Issues for Neutralized Drift Compression and Focusing of Heavy Ion Beams for HEDP

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Introduction

In order to study high energy density physics (HEDP) with heavy ion beams, the beam radius must be focused to < 1 mm and the pulselength must be compressed to < 1 ns. The typical scheme for temporal pulse compression makes use of an increasing ion velocity to compress the beam as it drifts and beam space charge to stagnate the compression before final focus. Shown schematically in Figure 1, beam compression in a neutralizing plasma does not require stagnation of the compression enabling a more robust method.[1] The final pulse duration can be minimized at the HEDP target can be programmed via an applied velocity tilt and theoretically is limited only by the longitudinal emittance. In the schematic for solenoidal focusing, the beam must transition from Brillouin flow equilibrium in vacuum into a plasma region with only weak solenoidal fields. The neutralizing plasma allows the high perveance beam to compress nearly ballistically before being transversely focused by a strong solenoid and discharge channel. In this section, several issues relevant to neutralized drift compression (NDC) are investigated mainly with the particle-in-cell code LSP.[2] The sensitivity of the compression and focusing to beam momentum spread, plasma, and magnetic field conditions is studied.

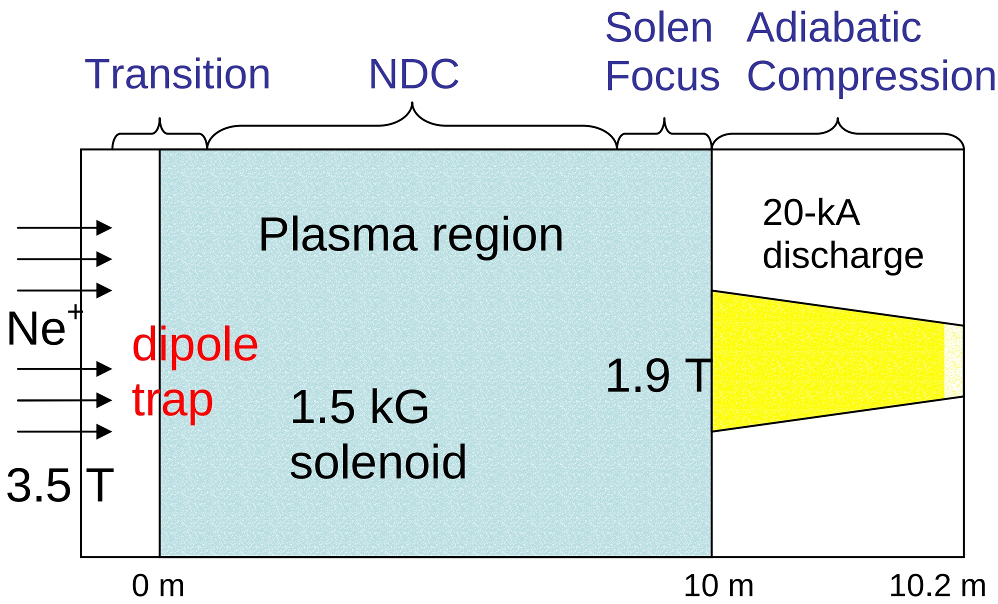

Figure 1 A schematic of a possible beam transport and final focus design using neutralized drift compression for HEDP is shown. The beam enters at the left in Brillouin flow equilibrium with a 5-10% velocity tilt, transitions to a NDC region, is focused by a strong solenoid, captured in an APT discharge channel and guided to the target.

Feasibility of achromatic beam focusing via a time-dependent solenoidal field

A major issue concerning NDC involves the final transverse focusing of the beam just before striking an HIF target or entering an adiabatic section of the discharge channel for further focusing. This focusing must accommodate a large energy spread (10--20%) for the 5--20-m drift length and hit a 1-mm radius. From the immersed envelope equation, we solve for the energy acceptance of the neutralized solenoidal focusing assuming small energy variation ΔE about E. With small beam emittance, K=0, and constant Ω_L, the entire beam is captured within some final radius given

$$\frac{\Delta E}{E} < \frac{8}{\pi r} \quad ,$$

with r being the ratio of the initial-to-final radius. Practically, the beam emittance ultimately limits the maximum tolerable focal length.

