SELF-PINCHED TRANSPORT THEORY FOR THE SABRE ION DIODE

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Abstract

The efficiency of delivering an ion beam to an inertial confinement fusion target depends on the ability to control the breakdown of the gas in the transport region. The gas in the reactor vessel must provide excellent charge neutralization and specified current neutralization to permit the beam transport and focusing to a <1 cm radius, spherical target. An interesting scheme for transport, using residual effective (or net) current for confinement, is the ”self-pinch” mode. Here, we present recent self-pinch theory results and ideas for beam conditioning, focusing and transport in the self-pinch mode for the SABRE experiment. Results from the IPROP hybrid code are discussed.

1 INTRODUCTION

For ion-driven inertial confinement fusion (ICF), an ion beam must be transported several meters. A sizable transport distance prevents damage to the accelerator from the target explosion and permits voltage-ramped beam bunching. The transport method is determined by the degree of ion charge and current neutralization in the ionizing gas. 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 the self-pinched transport for light-ion beams, the ion beam is focused to a small radius and confined as it propagates to the target. Previous simulations with the hybrid electromagnetic particle-in-cell code IPROP [1] have calculated that, in argon, a pressure of 5-100 mtorr permits a sufficient net force to confine even a hot ion beam.[2] [3]

In anticipation of a self-pinched experiment on the 4-MV (90 kA of Li^{+3}) SABRE diode at Sandia National Laboratories and the 2-MV (150 kA of protons) GAMBLE II diode at the Naval Research Laboratory, we have been examining the practical application of self-pinched transport. We are developing an analytic theory of self pinch that has provided insight into the physical mechanism of the low-pressure neutralization. We are also simulating the transport and propagation to examine equilibrium and stability issues. Focusing ion-diode experiments envisioned on SABRE and GAMBLE II involve non-ideal effects, including large beam divergence, large focusing angle and beam annularity. To address these problems, we have been studying the benefits of beam conditioning in the focus region between the diode and the self-pinched region after the beam has reached a small radius. We have found some benefit from including a passive conical structure and a low-pressure gas in the focusing region.

To illustrate the concept of self-pinched transport of light ions, we examine a high quality Li^{+3} beam with 32 MeV energy and 1-MA current (10-ns rise time). As seen in Fig. 1, the beam is extracted from a 8-12 cm radius annular diode with an RMS divergence of 6 mrad and a 100 mrad focusing angle. The beam is ballistically focused to a 0.75-cm aperture 1-m downstream. Due to the high energy tail of the transverse energy distribution, we only transport 83% of the beam through the aperture. At this point, we use IPROP’s magneto/electrostatic field solver, assuming an ambient plasma provides 100% charge neutralization and 87% current neutralization in the self-pinch region ($z > 1$ m as in Fig. 1) which yields a 105-kA effective current. The beam then confines itself for 2 meters.

Except for the low-current early-time portion of the beam (near z =300), the beam RMS radius remains at 0.4 cm to the endplate. Roughly 95% of the beam remains within a 0.7-cm radius with few ions extending to 1.2 cm. The beam RMS transverse velocity $\beta_\perp$ is 0.01 in the pinch region. A simple energy balance for a Bennett radial profile beam yields the matched effective current (units of 17 kA) $I_{eff} = (m_i/Zm_e)\beta_\perp^2/\beta_i$. Thus, the above I_{eff} exceeds that necessary for confinement (72 kA), accounting for the excellent beam confinement.

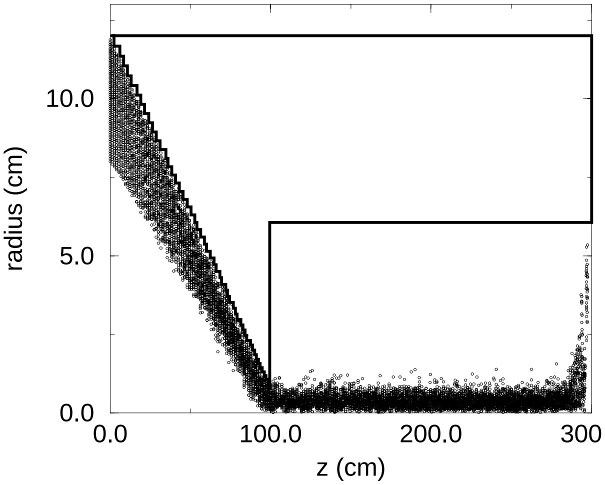

Figure 1: The 32-MeV 1-MA Li^{+3} beam is plotted 100 ns into a static field IPROP simulation. A uniform-density beam is extracted from a 8-12 cm radius annular diode with 6-mrad RMS divergence and a 100-mrad focusing angle.

