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500 mA LOW EMITTANCE PROTON AND DEUTERON BEAM PRODUCTION AT SMIS-37 ECR ION SOURCE

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Abstract

This work presents the latest results of high current proton and deuteron beam production at SMIS 37 facility at the Institute of Applied Physics (IAP RAS). This facility creates and heats up the plasma by 37.5 GHz gyrotron radiation with power up to 100 kW in a simple mirror trap meeting the ECR condition. High microwave power and frequency allow sustaining plasma of significantly higher density (Ne up to $2\cdot10^{13}$ cm^{-3}) in comparison to conventional ECRISes or other microwave ion sources. The low ion temperature, on the order of a few eV, is beneficial to produce ion beams with low emittance. Latest experiments at SMIS 37 were performed using a single-aperture two-electrode extraction system. Various diameters of plasma electrode apertures i.e. 5 mm, 7 mm, 10 mm, were tested yielding proton and deuteron beams with currents up to 500 mA with RMS emittance lower than 0.2 π·mm·mrad at extraction voltages up to 45 kV. The maximum beam current density was measured to be 800 mA/cm^2. A possibility of further improvement through the development of an advanced extraction system is discussed.

INTRODUCTION

Operation of modern high power accelerators often requires production of intense beams of hydrogen and deuterium ions. H+ (proton) beams are utilized or envisioned for use in linear accelerators e.g. the future European Spallation Source under design [1, 2]; some special applications such as neutron generators, i.e. IFMIF project [3], require D+ (deuteron) ion beams. Requirements for the brightness of such beams grow together with the demand of accelerator development and arising experimental needs. New facilities aiming at outperforming the previous generation accelerators are usually designed for higher beam currents. Enhancing the beam intensity and maintaining low transverse emittance at the same time is, however, quite a challenging task. The most modern accelerators require H^+/D^+ ion beams with currents up to hundreds of mA (pulsed or CW), and normalized emittance less than 0.2 π•mm•mrad [1, 3] to keep the beam losses at high energy sections of the linacs below commonly imposed 1 W/m limit.

This paper is a continuation of the work described in [4] and devoted to further investigation of high current proton and deuteron beams production at gasdynamic [5] ECR ion source - SMIS 37 facility [6] at the Institute of Applied Physics (IAP RAS), beam current and emittance enhancement.

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SMIS-37 EXPERIMENTAL FACILITY

The experimental research presented in this work was carried out on the SMIS-37 shown schematically in Fig. 1.

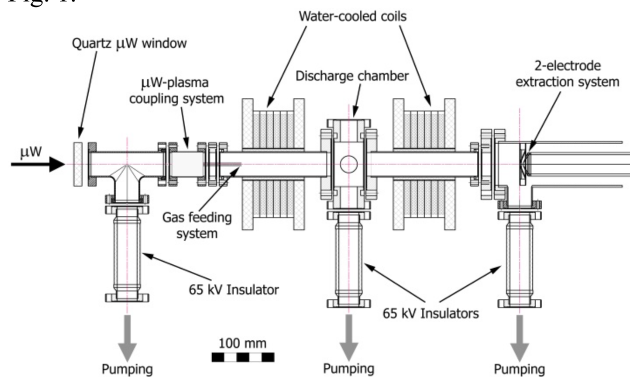

Figure 1: SMIS-37 experimental setup.

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 as a source of pulsed microwave radiation. 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-plasma coupling system shown on the left in Fig. 1, which has been designed for efficient transport of the radiation avoiding parasitic resonances and plasma flux impinging the quartz window. A simple mirror magnetic trap was used for plasma confinement, produced by pulsed solenoids, spaced 15 cm apart. The magnetic field variation during the microwave pulse was less than 3%. The peak magnetic field in the mirror was varied from 1.4 to 4.3 T (ECR field for 37.5 GHz is 1.34 T). A mirror-ratio (i.e. Bmax/Bmin) of the trap was fixed to 5. 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 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.

The ion extraction and beam formation was realized by two-electrode single gap plasma - puller electrode system. Aperture pairs in plasma and puller electrodes were 5mm-10mm, 7mm-22mm and 10mm-22mm respectively. The plasma electrode was placed 10 cm downstream from the magnetic mirror to limit the extracted ion flux as described in [7], which helps improving the beam transport through the puller. The maximum available extraction voltage was 45 kV. A Faraday cup with secondary electron suppression was placed right behind

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the puller electrode to measure the total beam current passing through the extractor.

Emittance of the extracted beam (all species together) was measured with "pepper-pot" method [8], which has been successfully tested earlier at SMIS 37 [9, 4]. A new pepper-pot plate was designed and manufactured, having 21-by-21 matrix of 200 µm diameter fine holes separated by 2 mm gaps, which leaded to substantial enhancement of emittance measurement precision in comparison to previous studies [4]. The pepper-pot plate was placed 25 mm downstream from the puller with another 55 mm gap before a CsI scintillator for beam imaging.

