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# Application of dense electron cyclotron discharge plasma for generation of high-current beams of multicharged ions

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The result of research at the A.V. Gaponov-Grekhov Institute of Applied Physics of the Russian Academy of Sciences was the development of a source of multicharged ions with high-density plasma, heated under conditions of electron cyclotron resonance (ECR) - a gasdynamic ECR source of multicharged ions. In such a source, due to the high frequency of electron collisions, the so-called quasi-gasdynamic regime of confinement in a magnetic trap is realized. The results of the first studies of the efficiency of the generation of multicharged ions in an ECR discharge with quasi-gasdynamic plasma regime in a continuous operation mode are presented.

**Keywords:** high-current ion source, electron cyclotron resonance, magnetic plasma confinement, multicharged ions, gyrotron.

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The progress in research in the field of heavy ion physics and synthesis of superheavy elements, the improvement of methods and technology for acceleration of charged-particle beams, and new frontiers in nuclear and quantum physics continuously pose ambitious challenges in engineering of ion sources with previously inaccessible characteristics. Among the most prominent current projects are the Superheavy Element Factory (Joint Institute for Nuclear Research, Dubna) in Russia and the Heavy Ion Accelerator Facility (HIAF) in China. Depending on the specific experiment, beams of multicharged ions (MCIs) up to uranium with a charge up to +40 and a current up to 1 mA may be required. The existing MCI sources do not satisfy all the requirements.

Systems based on electron cyclotron resonance (ECR) discharge plasma confined in open magnetic traps (ECR MCI sources) are one of the most promising types of injectors of multicharged ion beams. The primary trend in development of this type of sources was to increase the frequency and power of radiation used for plasma heating [1]. At present, the most intense traditional ECR MCI sources constructed on the basis of traps with the so-called „minimum-B“ configuration use gyrotron radiation with a frequency of 28 GHz and a power up to 10 kW. A source currently under construction at the Institute of Modern Physics of the Chinese Academy of Sciences has a classical arrangement with a record plasma heating frequency of 45 GHz and a power up to 20 kW [2]. However, even this flagship system cannot satisfy all the requirements of modern accelerator projects. In this context, the examination of new opportunities for production of high-current ion beams with extremely high charges is important and relevant.

One promising approach to the design (improvement) of MCI sources is associated with the use of a high-current quasi-gasdynamic source of multicharged ions [3] with subsequent additional ionization of ions in strippers. A high-current MCI source with quasi-gasdynamic confinement and microwave radiation from gyrotrons with a frequency up to 75 GHz used to sustain plasma was constructed at the Institute of Applied Physics of the Russian Academy of Sciences (IAP RAS). The use of high-power short-wave gyrotron radiation made it possible to obtain plasma with a density up to $10^{14}\,\mathrm{cm}^{-3}$, which ensured the transition to a regime of quasi-gasdynamic plasma confinement with a short lifetime (several tens of microseconds), and, accordingly, form plasma flows with an equivalent density up to $10\,\mathrm{A/cm}^2$. It was demonstrated that this regime is suitable for production of high-current low-emittance ion beams [4]. Specifically, in the pulsed operation mode of the source, experiments performed to date have revealed the possibility of production of beams of multicharged nitrogen ions with a total current exceeding 150 mA and a normalized emittance of $0.9\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$ [4]; beams of hydrogen ions with a current of 450 mA and deuterium ions with a current of 400 mA were obtained, and the emittance was $0.07\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$ in both cases [5]. This combination of parameters is a current record. Thus, the use of a quasi-gasdynamic MCI source pumped by high-power microwave gyrotron radiation makes it possible to form ion beams with record-high currents and a moderate average charge.

The new concept for generating high-current MCI beams is to use a quasi-gasdynamic ion source in combination with a linear system for preliminary ion acceleration and a solid-state system for their subsequent additional ionization in passing through thin foils. According to estimates, a current of 1 mA of heavy ions with a charge of +40 may be obtained via additional „stripping“ of a beam with a charge ranging from +10 to +20 and a current of 10 mA.

