Experimental determination of anisotropic ion velocity distribution function in intrinsic gas plasma

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For the first time, the ion distribution functions over energy and direction of motion for He^+ in He and Ar^+ in Ar have been measured at the arbitrary value of the electric field by the method of the plane one-sided probe. The experiment is carried out under conditions when the ion velocity, acquired at the mean free path, is of the order of and larger than the average thermal velocity of atoms, and resonance charge exchange is the dominating process in plasma. The obtained results make it possible to conclude that, in independent gas discharge plasma, even at moderate fields, the ion distribution function can have noticeable anisotropy and can strongly differ from Maxwell distribution.

The ion velocity distribution function (IVDF) is of interest in cases associated with the study of plasmachemical reactions occurring with the participation of ions, the determination of ion mobility in the plasma objects, processes of heating of the neutral plasma component, etc.

This work is devoted to the experimental and theoretical determination of the IVDF in intrinsic gas for a glow discharge in a constant electric field with allowance for the appearance of slow ions with atomic temperature as a result of charge exchange, which was considered the dominating process.

IVDF was measured by the method of the plane one-sided probe in the positive column of the glow discharge in inert He and Ar gases (the results of electron distribution function investigations are presented here [1]) at pressures of 0.02–0.2 Torr. The discharge was created in a quartz glass tube with a diameter of 30 mm and length of 300 mm between the plane impregnated indirect glow cathode with a diameter of 11 mm and molybdenum anode with a diameter of 20 mm. The discharge current was measured in the range of 0.05–0.5 A.

To measure the expansion coefficients of the IVDF over Legendre polynomials F_{ia}^{n}, second derivatives of the probe current I_U'', obtained by the radio-technical method of the double modulation, with respect to the probe potential were recorded. The experimental setup and the method of measuring the second derivative of the probe current with respect to the probe potential are described in detail in [2, 3].

Method of the Plane One-Sided Probe for the Recovery of the Total IVDF

The presented method is a development of the traditional methodology of the Langmuir probes [4]. It is intended for the diagnostics of axially symmetric plasma and makes it possible to reconstruct the total ion distribution function and components of its expansion over Legendre polynomials.

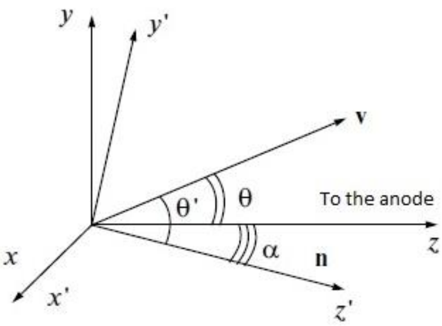

Fig. 1. Geometry problem: **n** is the vector, normal to the nonconducting surface of the probe

In such plasma, in the spherical coordinate system with the polar axis directed along the symmetry axis (Fig. 1), IVDF does not depend on the azimuthal angle and has the form:

$$F_{ia}(\mathbf{r}, \mathbf{v}) = F_{ia}(\mathbf{r}, v, \theta)\,, \tag{1}$$

where $v = |\mathbf{v}|$ and θ is the polar angle. The ion current on the probe from plasma:

$$I = qS\int v_n F_{ia}(\mathbf{v})d\mathbf{v} = \frac{2qS}{m^2}\int_0^{2\pi} d\phi' \int_{qU}^{\infty} \varepsilon d\varepsilon \int_0^{\theta'_{\max}} F_{ia}(\varepsilon,\theta',\phi')\cos\theta'\sin\theta' d\theta'\,. \tag{2}$$

Here v_n is the component of the vector of the electron velocity normal to the probe surface; $v_n = v\cos\theta' \geq v_{\min} = (2qU/m)^{1/2}$, *m* is the ion mass; *U* is the probe potential, positive with respect to plasma; $\varepsilon = mv^2/2$; φ' and θ' are azimuthal and polar angles of the vector $\mathbf{v}$ in the spherical coordinate system, the polar axis of which, coincides with the normal to the nonconducting surface of the plane probe. Differentiating (2) twice over the potential *U*, we obtain:

$$I''_U = \frac{q^3 S}{m^2}\left[\int_0^{2\pi} F_{ia}(qU,\theta'=0,\phi')d\phi' - \int_0^{2\pi} d\phi' \int_{qU}^{\infty} \frac{\partial}{\partial(qU)} F_{ia}(\varepsilon,\theta'_{\max},\phi')d\varepsilon\right] \tag{3}$$

In (3), we transfer to the laboratory coordinate system, in which IVDF has the form (1). To this end, we use the relation connecting the polar angle of the laboratory coordinate system θ with angles θ' and φ', and the angle α between polar axes of coordinate systems (Fig. 1): $\cos\theta = \cos\theta'\cos\alpha + \sin\theta'\sin\alpha\cos\phi'$. Then we come to the expression:

$$I''_U(qU,\alpha) = \frac{2\pi q^3 S}{m^2}\left[F_{ia}(qU,\alpha) - \frac{1}{2\pi}\int_0^{2\pi} d\phi' \int_{qU}^{\infty} \frac{\partial}{\partial(qU)} F_{ia}(\varepsilon,\theta^*)d\varepsilon\right], \tag{4}$$

Relation (4) is the integral equation for the sought IVDF. To find the distribution function, we present $F_{ia}(\varepsilon, \theta)$ and $I''_U(qU,\alpha)$ in the form of the expansion in Legendre polynomials [2]:

$$F_{ia}(\varepsilon,\theta)=\sum_{n=0}^{\infty}F_{ia}^{n}(\varepsilon)P^{n}(\cos\theta), \quad (5)$$

$$I_U''(qU,\alpha)=\frac{2\pi q^3 S}{m^2}\sum_{n=0}^{\infty}F^{n}(qU)P^{n}(\cos\alpha) \quad (6)$$

