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Application of dense plasma of electron cyclotron resonance discharge for production of positive and negative hydrogen ions

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One of the promising sources of high-current beams of positive and negative ions could to be a discharge maintained under electron cyclotron resonance conditions in open magnetic traps with powerful radiation in the millimeter wavelength range. Development of pulsed and continuous sources of positive ions of hydrogen isotopes with record characteristics of the quality and composition of the formed beams have being conducted at the IAP RAS. The latest results on ion beams generation for injection into accelerators were obtained at experimental facilities SMIS 37 and GISMO. Currently, the option of upgrading such systems for obtaining beams of negative ions is under investigations.

Keywords: electron cyclotron discharge, gyrotron, hydrogen ion beams.

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The methods of hydrogen plasma generation and extraction of different types of ion beams (H^+, H^{2+}, H^{3+}, D^+, H^-, D^-) are well studied in many aspects and allow realizing beam generation in pulsed and continuous modes in the current range from microamperes to hundreds of amperes. Various types of discharges are widely used in hydrogen ion sources: arc [1] and vacuum-arc [2], high-frequency (HF) induction [1,3], Penning [4], electron cyclotron resonance (ECR) [5,6]. Different discharges have certain advantages that make them optimal for different tasks. For example, arc discharges are convenient in terms of simplicity of design for pulsed modes with high rate, HF-systems are often used to generate wide-aperture homogeneous plasma flows and beams with large total current, ECR-discharges heated by magnetron radiation at 2.45 GHz are effective for producing high quality beams with currents up to 100 mA (protons or deuterons) for injection into accelerators.

The problem of producing beams of negative hydrogen ions has an even greater variety of approaches to the solution, since besides varying the method of primary plasma creation, different mechanisms of generation of negative ions themselves in it can be used. Two such mechanisms are now most commonly used: volumetric and surface. In the present work, only the volumetric, or volumetric-plasma method is considered, which is based on the creation of a gas-discharge plasma with a high concentration of negative ions. The formation of negative ions occurs in two stages: the excitation of hydrogen molecules to high vibrational levels and the subsequent dissociative sticking of an electron to such a molecule. The vibrational excitation of H_2 molecules by electrons with energy > 10 eV increases the efficiency of formation of negative ions, but destroys them just as effectively in subsequent collisions. To resolve this contradiction, the„tandem“ method is used, in which the plasma volume is divided into two regions: with hot electrons ($T_e > 10$ eV) to excite molecules and with cold electrons (T_e of order 1 eV) to form negative ions from excited H_2. A magnetic field transverse to the temperature gradient — a magnetic filter, for example, is used to separate the regions.

Because of the high degree of development of the above methods, further sequential enhancement of the characteristics of the generated beams of positive and negative hydrogen ions becomes more and more difficult. Nevertheless, constant scientific progress leads to new tasks requiring the production of ion beams with previously inaccessible characteristics. Often the way out in such situations is to consider new non-standard approaches. This paper presents the latest results of a set of studies conducted at the IPF RAS using an exotic approach to hydrogen plasma generation to develop sources of various hydrogen ions.

The application of dense strongly nonequilibrium plasma of an ECR-discharge supported by powerful (1–100 kW) gyrotron radiation of millimeter frequency range in open axisymmetric magnetic traps is considered in work. This approach differs fundamentally from standard heating by magnetron radiation at 2.45 GHz with a kilowatt power level in that the generated plasma has an order of magnitude higher density (up to 10^{13} cm^{-3}) and an order of magnitude higher electron temperature (50–100 eV) [7]. Such a combination of plasma parameters is not realized in other types of discharges and makes it possible to obtain dense plasma flows that can be successfully used to generate ion beams with record parameters.

