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E9-91-383

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THE MULTIPLY CHARGED ION PRODUCTION IN ECR ION SOURCES

Submitted to "4th International Conference
on Ion Sources", 30 cept.-4 oct., 1991
Bensheim, Germany

1991

INTRODUCTION

In recent times electron cyclotron resonance (ECR) sources have become important for the generation of intensive beams of multiply charged heavy ions in connection with accelerator and atomic physics facilities. ECRIS is plasma confined in the open magnetic trap. The plasma electrons are heated by microwave field operating with the frequency of the electrons in the longitudinal magnetic field in the trap. Special coils create the regions with the increased magnetic field or magnetic mirrors for electron confinement. Only electrons with velocity vectors in a small solid angle along the trap axis can be lost from the plasma. The electron lifetime is determined by the probability of electron scattering on plasma components, electron energy and the value of $R = B_{max}/B_{min}$. The ions have much less energy T_i than the electron energy T_e and its confinement conditions in magnetic mirrors are worse. The negative plasma potential appears when ions leave the trap and it regulates the rate of ion losses. The positively charged ions have been injected into ionization zone from the first stage of the source, or generated from residual gas as the result of electron impact ionization. The ionization degree increases with successive ionization during the ion lifetime. The mean ionization degree depends on the electron density and lifetime of the ions in the magnetic trap. The maximum ionization degree is limited by the electron energy because the electrons may only ionize ions with ionization potentials lower than the electron kinetic energy. The different ion charged states i have different lifetimes τ_i and leave the trap with various probabilities. It is the cause of strong difference between the ion charged state distributions in the output beam and in the source trap.

I. ION CONFINEMENT

Some theoretical models to calculate ion charged state distributions in ECRIS were created earlier /1-3/. The plasma losses from the open magnetic trap were studied in the connection with the problem of thermonuclear fusion. Despite the difference of the plasma parameters (hot ions and cold electrons in the thermonuclear fusion), the obtained results can be used to study ECR sources.

In a wide range of the plasma parameters the ion lifetimes are described quite well by a simple interpolation formula according to Pastukhov theory /4/.

$$\tau_i = \tau_{i1} + \tau_{i2} \qquad (1)$$

where τ_{i1} is the ion lifetime in the limit of frequent collisions. In that case the ion losses are defined by the gasdynamics flow value of particles running over the potential barrier of the trap /4/.

$$\tau_{i1} = R\ l\ \sqrt{AM/(2T_i)}\ \exp(iU/T_i), \qquad (2)$$

with: A-the atomic mass number; M-the nucleon rest mass; l-the effective source length; U-the electric plasma potential. U is determined by the condition of equality between the ion and electron currents leaving the trap:

$$n_e/\tau_e = \sum_{i=1}^{z} n_i/\tau_i \quad ,$$

where τ_e is the electron lifetime; n_i are the densities of different ion components.

The ion lifetime in the limit of rare collisions was found in /4/:

$$\tau_{i2} = \frac{\tau_{i0}\,G}{1+T_i/2iU}\,(iU/T_i)\ \exp(iU/T_i) \ , \qquad (3)$$

with $\quad G = \sqrt{\pi}\ (R+1)/(2R/\ln(2R+2)); \quad \tau_{i0} = 1/(\lambda_{ii}+\lambda_{i0}),$

where λ_{ii} and λ_{i0} are the collision frequencies among ions and between ions and neutral atoms /3/. As usual, τ_{i1} is much higher than τ_{i2} for the typical ECR plasma parameters.

The strong magnetic field in ECRIS suppresses the plasma instabilities and the basic mechanism of ion heating is via elastic Coulomb collisions with electrons. The collisions among the ions result in equal energy for all kinds of ions. Ion losses decrease the total energy of ion components. The balance condition of ion energies makes possible to define the ion temperature:

$$T_i = (dT_i/dt)\left(\sum_{i=1}^{z} n_i / \sum_{i=1}^{z}(n_i/\tau_i)\right) \qquad (4)$$

with

$$\frac{dT_i}{dt} = \frac{4\sqrt{2\pi}\ n_e\ Z^2\ r_e^2\ m^2\ \sqrt{m}\ c^4}{A\ M\ \sqrt{T_e}}\ L_{ei} \ , \qquad (5)$$

where Z is the charge of the nucleus, r_e and m are the classical radius and the rest mass of electron, $L_{ei} \cong 15 \div 20$ is, so called, Coulomb logarithm; c is the velocity of light.

