SELF-COMPENSATION OF THE FOCUSED ION BEAM SPACE CHARGE

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Magnitude and spatial distribution of the electric potential in the drift region are studied both theoretically and experimentally for the focused ion beam with average energy per a particle $\varepsilon_i \approx 2$ keV, beam current $\mathbf{I}_b \approx 10...300$ mA and the diameter in the crossover $d \approx 3$ mm. The gap of the electric potential for the compensating electrons is shown to be formed nearby the plane of the beam crossover. This allowed explaining the anomalous brightness and spatial distribution of the light emission of the gas in this region, as well as the deviation of ion trajectories from the ballistic ones.

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INTRODUCTION

A lot of fundamental and applied investigations of gas discharge plasmas as a source of intense particle beams are actively carried out at present. These studies are of a great importance since they are widely used in plasma accelerators and space propulsion engines, due to a number of technological applications, in high-current ion beams and neutral particles beam generation [1], plasma-surface interactions [2-3], etc.

At present, there are two ways for experimental simulation of plasma-surface interaction in a laboratory. Ion beam devices with a magnetic mass-separation provide high-energy ion beams, however, their particle flux is limited by value of $10^{19}...10^{20}$ m$^{-2}$s$^{-1}$. HiFIT ion beam device is capable to provide higher particle flux up to $3.6 \times 10^{21}$ m$^{-2}$s$^{-1}$ and heat flux up to 0.65 MW·m$^{-2}$, while mass-separation is excluded. In contrast, plasma devices can generate low energy particle fluxes $\approx 10^{22}$ m$^{-2}$s$^{-1}$ and heat fluxes in the range of 0.1...1 MW·m$^{-2}$. Therefore, the parameter range of particle fluxes $\approx 10^{22}$ m$^{-2}$s$^{-1}$ and heat fluxes $\approx 1$ MW·m$^{-2}$ is currently not achievable for most existing plasma and ion sources used in material research. However, in high heat and particle flux range, new phenomena related to ion-surface interactions, which can be extremely important for justifying the material selection, can be found.

To fill up the gap between the parameters provided by laboratory tools and ITER relevant conditions, our team from KKhNU has recently developed the FALCON ion source [4-6]. It is based on the design of closed drift thrusters (also known as Hall thrusters), which are typically used as space propulsions. Intrinsic characteristics of this type of ion sources are simplicity (that makes them affordable) and extremely high ion currents, both are tempting for use in material research. It is capable to generate ion beam that delivers high heat and particle fluxes to the sample surface. The fluxes are comparable or exceed ones provided by plasma devices. The FALCON ion source is capable to generate high-current ion beam ($\approx 5...300$ mA) focused into a spot of $\approx 3$ mm in diameter. The obtained ion current for H reaches 20 mA at pumping speed of 800 l/s, while ion beam for Ar peaks at 300 mA at pumping speed of 10,000 l/s. The beam intensity of the source strongly increases with the pumping speed of the vacuum system. This corresponds to the particle flux of $4 \times 10^{21}...3 \times 10^{23}$ m$^{-2}$s$^{-1}$ and heat flux of 0.3...21 MW·m$^{-2}$, which are comparable or significantly exceed the parameters of existing plasma and ion beam devices. These fluxes approach upper limits of ITER ones incident onto the divertor surface.

The ionized gas acceleration is well known to be accompanied by the separation of ions and electrons. This is one of the common features of all ion-beam systems. Electrical field arises as a result of eigen space charge of intense ion beam that drifts in the space free of external electromagnetic fields. This electrical field can be the reason of beam widening, slowing down and suppression in the case of virtual anode formation. The positive ion beam space charge compensation by electrons is necessary to eliminate these negative phenomena in the beam drift region. The secondary ion-electron emission from the beam collector or chamber wall as well as ionizing processes in the beam drift region can initiate the presence of electrons in the ion beam in the case of external electrons source absence.

The ions density in the focused beam crossover region can be in the range $1.5 \times 10^{10}...4.25 \times 10^{11}$ cm$^{-3}$. The space charge influence on the beam dynamics as well as focusing can be significant.

The aim of this paper is theoretical and experimental study of the focused cone-like beam space charge compensation, electrical potential and electrons density distribution in the beam crossover region.

STUDYING THE FOCUSED ION BEAM SPACE-CHARGE COMPENSATION

FALCON ion source was used in the experiments on beam space charge neutralization. No external electrons source was used. The beam compression coefficient obtained in this source indicated the absence of strong Coulomb ions repulsion in the transversal direction. This fact pointed out significant beam space charge
compensation in the absence of external source of electrons.

Electrons presence in ion beam can be caused by the ionizing processes within beam drift region, secondary ion-electron emission from the beam collector and electrons accumulation into the beam.

Ion trajectories deviation from ballistic ones and intensive spindle-shaped glow near the crossover region was observed (Fig. 1). These observations denoted on specific space charge and electrons density distribution in the focal region.

