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Beam charge and current neutralization of high-charge-state heavy ions*

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Abstract

High-charge-state heavy-ions may reduce the accelerator voltage and cost of heavy-ion inertial fusion drivers, if ways can be found to neutralize the space charge of the highly charged beam ions as they are focused to a target in a fusion chamber. Using 2-D Particle-In-Cell simulations, we have evaluated the effectiveness of two different methods of beam neutralization: (1) by redistribution of beam charge in a larger diameter, pre-formed plasma in the chamber, and (2), by introducing a cold-electron-emitting source within the beam channel at the beam entrance into the chamber. We find the latter method to be much more effective for high-charge-state ions.

1. Introduction

Ballistic focusing of heavy-ion beams to target spots of 2-3 mm will require at least partial space-charge neutralization in the target chamber for all cases except for the highest ion masses (lead, bismuth, or uranium), lowest charge state ($q=1$), and maximum kinetic energy and range (10 GeV, $R \sim 0.1$ g/cm²). One method of providing such partial neutralization is to pre-ionize a few percent of the 10^{-3} Torr background gas normally expected in power-plant chambers with liquid coolants, such as HYLIFE-II [1]. The large volume of low density plasma that results ($n_e \sim 2 \times 10^{11}$ cm⁻³) provides a reservoir of electrons that move to reduce the space-charge electric field in the beam channel by effectively distributing its positive charge over a much larger volume. For a 7.5 kA beam of 5.3 GeV Cs⁺¹ ions with 15 mm-mrad unnormalized emittance, for example, 2-D Particle-In-Cell (PIC) calculations by Callahan [2] showed such plasma neutralization could reduce the minimum spot radius from ~ 9 mm in vacuum (where the emittance-only spot size would have been 0.9 mm with perfect neutralization) down to 1.2 mm with no ion stripping included, or down to 2 mm with ion stripping included.

Such partial plasma neutralization also appears to meet requirements for a recent 2-D integrated heavy-ion target design by Tabak and Callahan [3], which uses distributed radiators of low areal mass ($R \sim 0.03$ g/cm²) driven by 10 kA beams of Pb⁺¹ ions at 3-4 GeV, focused to 2.7 mm spots [4]. However, a preliminary systems study [5] of a multi-beam induction linac delivering the 5.9 MJ total energy of such ions at 0.54 PW peak power required by that same target design, results in a high cost which motivates further work to reduce the cost. One way to reduce the cost (which is dominated by metglas and associated pulser supplies), is to use higher charge-state ions (e.g., $q = 8$ to 16), which both reduces linac voltage (length) and increases total beam current by a factor of q . The higher total beam current can reduce the dominant metglas and pulser costs, and the total accelerator cost could then be reduced if suitable hi- q ion sources and injectors can be developed to provide the higher beam currents without a large increase in the "front-end" costs. Using a model for femtosecond laser production of high-charge state ions in a

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solenoid injector, a comparative systems study [6] of induction linacs meeting the above target requirements for a matrix of ion masses and charge states showed a factor of two cost reduction, for example, using 93 beams of Xe^{+8} ions at 2.1 GeV, 28 kA each, instead of 22 beams of Xe^{+1} ions at 2.1 GeV, 15 kA each. Motivated by the potential costs savings, but cognizant of the greater degree of neutralization that 28 kA beams of Xe^{+8} ions would require for focusing, we undertook another study, described in this report, of chamber neutralization for this particular ion beam case using the same PIC code called BICrz [7] that was used in the previous neutralization studies.

2. Ballistic transport simulations for Xe^{+8} beams

The geometry for the 2-D particle-in-cell simulations is shown in Fig. 1 as part of a whole target chamber concept. Due to computational resource limitations at the higher particle densities required, we simulated only one beam length (~ 50 cm) of propagation into the chamber, shown in Fig. 1 as the dotted region. The beam ions enter at the chamber wall aimed at a common target focus. We modeled two cases, one with a low-density preformed plasma cylinder as shown, and another case without the plasma cylinder, but with cold electrons created at beam entry, at equal charge rates (i.e., eight electron equivalent negative particle charge for each Xe^{+8} ion), to simulate a net-electron source such as might be provided by a dense plasma focusing lens, for example. When neutralizing electrons are available near the chamber wall, we have found that most of the beam ion deflections away from the desired ballistic focus trajectories appears during neutralization in the first beam length of propagation, but future calculations need to check for further beam quality degradation closer to the target.