The ion fluxes out of the end of the confinement region are /2/ $d\Phi_i/dt = n_i l/\tau_i$ and the corresponding current densities can be valued as

$$I = 1.6\times10^{-19}\ i\ n_i\ l/\tau_i\ [A\ cm^{-2}]. \qquad (6)$$

One can come to the following statement after the analysis of the confinement conditions and equations (1)÷(5):

1). The decreasing of ion temperature is a cause which rises ion lifetimes and, thus, it increases the ion mean charge in the plasma;

2). The negative plasma potential is necessary for the ion confinement. The ions with the higher charge states have the larger lifetimes τ_i and it is more difficult for them to lose the plasma according to the formulas (2) and (3). So, the output ion charge distribution has the less mean charge in comparison with the charge distribution inside the trap.

II. ION COOLING

It has been experimentally discovered in the recent 4-5 years that the addition of light ions increases the extraction of multiply charged heavy ions in ECR sources (for example /6,7/). It was shown /5/ that the ion energy redistribution and temperature stabilization times have a microsecond time scale and much less than the millisecond time scale of ion lifetimes in the plasma. The electrons heat the light ions slower than the heavy ions /5/. But light ions take away some part of energy from heavy ions in a short time and decrease the common temperature. At the same time light ions have low charges and lifetimes τ_i (2-3). They are lost from the source taking away the energy of heavy ions. The decreasing of heavy ion temperature causes the rising of the heavy ion lifetimes and mean charge.

The results of numerical calculations of ion charge state distribution for MINIMAFIOS type ECRIS /6/ are shown in Figs. 1 and 2. The calculations for Krypton and Nitrogen ion mixture with T =5000eV and n $=2\times10^{12}cm^{-3}$ have been carried out. The normalized ion densities $n_i^*=n_i/\sum_{i=1}^{z}n_i$ are presented in Fig.1. Fig.2 shows the normalized densities of extraction current from the source $I_i^*=I_i/\sum_{i=1}^{z}I_i$.

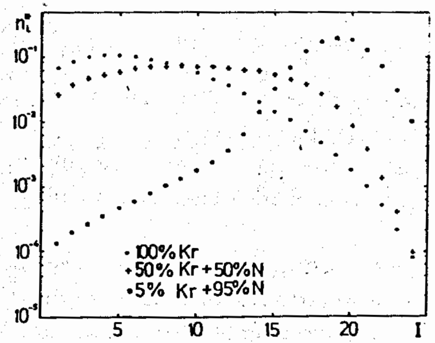

Fig.1. Relative normalized densities n_i^* for charge states of Kr ions in ECR plasma .

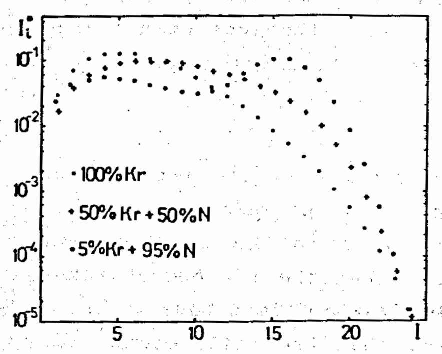

Fig.2. Relative normalized currents I_i^* from ECRIS for charge states of Kr ions.

In the Figs. small points correspond to pure Kr, the large points correspond to the calculation when the total densities of Kr ions are equal to the total densities of N ions and the large points for the densities of Kr ions are less than the densities of N ions in twenty times.

