High current gasdynamic electron cyclotron resonance ion sources with gyrotron plasma heating

V.A. Skalyga, S.V. Golubev, I.V. Izotov, R.L. Lapin, S.V. Razin, R.A. Shaposhnikov, A.F. Bokhanov, M.Yu. Kazakov, V.I. Belousov, G.I. Kalynova, M. Yu. Shmelev, M. Yu. Glyavin, A.I. Tsvetkov, M.V. Morozkin, M.D. Proyavin, E.A. Mironov, O.V. Palashov

Federal Research Center Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russian Federation

Abstract

Fundamental research of a powerful millimeter wave gyrotron radiation interaction with an electron cyclotron resonance (ECR) discharge plasma confined in an open magnetic trap carried out at the Institute of Applied Physics of Russian Academy of Sciences (IAP RAS) have resulted in development of a new type of ECR ion sources – a gasdynamic ECR ion source. The key feature of the source is the high plasma density up to 10^{14} cm^{-3} combined with almost 100% ionization degree and electron mean energy in the range from tens to hundreds eV. Such combination of the plasma parameters leads to a so-called quasi-gasdynamic confinement regime and allows production of very intense beams of protons either multicharged ions for different applications.

At SMIS 37 experimental facility equipped with 37,5 or 75 GHz / 100 kW gyrotrons in a pulsed operation a possibility of ion beams formation with current up to 500 mA, current density at the level of 600 – 700 mA/cm^2 in combination with low emittance (normalized RMS emittance below 0.1 π·mm·mrad) was demonstrated.

The next step in the research is a transition to continuous wave (CW) operation. For this purpose, preliminary studies of plasma parameters were performed using a CW source with 24 GHz/5 kW gyrotron heating. To continue development of the CW gasdynamic ion source a new experimental facility is under construction at the IAP RAS. Future source will utilize 28 and 37,5 GHz gyrotron radiation for plasma heating.

Introduction

One of the alternative methods for creation of a high-current ECR ion sources is based on powerful ECR plasma heating in an open magnetic trap with millimeter wave gyrotron radiation. Such approach allows to increase plasma density up to 10^{13} - 10^{14} cm^{-3} and accordingly increase outgoing plasma flux. At such level of plasma density and electron temperature about 100 eV a so called quasigasdynamic regime of plasma confinement [1] is realized. In such case the plasma lifetime is determined by ion escape from the trap with ion-sound velocity through magnetic mirrors : $\tau = LR/2V_s$, where R and L are the mirror ratio and the length of the magnetic trap, V_s is the ion sound velocity. For regular parameters of the gasdynamic ECR ion source the lifetime is of the order of 10 μs, which is significantly less than in traditional ECRIS. The short plasma lifetime combined with a high density makes it possible to obtain plasma fluxes with record densities at the level of 10 A/cm^2.

SMIS 37 – high current pulsed ECR ion source.

The main part of the experiments in a pulsed operation mode was conducted at SMIS 37 facility. During the years its configuration has been changing slightly, the latest one being schematically depicted in Fig. 1. The plasma was created and sustained inside a d=4 cm vacuum chamber (placed in a magnetic trap) by pulsed (1 ms) 37.5 GHz or 75 GHz linearly polarized gyrotron radiation with power up to 100 kW. The simple mirror magnetic field was created by means of pulsed solenoids positioned at a distance of 15 cm from each other, 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 and 2.7 T for 75 GHz. The microwave radiation was coupled to the chamber quasi-optically through a quartz window and a special coupling system, which protects the window from the plasma flux. 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 a puller. The diameter of the extraction aperture was varied from 1 to 10 mm. The distance between the extraction system and the magnetic plug at the center of the solenoid magnet was designed to be variable, which allows tuning the plasma flux density at the plasma electrode. The maximum applied extraction voltage was 60 kV, which was an absolute maximum for the used power supply.

