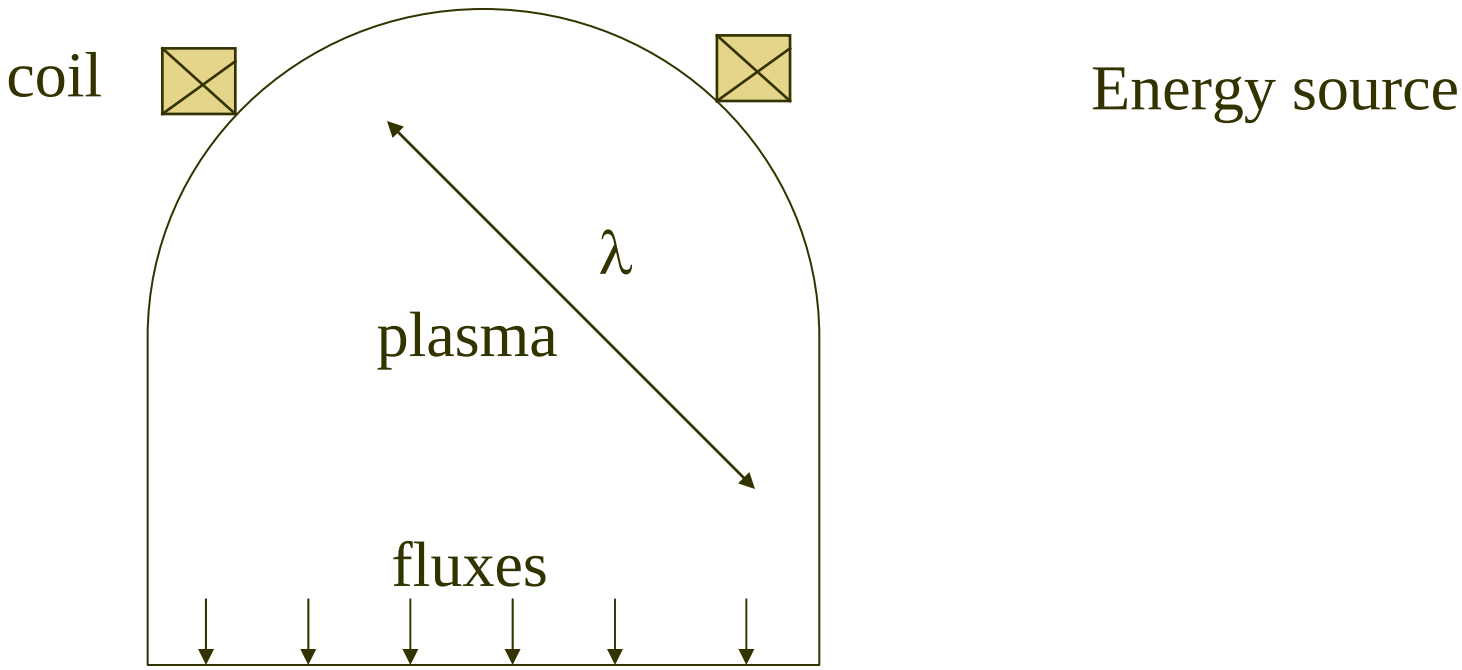
Nonlocal collisionless and collisional electron transport in low-temperature plasmas

Igor D. Kaganovich, Yevgeny Raitses*
Vladimir I. Demidov, Steve F. Adams**

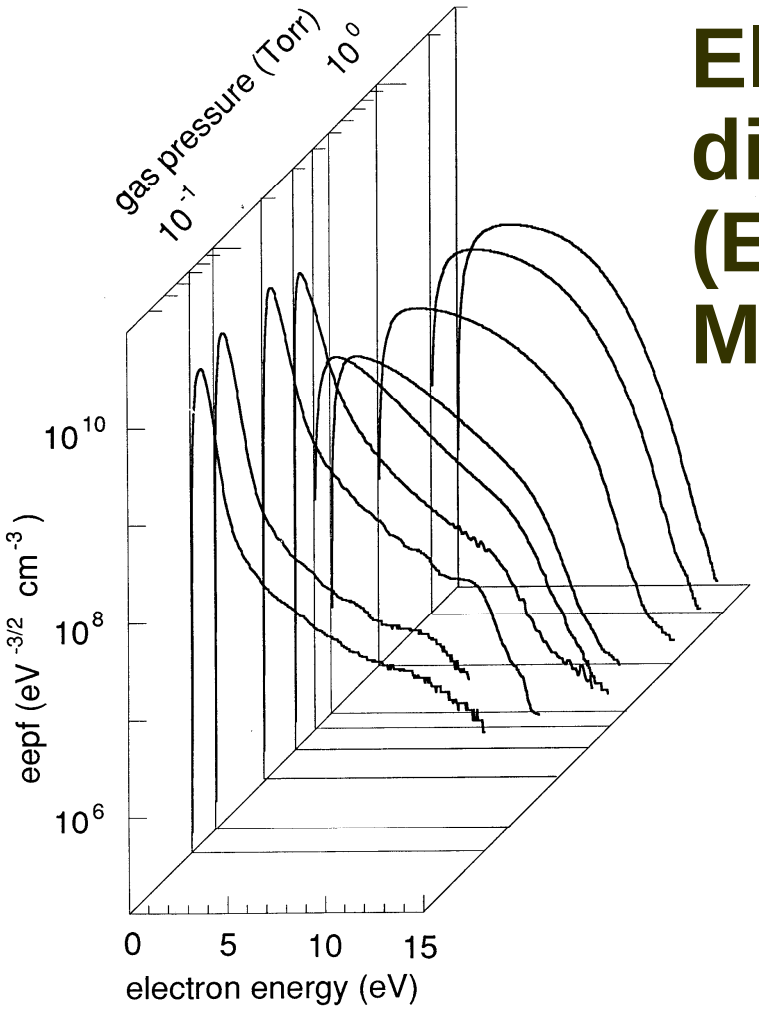
**Princeton Plasma Physics Laboratory, NJ, USA*
*** AFRL, Wright-Patterson, OH, USA*

Nonlocality is important for many plasma applications

Electron energy relaxation length is large; this allows remote plasma handling via nonlocal electron energy distribution function (EEDF).