The above criterion sets a limit on the maximum energy variation of a beam coupling to a fusion target directly or with an intermediate step to discharge channel. Given the goal of a 1-mm radius spot at the target and assuming a 2-cm radius beam, the accepted energy variation is roughly 13%. Coupling into a discharge channel of 2-cm radius increases the accepted spread to 26%. An adiabatic discharge channel with a 4-mm initial and 1-mm final radius can then compresses the beam to the 1-mm radius.

There have been two proposed schemes[3] to improve the energy acceptance which involve time-dependent solenoidal or static dipole fields. Although time-dependent solenoidal correction in vacuum looks feasible, it has been suggested that, given the long drift length, time-dependent correction in the plasma region would be easier. Of course the major issue here is the penetration of field into a highly conductive low-beta plasma.

We set up a quick 2D cylindrical LSP simulation of the idea with a solenoidal field ramping up from 0.15 to 1.5 kG in 100 ns. The solenoid extends 40 cm in length with a 14-cm inner radius. For convenience the coils are made up a purely azimuthal time-dependent current in vacuum. The 3-eV, 10^{11} cm^{-3} density C^+ plasma (the plasma beta increases to roughly 10^{-5}) is centered in the 15-cm radius drift tube with a 10-cm outer radius. At this point, the resemblance of the configuration to a theta pinch is uncomfortably evident. The response of the plasma is shown in Figure 2. Note that field does not readily penetrate the plasma but compresses it on axis resulting in a highly non-uniform field and plasma structure. Obviously, this brute force technique in a plasma is not appropriate.

The second technique is to use a series of dipole bends in a plasma to yield a first-order achromatic system. The problem is that the beam must cross these field lines while still maintaining adequate current and charge neutrality. The more gently varying fields of a solenoid are still mainly the direction of the beam and do not appear to present any problem. A simple quasi-neutral assumption for the plasma electron demands that the plasma electron transition to ExB drift in the dipole region, i. e. $v_{ze} = E_x / B_y$ where B_y is the applied field. For a given plasma and beam density (n_p and n_b), the induced transverse electric field $E_x = v_b B_y n_b/n_p$. The force from this field acts to resist the dipole field deflection of the beam; however, if the force is uniform, it can be compensated for. The necessary uniformity would set constraints on the uniformity of the plasma, but decreases with plasma density.

Once again, we test the concept with a series of LSP simulations. To best calculate the plasma response, the 10-cm wide beam is injected with a large mass (100x Ne), charge state +1, 7×10^{10} cm^{-3} density (50 A/cm^2 current density) and 0.15*c* velocity. The beam will not be noticeably offset spatially, but the impact on transverse phase space can be assessed. The plasma density is varied from n_p= 1, 4, 10, 40 n_b. The induced electric field well within the beam generally scales with that predicted, however as seen in Figure 4, the induced self magnetic has a similar scaling. This field decreases linearly with n_b/n_p. The net Lorentz self force on the beam is actually fairly small because the electric and magnetic components nearly cancel. This type of cancellation has long been observed in beam transport in an initially field free plasma as well. As seen in Figure 4, the self fields decrease and become increasing smooth as the plasma density increases. The transition to uniform fields is thicker both axially and radially for the lower densities. Some work in this regime has already been done with field distortion attributed to electron advection.[4] The impact on the beam transverse velocity is seen in Figure 5 where the beam velocity v_x as it propagates through the lens is plotted for the $n_p = n_b$ and 40 n_b simulations. Note the width of the velocity spread increases markedly with the lower density case but in the high density case, the distribution is simply offset as desired without additional spread. Thus, these simulations suggest that dipole field will not disrupt beam NDC as long as the plasma density is 10-100x that of the beam.

