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Numerical Simulation and Interpretation of the Results of Lead Ion Production in the ECR Ion Source at CERN

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Abstract

A new library of the computer codes for the mathematical simulation of heavy ion production in the ECR ion source is presented. These codes are based on the equations of model of ion confinement and losses in ECR ion sources.

The ECR4 developed at GANIL is now used for lead ion production for the accelerator complex at CERN. An ion pulse with a current of up to 100 eμA of Pb^{27+} has been regularly injected into the linac since May 1994.

The results of numerical simulation with these computer codes and interpretation of experimental data of lead ion production in the ECR source at CERN are presented.

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1. The accelerator complex of CERN accelerates heavy ions since the Autumn, 1994. A special Electron Cyclotron Resonance (ECR4) source at CERN was constructed at GANIL and it is used now for the production of lead ion beam. After thorough technical adjustment and optimization it produces a 1 ms pulse of Pb^{27+} with an output ion current of about 100 eμA. Like most ECR ion sources this source operates in the afterglow mode (pulse regime) with the gas mixing using oxygen as a support gas.

2. The ECR ion source is one of the most widely used ion sources with step-by-step ionization by electron impact for accelerator and atomic physics applications. Ionization processes of neutral atoms and charge changing transitions in the plasma and in ion sources with electron impact ionization, can be described with a set of nonlinear differential balance equations. In the simplest case, considering only single ionization and charge exchange processes, the balance equation for actual charge state *i* is

$$\frac{dn_i}{dt} = n_e v_e \sigma^{i}_{i} n_{i-1} - n_0 v_0 \sigma^{ex}_{i} n_i - n_e v_e \sigma^{i}_{i+1} n_i - n_0 v_0 \sigma^{ex}_{i+1} n_{i-1} - \frac{n_i}{\tau_i}$$

were σ^{i}_{i} are the cross-sections of electron impact ionization; σ^{ex}_{i} are the cross-sections of charge exchange process between neutral atoms and ions in the plasma; v_0 and v_e are velocities of neutrals and electrons in the plasma; n_e, n_0 and n_i are densities of electrons, neutrals and ions with charge states of *i* correspondingly; τ_i are the ion confinement times.

The complete set of equations for all possible charge states with taking into account single and double transition processes is given, for example, in Ref. 1 and 2. Often the ECR source is used as a continuous working device and all the processes in the source are stationary. In this case the left sides of the equations can be chosen equal to zero ($dn_i /dt = 0$). Then this set of balance equations transforms into a set of nonlinear algebraic equations.

3. The first calculations of the ion charge state distribution in ECRIS were made by Jongen[3] and then by Bliman & Chan-Tung[4]. These authors studied the static regime of the ECR source and used sets of algebraic equations with many assumptions and simplifications. Later West[5] considered two electron components and applied the theory of Pastukhov[6] to the determination of the plasma potential. He carried out a large number of calculations for the static case.

The next step was made 4 or 5 years ago[7-9]. The full set of algebraic equations was solved successfully for the first time and the Pastukhov theory was used in these calculations. Then, according to the development of “The Classical Model of Ion Confinement and Losses in ECR Ion Sources”[1,2] the main principles of the ion production and accumulation in the ECR sources were described. This model was the first one which was able to explain, physically, the ion cooling process in the gas mixing regime and the “afterglow effect” in the pulsed operation regime of ECRIS. A special computer code for the ion production from the mixture of two different elements for the static case was prepared. The mathematical simulation of ion cooling method with this code showed a good agreement with the experimental data[1,2]. There was also a numerical simulation for a sulphur - oxygen mixture[10].

4. A numerical solution of algebraic nonlinear equations has difficulties. On the right hand sides of the equations, the terms with ion life-time τ_i make a considerable contribution. The ion life-time τ_i is determined by the ion densities n_i. For this reason the set of equations is very nonlinear and therefore difficult to solve.

To facilitate the solution of the problem of determining the charge state distribution in ECR ion source, it was proposed, not to solve the algebraic equation, but to find the stationary solutions of the complete differential equations at given initial conditions[1,11,12]. Nonlinear differential equations can generally be solved more effectively with numerical methods and without high computing expense. The use of differential equations enables one not only to look for stationary solutions, but, what is more important, also to explore the dynamic or fast changing processes. The first variant of the computer codes based on the differential equations was used for mathematical simulation of afterglow regime in an ECR source [1,2].

