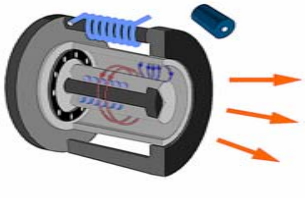
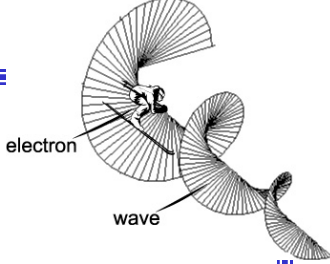
HTX





Electron cross-field transport in a miniaturized cylindrical Hall thruster

Artem Smirnov, Yevgeny Raitses, Nathaniel J. Fisch

Hall Thruster Experiment
Princeton Plasma Physics Laboratory
htx.pppl.gov

Nonlocal, Collisionless Electron Transport in Plasmas
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Abstract

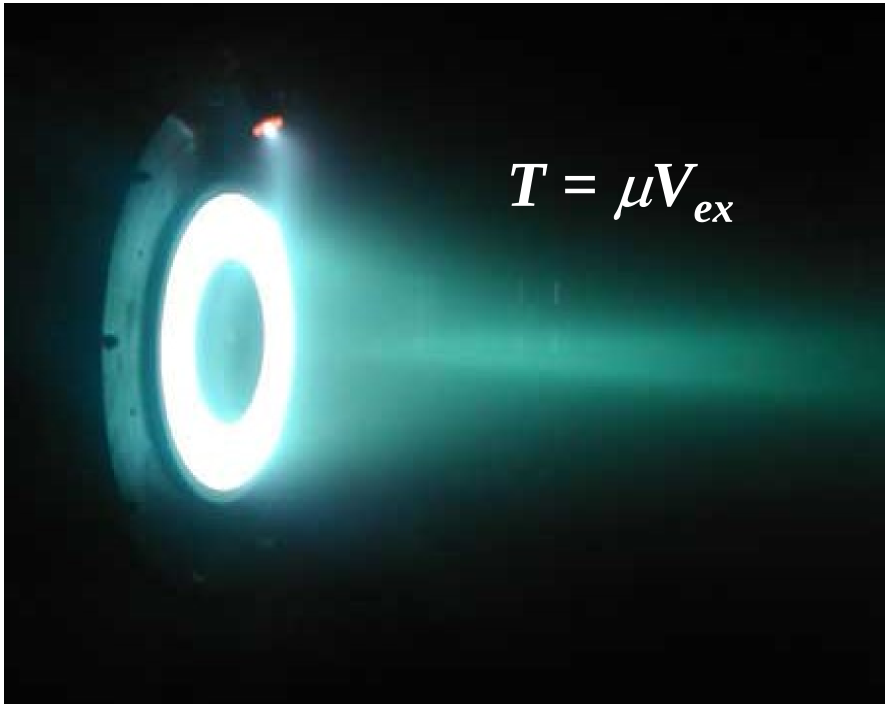
Conventional annular Hall thrusters become inefficient when scaled to low power. Their lifetime decreases significantly due to the channel wall erosion. Cylindrical Hall thrusters that have lower surface-to-volume ratio and, thus, seem to be more promising for scaling down, exhibit performance comparable with conventional annular Hall thrusters of the similar size [1,2]. Efficiency of a Hall thruster decreases with increasing electron current. Understanding of the mechanisms of electron transport in the discharge is, therefore, essential for the development of higher efficiency thrusters.

Electron cross-field transport [3] in a 2.6 cm miniaturized cylindrical Hall thruster (100 W power level) has been studied through the analysis of experimental data and Monte Carlo simulations of electron dynamics in the thruster channel. The numerical model takes into account elastic and inelastic electron collisions with atoms, electron-wall collisions, including secondary electron emission, and Bohm diffusion. It is shown that in order to explain the observed discharge current, the electron anomalous collision frequency ν_B has to be on the order of the Bohm value, $\nu_B \approx \omega_c/16$. The contribution of electron-wall collisions to cross-field transport is found to be insignificant.

This work was supported by grants from AFOSR and DOE.

[1] Y. Raitses and N.J. Fisch, Phys. Plasmas **8**, 2579 (2001).
[2] A. Smirnov, Y. Raitses, and N.J. Fisch, J. Appl. Phys. **92**, 5673 (2002).
[3] A. Smirnov, Y. Raitses, and N.J. Fisch, Phys. Plasmas **11**, 4922 (2004).

Background & motivation



$T = \mu V_{ex}$

Rocket Equation

$$m\frac{dV}{dt} = -\frac{dm}{dt}V_{ex}$$

$$\boxed{m_f = m_0 e^{-\Delta V / V_{ex}}}$$

Chemical rocket V_{ex} ~ 4000 m/s

Hall thruster V_{ex} ~ 16000 m/s

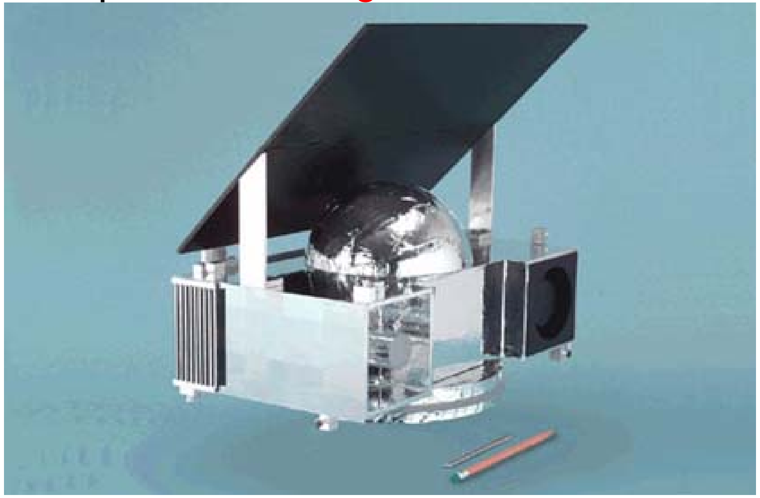
Mission:	ΔV (m/s)	Trip time (days)
orbit insertion	3000-5000	<180
Moon probe SMART-1	~4000	~500
repositioning	10-100	<30
drag compensation	10-1000	periodic

