Diagnostic suite for study of corpuscular flow dynamics in ion-optical system of neutron tube

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Abstract: In this work we developed a combined approach based on the experimental investigation of corpuscular flow at the outlet of an ion source and the computer simulations of beam transport inside ion-optical system that enabled us to recover the parameters of neutron tube operation.

A diagnostic suite was used to study the parameters of corpuscular flow emitted by a Penning-type ion source. The suite includes a single Langmuir probe, a three-electrode grid electrostatic probe, a Faraday cup assembly, an emittance meter, and a system of corpuscular beam trace imaging in the accelerating gap. The use of those devices enabled us to register the following parameters of corpuscular flows at the outlet of the ion source: electron temperature and ion density in the plasma escaping from the ion plasma source, the distribution of ions in the kinetic energy, total current of emitted ions and the distribution of the current density across the cross-section of the ion flow; emittance diagrams, and the trajectory of corpuscular beam in the accelerating gap.

The experiment for evaluation of electron temperature involved measuring the current flowing through a single Langmuir probe at different potential biasing with respect to the grounded walls of vacuum chamber, i.e. taking the current voltage ($I-V$) characteristics of the probe. Measuring the steep part of the $I-V$ curve made it possible to evaluate, from the tilt angle, the electron temperature $T_e = (5.0 \pm 1.2) \text{ eV}$ [1]. The probe current in the “ion saturation” regime enabled us to make an order-of-magnitude estimate of the ion density: $n_i \approx 10^8 \text{ cm}^{-3}$.

The study of energy spectrum of corpuscular flow was conducted using the retarding field method with the help of a three-electrode probe (figure 1) located at the outlet of the ion source instead of the Langmuir probe. The probe was comprised of two flat tandem grids and a collector (Faraday cup). Registration of retardation of the ion component of the corpuscular flow was performed by varying the collector’s potential bias with respect to the first grid which was grounded. The second grid had a negative potential (-60 V) with respect to the grounded first grid (for cutting off the electron plasma component).

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Figure 1. The view of the disassembled three-electrode probe.

Figure 2. The kinetic energy distributions of ions. Discharge voltage is 2.4 kV at argon pressure of $10^{-3}$ Torr.

The algorithm of recovering the kinetic energy distributions of ions is given in [2]. Using the results of [2] for the three-electrode probe measurements we obtained the energy distributions of ions (figure 2).

The assembly of Faraday cups, which almost completely covers the cross-section of ion flow, was used to measure the integral current of ions emitted by the source and to study the radial distribution of current density (i.e. in the plane of cross-section perpendicular to the ion flow). Current density was determined by dividing the current magnitude by the area of the input aperture of the Faraday cup.

The experimental setup for measuring the emittance of corpuscular beam at the outlet of the ion source (the emittance meter) is shown in figure 3.

An analysis of the obtained emittance diagrams (figure 4) enables us to conclude that at low acceleration voltages the beam extracted from the ion source is not focused whereas the further increase of the extracting voltage makes the beam an axial one.

Figure 3. Scheme of experimental setup for emittance measurements: 1 – ion source’s power supply; 2 – ion source’s cathode; 3 – ion source’s anode; 4 – power supply for positive biasing of the ion source with respect to the ground; 5 – sliding plate with the round diaphragm; 6 – ion source’s magnetic system; 7 – ballast resistance; 8 – sliding measuring probe; 9, 10 - ampermeters.
Figure 4. Emittance diagrams of corpuscular beam extracted from ion source at different acceleration voltages: a) $U_{acc} = 0$ kV and 1 kV; b) $U_{acc} = 4$ kV and 5 kV.

The “glowing ion beams” method [3], based on the visualization of the ion beam’s trajectory due to glowing of residual gas in the visible light range of spectrum, was implemented. The trajectories were registered using a camera. The results of imaging (figure 5) enabled us to identify the improvement of the focusing properties of the accelerating gap with increasing acceleration voltage.

To simulate the motion of particle beam in the accelerating gap a 2.5D relativistic electromagnetic particle-in-cell (PIC) code [4] was used. Figure 6 shows the results of computer simulations of deuteron beam motion in the accelerating gap of the neutron tube. The results correlate with the experimental results shown in figure 5.

Figure 5. Photographic image of the ion beam in the accelerating gap at various acceleration voltages: a) $U_{acc} = 0$ kV; b) $U_{acc} = -60$ kV. 1 – low-voltage electrode of the accelerating gap from the side of the ion source (ground potential), 2 – high-voltage electrode of the accelerating.
Figure 6. Projections of equipotential surfaces of electric field on the imaging plane, and the shape of the transported ion beam in the accelerating gap, shown with grey background, at various acceleration voltages: a) $U_{acc} = -10$ kV; b) $U_{acc} = -50$ kV. 1 – low-voltage electrode from the side of the ion source, 2 – high-voltage electrode of the accelerating gap from the side of the target, 3 – outlet of the ion source, 4 – the plane of target’s surface, 5 – the transported ion beam.

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