Discharge modeling needs to be kinetic!



Electron energy distribution functions (EEDF) are non-Maxwellian:

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

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

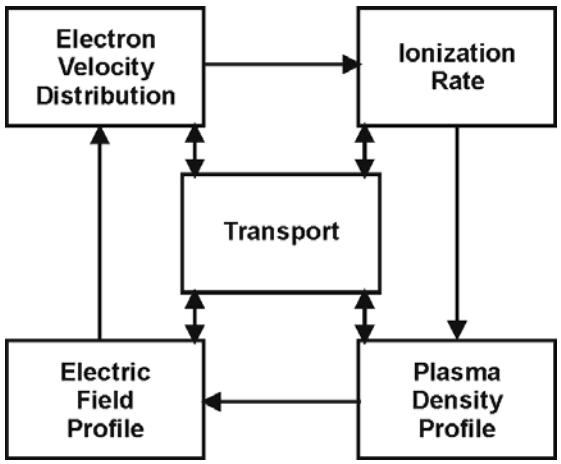
Formation of non-Maxwellian, non-uniform, *f(v,r,t)* in self-consistent electric field is strongly coupled to plasma density profile through ionization and transport.

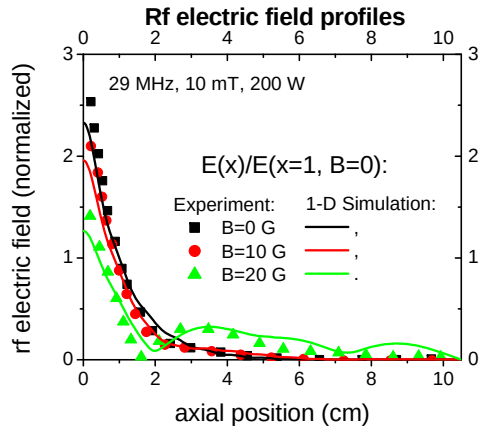
$$\left[\frac{\partial}{\partial t}+(\mathbf{v}\bullet\nabla)-e\mathbf{E}\frac{\partial}{m\partial\mathbf{v}}\right]f_0=\sum_k\left[\overline{\nu_k^{*}\,'\frac{\sqrt{u'}}{\sqrt{u}}f_0(\varepsilon+\varepsilon_k^{*})}-\overline{\nu_k^{*}}f_0\right]+St_{ee}\,,$$

$$\frac{\partial n_i}{\partial t}+\nabla\bullet(\mathbf{v}n_i)=\nu_{iz}n_i\,,\ \nu_{iz}n_i=\int_I^{\infty}f_o(u)v\sigma_{iz}d\mathbf{v}$$

$$\nabla\bullet\mathbf{E}=4\pi e(n_i-n_e)$$

$$M_i\left(\frac{\partial\mathbf{v}}{\partial t}+(\mathbf{v}\bullet\nabla)\mathbf{v}\right)=e\mathbf{E}-\frac{\nabla p_i}{n_i}-(\nu_{ia}+\nu_{iz})\mathbf{v}$$





I.D. Kaganovich *et al*, Phys. Rev. Lett. 1999, 2000, 2002; V.A. Godyak, *et al*, Phys. Rev. Lett. 1990,1992, 1996, 1998, 1999 + many others.

Outline

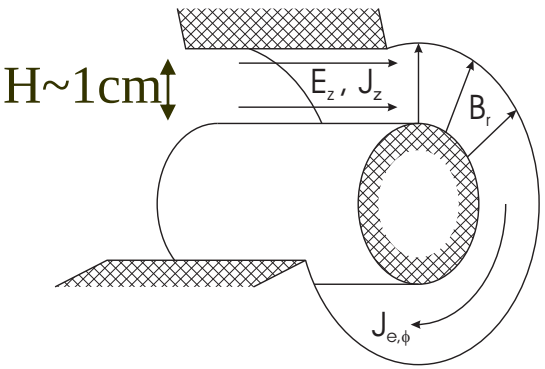
Nonlocal electron kinetics in collisionless plasma

- Hall Thruster Discharge
- Radio-frequency discharges

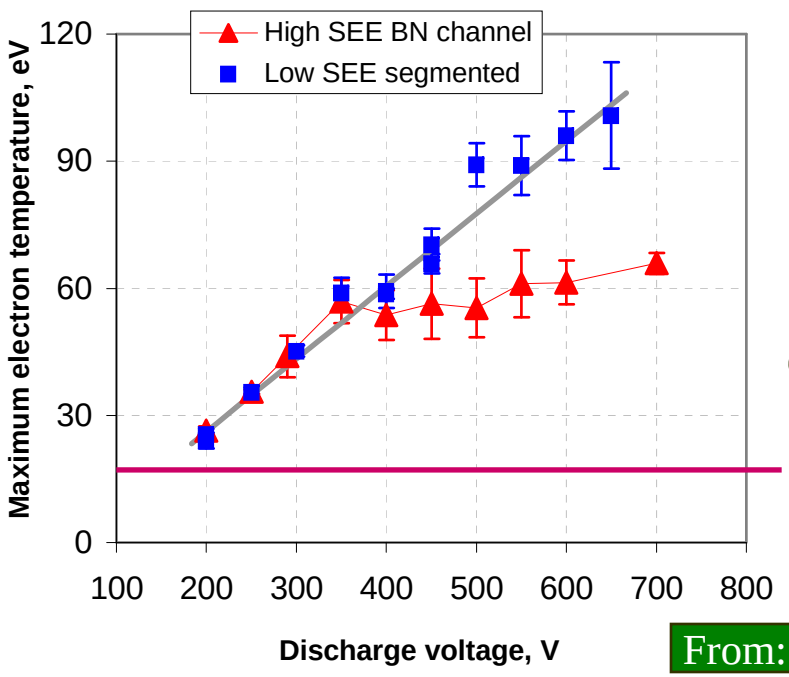
Nonlocal electron kinetics in collisional plasma

