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Status of new developments in the field of high-current gasdynamic ECR ion sources at the IAP RAS

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Abstract. The experimental and theoretical research carried out in the past at the Institute of Applied Physics (IAP RAS) resulted in development of a new type of electron cyclotron resonance ion source (ECRIS) – the gasdynamic ECRIS. The gasdynamic ECRIS features a confinement mechanism in a magnetic trap that is different from Geller's classical ECRIS confinement i.e. the quasi-gasdynamic one similar to that in fusion mirror traps . Such ion source type has demonstrated good performance producing high current (100-300 mA) multi-charged ion beams with moderate average charge (Z=4-5 for argon) and especially high efficiency for low emittance hydrogen and deuterium beam formation (500 emA current, current density up to 700 emA/cm^2 and RMS emittance below 0.07 π·mm·mrad). Experimental studies of gasdynamic ECRIS in a pulsed mode were performed at SMIS 37 facility.The obtained high-level results have stimulated a wide spectrum of research activities devoted to further extension of the gasdynamic ECR source principles to related fields of research and applications. The present report overviews recent investigations at the Ion Sources Laboratory connected with ECR plasma heating by powerful millimeter wave gyrotron radiation. Novel ideas such as using a magnetic field generated by a single coil for plasma quasigasdynamic confinement for proton beams production, applications of a dense ECR plasma for H- generation, development of a new CW gasdynamic ECR source with 28 GHz gyrotron heating among others are discussed.

INTRODUCTION

Investigations of pulsed ECR discharge in an open magnetic trap under conditions of powerful ECR heating with gyrotron mm-waveband radiation were carried out over the last 20 years at the Institute of Applied Physics (IAP RAS, Nizhniy Novgorod, Russia) [1-5]. In the beginning the work was devoted to development of a high frequency ECR source of multi-charged ions with outstanding parameters of plasma heating (37.5 GHz, 100 kW). According to Geller's scaling laws [6] such increase in frequency and power in comparison to conventional ECRIS was expected to boost the ion source performance and provide a significant progress in ECRIS development. However, due to short pulse operation mode and low repetition rate of the used gyrotrons (pulse duration < 1 ms, 0.1 Hz) breakdown and discharge conditions similar to a conventional ECRIS were unreachable. The minimum neutral gas pressure was two orders higher (10^{-4} mbar) and the plasma parameters differed significantly from conventional ECRIS. After years this work resulted in development of a new type of ion source – high current gasdynamic ion source.

The use of powerful mm-band radiation allows to increase the plasma density in the discharge significantly (proportional to the square of the radiation frequency [4-7]) in comparison to conventional ECRISs, which utilize microwave radiation with frequencies on the order of 10 GHz [6]. In experiments with 37.5 GHz and 75 GHz gyrotrons the plasma density reaches values of 10^{13} - 10^{14} cm^{-3}[8, 9]. Significant increase of the plasma density leads to a change of the confinement mode. A so-called quasi-gasdynamic confinement [4, 5] was realized in the presented experiments instead of the collision-less confinement [10], which is typical for modern ECRISs. The

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transition from collision-less to quasi-gasdynamic confinement occurs when the plasma density is high enough for the scattering rate of electrons into the loss-cone to be higher than the maximum possible electron loss rate caused by the ion-sound flux through the magnetic mirrors [11]. In such situation the loss-cone in the velocity space is populated, and the plasma lifetime does not depend on the collisional electron scattering rate into the loss-cone i.e. on the plasma density, but is determined by the trap size, magnetic field structure and ion sound velocity [11]. The plasma lifetime, which is much shorter than in conventional classical ECRISs, can be expressed as $\tau=(L\cdot R)/(2Vis)$, where L is the magnetic trap length, R the trap mirror ratio (ratio between magnetic field in the magnetic mirror and in the trap center) and Vis the ion sound velocity.

