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ION MIXING AND NUMERICAL SIMULATION OF DIFFERENT IONS PRODUCED IN THE ECR ION SOURCE

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1. Introduction

Since 1994 lead ions have been accelerated in the PS and SPS of the CERN accelerator complex . An Electron Cyclotron Resonance (ECR) source for lead ions was constructed in GANIL (France) and installed three years ago in the PS Division. The Large Hadron Collider project was adopted at the end of 1994 at CERN. The physics program of LHC will include investigations with beams of protons and lead ions. The acceleration of some other heavy and intermediate ions in the LHC is under consideration.

A program of theoretical investigations on the physics of ECR ion sources was started at the Joint Institute for Nuclear Research, Dubna in 1993 and continued then at CERN, Geneva. The recent results of this program have included[1,2)] the development of the physical model of ionization and accumulation of ions in the ECR source, the creation of a computer code library for the numerical simulation of heavy ion production in the static and dynamic regimes of the ECR ion source, the computer simulation of the highly charged ion production in the ECR source and proposals to improve the highly charged ion output from the ECR ion source.

Like some ECR ion sources, the source at CERN operates in the afterglow mode (pulse regime) using a gas (ion) mixture with oxygen. The gas mixing is an effective method of source operation and highly charged ion production. A study of the gas mixing effect and numerical simulation of production of different ions in the ECR source is the subject of this paper.

2. The condition of ECR plasma neutrality

The ECR plasma has a density in the range of 10^{12} cm^{-3}. The condition of electromagnetic wave propagation limits the electron density in the plasma

$$n_e \leq \frac{\omega_{ce}^2}{4\pi r_e c^2} \approx 1.24 \cdot 10^{-8} f^2 \qquad (1)$$

with ω_{ce} being the rotation frequency of the electron in the magnetic field; r_e - the classical radius of electron; c - the velocity of light; f corresponds to the plasma heating frequency in Hertz. The limit (1) is more than 10^{12} cm^{-3} for the radio frequency of heating in the range of 10 GHz. This value can be used for the rough estimation of the upper limit of the plasma density in the ECR source.

Positive ions neutralize the space charge of electrons to prevent the appearance of high electrical and magnetic fields in the plasma. One can consider the plasma as neutral or quasineutral in every point of its volume. This follows from the condition:

$$\sum_{i=1}^{Z} i\, n_i - n_e = 0 \qquad (2)$$

here n_i are densities of ions with different charged states i, Z is the maximum charge of ions in the plasma. If there is a mixture of ions of different elements in the plasma, then it is necessary to sum up all ion species. And in the case of several electron components with different parameters of electron densities, we should do the same.

The time conservation of condition (2) in the static case is the cause of equal flows of ions and electrons from the plasma:

$$\sum_{i=1}^{Z} \frac{d(i\, n_i)}{dt} - \frac{dn_e}{dt} = 0\,. \qquad (3)$$

The particle losses are determined by lifetimes or confinement time of particles in the plasma. The complete set of balance equations of ion and electron densities in the ECR source[3)] gives us the following well known expression

$$\sum_{i=1}^{Z} \frac{i\, n_i}{\tau_i} - \frac{n_e}{\tau_e} = 0 \qquad (4)$$

with τ_i being confinement times of ions and τ_e electron confinement time, correspondingly. These values were determined earlier in Ref. 1,2,3.

3. Ion Mixing

It has been discovered experimentally that the addition of light ions increases the extraction of multiply-charged heavy ions in the ECR sources (for example, Refs. 4 - 7). The role of light ions in the plasma is not completely clear at the moment and, probably, number of roles. Let us consider the most important of them. There are several effects the light ions result in the ECR plasma.

Ion cooling. The Maxwellian velocity and Boltsman energy distributions are established in the plasma due to the intensive elastic Coulomb collisions among the ions. It has been shown[3,8,9)] that the ion energy redistribution and temperature stabilization times have a microsecond time scale, much less than the millisecond time scale of ion lifetimes in the ECR plasma.

The ions have much less average energy or temperature T_i than the electron temperature T_e in the source and their confinement conditions in magnetic mirrors are worse. Negative plasma potential U appears as a result of different rate of the electron and ion losses when ions leave the trap and this regulates the rate of ion losses. Ions with an energy more than the potential barrier will be lost from the plasma volume. Different ion charge states of i have different values of the potential barrier ieU. So, various ions have equal temperature but different potential barriers in the plasma and different rates of losses from the source. The rate of ion losses can be described with the Pastukhov theory[10)].

This situation is shown schematically in Fig.1, where potential barriers are presented for different charged states with equal temperature.

