Ion velocity distribution function in the plasma of its own gas

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The paper proposed a new probe method for anisotropic ion velocity distribution function (IVDF) diagnostics. Potentialities of this method have been demonstrated under conditions, when on a mean free path an ion acquires velocity, comparable with average thermal velocity of atoms. Energy and angular dependencies of the first seven coefficients of IVDF expansion in Legendre series for Hg^+ in Hg, He^+ in He and Ar^+ in Ar have been measured, and the polar diagrams of the ion motion have been plotted. In order to verify the reliability and accuracy of the method the analytic solution of the kinetic Boltzmann equation for the ions in plasma of its own gas has been found. The conditions under which resonant charge exchange is a dominant process has been considered, whereas the electrical field magnitude is arbitrary. For the ambipolar field relation between the resonant charge exchange cross-section and the relative velocity has been taken into account. The results of theoretical and experimental data, with provision for the instrumental function of the probe method, correlate very accurately.

IVDF research is of special interest for modern applications: plasma technologies, ion surface treatment, technology of selective etching and creation of relief by ion bombardment, new generation of nanoelectronics (single-electron transistors, spintronics, etc). [1, 2].

In this context, experimental methods of IVDF measurements in different discharges, in particular, in DC self-sustained discharge plasmas are of special interest. The authors do not know papers, where the IVDF measurement data for such a discharge have been published. In reference to theoretical research, despite many existing papers it’s difficult to select the ones where IVDF for the DC self-sustained discharge plasmas has been calculated.

The ion drift was theoretically considered in [3-6]. In [3] the drift velocity for ions of inert gases in plasma of its own gas in proximity of the strong field was analyzed, the distribution of atoms according to energies being given by delta-function. The results of drift velocity calculations for inert gas ions in its own gas were presented in [4], however, the author did not publish the analytical expression for IVDF.

Neglecting all processes, except charge exchange, in [5] a time interval of the ion movement in its own gas has been calculated, during which an ion has a velocity component along the electric field in the range of v_{iz} and $v_{iz} + dv_{iz}$. These data have been calculated for interpretation of the experimental results of [7]. However it is difficult to obtain IVDF for the total velocity using these results.

The treatise considers [6] IVDF problem solution in its own gas neglecting the creation of ions if they have Maxwellian distribution by velocities as a result of a charge exchange. Thus, for the uniform cross-section of a charge exchange a Maxwellian type of IVDF has been obtained with the temperature, determined by an electrical field in plasma.

In [8, 9] a new method of calculation of matrix elements of collision integral is represented which is intended for solving the non-steady Boltzmann equation by a method of moments for ions in conditions, when the main process is resonant charge exchange. However, in strong fields, when thermal energy of an atom and ion, acquired on the mean free path, is less than 0.1, this approach is difficult for calculation of a steady IVDF.

In [10] an analytical solution of Boltzmann equation for ions in BGK-model [11] and a numerical solution for uniform cross-section of resonant charge exchange are compared. It should also be emphasized that the analytical solution gives incorrect asymptotics for the drift velocity of an ion in case of strong fields.

The paper [13] deals with analysis of IVDF in unbounded uniform plasma in the presence of steady (in time and space) electric fields and under condition that the main process that has an effect on the drift velocity of ions is resonant charge exchange. The problem is solved both numerically (by Monte-Carlo method) and analytically. When solving analytically a charge exchange cross-section is assumed to be independent on relative motion of colliding an ion and atom.

The paper [14] represents the problem of determining the IVDF in plasma in its own gas in the presence of strong E-field to have been analytically solved. Calculation results correspond well with the known experimental data for drift velocities in strong fields. It has been found, that IVDF differs significantly from Maxwellian and depends on two parameters. In addition, in [15] the authors state the IVDF for Hg^{+} in Hg vapors to have been measured for the first time. Experimental data correlate very accurately with calculation results.

In this work a new experimental probe method for full IVDF reconstruction in conditions of arbitrary electric field has been proposed. The main limiting factor for the method is a small thickness of Debye near-probe layer in comparison with the probe size.

In order to verify the reliability and accuracy of the developed method the analytical solution of Boltzmann kinetic equation for ions in plasma in its own gas has been found in case of resonant charge exchange being the dominant process. The E-field strength in plasma may be arbitrary and a charge exchange cross-section depends on relative velocities of an ion and atom.

