Point-like neutron source based on high-current electron cyclotron resonance ion source with powerful millimeter wave plasma heating

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Abstract. A possibility of an intense deuterium ion beam creation for a compact powerful point-like neutron source is discussed. The fusion takes place due to bombardment of deuterium (or tritium) loaded target by high-current focused deuterium ion beam with energy of 100 keV. The ways of high-current and low emittance ion beam formation from the plasma of quasi-gasdynamic ion source of a new generation based on an electron cyclotron resonance discharge in an open magnetic trap sustained by powerful microwave radiation are investigated.

1. Introduction
Currently, neutron sources of various types are used in a wide range of fundamental and applied research in areas such as nuclear physics, spectroscopy, neutron radiography, safety systems using neutron scanners, inspection, medicine, logging of mineral deposits, etc. Today a high number of neutron sources of different types are developed: isotopic sources, nuclear reactors, accelerators, D–D and D–T neutron generators. Neutron tomography is one of the most exciting recent achievements in nuclear physics. It opens up opportunities for a wide range of various microscopic studies of physical, chemical and biological objects. An increase of interest to this technique was caused by appearance of high neutron yield nuclear reactors, automatic neutron diffractometers, specialized detection and analysis systems in recent years.

It is of note that neutron tomography requires dedicated neutron source, i.e. paraxial sources with low angle spread. The only sources now able to deliver required neutron beams with sufficient intensity (10^8–10^9 s⁻¹cm⁻²) are nuclear reactors and large-scale accelerators in pair with collimators [1]. High price and complexity of these sources inhibits widespread of neutron tomography methods.

The use of point-like neutron sources based on laser plasma induced by focusing of powerful femtosecond laser radiation onto a neutron-producing target, for example set of deuterium clusters [2–5] was discussed lately. Ions are effectively accelerated [2] at certain conditions in such plasma, producing neutrons as a result of D–D collisions. The neutron yield of 10^6 per 1 J of laser energy has been detected at the source size of 100 µm [2]. It is of note that isotropic neutron flux from a point-like source with angular spread determined by its size seems to be useful for neutron tomography. High resolution comparable to one obtained with collimated neutron beams may be derived from the source of small size. However state-of-the-art lasers
having 0.1 J per pulse at 1 kHz repetition rate give average neutron yield of $10^8$ s$^{-1}$, thus significantly conceding reactor-based sources.

In recent papers [6] the possibility of creating a point-like neutron source with yield of $10^{10}$–$10^{13}$ s$^{-1}$, based on a new generation of high-current ion source is discussed. It is proposed to use D–D and D–T reactions occurring in deuterium or tritium loaded target bombarded by focused deuterium ion beam. The size of the neutron source, i.e. minimum size of the ion beam achieved on the target is determined by the ion beam quality and efficiency of the focusing system. This proposal is based on the recent developments [7–9] of unique high-current ion sources based on a discharge sustained by powerful electromagnetic radiation of millimeter wave gyrotron under conditions of the electron cyclotron resonance in open magnetic traps. The use of modern powerful high-frequency gyrotrons allows to increase plasma density by at least one order of magnitude if compared to the conventional electron cyclotron resonance (ECR) ion sources (up to $10^{13}$–$10^{14}$ cm$^{-3}$). With plasma density increase there is a change in plasma confinement: a so-called quasi-gasdynacicm confinement replaces traditional collisionless regime. The feature of quasi-gasdynamnicm confinement is a filled loss-cone in an electron velocity space. Plasma lifetime is determined by the time of ions escape from the trap, which happens with ion-sound velocity $\tau_g = LR/V$, where $R, L$—mirror ratio and the trap length respectively, $V = \sqrt{T_e/M}$—ion sound velocity ($T_e$—electron temperature, $M$—ion mass). Characteristic electron temperature is on the level of 100 eV. A compact simple mirror magnetic trap with 20 cm length is used for plasma confinement, which corresponds to $\sim 5$ µs lifetime (whereas plasma lifetime in conventional ECR ion sources is on the level of several ms). Short lifetime together with high plasma density provides a possibility of ion beam formation with current density more than 10 A/cm$^2$ ($j \sim N_e/\tau$, $N_e$ is plasma density and $\tau$—plasma lifetime). Even the first experiments with such plasma demonstrated possibility of hydrogen and deuterium ion beams production with 400 mA current using relatively low extraction voltage of 45 kV and simple two-electrode extraction system placed at some distance from the magnetic trap into the area of plasma spread along the magnetic field lines where the current density decreased significantly (respectively to the optimal one for the given extraction voltage). Bombardment of deuterium-loaded target by this high-current deuterium ion beam led to the neutron yield of up to $10^9$ s$^{-1}$ [10].

2. Experimental facility
Aforementioned approach to creation of the point-like neutron source is based on deuterium ion beam focusing onto a target within smallest possible area. Focusing efficiency is determined by

![Figure 1. SMIS-75 Experimental facility layout.](image-url)
Figure 2. Averaged current dependence on extraction voltage.

the ion beam current and its quality–emittance. Investigations were performed with SMIS-75 experimental facility (figure 1) previously described thoroughly in [11].

