Multiaperture ion beam extraction from gas-dynamic electron cyclotron resonance source of multicharged ions[a]

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Electron cyclotron resonance ion source with quasi-gas-dynamic regime of plasma confinement (ReGIS), constructed at the Institute of Applied Physics, Russia, provides opportunities for extracting intense and high-brightness multicharged ion beams. Despite the short plasma lifetime in a magnetic trap of a ReGIS, the degree of multiple ionization may be significantly enhanced by the increase in power and frequency of the applied microwave radiation. The present work is focused on studying the intense beam quality of this source by the pepper-pot method. A single beamlet emittance measured by the pepper-pot method was found to be $\sim 70\ \pi$ mm mrad, and the total extracted beam current obtained at 14 kV extraction voltage was ~ 25 mA. The results of the numerical simulations of ion beam extraction are found to be in good agreement with experimental data. © *2008 American Institute of Physics.* [DOI: 10.1063/1.2805640]

I. INTRODUCTION

This work continues the research aimed at searching for ways of forming high quality, intense, multicharged ion beams by using very high plasma density electron cyclotron resonance (ECR) sources based on the quasi-gas-dynamic plasma confinement in a magnetic trap.[1–4] The quasi-gas-dynamic regime of confinement[5–8] is characterized by high electron–ion collision frequency, $\nu_{ei} \gg V_S/L$, resulting in the filled electron loss cone. Here, L is the characteristic length of a magnetic trap and V_S is the ion-sound speed. Although the quasi-gas-dynamic regime of plasma confinement provides large ion flows from the magnetic plug, the averaged ion charge is typically lower, compared to that in the magnetic trap with the classical regime of confinement. The degree of multiple ionization can be, however, enhanced by the increase in power and frequency of the applied microwave radiation.[2] Therefore, ECR ion sources utilizing the concept of the quasi-gas-dynamic confinement (ReGIS) provide opportunities for extracting intense and high-brightness multicharged ion beam and look very promising for a variety of applications, ranging from industrial to accelerator physics and heavy ion fusion applications, where high intensity ion beams with moderate averaged charge are required. In the present work, we report new results obtained on the SMIS 37 experimental setup, which is a ReGIS built at the Institute of Applied Physics, Russia. Previously, it was demonstrated in Ref. 2 that the current density of a multicharged ion flow leaving the plasma of SMIS 37 may reach $\sim 1\ \text{A/cm}^2$. The present work is focused on studying the quality of the beam formed in a multiaperture (13 holes) extraction system. The pepper-pot method used in this work for diagnostics provides much better accuracy than that in Ref. 3. The experimental results show that the beamlets are separated in the phase space, providing high quality of the total beam, and a single beamlet emittance is accurately estimated.

II. HIGH CURRENT ION BEAM FORMATION

The ion beam is extracted from an ECR plasma confined in a cusp trap and created by a 37.5 GHz gyrotron radiation with a maximum power of 100 kW injected in pulses up to 1.5 ms duration. It has been shown[3] that, under these conditions, a quasi-gas-dynamic confinement regime is realized with a plasma density of about $10^{13}\ \text{cm}^{-3}$, an electron temperature $T_e = 50-100$ eV, and an ion lifetime of about 10 μs. Having been created in the trap, the plasma spreads along the magnetic field lines, along the system axis, and the density of the plasma flow falls down from its maximum value in the trap plug to low values in the region of weak magnetic field (see Fig. 1). This makes it possible to vary the ion current by placing the extracting aperture in plasmas with different densities.[1,2] The current density of interest in our studies ranged from $j = 100$ to $300\ \text{mA/cm}^2$. It should be noted that the optimal regime of extraction was observed when the extraction electrode was placed in the plasma spreading zone where the magnetic field is low ($B \sim 0.1$ T); hence, the influence of the magnetic field on the ion extraction was negligible.

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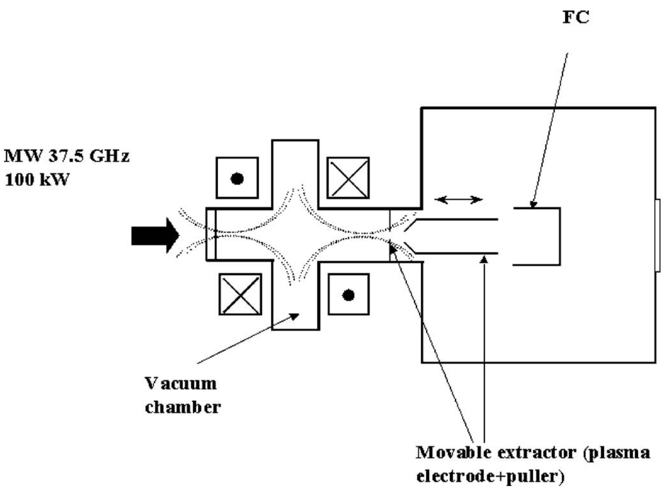

FIG. 1. Experimental setup of SMIS 37.

