Formation of Multicharged Ions at Quasi-Gasdynamic Plasma Confinement in a Mirror Trap

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I. INTRODUCTION

An increase in frequency and power of microwave radiation used for ECR plasma heating in an ion source reveals a rank of promising prospects regarding improvement of ion source performance. Namely, an increase in frequency and power of microwave pumping may lead to an increase in a density of a mirror-trapped plasma while the electron temperature is maintained at the optimal level for multicharged ions (MCI) stripping. The use of gyrotrons [1] in MCI sources has made it possible to reach the plasma density $N_e > 2\ 10^{13}$ cm^{-3}, which is an order of magnitude higher than in conventional ECR ion sources ($N_e\ \ 10^{12}$ cm^{-3}). A regime of magnetic confinement of such a dense plasma changes from the classical [2] to the so-called quasi-gasdynamic one [3,4,5]. A characteristic feature of the quasi-gasdynamic regime is that the rate of electron precipitation into the mirror loss-cone $D_p\ \ \nu_{ei}$ exceeds the one of plasma escape through the trap plugs $D_e\ \ V_s/kL$: $D_p > D_e$ (here, ν_{ei} is the electron-ion collision frequency, V_s is the ion acoustic velocity, L is a trap length, and k is a numerical factor). Thus, the mirror loss-cone is filled with electrons, and plasma confinement time $\tau\ \ D_e^{-1}$ is determined by the ion acoustic velocity and weekly depends on the plasma density. In this regime an increase in the plasma density is accompanied by an increase in the plasma confinement parameter $N_e\tau$ and causes a shift of the maximum of the ion charge state distribution (CSD) towards higher charge states. Moreover, MCI current, which is roughly estimated as N_e/τ, increases as the frequency of microwave pumping is increased [1].

Powerful ECR heating of a mirror-trapped plasma leads to formation of an anisotropic electron velocity distribution function (EDF) [5]: the average energy of the transverse, in respect to the magnetic field, electron motion is much greater than the energy of longitudinal motion. Theoretical studies of a mirror magnetic confinement of a multicomponent plasma with anisotropic (stretched along V) EDF in a simple mirror trap reveals an essential augment in multicharged ion confinement time due to the EDF anisotropy [4,6]. Consequently, the EDF anisotropy improves the ion CSD.

In the present paper we discuss results of experimental investigation of an ECR discharge sustained by powerful pulse microwave radiation of a gyrotron in a mirror magnetic trap. In particular, data on plasma X-ray emission spectrum and on ion CSD are presented. Formation of the ion CSD has been explored both experimentally and numerically.

II. EXPERIMENTAL SETUP

The experimental setup is sketched in Fig. 1.

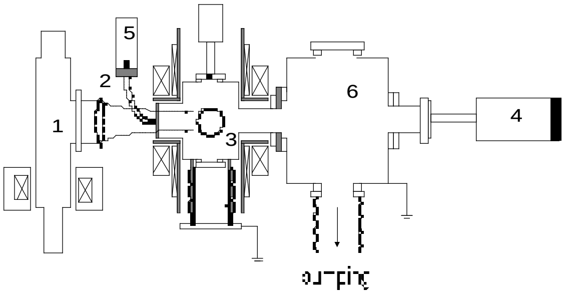

Fig. 1. Schematic of the experiment

The pulse mirror magnetic field (pulse duration is 13 ms), produced by two «warm» coils, achieved the maximum plug value of 2.5 T. The mirror ratio R and length L (the distance between the plugs) of the trap are equal to 3.4 and 25 cm, respectively. The linearly polarized gyrotron's (1) microwave radiation with the frequency of 37.5 GHz, power of 130 kW, and pulse duration of 1 ms, was focused by a dielectric lens (2) into the center of a discharge chamber (3). The trapped plasma was ECR-heated at the fundamental harmonic of the gyrofrequency. The ions, outflowing through the trap plugs along the magnetic field lines, got into the two-step five-channel ion analyzer (4). The ion analyzer enables one to investigate independently ion distribution over charge states and energy by means of electrostatic and magnetostatic analyses. The operating gas (argon) was admitted into the discharge chamber through a pulse valve (5). Exploiting a pulse gas influx, within a certain period of time (the microwave pumping was introduced at this very moment), it was possible to maintain inhomogeneous gas pressure: it amounted to $3\ 10^{-5} \div 10^{-4}$ Torr in the discharge chamber, while it was considerably lower (10^{-6} Torr approximately) in the diagnostic chamber (6) and in the ion analyzer. Under such conditions an effect of the MCI beam attenuation due to ion-neutral charge exchange along the path through the diagnostic chamber to the ion analyzer is nearly inessential. For instance, relative attenuation of the Ar^{+10} ion beam was evaluated to be ~ 6%.

