EPJ Web of Conferences **149**, 01004 (2017) DOI: 10.1051/epjconf/201714901004
10th International Workshop 2017 "Strong Microwaves and Terahertz Waves: Sources and Applications"

Powerful neutron generators based on high current ECR ion sources with gyrotron plasma heating

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Introduction

Neutron sources are widely used in fundamental and applied research. Manifold applications require neutron fluxes of various intensities, energy spectra and degrees of collimation. Several types of neutron sources have been developed for the purpose including nuclear reactors, radioisotope sources, D-D and D-T generators, plasma pinch machines, accelerators etc. Each neutron source type occupies a niche fulfilling the parameters desired in a given application.

The present paper presents the results of recent investigations devoted to development of a new generation of compact D-D (D-T) neutron generators based on a high-current quasi-gasdynamic ECR ion source, which utilizes powerful gyrotron radiation of mm-waveband for plasma creation [1]. Such approach allows to increase the plasma density in the discharge significantly in comparison to conventional ECRISs, which utilize microwave radiation with frequencies on the order of 10 GHz. In experiments with a 37.5 GHz gyrotron the plasma density reaches values of $2 \cdot 10^{13}$ cm^{-3}. Significant increase of the plasma density leads to a change of the plasma confinement mode. A so-called quasi-gasdynamic confinement was realized in the presented experiments instead of the collisionless one, which is common for modern ECRISs. The plasma lifetime, which is much shorter than in conventional classical ECRIS, can be expressed as $\tau = \frac{L \cdot R}{2V_{is}}$, where L – magnetic trap length, R – trap mirror ratio (ratio between magnetic field in the magnetic mirror and in the trap center), V_{is} – ion sound velocity. Short plasma lifetime provides high plasma flux density from the trap. Under our experimental conditions typical plasma lifetime is on the order of 10 μs. The described peculiarities of quasi-gasdynamic ECR discharge sustained by mm-waveband radiation, namely, short lifetime and high density, provide unprecedented plasma flux densities of several eA/cm^2.

Experimental results

Experiments aimed to demonstrate the benefits of the high current gasdynamic ECR ion source as a part of D-D neutron generator were conducted at SMIS 37 facility [2], schematically depicted in Fig. 1. The plasma was created and sustained inside a d = 4 cm vacuum chamber by pulsed (1.5 ms) 37.5 GHz linearly polarized radiation with power up to 100 kW. The simple mirror magnetic trap with 25 cm length was created by pulsed solenoids, providing a mirror ratio of 5. The magnetic field strength was varied in a range of 1–4 T at mirror plugs, whereas the resonant field strength is 1.34 T for 37.5 GHz.

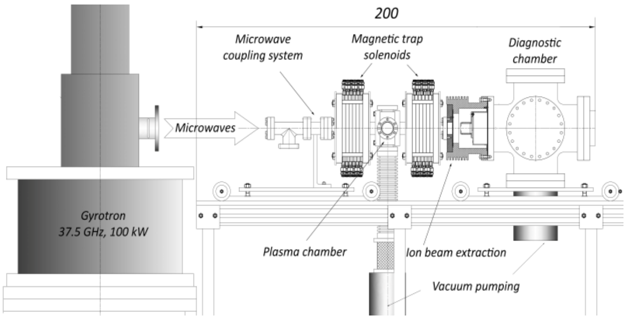

Fig. 1. SMIS 37 experimental facility

Microwave radiation was guided into the chamber quasi-optically through a special coupling system. The pulsed gas feed line was incorporated into the coupling system i.e. the neutral gas was injected axially. The ion extraction and beam formation were realized by a two-electrode (diode) system consisting of a plasma electrode and puller.

The best result was obtained with plasma electrode aperture of 10 mm. The maximum deuterium beam current was 500 emA, which corresponds to a current density of 630 emA/cm^2 at the plasma electrode. To our knowledge this is a record for ECR ion sources. Beam emittance was measured with the "pepper-pot" method and its normalized rms value was 0.07 pi·mm·mrad. Studies of the extracted charge state distribution have shown that 94% of it consists of atomic deuterons (D+) (contribution of molecular D_2^+ ions is less than 6%). For our knowledge such combination of parameters makes the obtained beam the brightest for any kind of ion sources with normalized rms brightness value of 100 A/(pi·mm·mrad)^2.

Measurement of the produced neutron flux was performed by bombarding a heavy ice target with 300 emA D^+ beam accelerated to 45 keV energy. An example of the neutron counter signal is presented in fig. 2-a and the corresponding amplitude spectrum (collected over 100 pulses) in fig. 2-b. The amplitude spectrum of the acquired signals matches the reference one, proving that the signals are generated by neutrons, not X-rays or electrical noise. The D_2O target yield was 10^9 s^{-1}. It is worth noting that the area of the target was about 1 cm^2, which corresponds to a neutron flux density of about 10^9 cm$^{-2}\cdot$s^{-1} at the target. Obtained results allow to deduce the prospects of D-D neutron generator development using deuterium ion source based on quasi-gasdynamic ECR discharge, sustained by powerful gyrotron radiation. Commercially available TiD_2 targets are capable of generating up to 10^8 s^{-1} neutrons per 1 emA of deuterium beam bombarding the target with 100 keV energy.

