Mono-energetic heavy ion beam source

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Monochromatic heavy ion beam production from a monochromatic electron (e-) beam is studied. Relating to such a mono-energetic ion source (MEIS), we have derived relevant analytical expressions and calculated the total ionization time (τ_{iZ}) needed for production of various nuclei or fully-stripped ions by step ionization process in an e-beam ion source (EBIS). It was found that the τ_{iZ} can be expressed by a simple function of the atomic number (Z), specially in the range of heavy ions, $Z \geq 4$. The results are graphically presented. Advantages of using the MEIS as pre-accelerators or nuclide sources are discussed.

Introduction

Multiply ionized ion sources are popular as an injector for accelerators because one may obtain high-energy particles without applying a high-voltage and a high magnetic field in linacs and cyclotrons, respectively. A z-times ionized ion, n_z (where $z = 1, 2, 3, \ldots, Z$), will see z-times larger acceleration potential than actually applied, V_a, in the diode gap of ion sources (IS's) or linacs, thereby achieving z-times higher kinetic energy when accelerated. This gain is even greater, z^2-times, in cyclotrons when n_z, rather than n_1 (singly ionized ion), is injected. For instance, a mere $V_a = 10.9$ kV supply would be sufficient for uranium ($Z = 92$) bare nuclei to be accelerated up to 1 MeV if its atomic electrons were completely stripped.

However, conventional multiple-ionization IS's are unable not only to reach such a high-z state but also to generate monochromatic ion beams due to the CW operation and the source of a variety of z's. Such an IS is a 'white-source' after accelerated in terms of the energy spectra. An expensive energy analyzer is thus necessary for extraction of a mono-energetic beam. This is a waste of beam energy since the other beams are unused although they are the same nuclear species. Insertion of an energy analyzer often cuts the beam size needed for later applications like a large area ion implantation. The mono-energetic ion source (MEIS) proposed here would extract ions out of the IS only after all members had reached a specified high-z state, thereby utilizing all the ions thus far produced and extracting only a mono-energetic ion beam. The MEIS is possible to conserve the original beam size, and furthermore, economical since one can skip a sector-magnet mass/charge spectrometer. Problem of contamination of working gas ions, if any, can be overcome by using the gas ions with opposite polarity from the ions to be accelerated.

In MEIS the e-beam energy, E_b, is high in order to achieve an extremely high z state, but ions are trapped by the electrostatic potential of the e-beam just like an EBIS.[1)] Recent concept of 'ion traps' is nothing but an EBIS-and-Penning IS hybrid which traps ions as well as electrons, thereby enabling to confine ions for more than a day.[2)] Differences of MEIS from EBIS are not only the high-E_b but also the carefully programmed waiting period with an explicit purpose of extracting unique (m/q)-component without relying on an energy analyzer. The MEIS will thus be operated in a pulse mode. Yet, the timing with the period of a given cyclotron should not be a problem because the relevant ion extraction/injection time from MEIS to accelerator can be matched exactly by adjusting the e-beam current density, j_e, as well as E_b. Obviously, the time averaged particle flux (dose) is the same for either pulse or CW modes of operation.

The electron beam ion trap

The MEIS concept relies on a long confinement time of ions. Let us consider an EBIS configuration where positive ions will be trapped inside a parabolic potential-well, ϕ, of an e-beam externally injected. The electrostatic potential of an e-beam can be calculated similarly to the case of a charge cylinder with radius, r_b. Solving the Poisson equation, $\nabla^2\phi \equiv (1/r)(\partial/\partial r)[r(\partial\phi/\partial r)] = -(\rho_o/\varepsilon_o)$, we obtain $\phi = -(\rho_o r^2/4\varepsilon_o)$ for $r \leq r_b$ and $= A\ln r + B$ for $r \geq r_b$. Here $\rho_o \equiv n_e e$, where $n_e \equiv I_b/Sev_e = (I_b/\pi r_b^2 e)\sqrt{m_e/2eV_b}$, since $(1/2)m_e v_e^2 = E_b \equiv eV_b$. Thus, the ion trapping e-beam potential can be expressed numerically,

$$\phi(r \leq r_b) = 1.52 \times 10^4 \left(\frac{r}{r_b}\right)^2 \frac{I_b[\mathrm{Amp}]}{\sqrt{E_b[\mathrm{eV}]}} \qquad [\mathrm{V}] \qquad (1)$$

In 'ion traps', the ion kinetic energy is cooled down by laser to satisfy the trapping condition, $(1/2)\kappa T_i \leq \phi_{\max} \equiv \phi(r = r_b)$, by which ions are confined indefinitely if no diffusion takes place. A large E_b essential for MEIS shall be compensated by producing a large beam current, $I_b \equiv Sj_e$, to achieve a large ϕ, according to Eq. (1).

