What are the main issues?

accelerator issues

- switchyard or moving experiments
- time-dependent focusing
- interface between the accelerator and neutralized drift

focusing issues

- solenoid or quadrupole focusing
- charge-state spread
- adiabatic plasma lens

plasma issues

- beam-plasma interaction and stability
- dipole and quadrupole fields in plasmas
- atomic physics (stripping, charge exchange, energy loss)

system issues

- requirements on momentum tilt Δp_z and thermal spread δp_z
- beam combining
- flexibility of beam parameters

interface issues with accelerator

What's in our toolbox for focusing and compression?

neutralized compression

large stationary solenoid lens for final focus.

dipoles for

- stopping electrons
- switch yard
- achromatic mutibeam concept
- must work in plasmas

solenoid to suppress instabilities

pulsed lenses to compensate chromatic problem from tilt

adiabatic funnel close to experiments

large convergence angle to obtain small focal spot

How important is scattering of beam ions?

small-angle scattering increases emittance only moderately

- **assume hydrogen plasma**

$$\left(\frac{d\langle\theta^2\rangle}{dz}\right)_{scat} = \frac{(n_e + n_p)8\pi q_b^2 e^4}{p_b^2 v_b^2 (4\pi\varepsilon_0)^2}\ln\Lambda \quad (\ln\Lambda = 16).$$

- **emittance increase**

$$\frac{d\varepsilon^2}{dz} = 2a_b^2\left(\frac{d\langle\theta^2\rangle}{dz}\right)_{scat}$$

- **consider** $n_p = 10^{21} m^{-3}$ (large), $20 Mev\ Ne\ \ (q_b = 10)$,

$a_b = 0.01m, 10m$ propogation

$\Delta(\varepsilon^2) = (1.45\times 10^{-5} m - r)^2$

marginal effect!

How effective is plasma neutralization?

Consider $1\mu\times$C, 6.3×10^{12} ions, Charge state $+7$, $10\times$ electrons

4.4×10^{14} electrons in beam pulse.

Required n_e in the pulse $<<10^{15}\,cm^{-3}$, except very close to the target.

For example $n_e=10^{15}\,cm^{-3}$, $\omega_{\text{pe}}=\sqrt{\dfrac{n_e e^2}{4\pi\varepsilon_0 m_e}}=5\times10^{11}\,s^{-1}$,

$\omega_{pe}\tau_p>>1$ always.

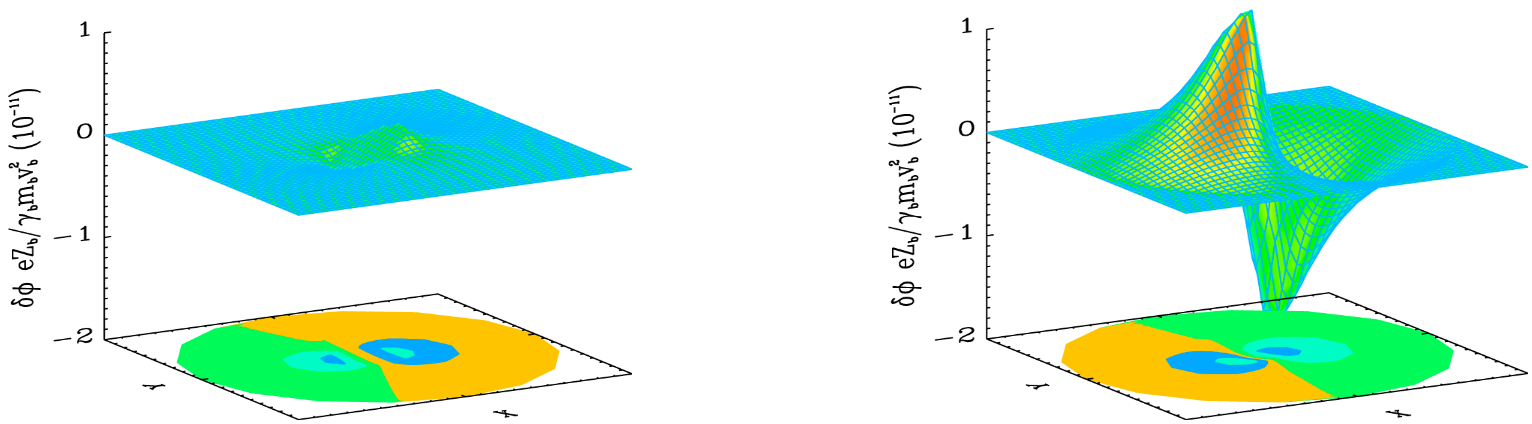
charge and current neutralization should be good, except for

- **possible two-stream instability**
- **possible charge separation in bends and quads**
- **effects of plasma non-uniformity**
- **making an extended hydrogen plasma may challenging**

Is two-stream instability likely to be a problem?

