Deuterium ion beam focusing for the point neutron source development

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Abstract. This work is a continuation of the studies on the point neutron source development. In the neutron source scheme proposed, neutron emission occurs in a relatively small region (less than 1 mm) as a result of the D–D fusion reaction initiated when the focused deuterium ion beam hits the deuterium-loaded target. The main goal of the project is to develop a simple and compact device that can be used in the high-quality fast neutron radiography. In the scheme proposed, the ion beam is extracted from the dense ECR discharge plasma that is confined in the simple magnetic mirror trap. After upgrading the extraction system and the magnetic lens, the deuterium ion beam with a total current in the focal plane of up to 150 mA was obtained, which considerably exceeds the current obtained previously. The numerical simulations of the beam magnetic focusing were performed using the IBSimu code and the results were compared to the experimental data.

1. Introduction
Unlike the X-ray radiography, which provides good resolution when studying the objects consisting of the heavy elements only, the fast neutron radiography is one of the promising non-invasive diagnostic methods that allows studying the composition and structure of the extended objects that contain both heavy and light elements. This opens up new opportunities for research not only in the field of physics, but also in chemistry and biology [1–3]. Among new neutron sources that are being currently developed for the neutron tomography applications, we would like to single out the point D-D neutron generator [4–6], which can be an alternative to the generators of the paraxial neutron beams. For point sources of any radiation, the image quality of the objects under study depends on the size of the emitting region. Then, in the case of the point fast neutron sources, the image quality is determined by the quality of the ion beam focusing onto the neutron-emitting target. Therefore, the problem of obtaining a focused high-current deuterium ion beam should be solved.

In the previous experiments conducted at the Institute of Applied Physics of the Russian Academy of Sciences, the point neutron source was developed based on the high-current ECR ion source. It provided a neutron flux of $10^{10}$ neutrons per second and a flux density of $10^{12}$ s$^{-1}$ cm$^{-2}$ in the 1-mm-sized emitting region. Such flux density is of the same order as that obtained using the neutron collimators that are used at the nuclear reactors and large accelerators to produce paraxial neutron beams. Thus, the possibility of creating the point neutron generator based on the D-D fusion reaction has been successfully demonstrated. Moreover, it became clear that such a generator can be considerably improved, if it is possible to further increase the ion beam current hitting the target.
In this work, we experimentally study the possibilities of obtaining and focusing the deuterium ion beam with a considerably higher current than that achieved previously.

2. Experimental facility
The experiments were conducted at the SMIS-37 facility with an upgraded system for the ion beam formation. The facility schematic is presented in Fig. 1. The discharge was sustained in the simple magnetic mirror trap (the maximum magnetic field strength is $B_{\text{max}} = 3$ T, and the mirror ratio is $B_{\text{max}}/B_{\text{min}} = 5$) using the microwave gyrotron radiation (the frequency is 37.5 GHz, and power is up to 100 kW) under conditions of the electron cyclotron resonance. The magnetic field in the trap was created by two coils with a distance of 15 cm between them. The current pulse duration in the coils was 6 ms. The ion extraction system consisted of two electrodes (the high potential plasma electrode and the grounded puller) with an extraction voltage of up to 65 kV. The extractor was located at a distance of 10 cm outside the magnetic mirror, where the plasma flux density decreases to the value optimal for the extraction voltage used in experiments. The magnetic lens with an aperture of 68 mm located at a distance of 7 cm from the extraction system was used for the beam focusing.

![Figure 1. Schematic of the SMIS-37 experimental facility. 1 microwave beam, 2 quartz window, 3 microwave-to-plasma coupling system, 4 discharge chamber, 5 magnetic trap coils, 6 region of the ion beam extraction and formation, 7 magnetic lens and 8 high-voltage insulators.](image)

3. Ion beam current measurements
The most convenient way to describe the extraction system configuration is to use three numbers $D_1$–$G$–$D_2$, where $D_1$ corresponds to the plasma electrode aperture in millimeters, $G$ is the gap between the electrodes, and $D_2$ is the aperture of the puller electrode. One of the main goals of the presented experiments was to optimize the extraction system configuration, and the 5–5–5 mm configuration was found to be the optimal one. The comparison of the results obtained using the optimal and the 5–7–10 mm (used in the previous experiments) extraction system configurations is presented below.

It was mentioned above that the magnetic lens aperture was increased to 68 mm, which is considerably larger than the 40-mm-aperture used in previous experiments; its length was 10 cm, and the maximum field strength was 3 T. The total current of the focused ion beam was measured in the lens focal region using the Faraday cup. The ion beam current as a function of the extraction voltage is shown in Fig. 2 for two different electrode configurations.
The use of the magnetic lens with a larger diameter made it possible to intercept and focus the most part of the extracted beam, which resulted in the expected increase in the ion current in the focal region. However, much higher increase in the ion current in the focal region was achieved by choosing the optimal geometry of the extraction system. Thus, as a result of using the larger magnetic lens and optimizing the extraction system, we achieved a beam current of 150 mA in the focal region (which is approximately three times higher than that in the previous experiments).

4. Ion beam focusing using the magnetic lens
The dependence of the ion beam current, measured using the Faraday cup with a transverse size of 48 mm, on the lens magnetic field is shown in Fig. 3. It characterizes the efficiency of the ion beam focusing. The extraction voltage was 50 kV.

Figure 2. Ion beam current as a function of the extraction voltage for the 5–7–10 (black dashed curve) and 5–5–5 (red solid curve) electrode configurations.

Figure 3. Ion beam current as a function of the lens magnetic field. The extraction voltage was 50 kV.
From the data obtained, one can see that the ion beam current is maximal (150 mA) at a lens magnetic field of 1.2–1.4 T. The further increase in the magnetic field results in the current decrease due to the over-focusing of the beam and its additional losses on the shielding electrode of the Faraday cup. The presented dependence is in good agreement with the results of numerical simulations performed using the open-access IBSimu software. As a result of the simulations, the ion trajectories were obtained for the given extraction system configuration and the lens magnetic field.

![Figure 4. Ion trajectories at different lens magnetic fields: (a) 0.8, (b) 1.3 and (c) 1.5 T.](image)

The trajectories (red color) of ions escaping from the puller electrode (blue color) are presented in Fig. 4. The focusing lens is green. The front shielding electrode of the Faraday cup is black. All ions reaching the right border of the computational domain fall onto the Faraday cup collector.

5. Conclusions
In this work, the possibility was demonstrated of obtaining the high current deuterium ion beams based on the ECR-discharge plasma confined in a simple magnetic mirror trap. By means of optimizing the extraction system and using the magnetic lens with a larger aperture, it is possible to considerably increase (up to 150 mA) the total current of the extracted beam. The obtained dependence of the total beam extraction current on the lens magnetic field made it possible to determine the magnetic field range optimal for the beam focusing, which turned out to be 1.2–1.4 T. The experimental results are in good agreement with the numerical simulation results. Thus, it was confirmed that the proposed system is promising in terms of the point neutron source development.

Acknowledgments
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