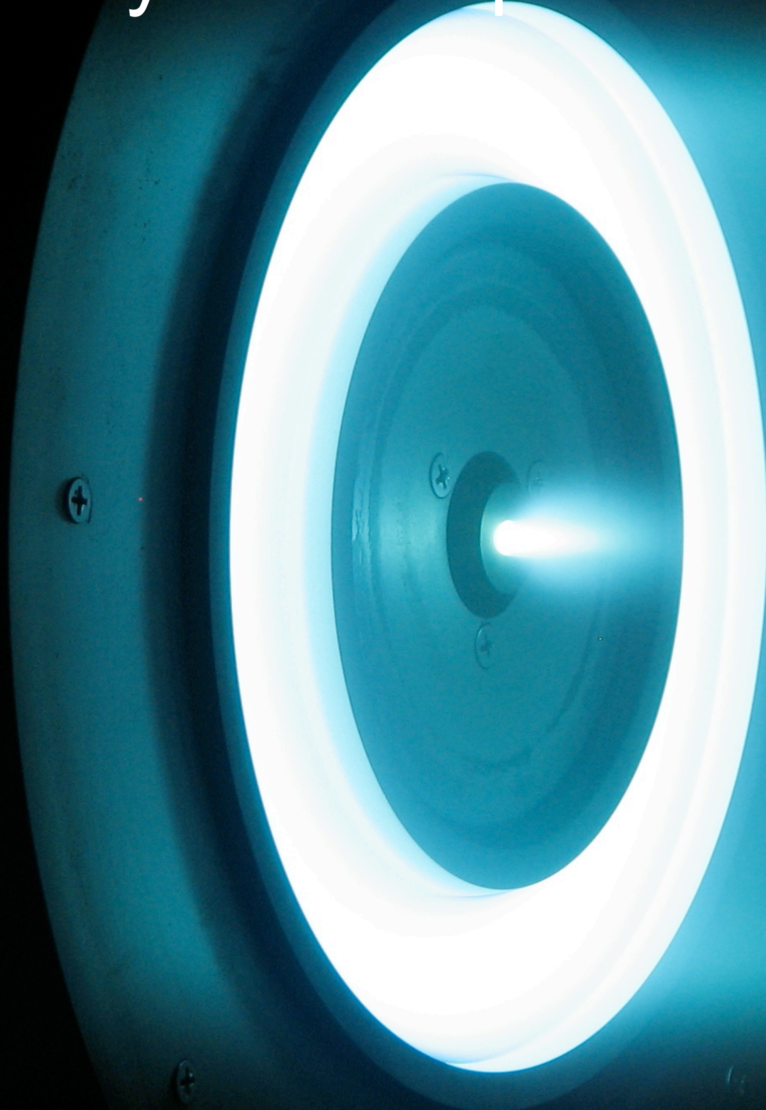
The Physics of Spacecraft Hall-Effect Thrusters



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ACKNOWLEDGMENTS

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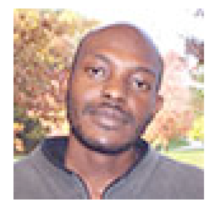

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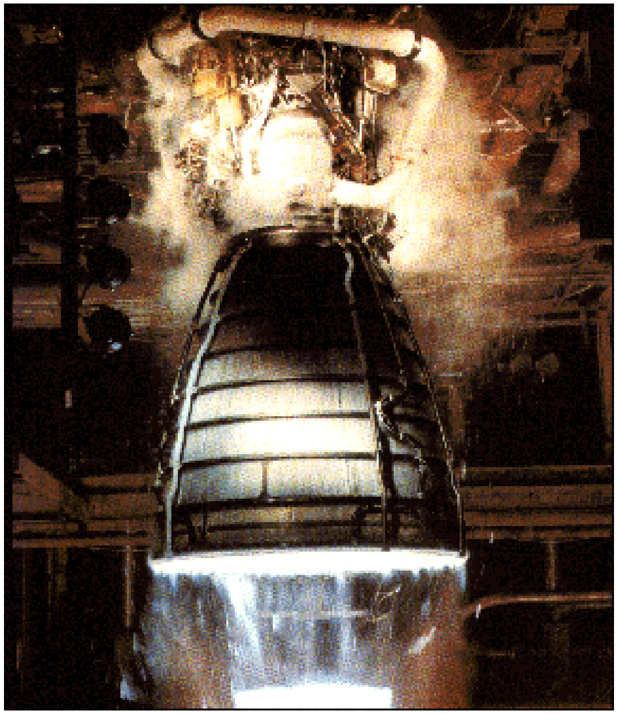
NASA Jenkins Fellowship Program

NASA Michigan Space Grant Consortium

H. H. Rackham School of Graduate Studies

GETTING AROUND SPACE

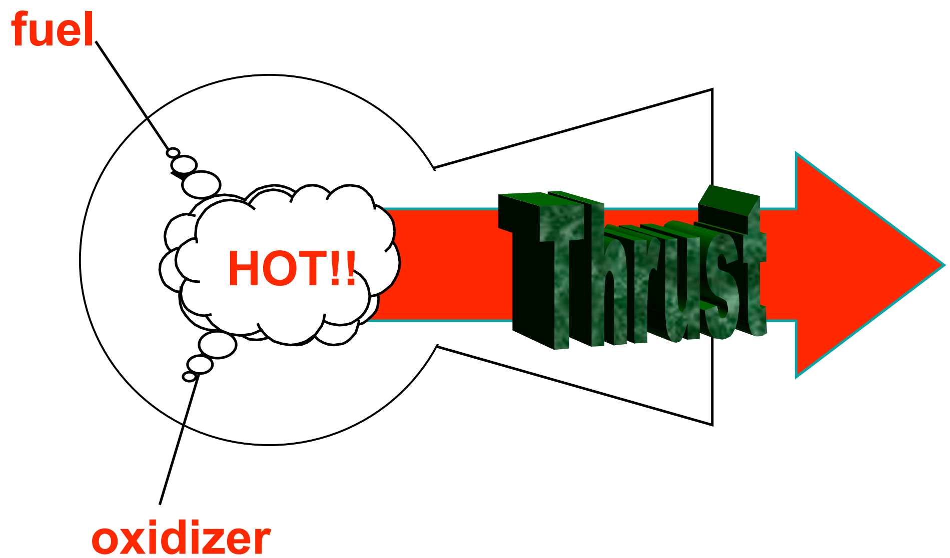


Rocket engines convert stored chemical energy into kinetic energy

Thrust: T = engine force (N)

T=M x a = M x ΔV/t

ΔV= velocity Increment (m/s)



$$T = \dot{m}\, u_e = \dot{m}\, g\, I_{sp}$$

$\dot{m}$ = mass flow rate (kg/s)

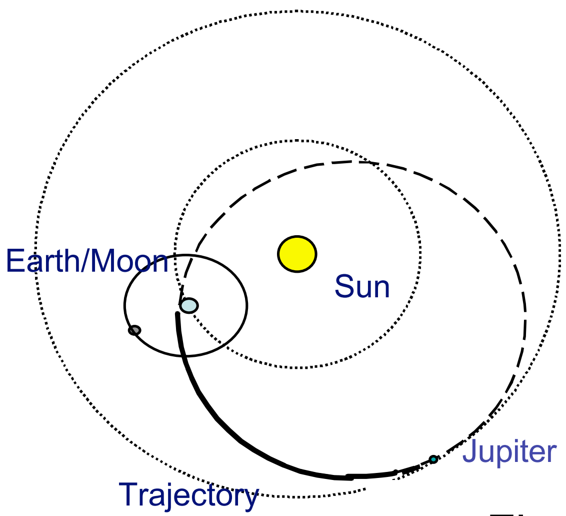
u_e = exhaust velocity (m/s)

g = sea level gravity (m/s^2)

I_{sp} = specific impulse *(s)*

rocket "miles per gallon"

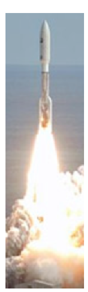
GETTING AROUND SPACE

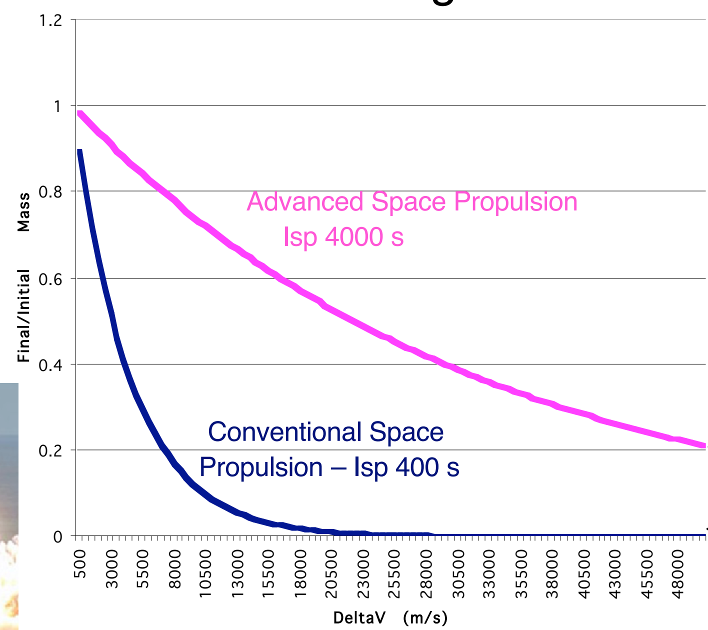


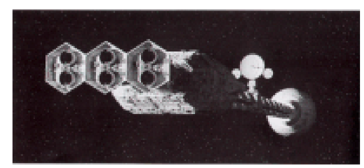
Typical ΔVs (km/s)

Earth to LEO (for reference)	7.6
LEO to GEO (<1 day)	4.2
LEO to GEO (8 months)	6.0
LEO to Mars (9 months)	5.7
LEO to Jupiter (6 months)	50
LEO to Mars (1 month)	90
LEO to 1000 AUs (30 Yrs)	175