Experimental studies of a gasdynamic ECRIS were performed at the SMIS 37 facility. The plasma was created by 37.5 and 75 GHz gyrotron radiation with power up to 100 kW. High frequency microwaves allowed to create and sustain plasma with significant density (up to $8\cdot10^{13}$ cm^{-3}) and to maintain the main advantages of conventional ECRIS such as high ionization degree and low ion energy. Reaching such high plasma density relies on the fact that the critical density grows with the microwave frequency squared. High microwave power provided the average electron energy on a level of 50-300 eV enough for efficient ionization even at neutral gas pressure range of 10^{-4} - 10^{-3} mbar. Gasdynamic ECRIS has demonstrated a good performance producing high current (100-300 mA) multi-charged ion beams with moderate average charge (Z=4-5 for argon). Gasdynamic ECRIS has appeared to be especially effective in low emittance hydrogen and deuterium beams formation. Proton beams with current up to 500 emA, RMS emittance below 0.07 π·mm·mrad have been demonstrated in recent experiments.

NEUTRON GENERATORS BASED ON HIGH-CURRENT GASDYNAMIC ECR ION SOURCES

This section presents the results of recent investigations devoted to development of a new generation of compact D-D (D-T) neutron generators based on a high-current quasi-gasdynamic ECR ion source, which utilizes powerful gyrotron radiation of mm-waveband for plasma creation [12]. Experiments aimed to demonstrate the benefits of the high current gasdynamic ECR ion source as a part of D-D neutron generator were conducted at SMIS 37 facility [13], schematically depicted in Fig. 1. The plasma was created and sustained inside a d=4 cm vacuum chamber by pulsed (1.5 ms) 37.5 GHz linearly polarized radiation with power up to 100 kW. The simple mirror magnetic trap with 25 cm length was created by pulsed solenoids, 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.

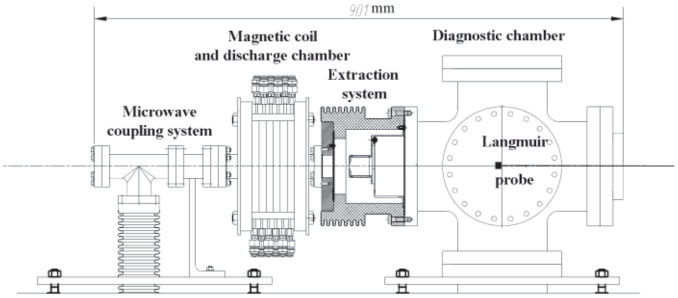


FIGURE 1. SMIS 37 experimental facility.

Microwave radiation was guided into the chamber quasi-optically through a special coupling system. 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 puller.

The best result was obtained with plasma electrode aperture of 10 mm. The maximum deuterium beam current was 500 emA, which corresponds to a current density of 630 emA/cm^2 at the plasma electrode. Beam emittance was measured with the “pepper-pot” method and its normalized rms value was 0.07 pi·mm·mrad. Studies of the extracted charge state distribution have shown that 94% of it consists of atomic deuterons (D+) (contribution of molecular D_2^+ ions is less than 6%).

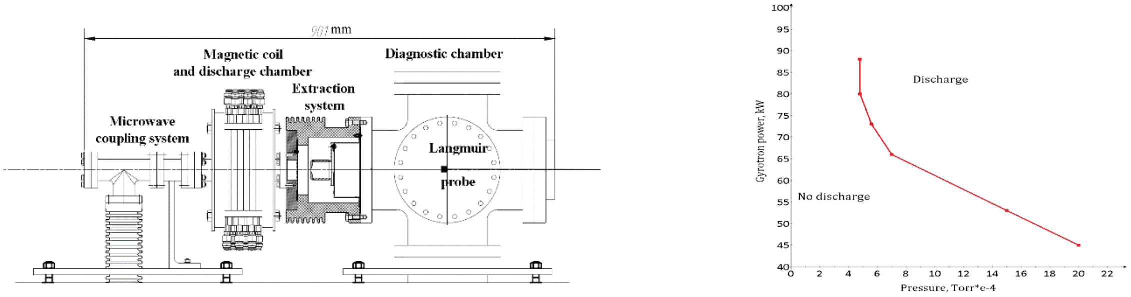
Measurement of the produced neutron flux was performed by bombarding a heavy ice target with 300 emA D^+ beam accelerated to 45 keV energy. The D_2O target yield was 10^9 s^{-1}. It is worth noting that the area of the target was about 1 cm^2, which corresponds to a neutron flux density of about 10^9 $cm^{-2} \cdot s^{-1}$ at the target.

