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Effects of preneutralization on heavy ion fusion chamber transport

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Abstract

Beams for heavy ion fusion are likely to require at least partial neutralization in the reactor chamber. Present target designs call for higher beam currents and smaller focal spots than most earlier designs, leading to high space-charge fields. Focusing is complicated by beam stripping in the low-pressure background gas expected in chambers. One method proposed for neutralization is passing an ion beam through a plasma before the beam enters the chamber. In this article, the electromagnetic particle-in-cell code LSP is used to study the effectiveness of this form of preneutralization for a range of plasma and beam parameters. For target chamber pressures below a few milliTorr of flibe gas, preneutralization is found to significantly reduce the beam emittance growth and spot size in the chamber.

Keywords: Charge neutralization; Current neutralization; Ion beam transport; PIC simulation

1. INTRODUCTION

Neutralized ballistic transport (NBT; Barboza & Callahan, 1996; Logan & Callahan, 1998; Vay, 1997, 1998; Sharp *et al.*, 1999; Rose *et al.*, 2001; Kaganovich *et al.*, 2001) is presently being studied for propagating intense heavy ion beams inside a reactor chamber to an inertial confinement fusion (ICF) target (Bangerter, 1996). Other beam transport schemes under consideration include self-pinched transport (Hahn & Lee, 1996; Olson *et al.*, 1996*a*; Welch & Olson, 1996; Rose *et al.*, 1999; Ottinger *et al.*, 2000) and discharge channel (Tauschwitz *et al.*, 1996; Peterson & Olson, 1997; Yu *et al.*, 1998) transport. Some form of neutralization is required to overcome the formidable space charge and magnetic fields of the high perveance and high-current ion beams currently under consideration. In the NBT scheme, the individual beams focus outside of the target chamber and enter through ports in the chamber walls. These beams are focused and directed such that they intersect before striking the target and then strike the target as they are expanding into an annular configuration (Callahan & Tabak, 1999). The target chamber is filled at low pressure with a gas such as flibe.

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A recent experiment (MacLaren *et al.*, 2002) examined the charge neutralization of a heavy ion beam, with perveance relevant to driver-scale beams ($>10^{-4}$), by electrons drawn from a localized source as the beam was focused. The electron source was a glowing tungsten filament placed in the beam path, enabling the supply of thermionically emitted electrons inside of the beam. The experiment dramatically demonstrated the effect of charge neutralization on a heavy ion beam, and these results were confirmed in a series of electrostatic particle-in-cell (PIC) simulations.

One method considered for aiding the neutralization of driver-scale beams as they enter the target chamber is to introduce one or more finite-thickness plasma "layers" near the beam port, through which the beam passes. Chamber transport using annular and solid plasma regions inside the transport chamber has been examined by a number of investigators (Magelssen, 1988; Callahan, 1996; Logan & Callahan, 1998; Welch *et al.*, 2002). The general concept studied in this article consists of an initially unneutralized beam passing through a finite thickness of plasma and dragging along plasma electrons for partial charge and current neutralization. Plasma electrons provide some degree of charge and current neutralization to the converging beams, presumably reducing emittance growth prior to the build-up of plasma by ion impact and photoionization of the background chamber gas. Typically, $n_p/Zn_b > 1$, where n_p is the plasma density and n_b and

Z are the beam density and charge state. The plasma is in electrical contact with a conducting boundary at large radius enabling a continuous supply of electrons.

A stationary plasma can only provide electron neutralization down to some minimum space-charge potential of an ion beam. Defined as the ratio of the beam space charge to kinetic energy, the perveance of a beam of current I_b, velocity $\beta_i c$ and relativistic factor γ_i is given by $K = 2I_b/I_A\beta_i^2$ where $I_A = \beta_i\gamma_i m_i c^3/eZ$ is the Alfven current. Provided $Km_i/Zm_e > 1$, electrons from this plasma can accelerate up in the beam space-charge potential to the beam velocity. This limit on neutralization is the $\frac{1}{2}m_e v_i^2$ potential limit first proposed by Olson (1986). Neutralization experiments (Olson *et al.*, 1996b; MacLaren *et al.*, 2002) have provided, to some degree, confirmation of this limit. Further confirmation of the plasma neutralization is planned for the upcoming neutralized transport experiment (NTX) at Lawrence Berkeley National Laboratory.

