Kinetic Effects In Hall Thruster Discharge

Igor Kaganovich, Yevgeny Raitses*
Dmytro Sydorenko, Andrei Smolyakov**

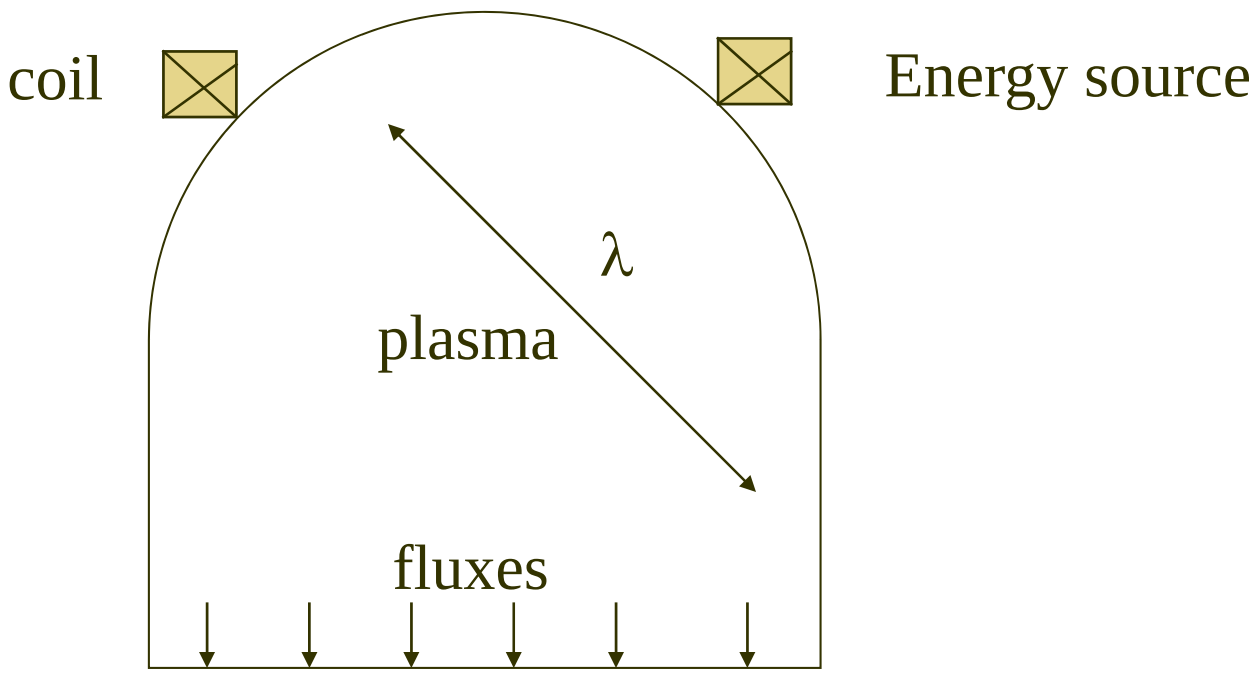
**Princeton Plasma Physics Laboratory, USA*
***University of Saskatchewan, Canada*

Main Subject of the Talk

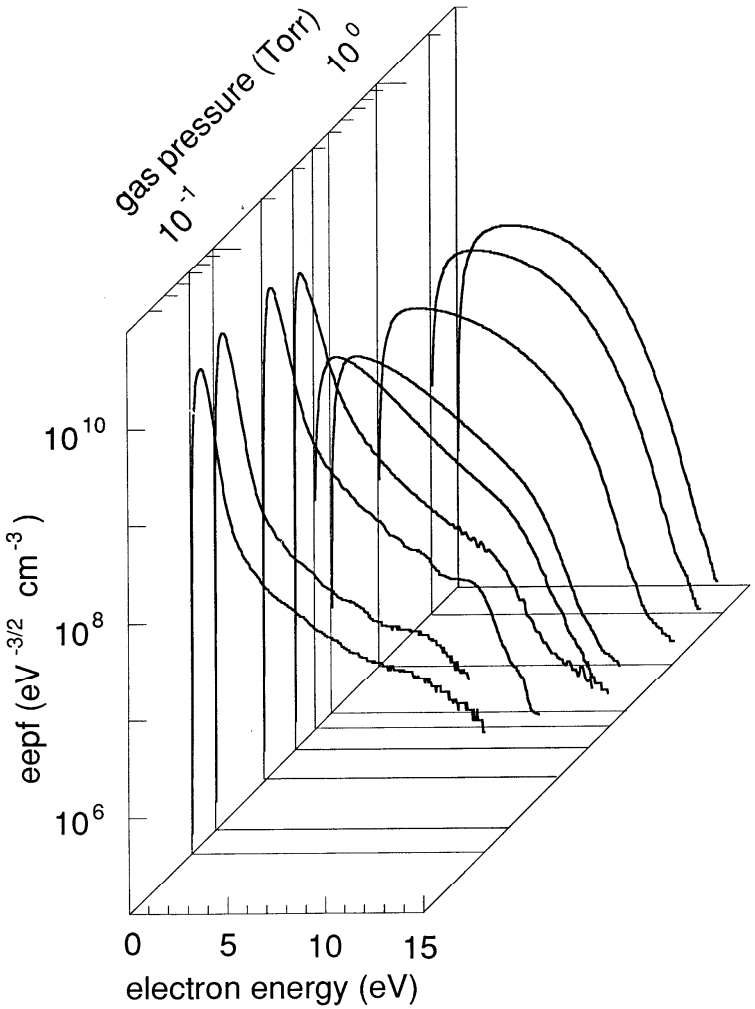
Nonlocality and collisionless kinetic effects in low-pressure plasmas.

Nonlocality is important for many plasma applications

- **Electron energy mean free path is large, this allows remote plasma handling via nonlocal electron energy distribution function (EEDF).**



The treatment has to be kinetic! (2/2)



Electron energy distribution functions are non-Maxwellian:

- **Parts of the EEDF are very flexible and are almost independent.**
- **An example of a capacitive discharge.**

For more info: V. Godyak, IEEE TPS 34, 755 (2006).

2005 PPPL workshop on “Nonlocal, Collisionless Electron Transport in Plasmas”

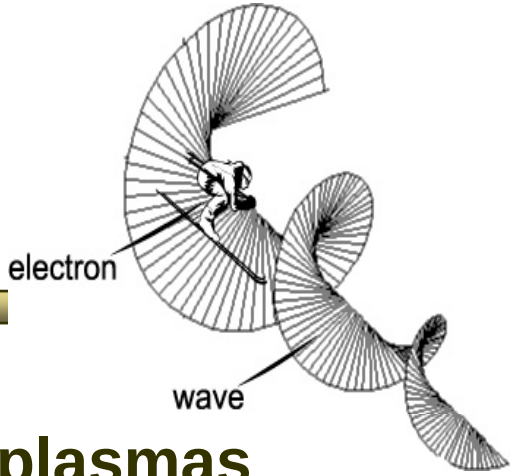
Special Issue of IEEE Trans. on Plasma Science vol.34, N3 (2006).

