3D probe diagnostics of plasmas

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This paper deals with the further development of the probe technique for the investigation of nonequilibrium anisotropic plasmas. The flat probe method, which allows to determine full electron velocity distribution function (EVDF) in plasmas with any degree of anisotropy, but only with axial symmetry, has been improved in direction of measurements in plasma without symmetry at all. The theoretical basis of the method has been developed. For probes of different geometries the analytical expressions, connecting the second derivative of probe current with respect to the probe potential with the Legendre components of the EVDF has been obtained. The method has been experimentally tested in positive column of glow discharge. It has been demonstrated, that proposed method provide a number of new possibilities, such as investigations near the plasma boundaries and obtaining of non-traditional information about the processes of particle escape to the walls, which could be useful for investigations of Langmuir paradox in plasma.

One of the current fundamental problems of plasma physics is the so-called "Langmuir paradox", which has been long known and widely discussed in the literature [1-5].

In the paper [6] L.D. Tsendin attempted to explain the Langmuir paradox in plasma of low pressure. As a result it has been concluded, that in this case the main mechanism of EVDF formation is escape of the electrons to the walls, determined by their elastic scattering in the so-called "loss cone".

The first systematic experimental investigations of EVDF in conditions, when Langmuir paradox is exist, have been undertaken by Y.M. Kagan with collaborators [7]. The result was the assumption that EVDF Maxwellization occurs due to the unknown “wall” mechanism.

Paper [8] demonstrates the results of experiments, where spherical and cylindrical probes, oriented perpendicular to the discharge axis have been used. At this orientation, the cylindrical probe is unable to "feel" the loss cone, and Maxwellian EVDF have been registered in a wide range of energies. Most clearly the depletion of EVDF, associated with the escape of the electrons to the walls, was observed in experiment [8], where flat wall probe has been used. In [9] also noted the differences in the second derivatives, recorded at the two perpendicular orientations of the cylindrical probe - along and across the discharge axis.

The first focused investigations of electron loss cone have been conducted by the authors of [10] in argon high-frequency discharge. The EVDF has been measured by flat probe, located at a distance of 1 cm from the wall. It has been established, that increasing of electrons energy leads to the emergence of EVDF characteristic features, associated with the escape of electrons from plasma volume.

In order to register the loss cone and move forward in research of Langmuir paradox, it is vital to develop new reliable method of plasma diagnostics, providing the possibilities of EVDF investigations with angular resolution near the plasma boundaries, measurements of radial electric field profiles, near-wall potential jump, electron concentration, etc.

To solve this problem we propose new probe method for diagnostics of plasmas with arbitrary symmetry. This method has been experimentally tested and experimental results, testifying in favor of the conclusions [6, 10] have been obtained.

Theory

The known method of flat single-sided probe consist in the EVDF expansion in a series of Legendre polynomials and registration of the second derivative at different angles of the probe orientation with respect to the discharge axis [11]. It allow us to obtain the most complete information about the strongly nonequilibrium anisotropic plasmas. The basis of the method is given by following set of equations:

$$j''_u(\vec{r}; eu; \phi_0) = \frac{2\pi e^3}{m^2} \sum_{j=0}^{\infty} F_j(\vec{r}; eu) P_j(\cos\phi_0); \tag{1}$$

$$F_j(\vec{r}; eu) = f_j(\vec{r}; eu) - \int_{eu}^{\infty} f_j(\vec{r}; \varepsilon) \frac{\partial}{\partial(eu)} P_j\left(\sqrt{\frac{eu}{\varepsilon}}\right) d\varepsilon. \tag{2}$$

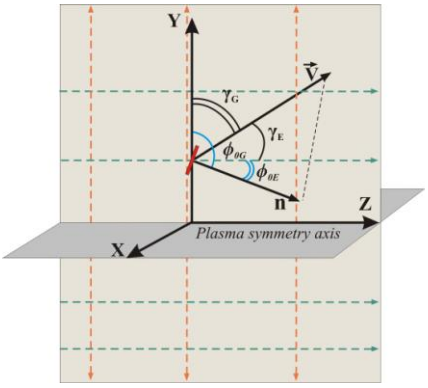

Fig. 1. The geometry of the problem in the case of probe, located in radial area of the interelectrode gap

However, the scope of this method is limited by the requirement of plasma axial symmetry. Fig. 1 demonstrates a case, where flat probe is located near the boundary of the plasma volume (radial area) and it is necessary to take into account the asymmetry, caused by presence of a radial electric field.

In this paper we propose new probe method for diagnostics of the plasma with arbitrary symmetry. In this case the equations of the flat probe method (1, 2) are transformed into the following equations:

$$j''_u(\vec{r}; eu) = \frac{2\pi e^3}{m^2} \sum_{j=0}^{\infty} \{F_{jE}(\vec{r}; eu) P_j(\cos\phi_{0E}) + F_{jG}(\vec{r}; eu) P_j(\cos\phi_{0G})\}; \tag{3}$$

$$F_{jE}(\vec{r}; eu) = f_{jE}(\vec{r}; eu) - \int_{eu}^{\infty} f_{je}(\vec{r}; eu) \frac{\partial}{\partial(eu)} P_j\left(\sqrt{\frac{eu}{\varepsilon}}\right) d\varepsilon; \tag{4}$$

$$F_{jG}(\vec{r}; eu) = f_{jG}(\vec{r}; eu) - \int_{eu}^{\infty} f_{jG}(\vec{r}; eu) \frac{\partial}{\partial(eu)} P_j\left(\sqrt{\frac{eu}{\varepsilon}}\right) d\varepsilon, \tag{5}$$

where ϕ_{0E}; ϕ_{0G} - the angles between the normal to the flat probe surface and directions of the charged particles fluxes, caused by electric field and diffusion, respectively.

