POSSIBILITIES OF IMPROVING PARAXIAL BRIGHTNESS IN RF ION SOURCES

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The paraxial brightness in rf ion sources can be improved by redistributing the beam phase density, increasing the beam current density and using beam extraction systems with low aberrations. Experimental data are presented for the central region of a hydrogen or helium ion beam extracted from a helicon rf ion source with permanent magnets. A high-voltage (~6 kV) extraction structure of the rf ion source was investigated with imposed external magnetic field. The evolution of phase sets in the extraction structure with emission hole size approaching Debye radius was calculated for the helium plasma density of ~10^{12} cm^{-3} with imposed nonuniform external magnetic field. The calculations were performed involving data on ion energy spread (~25 eV) of the helicon rf ion source with permanent magnets.

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1. INTRODUCTION

At present the increase of ion beam brightness in accelerator-based microprobe (MP) facilities remains a challenging problem [1]. As the beam current at the target is determined as the product of ion beam brightness and phase volume formed by the object and angular slits in the probe forming system, a higher current for the maximum possible phase volume can be attained by using ion sources with high brightness. High beam brightness can be achieved by extracting the beam with high current density and low emittance. Since the total beam current is increased by increasing the emission current density, the emission aperture or the outlet aperture of the ion source, and hence, the normalized ion source emittance can be reduced. A necessary condition for the attainment of high current density in plasma ion sources is a high plasma density in the source. One way of increasing the plasma density is to create an efficient inductively coupled rf discharge with an external magnetic field by means of compact permanent magnet systems [2,3].

The beam brightness in many accelerators worldwide is highly heterogeneous, with strong flux in the paraxial region [4]. This is desirable for nuclear microprobe operation because probe forming lens systems optimized for large demagnitification magnitude can exploit high brightness of the paraxial region. By redistributing the beam phase density in the extraction zone, increasing the beam current density and using beam formation structures with low aberrations one can improve the paraxial beam brightness.

The normalized brightness of a source is defined the following expression ([5]):

$$B_n = \frac{I}{\beta^2\gamma^2 V_4} = \frac{2I}{\pi^2\varepsilon_{nx}\varepsilon_{ny}} = \frac{I}{\beta^2\gamma^2 S\Omega} = \frac{I}{(\pi\varepsilon N)^2}, \quad (1)$$

where I is the beam current, $\beta = \frac{v}{c}$, $\gamma = (1-\beta^2)^{-\frac{1}{2}}$, v is the ion velocity, c is light velocity, $V_4 = \int dxdydx'dy'$ is the four dimensional phase volume, $\varepsilon_{nx} = \frac{S_x}{\pi}\sqrt{W}$ and $\varepsilon_{ny} = \frac{S_y}{\pi}\sqrt{W}$ are the normalized emittance for the xx' and the yy' projection, respectively, S_x and S_y are the areas of the corresponding emittance contours, $S = \pi r^2$ is the ion emission area, $\Omega = \pi\alpha^2$ is the ion emission solid angle, W is the ion beam energy, $\varepsilon N = \beta\gamma r\alpha$ is the normalized ion source emittance, r is the emission radius, and α is the emission half-angle.

An ion source to be used in a nuclear microprobe has to provide the following principal characteristics:

- high brightness;
- ion beam current sufficient to have reasonable measurement time (~1 μA);
- steady ion-optical parameters of the ion beam (emittance, brightness);
- sufficiently long service life (~1000 hrs);
- minimum possible gas load on the vacuum system (extracting electrode hole ~1 mm, length ~3 mm);
- economical performance (the source has to operate with a minimum possible amount of working substance and minimum power input into the plasma (<500 W);
- small dimensions of the ion source itself, its power and gas supplies (if the source is placed under the conductor in a single-ended Van de Graff accelerator).

The rf ion source is regarded as one of the most promising devices suitable for use in NP. It has a number of advantages: fairly long service life (over 1000 hours), steady ion-optical parameters, high degree of gas ionization, small size, sufficiently high ion current (1-100 μA), and high brightness (B_n~0.1… 100 A/(m^{2}rad^{2}eV)).