- **Aimed at updating the research advances in this field.**

For more info: **Talks and papers are available at**

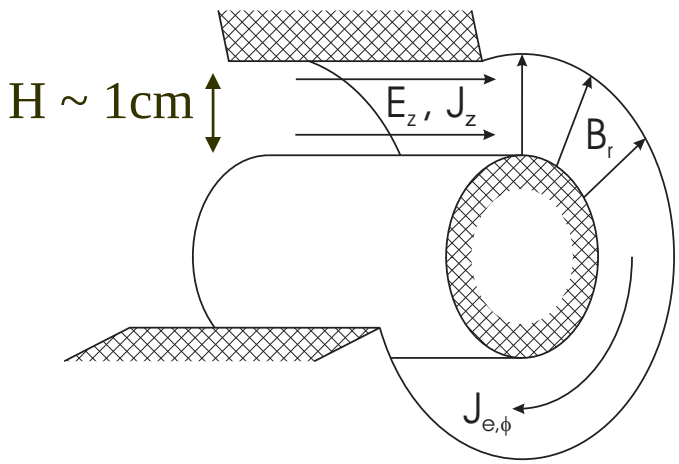
http://w3.pppl.gov/~ikaganov/PPPL2005/

Special Issue Topics:



- **Basic nonlocal, collisionless effects in plasmas**
- **Probe diagnostics**
- **Electron transport phenomena in plasma propulsion devices**
- **Non-local electron kinetics in direct current discharges**
- **Simulation of Electron Kinetics in Gas Discharges**

Kinetic Effects in Hall Thruster



P=0.1-1mTorr, the plasma inside the thruster channel is collisionless, $\lambda_{ec} >> H$.

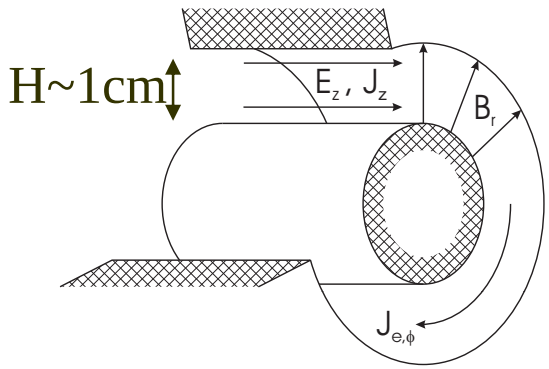
B ~ 100G, E ~ 100V/cm, T_e ~ 100eV.

For more info:

Artem Smirnov et al, CI2.00001: Experimental and theoretical studies of cylindrical Hall thrusters.

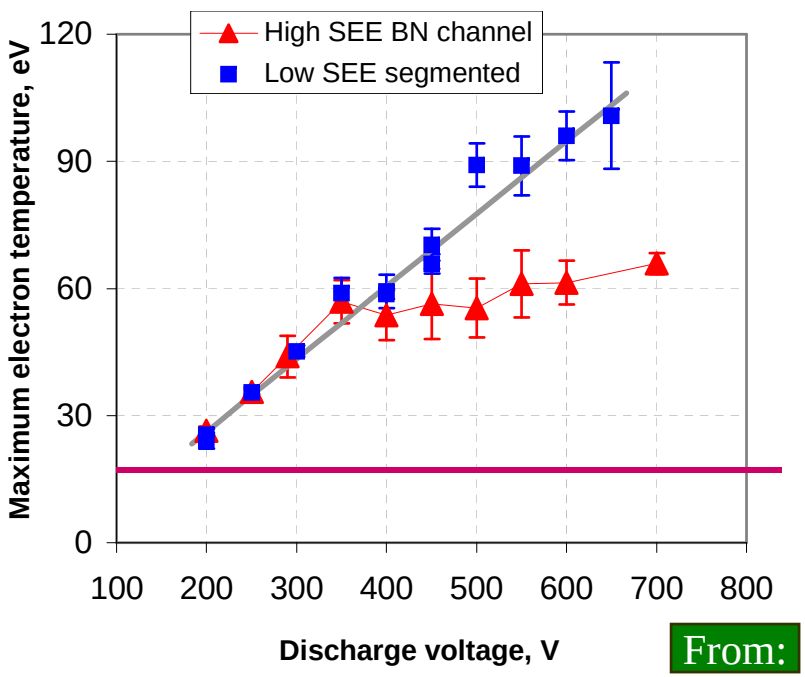
Yevgeny Raitses et al, VP1.00164: Experimental studies of wall material effects on the Hall thruster discharge.

Motivation: understanding of plasma-wall interactions in Hall thrusters



Large electron temperature and secondary electron emission result in large particle and wall losses to the wall.

How large?



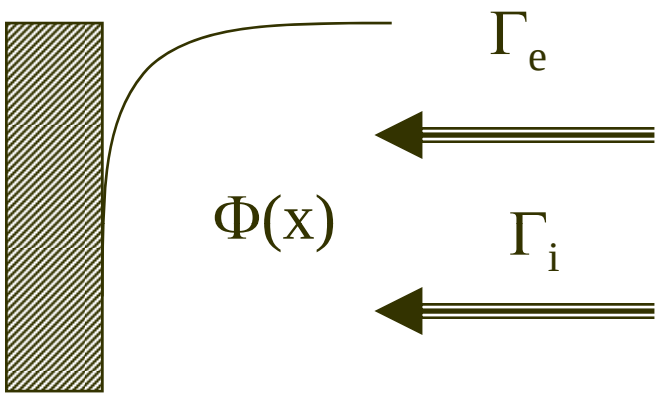
Temperature saturation:

- Large quantitative disagreement with fluid theories.

A fluid theory prediction.

From: Y. Raitses, et al., Phys. Plasmas **13**, 014502 2006.