Final-to-Starting Mass Ratio







$$\frac{M_{final}}{M_{initial}} = e^{-\Delta V / U_e}$$

1-out-of-5

1-out-of-150,000

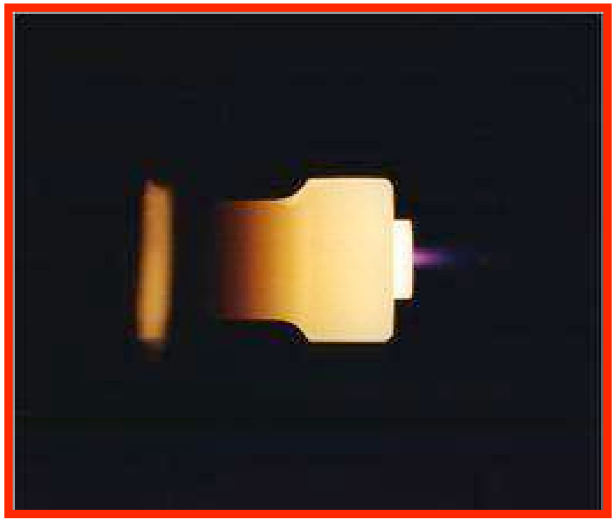
Earth to Jupiter in 6 months

ELECTRIC PROPULSION

EP uses heat addition, electromagnetic fields, and electric fields to add energy to a propellant stream

Electrothermal:

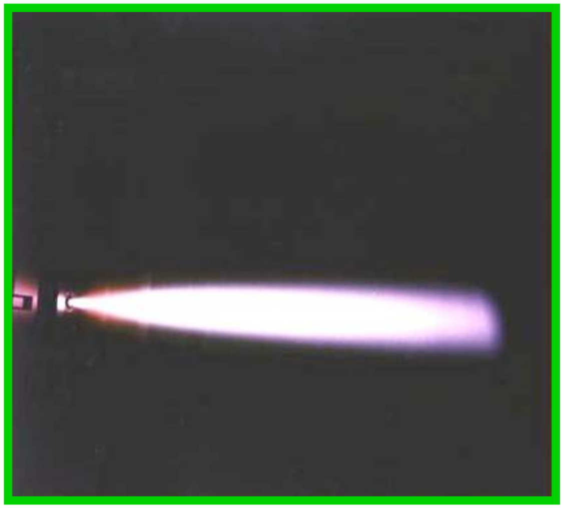
Gas heated and expanded through nozzle



- Resistojets
- Arcjets
- Microwave

Electromagnetic:

Plasma accelerated via interaction of current and magnetic field



- Pulsed Plasma
- MPD/LFA
- Pulsed Inductive

Electrostatic:

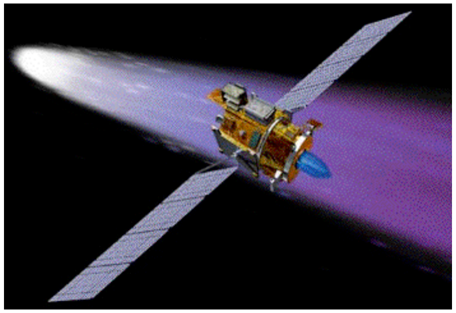
Ions created and accelerated in electric field

- Hall-Effect
- Ion
- Colloid
- Nanoparticle

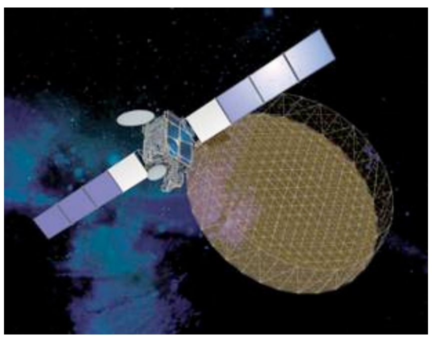
Courtesy Aerojet

APPLICATIONS FOR ELECTRIC PROPULSION

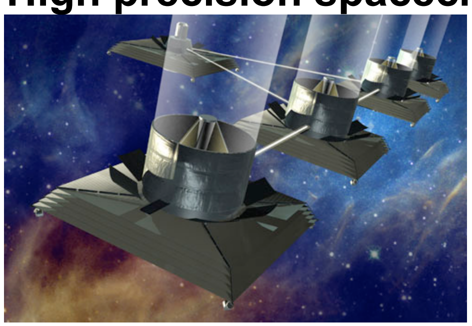
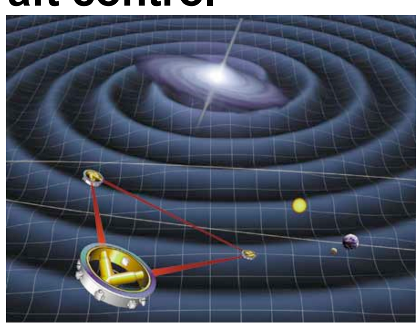
High ΔV space missions

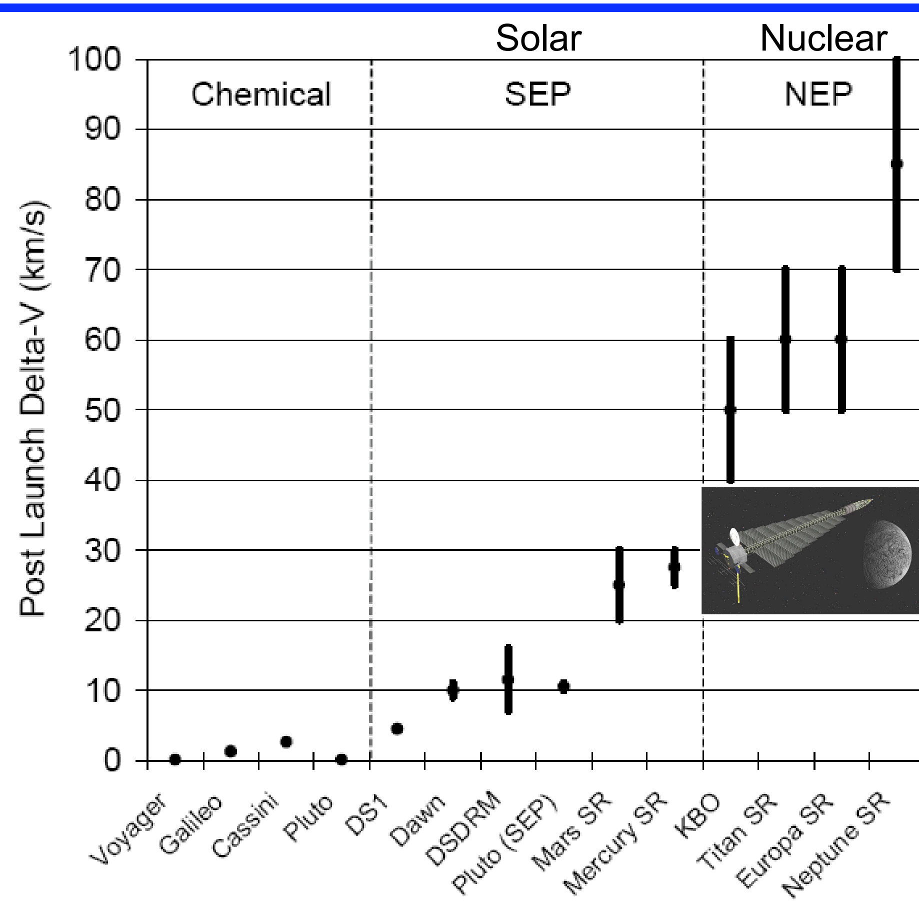


Low-disturbance station keeping



High precision spacecraft control



EP offers high I_{sp} but at low thrust

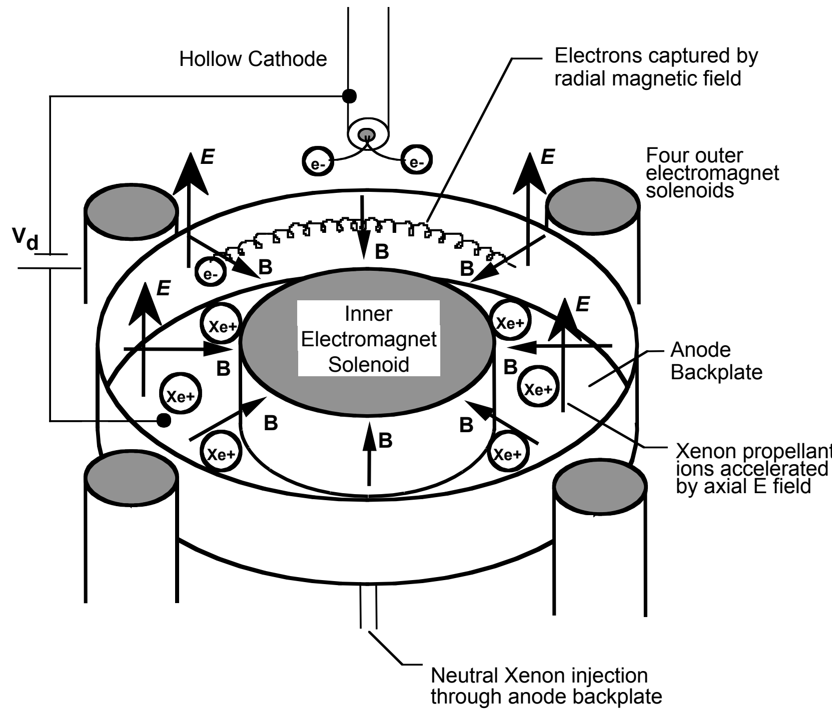
→ **NEED FOR LONG ENGINE LIFE**

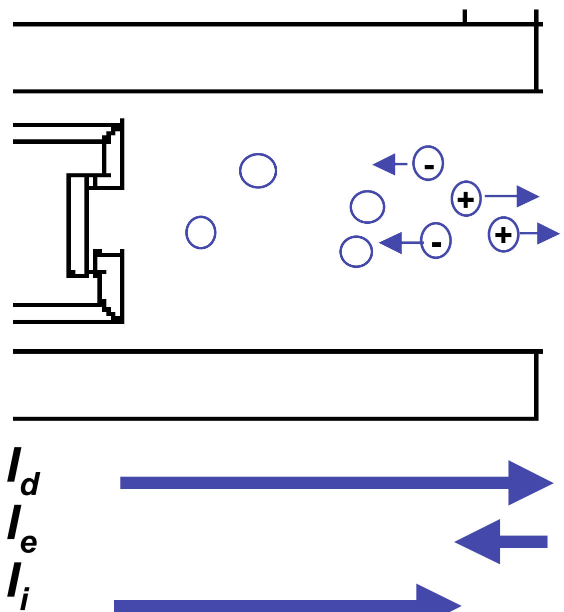
$$P_D = \eta \frac{\dot{m} u_e^2}{2} = \eta \frac{g T I_{sp}}{2}$$

Courtesy JPL

HALL THRUSTER PHYSICS

- Radial magnetic field from inner and outer electromagnets
- Axial electric field established between anode and external cathode
- Electron motion toward anode impeded by radial magnetic field – azimuthal **ExB** drift (HALL CURRENT)

