SIMULATION OF SELF-PINCHED CHAMBER TRANSPORT OF IONS FOR HEAVY ION FUSION*

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Abstract

In this paper, we explore the self-pinched transport of heavy ions in an inertial confinement fusion reactor chamber environment. The bulk of this work is carried out using a hybrid particle-in-cell code. The initial results show that a neutral flibe pressure of roughly 5–50 mtorr is sufficient to produce a net current capable of confining the ions at small radius (<5 mm). The source and sensitivity to chamber conditions of the self-pinch force are discussed.

1 INTRODUCTION

For heavy ion inertial confinement fusion (HIF), an ion beam must be transported several meters through the chamber to the target. A sizable transport distance prevents damage to the accelerator from the target explosion. For the high perveance beams under consideration, the transport method is largely determined by the degree of ion charge and current neutralization in the chamber. Complete neutralization permits ballistic transport. Self-pinched transport is possible for nearly complete charge neutralization and only partial current neutralization, yielding a net confining force. In self-pinched transport, the ion beam is focused to a small radius and confined as it propagates to the target. Previous simulations with a hybrid electromagnetic particle-in-cell code have calculated that, in argon, a pressure of 5–100 mtorr permits a sufficient net force to confine even a hot 4-MeV proton beam [1]. These results have since been supported in experiment [2]. In this paper, we examined the necessary conditions in a HIF chamber for self-pinched transport including gas pressure, plasma density and beam envelope.

2 BASIC THEORY OF SELF-PINCHED TRANSPORT

The neutralization of an ion beam requires that electrons be drawn from outside the beam, either radially or axially. In a low-pressure gas, neutralizing electrons are transported via $\boldsymbol{E} \times \boldsymbol{B}$ drift. In the beam body or late in time at a given axial position, *z*, electrons move forward axially due to the residual radial electric and azimuthal magnetic fields with $\beta_z = E_r/B_\theta$. A simple equilibrium theory, discussed in Ref. [1], predicts the electron axial velocity $\beta_z(z)$ as a function of the gas ionization rate due to beam impact. This theory shows that $\beta_z(z)$ approaches the ion velocity β_i in the beam nose (as the beam first reaches a given *z*). The theory calculates E_r and B_θ as a function of the charge and current neutralization for a trumpet-shaped beam temporal profile (large beam radius at $t = 0$, pinching down to smaller radius). The optimal pressure occurs when the mean-free path for beam ionization of the gas, λ_{mfp}, is of the order of the taper length of the beam envelope, τ. The simple theory predicts that the pinch force is optimized for,

$$R \equiv \tau / 4Z\lambda_{mfp} = 1,$$

where *R* is the normalized trumpet length and *Z* is the beam charge state. Thus, more efficiently ionizing beams have larger pinch currents at lower pressures.

Radial neutralization by plasma electrons, when the gyro radius < r_b, is accomplished through an $E_z \times B_\theta$ drift. The inward current is driven by un-neutralized beam space charge in the beam nose. This process continues until an axial inductive field is produced which negates the electrostatic field. A deficiency in the theory is that it neglected inductive fields that inhibit the rise of the net current and, thus, predicted net currents are too large. In the next section, the sensitivity of the self-pinch force to beam envelope shape and ambient plasma density is examined.

3 SIMULATIONS OF PINCH FORCE GENERATION

In this section, we simulate, using the electromagnetic particle-in-cell code LSP [3], the generation of the self-pinch force as a function of beam envelope shape and plasma density. LSP is an implicit code with detailed models of gas breakdown physics. In particular, we wish to define the conditions in which the pinch force of the beam is sufficient to confine the ion beam divergence. The matched RMS transverse angle (θ) or divergence of a Bennett profile beam is given by the well-known expression,

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$$I_{net} = \theta^2 I_A,$$

where $I_A = \beta_i\gamma_i m_i c^3/eZ$ is the Alven current.

We also consider a HIF driver-scale parameter set using a 4-GeV, Pb^+ beam with a square radius profile and a 0.5-cm minimum outer radius. The 6-ns long beam has a 10-kA peak current with a 2-ns linear rise (and fall) time. We consider a pencil beam (no radius variation head to tail) and a trumpet beam that has a 1-cm radius in the head that quadratically falls to a 0.5-cm radius in 2 ns (=τ). To optimize the pinch for this trumpet length, we use a nominal λ_{mfp} = 12 cm. We inject the beam with divergence θ = 0.002 radian which matches a 5-kA net current. The figure of merit we employ for these calculations is the effective current which we define as the net pinch force in units of current at outer beam radius r_b, i.e. $I_{eff} = \frac{1}{2} r_b(B_\theta(r_b) - E_r(r_b)/\beta_z)$. A small amount of un-neutralized beam charge in a sheath at the beam edge will factor strongly into I_{eff} for the $\beta_z = 0.2$ beam. The above definition overestimates the electric field contribution somewhat, however this effect could lead to gradual loss of beam at the edge.

