HIGH CURRENT PROTON AND DEUTERON BEAMS FOR ACCELERATORS AND NEUTRON GENERATORS

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Abstract

This paper presents the latest results of high current proton and deuteron beam production at SMIS 37 facility at the Institute of Applied Physics (IAP RAS). In this experimental setup the plasma is created and the electrons are heated by 37.5 GHz gyrotron radiation with power up to 100 kW in a simple mirror trap fulfilling the ECR condition. High microwave power and frequency allow sustaining higher density hydrogen plasma (n_e up to $2 \cdot 10^{13}$ cm^{-3}) in comparison to conventional ECRIS's or microwave sources. The low ion temperature, on the order of a few eV, is beneficial to produce proton beams with low emittance.

Latest experiments at SMIS 37 were performed using a single-aperture two-electrode extraction system. Experiments with hydrogen and deuterium show possibility of beams formation with currents up to 550 mA at high voltages below 45 kV with normalized rms emittance lower than 0.2 π·mm·mrad. Such beams have a high potential for application in future accelerator research.

Also in frames of the present paper it is suggested to use such an ion source in a scheme of D-D neutron generator. High current gas-dynamic ion source can produce deuteron ion beams with current density up to 700-800 mA/cm^2. Generation of the neutron flux with density at the level of $7\text{-}8 \cdot 10^{10}$ s^{-1}cm^{-2} could be obtained in case of TiD_2 target bombardment with deuteron beam accelerated to 100 keV. Estimations show that it is enough for formation of epithermal neutron flux with density higher than 10^9 s^{-1}cm^{-2} suitable for boron neutron capture therapy. Important advantage of described approach is absence of Tritium in the scheme.

EXPERIMENTAL SETUP

The experimental research presented in this work was carried out on the SMIS 37 shown schematically in Fig. 1 [1]. A gyrotron generating a Gaussian beam of linearly polarized radiation at the frequency of 37.5 GHz, with the power up to 100 kW, and pulse duration up to 1.5 ms was used for plasma production and heating. The microwave radiation is launched into the plasma chamber through a quasi-optical system consisting of 2 mirrors, quartz vacuum window and a special µW-to-plasma coupling system shown on the left in Fig. 1. A simple mirror trap was used for plasma confinement. The magnetic field in the trap was produced by means of pulsed solenoids, spaced 15 cm apart. Magnetic field in the mirror was varied from 1.4 to 4 T (ECR for 37.5 GHz is 1.34 T). Ratio of the maximum and minimum magnetic fields of the trap was equal to 5. Hydrogen and deuterium were used as a working gas. Its 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.

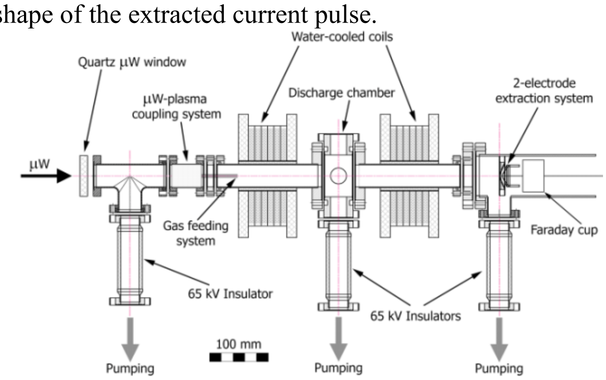

Figure 1: SMIS 37 experimental setup.

The ion extraction and beam formation were realized by two-electrode, i.e. single gap plasma electrode - puller electrode system. Diameters of the holes in plasma electrode and puller were of 10 mm and 22 mm respectively. The plasma electrode was placed 10 cm downstream from the magnetic mirror to limit the extracted ion flux as described in [2], which helps improving the beam transport through the puller.

The maximum available extraction voltage was 45 kV. A Faraday cup was placed immediately behind the puller electrode to measure the total beam current passing through the extractor.

EXPERIMENTAL RESULTS

The use of powerful millimeter wave radiation allows to significantly increase the plasma density in the discharge compared to traditional ECR sources (the density scales with the square of the radiation frequency). In our experiments with 37.5 GHz gyrotron frequency the plasma density could be higher than 10^{13} cm^{-3} [3]. High value of plasma density N_e in combination with quite low ion life-time τ (but still enough for 100% ionization degree) provides high density of ion flux from the trap ~ N_e/τ. In our experiments the total plasma (ion) flux

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density through the plug of the magnetic trap was up to 5 A/cm^2.

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 ion current. The optimal distance between magnetic plug and plasma electrode was found to be 10 cm and the gap between the electrodes 6 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 maximum obtained beam current was 500 mA, corresponding to 640 mA/cm^2 current density through the plasma electrode (see fig.2). To our knowledge, this current density is the record for modern ECR ion sources.

