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Electron kinetics in glows

Outline

- **Introduction; necessity and interest of kinetics**

- **The EDF non-locality:**
  - a positive column of glow discharge;
  - RF discharges;
  - Cathode region of a DC discharge;

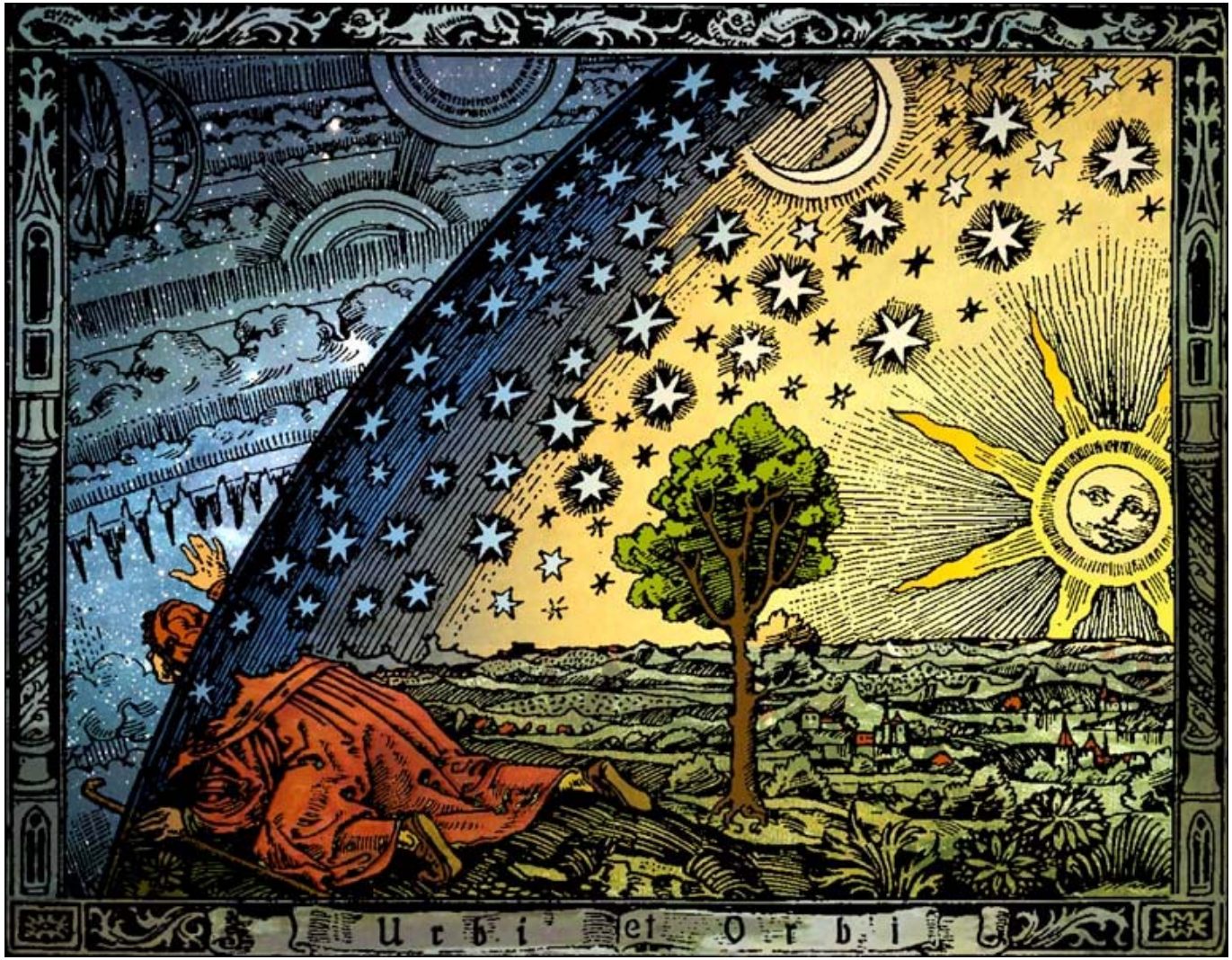
- **Striations**

- **Conclusions**

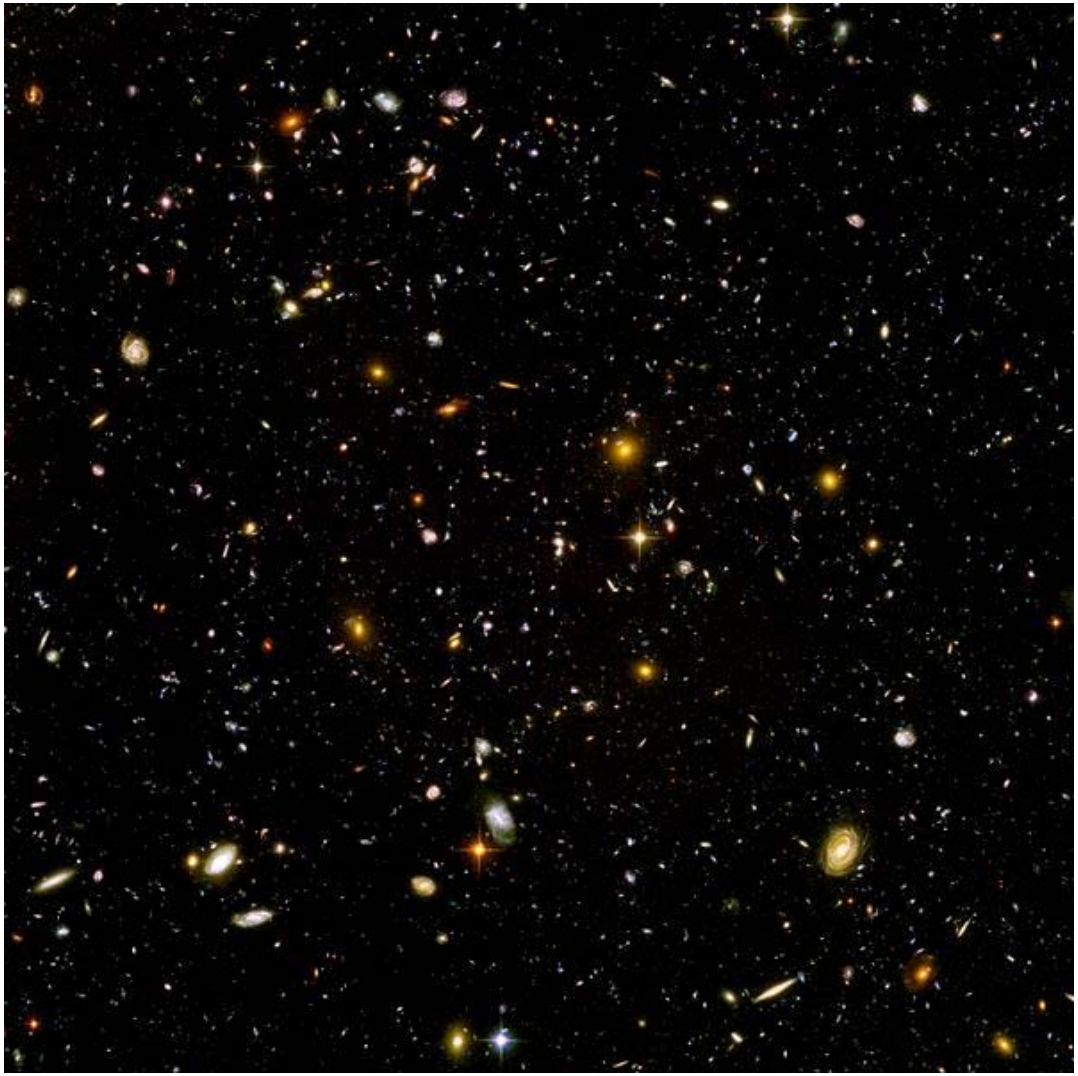
Motivation: Equilibrium is synonym of death!

- We are living in very comfortable environment – almost all around us is close to thermodynamical equilibrium.
- But the equilibrium is synonym of death!
- Every event happens due to non-equilibrium.
- What to do, when we are far from equilibrium?
- Apply kinetics!