The electrons heat all ions but light ions are heated slower than the heavy ions in the mixture of different ion species. And the light ions are heated due to the elastic collisions with highly charged heavy ions and their mean energy comes closer to the energy of heavy ions. The low charged ions have a low potential barrier and short lifetime in the plasma and, therefore, they are lost from the source taking away the energy of the heavy ions. The decrease of the heavy ion temperature causes the rise of the heavy ion lifetimes and their mean charge grows in the source correspondingly. These are the principles of the so-called "ion cooling" effect [9)].

Electron production in the plasma. The electron density is one of the most important parameters in the plasma that determines the sources capability for ion production. It depends strongly on the rate of electron production in the plasma.

The electrons are generated as the result of electron impact ionization of neutral gas and ions in the source chamber. A set of coupled balance equations describes the rate of electron production as well as ion production in the source[3)]. The balance equation for electron component in the plasma is:

$$\frac{dn_e}{dt} = \sum_i n_e\, v_e\, \sigma_i^i(v_e)\, n_{j\text{-}1} - \frac{n_e}{\tau_e}\,, \qquad (5)$$

where $\sigma_i^i(v_e)$ are the cross-sections of electron impact ionization as a function of electron velocity. It is necessary to use the average value $< \sigma_i\, v_e >$ here. One can obtain it as a result of the integration with the distribution function of electron energy. The rate of electron production depends on ionization cross section and density of ions and neutrals in the plasma according to equation (5).

Different theoretical models are used to calculate ionization cross-section for highly charged and low charged ions as well as neutral atoms or molecules. Lotz's formula is one of the most useful to calculate cross-sections for low energies[11)].

$$\sigma_i^k = \frac{4.5\cdot 10^{-14}}{E_e} \sum_{j=1}^{m} \frac{n_j}{I_j} \ln \frac{E_e}{I_j} \qquad (6)$$

with m being the number of atomic sub-shells occupied in the ion, n_j- the number of electrons in the sub-shell considered and I_j- the ionizing energy of actual sub-shell in eV.

The calculated cross sections of electron impact ionization of Pb, Xe, Kr, Ar and O using the Lotz's formula are presented in Fig.2. The calculations were made for the Maxwellian distribution of electron energy with temperature T_e = 5000 eV. One can see, that the dependence of impact ionization cross-section on the ionic charge state is very significant.

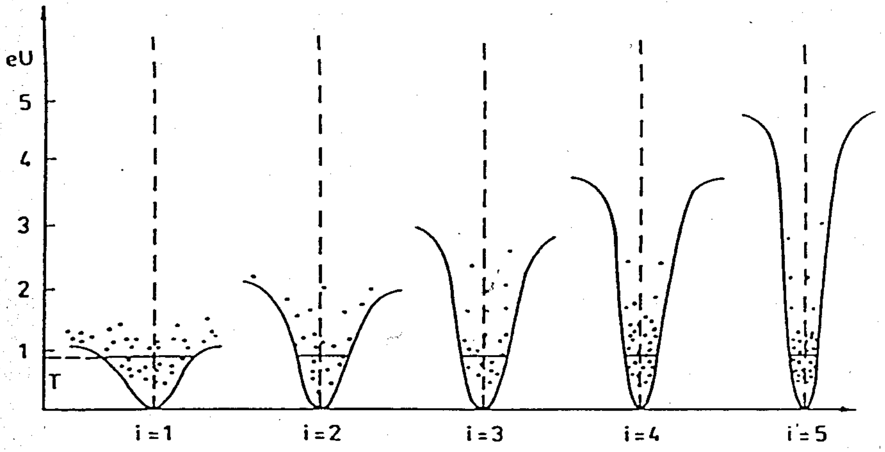


Figure 1. Relative position of ions with charge states i =1,2,3,4,5 at equal temperature T_i in a potential well of depth U.