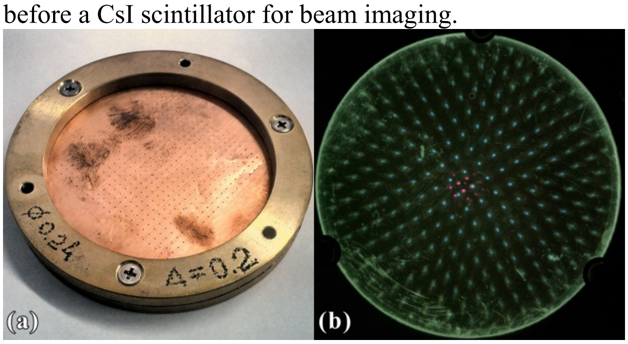

Figure 2: (a) "Pepper-pot" plate for emittance measurements. (b) CsI scintillator plate excited by ion beam.

RESULTS

A single-aperture extraction system was used for beam formation in the presented experiments. As only two fixed puller holes were available (i.e. 10 and 22 mm in diameter), the optimization of extraction electrode configuration was done varying the gap between the electrodes.

Plasma Electrode D=5 mm, Hydrogen

The optimal gap between electrodes appeared to be 10 mm, yielding the maximum beam current; diameter of puller electrode hole used was 10 mm.

Faraday cup current together with puller current are shown in Fig. 3(a), total beam current grows from 80 mA at steady state up to 140 mA at the end of the microwave pulse, which is explained by decreasing of plasma density down to the optimum value for used configuration and accelerating voltage of 42 kV and better beam focusing. Transversal emittance (hereinafter normalized) diagram is presented in Fig. 3(b), showing RMS value of 0.06 π•mm•mrad.

Plasma Electrode D=7 mm, Hydrogen

The optimal gap between electrodes appeared to be 6 mm, while the puller hole diameter was 22 mm.

Faraday cup current together with puller current are shown in Fig. 4(a), total beam current remains stable at the level of 300 mA within the whole microwave pulse duration. Accelerating voltage of 42 kV was used. Transversal emittance diagram is presented in Fig. 4(b), showing RMS value of 0.18 π•mm•mrad. Relatively big value of RMS emittance could be explained by used source settings turned in higher plasma temperature, for these settings yielded the maximum beam current. Relatively higher plasma temperature was confirmed by increased amount of bremsstrahlung observed in comparison with 5 mm case.

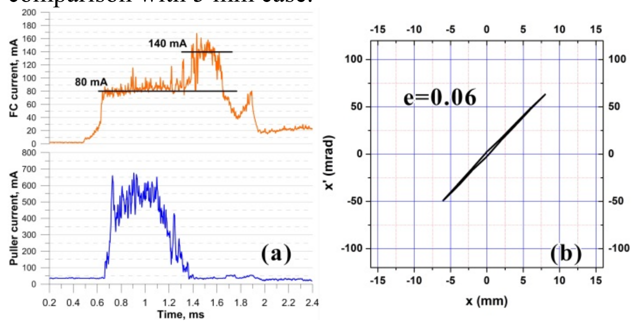

Figure 3: Hydrogen, 5 mm plasma electrode hole. (a) Faraday cup and puller currents. (b) RMS emittance diagram.

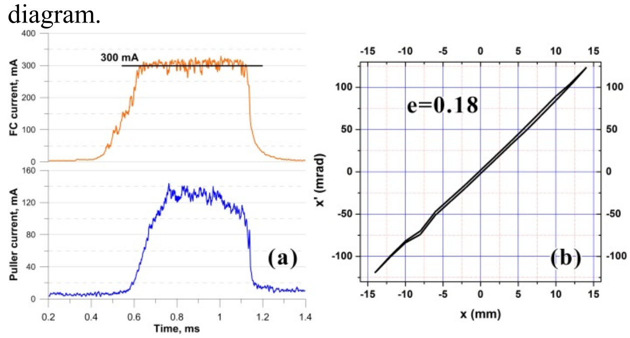

Figure 4: Hydrogen, 7 mm plasma electrode hole. (a) Faraday cup and puller currents, (b) RMS emittance diagram.

Plasma Electrode D=10 mm, Hydrogen

The optimal gap between electrodes for 10 mm plasma electrode hole appeared to be the same as for 7 mm extraction hole, i.e. 6 mm, while the puller hole diameter was 22 mm.

Faraday cup current together with puller current are shown in Fig. 5(a), total beam current remains relatively stable at the level of 450 mA within the 70% of the microwave pulse duration. Accelerating voltage of 41.5 kV was used. Transversal emittance diagram is presented in Fig. 5(b), showing RMS value of 0.07 π•mm•mrad.

