Modeling of Collision-less and Kinetic Effects in Thruster Plasmas

Igor Kaganovich

Princeton Plasma Physics Laboratory

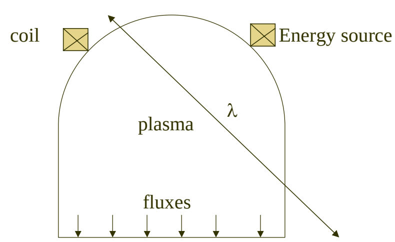
11/14/2005

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.**

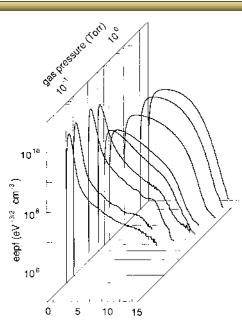


The treatment has to be kinetic! (1/2)

- **Most remote from thermodynamic equilibrium:**
  - **T_e differs from T_i**

3eV	3 10^{-2} eV	glow discharges
3 10^{-3} eV	3 10^{-2} eV	Afterglow, plasma jet
100eV	10eV	Hall thrusters
10keV	1eV	ECR ion sources

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



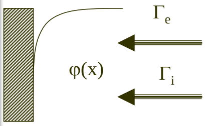
Electron energy distribution functions are nonMaxwellian:
- **Parts of the EDF are very flexible and almost independent.**
- **Example of capacitive discharge**

50 Years of History of kinetic studies in low-temperature plasmas

- **1954 - I. Bernstein and T. Holstein**
  - **Positive column of dc discharge**
- **1974 - L. Tsendin**
  - **Positive column of dc discharge**
- **1990 – I. Kaganovich**
  - **RF discharges**

For more info: M.A. Lieberman and A.J. Lichtenberg, "Principles of Plasma Discharges and Material Processing", John Wiley & Sons Inc., sec. ed., NY 2005.

Plasma potential relative to wall: kinetic treatment (1/3)



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

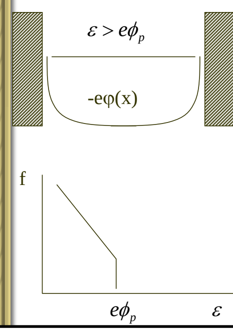
$$\Gamma_i = n\sqrt{\frac{T_e}{M}}$$

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

- **Relies on assumption of an Maxwellian electron energy distribution function.**
- **Is it?**

7

Plasma potential relative to wall: kinetic treatment (2/3)

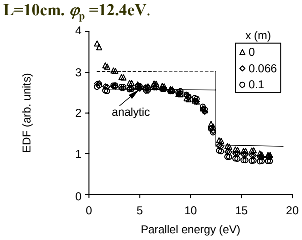


- **Most electrons are trapped in potential well.**
- **Electrons with $\varepsilon > e\phi_p$ quickly leave**
- **=> EDF is empty in the loss cone**
- **=> Plasma potential relative wall is smaller**

8

Plasma potential relative to wall: kinetic treatment (3/3)

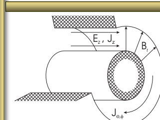
Results of particel-in-cell code for electron energy distribution function (EDF) at given total energy 1.5φ_p as a function of the parallel energy at various coordinates, solid lines correspond to the theoretical estimate at p=1mTorr, L=10cm. φ_p =12.4eV.



For more info: IEPC-096;
Kaganovich, I.D., et al, Phys. Rev. E. **61**, 1875 (2000).

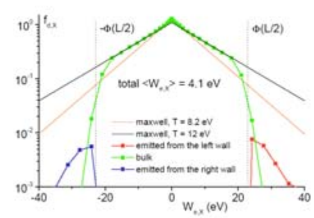
9

Kinetic Modeling of Hall Thruster



E_z=52 V/cm B=100G

T_x=12eV φ_p =22eV ! Not 5T_e



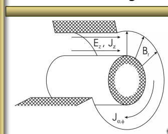
For more info

D. Sydorenko, et al.

IEPC-078 "Session 3-2, Tuesday, 4pm.