Plasma potential relative to wall: fluid treatment



$$\Gamma_e = n\sqrt{\frac{T_e}{2\pi m}}e^{-\phi/T_e}$$

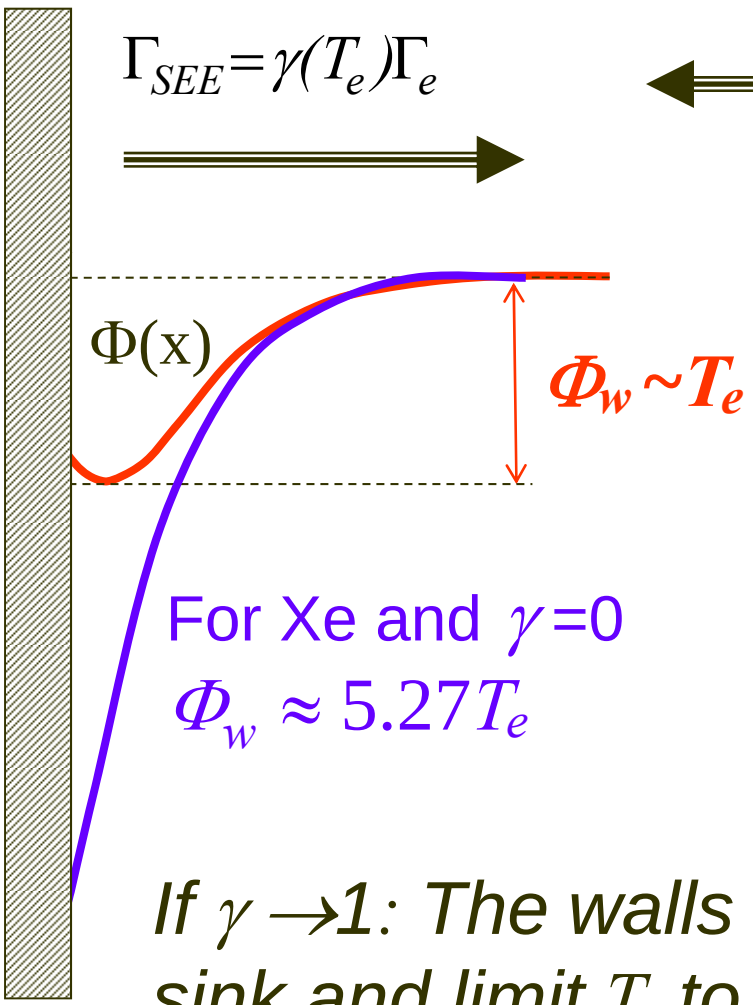
$$\Gamma_i = n\sqrt{\frac{T_e}{M}}$$

$$\Gamma_e = \Gamma_i$$

$$e\phi_p = T_e \ln\left(\sqrt{\frac{M}{2\pi m}}\right) \sim 5T_e$$

Relies on the assumption of a Maxwellian electron energy distribution function.

Wall losses strongly increases due to secondary electron emission.



$$\Gamma_{SEE} = \gamma(T_e)\Gamma_e$$

$$\Gamma_e = n\sqrt{\frac{T_e}{2\pi m}}e^{-\Phi_w/T_e}$$

$$\Gamma_{ion} = n\sqrt{\frac{T_e}{M}}$$

$$\Gamma_e = \frac{1}{1-\gamma}\Gamma_{ion}$$

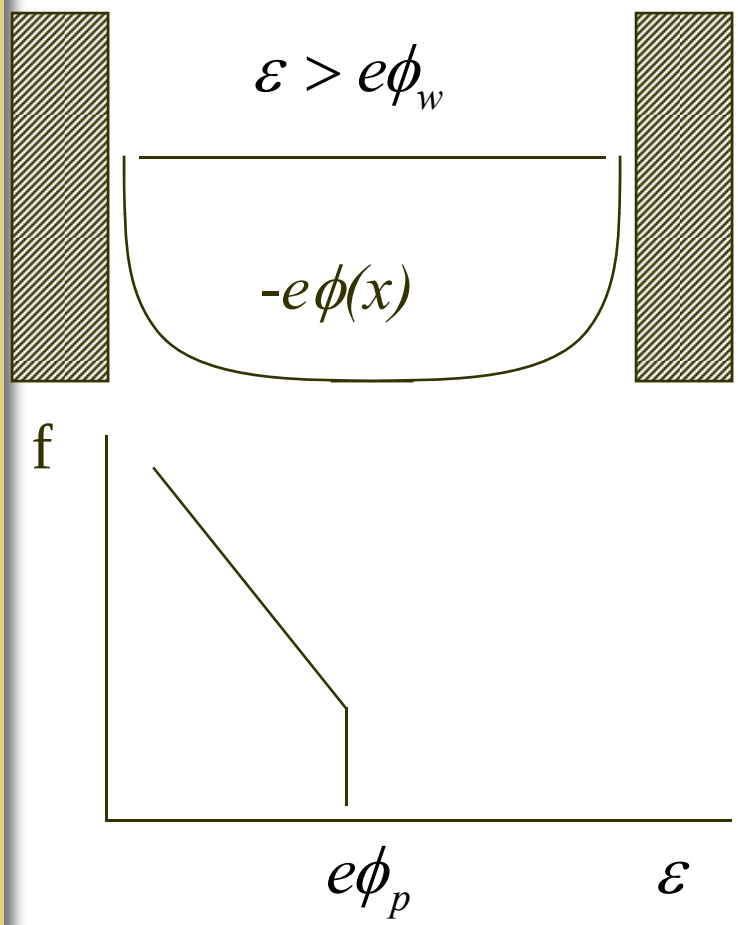
For Xe and γ=0

$\Phi_w \approx 5.27 T_e$

$$\Phi_w \approx -T_e \ln\left(\sqrt{\frac{M}{2\pi m}}(1-\gamma)\right)$$

If $\gamma \rightarrow 1$: The walls act as an effective energy sink and limit T_e to 18eV, where $\gamma(T_e)=1$.

Kinetic studies: high-energy electrons quickly leave and deplete the EVDF.



- **Most electrons are trapped in the potential well.**
- **Electrons with $\varepsilon > e\phi_w$ leave.**
- **=> Plasma potential relative to the wall is smaller.**
- **Existing kinetic studies predict an isotropic electron velocity distribution function (EVDF).**
- **=> No source of high-energy electrons to induce SEE.**

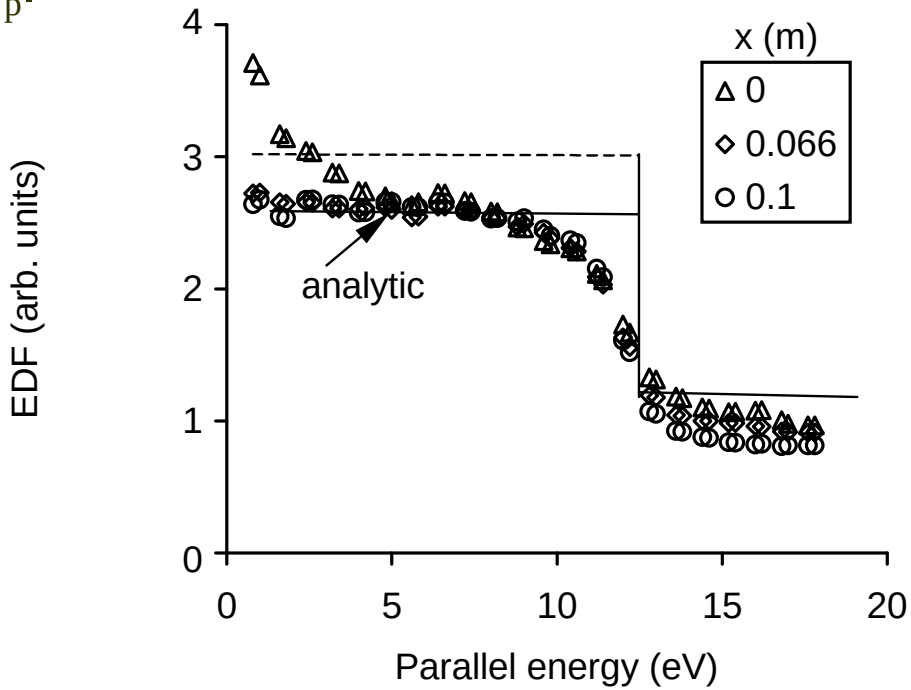
But is it so?