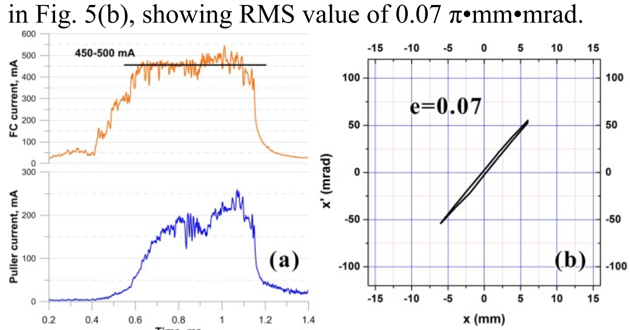

Figure 5: Hydrogen, 10 mm plasma electrode hole (a) Faraday cup and puller currents, (b) RMS emittance diagram.

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Plasma Electrode D=10 mm, Deuterium

The extraction system configuration was kept the same as for Hydrogen (10 mm plasma electrode hole, 6 mm gap, 22 mm puller electrode hole). Source settings were adjusted slightly from the optimal ones for Hydrogen beam to maximize the total current.

Faraday cup current together with puller current are shown in Fig. 6(a), total beam current rapidly reaches value of 400 mA, then slowly grows up to 500 mA and remains till the end of microwave pulse. Accelerating voltage of 42 kV was used. Transversal emittance diagram is presented in Fig. 6(b), showing RMS value of 0.07 π•mm•mrad.

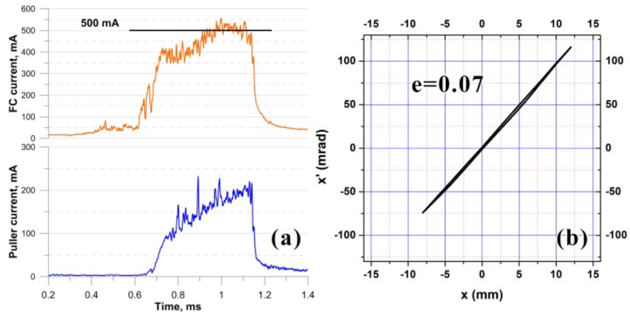

Figure 6: Deuterium, 10 mm plasma electrode hole (a) Faraday cup and puller currents, (b) RMS emittance diagram.

CONCLUSION

The experimental results described in this paper demonstrate a uniqueness of the gasdynamic ECRIS with high frequency plasma heating as a source of proton and deuteron beams of high brightness.

The ion beams with total current of 450 mA for protons and 500 mA for deuterons, RMS emittance not bigger than 0.07 π•mm•mrad and pulse length of 0.5 ms obtained. The maximum extracted current density had reached 800 mA/cm^2 (for 7 mm hole). The beam characteristics are summarized in Table 1. The fraction of atomic to molecular ions in the extracted beam was not measured simultaneously with presented studies, but it has been done for similar conditions in Ref. [4], where the typical ratio of H^+ and H_2^+ was 94% and 6% respectively.

Table 1: Results Summary

Hole diam.	Total current	RMS emittance
5 mm, H_2	80-140 mA	0.06 π•mm•mrad
7 mm, H_2	300 mA	0.18 π•mm•mrad
10 mm, H_2	450 mA	0.07 π•mm•mrad
10 mm, D_2	500 mA	0.07 π•mm•mrad

It is worth noting that beam pulse duration was limited by microwave generator power supplies, and can be extended up to tens of milliseconds without significant source modifications.

Besides pulse duration, demonstrated beams excessively meet the requirements of i.e. ESS [1,2] and IFMIF [3] projects. Particularly, SMIS-37-like ion source could fulfil requirements of IFMIF facility, being the only source of deuterons instead of two of them, thus avoiding building two linacs.

In presented studies total beam current was limited by accelerating voltage available, which can be seen from Fig. 7, where ion traces are simulated with IBSimu software [10] for Hydrogen plasma, 10 mm extraction hole diameter, 45 kV accelerating voltage. It is clearly seen that the beam is under-focused due to lack of the electric field.

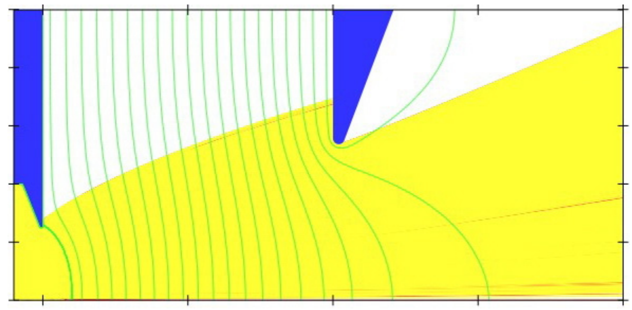

Figure 7: Ion traces simulated with IBSimu code, 10 mm case, Hydrogen plasma, 45 kV.

The extracted beam current could be further enhanced by moving the plasma electrode closer to the magnetic mirror and scaling the extraction voltage and geometry appropriately, and, according to simulations, exceed outstanding for conventional ECRISes 1 A while keeping the emittance low enough.

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