The brightness of an ion beam extracted from a plasma ion source, in particular, rf source, depends on many factors, e.g.

– plasma characteristics inside the ion source (electron temperature T_e, ion temperature T_i, plasma density n and degree of gas ionization),
– plasma boundary properties,
– extracting gap design where the beam is formed,
– beam space charge,
– aberrations in the ion-optic structure forming the beam.

The maximal brightness of a source can be calculated as

$$B_{th} = \frac{j_+}{4\pi}\left(\frac{c}{V_{T_i}}\right), \qquad (2)$$

where $j_+ = 0.4qn_+\sqrt{\frac{2kT_e}{m_i}}$ is the emission current density, n_+ is the ion concentration in the unperturbed plasma near the emission hole, q is the ion charge, $V_{T_i} = \sqrt{\frac{kT_i}{m_i}}$ is the ion thermal velocity. It should be noted that there is a limitation on the current density imposed by the Child-Langmuir law [6,7].

High brightness plasma ion sources must have plasma with high ion density and high electron temperature T_e. One of the most promising ways to increase plasma density (and thus, brightness) in rf ion sources is the generation of a helicon discharge with enhanced ionization efficiency.

The total beam current depends largely on the transmission losses in the extraction channel, while emittance on the extractor dimensions, aberrations in the optic beam formation system and working gas pressure in the extraction channel. High-brightness rf ion sources have to be operated with lowest possible gas inlet and maximum gas ionization to provide a minimum increase in the normalized emittance in the ion extractor owing to ion charge exchange and ion-neutral collisions.

The increase in the plasma density is a necessary, yet insufficient condition for the beam brightness to be improved. As the plasma density is increased, there is a need in higher extracting voltage and additional beam focusing in the extractor to reduce beam losses considerably. This paper presents experimental data obtained for high-voltage (~ 6 kV) extractors of rf ion sources with imposed external magnetic field. The magnetic field is applied to stabilize the plasma boundary and to perform beam focusing in the emission hole region.

It seems promising to improve the beam transmission in high-brightness ion sources by using counter-bored extractors [8]. This work includes calculations of the phase set evolution in the counted-bored extraction structure with an emission hole approaching Debye radius, for helium plasma density of $5\cdot(10^{10}\ldots10^{12})$ cm^{-3} with imposed nonuniform magnetic field.

2. EXPERIMENTAL SETUP

Fig. 1 shows a layout of the experimental setup designed for measuring current, emittance, and extracted ion beam mass composition [9]. The rf ion source comprises a helicon plasma generator (in which a longitudinal magnetic field is generated by a compact magnetic system of permanent circular magnets), an extraction system and a movable source outlet aperture. In the extraction system the cathode channel has a 3 mm length and a 0.6 mm diameter. The tube is made from quartz and has an outer diameter of 30 mm and length of 260 mm. The tube length was increased to implement a helicon discharge in an external magnetic field. The ion source has 4-turn helical antennas (copper wire of 4 mm diameter). The helicon plasma generator is designed to produce plasma of $10^{11}\ldots10^{13}$ cm^{-3} in the vicinity of the ion source emission hole. The movable source outlet aperture is used to achieve emittance with the highest integral phase density. Inside the diagnostic chamber there is an emittance-measuring device consisting of a plate with a series of holes and a movable vertical wire probe. The distance from the probe to the emission hole and to the source outlet aperture is 1000 mm and 900 mm, respectively. The plate with holes can be removed from the measurement area, permitting the beam current profile and the total current to be measured using a Faraday cup.

