Transport of Space Charge Dominated Multi Species Beam in a Solenoid Based LEBT

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Abstract. We have derived differential equations for the beam envelope of an axially symmetric space charge dominated multi-species beam and studied the transport of protons from 2.45 GHz microwave ion source in the presence of H_2^+, H_3^+ species. We have used slits in the beam line for the selection of beam of a particular species. Numerical results of the beam selection and transport have been presented for various values of the total beam current and different fractions of p, H_2^+, H_3^+ species.

Keywords: Space charge dominated beams, Particle beam transport.
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INTRODUCTION

Intense proton ion sources are widely used in the injection system of high intensity accelerators. The most desirable requirement from such sources is to have high proton fraction in the extracted beam. The typical value of the proton fraction from microwave ion sources is of the order of 80 - 85% of the extracted beam [1]. The major unwanted species are H_2^+ and H_3^+ ion beams. The presence of these unwanted species in a high intensity beam alters the dynamics of the main proton beam during the transport. Elimination of systematic errors in envelope modeling can improve the precision of the envelope matching which is important in limiting the generation of beam halo and related particle losses [2- 5].

We have developed differential equations for the beam envelope of an axially symmetric space charge dominated multi-species beam. To illustrate the usefulness of the theoretical development, we have studied the transport of protons from 2.45 GHz microwave ion source in the presence of H_2^+, H_3^+ species through a transport line consisting of two solenoids. We have used slits in the beam line for the selection of beam of a particular species. Numerical results of the beam selection and transport have been presented for various values of the total beam current and different fractions of p, H_2^+, H_3^+ species.

MULTI-SPECIES ENVELOPE EQUATION

We consider an axi-symmetric continuous intense multispecies charged particles beam propagating in a solenoid based low energy beam transport line. The equation of motion for a particle of species j can be written as

$$\gamma_j m_j \beta_j^{\,2} c^2 x'' = Fx_j^{ext} + \frac{q_j Ex_j^{(s)}}{\gamma_j^{\,2}} + q_j \sum_{\substack{k=1 \\ k \neq j}}^{n} (1-\beta_j \beta_k) Ex_k^{(s)} \tag{1}$$

For axisymmetric and uniform density beam we can obtain electric field due to space charge of jth species Ex_j as

$$Ex_j(x) = \frac{I_j}{2\pi\varepsilon_0 \beta_j c r_j^{\,2}} \cdot x \,;|x| \le r_j \quad \text{and} \quad Ex_j(x) = \frac{I_j}{2\pi\varepsilon_0 \beta_j c} \cdot \frac{x}{r^2} \,;|r| > r_j \tag{2}$$

I_j is the current, r_j is the radius and β_j is the velocity of the beam of species j. Using the expression of electric field, the equation of motion of a particle of species j in x-direction can be simplified to

$$x'' = gx_j^{ext} + a_j \frac{x}{r_j^2(s)} + \sum_{\substack{k=1 \\ k \neq j}}^{n} b_{jk} \frac{x}{r_k^2(s)} \cdot \Theta(r_k(s) - r) + \sum_{\substack{k=1 \\ k \neq j}}^{n} b_{jk} \frac{x}{r^2} \cdot \Theta(r - r_k(s)) \tag{3}$$

with $a_j = \dfrac{q_j I_j}{2\pi\varepsilon_0 m_j \beta_j^{\,3} \gamma_j^{\,3} c^3}$, $\quad gx_j^{ext} = \dfrac{Fx_j^{ext}}{m_j \gamma_j \beta_j^{\,2} c^2}$, $\quad b_{jk} = \dfrac{q_j (1-\beta_j \beta_k) I_k}{2\pi\varepsilon_0 m_j \beta_j^{\,2} \gamma_j \beta_k c^3}$.

For solenoid focusing, the coupled form of the equations of motion causes a macroscopic rotation of the beam about the longitudinal axis. These equations take a simpler form in the Larmor frame which rotates at Larmor frequency with respect to the laboratory frame. The equation of motion of species j in the Larmor frame can be written as [6],

$$x'' = -kl_j^{\,2}(s) x + \frac{a_j x}{r_j^2(s)} + \sum_{\substack{k=1 \\ k \neq j}}^{n} \frac{b_{jk} x}{r_k^2(s)} \cdot \Theta(r_k(s) - r) + \sum_{\substack{k=1 \\ k \neq j}}^{n} \frac{b_{jk} x}{r^2} \cdot \Theta(r - r_k(s)) \tag{4}$$

