# NUMERICAL SIMULATION OF ION PRODUCTION PROCESSES IN EBIS

Kalagin I.V., Ovsyannikov V.P.
RU-141980 Dubna, Joint Institute for Nuclear Research, LHE, Moscow reg., Russia

## Abstract

The numerical model of EBIS is presented. The calculation of Kr ionization by cooling with Ne ions was carried out taking into account charge exchange, ion heating by electrons, ion-ion energy exchange and ion escape processes. A good agreement with experimental data was observed. According to the model, the processes of Pb ionization in EBIS at close to ultimate parameters (the electron beam current is 10 A and the electron energy is 10 keV, the trap capacity is about $10^{12}$ e) by cooling with Ne ions were simulated.

## Introduction

The electron-beam method of multicharge ion production was suggested by E.D.Donets in 1967 [1]. The first attempt to create an Electron-Beam Ion Source (EBIS) theory was undertaken by R.Becker [2] and M.C.Vella in 1981 [3]. A more complete theory of the electron-beam method of multicharge ionization in an ion trap was created by the Livermore EBIT group (M.Levine, M.Penetrante, R.Marrs et al.) [4,5]. Based on these results, we present a simpler numerical model of multicharge ionization in EBIS. Simplifications follow from our previous papers [6,7]. The computer codes describing the Kryon-S experimental data can be used to predict EBIS basic parameters: charge state spectrum, ion-beam current and even ion temperatures.

## Physical processes in the trap

According to the Livermore papers, main processes in the EBIS trap are the following:

- -electron-impact ionization of ions,
- -radiative recombination of ions,
- -charge exchange between ions and neutral atoms,
- -ion heating by an electron beam,
- -ion-ion energy exchange,
- -ion confinement in the trap,
- -ion escape from the trap.

The processes were considerated in detail in previous parers [4,5,8,10].

## Numerical model

We suppose that the ionization proceed by single steps:

$$\begin{cases} \dfrac{dN_0}{dt} = -N_0\lambda_{0,1} + N_1\lambda_{1,0}, \\ \dfrac{dN_1}{dt} = N_0\lambda_{0,1} - N_1(\lambda_{1,2}+\lambda_{1,0}) + N_2\lambda_{2,1} - \left(\dfrac{dN_1}{dt}\right)^{radesc}, \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ \dfrac{dN_i}{dt} = N_{i-1}\lambda_{i-1,i} - N_i(\lambda_{i,i+1}+\lambda_{i,i-1}) + N_{i+1}\lambda_{i+1,i} - \left(\dfrac{dN_i}{dt}\right)^{radesc}, \\ \dfrac{dN_Z}{dt} = N_{Z-1}\lambda_{Z-1,Z} - N_Z\lambda_{Z,Z-1} - \left(\dfrac{dN_Z}{dt}\right)^{radesc}, \end{cases}$$

where $N_0$ .. $N_Z$ are the ion and atom densities, $\lambda_{0,1}$, $\lambda_{1,2}$, $\lambda_{i-1,i}$, $\lambda_{i,i+1}$, $\lambda_{Z-1,Z}$ are the ionization coefficients: $\lambda_{i,i+1} = \sigma_{i,i+1} j_e$, $j_e$ is the electron current density, $\sigma_{i,i+1}$ the ionization cross-section, $\lambda_{1,0}$, $\lambda_{2,1}$, $\lambda_{i+1,i}$, $\lambda_{i,i-1}$, $\lambda_{Z,Z-1}$ are the recombination and charge exchange coefficients:
$\lambda_{i,i-1}=\lambda_r+\lambda_p$, where $\lambda_r = \sigma_r \cdot j_e$, $\sigma_r$ is the recombination cross-section, $\lambda_p = \sigma_p \cdot N_0 \cdot \langle V_i\rangle$, $\sigma_p$ is the charge exchange cross-section, $N_0$ is the density of neutral atoms, $\langle V_i\rangle$ is the mean ion speed,
$\left(\dfrac{dN_i}{dt}\right)^{radesc}$ is the rate of ion diffusion escape from the trap.

The corresponding energy evolution is described by:

$$\frac{d(N_i kT_i)}{dt} = N_{i-1}kT_{i-1}\lambda_{i-1,i} - N_i kT_i(\lambda_{i,i+1}+\lambda_{i,i-1}) + N_{i+1}kT_{i+1}\lambda_{i+1,i} + \left[\frac{d(N_i kT_i)}{dt}\right]^{heating} + \sum_j \left[\frac{d(N_i kT_i)}{dt}\right]_j^{exchnge} - \left[\frac{d(N_i kT_i)}{dt}\right]^{redesc},$$

where $kT_i$ is the ion temperature,
$\left[\dfrac{d(N_i kT_i)}{dt}\right]^{heating}$ the rate of ion heating by the electron beam,
$\sum_j \left[\dfrac{d(N_i kT_i)}{dt}\right]_j^{exchnge}$ the rate of ion-ion energy exchange due to Coulomb collision,
$\left[\dfrac{d(N_i kT_i)}{dt}\right]^{redesc}$ the rate of the energy loss due to escaping ions.

