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ECR DISCHARGE IN A SINGLE SOLENOID MAGNETIC FIELD AS A SOURCE OF THE WIDE-APERTURE DENSE PLASMA FLUXES*

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Abstract

Sources of dense plasma fluxes with wide aperture are extensively used in applied science, i.e. surface treatment, and as a part of neutral beam injectors [1]. Electron cyclotron resonance (ECR) discharge in a solenoidal magnetic field (i.e. with no magnetic mirrors for plasma confinement), sustained by a powerful radiation of modern gyrotrons is under consideration at IAP RAS as a possible alternative to widely used vacuum arc, RF and helicon discharges. The use of a high frequency radiation (37.5 GHz) allows us to obtain a discharge at lower pressure, sustain almost fully ionized plasma with density more than 10^{13} cm^{-3}, whereas the power on the level of several hundreds of kW enables the creation of such a plasma in considerably large volume. In the present work fluxes of hydrogen plasma with the equivalent current density of 750 mA/cm^2 and the total current of 5 A were obtained. A multi-aperture extraction system design capable of forming the non-divergent ion beam was developed with the use of IBSimu code.

INTRODUCTION

The use of the powerful millimetre wavelength range gyrotron radiation for the plasma heating allowed us to create a concept of an unique gasdynamic ion sources at IAP RAS. In such sources the plasma density confined in the simple mirror trap reaches the level of 10^{13}-10^{14} cm^{-3} with the electron temperature on the order of 100 eV [2–5]. The presented research was conducted to investigate the possibility of creation of the plasma with comparable to the gasdynamic ECR ion source (ECRIS) parameters using the sole solenoid field for radial plasma confinement, leaving longitudinal confinement to a self-consistent ambipolar potential, which accelerates ions and slows down electrons. The system based on the single solenoid is very convenient for scaling, much more compact, is free of plasma bremsstrahlung due to the absence of hot electrons, and greatly reduces material costs when compared to the conventional ECRIS traps and with the simple mirror trap.

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EXPERIMENTAL FACILITY

The test bench was constructed on the base of SMIS37 facility [3]. The scheme of the experiment is shown in the Figure 1. The microwave radiation with the frequency 37.5 GHz and the power up to 100 kW is launched into the plasma chamber of 68 mm inner diameter through the microwave coupling system. The wedge-like coupling system was located inside the discharge chamber in order to prevent the plasma flux reaching the quartz vacuum window. The microwave launching part has an inner diameter of 38 mm, whereas the plasma chamber has an inner diameter of 68 mm. An influence of that fact on the obtained result is discussed in the conclusion section of the present paper. A stainless steel grid with a transparency of 70% was installed at the farther end of the discharge chamber, opposite to the injection side, in order to create a microwave cavity to improve the efficiency of plasma heating. In the presented research, the metal grid was a part of the discharge chamber and, accordingly, they were under the same potential, namely, they were grounded. The magnetic field in the centre of the coil was varied from 1 to 3 T, while the resonance field value for the radiation frequency of 37.5 GHz is 1.34 T. The plasma chamber is placed inside the pulsed solenoid, which provides the maximum field in its centre of up to 3 T.

The neutral gas is injected into the discharge chamber through the gas feed line embedded into the microwave cou-

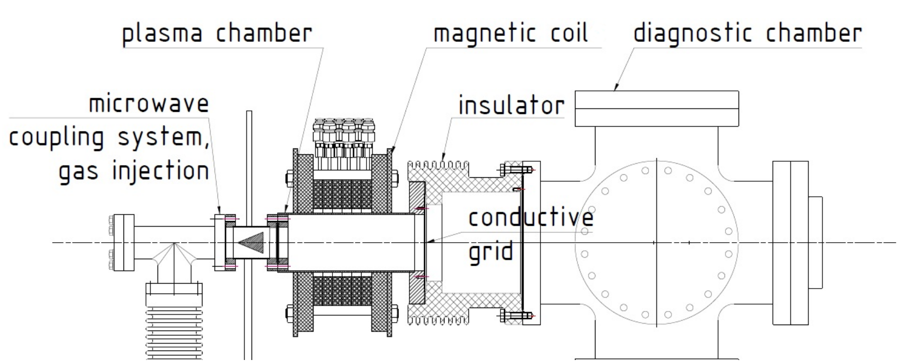

Figure 1: The principal scheme of the constructed experimental bench.

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pling system by means of a fast solenoid valve, much alike to SMIS37 facility. The working pressure range was $2{\cdot}10^{-4}$ – $8{\cdot}10^{-4}$ Torr. The residual gas pressure was on the level of 10^{-7} Torr.

EXPERIMENTAL RESULTS

The plasma flux was studied with a single flat Langmuir probe with 1 mm2 square, placed on a 3D movable rod mounted on the back flange of the diagnostic chamber providing measurement both in longitudinal and transverse directions with respect to the magnetic field. The probe was biased negatively, thus measuring the ion saturation current.

