Experiments on intense ion beam formation with an inhomogeneous electric field

S S Vybin, V A Skalyga, I V Izotov, S V Golubev, S V Razin, R A Shaposhnikov, M Yu Kazakov, A F Bokhanov and S P Shlepnev

Institute of Applied Physics of Russian Academy of Sciences, 46 Ulyanov Str., 603950, Nizhny Novgorod, Russia

E-mail: vybinss@ipfran.ru

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Abstract
The high efficiency of a new ion beam extraction system with a strongly inhomogeneous electric field has been experimentally demonstrated. Previously, this approach was proposed and analysed numerically by the authors. The experiment was carried out using a pulsed high-current electron-cyclotron resonance (ECR) ion source SMIS 37 with high frequency (37.5 GHz) and high power (100 kW) microwave plasma heating. The accelerating field strength is increased (when compared to a flat or a quasi-pierced geometry) in the plasma meniscus region due to its inhomogeneity. It allows for the increase of the ion acceleration rate and for expansion of the available range of current densities with effective ion beam formation. The experiment demonstrated the main advantages of this approach, such as: a significant decrease in the optimal accelerating voltage for certain values of current density; a possibility of ion beam formation with previously inaccessible current densities; a significant decrease in the ion flux to the puller in non-optimal modes of ion beam formation. Proton beams with a current density of up to 1.1 A cm$^{-2}$ were obtained for the first time with an ECR ion source.

Keywords: extraction system design, high current ion beam, proton beam, ion source

(Some figures may appear in colour only in the online journal)

1. Introduction
This article is devoted to the experimental verification of the proposals formed in reference [1]. The SMIS 37 [2] pulsed facility was chosen as an experimental base. It is a high-current ion source based on plasma of an electron cyclotron resonance (ECR) discharge, sustained by the radiation of a gyrotron with a frequency of 37.5 GHz and a power of up to 100 kW in a magnetic trap of a simple mirror configuration. The combination of high frequency and high microwave power allows for the formation of dense plasma fluxes (ion flux up to 10 A cm$^{-2}$) through the magnetic trap plugs, which are used to obtain ion beams with record brightness for ECR ion sources.

SMIS 37 is a promising ion source with the so-called quasi-gas-dynamic plasma confinement mode [3, 4], so-called a gas-dynamic ECR ion source [2]. Earlier, SMIS 37 demonstrated the possibility of generating beams with unique parameters: proton beams with a current of up to 500 mA at a current density of 800 mA cm$^{-2}$, a fraction of atomic ions of more than 95%, and a normalized rms emittance not exceeding 0.1π mm mrad [5]; beams of multiply charged nitrogen and argon ions with current up to 200 mA and an average charge of 4–5 [6].

Despite the record level of previously obtained results, there are a number of applications, which require the achievement of even higher currents (and current densities) of ion beams, while keeping the emittance low. The requirements of modern accelerators for light and multiply charged ion injectors are constantly growing, and to meet those of projects such as ISIS II [7] and HIAF [8] further enhancement of beam characteristics is needed.

In reference [1] the authors previously proposed and numerically substantiated the original approach to a significant expansion of the possibilities for the formation of ion beams,
associated with the use of shaped electrodes that provide a highly nonuniform distribution of the electric field in the inter-electrode gap. The shape of the electrode is chosen to achieve the major drop in the accelerating potential being located close to the plasma electrode, thereby increasing the rate of particle acceleration in the region most sensitive to self-action (the region with a low ion velocity, thus, high space charge). A feature of the proposed system is that it increases the electric field only in the area where it is necessary (in contrast to traditional systems in which the field increases throughout the accelerating gap).