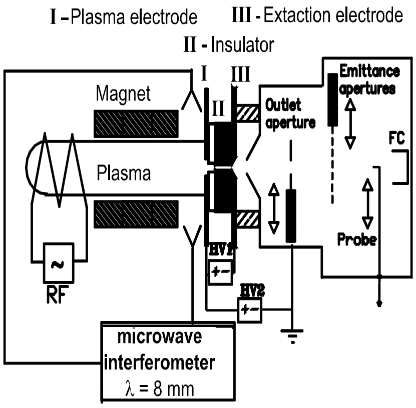

***Fig. 1.** Experimental setup*

3. TESTS OF AN ION SOURCE

In the source (Fig. 1) an rf discharge is set up with an external magnetic field and hydrogen plasma density of 10^{11} cm^{-3} for an rf power input into the plasma of 150 W (f_{rf}=27.12 MHz). The plasma density was determined from the emission current equation. The ion current density in the extracting electrode in the source was ~ 30 mA/cm^2 for 0.6 mm emission hole diameter with high percentage of protons in the beam (~80 %). As the rf power input is below 150 W, the optimized neutral gas pressure for the highest percentage of protons and the highest current density is normally 2…10 mTorr. High-brightness rf operation was achieved with the hydrogen beam brightness being 65 A/(m^{2}rad^{2}eV). For a fixed beam current the increase in brightness can be achieved by increasing the phase density of the beam

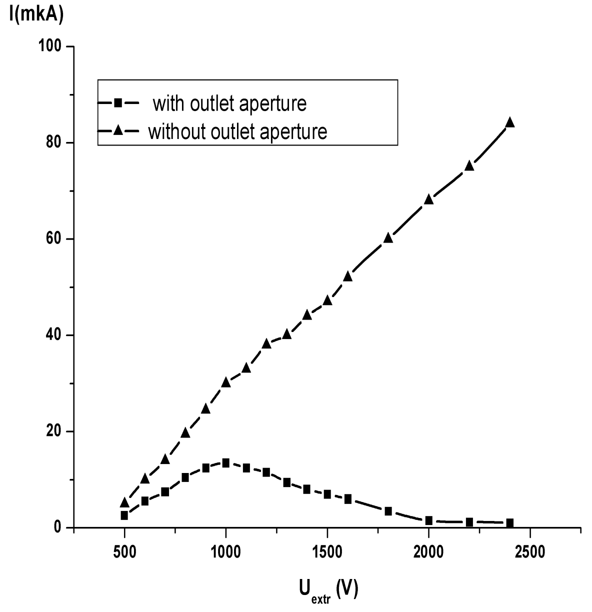

Fig. 2. *Measured hydrogen ion current versus the extracting voltage (P_{rf}=150 W, U_{acc}= 15 kV) with a 1.5 mm outlet aperture and without it*

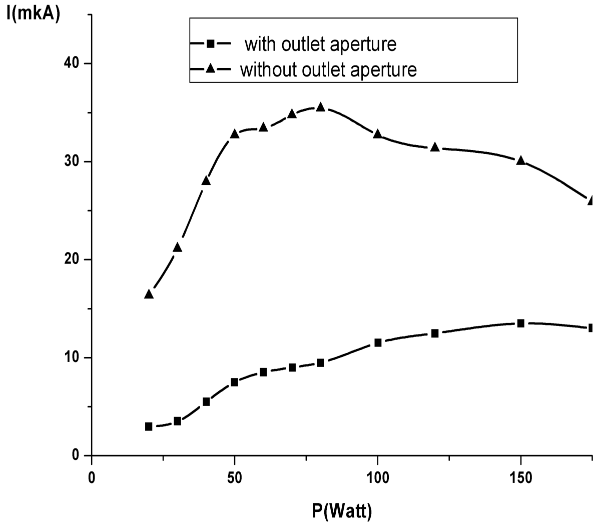

Fig. 3. *Measured hydrogen ion current versus the rf power (p=5 mTorr, U_{extr}= 1 kV, U_{acc}= 15 kV) with a 1.5 mm outlet aperture and without it*

core with subsequent beam collimation. In Fig. 2 the hydrogen ion current is represented as a function of the extracting voltage for stable operation mode of the rf ion source (P_{rf}=150 W, U_{acc}= 15 kV) with a 1.5 mm outlet aperture and without it. As can be seen in the figures, there are real opportunities for improving the current density in the vicinity of the source outlet aperture by means of an additional beam focusing system.