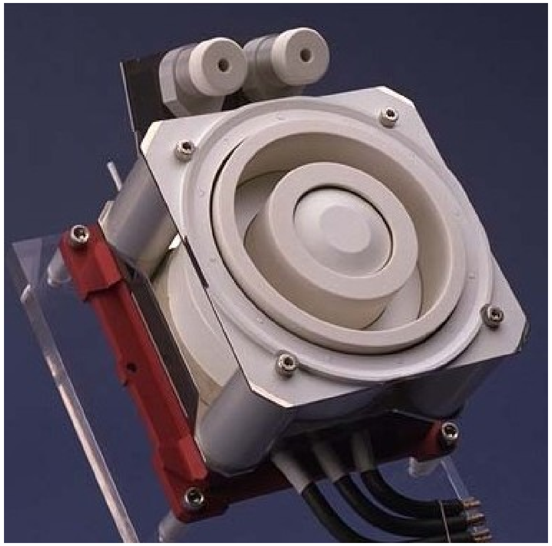
Primary propulsion with HTs

SMART-1: 287 kg, 1 m x 1 m x 1m

⇒

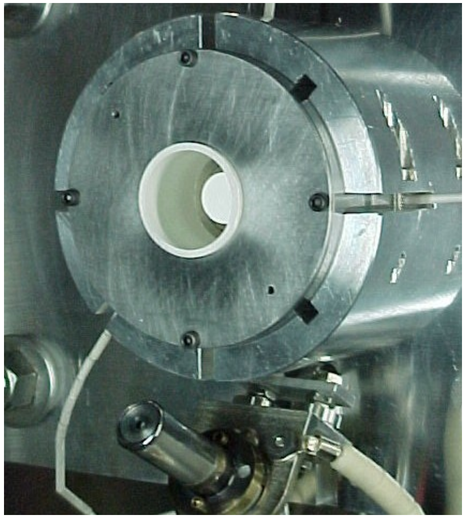
NASA Near-Earth-Object Rendezvous
Microspacecraft: 7 kg, 0.2m x 0.3m x 0.3m





PPS-1350: 1200 W, 10 cm OD, 68 mN

⇒



PPPL

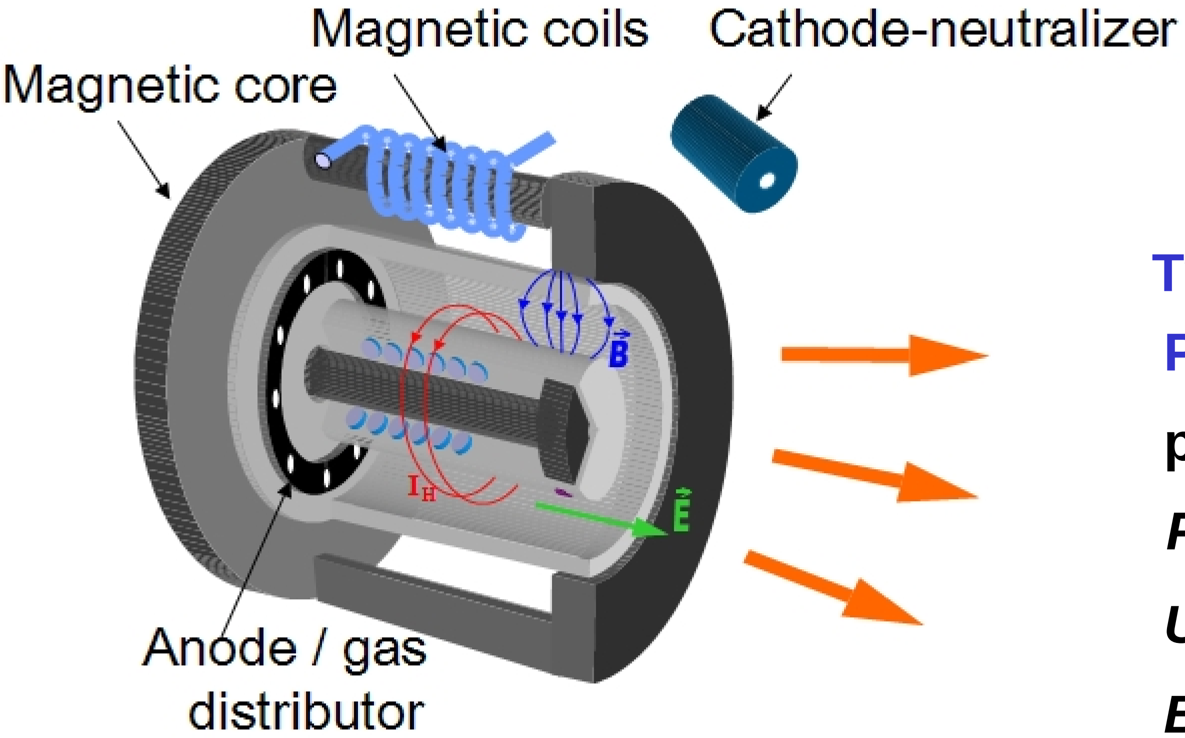
low-power HT

P = 50-300 W

OD = 2.6 cm

T = 2-12 mN

Conventional geometry Hall thruster



$$\boxed{\rho_e << L << \rho_i}$$

Typical Hall Thruster Parameters:

propellant - xenon

$P \sim 600$ W $\div$ 1000 W

$U_{anode\text{-}cathode} \sim 300$ V

$B_{max} \sim 100$ G

efficiency $\eta = \frac{\dot{m} V_{ex}^2}{2P_{in}}$ **~ 50-60%**

$n_e \sim 10^{11} \div 10^{12}$ cm^{-3}

$V_{ex} \sim 16000$ m/s

outer channel diam. ~10 cm

Why study electron cross-field transport?

