Modification of Electron Velocity Distribution in Bounded Plasmas by Secondary Electron Emission

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Introduction

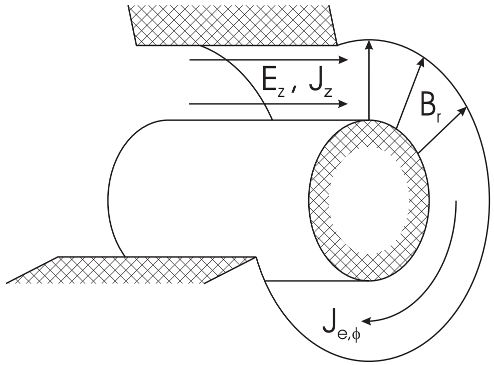
Operation of a Hall thruster (HT) depends crucially on the electron temperature and the secondary electron emission (SEE) from thruster's channel walls. The fluid theories [1-4] predict fast electron cooling due to wall losses and saturation of the electron temperature with the thruster current. However, recent experiments [5,6] reported the electron temperature inside the ceramic channel of HT several times higher than the predicted maximum value for the electron temperature [4].

The fluid theories assume that the electron velocity distribution function (EVDF) is well described by a Maxwellian EVDF. However, kinetic studies of HT [7,8] reveal the depletion of the high energy tail of EVDF and the reduction of the electron losses to the wall compared with fluid theories.

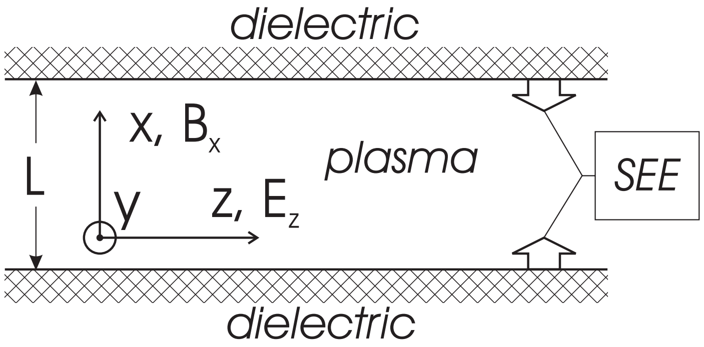
It was shown for the electron cyclotron resonance discharge [9] that EVDF near a wall is far away from a Maxwellian EVDF and is strongly anisotropic. Therefore, the kinetic plasma simulations capable to resolve the EVDF anisotropy are necessary for the proper analysis of plasma-wall interaction.

The numerical tool (particle-in-cell code)

Hall thruster, cylindrical geometry:



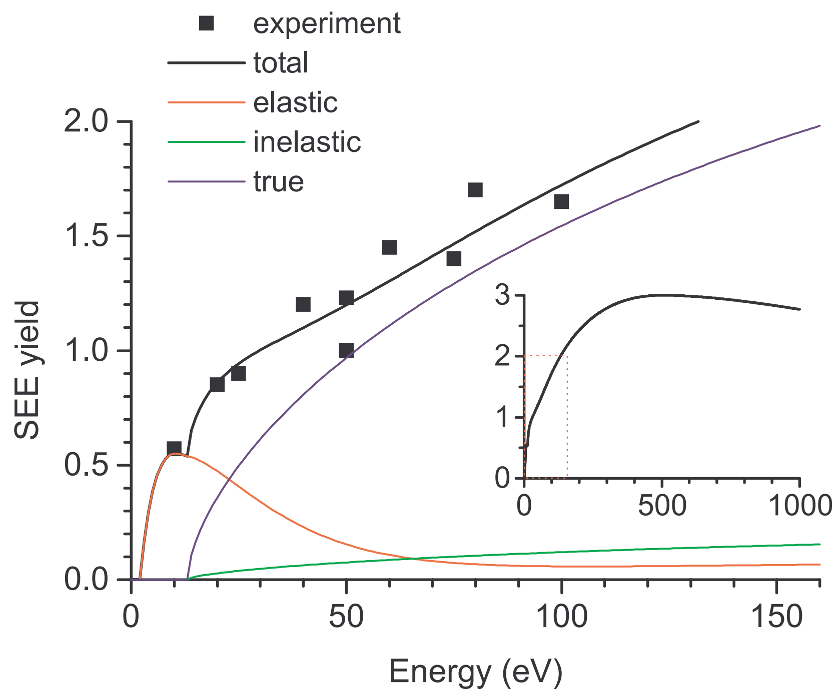
Plain geometry, approximation of the accelerating region of a Hall thruster:



The properties of the PIC code:

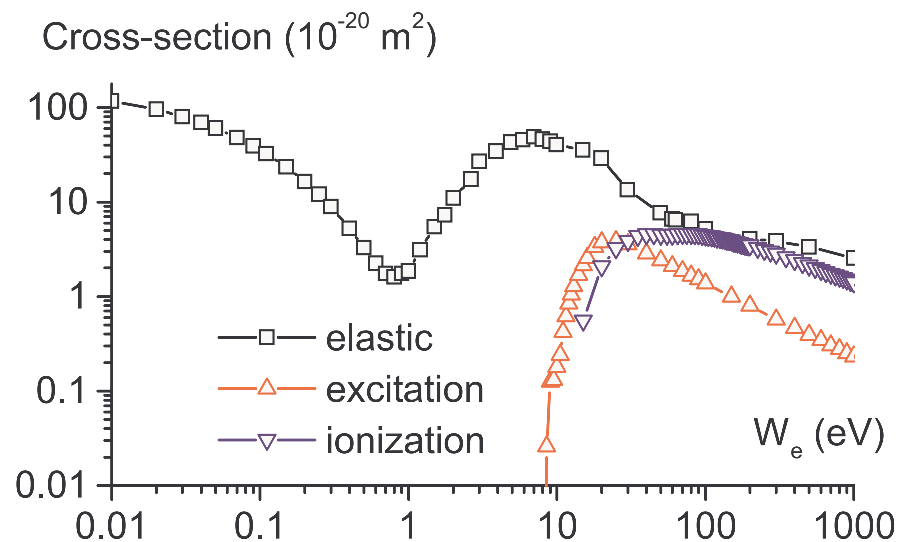
- 1d3v;
- resolves the radial direction in the channel of a Hall thruster, including the sheath regions;
- electrostatic;
- the external constant electric and magnetic fields;
- direct implicit algorithm [10];
- the Monte-Carlo model of electron-neutral collisions [11,12];
- the additional “turbulent” collisions reproducing the Bohm-like anomalous electron mobility [13];
- the model of secondary electron emission from the walls [12,14,15];
- parallelized with MPI.