where, $r^2 = x^2 + y^2 = x_L^2 + y_L^2$. We have a similar equation for y motion also.
Detailed derivation is given in ref. [6]. Here we write the final differential equation for envelope of each species due to the presence of other species which is given as,

$$r_j'' + kl_j^{\,2}(s) r_j - \frac{a_j}{r_j} - \frac{4\sum_{\substack{k=1 \\ k \neq j}}^{n} b_{jk} f\left(r_j(s), r_k(s)\right)}{r_j} - \frac{4\sum_{\substack{k=1 \\ k \neq j}}^{n} b_{jk} g\left(r_j(s), r_k(s)\right)}{r_j} - \frac{\varepsilon_j^{\,2}(s)}{r_j^{\,3}} = 0 \tag{5}$$

where $\quad f = \begin{cases} \dfrac{r_j^{\,2}(s)}{4 \cdot r_k^{\,2}(s)} & if \;\; r_j(s) \langle r_k(s) \\[2ex] \dfrac{r_k^{\,2}(s)}{4 \cdot r_j^{\,2}(s)} & if \;\; r_j(s) \rangle r_k(s) \end{cases}$ $\quad$ and $\quad g = \begin{cases} 0 & if \;\; r_j(s) \langle r_k(s) \\[1ex] \dfrac{1}{2} \cdot \left(1 - \dfrac{r_k^{\,2}(s)}{r_j^{\,2}(s)}\right) & if \;\; r_j(s) \rangle r_k(s) \end{cases}$

In order to select a particular species of the beam one has to put slits at appropriate places in the beam line. The current as well as the emittance of a species of the beam will be reduced if radius of that particular species at the slit is larger than the radius of the slit. After the slit, the resultant current of species j is $I_j = I_j \cdot \left(r_{slit} / r_j(slit)\right)^2$ if $r_j(s) > r_{slit}$ whereas $I_j = I_j$ when $r_j(s) \le r_{slit}$.

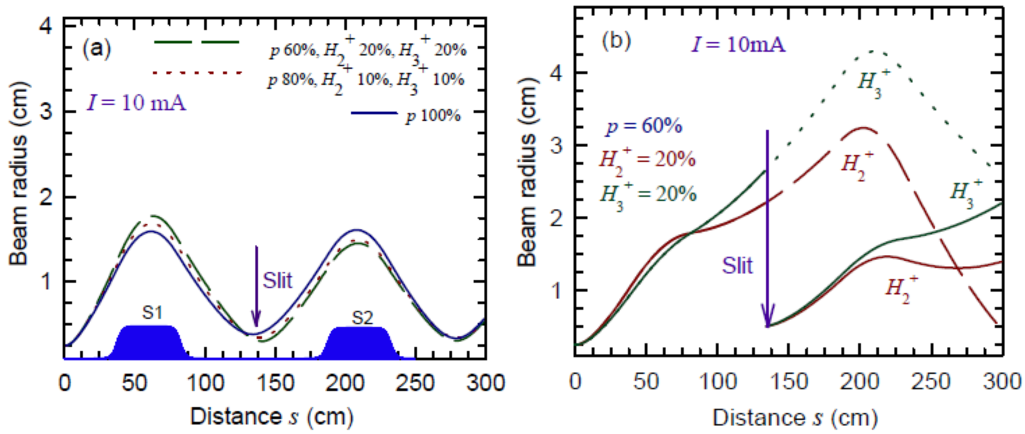

FIGURE 1. Evolution of the envelope radii of proton beam having three different fractions 60%, 80% and 100% in the total beam of 10 mA. In (b) we have shown the evolution of H_2^+ and H_3^+. The value of solenoid fields are S1 = 3.035kG and S2 = 2.883kG.

The modified emittance of species j, can be obtained by evaluating the phase space area that passes through the slit of radius r_{slit}. The effective emittance of species j after the slit is given by [6]

$$\varepsilon_{j\,eff} = \frac{\Delta A_j}{\pi} = \frac{2\varepsilon_j}{\pi} \cdot \left[p \cdot \sqrt{1-p^2} + \sin^{-1} p \right] \tag{6}$$

where, $p = r_{slit}/r_j(slit)$.