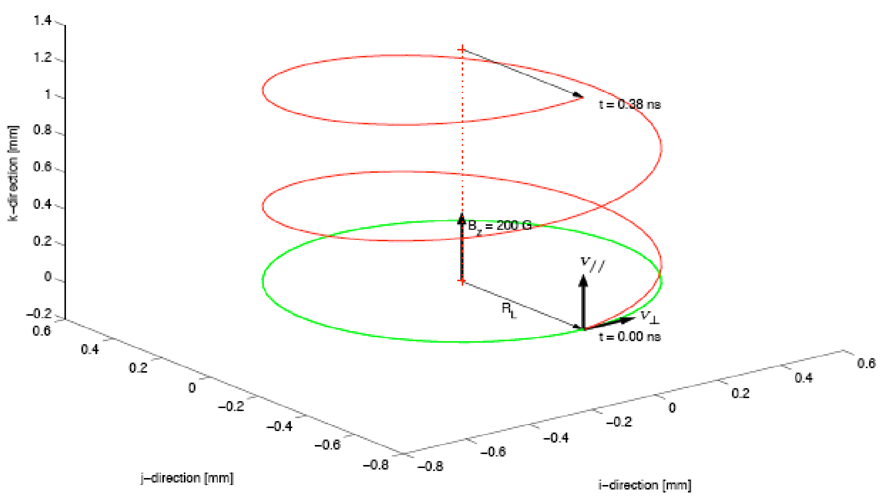




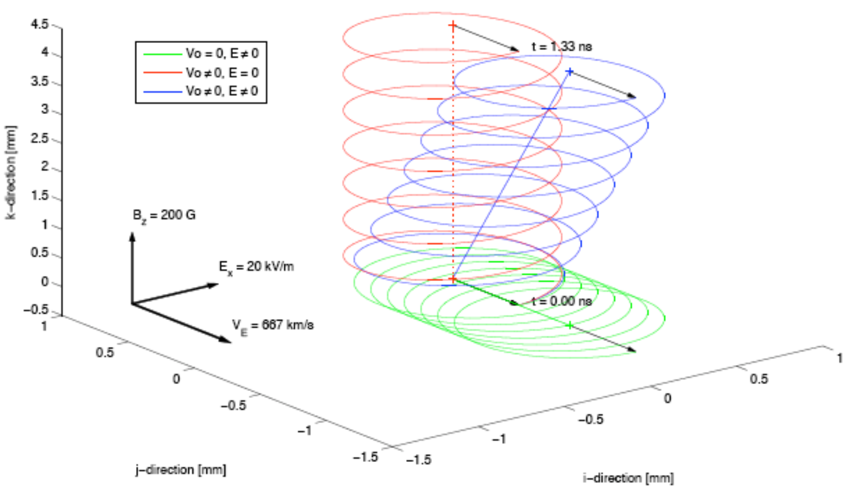
- Injected propellant ionized by Hall current
- Magnetic field not strong enough to magnetize more massive (240,000x) ions
- Axial electric field accelerates ions (I_i)
- Cathode supplies electrons for discharge (I_e) and to neutralize exhaust

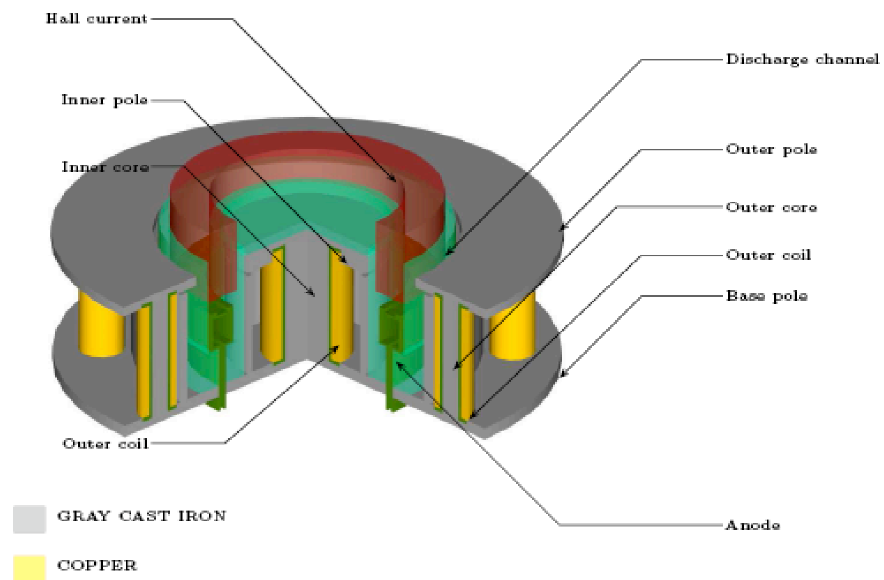
HALL THRUSTER PHYSICS

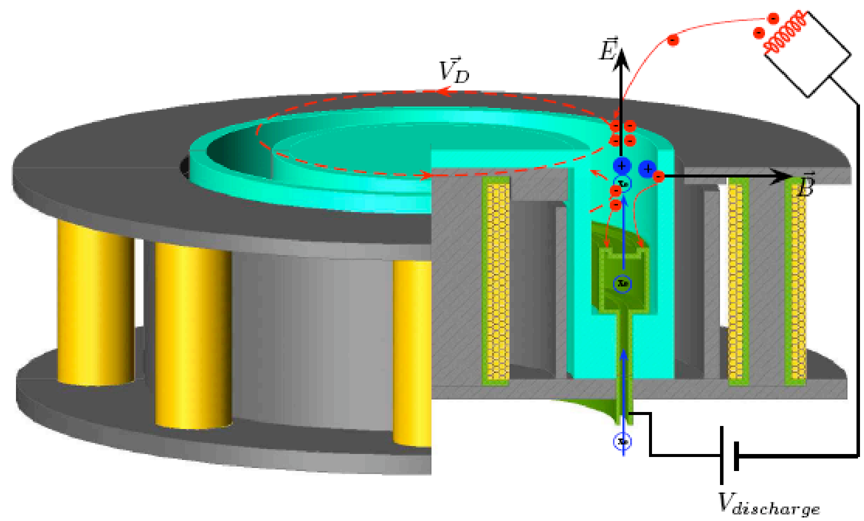
Magnetic Field



E x B Drift







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ANALYSIS APPROACH

Hofer-Reid Model Utilizes Plume Data to Understand Loss Mechanisms

Overall thrust efficiency (excluding divergence losses)

$$\eta_a = \frac{T^2}{2\dot{m}_a P_d} = \eta_q \eta_v \eta_b \eta_m$$

Charge utilization efficiency

$$\eta_q = \frac{\left(\sum \Omega_i / \sqrt{Z_i}\right)^2}{\sum \Omega_i / Z_i}$$

Voltage utilization efficiency

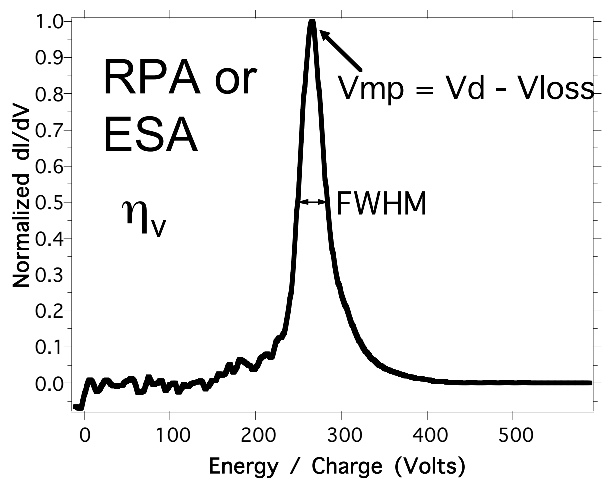
$$\eta_v = \frac{V_a}{V_d} = 1 - \frac{V_l}{V_d}$$

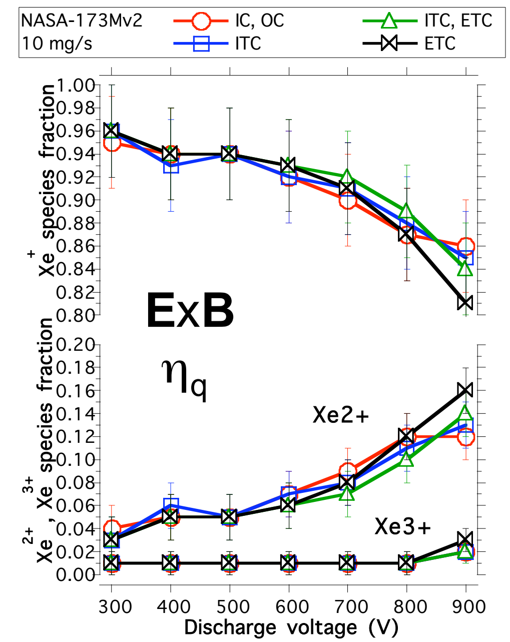
Current utilization efficiency

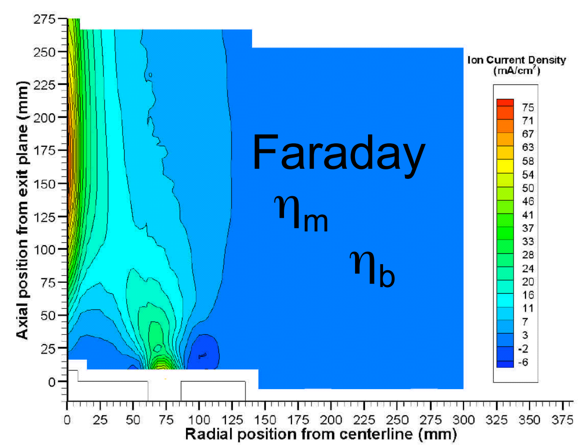
$$\eta_b = \frac{I_b}{I_d}$$

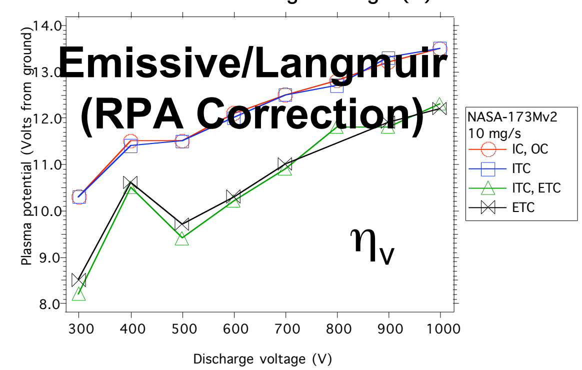
Mass utilization efficiency

$$\eta_m = \frac{\dot{m}_b}{\dot{m}_a}$$









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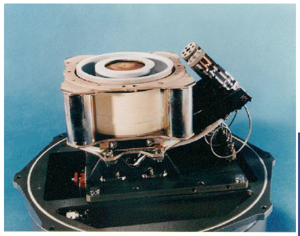
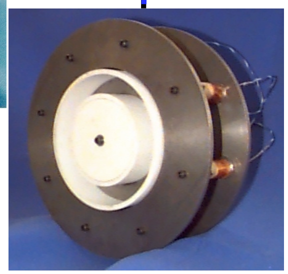
SPIRAL DEVELOPMENT