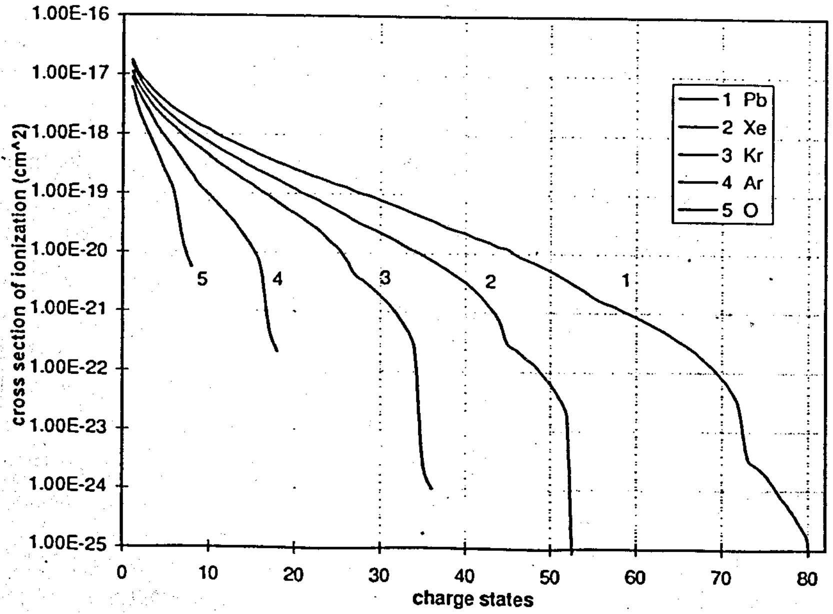


Figure 2. Calculated cross sections of electron impact ionization of Pb, Xe, Kr, Ar and O

The typical energy of electrons in the ECR plasma, in the range of several keV, is enough to produce heavy ions of 20+, 30+, 40+ and even higher charge states[2)]. The average charge state $<i>$ of ions increases after the plasma ignition due to the step-by-step ionization. Here

$$<i> = \sum_{i=1}^{Z} i\, n_i \Big/ \sum_{i=1}^{Z} n_i \,.$$

The total density of ions n ($n = \sum_{i=1}^{Z} n_i$) in the plasma decreases simultaneously to satisfy the condition of plasma neutrality (2). Therefore the rate of electron production dramatically decreases with the $<i>$ increasing due to the reduction of ionization cross-section and total ion density. The electron density in plasma decreases after reaching the maximum before setting to an equilibrium in the static regime of source operation. The equilibrium electron density is much less than the limit of wave propagation in the plasma (1). According to numerical simulations, this effect is very strong especially for the plasma of pure heavy ions. That is why different sources of additional electrons are used to increase the plasma density and improve the highly charged ion production. The most effective are biased electrodes [12)] and, as we shall see below, ion mixing with light ions.

Light ions increase the electron production in the plasma. In the mixture of heavy highly charged ions and light low charged species, the heavy ions are cooled and light ions are heated due to the elastic Coulomb collisions [9)]. Thus, the ion cooling works as a heating effect for light ions. Therefore light ions have very low values of lifetime and keep a low average charge state $<i_l>$ in the equilibrium plasma. According to our numerical simulations, the $<i_l>$ is in the range of 1+ to 3+ depending on the relation of atomic masses of light and heavy ions. Low charged ions also have a high ionization rate (Fig.2) and therefore produce a lot of secondary electrons to feed the plasma.

Fig. 3 and Fig. 4 show the calculated total number of light (series 1) and heavy (series 2) ions in the source chamber. These figures present the relative factor of plasma neutralization by heavy ions F, with

$$F = \sum_{i=1}^{Z} i\, n_i \Big/ n_e \,.$$

Only densities of heavy ions are summed up here. All calculations were done for ECR4 ion source parameters. This type of source is used for Lead ion production at CERN. It has the following parameters: Length of the plasma volume l = 20 cm; diameter of the plasma volume d = 6.5 cm; magnetic field mirror ratio R = 2.5. The values of the electron temperature T_e = 5000 eV and electron density $n_e = 5\cdot10^{11}$ cm^{-3}, were used in the calculations to satisfy the experimental data[2)]. The density of heavy neutrals outside the plasma volume was $2\cdot10^{8}$ cm^{-3} and light neutrals $4\cdot10^{10}$ cm^{-3} in those calculations.

One can see in Figures 3 and 4 that light ions with low charge states are the main component of the ions in the plasma. The ionization of light ions and neutrals is the main source of electrons in