PIC code: characteristics of the emission and the collisions with neutral atoms



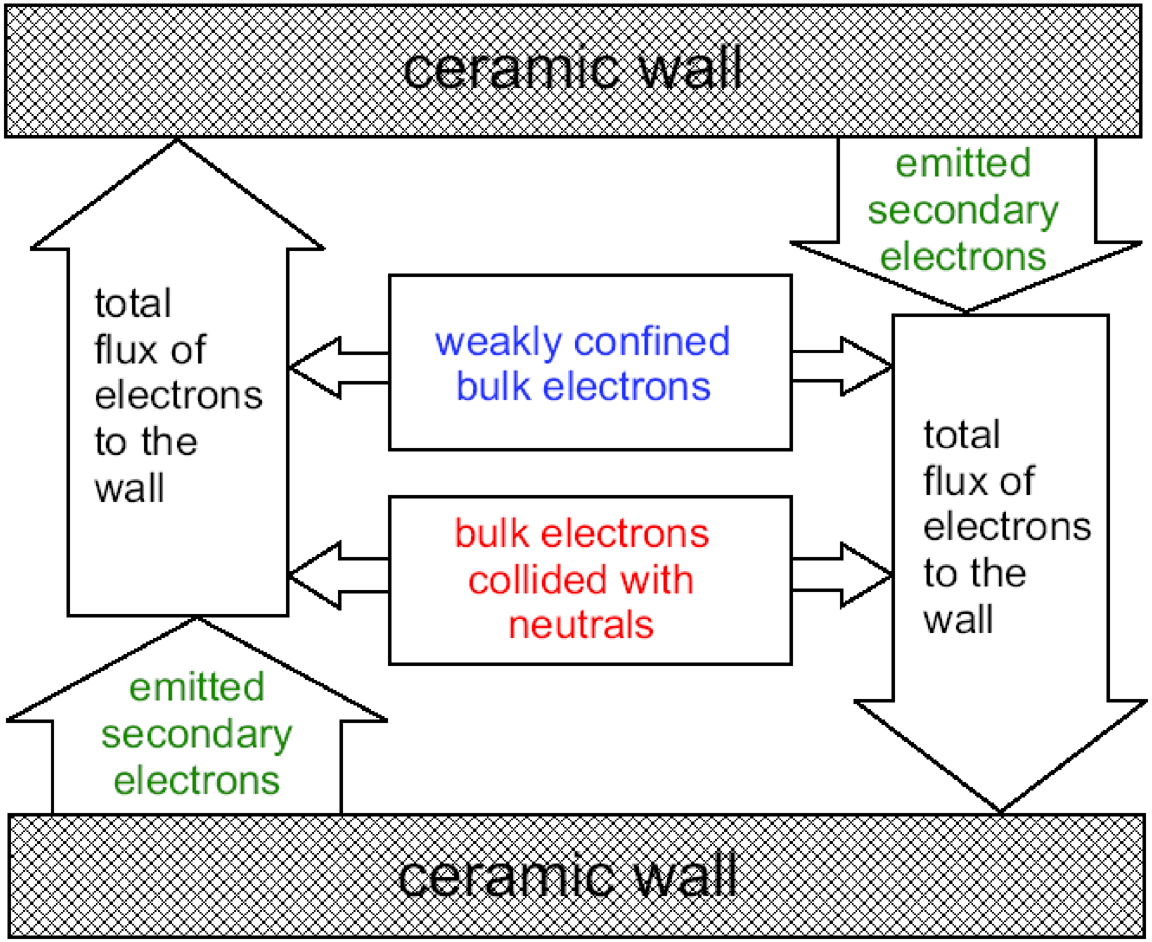
The SEE coefficient (ratio of emitted and incident electron currents) versus the energy of incident electrons.

The neutral gas density: $n_a = 2 \cdot 10^{18} m^{-3}$



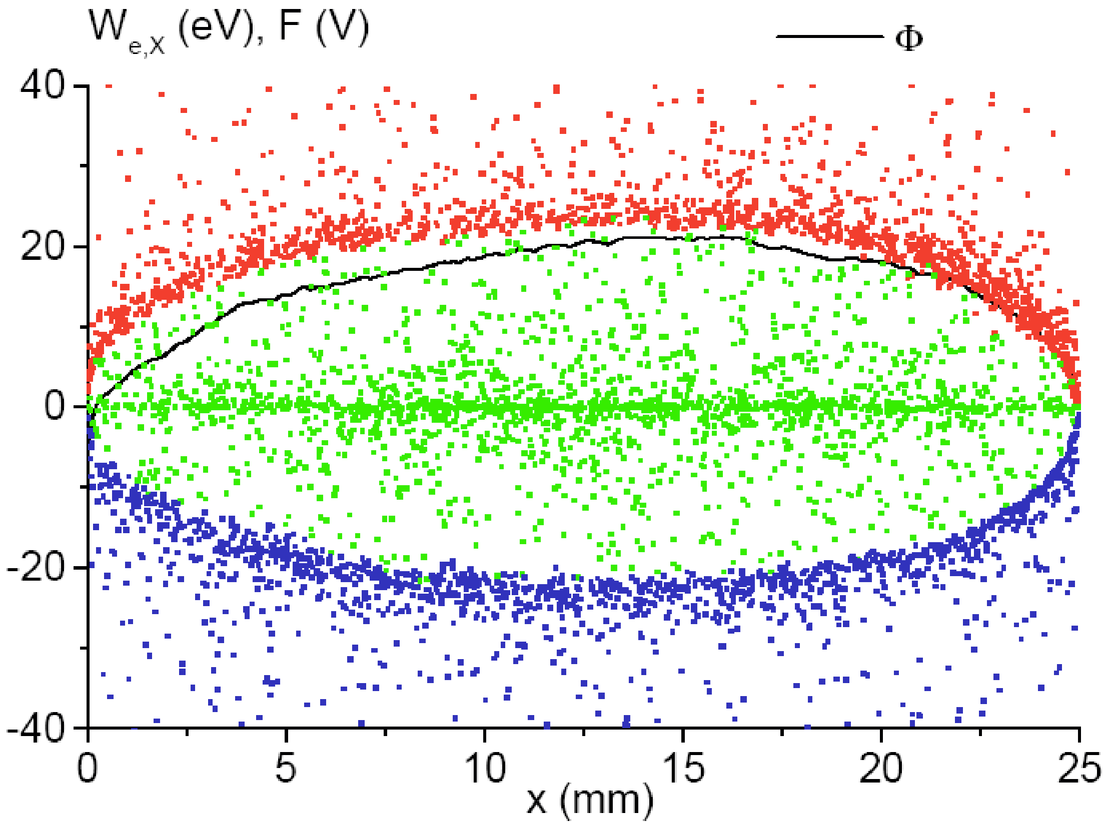
Cross-sections of different electron-neutral collisions versus the electron energy.

