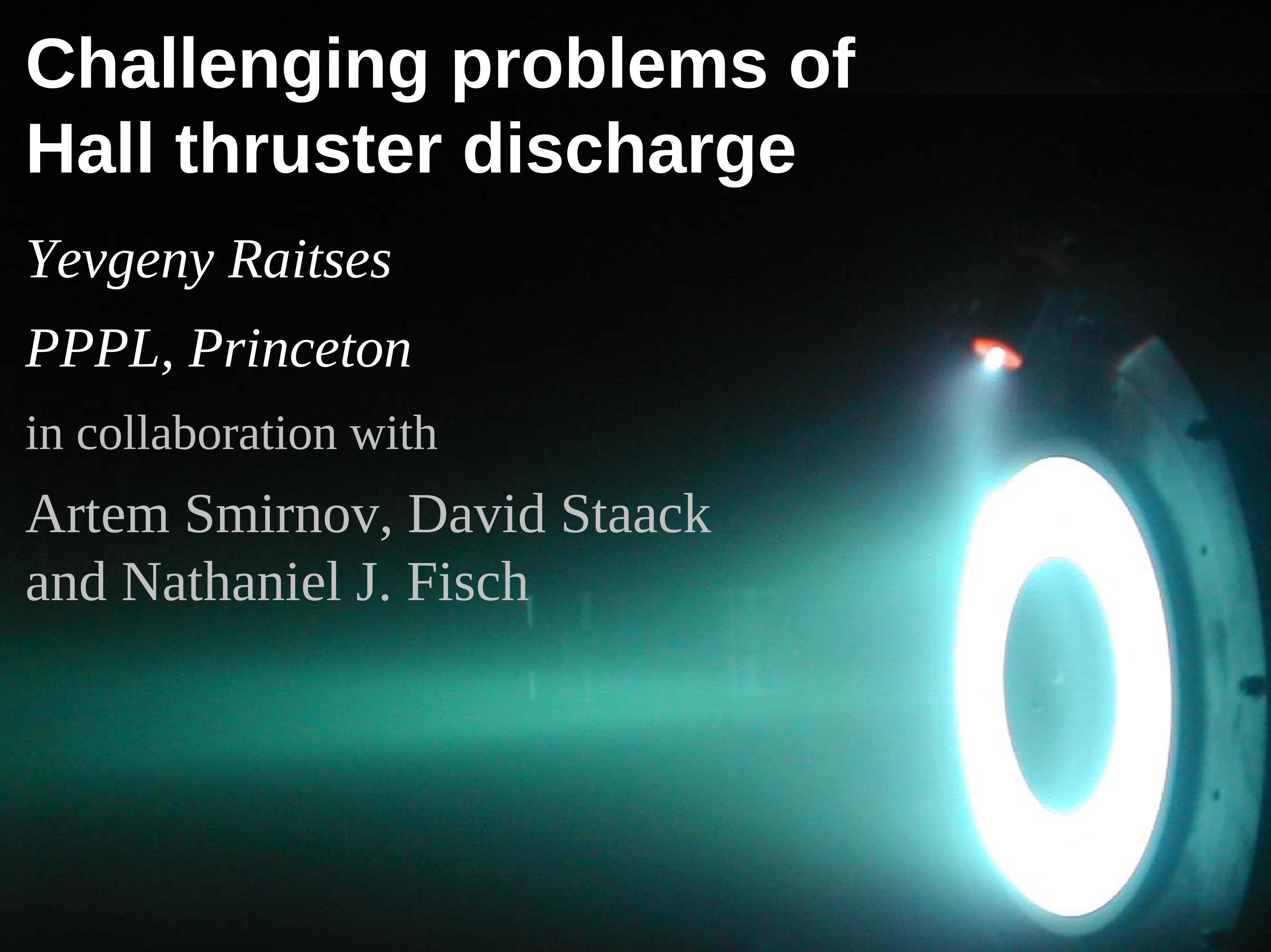
Challenging problems of Hall thruster discharge