5. The ECR ion source at CERN is used for the production of highly charged lead ions. It operates with oxygen as a carrier gas. The oxygen acts simultaneously as a coolant gas for the heavy ions. The microwave is pulsed with a pulse length of 50 ms and a duty cycle of 50%. The afterglow appears when the RF power is turned off.

Figs. 1 and 2 show some examples of experimental results in the ECR source at CERN. The Fig. 1 presents the charge state distribution of Lead ions during the afterglow. The peak for coincides with a strong O^{2+} line and is out of range in the figure. The time dependence of Pb^{27+} ion output in the afterglow is shown in the Fig. 2. The ion current measured after the extraction system has a very abrupt end after 1-2 ms. With certain source settings a smooth exponential decay can be obtained.

There is a great interest in the numerical simulation of lead ion production with the aim of interpreting the experimental results and improving the lead ion output from the ECR source at CERN.

6. A library of the computer codes for MS-DOS PC was created to solve this problem. About one hundred nonlinear algebraic or differential equations are used for these new codes. This library consist of:

- a data base of the ionization potentials for all electron shells and subshells for every charge state of different ions[13] for the most important gaseous and metallic atoms;
- a code for the numerical simulation of heavy ion production in the static regime in the mixture of two different elements in the ECR ion source;

- a code for the numerical simulation of heavy ion production in the dynamic regime for the mixture of two different elements in the ECR ion source. Some preparatory results of this numerical method were published in Ref. 14.

7. Figs. 3-6 show some examples of numerical simulation. Fig. 3 presents the calculated charge state distribution of lead ions in the mixture with oxygen for continuous source mode after 50 ms of the ion confinement. Fig. 4 shows the calculated charge state distribution of lead ions in the mixture with oxygen for afterglow mode after 50 ms of the ion confinement. The time dependencies of Pb^{27+} and Pb^{30+} in the continuous regime and Pb^{27+} in the afterglow are given in the Fig. 5 and Fig. 6. All calculations were done for the ECR4 ion source parameters. 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 energy $E_e = 5000$ eV and electron density $n_e = 5 \cdot 10^{11}$ cm^{-3} were used in the calculations presented in Fig. 3 and Fig. 4; $E_e = 4000$ eV and $n_e = 3 \cdot 10^{11}$ cm^{-3} were used in Fig. 5 and Fig. 6. These parameters were chosen according to the results of measurements on the ECR ion source used at CERN[15]. The value of electron density was selected according to the confinement time necessary for the Pb^{27+} ion production in continuous mode (40-50 ms) and the maximum ion output in the afterglow. The electron energy determines the shape of charge state distribution in the high charge region.

The numerical simulation gives us only the output current density. The extraction electrode usually has a hole with diameter about 1 cm in real ECR sources. Therefore the numerical values of output current density are comparable with the output ion current in the real experimental setup.

The calculated charge state distribution from Fig. 3 in comparison to the one of the measured distributions is shown in Fig. 7. The calculated data presented in this Fig. 7 were divided by a factor of 3.5 for the best coincidence with the measurements.

Analysis of the measurements allows us to conclude that the average electron energy $E_e = 3000 \div 5000$ eV and the electron density $n_e = 3 \div 5 \cdot 10^{11}$ cm^{-3} in the CERN ECR source.

8. The new library of computer codes based on the equations of the model of ion confinement and losses makes possible to simulate the charge state distribution of heavy (lead) ions in the mixture with support gas (oxygen) in the afterglow mode of source operation with accuracy of $10 \div 15\%$. Naturally this simulation is a kind of fitting with electron energy and density as variable parameters. The accuracy of this fitting depends on the accuracy of cross sections of ionization and charge exchange, coefficients of elastic collision rates in the plasma and other input parameters. But this numerical simulation allows us to estimate the density and average energy of electrons in the plasma, help us to interpret the experimental data and what is more to use these methods for numerical testing and examination of new ways of the source improvement[16].

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Figure captures

Fig. 1. Experimental charge state distribution of lead ions in the afterglow mode in the CERN ECR source.

Fig. 2 Experimental time dependence of Pb^{27+} output current in the afterglow mode in the CERN ECR source.

Fig. 3 Calculated charge state distribution of lead ions after 50 ms confinement time in the continuous mode.

Fig. 4 Calculated charge state distribution of lead ions after 50 ms confinement time in the afterglow mode.

Fig. 5 Calculated time dependence of Pb^{27+} and Pb^{30+} output currents in the continuous mode.

Fig. 6 Calculated time dependence of Pb^{27+} output current in the afterglow mode.

Fig. 7 Calculated charge state distribution of lead ions after 50 ms confinement time in the afterglow mode in comparison with measured distribution.