The components of the electron flux at the walls



In fluid approach the beams of secondary electrons, without the possibility to produce SEE, were recently considered in Ref.16.

E_z=200V/cm,<γ>=0.97: the electron phase plane "energy of motion in x-direction – x-coordinate"



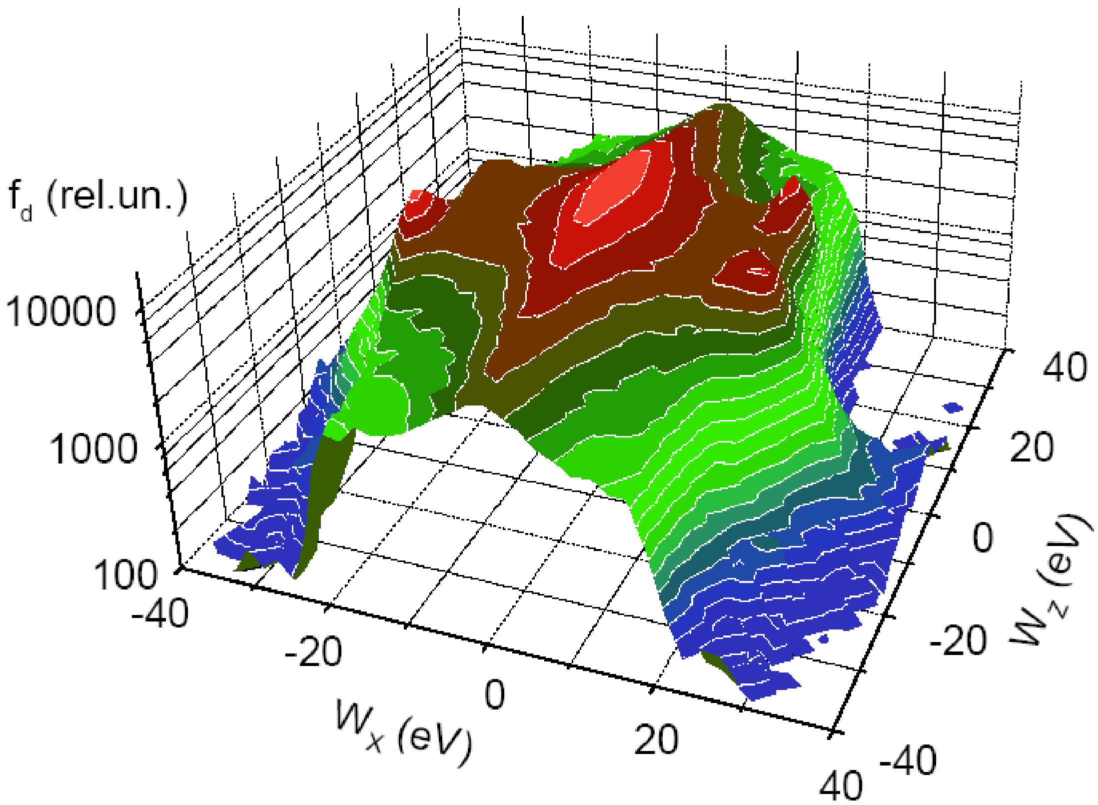
Red – emitted from the left wall (x=0);

green – the bulk plasma electrons;

blue – emitted from the right wall (x=25mm).

Black line – the instant profile of the electrostatic potential (Φ).

E_z=200 V/cm, <γ>=0.97: the general EVDF in the center of the plasma



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

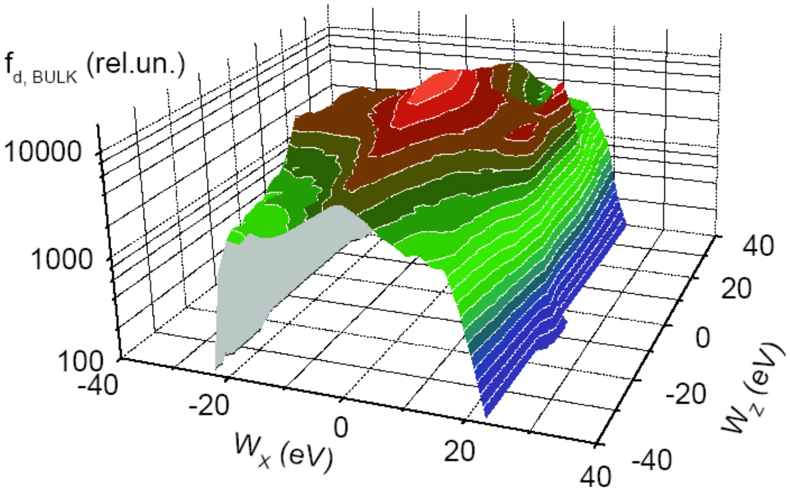
W_Z – the energy of electron motion along the accelerating field.