RESULTS AND DISCUSSION

The Variable Energy Cyclotron Centre at Kolkata is developing a 10 MeV, 5mA proton cyclotron. Its injection system consists of a 2.45 GHz microwave ion source and two solenoid magnets to transport and match the beam. The emittance of the beam from the ion source mainly depends on the ions temperature, slit size of the plasma electrode and the magnetic field in the extraction region. Typical values of normalised emittances for p, H_2^+ and H_3^+ ion species used in the numerical calculations are $\varepsilon_n(p)$ = 0.8 π mmmrad, $\varepsilon_n(H_2^+)$ =0.4π mmmrad and $\varepsilon_n(H_3^+)$= 0.27π mmmrad respectively.

The beam line consists of two solenoid magnets S1 and S2, each having physical length of 40 cm. The diameter of the beam pipe is 11cm. we have used a more realistic smooth field profile of the solenoids obtained using 3D magnetic field calculation. In Fig. 1(a) we have plotted the envelopes of proton beam along the axial direction for various proton fractions (60%, 80% and 100%) in the total beam current of 10 mA. Other components of the beam are H_2^+ and H_3^+. The location of the slit (radius 5mm) is indicated by an arrow. We can see that the proton beam envelopes for different fractions of proton behave differently in the presence of other components. For same total current, the presence of large fractions of H_2^+ and H_3^+ causes growth in the envelope of proton beam during the initial part. Before solenoid S1 the radii of H_2^+ and H_3^+ are smaller than the proton radius. Due to the space charge force of H_2^+ and H_3^+ the beam radius of proton diverges rapidly where the proton fraction is less. At the slit H_2^+ and H_3^+ fractions are reduced drastically with a substantial reduction in the space charge force on proton beam due to these components.

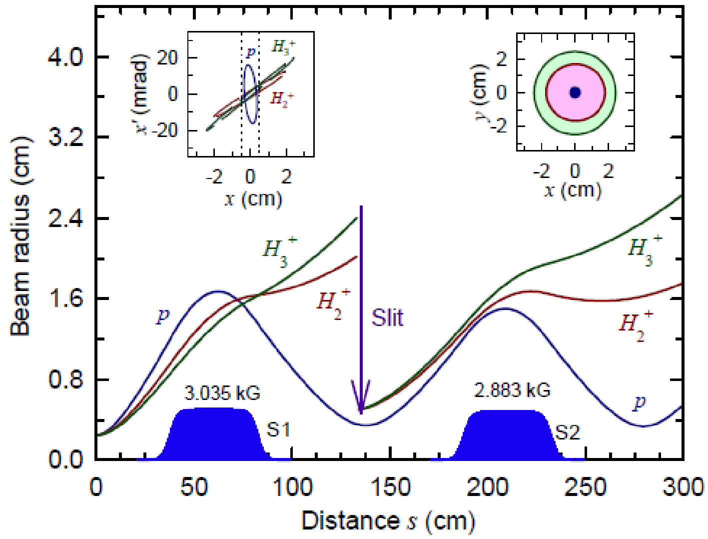

FIGURE 2. Evolution of envelope radii of p, H_2^+ and H_3^+ with fractions of 80%, 15% and 5% respectively in 10 mA at 100keV. The orientation of phase ellipse of different species at the slit and beam spot at the second waist of proton are also shown.

The evolution of beam envelopes of H_2^+ and H_3^+ are shown in Fig. 1(b) for total beam current of 10 mA in which proton current is 6 mA and currents due to H_2^+ and H_3^+ are 2mA from each. The major portions of the H_2^+ and H_3^+ beams are rejected at the slit and out of 4 mA beam only 0.172 mA passes through the slit. There is also reduction in the emittances of the both species.

Figure 2 shows the beam envelopes of p, H_2^+ and H_3^+ having fractions of 80%, 15% and 5% respectively in the total beam current of 10 mA. It is evident from the figure that the radius of the proton beam is greater than the radii of the other two species during the initial part of the transport line. In this region the nonlinear space charge forces due to species H_2^+ and H_3^+ of the beam will cause growth in the emittance of the proton beam. At the slit, large fraction of the H_2^+ and H_3^+ beams are rejected whereas proton beam passes through the slit without any loss of the beam current. The estimated fractions of p, H_2^+ and H_3^+ after the slit are 98.6%, 1.13% and 0.27% respectively. The estimated beam spot of these three species near the second waist of proton beam is also shown in Fig. 2. The orientations of phase ellipses of p, H_2^+ and H_3^+ beams at the slit location are shown in Fig. 2. Only those portions of phase ellipses of H_2^+ and H_3^+ which are within the edges of the slit (dotted line) will pass through the slit. As the nonlinear space charge forces experienced by the proton beam due to the other species are very small and also for a short duration in the transport line, we observed very small growth in the emittance of the proton beam.

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