X-ray radiation of a plasma was investigated by the XR-100T analyzer (7), which was exploited as a photon counter. The spectral resolution of the analyzer amounts to 200 eV. A cooled silicon pin-diode was used as a detector. The output signal of the analyzer represents a series of peaks with a duration of 20 μs and the amplitude proportional to the energy of recorded quantum. Computer processing of recorded signals made it possible to obtain spectra as well as absolutely calibrated intensity of plasma X-ray radiation with time resolution.

III. RESULTS OF EXPERIMENTS AND DISCUSSION

The research verified that two regimes of ECR discharge: the isotropic regime and the anisotropic one are possible under the experimental conditions. (It will be clear from what follows why the regimes are called this way.) Their realization depends on the power of microwave pumping and the rate of neutral gas flux into the vacuum chamber.

With the technique of pulse gas influx, employed in our experimental device, the density of the flux of neutral gas, which was admitted into the vacuum chamber, could alter significantly. Therewith, the conditions of plasma trapping and MCI generation could change.

In the regime of intensive gas influx, the current of Ar^{5+}-Ar^{6+} ions dominated. The corresponding ion CSD is shown in Fig. 2 (curve 2).

In order to determine the plasma density and the electron temperature, we carried out absolutely calibrated spectral measurements of the intensity of X-ray plasma radiation in the region of quantum energies from 2 to 15 keV. The spectrum of plasma radiation obtained by accumulating 250 identical plasma shots is given in Fig. 3. In processing the measurements we allowed for the dependence of the efficiency of quantum counts on their energy as well as for transmission coefficients of the aluminum filter and input beryllium window of the analyzer. The dependence of radiation intensity on quantum energy in a semilogarithmic scale is approximated sufficiently well by two straight lines. Estimates show that such a spectrum corresponds to plasma bremsstrahlung radiation with two-temperature electron distribution over energies. It is clear from the spectrum obtained that the first group of electrons has a temperature of 300-400 eV, and the second one 7-10 keV. The measured absolute values of X-ray radiation intensity enable one to determine the densities of these two groups of electrons too: the density of electrons amounted approximately to $N_w \approx 4\ 10^{13}$ cm^{-3} and $N_h \approx 10^9$ cm^{-3} for the low-temperature and the high-temperature groups, respectively. Observation of the cut-off of a diagnostic microwave signal at the 35.52 GHz frequency additionally confirmed the high plasma density: $N_e > N_{cr} = 1.5\ 10^{13}$ cm^{-3} [1]. Note that the temperature of the 'warm' electrons is nearing the level optimal for MCI stripping

In the regime of intensive influx, when the current of Ar^{5+}-Ar^{6+} ions prevails, an influence of the 'hot' electrons upon the processes of ionization and plasma confinement in the trap is virtually negligible. 'Hot' electrons do not contribute much to the total rate of ionization because of their too high temperature T_h and fairly low density N_h. One can assume the energy of 'hot' electrons to be stocked mainly in the transverse, in respect to the magnetic field, motion as it is theoretically predicted. However, the EDF anisotropy due to the fraction of 'hot' electrons is weak: $N_h / N_w << 1$, i.e., the 'hot' electrons in the second part of the microwave pulse almost do not affect plasma trapping. Thus, in the regime of intensive gas influx both the ionization process and the plasma confinement are completely determined by the fraction of 'warm' electrons. Under experimental conditions the EDF of 'warm' electrons is isotropic in the velocity space. Ref. [6] gives an estimate for the confinement time of ions of different charge states in a trap with multicomponent plasma under conditions of the quasi-gasdynamic regime with the isotropic (maxwellian) EDF:

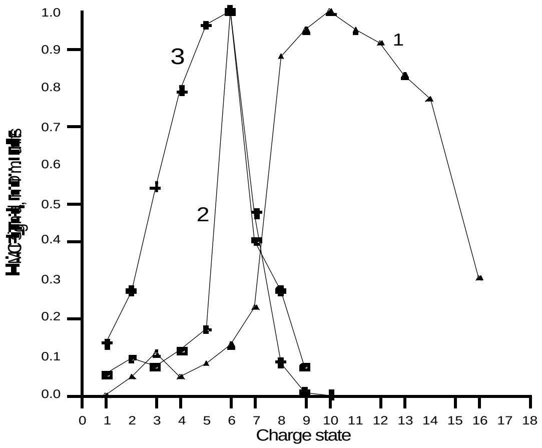

Fig. 2. The ion charge state distribution: curve 1 - experiment, anisotropic regime; curve 2 - experiment, isotropic regime; curve 3 - the calculated CSD for argon plasma with the parameters: $N_e = 4\ 10^{13}$ cm^{-3}, $T_e = 300$ eV.

