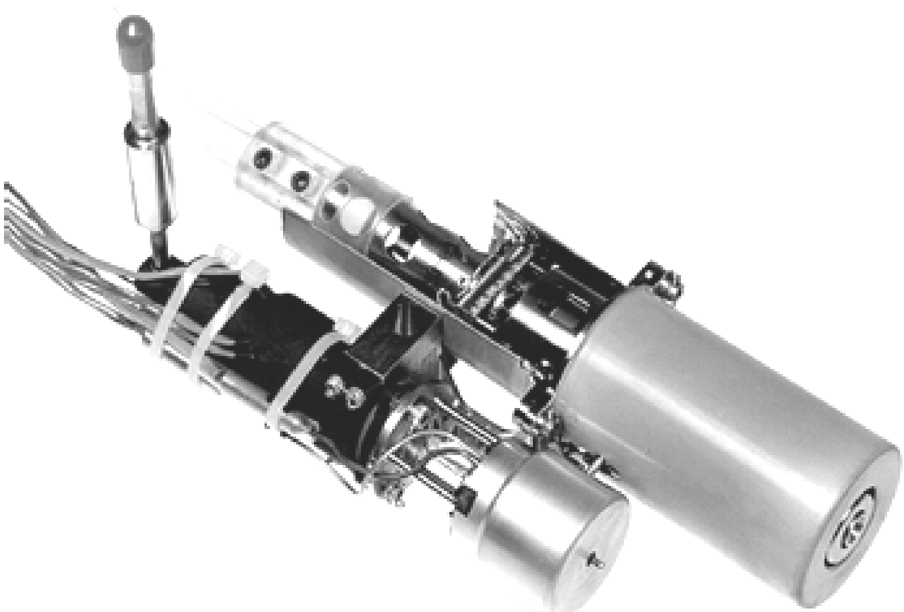
DEEP SPACE 1

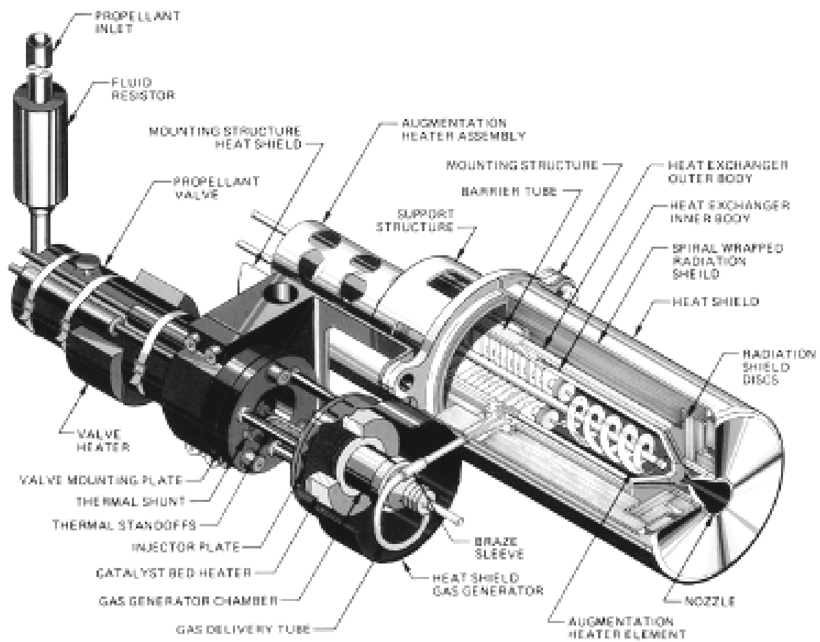
1960 1970 1980 1990 1994 1998

**< 10** **>10** **10s** **> 100**

# Electrothermal Resistojet

*Heat is transferred to propellant (hydrazine) from some solid surface, such as chamber wall or heater coil*






Power level: 750 Watts

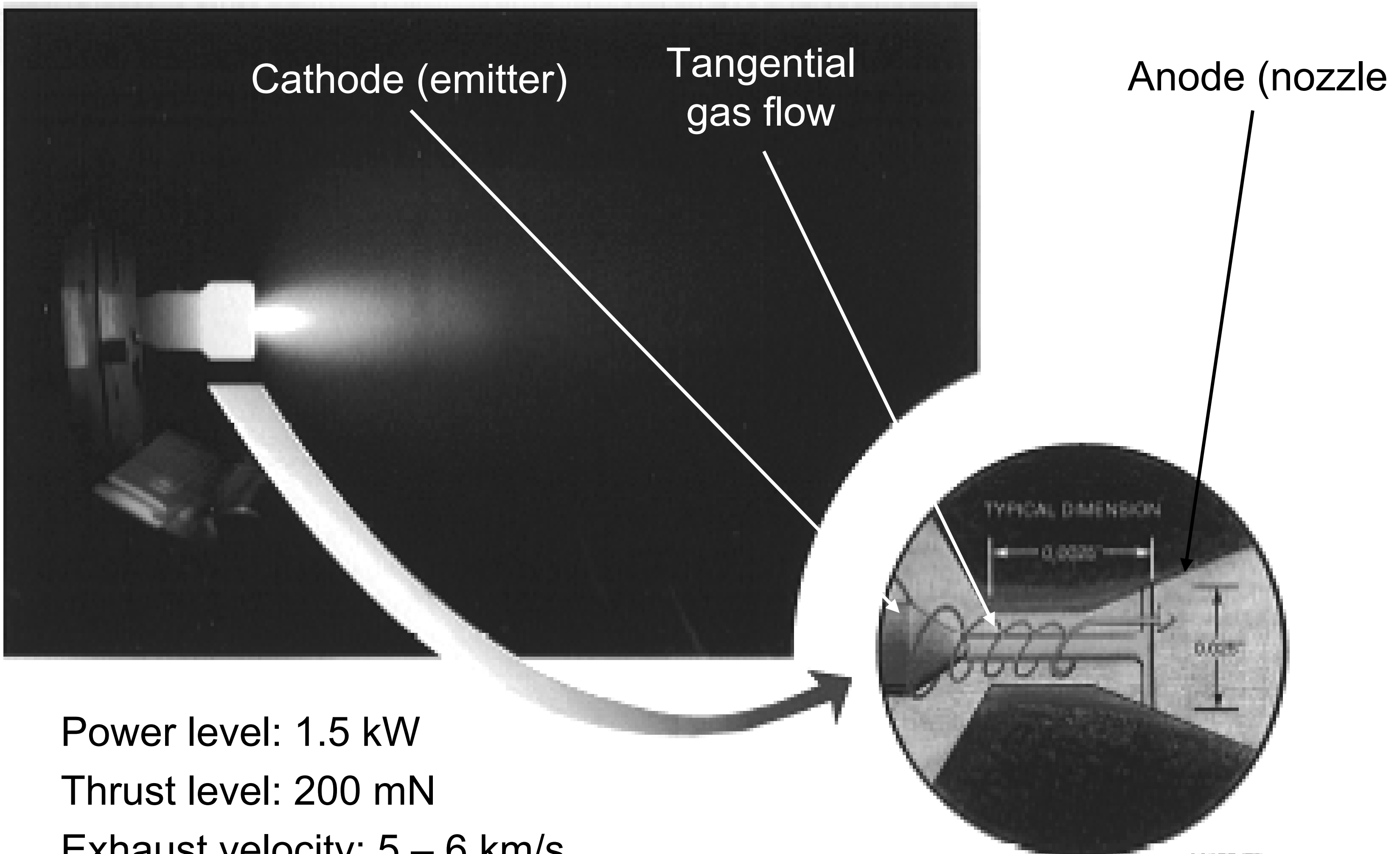
Thrust level: 300 mN

Exhaust velocity: 3.5 km/s

Efficiency: 80 %

# Electrothermal Arcjet

*Propellant (hydrazine) is heated by an electric arc driven through it*




Power level: 1.5 kW

Thrust level: 200 mN

Exhaust velocity: 5 – 6 km/s

Efficiency: 40 %

# Glossary of Plasma Propulsion

THRUST

$$T[mN] = V_i \cdot \langle \cos\Theta \rangle \cdot I_i \cdot \frac{M_i}{e} = \mu\, \eta_{ioniz} V_{jet}$$

SPECIFIC IMPULSE

$$I_{sp}[s] = \frac{V_{jet}}{g}$$

IONIZATION EFFICIENCY

$$\eta_i = \frac{I_i}{I_m}$$

ENERGY EFFICIENCY

$$\eta_W = \frac{1/2 \cdot M_i V_i^2 \cdot I_i \cdot < \cos^2\Theta >}{P_{in}}$$

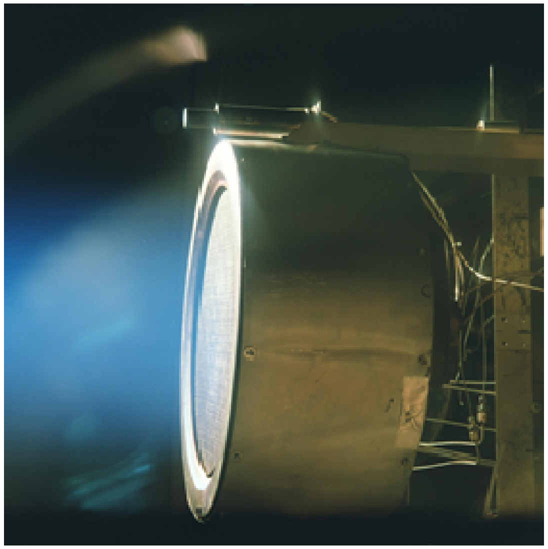
THRUST EFFICIENCY

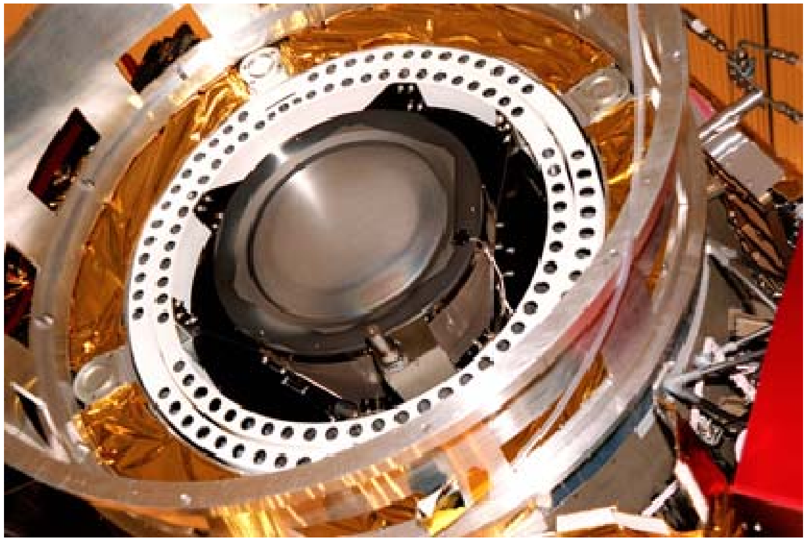
$$\eta = \eta_i \cdot \eta_W \cdot \eta_c \approx \frac{1}{2} \cdot \frac{T^2}{\dot{m} \cdot P_{in}}$$

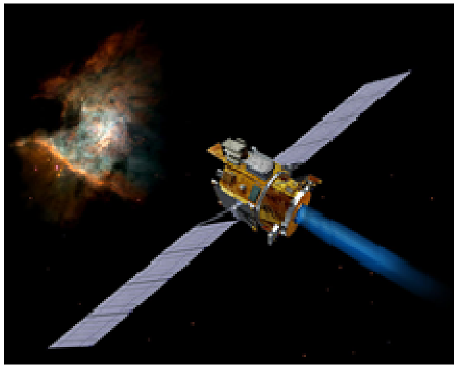
PLUME DIVERGENCE

$$\langle \cos^n \Theta \rangle \overset{def}{=} \frac{\int_{2\pi(outwards)} d\Omega(\Theta,\varphi) \cdot j_i(\Theta,\varphi) \cdot \cos^n\Theta}{\int_{2\pi(outwards)} d\Omega(\Theta,\varphi) \cdot j_i(\Theta,\varphi)}$$

# Ion Thrusters (Xe, Ar, Kr)







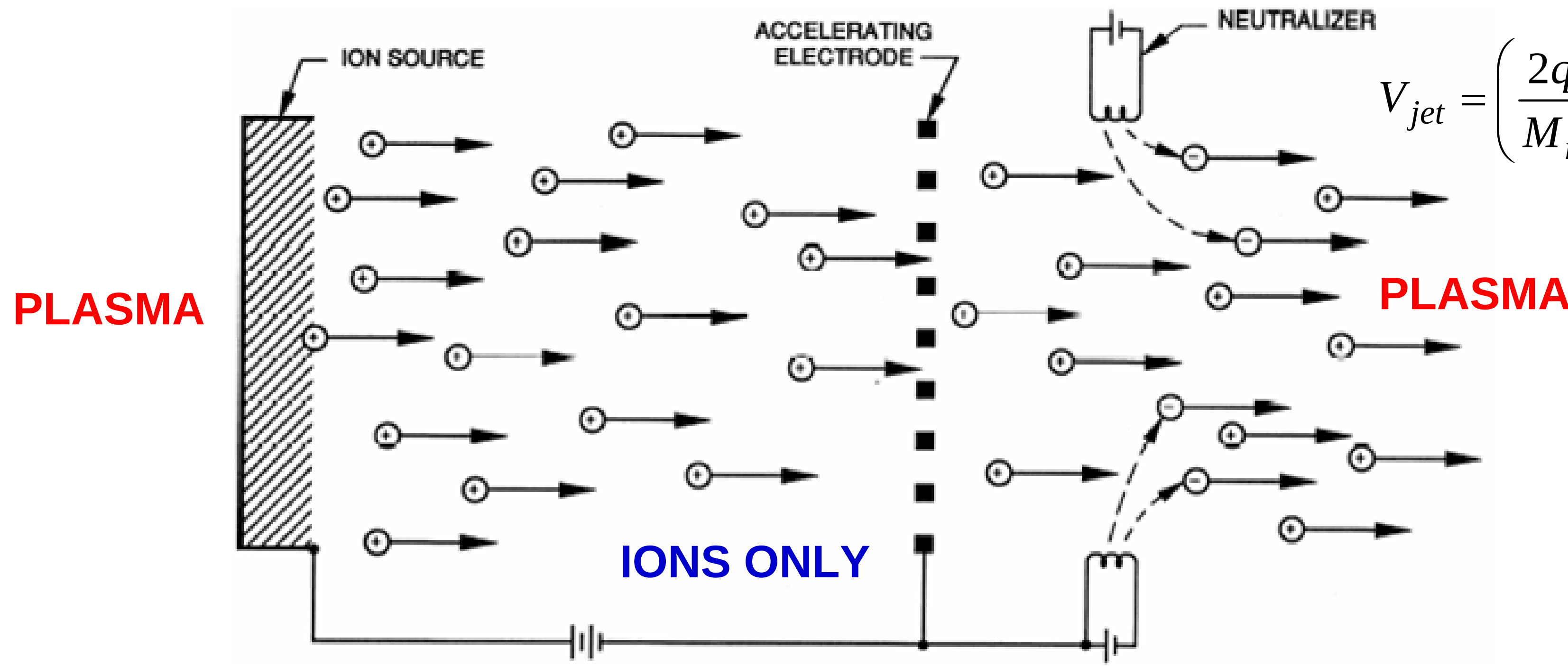
## Deep Space-1 Ion Engine Images

*launched from Cape Canaveral on October 24, 1998.*

$I_{sp}$ = 1500 – 4000 s     ***Diam*** = 2.5 – 150 cm     ***P*** = 50 W – 200 kW