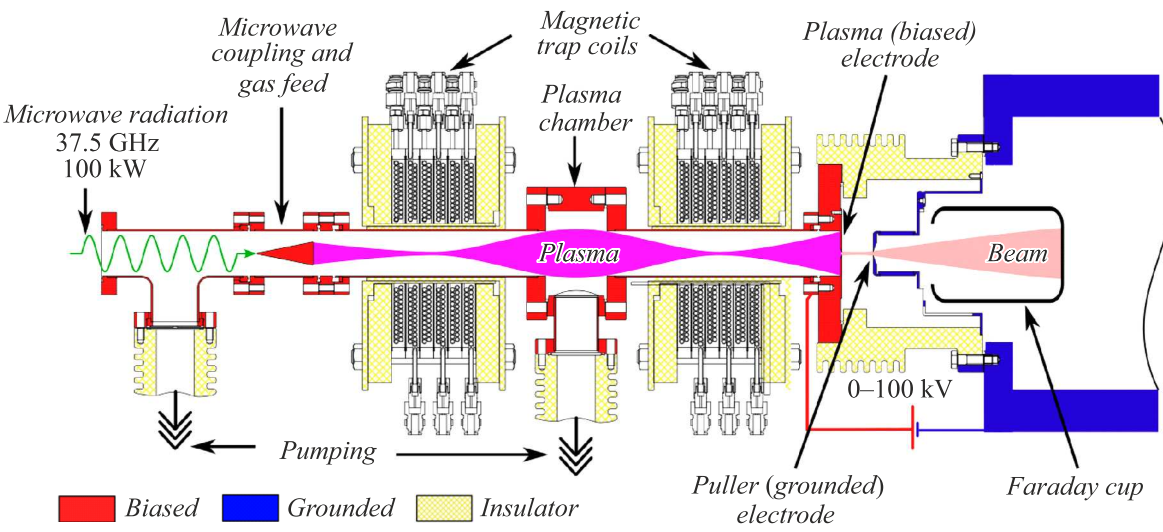

Figure 1. Schematic of the SMIS experimental setup (the microwave radiation source is not shown). A color version of the figure is provided in the online version of the paper.

ECR-ion sources investigated at IPF RAS are characterized by high frequency (28–75 GHz) and power (10–100 kW) of heating radiation. Also, taking into account the relatively small plasma volume, a high specific energy contribution (at the level of 200 W/cm^3) is achieved. There are two ion sources in the IPF RAS: SMIS (Simple Mirror Ion Source), which operates in pulse mode, and GISMO (Gasdynamic Ion Source for Multipurpose Operation) — a facility with continuous operation capability.

The schematic of the plasma part of the SMIS setup (the microwave-radiation source, the gyrotron, is not shown) is shown in Fig. 1. The plasma is created using pulsed microwave-gyrotron radiation at 37.5 GHz with power up to 100 kW and pulse duration of 1 ms (using gyrotron radiation at 75 GHz the power reached 200 kW). The microwave -radiation is injected into the discharge chamber by means of an electrodynamic system, which also incorporates a gas supply channel. The neutral gas is fed along the axis of the plasma chamber. The plasma chamber has an inner diameter of 38 mm. A simple magnetic trap is used to contain the plasma. The strike ratio is equal to $R = 5$. The distance between the plugs is $L_{plug} = 250$ mm. The magnetic field is generated by the coils in pulse mode. The maximum magnetic field in the cork reaches 4 T. The pulse repetition period is about 10 s. Characteristic parameters of hydrogen plasma are as follows: density at the level of $(2–6) \cdot 10^{13}$ cm^{-3}, electron temperature in the range of 50–300 eV, degree of ionization close to 100%. This combination of temperature and density provides a high plasma flux density from the trap and corresponds to the quasi-gasodynamic confinement regime with a characteristic plasma lifetime of about 10–20 μs. The high plasma concentration and short lifetime provide ion current densities in the plug exceeding 10 A/cm^2. To reduce the flux density to a level acceptable for beam formation, the extraction system is placed behind the magnetic trap plug in a region of weaker magnetic field.