Recovery of the complete IDF

After the substitution of (5) and (6) into (4), we find the following relationship:

$$F_{ia}^{n}(qU)=F^{n}(qU)+\int_{qU}^{\infty}F_{ia}^{n}(\varepsilon)\frac{\partial}{\partial(qU)}P^{n}\left(\sqrt{\frac{qU}{\varepsilon}}\right)d\varepsilon \quad (7)$$

The expression (7) is the Volterra integral equation of the second kind. Using its resolvent, (7) can be resolved with respect to F_{ia}^{n}:

$$F_{ia}^{n}(qU)=F^{n}(qU)+\int_{qU}^{\infty}F^{n}(\varepsilon)R^{n}(qU,\varepsilon)d\varepsilon \quad (8)$$

The substitution into (8) of the relationship for the n-th component in the expansion (5) over Legendre polynomials

$$F_{ia}^{n}(qU)=\frac{(2n+1)m^2}{4\pi q^3 S}\int_{-1}^{1}I_U''(qU,x)P^{n}(x)dx$$

leads to the main formula of the method (here $x=\cos\alpha$)

$$F_{ia}^{n}(qU)=\frac{(2n+1)m^2}{4\pi q^3 S}\int_{-1}^{1}\left[I_U''(qU,x)+\int_{qU}^{\infty}I_U''(\varepsilon,x)R^{n}(qU,\varepsilon)d\varepsilon\right]P^{n}(x)dx \quad (9)$$

Thus, the method of the plane one-sided probe consists in the measurement of $I_U''(qU,\alpha)$ values at different orientations of the probe in plasma and the subsequent calculation according to formulas (9) and (5) of corresponding components F_{ia}^{n} and total IVDF respectively.

Experimental data of the recovery of the total IVDF over energy and direction of motion

Figure 2 shows the measured IVDF at a pressure of 0.2 Torr and a temperature for neutrals of $T_a = 600\ K$. The strong field approximation [5] underestimates the distribution function in the region of the maximum and, on the contrary, overestimates it at higher energies. These discrepancies are apparently caused by the fact that, in the considered case, parameter ε_0 (the ratio of the average thermal energy of atoms to the energy of the ion acquired on the mean free path with respect to the process of charge exchange) is of the value $\varepsilon_0 \approx 0.124$ and the strong field approximation $\left(\sqrt{\varepsilon_0} \ll 1\right)$ strictly speaking, is not applicable. Analogously, Fig. 3 gives similar data but for ions Ar^+ in Ar. For Ar^+ in Ar the parameter $\varepsilon_0 \approx 0.689$ and the distribution function is less anisotropic and more low-energy than in the case of ions He^+ in

He in Fig. 2. It is seen that the divergence of calculations according to the strong field theory [5] with experimental data is even more essential.

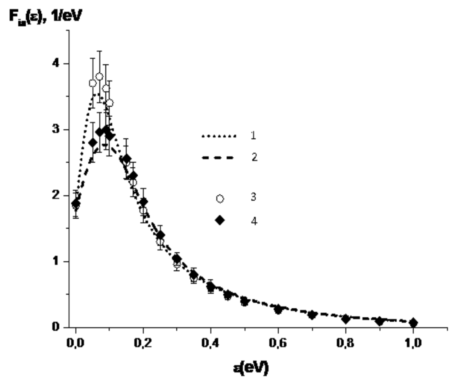

Fig. 2. Comparison of IVDF He^{+} in He in the strong field approximation [5] (1, 2); with experimental data obtained by the probe method (3, 4): $T_a = 600\,K; E/P_0 = 20\,V/cm \cdot Torr$, $P = 0.2\,Torr,\ \varepsilon_0 = 0.124$, at the differentiating signal Δ ε = 0.05 (1, 3) and Δ ε = 0.1 in (2, 4)

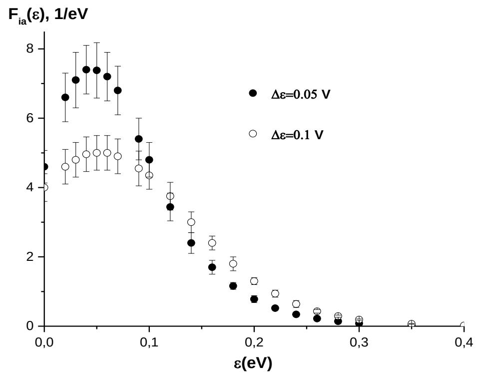

Fig. 3. IVDF of Ar^{+} in Ar, obtained by the probe method at $T_a = 450\,K;\ E/P_0 = 9\,V/cm \cdot Torr,\ P = 0.2\,Torr,\ \varepsilon_0 = 0.689$

Note that, as follows from the above experimental data, IVDF under the conditions of the measurements is far from the Maxwellian with the temperature determined by the field and (analogous to the results [5] obtained under strong field conditions) has the maximum at the energy values of ions on the order of the average thermal energy of atoms.

Using the described method, we measured the energy dependences of the first seven coefficients of the IVDF expansion over Legendre polynomials for He^{+} ions in He and Ar^{+} in Ar. The obtained data indicate the strong anisotropy of IVDF under conditions of the measurements.

In such a way, a new method of determination of IVDF over energy and direction of motion was proposed. Experiments were carried out under conditions where resonance charge exchange is the dominating process in plasma. The main requirement limiting the region of applicability of the method is the small thickness of the near-probe Debye layer in comparison with the probe sizes.

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