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in collaboration with

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Motivation & Challenges

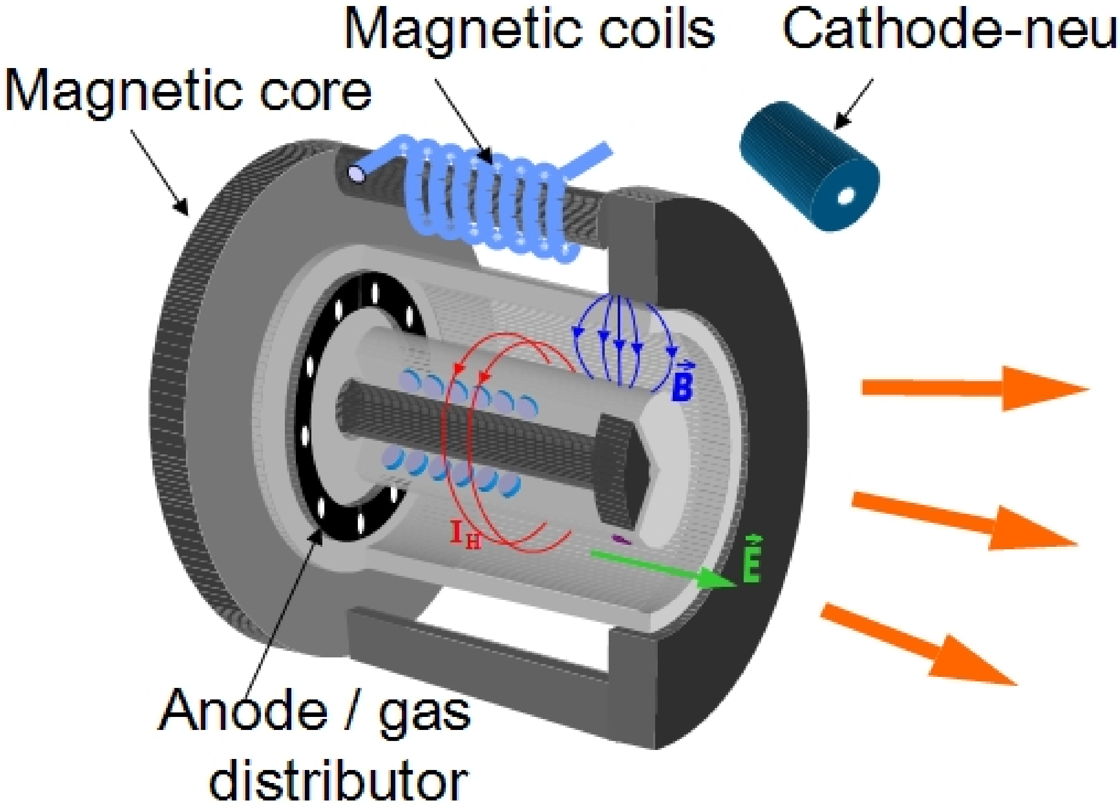
Hall thruster plasma: collisionless, magnetized electrons and non-magnetized ions, non-uniform, non-equilibrium, with hot electrons and high energy ions.

➢What is a role of plasma-wall interaction in the presence of a strong secondary electron emission?

➢ What mechanisms are responsible for enhanced electron cross-field transport in Hall thruster discharge?

Controlling of electron transport and plasma-wall interaction could lead to a technologically superior thruster

Hall Thruster (HT)



$$\rho_{Le} \ll \boldsymbol{L} \ll \rho_{Li}$$

Magnetic field ~10^2 Gauss
Discharge voltage ~ 10^2-10^3 keV
Ion kinetic energy ~ 10^2-10^3 keV
Ion beam density ~ 0.1-1 A/cm^2