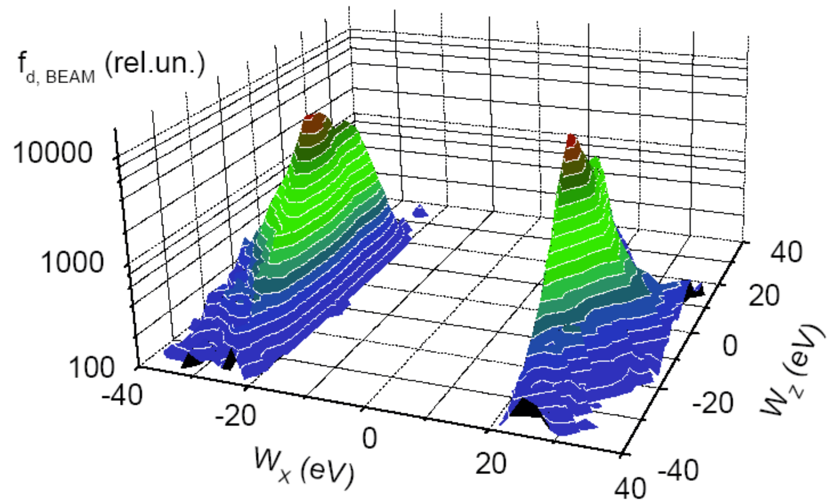
The general distribution is formed by the two components:

the plasma bulk and the SEE beams.

$<W_x>$=5.7 eV, $<W_z>$=24.5 eV

E_z=200 V/cm, <γ>=0.97: the distributions of the confined plasma and the beams of secondary electrons





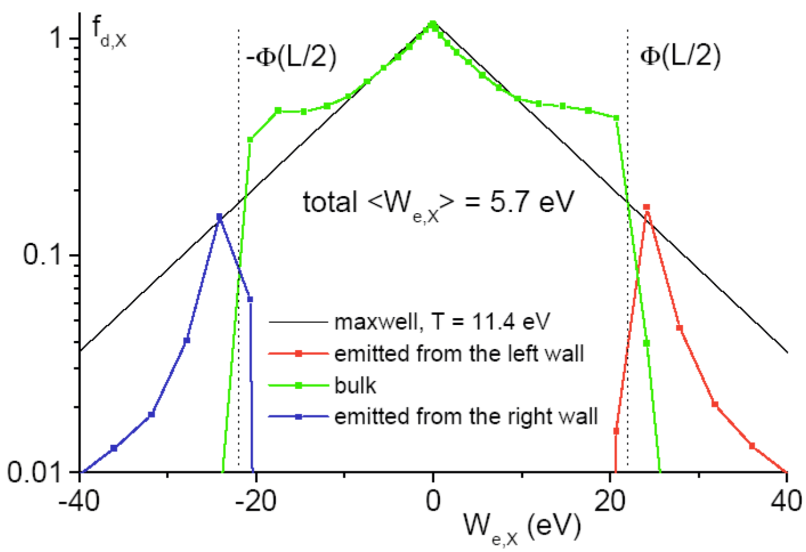
The plasma bulk:

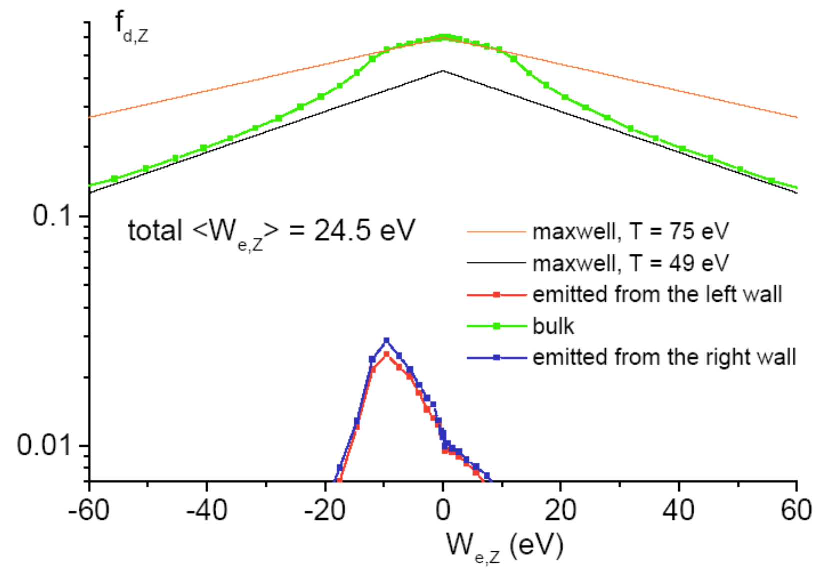
- anisotropic, with $T_z >> T_x$;
- strong depletion (cutoff) for the x-energies above the plasma potential;
- contains electrons lost by the SEE beams due to the two-stream instability.

The SEE beams:

- the x-energy is defined by the plasma potential;
- non-zero temperature of emission;
- considerable z-energy;
- significant density.

E_z=200 V/cm, <γ>=0.97: the one-dimensional EVDFs





Distribution over x-velocity (normal to the walls):

• for $|W_x|$ < 10 eV the bulk distribution (green) has temperature 5.7 eV.

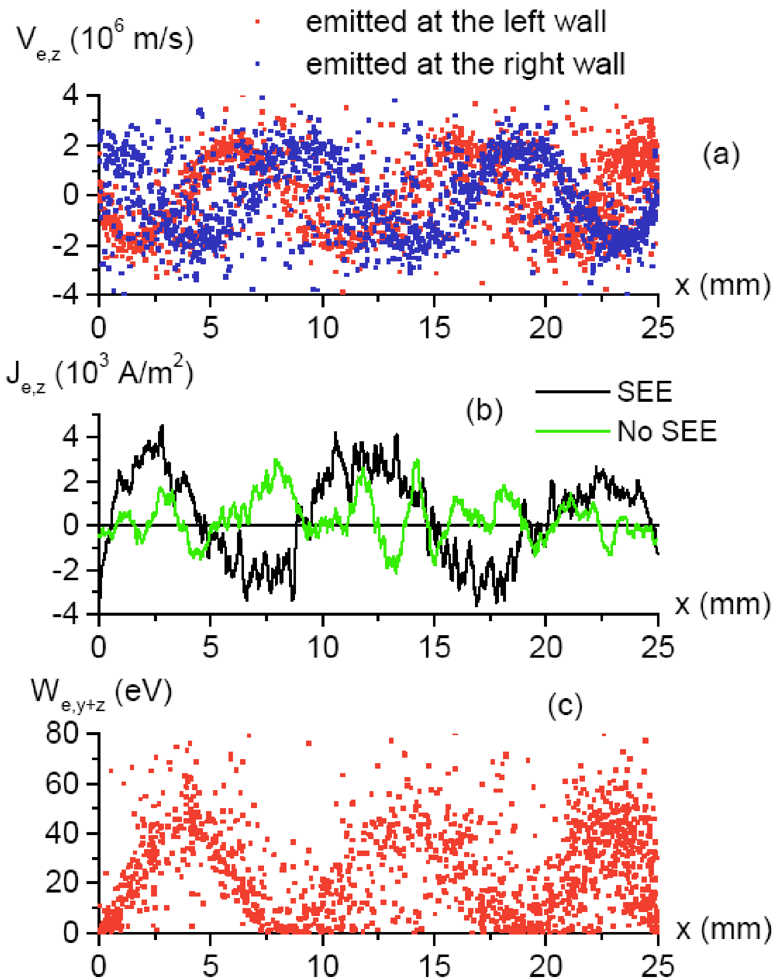
Distribution over z-velocity (along the accelerating field):