The summary of the new approach to the extraction system design advantages (mentioned in reference [1]) is the following. The new geometry allows us to decrease the optimal extraction voltage in the case when the current density is determined by the plasma emissivity. It also allows for an increase of the current density of the extracted beam at a constant accelerating voltage. The puller aperture can be significantly expanded without losing the beam quality. It leads to reduction of the ion beam flux to the puller and enhancement of the extractor reliability. The new design can be especially effective for ion beam sources with low emitter size compared to the interelectrode distance. An additional advantage of the new geometry is its weak sensitivity to the interelectrode distance, which makes it possible to effectively solve technical and engineering problems common for ion optics, in particular, those related to the electric breakdown resistance of the accelerating gap. On the other hand, the new extractor creates a more divergent ion beam than in the flat case. But it can be compensated by a smaller beam size. The new approach is not effective for single aperture (gridless) ion sources with a large emitter size compared to the interelectrode distance (such as Hall effect thrusters).

The considered system with inhomogeneity of the electric field is shown in figure 1(a). The increase of the puller hole diameter does not significantly affect the ion beam formation, but it reduces the ion flux on the puller and improves the extraction system reliability. For comparison, the flat extractor is also shown in the figure. A significant increase in the electric field is achieved in the new geometry at the same voltage. This is illustrated with color maps of the electric field modulus (a) and (b), and graphs of the electric field distributions on the system axis (c).

The new extraction system design is sought after for different kinds of ion sources because the new approach allows to improve the performance of the existing systems through an easy and low-cost upgrade. There are several cases where the new geometry can be applicable. First, the increase of the total ion beam current without losses in its quality is feasible when the ion source with extra emission ability is used as an injector for modern accelerators. Second, the new geometry allows an effective low energy ion beam formation which is required for ion implantation [9]. Third, the Child–Langmuir limitations in the planar case can be exceeded. The new electrode geometry can be especially beneficial for the formation of focussed ion beams (FIBs) because ion sources for FIB are characterized by small apertures of electrodes in comparison with interelectrode distances [10]. For such ion sources, decrease of the interelectrode distance is limited by the electrical breakdown of the interelectrode gap and by technological difficulties (accuracy of positioning the electrodes). This aspect ratio is far from optimal in the case of the flat geometry, and the use of the proposed geometry greatly simplifies the solution of the problem. Fourth, it should be noted that the new approach to the formation of an ion beam is also applicable to a multicomponent plasma. In particular, when forming a beam of negative ions, it is possible to decrease the power of the co-extracted electron beam [11]. The use of the new approach makes it possible to unleash the potential of those facilities, where the plasma emission ability exceeds the capability of the extraction system [2].

Within the framework of this paper, we will limit our analysis to consideration of diode-type single-aperture extraction systems. The developed principle can be applied without any restrictions for multi-electrode systems, since it only involves changing the geometry of the first two electrodes. It can be applied to multiple aperture extractors but there are some restrictions. The distance between extraction holes should be increased in order to create a narrow tip in the plasma electrode for each beamlet. It leads to lower plasma flow transmittance of the new geometry compared to the conventional one. However, there are some applications where transparency of the plasma electrode is limited by other factors (such as cooling requirements) and the new approach can be applied in these cases.

To verify the efficiency of the new approach, we compared the parameters of the beams formed by the conventional flat-electrode extraction system with the proposed one.

2. Experimental facility

The SMIS 37 facility scheme is shown in figure 2. Plasma is created using a pulsed microwave gyrotron radiation at a frequency of 37.5 GHz, power up to 100 kW and a pulse duration of 1 ms. Microwave beam is coupled to the discharge chamber using an electrodynamic system with an embedded gas feed line. Neutral gas is injected along the axis of the plasma chamber. The chamber inner diameter is 38 mm. A simple magnetic trap with the mirror ratio of \( R = 5 \) is used to create and confine the plasma. The distance between the plugs is 250 mm. The magnetic field is created by the pulsed coils. The maximum magnetic field in the plug reaches 4 T. The resonant value of the magnetic field for a frequency of 37.5 GHz is 1.34 T. The pulse repetition period is about 20 s.