Tsendin, L.D., Sov. Phys. JETP **39**, 805 (1974).

Depletion of fast electrons due to wall losses in ECR discharge

The EEDF as a function of the parallel energy at various coordinates. Solid lines - the theoretical estimate at p=1mTorr, L=10cm, φ_p=12.4eV.

The EEDF is obtained in particle-in-cell simulations at given total energy $1.5\varphi_p$.



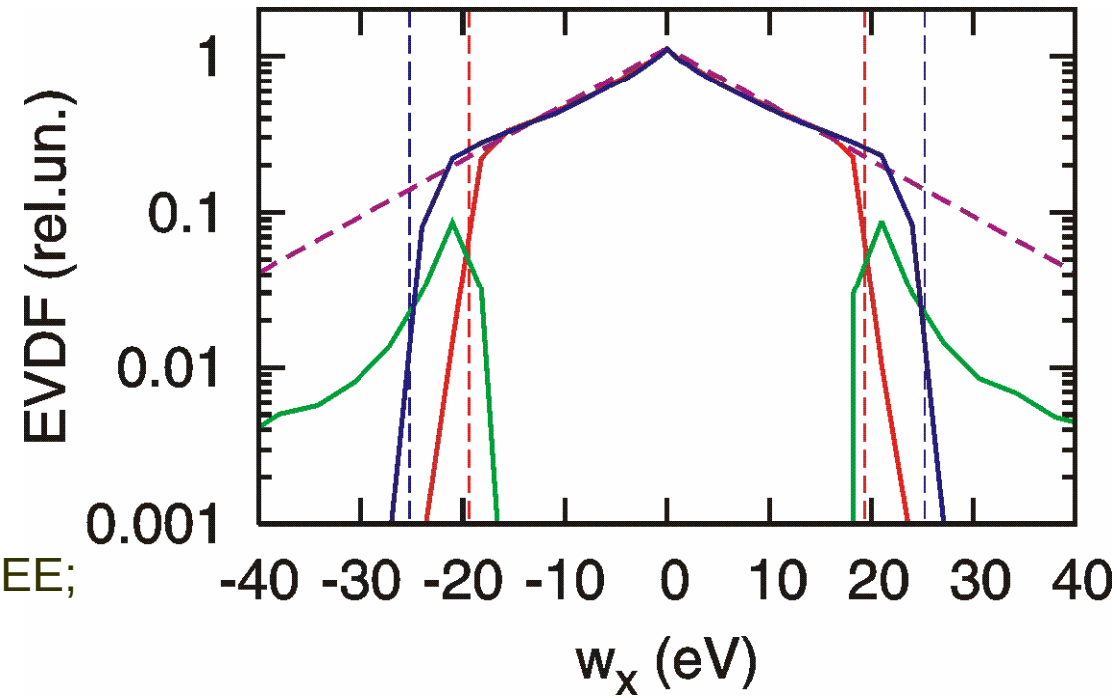
For more info: Kaganovich, I.D., et al, Phys. Rev. E. **61**, 1875 (2000).

Depletion of fast electrons due to wall losses in a Hall thruster channel

E_z=200 V/cm, B_x=100G

T_{ex}=12eV, Φ_w =19.4eV !

Not $5T_e$



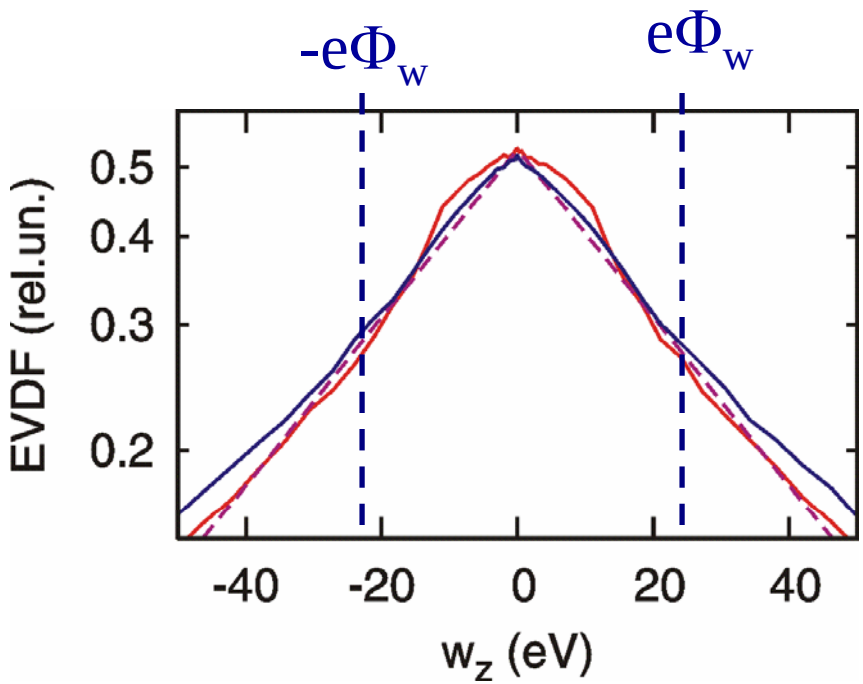
Solid: **red** – bulk electrons, SEE;
green – SEE beam;
blue – no SEE.

Dashed: **red** – plasma potential, Φ_w =19.4 V, SEE;
blue – plasma potential, Φ_w =25.3 V, no SEE;
magenta – Maxwellian, T_X = 12.1 eV

$$w_x = m v_x |v_x| / 2$$

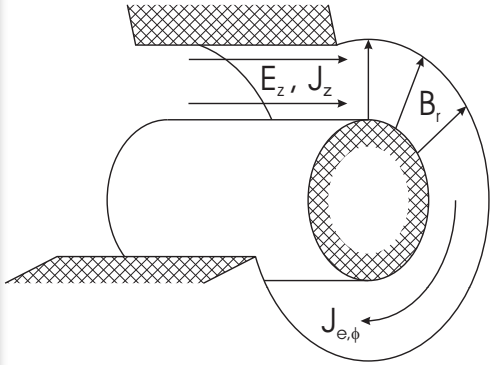
EVDF over velocity parallel to the walls