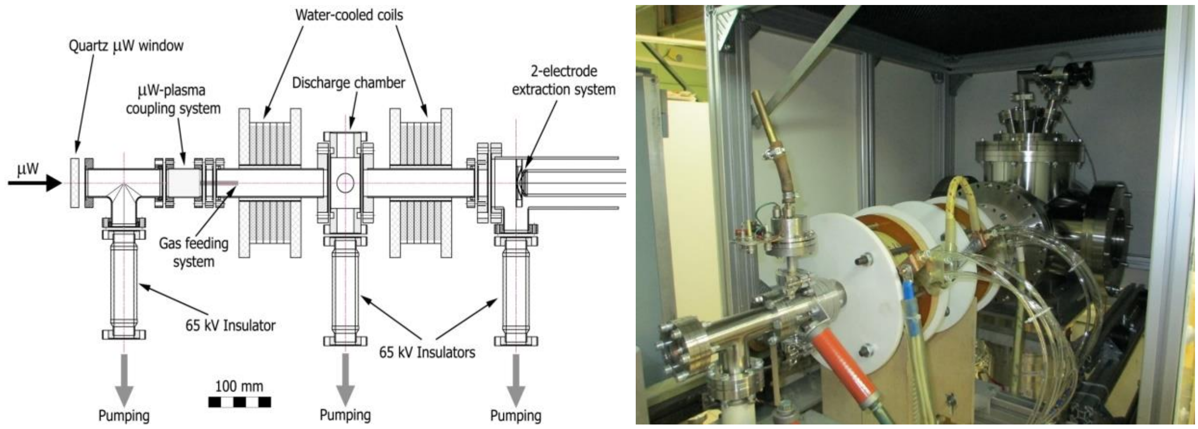

Fig.1. Schematic view and photograph of SMIS 37 experimental facility.

A number of papers were devoted to multi-charged beam production at SMIS 37 [1-5]. In these experiments a single aperture two electrode extraction systems with single 1 mm hole or 13-hole (each 3 mm in diameter) were used for beam formation providing total ion current up to 5 mA [2] and 160 mA [5] correspondingly, which corresponds to current density of 600 mA/cm^2. Presented results demonstrated that gasdynamic ion source is able to produce hundreds of emA of moderately charged (Q up to 6+) beams with low emittance.

The average electron energy in plasma of ECR discharge with quasi-gasdynamic confinement sustained by gyrotron radiation varies from 50 to 300 eV and it is optimal for efficient hydrogen ionization. Due to this coincidence it was decided to test the gasdynamic ECR source performance for proton and deuteron beams formation [6, 7]. A single-aperture extraction system was used for beam formation in the presented experiments. The biggest hole diameter in plasma electrode was 10 mm. The Faraday cup current, emittance diagram and ion beam spectrum are shown in Fig. 2. The total beam current remains relatively stable at the level of 450 mA through 70% of the microwave pulse. Accelerating voltage up to 50 kV was used. Transversal emittance had RMS value of 0.07 π•mm•mrad.

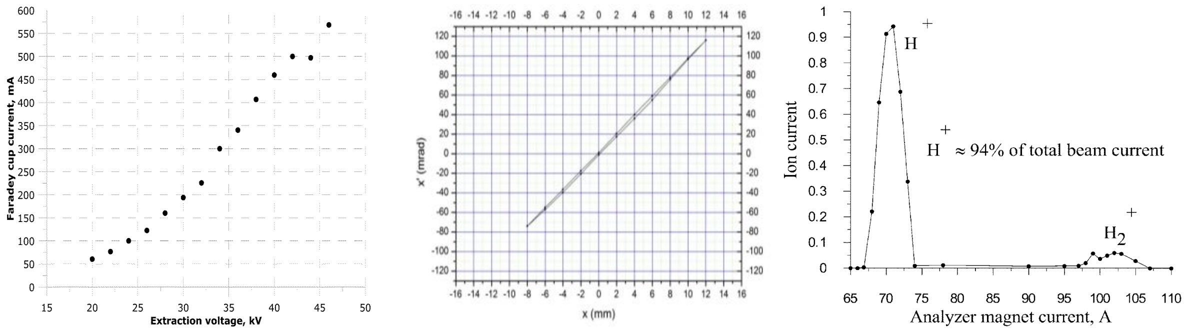

Fig.2. Hydrogen ion beam properties: beam current, emittance diagram and beam spectrum.

GISMO – CW operational Gasdynamic Ion Source for Multipurpose Operation

This report discusses a design of a high-current ion source for continuous working operation with a quasigasdynamic confinement regime. Future facility have been named GISMO (Gasdynamic Ion Source for Multipurpose Operation). This facility is aimed to produce continuous high-current (>200 mA) ion beams with low emittance (<0.2 π·mm·mrad). The scheme of the future experimental facility is show in figure 1. The key element of the setup is 28 GHz / 10 kW or 37,5 GHz / 20 kW CW gyrotrons manufactured by Gycom [8]. This microwave generator will be equipped with power supplies suitable for CW or pulsed operation.

A fully permanent magnet magnetic trap will be used for plasma confinement [9]. For effective plasma heating a set of requirements were applied to the system. Magnetic field configuration was designed to be similar to a simple mirror trap close to the system axis with field strength at magnetic mirrors not less than 1.4 T and not less 0.2 T at the trap center.