In Fig. 3 the hydrogen ion current is represented as a function of the rf power for optimal operation mode of the rf ion source (p=5 mTorr, U_{extr}= 1 kV, U_{acc}= 15 kV) with a 1.5 mm outlet aperture and without it.

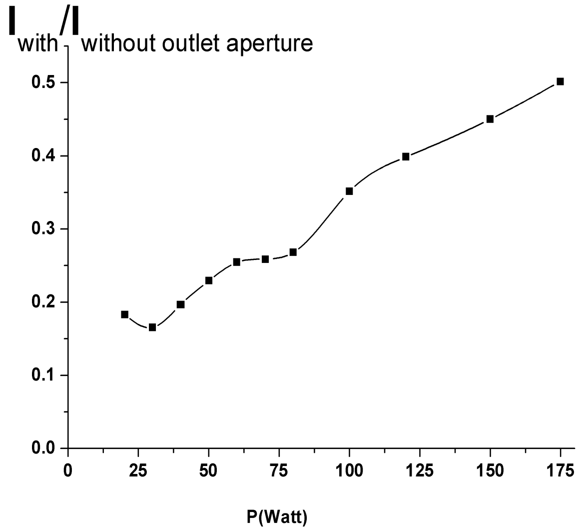

Fig. 4. *Fraction of ion current for central part beam versus the rf power (p=5 mTorr, U_{extr}= 1 kV, U_{acc}= 15 kV)*

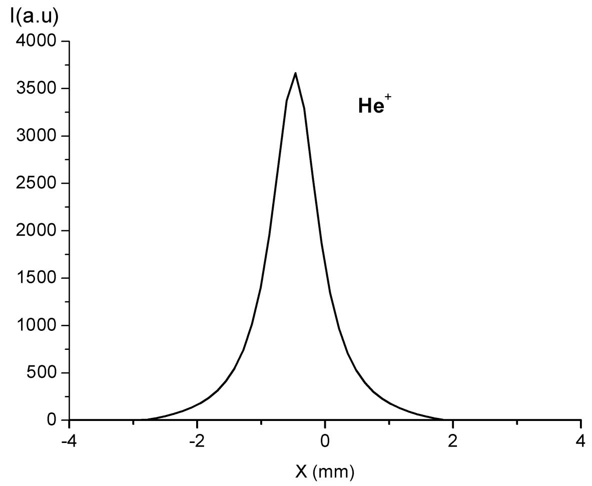

Fig. 5. *Measured He^+ ion beam profile for helicon operation mode of the rf ion source*

This circumstance can be ascribed to differing structure of the plasma density profiles in the H-mode and W-mode. The highest absorption of the rf-power in the W-mode occurs along the source axis while in the H-mode near the antenna [10].

4. TESTS OF EXTRACTION SYSTEMS

Current extracted from an ion source depends upon various parameters: extraction probe voltage; extraction geometry, plasma density which in turn depends on rf power, gas pressure and magnetic field. During the present experiment helium beam current from helicon ion source (see Fig. 1) was measured for three different extraction systems with a nonuniform magnetic field. The magnetic field structure and its magnitude are given in [3]. In the extraction systems the cathode channel has a 3 mm length and a 0.6 mm diameter.

In the first extraction structure (extractor1) the cathode is separated from the plasma by quartz disk with a 1 mm hole and 1 mm thickness. In Fig. 6 the helium ion current is represented as a function of the

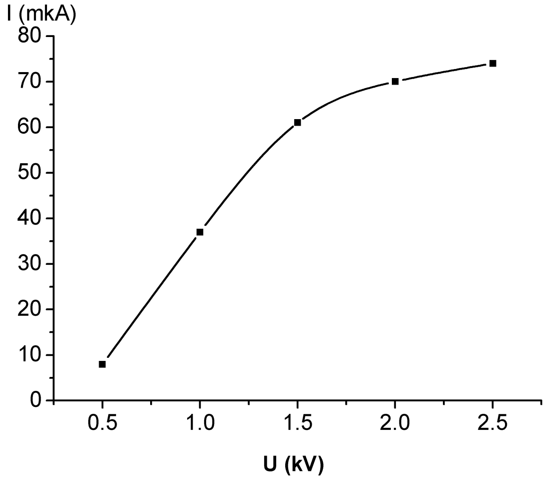

Fig. 6. *Measured helium ion current versus the extracting voltage for high-brightness operation mode of the helicon ion source with extractor1 (P_{rf}=100 W, p=5 mTorr)*