- ✓ Thruster efficiency $\eta \propto \dfrac{I_i}{I_i + I_e}$

  With all other parameters held constant, efficiency reduces with increasing electron current

- ✓ Enhanced conductivity: Anomalous (Bohm) diffusion & near-wall conductivity

- ✓ Kilowatt thrusters – *B* ~ 100 - 200 G

  Models show $\nu_a = \kappa_B \dfrac{\omega_{ce}}{16}$, where $\kappa_B \sim 0.1 - 0.4$

  Low-power scaling: $L \propto k$ and $B \propto k^{-1}$ (*k* – scaling parameter)

  The rate of anomalous transport in the strong magnetic field of a low-power thruster may be different from that in kilowatt thrusters

Linear scaling down to low power

Scaling factor k < 1

Ionization probability $\lambda_{ion}/L \sim const$

Electron gyroradius $r_{Le}/L \sim const$

$\Rightarrow$

Channel dimensions ~ k

Magnetic field ~ 1/k

Crucial issues:

- Magnetic saturation of miniaturized iron parts, non-optimal B-field profile
- Enhanced electron transport and wall losses
- Small volume-to-surface ratio, heating and erosion of the thruster parts

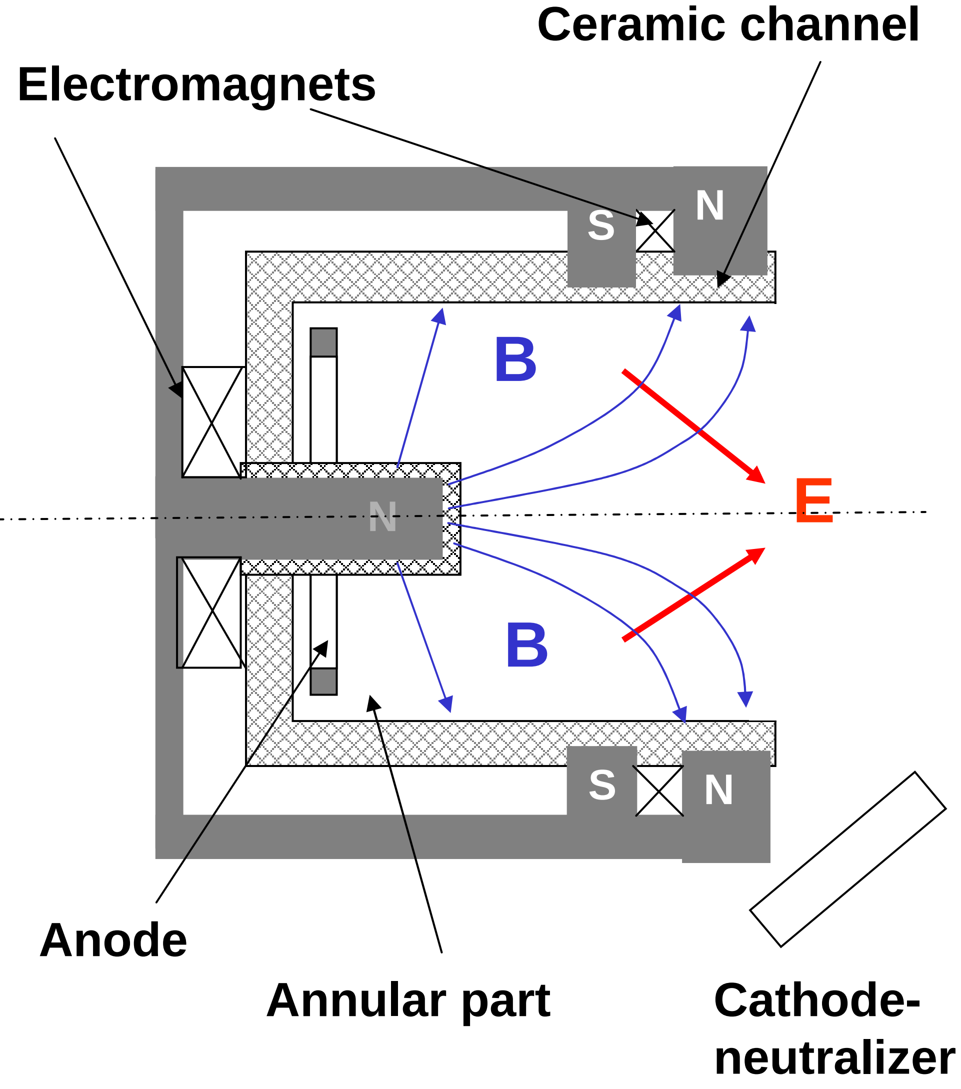
$\Downarrow$

Lower thruster efficiency

6 ÷ 25% at 100 W, 25 ÷ 40% at 200 W for the existing low-power HT's

Shorter life time due to erosion of the channel walls

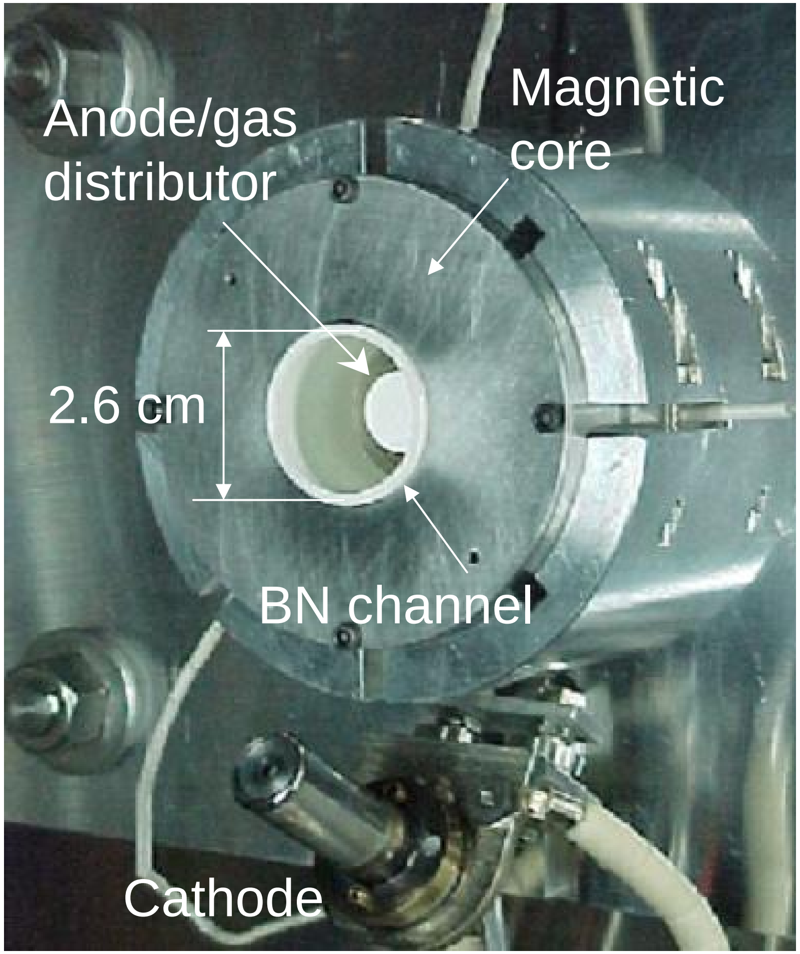
Cylindrical Hall thruster has larger volume-to-surface ratio than conventional thrusters



- CHT has larger volume-to-surface ratio ⇒ Promising for low-power scaling
- Mirror magnetic field in the cylindrical part of the channel and mostly radial field in the annular part
- Ion axial acceleration ~ $I_{e\theta} x B_r$ Lower erosion ⇒ Potentially longer thruster lifetime

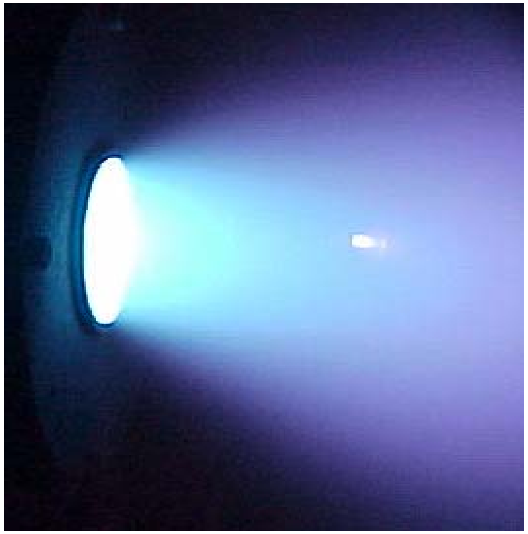
*Y. Raitses and N.J. Fisch, Phys. Plasmas **8**, 2579 (2001)*