- Afterglow
- Direct current discharges

Plasma-wall interactions in Hall thrusters



B ~ 100G, E ~ 100V/cm, T_e ~ 100eV. P=0.1-1mTorr, the plasma inside the thruster channel is collisionless, λ_{ec} (~1m) >> H (~1cm). => intense particle and heat wall losses!



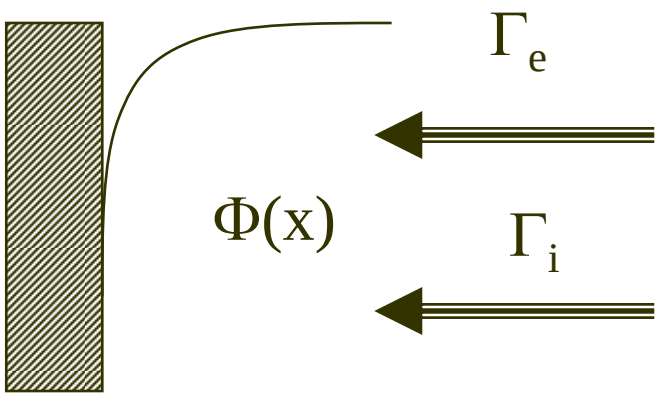
High electron temperature is observed in experiments

- *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



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

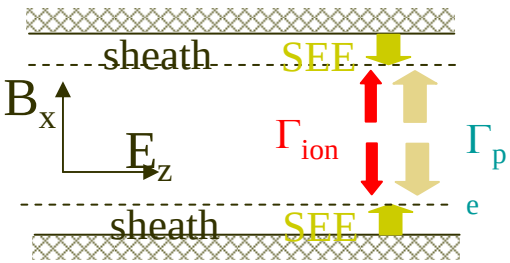
$$\Gamma_i = n\sqrt{\frac{T_e}{M}}$$

$$\Gamma_e = \Gamma_i$$

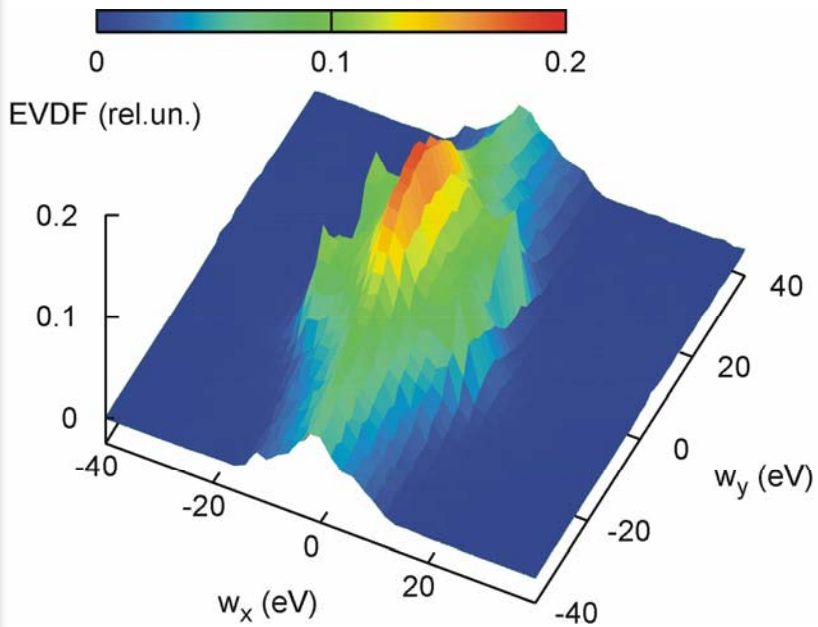
$$e\phi_p = T_e \ln\left(\sqrt{\frac{M}{2\pi m}}\right) \sim 5T_e$$

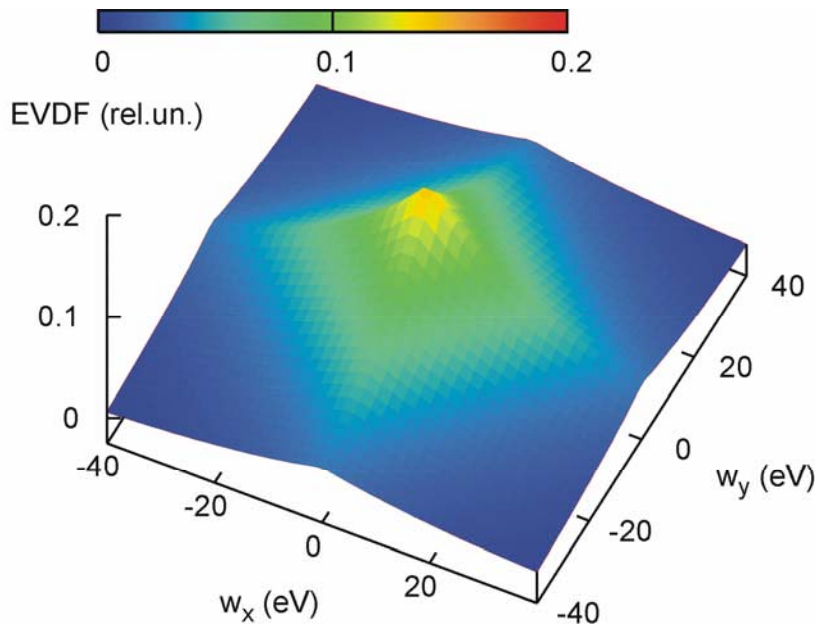
Relies on the assumption of a Maxwellian electron energy distribution function.