A gyrotron generating a Gaussian beam of linearly polarized radiation at the frequency of 75 GHz, with the power up to 200 kW, and pulse duration up to 1.5 ms was used as a source of pulsed microwave radiation. Microwaves were focused by means of special quasi-optical microwave-to-plasma coupling system in the center of discharge chamber with 25 cm length and 4 cm diameter placed into the mirror magnetic trap. The magnetic field in the trap was produced by means of pulsed solenoids, spaced 15 cm apart. The current pulse with the shape close to half period of a sinusoid had the duration of 11 ms with the magnetic field variation during the microwave pulse being less than 3%. Magnetic field in the mirror was varied from 1.4 to 4 T (ECR for 75 GHz is 2.68 T). Ratio of the maximum and minimum magnetic fields of the trap was equal to 5 (i.e. $B_{\text{max}}/B_{\text{min}}$). Deuterium was used as a working gas. The gas inlet into the source was realized through an opening incorporated with the microwave coupling system. The delay between gas injection and subsequent microwave pulse (300–3000 µs) as well as the gas pulse duration (about 5 ms) were adjusted for each experimental condition in order to maximize the beam current and optimize the temporal shape of the extracted current pulse.

Upgraded two electrode extraction system with reduced sizes of apertures was used for research of possibility to obtain extremely low emittance values. The ion extraction and beam formation were realized by a single gap two-electrode (i.e. plasma electrode–puller electrode) system. Holes in plasma electrode and puller were 5 mm and 10 mm respectively with the gap between them of 11 mm. The plasma electrode was placed 10 cm downstream from the magnetic mirror to limit the extracted ion flux as described in [11], which helps improving the beam transport through the puller.

The maximum available extraction voltage was 50 kV. A Faraday cup was placed immediately behind the puller electrode to measure the total beam current passing through the extractor.
3. Experimental results
A single-aperture extraction system was used for beam formation in presented experiments. The optimization of extraction electrode configuration such as adjusting the gap between the electrodes and the position relative to the magnetic plug of the trap was performed in order to maximize the extracted proton current. The optimal distance between magnetic plug and plasma electrode was found to be 10 cm and the gap between the electrodes 11 mm. Shift of the extraction system closer to the plug was not reasonable because of too high plasma flux density for high voltage range available in experiments. The dependence of the Faraday cup current on the acceleration voltage is shown in figure 2 for the optimal extraction electrode configuration. A representative example of the beam current waveform is shown in (figure 3). The maximum obtained deuterium ion beam current was 120 mA, corresponding to 600 mA/cm$^2$ current density through the plasma electrode. To our knowledge, this current density is the record for modern ECR ion sources.

It should be mentioned that in [12] it was demonstrated that atomic fraction in such a beam can reach 94% (other 6% are molecular ions).

Ion beam emittance study was performed using pepper-pot method. Pepper-pot plate was placed in 1 cm behind puller end. In case of all extraction system configurations measurements gave the same result. Example of the reconstructed emittance diagram is shown in figure 4. The rms normalized emittance appeared to be $0.03\pi$ mm mrad.

Figure 3. Example of ion beam current oscillogram. Extraction voltage is 50 kV, average beam current 120 mA.
Figure 4. Ion beam emittance diagram. The extractor: 5 mm plasma electrode aperture and 10 mm puller aperture with 11 mm gap; rms normalized emittance is 0.03π mm mrad.

To estimate the prospects of the use of ion beams in the creation of a point-like neutron source it is necessary to estimate the dimensions of the beam in the waist with his focus. Let’s consider the simplest focusing system: magnetic lens providing the half angle of the ion beam convergence $\alpha$ at the level of 30° while the spot size in the focus area, defined as $\Delta r = \varepsilon_{n}/(\beta\alpha)$ [13], is 8 µm for the measured emittance value. Lens focal distance, defined as $f = (8MU)/(qLB^2)$, (where $M$—ion mass, $q$—ion charge, $U$—beam energy, $B$—maximum magnetic field intensity, $L$—half-width of $B$—field profile [13]) has to be equal to the diameter of the lens aperture to achieve this angle of convergence of the parallel ion beam. For the 30 mm of the lens aperture diameter and 50 keV deuterium beam the maximum magnetic field intensity is equal to the 1.6 T when the half-width of the magnetic field profile is 10 cm which seems to be quite real.

However it should be noted that at beam currents on the level of hundreds of mA the beam space charge plays a significant role preventing focusing predicted by emittance only. Therefore, space charge compensation by electrons must be used [13]. High degree of space charge compensation could be achieved in case of using three and more electrodes in the extraction system, which is a common practice in high current beams applications [14].
4. Conclusion
The use of high-current ECR ion source with quasi-gasdynamic plasma confinement and heating by gyrotron microwave radiation allows producing light ion beams with uniquely low emittance (for a given current level). Such a low emittance enables the focusing of the ion beam into the spot of several tens of \( \mu m \) in diameter. Suggested approach could be very efficient for development of the point-like neutron source with the size of emitting area comparable to femtosecond laser systems, but with significantly higher neutron yield (comparable to collimated beams of neutrons produced in a nuclear reactor). With the increase of the extraction voltage up to realistic 100 kV a cross-section of D–D reaction raises significantly \([15]\), and the total extracted current may reach the value of 1 A, yielding the neutron flux up to \( 10^{11} \) s\(^{-1} \) for D-target, and up to \( 10^{13} \) s\(^{-1} \) for T-target. Such neutron flux corresponds to a flux density of \( 10^8 \)–\( 10^{10} \) s\(^{-1} \)cm\(^{-2} \) at 10 cm distance from the source, which may be effectively utilized for neutron tomography, thus making this technique widely available.

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