In this article, the LSP (Hughes *et al.*, 1999; Welch *et al.*, 2001) PIC code is used to simulate NBT transport and evaluate the preneutralization concept. We will first discuss the idealized behavior of the neutralization in Section 2. In Section 3, detailed two-dimensional simulations of the beam transport with realistic geometry and interactions with the ambient flibe gas are presented. Conclusions are given in Section 4.

2. IDEALIZED SIMULATIONS OF PRENEUTRALIZATION

We first examine the neutralization process of a localized plasma with two-dimensional PIC simulations of a "weak" beam passing through a finite length of plasma. We expect the plasma in this regime to provide a "space-charge-limited" supply of electrons. In this section, electromagnetic PIC simulations are carried out to quantify the neutralization of the beam space-charge potential by the entrained electron population with respect to the $\frac{1}{2}m_e v_i^2$ limit.

Using LSP, we simulate the neutralization process of a paraxial beam passing through a plasma and follow the beam 25 cm beyond. The parameters for the Pb^+ beam are varied from 30 to 1000 A and 1 to 9 GeV. The beam number density varies from 10^{10} to 3×10^{11} cm^{-3}. The 1.67-ns duration uniform-density beam is injected through the left-hand wave-transmitting boundary at $z = 0$ (see Fig. 1). The plasma, extending out to the outer wall and from $z = 5$–15 cm, also has uniform density chosen to keep n_p/n_b fixed at 10. The initial plasma electron temperature is 5 eV. The simulation box is 3 cm in radius and 40 cm long. Where the plasma is in contact with the outer wall, electron space-charge-limited emission is permitted. This boundary enables the supply of low-energy electrons to maintain quasi-neutrality of the plasma during the simulation. These PIC simulations are collisionless with no beam stripping or ionization processes.

As expected, the beam, as it leaves the plasma, carries with it a supply of neutralizing electrons. For a 310-A, 4-GeV ion beam, the particle positions and electron density after 6 ns are shown in Figure 2. By this time, the 10-cm-long beam has passed entirely through the plasma. The density of plasma electrons that have been accelerated up to the beam velocity is roughly that of the beam over much of the beam length, indicating good neutralization. Note that the electrons have not yet thermalized, as indicated by their strong radial oscillation.

As seen in Figure 2, the charge neutralization for many simulations does indeed approach that of the Olson limit. In the figure, the beam space-charge potential and the residual unneutralized beam charge are normalized by $\frac{1}{2}m_e v_i^2$. We see that as the normalized beam potential (ϕ_b) exceeds unity,