Particle-in-cell simulations of Hall thruster plasma



Complex structure of strongly anisotropic electron velocity distribution function (EVDF) in the channel of a Hall thruster discharge (left) versus an isotropic Maxwellian EVDF (right).





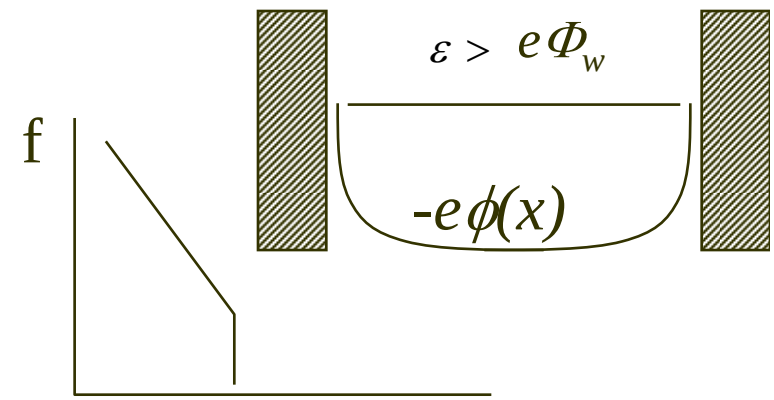
=> Completely different implications follow from kinetic or fluid description for the Hall thruster operation.

High-energy electrons leave quickly, the EVDF is depleted => wall flux is small.

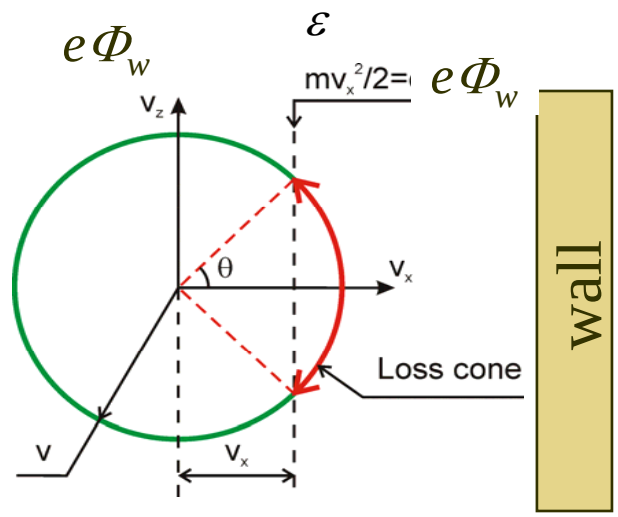
Most electrons are trapped in the potential well.

Electrons with $\varepsilon > e\Phi_w$ leave.

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



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



Wall flux is 100 times smaller than the fluid predictions and wall potential is ~$1T_e/e$ instead of $5T_e/e$.

See: D. Sydorenko et al 6 papers in PoP, IEEE TPS

Reasons for the EVDF anisotropy

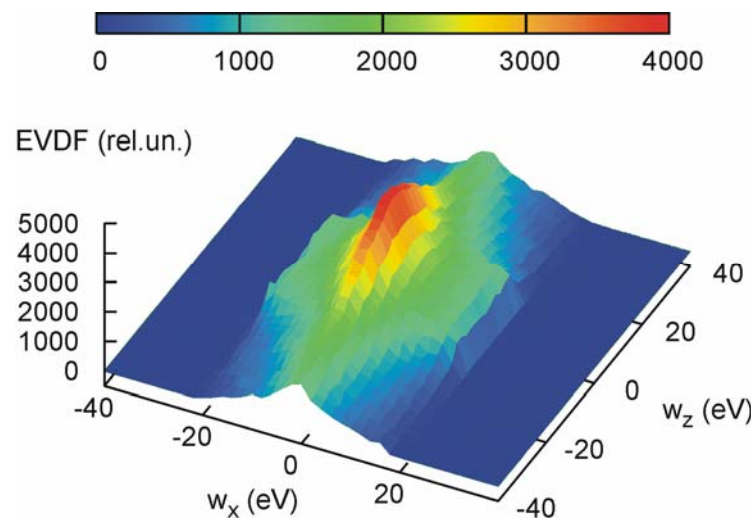
$\nu_{en}\tau \sim 1$ – **electrons undergo few collisions with atoms before escaping to the walls.**

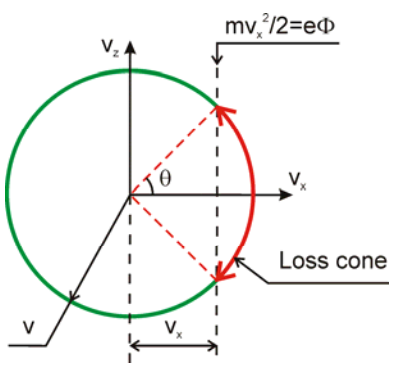
$\nu_{iz} \sim \nu_{en}$ **- Xenon inelastic cross sections are large.**

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

E_z=200 V/cm, B_x=100G

T_x = 12eV, T_z = 37eV!



