Microwave injector of plasma formed in a narrow coaxial resonator: experiment and computer simulations

A A Balmashnov¹,², N B Butko¹, A V Kalashnikov¹, S P Stepina¹ and A M Umnov¹
¹ RUDN University, Moscow, Russia
² Email: abalmashnov@rambler.ru

Abstract. Under the conditions of simultaneous extraction of the ion and electron plasma components and the formation of a current-compensated plasma flow created in a narrow coaxial resonator by the ECR radiation, the radial distributions of the ion current at different mass flow rates of the working gas (argon) were obtained. The computer PIC simulations were performed using the three-dimensional numerical model in order to determine the intensity of the plasma flow as a function of the experimental parameters.

1. Introduction

Along with the undoubted interest in the development of plasma injectors with an electrodeless system for extracting plasma particles, which is ultimately concerned with the prospects of their use as cruise engines for spacecrafts, there is still some interest in the systems, in which the particles are extracted using the mesh electrodes. Due to the small mass and dimensions, these systems can be efficiently used for the correction of orbits of the ultra-light Earth satellites [1]. In this case, the energy efficiency of such injectors is very important; it depends on the method of energy input into the plasma. In this respect, using resonant processes in plasma creation is very promising, in particular, the processes involving the electron cyclotron resonance (ECR).

Experimental studies of plasma formation in a narrow coaxial resonator by means of the ECR discharge in the axially symmetric magnetic field [2] showed that, under some conditions (working gas pressure and microwave input power), the concentration of charged particles can exceed the critical value for the used microwave field frequency \( \omega_0 = 2\pi f_0 = 1.5 \times 10^{10} \text{ s}^{-1} \). At a microwave power input into the resonator of 20 W and a gas mass flow rate (Ar) of 0.2 mg/s, the calculated ion current is 44 mA [3]. We have also previously ascertained that it is possible to simultaneously extract the ion and electron plasma components using a system of mesh electrodes and to form the plasma flow with equal ion and electron currents [4]. However, in this case, the ion current was 5.6 mA at a mass flow rate of the working gas (Ar) of 0.2 mg/s and a microwave power input into the resonator of 20 W. The analysis of the obtained results allowed us concluding that a significant increase in the ion current can be achieved if we will use the additional mesh electrode that is in direct contact with the central electrode of the coaxial resonator.

The goal of this work was to study the parameters of the plasma flow formed in a narrow coaxial resonator by the ECR discharge under the conditions of simultaneous extraction of the ion and electron plasma components.
2. Problem statement and methods of its solution

One of the injector components is a narrow cylindrical coaxial resonator (Figure 1). One of its walls is a set of axially arranged mesh electrodes, which allows extracting the ion and electron plasma components.

![Figure 1. Scheme of the injector. (1) ring magnets, (2) cylindrical resonator housing, (3) central electrode of the coaxial resonator, (4) mesh electrode, (5) mesh electrodes for ion extraction, and (6) mesh electrodes for electron extraction.](image1)

![Figure 2. Magnetic field profile. (1) ion extraction region, (2) electron extraction region, (3) axial resonator electrode, (4) mesh electrode, and (5) ECR interaction region.](image2)

In this experiment, the resonator size (diameter) and the magnetic field profile differ from those previously presented in [3]. The resonator diameter is 5.2 cm (previously, it was 7 cm), and the distance to the mesh electrode of the extraction system (4) is 1.0 cm. The working gas was inputted in the radial direction through the opening in the cylindrical wall of the resonator. We used the magnetron generator with a stabilized power source ($\omega_0 = 2\pi f_0 = 1.5 \times 10^{10}$ s$^{-1}$). The microwave power was applied to the resonator axial electrode with a diameter of 0.4 cm. The standing wave ratio of the unloaded resonator was 1.15, and, in the mode of the injector operation, it did not exceed 1.05. The azimuthally symmetric stationary magnetic field was produced by the neodymium ring magnets (the outer diameter is 5 cm). The distribution of the magnetic and microwave electric fields determined the location of the azimuthally symmetric ECR interaction region. In this case, it was located at distances of $R_c = (1.6 \pm 0.2)$ cm from the resonator axis and $Z_c = (0.5 \pm 0.2)$ cm from its solid end wall (Figure 2).