With hydrogen as a working gas, the plasma density reaches the level of \( 2 \times 10^{13} \text{ cm}^{-3} \), electron temperature — 50 eV and ionization degree is close to 100%. This combination of temperature and density provides a high density of the plasma flux from the trap and corresponds to the quasi-gasdynamic confinement regime. The difference between this regime when compared to the classical collision-less regime is that electrons fill the loss cone in the velocity space due to the high frequency of Coulomb scattering. The flux of electrons leaving the trap is limited by the ion flux, the maximum velocity of which is equal to the ion-sound one \( V_s = \sqrt{2e/M} \). The lifetime of electrons is determined by the mirror ratio, ion-sound velocity and trap
Figure 1. The comparison of the flat extractor and the system with inhomogeneity of the electric field. The interelectrode distances \(d_1 = d_2\) and bias voltages are equal. The significant increase of the electric field modulus near the plasma electrode tip is demonstrated with colormaps (a) and (b) and distribution on the system axis (c). The plots are based on simulations from reference [1].

Figure 2. The SMIS 37 facility scheme. Plasma is sustained using a microwave radiation and confined by magnetic field which is created by coils. Ion beam is formed using a two-electrode extraction system. The beam current is measured using the Faraday cup (FC).

length: \(\tau_e = LR/V_s\). Substituting the typical values, one gets \(\tau_e \approx 20\ \mu s\). High plasma density and short lifetime provides an ion current density in the plug of more than \(10\ \text{A cm}^{-2}\). To reduce the flux density to a level acceptable for beam formation, the extraction system is moved from the plug to the region of a weaker magnetic field. The distance from the plug of the magnetic trap to the plasma electrode is \(120\ \text{mm}\). The value of the magnetic field at the edge of the plasma electrode is about 10 times lower than in the plug.

3. The beam extraction system

The two-electrode system for the ion beam formation, consisting of a plasma electrode and a puller, was used. The maximum available extraction voltage on the facility is \(100\ \text{kV}\). In the experiment, the current of the ion beam passed through the formation system was measured using a FC, the size of which ensures the interception of the entire beam. Single-aperture two-electrode extraction systems are characterized by three parameters: the plasma electrode aperture \(D_1\), the interelectrode distance \(L\), and the puller electrode aperture \(D_2\).

The interelectrode distance is longer than plasma electrode and puller apertures for the majority of flat extraction systems. These extractors suffer from secondary electron emission in the case when the ion beam current density is too high and the beam significantly diverges in the interelectrode region. Therefore, the extraction system with significantly wider puller aperture was used (see figure 3).

In reference [1] it was shown that the new approach allows for a significant increase in \(D_2\) without a noticeable decrease in the quality of beam formation, while the flat extraction system efficiency suffers a lot from the increase in the puller aperture. The diameter of the puller hole in the flat geometry in the experiment was significantly smaller than in the new one (see figure 3). The plasma electrode in the flat geometry has a
4. Experimental results

In the general case, the dependence of the beam current on the extraction voltage $I_{FC}(U_{ext})$ has two regions with different modes of beam formation. At low extraction voltages, a space charge limited mode is realized, which is characterized by $I_{FC} \sim U_{ext}^{3/2}$ and corresponds to the Child–Langmuir law. At higher voltages, the plasma-density-limited mode (saturation mode) is realized, which is characterized by a constant current value. An experimental comparison of the efficiency of the extraction systems was made for two extraction systems with 3 mm and 5 mm plasma electrode aperture. The experiments were carried out in modes with different plasma emissivity.

4.1. Decrease of the optimal extraction voltage

Graphs of $I_{FC}(U_{ext})$ are shown for the 3 mm extraction hole case in figure 4. In this case, the plasma emissivity was moderate, which made it possible to achieve two extraction modes (firstly, the space charge limited mode and then the plasma density limited mode) at available accelerating voltages.

The use of the new ion beam formation system can significantly reduce the optimal extraction voltage. Consider the point of intersection of the approximation curves of the two extraction modes described above. For the flat case, the voltage of the characteristic point is 22 kV and for the new geometry—10 kV. Therefore, a significant decrease in the optimal extraction voltage (by a factor of 2) is shown when using the new geometry of electrodes.