Parameters of Hall thruster plasma

Neutral density ~ 10^{12}-10^{13} cm^{3}

Plasma density ~ 10^{11}-10^{12} cm^{-3}

Highly ionized flow: Γ_{ion}/Γ_{n}~ 80%

Electron temperature ~ 20-60 eV

Ion temperature ~ 1 eV

Ion kinetic energy ~ 10^{2}-10^{3} keV

$\lambda_{ea}/h \sim 20 – 200$

$\lambda_{ei}/h \sim 4\times10^{3}$

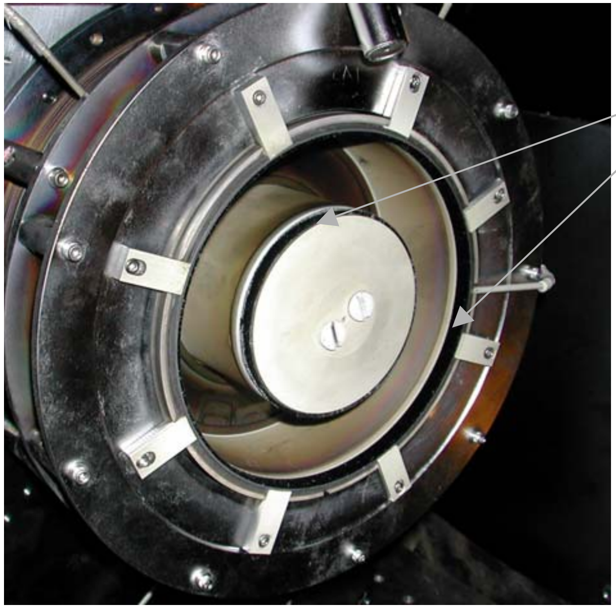
$\lambda_{ia}/h \sim 10\text{-}100$

Energy relaxation length in the inelastic range

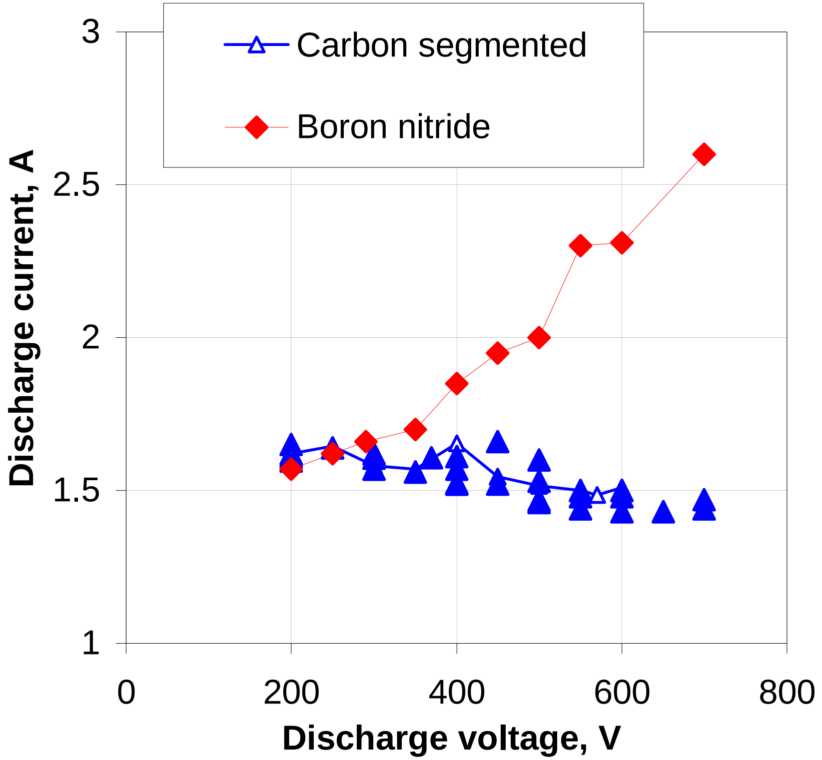
$\lambda^{*}/h \sim 30 - 300$

Collisionless, non-equilibrium plasma with magnetized electrons and high energy, non-magnetized ions

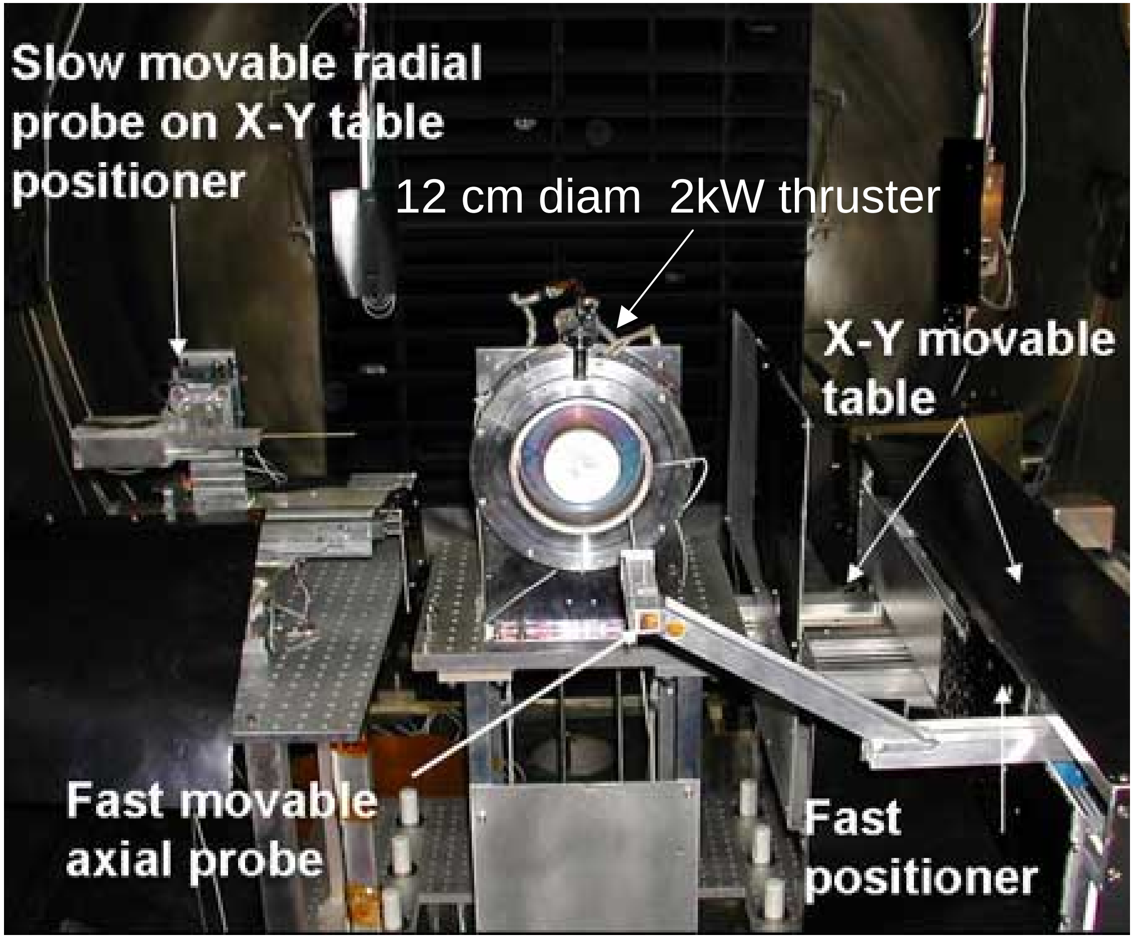
Non-local effect of electron-wall interaction on the V-I characteristics



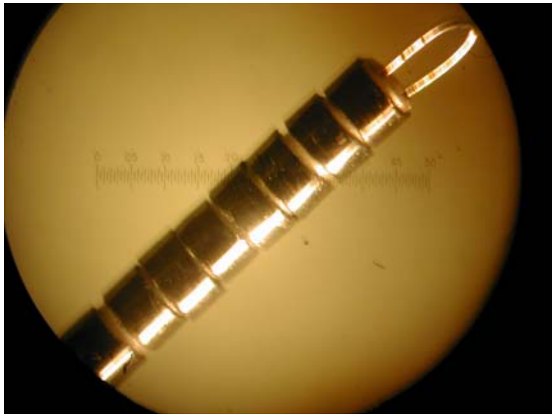
Narrow low-SEE segments at the channel exit drastically change V-I characteristics