1995

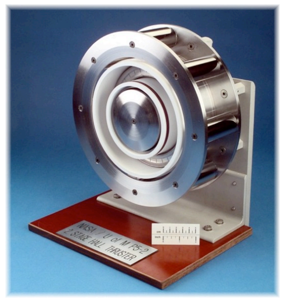


300 V - 4.5 A
I_{sp} - 1550 s
η_{th} - 47%

1998



2001

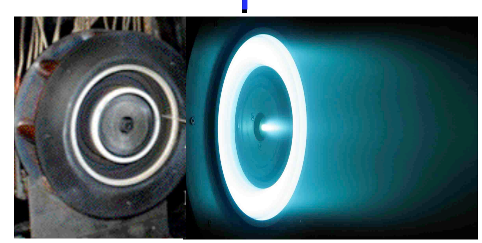


2002

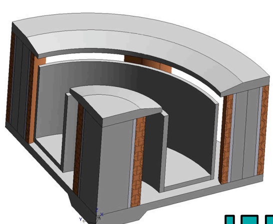
2003

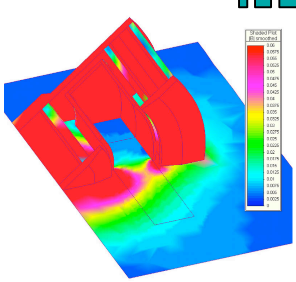
2007

300 V - 20 A
I_{sp} - 1950 s
η_{th} - 64%

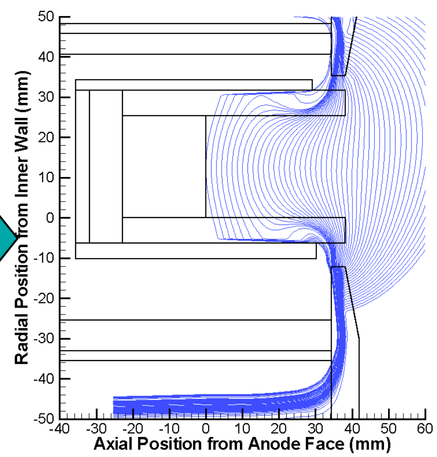


3D Magnetostatic Design Tool





3D Design



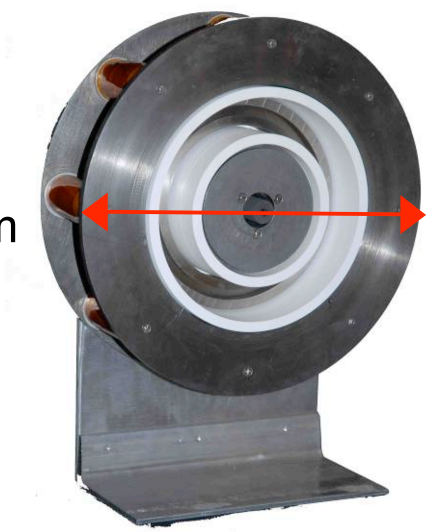
Plasma Lens Field Line Topology

Plasmadynamics and Electric Propulsion Laboratory

TEST FACILITY AND THRUSTER

- **Large Vacuum Test Facility**
  - 6 m diameter, 9 m length
  - Nominal xenon pumping speed of 240,000 l/s (7 cryopumps)
  - Base pressure of ~1×10^{-7} torr

Ø 30 cm



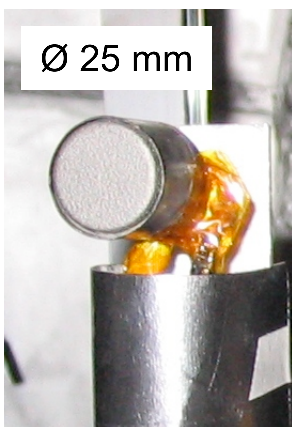
- **6-kW Laboratory Model Hall Thruster**
  - Center-mounted LaB_6 cathode
  - Highly throttleable
  - New propellant injection
  - Second-generation magnetic lens topology
  - Removable erosion rings
  - State-of-the-art performance

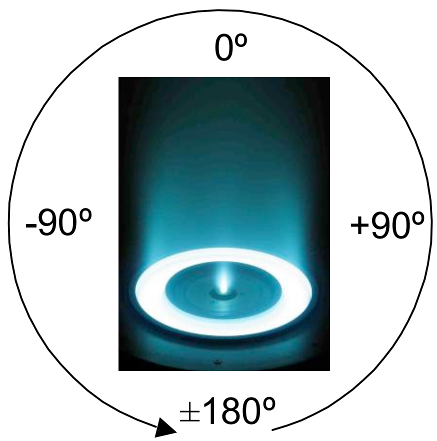
FAR-FIELD ION CHARGE FLUX

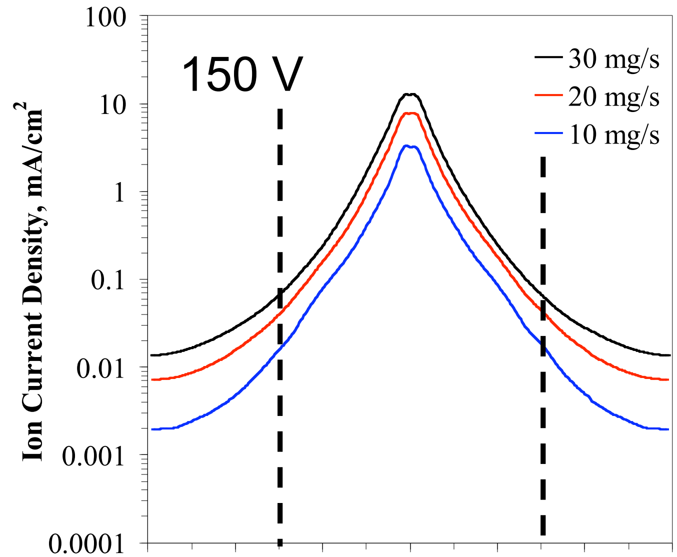
Where does the plasma go?

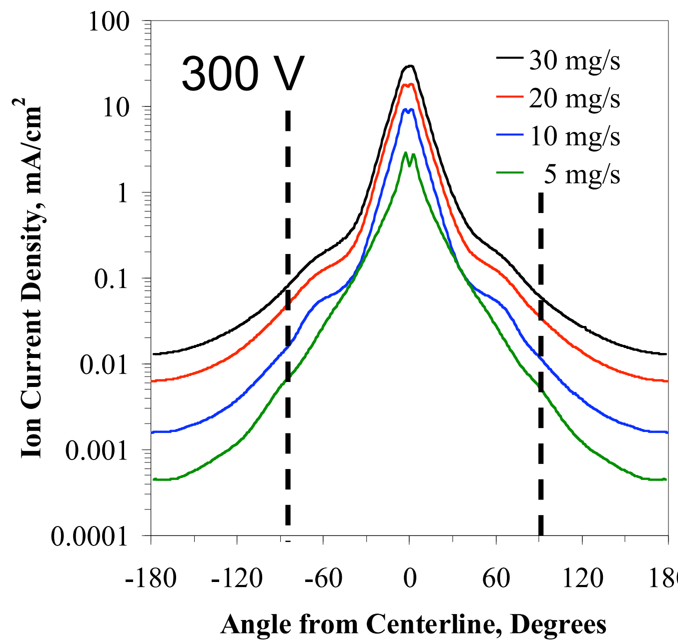
Far-Field Faraday Probe Measurements

- Measures angular ion charge flux distribution
- Spacecraft integration concerns
- Global plume divergence and ion current









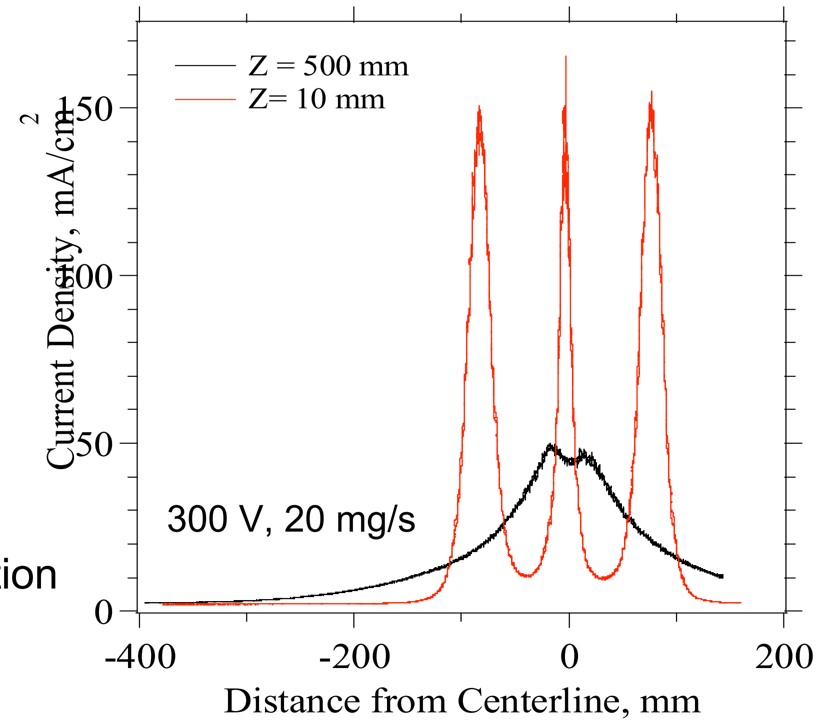
Plasma is concentrated within ±40º, more plasma in "wings" with increased neutral flow

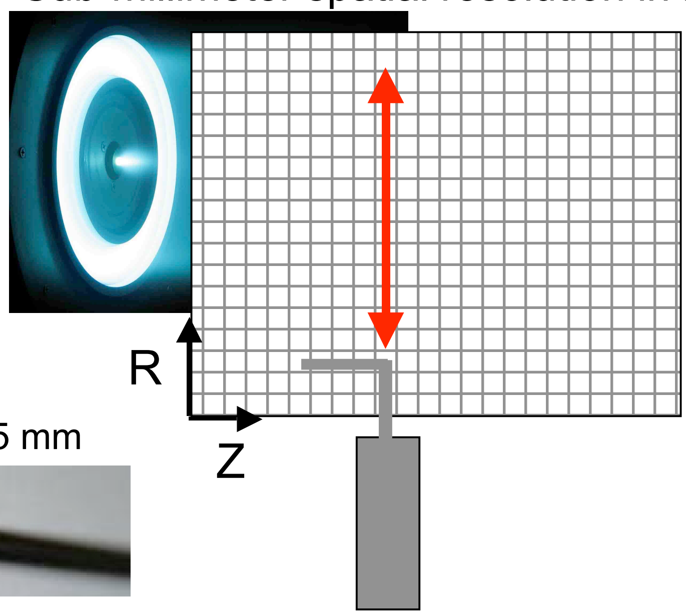
NEAR-FIELD ION CHARGE FLUX

How much of the plasma is useful?