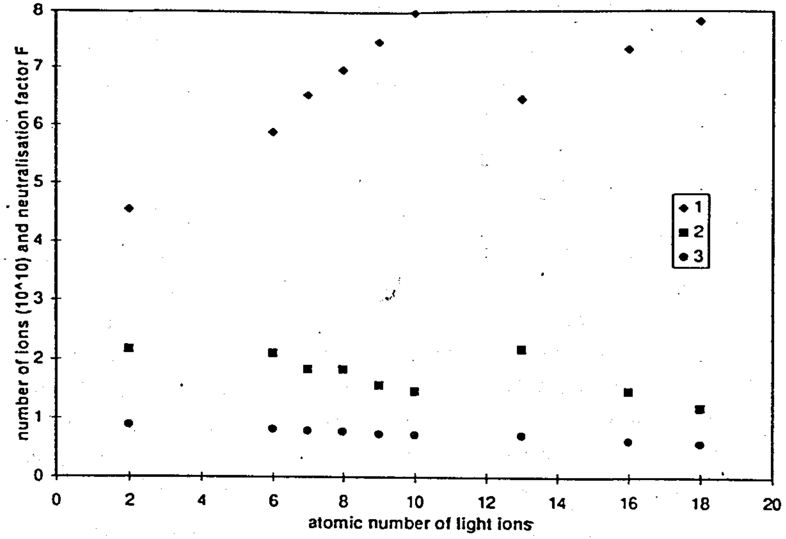


Figure 3. Calculated total number of light (series 1) and lead (series 2) ions in the source chamber. The relative factor of plasma neutralization by lead ions F (series 3).

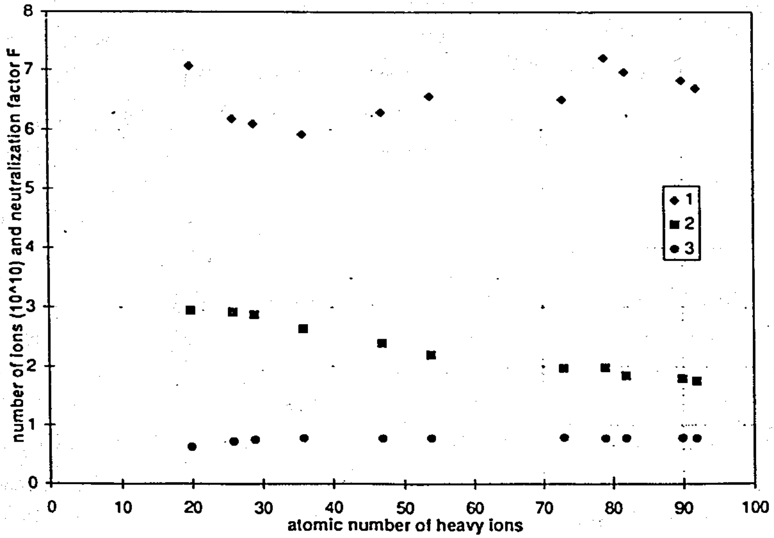


Figure 4. Calculated total number of oxygen (series 1) and heavy (series 2) ions in the source chamber. The relative factor of plasma neutralization by heavy ions F (series 3).

the plasma according to equations (5) and (6) and Fig.1. Light ions have low values of life time (in the range of 0.1 to 0.3 ms) to satisfy conditions (3) and (4). On the other hand, the space charge of heavy ions dominates and regulates the neutrality of the plasma according to condition (2) as it is possible to see with series 3 in Figures 3 and 4. It is necessary to keep the density of light ions much higher than the density of heavy neutrals for good ion cooling and electron refilling in the plasma.

Concentration of heavy ions in the center of ECR plasma. The recent X-ray measurements[13,14] have shown that electrons in the ECR source have maximum energies and density in the central region of the plasma. According to the above consideration (Fig.1) and numerical simulation[2, 3, 8, 9, 15], the energies of cooled highly charged ions in the ion mixture are much less than the potential barrier in the plasma. Therefore the amplitudes of heavy ion oscillations in the potential well are much less than the plasma dimensions. This means that mixing with light ions results in increasing ionization rate of highly-charged ions due to their concentration at the bottom of the potential well in the middle of the ECR source where the density and energy of electrons are higher. This could be an additional factor able to explain the improvement of highly charged ion production in the mixture of heavy and light ions.

4. Numerical simulation of ion production in different mixtures

The calculation of charge state distribution (CSD) of Lead ions in the so-called afterglow mode of source operation, is shown in Fig. 5 in comparison with one of the typical experimental CSD of the ECR source at CERN. These calculations and the above parameters of the source were used as a "base variant" for numerical simulations in Ref.2. This base variant will be used below to present the calculated data.

According to West[16] the ion current density for different charge states leaking through the end of the source can be evaluated as

$$j_i = e\, i\, n_i\, V/(2\, S\, \tau_i)\ (A\, cm^{-2})\,. \qquad (7)$$

Here S is the surface area of the end and V the volume of the plasma. This formula gives the extracted current for a source extraction hole of 1 cm diameter as

$$I_i = e\, i\, n_i\, l/(2\tau_i)\ (A) \qquad (8)$$

where l is the length of plasma region. And the output current in the afterglow can be estimated: accordingly

$$I_i = e\, i\, n_i\, l/(2\tau_p)\ (A) \qquad (9)$$

where τ_p is the duration of afterglow pulse.