• for $|W_x|$<12eV the bulk temperature is 75 eV;

• for $|W_x|$>30eV the bulk temperature is 49 eV;

• the SEE beams distributions are non-symmetric due to the cyclotron rotation.

E_z=200 V/cm, <γ>=0.97: the effects of the cyclotron rotation of the emitted electrons



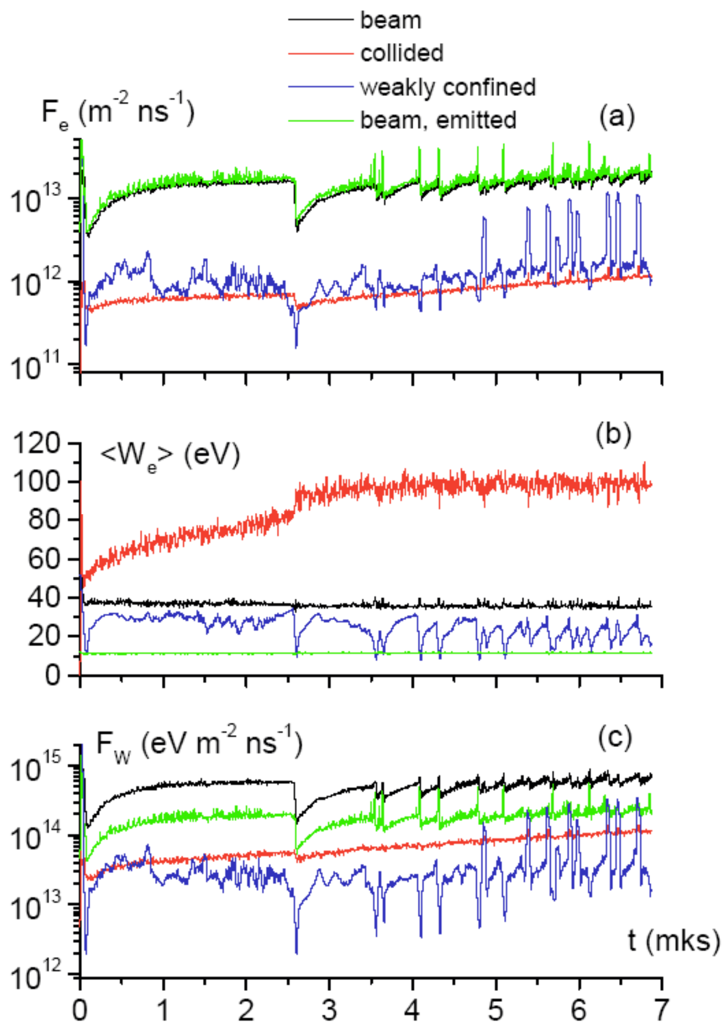
The emitted electrons rotate in the plane normal to the radial magnetic field during their trip between the walls.

The average axial velocity is non-zero, i.e. the near-wall conductivity (NWC) appears [17].

Due to the NWC the electric current about 3 times exceeds the collisional value, although the SEE is not in the space charge limited (SCL) mode.

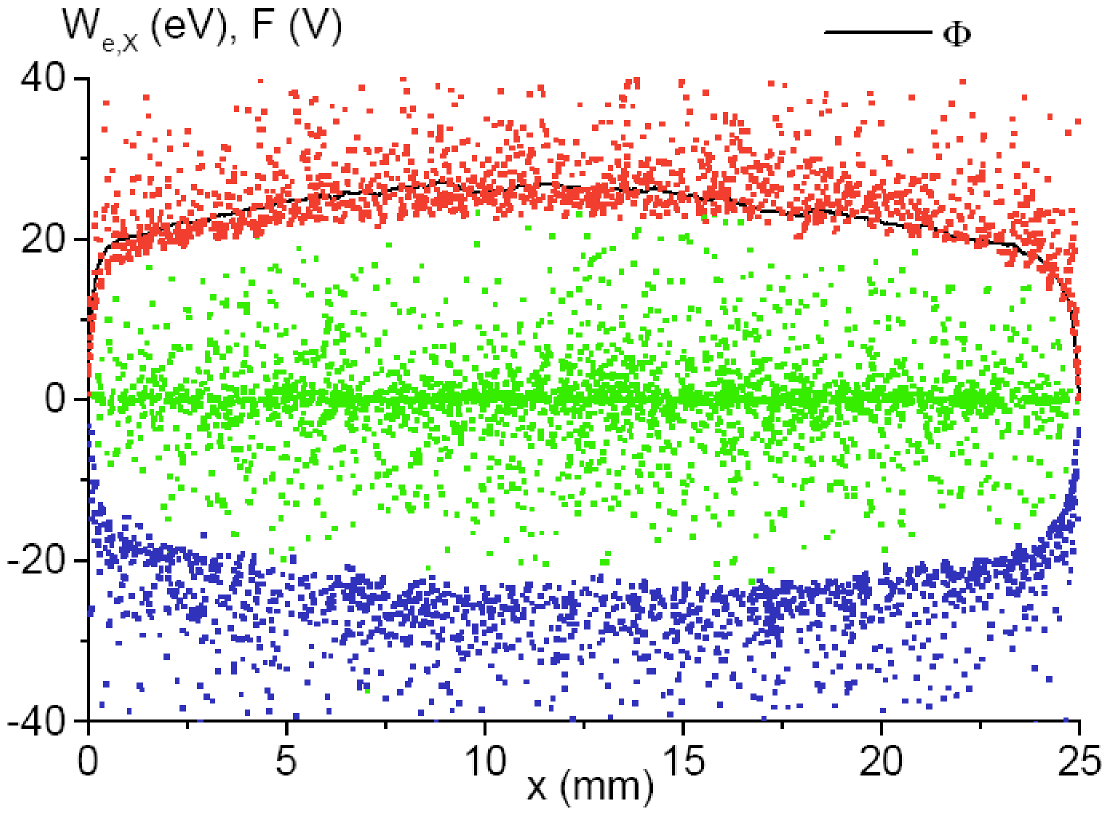
The energy of the rotational motion of emitted particles can be significant. However, this energy is not transferred to the bulk plasma and is spent on producing SEE at the walls.

