INVESTIGATION OF ECR MULTI-CHARGED ION SOURCE WITH PUMPING BY POWERFUL MILLIMETER WAVE RADIATION

A.V. VODOPYANOV, S.V. GOLUBEV, S.V. RAZIN, V.G. ZORIN

Institute of Applied Physics of Russian Academy of Sciences
46 Ul'yanov St., Nizhny Novgorod, 603600, Russia

Essential increase of operation efficiency of electron cyclotron resonance (ECR) multiply charged ion (MCI) sources (that is the increase of the average charge number and current of ion beams) connects with possibility to achieve more dense plasma and to transfer to so called quasi-gasdynamic regime of the plasma confinement in mirror traps under the use of pumping with higher frequency. Results of experimental investigation of ion charge state distribution in a pulsed ECR source of MCI with pumping by millimeter wave radiation of powerful gyrotron are presented in the paper. Millimeter wave radiation with maximum power W=130 kW, frequency f=37.5 GHz and pulse duration up to 1.5 ms is used for the experiments. The charge state distribution maximum corresponded to argon charge (+13)-(+15). Total ion saturation current density of the probe achieved 2 A/cm^2.

1 Introduction

One of the way of new generation ECR multi-charged ion (MCI) connects with significant increase of frequency and power of microwave pumping [1]. The increase of microwave pumping frequency allows essentially (proportionally ω^2) to increase of plasma density in a trap and to hope for increase of multi-charged ion current. The use of millimeter wave radiation of modern gyrotrons makes it possible to hope for such increase of plasma density that allows changes in the character of plasma confinement in the trap, when the filling rate of the loss-cone is higher than the precipitating rate (filled loss-cone). This regime was called as quasi-gasdynamic regime of plasma confinement [2] [3]. In this case plasma loss is determined by ion sound velocity and plasma life time weakly depends on its density [4]. In such situation confinement parameter $N_e\tau$ (here N_e is plasma density, τ is ion confinement time in a trap) increases with growth of plasma density, that leads to a sufficient shift of ion charge state distribution to the region of large ionization states.

This paper contains experimental data on high-power pulsed ECR discharge sustained by short-wave gyrotron radiation. In particular, ion distribution over charge states is presented here.

2 Experimental Setup

An experimental scheme is shown in Fig. 1 (see also [5]). Microwave radiation from the pulse-mode gyrotron (1) (frequency 37.5 GHz, pulse duration up to 1.5 ms and power 130 kW) was focused by dielectric lens (2) into a vacuum discharge chamber (3). The wave was linearly polarized. The discharge chamber with an input window 70 mm in diameter was placed into a mirror magnetic trap formed by two solenoids (duration of the magnetic field pulse was about 13 ms). The trap length was 25 cm, mirror ratio was 3,2. The maximum value of magnetic field strength in the plug was 2,3 T. The ECR heating of plasma was performed at fundamental harmonic of gyrofrequency. Microwave input was arranged along magnetic lines as it is shown on Fig. 1. To

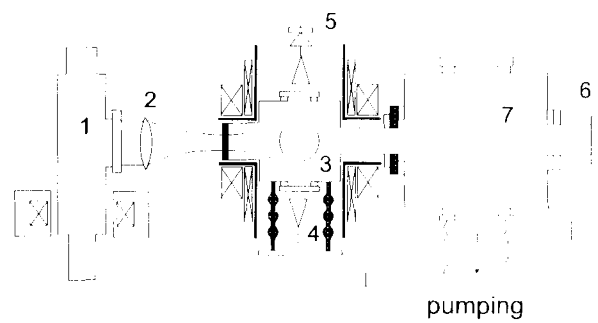

Fig. 1. The experiment scheme.

evaluate plasma density and electron temperature in the discharge, transmission factor of the diagnostic microwaves through the plasma (4, 5) and spectrum of X-ray bremsstrahlung were measured. The diagnostic microwave radiation with frequency 35.52 GHz and polarization corresponding to the ordinary wave was injected into the trap center perpendicularly to the magnetic field. The ions coming out from the plasma freely along the magnetic field lines were investigated with a two-step (magnetic and electrostatic analysis) five-channel analyzer (6) with mass resolution 3 attached to the discharge chamber through coupling section (7). Secondary emission multipliers are used as sensitive elements. The pressure of operating gas (Argon) was set using a pulse valve and was more than $3 \cdot 10^{-5}$ Torr. Gas was admitted into the discharge chamber while pressure in the analyzer and coupling section was low (about 10^{-6} Torr).

3 Experimental Results

The peculiarity of these experiments was that efficiency of MCI generation was investigated at rather high plasma density (an order of magnitude higher than in traditional ECR sources of MCI). In these experiments the shielding of diagnostic microwaves by the discharge was observed (Fig. 3), thus testifying that plasma density with value close to $2 \cdot 10^{13}$ cm^{-3} was obtained. Electron temperature was measured from spectrum of X-ray bremsstrahlung of the discharge jointly with Japanese colleagues S. Miyake, N. Abe from Osaka University and T. Mieno from Shizuoka University [6]. This measurements were performed by X-ray detector XR 100T, region of spectrum observation was from 1 to 20 keV (see Fig. 2). Two groups of electrons were found: first one with temperature of 300 eV and electron density about $2 \cdot 10^{13}$ cm^{-3} and the second one with temperature 10 keV and electron density ~ $1.5 \cdot 10^{9}$ cm^{-3}. It should be noted that the temperature of main group is very close to the optimal for multi-charged ion generation.