At the SMIS facility, a hydrogen ion current of 500 mA was obtained during beam extraction through a 10 mm diameter hole with a proton content in the beam of about 94%, which exceeds the record values for ECR-ion sources at 2.45 GHz. Using an inhomogeneous electric field extractor [8] at the SMIS facility, an ion beam with a current of 225 mA was produced through an opening of 5 mm, which corresponds to a record beam current density of more than 1.15 A/cm^2.

For negative ion generation studies on the SMIS bench, the magnetic system was augmented with another coil so that two consecutive simple magnetic traps were obtained. This approach made it possible to implement a tandem ion source scheme consisting of two parts: the first — the primary hydrogen plasma source and the second — the negative ion generation region with specially optimized parameters. In the scheme used, the plasma was heated in the first trap, excited molecules from it entered the second trap, where they interacted with the cold electrons generated by ionization of the gas in the second trap. Two characteristic regimes were identified in the experiments: the regime of quasi-stationary generation of negative hydrogen ions during the entire pulse supporting the gyrotron microwave discharge, and the regime with a burst of negative ion current after the end of the microwave pulse (the„mode of afterglow“). Experiments have shown that the best mode of generation of atomic hydrogen ions H^- in the ECR-discharge on the SMIS 37 bench is achieved under the following conditions: the power of the microwave-gyrotron radiation supporting the discharge is maximal ($\sim$ 100 kW), gas injection into the discharge and reactor traps is pulsed. The maximum current density of negative ions reached 20 mA/cm^2. The accompanying electron current exceeded the ion current by a factor of 50–100 depending on the

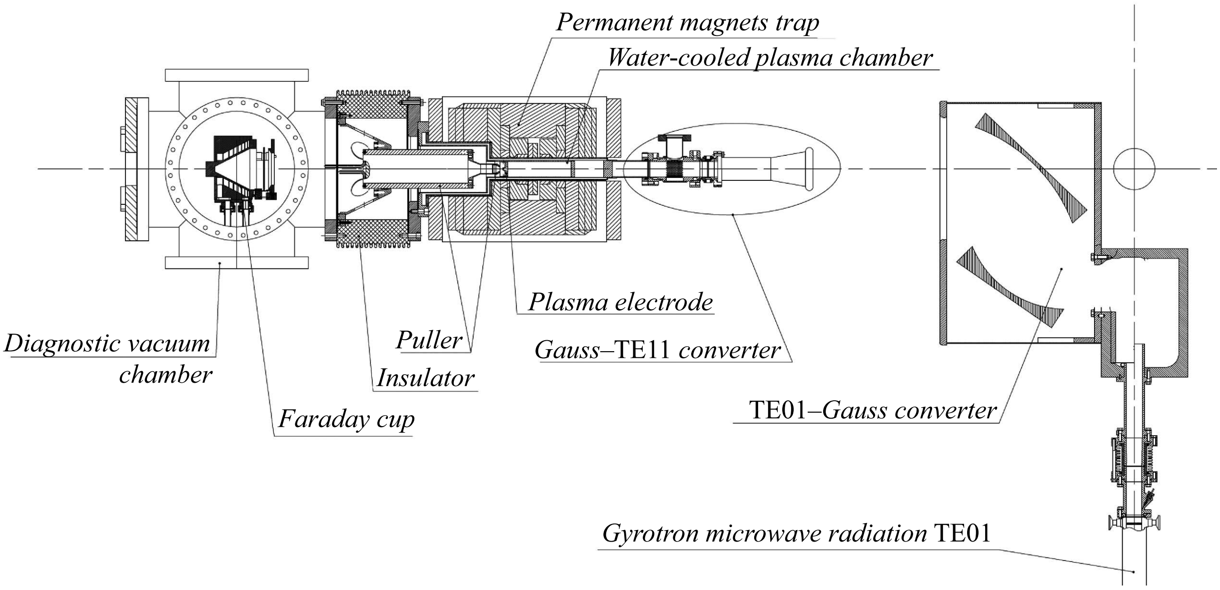

Figure 2. Schematic of the GISMO experimental setup (the microwave-radiation source is not shown).

mode. To separate the electron fraction, an additional magnetic filter was installed after the beam extraction system to provide a magnetic field transverse to the beam with the strength necessary to deflect electrons from the propagation path and prevent them from entering the ion diagnostic systems.

