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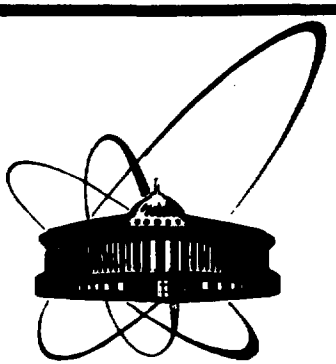

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FUNDAMENTAL PROCESSES DETERMINING THE HIGHLY CHARGED ION PRODUCTION IN ECR ION SOURCES

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INTRODUCTION

Recently 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 electron Larmor rotation 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 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 charge-exchange process of multy charged ions with residual gas neutral atoms restricts the ion charge states ,too, particularly, in one stage sources. Different ion charged states 'i' have different lifetimes τ_i and leave the trap with various probabilities. It has been shown /1/, that it is the cause of great 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 /2-4/. The plasma losses from the open magnetic trap were studied in 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.

The ECR plasma is in the strong longitudinal magnetic field with azimuthal multipole variations. The magnetic field configuration highly reduces the probability of the plasma instabilities and turbulences. Therefore, we can consider the ion distribution function as Maxwell distribution and use the classical theory to study ion confinement. In the strong axial magnetic field the main ion losses are take place at the ends of the source. So, in a wide range of the plasma parameters the ion lifetimes are described quite well with a simple interpolation formula according to Pastukhov theory for the open magnetic trap /5/.

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

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 /5/.

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

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

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

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

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

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

with: $G = \sqrt{\pi}\ (R+1)/(2R/\ln(2R+2))$; λ_{ii} and λ_{i0} are the collision frequencies among ions and between ions and neutral atoms /4/. As usual, τ_{ii} is much higher than τ_{i2} for the typical ECR plasma parameters.

Without the plasma instabilities and turbulences 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 /6/. Ion losses decrease the total energy of ion components. The balance condition of ion energies makes possible to define the ion temperature:

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

with

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

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 - the velocity of light.

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

1). The negative plasma potential is necessary for ion confinement;

2). The ions with the higher charge states have the larger lifetimes τ_i and it is more difficult for them to loose the plasma according to the formulae (2) and (3);

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

So, the output ion charge distribution has the less mean charge in comparison with the charge distribution inside the trap.

II. ION COOLING

The first idea of ion cooling in the multiply charged ion sources appeared about 10 years ago /7/. It has been experimentally discovered that the addition of light ions increases the extraction of multiply charged heavy ions in ECR sources (for example /9-10/). This effect was named as "gas mixing". The first numerical calculations of ion charge state distribution for gas mixing were carried out in /6/ and /10/.

It was shown /6/ 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. But light ions take away some part of energy from heavy ions in a short period of time and decrease the common temperature. At the same time light ions have low charges and lifetimes τ_i (see (2) and (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 their mean charge.

The results of numerical calculations of ion charge state distribution for MINIMAFIOS type ECRIS /8/ are shown in Figs. 1 and 2. The calculations have been carried out for Krypton and Nitrogen ion mixture with T_e = 5000eV and $n_e = 2 \times 10^{12} cm^{-3}$. Here we have used the software package to calculate the charge state distribution in ECRIS for static regime /4/ with the results obtained above for ion confinement times. The software package was adapted specially for gas mixing regime. The ion densities n_i are presented in Fig.1. Fig.2 shows the densities of extraction current from source I_i. In these Figs. small points correspond to pure Kr. The large points correspond to the calculation when the total electric charge of Kr ions are by three times more than the total electric charge of N ions. Crosses correspond to the case of equal electric charges for Kr and N ions. The triangles are for the electric charge of Kr ions by two times less than charge of N species.

The calculations have shown that the addition of N ions

into the plasma with separated parameters reduces the ion temperature from 16eV to 3eV and increases the mean charge state of Kr ions in the plasma from 7 to 28. At the same time the multycharged ion output is increasing, but not in such a high degree as the density of the multiply charged ions in the trap. By decreasing of ion loss rates for ions with the higher charge states is caused this effect. In our calculations we have supposed, that nitrogen is injected into the main stage of the source as nitrogen ions and there are no charge exchange processes between Kr ions and neutral nitrogen.