Beam Two-Stream Instability

A possible obstacle to beam compression is caused by the relative velocity of the beam ions and background plasma electrons. The electrostatic beam-plasma electron two-stream or Buneman instability has a 1D dispersion relation given by

$$\frac{\omega_b^2}{\left(\omega - k v_b\right)^2} + \frac{\omega_p^2}{\omega^2} = 1,$$

where ω_b is the beam-plasma frequency. The key parameters to evaluate the instability growth are then for transport distance $\zeta = z\omega_b/v_b$ and for beam pulse duration $\tau = t\omega_p$. Changing beam and plasma frequencies, as well as 2D effects, have a stabilizing influence on the instability. The instability can result in modulation of the beam longitudinal and transverse emittance which ultimately limits the final pulse time and spot. Previous LSP simulations have shown that the effect of the growth in the longitudinal emittance is weak, however, two dimension effect could degrade the beam transverse emittance as well.

In the worst case scenario, a uniform $3\text{x}10^{11}$ cm^{-3} density, sharp-edged beam is injected into a uniform plasma in a 2D cylindrical LSP simulation. The Ne^+ beam has a 15-kA current, 220 MeV energy, and a 10-cm uniform density. A nominal 500-G uniform solenoidal field permeates the drift tube. We should see strong growth of the instability in this case. With v_b / ω_b = 50 cm and 10-m propagation length ζ_{max} = 20 and for the 100 ns pulse, τ_{max}=3000. In the entirely uniform density simulation, the transverse normalized emittance grows 10x from $2\text{x}10^{-4}$ pi-cm-rad to $2\text{x}10^{-3}$ pi-cm-rad as seen in Figure 6. Note that the emittance growth saturates by the 8 m position. We attempt to reduce the growth in three subsequent simulations varying one parameter at a time. For the axially varying plasma density simulation, the plasma density is given a variation from $1.5\text{x}10^{11}$ to $6\text{x}10^{11}$ cm^{-3} with a 8 m wavelength. In this case, the saturated emittance grew to $1.5\text{x}10^{-3}$ pi-cm-rad. In the third simulation, the plasma was given a gaussian radial variation from $6\text{x}10^{11}$ cm^{-3} on-axis to 1.5×10^{11} cm^{-3} at the beam edge. Here, the beam emittance growth was smallest with a growth to 1.1×10^{-3} pi-cm-rad. Finally, we give the beam a gaussian profile out to an e-fold keeping the current constant. Again seen in Figure 6, the saturated beam emittance grew to 1.2×10^{-3} pi-cm-rad. We also looked at increasing the applied solenoidal field 500 G to 2 kG with uniform densities. This had only a modest positive effect reducing the emittance growth roughly 10%. These results are encouraging since we have identified at least three different mechanisms to reduce saturated growth that could possibly be additive and yield a more managable emittance growth.