We first calculate the dependence of I_{eff} on the beam shape to demonstrate the necessity of having a trumpet shaped beam. As seen in Fig. 1, the magnetic and electric fields at the beam edges are distinctly different. In the pencil case (constant 0.5-cm beam radius), the electric field force dominates resulting in a –26 kA effective current. For the trumpet shape where we use the optimum λ_{mfp} = 12 cm, the field forces are reversed and the effective current is +5.8 kA. As predicted in the theory, we obtain an I_{eff} that is a good fraction of the total beam current.

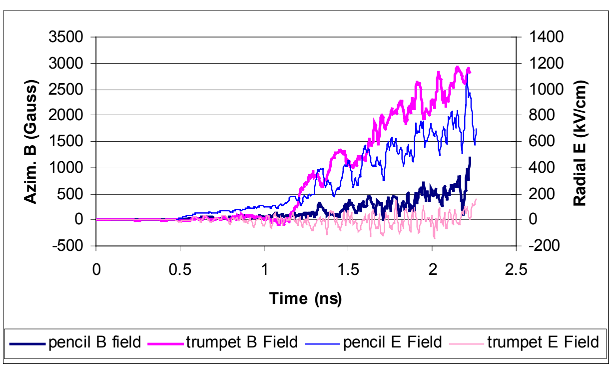

Figure 1: The azimuthal B field and radial E field are plotted versus time at z = 3 cm and r = 0.5 cm for pencil and trumpet-shaped beam envelopes.

We now examine the sensitivity of the pinch force to a deviation from the optimal λ_{mfp} and by adding an initial plasma density. Here, the ratio R varies as $R = (12\text{ cm}/\lambda_{mfp})$. The ratio of the ambient plasma density to the peak beam density is referred to as N. We see in Fig. 2 that the optimum R for peak I_{eff} is slightly larger than the predicted value of unity. The curve defines an idealized self-pinched propagation window. These calculations are encouraging in that the window is at least an order of magnitude wide in mean-free path and hence gas density. Given typical values for ionization cross section σ / Z of 3×10^{-16} cm^2 for flibe, we expect a propagation window of 5–50 mtorr.

The sensitivity to ambient plasma density is also defined in Figure 2. We see that there is a weak optimum near N = 0.1 and that I_{eff} falls off to less than 2 kA as the plasma density approaches that of the beam. This too is an important consideration for chamber transport in that photo-ionization of the gas from a heated target produces a high fractional ionization near the target [4].

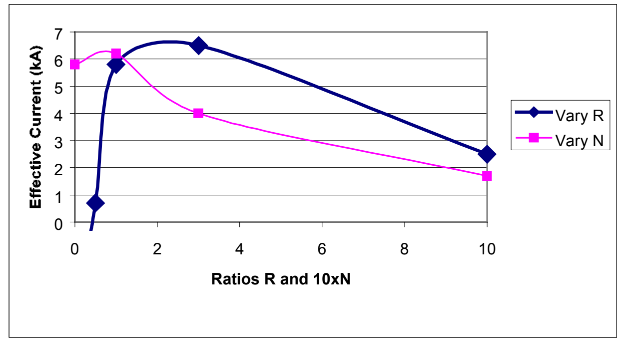

Figure 2: The effective current for the trumpet beam envelope is plotted as a function of the ratio R and the ratio N of the initial plasma to beam density (R = 1).

We now examine in more detail the trumpet beam simulation with R = 1, without ambient plasma. The beam is injected into a 1-m long, 4-cm radius tube. Recall, the beam divergence is matched to a 5-kA effective current. Such a pinch current yields a > 6-m betatron wavelength ($\lambda_\beta = 2\pi r_b (I_A / I_{eff})^{1/2}$), much longer than the simulation box. We can, however, calculate the evolution of the effective current far from any walls as well as the impulse given the beam due to these fields. After the beam has propagated 15 ns or 90 cm into the box (see Fig. 3 showing the mean radial velocities normalized by c), we find that the bulk of the beam has been given an inward impulse due to the self fields. The green and red contours, indicating significant outward motion, are isolated to the outer edge of the beam trumpet. Some regions of outward motion are seen in the beam body again at the extreme radial edge. Some of this motion is indicative of a sorting of the beam random velocities and not of actual loss of confinement. The darker blue contours indicate a strong net inward motion mostly at peak current.