The GISMO source differs from SMIS in that it is more technologically advanced and can operate continuously. The diagram of the setup is shown in Fig. 2. To realize such advantages, it creates plasma using continuous microwave-radiation from a gyrotron at 28 GHz with power up to 10 kW. A magnetic trap assembled from permanent magnets is used to contain the plasma. From for the permanent magnet based design, the magnetic configuration is a mirror machine with two traps with counter fields (or caspas) after the main tubes. The trap with counter fields on the input side of the microwave-radiation does not participate in the plasma dynamics in any way. The counter-field trap on the extraction side of the ion beam is either also cut off by the extraction system and does not affect the plasma confinement during the generation of positive ion beams, or it is used as the second stage of the „tandem“ scheme during the generation of negative ions, in which case the ion extraction system is placed after it. In other aspects, the GISMO rig is conceptually similar to the SMIS rig.

The GISMO bench produced continuous proton beams with currents up to 130 mA during extraction through a 4 mm diameter hole, corresponding to a current density of more than 1 A/cm ^{2}. A unique property of such beams is virtually absolute purity from molecular ions. The GISMO facility was used to find the modes of discharge combustion (heating power more than 2 kW, gas pressure in the discharge chamber $2 \cdot 10^{-3}$ Torr), in which the proton content

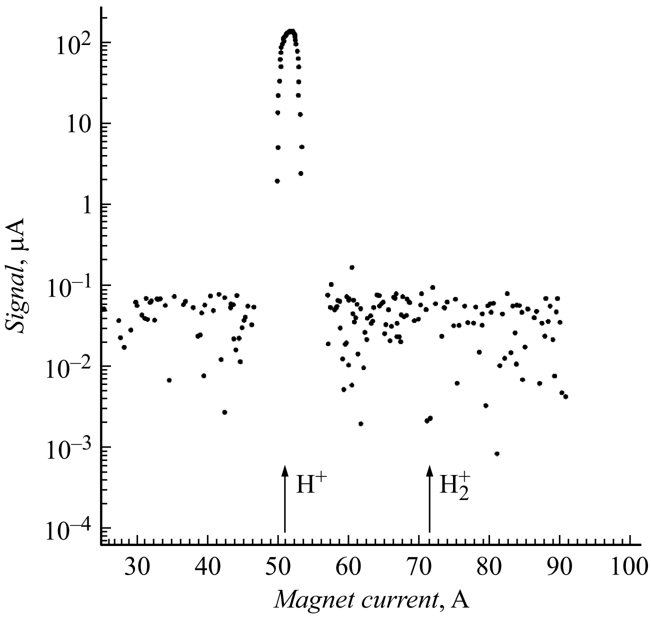

Figure 3. Composition of the extracted ion beam at a heating power of 5 kW and pressure in the discharge chamber $2 \cdot 10^{-3}$ Torr (dependence of the beam current passed through the magnetic analyzer on the magnet current).

in the beam exceeds 99.9%, and the signals corresponding to the charge ratio–mass for impurities (ions H_2^+, H_3^+, etc.) cannot be distinguished against the background noise. The spectrum of the ion beam in the optimized regime is shown in Fig. 3.

In the case of plasma confinement in the mirror machine and cusp system, i.e., when the „tandem“ scheme was implemented on the GISMO, the ion current density H^- up to 10 mA/cm ^{2} was achieved under optimized conditions. In these experiments, an independent injection of neutral gas into the second trap of the„tandem“ scheme was not realized. This will be done in future studies, as this approach allowed to increase the yield of negative ions on the SMIS bench.

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Conflict of interest

The authors declare that they have no conflict of interest.

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