The dependence of the plasma flux density on the magnetic field in the solenoid as a function of the injected microwave power is shown in Figure 2.

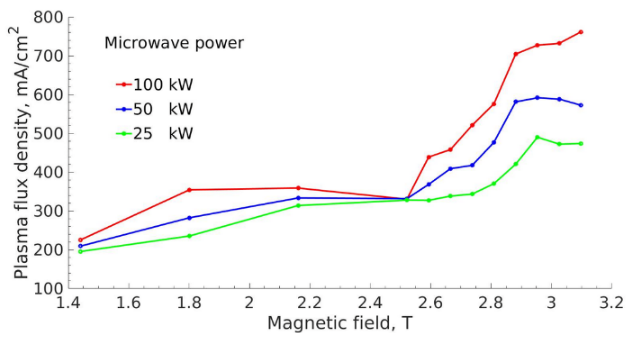

Figure 2: Plasma flux density dependence on the magnetic field value as a function of the injected microwave power.

In this measurement the probe was placed on the system axis as close to the metal grid as possible, resulting in the distance of 74 mm between the probe and the solenoid centre. It is clearly seen from Figure 2 that the plasma flux density increases with the magnetic field magnitude and reaches 750 mA/cm^2 at 3.1 T and the microwave power of 100 kW. A clear change of dependencies behaviour is observed above 2.5 T, which is presumably explained by the fact that at this field strength the farthest from the microwave launching system ECR zone touches the grid. The effect of ECR surface position would be studied in further experiments.

We have also confirmed that the dependence of the plasma flux density on the coordinate along the system axis follows the magnetic field strength, thus the plasma flux is magnetized within the whole volume of the discharge chamber, which may be beneficial for the extractor design providing a flexible tool to control the flux density by moving the extraction system along the system axis.

To study the homogeneity of the plasma flux, we measured the radial profile at the same distance of 74 mm from the solenoid centre, i.e. as close to the grid as possible. The measurement was done with the optimal parameters, being 3.1 T and 100 kW of microwave power and its result is presented in Figure 3. While the maximum density was 750 mA/cm^2, the corresponding total ion current reached 5 A, evaluated straightforward as an integral of the profile over transverse coordinate, assuming the axial symmetry of the flux.

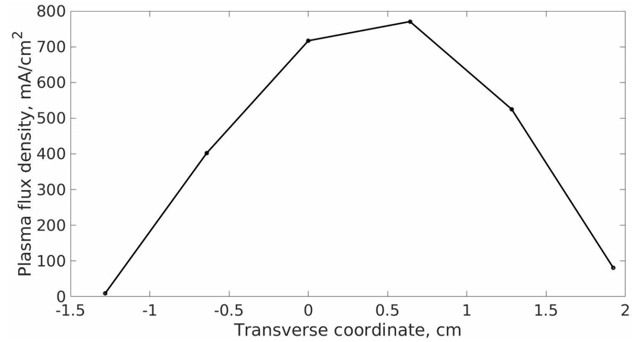

Figure 3: Plasma flux transverse profile at 74 mm from the solenoid centre. Microwave power is 100 kW, gas pressure is $8 \cdot 10^{-4}$ Torr, magnetic field in the coil centre is 3.1 T.

Also, it could be seen that plasma flux FWHM is on the order of 25 mm, while the plasma chamber is 68 mm in diameter. This may be explained by the structure of magnetic field lines together with the plasma chamber geometry. The plasma flux in the system is likely constrained by the diameter of the microwave coupling. This fact additionally underlines the importance of the microwave injection scheme for the discharge parameter optimization. More studies on the microwave coupling scheme are needed even in such a simple configuration.

EXTRACTION SYSTEM DESIGN

n order to form non-divergent beam with current density on the level of 750 mA/cm^2 and total current of several A it is necessary to use a custom multi-aperture or gridded extraction system, as the current density-induced space charge of the beam is considerably high. Simulations of the system capable of dealing with such a beam were performed with IBSimu code [6]. Numerical studies have shown that the least divergent beam may be obtained with the use of 3 multi-aperture electrodes: plasma electrode, middle electrode and puller electrode, separated by 4 and 5 mm respectively. The assembly is intended to be installed at the same position as the grid was installed to in presented experiments, i.e. 74 mm from the solenoid centre, thus the plasma electrode would be acting as a microwave cavity plug. The optimal potentials were numerically found to be +80 kV at the plasma electrode and the plasma chamber, +70 kV at the middle electrode, whereas the puller electrode is conventionally grounded. All of the electrodes have the same shaped holes of 1 mm in diameter and total transparency of 70%. The result if simulation is presented in Figure 4.

According to simulations, it is possible to form a slightly divergent beam with the current density of 750 mA/cm^2 in the accelerating gap and on the level of 500 mA/cm^2 further downstream the beamline.

