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DEVELOPMENT OF COMPACT 2.45 GHz ECR ION SOURCE FOR GENERATION OF SINGLY CHARGED IONS

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Abstract

2.45 GHz ECR ion sources are widely used for production of single charged heavy ions and secondary radioactive ion beams. This paper describes the development of a compact ECR ion source based on coaxial quarter wave resonator. The first results of extracted current measurements at different resonator configuration as a function of UHF frequency, power and gas flow are presented. At the extraction voltage about of 10 kV and UHF power about of 100 W more than 500 μA of He^+ ions were produced with the extraction hole of 3 mm in diameter that corresponds to the current density 7.5 mA/cm^2.

INTRODUCTION

Several ECR ion sources for production of radioactive ion beams operating at 2.45 GHz were developed at the FLNR JINR [1]. Such ion sources are used for production of $^6He^+$ ions in the DRIBs project [2] and at the MASHA mass-spectrometer [3]. The magnetic system of such sources is composed of NdFeB permanent magnet rings, and it provides the creation of pseudo-closed resonant surfaces (875 Gs). The plasma chamber of such sources is based on a single-mode cylindrical resonator with an internal diameter of 90 mm and a length of 100 mm. The measured gas efficiency of those sources is about 90% for noble gases (Ar, Kr). The transformation time of atoms into ions of this ion source has not been investigated yet, however, according to the results of paper [4], this time decreases with the decrease of the plasma chamber volume.

The volume of plasma chamber can be reduced if the chamber will be based on a coaxial resonator loaded with a capacitor. Pseudo-closed surfaces should be located in the gap of the capacitor to achieve optimum conditions for plasma confinement. In this paper we present the further investigations of the developed ion source [5].

DESIGN OF THE SOURCE

The magnetic system of the source is composed of a radially magnetized ring with an external diameter of 52 mm, an inner diameter of 22 mm and a thickness of 10 mm. The distribution of the magnetic field on the axis of the ring is shown in Fig. 1, the lines of an equal field are shown in Fig. 2. It can be seen that this magnetic system provides creation of pseudo-closed surfaces with a field level from 875 Gs up to 1750 Gs.

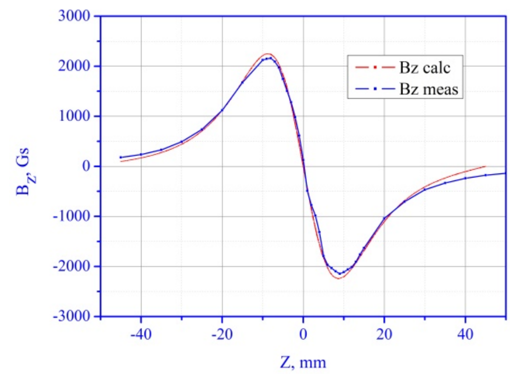

Figure 1: Axial magnetic field distribution of a ring magnet.

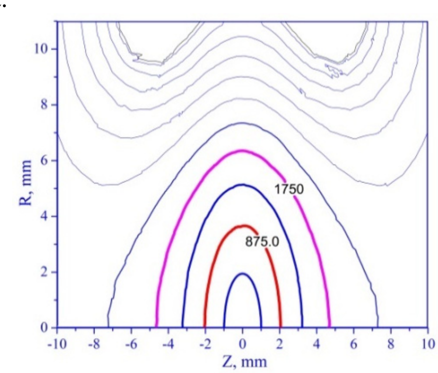

Figure 2: Magnetic field contour plot.

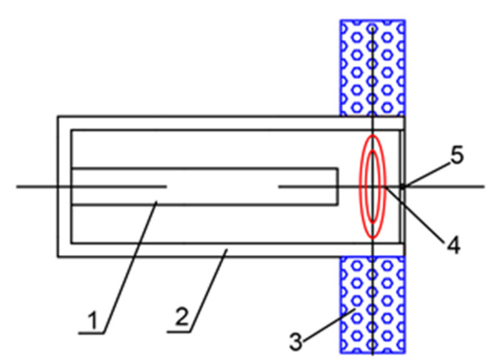

Figure 3: Schematic structure of the ECR ion source based on a coaxial resonator. 1 - central conductor of a coaxial resonator; 2 - resonator casing; 3 - magnetic

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ring; 4 - closed lines of the magnetic field; 5 - extraction hole.