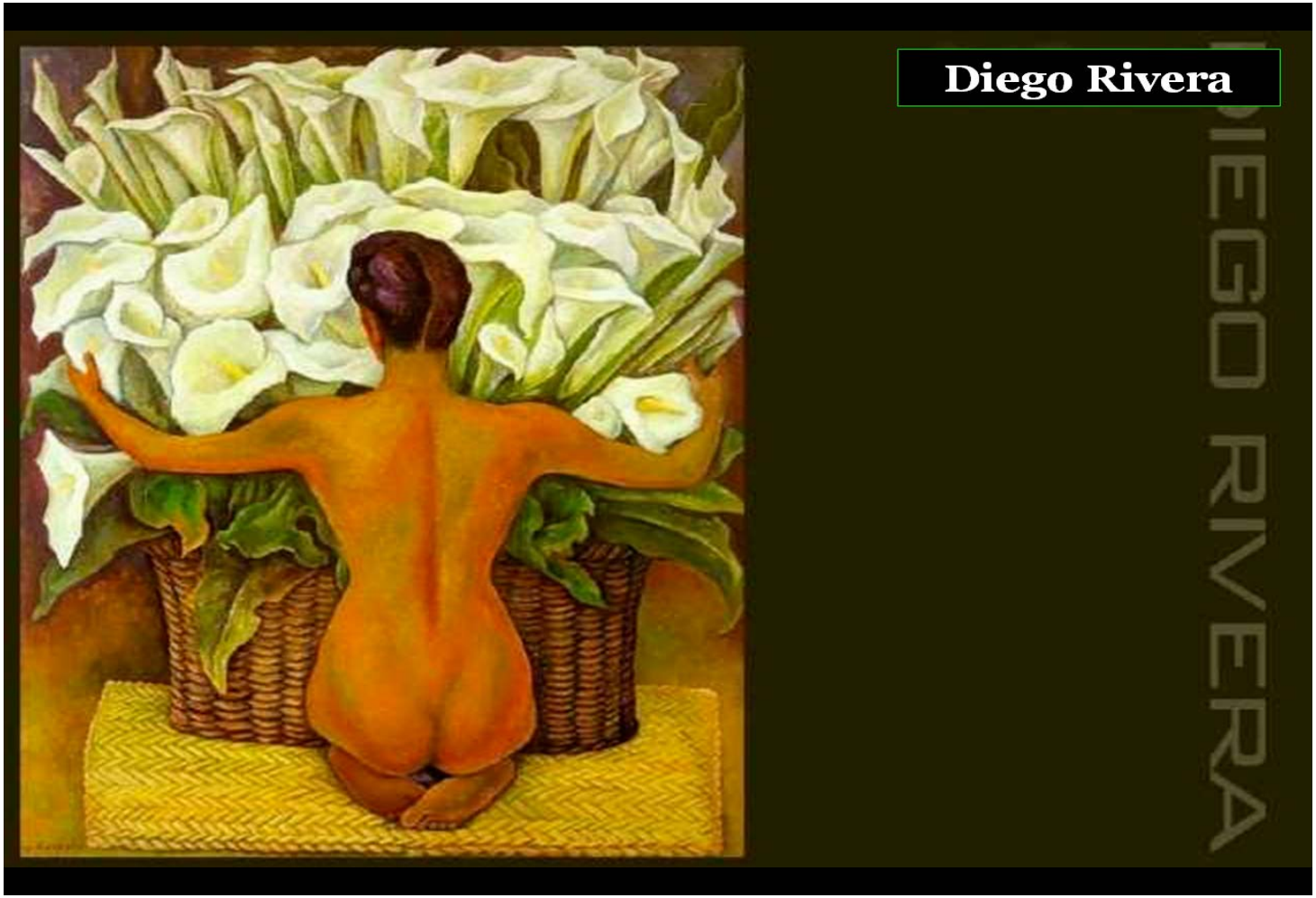
1. The Universe



1. The Universe



2. The life (beautiful side)

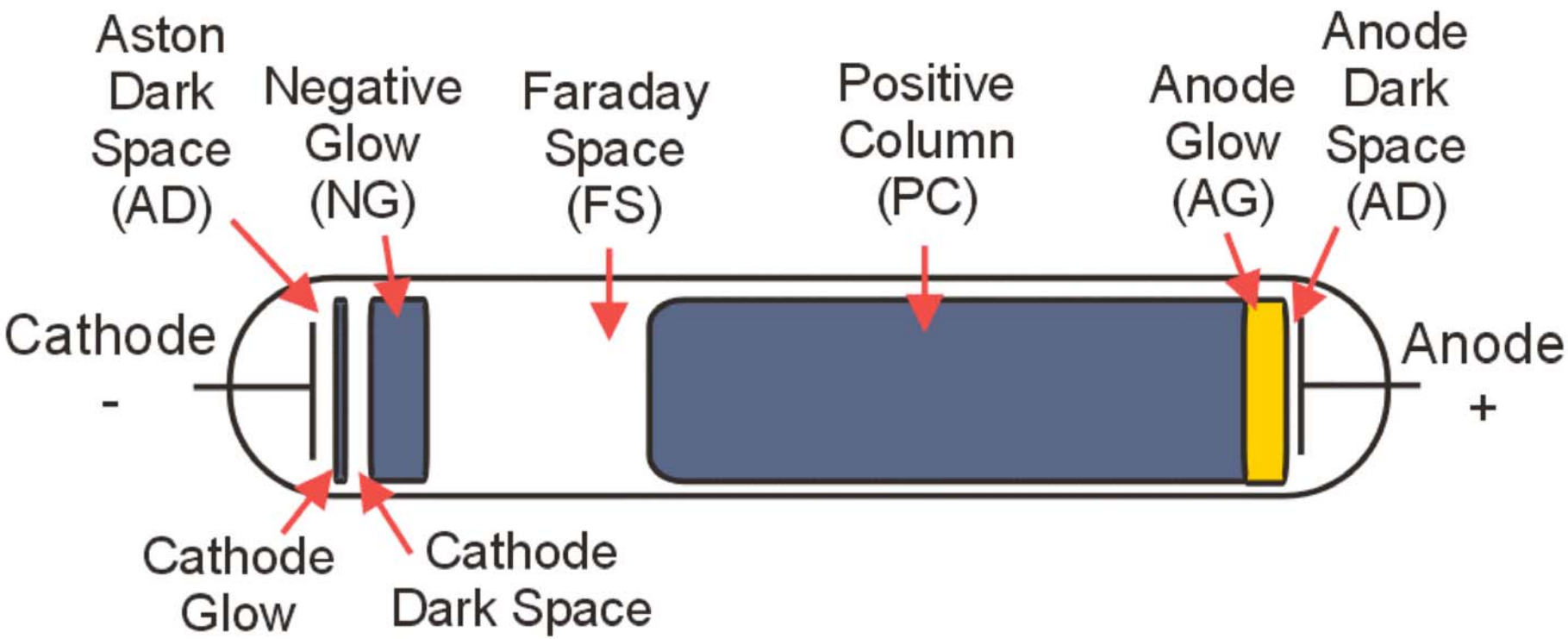


2. The life (ugly side)

Hard work shortens your prison sentence! (Gulag poster)

3. Glow discharges (DC, RFC and RFI)

Structure of the direct current discharge



Plasma Parameters

- Plasma density: 10^8 - 10^{12} cm^{-3}
- Gas pressure: few mTorr – atmosphere
- Small degree of ionization < 10^{-4}
- Electron “temperature”: T_e - few eV
- Ion temperature: T_i - 0.03 eV
- Spatial scale: mm - m

The first two objects are

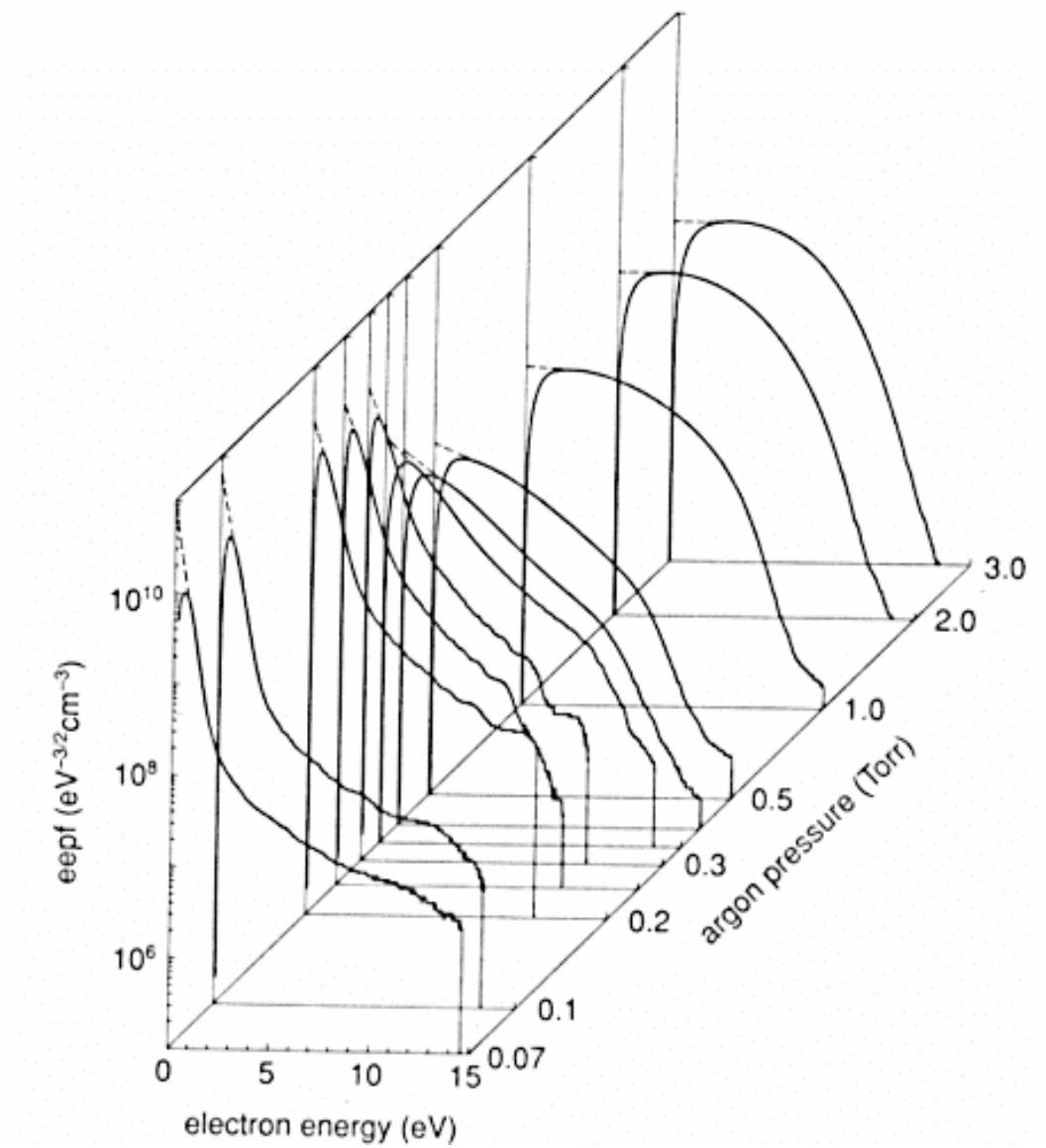
- Vitally important, but
- Tremendously complex!
- The third (the glows) is a little bit simpler!
- It is important, too.

Therefore, we start our study of the Kinetics from analyzing glow discharges.

Correct understanding = correct predictions.

Numerous phenomena need kinetics.

EEDF Can Drastically Change for Different Discharge Conditions

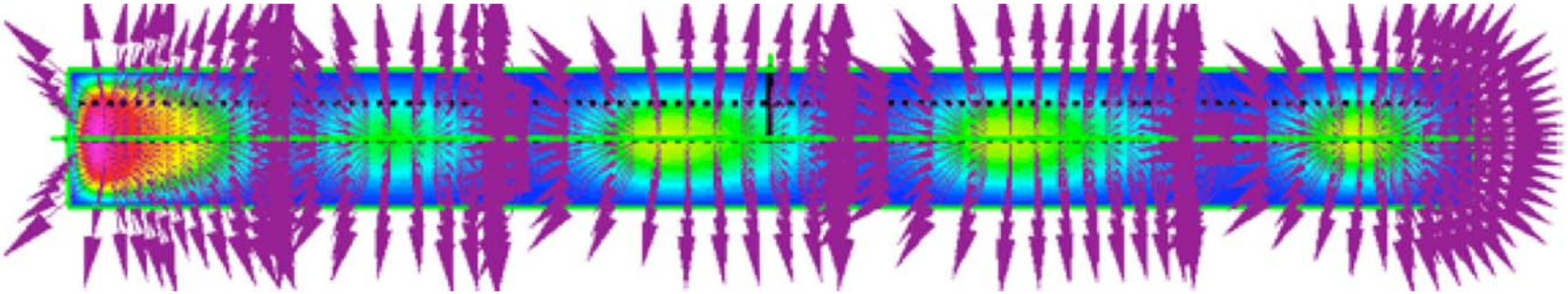


FOR MORE INFO...

V.Godyak R.Piejak PRL **65** 996
Argon 0.1Torr, f=13.56 MHz, L=2cm

Striations

- At low currents – 0.1-10 mA the coherent structure exists 10s of meters in spite of 1000s of collisions, and even recombination.
- The potential drop over the spatial period is close to the ionization potential.
- Electrons remember what energy to have with respect to cathode.
- How do they do it?



Distinctions between the kinetic and traditional fluid approaches

All electrons are described by only five global characteristics:

Density $n(x, y, z, t)$

Three components of average directed velocity $\vec{v}(x, y, z, t)$

Temperature $T(x, y, z, t)$

The only characteristic is the electron distribution function (EDF) – the electron density in phase space

$$f(\vec{v}, x, y, z, t)$$

Far more detailed!

