PROTON BEAMS FORMATION FROM DENSE PLASMA OF ECR DISCHARGE SUSTAINED BY 37.5 GHZ GYROTRON RADIATION

V.Skalyga[1,2], I. Izotov[1], S. Razin[1], A. Sidorov[1,2], V. Zorin[1,2]
[1]Institute of Applied Physics, RAS, 46 Ul`yanova st., 603950 Nizhny Novgorod, Russia,
[2]Lobachevsky State University of Nizhni Novgorod (UNN), 23 Gagarina st., 603950, Nizhny Novgorod, Russia
T. Kalvas[3], H. Koivisto[3], O. Tarvainen[3]
[3]Department of Physics, P.O. Box 35 (YFL), 40500 Jyväskylä, Finland

Abstract

Formation of hydrogen ion beams with high intensity and low transverse emittance is one of challenging tasks determining success in the field of accelerator research for last tens of years. Now there are a few modern projects like ESS and IFMIF whose requirements for the ion beam could not be fulfilled with the most advanced proton (or deuteron) sources.

Present work is devoted to experimental investigation of proton beams production from dense plasma (Ne>1013 cm-3) of ECR discharge sustained by 37.5 GHz, 100 kW gyrotron radiation at SMIS 37 facility at IAP RAS. Extraction systems with different configuration were used. It was demonstrated that ultra bright proton beam with 4,5 mA current and 0.1 π·mm·mrad normalized emittance (corresponding brightness is 45 A/(π·mm·mrad)2) can be formed with single-aperture (1 mm in diameter) extraction.

For production of high current beams a 13-hole extractor was used. 200 mA and 1.1 π·mm·mrad normalized emittance proton beam was obtained. A possibility of further beam parameters enhancement by developing of extraction system and its power supply is discussed.

INTRODUCTION

Operation of modern high power accelerators often requires production of intense beams of hydrogen ions. H+ (proton) beams are utilized or envisioned for use in linear accelerators e.g. the future European Spallation Source under design [1], H- ions are favored in applications based on charge exchange injection into storage rings or circular accelerators, e.g. the US Spallation Neutron Source [2] and some special applications such as the 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 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 CW), and normalized emittance less than 0.2-0-3 π·mm·mrad [1, 3] to keep the beam losses at high energy sections of the linac below commonly imposed 1 W/m limit.

This paper is devoted to investigating the generation of high current proton beams at SMIS 37 facility [4] at the Institute of Applied Physics (IAP RAS). SMIS 37 has been constructed for production of high current beams of multicharged ions. However, due to the substantial potential exhibited by the setup, we found it reasonable to test its capabilities for proton beam production.

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 μW-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%. 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 (i.e. Bmax/Bmin). The hydrogen inlet into the source was realized through an opening incorporated with the microwave coupling system.

ISBN 978-3-95450-123-6

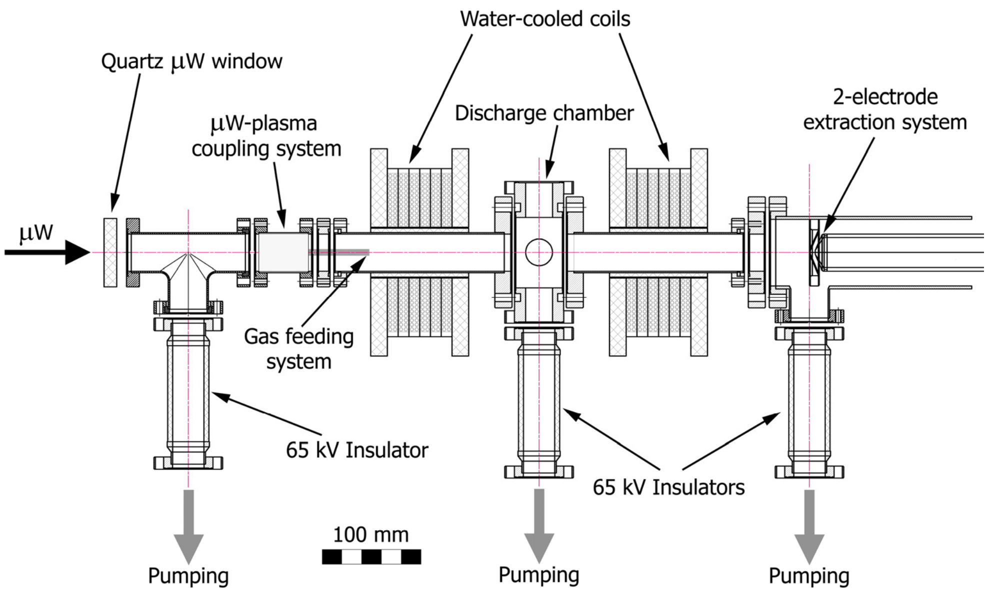

Figure 1: SMIS 37 experimental setup.

