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SIMULATIONS OF ION BEAM NEUTRALIZATION IN SUPPORT OF THE NEUTRALIZED TRANSPORT EXPERIMENT*

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I. INTRODUCTION

Heavy ion fusion (HIF) requires the acceleration, transport, and focusing of many individual ion beams.[1] Drift compression and beam combining prior to focusing result in ~100 individual ion beams with line-charge densities of order 10^{-5} C/m. A focusing force is applied to the individual ion beams outside of the chamber. For neutralized ballistic chamber transport (NBT), these beams enter the chamber with a large radius (relative to the target spot size) and must overlap inside the chamber at small radius (roughly 3-mm radius) prior to striking the target. The physics of NBT, in particular the feasibility of achieving the required small spot size, is being examined in the Neutralized Transport Experiment (NTX) at Lawrence Berkeley National Laboratory.[2,3] Interpreted by detailed particle-in-cell simulations of beam neutralization, experimental results are being used to validate theoretical and simulation models for driver scale beam transport.

In the NTX experiment, a low-emittance 300-keV, 25-mA K^+ beam is focused 1 m downstream into a 4-cm radius pipe containing one or more plasma regions. The beam passes through the first 10-cm-long plasma, produced by an Al plasma arc source, just after the final focus magnet and propagates with the entrained electrons. A second, 10-cm-long plasma (produced with a cyclotron resonance plasma source) is created near focus to simulate the effects of a photo-ionized plasma created by the heated target in a fusion chamber. Given a 0.1-π-mm-mrad beam emittance, two and three-dimensional particle-in-cell (PIC) LSP[4] simulations of the beam neutralization predict a < 2-mm beam rms radius at focus with only the first plasma. The beam radius can be further improved with the addition of the second plasma located further downstream.

II. PHYSICS OF NEUTRALIZED BALLISTIC TRANSPORT

NBT[5-12] is presently the main line focusing scheme for propagating intense heavy ion beams inside a reactor chamber to an inertial confinement fusion (ICF) target.[1,13] As with the driver scale HIF beams, some form of neutralization is required to overcome the beam space charge of the high perveance NTX ion beam. As in the NBT scheme, a series of magnetic quadrupoles direct the beam to a focus roughly 1 m downstream. Outside the quadrapole fringe fields, localized plasma (plasma plug) is created with a sufficient reservoir of electrons to neutralize the ion beam as it passes.[14] The initially unneutralized beam passes through a finite thickness of plasma. As the beam ions leave the plasma, their space charge accelerates plasma electrons to the ion velocity for partial charge and current neutralization. Plasma electrons then provide some degree of charge (and current) neutralization to the converging beams. 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, respectively. For best results, the plasma should be in electrical contact with a conducting boundary at large radius enabling a continuous supply of electrons.

A stationary plasma plug can only provide electron neutralization down to some minimum space-charge potential of an ion beam. A residual electrostatic potential sufficient to accelerate and trap the electrons must exist. Provided $Km_i/Zm_e >$ 1, electrons from this plasma can accelerate up in the beam space-charge potential to the beam velocity. (Here, beam perveance K is the ratio of the beam space charge-to-kinetic energy, $K = 2I_b / I_A \beta_i^2$, where $I_A = \beta_i \gamma_i m_i c^3/eZ$, I_b is the beam current, and $\beta_i c$ is the beam velocity). This limit on neutralization is the $½m_e v_i^2$ potential first proposed by Olson.[15] A beam passing through a large volumetric plasma, again with $n_p/Zn_b >> 1$, can achieve even higher neutralization fractions.

III. LSP SIMULATIONS OF THE NTX EXPERIMENT

LSP[4] is used to simulate the focusing of the NTX beam and evaluate the plasma neutralization concept. We examine the neutralization of a "weak" ion beam passing through a localized plasma using an electrostatic 3D cylindrical simulation. The LSP simulation uses a particle distribution extracted from a WARP simulation[3] of the accelerator from injection to the point of neutralized transport. The simulation box is 3.8 cm in radius and 130 cm long. Injected through an open (Neumann) boundary at z = -30 cm (see Fig. 1), the uniform density K^+ beam has a 2-cm outer radius with 25-mA current and 300-keV energy. At initialization, the Al^{+2} plasma filled the pipe and extends from z = -10–0 cm, with a uniform density of electrons and ions at 3 eV. It should be noted that this temperature is comparable to the critical potential $½m_e v_i^2 \approx 4$ eV and could influence the neutralization process to some extent. Where the plasma is in contact with the outer wall, space-charge-limited emission (SCLE) of cold electrons is permitted. This boundary enables the resupply of low-energy electrons to maintain quasi-neutrality of the plasma during the simulation. Because each impacting beam ion will stimulate the emission of many electrons, we also permit SCLE of electrons at the z = 100-cm wall. To prevent electrons from drifting upstream into the magnetic focusing region, an electron trap consisting of a negatively biased ring electrode (held in the simulation at -1 keV) is placed at z = -19--18 cm. Finally, these PIC simulations are collisionless with no beam stripping or ionization processes included.

The beam conditions at focus (z = 75--80 cm) reach steady state after roughly 1000 ns. The beam and plasma electron particle positions at 1134 ns are shown in Fig. 1. As expected, the beam entrains neutralizing electrons as it leaves the plasma. The electrons also move upstream and stagnate against the potential of the electrons trapped at roughly z = -17 cm. With perfect neutralization, we expect an rms radius of 0.9 mm and, without any neutralization, the beam focuses to only 1-cm radius. The beam rms radius is close to that of ballistic transport reaching a broad (in z) minimum of 1.5 mm at focus (roughly z = 75 cm). From simulations where the beam neutralization is specified, we see the beam spot and calculated 96% charge neutralization are consistent with twice the residual $½m_e v_i^2$ potential limit suggesting that the 3-eV plasma temperature did not significantly affect beam neutralization. The extra factor of two in the potential, also seen in driver scale simulations, is a result of the compression and heating of the entrained electrons as the beam focuses. The calculated size at focus is consistent with preliminary NTX data.