E_z=200 V/cm, <γ>=0.97: the electron fluxes at the wall



- The beam of electrons emitted from one wall is the largest part of the flux of electrons towards the other wall.
- The energy, acquired by the beam electrons due to the rotation in the crossed electric and magnetic fields, is comparable to the energy of the anisotropic confined plasma.
- The total SEE coefficient is below the SCL threshold γ*=0.983 because the contribution due to the low energy "weakly confined" electrons is insufficient.
- Most of the flux of electron kinetic energy towards one wall is formed by the beam of electrons emitted from the opposite wall.

E_z=52V/cm,<γ>=0.73: the electron phase plane "energy of motion in x-direction – x-coordinate"



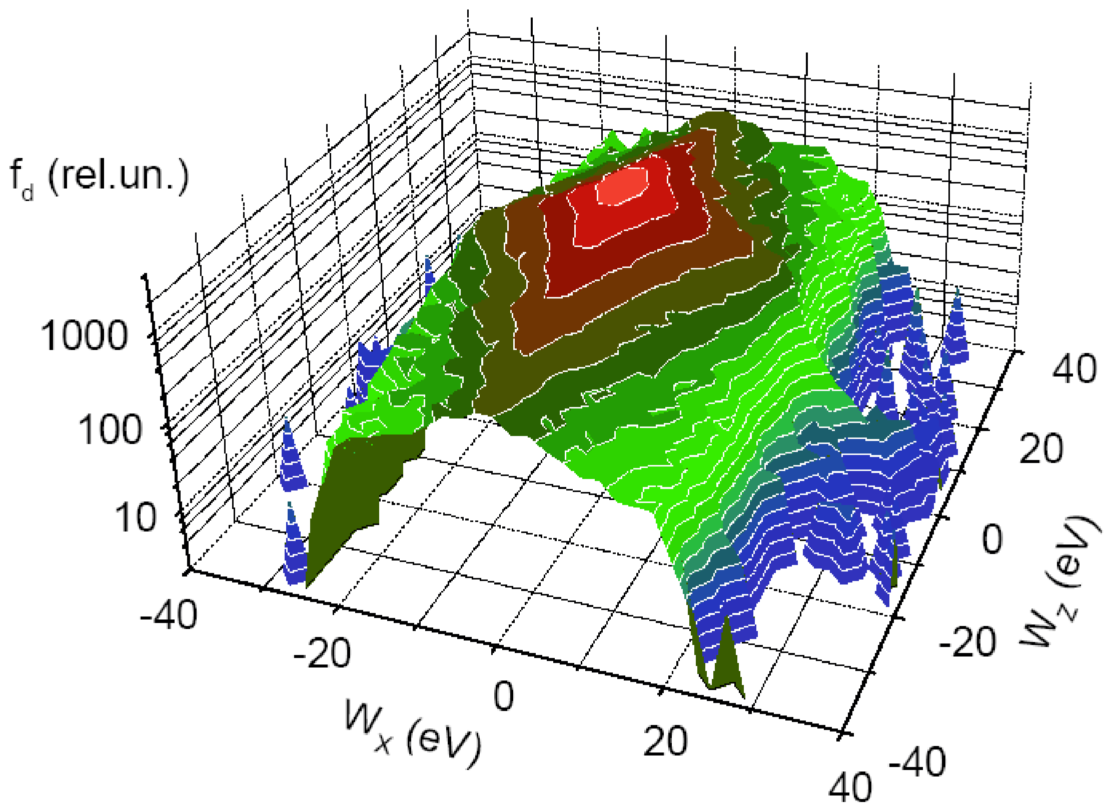
Red – emitted from the left wall (x=0);

green – the bulk plasma electrons;

blue – emitted from the right wall (x=25mm).

Black line – the instant profile of the electrostatic potential (Φ).

E_z=52 V/cm, <γ>=0.72: the general EVDF in the center of the plasma



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

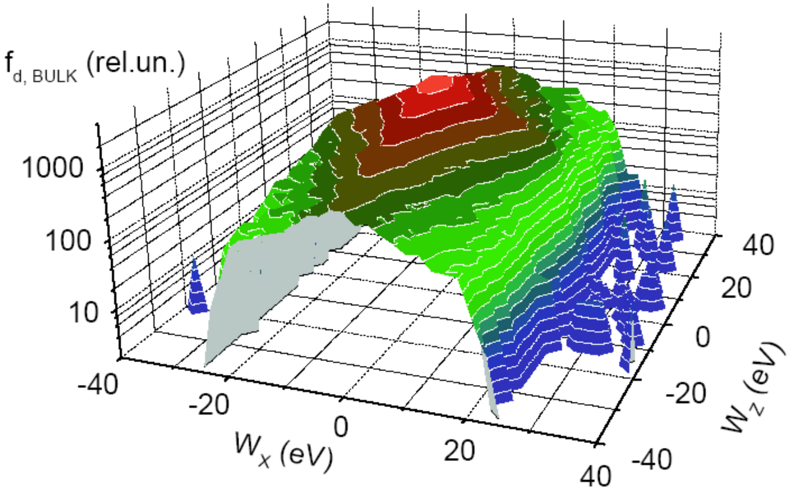
W_Z – the energy of electron motion along the accelerating field.