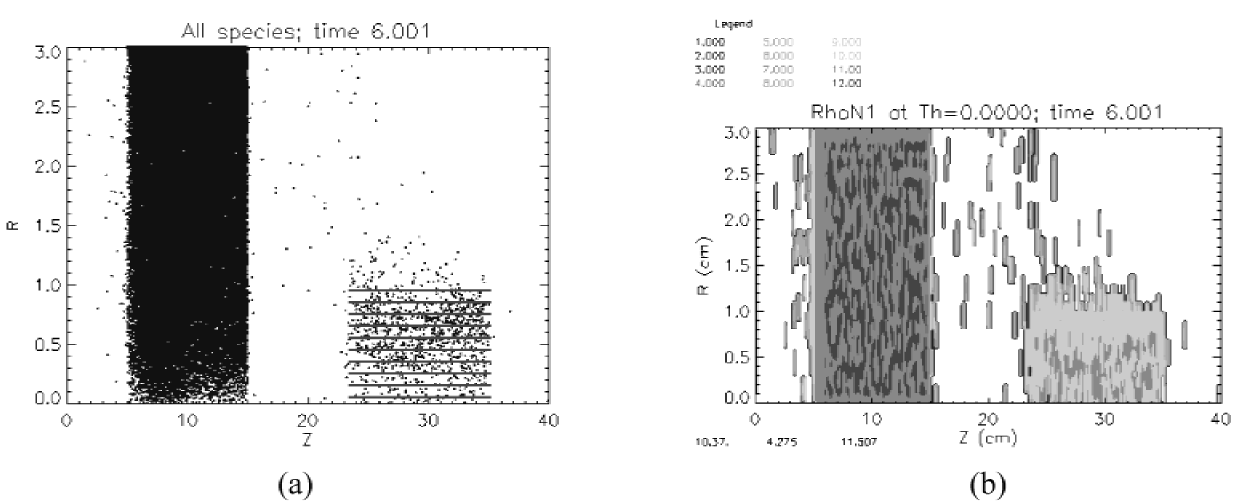

Fig. 1. Electron and beam particles (a) and electron density (b) from the 310-A, 4-GeV beam simulation are plotted after 6 ns. The beam density is 10^{11} cm^{-3}. The contours of the electron density ($\log n_p$) are shown in the legend.

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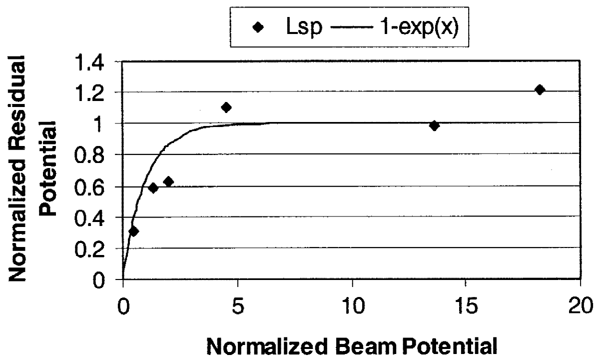

Fig. 2. The residual (unneutralized) beam space-charge potential is plotted versus the beam potential. Here, the potentials are normalized by $\frac{1}{2}m_e v_i^2$.

the residual charge limits to roughly unity. At small normalized beam potentials (<1), the residual potential (ϕ_r) approaches the beam potential (zero neutralization limit). A decent fit, $\phi_r = 1 - e_b^{\phi}$, to the simulation data is also plotted.

These calculations are useful in understanding the initial neutralization near the plasma. However, for a focusing beam, the problem is more complicated in that, as the ion beam compresses, the electron population heats, degrading the neutralization somewhat as the plasma Debye length increases. In addition, the beam ions will ionize and be stripped to higher *Z* by the ambient flibe neutrals. In the next section, we address these issues.

3. SIMULATION OF NEUTRALIZED BALLISTIC TRANSPORT

In this section, we increase the complexity of the simulations and study neutralization far from the plasma. The first step is to follow a focusing driver-scale beam to a target 3–6 m downstream of the preformed plasma. We again use a Pb^{+1} ion beam with 4 GeV energy and currents ranging from 250 to 4000 A (only 1- and 4-kA currents were simulated at a 6-m focal length). The beam perveance, used in the simulations, ranges from 10^{-5} to 1.6×10^{-4} corresponding to normalized beam potentials of 4–60. The injected beam radius is 3 cm for the 3-m focal length and 6 cm for the 6-m focal length. The beam normalized emittance is held fixed at 1.1 π-mm-mrad. As in the previous section, the simulation setup includes a preformed 3×10^{11} cm^{-3} density plasma extending 10–30 cm from the beam injection plane. The 13-cm radius outer wall is permitted to emit electrons where the plasma is in contact.

First, we examine vacuum NBT transport without collisions. The results are summarized in Figure 3 for the 3- and 6-m focal length simulations. The root-mean-squared (rms) radii at focus ranged from 6 to 8 mm for the 3-m focal length, and 1 to 1.3 mm for the 6-m focal length. All these spot sizes are sufficient to efficiently couple into the distributed radiator target (Callahan & Tabak, 1999). This target actually calls for an elliptical spot, not modeled in these two-dimensional simulations, with 1.8- $\times$ 4-mm dimensions. The overall charge neutralization scales similarly as calculated in Section 2. Using an envelope solution of the final spot size (Olson, 1982), which assumes an initially linearly focusing beam and ignores both chromatic and geometric, we can approximate an effective residual potential. The normalized residual potential ranges from 1 for the 250-A current beam to 2 for the 4-kA beam case. This potential does not degrade significantly as the focal length increases. We see that the compression and heating of the neutralizing electrons, as the beam focuses, reduces the effective neutralization from the ideal value of unity seen in the idealized calculations in the previous section, but by no more than a factor of two. The beam and plasma electron densities for the 4-kA, 6-m focal length beam simulation are shown in Figure 4 several times into the simulation. The envelope of the neutralizing electron cloud does expand relative to the beam as the beam focuses, but the central core density remains roughly that of the beam, indicating good bulk neutralization.