The delay between hydrogen 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.

Ion extraction and beam formation were realized by two-electrode, i.e. single gap plasma electrode - puller electrode, system. In the experiments two different configurations were used: single-aperture system (see Fig.2-a) and 13-hole system (see Fig.2-b). Plasma electrode is 7 cm in diameter and puller diameter is 3 cm and length is 10 cm. The extraction was placed in the range of 10 to 15 cm downstream from the magnetic mirror to limit the extracted flux of ions as described in [5], which helps improving the beam transport through the puller. The density of outgoing plasma flux on the downstream side of the magnetic mirror decreases proportionally to magnetic field and therefore, the extracted current density can be tuned by moving the extraction system. Positioning the extraction at lower magnetic field helps to limit the emittance of the extracted beam, which theoretically depends almost linearly on the magnetic field at the extraction (assuming low ion temperature) [6, 7]. The position of the extraction can also help mitigating beam current fluctuations as shown in [8] where the oscillation of beam current was compensated by tuning the beam divergence angle.

The maximum available high voltage level, limited by the power supply or the voltage holding capability of the extraction during beam pulses, was 55 kV for single-aperture and 47.5 kV for multi-aperture system. A Faraday cup was placed just behind the end of puller electrode to measure the total beam current passing through the extractor. A traditional magnetostatic analyzer (bending magnet was placed in 1 m from extraction) and another Faraday cup located at the end of the beam line (1 m behind the magnet) were used for studying the species fraction of the extracted ion beam.

Emittance of the extracted beam (all species together) was measured with “pepper-pot” method [9], which has been successfully tested earlier at SMIS 37 [10]. “Pepper-pot” plate was placed 1 mm downstream from the puller with another 55 mm gap before a CsI scintillator for beam imaging.

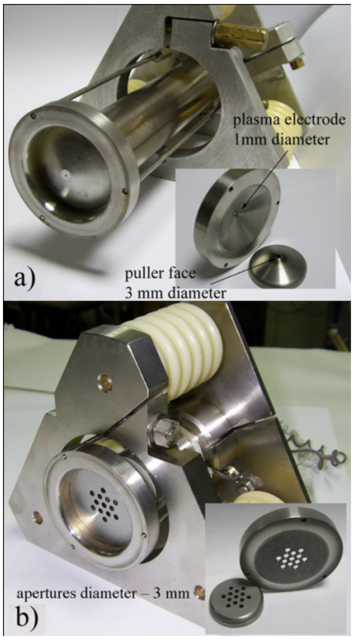

Figure 2: Extraction systems: (a) single-aperture extraction, (b) multi-aperture extraction with13 holes. The plasma and puller electrodes are shown separately on the lower right corner.

RESULTS

Single-Aperture Extraction System

During the experiments the configuration, i.e. distance between electrodes, and positioning of the extraction system was optimized to achieve maximum beam current. In the case of single-aperture extraction the optimal distance of the puller, measured from the magnetic mirror of the trap, was 80 mm and distance between electrodes 5 mm, respectively. An example of typical beam current oscillogram is shown in Fig. 3. It takes about 200 μs to reach the saturation level of the beam current, which is quite typical for pulsed proton/deuteron sources [11, 12] operating with 2.45 GHz microwaves. The dependence between the Faraday cup current and extraction voltage is plotted in Fig. 3. The maximum achieved current was 4.5 mA at 50 kV source potential, which corresponds to current density of 570 mA/cm2 transported through the extraction. According to our knowledge the result obtained with SMIS 37 is a record for ECR ion sources. It is evident from Fig. 4 that the beam current is not limited by the plasma density but, instead, the extraction voltage. The amplitude of the beam current fluctuation after reaching the saturation is approximately 10-15 %. For comparison it is noted that the amplitude of beam current oscillation is typically 5 - 20 % for minimum-B ECR ion sources operated in CW mode [13].