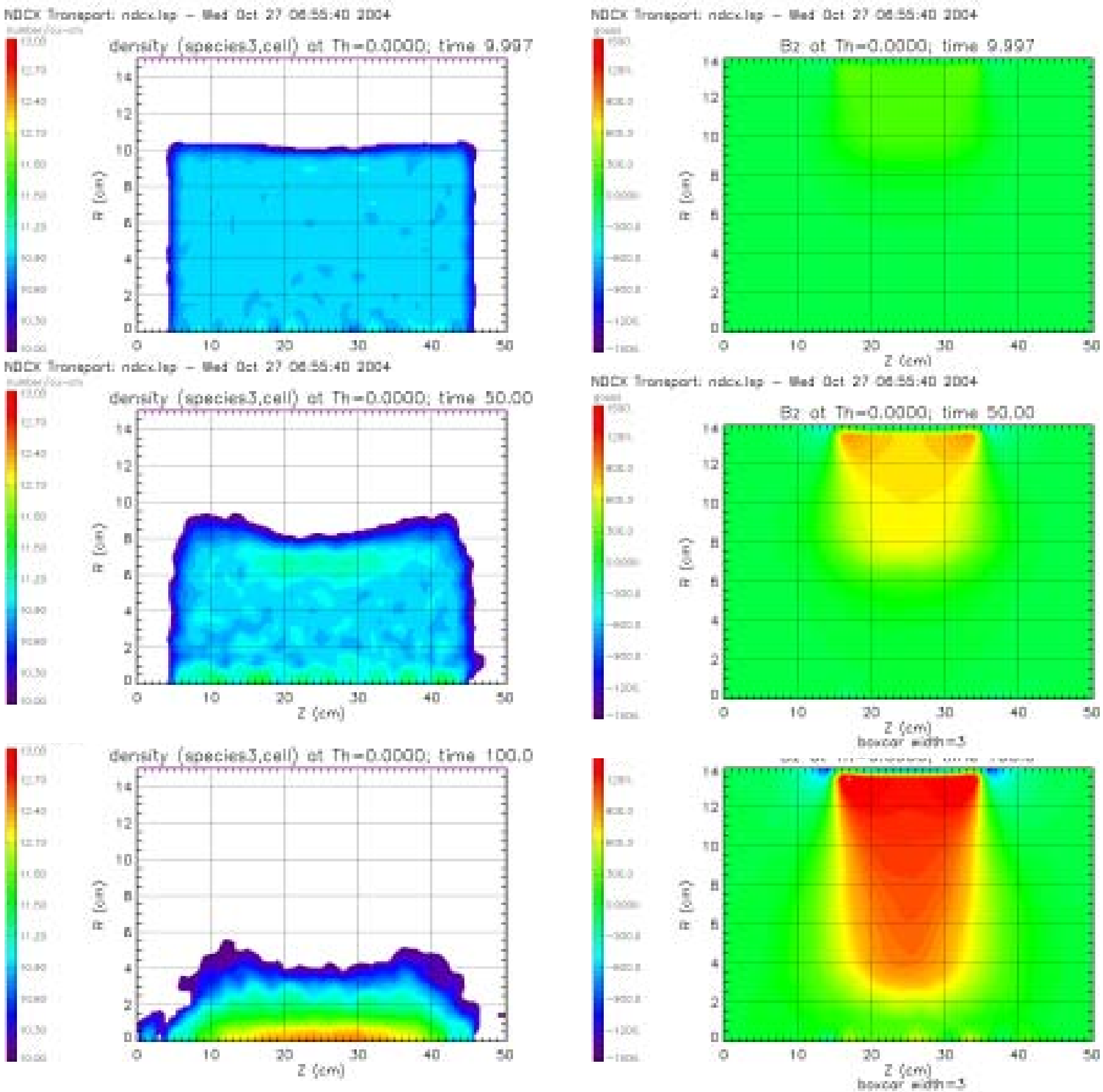

Figure 2 The plasma density (left) and axial magnetic field (right) evolution are shown at 10, 50 and 100 ns. The solenoidal current ramps up in 100 ns (z=15 to 35 cm with a 14-cm inner bore) in the 2D cylindrical LSP simulation.