A beam is formed by a multiaperture extraction system with 13 holes 3 mm in diameter in each of the three electrodes: plasma electrode (PE), screening electrode (SE), and ground (GE) electrode described in Ref. 9. The distance between PE and SE was 5 mm (between SE and GE, 10 mm) and the length of the grounded electrode (puller) was 10 cm. The extracted beam current I_{FC} was measured by the Faraday cylinder placed at the puller exit (see Fig. 1). Figure 2 shows the dependence of the extracted beam current I_{FC} on the extraction voltage U. The corresponding ion charge state distribution in the extracted beam is presented in Fig. 3. Typical oscillograms of I_{FC} and I_P (current to puller) are shown in Fig. 4. It is evident that changing the gap between the PE and SE as well as the distance from the magnetic plug to PE results in the variation of the extracted beam current. The latest experiments with an improved geometry of the extraction system let us achieve a beam current to the Faraday cylinder of 100 mA with almost the same ion charge state distribution, as the one shown in Fig. 3.

III. BEAM EMITTANCE MEASUREMENTS

Besides the amount of extracted beam current, the beam transverse emittance is of great practical interest. In this section, we present results of beam emittance measurements by the pepper-pot method. The scheme of the experiments is shown in Fig. 5. A pepper pot was placed at a distance of l_p=240 mm downstream from the puller exit, perpendicular to the direction of the ion beam propagation. The pepper pot was designed as a metal screen with nine small holes of diameter d_p=0.3 mm at a distance of S=7 mm from each other, arranged as shown in Fig. 5. Behind the pepper pot, a CsI scintillation plate was placed at a distance of l_s =100 mm. Ions passing through the pepper-pot holes bombard the scintillator, stimulating the CsI plate luminescence, which was registered by a camera through a glass window.

A typical picture of scintillator luminescence is shown in Fig. 6. The image was obtained for an extraction voltage of U=13.6 kV; it comprises nine sets consisting of 13 spots each. The sets correspond to 9 holes in the pepper pot and the spots correspond to 13 holes in the extraction system.

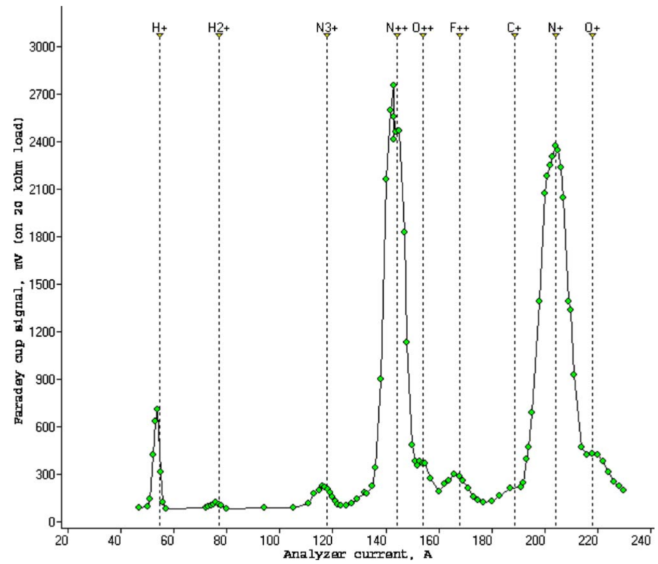

FIG. 3. (Color online) The ion charge-state distribution.

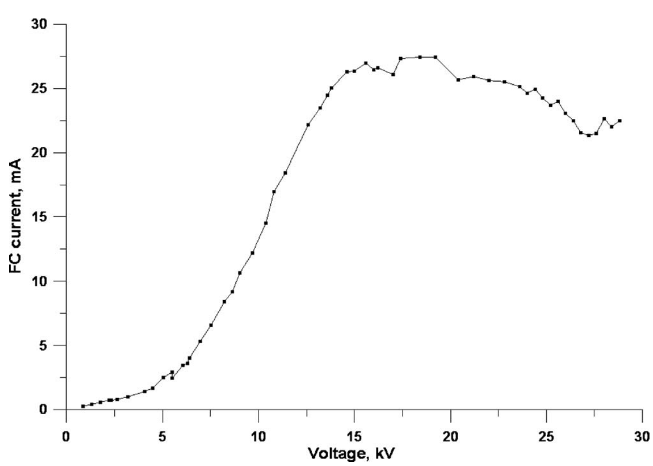

FIG. 2. Extracted ion beam current averaged over 500 μs vs extraction voltage.

