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The EBIS/T as a Coulomb Target for Ions

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Abstract. A partially neutralised electron beam can be considered as a well defined target of ions. Trapped in the electrostatic 3D-trap of the electron beam in an EBIS, they will - for low loss rates - acquire an energy distribution according to Boltzmann’s law. The resulting spatial distribution then is well defined, once the ion temperature and the amount of ions are known. Both are related to each other by a monotone dependence, hence determination of either, the ion temperature, or the number of ions will give the second quantity.

Such a Coulomb target provides friction to the radial movement of newly injected ions, hence can be used to facilitate the trapping of low charged injected ions (external ion source, charge breeder) or of cooling of highly charged ions (created by deceleration). Due to the well known properties of such a target, it also may be used for collision studies between trapped ions and either a beam of atoms or of additionally injected ions.

INTRODUCTION

The neutralization of electrons beams by ions, created by collisions of the beam electrons and the corresponding atoms, has been treated quite often in the past as a mere reduction of the primary beam space charge by a factor of neutralization. A closer approach to reality is obtained by considering the first ions being born in the empty potential with an average transverse energy corresponding to half of the electron beam potential depression and the assumption that this energy will be distributed to all degrees of freedom by mutual collisions of the ions, ending with a thermal distribution, characterized by a temperature. These thermal ions, however, will exhibit a spatial distribution resulting from Boltzmann’s law, hence will have highest density in the center of the electron beam and extend outside of it to the tubes, where they must be considered as to be lost. If these losses are significant with respect to the amount of trapped ions and the time of consideration, the simple picture of a Boltzmann distribution no longer will hold and we need to solve the Boltzmann transport equation. In the electron beams of EBIS/T devices, however, equipartitioning of ion energies by collisions is much faster than the inverse loss rate, typically some µs as compared to ms. Therefore, losses can be neglected and the local ion distribution may be considered as a result of Boltzmann’s law acting on the local radial potential in the electron beam. Then a simulation of the stationary and very nonlinear case is possible. As a result the temperature and the
radial distribution function of the ions are related to each other, expressed by a monotonic dependence of the central degree of neutralization in dependence of the temperature.

As a consequence, the ion target of a partially neutralized electron beam is well defined and can be used for EBIS/T physics applications as well as for atomic physics studies, where otherwise a definition of the overlap integral is the most critical issue.

**NEUTRALISATION OF THE ELECTRON BEAM**

The radial Poisson equation

\[ \Delta U(r) = \frac{\partial^2 U}{\partial r^2} + \frac{1}{r} \frac{\partial U}{\partial r} = -\frac{\rho_b + \rho_c}{\varepsilon_o} \]

where \( U \) stands for the potential, \( \varepsilon_o \) denotes the dielectric constant, and \( \rho_b \) and \( \rho_c \) give the space charge of beam and compensating particles, being defined by:

\[ \rho_b = \frac{I_b}{\pi r_b^2 \sqrt{2eU_0}} \]

where \( I_b \) is the beam current, \( r_b \) is the beam radius, and \( U_0 \) the potential difference on the axis to the cathode

and \( \rho_c(r) = -f_c \rho_b \exp \left\{ -\frac{e[U(r) - U(r_s)]]}{kT_c} \right\} \]

where \( f_c \) is the degree of central compensation, has been solved [1] for various ratios of

\[ \mu_b = \frac{e[U(r_s) - U(r_c)]}{kT_c} \]

which measures the potential difference in the uniform (uncompensated) beam in units of the thermal temperature of the compensating particles. For any given temperature \( T_c \), there is one distinguished solution where the tube surrounding the beam contains per length the same amount of positive and negative charges. This is considered as "full" compensation, although the degree of central compensation \( f_c \) has a characteristic value smaller than unity (Fig. 1). Another important quantity for the understanding of space charge compensation is the potential difference between the axis and the surrounding tube, also related to the thermal energy of the ions:

\[ \mu_t = \frac{e[U(r_s) - U(r_c)]}{kT_c} \]

The variation of \( f_c \) and \( \mu_t \) in dependence of \( \mu_b \) is shown in Fig. 2 for a ratio of beam to tube radius of 1:10. It may be concluded, that the colder the temperature of the compensating
particles, the higher becomes the central compensation. A complete neutralisation is not possible at finite temperature as long as the ion production rate is low enough. The dynamics of neutralisation provides cooling of all ions, because newly created ions always are colder than existing ones. The remaining potential difference between the axis and the tube, measured in units of $kT_e$ shows an important result: For colder particles, the repelling potential wall becomes relatively higher and steeper (compare Fig. 1), although it decreases towards higher neutralisation. This confines the neutralising particles more and more to the beam, the higher the degree of neutralisation becomes, which is a surprising result at first glance, but very useful for EBIS devices.