Emittance of the extracted beam was measured with "pepper-pot" method [4], which had been successfully tested earlier at SMIS 37 [2]. "Pepper-pot" plate was placed 1 mm downstream from the puller with another 55 mm gap before a CsI scintillator for beam imaging. Emittance diagram for the 500 mA beam is shown in figure 2. The normalized rms emittance was of 0.07 π mm mrad.

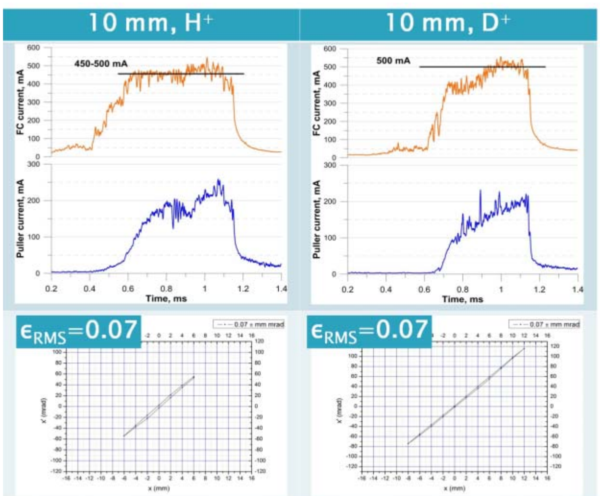

Figure 2: Faraday cup (FC) and puller current oscillograms for H+ and D+ beams and corresponding emittance diagrams obtained with 45 kV extraction voltage.

The spectrum of the extracted ion beam was also measured. The spectrum shown in fig. 3 appeared to be similar to the one demonstrated in [5] for multiaperture extraction. The data is normalized with respect to the total beam current measured with the Faraday cup downstream from the bending magnet. In this case H_2^+-current is less than 6% of the total beam current. Only trace amounts of H_3^+ were observed.

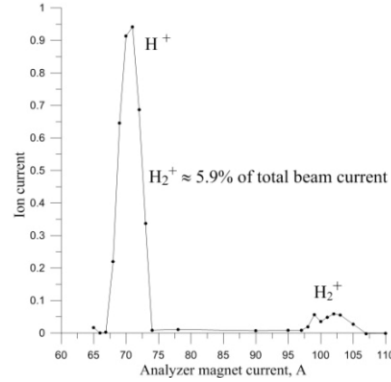

Figure 3: Mass-analyzed ion beam spectrum normalized to the total beam current.

Obtained high current deuteron beams were used for D-D neutron generation: beams were accelerated across high voltage potential (up to 45 kV) to the target containing deuterium (for the most part of experiments it was TiD_2). Due to the D-D reaction 2.5 MeV neutrons were generated. Preliminary thermalized neutron flux was measured by ^{3}He proportional counters.

Neutron yield obtained for different targets presented in the Table 1. The lower yield for titanium targets was due to the target quality (i.e. degree of deuterium implementation). The yield from the "heavy ice" target was close to the theoretical one for 45 kV. It should be noted that it is only the results of preliminary experiments for neutron generation. In these experiments acceleration voltage didn't exceed the value of 45 kV where the cross section of the D-D reaction is quite small.

Table 1: Neutron yields for different targets.

Target type	Neutron yield/mA	Total yield
TiD2(sample 1)	$7 \cdot 10^5$ s^{-1}	$2 \cdot 10^8$ s^{-1}
TiD2(sample 2)	$1 \cdot 10^6$ s^{-1}	$3 \cdot 10^8$ s^{-1}
D2O ("heavy ice")	$4 \cdot 10^6$ s^{-1}	10^9 s^{-1}

CONCLUSION

The experimental results described in the present paper demonstrate the feasibility of high power millimeter wave quasi-gasdynamic ECR ion sources for the production of high brightness proton and deuteron beams with favorable species fraction.

Especially it looks prospectively for neutron production. The performance of commercially available targets is about 10^8 neutrons/second per 1 mA current of the incident deuteron beam accelerated to energy of 100 keV [6]. Thus, bombardment of such target by deuteron beam equivalent to that demonstrated above (and further accelerated to 100 keV) would theoretically yield a neutron flux up to $6 \cdot 10^{10}$ neutrons per second from rather small surface with dimensions of about 1 cm. Neutron

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generator with these parameters seems to be promising for such applications as boron neutron-capture therapy.

As the next step a possibility of D-D neutron generator creation using a source of deuterium ions on the basis of CW ECR discharge supported by powerful microwave technological gyrotron with frequency of 24-28 GHz and a power level of 10 kW should be studied.

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