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ION ACCUMULATION AND SPACE CHARGE NEUTRALIZATION IN INTENSIVE ELECTRON BEAMS FOR ION SOURCES AND ELECTRON COOLING

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Introduction

The electron beams of the electron cooling method suggested by G.I.Budker [1] in Novosibirsk, the Electron Beam Ion Sources (EBIS) constructed in Dubna by E.D.Donets [2] and Electron Beam Ion Traps (EBIT) developed in Livermore [3] have the beam parameters in the same ranges of magnitudes. EBIS and EBIT produce and accumulate ions in the beam due to the electron impact ionization during a long range ion confinement in the electrostatic potential trap of the electron beam. The cooling electron beam accumulates positive ions from the residual gas in the accelerator chamber during the cooling cycle. The space charge neutralization of cooling beam is used to reduce the electron energy spread and enhance the cooling ability [4].

The report presents the analysis of the most important processes connected with ion production, accumulation and losses in intensive electron beams of ion sources and electron cooling systems for proton and ion colliders. The theoretical results are illustrated with evaluations and calculations of real parameters and physical effects in the electron beams of two electron cooling set ups and KRION-2 beam source.

The ions and secondary electrons are generated in the electron beams by electron impact ionization. Sometimes (in the EBIS, for instance) ions are "cooked" outside the main beam and injected into it along the axis. The electron beam creates a negative electrical potential in the radial direction. This potential exists as a potential well for the positive ions. Special potential barriers at the beam ends limit the ion losses along the beam axis in EBIS. The trapped ions could undergo the subsequent step-by-step ionization in the electron beam. The secondary electrons are pushed out from the beam with negative potential and in the case of axial magnetic field, they drift along the beam and are lost at the chamber walls, anode or special cleaning electrodes. The accumulated ions neutralize the electron space charge and decrease radial negative potential in the electron beam .

Collision processes

There are different kinds of scattering among electrons, ions and residual neutrals in the beam. In general, scattering of atomic particles could be divided into two different physical types. The first one is inelastic collisions that include all the types of interactions with the change of the internal state of colliding particles. The state change of the atomic or ionic electron shell is meant in our consideration. Thus, the electron impact ionization and excitation, charge exchange process between neutral atoms and ions, all types of ion recombination with electrons and etc. are inelastic collisions. The electron impact ionization is the most important inelastic process in the intensive electron beam of the keV and higher energy. The charge exchange process is very significant in the case of highly charged ion production and it is one of the main limits to produce extremely high charge states in the ion sources. The second type of particle scattering is elastic collisions among charged particles. The elastic collisions mean Coulomb interaction between charged particles that changes the energy and momentum of the particle motion and causes redistribution of the particle energy. The elastic collisions in the electron beams may be a cause of the beam dimension increasing, heating and loss of trapped ions and the energy redistribution among the ions of different charge states and species in the beam. It is well-known that the elastic collisions are a physical basement of the electron cooling method in accelerators and of, the so-called, ion cooling in ion sources.

Electron Impact Ionization. Electrons can ionize only the ions having ionization potentials I lower than the electron kinetic energy E_e. There are a lot of experimental data for electron impact ionization for neutral atoms and low charged ions in the literature [5]. Different theoretical models are used to calculate ionization cross-section for highly charged ions as well as for low charged ions and neutral atoms or molecules. Lotz's formula is one of the most useful for calculating cross-sections at non-relativistic electron energies [6]·

$$\sigma_k^i = \frac{4.5 \cdot 10^{-14}}{E_e} \sum_{j=1}^{l} \frac{n_j}{I_j} ln \frac{E_e}{I_j} \qquad (1)$$

with l being the number of atomic subshells occupied in the ion, n_j - the number of electrons in the sub-shell considered, and I_j - the ionizing energy of the given sub-shell in eV.

Ionization potential I_k increases with ion charge state k approximately as $I_k \sim k^2$. From equation (1) follows that $\sigma_k^i \sim I_k^{-2}$ is in essence a function of (E_e / I_k). So, the dependence of the impact ionization cross-section on the ionic charge state is very significant. It can be considered approximately as $\sigma_k^i \sim k^{-4}$.

According to formula (1), the cross-section σ_k^i has the maximum when $(E_e / I_k) = 2 \div 3$ The rate of ionization is determined by the value $v_e \sigma_k^i$, where v_e is the electron velocity. The cross-section (1) depends on the electron energy and the average value of ionization rate $< v_e \sigma_k^i >$ must be calculated using the energy distribution function for electrons in the source. The ionization rate has a maximum for $(E_e/I_k) = 5 \div 8$.

Charge Exchange Process. Working in opposition to the electron impact ionization, charge exchange processes reduce the mean charge of ions, increase the total ion number in the beam and can be considered as a very undesirable process in the sources of highly charged ions. The cross-section of the charge exchange process for the low collision energy does not depend on the energy and can be estimated from the well-known empirical formula of Muller and Salzborn [7]:

$$\sigma_k^{ex} = 1.43 \cdot 10^{12} k^{1.17} I_0^{-2.76} \tag{2}$$

where k is the charge state of the ion and I_0 - the ionization potential of the neutral. One can see that exchange cross-section has a strong dependence on the ionization potential of neutral atom. Different neutrals have ionization energies in the wide range from 4 to 24 eV. The probability of charge exchange between two ions could be roughly estimated also using formula (2) with ionization energy of ion-donor. But this probability for positive ions is negligible in the most real situation due to strong dependence of ionization potential on the ionic charge state.

