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## High current proton beams production at Simple Mirror Ion Source 37a)

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## High current proton beams production at Simple Mirror Ion Source 37<sup>a)</sup>

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This paper presents the latest results of high current proton beam production at Simple Mirror Ion Source (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. Latest experiments at SMIS 37 were performed using a single-aperture two-electrode extraction system. Proton beams with currents up to 450 mA at high voltages below 45 kV were obtained. The maximum beam current density was measured to be 600 mA/cm<sup>2</sup>. A possibility of further improvement through the development of an advanced extraction system is discussed. © 2013 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4825074>]

### I. INTRODUCTION

Operation of modern high power accelerators often requires production of intense beams of hydrogen ions. H<sup>+</sup> (proton) beams are utilized or envisioned for use in linear accelerators, e.g., the future European Spallation Source under design,<sup>1,2</sup> H<sup>-</sup> ions are favored in applications based on charge exchange injection into storage rings or circular accelerators, e.g., the US Spallation Neutron Source<sup>3</sup> and some special applications, such as the International Fusion Materials Irradiation Facility (IFMIF) project,<sup>4</sup> require D<sup>+</sup> (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 hydrogen beam intensity and maintaining low transverse emittance at the same time is, however, becoming increasingly difficult. The most modern accelerators require hydrogen ion beams with currents up to hundreds of mA (pulsed or continuous wave (CW)), and normalized emittance less than 0.2–0.3  $\pi$  mm mrad<sup>1,4</sup> to keep the beam losses at high energy sections of the linac below commonly imposed 1 W/m limit.

This paper is a continuation of the work described in Refs. 5 and 6 and devoted to investigation of high current proton beams production at SMIS 37 facility<sup>6</sup> at the Institute of Applied Physics (IAP RAS). SMIS 37 has been constructed for production of high current beams of multicharged ions. However, during recent experiments it has demonstrated significant potential for proton beams generation.

### II. SMIS 37 EXPERIMENTAL FACILITY

The experimental research presented in this work was carried out on the SMIS 37 shown schematically in Fig. 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 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  $\mu$ W-plasma coupling system shown on the left in Fig. 1. The setup has been designed for efficient transport of the radiation avoiding parasitic resonances and plasma flux impinging the quartz window. 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. 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%. The peak 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

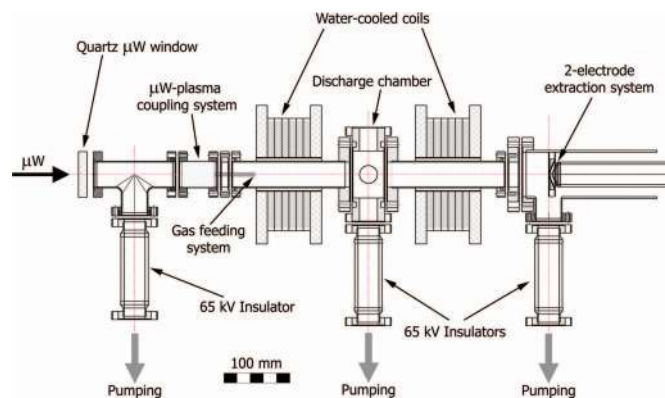


FIG. 1. SMIS 37 experimental setup.

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FIG. 2. Puller (22 mm hole) and plasma electrode (10 mm hole).

5 (i.e.,  $B_{\max}/B_{\min}$ ). The hydrogen inlet into the source was realized through an opening incorporated with the microwave coupling system. The delay between hydrogen injection and subsequent microwave pulse (300–3000  $\mu\text{s}$ ) 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 were realized by two-electrode diode setup, i.e., single gap plasma electrode-puller electrode system. Apertures in the plasma electrode and the puller were 10 mm and 22 mm, respectively. Both electrodes are shown in Fig. 2. The plasma electrode was placed 10 cm downstream from the magnetic mirror to limit the extracted ion flux as described in Ref. 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 immediately behind the puller electrode to measure the total beam current passing through the extractor. A conventional bending magnet analyzer (located 1 m from the extraction) and another Faraday cup located at the end of the beam line (1 m downstream from the magnet) were used for studying the species fraction of the extracted ion beam.

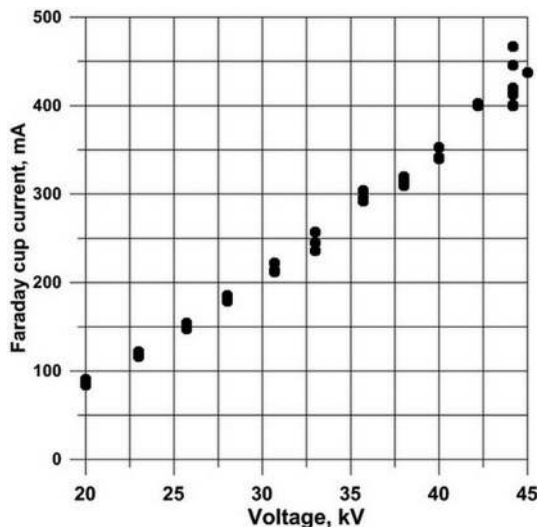


FIG. 3. Faraday cup current versus extraction voltage.