Feasibilities of the developed method are demonstrated in this work. The energy and angular dependencies of seven Legendre coefficients have been measured and full IVDF for Hg^+ in Hg, He^+ in He and Ar^+ in Ar has been reconstructed for the first time (fig. 1a, b). A comparison of measured and calculated of Legendre coefficients and corresponding IVDF angular dependencies for Hg^+ в Hg, He^+ in He and Ar^+ in Ar has been made (Fig 1 and 2, respectively). The results of calculation and experimental data give good fit.

Figure 2a shows that when ion velocities are less than the average thermal velocity of atoms, IVDF is isotropic, despite the presence of a strong field. When ion velocities increase the distribution becomes more elongated in the direction of the electric field (fig. 2b), indicating its increasing anisotropy.

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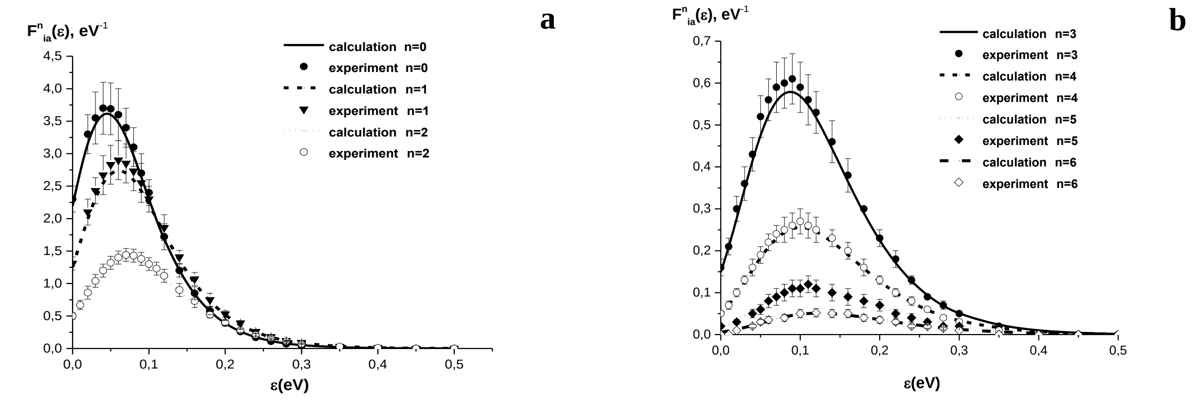

Fig. 1a. The energy dependencies of the first three expansion coefficients (n=1-3) of IVDF Ar^+ in Ar by the Legendre polynomials for value of differentiating signal $\Delta\varepsilon = 0.05\ V$. **Fig. 1b.** The same conditions but n=3-6.

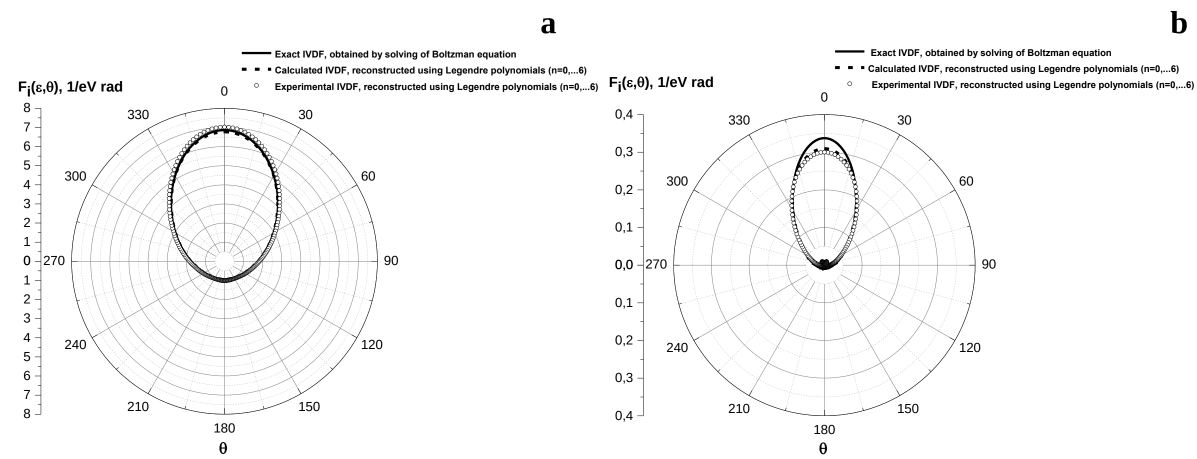

Fig. 2a. Angular dependency of the IVDF for the same conditions as indicated in fig. 1, a. Ions energy $\varepsilon = 0.1\ eV$. **Fig. 2b.** The same, but for ions with energy $\varepsilon = 0.3\ eV$.

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