A slit-based method of a high-current ion beam transversal distribution diagnostic

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Abstract. This article presents the results of experimental studies that are part of the research aimed at the development of a point-like neutron source for fast neutron tomography. In frames of the used approach neutrons are produced in D-D fusion at the deuterium-loaded target bombarded with the focused deuterium ion beam. It was proposed to use a high-current ECR ion source to obtain the ultimate beam intensity at the target and maximize the neutron density yield. An important parameter of the neutron source is the size of the emitting region, which, in turn, is determined by the quality of the ion beam focusing. The presented work is dedicated to the development of the diagnostic system able to measure the ion beam transverse distribution. This system is based on the movable plates with orthogonal slits as an alternative to previously used scintillator-based method. The proposed system allows to determine the high-current deuterium ion beam size with an accuracy higher than 1 mm. This work presents verification of the previously obtained results of the high current focused deuterium ion beam formation by means of a slit-based method reliable in measuring beams of high intensity.

1. Introduction
Neutron tomography is a non-invasive method that allows to investigate the inner structure and the composition of the samples. The traditional neutron tomography utilizes thermal or cold neutron fluxes for object irradiation. Image reconstruction is performed by analysis of the neutron scattering and absorption. Simultaneous detection of the secondary X-ray radiation also allows one to study the chemical content of the object. The advantages of neutron methods over x-ray are especially pronounced when objects containing light elements are of the interest, and remain effective even in case when the inner light part of the object is surrounded by a shell of heavy elements. However, the efficiency of thermal neutron tomography is reduced when it is necessary to analyze thick objects. Given such an object, it is beneficial to use fast neutrons due to their higher penetration depth compared with thermal ones.

Modern tomography systems, like X-ray ones, use point-like radiation sources to reduce the minimal dose necessary for the imaging. While the point-like thermal neutron source is something that could not be really created, utilization of fast neutrons allows one to use all of the state of the art tomography techniques. Thus, development of the intense and compact point-like source of fast neutrons is of great interest for many applications in the field of material science or security scanners for drugs and explosives detection.

At the IAP RAS, it was suggested to create such a source using a scheme of a D-D neutron generator with sharp focusing of an ion beam onto a target [1, 2]. The key idea of the approach is to use a dense
plasma of high-frequency ECR discharge for deuterium ion beam formation with ultimate parameters. It was shown [3-5] that the ECR discharge plasma confined in the simple mirror trap and heated by powerful gyrotron millimeter wave radiation could provide ion beams with \(1\ A/cm^2\) current density and uniquely low emittance. Such combination of high beam current and its quality opens a possibility of its effective focusing and reaching of extreme intensities at the focal spot. Deuterium beam size at the target determines the neutron emitting area dimensions and the space resolution of the imaging [6]. Thus, it is necessary to provide the smallest ion beam size at the target in order to obtain the high quality and use the highest beam current to increase neutron yield to reduce necessary exposure time.

The ion beam focusing to the area with the size of 1 mm was demonstrated in the previous experiments with 60 mA of the beam current. The beam size was determined by the detection of a CsI scintillator luminescence illuminated with the D+ beam. Apparently, this technique was not suitable for the level of ion beam intensity reached in the experiments. The total energy deposited in the ~1 μm layer of the scintillator during the 1 ms pulse was at the level of a few Joules, resulting in the crystal being overheated locally above its melting point. Accumulation of the scintillator surface defects limited the measurement precision at 1 mm level. In order to increase the experiment accuracy a system of movable plates with orthogonal slits for the high-current focused deuterium ion beam diagnostics was developed and used for simultaneous measurements of the ion beam current and its space distribution. Additional studies on the ways to increase the ion beam current at the focal plane were performed to reach higher overall system efficiency.

2. Experimental facility

The prospects of using powerful high-frequency gyrotrons for the heating of the ECR discharge plasma that is confined in the quasi-gasdynamic confinement regime in the simple mirror trap [3-5] for applications requiring high-current light ion beams were demonstrated at the experimental facility SMIS 37 at IAP RAS. The quasi-gasdynamic regime of the plasma confinement is characterized by a filled loss-cone in an electron velocity space. Then, the plasma lifetime \(\tau_e\) is determined by the ion sound speed: \(\tau_e = LR/V_s\), where \(L\) is the trap length, \(R\) is the magnetic mirror ratio, \(V_s = \frac{\tau_e}{\sqrt{M_i}}\) is the ion sound speed, \(T_e\) is the electron temperature, \(M_i\) is the ion mass. The maximum plasma density is limited by the heating frequency: \(N_e^{\text{max}} = \frac{\omega^2m}{4\pi^2e^2}\), where \(\omega\) is the heating radiation frequency, \(m\) is the electron mass, \(e\) is the electron charge. Thus, the use of high frequency gyrotrons enables sustaining the plasma with density of more than an order of magnitude higher when compared to the conventional ECR ion sources, while the output power of modern gyrotrons (tens of kW) allows it to compensate for increased energy losses in quasi-gasdynamic confinement regime. So, the possibility to sustain plasma with the electron temperature on the level of tens of eV and the density of \(10^{13} - 10^{14}\ cm^3\) was demonstrated at SMIS 37 facility, where the gyrotron radiation at a frequency of 37 GHz and a power of 100 kW was used. Given the numbers above, a plasma life-time is on the order of 10 μs, which makes it possible to obtain high current density ion beams.