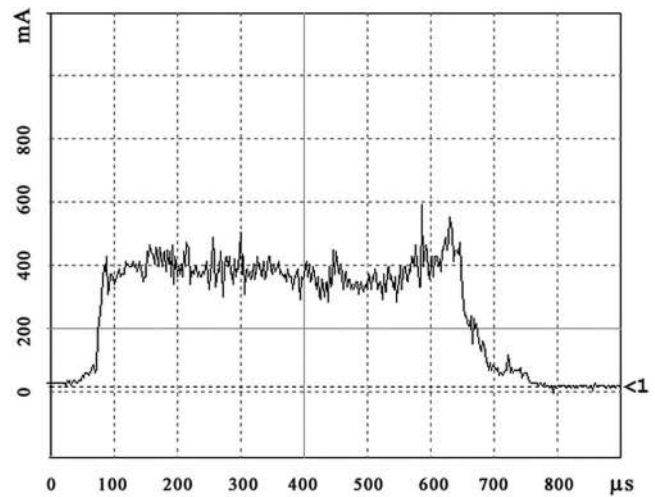


FIG. 4. Example of Faraday cup current waveform.

Emittance of the extracted beam (all species together) was measured with “pepper-pot” method,<sup>8</sup> which has been successfully tested earlier at SMIS 37.<sup>9</sup> “Pepper-pot” plate was placed 25 mm downstream from the puller with another 55 mm gap before a CsI scintillator for beam imaging.

### III. RESULTS

A single-aperture extraction system was used for beam formation in the 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 6 mm. The dependence of the Faraday cup current on the acceleration voltage is shown in Fig. 3 for the optimal extraction electrode configuration. A representative example of the beam current waveform is shown in Fig. 4. The maximum obtained beam current was 450 mA, corresponding to 600 mA/cm<sup>2</sup> current density through the plasma electrode. To our knowledge, this current density is the record for modern ECR ion sources.

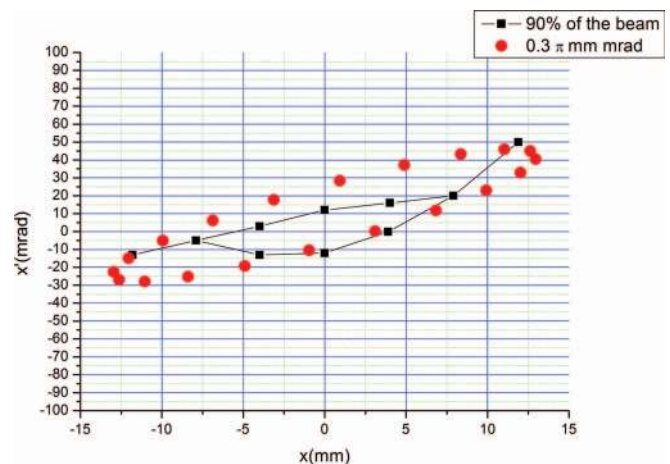


FIG. 5. An example of the phase space distribution of the 450 mA beam.

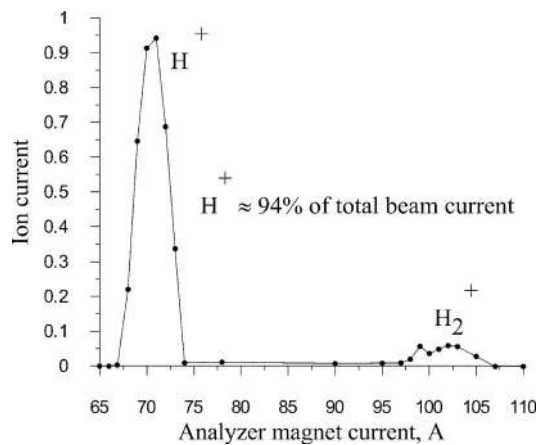


FIG. 6. Mass-analyzed ion beam spectrum normalized to the total beam current.

The value of the hydrogen beam emittance was estimated with “pepper-pot” method.<sup>8</sup> The normalized emittance of the beam is  $0.3 \pi$  mm mrad. The phase space distribution of the beam is shown in Fig. 5.

The spectrum of the extracted ion beam was also measured. The spectrum shown in Fig. 6 appeared to be similar to the one demonstrated in Ref. 5 for multiaperture extraction. The data are 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. The proton fraction of about 94% is slightly better than typically achieved with 2.45 GHz microwave ion sources,<sup>9,10</sup> which are the state-of-the-art proton sources for various applications.

#### IV. 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 beams with favorable species fraction. In the experiments, the maximum beam current was limited by the extraction voltage. The extracted beam current could be improved further by moving the plasma electrode closer to the magnetic mirror and scaling the extraction voltage and geometry appropriately. This is because the plasma density on the downstream side of the mirror scales with the magnetic field.<sup>7</sup> The possibility of increasing the beam current of SMIS 37 by using a 3-electrode extractor has been demonstrated in Ref. 7 for multicharged nitrogen ion beams. Optimizing the extraction system for protons, i.e., maximizing current and minimizing emittance growth, requires dedicated simulation effort.

A possible future step of this investigation is the construction of a CW gasdynamic proton source based on 24 GHz, 10–15 kW gyrotron. It is expected that with an optimized extraction geometry such a source would match or even exceed the performance of the current SMIS 37 setup in terms of extracted beam current. Obviously the maximum value of

plasma density in this case would be lower in comparison to 37.5 GHz source but it is plausible to claim that it would still be able to produce plasma flux densities up to  $1 \text{ A/cm}^2$ .

In case of strict beam stability requirements a few previously developed methods could be used to face them. To avoid beam fluctuations connected with plasma instabilities a cusp magnetic trap for plasma confinement can be used. Efficiency of the gasdynamic ECR ion source with such magnetic field topology was shown in Ref. 11. Also the position of the extraction can also help mitigating beam current fluctuations as shown in Ref. 12, where the oscillation of beam current was compensated by tuning the beam divergence angle.

Thus such a versatile high brightness proton source would be useful as an injector for accelerators as well as for specific applications such as development of compact powerful neutron generator.<sup>13</sup>

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