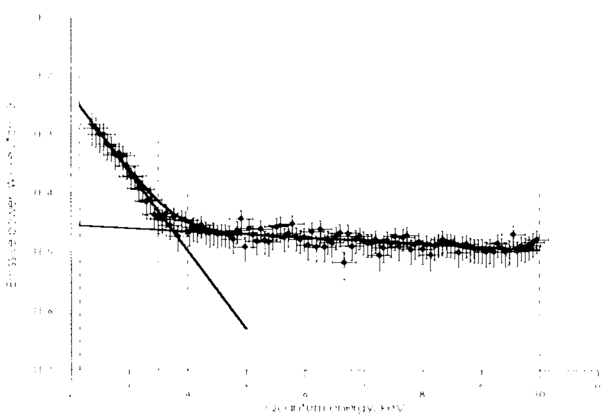

Fig. 2. Spectrum emissive power of plasma in the region of the X-rays.

The measured plasma parameters give evidence in favor of quasi-gasdynamic regime of plasma confinement in the mirror trap. According to modern concept the quasi-gasdynamics become of main importance in the discharge dynamics with large enough electron density when the filling rate of the loss-cone is higher than the precipitating rate $k_f > k_g$, according to ref [7] and [8] k_f, and k_g can be estimate as $k_f \approx \nu$, $k_g \approx \kappa L V_s^{-1}$, where ν is electron-ion collision frequency, L - length of the trap, V_s - ion sound velocity. With the parameters achieved in the experiments it looks to be definitely so. It should be noted that there are some peculiarities of quasi-gasdynamic process under conditions of intense energy deposition from ECR pump into the energy of transverse electron motion [9].

The efficiency of MCI generation and ion energy depended essentially on the gas pressure and power of microwave radiation. Energy of ions flowing out from plasma was between 100 eV and 1keV per charge. The Fig. 3 shows a waveform of current of Langmuir probe situated far away from the trap along magnetic field lines (upper curve) and transmission factor of diagnostic microwaves though the plasma (lower curve). Zero level of transmission factor corresponds to a mark «2» on left part of the picture. Waveforms of current of the secondary emission multipliers of the analyzer with magnet current corresponding to the Ar^{+14} are shown on a Fig. 4.

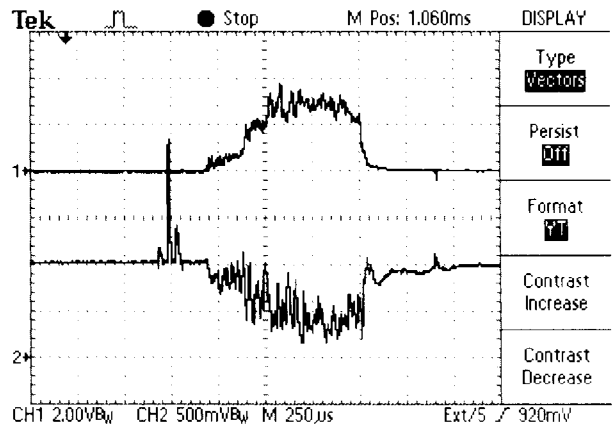

Fig. 3. Upper waveform is the probe current. Lower waveform is transmission factor of diagnostic microwaves through the plasma, sign «2» shows zero level of transmission.

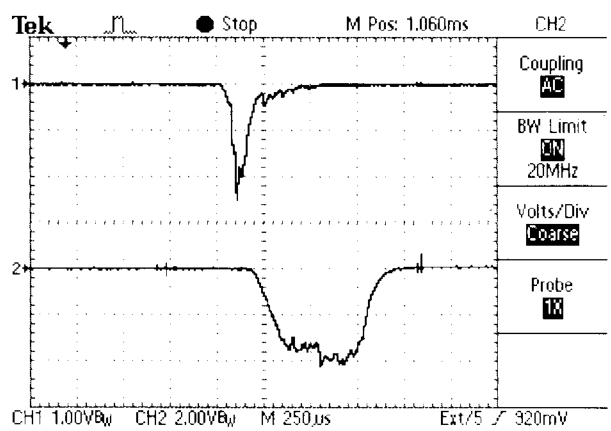

Fig. 4. Upper waveform is ion current for Ar^{14+} with ion energy 300 eV per charge of ion, lower waveform is ion current for Ar^{14+} with ion energy 100 eV per charge of ion.

The typical current of the secondary emission multipliers as a function of magnet current (that reflects the ion charge state distribution) at optimum gas pressure (about 10^{-4} Torr) is shown in Fig. 3. The magnet currents corresponding the Argon ions with different charges are shown on upper part of the picture. As it is seen from this figure, the distribution obtained in our experiments is shifted to the larger ionization states (maximum corresponds to ion charge 13 - 15 while in traditional sources it is about 8 - 12).