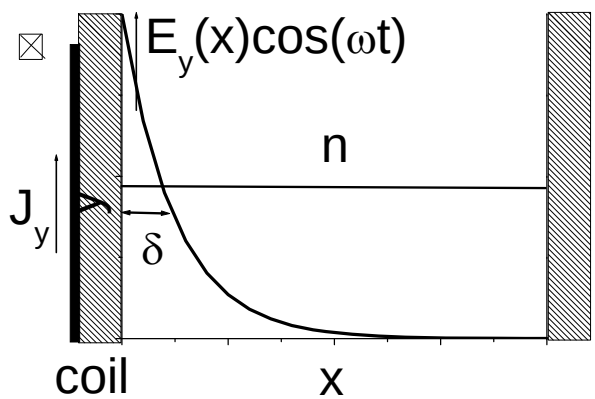


The wall potential in Hall thrusters is small, $e\Phi_w \sim T_e$. => Most electrons leave plasma and undergo collisions with the same frequency.

Nonlocal electron kinetics in radio-frequency discharges

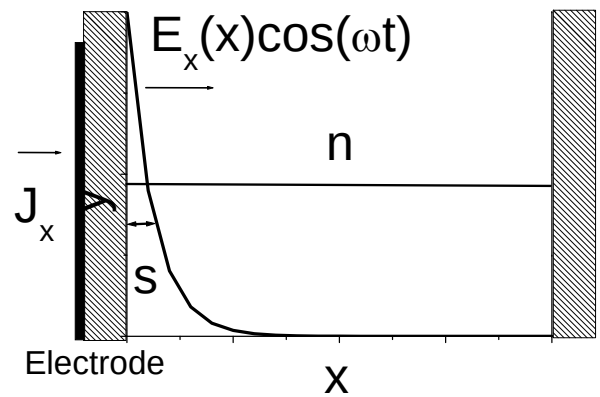
Inductive rf field $E_y = E_{y0} e^{-x/\delta_0}$

Normal skin effect $\delta_0 = c/\omega_p$

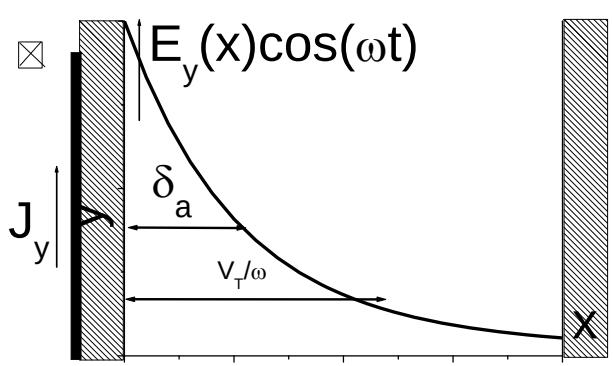


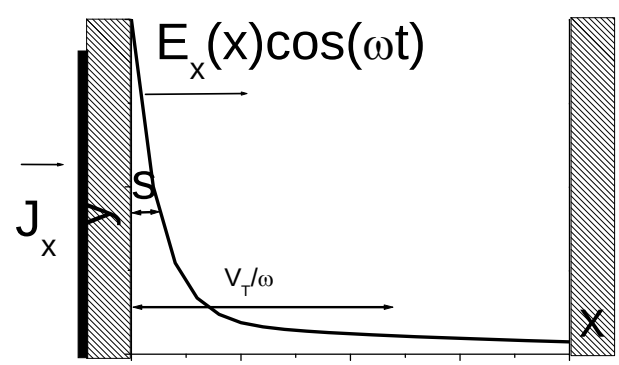
Capacitive rf field

Normal rf sheath $s = V_T / \omega_p$



Anomalous skin and sheath effects: rf field and current profiles are spread due to electron thermal motion on distances V_T/ω.

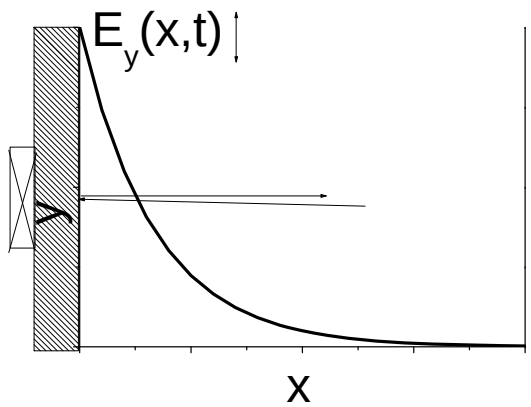




Nonlocal Electron Conductivity

Electron velocity is given by an integral over electric field profile

$$\frac{d}{dt}v_y = -\frac{e}{m}E_y \qquad j_y \neq \frac{e^2 i n_e E_y}{m\omega}$$



$$v_y = \frac{e}{m}\int_{-\infty}^{t} E_y[x(\tau),\tau]d\tau$$

spatial dispersion

$$J_y(x) = \int_0^x G(x,x')E_y(x')dx' + \int_x^L G(x',x)E_y(x')dx'$$

$$E_y(x) = \frac{2i\omega I}{c^2}\int_{-\infty}^{\infty}\frac{e^{ikx}}{k^2-\omega^2\varepsilon_t(\omega,|k|)/c^2}$$