A number of theoretical and experimental investigations of electrical potential and electrons density distribution were carried out. Electrical potential distribution was studied on the base of analytical solution of Poisson equation. It was supposed that ion trajectories are ballistic ones and ion energy distribution function is Maxwellian one. Electrons density spatial distribution was defined with taking into account the Boltzmann distribution of electrons. The Poisson equation for the model of the ion beam with Maxwellian electrons is as follows:

\[
\Delta \Phi = -4\pi e \left[ n_i - n_{e0} \exp \left( \frac{e\Phi}{kT_e} \right) \right].
\]  

This equation is convenient to be transformed into the dimensionless form. Let introduce the following notations:

\[
\varphi = \frac{e\Phi}{kT_e}, \quad r = \frac{R}{R_{De}},
\]  

where R is radial coordinate, R_{De} is Debye length of electrons.

Poisson equation was solved in polar coordinates with zero-point in the vertex of a cone of the beam (crossover region): \( \alpha \) - polar angle, \( r \) – radius. The solution was found for three regions: 1) inside the cone of the beam: \( 0 < \alpha < \alpha_1 \); 2) in the beam region: \( \alpha_1 < \alpha < \alpha_2 \); 3) outside the beam: \( \alpha_2 < \alpha < \alpha_3 \). The following boundary conditions were applied: continuity of both electrical potential \( \varphi \) and its gradient \( \nabla \varphi \), and absence of the electric field on outer boundary. The solutions for the first and third regions were found in the form:

\[
\varphi = \ln \left[ \frac{2 \left( A^2 + B^2 \right)}{ar^2 ch^2 \left( A ln r + B \alpha + C \right)} \right],
\]  

where the constants of integration A, B, C could be found from the boundary conditions.

Poisson equation for the beam region took the form of cylinder Dirichlet problem in approach of strong beam space charge compensation. This Dirichlet problem was solved with the help of Fourier method of separation of variables [7]. The numerical solution for three regions in Cartesian coordinates is shown on Fig. 2. It showed qualitatively the spatial potential distribution in focused ion beam.

One can conclude from this qualitative solution that the potential well for electrons is formed in the focused beam crossover region. The well potential maximum is localized in the crossover region (Fig. 2).

Observed gas glow can be caused by neutral gas excitation as a result of interaction with beam ions as
Ion beam potential spatial distribution was measured by single Langmuir probe. The results of these measurements are presented on Fig. 3.

The equipotential lines topography and lines of equal electrons density are in good agreement with observed beam glow. Measured spatial distribution is in good qualitative agreement with the theoretical solution. This agreement confirmed the assumption that an electron bunch is formed near the crossover region. This bunch density is close to ion beam density. Electron bunch formation neutralizes the ion beam space charge and initiates the observed glow as a result of interaction with neutral gas.

Longitudinal potential asymmetry was observed during the measurements. It was the essential difference between theoretical and experimental data. This difference can be caused by the neglecting of the electrical fields influence on ion trajectories.

Essential longitudinal potential gradient after the beam crossover plane can initiate significant deviation of ions trajectories. Average transversal ion beam energy is \( \varepsilon = \varepsilon \cos 2\theta = 130 \ldots 170 \) eV under our experimental conditions and is comparable to maximum measured potential \( \approx 120 \) eV. Beam glow indicates the deviation of ion trajectories from the ballistic ones.

CONCLUSIONS

The focused ion beam potential spatial distribution was measured in beam drift region. The focused cone-like beam was generated by recently developed FALCON ion source.

Poisson equation for the beam was converted to cylinder Dirichlet problem in assumption of strong beam space charge compensation. This Dirichlet problem was solved with the help of Fourier method of separation of variables. Calculated topography of potential spatial distribution in a focused ion beam in arbitrary units was obtained. These theoretical calculations are in good agreement with measured potential spatial distribution.

An electric potential well for compensating electrons was shown to be formed near the beam crossover region. It allowed explaining the anomalous brightness, gas glow spatial distribution as well as ion deviation from the ballistic trajectories.

Obtained results could be taken into account for the high-current ion source development and high-current beams transport experiments.

REFERENCES


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АВТОКОМПЕНСАЦИЯ ПРОСТРАНСТВЕННОГО ЗАРЯДА СФОКУСИРОВАННОГО ИОННОГО ПУЧКА

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Проведено теоретическое и экспериментальное исследовании величины и пространственного распределения электрического потенциала в пространстве дрейфа сфокусированного ионного пучка со средней энергией частиц \( \varepsilon \approx 2 \) кэВ, током пучка \( I_b \approx 10 \ldots 300 \) мА и диаметром \( d \approx 3 \) мм в области кроссовера. Показано, что вблизи плоскости кроссовера пучка формируется электрическая потенциальная яма для компенсирующих электронов, что позволяет объяснить аномальную яркость и распределение свечения газа в этой области, а также отклонение траекторий ионов от баллистических.

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Проведено теоретическое и экспериментальное исследование величины та пространственного распределения электрического потенциала в простори дрейфа сфокусированного ионного пучка з середньою енергією часток \( \varepsilon \approx 2 \) кВ, струмом пучка \( I_b \approx 10 \ldots 300 \) мА та діаметром \( d \approx 3 \) мм в області кроссовера. Показано, що поблизу площини кроссовера пучка формується електрична потенціальна «ям» для компенсиюючих електронів, що дозволило пояснити аномальну яскравість та розподіл світіння газу в цій області, а також відхилення траекторій іонів від балістичних.