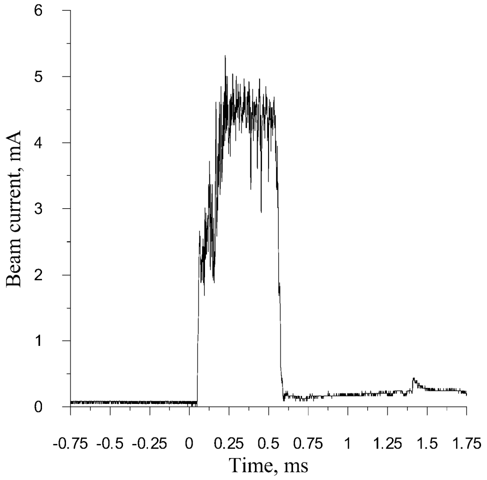

Figure 3: Typical oscillogram of hydrogen beam current obtained with the single-aperture extraction.

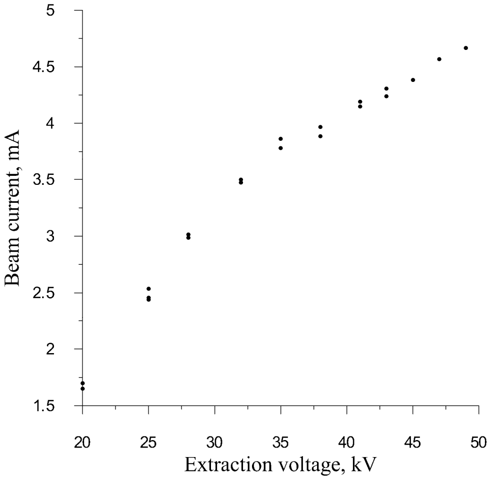

Figure 4: Beam current dependence on the extraction voltage for the single-aperture extraction.

The value of the hydrogen beam emittance was estimated by using "pepper-pot" method [9]. The normalized emittance of the beam is 0.03 π mm mrad and the brightness 5 A/(π·mm·mrad)^2.

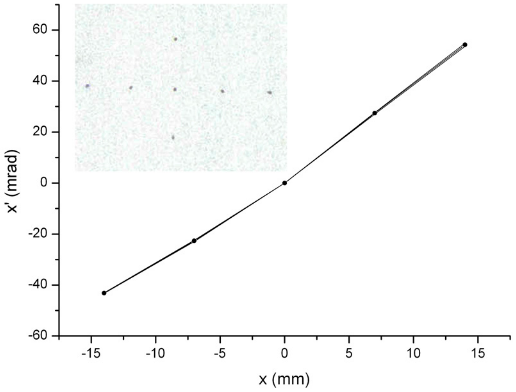

Figure 5: An example of the phase space distribution of the beam for single-aperture extraction. The corresponding scintillator luminescence image is shown on the upper left corner.

Multi-Aperture Extraction System

In the case of multi-aperture extraction system the optimal distances from the magnetic mirror and electrode spacings were 160 mm and11 mm respectively. The maximum Faraday cup current achieved was 200 mA at 46 kV, corresponding to 220 mA/cm2 current densities transported through the extraction. The dependence of the Faraday cup current on the source potential for the 13-hole extraction system is presented in Fig. 6. Again, the beam current is not limited by the plasma density but the extraction voltage. A representative oscillogram of the current pulse is shown in Fig. 7 for the 13-hole extraction system. The given example featuring saturation current of about 200 mA was measured with 46 kV extraction voltage. Reaching this current level takes about 150 μs, the amplitude of current fluctuation being 10-25 % after the fact.

ISBN 978-3-95450-123-6

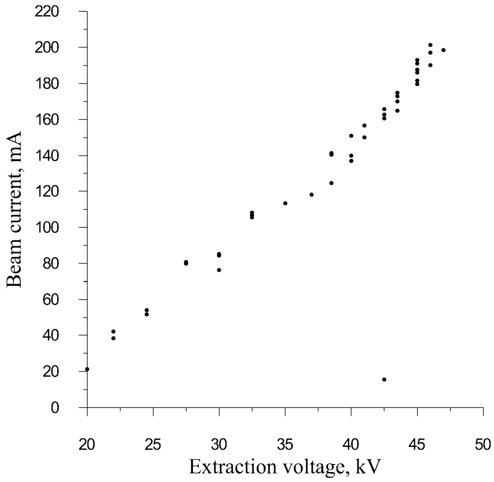

Figure 6: Dependence of the Faraday cup current on the source potential for the 13-hole extraction system

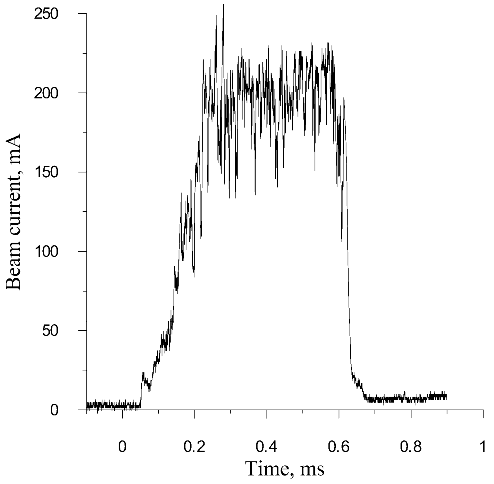

Figure 7: Oscillogram of the current pulse for the 13-hole extraction system.