4.2. Reduction of the puller current

In the following case the plasma emissivity was higher. For the flat case only the space charge limited regime was achieved. Graphs of the FC and puller currents dependencies on the extraction voltage are shown for the 5 mm extraction hole case in figure 5. It is clearly seen that in this case the flat system of electrodes did not allow for the utilization of the available plasma flow, while the new system ensured the saturation of the extracted beam current and its significantly higher value. The use of a tubular puller with a large aperture in the new geometry made it possible not only to increase the beam current, but also to significantly reduce the ion flux to the puller (see figure 5(b)). This effect was predicted in reference [1] and it is a significant technological advantage of the developed extraction system.

Let us compare the efficiency of the new geometry for the given configurations. For this, we estimate the ratio of pervanees $P$ of different extraction systems. The following quantity is called perveance

$$P = \frac{I_{beam}}{U_{ext}^{3/2}}.$$  

The value of perveance indicates how significant the space charge effect is on the beam’s motion and is constant for the fixed geometry while operating in a space-charge-limited mode. The value of the perveance ratio for the 3 mm extraction hole case is $P_{new}/P_{old} = 3.3$ and for the 5 mm case is $P_{new}/P_{old} = 2.3$.

The increase in perveance ratio, thus, the efficiency of the new extraction system, becomes greater with the higher $L/D_1$ ratio. This fact confirms the conclusions drawn in reference [1].
4.3. The record current density beam formation

The most significant experiment which proves the advantages of the proposed extraction system with an inhomogeneous electric field distribution is the demonstration of the possibility of the ion beam formation with a record current density. The graph of $I_{FC}(U_{ext})$ is shown for the 5 mm extraction hole case in figure 6.

Starting from a voltage of about 35 kV, the current to the puller reaches its minimum value. In this configuration, ion beams with currents from 150 mA (which corresponds to an average current density of 0.77 A cm$^{-2}$) at the extraction voltage of 40 kV to 225 mA (which corresponds to an average current density of 1.15 A cm$^{-2}$) at the voltage of 53 kV were obtained. Waveforms of the beam current for points A, B in figure 6 are shown in figure 7.

5. Conclusion

The new extraction system geometry makes it possible to overcome the limitations on the ion beam current density, caused by the Child–Langmuir law for flat geometry. The assumptions (theoretically substantiated in reference [1]) about the effectiveness of using the new geometry of the electrodes for obtaining high-current ion beams were successfully confirmed experimentally. It is shown that under the same conditions
the optimal voltage required for high-quality beam formation using the system with inhomogeneity of the electric field is reduced by a factor of two when compared to the flat geometry. This result demonstrates the possibility of a significant increase in the beam current in systems with a fixed extraction voltage with a sufficient emissivity of the plasma. The relaxation of the requirements for the puller geometry not causing the deterioration of the beam quality was clearly demonstrated. An increase in the puller aperture, and even the use of the tubular puller, made it possible to minimize the contact of the puller electrode with the ion beam, eliminate secondary electrons emission from the puller and increase the electrical breakdown resistance of the interelectrode gap. During the tests of the new system, a proton beam with a record current density for any type of ECR ion sources at the level of 1.15 A cm$^{-2}$ was obtained. Experimental demonstration of the new extraction system efficiency makes it possible to proceed to the next stages of its implementation at facilities of various classes and purposes, sources of multiply charged ions, sources for ion implantation, sources of negative ions, etc.

The new approach to the extraction system design was still considered for a single aperture extractor. A search for a way of implementing the new idea for multiple aperture extraction systems is under investigation now. The obvious disadvantage of the suggested approach is the limited electrode transparency. But still there are some applications like neutral beam injection where electrode transparency is limited by other factors like strong cooling necessity. The related analysis is in progress now.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

S S Vybin https://orcid.org/0000-0003-1036-250X
I V Izotov https://orcid.org/0000-0003-2584-0375
S V Golubev https://orcid.org/0000-0003-0585-2475
R A Shaposhnikov https://orcid.org/0000-0001-5980-6023

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