The distinction is the same, as between a totalitarian and free society

- Every individual is representative.
- Every EDF part is independent from other ones.

Glow is maintained by electron impact ionization and thus depends crucially on *electron* kinetics

A discharge is maintained by the electron impact ionization.

Ionization is produced by energetic electrons $I >> T_e$.

The ionization is sensitive to the EDF tail.

The discharge self-organization depends crucially on the *electron* kinetics!

Joule heating = Diffusion in energy

- **Because the EDF is almost isotropic, the energy gain and loss have equal probabilities.**
- **Electron interaction with electric field is the random walk = diffusion along the energy axis.**
- **The diffusion coefficient is** $D_\varepsilon = (\Delta\varepsilon)^2 \nu$

$(\Delta\varepsilon)^2, \nu$ -- are the average square of the energy step and the steps frequency

We need to introduce concept of diffusion in energy as the proper language for description of electron kinetics.

EDF Non-locality

- The energy relaxation length, λ_ε , far exceeds the momentum relaxation one (mean free path) because energy change in one collision is small.

- $mv^2/2 < I$

$$\lambda_\varepsilon = \lambda\sqrt{M/m}$$

- $mv^2/2 > I$

$$\lambda_\varepsilon = \lambda\sqrt{\sigma_{el}/\sigma_{inel}}$$

DC electric field

$$D_\varepsilon = \left(eE_z\lambda\right)^2 v/3;$$

$$D = \left(\lambda\right)^2 v/3.$$

2D diffusion equation for the isotropic EDF:

$$\frac{\partial f_0}{\partial t} = \left[\vec{\nabla} v D \vec{\nabla} f_0 + \frac{\partial}{\partial \varepsilon} v D_\varepsilon \frac{\partial f_0}{\partial \varepsilon}\right] / v + v^* f_0$$

The spatial derivatives are to be calculated at constant **total** energy

$$\varepsilon = w + e\phi(r)$$

Totally non-local EDF

$$\lambda_\varepsilon >> R$$

the EDF depends *only* on the total energy

Non-local DC positive column

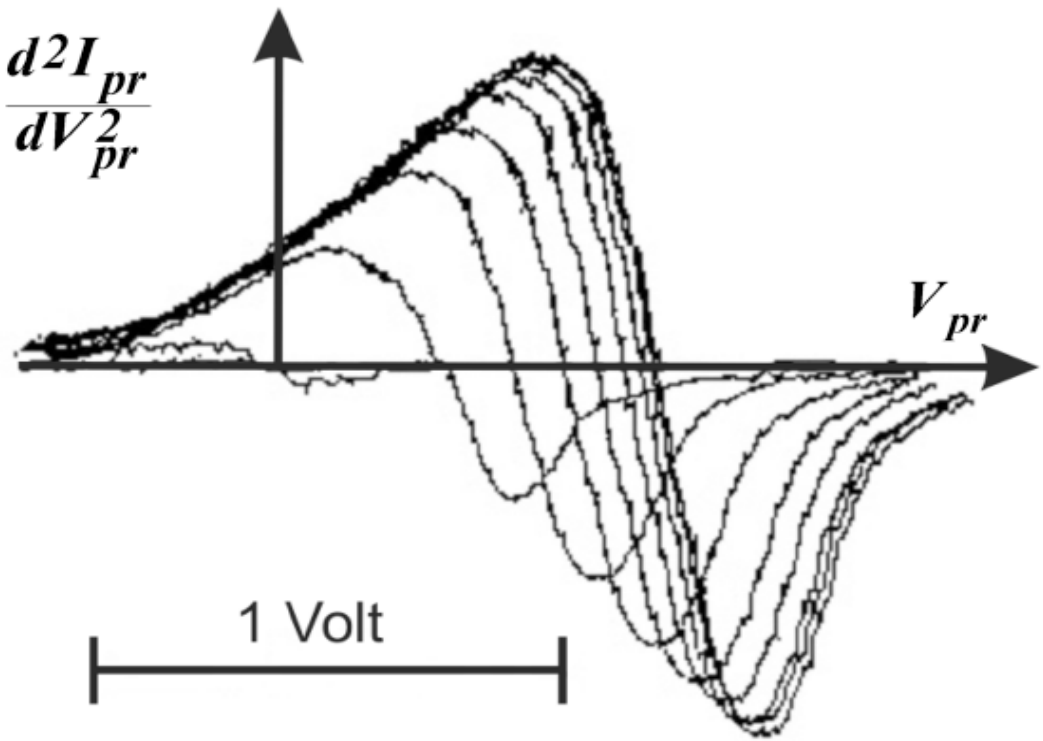
The averaged kinetic equation becomes similar to the local case but contains averaging over entire available space!

$$\frac{d}{d\varepsilon}\overline{\nu D_\varepsilon}\frac{df_0(\varepsilon)}{d\varepsilon}=\overline{St^{inel}(f_0(\varepsilon))}=\nu^*_{av}f_0(\varepsilon).$$

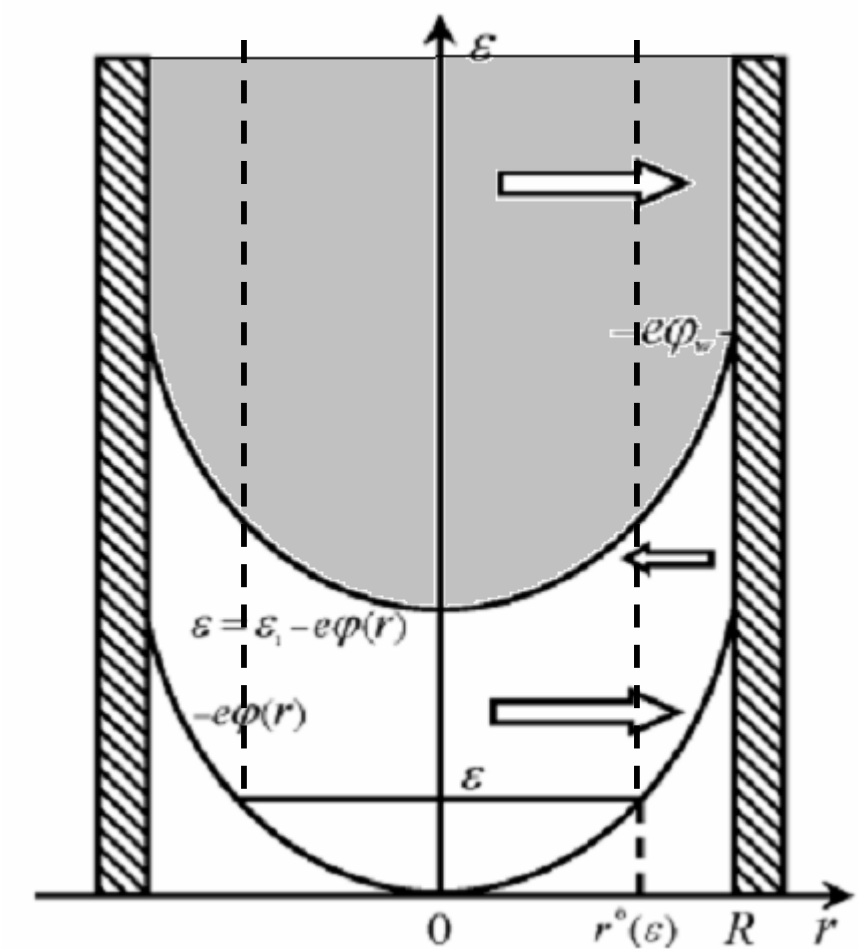
I.B. Bernstein and T. Holstein, Phys. Rev. **94**, 1475 (1954).

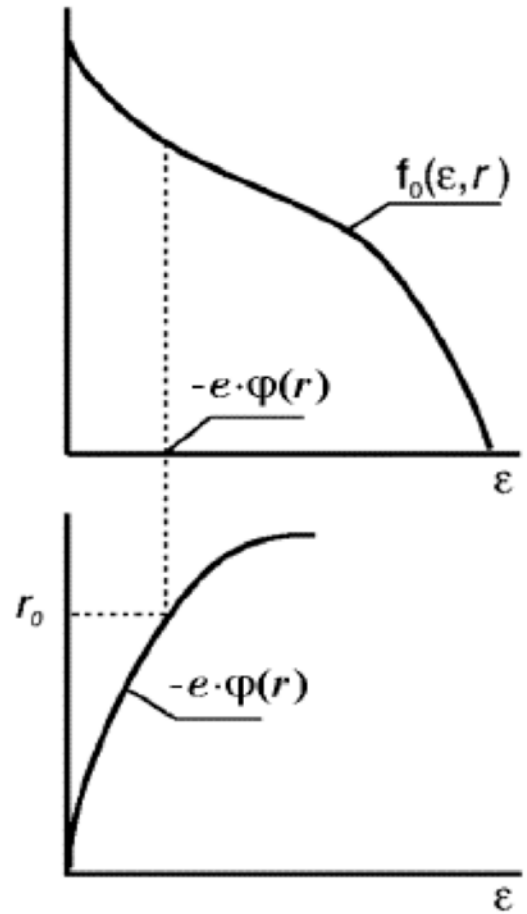
L.D. Tsendin, Sov. Phys. JETP **39**, 805 (1974).

Non-local EDF in Xe, 0.1Torr and 1mA



EDF in a non-local Positive Column





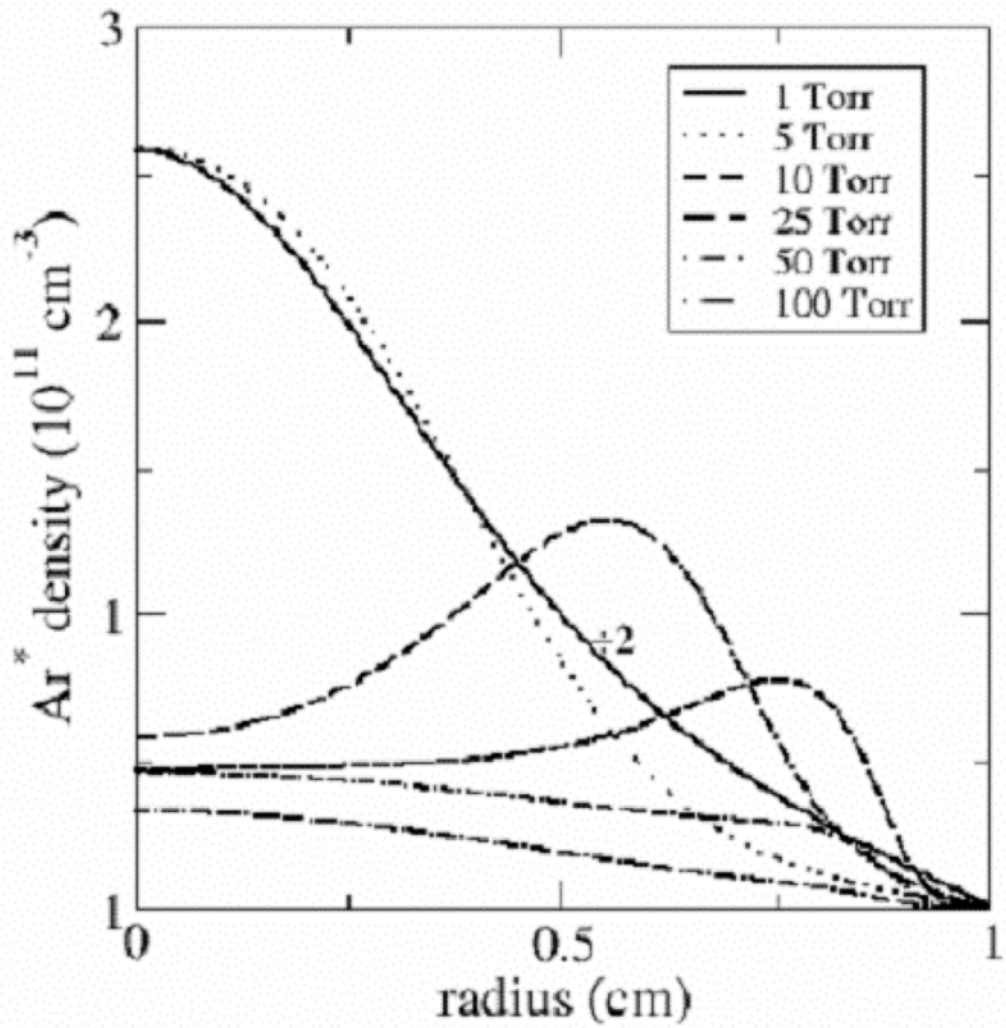
EDF in the center determines EDFs everywhere.