Plasma measurements in PPPL HT with emissive and biased probes

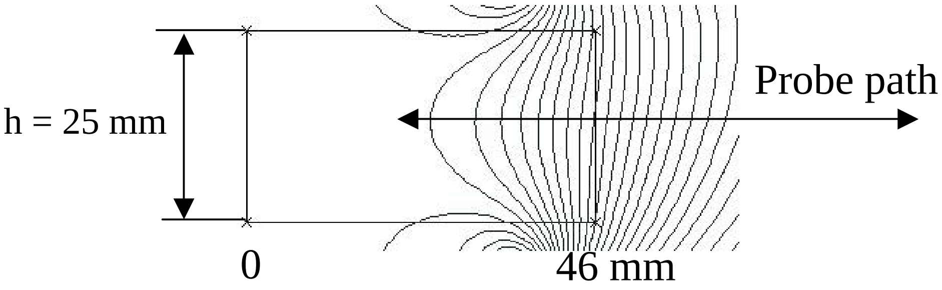


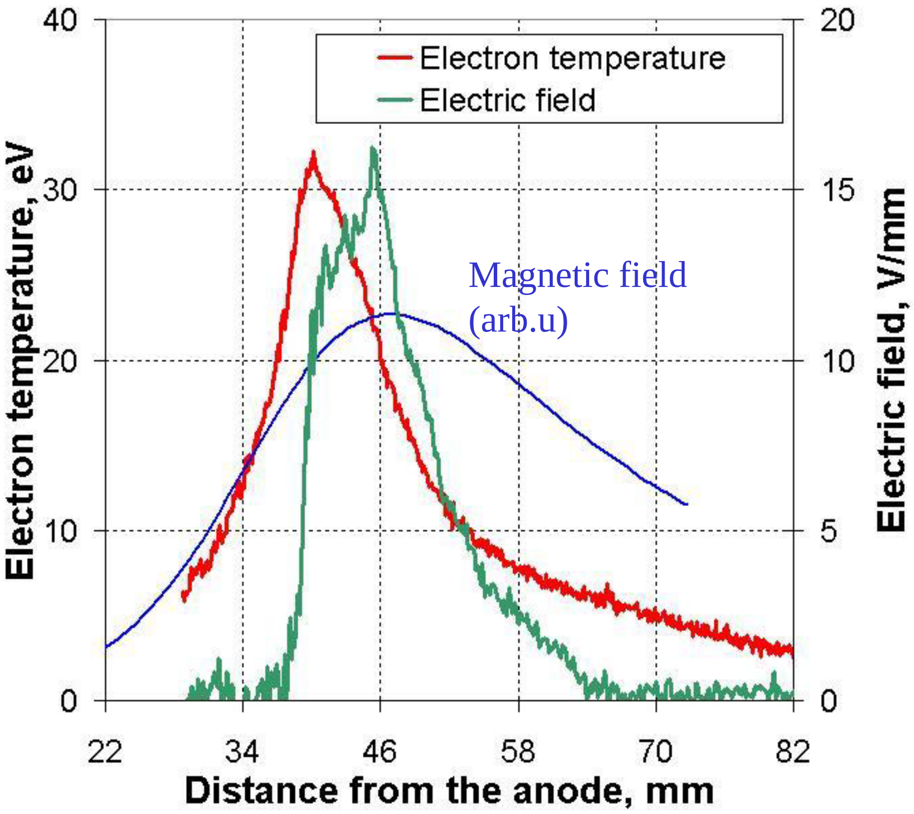
Low disturbing shielded emissive probe



Find more at *htx.pppl.gov*

Ionization and ion acceleration in a short region





Electron energy balance

$$\frac{d}{dz}\left(\frac{5}{2}T_e\Gamma_{ez}\right) = P_J - Q_{ea} - Q_{wall}$$

P_J - *Joule heating*

Electron energy losses:

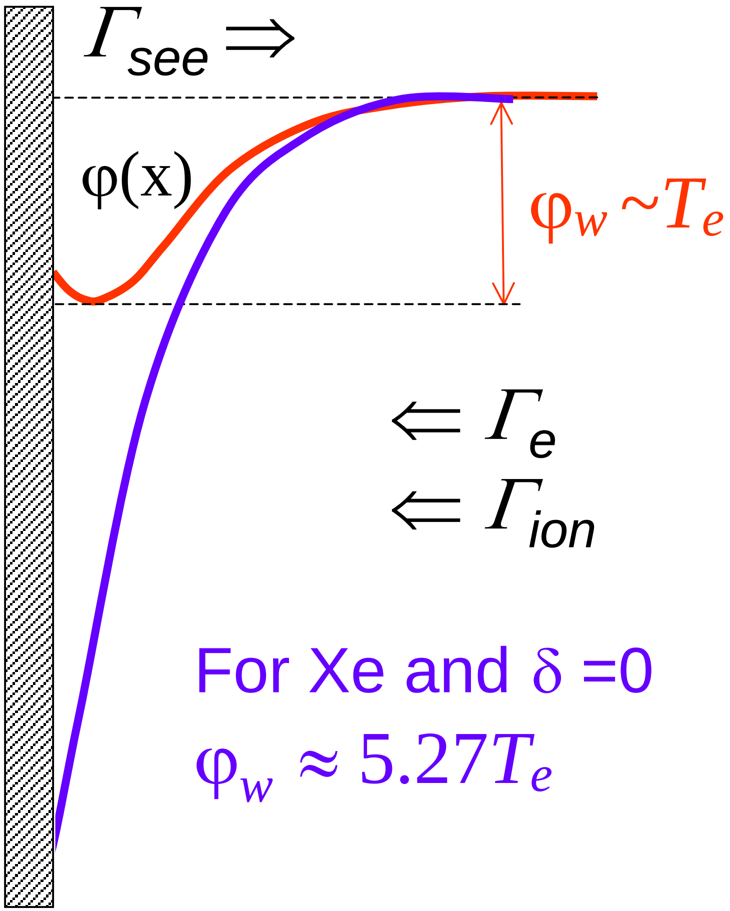
$Q_{e\text{-}a}$ – *inelastic losses*

Q_{wall} – *wall losses*

If no-SEE:

$$Q_{wall} = v_{iw} N_e \varepsilon_w \approx \frac{V_{Bohm}}{h} N_e \varepsilon_w$$

Near-wall sheath with SEE



For Xe and δ =0

$\varphi_w \approx 5.27 T_e$

$$\Gamma_e = \frac{\Gamma_{ion}}{1 - \delta_{eff}(T_e)}$$

•Strong SEE from ceramic walls: for Maxwellian EEDF and Boron nitride , $\delta_{eff} = \Gamma_{SEE} / \Gamma_{ep} \sim 100\%$ at $T_e \approx 20$ eV.

•Space-charge saturation of the wall sheaths: **SEE does not exceed 1**

For Xenon: $\delta_{eff} = \delta_c \approx 0.983$

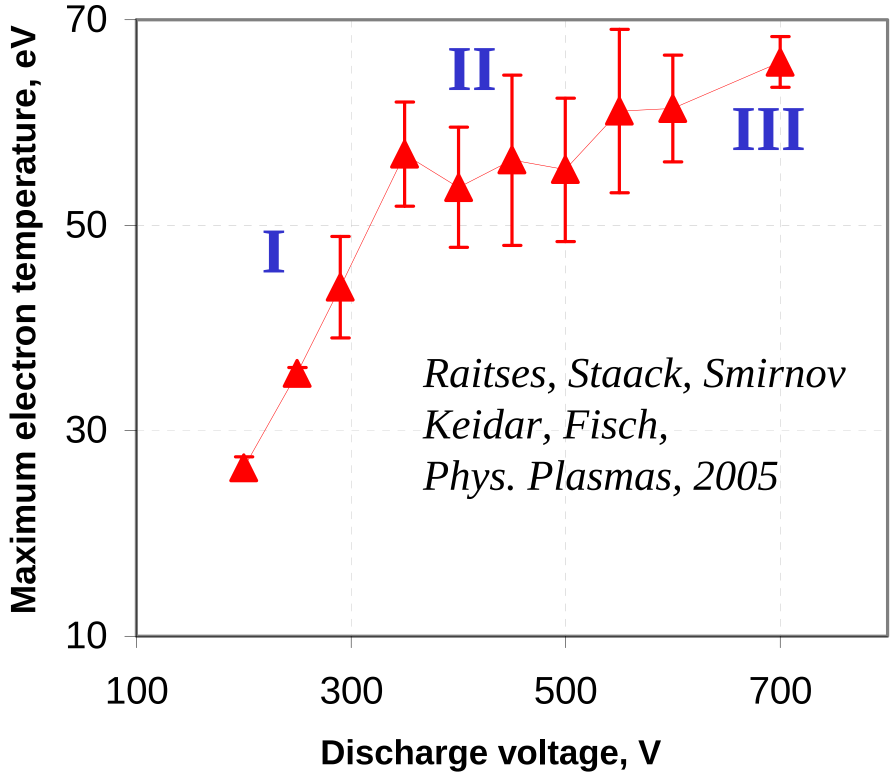
$$\nu_{ew} \approx \frac{1}{h}\left[\frac{1}{1-\delta_c}\right]\sqrt{\frac{T_e}{M_{ion}}}$$