Collisions of the beam with the background flibe vapor deleteriously affect the beam focal spot. Above 1-mTorr flibe pressure, beam stripping becomes significant, increas-

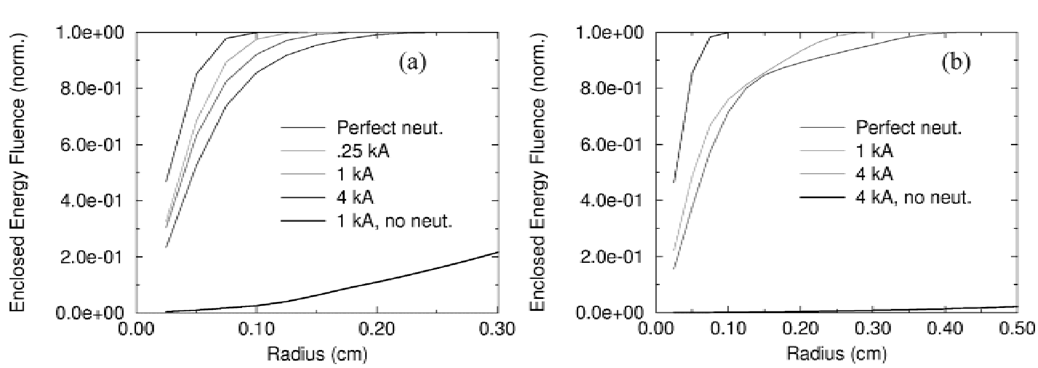

Fig. 3. The time-integrated beam energy, normalized to the total injected energy, enclosed within a given radius is plotted for the (a) 3-m and (b) 6-m focal length.

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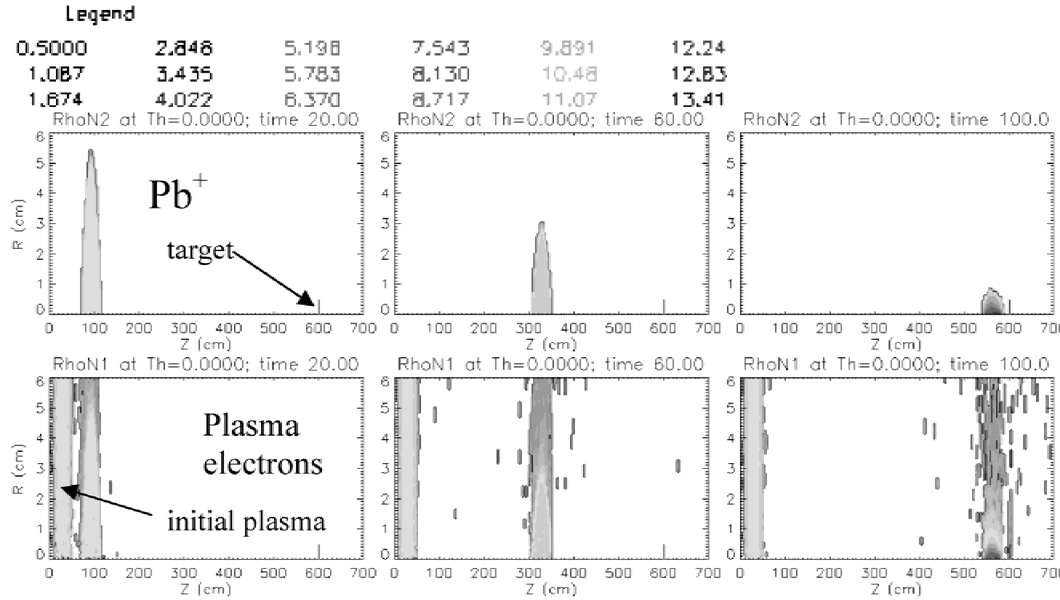