For estimation of ion beam current that can be extracted from the trap, the current on plate Langmuir probe with area of 1 cm^2 situated into the plasma flowing out from the trap was measured. The volt-ampere characteristics of the probe for different distance between plug and probe are presented on Fig. 4. Ion and electron saturation currents were approximately equal to each other that connected with existing of strong magnetic field at the region of the measurement. Value of the ion current can't be obtained with probe voltage more than 200 V due to a breakdown between probe and chamber walls. Total ion saturation current density of the probe achieved 2 A/cm^2. So high ion current of the probe in our system provide a hope to achieve MCI beams with the previously unattainable currents.

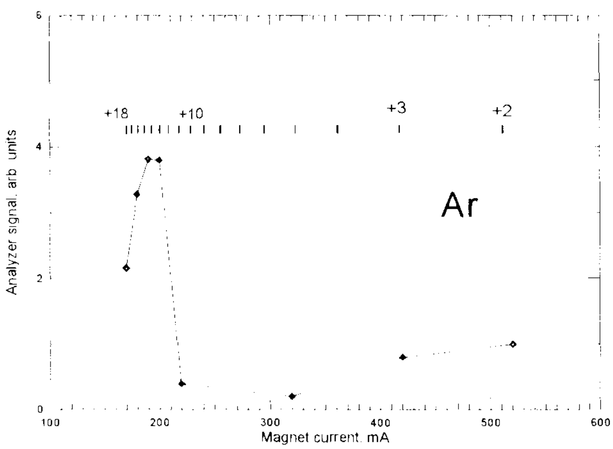

Fig. 5. Dependence of ion analyzer signal on current of analyzer magnet. The magnet currents corresponding the Argon ions with different charges are shown on top.

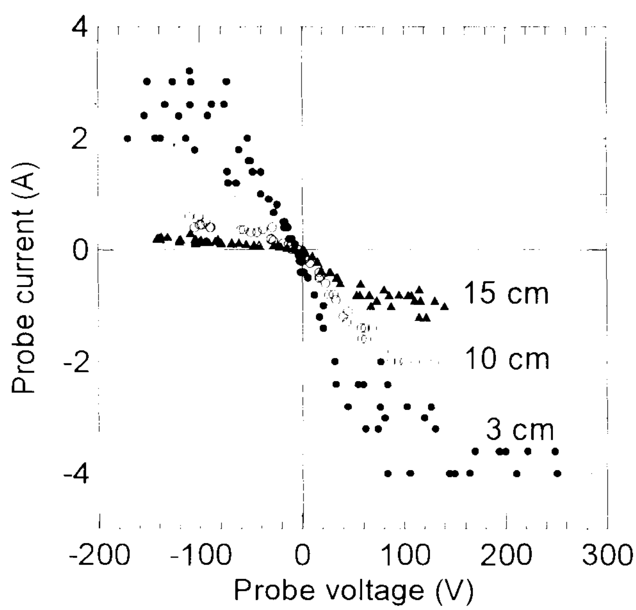

Fig. 6. The volt-ampere characteristics of the probe for different distance between plug and probe.

4 Conclusion

Thus, using more powerful and more short-wavelength gyrotron radiation we suppose to succeed in realization of the quasi-gasdynamic regime of plasma confinement that increased $N_e\tau$ parameter and provided the corresponding shift of ion charge state distribution in the direction of larger ionization states and increased total ion current considerably.

References

[1] R. Geller, *Review of Scientific Instruments*, **69**, 1302 (1998).

[2] S.V. Golubev, V.G. Zorin, T.N. Zorina, and S.V. Razin, *Proceedings of International Workshop on Strong Microwaves in Plasmas* (Nizhny Novgorod, **1**, 1991), p. 485.

[3] A.V. Turlapov and V.E. Semenov, *Phys. Rev.* **E 57**, 5937 (1998).

[4] The lifetime in the quasi-gasdynamic regime of dense plasma confinement with magnetized collisionless electrons and cold ions, in the case when the electron scattering into a loss cone due to interaction with a resonant microwave pump controls the losses, is determined by relation $\tau = L\,K\,/\,V$, where L is characteristic size of the trap, V is ion sound velocity, and K is coefficient that weakly depends on plasma density.

[5] S.V. Golubev, V.G. Zorin, S.V. Razin, *Review of Scientific Instruments*, **69**, 634 (1998).

[6] A.V. Vodopyanov, S.V. Golubev, S.V. Razin, M.A Shilov, V.G. Zorin, S. Miyake, N. Abe, T. Mieno. To be published.

[7] V.P. Pastukhov, *Nuclear Fusion*, **14**, 3 (1974).

[8] D.D. Rutov, *Plasma Physics and Controlled Fusion*, **28**, 191 (1986).

[9] S.V. Golubev, V.E. Semenov, E.V. Suvorov, and M.D. Tokman, *Proceedings of International Workshop on Strong Microwaves in Plasmas* (Nizhny Novgorod, **1**, 1994), p. 347.