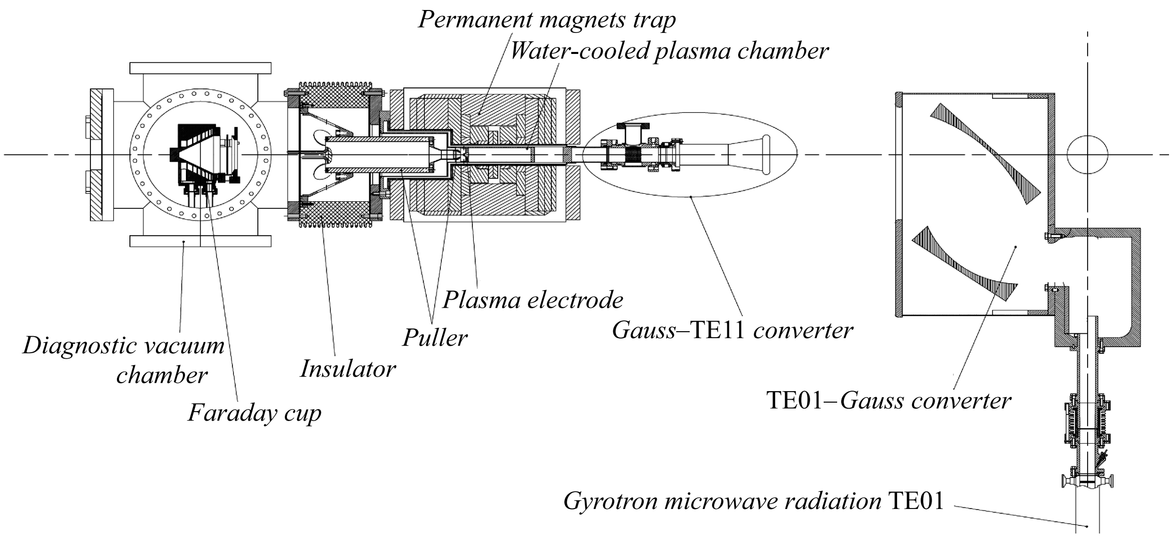


**Figure 1.** Schematic diagram of the GISMO experimental setup (the microwave radiation source is not shown).

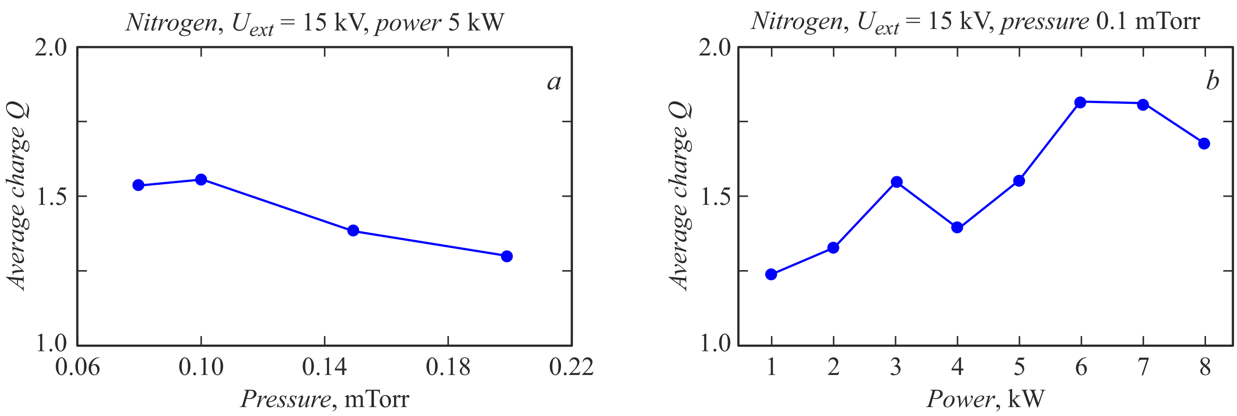


**Figure 2.** Dependences of the average charge of nitrogen ions on discharge pressure (*a*) and microwave heating power (*b*).