Ionization time needed for production of fully stripped ions

Atoms in an MEIS are ionized by free-electron impacts if $E_b \geq E_\infty^o$. Here, E_∞^o denotes the ionization energy of neutrals. The multiply ionized ions, n_z (where $z \geq 2, 3, \ldots, Z$), are then produced from n_{z-1} if $E_b \geq E_\infty^{z-1}$ [step-wise ionization]. If bound-electrons of the n_{z-1} ion are readily excited to the level $n = 1, 2, 3, \ldots$, its binding energy can be expressed by the Rydberg formula:

$$E_\infty^{z-1} - E_n^{z-1} \approx \frac{z^2 E_H}{n^2}, \quad E_\infty^{Z-1}(1s) \approx 13.6Z^2 \qquad (2)$$

Here, $E_n^{z-1} = 0$ for $n = 1$, $E_H \equiv 13.595$ eV, and Z is the atomic number (notice the difference of capital Z from small z). The second formula in Eq. (2) is the ionization energy needed to ionize the last $1s$-electron in the K-shell for obtaining fully stripped ions.

Figure 1 compares various ionization potentials, where data by Lotz[3] were plotted till $Z \leq 26$ and Atomic Data were used for $Z \geq 26$. The theoretical best fit curves are $E_\infty^{Z-2}(1s^2) \approx 6.83Z^{2.2}$ and $E_\infty^{Z-3}(2s) \approx 0.6Z^{2.5}$.

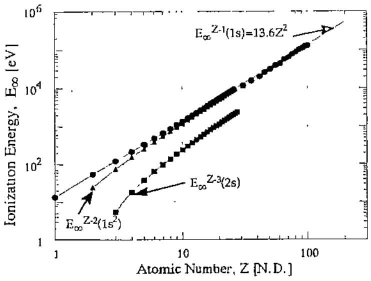

Fig. 1. Ionization potentials of K and L shells, and its theoretical best fit curves.

The rate with which n_z ions are produced by the electron impact against n_{z-1} ions is given by

$$\frac{dn_z}{dt} = n_e < \sigma_{z-1,z} v_e > n_{z-1} - \frac{n_z}{\tau} - \eta_e n_e n_z \quad \left[\frac{1}{\text{cm}^3\text{sec}}\right] (3)$$

Here, $\sigma_{z-1,z}$ is the cross-section of step ionization from $z-1$ to z ions, η_e the ion-electron recombination coefficient, τ the time constant of n_z confinement inside the e-beam, and the rests are of usual meanings. The last (recombination loss) term in Eq. (3) is negligible compared with the second (diffusion loss) term in MEIS. Then, since $< \sigma v >= \sigma v$ for mono-energetic e-beam, the general and steady state ($dn_z/dt = 0$) solutions of Eq. (3) are: $n_z/n_{z-1} = n_e \sigma_{z-1,z} v_e \tau[1 - \exp(-t/\tau)]$, and $n_z/n_{z-1} = n_e \sigma_{z-1,z} v_e \tau$, respectively. The condition, $n_z/n_{z-1} = 1$, is achieved by the time $\tau_i = 1/n_e \sigma_{z-1,z} v_e$. Thus, the total of multiple ionization times needed to convert neutrals ($z - 1 = 0$) into $z = Z$ charge state is

$$\tau_{iZ} = \frac{e}{j_e} \sum_{z=1}^{Z} \frac{1}{\sigma_{z-1,z}} \quad [\text{sec}], \qquad j_e \equiv e n_e v_e \quad \left[\frac{\text{A}}{\text{cm}^2}\right] (4)$$

where $e = 1.6 \times 10^{-19}$ [A/sec].