Paradox: radial excitation profiles move to periphery.

Plasma Density is peaked in center.

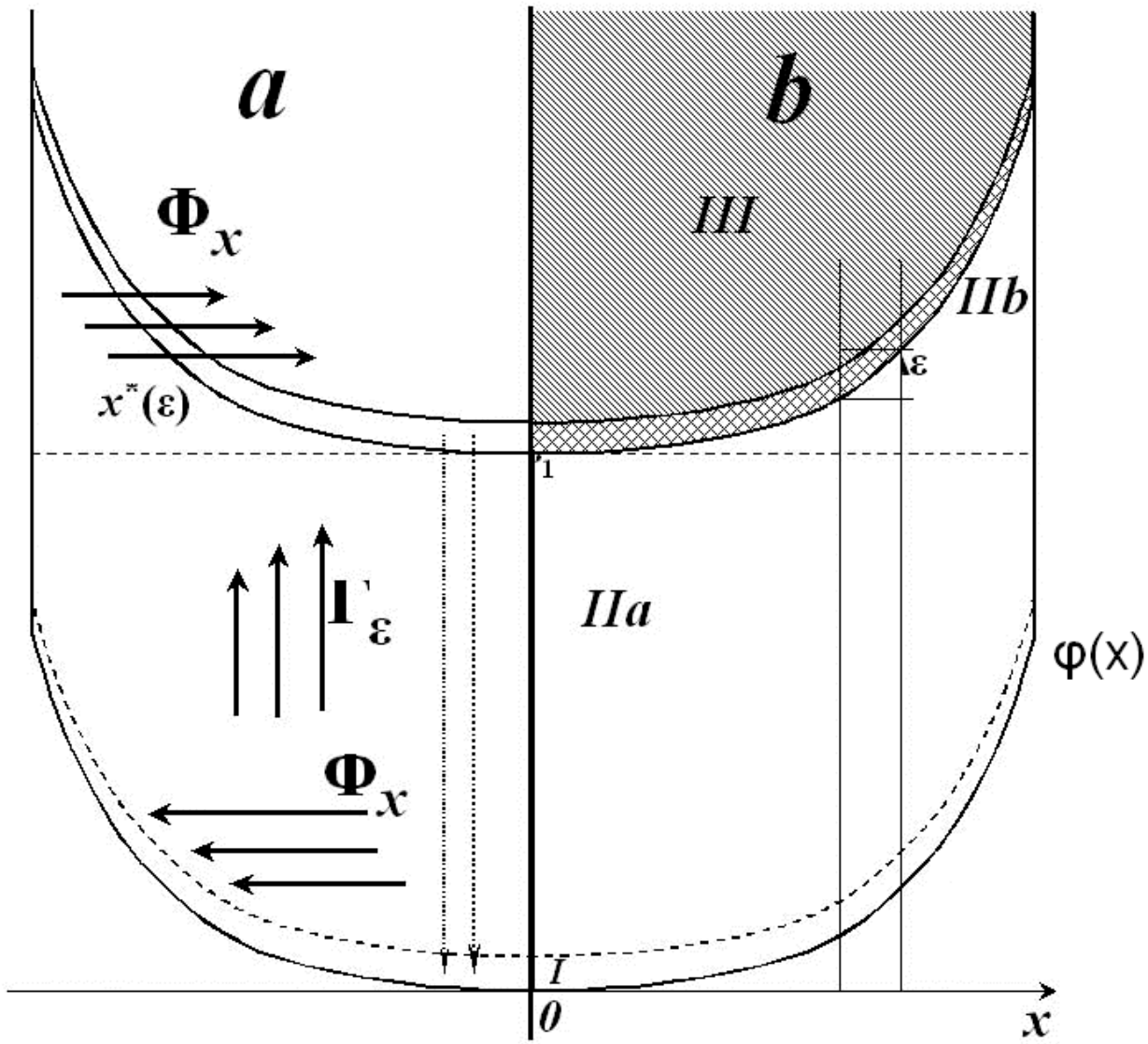
Axial electric field (heating) is uniform.

Why then excitation profiles move to periphery?



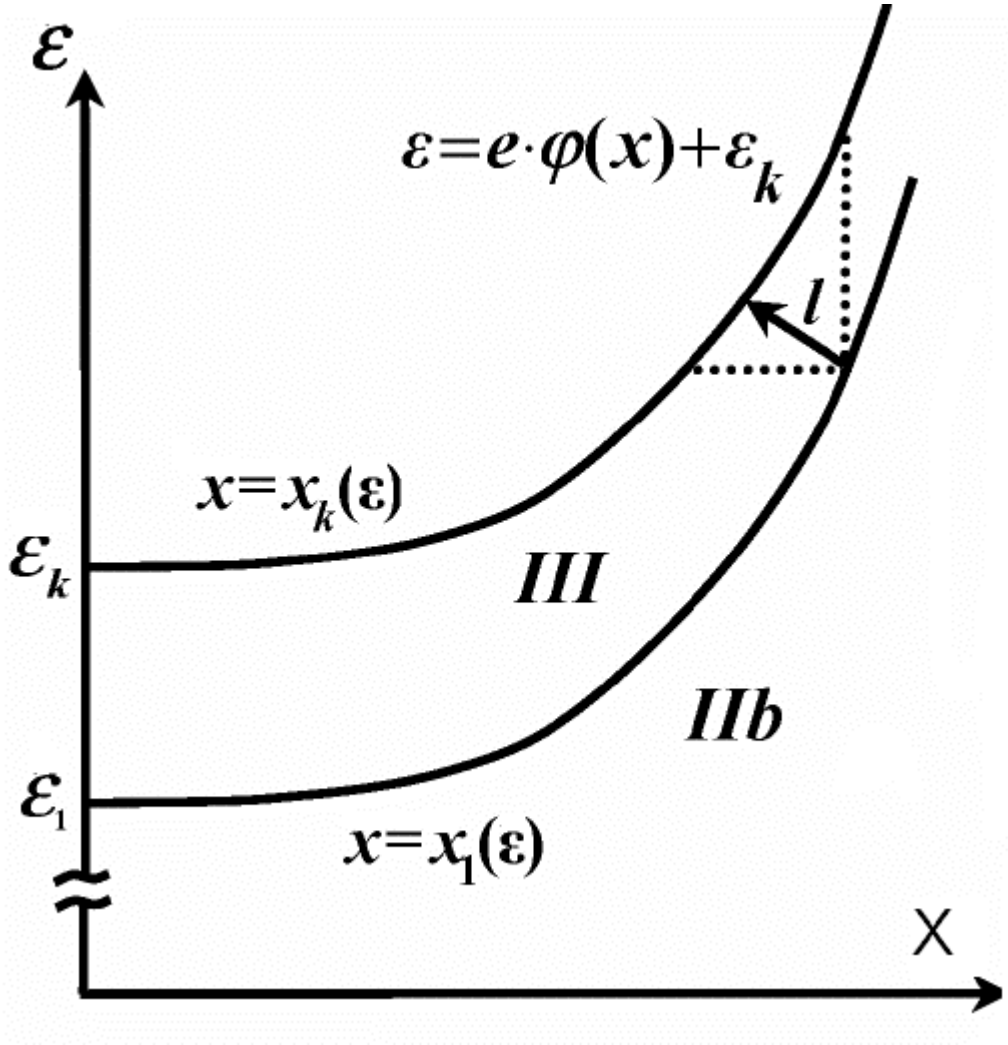
Radial profiles of excited Ar* species at different pressures.