![Radial voltage variation and radial distribution of space charge densities](image)

**FIGURE 1.** Radial voltage variation (left panel) and radial distribution of space charge densities (right panel) for the neutralization of an uniform (cold) beam by thermal ions. Parameter is the normalized temperature of the ions $\mu_b$. The electron current is 0.62 A, producing at 10 keV beam energy a potential depression inside the beam of 100 V.

A very different view on beam neutralisation is obtained, by solving the Poisson equation continuously and slowly adding more and more ions. This is kind of a dynamical simulation, showing, how the neutralisation of the electron beam develops with time [2]. In this case, the temperature of the trapped ions continuously decreases, while the central degree of neutralisation increases until it reaches the state of “full” neutralisation, where still electrostatic fields exist, because the radial distribution of electrons and ions is different, as shown in Fig. 1b. For the use of an electron beam as an ion target it is also interesting to look at the overlap between electrons and ions, which is plotted in Fig. 3 in dependence of the neutralisation time. Obviously the overlap is all the time somewhat below 80%, which will give – if not taken into account – ionisation cross sections, which are by about 20% too low.
FIGURE 2. Central degree $f_c$ of neutralization for a uniform (cold) beam by thermal ions (left scale) and depth of the potential well between axis and tube $\mu_t$, in dependence of the temperature of ions $\mu_b$ (see definitions in the text).

FIGURE 3. Degree of central compensation $f_c$ and electron-ion overlap with time (the straight line shows, how compensation is reached without losses, by this scaling the time).
COULOMB COLLISIONS

As demonstrated by experiments of many EBIS/T groups, evaporative heating works quite efficiently to exchange energies between different ion species in the trap of an electron beam. Without losses, however, this leads to equipartitioning of energies, while with losses, lower charged ions are lost preferentially. Basis of the energy exchange are soft collisions of ions with different mass and charge and a velocity distribution according to their temperatures. We use the classical binary encounter approximation for Coulomb collisions between two ions i and j [3], where i will be associated with the target ion, while j stands for the injected ions:

\[
\tau_{i,j} = \frac{2\pi}{j_e j_e} \ln \Lambda \left( \frac{e_i m_i}{q_i q_j} \right)^2 \left( \frac{v_{i,j}}{e} \right)^3
\]

where

- \( e = 1.60218 \times 10^{-19} \text{ As} \) (elementary charge)
- \( m_e = 0.910939 \times 10^{-30} \text{ kg} \) (mass of the electron)
- \( m_u = 1.66054 \times 10^{-27} \text{ kg} \) (atomic mass unit)
- \( m_{i,j} = m_p A_{i,j} \) (atomic weight of ions i,j)
- \( m_r = m_i m_j / (m_i + m_j) \) (reduced mass)
- \( U_e \) = electron beam acceleration voltage
- \( f_c \) = local degree of neutralisation
- \( j_e \) = electron current density in A/m²
- \( \epsilon_0 = 8.85419 \times 10^{-12} \text{ As/Vm} \) (dielectric constant)
- \( q_i \) = charge of the target ion (at rest)
- \( q_j \) = charge of the injected ion with velocity
- \( v_{i,j} \) = relative velocity of ions i and j in m/s
- \( \ln \Lambda = 12 \) (Coulomb logarithm)

For reasonable values \( (U_e=10000 \text{ V}, j_e=10^7 \text{ A/m²}, f_c=1, v_{i,j} \) corresponding to an energy of 10 eV/ion) collision times as given by eq. 6 are compared with the time-of-flight time for travelling twice a 1 m long EBIS and for the ionisation time of the respective ions.

