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THE ION COOLING IN EBIS

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INTRODUTION

The electron beam ion source EBIS is an electron accelerator with a drift tube. The electron beam is strongly focused by the longitudinal magnetic field. The ions are produced as the result of electron impact ionization of the neutral atoms or molecules in the beam or in a special preionization stage of the source. The ions are caught and kept by the negative potential well of the beam and they undergo further ionization step-by-step. The ion charge states are determined by the electron density, confinement time and electron energy. There are potential barriers at the ends of the beam for the ion confinement in the longitudinal direction. Xe^{53+} and Xe^{54+} ions were obtained in KRION-2 EBIS /1/. The times about 10s are required for obtaining the super high charged ions. One of the main problems is great losses of highly charged ions at the prolonged time confinement. This article touches the problems of highly charged ion losses and ion cooling in EBIS.

I. ION LOSSES FOR BOLTZMAN DISTRIBUTION OF ION ENERGIES IN EBIS BEAM

It was shown that the ion heating in elastic collisions with electrons at ionization times during some seconds may be one of the main causes of the ion losses. The more accurate calculations require to take into consideration the peculiarity of distribution function for ion energies. There are the intensive elastic collisions among the ions in the electron beam of EBIS. The collision rate of the ions with charge state i, mass number A, temperature T_i with the ions of all ion components is

$$\nu_i = \frac{4\pi\, m^2\, c^4\, r_e^2\, i^2}{\sqrt{M}} \times \sum_{k=1}^{n} \frac{k^2\, L_k\, n_k \sqrt{A_i A_k}}{(A_k T_i + A_i T_k)^{3/2}}\, , \quad (1)$$

where r_e and m are the classical radius and the rest mass of electron, c is the velocity of light, $L_k \cong 15$ is, the so called, Coulomb logarithm, n_k is the ion density of one of n ion components. For typical EBIS parameters $\nu_i = 10^4 \div 10^6 s^{-1}$. The ion thermolization takes place in the beam at the times $\Delta t_i \approx 1/\nu_i$. The distribution functions of all ionic species became Boltzman distribution of equality temperature T_i for every kinds of ions:

$$f_i(E_i) = \frac{2}{\sqrt{\pi}} \frac{1}{T_i} \sqrt{E_i/T_i}\, e^{-E_i/T_i} \qquad (2)$$

The highly ionized ions with energy higher than E_{im}, where $E_{im} = imc^2 r_e N_e (1-f)$, go away from the beam volume. Where $f = \sum_{i=1}^{z} iN_i/N_e$ is the beam neutralization factor, N_e and N_i are the linear densities of electrons and ions, Z is the maximum ion charge state. In our case Z equals to the nuclear number. The ions don't depend much on the electrons and vice versa, in the case when the ions are outside the beam most of the time. So, we consider such ions to be the lost particles /3/. The linear density of the lost particles is:

$$\Delta N_i = N_i \int_{E_{im}}^{\infty} f_i(E)dE = (2N_i/\sqrt{\pi}\,)\times\Gamma(3/2, E_{im}/T_i) \qquad (3)$$

where $\Gamma(\alpha, x)$ is incomplete Γ-function. There are some particles always with $E > E_{im}$ for every ion temperature $T_i < E_{im}$. These ions are lost from the beam. The ion collisions rehabilitate the distribution function, the ions with high energies are lost and so on. Thus, we have continuous ion losses and ion energy outflow. This process must be described with balance equations for total energy and ion number in the beam. It was supposed to use light low charged ions for temperature decreasing of highly charged ions with the aim to reduce ion losses from the beam /4/. This effect was experimentally discovered /1,5/ and was theoretically explained in ref./2/. The evolution of ion accumulation and ion cooling in the electron beam ion trap were studied in Livermore