Near-Field FP Measurements (η_b,η_m,div)

- Axial ion charge flux collected across plume every 5 mm in axial direction
- Data collected at 100 kHz
  - Plasma oscillations captured in ion flux fluctuations
  - Sub-millimeter spatial resolution in radial direction



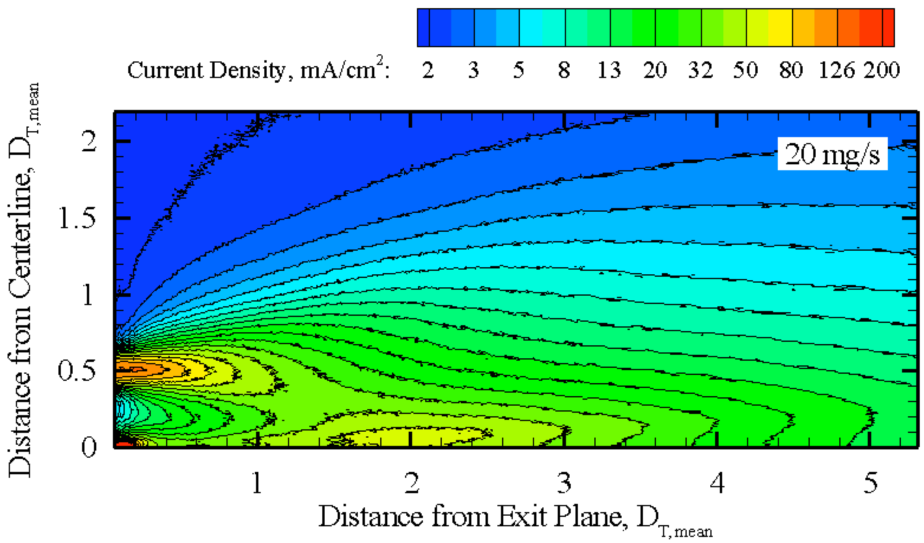


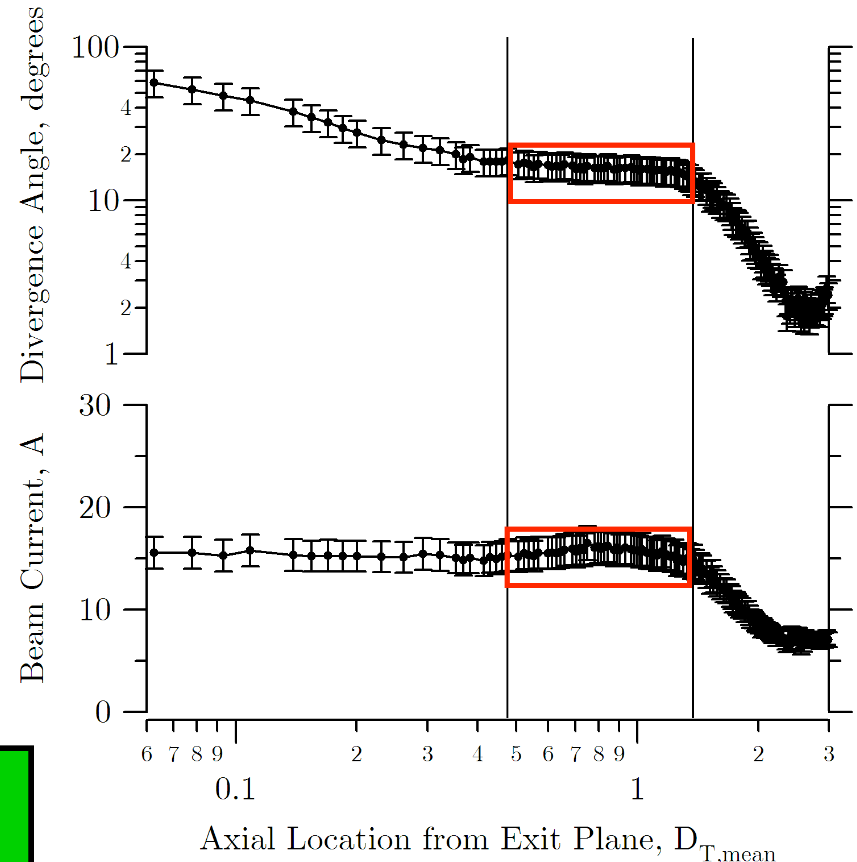
Ø 3.5 mm

Must measure amount and divergence of ions before facility-induced collisions alter the plasma

NEAR-FIELD FP ANALYSIS

What does this measurement tell us?





- Consistent beam current value up to one diameter (~78 ± 1% discharge current)
- Consistent plume divergence value up to one diameter (16 ± 2º)
- Mass utilization* >90% (most of the propellant converted to beam ions)

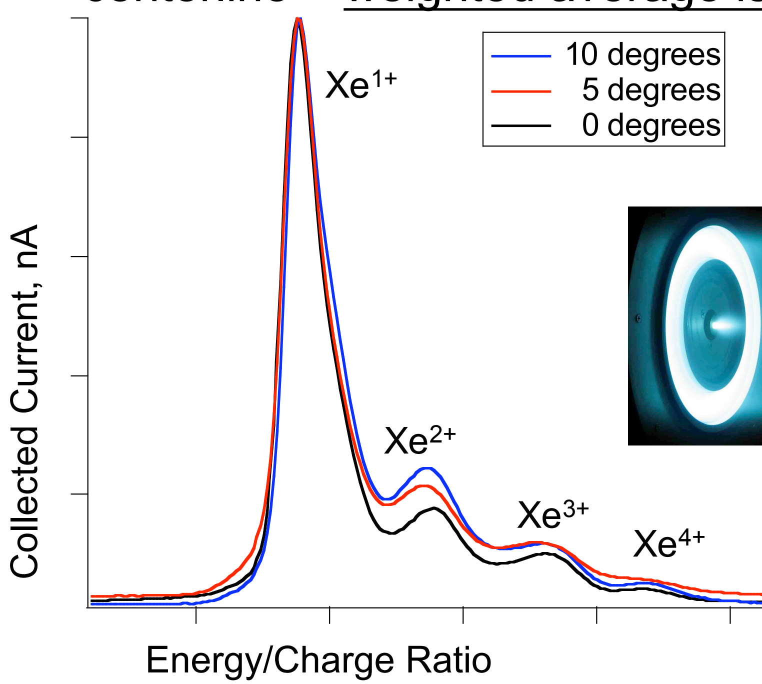
***Relies on RPA and EXB data*

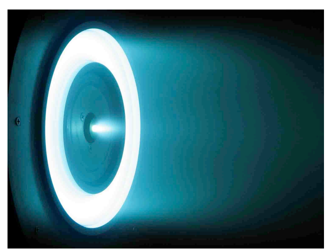
ANGULARLY-RESOLVED EXB

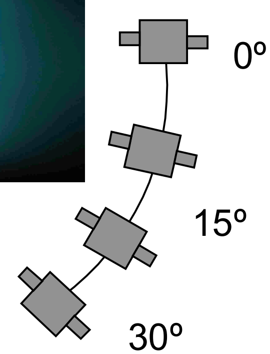
How many ions achieve a higher charge state?

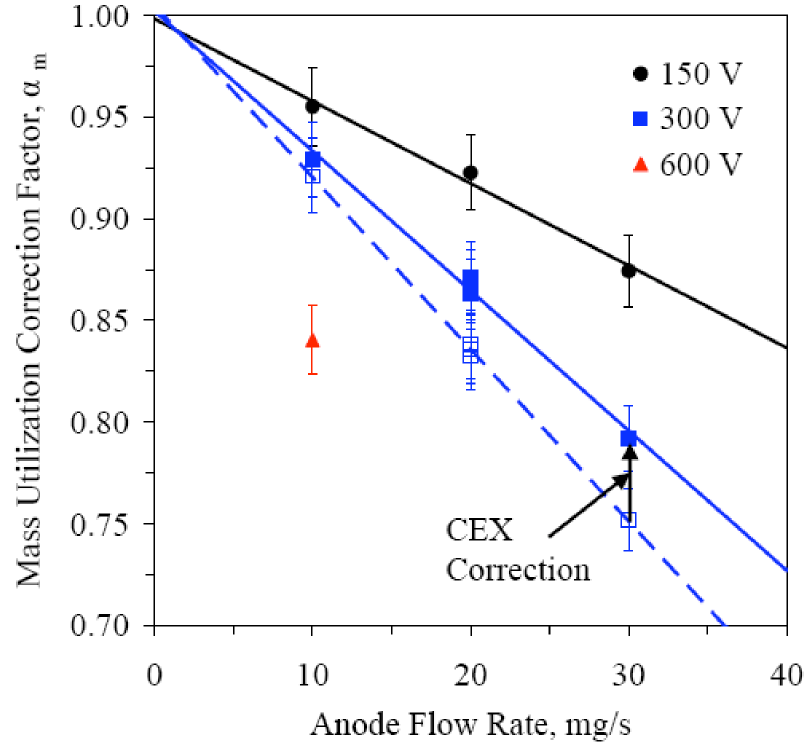
Far-Field ExB Measurements (η_q)

- Each peak corresponds to a particular ion species (1+, 2+, 3+, etc)
- Species fractions change with angle from centerline – weighted average is needed