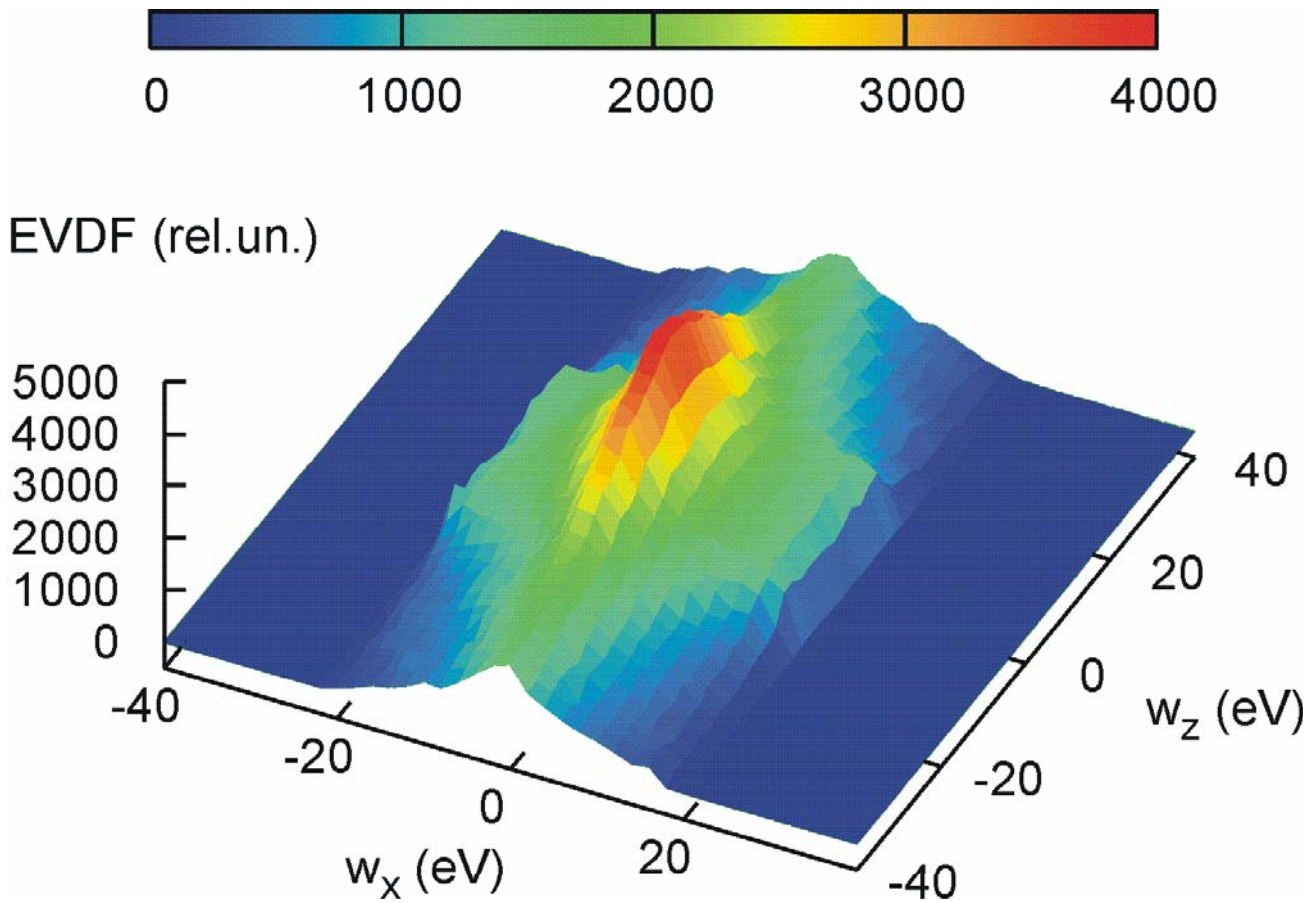
- $\lambda_{ec} >> H$, $\Rightarrow$ EVDF is not depleted in the E- field direction.
- $\Rightarrow$ *There is a supply of high energy electrons,* $w > e\Phi_w$ *!*



Bulk electrons with SEE
Bulk electrons with no SEE
Maxwellian EVDF, T_z = **36.7 eV**

3D view of EVDF





E_z=200 V/cm

B_x=100G

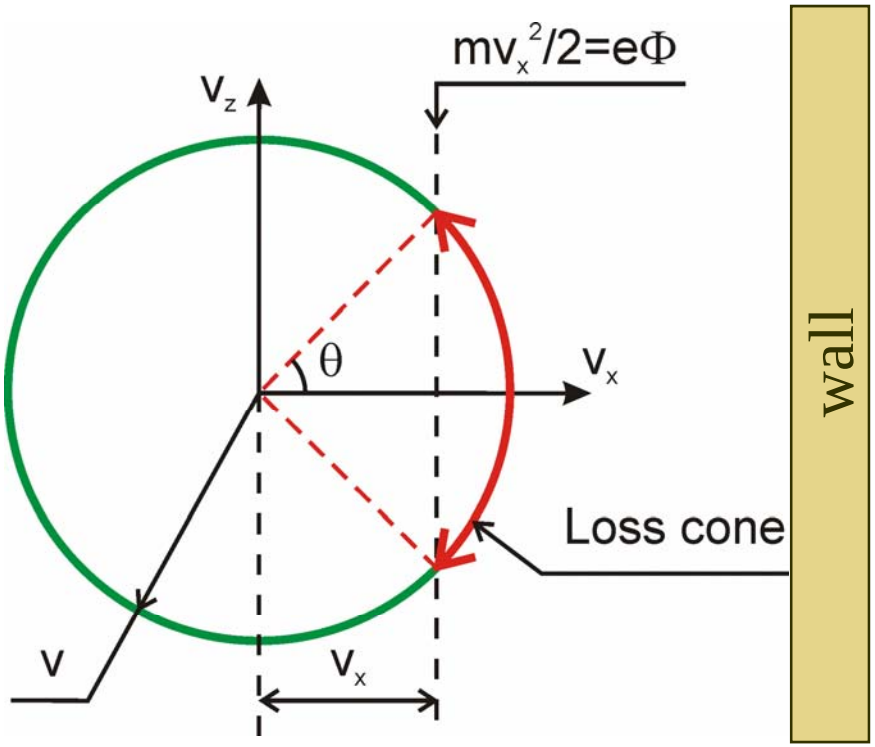
T_x = 12.1 eV

T_z = 36.7 eV

For more info: D. Sydorenko et al, Phys. Plasmas, **13**, 014501 **(**2006).

The loss cone concept is the key to open kinetic "door" of understanding

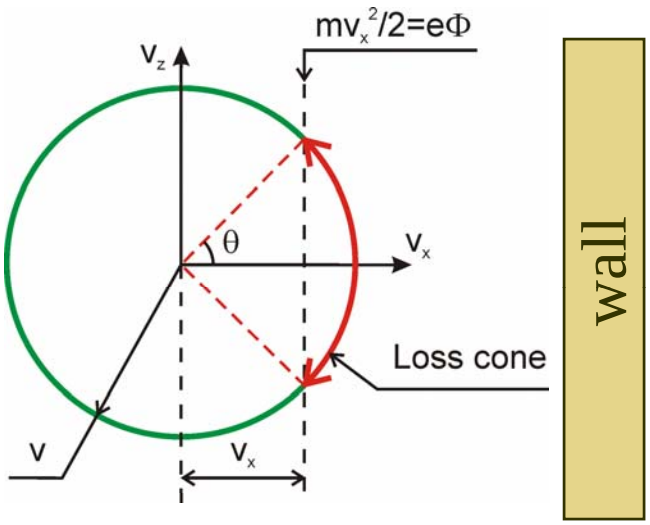
- The green circle : particles with energy $w > e\Phi_w$ in the two-dimensional velocity space (v_x, v_z).
- The red section of the circle is the loss cone.