*In the US, ion engines were developed at NASA's Lewis Research Center in the late 50-s under the guidance of Dr. Harold Kaufman. Flight experiments started from 1965.*

# Electrostatic Acceleration of Ions by Applied DC Voltage




$$V_{jet} = \left( \frac{2qV}{M_{ion}} \right)^{1/2}$$

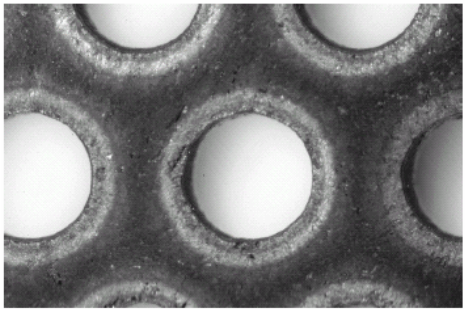
$$j = \frac{4\varepsilon_0}{9} \left( \frac{2q}{M} \right)^{1/2} \frac{V^{3/2}}{d^2}$$

Child-Langmuir law limits maximum ion current density that can be extracted from ionization stage (ion source)

$$\frac{T}{A} = \frac{\dot{m} V_{jet}}{A} = \frac{j M_{ion} V_{jet}}{q} = \frac{8\varepsilon_0}{9} \left( \frac{V}{d} \right)^2$$

Maximum thrust density does not depend on the mass flow rate

# Key Issue of Ion Thrusters



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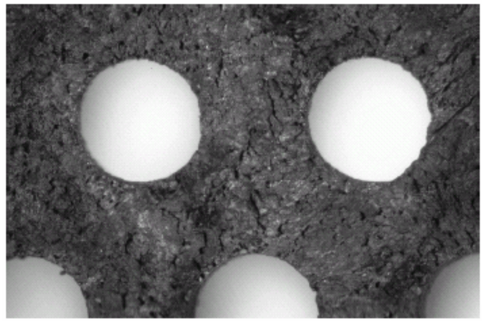

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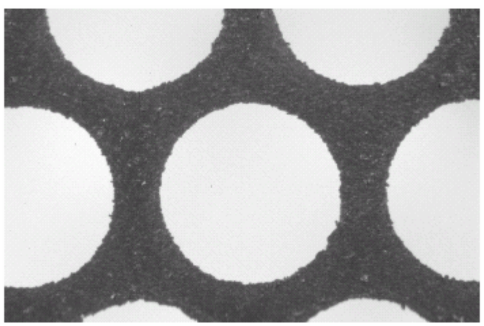
***Accelerator grid***

***Upstream side***

*Y. Hayakawa, S. Kitamura, and K. Miyazaki. Endurance Test of C/C Grids for 14-cm Xenon Ion Thrusters. AIAA 2002-3958*



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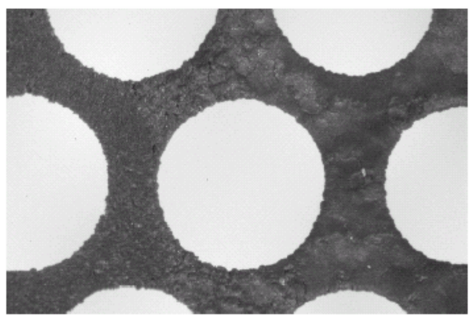

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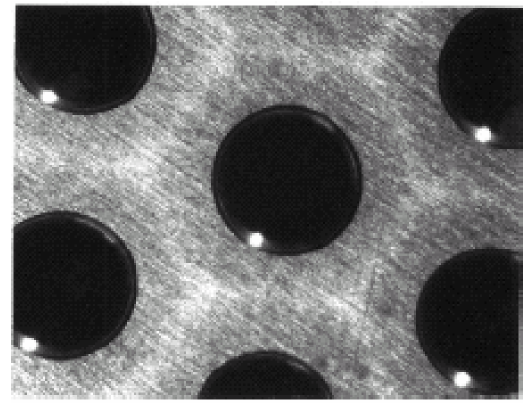
***Screen grid***

***Downstream side***

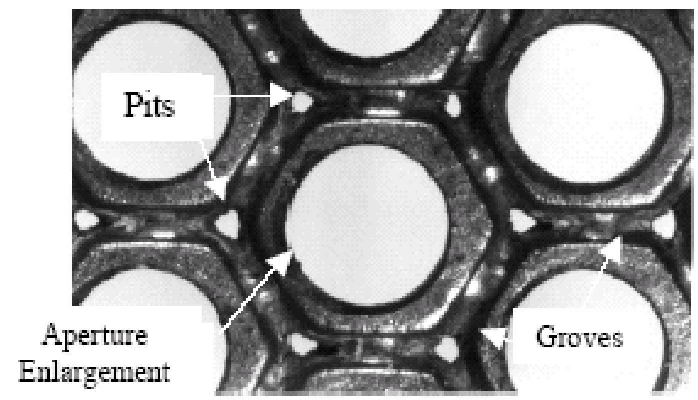


normal

***Accelerator grid***

***Downstream side***

damaged




*Soulas, G. C., "Improving the Total Impulse Capability of the NSTAR Ion Thruster with Thick-Accelerator Grid Ion Optics," IEPC-01-081*

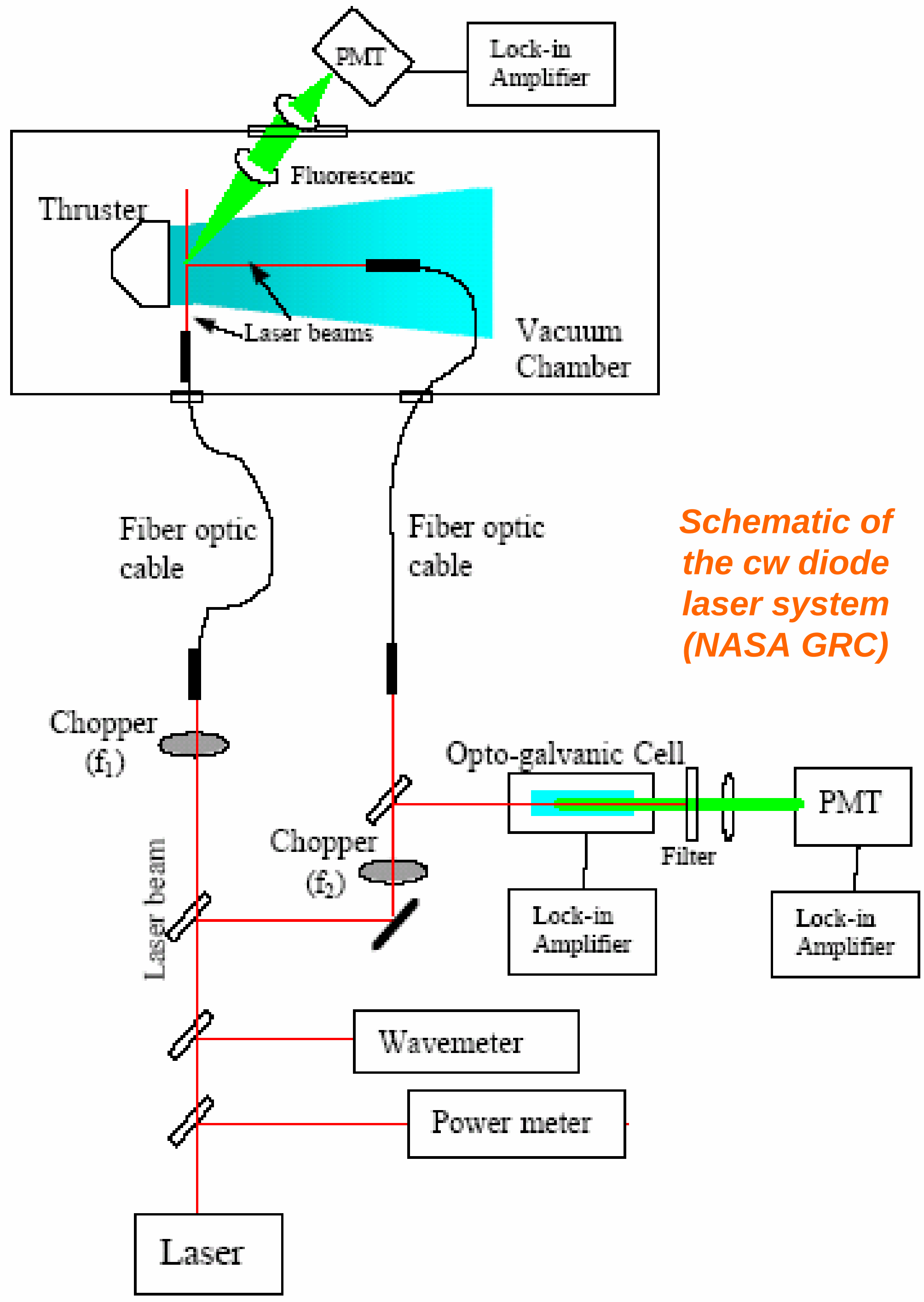
***Grid erosion due to ion bombardment limits thruster lifetime***

# Ion Thruster Diagnostics (Non-Intrusive )

***Laser-Induced Fluorescence*** – *for measurements of ion velocity and energy*

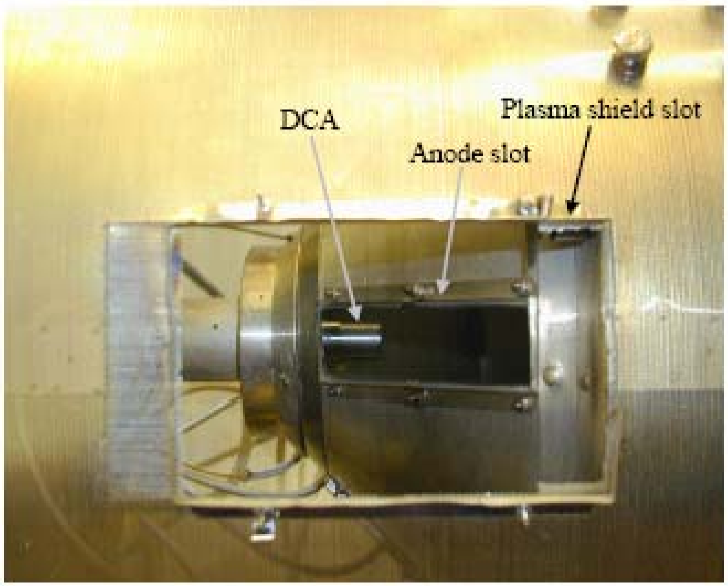
***Laser Interferometry*** – for measurements of electron, ion, and neutral densities

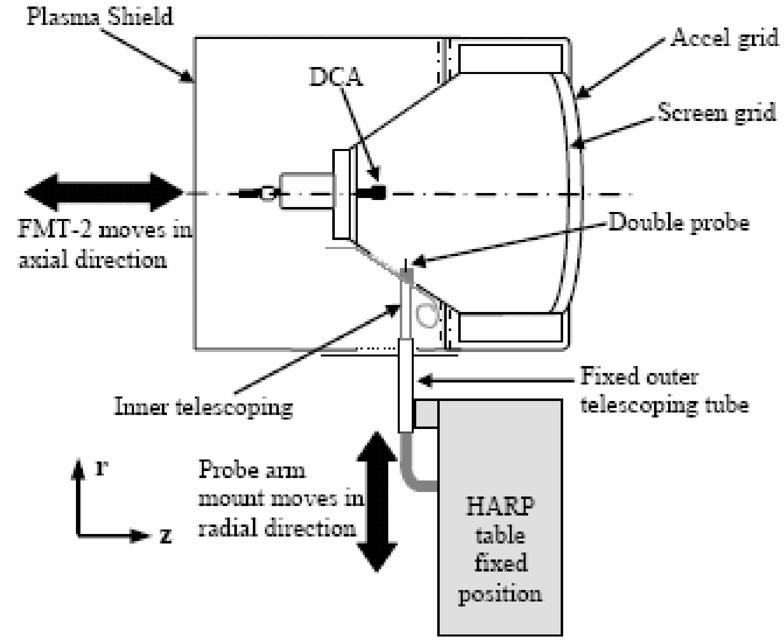
***Spectrographic analysis*** of quartz crystal microbalances and fused silica samples placed in the plume – for determining the content and origin of the non-propellant flux coming out (erosion assesment)



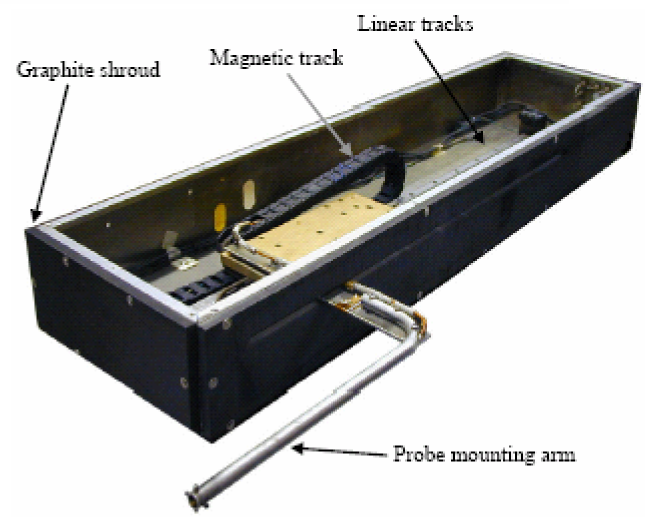

*Schematic of the cw diode laser system (NASA GRC)*

# Ion Thruster Diagnostics (Intrusive )




Double and single Langmuir probes were employed at ***PDEPL (Michigan)*** to measure 2-D electron temperature and density profiles inside the IT, which can give an insight to the issue of Discharge Cathode Assembly (DCA) erosion – another lifetime limiting process in IT.