The system for the plasma particle extraction consisted of the mesh electrodes installed in series at distances of 0.2 cm (Figure 1). The electrode (4) was in direct contact with the axial electrode of the resonator. Extraction of the ion component was performed using the electrodes with a diameter of 2.4 cm. The ring-shaped electrodes for the extraction of the electron component with internal and external diameters of 3.0 and 4.7 cm, respectively, were installed coaxially with them (Figure 1). The potentials on the electrodes of the extraction system could vary. Diagnostics of the plasma flow parameters was carried out using the disk-shaped electrode (with a diameter of 6 cm) and the electric probe with a guard ring, which can be displaced in both the longitudinal and transverse directions (the diameter of the active part of the probe is 0.2 cm). In processing of the measurement results, the effect of the constant magnetic and microwave electric fields was neglected. A turbomolecular pump was used in the experiment. The mass flow rate of the working gas was calculated using data on the vacuum system pressure and the performance of the pump used. Pressure was measured in the traditional way. Argon was used as a working gas.
3. Computer simulations

The plasma flow intensity as a function of the mesh electrode potentials was calculated using the 3D model described in [5], which was adapted for solving this problem. In this model, the PIC simulation method was used and the electrostatic interactions were taken into account. The model also takes into account all the main operating parameters of the source described above: the magnetic field configuration, the microwave field structure and strength, and the potential differences between the mesh electrodes and the resonator wall. The Poisson equation was solved using the fast Fourier transform. The intrinsic magnetic field of the plasma was not taken into account in the model, since, for the parameters under consideration (density and average energy of the electron component), its effect on the processes occurring in the injector is negligible. The equation of electron motion was solved in accordance with the Boris scheme described in [6]. In the model, the simulated ions (argon) are non-magnetized and singly ionized. The equation of ion motion was solved using the “leap-frog” scheme. The calculations were carried out until the plasma parameters reached their quasi-stationary values.

At the zero time, the low-temperature plasma ($T_e = 10$ eV) was generated in the ECR interaction region. The potential difference between the mesh electrodes and the injector walls varied in the range of $0 < U < 300$ V and the plasma density in the ECR interaction region was $n = 10^{10}$ cm$^{-3}$.

Figure 3 shows the typical spatial distribution of the plasma components obtained at equal potentials at the mesh electrodes used for the extraction of ions and electrons $U = 250$ V.

Figure 4 shows the plasma flow intensity as a function of the potential on the meshes.

The spatial separation of the plasma components is clearly visible in Figure 3. The electron component distribution in the XY section remains almost unchanged as compared to the initial distribution, while, with decreasing potential, the ion component can occupy almost the entire central region.

Figure 4 shows the plasma flow intensity as a function of the potential at the mesh electrodes. In calculations, the potentials at the mesh electrodes for the ion and electron extraction were equal. The presented results obtained by computer simulations are completely consistent with the experimental results previously presented in [4].

4. Experimental results and discussion

It was ascertained that, under conditions of compensation of the flows of the extracted ions and electrons (potentials on the first and second mesh electrodes (6) are (30–50) V and (60–80) V, respectively), at the negative potentials on the electrodes (5) of (60–100) V and (200–400) V,
the plasma flow is formed, the ion current in which exceeds the previously obtained values [4]. Figure 5
shows the radial distributions of the ion saturation current in the circuit of the electric probe located at
a distance of 7 cm from the plasma injector, in the absence and presence of the mesh electrode (4) [4]. The
flow rates of the working gas (m) and the microwave power inputs into the resonator of the plasma source (P) in both cases were 0.2 mg/s and 20 W, respectively.

Based on the experimental results, the calculations of the integrated ion currents and measurements using the disk-shaped electrode were performed. The results are in good agreement. In the absence and presence of the electrode (4), the ion currents are 5.6 and 28.5 mA, respectively. We note that using electrodes with coaxial apertures and high transparency instead of the mesh electrodes can considerably increase the current. It was experimentally ascertained that the presence of the additional mesh electrode increases the ion current approximately by 5 times.

The results of the study may be of practical interest in view of the possibility of their use in the development of compact plasma injectors.

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