| \( A_i \) | \( q_i \) | \( A_j \) | \( q_j \) | \( \tau_{i,j} \) | \( \tau_{tof} \) | \( \tau_{ionisation} \) |
|---|---|---|---|---|---|---|
| 4 | 2 | 200 | 1 | 1.8876E-08 | 6.4621E-04 | 1.0000E-06 |
| 14 | 6 | 200 | 1 | 2.3347E-08 | 6.4621E-04 | 1.0000E-06 |
| 20 | 8 | 200 | 1 | 2.5359E-08 | 6.4621E-04 | 1.0000E-06 |
| 40 | 16 | 200 | 1 | 2.1309E-08 | 6.4621E-04 | 1.0000E-06 |
| 4 | 2 | 236 | 92 | 1.7503E-12 | 7.0196E-04 | 1.1462E+02 |
| 14 | 6 | 236 | 92 | 2.1956E-12 | 7.0196E-04 | 1.1462E+02 |
| 20 | 8 | 236 | 92 | 2.4037E-12 | 7.0196E-04 | 1.1462E+02 |
| 40 | 16 | 236 | 92 | 2.0679E-12 | 7.0196E-04 | 1.1462E+02 |
The values in the table show clearly that the Coulomb collision time is always short with respect to the time-of-flight and the ionisation time. This means that within the time-of-flight or the ionisation time, equipartitioning by Coulomb-collisions has taken place between all ions inside the electron beam. The kind of target ions is of minor importance, since with heavier mass always the charge charge state also increases. Then, however, it will be much easier to provide a cold target of helium ions than one with already highly charged argon ions.

**APPLICATION OF COULOMB TARGETS**

1) Injection of singly charged ion for charge breeding

![Axial potential scheme inside of an EBIS for continuously trapping by ionization of singly charged ions for charge breeding (ACCUEBIS)](image)

FIGURE 4. Axial potential scheme inside of an EBIS for continuously trapping by ionization of singly charged ions for charge breeding (ACCUEBIS)

In Fig. 4 the operation of an ACCUEBIS [4] for charge breeding is shown. The basic idea is trapping of injected single charged ions, which are just able to overcome the trap barrier at the right-hand side by ionization events inside the trap. Table 1 shows, that this is very likely to occur. Coulomb collisions of these ions with ions forming a Coulomb target by partially neutralizing the electron beam, however, will be even more frequent and will assist in cooling these ions, enhancing the trapping efficiency.
2) Cooling of highly charged ions

![Diagram showing axial potential scheme inside of an EBIS for continuously injecting and cooling highly charged ions by Coulomb collisions (TOFEBIS-COOLER).]

Using buffer gas cooling in a radial focusing channel, the emittance of singly charged ions may be improved by orders of magnitude. For highly charged ions, however, gas pressures as used in these devices in the range of $10^{-2} - 10^{-3}$ mbar are lethal for highly charged ions. In Coulomb collisions, however, the distance of the ions remains sufficient distant to prevent charge exchange. Therefore a partially neutralized electron beam may be well suited to cool highly charged ions in a double pass of time-of-flight forward and backward along the electron beam. In this case the collision times are so short with respect to the time-of-flight, that much higher ion energies than 10 eV are acceptable for efficient cooling. This allows for a sufficient raise of the potential barrier at the right hand side to trap the ions, which are forming the Coulomb target. These ions will remain cold by a continuous loss over the not perfectly closed barrier and by a continuous feeding of new gas.

3) Ion-Ion-collision studies

By extracting all ions of the Coulomb target in a short pulse, as usual for EBIS ion extraction, their amount can be determined. In comparison with the well know radial distribution this will allow to determine the degree of central neutralization and consequently, using the monotonic relation shown in Fig. 3, the temperature of these ions. With this the ion target is well defined to be used as a target for ion-ion and ion-neutral collision studies.
CONCLUSIONS

It has been shown that Coulomb collisions of different ion species are very effective and that a partially neutralized electron beam of an EBIS/T device can be used as a target for injected ions. These may be singly charged ones for charge breeding or very highly charged ones for ion-ion-cooling. Since the radial and temperature distribution of this target is well known and the relevant parameters as the central degree of neutralization and the temperature of the ions may be easily determined by ion extraction, this target is also well suited for atomic physics studies on ion-ion-collisions.

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