## Calculations and comparison with experimental results

The dependences of Kr ion densities, electron beam compensation values, Kr ion temperatures on time at taking into account ionization, charge exchange, ion heating by the electron beam, ion energy exchange and ion escape processes were calculated in [10].

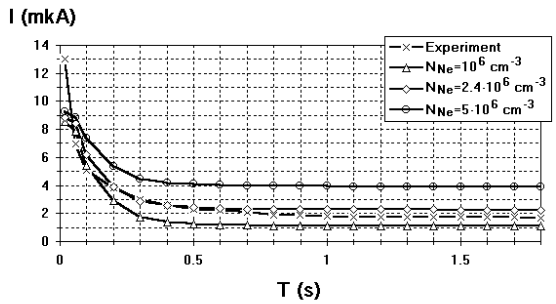


Fig. 1

The experimental data of the Kr current at the EBIS Krion-S exit measured over an ion extraction time of 100 μs and the calculated results obtained at $j_e=1.77\cdot10^{21}$ 1/(cm$^2\cdot$s), $U_e=7\cdot10^3$ eV, $N_{Kr}(0)=6\cdot10^9$ cm$^{-3}$, $r_p=0.015$ cm, B=1.2 T, by cooling Kr ions with Ne ones.

The next step was to consider ion cooling processes. The method of ion cooling in EBIS was suggested by E.D. Donets and G.D. Shirkov [8]. Equation systems for charge and energy evolution created for Kr and Ne were solved simultaneously. We supposed that the concentration of Ne atoms ($N^0$) in the electron beam is a constant [10].

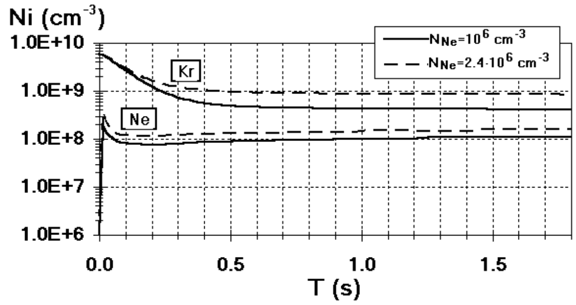


Fig. 2

Dependence of common Kr and Ne ion densities on confinement time corresponding to Fig. 1.

The calculated results for Kr ionization by cooling with Ne ions were compared with the experimental data of Kr current measurements at the EBIS Krion-S exit. The experimental current dependence on time was measured over an ion extraction time of 100 μs. The best numerical approximation was obtained at the current density equals to $j_e=1.77\cdot10^{21}$ 1/(cm$^2\cdot$s), the electron energy $U_e=7\cdot10^3$ eV, the start concentrations of Kr atoms $N_{Kr}(0)=6\cdot10^9$ cm$^{-3}$, the electron beam raius $r_p=0.015$ cm and the magnetic field induction B=1.2 T. The results for output current are shown in Fig. 1. The total numbers of ions, the values of beam compensation and the average ion temperatures corresponding to Fig. 1 are shown in Fig. 2, Fig. 3, Fig. 4.

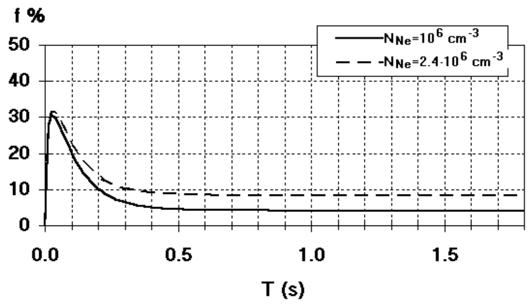


Fig. 3

Dependence of beam compensation values on confinement time corresponding to Fig. 1.

The time evolution of Kr ion densities at $N_{Ne}=2.4\cdot10^6$ cm$^{-3}$ corresponding to Fig. 1 is shown in Fig. 5.

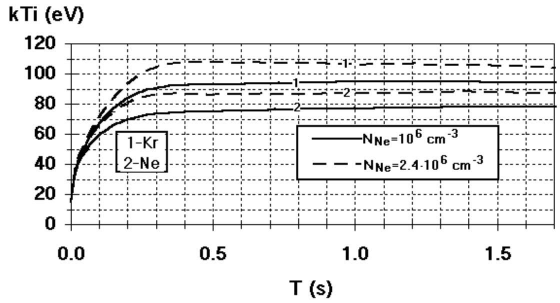


Fig. 4

Dependence of the average Kr and Ne ion temperature on confinement time corresponding to Fig. 1.

The results were confirmed by an experimental observation of Kr higher charge state evolution at the LU-20 output when the EBIS Krion-S was installed on the linac pre-injector [9].

