# MULTIPLE BEAM INTERACTION STUDIES IN HEAVY ION FUSION

D. R. Welch, D. V. Rose, Mission Research Corp., Albuquerque, NM,
S. S. Yu, Lawrence Berkeley National Laboratory, Berkeley, CA,
C. L. Olson, Sandia National Laboratories, Albuquerque, NM

## *Abstract*

Beam combining and compression in a neutralized plasma is simulated with a three-dimensional particle-in-cell code. The sensitivity of these processes to perveance and plasma conditions is studied.

## INTRODUCTION

Heavy ion fusion (HIF) requires the acceleration, transport, and focusing of many individual ion beams. Drift compression and beam combining prior to focusing results in 10--100 individual ion beams with $10^{-5}$--$10^{-4}$ C/m line-charge densities. A focusing force is applied to the individual ion beams outside of the chamber. For neutralized-ballistic 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 (~ 3 mm) prior to striking the target. In this paper, we consider the combining of many beams in the presence of a neutralizing plasma over roughly 10 m just upstream of a preformed discharge channel specifically for pinched transport modes. Shown schematically in Fig. 1, the individual ion beams combine, drift, and possibly compress before being captured in an adiabatic discharge lens still outside of the chamber and injected at small radius into the chamber. Recent work for assisted-pinched transport (APT) has shown that a discharge channel can efficiently capture and transport a very high current ion beam to a 5-mm spot on the fusion target[1]. The target is actually heated on two sides requiring two beam-guiding discharge channels and two return-current channels to maintain symmetry. In the APT scenario, possible deleterious effects of beam overlap and combining may include instabilities and increased emittance growth. Implicit particle-in-cell (PIC) simulations indicate there are perveance limits above which beam filamentation can prevent good coupling to the discharge channel. The goal of these calculations is to elucidate the basic physics issues of plasma-neutralized beam combining.

The calculations are performed with the 3-D parallel LSP[2] PIC code to address the issues concerning high plasma densities. In particular, an energy-conserving implicit algorithm is used for dense plasma where the details of electron plasma oscillations can be ignored. We initially treat both plasma electron macroparticles with fluid equations, and ion species are treated with kinetic equations. This algorithm has also been employed in modeling heavy ion beam propagation in the 1–100-mtorr pressure regime.[3,4] In order to initialize a reasonable beam-plasma equilibrium, a neutral beam is injected at the $z = 0$ plane that was stripped to charge state +1 in the first 10 cm of transport in the plasma. Previous attempts to initialize an ion beam resulted in large electromagnetic fields in the sheath at the injection plane that increased beam emittance.

## SIMULATIONS OF BEAM TRANSPORT

We first examine the 2-D propagation of already combined beams in a 10-m length conical drift section filled with a plasma of density roughly that of the focused beam. The outer wall radius is set at 1.5 times that of the ballistically focusing beam and provides a space-charge- limited supply of electrons. The goal is to strike the adiabatic channel with a spot radius of 1 cm. The channel radius decreases from 2 cm to 0.5 cm, compressing the beam to a 5-mm radius. We examine several beam ions: $Ne^+$, $K^+$, $Xe^+$, and $Pb^+$. The total energy on target is fixed at 6 MJ (3 MJ on each side). The beam velocity is also held constant with a tilt from 0.125-0.165 *c*. Over the 14.5-m drift length to the target, the 100-ns beam pulse will compress to 8 ns. This configuration tests the concept of plasma-neutralized drift and compression and is not an actual design. The large velocity tilt obviously requires an achromatic final focusing lens. The combined beam is injected with uniform density as an annulus with 5-cm inner radius and 10-cm outer radius. For a $Ne^+$ beam, the ion average energy is 210 MeV with a 150-kA initial current. As the ion mass increases, its energy increases and the beam current decreases to maintain the total 3-MJ energy. The density of the $Ne^+$ beam is shown in Fig. 2. By 240 ns (the beam pulse has already compressed by a factor of 2), the ion density is compressed preferentially at the beam edges. The ensemble emittance grows from an initial 50 π-mm-mrad to 75 π-mm-mrad resulting in a fairly large spot at 10 m. The bulk of the beam actually strikes the outer wall of the tube near $z = 10$ m. The radial filamentation is a result of imperfect current neutralization at the beam edges with roughly 10--20 kA of net current (beam + plasma current). These currents are in rough agreement with analytic models of beam plasma neutralization that predict a 97% current neutralization for this case.[5] The propagation gets progressively better with increasing ion mass. The $Xe^+$ beam focused to the required 1-cm radius with only 30% emittance growth over the initial 13 π-mm-mrad. This beam and the $Pb^+$ beam produced a sufficiently small beam spot to couple to the discharge channel and, ultimately, the target. We also tried applying a 1--4 kG solenoidal magnetic field to reduce the growth of the filamentation for the $Ne^+$ beam. Preliminary calculations show the transport was more stable with a 4-kG applied field.

