MASS-SEPARATION OF IMPURITIES IN THE ION BEAM SYSTEMS WITH REVERSED MAGNETIC BEAM FOCUSING

O.I. Girka, I.A. Bizyukov, A.A. Bizyukov, K.N. Sereda, S.S. Herashchenko
V.N. Karazin Kharkov National University, Kharkov, Ukraine
E-mail: alexxxgir@gmail.com

This paper describes the intrinsic capability of ion systems with reversed magnetic beam focusing for impurities mass-separation. Numerical calculation of the ion trajectory deviation with taking into account the experimental ion energy distribution function for hydrogen-oxygen gas mixture was carried out. It is demonstrated that O+ impurities which are present in the beam are separated and form the circle with a diameter of ≈6 mm. Therefore, the central part of the spot is free of impurities due to magnetic separation. As a result, the source generates steady-state hydrogen ion beam, which irradiates the surface with high heat and particle fluxes, which approach the upper limit for the flux range expected in a fusion reactor.

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INTRODUCTION

At present, there are two ways for experimental simulation of plasma-surface interaction in a laboratory. Ion beam devices [1] with a magnetic mass-separation provide high-energy ion beam, however, their particle flux is limited by value of $10^{19}...10^{20}$ $m^{-2}\cdot s^{-1}$. HiFIT ion beam device is capable to provide higher particle flux up to 3.6×10^{21} $m^{-2}\cdot s^{-1}$ and heat flux up to 0.65 $MW\cdot m^{-2}$, while mass-separation is excluded. In contrast, plasma devices can generate low energy particle fluxes $\approx10^{22}$ $m^{-2}\cdot s^{-1}$ and heat fluxes in the range of 0.1...1 $MW\cdot m^{-2}$. Therefore, the parameter range of particle fluxes $>10^{22}$ $m^{-2}\cdot s^{-1}$ and heat fluxes >1 $MW\cdot m^{-2}$ is currently not achievable for most existing plasma and ion sources used in material research. In the high heat and particle flux range new phenomena related to ion-surface interactions can be found. These phenomena can be extremely important for justifying the material selection.

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 [2-4]. 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 their simplicity (that makes them affordable) and extremely high ion currents, both are tempting for use in material research.

Small percentage of impurities in the beam can distort the results of the plasma-surface interactions experiments. That is why the beam purity is of a great importance for fusion-relevant material research experiments.

The aim of this paper is the numerical study of the capability for impurities mass-separation [5] of systems with reversed magnetic beam focusing.

EXPERIMENTAL TECHNIQUE AND CALCULATED IMPURITIES MASS-SEPARATION POSSIBILITY

The principal design of the FALCON ion source is presented in Fig. 1. It is based on design of Hall thrusters.

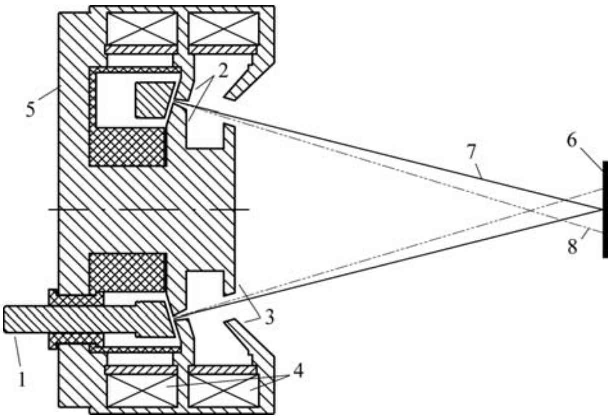

Fig. 1. The high-flux FALCON ion source principal design: 1 – anode; 2 – ballistic focusing cathodes; 3 – magnetic focusing lens; 4 – magnetic field coils; 5 – magnetic circuit; 6 – the target placed in the H^+ crossover plane; 7 – Hydrogen ions beam trajectory; 8 – impurities trajectory

The biased anode (1) and cathode at the ground potential (2) form the discharge gap designed to provide the drift of thin (≈1 mm) electron layer in crossed E×B fields. Main ionizing processes and acceleration of the ions occur within this electron drift layer. The ion source has an ion focusing system consisted of two parts. The first part is the ballistic focusing system, consisted of tilted anode (1) and cathode (2); it forms ion beam of the conical shape. The magnetic focusing system (3) focuses the ion beam further by cancelling a momentum, which ions gain in the magnetic field of the discharge gap. The reversed magnetic field configuration is powered by two magnetic coils (4); the magnetic circuit delivers the generated magnetic fluxes to the respective gaps.