Determined plume-averaged charge utilization

Fraction of multiply-charged ions increased with mass flow rate

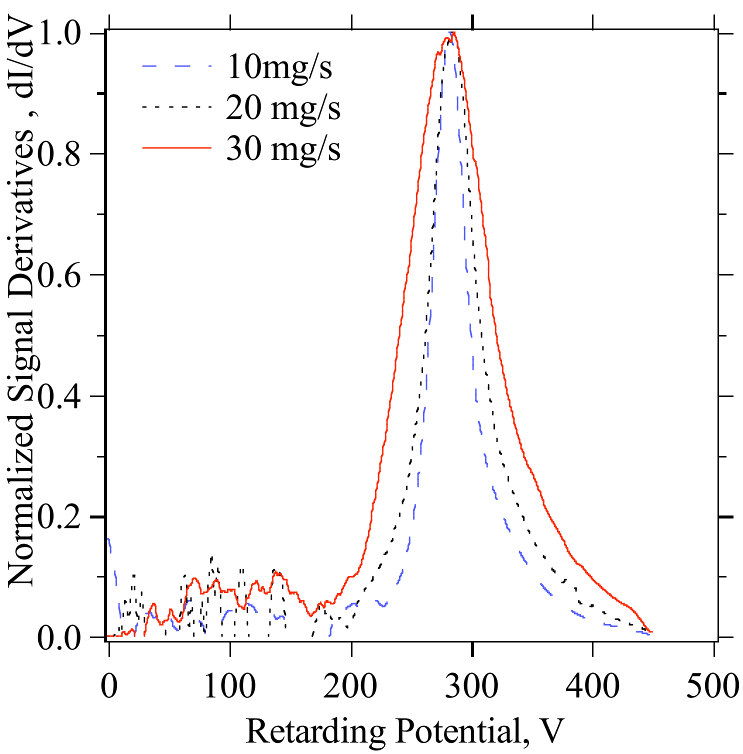
Typical charge utilization >95%

RETARDING POTENTIAL ANALYZER

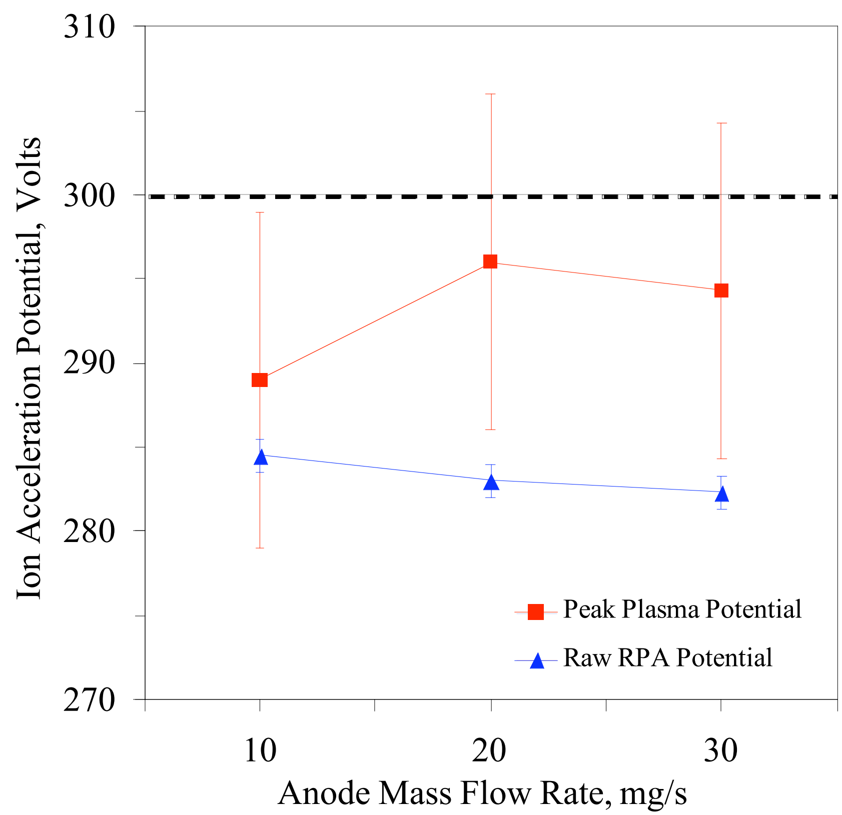
How close do ions get to full acceleration?

Far-Field RPA Measurements (η_v)

- Measure of bulk ion acceleration
- Full Width at Half Max increases with flow rate (collisions in plume cause spreading)



- Bulk of ions are accelerated to within ~17 V of anode-cathode drop
- Indicates 5-10 V lost within anode sheath



Typical voltage utilization >90%

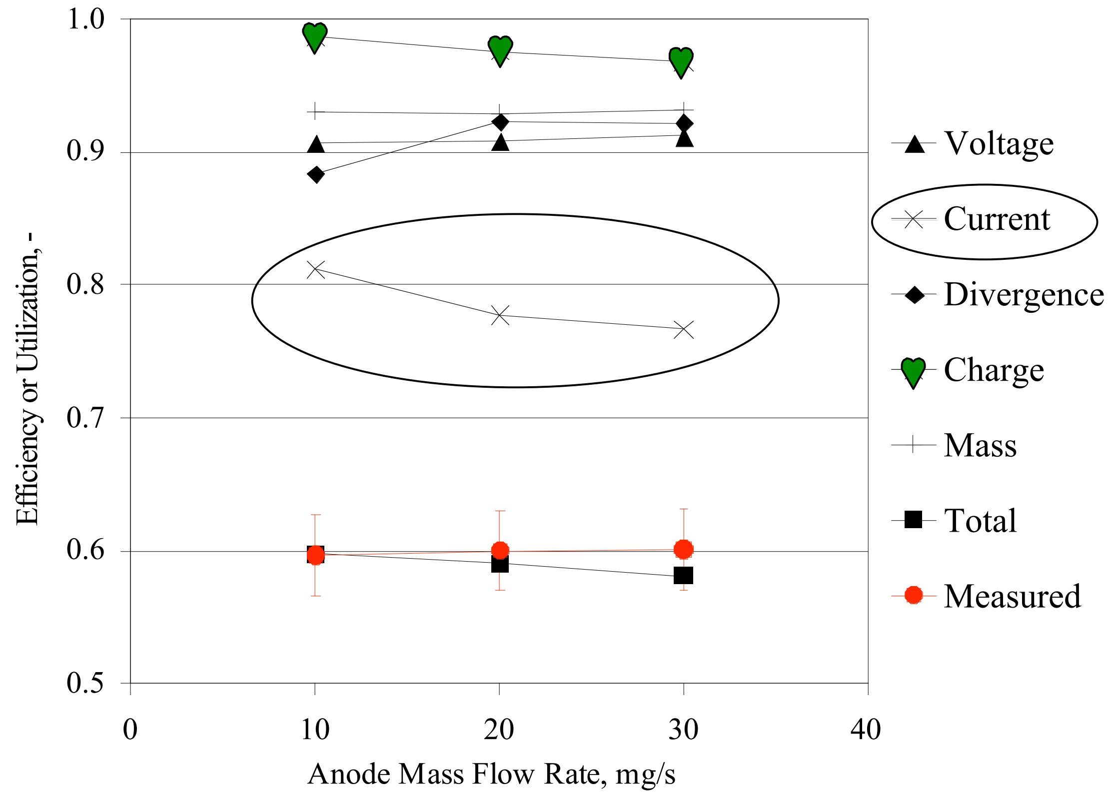
EFFICIENCY ANALYSIS RESULTS

What are the major loss mechanisms?

Results:

- **Voltage utilization >90%**
- **Current utilization ~70-80%**
- **Divergence utilization >90%**
- **Charge utilization >95+%**
- **Mass utilization >90%**

Thruster efficiency (50-70%)

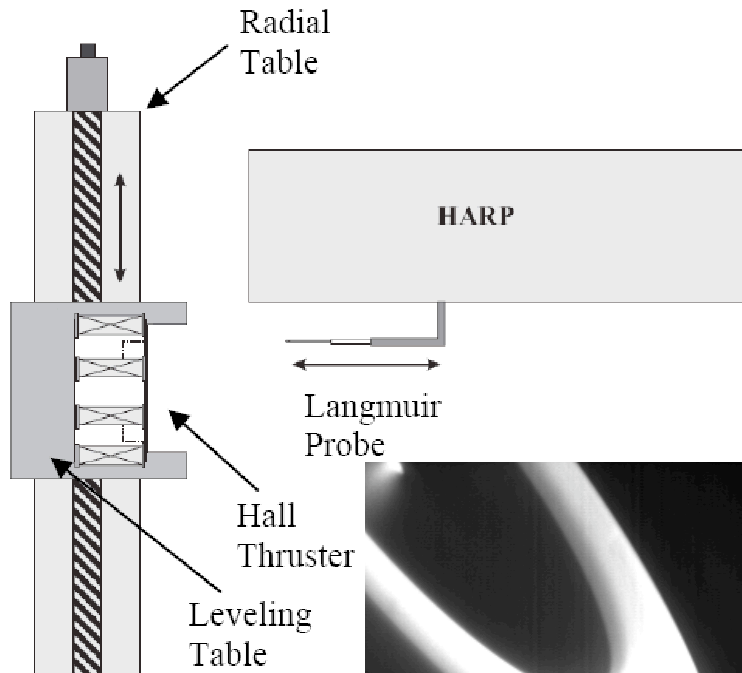


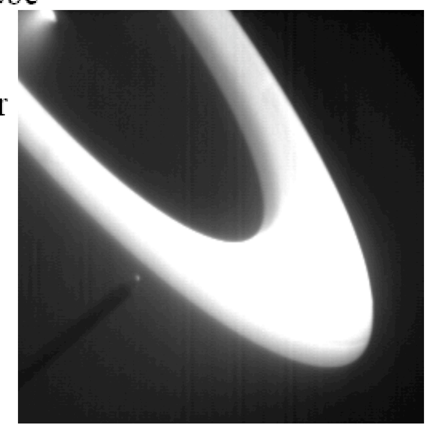
Primary efficiency loss is from current utilization η_b; i.e., electron backstreaming to the anode

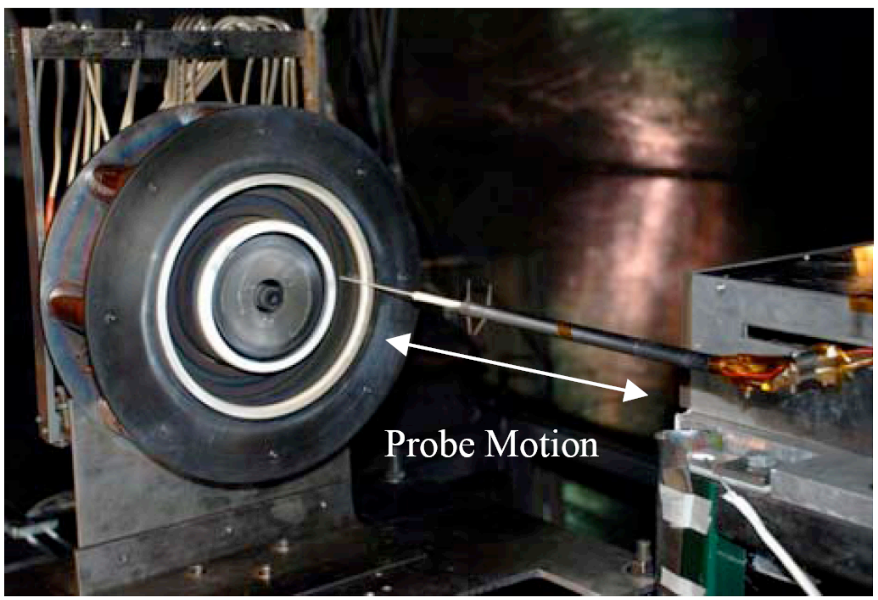
Speaks to the need to understand internal Hall thruster physics