Recombination. Recombination is a capture of free electron by an ion. According to the laws of quantum mechanics, the third particle should be involved in the process of electron capture except electron and ion. One of the possible canals of this reaction is an electron capture into the excited state of the electron shell with the simultaneous emission of photon. It is a radiative recombination, the Kim and Pratt formula [8] gives the following dependence of cross section σ_i^r on effective ion charge $Z_{eff} = (Z + i)/2$ and electron energy E_e : $\sigma_i^r \sim Z_{eff}^2 / E_e$,

Z is the nuclear charge and i - the charge state of the ion. Sometimes this process is important for highly charged ions in the beam with electrons of relatively low energies. An other process is the electron capture into the fixed excited state of electron shell with the simultaneous transition of one electron of the shell at the exited level. This is a dielectronic recombination. It is a resonant process negligible for the electron beam energy of the keV region.

Elastic collisions. The high energy electron beam with the length in the range of meters, focused by the strong longitudinal magnetic field in the beam tube at high vacuum conditions, does not undergo serious transversal scattering with the residual gas neutrals and trapped ions. But electron-ion and ion-ion elastic collisions are very important to study ion accumulation. The rate of ion heating due to the elastic Coulomb collisions with electrons is [9]:

$$\frac{dE_i}{dt} = \frac{4\pi\, n_e\, Z^2\, r_e^2\, m_e^2\, c^4 \sqrt{m_e}\, L_{ei}}{AM\sqrt{2E_e}} \tag{3}$$

Here the average ion energy is E_i; A and M are the atom mass number and mass of a nucleon, correspondingly; L_{ei} is, the so called, Coulomb logarithms; r_e and m_e are the classical radius and mass of electron; c - the velocity of light. Value ν_{ik} is the ion-ion collision frequency[9]:

$$\nu_{ik} = \frac{3\sqrt{6}\pi\, r_e^2\, m_e^2\, c^4\, i^2}{\sqrt{M}} \sum_{j=1}^{k} \frac{\sqrt{A_i A_j}\, j^2\, n_j\, L_{ij}}{\left(A_i E_j + A_j E_i\right)^{3/2}} \tag{4}$$

where i and j, $1 \le I, j \le k$ correspond to one of the k ion species.

The rate of ion heating dE_i/dt and ion-ion collision frequency ν_{ik} for the typical beams of EBIS and electron cooling applications are presented in the Table. One can see that elastic collisions are very intensive in the beams of EBIS and should be a subject of careful consideration for every beam of electron cooling application.

Ion accumulation and beam neutralization.

Ion distribution function. All types of interactions in the electron beams and plasma depend on the spatial and velocity distribution or the distribution function of particles. In most cases of ion sources and electron cooling applications the electron beam is formed and transported in the strong axial magnetic field and very often could be assumed as a beam of constant density and fixed energy. Opposite to electrons, the ions are generated from neutrals, undergo the step-by-step ionization and have a complicated movement with oscillations in the self consistent electric and magnetic fields. In the general study the distribution function of ions is the solution of Vlasov kinetic equation complicated by the complete set of Maxwell equations with consideration of collision processes. A set of coupled kinetic equations should be used while considering several ion components in the electron beam or plasma. All types of collision and charge transition processes can be taken into account in the complete kinetic equations. Very complicated numerical methods are used for solving Vlasov kinetic equations. The detailed consideration of this problem is beyond the tasks of our paper.

Several analytical solutions of the kinetic equation were found for some simple but practically important cases of electron beams [10]. The processes of ion accumulation and confinement are relatively slow in the long-lived electron beams. If there are not many ions, then the ion-ion collisions could be assumed as a negligible factor and ion distribution function f_i can be considered to be approximately stationary. In this case the kinetic equations are transformed to a simple stationary form - $df_i/dt = 0$. The stationary distribution function can only be a function of the integrals of motion. In this consideration every ion has two integrals of motion, namely the angular momentum relative to the beam axis $M_\varphi = AM\, v_\varphi\, r$ and total ion energy $E_i = AMv^2/2 + ie\, U(r)$, r is the ion distance to the beam axis, v_φ is the angular velocity and $U(r)$ - the potential of the beam electric field. If the beam is azimuth symmetric and the initial energy of ions could be assumed negligible, then the ion distribution function has the following form [10]:

$$f_i = f_i(E_i)\, \delta(M_\varphi) \qquad (5)$$

where $\delta(x)$ is the Dirac-δ-function. This equation is able to describe the ion oscillations in the self potential of electron beam, for example.

This equation was solved for the single-charged ions and constant density of electrons and neutrals in the beam [11]:

$$f_i = \frac{N_1 AM}{\pi^2 a^2 w_1} \sigma(E_m - E_i)\, \delta(M_\varphi) \qquad (6)$$

where $E_m = N_e\, r_e\, m_e\, c^2$ is ion energy on the beam border; $\omega_i^2 = \frac{iN_i\, r_e\, m_e c^2}{AMa^2}$ is the frequency of ion harmonic oscillations in the beam if the electron density is constant; a is the electron beam radius; N_e and N_i are the linear densities of electrons and ions ($i=1$ for single-charged ions); and the function $\sigma(x)$ is defined as $\sigma(x) = 1$ for $x \geq 0$ and $\sigma(x) = 0$ for $x<0$.