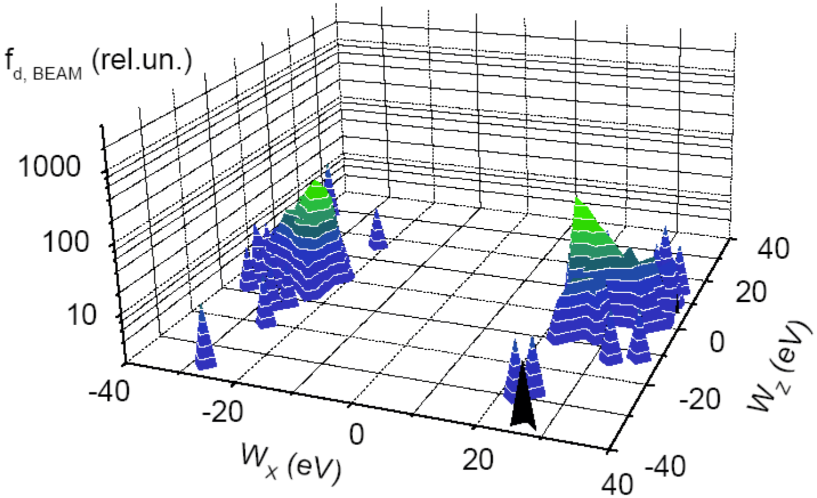
The general distribution is formed by the two components:

the plasma bulk and the SEE beams.

$\langle W_x \rangle$=4.1 eV, $\langle W_z \rangle$=14.4 eV

E_z=52 V/cm, <γ>=0.72: the distributions of the confined plasma and the beams of secondary electrons





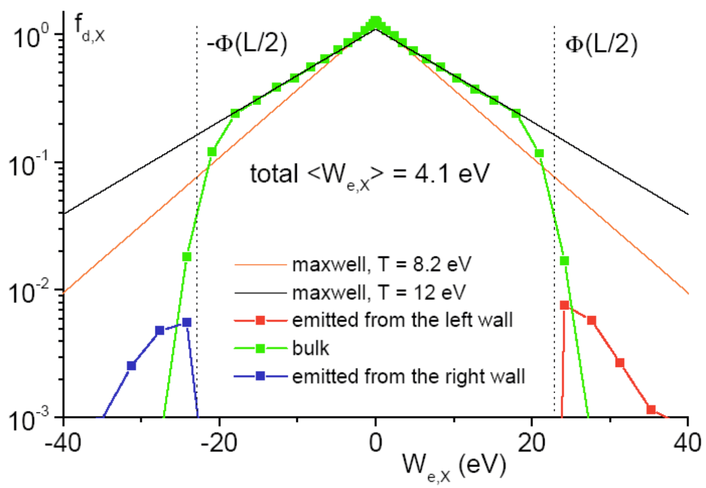
The plasma bulk:

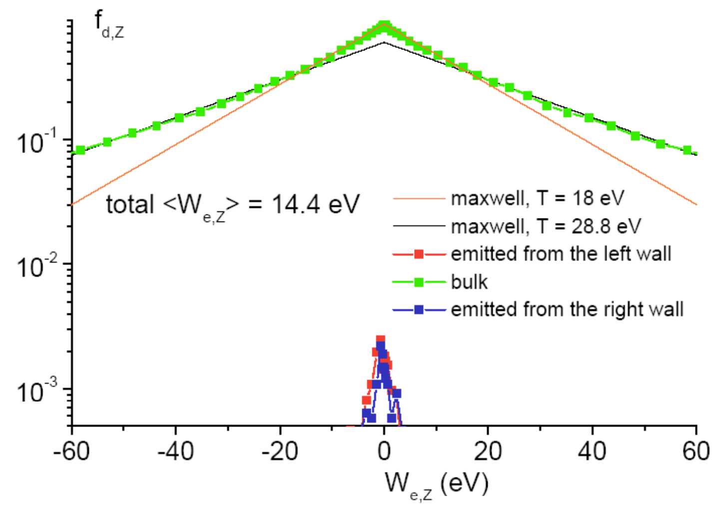
- anisotropic, with $T_z >> T_x$;
- strong depletion (cutoff) for the x-energies above the plasma potential;
- the tails in x-energy are replenished mostly due to the collisions with neutrals.

The SEE beams:

- the x-energy is defined by the plasma potential;
- non-zero temperature of emission;
- low z-energy and low density.

E_z=52 V/cm, $\langle\gamma\rangle$=0.72: the one-dimensional EVDFs





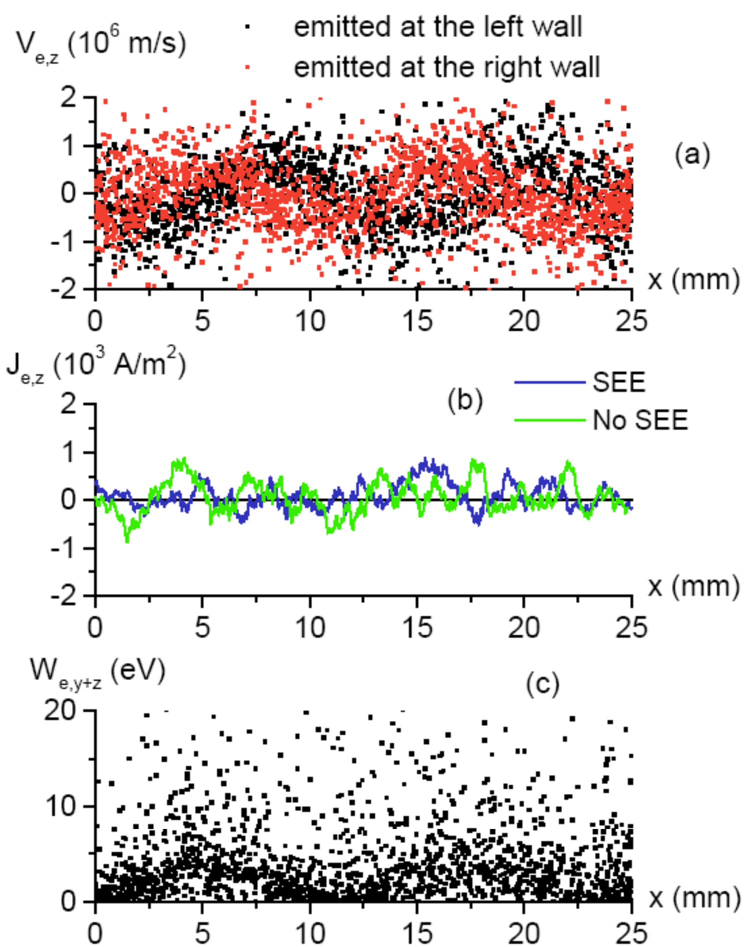
Distribution over x-velocity (normal to the walls):

- for $|W_X|$ < 8 eV the bulk temperature is 8.2 eV;
- for 10 eV < $|W_X|$ < 18 eV the bulk temperature is 12 eV.