PoP, IEEE TPS (2005)

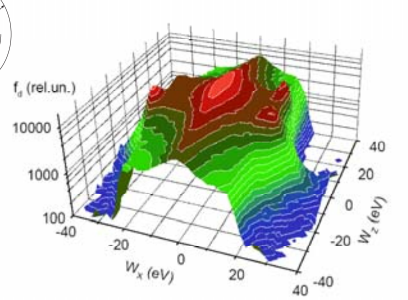
EEDF is anisotropic + beams due to secondary electron emission



E_z=200 V/cm
B=100G

$\langle W_x \rangle$=5.7 eV

$\langle W_z \rangle$=24.5 eV

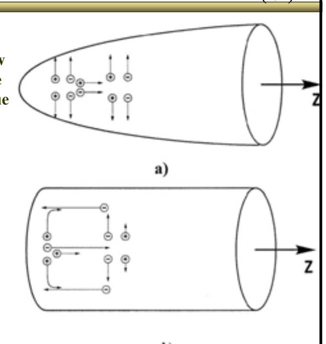


Plasma Expansion Along Magnetic Field Lines (1/2)

The scheme of non-ambipolar diffusion accompanied by short-circuiting currents. Arrows show the electron and ion motion. The arrow length represents the value of particle fluxes.

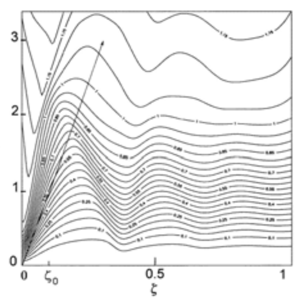
(a) Hypothetical ambipolar expansion.

(b) Real non-ambipolar fluxes.



Plasma Expansion Along Magnetic Field Lines (2/2)

Ion trajectory (streamlines of ion flow) in cylindrical geometry. Ion jet propagates with a supersonic velocity along ζ and expands radially due to the electron temperature. The arrow shows the characteristic angle of plasma expansion at the sound velocity.



For more info: IEPC-096;
Kaganovich, I.D., et al, Plasma Sources Sci. Technol. **5**, 743 (1996).

13

Conclusions (1/3)

- **Low-pressure plasma has to be treated kinetically**
- **Fluid approach can lead to quantitatively and qualitatively incorrect results.**
- **The electron energy distribution function is often non-Maxwellian.**
- **Electrons tend to stratify into different groups depending on their origin and confinement, i.e., weather they are trapped or not by the plasma potential.**
- **These different groups of electrons have to be treated separately, can not be lumped together into one Maxwellian EEDF.**

14

Conclusions (2/3)

- **The concept is demonstrated on an example of calculation of particle and heat losses from bounded plasma in presence of strong secondary electron emission as pertains, but not limited to a Hall thruster.**
- **It was shown that EEDF is nonMaxwellian and strongly anisotropic with $T_x << T_z$.**
- **This strongly influence the plasma potential relative to sheath and particle and heat fluxes to the bounding walls.**

15

Conclusions (3/3)

- **The plasma jet's radial expansion is studied in presence of strong axial magnetic field.**
- **Electrons can flow fast along the magnetic field lines and simultaneously diffuse radially far from jet injection point and then come back along another magnetic field line. As a result, ions flow freely to the radial position where electrons are available due to such complex loop-like electron trajectories. These short-circuiting flows result in a cylindrical shape of the jet in contrast to conical.**
- **A practical application of this result can be analysis of differences between testing, laboratory environment and real space environment.**

16

Related Talks:

- **Y. Raitses,**
  - *PPPL*
  - IEPC-052, "Electron Temperature Saturation With The Discharge Voltage In Hall Thrusters",
  - Session 5-1, **Wednesday, 5pm.**
- **D. Sydorenko,**
  - *University of Saskatchewan*
  - IEPC-078 "Kinetic Simulation Of Effects Of Secondary Electron Emission On Electron Temperature In A Hall Thruster" ,
  - Session 3-2**, Tuesday, 4pm.**

17

Is it simple?

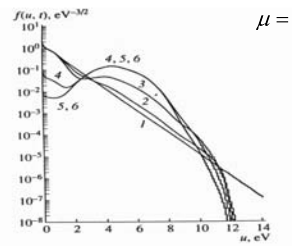
- **Plasma is highly**
  - **Nonlinear**
  - **Nonlocal**
  - **Collisionless**
- **Results are often unexpected and surprising**

18

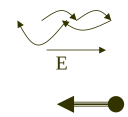
Non-monotonic EEDF yields Negative Plasma Conductivity!

EDF afterglow Ar:NF_3, E/N=2 10^{-17} Vcm^2 0, 0.25, 1, 3, 5, 10 ns.

N.A. Dyatko, *et al.*, Plasma Phys. Rep. 1998



$$\mu = -\frac{2e}{3m}\int u^{1/2}\lambda \frac{df(u)}{du}du < 0$$



Total electron flux is directed opposite to the electric field