In the real physical setups the border of the electron beam is often not very sharp and the electron density in the beam cross-section is approximated with Gaussian distribution function $\rho_e = (exp(-r^2/2a^2)/a^2)$. The following uniform distribution function for all ionic charge states is found in this case [10]

$$f_i = \frac{N_i AM}{\pi^2 a_i^2 w_i} exp\left\{-\frac{r^2 + v^2/\omega_i^2}{2a_i^2}\right\} \delta(M_\varphi) \tag{7}$$

with a_i is the root-mean-square of ion components in the beam. The ion densities can be found from distribution function (6) and (7) after integration in the velocity space. The ion densities are [10]

$$\rho_l = \frac{N_1}{2\pi^2 a^2} \frac{\sqrt{a^2 - r^2}}{r}, \tag{8}$$

and

$$\rho_l = \sqrt{\frac{2}{\pi}} \frac{exp(-r^2/2a_i^2)}{a_i r} \tag{9}$$

for the constant electron density and Gaussian distribution, accordingly.

Densities (8) and (9) have non-physical singularity ($1/r$) on the beam axis that is connected with the assumption of zero energies of single-stage ions in the moment of ionization and with the contempt of real elastic collisions in the beam. But from the mathematical point of view, this singularity is not of a problem because this function can be integrated. The above assumptions made it possible to determine the dependence of average, or root-mean-square dimensions of ion components on the ionic charge state. It was shown that for constant electron density and step-by-step ionization, for $i >> 1$ [10,12]

$$a_i^2 = a^2/\sqrt{\pi i}, \tag{10}$$

and in this case the average energy of ions E_i in potential well U of the electron beam has square root dependence on the charge state i:

$$E_i = \sqrt{i/\pi}\ eU, \tag{11}$$

For the Gaussian electron density the dependence on ionic charge state is stronger [10]

$$a_i^2 = a^2 / 2i \tag{12}$$

and the average ion energy E_i does not depend on the charge state at all

$$E_i = E_I = eU / 2 \tag{13}$$

Formulae (8-13) can be used to study ion distributions if, the so-called, neutralization factor $f = \sum_i (in_i)/n_e << 1$ and the electron heating as well as the energy redistribution among ions, are not very significant in the beam.. The numerical simulation of ion accumulation in the electron beams using the method of finite particles with self consistent electrical fields, has shown the applicability of these formulae up to $f = 0.1\text{-}0.2$ [10]. Meanwhile, these results make it possible to conclude that the ions are concentrated near the axis and form an ion kern in the beam center if the neutralization factor is not very high. The ion kern increases the ion-ion interaction rate, in particular, elastic collisions in the stable electron beam.

One should use formula (3) to calculate the energy increasing in addition to (11) or (13) at a high rate of ion heating due to the elastic collisions with electrons. Formula (4) is used to estimate the ion energy redistribution rate while intensive ion-ion Coulomb collisions. In the both cases formulae (5-9) don't work and the distribution function of all ions approach to the Maxwellian velocity and Boltzman energy distributions with the common temperature T_i for all ionic species.

$$f_i(E_i) = \frac{2}{T_i}\sqrt{\frac{E_i}{\pi T_i}} exp\left(-\frac{E_i}{T_i}\right) \tag{14}$$

Beam potential. The electron beam with constant density in the cross section has an electrostatic potential $U_0(r)$

$$U_0(r) = \begin{cases} eN_e\, r^2/a^2, & 0 < r < a \\ eN_e\,(1 - 2\ ln\,(r/R)), & a < r < R \end{cases} \tag{15}$$

For Gaussian beams the potential differs but not very much. It could be assumed in the same form in the central region of the beam.

The ion accumulation in the beam reduces the value of the potential. One can describe in general the potential of the neutralized beam as $U = U_0\,(1\text{-}f)$ where f-is the neutralization factor. But really, the situation is not so simple due to the peculiarity of ion accumulation. The ions are concentrated around the beam axis and disturb the shape of the potential in the region of $r \approx 0$. The dependence of the beam potential on the neutralization factor is illustrated with Fig.1 [10]. This Figure presents the results of numerical simulation of the ion accumulation in the electron beam. The method of finite particles was used for this simulation. The calculations collaborate the above considerations and demonstrate the local maximum of potential in the beam center due to the ion concentration.

These results have shown the second important effect - the potential well does not disappear at all if $f \cong 1$. In this case the electron beam does not keep the ions properly and the oscillation amplitudes of most ions are larger than the beam radius. Thus, we have the focused electron beam with the ion cloud around. The ions have the same space charge but lower self field due to the large average diameter of the ion beam and thus, they do not not fully compensate the negative potential inside the electron beam.