**High Speed Axial Reciprocating Probe (HARP) positioning table (probes can't spend much time inside thruster)**

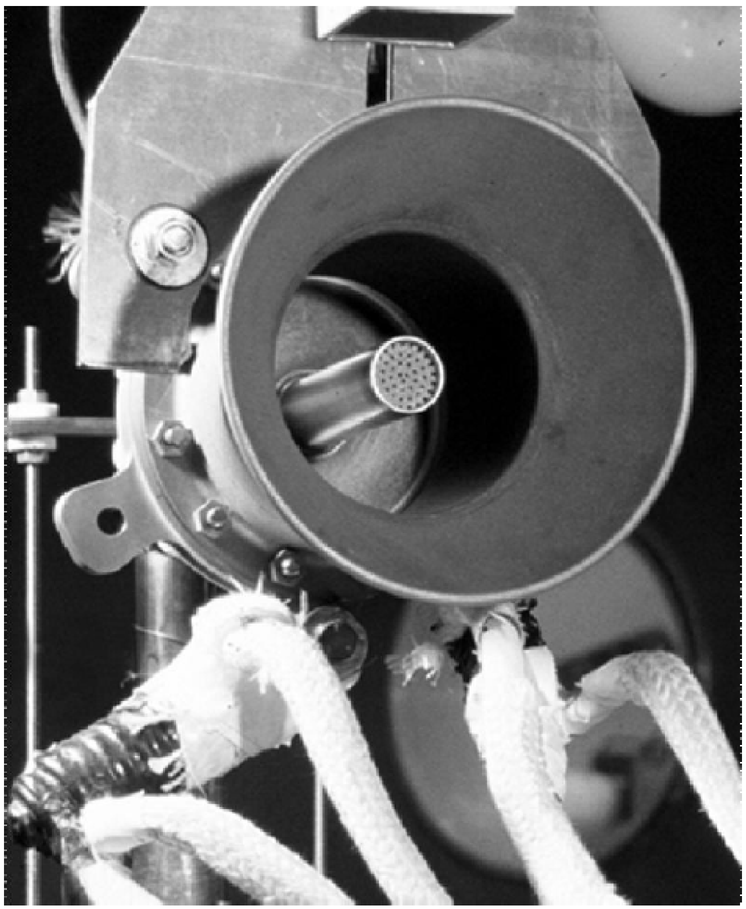
# E&M Propulsion: MPD Thrusters

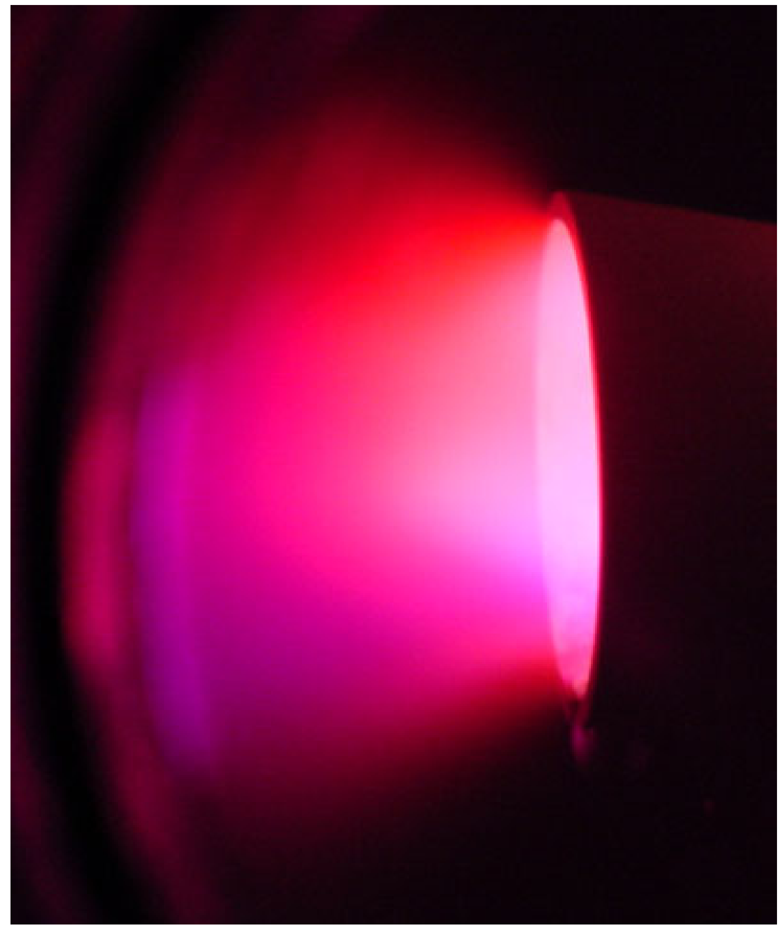
*I sp* = 1500 -8000 sec

Efficiency > 40%

Power: 200 kW – 1 MW

Thrust Density: $10^5$ N/m$^2$



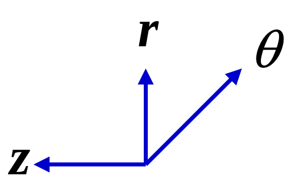


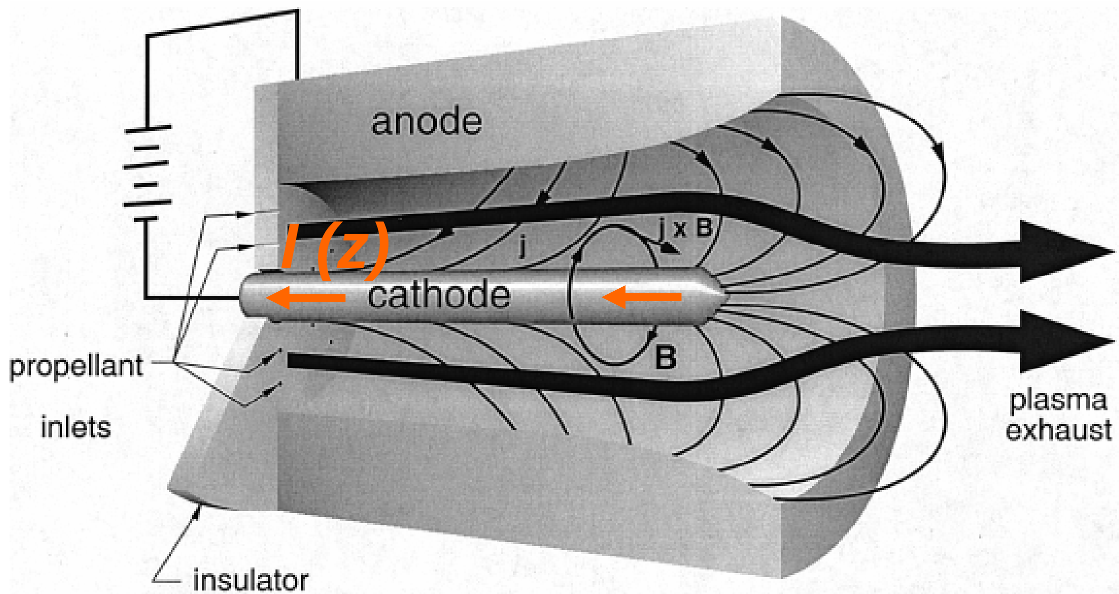
Princeton 100 kW-class Lithium Lorentz-Force Accelerator (MPD-T)

# Simple Thrust Formula for MPD Thrusters

$$T = \frac{\mu_0}{4\pi} I_{tot}^2 \left( \ln \frac{r_c}{r_a} + A \right)$$

*A ≤ 1 – geometrical factor*




1. $dF_z = -j_r(z,r)\, B_\theta(z,r)\, dV$

2. $B_\theta(z,r) \cong \dfrac{\mu_0 I(z)}{2\pi r}$

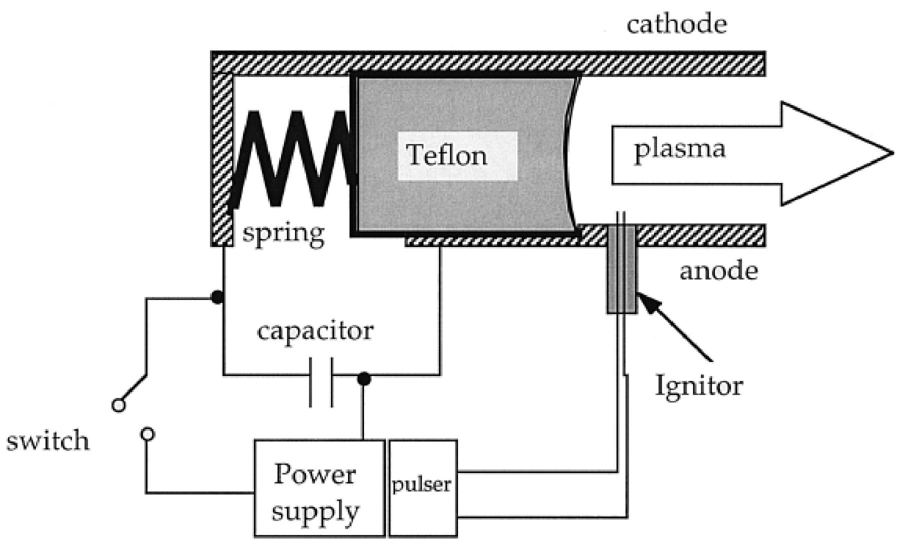
3. $\dfrac{dI}{dz} = j_c 2\pi r_c$

4. $j_r(z,r) \cong \dfrac{j_c(z) r_c}{r}$

5. $T = \displaystyle\int_0^L dz \int_{r_c}^{r_a} 2\pi r dr \left( j_r\ B_\theta \right) = \frac{\mu_0}{2\pi} \int_0^L dz \frac{dI}{dz} I \int_{r_c}^{r_a} \frac{dr}{r} = \frac{\mu_0}{4\pi} I_{tot}^2 \ln \frac{r_c}{r_a}$

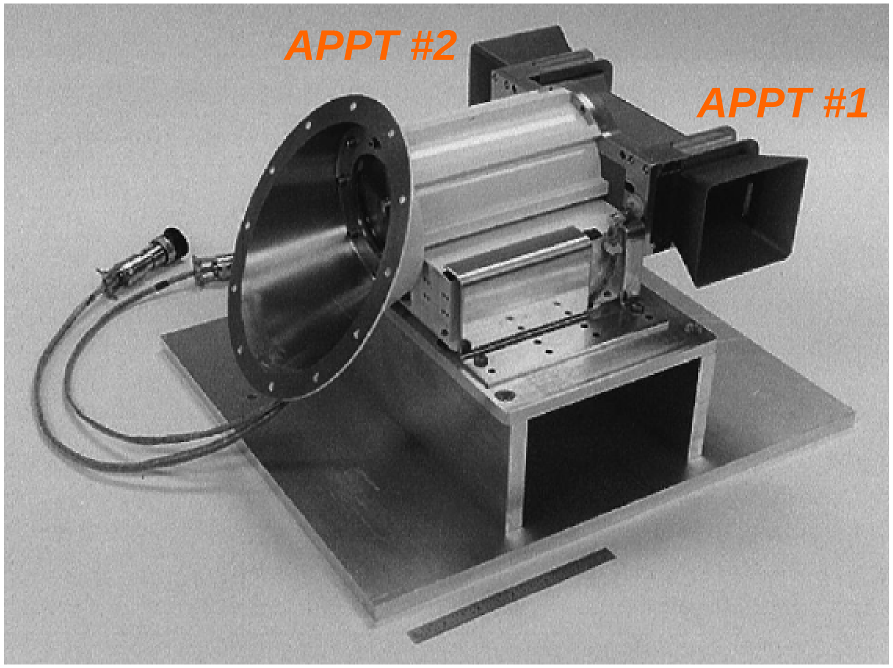
# Pulsed Plasma Thrusters

*Small power systems to drive plasma thrusters in short (10-usec) bursts of high instantaneous power (10 MW).*