Fluxes in space and along energy

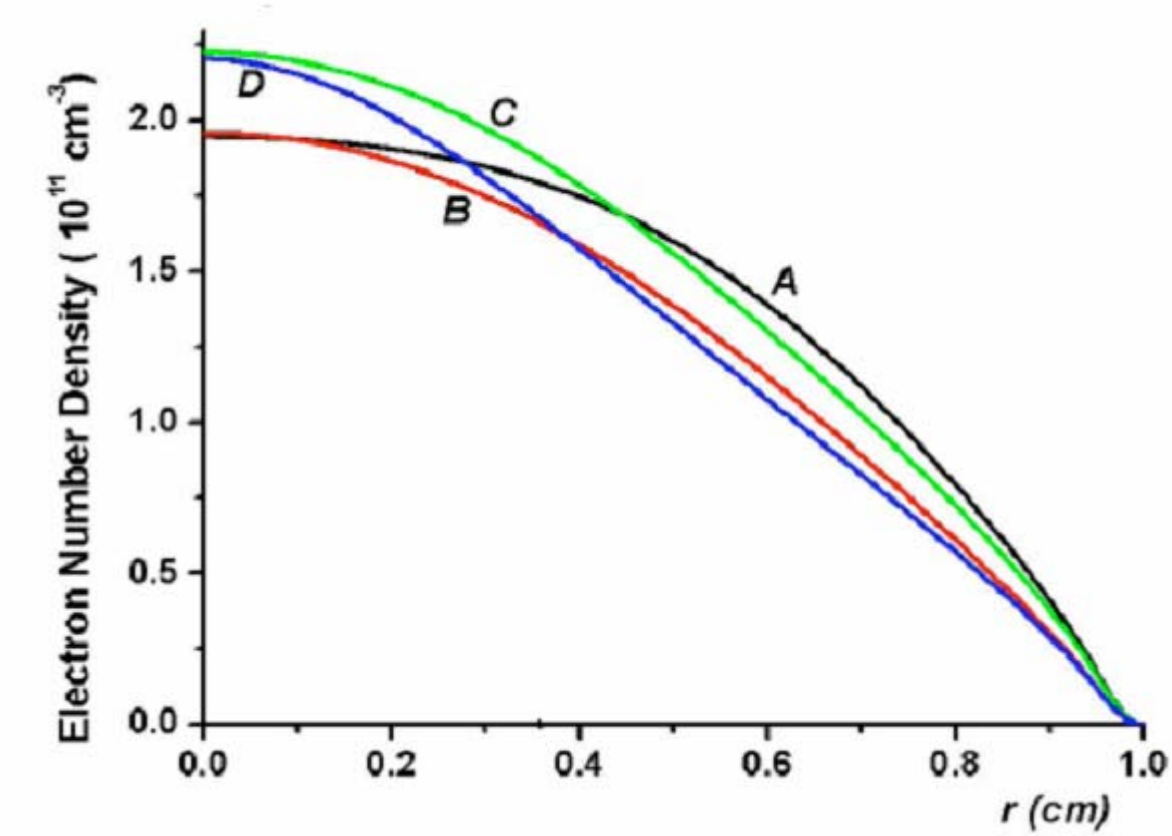


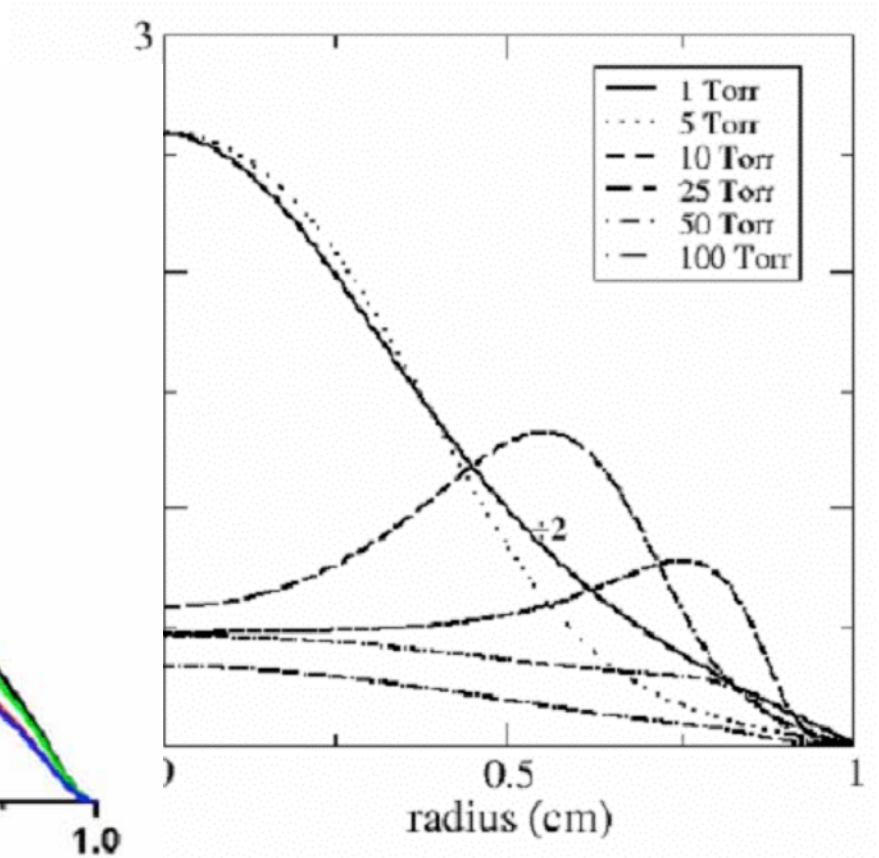
Excitation of higher levels

Exponentially depends on thickness



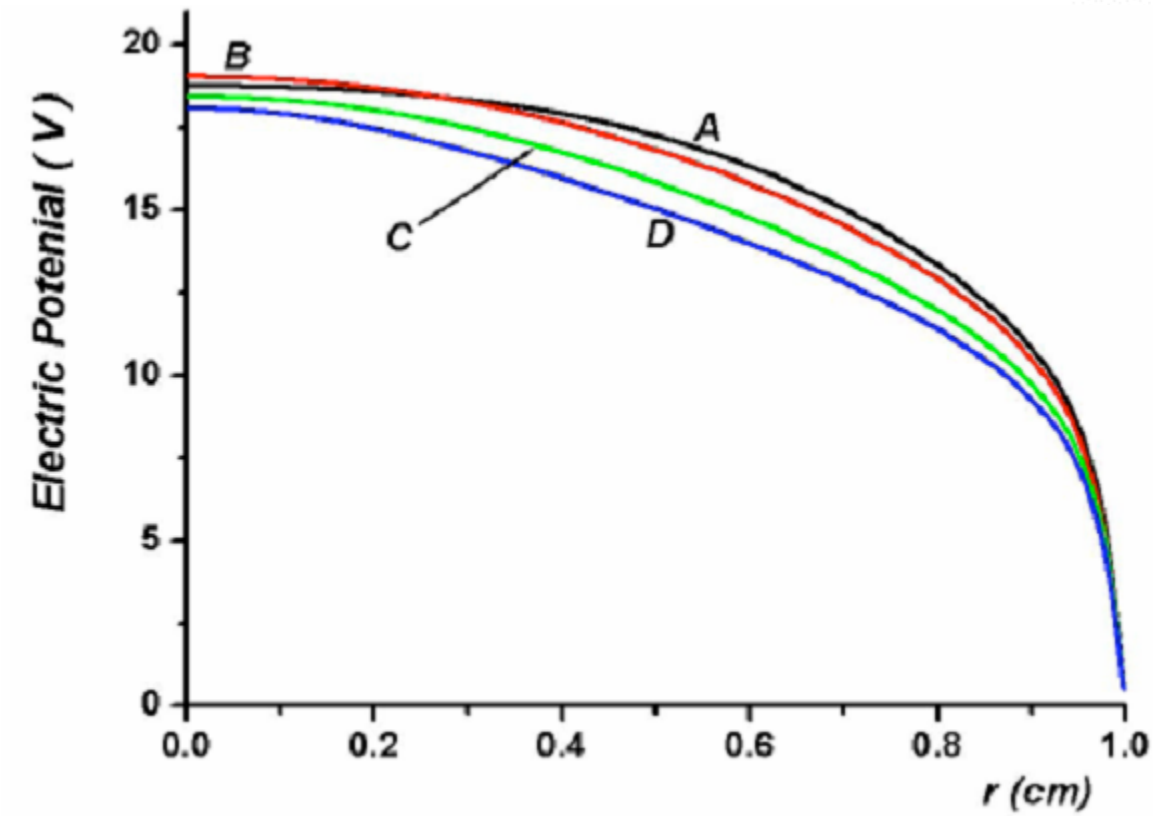
The plasma density profiles are nearly the same.

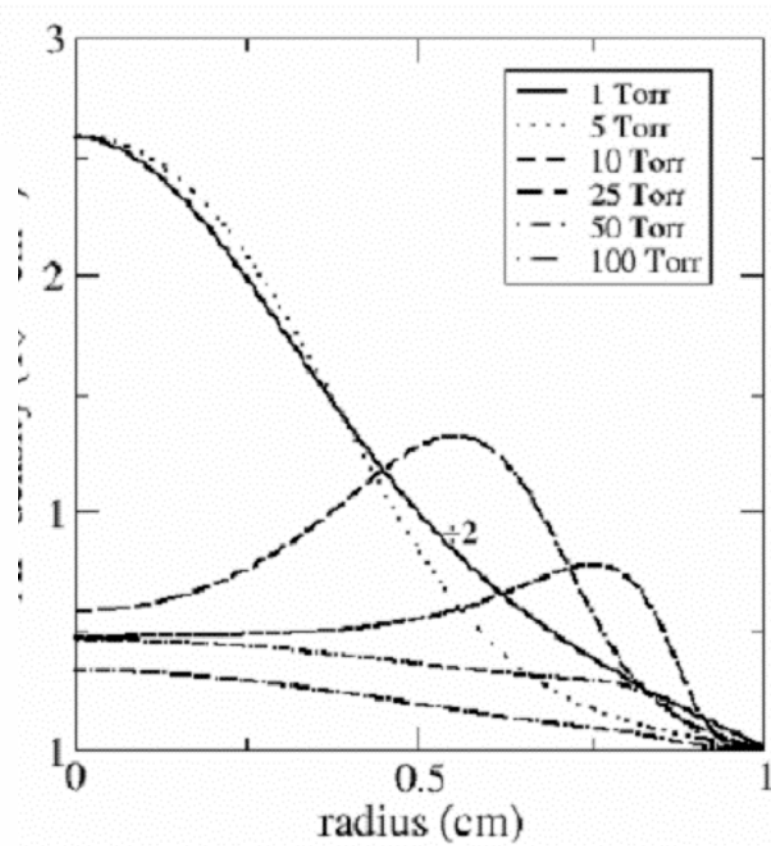




profiles of excited Ar* species at different press

The radial potential profile are nearly the same.