Typical error is to loose |k.|

$$\int_{-\infty}^{\infty} dk\frac{e^{ikx}}{D(|k|)} = \int_{-\infty}^{\infty} dk\frac{e^{ikx}}{D(-k)} + \int_0^{\infty} dk e^{ikx}\left(\frac{1}{D(k)} - \frac{1}{D(-k)}\right)$$

$$\frac{e^{ik_p x}}{D'(-k_p)}$$ exponential part non-exponential part

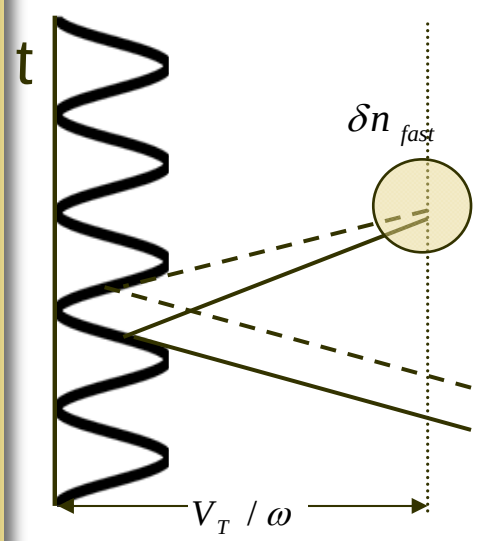
Revisiting capacitive sheath model

$$E_x(x) = \frac{1}{\varepsilon} E_0 + \frac{1}{i\pi} \int_{-\infty}^{\infty} \frac{dk e^{ikx}}{k \varepsilon_{\|}(\omega, |k|)}$$

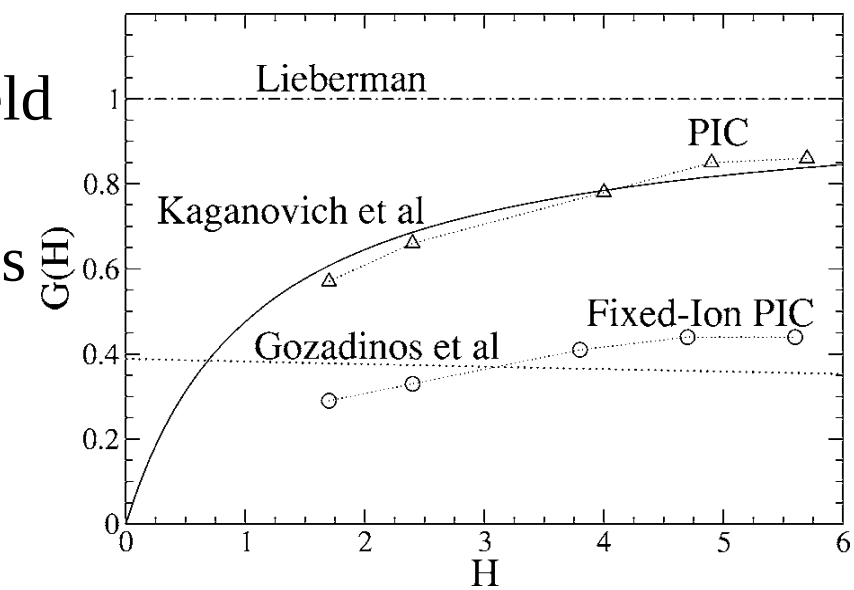
Forgotten Landau's solution
L. D. Landau, J. Phys. (USSR) **10**, 25 (1946).

$$\int_{-\infty}^{\infty} dk \frac{e^{ikx}}{\varepsilon_{\|}(|k|)} = \int_{-\infty}^{\infty} dk \frac{e^{ikx}}{\varepsilon_{\|}(-k)} + \int_{0}^{\infty} dk e^{ikx} \left(\frac{1}{\varepsilon_{\|}(k)} - \frac{1}{\varepsilon_{\|}(-k)} \right)$$

Debye screening $e^{-x\omega_p / v_T}$ non-exponential part



Electron bunches produce electric field near sheath on distances V_T/ω => modify collisionless heating, confirmed by PIC simulations by E. Kawamura, PoP 2006.



Nonlocal electron kinetics in afterglow

Collisional plasma, but energy relaxation length is large compared to the discharge dimensions => EEDF is nonlocal.

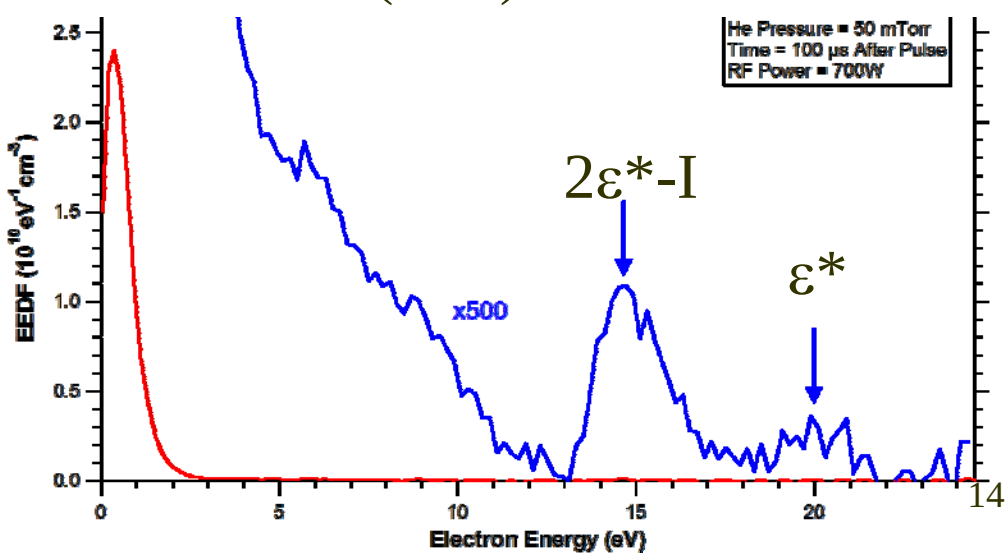
$$\lambda_\varepsilon = 2\sqrt{D_e}\left(\nu_e + \frac{2m}{M}\nu_a + \nu^*\right)^{-0.5}$$

D_e = electron diffusion coefficient
ν_e = e – e collision frequency
ν_a = elastic e – atom coll. freq.
ν^* = inelastic e – atom coll. freq.