Distribution over z-velocity (along the accelerating field):

- for $|W_Z|$<10eV the bulk temperature is 18 eV;
- for $|W_Z|$>20eV the bulk temperature is 28.8 eV;
- the displacement of the SEE beams distributions due to the cyclotron rotation is insignificant.

E_z=52 V/cm, <γ>=0.72: the effects of the cyclotron rotation of the emitted electrons

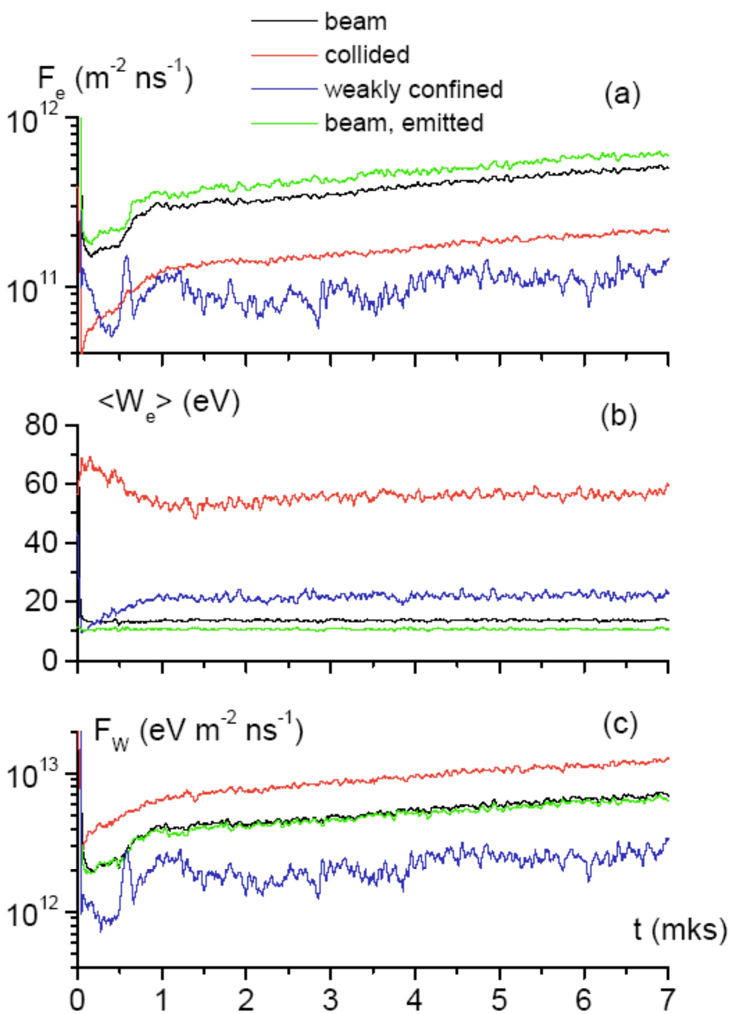


The perturbation of the tangential velocity of emitted electrons by the accelerating electric field is small: $V_{ExB\ drift}$ / V_{inject}<1.

The contribution of the twisted electron flow to the overall electron mobility is negligible compared to the collisional mobility.

The additional energy due to the rotation of emitted particles in the crossed fields does not exceed the initial energy of injection.

E_z=52 V/cm, <γ>=0.72: the electron fluxes at the wall



- The largest electron current to the wall is created by the beam of electrons emitted from the other wall.
- The energy of electrons of the SEE beam (when they hit the wall) is much smaller than the energy of electrons coming from the bulk plasma.
- Most of the flux of electron kinetic energy towards the walls is formed by the high energy electrons from the bulk plasma, which turned to the walls after collisions with neutral atoms.
- The total rate of wall energy losses increases insignificantly compared to the case with completely absorbing walls.

Summary

- The PIC simulations show that in the accelerating region of a Hall thruster the EVDF is strongly anisotropic. The energy of electron motion in the direction normal to the walls is several times smaller than the energy of electron motion parallel to the walls. The distribution over the velocity normal to the walls is strongly depleted for energies above the plasma potential.
- The anisotropy develops because:
  - the accelerating electric field contributes to the energy of motion parallel to the walls;
  - the time between the collisions considerably exceeds the time during which the electron with energy (in the direction normal to the walls) sufficient to penetrate through the sheath exists in the system.
- The electron flux to the wall consists of several components:
  - the electrons emitted from the opposite wall,
  - the electrons from the plasma bulk, which collided with neutral atoms,
  - the weakly confined electrons, which penetrate through the sheath due to the field fluctuations.

Summary

- The total relative emission yield will be below the space charge limited emission threshold despite the high energy of bulk plasma particles if the contribution of other components of the electron flux is insufficient.
- The emitted electrons form two beams in plasma. These electrons can acquire considerable energy during the rotation in the crossed radial magnetic and axial electric fields if the energy of drift in the crossed fields exceeds the transverse energy of emission (which is usually small).
- The beams of emitted electrons with significant rotational energy may:
  - maintain the high emission current;
  - increase the average plasma electron mobility due to the near-wall conductivity effect;
  - create the intense flux of energy to the walls.
- If the electric field is small, the energy of the emitted electrons changes insignificantly after their trip through the plasma. In this case the energy flux to the wall is mostly created by the electrons from the plasma bulk, as a result the overall energy loss at the walls does not change compared to the case with completely absorbing walls.

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