

VOLUMETRIC CONTROL OF ANISOTROPIC ELECTRON DISTRIBUTION FUNCTION IN PLASMAS WITH LANGMUIR OSCILLATIONS

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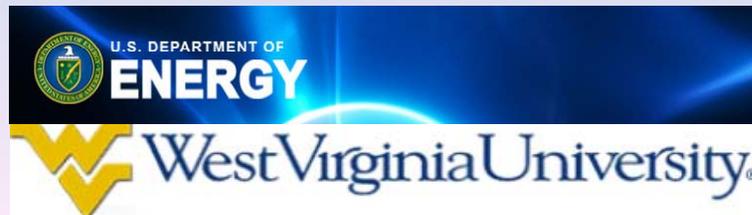
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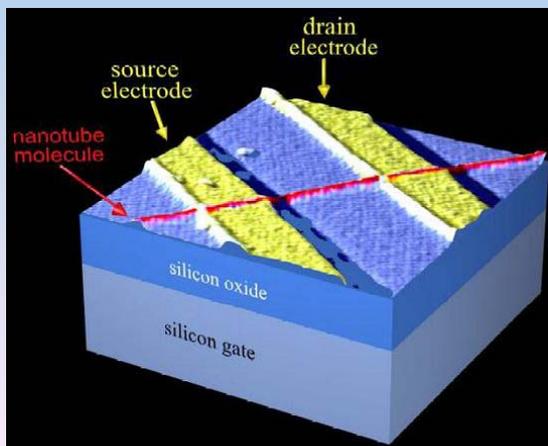


Future reactors will be based on anisotropic plasma

Achievements of the nanoelectronics of future will largely depend on progress in creating effective anisotropic plasma reactors for the development of trillions one-electron transistors, with dimensions of 5 nm to 2024.

A modern reactors of isotropic plasma does not allow to reach that size. To solve this problem can only use the reactors with anisotropic plasma*.

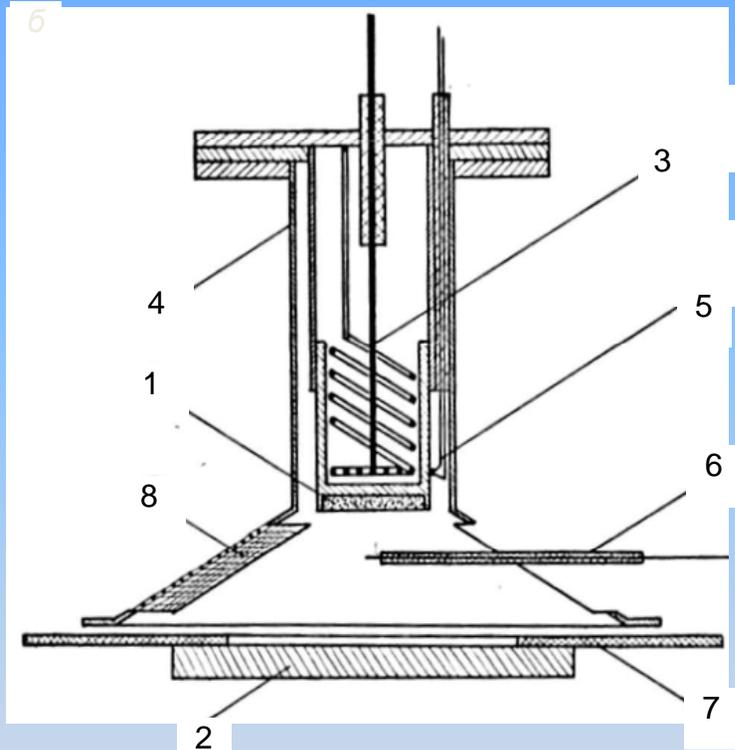
**Lieberman M. Plasma Processing for Nanoelectronics - History and Prospects, Bull. APS, 2010, V. 55, №7, P. 105 (7th ICRP & 63th GEC, 2010, Paris, France).*



OUTLINE

- Developed probe diagnostics for measurements of anisotropic electron velocity distribution function (EVDF).
- Studied mechanisms of collisionless EVDF relaxation on plasma waves in discharge conditions.
- Developed methods of EVDF control using cathode geometry for optimization of current stabilizers based on dc discharge.

Measurements were performed in dc discharge with hot cathode.

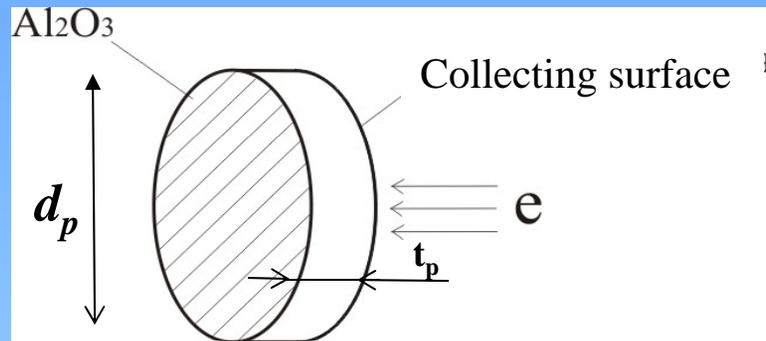


1 – cathode W; 2 – anode Mo; 3-heater;
4 – heat screen; 5 – thermal-couple W-
Re; 6 – movable probe; 7 – protection
rings; 8 – Pierce screen and Mo window
for radiation exit.