Previous experiments with a quasi-gasdynamic ECR source at IAP RAS have been conducted in a pulsed mode with a low pulse repetition rate (0.1 Hz), which led to a significant amount of impurities in plasma and made it difficult to control its parameters. To solve this problem, an experimental facility referred to as GISMO (gasdynamic ion source for multipurpose operation) [6] providing an opportunity to perform experiments under the conditions of a continuous ECR discharge was constructed. The diagram of the setup is shown in Fig. 1. A gyrotron with a frequency of 28 GHz and a power up to 10 kW is used for plasma heating. Plasma is confined in a simple mirror magnetic trap with a field strength up to 1.5 T (in plugs) made of permanent magnets. The plasma volume in a discharge is approximately 40 $cm^3$; combined with the heating power, this provides a very high level of specific energy input into plasma (up to 250 $W/cm^3$). The GISMO facility has the capacity to operate in both pulsed and continuous modes.

It is fitted with a magnetostatic analyzer for analysis of the ion beam composition. The analyzer is coupled by a Faraday cup designed to measure the current of high-current ion beams in the continuous mode. In measurements, this analysis system is attached to the flange of the diagnostic chamber on the longitudinal axis (not shown in Fig. 1).

Proprietary designs of extraction systems with quasi-spherical electrodes [7], which provide a high rate of ion acceleration in the vicinity of the plasma electrode, thereby reducing the negative impact of the beam space charge at high current densities, are used to produce high-quality high-current beams.

Proton beams with record-high characteristics have already been obtained at GISMO [8]. In the present study, we performed the first experiments on production of beams of multicharged nitrogen ions. The aim of these experiments was to confirm the possibility of generation of plasma without impurities at its high density ($10^{13}$ $cm^{-3}$) and verify the key dependences of efficiency of multiple ionization on the parameters of operating modes, heating power, and discharge pressure.

Currents up to 3 mA were obtained in the first experiments in nitrogen with an ion beam extraction aperture 1 mm in diameter; the corresponding current density

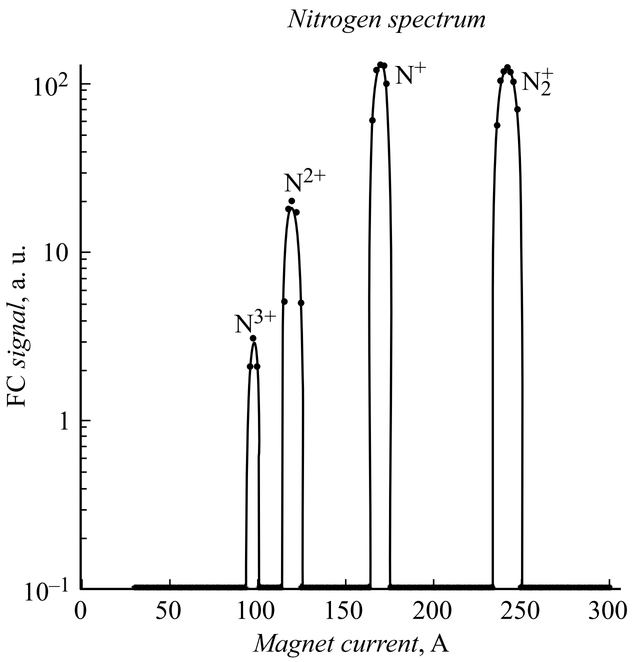


**Figure 3.** Complete spectrum of the ion beam extracted from a discharge in nitrogen at a pressure of 0.1 mTorr and a heating power of 5 kW.

was 380 mA/cm$^2$. Figure 2 shows the dependences of the average charge of extracted ions on discharge pressure and heating power. It is evident that the average ion charge increases as the discharge pressure decreases. This is attributable to an increase in temperature of electrons. A similar effect is observed when the heating power is increased under a fixed pressure.

Figure 3 presents the complete spectrum of an ion beam during a discharge in nitrogen. A total lack of impurities (hydrogen, carbon, and oxygen) in the beam, which is the result of transition to a continuous discharge mode, is evident.

Future experiments will be aimed at enhancing the specific energy input into plasma, which is needed in order to increase the average charge of extracted ions. Experiments with a high pulse repetition rate in a pulsed operation mode are also planned to be performed. Such conditions should enable research to be conducted in plasma without impurities and allow us to determine the limiting parameters of ion beams that may be obtained within the discussed approach.

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## Conflict of interest

The authors declare that they have no conflict of interest.

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