Fig. 2 shows the distribution of the magnetic field strength along the discharge gap and the magnetic focusing system. It is possible to adjust beam focusing via varying the ratio of magnetic field fluxes in gaps of the magnetic conductors (varying the ratio of currents in the magnetic coils (4)). This allows precise compensating of the momentum gained by the ion in the discharge gap and, as a result, obtaining small ion beam spot on the target surface. Another advantage of this configuration is the intrinsic capability for mass-separation of the impurities (like oxygen). Ions of hydrogen and impurities obtain different momentum in the same magnetic field. As the result, the trajectories of hydrogen ions (7) cross the target (6) plane primarily in the central part of the target, while trajectories of the impurity ions (8) are located farther from the central part (see Fig. 1).

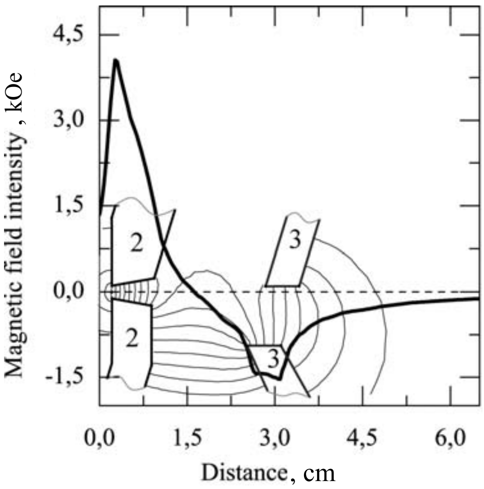

Fig. 2. The distribution of the magnetic intensity (bold solid line) that is perpendicular to the ion flux direction obtained via numerical calculations. Dashed line shows the ion flux. Thin lines show the lines of equal magnetic intensity

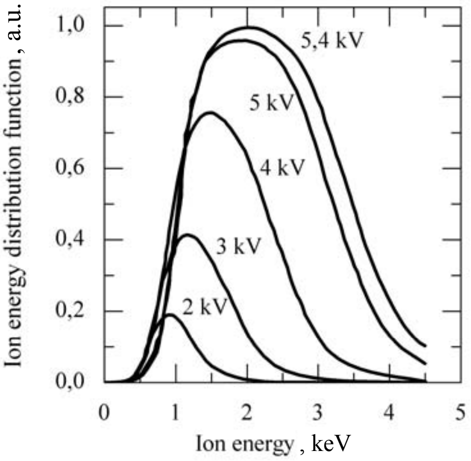

Fig. 3. The beam ion energy distribution function measured by energy analyzer. The resolution of energy analyzer is 30 eV

The energies of the beam ions are spread over the range from ≈650 eV and up to accelerating voltage of few kilo electron-volts; typical distribution of the ion energies is shown on Fig. 3. The peak of the distribution function is located at ≈40 % of the accelerating voltage.

Fig. 4 shows the calculated single particle location of ions bombarding the target surface [3]. One can see that heavy O^+ and Ar^+ ions are located within the narrow circle with the diameter of 6 mm. The target is etched primarily by hydrogen ions of average energy, which are of highest intensity.

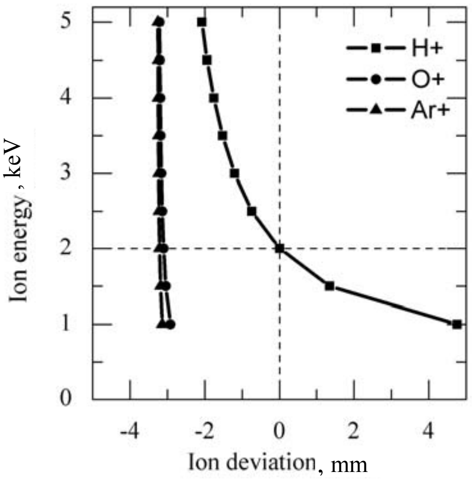

Fig. 4. Calculated deviation of ions from central point in the target plane as a function of ion energy for different ion species. Intersection of dashed lines shows the 2 keV H^+ crossover region

Fig. 5 shows the spatial distribution of H+ ion beam current in the 2 keV crossover plane. It was obtained via numerical calculation of the ion trajectory deviation with taking into account the experimental ion energy distribution function. Z axis shows the ratio between the current of ion with given energy and total beam current.