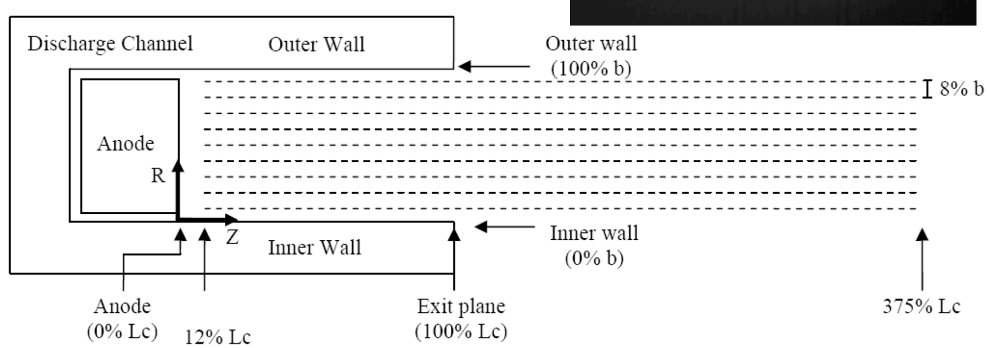
HARP

- High-speed Axial Reciprocating Probe
  - Probe is injected and removed axially
  - Capable of 2.5 m/s travel, up to 7 g's
  - Maintain residence time <100 ms
- Thruster moved radially (every ~8% of channel width)









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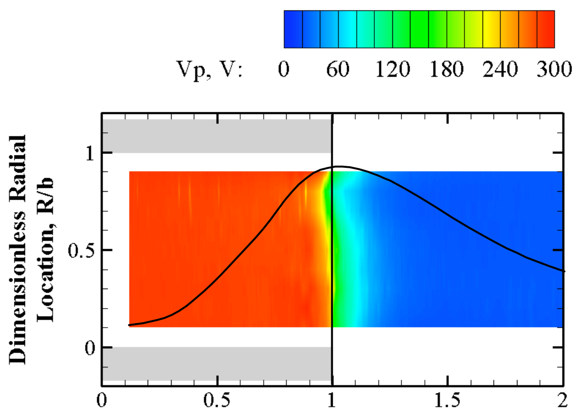
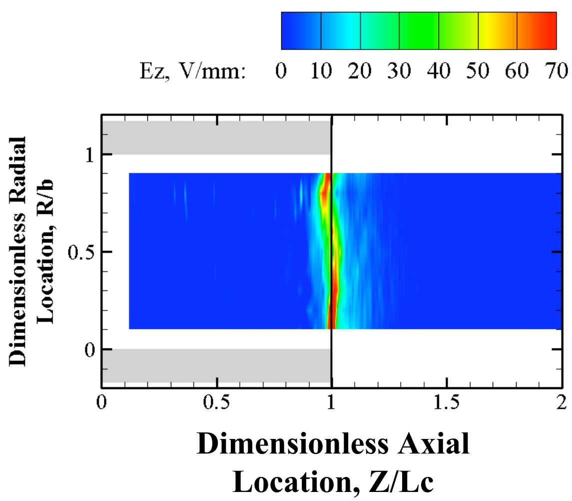
INTERNAL PLASMA PROPERTIES

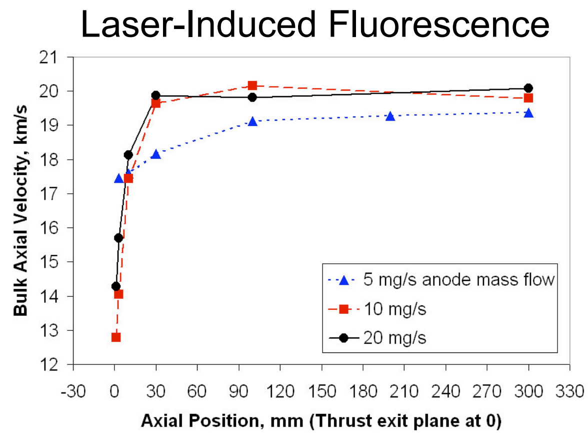
Plasma Potential



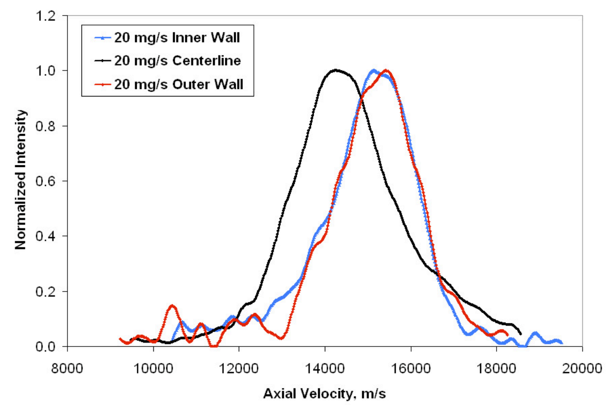
Axial Electric Field



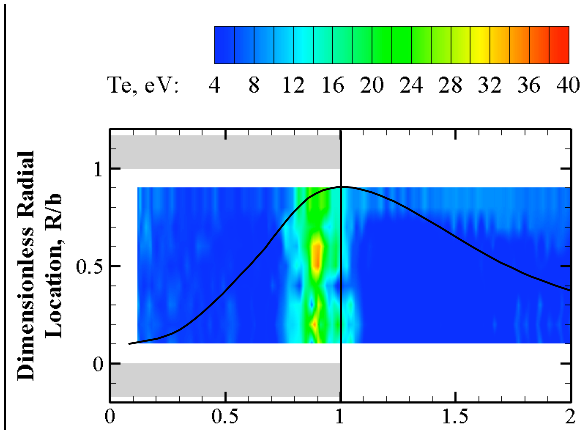
Ion Drift Velocity



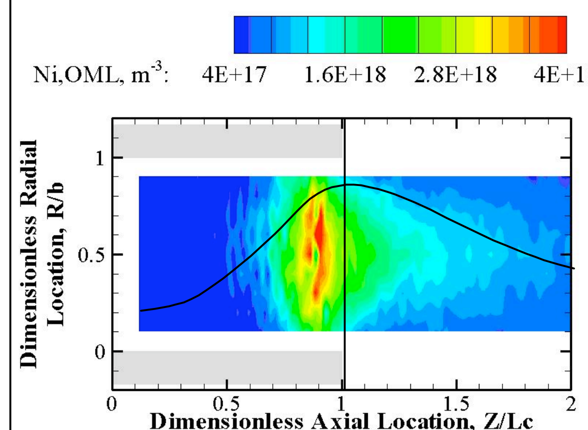
Ion Energy Distribution



Electron Temperature



Ion Density



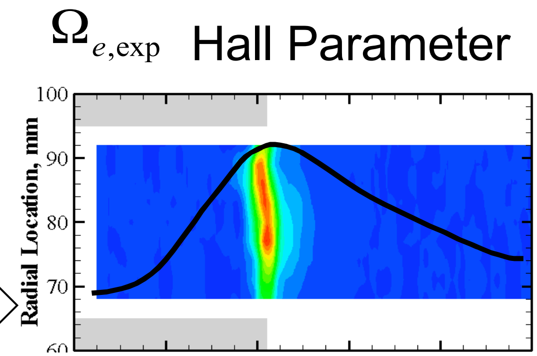
20 mg/s anode - 20 A — 300 V

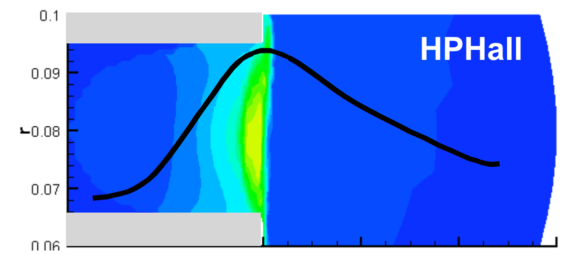
INTERNAL PLASMA PROPERTIES

How are electrons trapped in the thruster?

Hall parameter defined as ratio of cyclotron to collision frequencies

$$\Omega_{e,\exp} = 2\frac{J_{theta}}{J_{axial}}$$

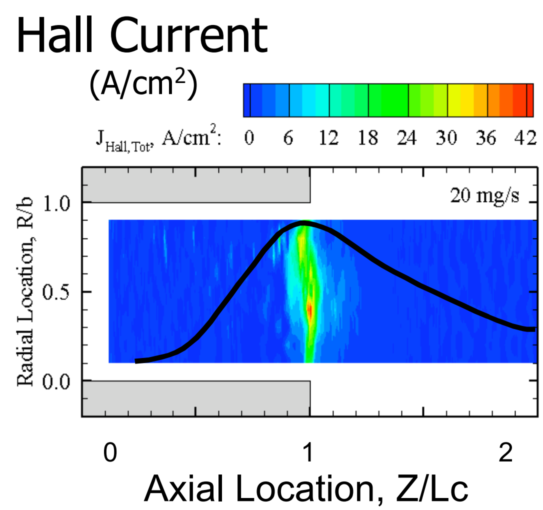




- Also, number of orbits before encountering a momentum transfer collision — primarily with neutrals
- Also, ratio of azimuthal (Hall) to axial electron current
- Simulations show relatively good agreement in shape, location, and magnitude