As it was demonstarted a high-current ECR ion source with quasi-gasdynamic plasma confinement and heating with gyrotron microwave radiation allows the formation of light ion beams with uniquely low emittance (for a given current level). Such a low emittance enables focusing of the ion beam into a small spot. So it could be used as alternative approach for creation of a point-like neutron source for neutronography. This topic is discussed in [12-14].

ALTERNATIVE OPEN MAGNETIC SYSTEMS FOR PLASMA CONFINEMENT IN HIGH-CURRENT GASDYNAMIC ECR ION SOURCES

It was proposed to investigate the prospects of creation a source of hydrogen ions on the basis of ECR discharge in a single solenoid sustained by powerful gyrotron radiation. Opposed to simple mirror trap this system is MHD stable and high power of microwave radiation could allow maintaining electron temperature on a sufficient level for high ionization efficiency of light gas.

The first experiments were aimed to investe the possibility of igniting the discharge in this system, determine plasma parameters and properties of the extracted ion beam. The experiments were carried out at SMIS 37 experimental facility where simple mirror magnetic trap was replaced with a single coil. Schematic view of the experimental setup (without gyrotron) is shown in Fig. 2(a). Pulsed gyrotron radiation with a frequency of 37.5 GHz, power up to 100 kW and duration up to 1.5 ms was used for plasma ignition and heating. The magnetic field in the coil varied from 1 to 4 T (ECR for 37.5 = 1.34 T). The microwave radiation was injected into the plasma through a quasi-optical coupling system. Plasma was created in a specialized discharge chamber (working pressure from 10^{-7} to 10^{-3} Torr), the working gas (hydrogen) was fed into the discharge chamber along the system axis. Gas breakdown and plasma heating were performed under electron-cyclotron resonance conditions at the main harmonic. For beam extraction a two electrode extraction system was used. A plasma electrode with aperture diameter of 1 mm and a puller electrode with 3 mm aperture were placed in 6 mm from each other. Plasma electrode was placed outside of the coil in 12 cm from magnetic field maximum. At the first step experiments with a constant neutral gas injection were performed to study the possibility of the discharge ignition and to determine a threshold microwave power for it at various pressures. Breakdown curve plotted according to the experimental data is shown in Fig. 2(b). Also it was demonstrated that discharge could be realized only if maximum magnetic field in the chamber is above ECR value.



(a) (b)

FIGURE 2. (a) Scheme of the experimental facility plasma part. (b) Breakdown threshold curve for hydrogen.

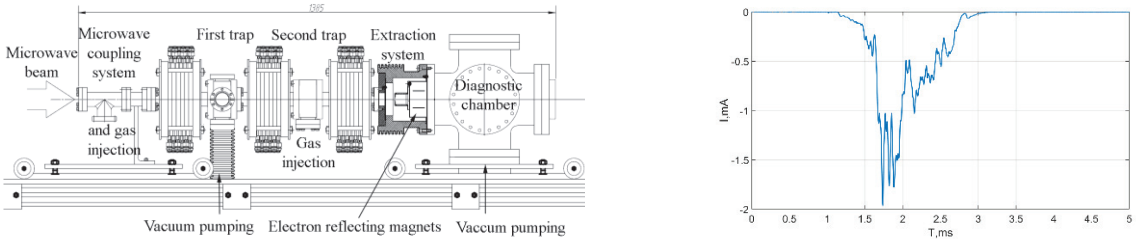
In frames of experimental investigations using a single Langmuir probe technique placed in the region with low magnetic field plasma flux parameters have been studied. It was demonstrated that under such conditions plasma with density close to critical value for certain radiation frequency could be created with electron temperature about 50 eV. Precise studies of ion beam parameters those could be obtained at such ion source is the point of future research.

FIRST EXPERIMENTS ON H$^-$ IONS PRODUCTION WITH HIGH-CURRENT GASDYNAMIC ECR ION SOURCES

H$^-$ ion sources are of great demand for charge exchange injection into cyclotrons and storage rings. It has been recently demonstrated that a gasdynamic ECR ion source based on ECR discharge in a simple mirror trap is very efficient for proton beam production [15, 12]. Therefore, it was suggested to use the gasdynamic plasma source as the first stage of an H$^-$ ion source based on volumetric production through dissociative electron attachment [16-17] (DEA).