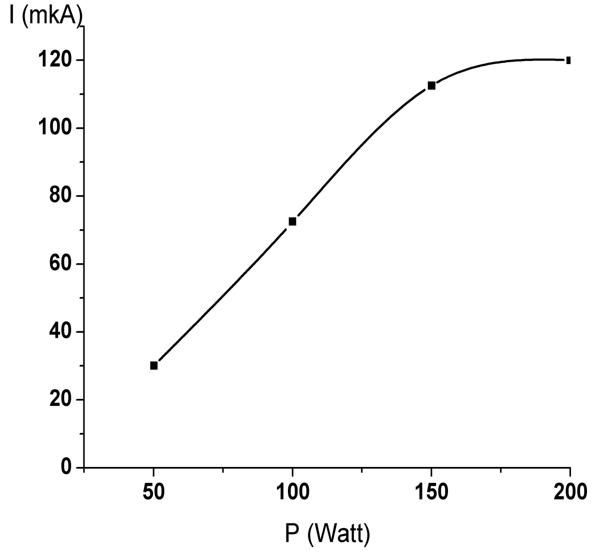

Fig. 7. *Measured ion current versus rf power for stable operation mode of the helicon ion source with extractor1 (U_{extr}=2.4 kV)*

extracting voltage for high-brightness operation mode of the helicon ion source (P_{rf}=100 W, p=5 mTorr).

The measured ion current versus rf power for extraction voltage U_{extr}=2.4 kV is plotted in Fig. 7.

As can be seen in the figures, measured ion current is higher than needed for operation mode of accelerator-based microprobe (0.1…10 μA). The decrease in the ion current (for a fixed current density) can be achieved by using outlet aperture (see Fig. 2) or reducing emission hole for fixed another parameters of an extraction structure.

In the second extraction structure (extractor2) we use a tungsten plasma electrode (see Fig. 1) with an emission hole of 0.6 mm. In Fig. 8 the helium ion current is represented as a function of the extracting voltage

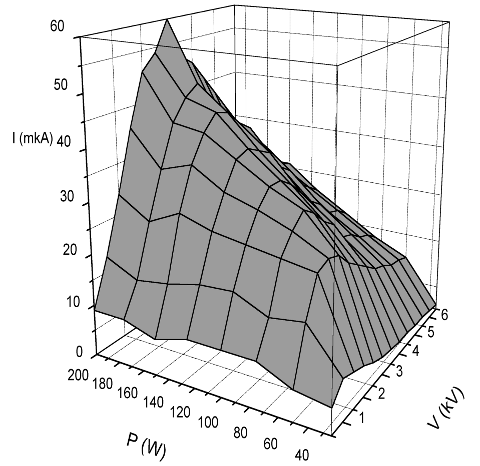

Fig. 8. *Measured helium ion current versus the extracting voltage and rf power for stable operation mode of the helicon ion source with extractor2 (p=5 mTorr)*

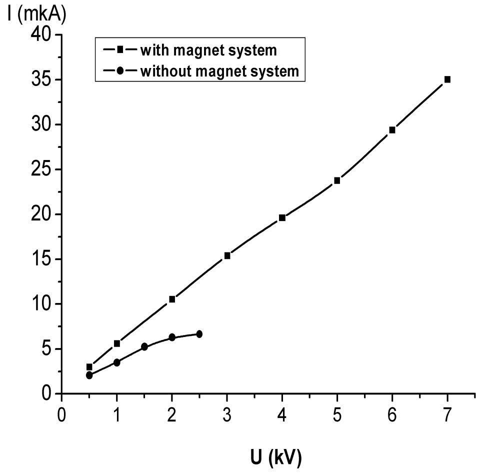

Fig. 9. *Measured helium ion current versus the extracting voltage for the helicon ion source with extractor3 (P_{rf}=100 W, p=5 mTorr)*

voltage and rf power for a helicon ion source with extractor2 (p=5 mTorr). As can be seen in the figures, there are real opportunities for further reduction of the diameter of the emission hole.