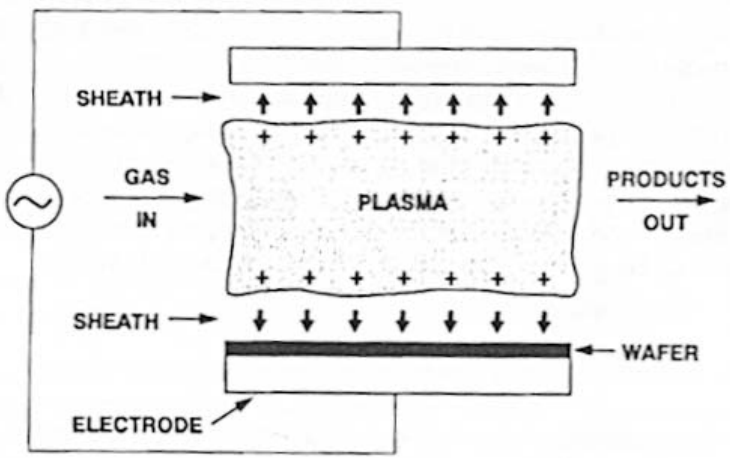


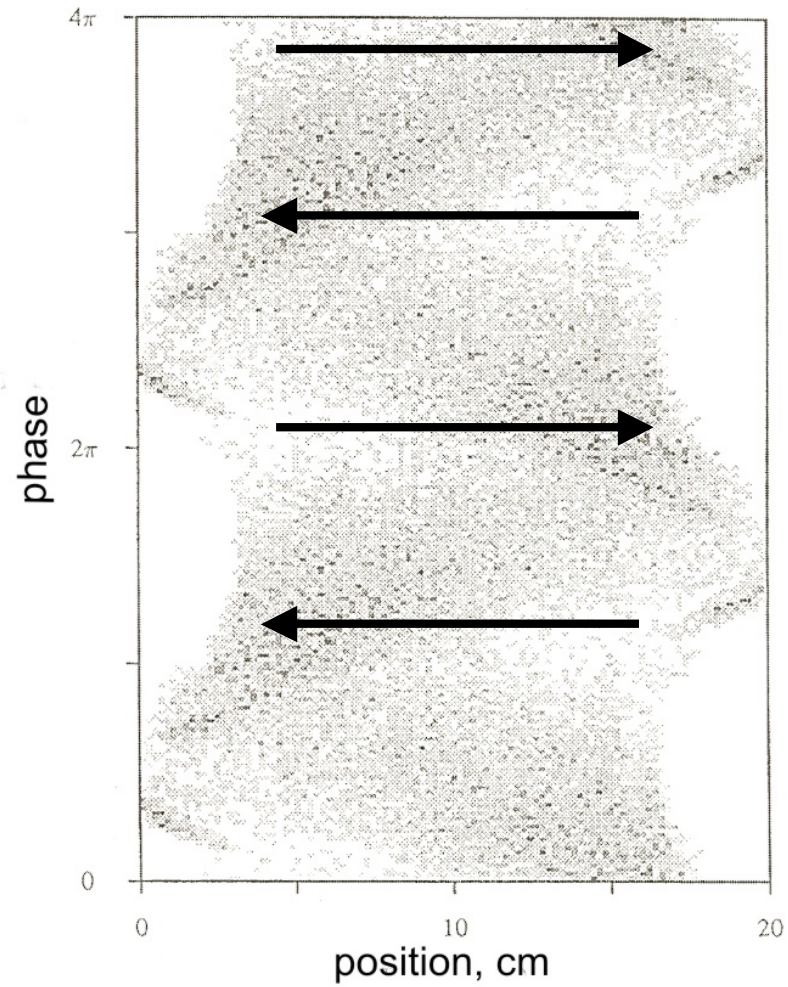


ial profiles of excited Ar* species at different pres

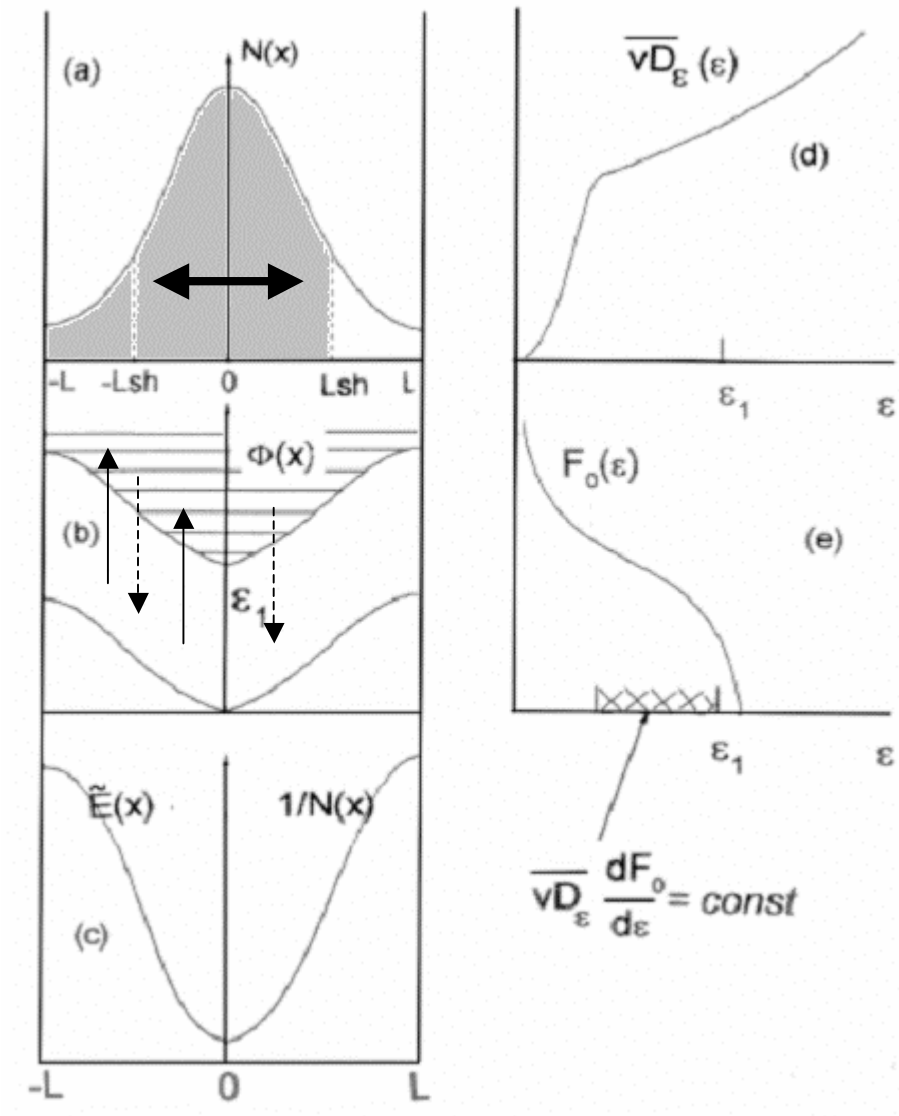
Radio frequency glows

- **Capacitive coupled plasma (CCP)**





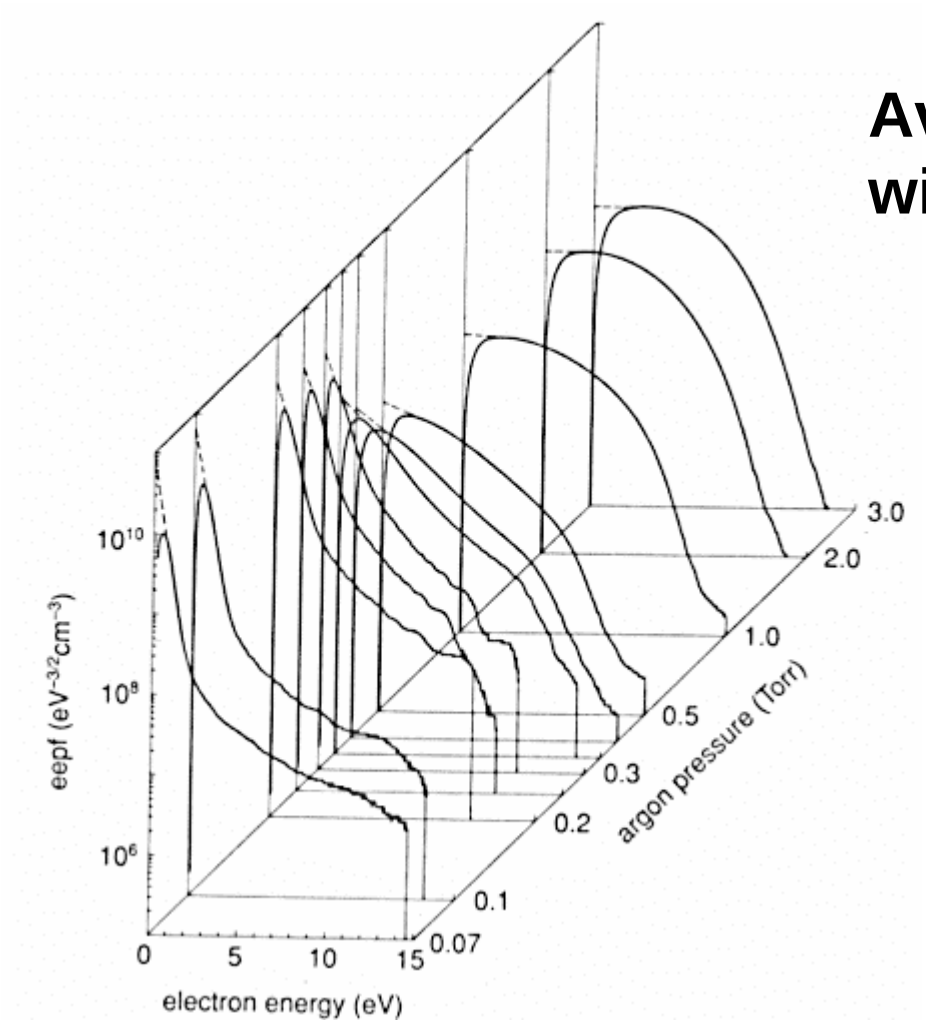
Non-local (low-pressure) RFC discharge



$$D_\varepsilon = \frac{e^2 E_{o\omega}^2 v^2 \nu}{6\left(\omega^2 + \nu^2\right)}$$

The low-energy electrons cannot reach the plasma periphery, where the oscillatory field is high.
As a result, the diffusion coefficient along energy for them is low, and the low-energy-electrons-enriched EDF is formed.

EEDF Can Drastically Change for Different Discharge Conditions



Average energy can decrease with increase of the power input

FOR MORE INFO...

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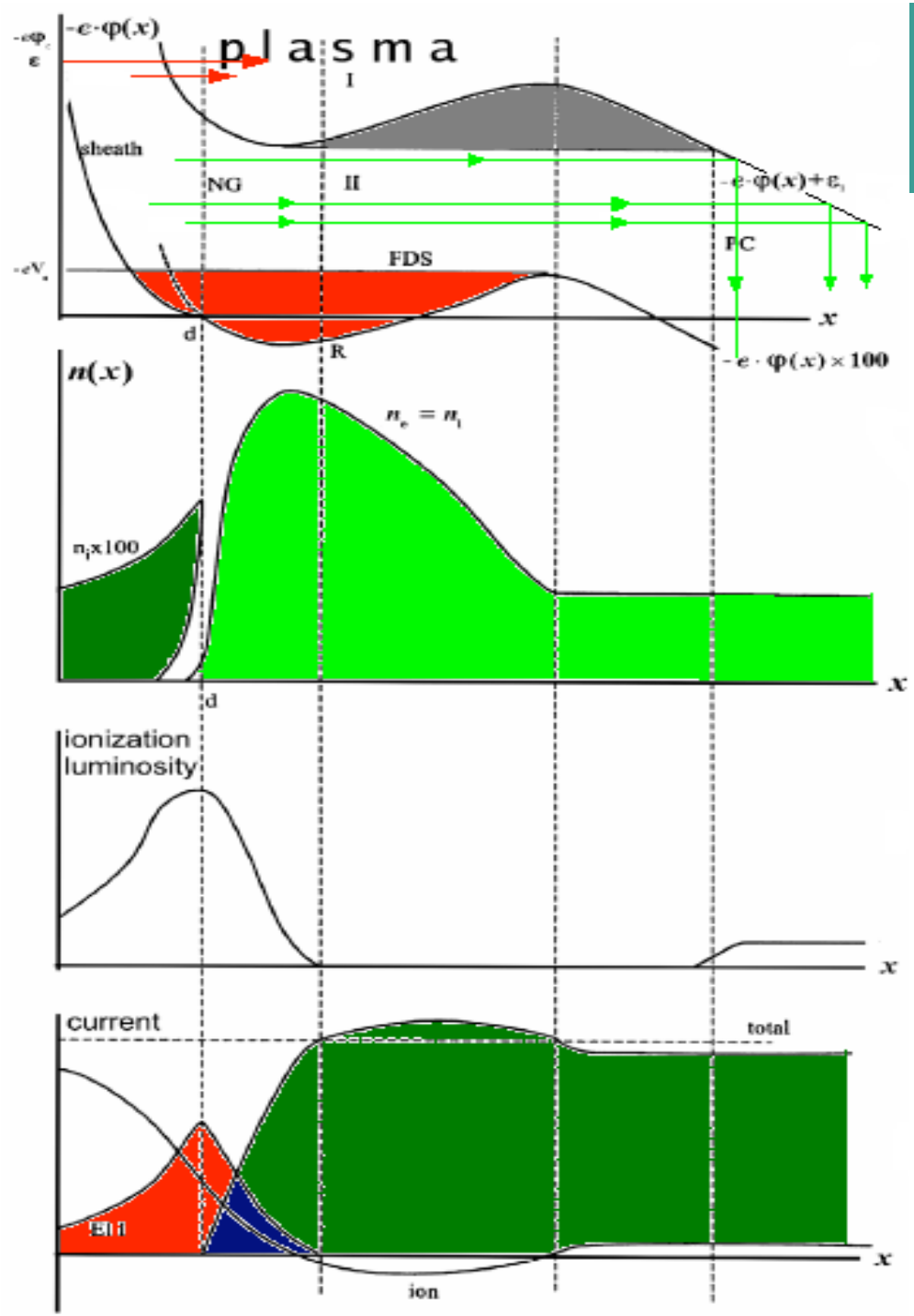
Argon 0.1Torr, f=13.56 MHz, L=2cm