Approximation of the total ionization time

We calculate Eq. (4) by using an empirical formula of the step-wise electron impact ionization cross-section, developed by Lotz[3] based on the Born-Bethe approximation,

$$\sigma_{z-1,z} = \frac{a_z q_z \ln U_z}{(E_\infty^{z-1})^2 U_z} \{1 - b_z \exp[-c_z(U_z - 1)]\} \quad [\text{cm}^2](5)$$

Here, $U_z \equiv E_b/E_\infty^{z-1} \geq 1$, $a_z = 1.6 \sim 4.5 \times 10^{-14}$ cm^2 (eV)^2 for $z \geq 1$ and $= 4.5 \times 10^{-14}$ cm^2(eV)^2 for $z \geq 4$, $b_z = 0 \sim 0.92$ for $z \geq 1$ and $= 0$ for $z \geq 4$, and $c_z = 0.2 \sim 0.6$ for all z's. The q_z is the number of equivalent electrons in the z-th sub-shell. Equation (5) was found to agree almost perfectly with experimental results as well as a different theory[4] provided that $E_b = 2\kappa T$ is used for thermal ($T_e = T_i = T$) plasmas.

Obviously, the dominant terms in Eq. (4) are of the smallest cross-sections for removing the $1s$ and $1s^2$ electrons in the inner-most (K) shell. For $1s$ electrons, we have $q_z = 1$, $E_\infty^{Z-1}(1s)$ given by Eq. (2), and $b_z = 0$ for heavy ions ($Z \geq 4$) in Eq. (5). Hence, the last ($1s$) electron ionization cross-section is,

$$\sigma_{Z-1,Z} \approx \frac{2.43 \times 10^{-16}}{Z^4} \frac{\ln U_z}{U_z} = \frac{8.94 \times 10^{-17}}{Z^4} \quad [\text{cm}^2] \quad (6)$$

The last term of Eq. (6) is the peak of the $\sigma_{Z-1,Z}$ since $\ln U_z/U_z$ takes the maximum value 0.36792 at $U_z = 2.718$ or when $E_b = 36.96Z^2$ [eV].

For $1s^2$ electrons, on the other hand, $q_z = 2$ and $E_\infty^{Z-2}(1s^2) \approx E_\infty^{Z-1}(1s)$ for $Z \geq 4$ as seen in Fig. 1. Thus, we obtain an asymptotic formula of Eq. (4) for $Z \geq 4$, with which the minimum ionization time needed for producing heavy nuclei can be calculated:

$$\tau_{iZ} = \frac{1.78 \times 10^{-3} Z^4}{j_e[\text{A/cm}^2]} \left[1 + \frac{1}{2} + \ldots\right] \approx \frac{2.67 \times 10^{-3} Z^4}{j_e[\text{A/cm}^2]} [\text{sec}] \quad (7)$$

The third term in bracket is quite small because, although $q_z = 1$ for $2s$ electron, $E_\infty^{Z-3}(2s)$ is smaller than $E_\infty^{Z-2}(1s^2)$ by approximately 6-times, as seen in Fig. 1. Therefore, the approximation error in Eq. (7) should be less than 3%.

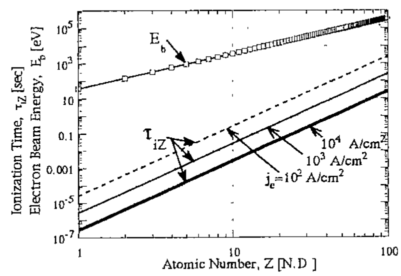

Fig. 2. Ionization times for production of various nuclei from the atoms, and the electron beam energy to minimize the process time.

Figure 2 plots Eq. (7) with different current densities as a parameter, together with $E_b = 36.96Z^2$ [eV] which is the energy required for the nuclide production by the minimum process time. For an example, if $j_e = 10^4$A/cm^2, the U^{+92} production by $V_b = 313$ keV e-beam requires $\tau_{iZ} = 22.6$ sec. Further, Eq. (7) gives $\tau_{iZ} = 26.7$ msec in the case of Ne^{+10}. This agrees with experiment; the time to achieve $n_{10}/n_9 = 1$ in Ne ions was indeed $19 < t < 80$ msec experimentally,[1] as seen in Fig. 3.

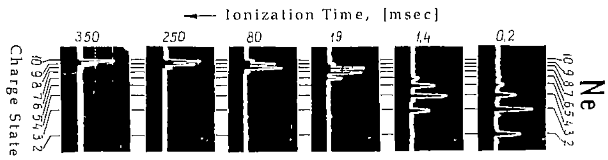

Fig. 3. An experimental result showing time dependent charge state of Ne ions, after Donets[1].

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