In Fig. 9 the helium ion current is represented as a function of the extracting voltage for operation mode (P_{rf}=100 W, p=5 mTorr) of the helicon ion source with high-voltage extraction system (extractor3) with a hole of 1.2 mm and increased thickness of insulators (see Fig. 1) from 1 mm to 2.4 mm.

The high-voltage extractors with imposed magnetic field are attractive for use in rf ion source with high plasma density (~10^{13} cm^{-3}). The results obtained show that by applying a nonuniform magnetic field of special configuration [3] the plasma boundary can be stabilized. This permits steady operating conditions of the ion source to be achieved in which a cathode is separated from the plasma by a Duran glass disk with a 1.2 mm hole and 2.4 mm thickness for the extracting voltage up to 7 kV (without magnetic field non higher than 2.5 kV).

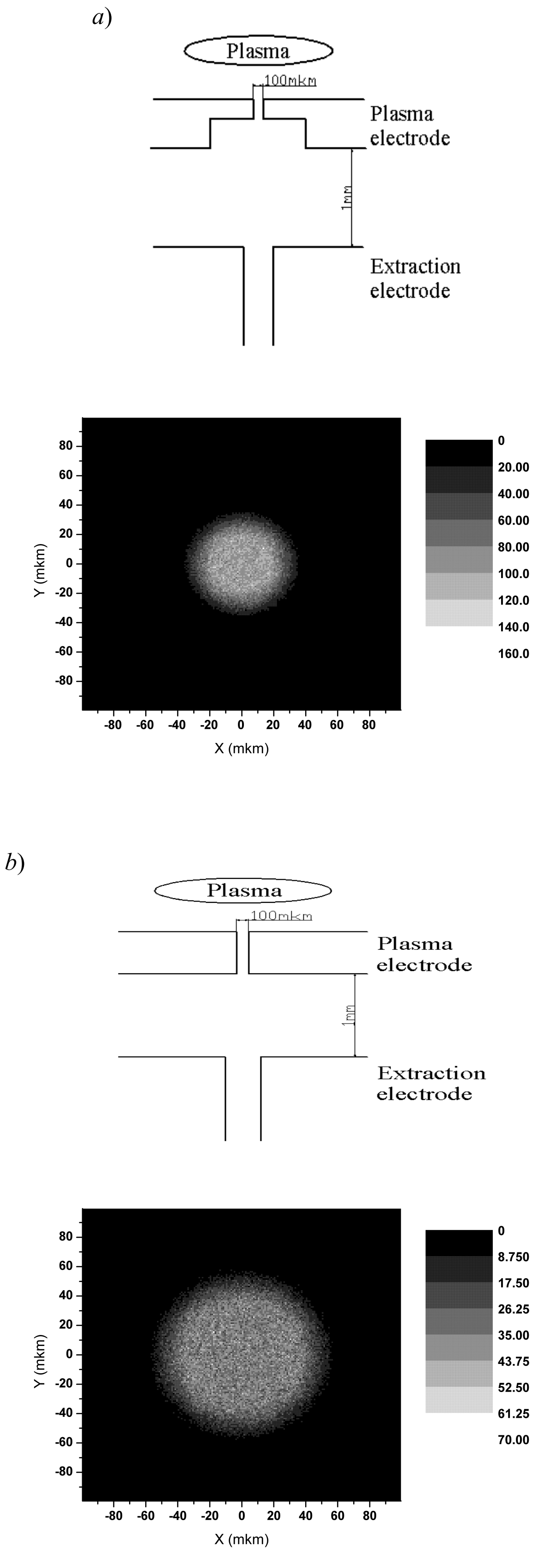

Fig. 10. *Calculated image of the ion beam in the vicinity of the extraction electrode for counter-bored (a) and "through-hole" (b) extractors*