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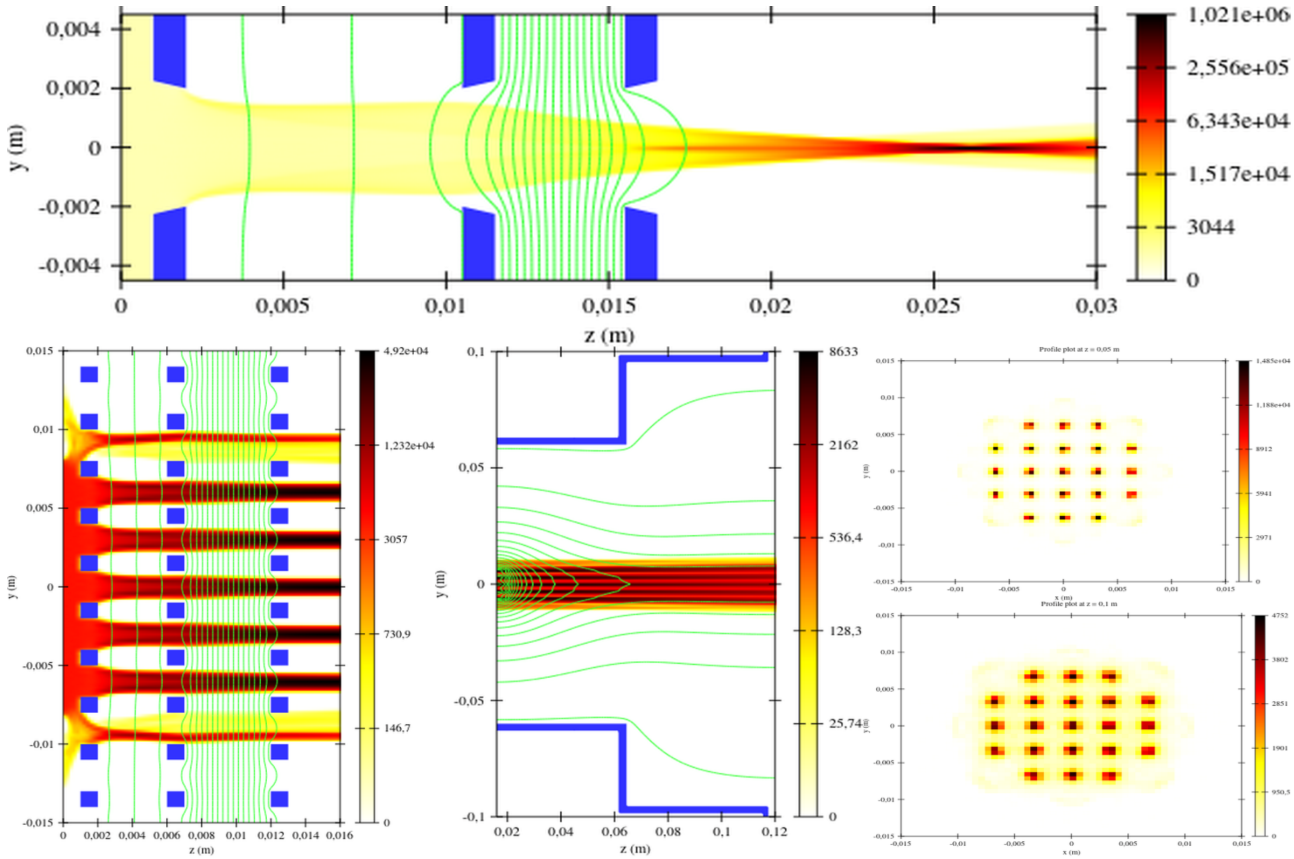

Figure 4: IBSimu simulation of a multi-aperture extraction system. Electric potential (green lines) and current density (false colour) are shown for the single beamlet (top), all beamlets in the extraction region (bottom left), extender region (bottom middle). Cross-sections of the beam current density close to the extraction system (middle right) and 200 mm downstream the beamline (bottom right) are shown in false colour.

CONCLUSION

Wide-aperture plasma fluxes from the ECR discharge in the magnetic field of a single solenoid were obtained. It was found that the flux density increases with the microwave power and magnetic field. The maximum value of the flux density was 750 mA/cm^2, and corresponding total ion current was equal to 5 A. It was also found that the plasma follows magnetic field lines while expanding into the diagnostic chamber.

The obtained results may be supposedly improved with the increase in the frequency and the power of heating microwaves. An increase in the flux aperture could be provided by the use of discharge chambers of larger diameters simultaneously with a specific design of the microwave injection, optimized for more uniform electromagnetic field distribution in the volume.

The obtained results demonstrate perspectives of the proposed system based on a single coil for wide-aperture plasma flux formation, including its probable application for neutral injector development.

Further investigations will be dedicated to the obtaining of plasma fluxes with apertures of 100 cm^2 and a flux density of 1 A/cm^2. The numerically tested extraction system will be tested experimentally.

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