We first tried neutralizing the Xe beams with a plasma cylinder that was more than 8 times denser than the plasma that adequately neutralized Cs^{+1} ion beams reported in [2]. The cold plasma ion motion was neglected, and electrons from the plasma cylinder moved into the beam channel, reducing the positive space charge within the beam by redistributing the net positive beam charge (which was conserved) over the larger volume of the plasma channel. In the process, initially cold plasma electrons (created with a nominal 100 eV temperature), acquired a much higher effective temperature by falling into the potential “well” of the beam channel from different starting positions in the plasma cylinder. The high electron temperature results in a Debye-shielding length λ_D that can be a significant fraction of the beam channel radius “a”. For the Xe^{+8} beam case, the BICrz simulation found an effective electron temperature of 32 keV with the plasma cylinder, resulting in a ratio $a/(\sqrt{2} \lambda_D) = 16$. Lemons and Thode [8] calculated the possible neutralization as a function of beam radius and the parameter $a/(\sqrt{2} \lambda_D)$. For $a/(\sqrt{2} \lambda_D) = 16$, and a uniform ion beam density, their theory predicts an electron density profile shown in Fig. 2(a), which shows incomplete neutralization over the outer third of the beam profile, containing about half of the beam ions. Fig. 2(b) plots the deflection angle (radial velocity change over the parallel beam velocity) of beam ions away from the desired beam focus angle $(v_r - v_{r,o})/v_{\text{beam}}$ as a function of radius r in cm within the beam channel at one beam length into the chamber. The nominal beam radius is 5 cm. One sees in Fig. 2(b) positive values of $(v_r - v_{r,o})/v_{\text{beam}}$ (ions under-focused due to outward space charge forces) over the outer third of the beam profile, consistent with the un-neutralized beam edge regions shown in Fig. 2(a). The negative spike in $(v_r - v_{r,o})/v_{\text{beam}}$ near $r = 0$ in Fig. 2(b) is caused by an excess electron space charge over-focusing

ions near the axis, an artifact that BICrz allows no change in angular momentum of the particles, so that electrons tend to pass close to the axis. We calculated from the data in Fig.2(b) that only 58% of the beam ions could ballistically transport to a target spot of 2.7mm, assuming no further degradation of the beam beyond the one beam length of propagation.

We then ran BICrz with the same Xe^{+8} beam using the second method of neutralization with a cold electron source, and no plasma cylinder. The beam ion space charge “entrains” electrons from the cold source primarily in the axial direction, resulting in a lower perpendicular electron temperature of 15 keV, less than half that with a plasma cylinder, giving $a/(\sqrt{2} \lambda_D) = 23$. Fig. 2(c) shows the corresponding electron and beam ion density profiles, with good neutralization closer to the edge of the beam than in Fig.2(a). The corresponding profile of beam angular deflections after one beam length of propagation shown in Fig.2(d) is also much flatter out closer to the edge of the beam; in fact the BICrz simulation shows better neutralization than predicted by the Lemons and Thode theory. Also, no negative spike near $r = 0$ is seen in Fig.2(d), because with no plasma cylinder, there are no electrons falling radially into the beam potential well. We calculate that 91% of the ions in Fig.2(d) would ballistically transport to a 2.7 mm radius target spot. Thus, use of a cold electron source for neutralization may be sufficient for ballistic focusing of charge state 8+ ions.

Fig. 3 shows the radial electric field for both plasma cylinder and cold electron source cases from the center of the beam channel out to 0.2 m distance, where an adjacent beam in a multi-beam array could sample any residual fields outside the first beam channel. Fig. 3 shows a high electric field falling off as $1/r$ for the plasma cylinder case, as one would expect from conservation of total beam positive charge. One can estimate that such electric fields would cause uncorrectable deflections of Xe^{+8} ions in adjacent beams much larger than the allowed target spot size. However, for neutralization with a cold electron source, Fig. 3 shows the radial electric field is essentially zero both inside and outside the beam channel. Thus, the cold electron source should also solve the problem of beam-beam deflections for high-charge state ions, because the net beam positive charge is effectively neutralized between beams. For neutralization both with the plasma cylinder as well as with the cold electron source, we find inductive effects, combined with a sufficiently high electron conductivity, cause a nearly perfect neutralization of the ion beam current, (better than 90% with plasma cylinders, and better than 99% with cold electron sources), such that beam-beam deflections due to residual magnetic fields can be neglected.

3. Summary

We find that beam neutralization with pre-formed plasma in the target chamber, while sufficient for singly-charged heavy-ions, is not sufficient for high-charge-state ions, at least, for the 28 kA, 2.1 GeV Xe^{+8} case we examined. However, we found that use of some cold electron source near the beam entrance provides a much better neutralization, and might work well enough. Future calculations need to be done for ballistic transport all the way to the target, and for other high-charge-state ion species. We also note that electric fields set up as a charged beam enters a neutralizing plasma or electron source are not linear in general, so future work to evaluate beam emittance growth caused by various neutralization processes is needed.

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Figure captions:

- Fig 1: Geometry of particle-in-cell simulations for chamber neutralization of 28 kA Xe^{+8} ion beams.
- Fig 2: Comparison of Lemons and Thode's theory (using T_e (perp) from PIC simulations in λ_D), with PIC simulations of velocity deflections as a function of radius across the beam. Theory (a) and PIC (b) for neutralization using a plasma cylinder, and theory (c) and PIC (d) for neutralization with a cold electron source.
- Fig 3: Radial electric field at midpulse after 0.5 m propagation for a 28 kA beam of Xe^{+8} in focusing geometry.

**Beam-to beam spacing
~ 0.25 m (for estimating
beam-beam deflections)**

**28 kA beam of
2.1 GeV Xe+8
ions, with 1 deg
focusing angle,
length 0.5 m**

**Cold electron source
($T \sim 100 \text{ eV}$) at beam
entrance
[E.g., plasma lens]**

**Region (dotted) for
PIC simulations**

**Chamber
radius
 $R = 3 \text{ m}$**

**Heavy-ion
target with
required spot
size $r = 2.7 \text{ mm}$**

**Plasma cylinder
 $n_e = 9 \times 10^{11} \text{ cm}^{-3}$
(2 % ionized Flibe
vapor)**

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