2.6 cm diameter cylindrical Hall thruster

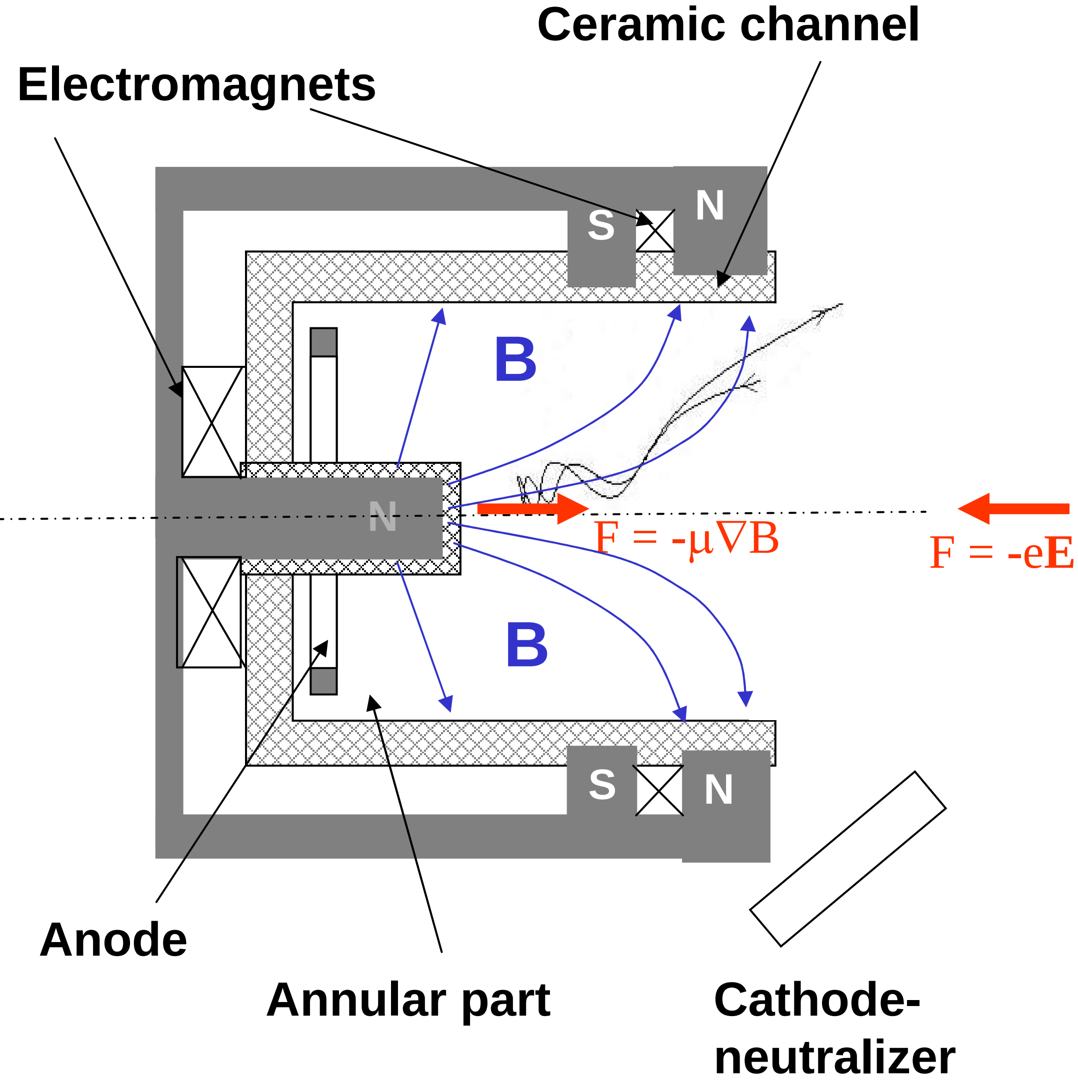


- Channel OD and Length = 2.6 cm
- Power range: 50 – 300 W
- Anode efficiency: 10 – 32 %
- Thrust: 2.5 – 12 mN
- Performance comparable with that of the state-of-the-art annular low-power HTs
- Larger propellant utilization & thrust density
- Potentially longer lifetime

A. Smirnov, Y. Raitses, and N.J. Fisch,
J. Appl. Phys. **92**, 5673 (2002); **94**,852 (2003)



Fundamental difference from conventional HTs



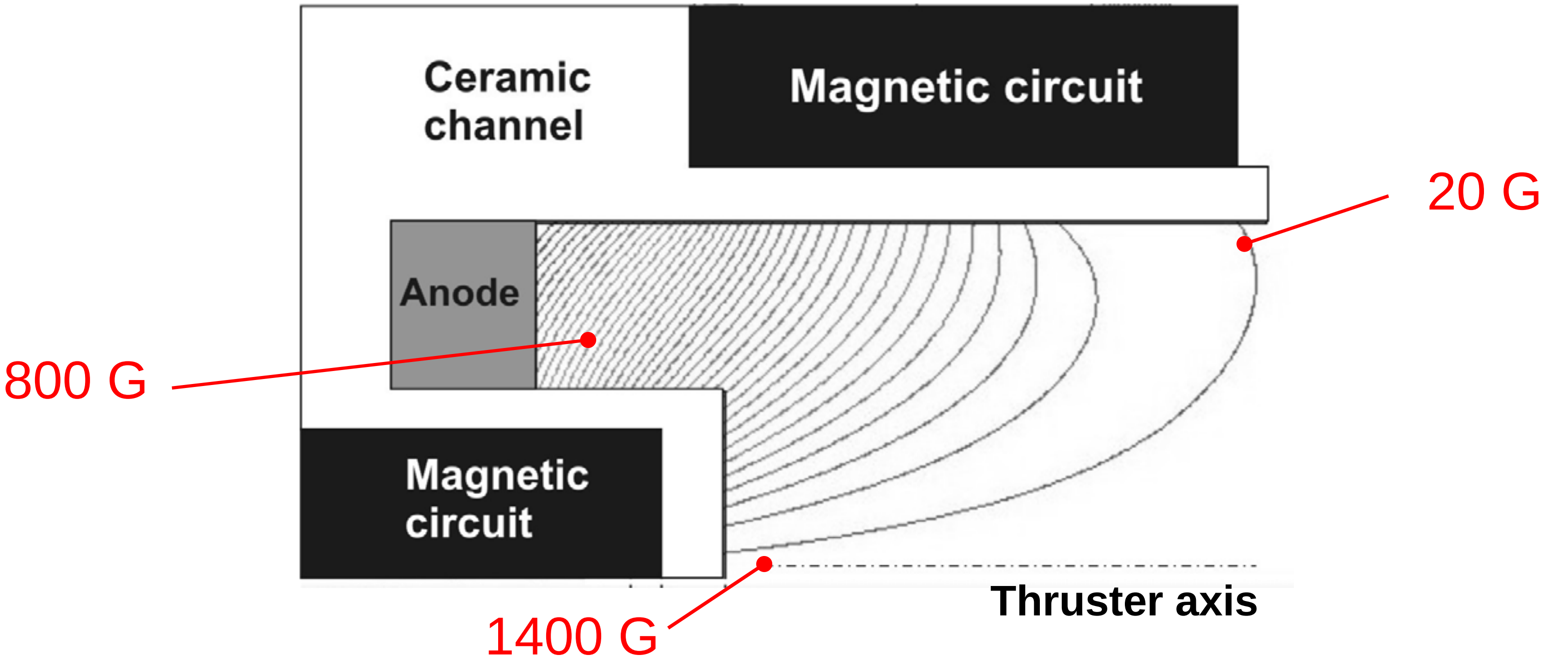
- Fundamentally different from conventional HTs in the way the electrons are confined and the ion space charge is neutralized

- Electrons are confined in the hybrid magneto-electrostatic trap

- One of the fundamental constraints of the conventional HT geometry is loosened

- New interesting physics:
  Electron transport,
  ionization of neutrals,
  potential distribution,
  waves and instabilities, etc…