Simulations of actual 3-D beam combining were performed in Cartesian coordinates with ¼ the actual volume. Symmetry boundary conditions were employed at the $x$ = 0 and $y$ = 0 planes to speed the calculations but maintain beam-beam interaction. As before, the beams are transported in a 10-m conical tube. We injected two uniform-density beams of 3-cm radius centered at $x$ = 6.50 cm and $y$ = 3.75 cm, and $x$ = 3.75 cm and $y$ = 6.50 cm. Their edges just touch at the injection plane. This configuration of two beams per quadrant represents eight beams in the full volume, however, only interactions between nearest neighbors is modeled. As observed in the 2-D simulations, the lighter beam ions exhibit filamentary structure. Shown in Fig. 3, the $Ne^+$ beams quickly develop five distinct filaments. The combined beam emittance grows to 86 π-mm-mrad---15% larger than the 2-D case. The most interesting case was the $K^+$ beam which exhibited both 2-D and 3-D structures. The individual beams develop an annular structure before combining and eventually filamenting in azimuth. The filamentation then saturates at a modest level and relaxes to a more 2-D state. As before, the $Xe^+$ beams combined quiescently with an adequate 1-cm spot at 10 m with a combined beam emittance of 15 π-mm-mrad. The final emittance of the combined $Xe^+$ beams grew to 15 π-mm-mrad only 10% more than the sum of the injected emittances of the eight individual beams.

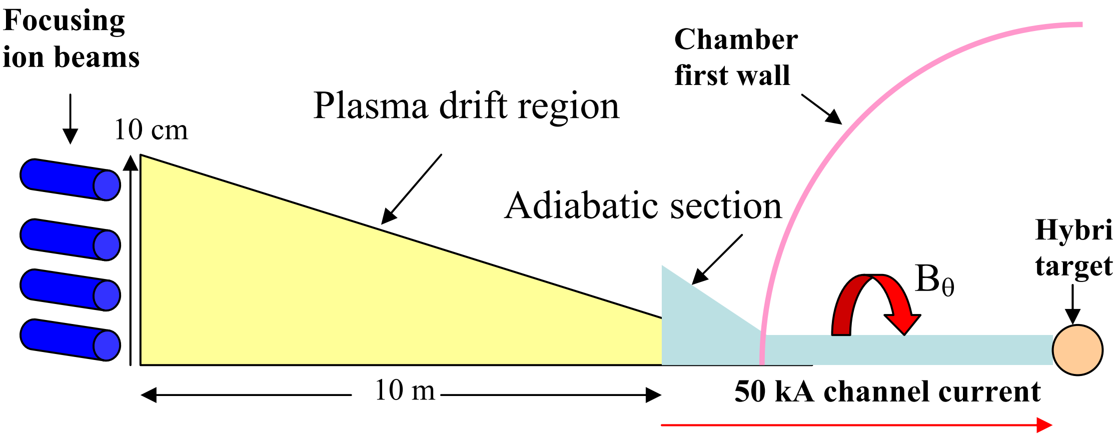

Figure 1. A schematic of the final focus and transport of ion beams for assisted-pinched transport is shown. The focusing beams enter at the left.

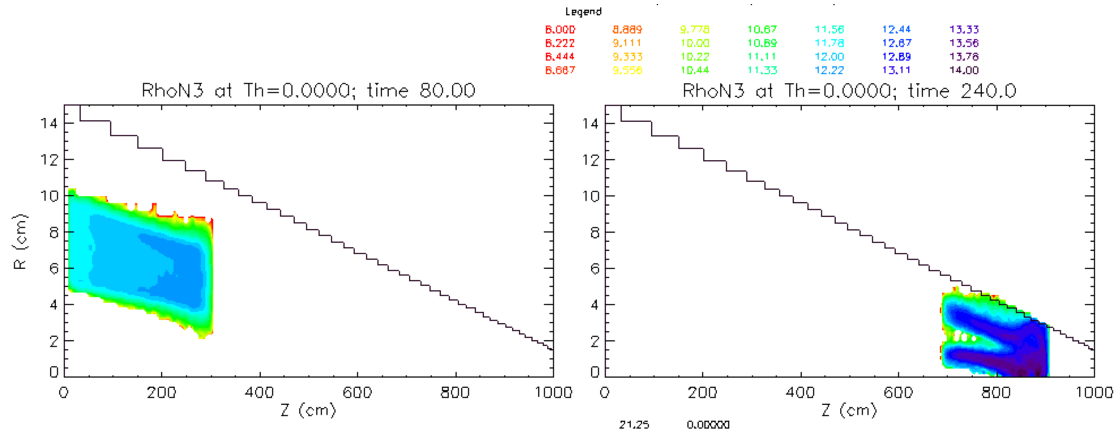

Figure 2. The $Ne^+$ beam density (log with legend above) after 80-ns (left) and 240-ns (right) transport in 4 x $10^{14}$-$cm^{-3}$ plasma is shown. Note the radial filamentation.