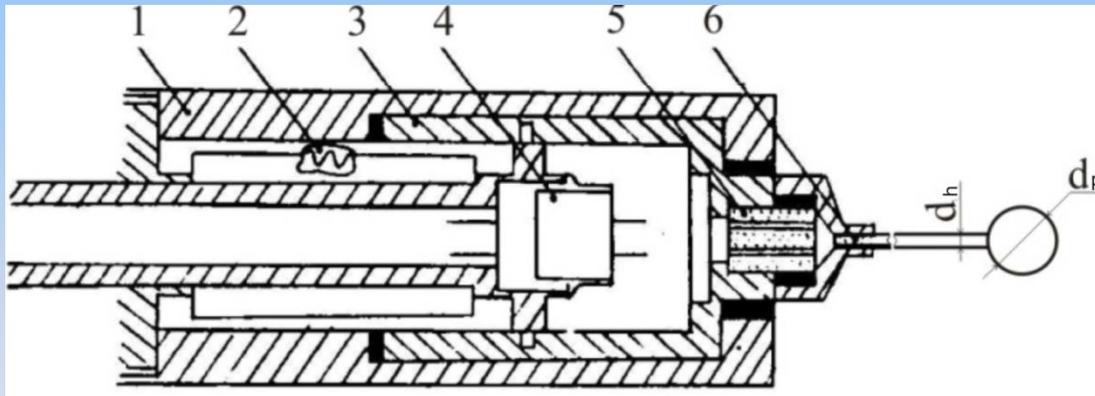
Cathode diameter 1cm, Anode
diameter 3 cm, discharge gap 1 cm.
Pressure $10^{-3} \div 30$ Torr.

Anisotropic Electron Velocity Distribution function was measured with flat probe



Sensitive element of the flat probe

$d_h = 0,1 \text{ mm}$
 $d_p = 0,5 \text{ mm}$
 $t_p = 0,03 \text{ mm}$



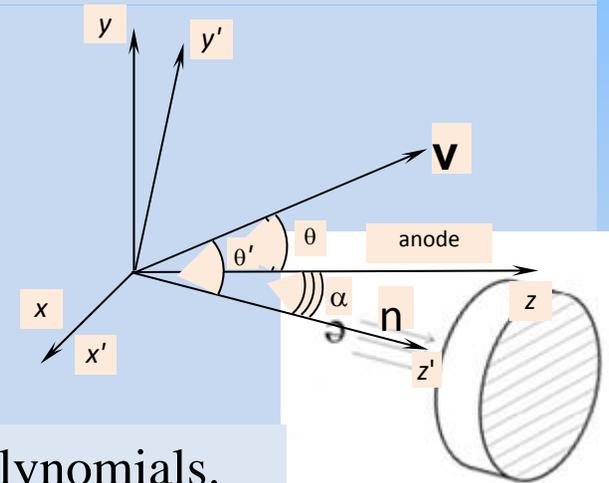
System of the regulation the probe orientation relative to the discharge axis : 1 - stationary corps 2 - bellows connection 3 - rotating bush, 4 --metal current-input, 5 - ceramics, 6 - isolation of the probe; d_h - the diameter of the probe holder, d_p - the diameter of the probe.

Connection between probe signal and anisotropic electron distribution function

The electron current to the probe from the anisotropic plasma,

$$I(eU, \alpha) = qS \int v_n f(\vec{v}) d\vec{v} = \frac{2qS}{m^2} \int_0^{2\pi} d\phi' \int_{qU}^{\infty} \varepsilon d\varepsilon \int_0^{\theta'_{\max}} f(\varepsilon, \theta', \phi') \cos \theta' \sin \theta' d\theta'$$

$$I''_U(eU, \alpha) = \frac{2\pi q^3 S}{m^2} \left[f(eU, \alpha) - \frac{1}{2\pi} \int_0^{2\pi} d\phi' \int_{qU}^{\infty} \frac{\partial}{\partial (eU)} f(\varepsilon, \theta^*) d\varepsilon \right]$$



Integral equation is solved by expanding in Legendre polynomials.

$$f(\varepsilon, \theta) = \sum_{j=0}^{\infty} f_j(\varepsilon) P_j(\cos \theta) \quad I''_U(qU, \alpha) = \frac{2\pi q^3 S}{m^2} \sum_{j=0}^{\infty} F_j(qU) P_j(\cos \alpha)$$

Solution for anisotropic velocity distribution function as a function of the second derivative of the current with respect to voltage

$$f_j(qU) = \frac{(2j+1)m^2}{4\pi q^3 S} \int_{-1}^1 \left[I_U''(qU, x) + \int_{qU}^{\infty} I_U''(\varepsilon, x) R_j(qU, \varepsilon) d\varepsilon \right] P_j(x) dx$$

$$f(\varepsilon, \theta) = \sum_{j=0}^{\infty} f_j(\varepsilon) P_j(\cos \theta) \quad R_j(qU, \varepsilon) = \frac{2^{-(j+1)}}{qU} \sum_{k=0}^{[j/2]} a_{kj} \left(\frac{\varepsilon}{qU} \right)^{\frac{j-2k-1}{2}}$$