5. CALCULATIONS OF THE PHASE SET EVOLUTION IN THE COUNTER- BORED EXTRACTION STRUCTURE

The evolution of phase sets in the extraction structures (counter- bored and conventional "through – hole"[8]) was calculated for an emission hole of 100 μ m. The calculations were performed involving data of the helicon rf ion source with permanent magnets [3]. The phase set degradation due to aberrations in the rf ion source was simulated with allowance for four-order approximation in series expansion of the electrostatic potential and third order approximation in series of the magnetic fields.

Calculations were performed of the nonlinear beam dynamics in the axially symmetric electrostatic and magnetic fields in the beam formation system. In the calculations the matrix method was used to solve the nonlinear equation of motion [11,12]. The electrostatic and magnetic fields were calculated by means of POISSON–SUPERFISCH [13] and LAPLACE-2 [14]. Fig. 10 represents the calculated image of the ion beam in the vicinity of the extraction electrode for two different extractors (counter- bored and "through – hole").

As is evident from the figures, the counter- bored extractor is preferable for use in high-brightness ion source. There is an improvement of the beam transmission in ion sources at expense of counter-bored extractors.

6. SUMMARY

There are real possibilities for further improvement brightness of commercially available rf sources for nuclear microprobes. The increase in the beam current density and use of beam formation structures with high transmission and low aberrations can improve the paraxial beam brightness. The counter- bored extractor is preferable for high-brightness ion sources owing to improved beam transmission in the extraction structure.

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ВОЗМОЖНОСТИ ПОВЫШЕНИЯ ОСЕВОЙ ЯРКОСТИ ВЧ-ИСТОЧНИКОВ ИОНОВ

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Рассмотрены возможности повышения осевой яркости ВЧ-источника ионов за счет перераспределения фазовой плотности пучка, повышения плотности тока пучка, применения систем экстракции с низкими аберрациями. Приведены экспериментальные данные по исследованию характеристик приосевой области пучка ионов водорода, гелия, аргона, извлекаемого из геликонового ВЧ-источника ионов с системой постоянных магнитов. Приведены результаты исследования высоковольтной (~6 кВ) системы экстракции ВЧ-источника ионов при наложении внешнего магнитного поля. Проведен расчет эволюции фазовых множеств в системе экстракции с эмиссионным отверстием порядка радиуса Дебая для плотности гелиевой плазмы (~10^{12} см$^{-3}$) при наложении внешнего неоднородного магнитного поля. В расчетах использованы данные об энергетическом разбросе ионов (~25 эВ) геликонового ВЧ-источника ионов с системой постоянных магнитов.

МОЖЛИВОСТІ ПІДВИЩЕННЯ ОСЬОВОЇ ЯСКРАВОСТІ ВЧ-ДЖЕРЕЛА ІОНІВ

С.М. Мордик, Д.П. Шульга, В.І. Мірошниченко, В.Ю. Сторіжко, В.І. Возний

Розглянуто можливості підвищення осьової яскравості ВЧ-джерела іонів за рахунок перерозподілу фазової щільності пучка, підвищення щільності струму пучка, застосування систем екстракції з низькими абераціями. Приведено експериментальні дані по дослідженню характеристик привісьової області пучка іонів водню, гелію, аргону, що витягається з геліконового ВЧ джерела іонів із системою постійних магнітів. Приведено результати дослідження високовольтної (~6 кВ) системи екстракції ВЧ-джерела іонів при накладенні зовнішнього магнітного поля. Проведено розрахунок еволюції фазових множин у системі екстракції з емісійним отвором порядку радіуса Дебая для щільності гелієвої плазми (~10^{12} см$^{-3}$) при накладенні зовнішнього неоднорідного магнітного поля. У розрахунках використані дані про енергетичний розкид іонів (~25 еВ) геліконового ВЧ-джерела іонів із системою постійних магнітів.