Efficiency ~ 15 – 20%

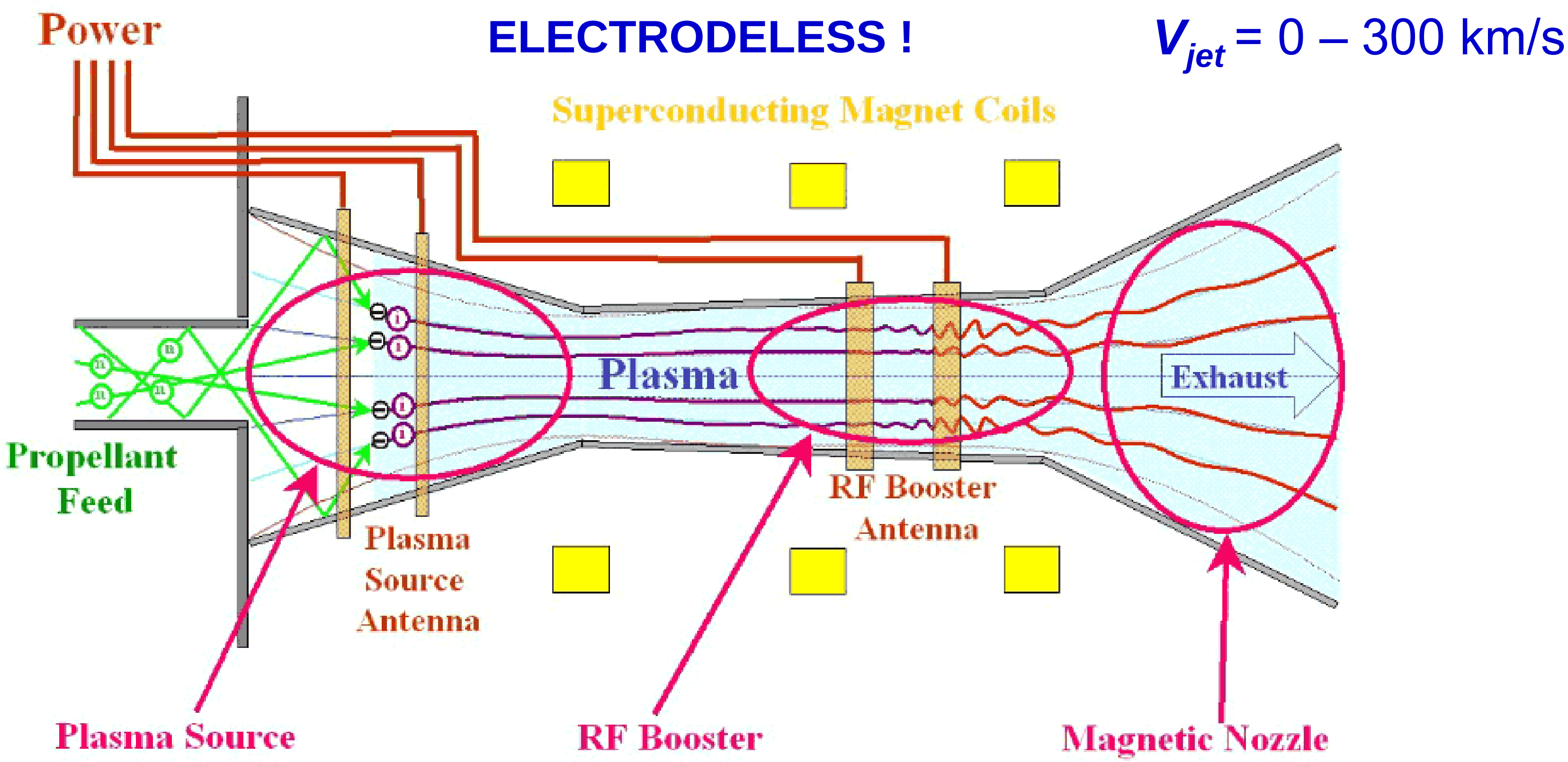
$I_{sp}$ ~ 5000 sec




*Flight-ready Teflon APPT module with 2 thrusters*

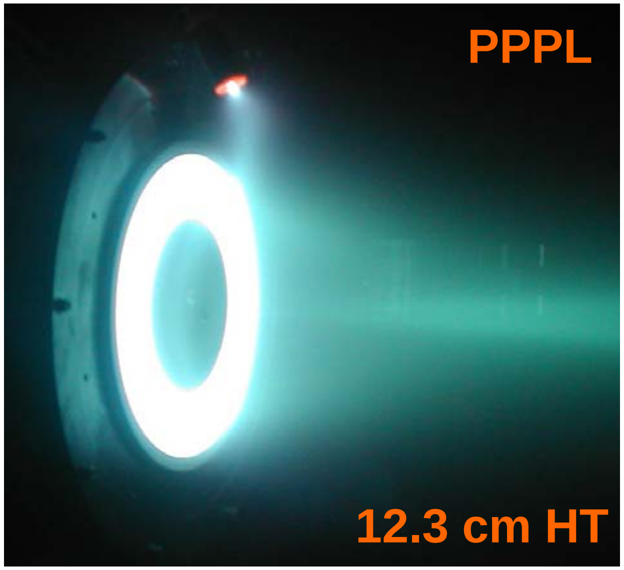
In ***Ablative Pulsed Plasma Thruster (APPT)***, the surface of a Teflon© block is successively eroded by intermittent arc pulses driven across its exposed face, and the ablated material is accelerated by a combination of thermal expansion and self-field electromagnetic forces.

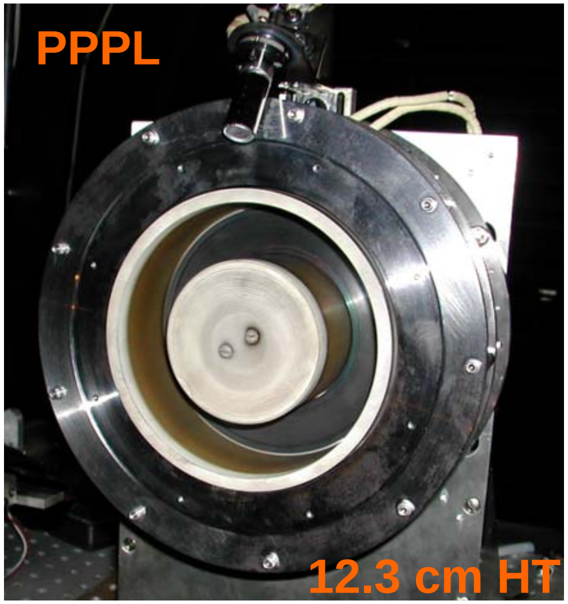
# Variable Specific Impulse Magnetoplasma Rocket (VASIMR)




1. Neutral gas (hydrogen) is injected into the **forward cell**, where it is ionized.
2. The resulting plasma is then heated in the **central cell**, to the desired temperature and density, by use of radio-frequency excitation and ion cyclotron resonance.
3. Once heated, the plasma is magnetically and gas-dynamically exhausted by the **aft cell** (asymmetric magnetic mirror = magnetic nozzle) to provide modulated thrust.