The numerical simulations of afterglow regime in Ref. 2 are in good agreement with the experimental data (Fig.5), but the shape of the calculated pulse of ion current does not coincide with

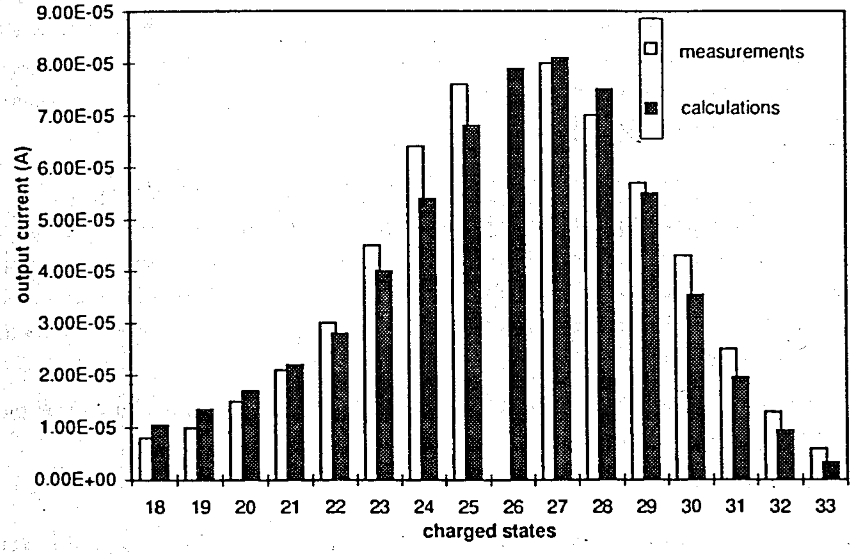


Figure 5. Calculated charge state distribution of lead ion in the afterglow mode of ECR ion source in comparison with experimental data

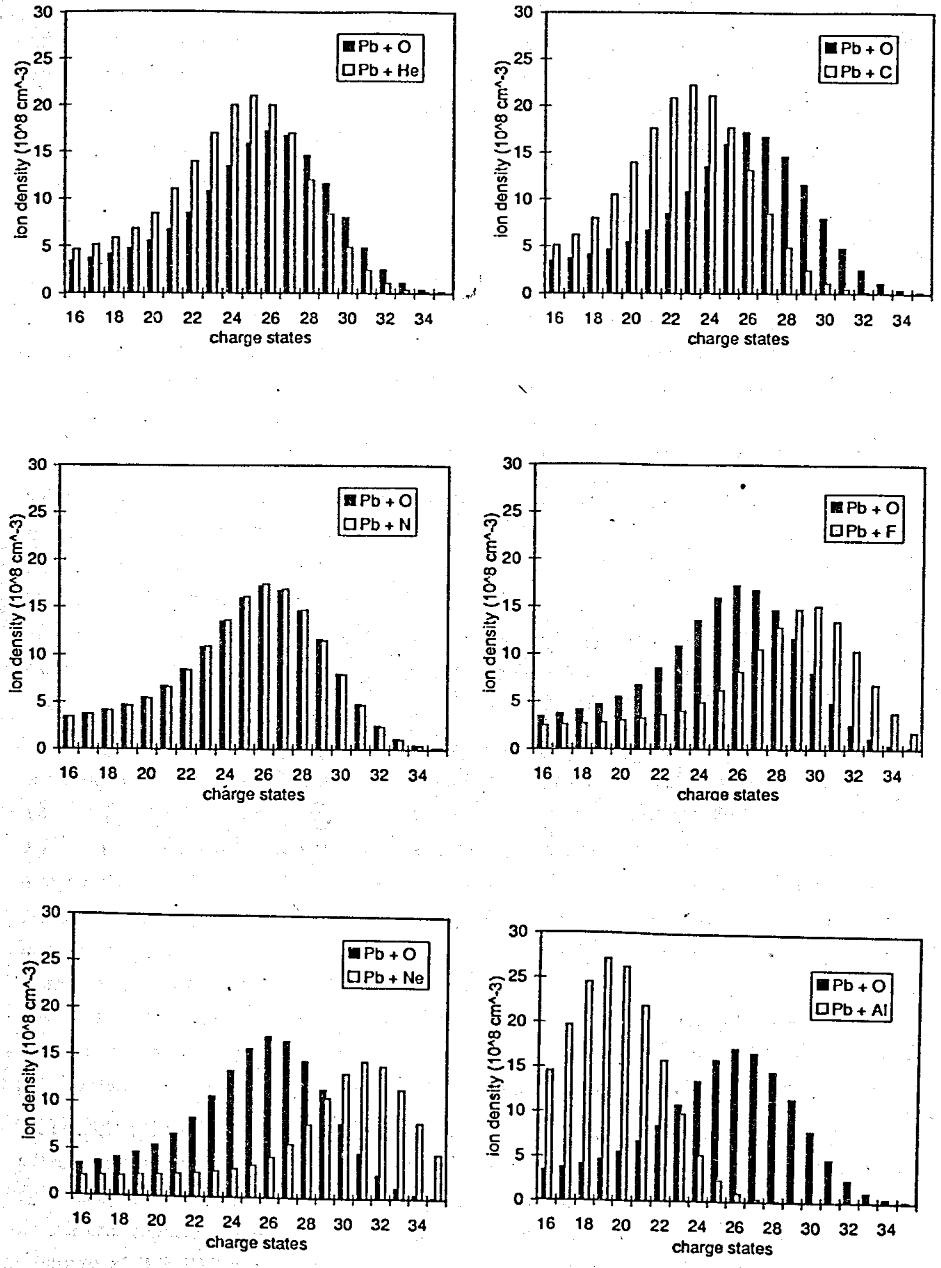
the best experimental pulses of stable afterglow[17]. These experimental pulses have a long tail with the decay time of 2 to 3 ms. The calculated pulses of heavy ion afterglow have a duration of less than 1 ms and an amplitude that is by 2 or 3 times greater.