DC discharge

- For which purpose the Faraday dark space is necessary for Nature?
- Why the electron “temperature” (average energy) behavior is so complicated and has nothing in common with the plasma luminosity?

DC discharge cathode region



Potential profile

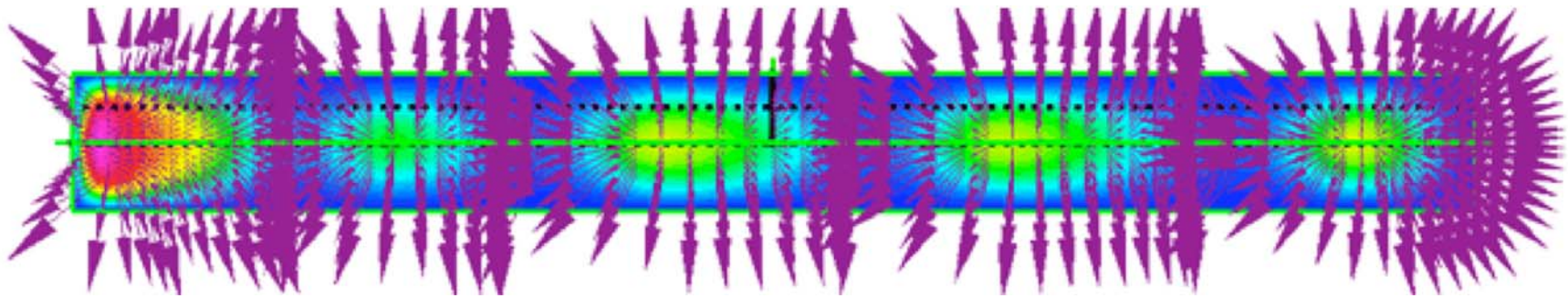
Particle density profiles

Luminosity & ionization rates

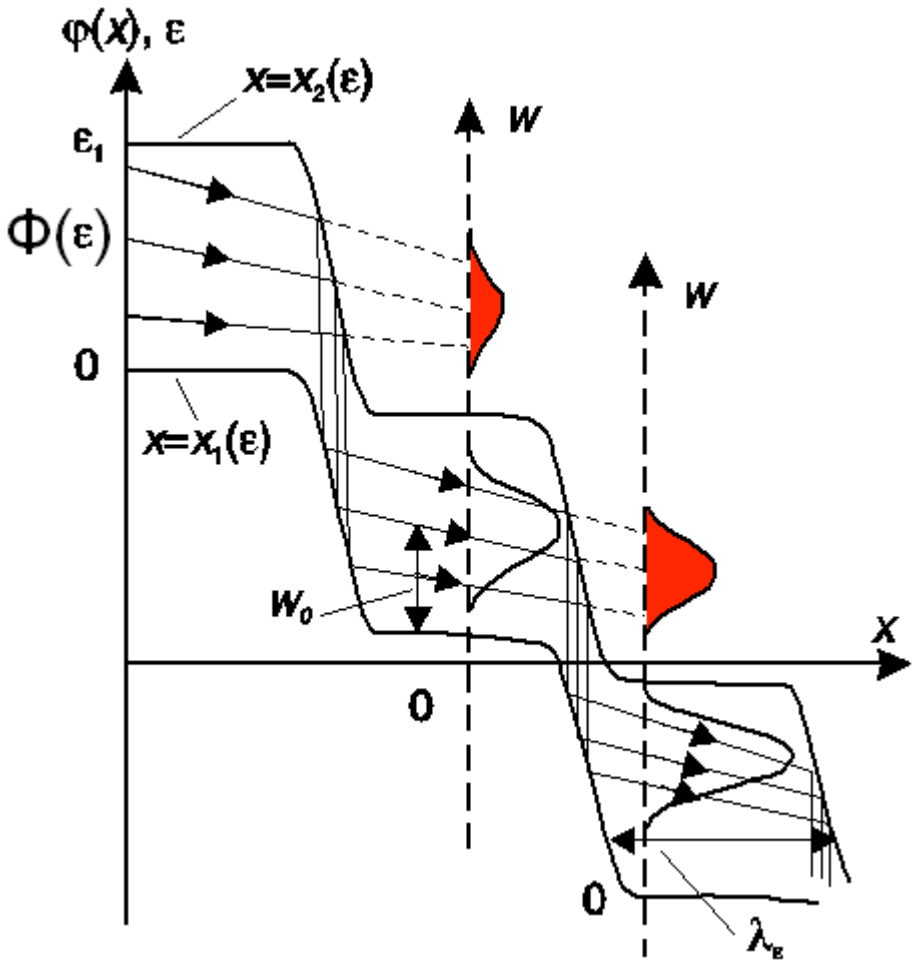
Currents

Striations

- At low currents – say, 0.1-10 mA
- The electron-electron collisions are absent.
- The potential drop over the spatial period is close to fractions of the ionization potential.
- Electrons remember, which energy to have with respect to the cathode.
- How do they do it?



EDF bunching in S-striations



- One-level black wall model.
- The potential period is equal to the excitation energy.

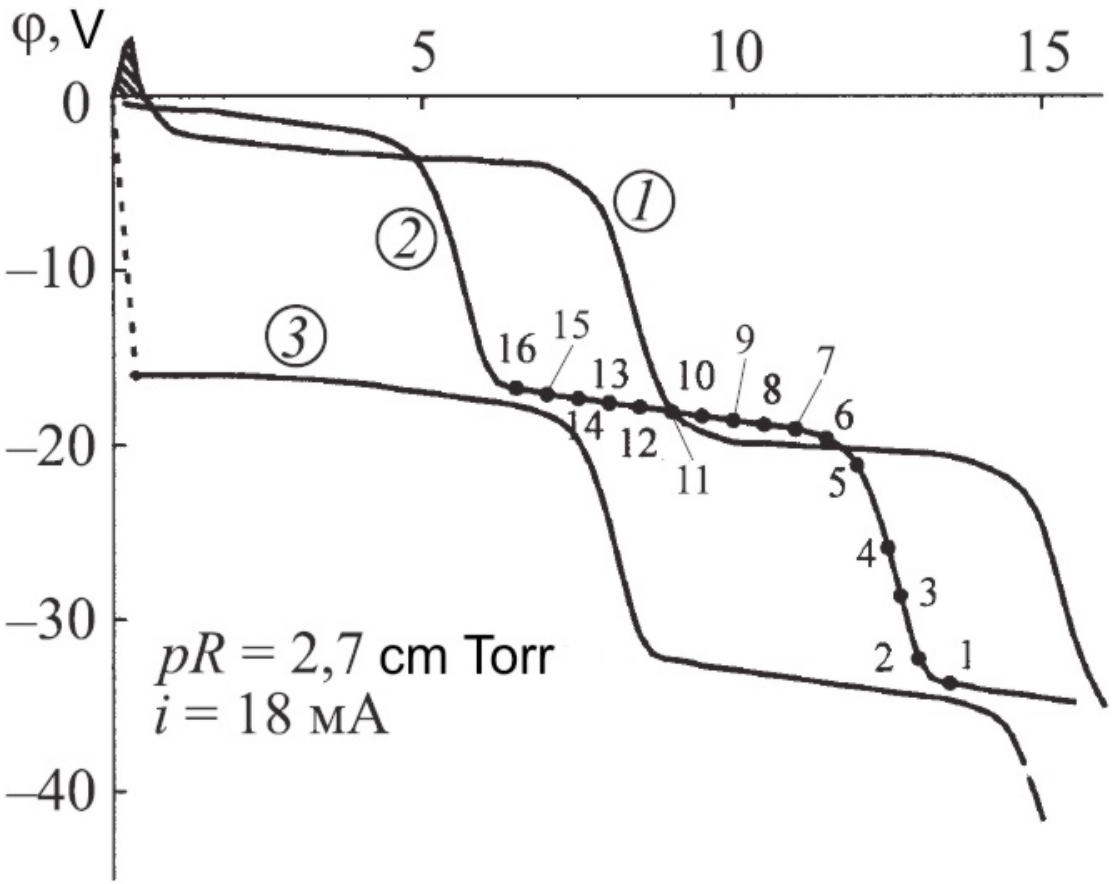
The small energy loss in elastic collisions results in the EDF bunching to the resonant energy!

An arbitrary EDF tends to delta-function!