# Hall Thrusters




*Power* = 0.2 – 3 kW

*Voltage* = 0.1 – 1 kV

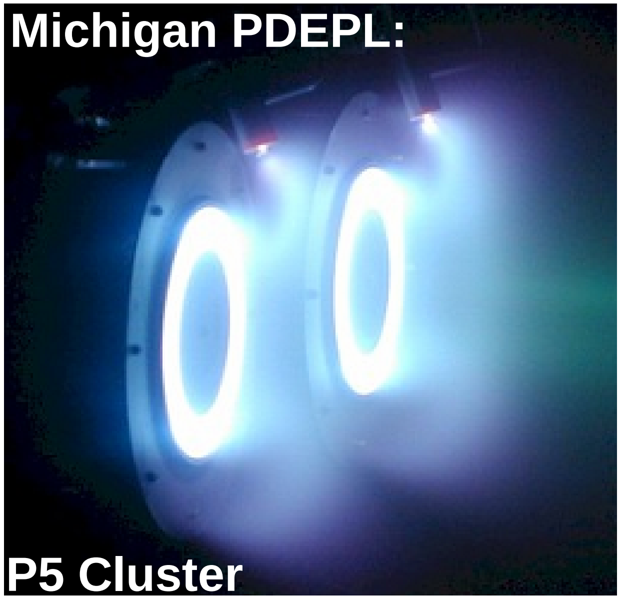
*Current* = 2 – 5 A

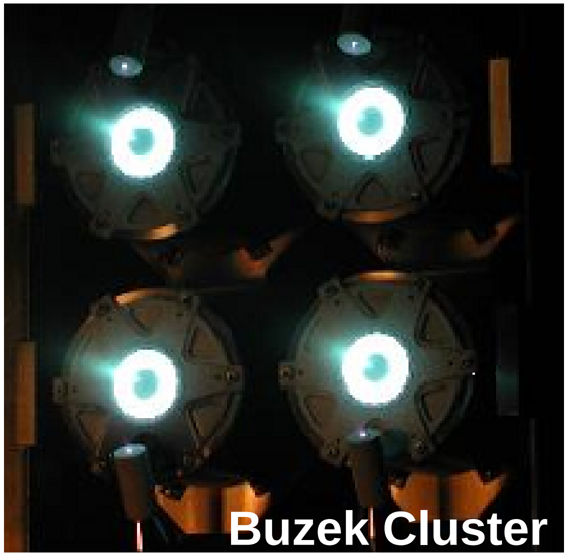
$\mu$ *(Xe)* = 2 – 5 mg/s

$V_{jet}$ = 15 – 25 km/s

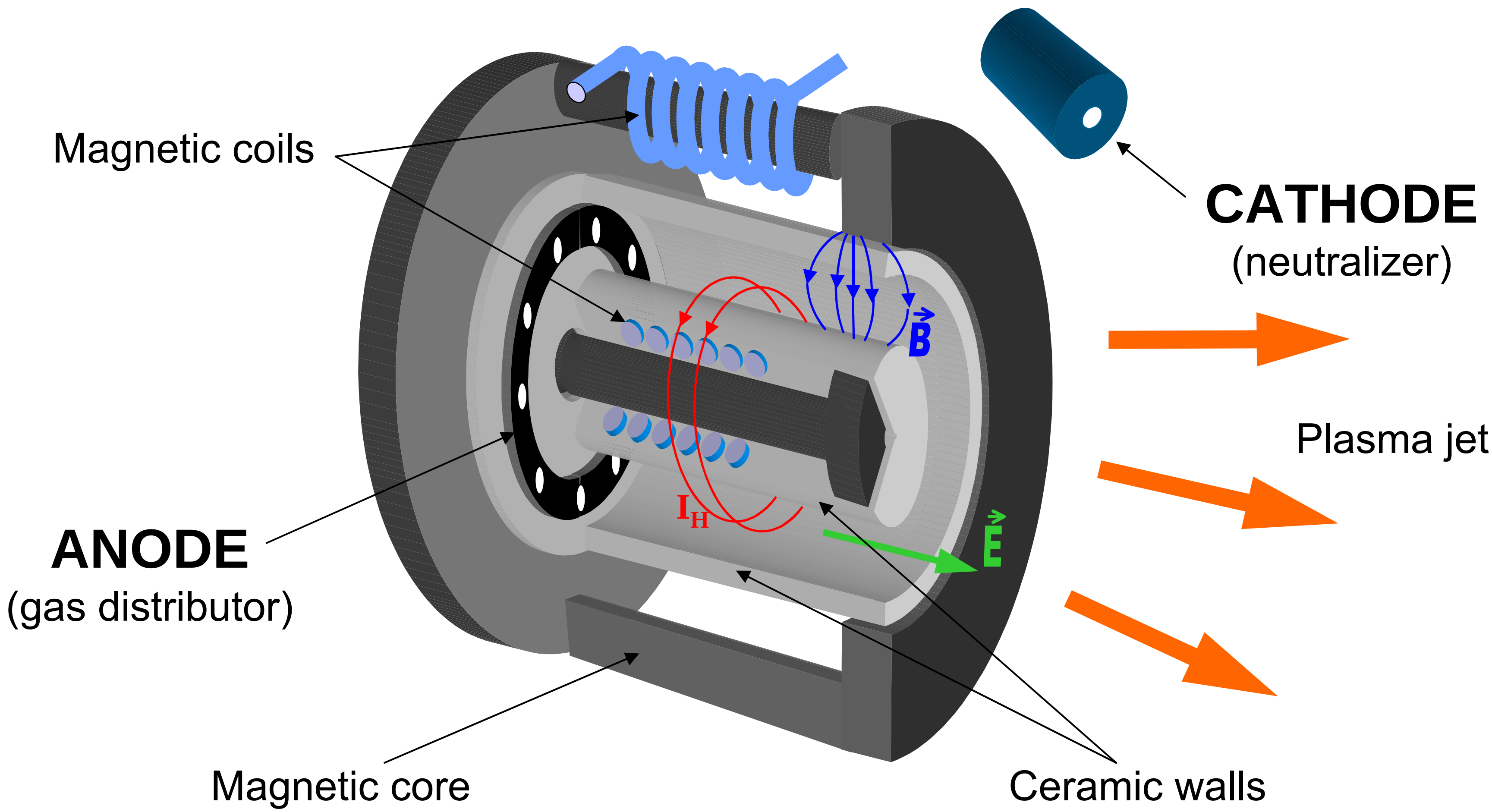
*Thrust* = 40 – 80 mN

*Efficiency* ~ 50%



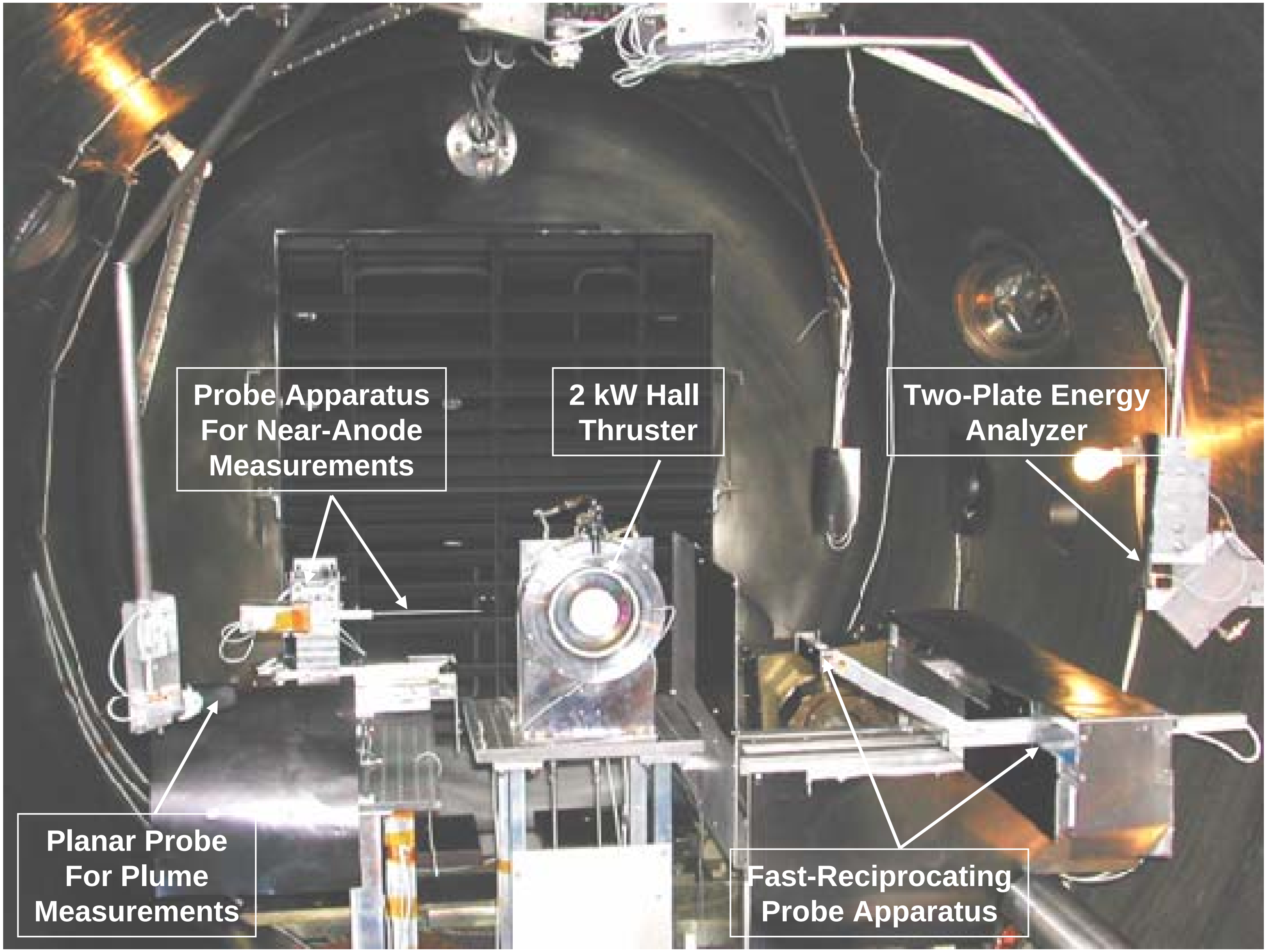



# Hall Thruster is an ExB Discharge Device

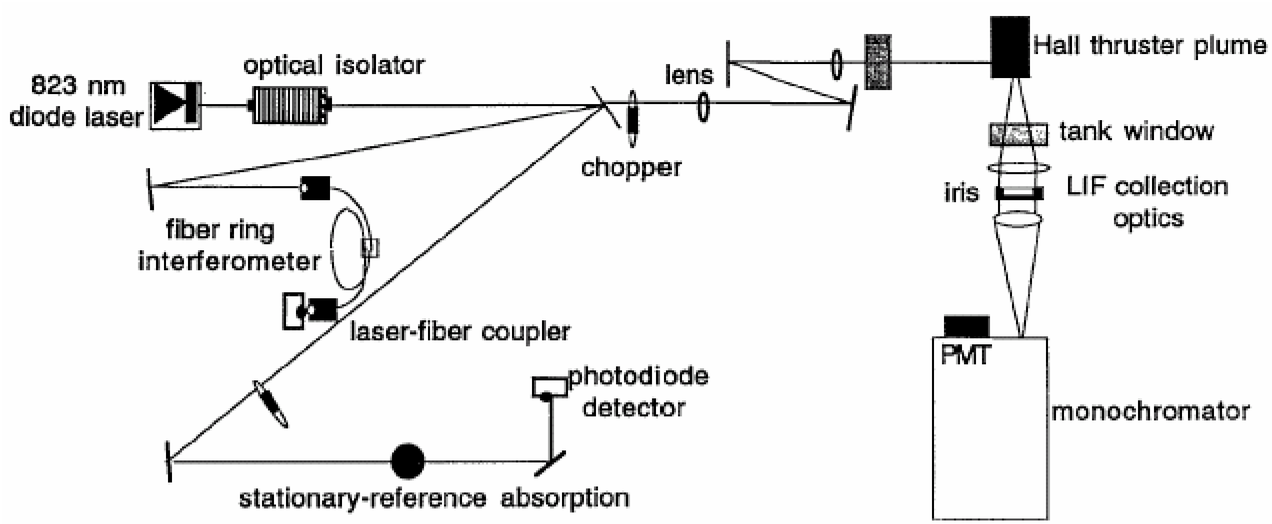



$$r_{Li} >> L_{channel} >> r_{Le}$$

# Hall Thruster Experiment at PPPL

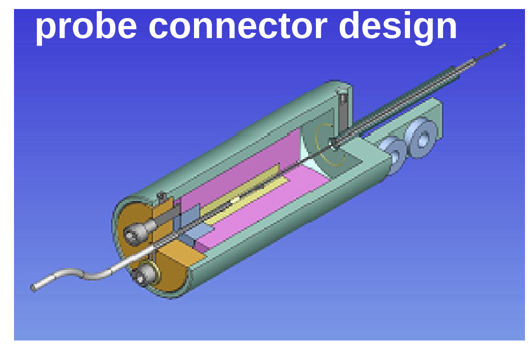


# Hall Thrusters Diagnostics (LIF and HF)



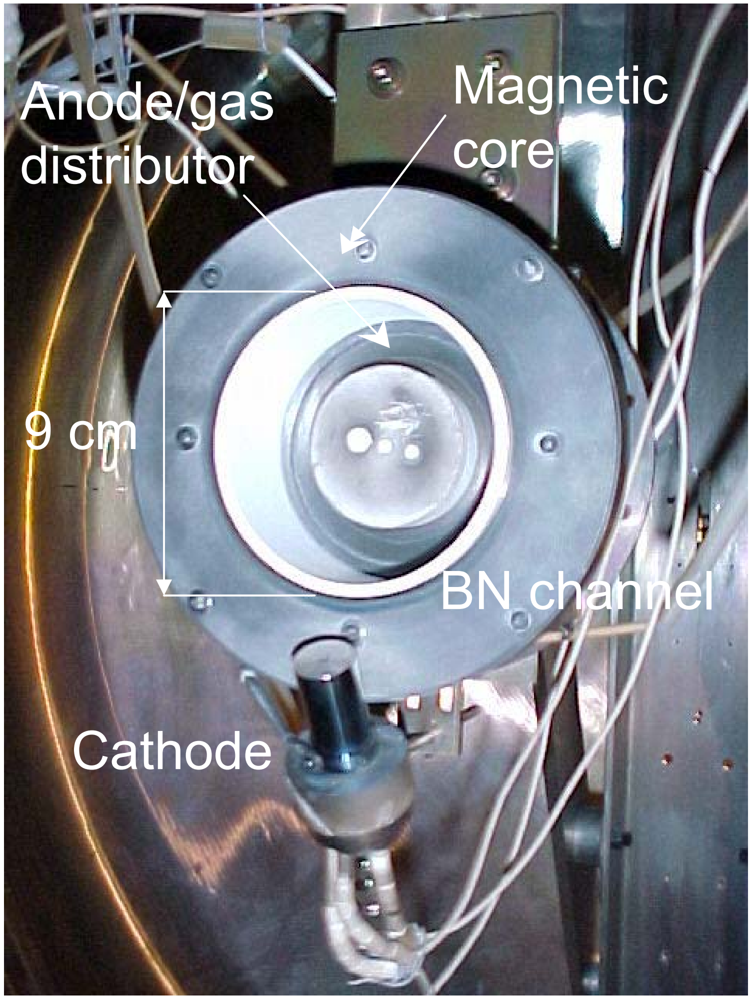

***Laser-Induced Fluorescence*** **apparatus was developed and used at** ***Stanford Hall Thruster Facility (Plasma Dynamic Laboratory)*** **for neutral velocity measurements in the near plume to gain a better understanding of the charge exchange process in Hall Thrusters.**


**1 – well with**
**the capsule inside,**
**2 – thruster,**
**3, 4 – probe connectors**




***High-Frequency (HF)*** probe diagnostics were developed and employed at ***HTX (PPPL)*** to characterize 1 – 100 MHz plasma density oscillations through measuring ion saturation current near the thruster exit.

# PPPL 9cm-Diameter Cylindrical Hall Thruster




Power range: 200 – 1000 W

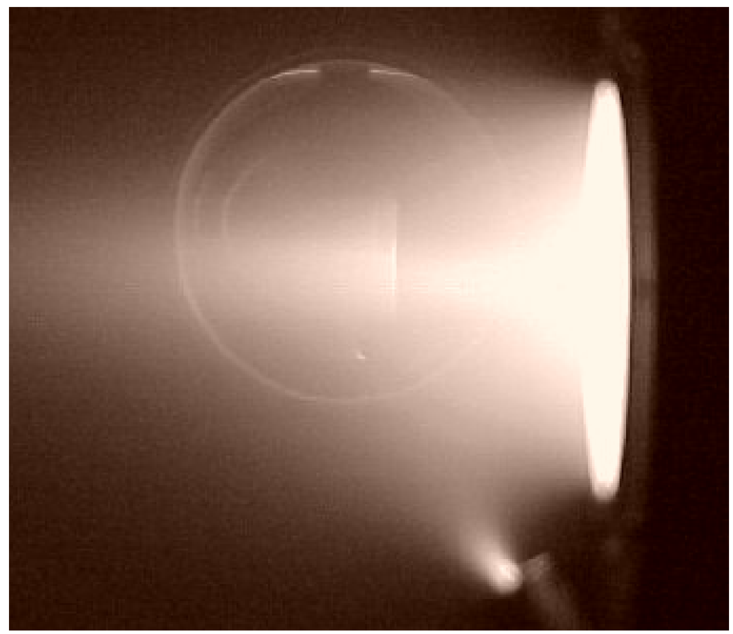
Discharge voltage: 200 – 300 V

Xenon mass flow rate: 1 – 3 mg/s

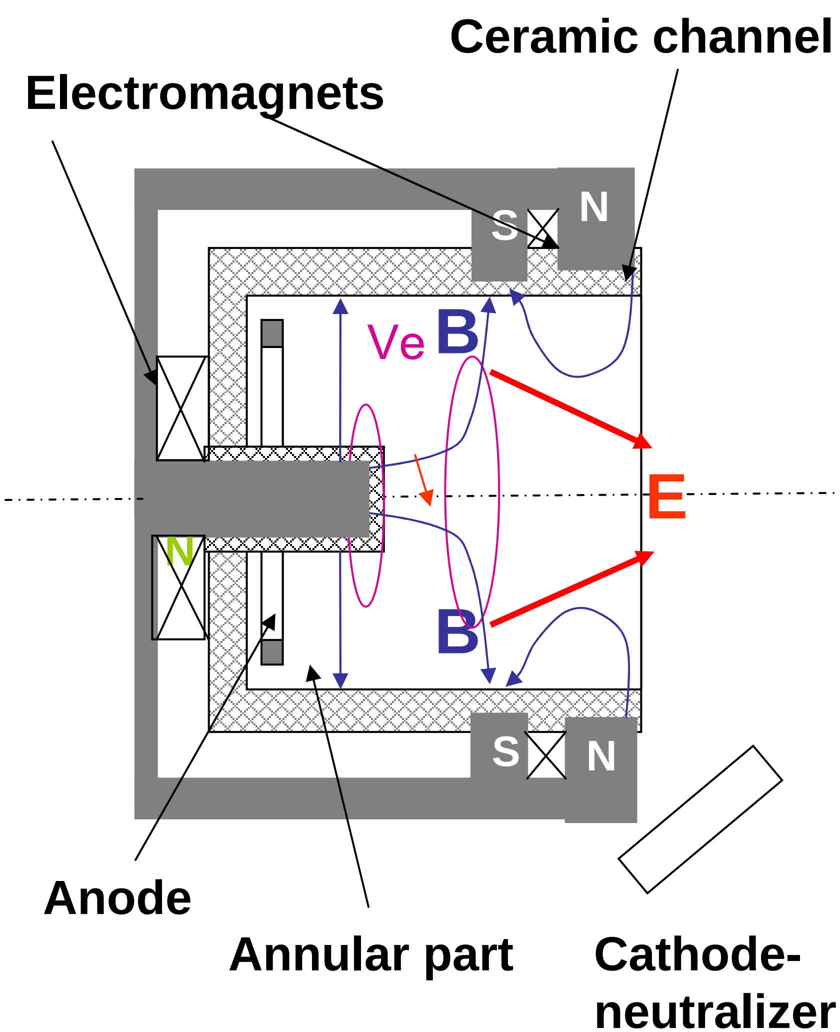
Thrust: 13 – 40 mN

Efficiency: 30 – 45 %

Channel OD = 9 cm



# Cylindrical Hall Thruster has larger volume to surface ratio than conventional thrusters

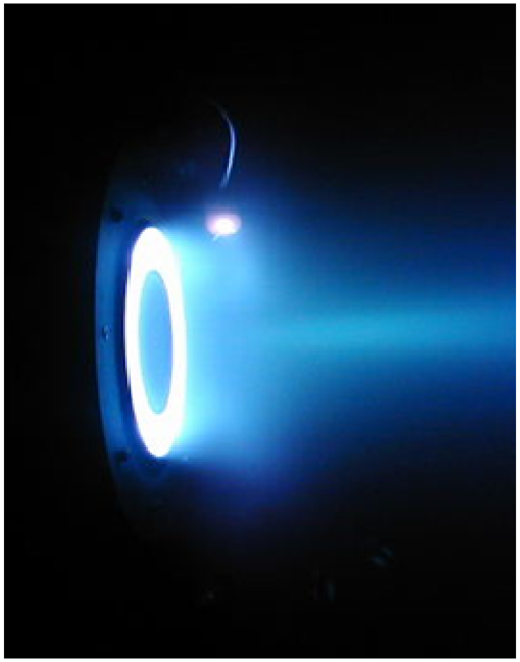



- Electron drift is azimuthal ⇒ closed drift
- Ion axial acceleration $\sim I_{e\theta} x\ B_r$
- In a short annular part the density of neutrals is higher ⇒ better for ionization
- Length of the annular region $\sim \lambda_{ion}$
- Compared to a conventional (annular) Hall thruster, the CHT has lower surface-to-volume ratio ⇒ potentially smaller wall losses in the channel