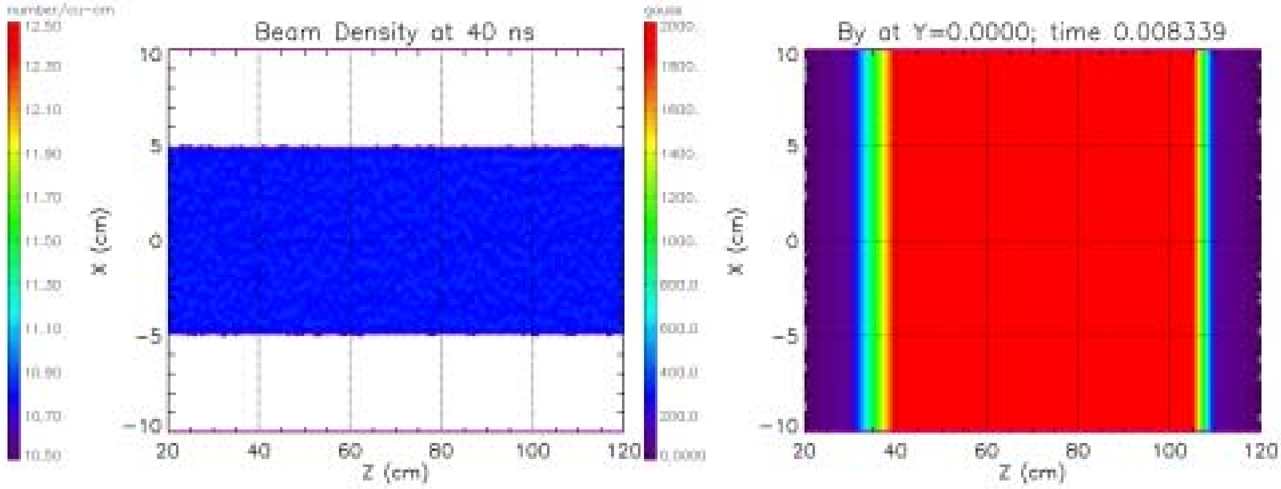

Figure 3 The beam density (left) and dipole magnetic field (right) are plotted for the series of LSP dipole field plasma neutralization simulations. The beam density is 10^{11} cm^{-3} with a 0.15*c* velocity (50 A/cm^2) . The dipole field strength is 2 kG and extend from z = 35-105 cm.