Magnetic field in the 2.6 cm CHT

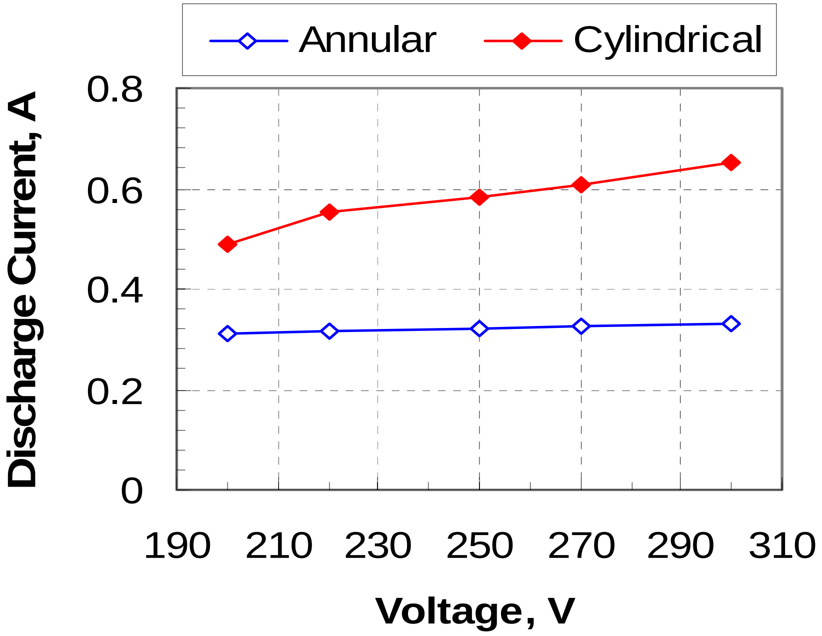


- Magnetic field in the annular part of the channel is predominantly radial
- Strong magnetic mirror at the thruster axis

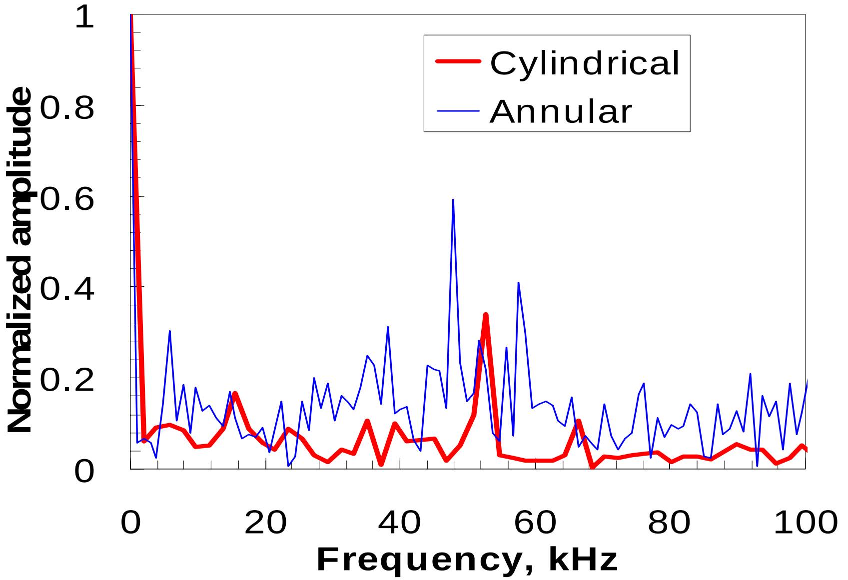
Cylindrical HT vs. Annular HT

μ = 0.4 mg/s of Xe

I_d is minimized w.r.t. coil currents



Spectra of discharge current oscillations

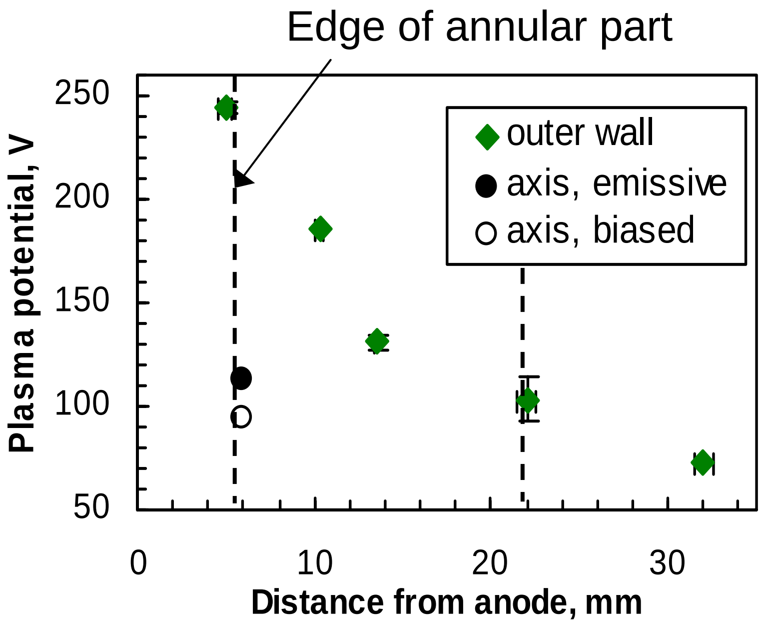


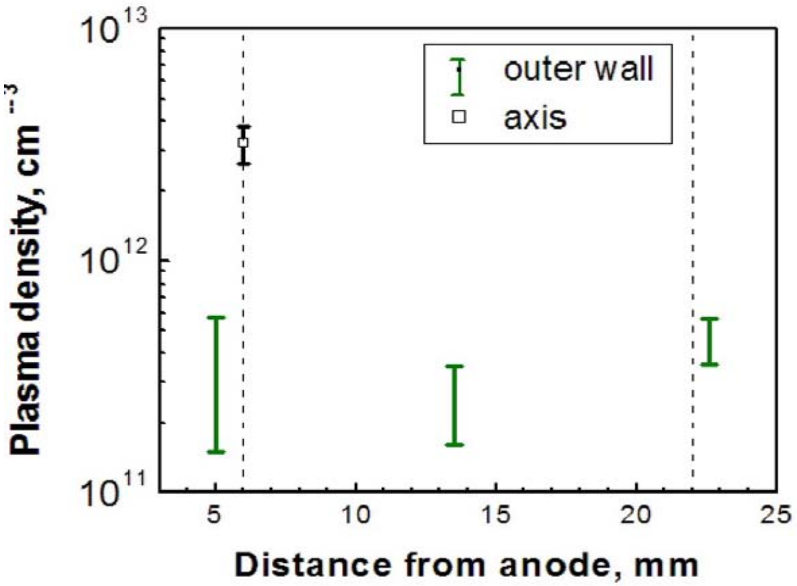
- $I_{cyl} \approx I_{an} \times (1.5 \div 2)$.