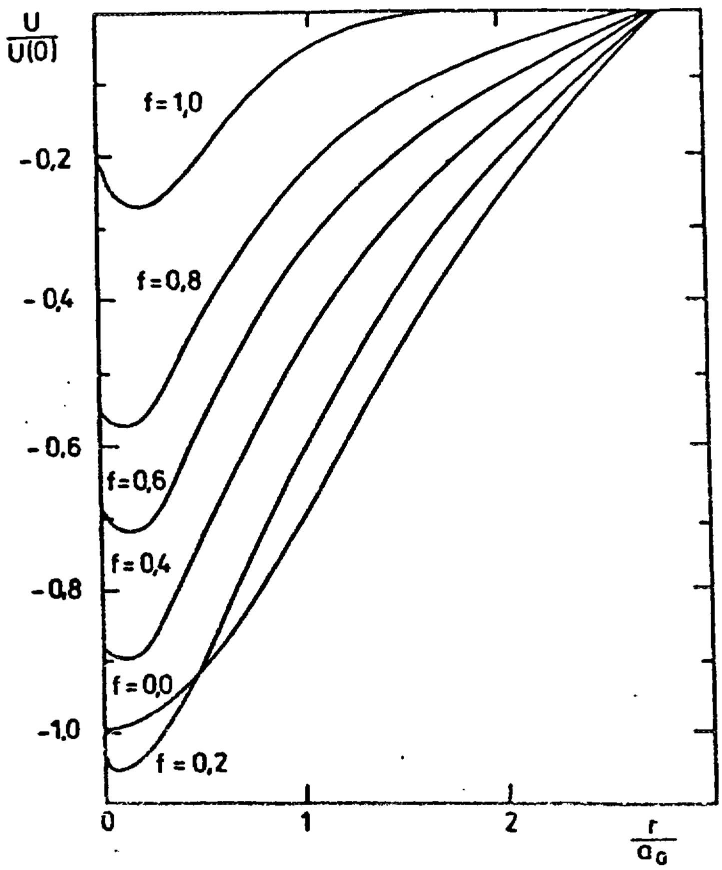

Figure 1. Dependence of the electrical field potential U on the beam radius r for various value of neutralization factor f [10].

Balance equations Ionization processes of neutral atoms and ions, all other charge changing transitions in every point of the plasma or electron beams, depend on the ion and electron distribution functions and can be described in the general form with a set of collision kinetic equations. The knowledge or any reasonable assumption of the energy distribution function leads to a set of balance equations for every ionic charge state. It is a set of nonlinear differential equations for the ion and electron densities which can describe all transition processes among the charged particles. In the simplest case, considering only single ionization and charge exchange processes, the balance equation for actual charge state i is

$$\frac{dn_i}{dt} = n_e v_e \sigma_i^i n_{n-1} - n_0 v_0 \sigma_i^{ex} n_i - n_e v_e \sigma_{i+1}^i n_i - n_0 v_0 \sigma_{i-1}^{ex} n_{i-1} - n_i / \tau_i \qquad (16)$$

here τ_i is the rate of ion losses. The complete set of equations for all possible charge states taking into account single and double transition processes is written, for example, in Ref. [13].

Often the setup with ion accumulation is used as a continuous working device and all the processes in it 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. The number of equations is equal to the number of the beam components and can be of one hundred order for the heaviest ions. Solving the balance equations with numerical methods is not a trivial problem as a rule, but it is not so complicated as for the case of kinetic equations.

Ion accumulation and beam neutralization. The main process that determines the rate of ion accumulation and beam neutralization is the electron impact ionization of neutrals in the beam. The created ions have been kept into the potential well of electrons and neutralize the electron spatial charge. The balance equations lead us to the simplest equation that is able to estimate the total ion number in the beam:

$$\frac{dn_1}{dt} = n_e v_e \sigma_0 n_0 \qquad (17)$$

There are several methods to predict the most probable charge state in the ion source [4]. Quite an accurate and simple expression follows from balance equations (16):

$$j \tau_i = \Sigma_i (1/\sigma_i) \qquad (18)$$

here $j \tau_i = n_e v_e \tau_i$ is the ionization factor.

This value defines the ionization ability of the ion source and allows to estimate the ionization time τ_i to produce the ions with charge state i for the given energy and density of electrons. Fig.2 shows the calculated values of $j\ \tau_i$ for the optimum electron energies for every charge state. This Figure was taken from Ref.[2] and added with the data of nitrogen.

The time of beam neutralization is $\tau_n = 1/\ (<i>\ \ v_e \sigma_0\ n_0\ )$ where $<i>$ is the average ion charge state in the beam. Formula (18) and Fig.2 be used to estimate this value.

Ion losses. There are two main types of ion losses from electron beams. The first one is the loss of ions with the energy over potential barrier at the side beam border or ends. The second type is different instabilities that can arise in the beam during the beam confinement and ion accumulation. We shall not consider the instabilities here.

The physics of ion losses over potential barrier can have peculiarities. In one case the ions have the energy distribution function of type (6) with the limited ion maximum energy. The potential barrier reduces in time due to the beam neutralization or ion average energy increases as the result of electron heating. If the average value of ion energy becomes close to the barrier value and the energy of some ions goes beyond the barrier, then the ion losses appear and in the static case there is some balance between the ion production and losses at the fixed neutralization factor and potential of the beam. The second possibility takes place if the rate of ion-ion collisions is relatively high. In this case the Boltzman energy distribution with the common temperature of all ion species is established quickly. The Boltzman distribution has a very long energy tail and for any relation between the potential barrier and ion temperature it has a group of particles with the energy beyond the barrier. This is illustrated in Fig. 3 where the Boltzman energy distribution of ions is presented. The values of potential barriers for ions with charge states $i = 1 - 5$ are also shown in this Figure.