Schematic structure of the source is shown in Fig. 3, the closed surfaces of the magnetic field are located in the gap between resonator electrodes.

In the source design we decided to use existing N-type connector with KF16 (16 mm internal diameter and 7 mm diameter of central conductor) flange. From the constructional point of view the geometry of resonator with cone transition from internal diameter 25 mm to diameter 16 mm, which fits the internal diameter of the magnet, was chosen. The resonator was designed using CST Studio Suite [6]. The computational model of resonator with cone transition is shown in Fig. 4.

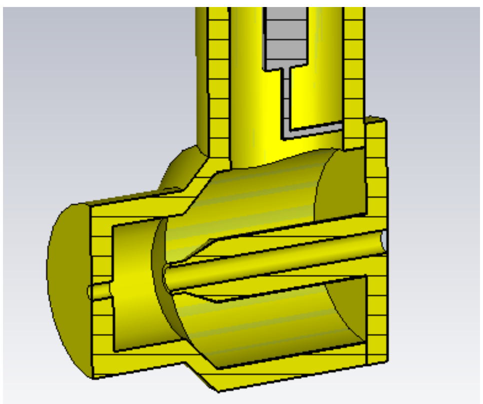

Figure 4: Computational model of coaxial resonator with cone transition.

In a process of calculations the geometrical parameters of resonator were determined for discharge gaps 5, 8 and 10 mm (see Fig. 2). These gaps contain the closed lines of magnetic field 875, 1313 and 1750 Gs correspondingly. The Q factor of resonator was determined about 3500 for all gaps value. Figure 5 shows the calculated electric field in the resonator gap as a function of power for different gap value.

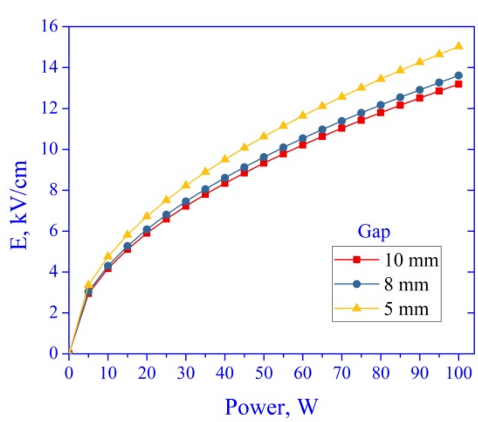

Figure 5: Electric field in the resonator gap as a function of input power.

Based on the modelling results, an ECR ion source was designed and manufactured. Assembly drawing of the source is presented in Fig. 6. The view of the source is presented in Fig. 7.

For changing the resonator gap three sets of the replaceable internal parts of resonator and replaceable plasma electrodes were used, providing the gap sizes of 5, 8 and 10 mm. The diameter of the extraction hole in plasma electrodes is 2 mm.

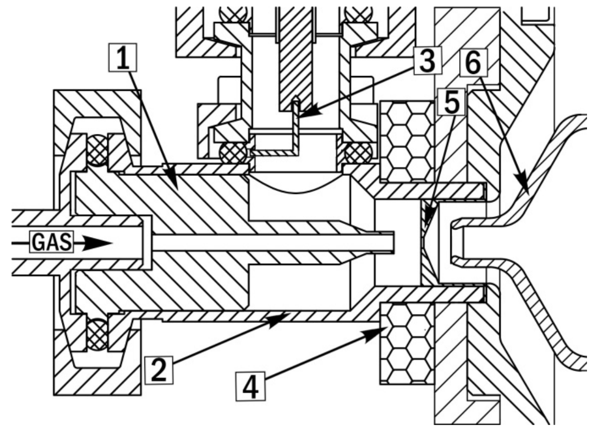

Figure 6: Assembly drawing of ECR ion source: 1 - replaceable internal part of the resonator, 2 – resonator casing, 3 – coupling loop, 4 – permanent magnet ring, 5 - replaceable plasma electrode, 6 - pulling electrode.