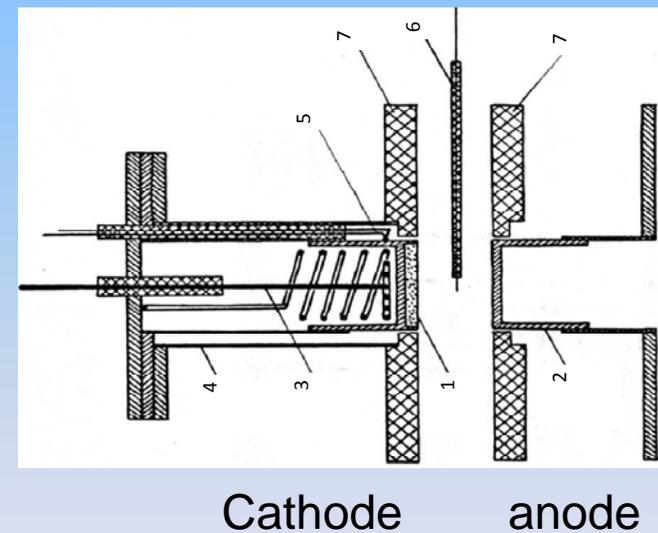
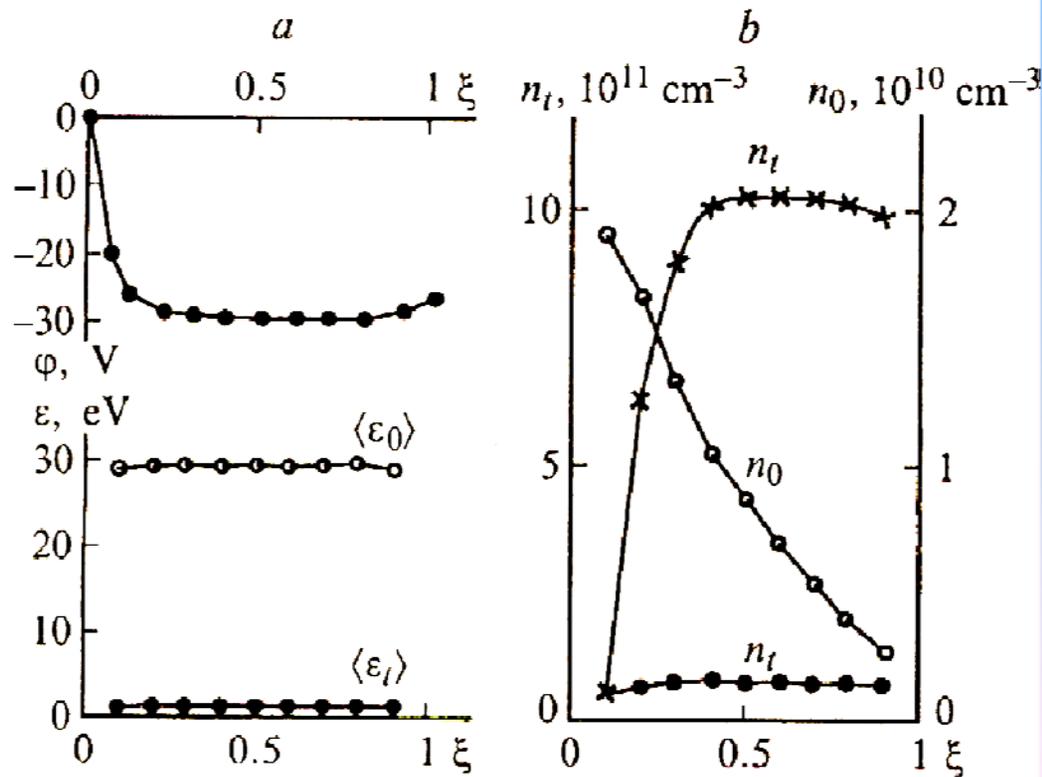
Thus, the method of flat one-sided probe consists in measuring the values of $I_U''(qU, \alpha)$ at different angles and subsequent calculation EVDF and its Legendre components.

The method of flat one-sided probe is valid for any degree of plasma anisotropy.

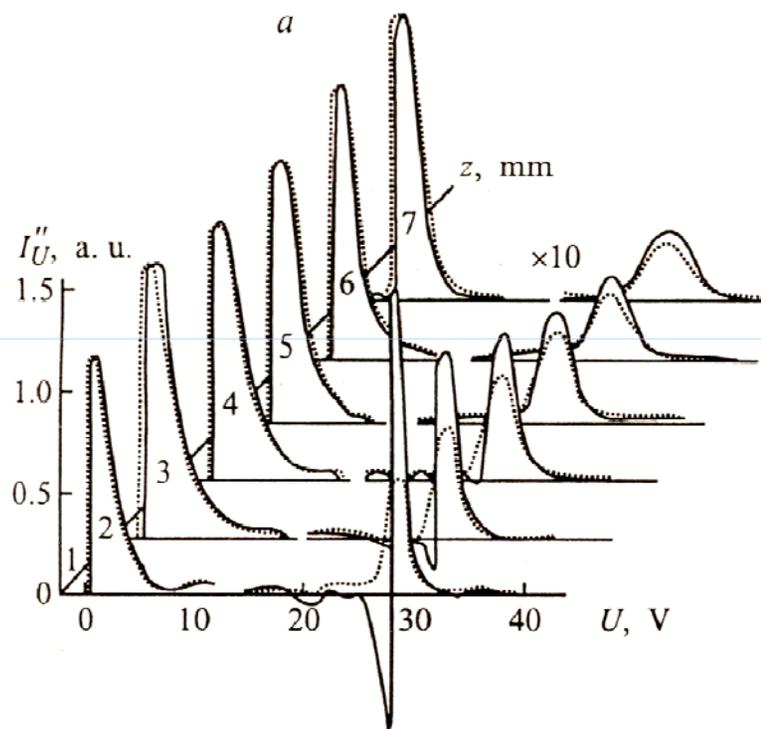
Measurements of plasma parameters in discharge with hot cathode