The ions from the tail with the energy higher than the potential barrier, will be lost from the beam but after the time of ion energy redistribution $\tau \sim 1/\nu_{ik}$ the tail will "grow" again, new particles will be lost once more and so on. One can name this kind of losses as "under barrier ion losses" because they can take place for the ion temperatures much less than the potential barrier in the beam. Thus, the continuous ion losses will start as soon as the Boltzman distribution is established.

The under barrier losses are very dangerous for the EBIS beams, especially, if the main ions are cooked outside the beam trap for the subsequent long-time ionization. According to the results of Ref.[14], this kind of losses is one of the main limits of the ion number for the highly charged ion production in EBIS. Ion cooling is the most effective and widely used method to suppress ion losses and significantly improve the highly charged ion production in EBIT and EBIS now.

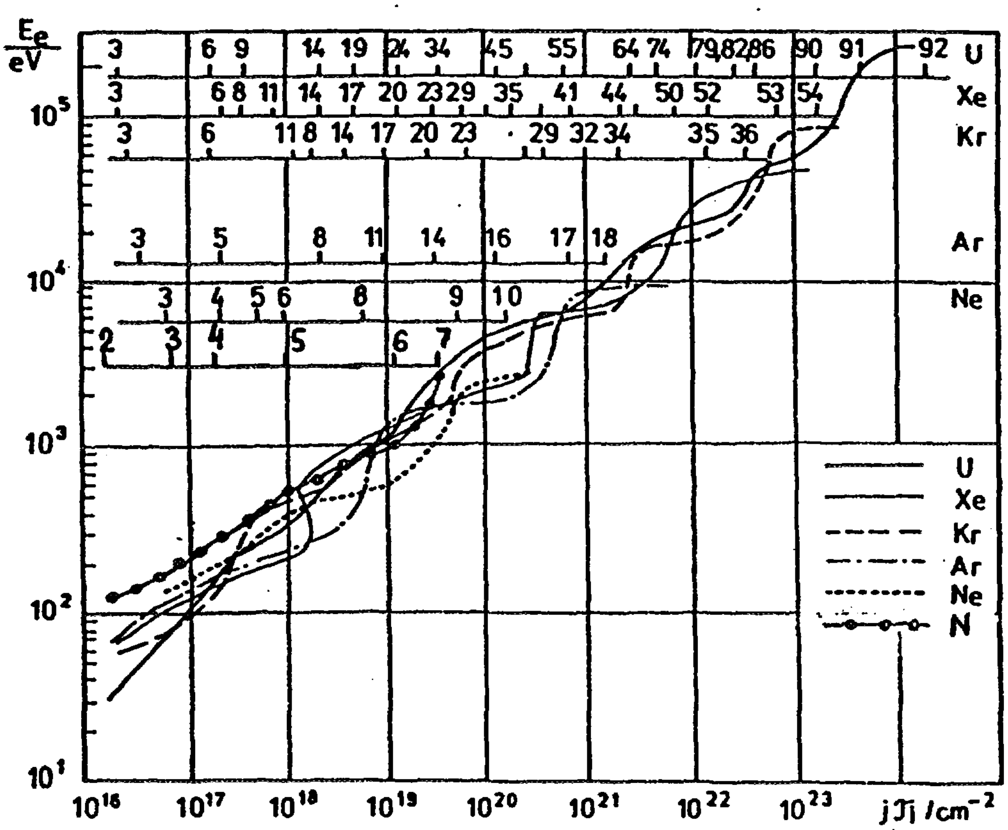

Figure 2. Calculated values of $j\tau_i$ required for producing Ne, Ar, Xe and U ions of a given charge state at corresponding energies of the electrons [2] added with the data for N.

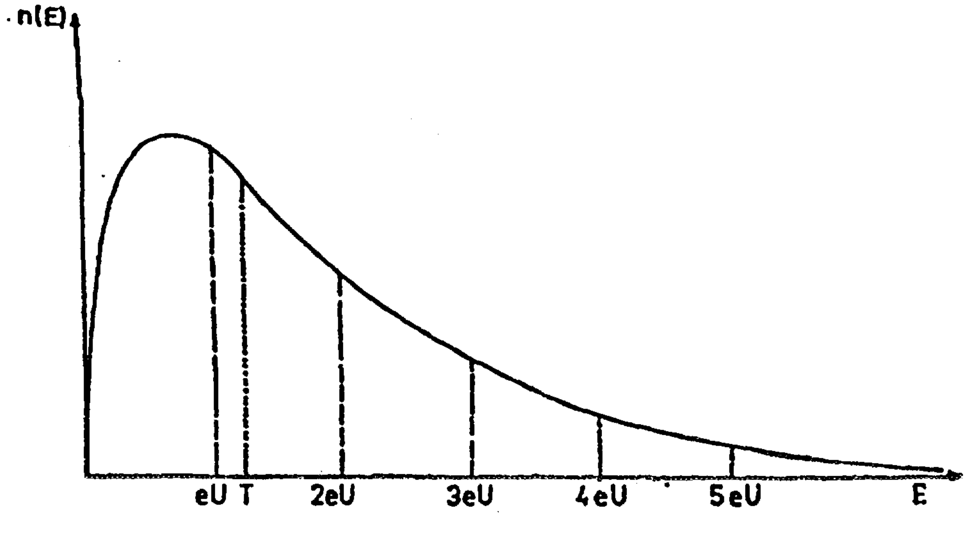

Figure 3. Boltzman energy distribution for the ions with temperature T and values of potential barrier for the charge states of $i = 1 - 5$ [13].