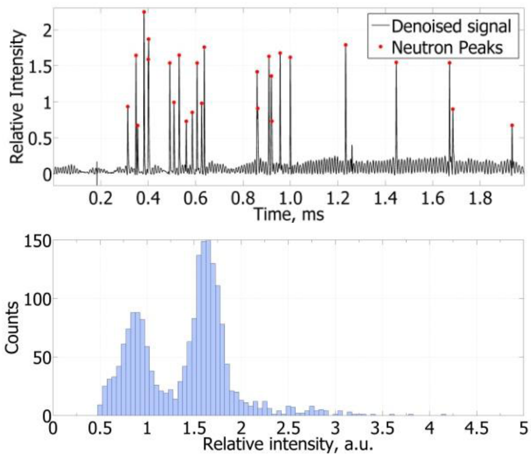

Fig. 2. (a) Single pulse waveform from neutron counters

Each peak corresponds to a single detected neutron. (b) - Amplitude spectrum of the neutron signals collected over 100 pulses. Two peaks on the spectrum correspond to different counters.

In the case of target bombardment with the demonstrated beam current (current density 630 mA/cm^2) in the present work and accelerated up to 100 keV energy the neutron flux density could reach $6\cdot10^{10}$ s$^{-1}\cdot$cm^{-2}.

Point-like neutron source

One of the applications of high density neutron fluxes is neutronography. Traditionally for this purpose paraxial neutron beams from nuclear reactors and accelerators are utilized [3]. Another approach is to create a point-like source.

The use of a high-current ECR ion source with quasi-gasdynamic plasma confinement and heating with gyrotron microwave radiation allows the formation of light ion beams with uniquely low emittance (for a given current level). Such a low emittance enables focusing of the ion beam into a small spot. By numerical modeling with open IBSimu code [4] it was shown that an ion beam with the properties listed above could be focused with a simple magnetic lens into 100 µm scale spot. Results of these calculations are shown in fig. 3.

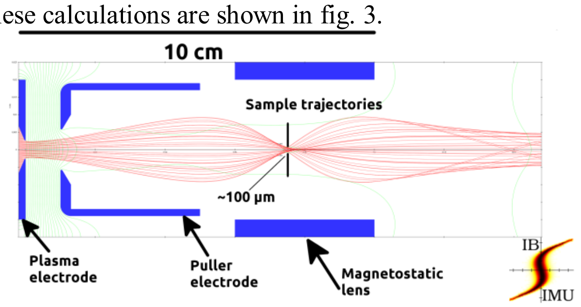

Fig. 3. Simulation of the beam focusing with IBSimu software

Estimation presented in [5] show that the point-like source based on high current ECR ion source could produce a neutron yield up to 10^{11} s^{-1} for D-target, and up to 10^{13} s^{-1} for T-target.

D-D neutron generator for BNCT

One of the most interesting and important applications of high yield neutron generators discussed above is boron-neutron capture therapy (BNCT) of oncologic diseases [6]. The main problem hindering the development of BNCT is the necessity of neutron fluxes exceeding 10^9 s$^{-1}\cdot$cm^{-2}. The only machines able to produce the required neutron flux are nuclear reactors and large-scale accelerators plagued by tremendous price and strict safety rules for protecting the staff and patients. The D-D neutron generator scheme discussed here is free of those shortcomings as it does not use radioactive isotopes including tritium and/or high energy particles, thus not requiring heavy X-Ray shielding. Moreover, the device is compact allowing it to be installed in literally any existing clinic, and has significantly lower price in comparison to the aforementioned technologies.

The described experiments were performed in pulsed mode. BNCT, however, requires continuous (CW) flux of neutrons. Thereby a CW D-D neutron generator using deuterium ion source based on CW ECR discharge in a permanent magnet trap, sustained by 28 GHz / 10 kW gyrotron is under construction at IAP RAS. Schematic view of the future facility is shown in fig. 4.

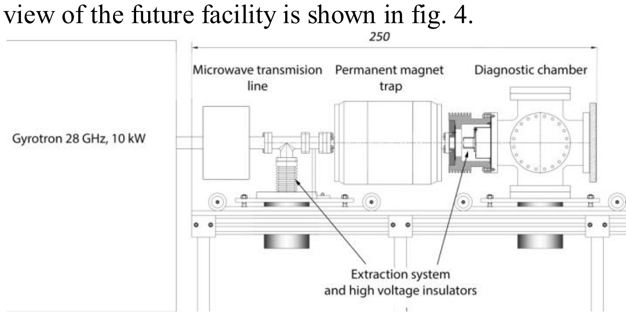

Fig.4. Scheme of the CW ECR ion source for neutron production

The first experiments on plasma confinement in the quasigasdynamic regime in CW mode have demonstrated that 24 GHz/5 kW gyrotron radiation can provide plasma flux from a trap with 1 A/cm^2 density. Thus, it is possible to obtain continuous ion beams with similar parameters as reported above.

Acknowledgments. The reported work devoted to the CW neutron production was supported by Russian Science Foundation, grant #16-12-10343. The reported work devoted to the point-like neutron source creation was supported by Russian Science Foundation, grant # 16-19-10501.

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