The duration and shape of the ion pulse in the afterglow are determined by the plasma destruction time as a result of electron losses without RF heating. The electron confinement time in the open magnetic trap and losses from the source depend strongly on the electron energy. The model for numerical simulation uses the Maxwellian distribution for electrons with the fixed temperature of several keV. The real energy distribution in the ECR plasma is rather complicated and not thoroughly determined at the moment. X-ray spectra measurements have shown the presence of electrons with energies of up to 100 keV and over. These high energy electrons have a long life time in the open magnetic trap and, probably, determine the long tail of the output ion current in afterglow. It will be necessary to use the electron energy distribution with different electron components as the next step to improve the model.

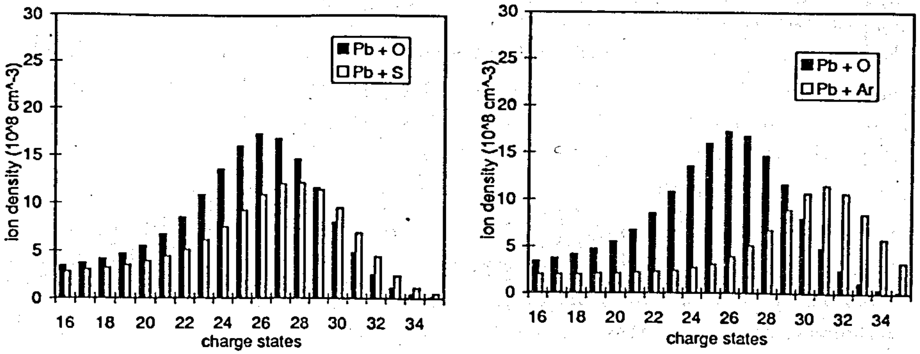
When the RF power is switched off and the electrons begin, losing then the electron density reduces, the negative potential which traps the ions, disappears and ions escape from the trap as the so-called afterglow. The CSD of the output ion current in afterglow reflects the CSD of accumulated ions in the equilibrium plasma before the RF power is switched off. The numerical simulation of ionization and accumulation of ions in this plasma gives us information on ion densities or total number of ions of all the charge states in the source and enables us to estimate how many ions the source will produce during the afterglow.

Numerical simulation of lead ion production in the mixture with different light ions. Different light ions have different abilities to cool heavy ions and produce secondary electrons to feed the plasma. Different light neutrals have different ionization potentials and, respectively, different rates of charge exchange with highly charged ions. According to the previous paper[2], the charge exchange process is very dangerous for heavy ions due to the competition with electron impact ionization and limits the production of highly charged ions. A series of numerical simulations of the lead ion accumulation in the CERN-like ECR source, was carried out to study the effect of different light ions in the mixtures. Figures 6 to 13 present the CSD of lead ions in ECR source in the mixture of different light ions from He up to Ar. All CSD are given in comparison with the "base variant" of Pb - O mixture[2]. It is necessary to stress that we do not discuss here the technical problems to realize these ion mixtures experimentally, for example Pb + F or Pb + Al mixtures.