Ion cooling. An idea of using light low charged ions to cool heavy highly charged ions and evacuate the ion energy from the beam of EBIS, appeared about 15 years ago in Dubna [15] . The idea was stimulated by famous Novosibirsk method of "Electron cooling" and named "Ion cooling".

Different ion charge states of i have different values of potential barrier ieU in the electron beam. Various ions have equal temperature due to the intensive ion-ion elastic collisions but different potential barriers and different rates of losses from the beam. The electrons heat all the ions but light ions are heated slower than the heavy ions (3) in the mixture of different ion species. Simultaneously the light ions are heated due to the elastic collisions (4) with highly charged heavy ions. This process increases the light ion temperature and decreases the temperature of heavier species. The low charged ions have a low potential barrier and, therefore, they are lost or evaporated from the beam taking away the energy of the heavy ions. The decrease of the heavy ion temperature prevents the heavy ion losses and provides the highly charged ion production. Low charged light ions could be produced outside and continuously injected in the main beam or the pressure and composition of residual gas in the beam tube can be chosen to feed the beam with light ions. Special regimes of ion cooling were also proposed to prevent the under barriers ion losses [14].

To summarize, two conditions are necessary for ion cooling:

- the negative potential for ion confinement;
- high rate of elastic ion-ion collisions for the ion energy thermalization in the beam.

Ion cooling or evaporation cooling is one of the most effective methods to produce highly charged ions not only in EBIS and EBIT now but in the Electron-Cyclotron Resonance ion sources as well [13].

Results

Let us apply the above theoretical methods and models to concrete electron beams for electron cooling and ion sources with real parameters. Three beams are considered here: Model of Solenoid (MOSOL) in Novosibirsk [16]; LEAR at CERN [17] and ion source KRION-2 at Dubna. The main beam parameters are given in the upper part of the Table.

Table

setup	MOSOL	LEAR		KRION-2	
electron energy, keV	0.5	2.5	27	5	100
beam current, A	0.003	0.25	1.5	≤ 0.2	≤ 0.2
beam radius, cm	0.1	2.5	2.5	0.015	0.015
beam length, cm	0.4 - 2.7	3.2	3.2	1.2	1.2
magnetic field, kG	1.5	0.4 - 0.6	0.4 - 0.6	22.5	22.5
ion atomic number	1 - 14	1 - 14	1 - 14	12-84	12 - 131
vacuum pressure, nTorr	0.3	0.03	0.03	0.001	0.001
electron density, 10^9 cm^{-3}	0.5	0.025	0.05	≤ 500	≤ 100
neutralization factor	0.9	0.7	0.9	0.1 - 0.5	0.5 - 0.9
electron beam potential, V	2	70	150	50	10 - 30
ionisatio rate, $10^{18} cm^{-2} s^{-1}$	≤ 1.0	≤ 0.1	≤ 0.5	≤ 200	≤ 2000
charge states	$\leq N^{5+}$	$\leq C^{4+}$, O^{6+}	$\leq C^{4+}$, O^{6+}	$\leq N^{7+}$	$\leq Kr^{36+}$, Xe^{54+}
neutralization time, s	1(H^+), 0.1(N^{4+})	10(H^+), 2(C^{2+})	40(H^+), 3(C^{3+})	10^3(H^+), 30(N^{5+})	10^3(H^+), 30(N^{5+})
ion heating rate, eV/s	1.0	0.02	0.01	1000	200 - 400
ion-ion colling rates, s^{-1}	$\leq 10^5$	< 10	< 10	$\leq 10^4$	$\leq 10^6$

MOSOL. The MOSOL beam has a relatively low electron energy and beam current. The beam has low radial electric field but the electron and, accordingly, ion densities are not bad because of a small beam radius. Therefore, the electron-ion and ion-ion collision rates are high and neutralization time is very low (see Table). One could suggest the following general picture of ion accumulation and loss.

The ions fill the beam during the time of 100 ms. The Boltzman energy distribution is established momentary because of the high rate of ion collisions. If the residual gas contains hydrogen, then H^+ ions work as a coolant for nitrogen ions and leave the beam. Thus, nitrogen ions are dominant in the beam, they have good confinement conditions in the trap and charge states of 4+ or 5+ (6+ is low, probably, due to the low electron energy). The ions have the Boltzman energy distribution and the under barrier losses can play an important role. It may be a reason of incomplete compensation of the beam space charge at high vacuum conditions. A possible way to improve the situation and grow up the rate of beam compensation is to make the neutralization rate comparable with the ion collision rate. The most evident way of that is to increase the density of residual gas in MOSOL.