⇒ walls act as effective energy sink

⇒ near-wall electron conductivity

Comparing theory with experiment

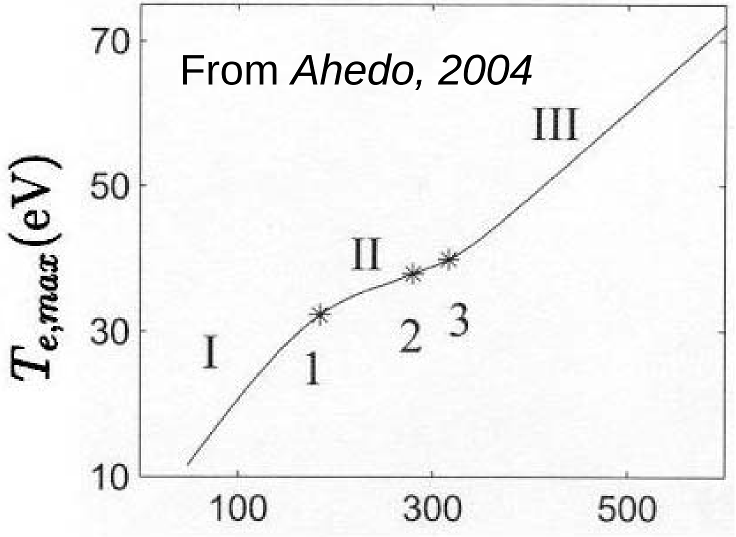
PPPL experiment



Raitses, Staack, Smirnov
Keidar, Fisch,
Phys. Plasmas, 2005

II and III predicted for space charge saturated sheath

Barral et al, Phys. Plasmas, 2003
Ahedo et al., J. Appl. Phys., 2004



From *Ahedo, 2004*

T_{emax} saturation:

Experiment ≈ 55 eV at V_d > 350 V

Theory ≈ 30 eV at V_d > 150 V (but for a lower SEE BN)

Electron-wall collision frequency

Experimental vs. Theoretical

Similar to the models:

- Maxwellian EEDF
- Temperature saturation due to SCS wall sheaths

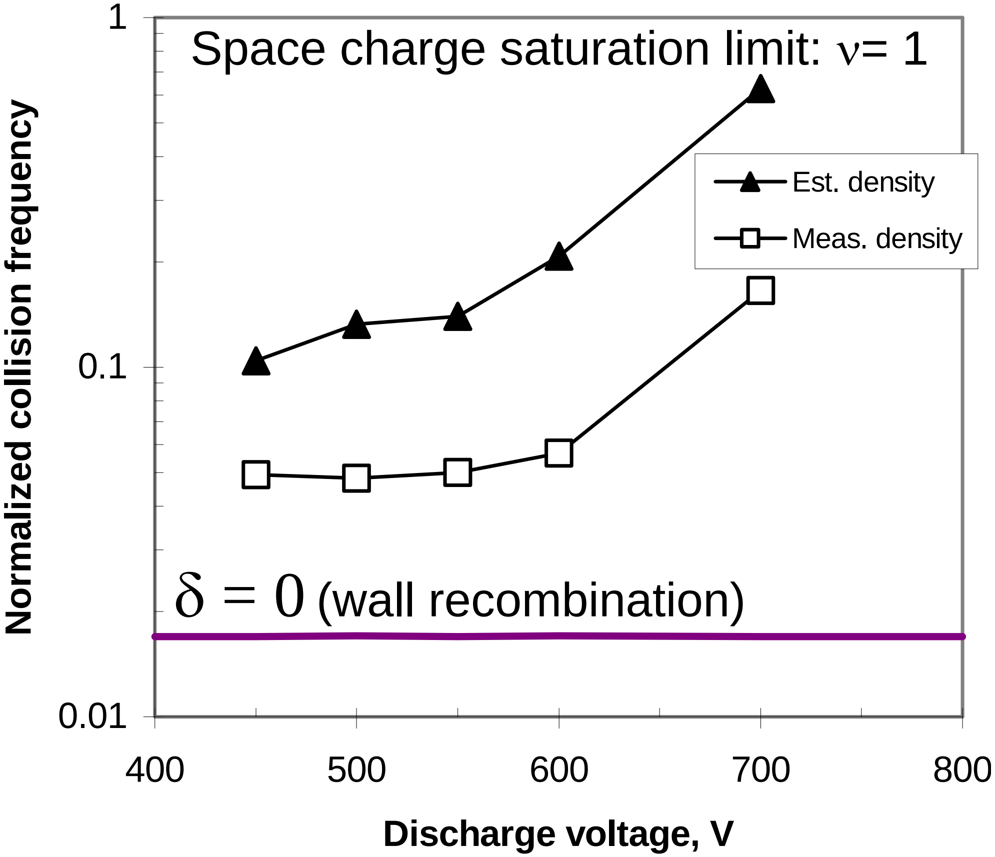
Experimental frequency:

$$\nu_{exp}^{SCS} \approx \frac{P_J}{2T_e}$$

Theoretical frequency:

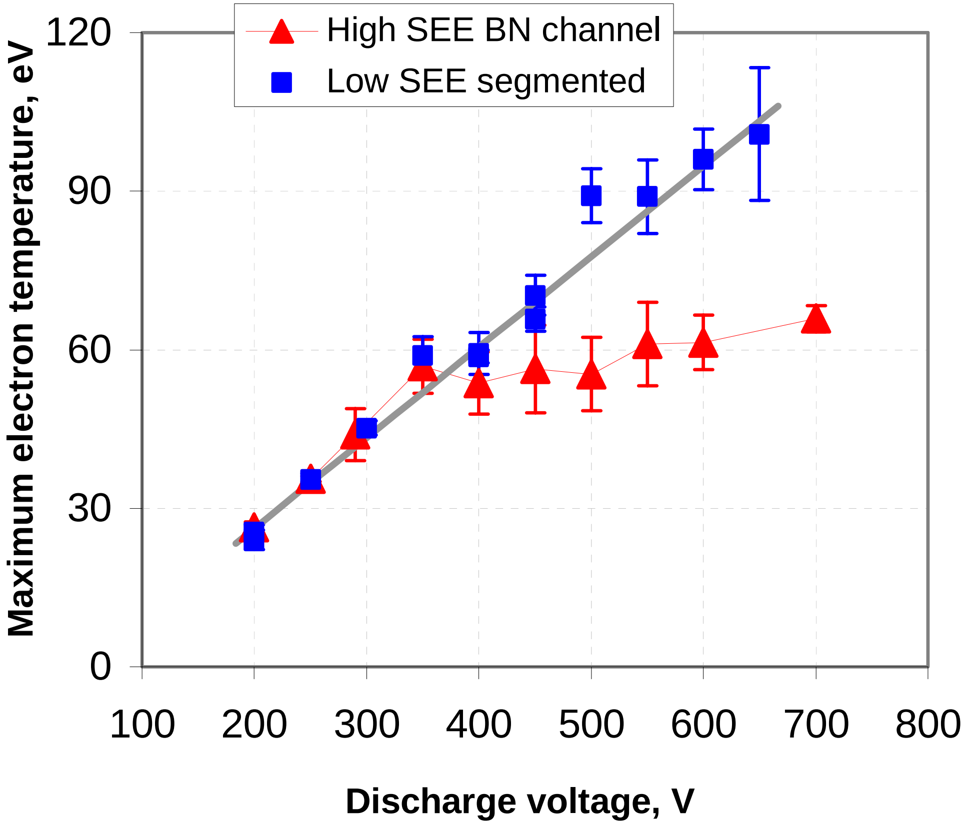
$$\nu_{th}^{SCS} \approx \frac{1}{h}\sqrt{\frac{T_e}{M_i}}\frac{1}{1-\delta_c}$$

$\delta_c \approx 0.983$



Raitses, Staack, Smirnov and Fisch, Phys. Plasmas, 2005

$T_{emax}(V_d)$ dependence for different SEE wall materials



SEE is likely responsible for the temperature saturation obtained for the thruster discharge with BN channel walls

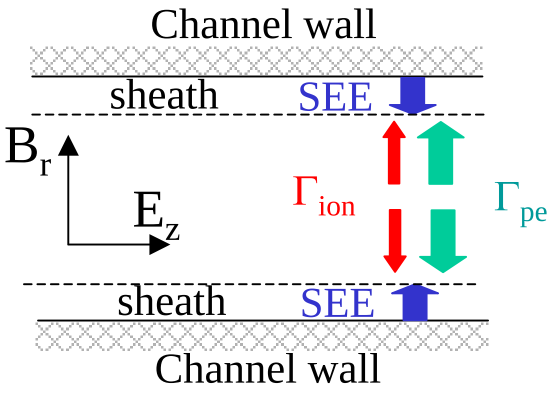
Kinetic effects may explain the reduced sensitivity to SEE

✓ Non-Maxwellian electron EDF

i) depleted tail (at $\varepsilon > \varphi_{\text{sheath}}$): $T_{\text{tail}} < T_{\text{bulk}}$ (*Smirnov's poster, today*)

ii) EDF anisotropy due to heating ⊥ **B** and mostly forward e-a scattering. At $T_e \sim 40$ eV $\sigma_{<30°}/\sigma_{>30°} \sim 2$

✓ Secondary electrons emitted from opposite channel walls form counter-streaming beams



$$\Gamma_i - \Gamma_{ep} + \Gamma_{see} - \delta_b \Gamma_{see} = 0$$

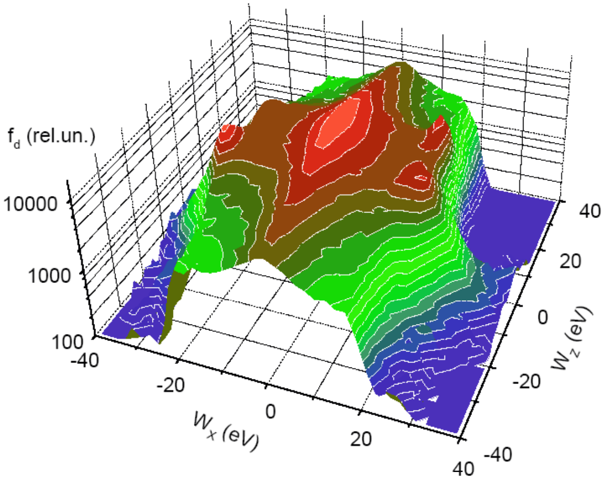
$$\Gamma_{ep} = \frac{\Gamma_i}{1 - \boxed{\delta_{see}(1 - \delta_b)}}$$

δ_{see} can be > 1 if $\delta_{see}(1-\delta_b) < 1$

PIC simulations: Anisotropic electron EDF

(See today's poster by D. Sydorenko et al.)