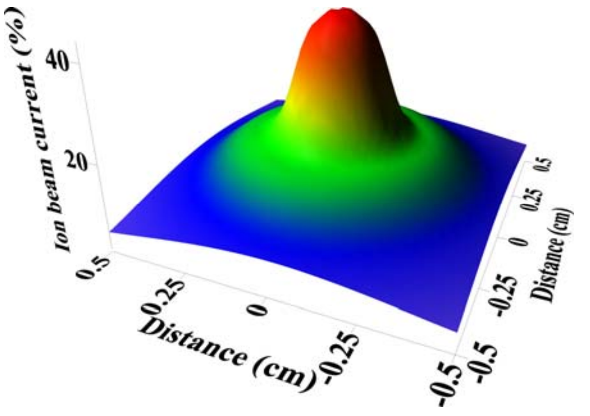

Fig 5. The spatial distribution of H+ ion beam current in the 2 keV crossover plane

Fig. 6 shows the result of numerical calculation of the ion trajectory deviation with taking into account the experimental ion energy distribution function for hydrogen-oxygen gas mixture.

The impurity is modelled by adding 5 % of oxygen to working gas. It is shown that 5 % O^+ impurities being present in the beam are separated and form the circle with the diameter of ≈6 mm. For material oriented experiments one can use pre-filtering of the working hydrogen gas with palladium filter to obtain best possible purity of the ion beam. Therefore, there are all the bases to conclude that magnetic separation provides the purity of the central part of the beam spot in the respect of impurities.

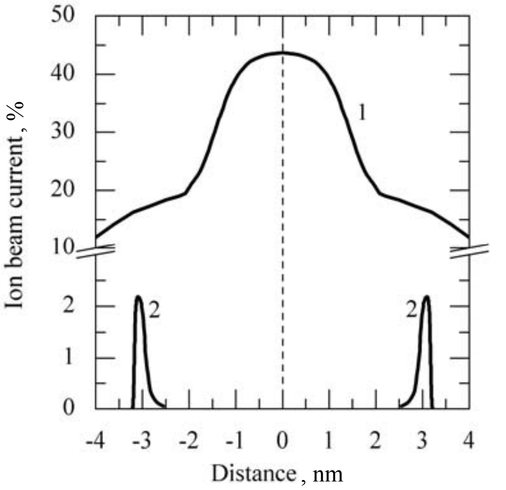

Fig. 6. The distribution of 95 % H+ (“1” b) and 5 % O+ (“2” b) ions specie in the H^+ 2 keV crossover plane

CONCLUSIONS

The numerical study of the intrinsic capability for impurities mass-separation of systems with reversed magnetic beam focusing was carried out. The ion trajectory deviation was studied numerically with taking into account the experimental ion energy distribution function for hydrogen-oxygen gas mixture. It was shown that O+ impurities in the beam are separated and form the circle with the diameter of ≈6 mm. Therefore, the central part of the spot is free of impurities due to magnetic separation. As the result, the source generates steady-state pure hydrogen ion beam, which irradiates the surface with high heat and particle fluxes, which approaches the upper limit for the flux range expected in a fusion reactor.

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

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МАСС-СЕПАРАЦИЯ ПРИМЕСЕЙ В ИОННО-ПУЧКОВЫХ СИСТЕМАХ С РЕВЕРСИВНОЙ МАГНИТНОЙ ФОКУСИРОВКОЙ ПУЧКА

А.И. Гирка, И.А. Бизюков, А.А. Бизюков, К.Н. Середа, С.С. Геращенко

Исследованы особенности масс-сепарации примесей в ионно-пучковых системах с реверсивной магнитной фокусировкой пучка. Численно рассчитаны отклонения траекторий ионов с учетом экспериментально измеренной функции распределения энергии ионов для водородно-кислородной газовой смеси. Показано, что примеси O^+ в пучке сепарируются и формируют кольцо диаметром ≈ 6 мм. Таким образом, центральная часть пучка чиста от примесей вследствие магнитной сепарации. В результате источник генерирует стационарные мощные потоки тепла и ионов водорода, которые близки по своим параметрам к потокам, ожидаемым на материалы стенки термоядерного реактора.

МАС-СЕПАРАЦІЯ ДОМІШОК В ІОННО-ПУЧКОВИХ СИСТЕМАХ З РЕВЕРСИВНИМ МАГНІТНИМ ФОКУСУВАННЯМ ПУЧКА

О.І. Гірка, І.О. Бізюков, О.А. Бізюков, К.М. Середа, С.С. Геращенко

Досліджено можливість мас-сепарації домішок в іонно-пучкових системах з реверсивним магнітним фокусуванням пучка. Чисельно розраховано відхилення траєкторій іонів з урахуванням експериментально зміненої функції розподілу енергії іонів для воднево-кисневої газової суміші. Показано, що домішки O^+ в пучку сепаруються та формують кільце діаметром ≈ 6 мм. Таким чином, центральна частина пучка є чистою від домішок унаслідок магнітної сепарації. В результаті джерело генерує стаціонарні потужні потоки тепла і іонів водню, які близькі за своїми параметрами до потоків, очікуваних на матеріали стінки термоядерного реактора.