Fig. 4. For the 4-kA, 6-m focal length LSP simulation, the log of the beam and plasma electron densities is plotted at 20, 60, and 100 ns. The legend at the top assigns contour values for all six plots.

ing the mean Z of a Pb ion to $+5$ in 3 m. Sources of plasma can help improve the neutralization. The beam ionizes the gas and the heated fusion target emits radiation that also ionizes the gas in the vicinity of the target (Sharp *et al.*, 2001). For this case, we consider a 30-ns, 3-GeV, 1-kA Pb^{+1} beam with 6×10^{-5} perveance. The beam emittance is again 1.1 π-mm-mrad. These parameters are characteristic of a lower-current foot pulse required to heat the hohlraum up to roughly 70 eV before the main pulse arrives (Callahan & Tabak, 1999). The foot pulse, unlike the main pulse, does not have the benefit of the neutralizing photoionization plasma and is thus expected to be more difficult to focus to a small spot (Welch *et al.*, 2002). To demonstrate this, we ran two foot-pulse simulations with 1-mTorr and 3-mTorr flibe pressure (1.7×10^{13} and 5×10^{13} cm^{-3} number density). The time-integrated radial beam profiles at the target are shown in Figure 5. We see that the spot size is quite sensitive to the flibe pressure, with 90% of the beam ions contained within a 2-mm spot for the 1-mTorr case (1.1-mm rms radius) and 3 mm for the 3-mTorr case (1.7-mm rms radius). The 1-mTorr simulation predicts an adequate spot size for the distributed radiator target.

The upcoming NTX experiment will attempt to quantify the effects of preneutralization. Here a 400-keV, 75-mA, 0.1-π-mm-mrad emittance K^+ ion beam (Henestroza *et al.*, 2003) will be injected into a meter-long transport cell. As in the driver scenario, a plasma of density 10^{10}–10^{11} cm^{-3} and 10-cm width is initialized after the focusing magnets to provide neutralization to the beam with perveance $>10^{-3}$. LSP electrostatic simulations of the preneutralization show a similar scaling for the neutralization ($>$90%) of this beam as in the above high-current simulations. The simulations predict an emittance $<$0.3 π-mm-mrad is sufficient to observe a significantly smaller beam spot at focus (3 mm versus $>$1 cm without neutralization) with the plasma present.

4. CONCLUSIONS

Simulations of beam transport using neutralization from a preformed plasma near the entrance to the target chamber have been carried out to quantify the degree of neutralization and assess the impact on focal spot size. The simulations show that in vacuum, the residual unneutralized beam space-charge potential is close to the theoretical $\frac{1}{2} m_e v_i^2$ limit. Radial compression of the comoving electrons as the beam focuses increases the residual potential by as much as a factor of two above this limit. With the preformed plasma,

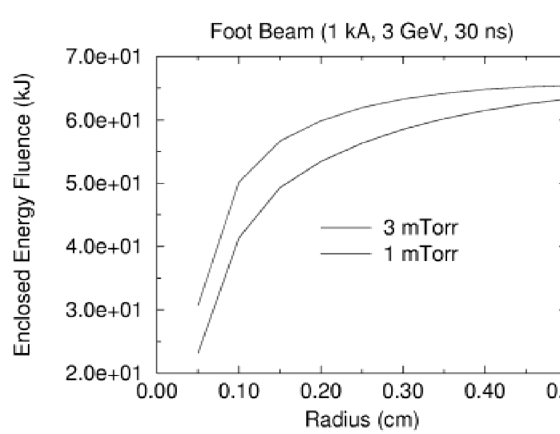

Fig. 5. The time-integrated energy enclosed within a given radius is plotted for the 3-GeV, 1-kA foot-pulse beam in 1-mTorr and 3-mTorr flibe.

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simulations including the adverse effects of beam stripping show that flibe pressure near or below 1 mTorr does not significantly degrade transport efficiency. These calculations suggest that NBT over 3–6 m can yield a spot size sufficiently small to couple to the heavy ion fusion (HIF)-baseline distributed radiator target. This concept will be examined in the upcoming NTX experiment. Future work will include more detailed simulations of the foot and main pulses including transport in the beam port and a time-dependent photoionization of neutrals and photostripping of the beam.

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