Axial profiles of the plasma parameters in helium $p_{\text{He}} = 2$ torr for $d = 1.2$ cm, $T_c = 0.1$ eV, and $j_s = (\bullet) 0.14$ and $(x) 0.84$ A cm⁻²:

(a) the potential ϕ and the mean energies $\langle \varepsilon_0 \rangle$ and $\langle \varepsilon_t \rangle$ of the slow and fast electrons and (b) the densities n_t and n_0 of the slow and fast electrons.



Measurements of Spatial Relaxation of Electron Beam Using Flat Probe



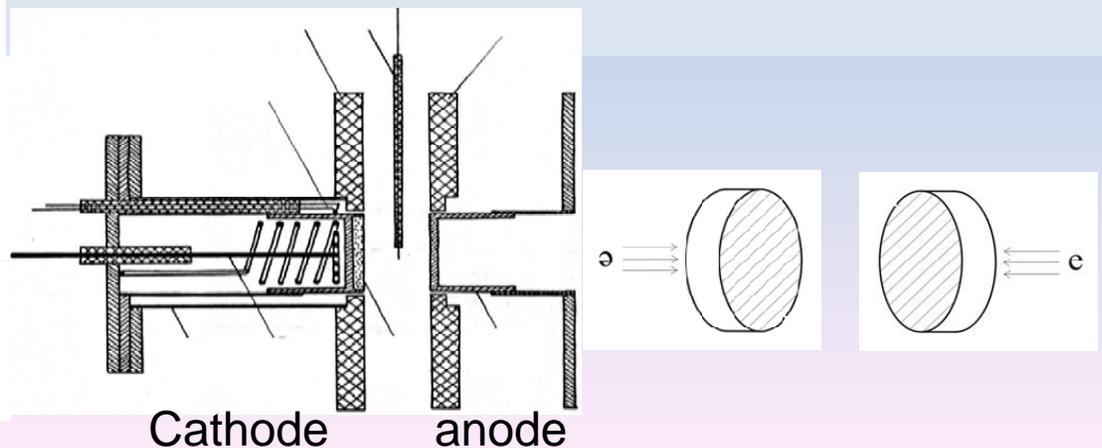
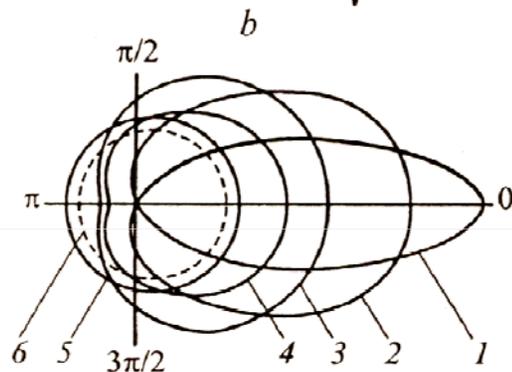
Evolution of the I_U'' profile (a) and polar diagrams of the beam EVDF (b) in a collision-dominated plasma for $p_{\text{He}} = 2$ torr, $j_s = 0.14$ A cm⁻², and $U_a = 29$ V, $d = 1.2$ cm,

positioned at the distances from the cathode at

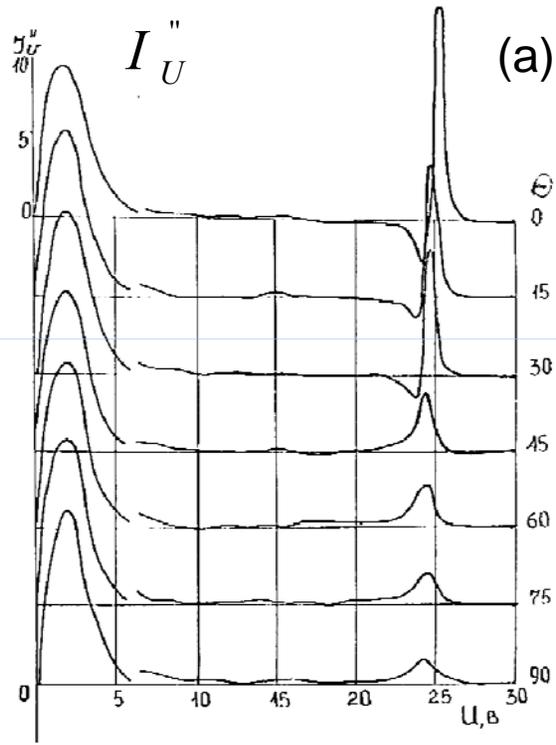
(1) $z = 0.5$ mm; (2) $z = 1$ mm; (3) $z = 1.5$ mm, (4) $z = 2$ mm, (5) $z = 3$ mm, and (6) $z = 6$ mm.