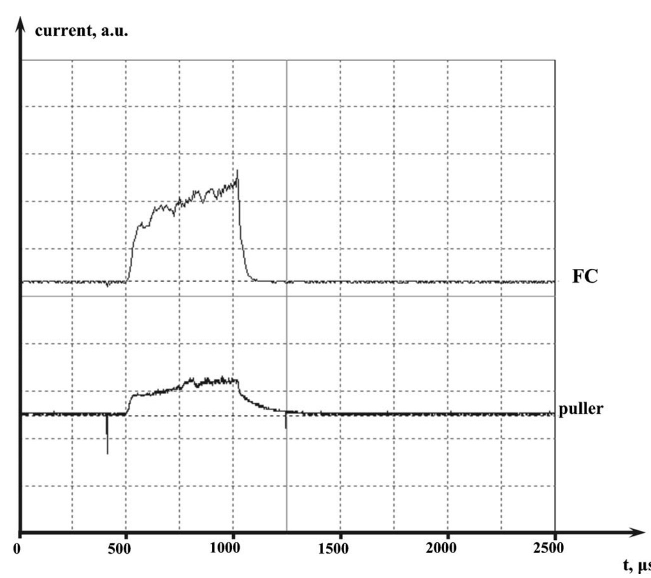

FIG. 4. Oscillograms of the current to the Faraday cylinder (upper trace) and to the puller (lower trace).

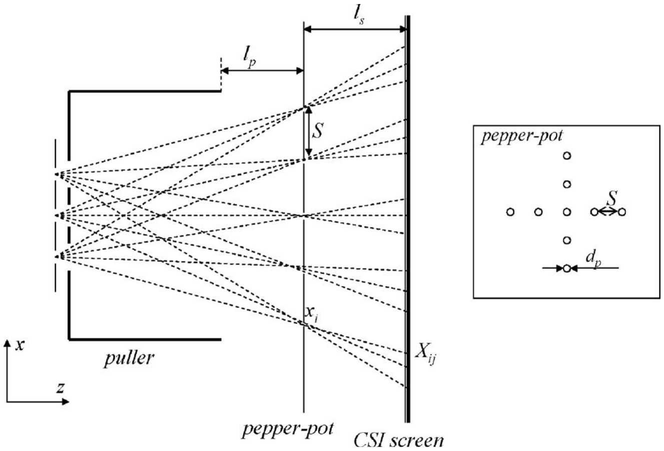

FIG. 5. Scheme of experimental beam emittance measurements by the pepper-pot method (cross section at $y=0$). The small graphical insert on the right corresponds to pepper-pot design.

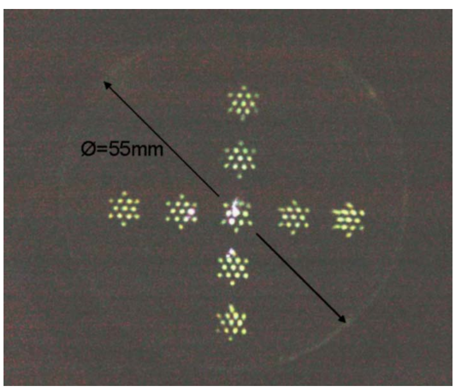

FIG. 6. (Color online) Photograph of the scintillator plate luminescence. Extraction voltage $U=13.6$ kV.

The process of spot formation is depicted schematically in Fig. 5. Several extremely bright spots in the center of the photograph (Fig. 6) correspond to the image of plasma discharge.

The transverse size of each spot is determined not only by the size of holes in the pepper pot but also by the thermal velocity spread of a beamlet, caused by a nonzero ion temperature within the plasma. Detailed analysis of the image (Fig. 6) provides fruitful information about the beam phase space structure, in particular, allows one to estimate its transverse emittance. Let us reconstruct, for example, the $x-V_x/V_z$ phase space of the beam at the location of the pepper pot. The normalized transverse velocity of the jth beamlet, $v_j=V_{xj}/V_z$, at the site of the ith small hole in the pepper-pot with coordinate x_i, may be determined as $v_j=(X_{ij}-x_i)/l_s$ (see Fig. 5). Here, V_z is the longitudinal ion velocity, and X_{ij} is the coordinate of the spot center produced by the jth beamlet ions passing through the ith hole in the pepper pot. The reconstructed $x-V_x/V_z$ beamlet phase spaces for three central and four beamlets of the first lower row are shown in Figs. 7(a) and 7(b), respectively. Figure 7 show that the phase portrait of the total beam is represented by a combination of almost parallel straight stripes of thickness Δv_T, where each stripe corresponds to a single beamlet phase space. The stripe width Δv_T determines the thermal velocity spread of a single beamlet. It should be noted that only a small fraction of the total beam passes through the holes in the pepper pot; hence, space-charge forces may be neglected when the ions travel from the pepper pot to the scintillator. In the case of zero velocity spread, $\Delta v_T=0$, a spot diameter on the CsI plate, d_s^0, given by straight line ion motion would be $d_s^0=d_p(1+kl_s)$, where $k\approx 3$ mrad/mm is the beamlet slope in the phase space (Fig. 7). However, a spot diameter d_s was found to be almost twice as large, $d_s\approx 2d_s^0=0.76$ mm. This difference is apparently due to the presence of thermal spread, Δv_T, which can now be calculated as