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2 SELF-PINCHED TRANSPORT THEORY

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 $E \times B$ 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,[3] that predicts $\beta_z(z)$ as a function of the gas ionization rate due to beam impact, has shown 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). A free parameter in this theory is the radius of the plasma electron envelope, r_e. In the absence of inductive electric fields, we assumed that the electrons are drawn into the beam and $r_e = r_b$. This theory predicted large effective pinch currents are possible in the 5-100 mtorr pressure range. The optimal pressure occurs when the mean-free path for beam ionization of the gas is $\lambda_{mfp} = \tau\beta_i c/4Z$, where τ is time for the beam to reach its minimum radius. Thus, more efficient ionizing beams have large pinch currents at smaller pressures.

Radial neutralization by plasma electrons, when the Larmor radius $\ll r_b$, is accomplished through an $E_z \times B_\theta$ drift. The inward current is driven by unneutralized 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 earlier theory is that it neglected inductive fields that inhibit the rise of I_{eff}, $I_{eff} = 0.5r_b(B_\theta(r_b) - E_r(r_b)/\beta_i)$. To include inductive effects, we assume that the axial inductive field is given by $E_{ind} = \partial I_{eff}/\partial t$ and the axial electrostatic field is equal to the radial electrostatic field, E_{es}, which scales strongly with beam radius. E_{es} is calculated as before except that r_e is constrained. At each time in the beam frame, r_e is chosen such that $E_{ind} \leq E_{es}$. If the inductive fields are sufficiently weak, the r_e is, as before, set equal to the beam radius.

The inductive effects included in the new theory limit I_{eff} for beam with large radii and small β_i. The scaling of I_{eff} with energy in an Ar gas is shown in Fig. 2 for a 50-ns Li^{+3} beam with 1.5-cm radius, 1-ns current rise and a 10-ns trumpet radial shape. We see that the maximum fraction of I_{eff}/I_b is largest (nearly 0.9 at 10 mtorr Ar) for the fusion quality 32-MeV beam. As the beam energy is reduced to 4 MeV, the optimal Ar pressure decreases to 1-mtorr and the fraction falls to 0.1. As in the earlier theory, the results are independent of beam current, suggesting the pinch current available for ICF quality beams is well beyond that required (1-10%). However, near term experiments at lower voltages may not generate sufficient current to observe a tightly pinched beam.

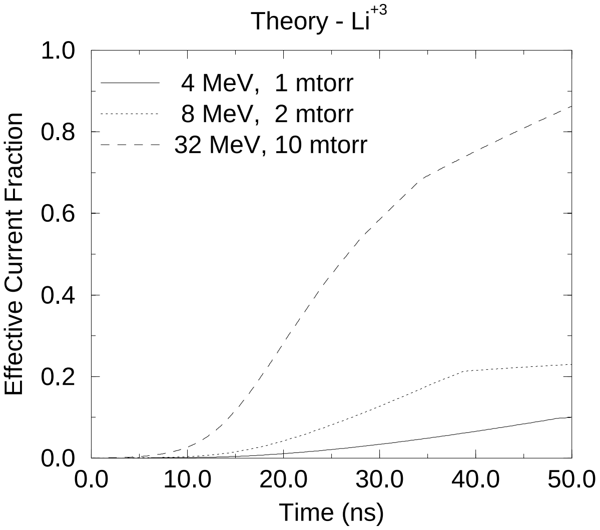

Figure 2: The fraction of I_{eff} to beam current for a Li^{+3} beam with 4, 8 and 32 MeV energy (1-ns current rise time) is plotted versus time into the beam pulse. The beam radius was initially 3-cm pinching to 1.5 cm with a 10-ns gaussian ”trumpet” shape.

We simulate the breakdown of a gas in the presence of an ion beam using the hybrid simulation code IPROP.[1] IPROP has shown good agreement with GAMBLE II experiments in which net currents were measured outside a nominal 10 kA, 1-MeV proton beam.[4] We have calculated fractional effective currents of up to 0.5 for beams with $\beta_i \geq 0.1$.[2] The optimal pressures are consistent with the above theory. We have just begun to look at the slow beams $\beta_i \approx 0.03 - 0.05$ expected in the near term experiments.

To speed up the simulations, we examine a 50-kA Li^{+3} beam with 32 MeV energy ($\beta_i = 0.1$). From the above theory, we can expect roughly a 0.2 fractional effective current. This 10-kA effective current matches a 50-mrad divergence with which we initialize the beam. The beam is injected into a 8-cm radius, 50-cm long conducting tube filled with 20-mtorr argon. We see in Fig. 3 that the beam core remains well pinched with some hotter particles escaping to larger radius. A trumpet developed with a characteristic time $\tau \approx 5$ ns (15 cm in z) and the maximum effective current reached 9 kA. IPROP calculates an optimal pressure near 5 mtorr for this beam with a 15-kA effective current in rough agreement with the theory. We have also looked at lithium beams in the focusing geometry (see Fig. 1). We find that, unlike the thermal transverse energy beams discussed above, these beams are more difficult to contain because all the beam ions have large transverse energy. Thus, we have been examining methods for beam conditioning which maximize the beam transport to small radius and ways to thermalize the beam transverse energy by removing the macro focusing angle.