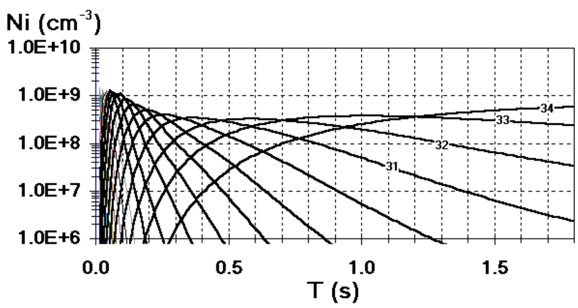


Fig. 5

The time evolution of Kr ion densities corresponding to Fig. 1.

According to the model, the processes of Pb ionization in EBIS at close to ultimate parameters (the electron beam current is 10 A and the electron energy is 10 keV) were simulated. The electron gun for the source with the perveance equals to 3 μA/V$^{3/2}$ at the cathode diameter of 3.4 mm, the cathode emission density of 111 A/cm$^2$, the first anode voltage of 22.3 kV and the second anode one of 10 kV can be produced in the firm “ISTOK” (Friasino, Moscow reg., Russia) [11]. After instalation of the e-gun in the EBIS, the value of DC current power at the EBIS collector will be equal to 100 kW.

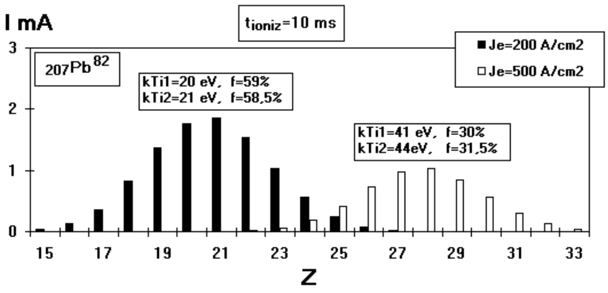


Fig. 6

Figs.6,7,8. The values of Pb ion currents at the EBIS output after 10, 50 and 100 ms ionization at $U_e$=10 keV, $I_e$=10 A, B=1.2 T, $j_e$=200 A/cm$^2$ and $j_e$=500 A/cm$^2$.

To avoid problems due to collector heating a pulse regime of ionization is suggested. At the pulse duration is about t≈0.1 s the collector system can be cooled by water at the rate of flow is about G≈3 l/min. We suppose that the process of electron beam formation to reach the current density $200 \le j_e \le 500$ A/cm$^2$ (as it takes place in Krion-S) won’t be a very difficult problem. The time of ion extraction from the trap can be decreased from 100 μs to 10 μs. Therefore we carried out calculations of Pb atom ionization processes during 0.1 s at $j_e$=200 A/cm$^2$ and $j_e$=500 A/cm$^2$ by cooling the Pb ions with Ne ones and without one.

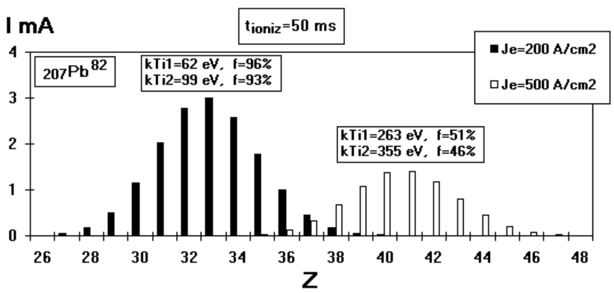


Fig. 7

The results for output ion currents at the ion extraction time of 10 μs for different ionization periods are shown in Fig. 6, Fig. 7, Fig. 8. In the calculations, the values of Pb ion currents for calculations with cooling are very close in amplitude to ones without cooling at the same ionization period. Therefore we present the ion currents for calculations with cooling only. The electron beam compensation values f and the average ion temperatures presented for both calculation types (with cooling- kTi1 and without one- kTi2) are shown above the currents.

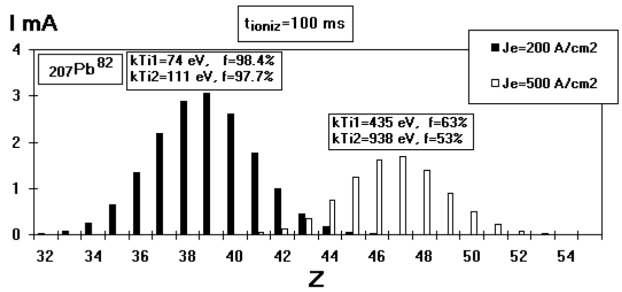


Fig. 8

## Conclusion

The workable numerical model of EBIS has been created. The calculated results for Krion_S are close to the experimental ones. The model made more understandable the influence of different processes in the trap on the EBIS output parameters. It allows us to undertake some attempts to predict future results.


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