Distance between magnetic mirrors should be about 12-15 cm. The mirror ratio should be in the range $3 \leq Bmax / Bmin \leq 7$. The inside diameter must be not less than 5 cm in order to allow assembling together with insulated plasma chamber with minimum diameter of 4 cm. For ion beam extraction it is planed to use 3 or 4-electrode system with maximum acceleration voltage up to 100 kV. Such extraction requires development of an appropriate high-voltage insulation of the discharge chamber from other parts. In this regard, one of the key elements of the installation is the DC-break of the microwave transmission line. It was proposed to be implement a quasioptical system shown in Fig. 3. The electromagnetic radiation of the gyrotron (mode TE21) is fed to the converter to Gaussian beam. The Gaussian beam passes through the air gap of 15 cm which is used as a DC-break. After that gap the radiation goes to the converter into TE11 mode of a circular waveguide and then to a microwave coupling system implemented with plasma chamber. The plasma chamber will be 30 cm in length and 4 cm in diameter. It is equipped with water cooling along the whole surface from the coupling system to the flange.

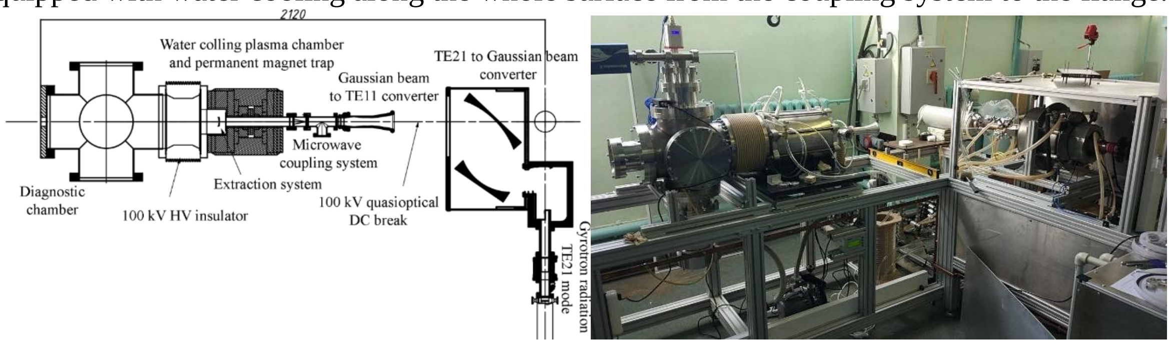

Fig. 3**.** Scheme of the GISMO 28 CW high current ion source.

Acknowledgments

Presented work is being supported in frame of realization of Federal targeted program R&D in Priority Fields of the S&T Complex of Russia (2014-2020) contract #14.604.21.0195 (unique identification number RFMEFI60417X0195).

References

1) S.V Golubev, S.V. Razin, A.V. Sidorov, V.A. Skalyga, A.V. Vodopyanov, V.G. Zorin. Review of Scientific Instruments. v.75, n5, p. 1675-1677, 2004.
2) S.V. Golubev, I.V. Izotov, S.V. Razin, V.A. Skalyga, A.V. Vodopyanov, V.G. Zorin. Transactions of Fusion Science and Technology, v. 47, n. 1T , fuste8, p. 345-347, 2005.
3) A. Sidorov, I. Izotov, S. Razin, V.Skalyga, V. Zorin, A. Balabaev, S. Kondrashev, A Bokhanov. Review of Scientific Instruments. v.77, n3, p. 03A341-1 – 03A341-4, 2006.
4) V. Skalyga, V. Zorin, I. Izotov, S. Razin, A. Sidorov, A. Bohanov. Plasma Sources Science and Technology 15 (2006) 727-734.
5) S. Golubev, I. Izotov, S. Razin, A. Sidorov, V. Skalyga, A. Vodopyanov, V. Zorin, A. Bokhanov. Nuclear Instruments and Methods in Physics Research B, v. 256, p. 537 – 542, 2007.
6) V. Skalyga, I. Izotov, A. Sidorov, S. Razin, V. Zorin, O. Tarvainen, H. Koivisto, T. Kalvas. *JINST*, v.7, P10010 (2012)
7) V. Skalyga, I. Izotov, S. Razin, A. Sidorov, S. Golubev, T. Kalvas, H. Koivisto, and O. Tarvainen. Review of Scientific Instruments, v. 85, no. 2, 2014, p. 02A702-1 – 02A702-3.
8) www.gycom.ru
9) V. A. Skalyga, I. V. Izotov, E. A. Mironov, A. V. Voitovich, and O. V. Palashov. AIP Conference Proceedings 1771, 070014 (2016)