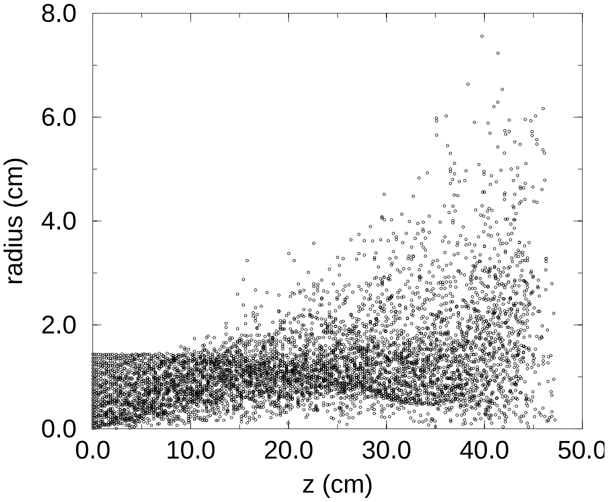

Figure 3: The 32-MeV, 50-kA (3-ns rise time) Li^{+3} beam is plotted 15 ns into a electromagnetic IPROP simulation. A uniform 50-mrad divergence beam is injected normally into a 8-cm radius tube filled with 20-mtorr argon gas.

3 BEAM CONDITIONING FOR THE SABRE EXPERIMENT

In the SABRE experiment, we plan to focus a lithium ion beam to small radius and propagate the beam in the self pinch mode as illustrated in Section 1. The Li^{+3} beam will exit the diode with a ≈ 40 mrad divergence and a shallow focusing angle of roughly 75 mrad. The beam is annular with an 4.6-cm inner radius and a 6.6-cm outer radius. The above theory predicts a small radius ($\leq$ 3 cm) is required to optimize beam self pinch. Therefore, we have been considering ways to efficiently transport this beam through a 3-cm radius aperture from the 4.6-6.6-cm annular SABRE diode. With ballistic transport of the focusing beam 75-cm downstream and a 3-cm aperture, we will lose roughly 50% of the current given a 40-mrad divergence (a conservative estimate based on Li divergence measurements).

If we can generate a > 20 kA effective current within a concentric conical structure, the beam ions can be kept off the cone and redirected through the aperture. With an inner conductor, the self-fields act to preserve the annulus. Using the IPROP, we simulated a 75-kA (10-ns rise), 32 MeV Li^{+3} in the geometry described above. The inner cone had a 4-cm radius at the diode exit (z=0) and reached the axis at z= 75 cm. The outer cone had an inner radius of 7.2 cm at z=0 reaching a 3-cm radius (the aperture) at 75 cm. The 40-mrad divergence beam injected into 10 and 20-mtorr Ar is efficiently guided to the aperture at 75 cm. The transport efficiency was considerably better than that for ballistic transport with 85% and 72% of the beam maximum current transported for the 10 and 20-mtorr pressures, respectively. The beam self fields direct the beam to the center of the cone with peak fields near the axis reaching 7 and 4 kG for the two pressures. While improving overall transport efficiency, one drawback is that the beam is somewhat hollow at the start of the self-pinch region which may not be desired for self pinch.

A second, similar method is to inject the beam into the above geometry cone but in vacuum. In this case, electrons emitted from the metal structure $E \times B$ drift in the self fields. The beam is initially well neutralized in charge and current, however, the current neutralization at the far wall degrades in time as the neutralizing electrons pile up at the endplate where the radial electric fields are shorted and the drift slows. The neutralizing electrons carry sufficient charge forward to neutralize the beam column and move with velocity β_i. As these electrons stagnate, they carry sufficient charge to neutralize the beam space charge in a wave moving backwards at roughly the beam velocity. Because their forward velocity drops to 0, there is no current neutralization. Thus, we have a time-dependent lens effect with focusing or defocusing magnetic fields depending on if an inner metal cone exists. The inner cone carries return current which results in a defocusing magnetic field. If none exists, the magnetic fields are positive and radially focusing. IPROP calculates strong pinch forces moving back from the endplate with this method.

4 CONCLUSIONS

The self-pinched transport mode for ion ICF provides standoff from the target explosion. We are developing a physics understanding of this mode leading up to experiments on SABRE and GAMBLE II. Theory and simulation predict large effective currents that can confine the transverse beam momentum. The self pinch theory has been improved to include inductive effects that tend to limit the effective currents for lower energy and larger radius beams. Optimal argon pressures of 1-10 mtorr, independent of current, are calculated for a Li^{+3} beam with 4-32 MeV energy. We are continueing to explore methods for beam conditioning that facilitate the transition from the beam focusing region into the self pinch region. Future work will involve three-dimensional IPROP simulations to examine stability issues.

5 ACKNOWLEDGMENTS

This work is supported by Sandia National Laboratories.

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