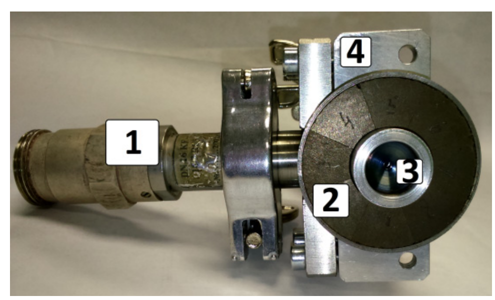

Figure 7: The view of ECR ion source: 1 – coaxial feedthrough, 2 – magnet ring, 3 – plasma electrode, 4 – resonator casing.

EXPERIMENTAL RESULTS

Preliminary Tests

For the preliminary tests the source was mounted on the vacuum volume pumped by the 150 l/s turbopump providing the base vacuum about of 2 ÷ 4×10^{-6} torr. During the source operation the pressure in vacuum chamber was about of $1.2\text{x}10^{-5}$ torr. Solid state UHF generator with the output power up to 100 W in the frequency range of 2.4 ÷ 2.5 GHz was used to feed the source. The UHF power was fed to the coupling loop through a coaxial cable and tuner. Control of the gas flow was performed by the piezoelectric leak valve. A negative potential about of 300 V was applied to the pulling electrode. During tests the current of ions

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incident on the pulling electrode was measured. Argon was used as a working gas. The distance between the plasma electrode and pulling electrode equals to 5 mm in all experiments.

The source was successfully ignited, and Fig. 8 shows the argon plasma view through the gridded plasma electrode. The diameter of the hole covered by grid equals to 12 mm.

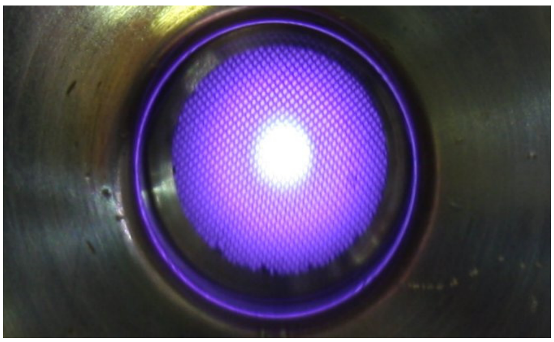

Figure 8: Ar plasma view through the gridded plasma electrode at 20W, 2450 MHz.

As a first test we study the minimal ignition power for different resonator gaps as a function of frequency at fixed gas flow (Fig. 9). We consider the discharge is ignited when pulling electrode current of few microamperes is registered. It can be concluded that in a certain frequency range 2450 ÷ 2465 MHz for 10 mm gap, 2430 ÷ 2460 MHz for 8 mm gap and 2425 ÷ 2435 MHz for 5 mm gap, the lowest power (about of 0.5 W) required for ignition is observed. The average required power over the whole frequency range is minimal for 5 mm gap, and maximal for 10 mm.

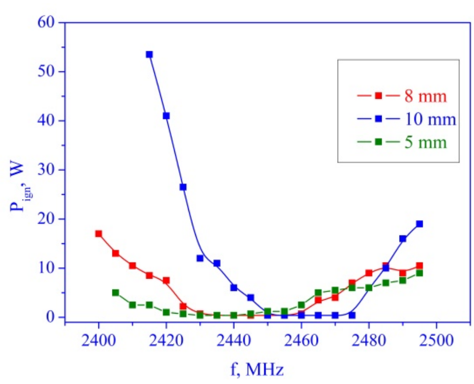

Figure 9: Dependence of the ignition power on the generator frequency for different resonator gaps at fixed gas flow.