A series of 2D electromagnetic simulations has shown the focusing system to be fairly robust to variations in plasma conditions. If electrical connection is maintained to the chamber wall through electron SCLE, the beam spot shows little variation for plasma densities ranging from 3×10^8–3×10^{10} cm^{-3} for an initial plasma temperature of 3-eV. Without electron emission from the wall, the plasma plug charged up due to loss of electrons and the spot size degraded in time---particularly for smaller plasma densities. For a 6-eV initial plasma temperature (> $½m_e v_i^2$), the beam spot size was roughly 50% larger than the 3-eV plasma case. The sensitivity of the beam spot to incoming beam emittance is calculated to be weak with only a 30% spot variation for a factor of 3 change in emittance. This weak sensitivity indicates the NTX experiment should be in a position to verify the calculated neutralization fraction.

In addition to the localized plasma, a second plasma that extends the entire neutralized transport distance to the target should provide the smallest spot. We now add such a volumetric plasma of 10^{11}-cm^{-3} density and 3-eV temperature over the entire transport distance to focus (z = -10--100 cm). Shown in Fig. 2, a 1-mm spot was achieved that is within 10% of the ballistic limit. Using the actual measured plasma densities of the NTX volumetric rf source[16], a 1.1-mm radius spot was calculated when the peak density of the 10-cm- long plasma was situated 15 cm upstream of the beam focus. If the source is moved 10 cm closer to focus, the beam spot is not significantly improved over that of just the plasma plug. Thus, given a finite width plasma, more benefit is achieved by moving the source upstream from the focus since emittance growth near the focus cannot significantly affect the spot.

IV. CONCLUSIONS

The physics of NBT is currently being studied on the NTX experiment. LSP simulation predictions for minimum beam spot are consistent with NTX measurements. For a localized plasma, the beam neutralization is roughly 96% and yields a 1.5-mm rms beam spot at focus. We find the focal spot is insensitive to plasma density if electrical connection of the plasma to the wall is maintained. Spot degradation is calculated for plasma temperatures > $\frac{1}{2}m_e v_i^2$, which is consistent with neutralization theory. Finally, LSP calculates spot sizes within 10% of the ballistic limit if a volumetric plasma source is initialized over the entire transport region. Direct comparisons of experimental and simulated NTX results are presently being carried out.

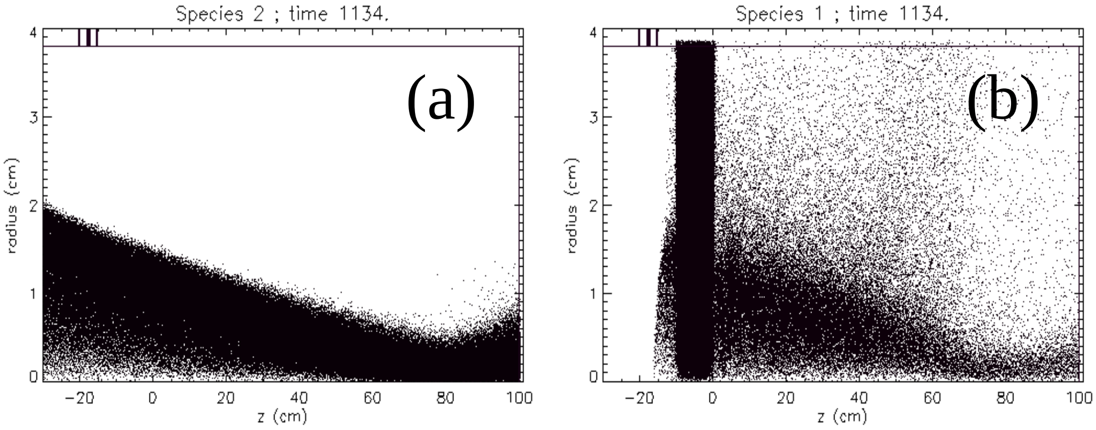

Figure 1. The beam (a) and plasma electrons (b) are plotted 1134 ns into the LSP simulation. The 25-mA, 300-keV K+ ions are injected at the left. The plasma initially has 3 x 10^9-cm^{-3} density from *z* = -10—0 cm.

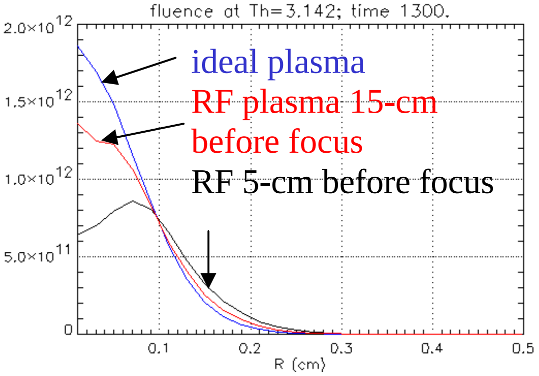

Figure 2. The time integrated beam fluence is plotted versus radius for the simulations including the rf volumetric plasma. The three curves were produced from an ideal plasma and a measured rf plasma source centered 15 and 5 cm upstream from focus.

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