Mean free path $l_0 = 2.5$ mm,

The solid (dashed) curves refer to a probe whose absorbing surface faces the cathode (anode).

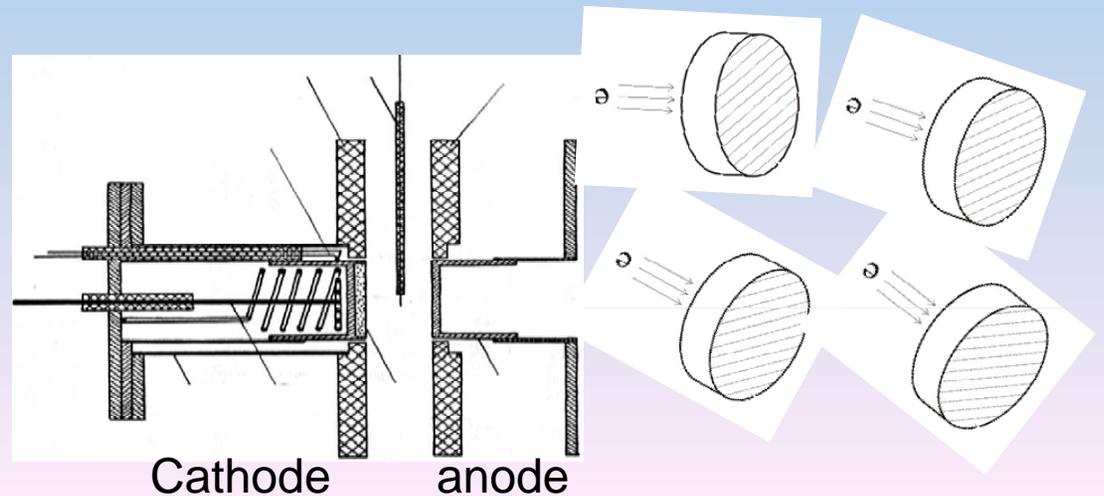
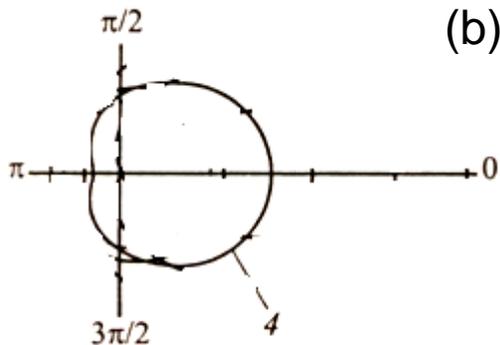


Measurements of Spatial Relaxation of Electron Beam Using Flat Probe



(a) I''_U profile as function of probe angle at 15° intervals

(b) polar diagrams of the beam EVDF in a collision-dominated plasma for $p_{\text{He}} = 2$ torr, $j_s = 0.14 \text{ A cm}^{-2}$, and $U_a = 29 \text{ V}$, $d = 1.2 \text{ cm}$, positioned at the distances from the cathode at $z = 2.5 \text{ mm}$. Mean free path $l_0 = 2.5 \text{ mm}$,



Cathode

anode

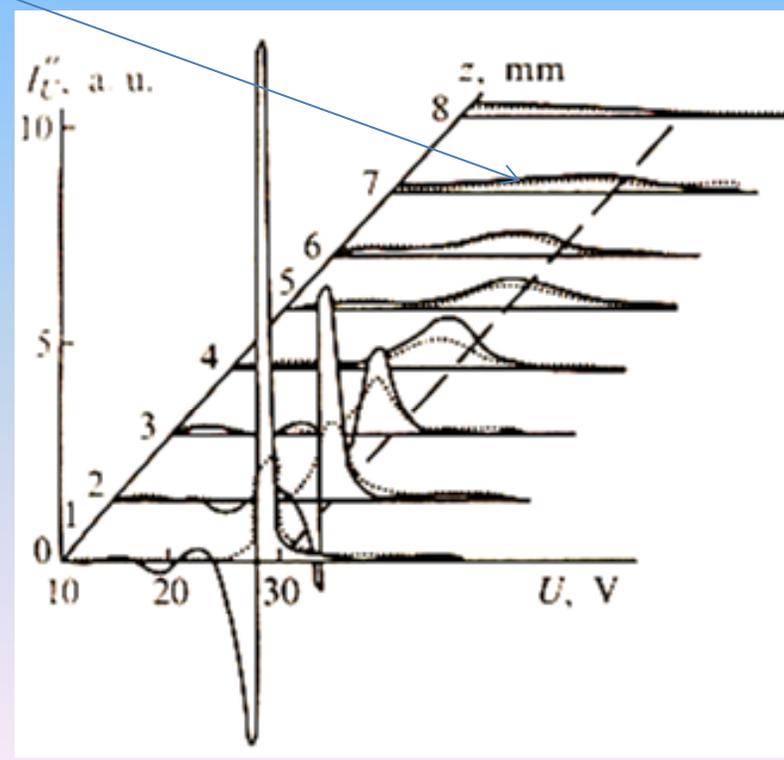
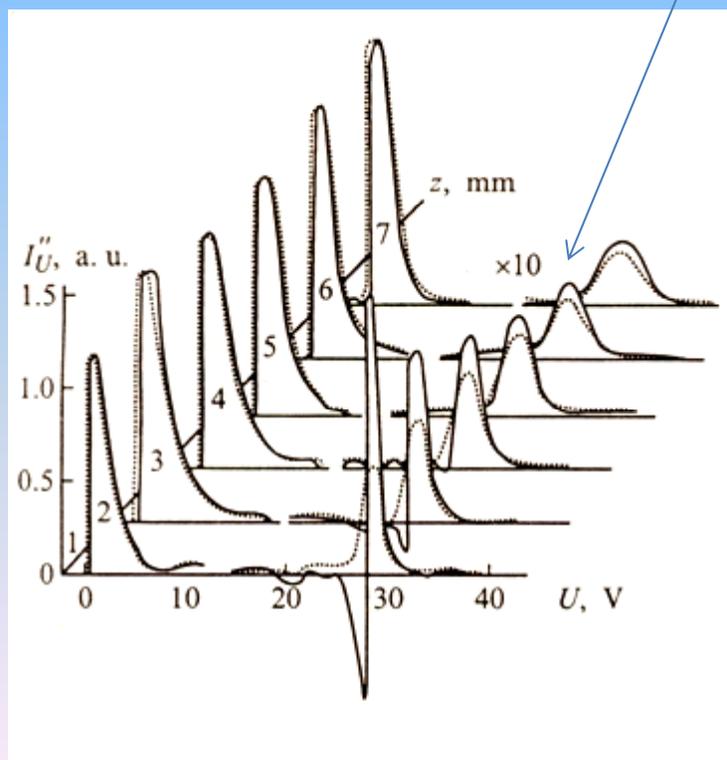
Observation of non-collisional (collective) beam energy loss even at 2Torr pressure