In the afterglow, electrons cool rapidly to $T_e \sim 0.2$ eV. However, a small amount of fast electrons with energy few eV arise from slowly decaying metastables, due to, e.g., the Penning ionization

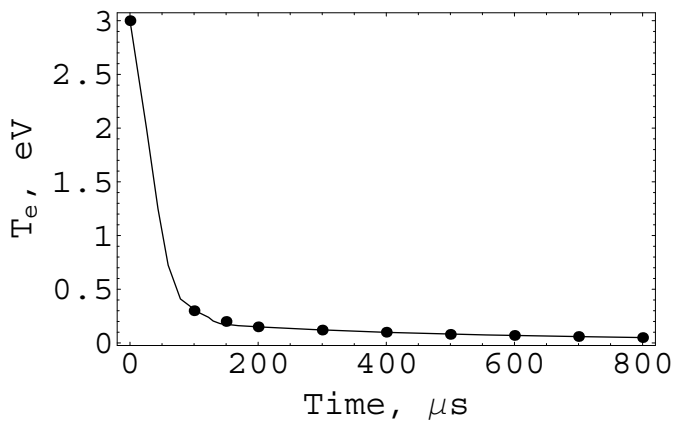
$A^* + A^* \rightarrow A + A^+ + e_f$.

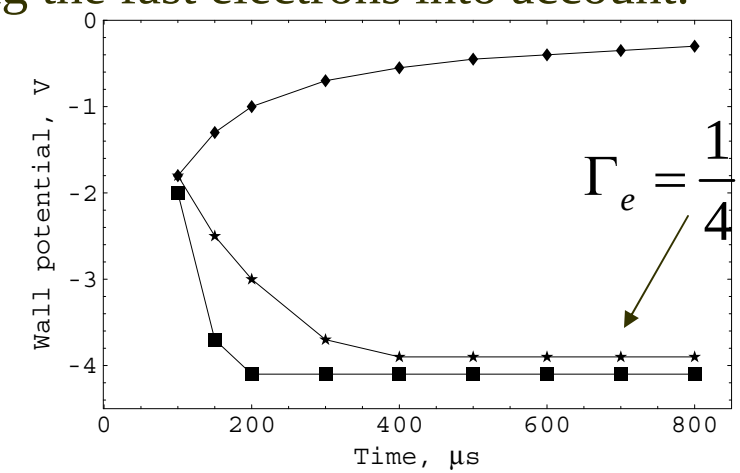
Experimental EEDF in He afterglow, V.I. Demidov (2005)



Anomalously large wall potential in after-glow due to addition of energetic electrons

Afterglow in 0.2Torr Xe. Left - exp. data for electron temperature. Right - the wall potential in xenon afterglow plasma, stars – exp. data, diamonds - $5T_e$ and squares – calculation results taking the fast electrons into account.





$$\Gamma_e = \Gamma_i$$

$$\Gamma_e = \frac{1}{4} n V_T e^{-\phi/T_e} + \Gamma_{ef}$$

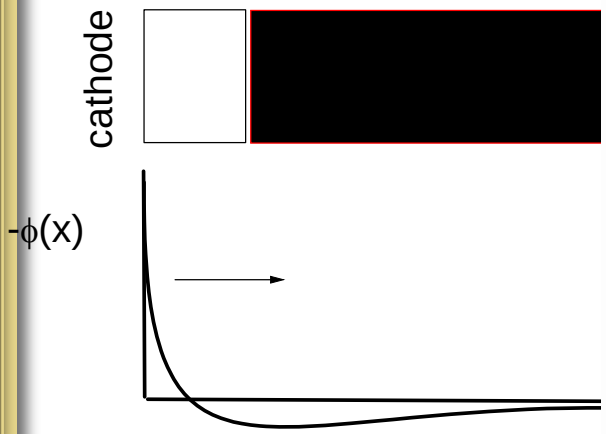
$2\varepsilon^*-I$

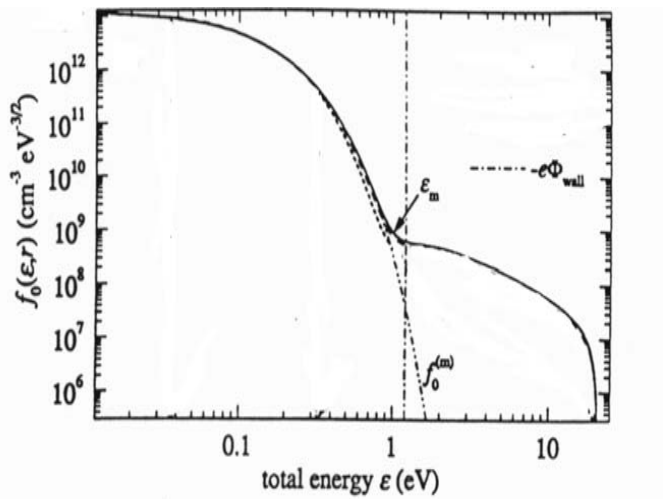
V.I. Demidov, et al, PRL **95**, 215002 (2005).

Near-wall potential drop can be much greater than Te =>

This large wall potential can lead to an <u>increase</u> in electron density, diffusion cooling can be reduced to near the point of elimination.