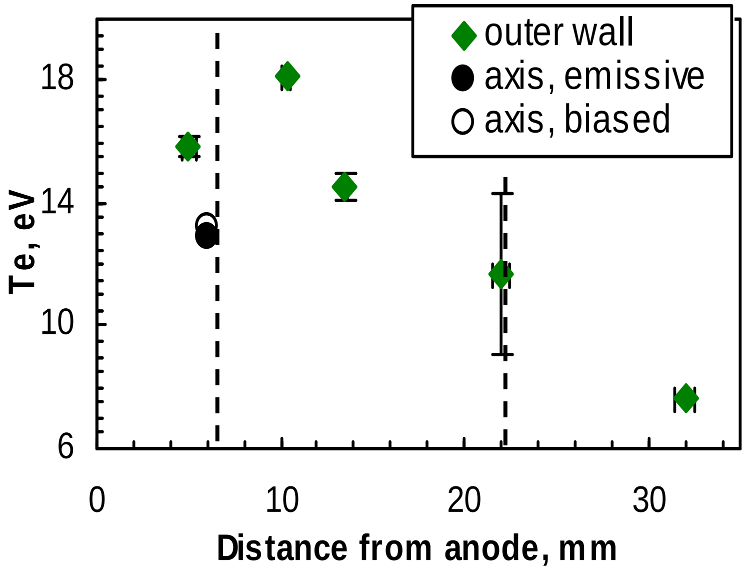
  Experiments showed that both I_{ion} and I_{el} are larger in the cylindrical thruster than in the annular one.

- The level of low-frequency discharge current oscillations in the CHT is lower than in the annular thruster. $W_{cyl}^{osc} \sim 0.1 \times W_{ann}^{osc}$

Plasma parameters of the 2.6 cm CHT







- Plasma measurements inside the 2.6 cm CHT

U_d=250 V, I_d=0.6 A, μ=0.4 mg/s of Xe.

A. Smirnov, Y. Raitses, and N.J. Fisch, *J. Appl. Phys.* **95**, 2283 (2004)

PPPL Hall thruster Monte Carlo code

Geometry

3D particle tracer 2D (R-Z) field interpolator

3D (R-Z-ε) phase space

Particle tracer

Explicit leap-frog scheme (Δt^2 error term) $\omega_c \Delta t = 0.1$

Collisions

✓ e-atom collisions:
Elastic, ionization, excitation

✓ Bohm diffusion ⊥ *B*, $\boldsymbol{\nu_a = \kappa_B \omega_c / 16}$, κ_B is a fitting parameter

✓ Electron-wall collisions:
Attachment, backscattering, true secondary emission

✓ Isotropic scattering (except for Bohm diffusion)