LEAR. The LEAR beam has a wide range of electron energies and currents. But one could see from the Table that the ion processes do not differ much either for the minimum or maximum parameters. The beam has high current and electrical potential. But the beam diameter is very large and the electron density is, accordingly, low. Therefore, the beam has a low rate of elastic collisions and the formulae and relations (6 - 13) can be applied for ion consideration before the beam neutralization. But the rate of electron heating of beam ions is extremely low and the ions with charge states $i > 1$ should have their energies much less than the potential barrier and be concentrated along the beam axis according to the above formulae. This increases the ion-ion collision rate, causes the ion energy thermalization and under barrier losses of ions, in particular, low charge state species. Thus, it can be a cause of equilibrium with incomplete beam neutralization in LEAR, especially, for the low beam energy.

Hydrogen usually dominates in the chamber at such high vacuum conditions as LEAR has, and the residual gas consists of H_2 (90%), CO and C_2H_4. Nevertheless, the H^+ ions can not accumulate in the beam due to the low ionization rate of neutral hydrogen and intensive under barrier losses of the H^+ ions as the result of energy transfer from heavier ions in the beam. So, most probable ions should be C^{2+} or O^{3+}.

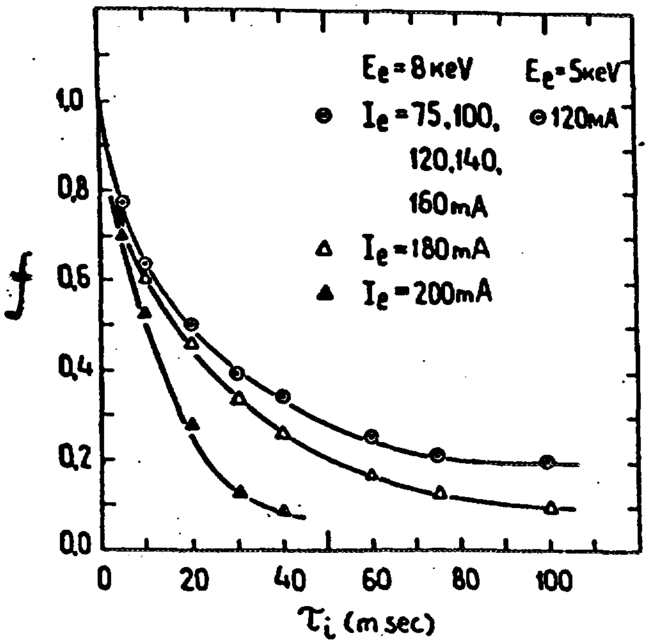

Figure 4. The dependence of beam neutralization factor f on the confinement time of the beam [2].

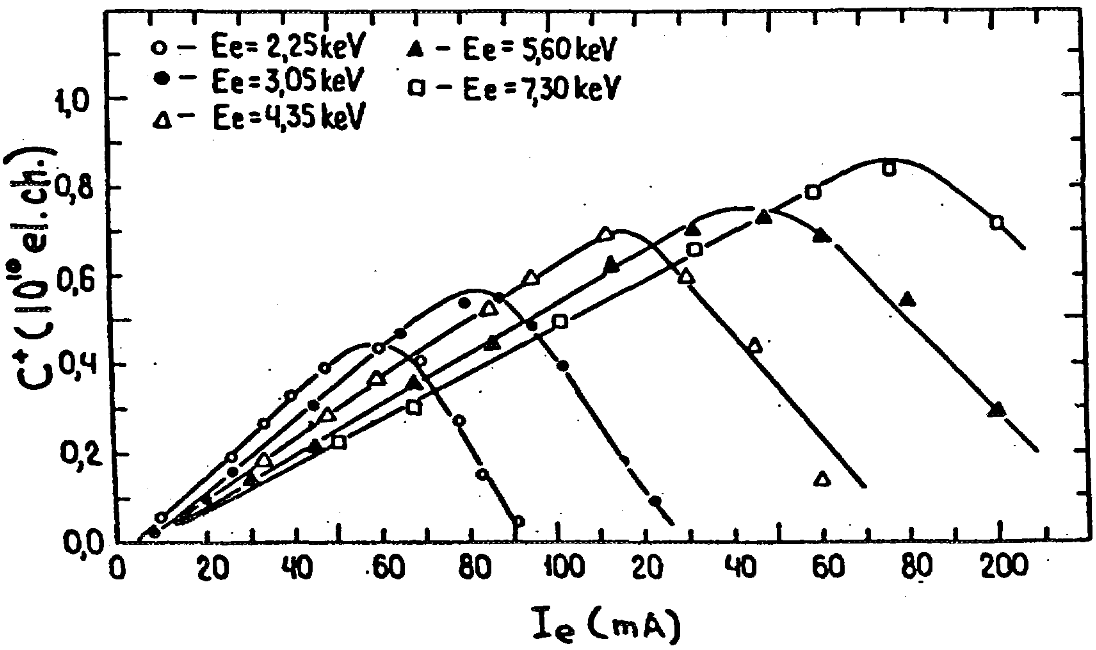

Figure 5. The dependence of the beam capacity on the beam current I for the different electron energies [2].