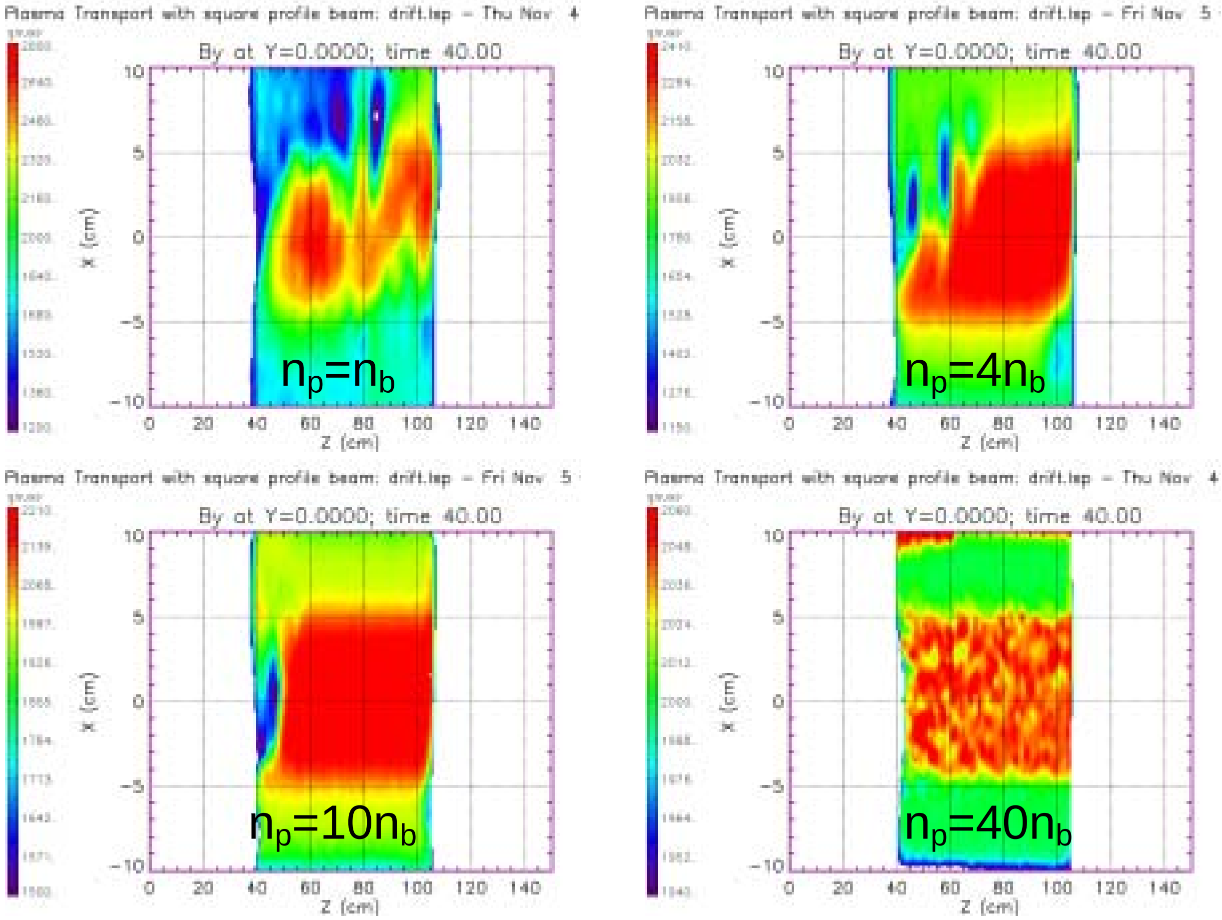

Figure 4 The (self + applied) dipole magnetic field is plotted after 40 ns into the LSP simulation with plasma densities of 1, 4, 10 and 40n_b. The applied dipole field magnitude is 2 kG.

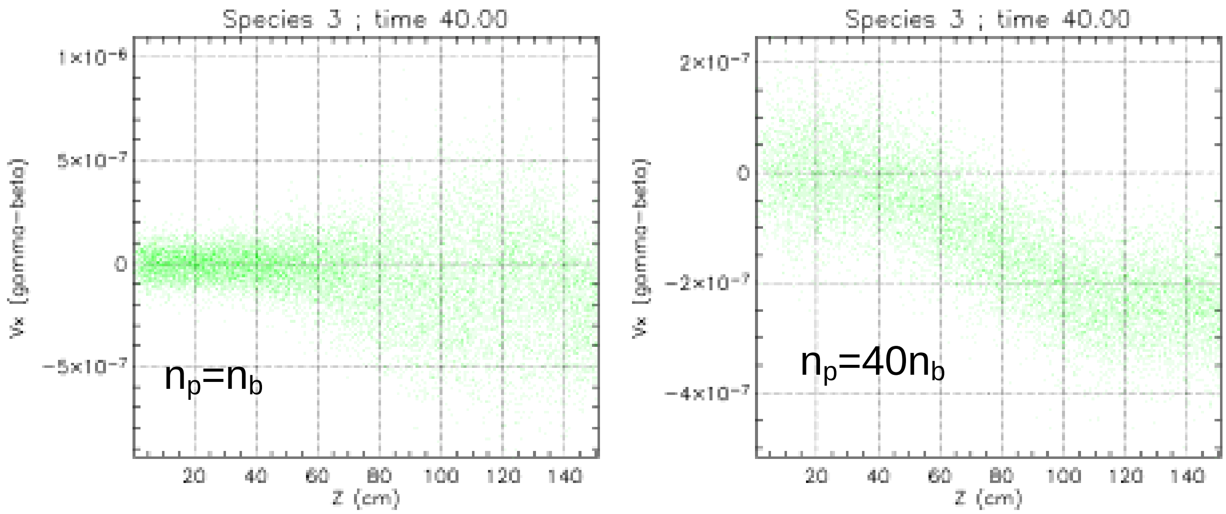

Figure 5 The beam transverse velocity v_x is plotted versus z for the simulations with plasma density equal and 40x the beam density.