# Key Problem of Hall Thrusters

PPPL 1 kW HT

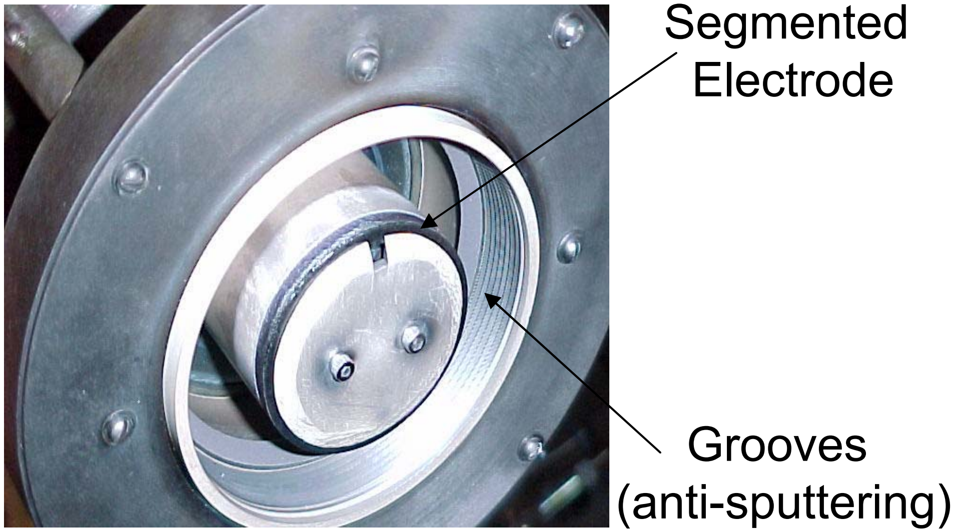
PPPL 1 kW HT with S.E.

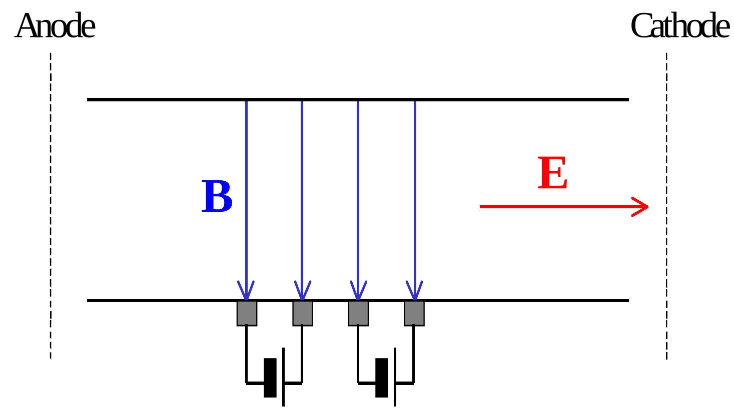


PDEPL P5 HT (Michigan)

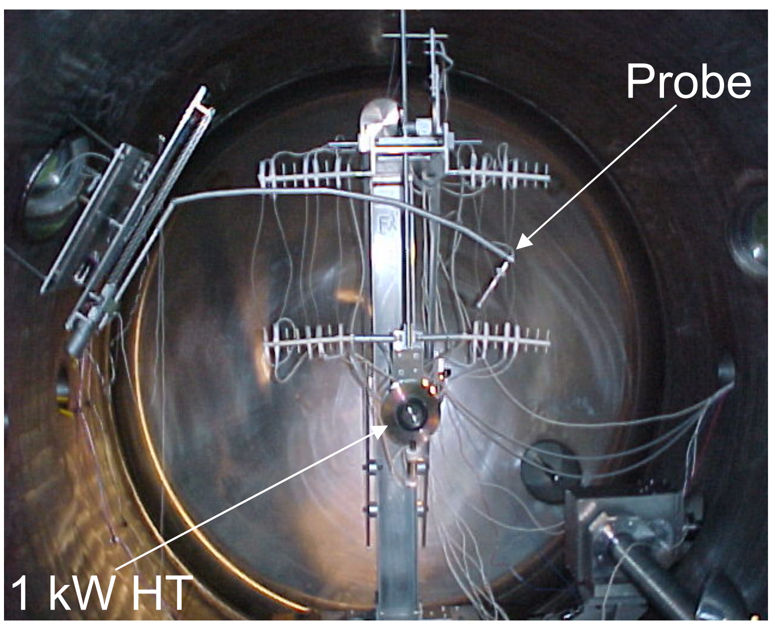
***Large plume divergence (~90 deg)*** ***decreases thrust and efficiency. Most importantly, it limits lifetime of the satellite – ion bombardment damages solar panel dramatically. Outgoing plasma jet may also interfere with radio-communication between the ground control and the satellite.***

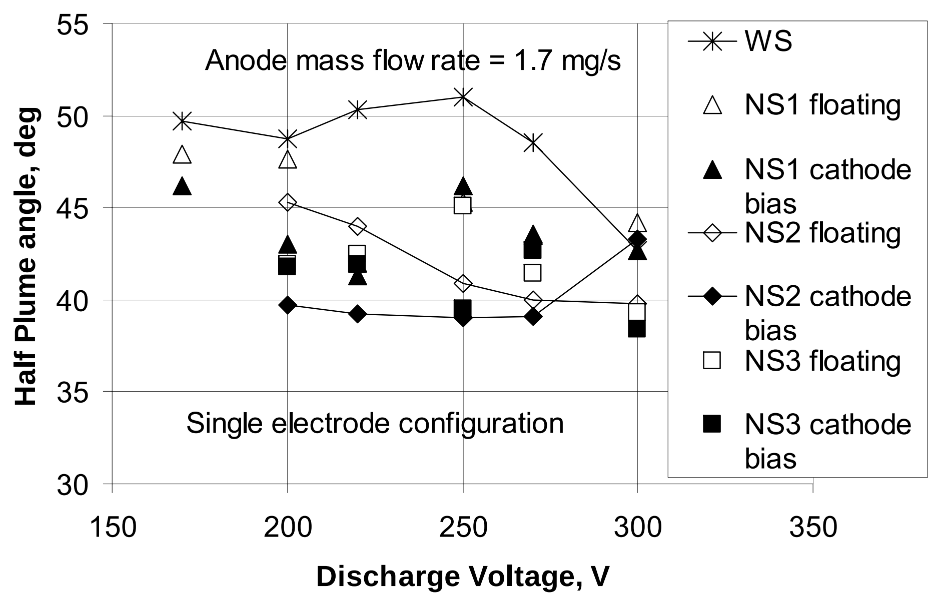
# Controlling Plume with Segmented Electrodes



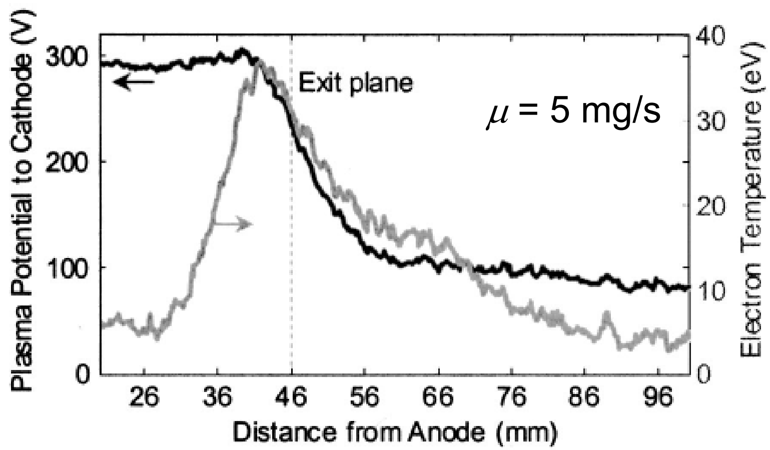



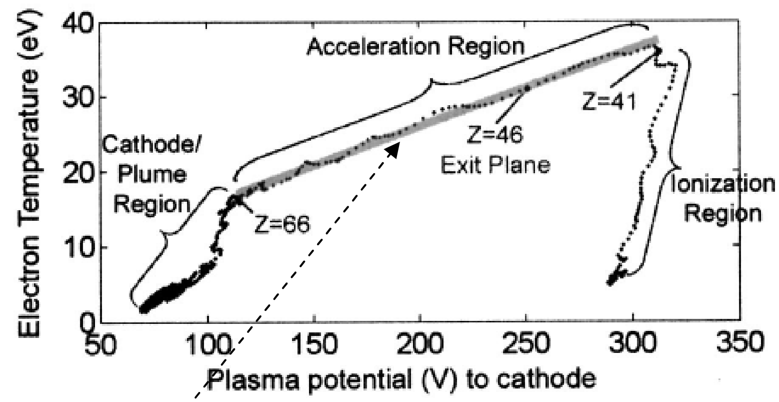

Segmented electrodes
(localize potential drop -
reduce beam divergence

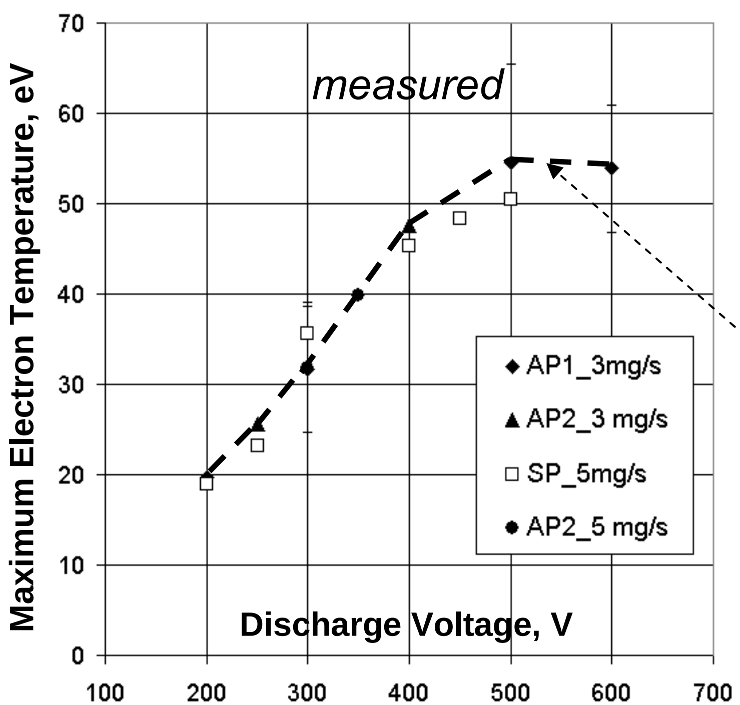


# Temperature Profile in Hall Thrusters




## RESULTS:

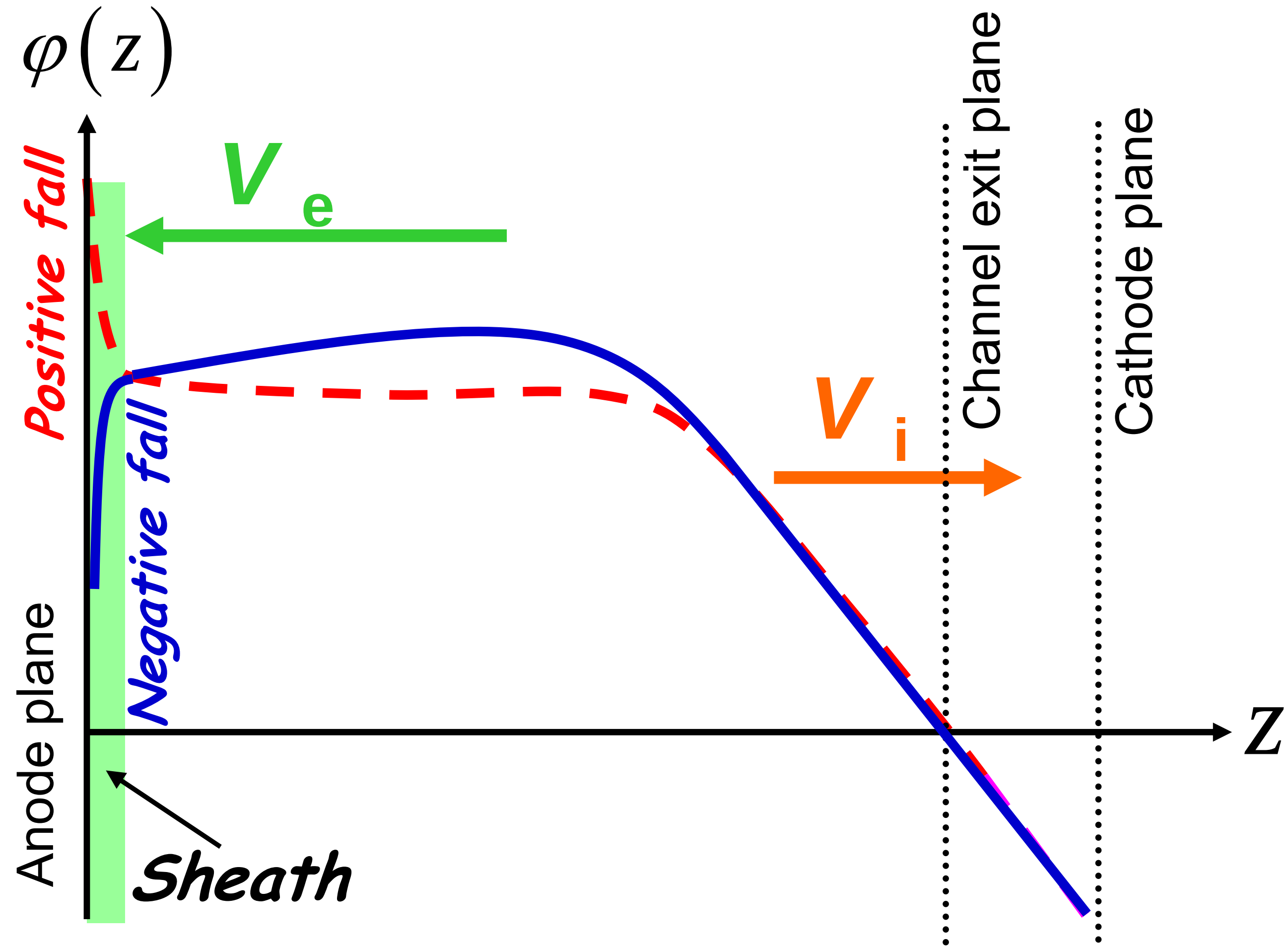
1. In acceleration region:

$$T_e = \beta \, \phi_{pl}$$

$$\beta = 0.08 - 0.14$$

2. Maximum electron temperature saturates with discharge voltage

# Anode Sheath = Adjoint Space-Charge Layer



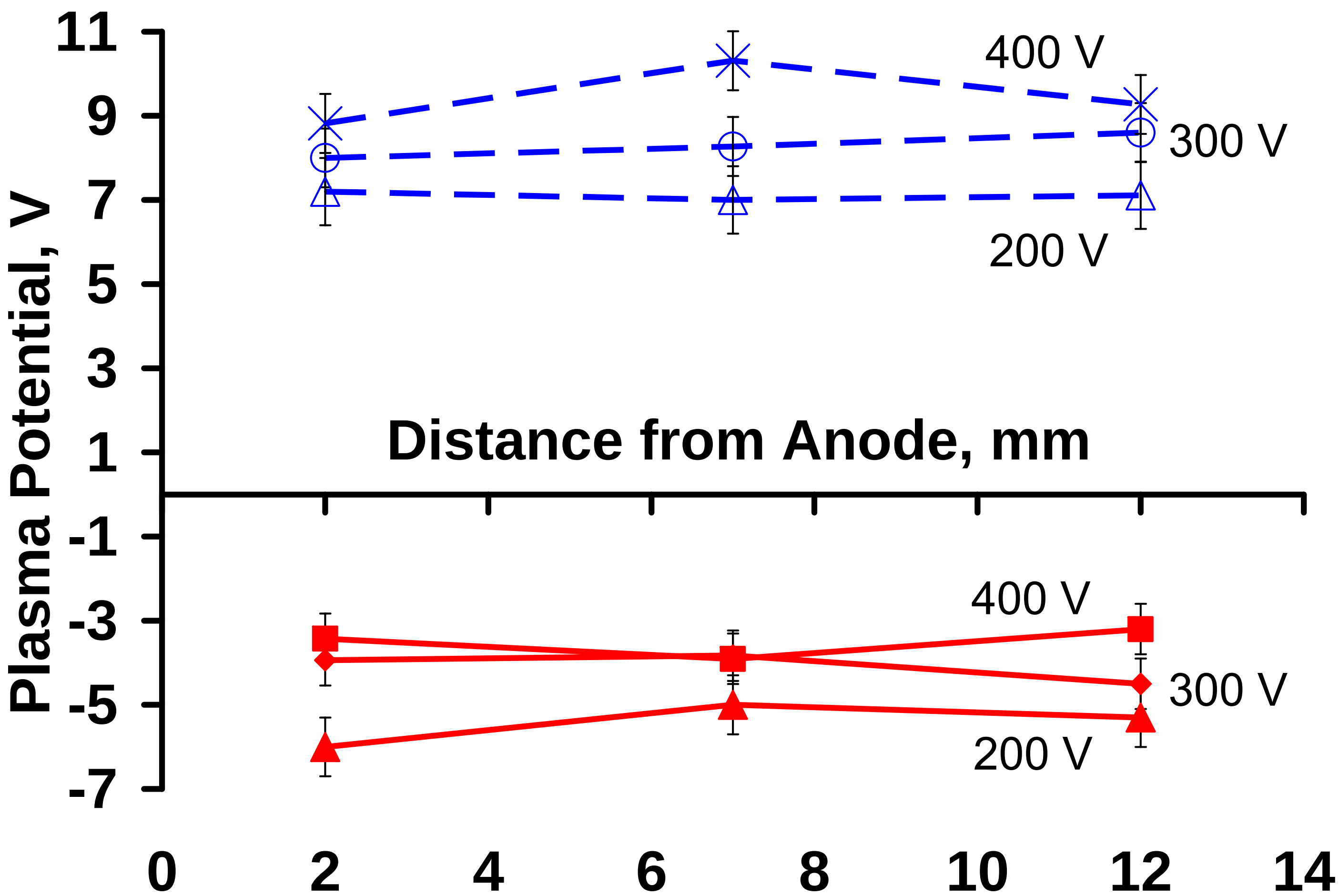

Positive Anode Fall = Electron-attracting Anode Sheath

Negative Anode Fall = Electron-repelling Anode Sheath

# Decreasing Anode Area Reverses Anode Fall

***CLEAN ANODE = NEGATIVE ANODE FALL***

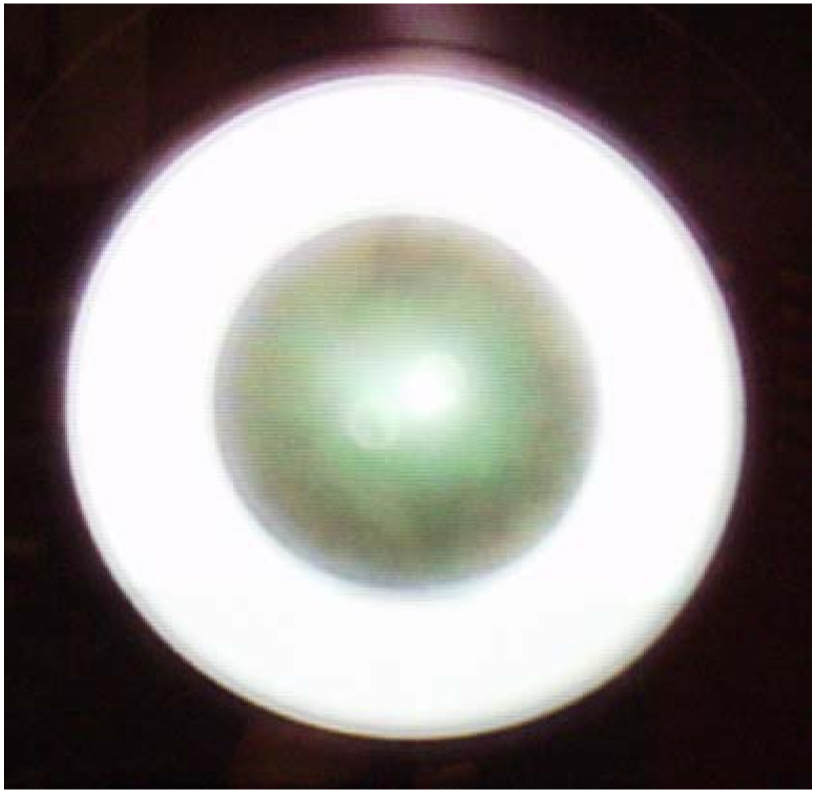
***COATED ANODE = POSITIVE ANODE FALL***




At channel median $\dot{m}$ = 5 mg/s $\varphi_{an}$ = 0, *biased probe*

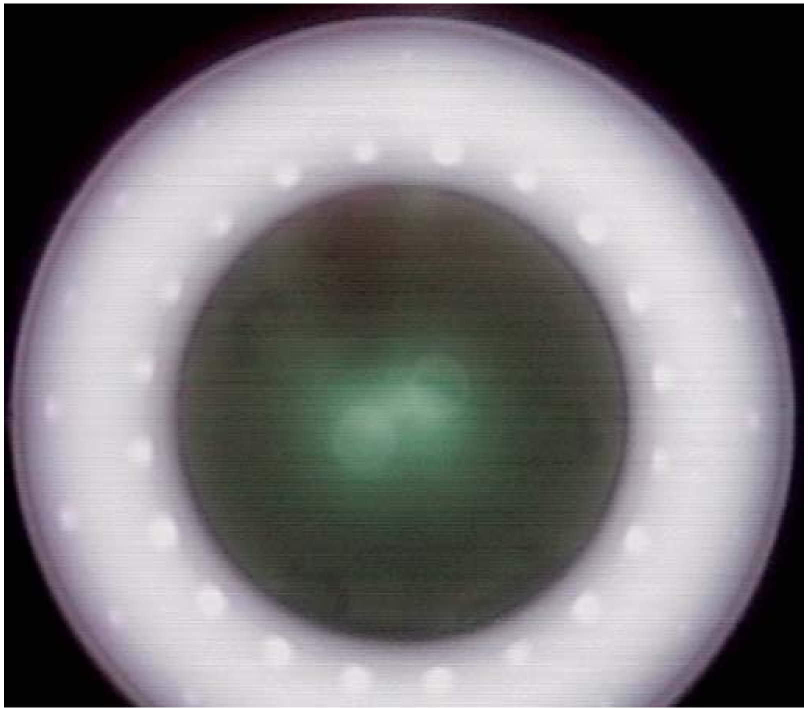
# Decreasing Anode Collecting Surface Area Manifests Itself