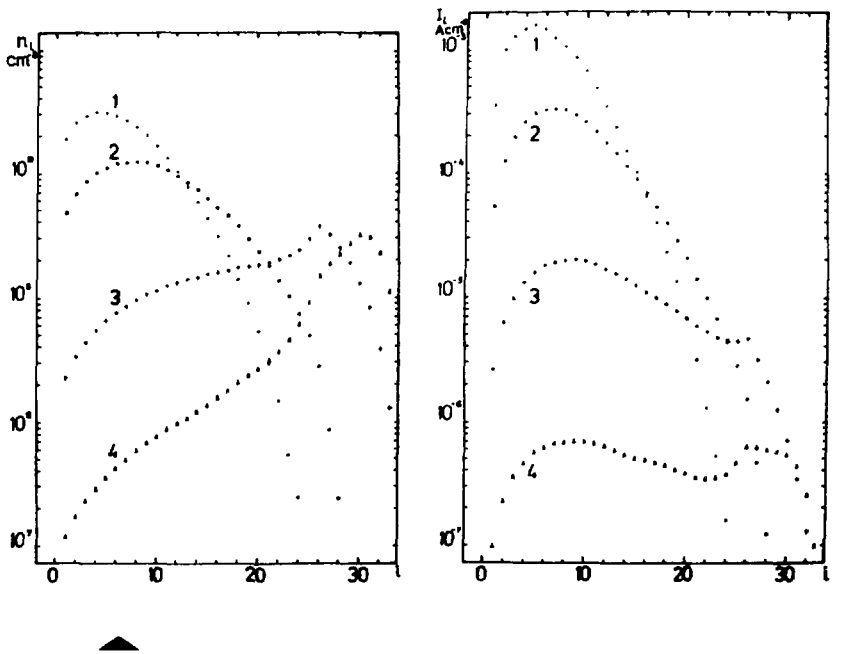

Fig.1. Ion densities n_i for krypton charge states i in ECR plasma for various mixture of krypton and nitrogen ions.

Fig.2. Ion currents I_i for krypton charge states i from ECRIS for various mixture of krypton and nitrogen ions.

In Fig.1 and Fig.2 the designations are: "1" - pure krypton; "2" - 75% ion charge is Kr and 25% ion charge is N; "3" - 50% - Kr and 50% - N; "4" - 33% - Kr and 67% - N;

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" /11,12/. 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 all the charged states are escaping from the trap. So, the pulse of ion current with the domination of high charged ions appears. The pulse duration is determined by lifetime of hot electrons in the source.The set of differential equations has been used to determine the time dependence of ion output in pulse regime /14/.

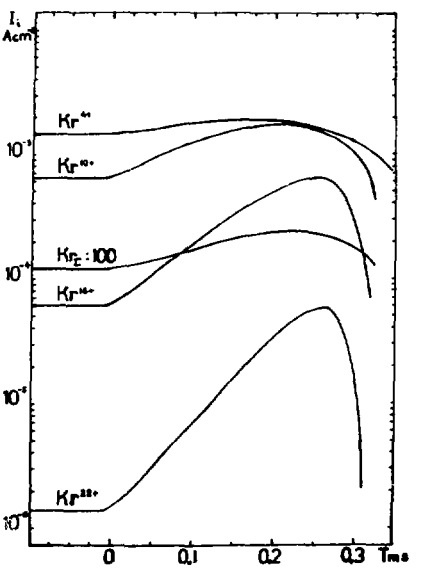

Fig.3. Time dependence of ion output currents I from ECRIS in RF pulsed operation mode for Kr^{4+} ,Kr^{10+} ,Kr^{16+} ,Kr^{22+} ions and total ion current.

The numerical simulation has been carried out in the real time scale of time dependence of krypton ion output from MINIMAFIOS type ECRIS after RF power being switched off. It has been 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:

$$n_e \, dT_e/dt = T_e \, (dn_e/dt) = -T_e \, n_e \, /\tau_e \, .$$

It was supposed also that T_e = 5000eV and $n_e = 2 \times 10^{12} cm^{-3}$ at the initial moment. The time dependence of output current densities for Kr^{4+}, Kr^{10+}, Kr^{16+}, Kr^{22+}, 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. The ion current rises and multiply charged ion output increases especially. So, for example, the current density of Kr^{25+} ions increases more than by one hundred times and reaches the value of 4 $\mu A cm^{-2}$. The calculations have shown that ion pulse duration depends on the initial density and temperature of electrons. If RF power is turned on the time necessary for regeneration of the plasma parameters must be several times more than τ_i and τ_e and equal to tens ms.

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 variants is to remove one or two magnetic mirrors at the ends of the trap. One can use the pulse of current with the opposite polarity in the main coils creating the magnetic mirrors, or in the additional small coil placed 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 the experiments on succeeding the magnetic field structure /13/.

The similar result may be obtained if the beam of positive ions is injected in to the working region of the source. The additional ion pulse will collapse the potential well and the

stored ions will appear outside the source. In this short time pulse regime the output ion pulse duration is determined by the potential well wrecking or if this time is short, by the time $\tau_{i\bullet}$ of ion escape from the source. This time can be valued with the formula (2) for U = 0 and $\tau_{i\bullet} = 10^{-5} - 10^{-4}$ s.

IV. THE PULSE REGIME WITH ION COOLING

We may expect the strongest effect in simultaneous application of pulse regime with gas mixing. The ion cooling decreases the ion temperature and the ion charge state distribution inside plasma shifts to the region of highly charged states. So, when the RF power is switched off, or potential well for ions is broken by any other kind of outside distribution, the accumulated ions are thrown out as a pulse of highly charged ions.

It is possible to make a simple calculation here.

The total electric charge of the stored ions in the source is equal to the electron charge:

$$Q = \bar{Z}\, N_i = N_e = \bar{Z}\, n_i\, V = n_e\, V\ ,$$

here $\bar{Z}$ is the average ion charge state, N_e and N_i - the number of electrons and ions and V - the plasma volume.