The calculations have shown that the addition of N ions into the plasma with separated parameters reduces the ion temperature from 16eV till 5eV and increases the mean charge state of Kr ions in the plasma from 7 till 17. At the same time the multycharged ion output is increasing, but not in such a high degree as the density of multiply charged ions in the trap. The decreasing of ion loss rates for ions with the higher charge states causes this effect.

III. RF PULSE MODE

To increase the multiply charged ion flux from ECRIS one can take off the potential which confined the ions in the trap. The ions inside the trap will "pour out" from the source and one can obtain the ion current pulse with the charged state distribution like the ions accumulated in the trap. Such a result may be obtained, for example, when the electron heating is switched off in so called "pulse regime" /8,9/. When the RF power is turned off the electrons become cool in the short time, the electron confinement conditions are getting worse, the electron density reduces and the ions of every charged states are ascaping from the trap. So, the pulse of ion current with the domination of high charged ions appears.

The numerical simulation have been carried out in the real time scale of time dependence of argon ion output from MINIMAFIOS type ECRIS after RF power being switched off. It was supposed in calculations that the main energy loss of electron component is connected with the electron losses from the trap. Hence, when the heating is over the electron energy changes as:

$$dT_e/dt=T_e\times(dn_e/dt)=-T_en_e/\tau_e \ .$$

It was supposed also that T_e=5000eV and $n_e=2\times10^{12}cm^{-3}$ at the initial moment. The time dependences of output current densities for A^{5+}, A^{9+}, A^{11+}, A^{13+} ions and total output current density are presented in Fig.3. One can see that when RF power is turned off the charge state distribution is similar to the distribution for pure Kr in Fig.1.

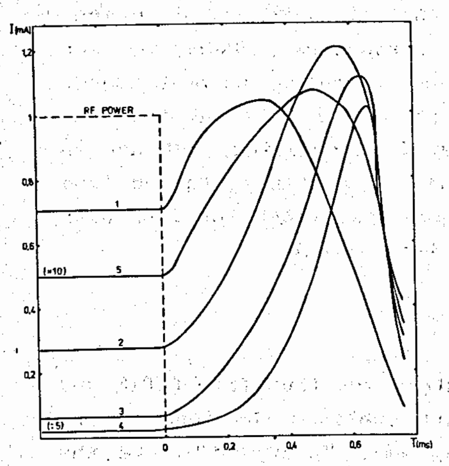

Fig.3. Time dependence of ion output currents I from ECRIS in RF pulsed operation mode for A^{5+} (1), A^{9+} (2), A^{11+} (3), A^{13+} (4) and total ion current (5).

The ion current rises and multiply charged ion output increases especially. So, the current density of A^{15+} ions increases more than in one hundred times and reaches the value of 7.5 μAcm^{-2}. The calculations have shown, that ion pulse duration depends on the initial density and temperature of electrons. If the RF power is turned on the necessary time for regeneration of the plasma parameters must be several times more than τ_i, τ_e and equals to tens ms.

IV. PROPOSALS FOR FUTURE EMPLOYMENT

The results obtained above make possible to suppose that there may be some other ways to produce the pulse beams of highly charged ions. It is necessary to break the confinement conditions for ions in the potential trap to produce the pulse of multiply charged ions. One of the possible ways is to remove one or two magnetic mirrors at the ends of the trap. One can use the pulse of current with 1-2ms duration with the opposite polarity in the main coils creating the magnetic mirrors, or in the additional small coil situated near the main one. After the time about 1ms the electron component will be lost and the multiply charged ion pulse will be obtained. The analogous effect was observed in experiments on succeeding the magnetic field structure /10/.

The similar result may be obtained if the beam of positive ions is injected in the working region of the source. The

addition ion pulse will collapse the potential well and the stored ions will appear outside the source.

V. CONCLUSIONS

The considered model for ion confinement in the open magnetic trap explains and makes possible to describe quantitatively the observed increasing of multiply charged ion extraction in light ion cooling and RF pulse heating regimes. We may expect the stronger effect in simultaneous application of these two methods. One must reduce the ion temperature and the plasma potential to optimize the multiply charged ion production in ECR ion sources.

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Received by Publishing Department
on August 15, 1991.