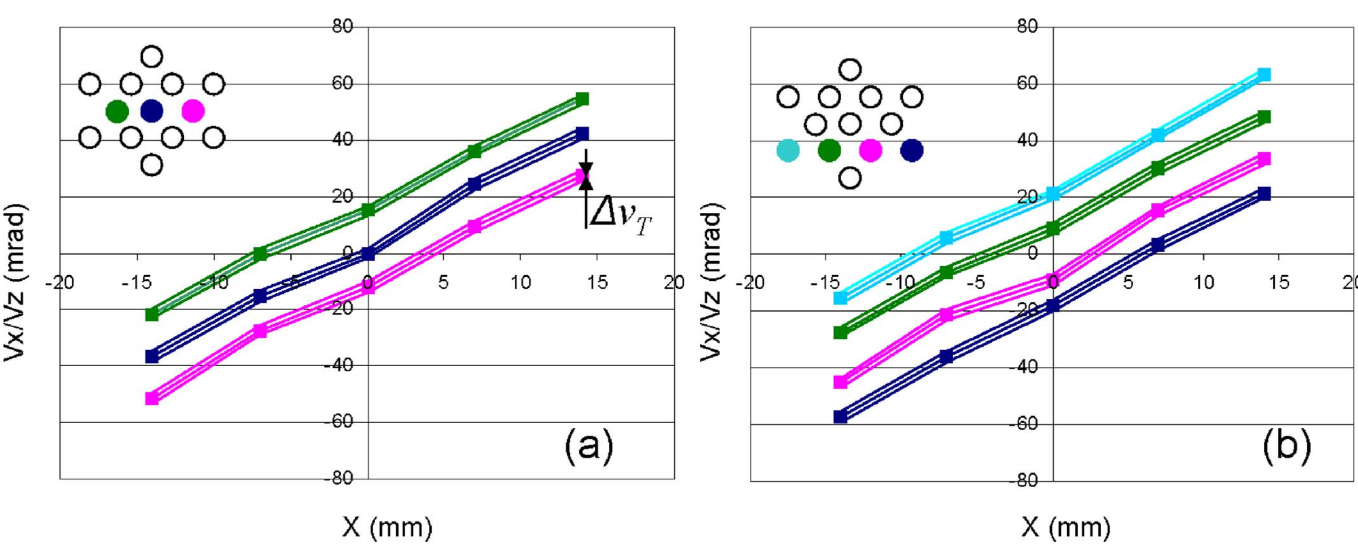

FIG. 7. (Color online) The $x-V_x/V_z$ beamlet phase portraits reconstructed from Figs. 5 and 6. (a) Phase portraits of the three central beamlets (see the corresponding small graphical insert) and (b) phase portraits of the four beamlets of the first lower row (see the corresponding small graphical insert).

$$\Delta v_T = (d_s - d_s^0)/l_s \approx 3.6 \text{ mrad}. \quad (1)$$

The area A of a single beamlet in the $x - V_x/V_z$ phase space can be estimated as $A \sim L\Delta v_T$, where $L \sim 65$ mm is the total beam aperture at the location of the pepper pot. The average emittance of a single beamlet is given by

$$\varepsilon_x \sim L\Delta v_T/\pi \ (\pi \text{ mm mrad}), \quad (2)$$

and the substitution of numerical values gives $\varepsilon_x \sim 70\ \pi$ mm mrad. It is a matter of considerable interest to estimate the ion beam temperature T_i. Assuming Maxwell distribution of ions in velocity and a uniform (step function) beam density profile, the transverse beam emittance is given by[10] $\varepsilon_x = d_{PE}\sqrt{T_i/(m_i V_z^2)}$ and, assuming the spread caused by the nonzero ion temperature, we readily obtain $T_i \sim 25$ eV. Here, m_i is the ion mass, and d_{PE} is the diameter of a single hole in the plasma electrode.

The measuring error of the spot diameter d_s was ~20%, so, according to Eq. (1) and the fact that d_s is more or less close to $2d_s^0$, one can assume that the measuring error of Δv_T and so of ε_x was about 40%–50%. Thus the measuring error given by this method is big enough. Also, note that only the central part of the beam is covered by the pepper-pot holes; therefore, there is no information about the phase-space structure of the beam edge in the presented experimental data. However, the latest experimental setup for the emittance measurements has the pepper-pot plate placed much closer to the puller exit; hence, it now covers the whole beam. The results of these experiments are to be reported soon.

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