The fields relax somewhat away from the injection plane where Hall currents are driven by strong electron density gradients. In Fig. 4, the contours of constant $\frac{1}{2} rB_\theta$, 15 ns into the simulation are plotted. These contours are indicative of enclosed net current. The maximum net current is roughly 3 kA, down from the 5.8-kA effective current measured near the injection plane. This smaller net current remained fairly constant after the beam had propagated 20 cm from the injection plane. The radial electric field contour plot (Fig. 5) shows the regions of under and over neutralization by the electrons. In the same regions that the mean beam velocity is moving outward, the radial electric field is positive. The largest values within the beam are of order 100 kV/cm in the beam front. Only a few ions actually reside in these regions of positive field. In the beam interior and particularly in the front, the electrons have over-neutralized the ion charge producing a negative field (darker blue contours) with peak 250 kV/cm magnitudes.

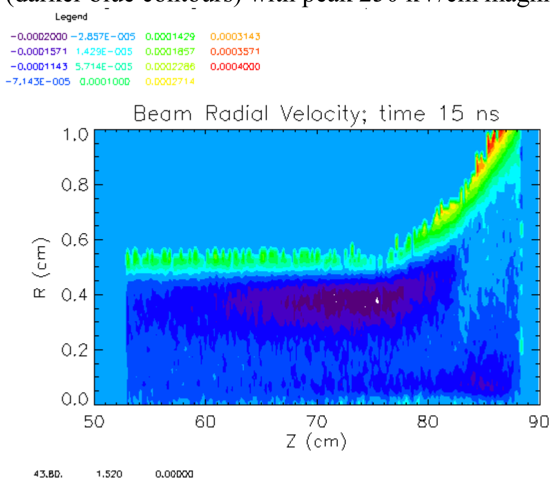

Figure 3: The beam radial velocities (normalized by *c*) are plotted after 15 ns. The simulation used a trumpet beam with $R = 1$, without an ambient plasma.

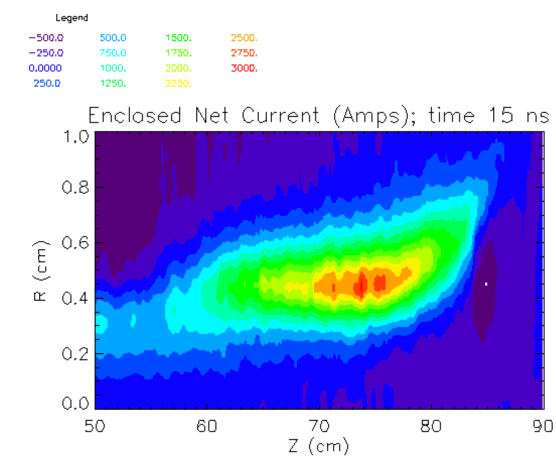

Figure 4: The contour lines of constant enclosed net current (in Amps) are plotted after 15 ns with 3-kA peak net current. The simulation used a trumpet beam with $R = 1$ and without ambient plasma.

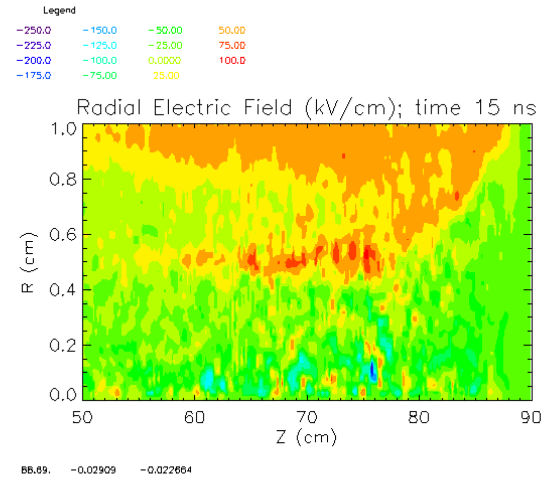

Figure 5: Contours of the radial electric field (in kV/cm) are plotted after 15 ns. The simulation used a trumpet beam with $R = 1$, without an ambient plasma.

5 CONCLUSIONS

We have examined in detail with the LSP code the mechanics of self-pinched transport in a gas. As predicted in theory, simulations show the magnitude of the pinch force is maximized for a trumpet length of order the ionization mean-free path. Considering only beam ionization, LSP predicts the self-pinched propagation window spans at least an order of magnitude in gas density. For flibe, this corresponds to 5–50 mtorr. The presence of an ambient plasma density, such as a photo-ionized gas near the heating target, can reduce the pinch force somewhat as the plasma density exceeds 1/3 that of the beam. The pinch force does not fall precipitously, however, with 2.5-kA effective current even with a ratio of plasma to beam density of unity.

6 REFERENCES

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