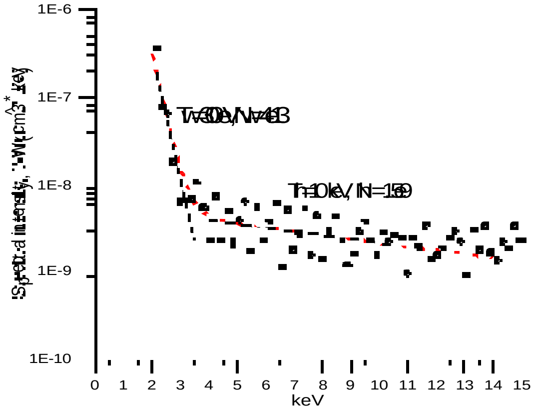

Fig. 3. Spectral intensity of plasma bremsstrahlung

$$\tau_i \quad \frac{\sqrt{e}RL}{2\sqrt{Z_i T_e / M_i}}, \qquad (1)$$

where Z_i and M_i are the ion charge and mass, respectively; L and R are the trap length and mirror ratio; T_e is the mean electron energy (effective temperature), and e is the base of the natural logarithm. This formula is valid at $T_i << T_e$, which is a relation between electron and ion temperatures typical of ECR MCI sources. In plasmas with experimentally observed parameters: N_e=4 10^{13}cm^{-3}, T_e=300 eV, and average ion charge $<Z>$=6, the product $\nu_{ei}\tau_e \approx \nu_{ei}\tau_{<Z>} \approx 20$ (here, τ_e is the electron confinement time). Thus, during the plasma confinement time, the 'warm' electrons collide about 20 times with considerable alterations in momentum. This means that the 'warm' electrons isotropize their distribution. At the same time, this means the fulfillment of the inequality $D_p > D_e$ discussed in the introduction. Consequently, the quasi-gasdynamic regime with isotropic EDF is realized under the experimental conditions and (1) can be exploited to estimate the ion confinement time.

Computer simulation of ion CSD formation in the MCI source was done for Argon plasmas within the framework of a 0-dimensional nonstationary set of differential equations for ionization balance. The temperature of the 'warm' electrons was regarded to be a given parameter which can be determined experimentally. The time dependence of neutral gas pressure in a pulse was also taken from the experiment. The confinement times of ions with different charges were determined from (1). The calculated ion CSD for steady-state plasma (when ionization of operating gas is compensated by plasma longitudinal losses) is shown in Fig. 2 (curve 3). The results of numerical simulation agree well with the ion CSD observed in the regime of intensive gas influx.

Such an agreement testifies to the validity of (1) and the absence of instabilities essentially diminishing the plasma confinement time. With the aid of a pinhole camera placed on the axis of the magnetic trap, a soft X-ray image of a discharge plasma was obtained. This enabled one to judge about the spatial distribution of a plasma. The image was ring-shaped. It's common knowledge that such a spatial distribution of electrons can suppress plasma MHD instabilities. This effect, to all appearances, was observed in our experiments.

At weaker, within a microwave pulse, densities of neutral gas flux, a considerable shift of the ion CSD towards higher charge states was observed (Fig. 2, curve 1). The experimentally obtained ion CSD had a much greater average ion charge as compared with the CSD, which could be calculated relying on (1) with T_e ranging widely. Therefore, the shift of the ion CSD towards higher charge states, which was experimentally observed for low rates of gas influx, can't be attributed to MCI generation enhancement due to a possible rise in the electron temperature. It seems likely that in this case the plasma density is not very high, and ECR heating of electrons proceeds more effectively than collisional isotropization of EDF in the velocity space. Formation of the strongly anisotropic EDF leads to an essential increase in the plasma confinement time τ. Thus, the EDF anisotropy becomes important and one must use the modified expression for the plasma quasi-gasdynamic confinement time [4,6].

IV. CONCLUSION

We have demonstrated that the quasi-gasdynamic regime of confinement of a plasma with isotropic and anisotropic electron velocity distribution function in a mirror trap is quite feasible. The regime with the anisotropic electron distribution is the most promising regime for formation of the ion charge state distribution with a high mean charge. Its implementation needs a considerable enhancement of the power of microwave pumping in comparison with conventional ECR sources of multicharged ions.

References:

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