MAPPING

$$\Phi(\varepsilon-\varepsilon_1)=\Phi(\varepsilon)+\kappa\Psi(\varepsilon); \quad \kappa \ll 1$$

S-striations in *Ne*



Potential period

$$\Delta\varphi$$

Bunching condition

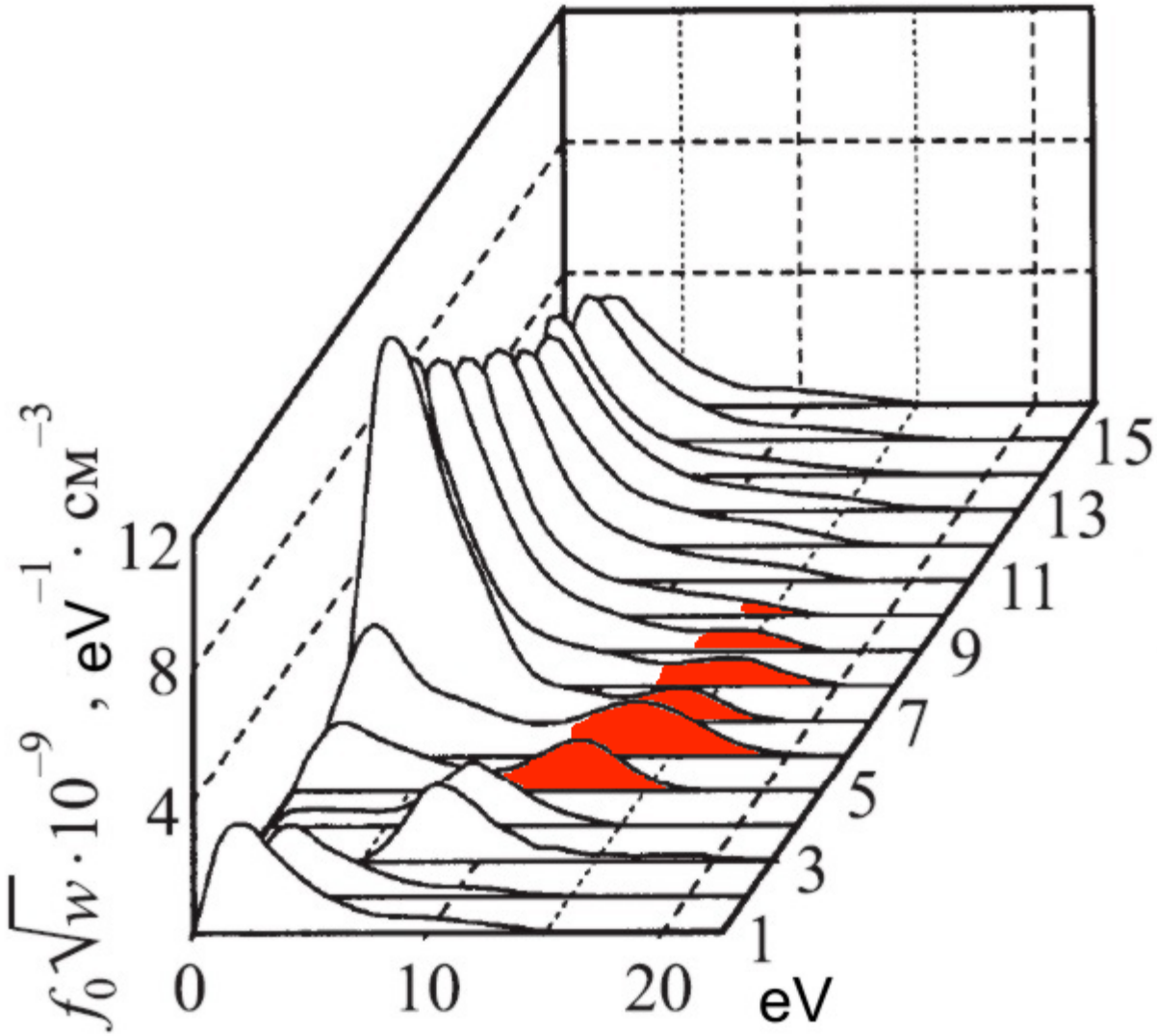
$$N\Delta\varphi = \varepsilon_1$$

N=1 – S-striations

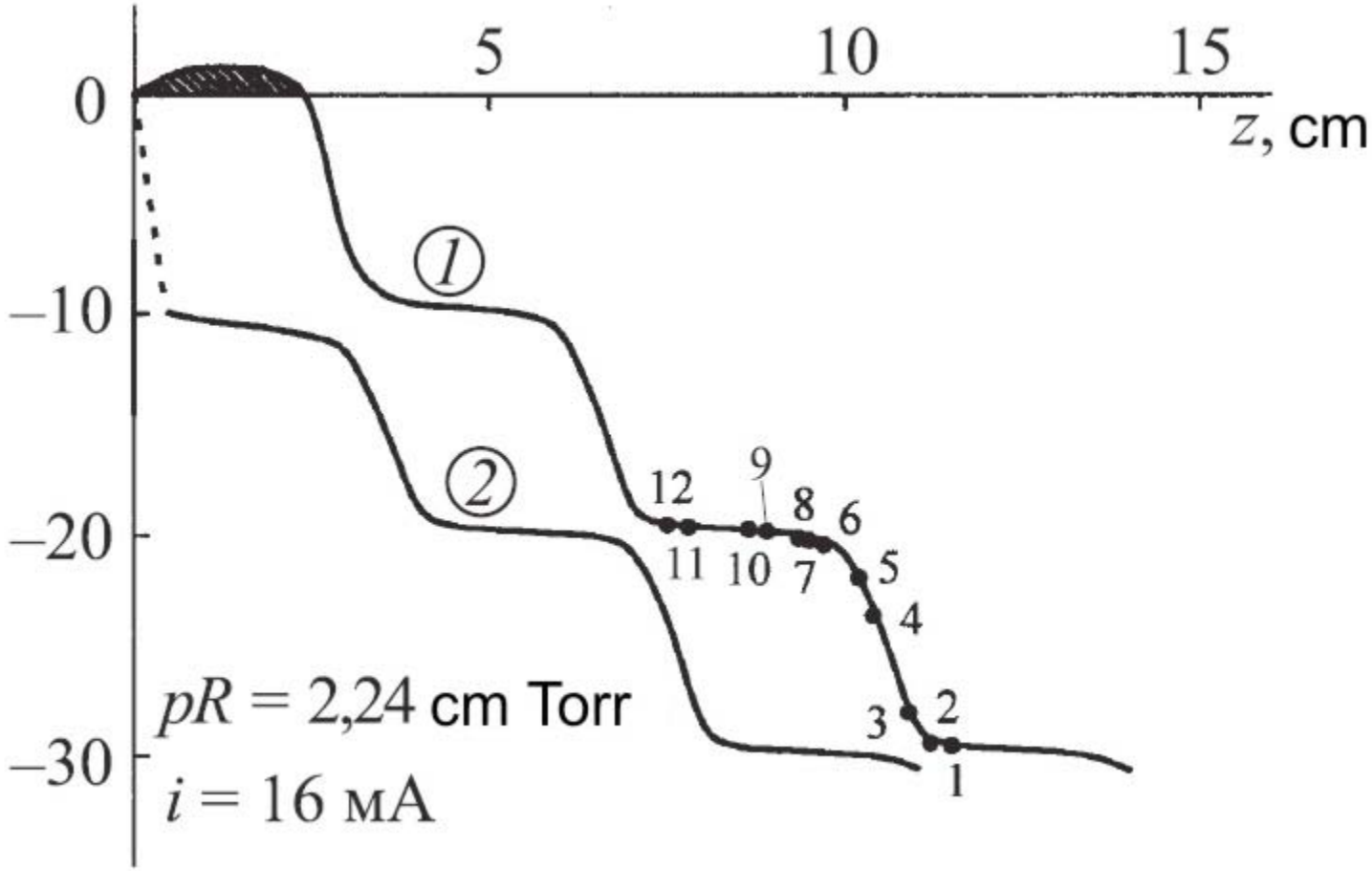
N=2 – P-striations

N=3/2 – R-striations

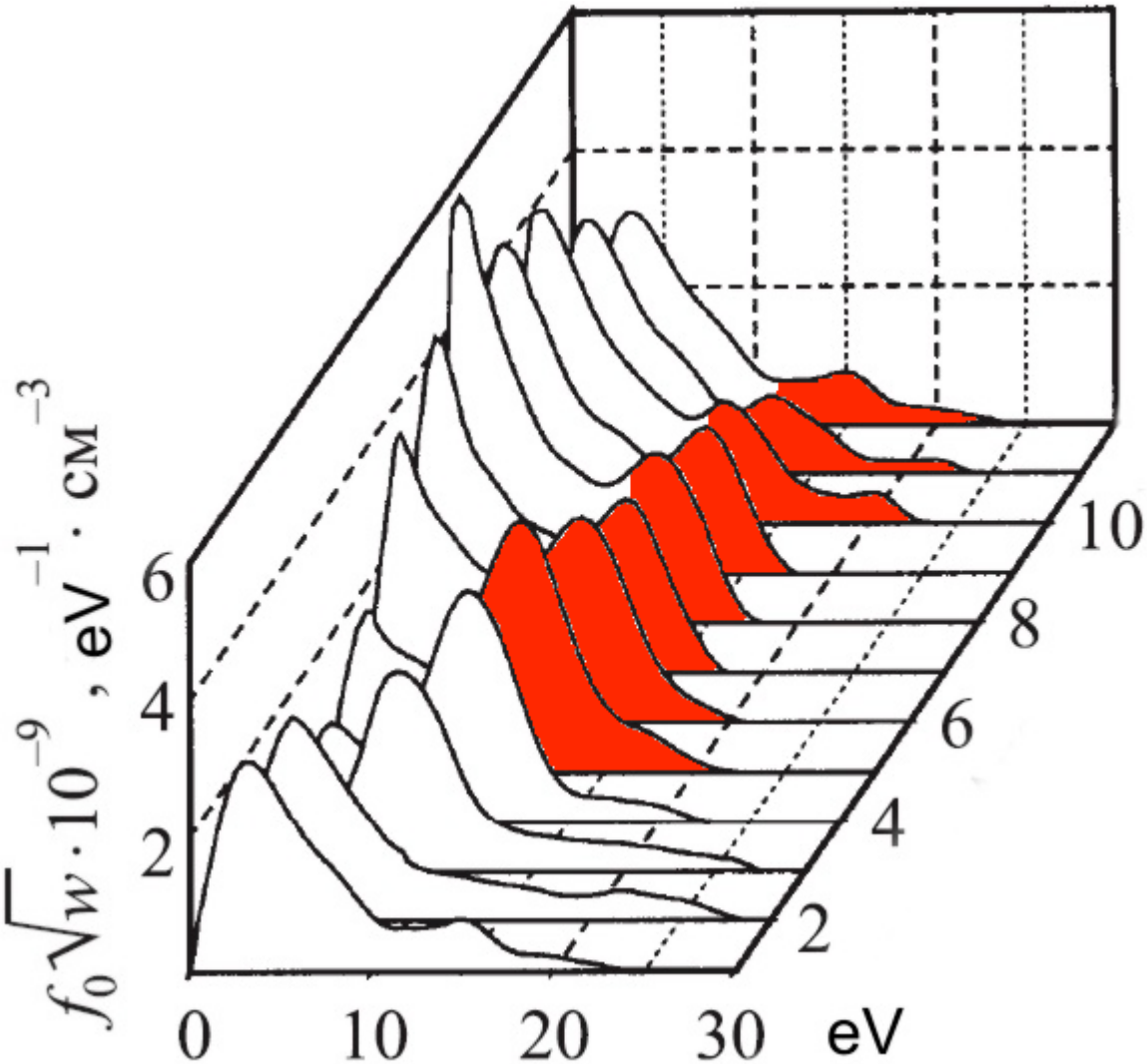
EDFs in S-striations; Ne



P-striations in *Ne*



EDFs in P-striations in *Ne*



Conclusions

- **The glows are extremely non-equilibrium systems and demand the kinetic description.**

- **Kinetic description allows explaining naturally such important phenomena:**
  - Spatial profiles of luminosity and particles species
  - Energy spectra of wall fluxes
  - Striations

Thank you for your interest and attention!