The emittance of the beam produced by the multi-aperture extraction was also estimated using the "pepper-pot" method. A picture of the scintillator luminescence screen obtained with 45 keV, 200 mA beam is shown in the upper left corner of Fig 8. Nine sets of beamlets each consisting of 13 spots are clearly visible. The sets correspond to the holes in the pepper-pot and the spots correspond to the plasma electrode apertures. The reconstructed x-x' phase space for all 13 holes is shown in Fig. 8. The normalized emittance corresponding to 200 mA beam is 1.1 π·mm·mrad.

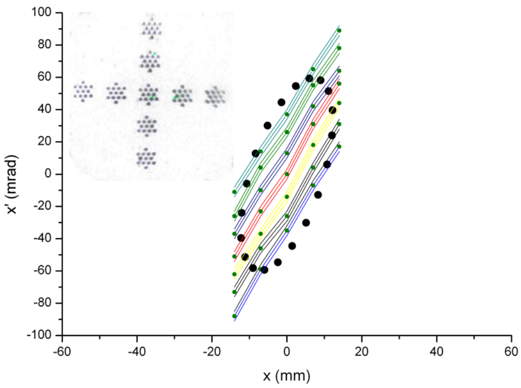

Figure 8: Phase space presentation and emittance diagram of the beam in the case of 13-aperture extraction. Corresponding scintillator luminescence image is shown in the upper left corner.

Ion Beam Spectrum

The fraction of atomic to molecular hydrogen (H^+/H_2^+) in the extracted beam was studied with all aforementioned extraction systems by measuring the ion beam spectrum with the bending magnet. No significant differences were found between the extraction systems. A typical spectrum is presented in Fig. 11. The data is normalized with respect to the total hydrogen 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 hydrogen 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 [14, 11] being the state-of-the art proton sources for various applications.

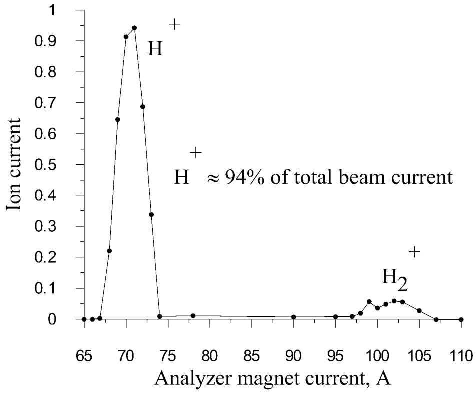

Figure 11: Mass-analyzed ion beam spectrum normalized to the total hydrogen beam current.

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. With all extraction geometries the maximum beam current was limited by the extraction voltage. The extracted beam current could be improved further by moving the plasma electrode inwards 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 [5]. It is also shown in the table that the current measured from the puller electrode is rather high i.e. a significant portion of the beam intercepts with the puller (up to 35 % of the puller current is estimated to be due to secondary electrons [15]). This demonstrates that improving the extraction geometry and its voltage holding capabilities could help improving the proton current density transported through the extraction by several tens or percent. The possibility of increasing the beam current of SMIS 37 by using a 3-electrode extractor has been demonstrated in [5] for multicharged nitrogen ion beams. Optimizing the extraction system for protons, i.e. maximizing current and minimizing emittance growth, requires dedicated simulation effort, which is out of the scope of this feasibility study.

A possible future step of this investigation is 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 proton beam production. 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 A/cm^2. Such a versatile high brightness proton source would be useful as an injector for accelerators as well as for specific applications.

ACKNOWLEDGMENTS

Work was supported by RFBR grant # 11-02-97056. Work was performed in frame of realization of federal targeted program “Scientific and pedagogical labor force for an innovative Russia” for 2009 – 2013 yy.

Work was supported by the Academy of Finland under the Finnish Centre of Excellence Programme 2012-2017 (Nuclear and Accelerator Based Physics Research at JYFL) and researcher mobility grants 253482 and 253173.