The dependence of the ion current on the generator frequency for various resonator gaps at fixed power (20 W) and gas flow is shown in the Fig. 10. For all values of resonator gap the current increases with the frequency of generator. The highest current was produced with resonator gap of 8 mm. All other measurements were performed with this gap value.

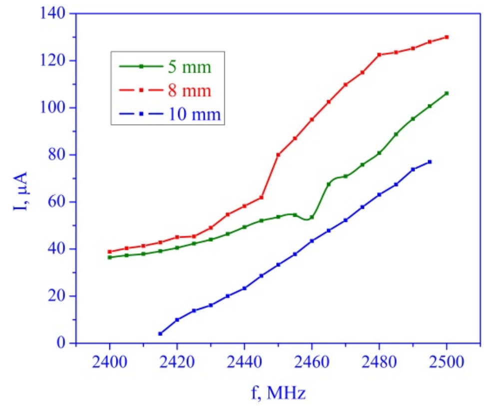

Figure 10: Dependence of the ion current on the generator frequency for different resonator gaps at 20 W.

Figure 11 presents the dependence of the ion current on the generator power at fixed and adjustable gas flow. At fixed gas flow the current shows the saturation with the power more than about 30 W, while with adjustable gas flow the current is increasing linearly with the power level above 30 W.

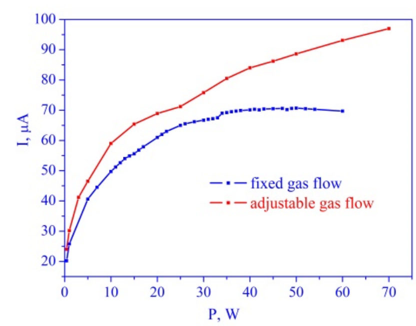

Figure 11: Dependence of the ion current on the generator power at fixed and adjustable gas flow at the frequency 2450 MHz.

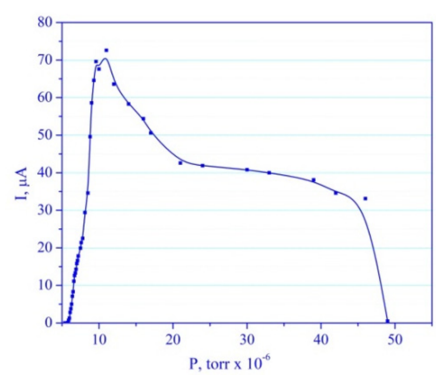

Figure 12: Dependence of the ion current on gas flow.

Figure 12 presents the variation of the ion current with the gas flow (the pressure in the vacuum chamber) at 2450 MHz and 20 W of injected power. By varying the gas flow, one can tune the source for the maximal value of ion current.

Also we checked the influence of the magnet ring centre displacement with respect to resonator gap

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centre on the ion current. It was possible to shift the ring towards the plasma electrode to the distance up to 2 mm. The measurements show that the displacement of the magnet ring leads to the decrease of the ion current for the resonator gaps 8 mm and 10 mm.

Experiments At the ECR Test Bench

After preliminary tests the ion source was installed at the ECR test bench which represents a low energy beam transport line with focusing solenoid and 90° analysing magnet. The source can be biased with respect to ground up to 15 kV. All the experiments were performed with He due to insufficient magnetic rigidity of the beam line designed for analysis of multiply charged ions.

At the test bench the influence of the coupling loop length on the value of extracted current was investigated. The geometry of the coupling loop is shown in Fig. 13. The initial length of the loop 8 mm was chosen according to calculations from the point of view minimal VSWR and equivalence of intrinsic and external Q-factor of resonator.

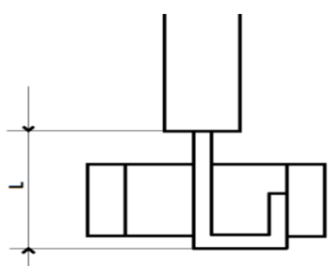

Figure 13: Geometry of the coupling loop.