The scheme of the experimental facility is presented in Figure 1. The gyrotron microwave radiation (1) is launched through a quartz window (2) and coupled (3) to the discharge chamber (4). The plasma is confined in the simple mirror trap formed by two coils (5), which maximum field strength is 3 T. Ion beam is formed with two-electrode system (6), consisting of biased plasma electrode and grounded puller electrode. The high-voltage insulators allow to apply the extraction voltage on the level of 60 kV. The extracted ion beam is focused by the magnetic lens (7) with the aperture of 68 mm and the maximum field strength of 3 T on the axis. The slit system (8) intended for the transversal ion beam profile diagnostics is located 154 mm downstream from the magnetic lens in the vacuum volume of the diagnostic chamber.
Figure 1. Scheme of the experimental facility SMIS-37. 1 - incident microwave radiation; 2 - quartz window; 3 - microwave-to-plasma coupling system; 4 - plasma chamber; 5 - magnetic trap coils; 6 - ion beam extraction and formation region; 7 - magnetic lens; 8 - slit based diagnostic system; 9 - high voltage insulators.

3. A slit-based ion beam diagnostic system
Two movable plates placed 5 mm apart with orthogonal slits of 0.5 mm width oriented normally to the beam propagation axis are used as the transversal beam profile diagnostic system. The slits are equipped with step motors, gearbox and feedback system, allowing to position the slits in 0.15 mm steps both in vertical and horizontal directions. The system is governed by a microcontroller able to move, monitor and calibrate the spatial orientation of the slits. A photo of the system is presented in Figure 2.

Figure 2. The system of movable plates with slits for the ion beam diagnostics.

A Faraday cup equipped with a secondary electrons suppression electrode (biased at -100 V with respect to the collector electrode) is located downstream the system for measuring the ion beam current which passes through the hole formed by the slits. The aperture of the Faraday cup is wide enough to measure the passed current regardless of the slits position. The first plate is also connected to the current measuring system, allowing to control the total current of the incident beam. Thus, the beam transverse profile is measured by moving the slits and recording the waveforms of the currents pulse by pulse. Then, the waveforms are averaged to exclude statistical spread.
4. Transverse distributions of ion beam current

The measurements of the dependencies of the total ion beam current and the current passing the hole formed by slits allowed us to find the optimal range of the magnetic lens field providing the best focusing. In addition, the optimization of the extraction system was performed, as the divergence of the ion beam entering the focusing magnetic field is greatly affecting the focusing efficiency. The transverse profiles of the ion beam formed with the extraction system utilized in previous experiments and the new electrode configuration found as the optimal one are compared. It is convenient to use three numbers to describe the extraction system: $D_1$-$G$-$D_2$, where $D_1$ corresponds to the plasma electrode aperture, $G$ corresponds to the gap between electrodes and $D_2$ corresponds to the puller electrode aperture (all dimensions are in millimeters). The extraction configuration used in previous experiments is 5-7-10, whereas the configuration of 5-5-5 was found to be the optimal one. The dependencies of the ion beam current passing through the slits on the magnitude of the focusing field for both extraction systems are presented in Figure 3. An extraction voltage of 40 kV was in these experiments, which however is below the voltage needed to provide a previously achieved result of 60 mA focused to a 1 mm spot (due to higher beam divergence), but ensures sustainable heat load to the slit system in the first tests.

As it has been mentioned above, the beam divergence greatly affects the focusing efficiency, which is clearly seen in Figure 3, where the maximum beam current is acquired at a different lens field. Apparently, the configuration of 5-5-5 provides less divergent beam, resulting in its better focusing. Figure 4 shows the results of transversal beam profile measurements for both extraction configurations utilizing the slits method. It is clearly seen that the optimal configuration (5-5-5) provides sharper focusing, resulting in a narrower beam and a higher peak beam intensity.
5. Conclusion

In the framework of the presented investigation the system based on the movable plates with orthogonal slits for the transversal ion beam profile diagnostics was developed. Using the new method, transverse beam profiles were measured for different configurations of the extraction system. The system was successfully tested with the 40 keV proton beam focused to the 0.8 mm spot, yielding the peak current density of 450 mA/cm². Unlike the scintillator-based method, the created system showed no noticeable degradation under the intense beam. Given the same operational conditions, the slits-based method provides more accurate and reliable data, which is especially important while tuning the extraction and focusing systems in order to obtain the high-current beam focused to a sub-mm size level. Thus, the developed system will be further used for a precise measurements of the transverse distribution of a sharply focused high intensity beam.

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Acknowledgments

The work was supported by the project of the Russian Science Foundation Grant No. 16-19-10501.