**Negative anode fall**



**CLEAN ANODE**

**Positive anode fall**



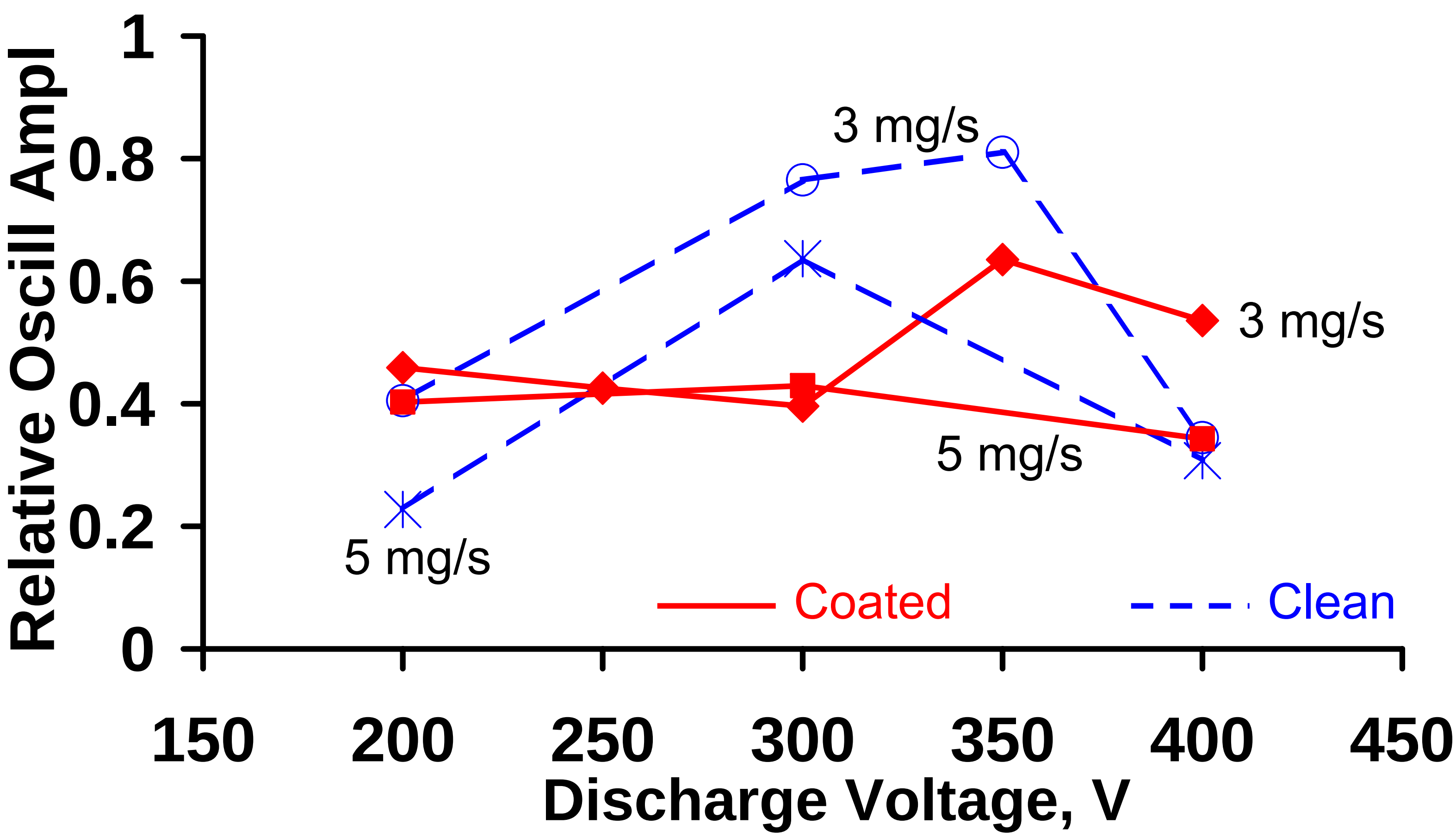
**COATED ANODE**

# Discharge Current Oscillations Measurements

*Hall thruster operation appears to be*

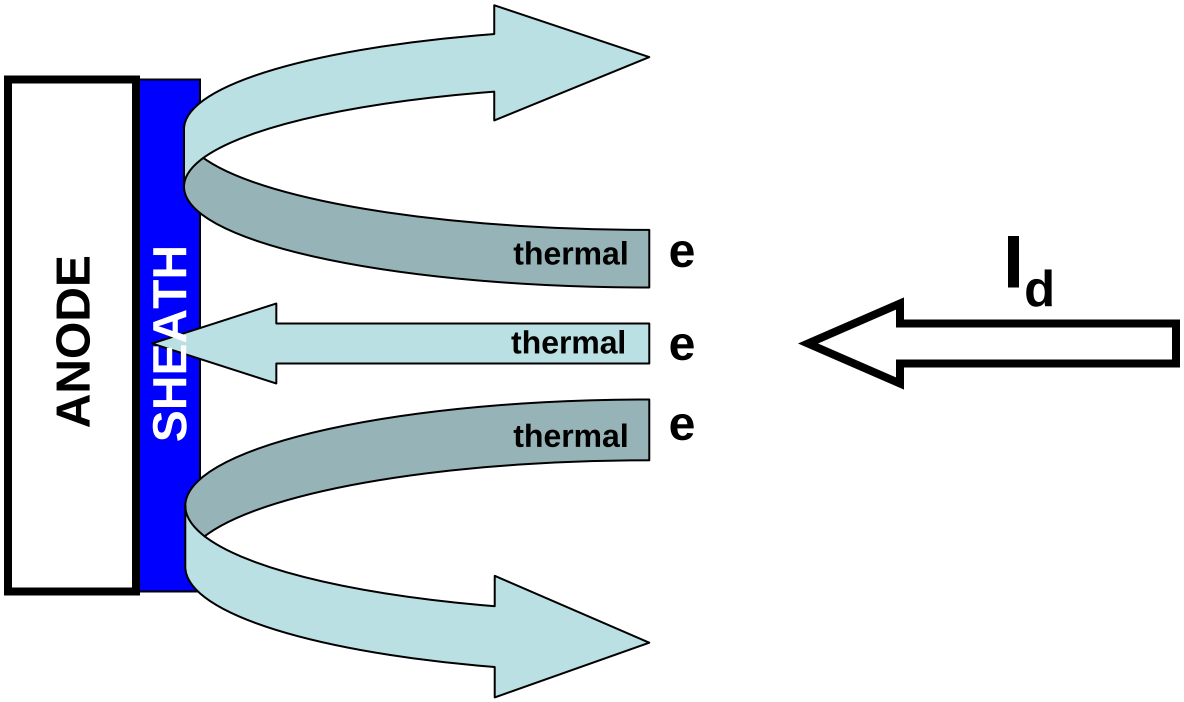
***MORE STABLE WITH COATED ANODE***

*(i. e. with Electron-Attracting Anode Sheath or Positive Anode Fall)*



# Negative Anode Fall Formation Mechanism

**Formation of an electron-repelling anode sheath (negative anode fall) is required to repel an excessive electron thermal flux from the anode.**

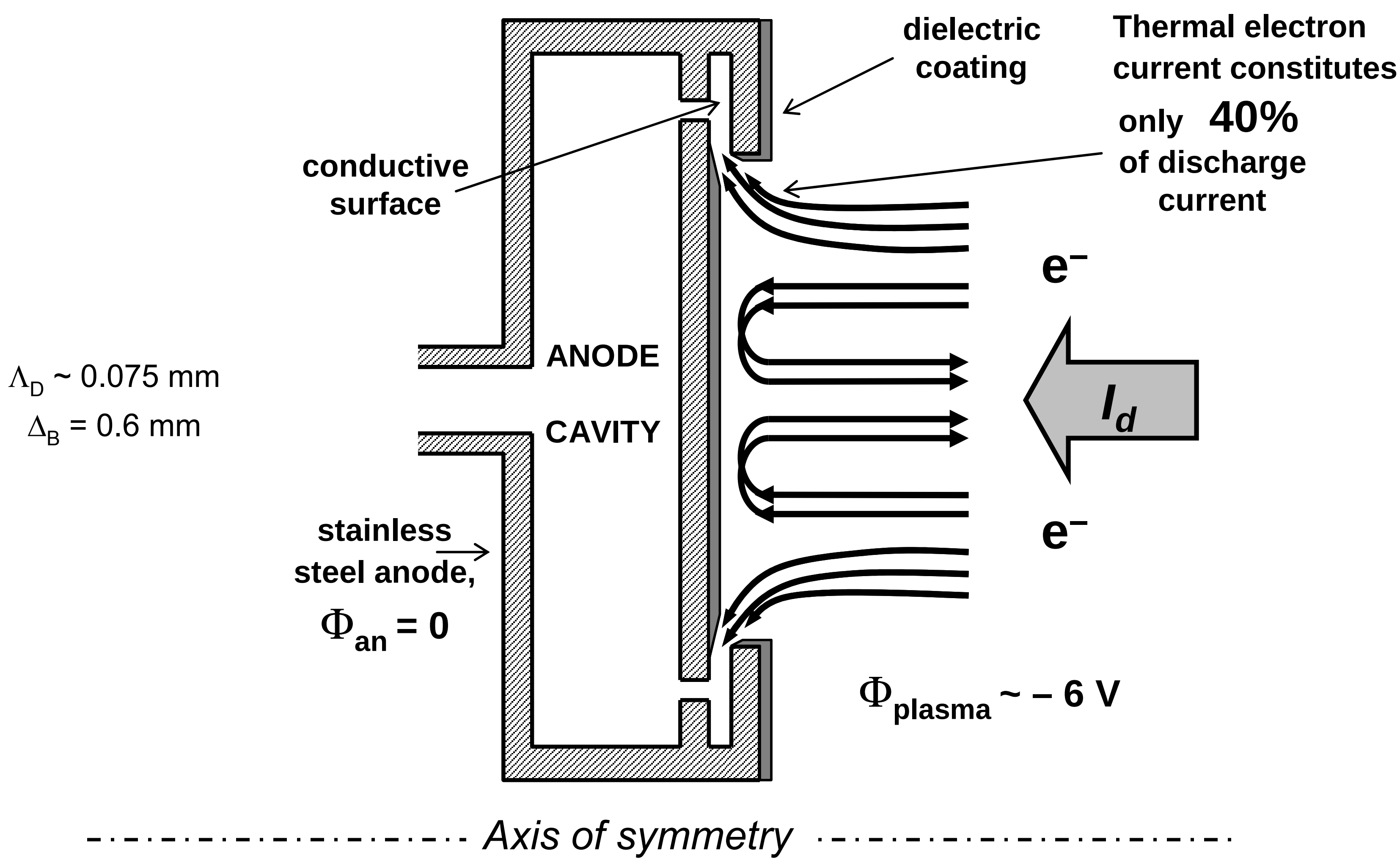



Electron-neutral collisions are very weak near the anode, so is the magnetic field in the conventional configuration.

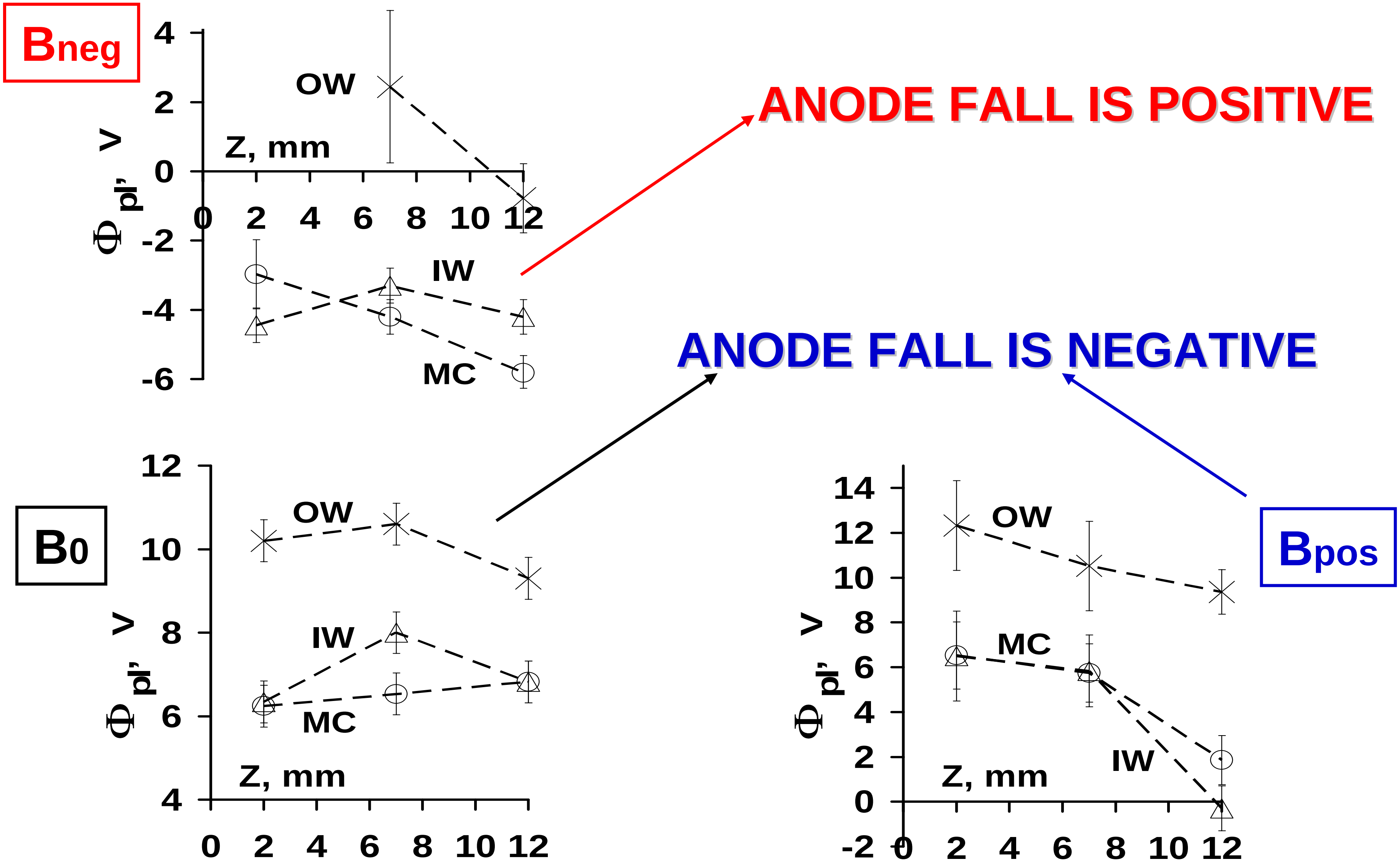
$$\Lambda_{en} \sim \Lambda_{nn} \approx 12\,\text{cm}$$

# Positive Anode Fall Formation Mechanism

**Additional electron flux gets drawn into the anode by the electron-attracting sheath that appears at the inner, metal anode surfaces.**



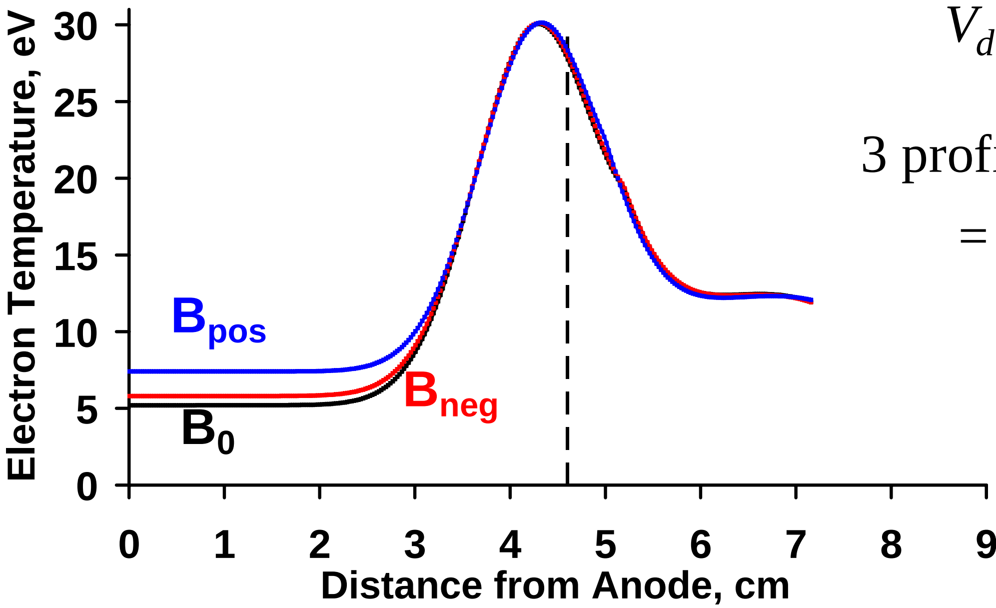
# Zero-*B*-Field Configuration = Reversed Fall




$V_d$ = 300 V; *m* = 3 mg/s; *Z* = 0 = *Anode;* *Φ* = 0 = *Anode*

# Quasi-1D Model

**1.** Input parameters:




$V_d = 300\,\text{V}$ $\dot{m} = 3\,\text{mg/s}$

3 profiles $B_r(z)$, $I_d$, $n_0$, *sheath* =

= Experimental values

**2.** System of fluid equations for 3-species (*e, i, n*) quasineutral plasma. Includes ion wall losses terms → "quasi-1D"

**3.** Fitting parameter, $\alpha$, for electron cross-field mobility, $\mu_e$:

$$\mu_e = \frac{\alpha}{16\left|B_r(z)\right|}$$

# Boundary Conditions

- Reduced system: $dJ_i/dz = F(J_i,\ n,\ I_d, \mu_e)$

$$dn/dz = G(J_i,\ n,\ I_d, \mu_e)/(1 - V_i^2/V_s^2)$$

- $I_d,\ n_0\ =\ Experimental,$ $\quad V_{i0} = \begin{cases} -V_s, & B_0 \text{ and } B_{pos} \\ 0, & B_{neg} \end{cases}$

- $\mu_e = \dfrac{\alpha}{16|B_r(z)|}$ There is only one value of $\alpha$, which allows a solution to be **regular at the sonic transition point**: $V_i = V_s$.

- $$\int_0^{L_{cath}} E(z)\,dz = V_d \quad \Rightarrow \quad L_{cathode}(V_d)$$