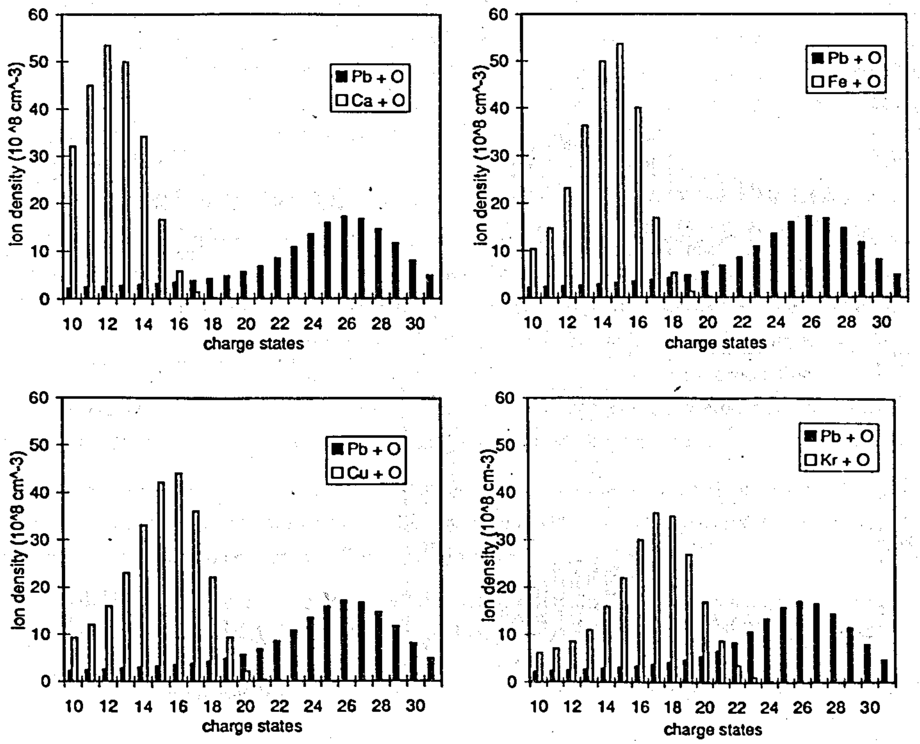
Figures 6 to 13 show the dependence of lead CSD on the type of the second light ions in the source. The location of the CSD maximum depends on the rate of charge exchange processes in the plasma according to Ref.2. Neon and argon mixtures give the highest charge states due to the high ionization potential of the neutral atom. To improve the production of highly charged lead ions, a short experimental test of "neon cooling" was performed in August 1995 at CERN ECR source[18]. But this result is to be confirmed.



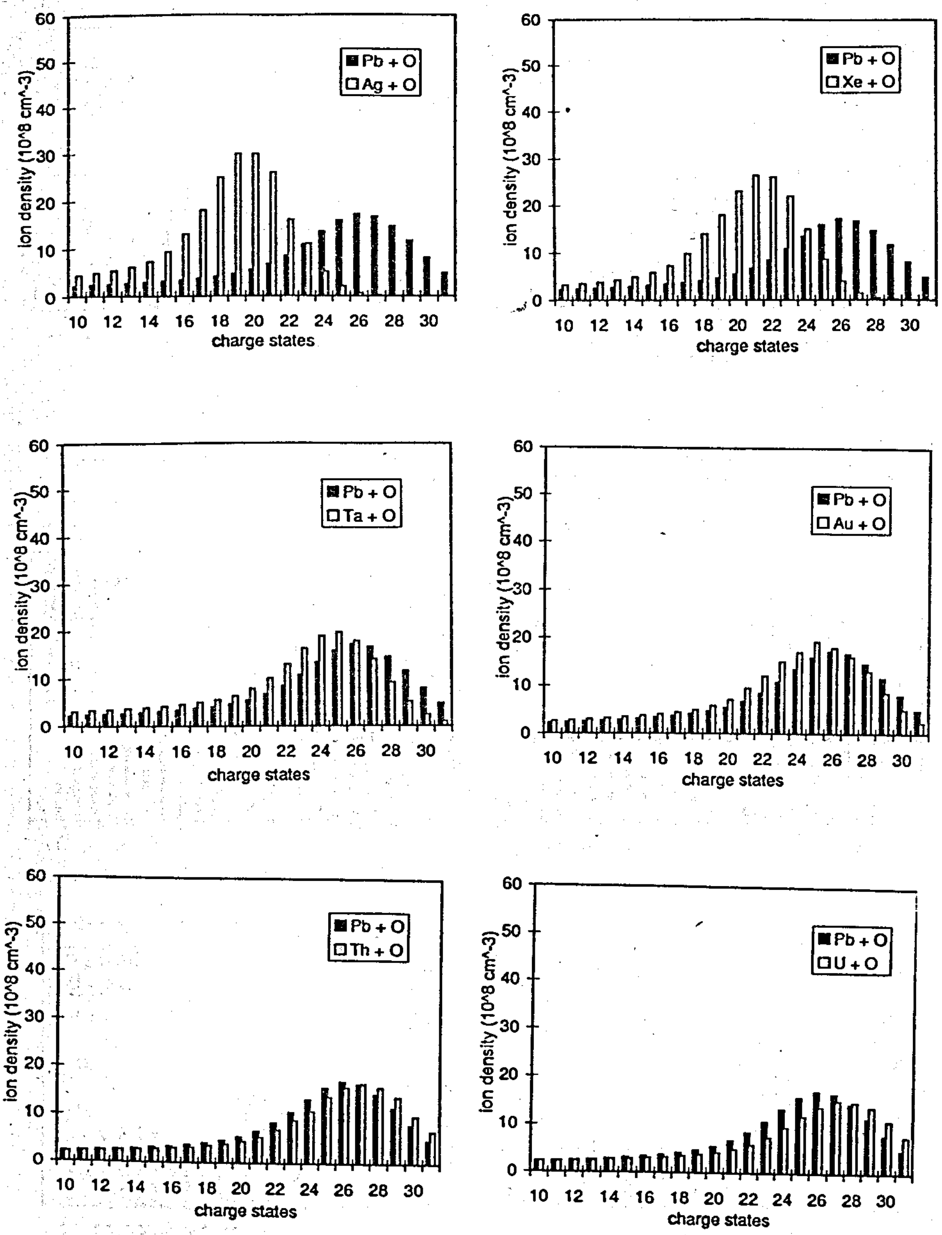
Figures 6 - 11. Calculated CSD of lead ions in the ECR source in the mixture with He, C, N, F, Ne and Al in comparison with "base variant" of Pb - O mixture.