The EVDF in the loss cone is:

- replenished due to the elastic scattering (from outside of the loss cone),
- emptied by the free flight to the walls with the rate determined by the transit time ($\sim H/v_x$).

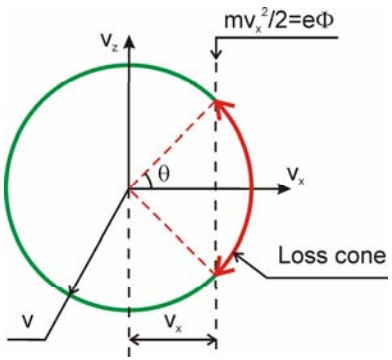
Electron scattering due to elastic collisions with atoms and ions governs the electron wall fluxes



$$\Gamma_e = \frac{H}{8\lambda_c} n_e \sqrt{\frac{8T_{ez}}{\pi m}} \exp\left(-\frac{\Phi}{T_{ez}}\right)$$

- **The wall electron flux is reduced by a factor of H/λ_c compared with the calculation assuming an isotropic EVDF.**
- For typical thruster conditions $H/\lambda_c \sim 10^{-1}$-10^{-2}.

Due to the low electron flux to the wall, the wall potential is small



$$\Gamma_e = \frac{H}{8\lambda_c} n_e \sqrt{\frac{8T_{ez}}{\pi m}} \exp\left(-\frac{\Phi}{T_{ez}}\right)$$

$$\Gamma_{ion} = n\sqrt{\frac{T_e}{M}}$$

$$\boxed{\Phi = \frac{T_{ez}}{e} \ln\left(\frac{H}{\lambda_c}\sqrt{\frac{T_{ez}}{T_{ex}}}\sqrt{\frac{M}{2\pi m}}\right) \approx \frac{T_{ez}}{e}}$$

Since $H/\lambda_c \sim 10^{-2}$, the wall potential decreases from $5T_e$ to $1T_e$!

In self-sustained discharges the EVDF is almost isotropic!

- **Self-sustained => $\nu_i \tau = 1$**
  - **Ionization balances the wall losses.**

- **Elastic cross sections are large: $\nu_{en} >> \nu_i$ => $\nu_{en}\, \tau >> 1$.**

- **EVDF is nearly isotropic, i.e., $v_T >> v_c$.**
  - **Thermal velocity, v_T is large compared with mean velocity, v_c, associated with a current.**

For more info: I.D. Kaganovich and L.D. Tsendin, IEEE TPS **20,** 66, (1992).

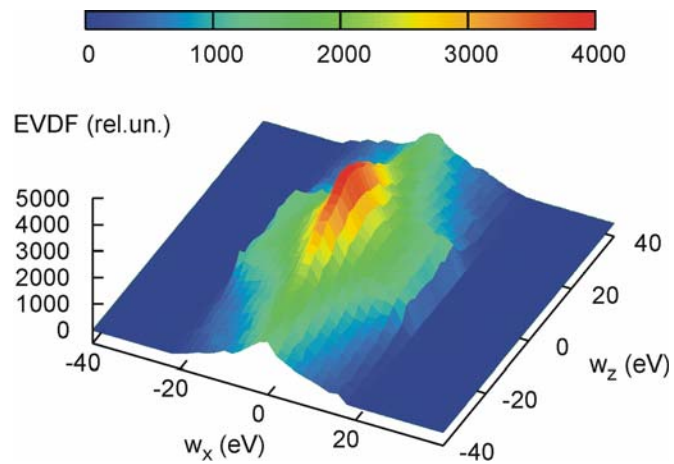
The reasons for the EVDF anisotropy

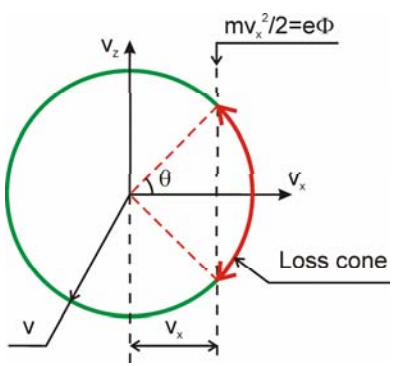
1. $\nu_{en}\tau \sim 1$ – **an electron suffers several collisions before escaping to the walls.**

2. $\nu_i \sim \nu_{en}$ **- Xenon inelastic cross sections are large.**

3. **Consequence:** $T_x < T_z$ and $v_T \sim u_d$.

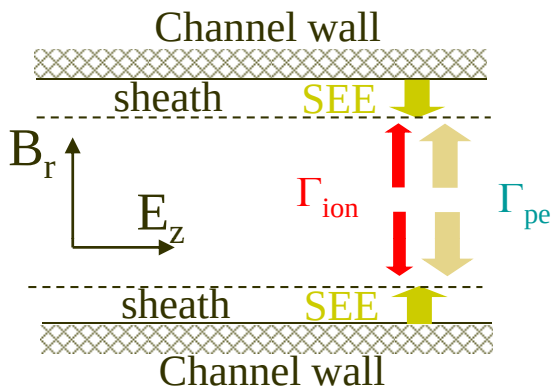
E_z=200 V/cm, B_x=100G
T_x = 12.1 eV, T_z = 36.7 eV



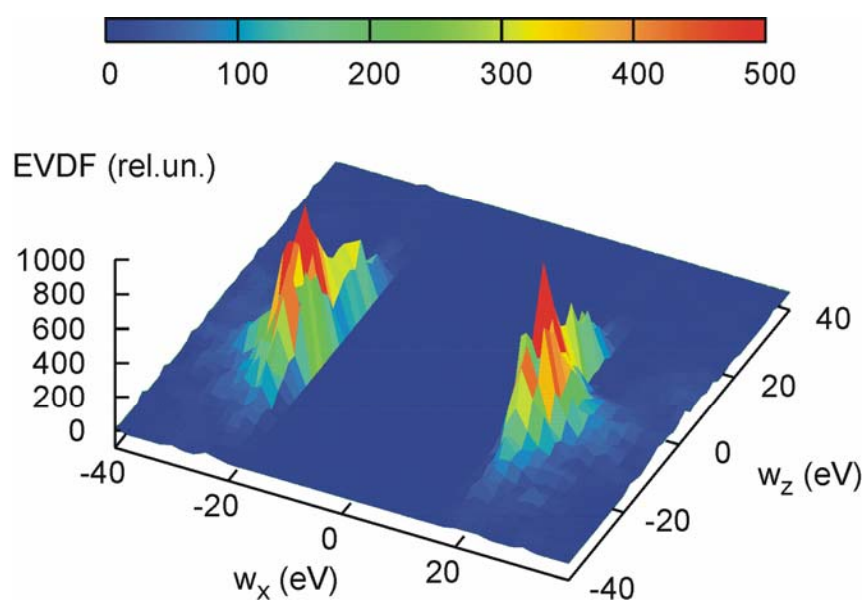


The wall potential in Hall thrusters is small, $\Phi_w \sim T_e$. => Most electrons leave plasma and scatter with the same frequency.