KRION-2. The peculiarities of ion accumulation and confinement were studied in details experimentally [2] and theoretically [5] and published. We shall remind here the most important of them. KRION has a very thin, high density and energy electron beam. The main purpose is to produce extremely high charge states of heavy ions. The beam has a very high ionization rate as well as elastic scattering rate. Thus, the main disadvantage of EBIS and EBIT is the high rate of electron heating and under barrier ion losses [14]. The great problem is to keep heavy highly charge ions in the beam till the end of the ionization cycle that is in the range of seconds or even minutes now. Ion cooling is the most effective way to decrease ion losses in EBIS and EBIT. The second problem is the charge exchange process between residual neutrals and highly charged ions. This process is able to limit the value of attainable charge states in the sources and requires the vacuum pressure better than 10^{-12} Torr in the beam tube.

The problem of beam neutralization was studied carefully in the first variants of KRION-2. It was found that the neutralization factor increases during the first short period of beam confinement up to the full beam compensation and then decreases to saturation. The equilibrium value of neutralization factor or the beam capacity depends strongly on the electron current and energy. And the beam capacity has the maximum with the beam current increasing for the given electron energy. These effects can be explained very well with electron heating and loss of ion during the confinement time. In the table one can see that electron heating and ion-ion energy exchange are in the same oder of magnitude for the low electron energy of KRION. Thus, ion losses appear after ion injection into the trap and heating within tens of ms. The equilibrium between electron heating and under barrier losses of ions is established and it depends on the beam current or heating rate.

Fig. 4 shows the dependence of beam neutralization on the confinement time of the beam. Fig. 5 presents the dependence of the beam capacity on the beam current for different electron energies. These results were obtained for the low beam energies of KRION and might be very interesting now for the problem of beam neutralization for electron cooling.

Conclusions and Acknowledgments

The above considerations have shown that inspite of different aims of the electron beams for cooling systems and ion sources, they have very similar physical processes of ion accumulation, confinement and losses. Some results of the ion sources study can be successfully applied for the electron cooling beam consideration to explain the experimental results from the physical point of view and simulate them mathematically. These methods will be useful, probably, to develop the electron cooling technique with beam neutralization, for example, to regulate beam neutralization and charge states of accumulated ions. Naturally it is the first experience of such collaboration but it brings us the reasons for further joint investigations.

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Накопление ионов и нейтрализация пространственного заряда в электронных пучках для ионных источников и электронного охлаждения

Электронно-лучевые ионные источники (EBIS), электронно-лучевые ионные ловушки (EBIT) и электронные пучки для электронного охлаждения имеют близкие значения параметров. Ионы образуются и накапливаются в EBIS и EBIT в результате ионизации электронным ударом. Пучок для электронного охлаждения накапливает положительные ионы из остаточного газа в ускорительной камере в течение цикла охлаждения. Зарядовую нейтрализацию охлаждающего пучка используют для уменьшения энергетического разброса электронов и увеличения эффективности охлаждения. В работе результаты многолетних экспериментальных исследований и теоретических моделей электронных пучков EBIS применены для изучения проблемы нейтрализации пучка в устройствах электронного охлаждения.

В работе представлен анализ наиболее важных процессов, связанных с получением, накоплением и потерями ионов в интенсивных электронных пучках ионных источников и систем электронного охлаждения для протонных и ионных коллайдеров. Обсуждаются процессы упругого и неупругого столкновения частиц в электронном пучке. Неупругие столкновительные процессы, такие как ионизация, перезарядка и рекомбинация изменяют зарядовые состояния ионов и нейтральных атомов в пучке. Упругие кулоновские столкновения изменяют энергию частиц и вызывают перераспределение энергии между компонентами в электрон-ионных пучках. Определены характерные времена и особенности процесса ионизации, нейтрализации пучка, нагрева и потерь ионов в электронных пучках ионных источников и установках электронного охлаждения. Изучается зависимость отрицательного потенциала в поперечном сечении от фактора нейтрализации пучка.

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Ion Accumulation and Space Charge Neutralization in Intensive Electron Beams for Ion Sources and Electron Cooling

The Electron Beam Ion Sources (EBIS), Electron Beam Ion Traps (EBIT) and electron beams for electron cooling application have the beam parameters in the same ranges of magnitudes. EBIS and EBIT produce and accumulate ions in the beam due to electron impact ionization. The cooling electron beam accumulates positive ions from the residual gas in the accelerator chamber during the cooling cycle. The space charge neutralization of cooling beam is also used to reduce the electron energy spread and enhance the cooling ability. The advanced results of experimental investigations and theoretical models of the EBIS elctron beams are applied to analyze the problem of beam neutralization in the electron cooling techniques.

The report presents the analysis of the most important processes connected with ion production, accumulation and losses in the intensive electron beams of ion sources and electron cooling systems for proton and ion colliders. The inelastic and elastic collision processes of charged particles in the electron beams are considered. The inelastic processes such as ionization, charge exchange and recombination change the charge states of ions and neutral atoms in the beam. The elastic Coulomb collisions change the energy of particles and cause the energy redistribution among components in the electron-ion beams. The characteristic times and specific features of ionization, beam neutralization, ion heating and loss in the ion sources and electron cooling beams are determined. The dependence of negative potential in the beam cross section on neutralization factor is studied.

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

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