/6,7/. The low charged ions receive the energy of heavy ions, leave the beam and take the energy away. Let us suppose that the temperature of heavy highly charged ions is kept at the constant level. Then the rate of ion losses is defined from equation:

$$dN_i/dt = -\Delta N_i/\Delta t_i \qquad (4)$$

One can obtain, using the formulas (1) and (3):

$$N_i = N_{io}/(1+t/\tau_i) \;,$$

with

$$\tau_i = \frac{1}{2}\sqrt{\frac{\pi\ A\ M\ N_e}{2\ Z\ m\ r_e}\,\frac{a^2\ N_e}{Z^2 N_{io}\, c\ L_i}}\,\left(\frac{T_i}{E_{im}}\right)^2 \exp\left(\frac{T_i}{E_{im}}\right)^{-1}(1-f)^{3/2}, \qquad (5)$$

Here a is the beam radius. It was used that $T_i = T_k$ in (1) and $\Gamma(3/2, x) \approx \sqrt{x}\,\exp(-x)$ for $x \gg 1$ in (3).

The typical lifetimes (in seconds) for different elements for KRION-2 type ion source ($N_e = 3\times10^8 cm^{-1}$, a = 0.0015cm, f = Z N_o/N_e = 0.5) are presented in the table.

Table. Dependence of lifetime τ_i in seconds on T_i to E_{im} relation for A, Kr, Xe and U ions.

T_i/E_{im}	A	Kr	Xe	U
2	$4.7\ 10^{-5}$	$2.4\ 10^{-5}$	$1.6\ 10^{-5}$	$1.0\ 10^{-5}$
5	$1.5\ 10^{-4}$	$7.7\ 10^{-5}$	$5.3\ 10^{-5}$	$3.2\ 10^{-5}$
10	$5.6\ 10^{-3}$	$2.9\ 10^{-3}$	$1.9\ 10^{-3}$	$1.2\ 10^{-3}$
15	0.37	0.19	0.13	0.078
20	31	16	11	6.5
25	2900	1500	1000	620

According to these results it is necessary to keep the temperature at the level of $T_i \simeq E_{im}/20$ to preclude the possibility of ion losses at beam lifetime about 10s.

Let us use the designations: the index "1" is for heavy working ions and index "2" is for light ions for cooling. The charge states for all kind of ions can be expected equal to nuclear number for prolonged confinement times. Then for cooling it is necessary to keep the ion temperature $T_i > E_{2m}$, where $E_{2m} = Z_2 m c^2 r_e N_e (1-f)$. Hence $E_1/E_2 = Z_1/Z_2$, and $Z_1/Z_2 > 20$. So, it follows that one should use the most light elements for cooling, for example, the ions of helium.

II. HEAVY ION COOLING WITH LIGHT ION FLOW

It is possible to cool the highly charged ions with continuous flow of light ions along the beam. The light ions are injected with energy $E_{20} < E_{2m}$, they receive the energy from heavy ions, heat to the energy more than E_{2m}, are lost and take away the energy from the beam. The heavy ions take the energy from electrons and return it to the light ions. Two requirement must be fulfilled in stationary conditions:
1). The heating rate is not higher than the cooling rate for heavy ions:

$$dE_1^+/dt \le dE_1^-/dt \qquad (6)$$

2). The light ions have time to get the energy more than E_{2m} during transit time along the beam:

$$l\, dE_2^+/dt \ge (E_{20} - E_{2m})\, v_2 \qquad (7)$$

where l is the beam length, $v_2 = \sqrt{2\, E_2/A_2 M}$ is the mean velocity of light ions.

The heating rate of heavy ions in elastic collisions with electrons is:

$$\frac{dE_1^+}{dt} = \sqrt{\frac{2m}{E_e}}\, \frac{r_e^2\, Z_1^2\, N_e m^2 c^4 L_e}{a^2\, A_1\, M} \qquad (8)$$

with E_e - electron energy, $L_e \approx 10$ - the so called Coulomb logarithm. The cooling rate of heavy ions with light ions is:

$$\frac{dE_1^-}{dt} = \frac{4\, N_2\, r_e^2\, m^2\, c^4\, Z_1^2\, Z_2^2}{a^2\, A_1} \sqrt{\frac{A_2}{M}}\, \frac{(E_1 - E_2)}{E_2^{3/2}}\, L_i \qquad (9)$$