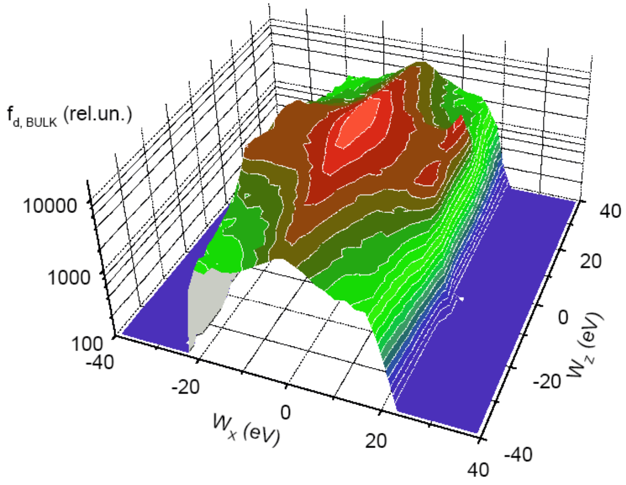
Distribution of all electrons in the middle of the plasma:



W_X – the energy of electron motion normal to the walls.

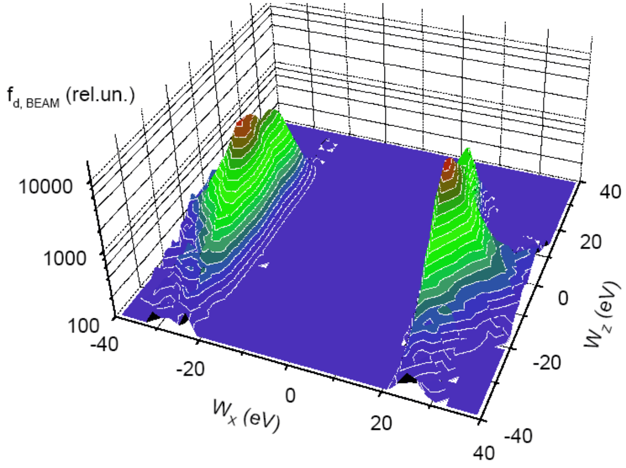
W_Z – the energy of electron motion along the accelerating field.

The complete distribution can be separated into:



1. The plasma bulk:

- anisotropic, with $T_z \gg T_x$,
- confined by the plasma potential.



2. The SEE beams:

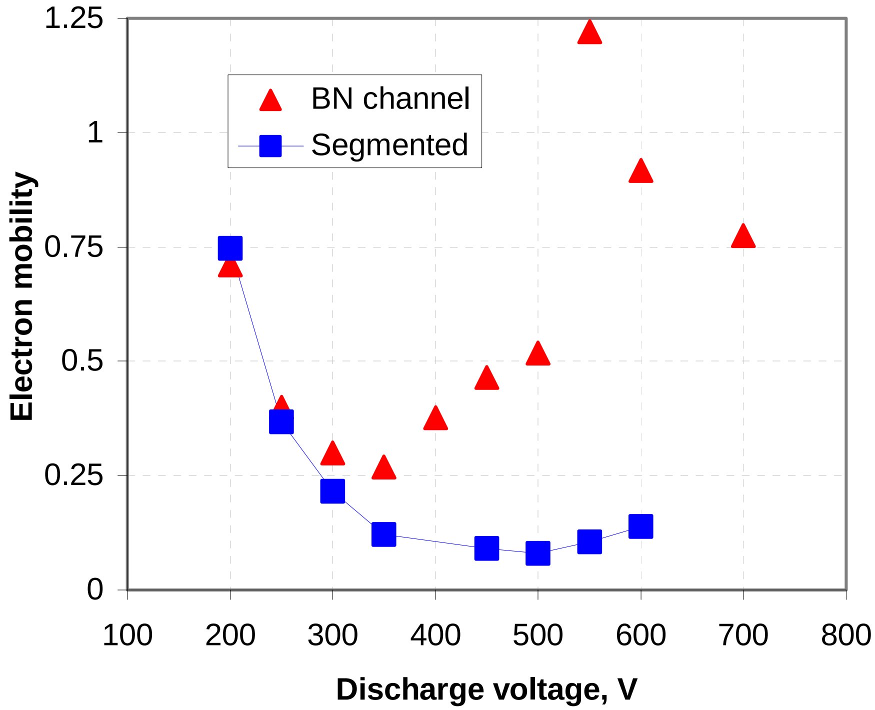
- non-zero temperature of emission,
- produce most of the electron current to the walls.

Electron cross-field transport in HT

Classical transport is not sufficient to explain thruster V-I

$$\nu_{e\text{-}a} \sim 10^6\ \mathrm{s}^{-1} < \nu_{eff} \sim 10^7\ \mathrm{s}^{-1}$$

HT models use empirical parameters: Bohm-type and near-wall conductivity (NWC)



- PIC simulations: NWC exceeds the collisional value by a factor of 3 times, but sheath is not space charge saturated.
- Experiment: for low-SEE segmented channel, cross-field mobility reduces with the discharge voltage

Summary

- The electron-wall interaction in the presence of a strong SEE limits the maximum electron temperature in Hall thruster discharge.

- In experiments, the maximum temperature exceeds the predicted value for the SCS regime obtained under the assumption of the Maxwellian electron EDF.

- The reduced sensitivity to the SEE indirectly support recent kinetic studies, which suggest:

  - ✓ Strongly anisotropic electron EDF.
  - ✓ Secondary electrons from opposite walls form beams.
  - ✓ SEE coefficient due to the plasma bulk electrons can exceed 1 if the beam of secondary electrons reaches the opposite wall.

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