In the strong longitudinal magnetic field the dominant ion losses take place at the butt-ends of the source. The current densities for all ion species can be valued as

$$j_i = V\, e\, n_i/(2S\, \tau_i)$$

where S is the square of the butt-end of the plasma volume, and e is the electron charge. And for the total current density:

$$j_{tot} = e\, \bar{Z}\, n_i\, V/(2s\, \tau_i) = (n_e l/2\tau_e)\ ,$$

where l is the length of plasma.

In the pulse regime the total current is

$$j_{tot} = e\, n_e l/2\tau_{pulse}$$

where τ_{pulse} is about τ_e for RF pulse mode, and τ_{pulse} is about $\tau_{i\bullet}$ for the short pulse regime.

The real charge state distribution usually contains some charge states about everage charge state $\bar{Z}$. For heavy ions the width of distribution Z_n is about 10 or 20. So, we can obtain approximately:

$$j_i = e\, n_e\, l/40\tau_e$$

and $j_i = e\, n_e\, l/40\tau_{ie}$ for short pulse regime.

Let us consider some examples for MINIMAFIOS type ECRIS with: RF = 15 GHz, $n_e = 2\times10^{12}cm^{-3}$, $V = 10^3cm^3$, $S = 40cm^2$ and $l = 25cm$. According to our calculation $\tau_e = 0.3 \div 1.0\times10^{-3}s$ and $\tau_i = 10^{-4} \div 10^{-2}s$ for different charge states. We can obtain from the above formulae:

$Q = 2\times10^{15}$, $j_{tot} = 5\text{-}10\ mA\ cm^{-2}$, and $j_i = 0.3\text{-}1.0\ mA\ cm^{-2}$ for maximum components of charge distribution. These values are in agreement with the above calculations and with the best results of MINIMAFIOS type ECR ion sources.

When we use ion cooling the charge everage state reduces. In continuous operation mode the highly charged ions are at the bottom of the potential well and the highly charged ion currents increase, but not in such degree as ion densities (Fig. 1 and 2). But when we use pulse regime with ion cooling all the accumulated ions will be thrown out from the well and it will be possible to obtain the pulse with duration $\tau_{pulse} = 0.3 \div 0.5$ ms of Kr^{30+}, or, probably, Pb^{40+} with current $j_i = 0.1 \div 0.3\ mA\ cm^{-2}$. Here we take into account that one half or two-thirds of the total ion charge correspond to the coolant light ions and suppose that the charge-exchange processes with neutrals are negligible. In the short operation mode $\tau_{pulse} = \tau_{ie} \cong 0.1$ms and we may expect $j_i \geq 1$mA.

These values are by few times more than up-to-date results at ECRIS. For future ECRIS with PF = 20-30GHz the electron density in plasma will increase probably and ion yields will increase, too.

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. One should reduce the ion temperature and the plasma potential to optimize the multiply charged ion production in ECR ion sources. But the most promissing way to increase the highly charge ion yields in ECRIS is the pulse regime with ion cooling, particularly, for pulse type heavy ion accelerator and storage rings.

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Ширков Г.Д. E9-92-33

Основные процессы, определяющие возможность получения высокозарядных ионов в ECR источниках ионов

Проанализированы условия удержания и потерь ионов в открытых магнитных ловушках. В ECRIS ионы удерживаются в отрицательном плазменном потенциале. Время жизни ионов увеличивается, а вероятность выхода из плазмы уменьшается с ростом ионного заряда. Показано, что средний заряд ионов внутри ловушки выше, чем при экстракции ионов; определены общие методы повышения выхода многозарядных ионов из ECRIS. Обосновано использование ионного охлаждения для увеличения зарядности ионов в плазме. Объяснен импульсный выход многозарядных ионов в импульсном режиме ECRIS. Проведено численное моделирование ионного охлаждения и импульсного режима для ECRIS типа MINIMAFIOS. Предложено одновременное использование ионного охлаждения и импульсного режима для инжекций в ускорители и накопители тяжелых ионов импульсных пучков высокозарядных ионов.

Работа выполнена в Лаборатории сверхвысоких энергий ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1992

Shirkov G.D. E9-92-33

Fundamental Processes Determining the Highly Charged Ion Production in ECR Ion Sources

The ion confinement and loss conditions in the open magnetic traps have been analyzed in this article. In ECRIS the ions are confined in the negative potential well. The ions with higher charge states have the longer lifetimes and the less probability of output in the negative potential well. The mean ion charged state in the trap is higher than in the output ion beam. The general methods to increase the multiply charged ion extraction from the ECRIS are determined. The usage of ion cooling mode to increase ion charge states in plasma is substantiated. The large output pulse of multiply charged ions in the RF pulse mode is explained. The numerical simulation of the ion cooling and RF pulse processes for MINIMAFIOS type ECRIS has been carried out. The simultaneous application of ion cooling and pulse regime is proposed for pulse injection of highly charged ions in heavy ion accelerators and storage rings.

The investigation has been performed at the Particle Physics Laboratory, JINR.

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