Three additional loops were manufactured (9, 13 and 15 mm) to establish over coupling mode of communication with the resonator. Over coupling mode is more preferable, since the quality factor of the plasma loaded resonator differs from the intrinsic quality factor of the "empty" resonator, therefore, in the critical coupling mode when the discharge is ignited in the source chamber, the Q factor of the resonator decreases, the VSWR increases and strong reflections arise. Unfortunately, it is nearly impossible to numerically determine the deviation of the intrinsic Q factor from the loaded one using mathematical modelling because of complexity of the processes taking place in the plasma. Therefore, the loops were alternately tested at the source.

The dependence of the He^+ ion current on the generator frequency was measured for different coupling loop length (Fig. 14). The pressure in the beam line was maintained at the level of ~ 10^{-6} torr, extraction voltage U = 8.8 kV, microwave power P = 60 W. For the loop with length of 9 mm the results were very similar to results obtained with the initial loop length. The maximal current (260 μA) was reached for a loop with the length of L = 13 mm, therefore, optimal matching conditions are observed. All further tests were carried out with this loop.

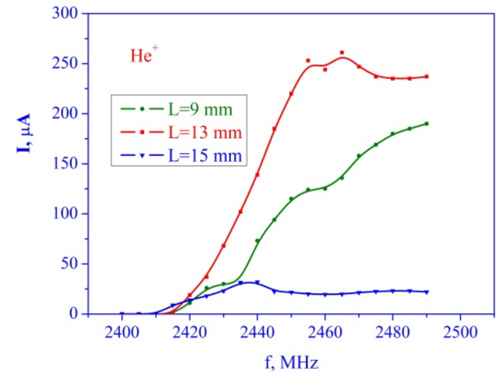

Figure 14: Dependence of the He^+ ion current on the generator frequency for different coupling loops length.

With the optimized loop we performed the study of influence of injected power, frequency and gas flow on He^+ ion current. The results were very similar to these one obtained at the preliminary tests. Figure 15 shows the dependence of the He^+ current on the frequency at different power level. The dependence of the He^+ ion current is shown at the Fig. 15.

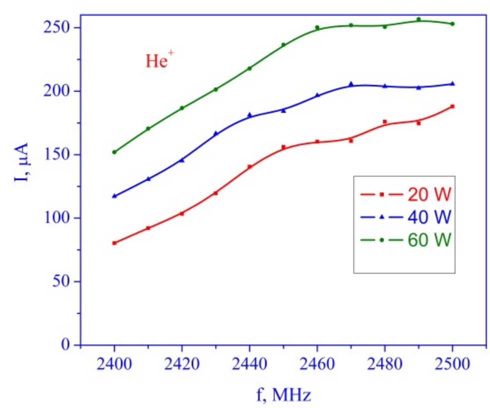

Figure 15: Dependence of the He^+ ion current on the generator frequency for different power level.

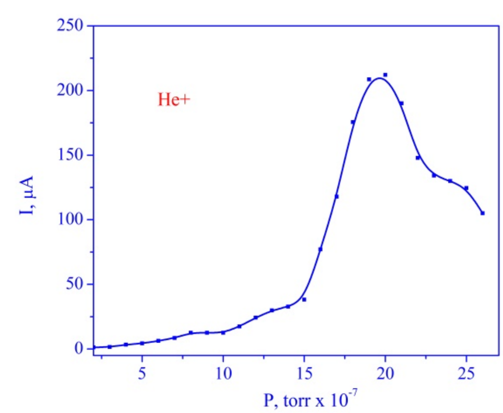

Figure 16: Dependence of the He^+ ion current on the gas flow at power 20 W, and frequency 2470 MHz.

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The dependence of the He^+ ion current on the power at fixed gas flow shows saturation at the power level above 30 W (Fig. 17).