Evolution of the profile along the discharge axis in a collision-dominated plasma for $p_{\text{He}} = 2$ torr, $d = 1.2$ cm, $U_a = 29$ V; mean free path 2.5 mm,

Left $j_s = 0.14$ A cm⁻²

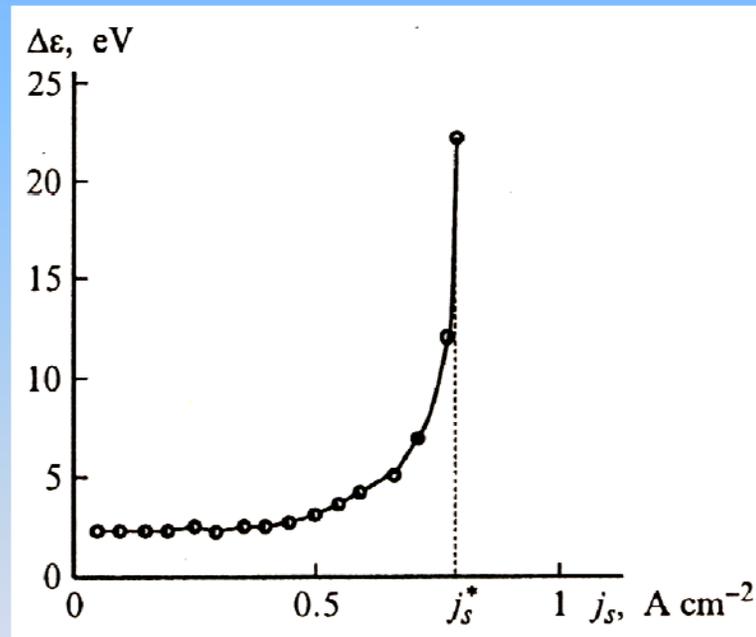
Right $j_s = 0.8$ A cm⁻²

Observe large energy loss at higher current



Observation of non-collisional (collective) beam energy loss even at 2 Torr pressure

Energy spread $\Delta\varepsilon$ of the beam electrons vs. the discharge current density j_s at the point $z = 9\text{mm}$ for the same discharge parameters



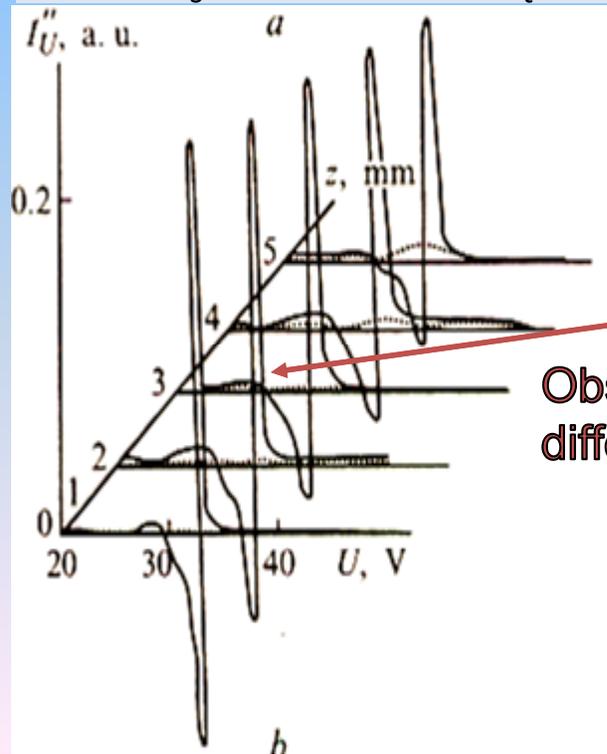
Observation of non-collisional (collective) beam energy loss and scattering at 0.5 Torr pressure