Similarly to the method of the flat probe, reconstruction of the components f_{jE} f_{jG} is connected with the solution of corresponding integral Volterra equations of second kind, binding Legendre components of the EVDF and of the second derivative.

Experiment

Probe measurements have been carried out in the range of helium pressure 0.1-1 torr and discharge current 0.1 A to 0.5 A at a distance of 1 cm from the plasma wall for two orientations of the probe with respect to the discharge axis (0 and 180^0). Corresponding second derivatives have been registered, angular structure of the EVDF in the loss cone has been reconstructed and polar diagrams of the electron motion have been plotted (Fig. 2).

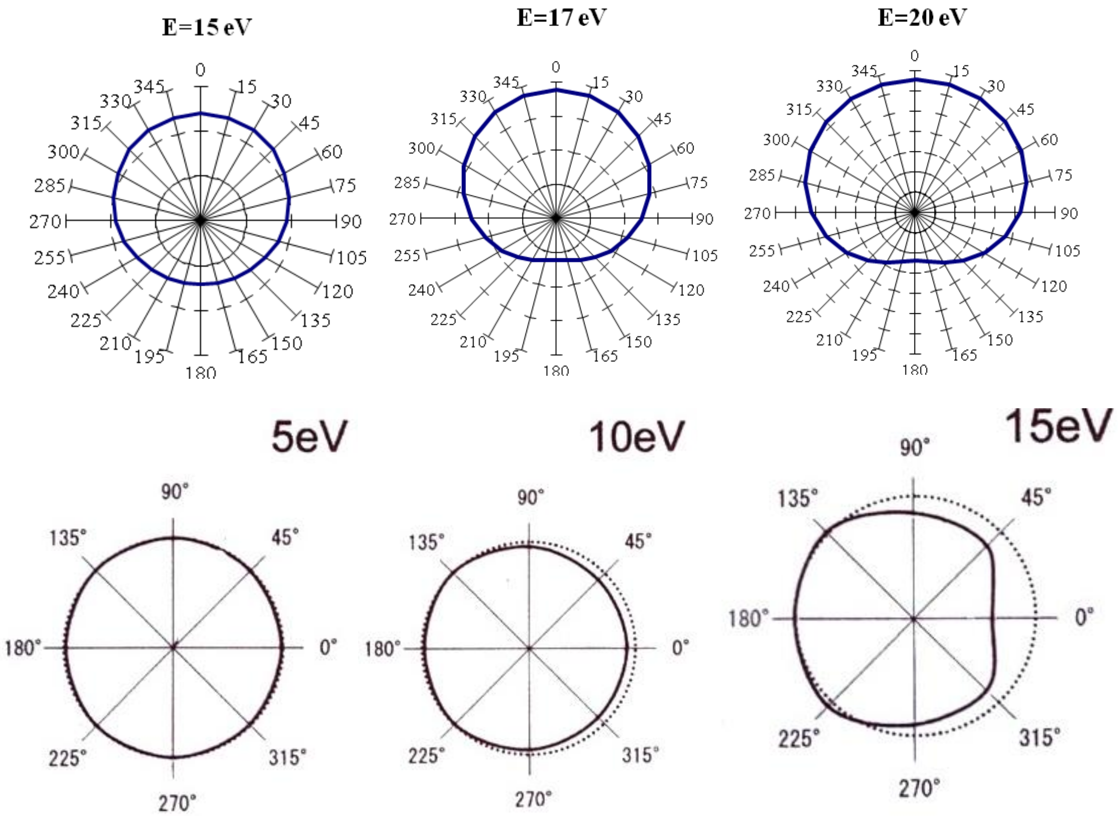

Fig. 2. Above – angular structure of the EVDF, registered at a distance of 1 cm from the plasma wall in the positive column of helium glow discharge. P_{He} = 0,5 torr, I = 0,5 A. Angle 180^0 – collecting surface of the probe is turned to the wall.

Below - angular structure of the EVDF, registered in plasma of high-frequency discharge in argon by authors [10]. Angle 0^0 – collecting surface of the probe is turned to the wall

According to the paper [10], when energy of the electrons increase, on the diagrams of electron motion is clearly visible the depletion of EVDF, associated with the escape of electrons to the walls. If the wall potential exceeds the potential of the probe, the probe "feels" EVDF in the loss cone. Increasing of current and pressure does not affect on EVDF shape. Rotation of the probe by 180^0 let us to measure EVDF in the main part of the plasma volume. In this case the polar diagrams demonstrate us isotropic EVDF, typical for positive column of glow discharge.

The obtained data correlate quite accurately with theoretical and experimental results of [6, 10]. This is evident about reliability of the developed method and could be a confirmation of the hypothesis, that Langmuir paradox in plasma is associated with physical characteristics of the EVDF formation as a combination of known mechanisms, not with a hypothetical mechanism of EVDF Maxwellization.

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