Large Hall parameter indicates existence of large Hall current

Measured Hall Current



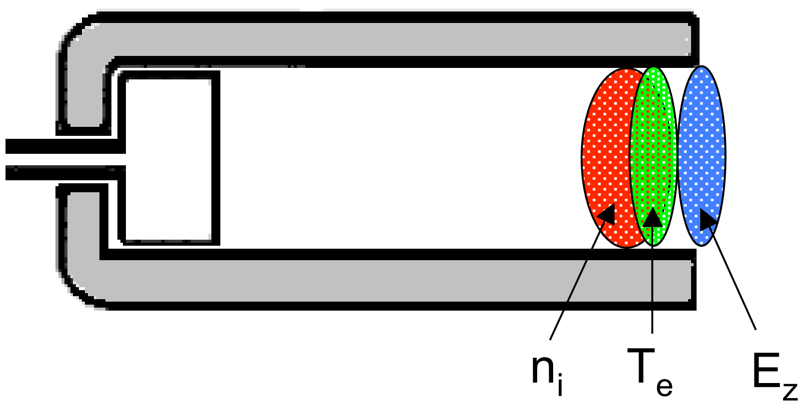
INFLUENCE OF THE NEUTRALS

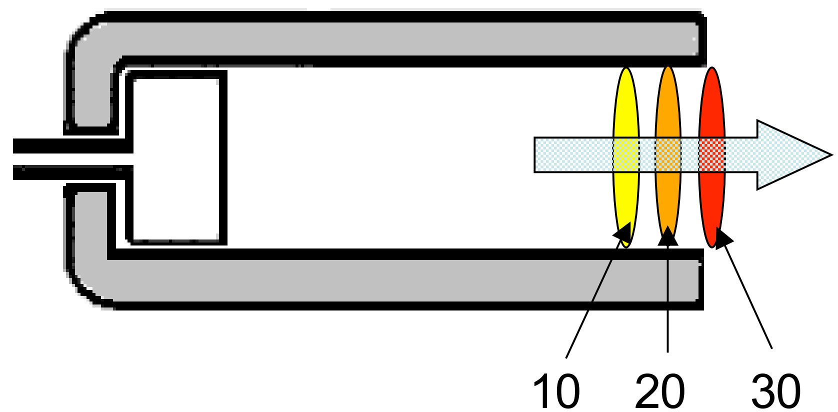
Neutrals contribute to moderation of electron temperature

- Te decreases with increased flow rate (increased electron-neutral collisions)
- Simulations show similar results

Neutrals contribute to locations of ionization/acceleration zones

- Ion production zone overlaps with peak Te zone, upstream of peak Ez
- Ionization and acceleration 'zones' move downstream with flow rate





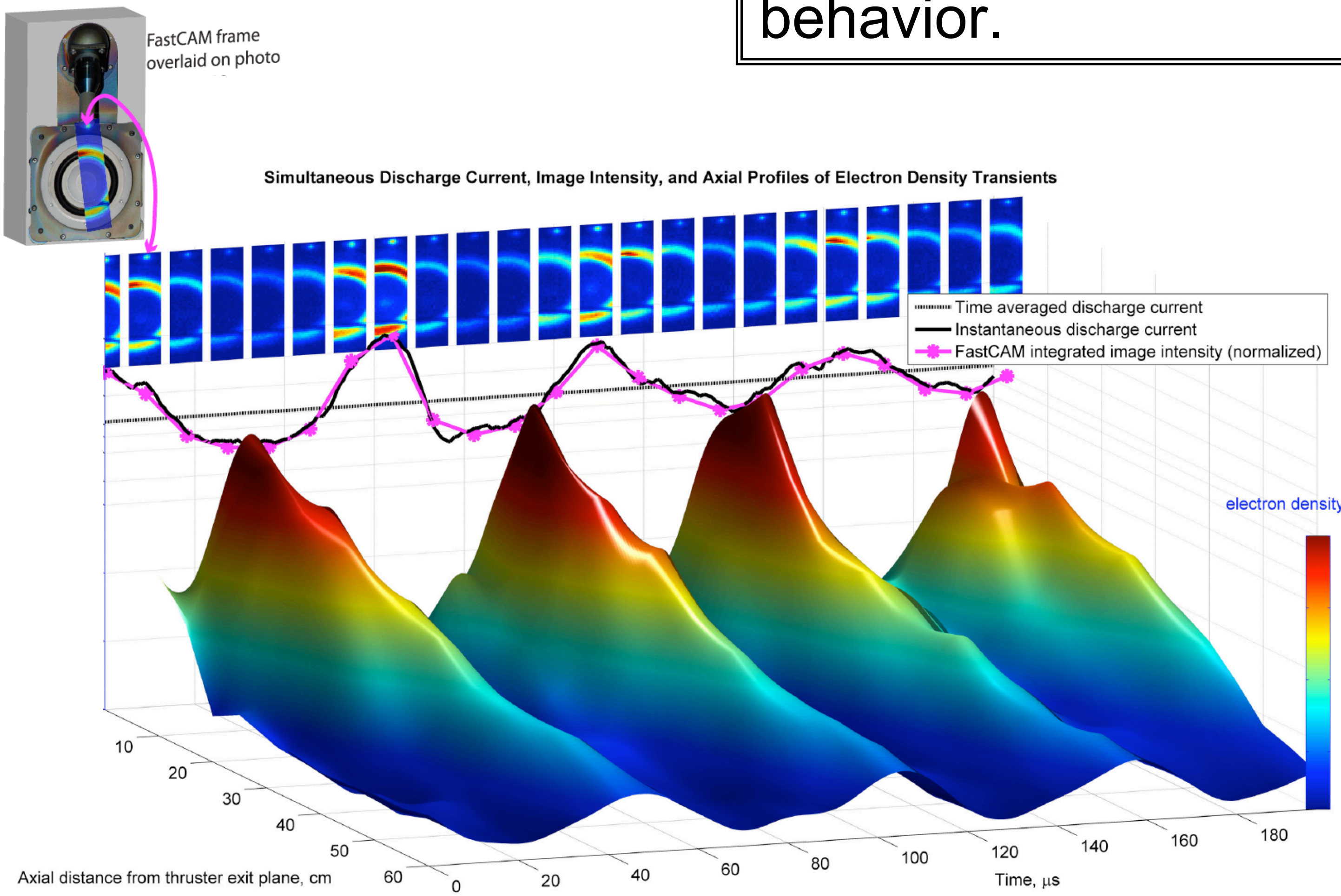
Picture not complete without considering plasma-wall interactions and discharge oscillations

HIGH-SPEED IMAGING OF HALL THRUSTER OSCILLATIONS

Visible plasma oscillations during Hall thruster operation

- Captured with FASTCAM at 109,500 fps
- Coupled with high-speed thruster I-V measurements

Goal: Correlate discharge channel oscillations with cathode, plume and thruster behavior.



CONCLUSIONS

Thruster Technology

- PEPL, in collaboration with the USAF and NASA, has successfully designed, built, and operated Hall thrusters with state-of-the-art performance on xenon and krypton.
- Spiral development approach of experimentation with M&S has enabled progress
- Near the top of the technology “S-curve” — additional gains are difficult to achieve

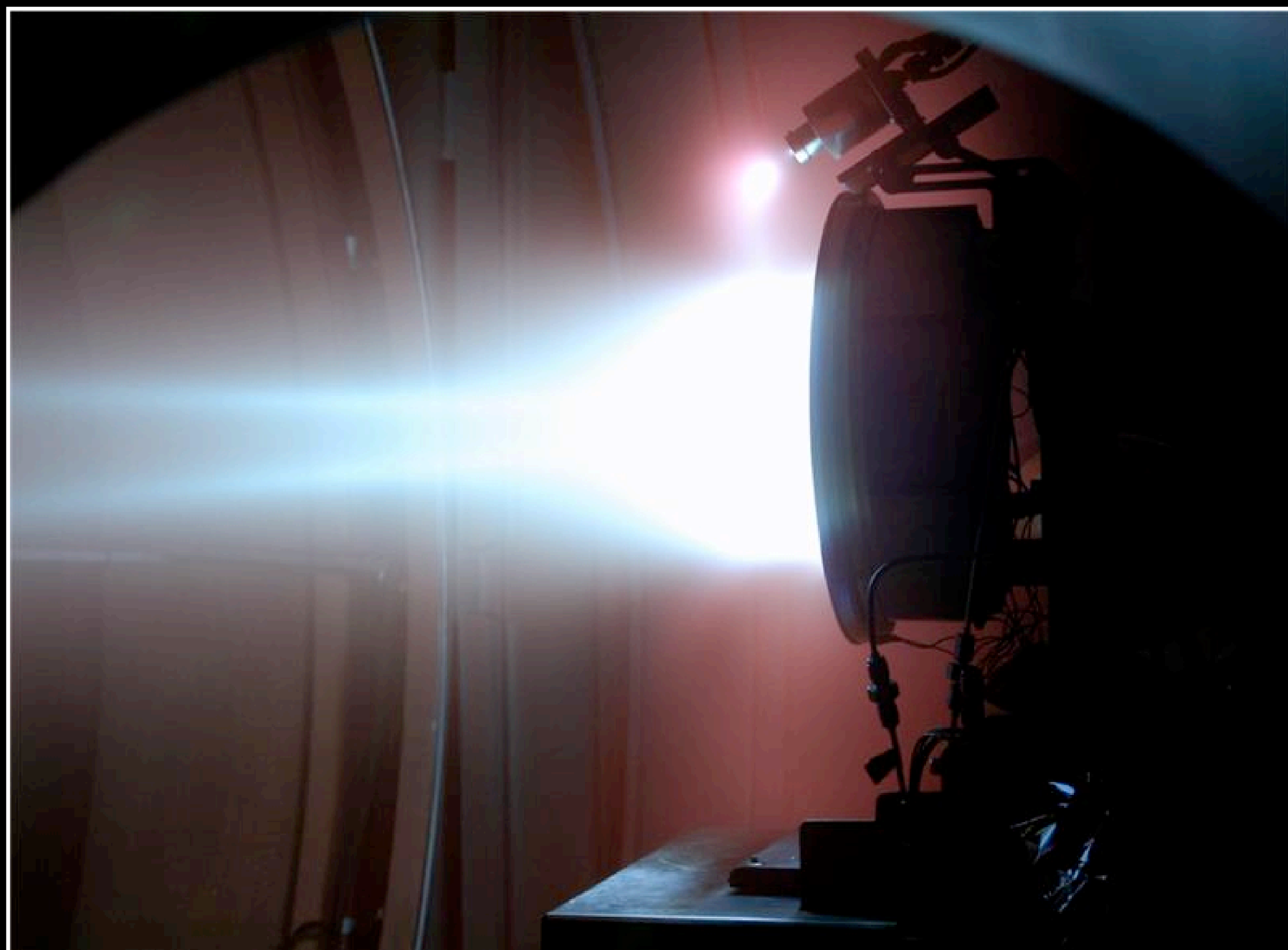
Plume Measurements

- Multiple plume property measurements can shed light on thruster physics and performance loss processes
- Electron back-streaming the principal loss mechanism in SOA Hall thrusters

Discharge Channel Measurements

- Strong property gradients within discharge channel
- Propellant neutrals drive location of Hall current, and acceleration and ionization zones
- Electron back-streaming influenced by propellant neutrals — but not exclusively
- Hall thruster discharge operation is oscillatory — *Predator Prey* (aka Breathing Mode)

THANKS



Questions?