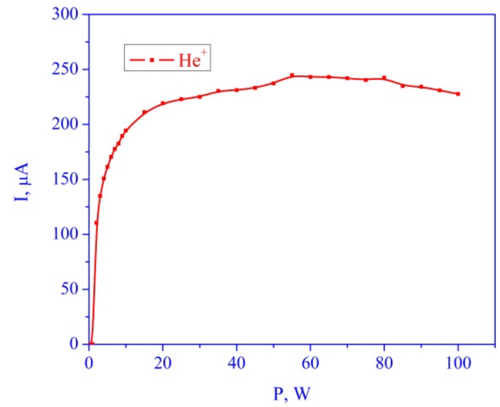

Figure 17: Dependence of the He^+ ion current on the power at frequency 2470 MHz and fixed gas flow.

The dependence of extracted current on the diameter of the extraction hole was investigated. The diameter of extraction hole in the plasma electrode was increased from 2 to 3 mm. Injected power was raised to 100 W. All other parameters were kept by its previous value. By this means, extracted current of He^+ ions increased from 260 µA to 534 µA, that corresponds to the current density j = 7.5 mA/ cm^2.

For the further increase of extracted current we tried to employ well known technique of biased electrode. An insulated aluminium rod 2 mm in diameter was inserted to discharge region axially through the central conductor of resonator (see Fig. 6). Figure 15 presents the He^+ ion current and biased electrode current on bias voltage. He^+ ion current is increased by factor about of 1.4. The saturation of extracted current and biased electrode current with voltage above 30 V is caused by the current limit of power supply. The measurements were performed at 20 W, 2481MHz and extraction voltage 10 kV.

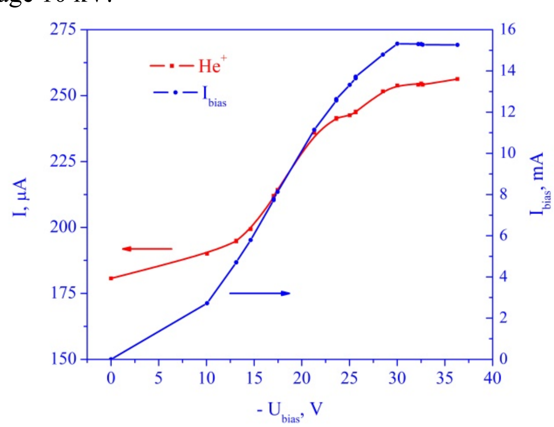

Figure 18: Dependence of He^+ ion current and biased electrode current on bias voltage.

The source was also tested for production of hydrogen ions. The spectrum of hydrogen ions is shown in Fig. 16. The spectrum contains more than 80% of molecular H_2^+ ions, and about of 3% of protons.

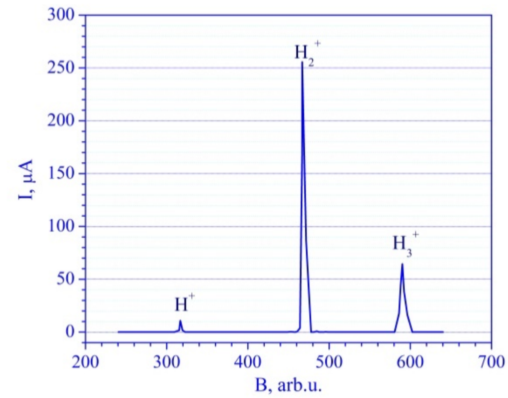

Figure 19: Spectrum of hydrogen ions at 2450 MHz, 60 W and diameter of extraction hole is 2 mm.

CONCLUSION

Compact ECR ion source was designed and tested. The source is suitable for production of low and medium currents of singly charged ions. The current of He+ ions more than 500 µA is reached with the diameter of extraction hole 3 mm, that corresponds to the current density of 7.5 mA/cm^2. Promising results are obtained with the use of biased electrode technique. The further study will include the test of the source with heavy ions, such as Kr and Xe, measurements of the gas efficiency and time response of the ion source.

Further investigations required for increasing the proton fraction in the extracted beam.

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