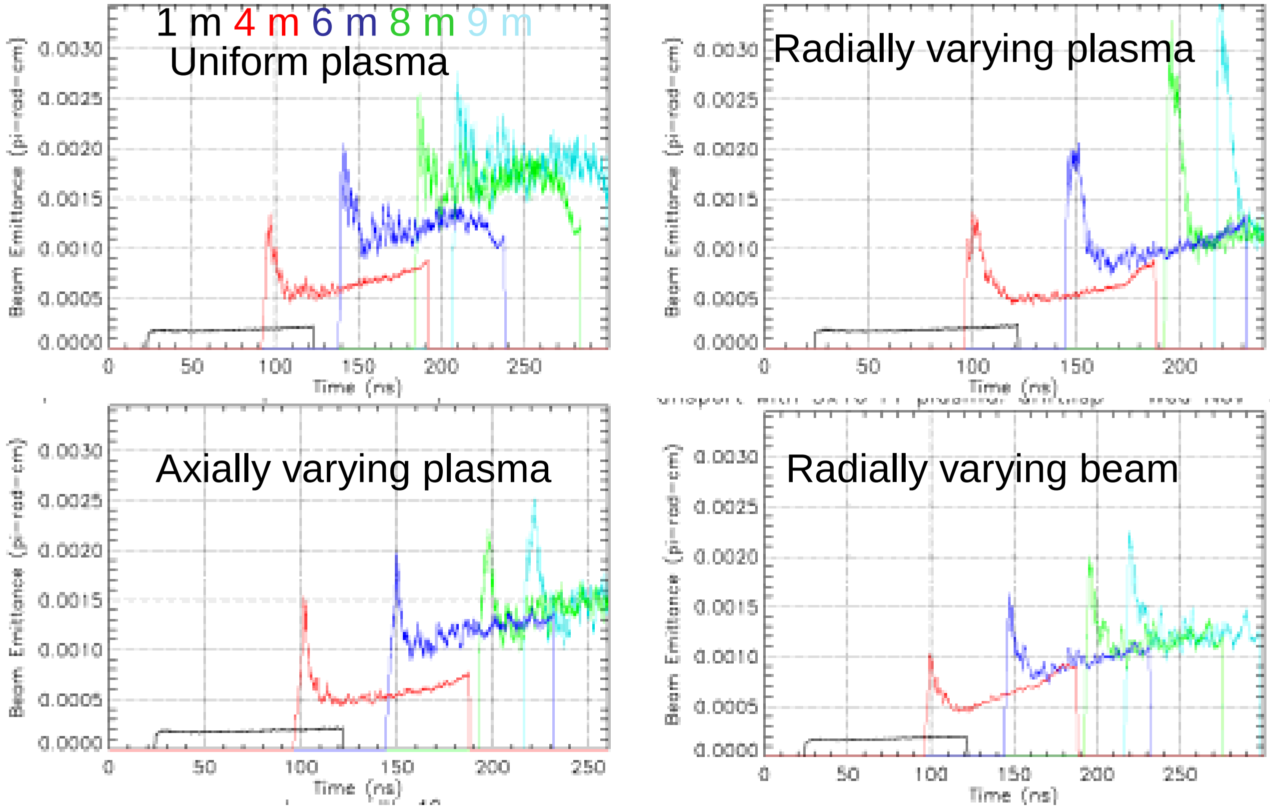

Figure 6 The transverse emittance for a 15-kA 100-ns 220 MeV Ne^+ beam is plotted at z = 1, 4, 6, 8, and 9 m downstream from injection. The plasma had a nominal 3x1011 cm-3 density. The 4 simulations had uniform, axially varying plasma, radially varying plasma and radially varying beam densities.

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[2] D. R. Welch, D. V. Rose, B. V. Oliver, and R. E. Clark, Nucl. Instrum. Meth. Phys. Res. A **464**, 134 (2001); LSP is a software product of Mission Research Corporation (http:\\www.mrcabq.com).
[3] E. Lee, private communication (2004).
[4] B. V. Oliver and R. N. Sudan, Phys. Plasmas **3**, 4730 (1996).