In addition we have $N_2 dE_2^+/dt = N_1 dE_1^-/dt$ and, thus, it is possible to obtain:

$$\frac{I_2}{I_e} = \frac{Z_2 v_2 N_2}{v_e N_e} \ge \frac{m^2\, c^2\, N_e\, r_e}{4\sqrt{2}\; A_2\, M\, E_e}\, \frac{(1 - f + \varepsilon_o)^2}{(2\varepsilon_1 - \varepsilon_o - 1 + f)} \qquad (10)$$

where $\varepsilon_o = E_{20}/Z_2 mc^2 N_e r_e$ and $\varepsilon_1 = T_i/Z_2 mc^2 N_e r_e$. If T_i is supposed equal to $E_{1m}/20$, then $\varepsilon_1 = Z_1(1-f)/(20Z_2)$ and finally

$$\frac{I_2}{I_e} \ge 1.4\times 10^{-10}\, \frac{N_e\, Z_2}{E_e\, A_2}\, \frac{(1 - f + \varepsilon_o)^2}{((1 - f)(Z_1 - 10Z_2) - 10Z_2\varepsilon_o)}$$

The condition (7) results to relation:

$$\frac{(1 - f - \varepsilon_o)(1 - f + \varepsilon_o)^2}{(1 - f)(Z_1 - 10Z_2) - 10Z_2\varepsilon_o} \le \frac{2\sqrt{2}}{5}\, \frac{Z_1\, A_2\, L_e\, l}{Z_2\, A_1\, N_e\, a^2} f = \alpha f. \qquad (11)$$

We have l = 100cm for KRION-2 and α = 0.01. The relations (10) and (11) make possible to determine the required current and initial energy of light ions for the permissible value of neutralization factor f. Dependencies of f factor on energy ε_o are presented in Fig. The curves 1 correspond to α = 0.05, the curves 2 correspond to α = 0.01 and the curves 3 to α = 0.002. The curves 4 relate to condition $E_1 = E_2$, when the numerators in formulas (10) and (11) become equal to zero. In the Fig. the solid lines show the results for Xe ions (Z_1 = 54) and the dashed lines relate to U ions (Z_1=92). The working values of f and ε_o fall inside one of the curves 4 and one of the curves 1, 2 or 3, respectively. So, for KRION-2, if $E_e = 10^5$eV and ε_o =0.7 (E_o = 60eV), we can obtain for Xe ions: $I_2 > 4.2\times10^{-8}\ I_e = 4.2\times10^{-2}$A, 0.6 > f > 0.3. Similar for U ions: $I_2 > 5\times10^{-9}$A, 0.8 > f > 0.25.

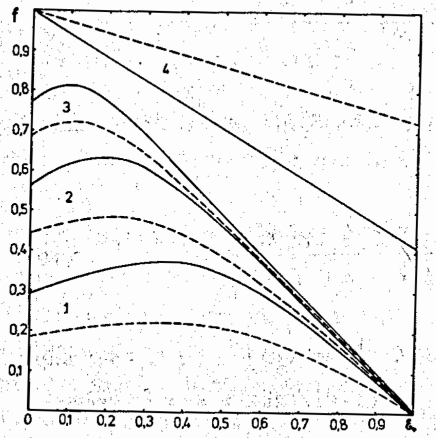

Fig. Dependence of neutralization factor f on initial energy of light ions ε_0 in relative units. Here curves 1 are for $\alpha = 0.05$, curves 2 are for $\alpha = 0.01$ and curves 3 are for $\alpha = 0.002$. The curves 4 are the conditions of positive value of expressions (10) and (11). The solid lines are for Xe ions and the dashed lines are for U ions.

III. CONCLUSION

Thus, in the conclusion we can summarize that the elastic ion collisions in EBIS electron beam are the cause of great losses of highly charged ions during the confinement times of some seconds. It is necessary to use the most light ions (H^+ and He^{++}) for cooling till the temperatures not less than twenty times lower than the potential barrier. It is possible to cool the heavy highly charged ions by light ion flow with the current about some nA and accurately selected initial energies. The probability of ion losses, when the parameters of cooling flow are not chosen correctly the problem of ion losses requirs additional investigations.

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