Secondary electron emission affects plasma properties

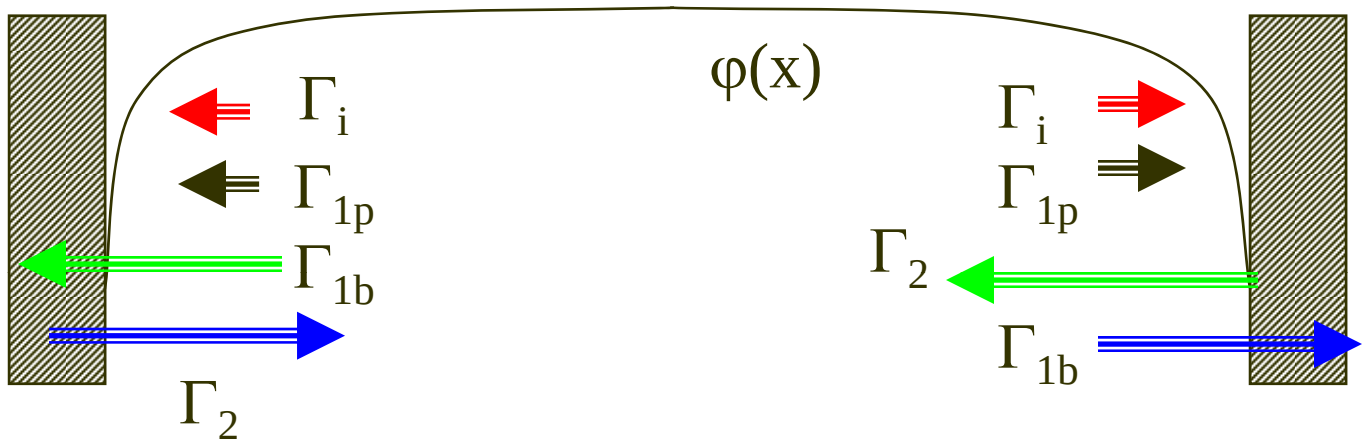


Secondary electrons emitted from opposite channel walls form counter-streaming beams.



For more info: D. Sydorenko et. al, IEEE Trans. Plasma Sci. **34**, 815 (2006).

The balance of the SEE fluxes from the opposite walls affects the wall potential.



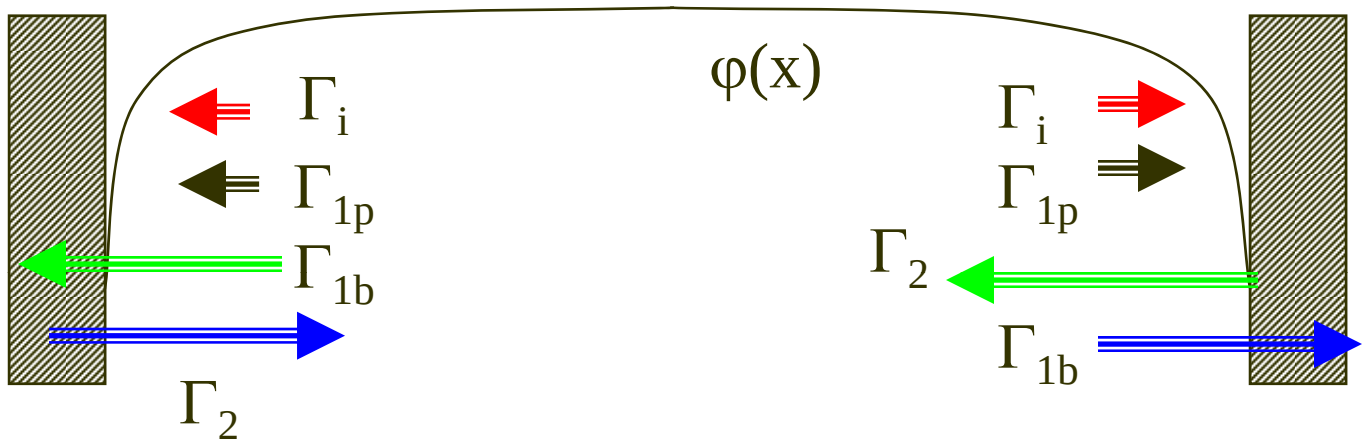
1- primary
2- secondary

$$\Gamma_i = \Gamma_{1p}\left(1-\gamma_p \frac{1-\alpha}{1-\alpha\gamma_b}\right)$$

SEE coefficients:

$\gamma_p \equiv \Gamma_{2p} / \Gamma_{1p}$ - SEE due to plasma electrons
$\gamma_b \equiv \Gamma_{2b} / \Gamma_{1b}$ - SEE due to beam electrons
$\alpha \equiv \Gamma_{1b} / \Gamma_2$ - penetration coefficient of the SEE beams

If the SEE flux fully penetrates from a wall to the opposite wall, the SEE currents cancel each other.



If $\alpha = 0$ $\quad \Gamma_{1p} = \Gamma_i / (1 - \gamma_p)$

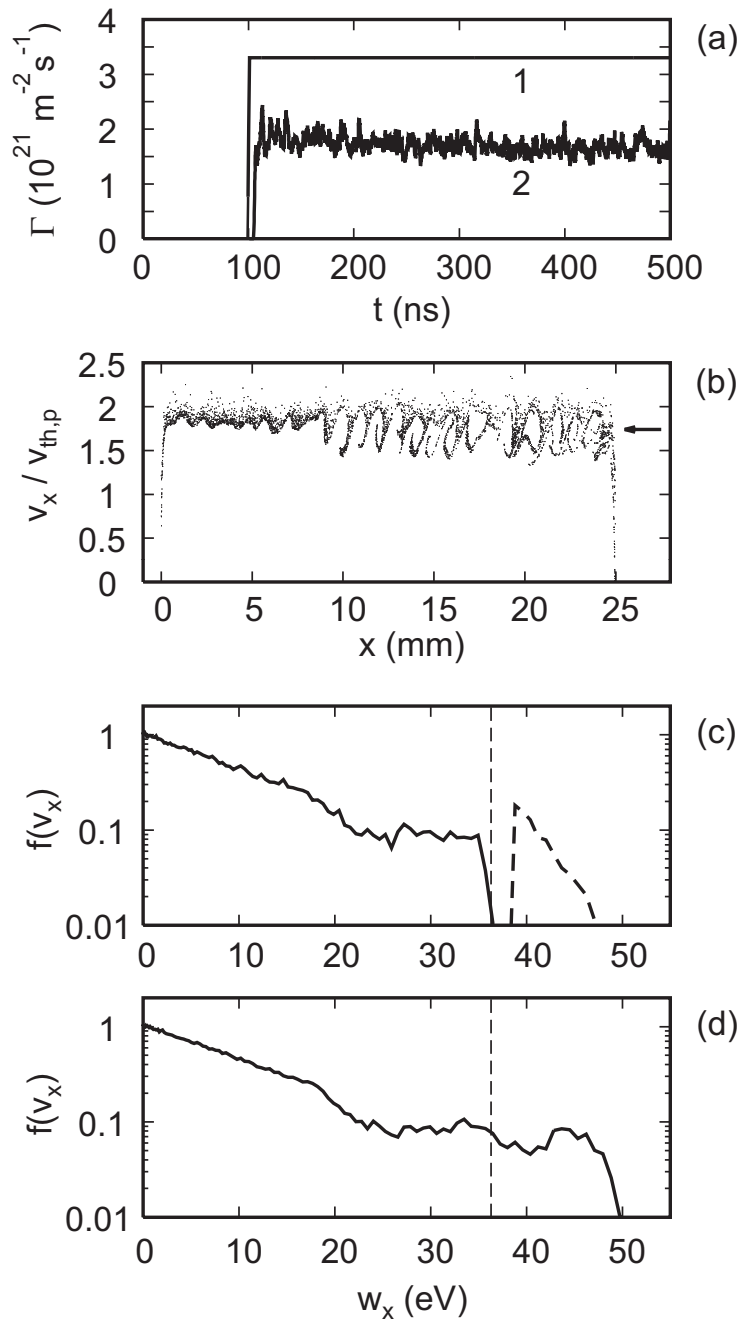
If $\alpha = 1$ $\quad \Gamma_i = \Gamma_{1p}$ $\Rightarrow$ *The SEE contribution to the current balance is canceled.*