REFERENCES

[1] S. Gammino, L. Celona, R. Miracoli, D. Mascali, G. Castro, G. Ciavola, F. Maimone, R. Gobin, O. Delferrière, G. Adroit, F. Senée, Proc. Linear Accelerator Conference LINAC2010, Tsukuba, Japan, THP116, available online at jacow.org.

[2] M.P. Stockli, B.X. Han, T.W. Hardek, Y.W. Kang, S.N. Murray, T.R. Pennisi, C. Piller, M. Santana, and R. Welton, Rev. Sci. Instrum., 83, 02A732 (2012).

[3] R. Gobin, G. Adroit, D. Bogard, G. Bourdelle, N. Chauvin, O. Delferrière, Y. Gauthier, P. Girardot, P. Guiho, F. Harrault, J. L. Jannin, D. Loiseau, P. Mattei, A. Roger, Y. Sauce, F. Senée, and T. Vacher, Rev. Sci. Instrum., 83, 02A345 (2012).

[4] S. Golubev, D. Mansfeld, S.V. Razin, V. Skalyga, A. Vodopyanov, V. Zorin, R. Geller, T. Lamy, P. Sortais, T. Thuillier, V. Murugov, A. Senik, A. Kravchenko, D. Litvin, V.Misko, S. Petrov. Progress Report of Investigations on Gyrotron ECR Ion Source SMIS 37. Proc. of the 15th International Workshop on ECR Ion Sources (ECRIS’02). Jyväskylä , Finland, June 12 – 14, 2002, p. 21-24.

[5] A. Sidorov, I. Izotov, S. Razin, V.Skalyga, V. Zorin, A. Balabaev, S. Kondrashev, A Bokhanov. Beam Formation from Dense Plasma of ECR Discharge. Review of Scientific Instruments. v.77, n3, p. 03A341-1 – 03A341-4 (2006).

[6] Z.Q. Xie, Thesis, Michigan State University, MSU CP-60, p. 58 (1989).

[7] M.A. Leitner, D.C. Wutte, C.M. Lyneis, Proc. 2001 Particle Accelerator Conference (PAC’01), Chicago, IL, USA, MOPB004, IEEE 0-7803-7191-7/01, available online at jacow.org

[8] A. Sidorov, M. Dorf, V. Zorin, A. Bokhanov, I. Izotov, V. Skalyga, A.Vodopyanov, Noise Suppression And Stabilization Of An Ion Beam Extracted From Dense Plasma, Journal of Applied Physics, Vol.102, No.5, p. 054504 (2007).

[9] Applied Charge Particle Optics.// Edited by A. Septier. New York: Academic Press, p. 214 (1980).

[10] A. Sidorov, M. Dorf, A. Bokhanov, I. Izotov, S. Razin, V. Skalyga, V. Zorin, A. Balabaev, P Spädtke, J. Roßbach. Multi-aperture ion beam extraction from gas-dynamic electron cyclotron resonance source of multicharged ions. Review of Scientific Instruments, 79, 02A317 (2008).

[11] R. Xu, J. Zhao, S.X. Peng, Z.X. Yuan, Z.Z. Song, J.X. Yu, and Z.Y. Guo, Rev. Sci. Instrum., 79, 02B713 (2008).

[12] R. Gobin, P.-Y. Beauvais, D. Bogard, G. Charruau, O. Delferrière, D. De Menezes, A. France, R. Ferdinand, Y. Gauthier, F. Harrault, J.-L. Jannin, J.-M. Lagniel, P.-A. Leroy, P. Mattèi, J. Sherman, A. Sinanna, P. Ausset, S. Bousson, and B. Pottin, Rev. Sci. Instrum., 73, 2, p. 922 (2002).

[13] Geller R. Electron cyclotron resonance ion sources and ECR plasmas. // Institute of Physics. Bristol (1996).

[14] J.D. Sherman, T.L. Figueroa, L.D. Hansborough, D.M. Kerstiens, J.D. Schneider, H.V. Smith, Jr., M.W. Stettler, R.R. Stevens, Jr., M.E. Thuot, D.S. Warren, T.J. Zaugg, A.A. Arvin, A.S. Bolt and J.E. Boers, Rev. Sci. Instrum., 73, 2, p. 917 (2002).

[15] L.N. Large and W.S. Whitlock, Proc. Phys. Soc., Vol. 79, p. 148 (1962).

ISBN 978-3-95450-123-6