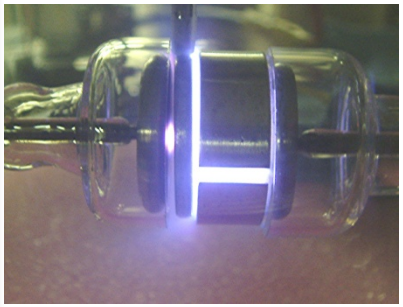
Negative glow of direct current discharge is a perfect tool for nonlocal electron kinetics

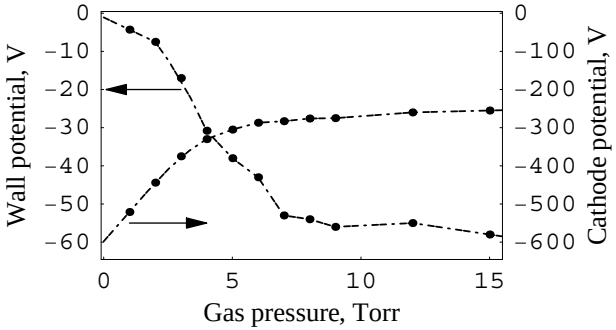




R.Araslanbekov, A. Kudryavtsev PRE 1998.

Several groups of electrons are present in negative glow: very cold electrons with T_e~0.1eV, fast electrons from cathode sheath with energy ~100eV, and electrons with energy few eV. (V. I. Kolobov, L.D. Tsendin *Phys. Rev. A* 1992).

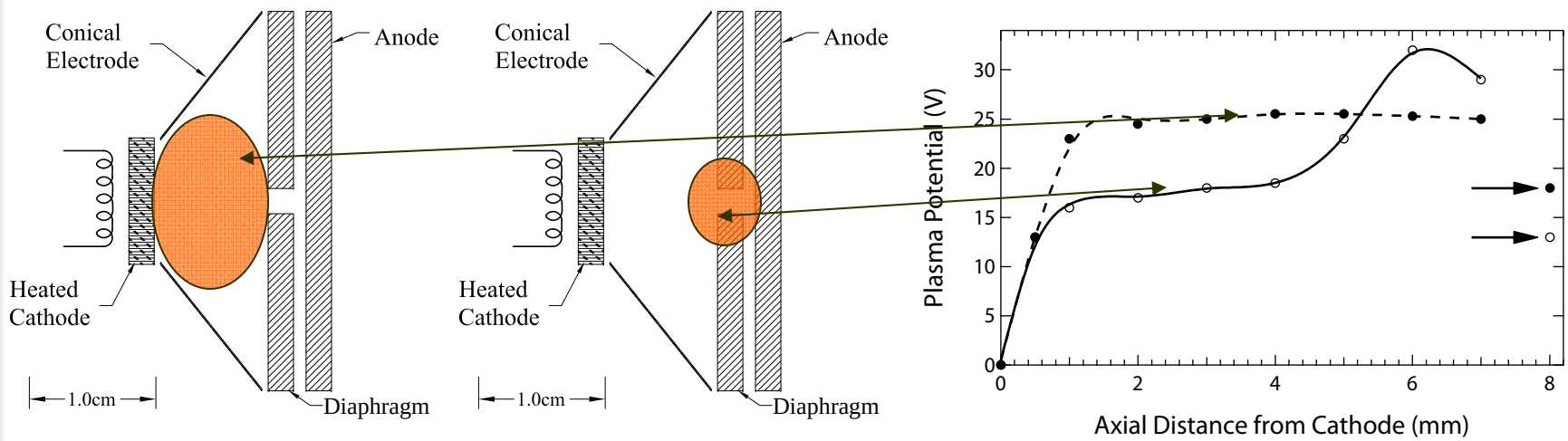




Experimental device and typical results of the floating wall and cathode potentials as functions of argon gas pressure for the discharge current 3 mA.

Controlling plasma properties by managing fast electrons

Changing voltage on diaphragm electrode leads to transitions between two very different discharge modes.



Left: Schematic diagram of the experimental device of dc discharge with hot cathode and plasma glow, He 1 Torr.
Right: Axial profiles of the plasma potential for voltages on diaphragm 18V and 13V.

Conclusions

Electron energy distribution function in low temperature plasmas is typically non-Maxwellian and discharge modeling has to be done kinetically.

Kinetic analysis for the plasma-wall interaction for a Hall thruster conditions yields completely different results than fluid models.

Kinetic theory was developed for rf discharges taking nonlocal conductivity models and collisionless heating in inhomogeneous plasmas into account.

It was shown experimentally and in simulations that a small amount of energetic electrons can greatly affect the wall and plasma potentials. This property can be used for effective control of plasma properties.

PLASMA SCIENCE CENTER

PREDICTIVE CONTROL OF PLASMA KINETICS: MULTI-PHASE AND BOUNDED SYSTEMS

Prof. Mark J. Kushner, Univ. of Michigan
Director

Associate Directors and Thrust Leaders:

Dr. Igor Kaganovich, PPPL
Prof. Steven Girshick, Univ. of Minnesota
Prof. David B. Graves, Univ. of California-Berkeley

PLASMA SCIENCE CENTER:
PREDICTIVE CONTROL OF PLASMA KINETICS: MULTI-PHASE AND BOUNDED SYSTEMS

Premise:

LTPs provide societal benefit based on channeling power from electromagnetic and electrostatic fields into desired modes of atoms, molecules and surfaces.

Requires the ability to control *f(v,r,t)* of electrons and ions, uniquely facilitated by partially ionized nature of plasma.

Science Challenges:

Innovating methods to control *f(v,r,t)* in pristine and multiphase plasmas, and onto surfaces, from application of fields from its boundaries.

Developing knowledge base of diagnostics, fundamental data, algorithms and computer models to capture these methods and transfer to broader plasma community.