For more info: E. Ahedo and F.I. Parra, Phys. Plasmas **12, 073503, (2005**).

I.D. Kaganovich, et al., submitted to Phys. Plasmas **(2006**).

The two-stream instability of secondary electron beams

- The two-stream instability results in decrease of the SEE fluxes penetrating through the plasma.
- The penetration coefficient (the ratio of penetrated and emitted fluxes) $\alpha<1$.
- The instability is sensitive to the shape of emission EVDF.



For more info:

D. Sydorenko, et al, VP1.00163
Thursday 2 pm.

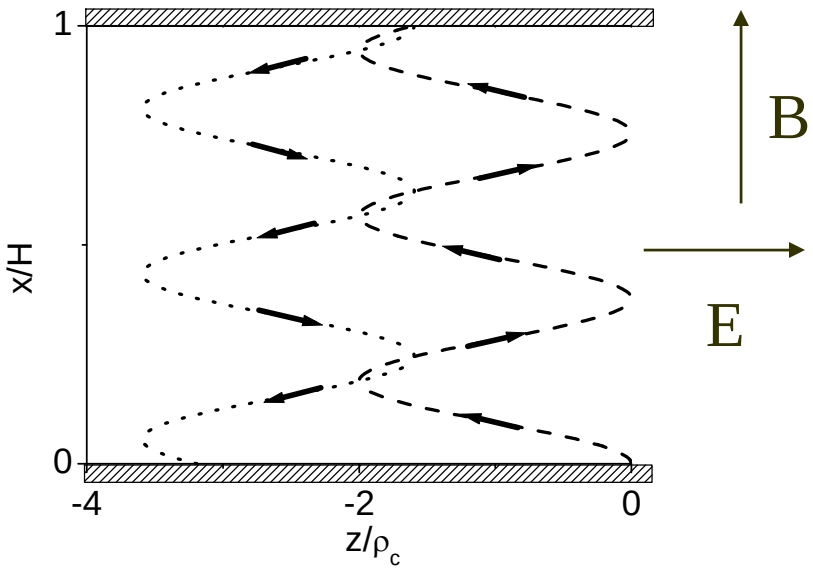
To be published in Physics of Plasmas (2006).

The beams of secondary electrons contribute to the electron cross-field current.

The large flux in the z direction created by the secondary electrons results in additional conductivity in the Hall thruster channel.

The displacement $\rho_c = v_\perp / \omega_c$, $v_\perp = u_d = \dfrac{E_z}{B_x}$ during the flight time H/u_{bx}

gives average velocity $\langle u_z \rangle \sim u_d u_{bx} / H\omega_c$ and current $J_{bz} \approx \dfrac{m}{H}\dfrac{\gamma_p}{1-\gamma_b} n_e \sqrt{\dfrac{T_{ex}}{M}} \dfrac{E_z}{B_x^2}$.

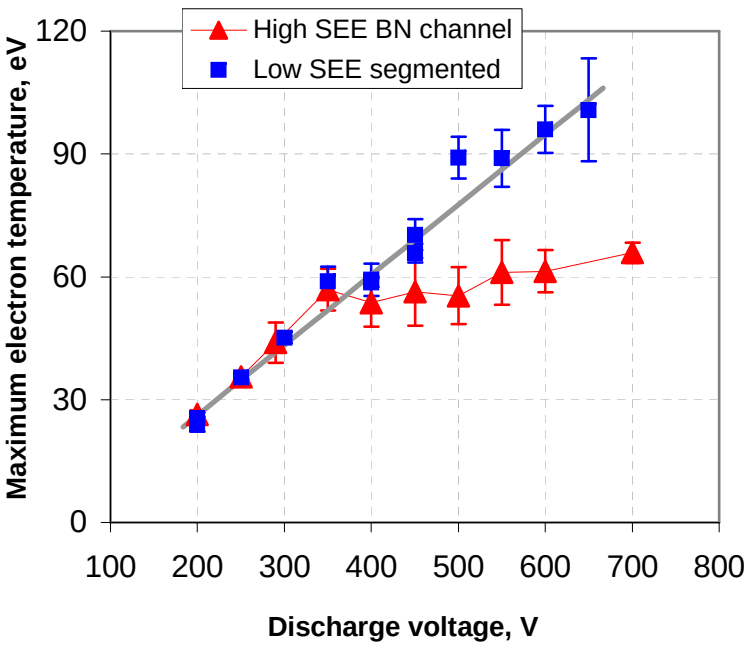


The SEE beams electrons contribute to reduction of the electric field in the channel.

$$J_{bz} \approx \frac{m}{H}\frac{\gamma_p}{1-\gamma_b} n_e \sqrt{\frac{T_{ex}}{M}} \frac{E_z}{B_x^2}$$

An additional current due to SEE electrons results in low electric field and, hence, lower electron temperature.

E_Z [V/cm]	52	200
$J_{Z,TOTAL}$ [A/m^2]	82	85
$J_{Z,SEE\ BEAM}$ [A/m^2], PIC	2.3	58.4
$J_{Z,SEE\ BEAM}$ [A/m^2], estimated	3.2	68.1



Conclusions

- **The Kinetic calculations give values of the electron flux of a few orders of magnitude smaller than the values obtained from the fluid models.**
- **The wall electron flux is determined by the elastic scattering of electrons due to collisions with atoms and Coulomb collisions.**
- **The EVDF is found to be strongly anisotropic: $T_{ez} / T_{ex} > 2$.**
- **The secondary electron emission (SEE) affects the electron cross-field transport, but not the wall potential. The electron energy losses to the walls are almost insensitive to the SEE, in contrast to conventional wisdom.**
- **Simplified analytical formulas for the plasma potential, the wall electron flux, and the electron temperatures of the Hall thruster are derived.**