## SUMMARY

We have simulated the drift, combining, and compression of HIF beams in two and three dimensions with the LSP code. The implicit simulations were designed to model the drift section prior to beam capture in the adiabatic discharge channels envisioned for APT. Maintaining a constant ion beam energy of 3 MJ, the simulations identified the consequences of a few percent of unneutralized beam current. The 10--20 kA of net current for the $Ne^+$ beams was sufficient to filament and disrupt focusing to the desired 1-cm spot after 10 m drift. The $Xe^+$ ions exhibited much less severe behavior than the $Ne^+$ beams producing an adequate spot for APT with only 10% emittance growth. Using an extreme 30% beam velocity tilt, the compression of the beams from 100 ns to 8 ns on target did not appear to cause additional problems beyond the effect of increasing the combined beam current (and net current).

A sufficiently large solenoidal field has the potential to reduce magnetic pinch effects by forcing purely axial electron neutralization. The effect of a solenoidal magnetic field on the 2-D transport of the $Ne^+$ did reduce the instability growth in 2-D simulations. Future work must include larger (> 1 Tesla) and fields that are tailored to the beam trajectory. Simulations in the full 3-D volume are required to study the evolution of dipole instabilities.

## ACKNOWLEDGEMENTS

We express our appreciation for useful discussions and support to Grant Logan, Alex Friedman, William Sharp, Christine Celata, Igor Kaganovich, and the ARIES Team. Work supported by ARIES, the Virtual National Laboratory for HIF, the Department of Energy through Princeton Plasma Physics Laboratory, and Lawrence Berkeley National Laboratory.

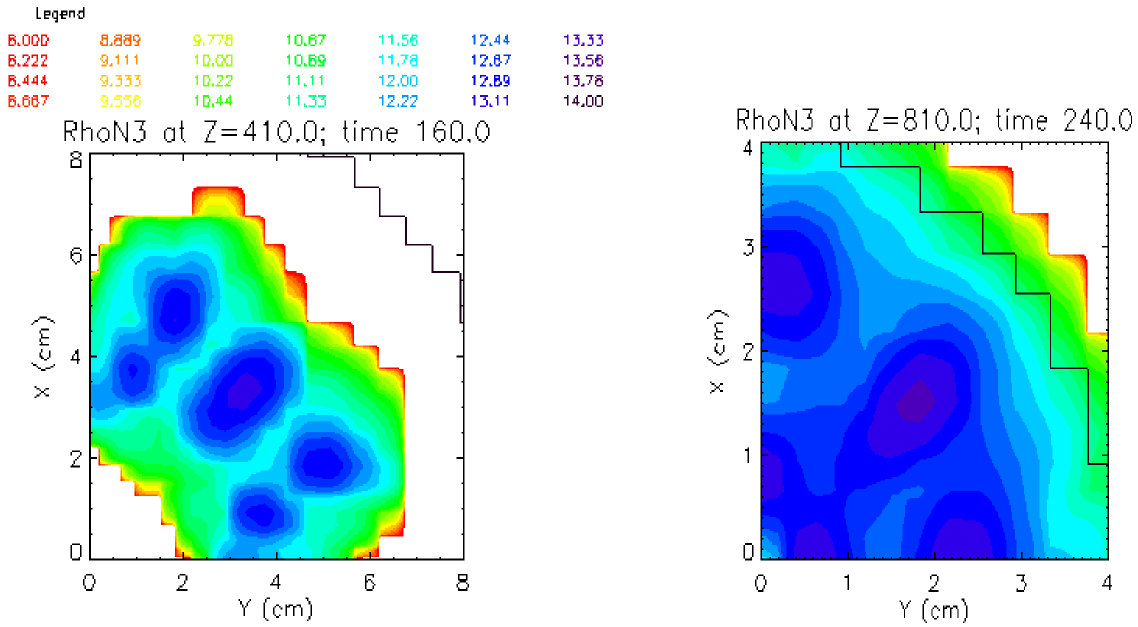

Figure 3. For the 3-D LSP simulation, the $Ne^+$ beam density (log with legend above) after 160-ns (left) and 240-ns (right) transport in 4 x $10^{14}$-$cm^{-3}$ plasma is shown at the $z$ = 410-cm and 810-cm planes, respectively. Note the azimuthal filamentation.

## REFERENCES

[1] D.A. Callahan, M.C. Herrmann, and M. Tabak, Laser and Particle Beams **20**, 405-410 (2002).

[2] LSP is a software product of Mission Research Corporation (http:\\www.mrcabq.com).

[3] D.R. Welch and C.L. Olson, Fusion Eng. Des. **32--33**, 477 (1996).

[4] D.V. Rose, P.F. Ottinger, D.R. Welch, B.V. Oliver, and C.L. Olson, Phys. Plasmas **6**, 4094 (1999).

[5] D.R. Welch, D.V. Rose, B.V. Oliver, T.C. Genoni, R.E. Clark, C.L. Olson, and S.S. Yu, Phys. Plasmas **9**, 2344 (2002).