Evolution of the I''_U profiles (cathode and anode facing) and along the discharge axis of beam electrons in a collisionless plasma for $p_{\text{He}} = 0.5$ Torr, $d = 0.6$ cm, mean free path, $l_0 = 1$ cm,

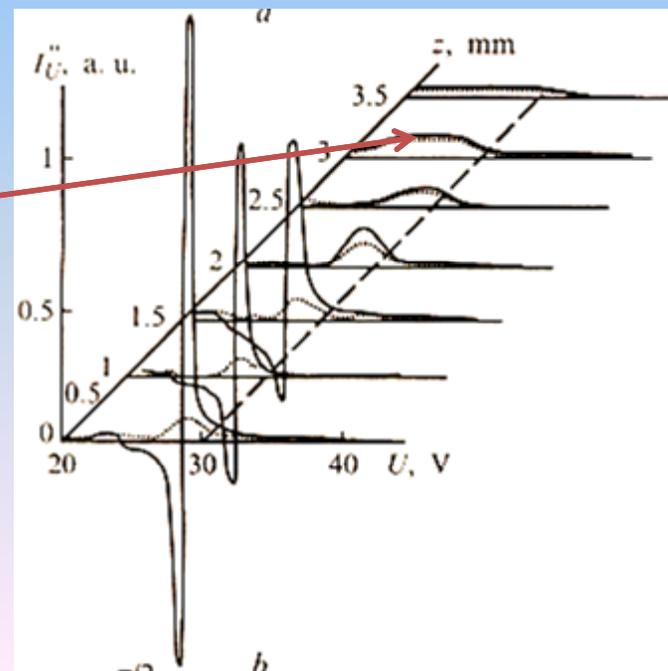
current density, density of cold electrons and beam electrons

Left: $j_s = 0.1$ A cm⁻², $n_t = 6.7 \times 10^{10}$ cm⁻³, and $n_0 = 9 \times 10^9$ cm⁻³

Right: $j_s = 0.5$ A cm⁻², $n_t = 2.8 \times 10^{11}$ cm⁻³, and $n_0 = 6 \times 10^{10}$ cm⁻³



Observe big difference at 3 mm



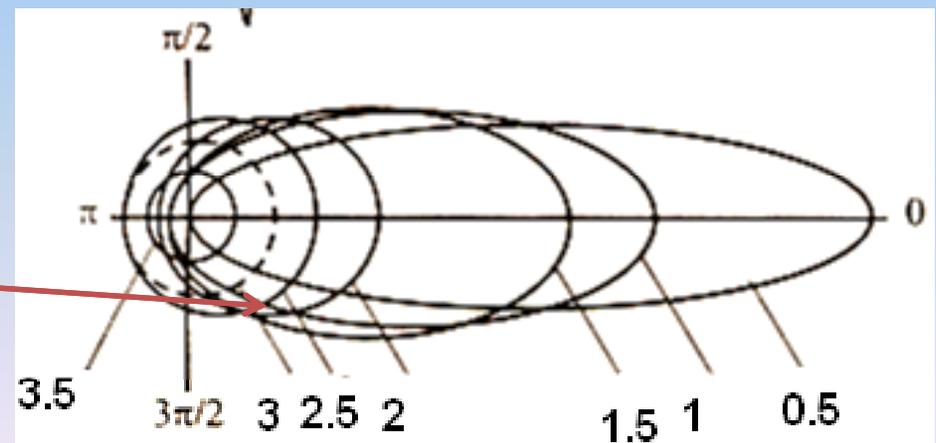
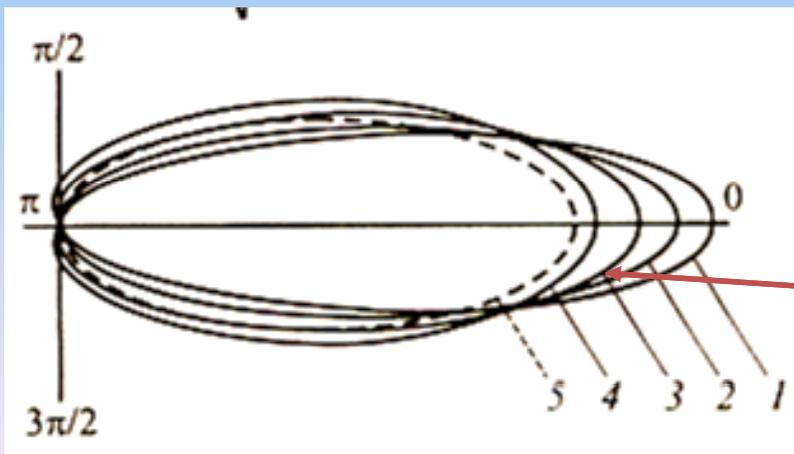
Observation of non-collisional (collective) beam energy loss and scattering at 0.5 Torr pressure

Evolution of the polar diagrams of the beam electrons along the discharge axis of beam electrons in a collisionless plasma for $p_{\text{He}} = 0.5$ Torr, $d = 0.6$ cm, numbers correspond to distance in mm from the cathode, the mean free path, $l_0 = 1$ cm, current density, density of cold electrons and beam electrons