The first experiments were performed in a pulsed mode with 37 GHz / up to 100 kW gyrotron radiation in a dual-trap magnetic system, consisting of two identical simple mirror traps. The schematic of the experimental facility is presented in Fig. 3(a). The first trap was used for plasma production under ECR conditions. Dense hydrogen plasma flux (with estimated current density of about 1-5 A/cm^2) from the first trap was allowed to flow into the second trap through a perforated conducting plate. The grid placed between the traps prevents microwave leakage into the second part to avoid electron heating there. Such configuration was chosen to produce a flux of “hot” electrons (energy 50 – 100 eV), which can effectively ionize and excite high vibrational states of hydrogen molecules in the second trap, and to produce anions there as the result of DEA with “cold” electrons (energy < 10 eV). Thus, the plasma confined in the second trap presumably consists of two electron populations enabling the volume production of H$^-$ ions. Such approach is similar to the one suggested in [18] where heating 2.45 GHz ECR discharge was used as a plasma cathode producing “hot” electrons.

A simple two-electrode extraction system was used for the ion beam extraction. Diameters of a plasma electrode and a puller were 5 and 10 mm respectively. The plasma chamber and plasma electrode had a negative potential up to -15 kV with respect to the ground. To reflect electrons extracted from the plasma together with the negative ions two pairs of rectangular permanent magnets were installed just after the puller. Both magnet pairs produced a magnetic field transversal to the extracted beam and had opposite directions to compensate each other’s influence on the ion trajectories. In the experiments a scheme with separate independent neutral gas injection into both magnetic traps was realized. Such gas-feeding scheme was used to perform experiment with significantly different neutral gas pressures in each trap as a result of the delay between the valve opening and microwave pulse being less than the time necessary for the gas molecules to travel to the first trap with sound velocity. Maximum negative ion current was up to 2 mA. Further experiments on ion source operation optimization will be performed during the next experimental campaign.



(a) (b)

FIGURE 3. (a) Scheme of the experimental facility. (b) Typical negative ion current waveform. Microwave power 80 kW, constant gas flow into the first trap and pulsed injection into the second one.

NEW GISMO EXPERIMENTAL FACILITY AT THE IAP RAS

The main part of previous experiments were carried out in a pulsed operation mode. Preliminary studies of plasma parameters were performed using a CW source with 24 GHz/5 kW gyrotron heating [19]. Obtained experimental results have demonstrated that all gasdynamic source advantages could be realized in CW operation. To continue development of a CW gasdynamic ion source a new experimental facility named GISMO (Gasdynamic Ion Source for Multipurpose Operation) [20] is under construction at the IAP RAS. 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 Fig. 4. The key element of the setup is a 28 GHz, 10 kW CW gyrotron manufactured by Gycom [21].

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 [8]. Magnetic field configuration was designed to be similar to a simple mirror trap close to the system axis with field strength at magnetic mirrors of 1.5 T and mirror ratio close to 6. Distance between magnetic mirrors is about 12 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. 4. Plasma chamber will be 30 cm in length and 4 cm in diameter. It is equipped with water cooling along whole surface from the coupling system to the flange.

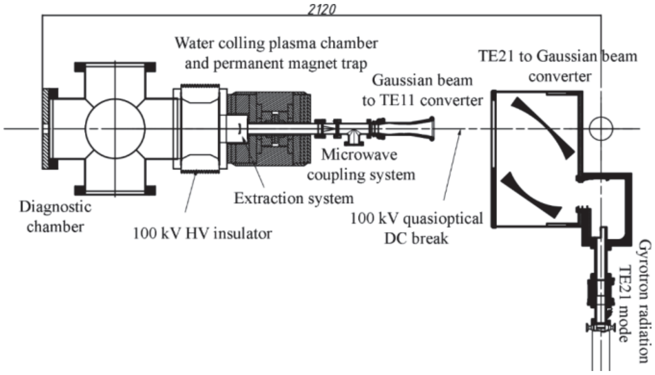


FIGURE 4. Scheme of the GISMO 28 CW high current ion source.

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