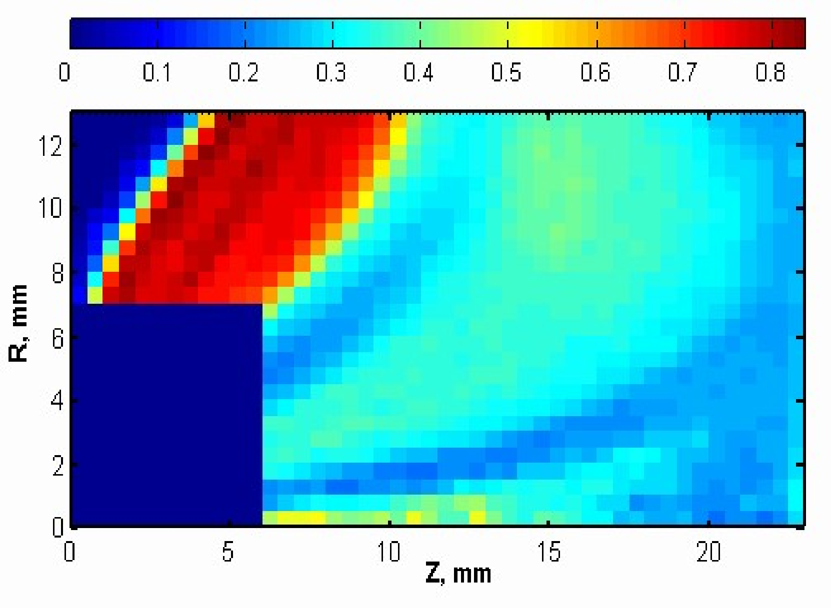
Field structure

✓ Calculated B field distribution

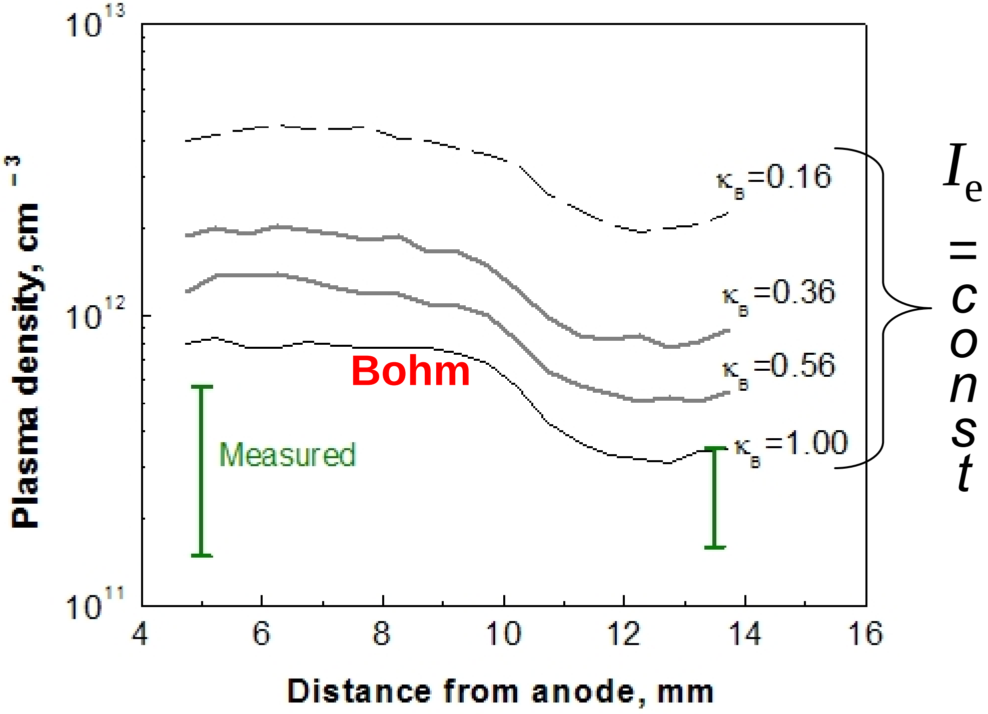
✓ E field distribution is reconstructed from the plasma potential measurements, assuming the magnetic surfaces to be equipotential

Electron density and anomalous collisions

Electron density, 1×10^{12} cm^{-3}

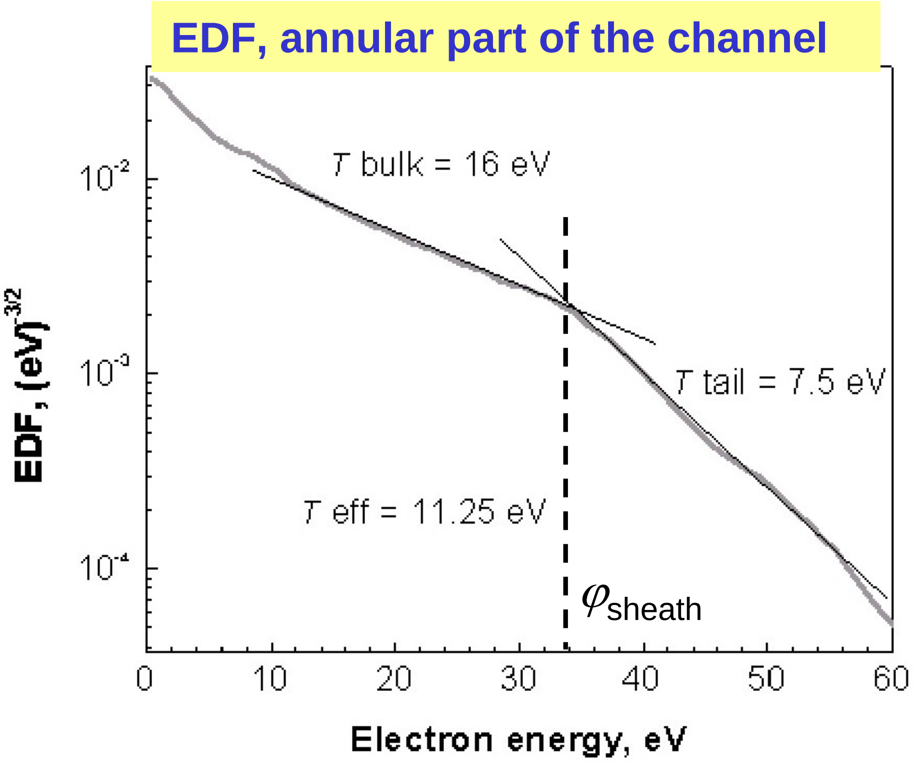


Electron density near the outer wall



The electron anomalous collision frequency ν_a should be on the order of the Bohm value $\nu_a \sim \omega_c/16$.

EDF and wall collisions


EDF, annular part of the channel

A. Smirnov, Y. Raitses, and N.J. Fisch, *Phys. Plasmas* **11**, 4922 (2004)

- Wall collisions deplete the tail of the EDF. The resultant shape of the EDF appears to be bi-Maxwellian.

- The electron-wall collisions make an insignificant contribution to the electron cross-field diffusion

$$\nu_{ew} \sim 1\times10^{7}\ \mathrm{s}^{-1} \le \nu_{ea} \sim 2.4\times10^{7}\ \mathrm{s}^{-1}$$

$$\nu_{ew},\ \nu_{ea} \ll \nu_{a} \sim 7\times10^{8}\ \mathrm{s}^{-1}$$

- Qualitatively similar results were obtained for a conventional HT by solving the electron Boltzman equation.

N.B. Meezan and M.A. Cappelli, PRE, 2002.

Conclusions

✓ Cylindrical Hall thruster is a novel Hall thruster geometry that has one of the fundamental constraints of the conventional (annular) design loosened. Namely, electrons in the cylindrical thruster are confined differently: They are allowed to move axially, while being trapped in the magneto-electrostatic trap. This changes the thruster physics significantly.

✓ Cylindrical Hall thrusters have larger volume-to-surface ratio than conventional geometry Hall thrusters, and therefore, might be more suitable for low-power scaling. The existing cylindrical Hall thrusters exhibit performance comparable with that of conventional geometry Hall thrusters of the similar size.

✓ The electron cross-field transport in the 2.6 cm CHT was studied though the analysis of experimental data and MC simulations of electron dynamics.

✓ In order to explain the observed plasma density, the electron anomalous collision frequency ν_a should be on the order of the Bohm value $\nu_a \sim \omega_c/16$, which is a is a few times larger than the values typically obtained in the modeling of conventional Hall thrusters ($\nu_a/\omega_c \sim 1/100$).

✓ EDF in a Hall thruster is depleted at high energy due to electron loss at the walls. The contribution of electron-wall collisions to cross-field transport is likely insignificant.