Left: $j_s = 0.1 \text{ A cm}^{-2}$, $n_t = 6.7 \times 10^{10} \text{ cm}^{-3}$, and $n_0 = 9 \times 10^9 \text{ cm}^{-3}$

Right: $j_s = 0.5 \text{ A cm}^{-2}$, $n_t = 2.8 \times 10^{11} \text{ cm}^{-3}$, and $n_0 = 6 \times 10^{10} \text{ cm}^{-3}$

Observe big difference at 3 mm

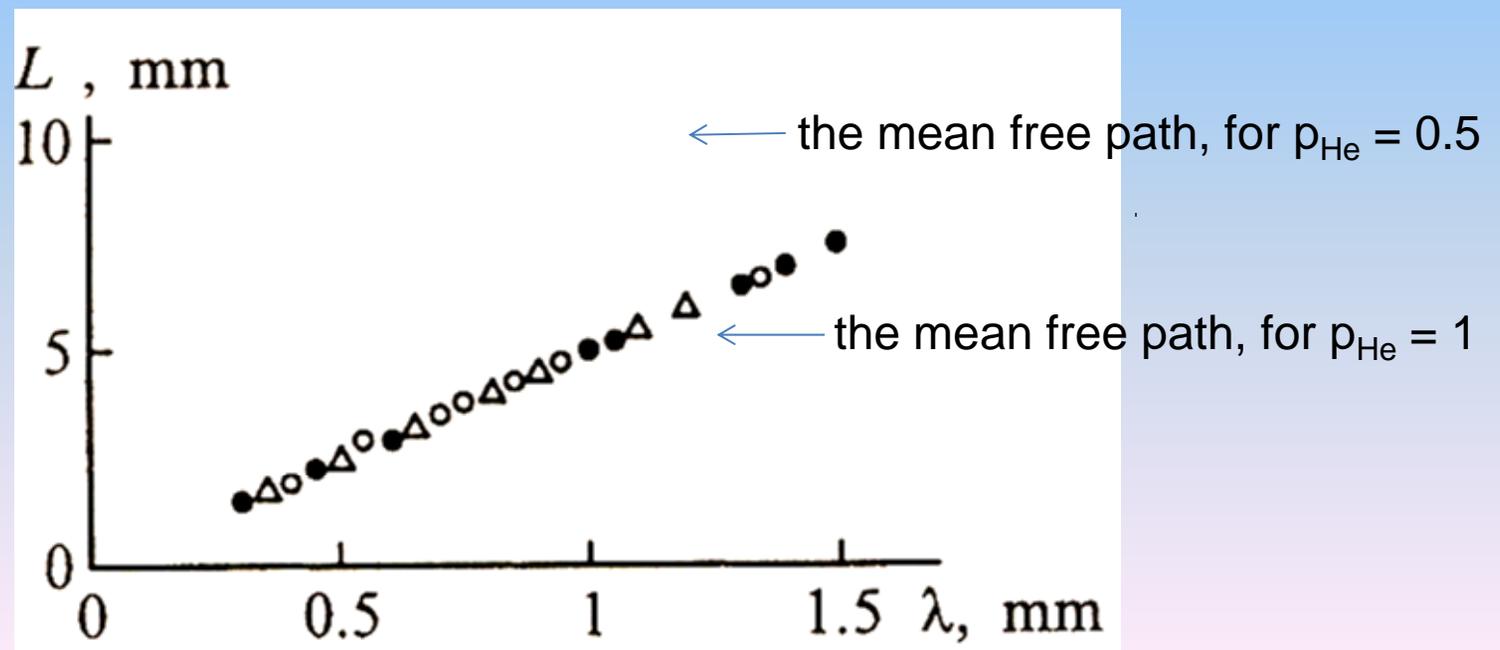


The non-collisional (collective) beam scattering length is proportional to the wavelength λ of Langmuir oscillations excited by the beam

The length of the beam isotropisation versus the wavelength λ of Langmuir oscillations excited by the beam for $p_{\text{He}} = (\bullet) - 0.25$, $(\circ) - 0.5$, $(\Delta) - 1$.

the mean free path, for $p_{\text{He}} = 0.25 - 20\text{mm}$; $p_{\text{He}} = 0.5 - 10\text{mm}$; $p_{\text{He}} = 1 - 5\text{mm}$.

In the discharge mode marked by the cross, the beam relaxation by Langmuir waves is followed by the relaxation by binary collisions, so that the relaxation length L_ϵ sharply increases



CONCLUSIONS

- The relaxation dynamics of the energy and momentum distribution functions of intense electron beam has been studied by probe measurements.
- The experiments reveal that the intense electron beam scatter due to the excitation of waves even in weakly- collisional plasma and there is a critical discharge current: at current below the critical value, the beam relaxation mechanism is collisional, above – collisionless. The corresponding jump-like transition from one relaxation mechanism to another have been measured.
- The phenomenon of the isotropization of an electron beam in the course of its interaction with the plasma waves in weakly- collisional plasma has been observed experimentally. The collisionless nature of the mechanisms for the relaxation of an intense electron beam has been demonstrated. It is established that the beam relaxation process occurs in two stages.
 - First, the electron momentum distribution function becomes essentially isotropic, in which case the beam energy decreases only slightly (the isotropization stage).
 - Second, the beam relaxes to a state with a plateau-like EDF (the energy relaxation stage).

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