Figures 12, 13. Calculated CSD of lead ions in the ECR source in the mixture with S and Ar in comparison with "base variant" of Pb - O mixture.



Figures 14 - 17. Calculated CSD of Ca, Fe, Cu and Kr ions in the ECR source in the mixture with oxygen in comparison with "base variant" of Pb - O mixture.



Figures 18 - 23. Calculated CSD of Ag, Xe, Ta, Au, Th and U ions in the ECR source in the mixture with oxygen in comparison with "base variant" of Pb - O mixture.

On the other hand, the amplitude of CSD, or the number of ions in the maximum of distribution, decreases with the increase of the average charge state $<i>$. Two factors are able to explain this phenomenon: the higher value of $<i>$ requires a lower value of total ion number n according to the condition of neutrality of plasma (2) and the CSD with higher values of $<i>$ has more charge states with densities close to the maximum one and, therefore, has a lower density in every charge state.

Numerical simulation of heavy and intermediate ion production in the mixture with oxygen ions. The accelerator complex at CERN produces lead ion beams for experimental application in high energy physics. Oxygen and sulfur were used for this purpose some years ago. The new LHC project at CERN foresees using ion beams of different heavy and intermediate elements. Series of numerical simulations of different ion production in the ECR4 type source were carried out to predict the possibilities of ion production. Figures 14 to 23 present the CSD of different ions from Ca up to U in the ECR source in the mixture with oxygen. All CSD are given in comparison with our "base variant" of Pb - O mixture.

Figures 14 to 23 show the strong dependence of CSD on the type of ions in the source. The heavier ions have higher charge states and lower number of ions in the charge state with the maximum density. For example, the ECR source is able to produce by 3 or 4 times more ions of calcium or iron with charge states of 12-15 than uranium, thorium or lead ions with 26-28. The explanation above could be used here to explain this phenomenon.

5. Conclusions

This work continues theoretical investigations and numerical simulations in the physics of ECR ion sources according to the CERN program of heavy ion acceleration. The ion mixing effect in ECR sources is considered in this paper using a new approach. It is shown that the addition of light ions to the ECR plasma improves highly charged ion production not only due to the well known ion cooling effect, but also because of the increase of electron production rate and consequently the density of plasma. There is also an effect of concentrating highly charged ions in the central region of the source having a high energy and density of electrons.

The numerical simulations of the production of different heavy and intermediate ions in the ECR source have shown the difference in CSD and source efficiency for different ions and will be, probably, useful in the ionic part of LHC project at CERN.

This report was prepared during the visit to CERN and the author would like to express a recognition to his colleagues from PS/HI group and group leader Dr. H.Haseroth.

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