two-stream instability for dispersion relation for azimuthal mode l=1

$$[(\omega - k_z V_b + ik_z v_{Tb})^2 - \omega_b^2][(\omega + ik_z v_{Te})^2 - \omega_e^2] = \omega_f^2$$



$t = 0$

$t = 200/\omega_{\beta b}$

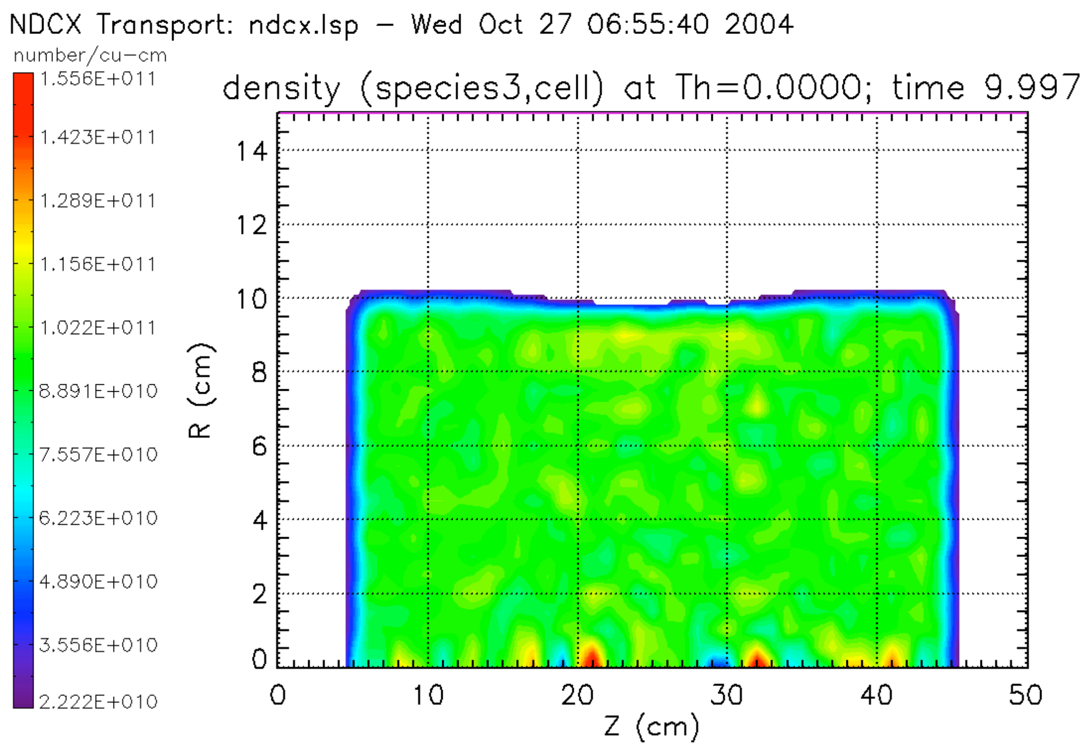
Unlike the classical two-stream instability, transverse dynamics is important.

Damping mechanisms and nonlinear stage of the instability are nontrivial.

Can we apply a time-dependent chromatic correction to a beam in a plasma?

test problem for solenoidal penetration into a plasma

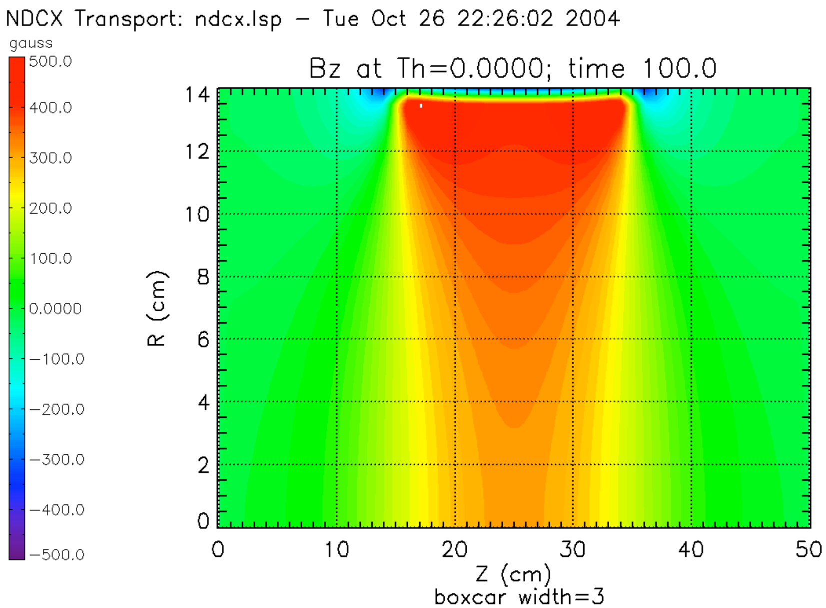
- **10-cm radius 10^{11} cm^{-3} C^{+1} plasma in a 15-cm tube**
- **14-15-cm radius solenoid**
- **B_z field ramps from 0.15 to 1.5 kG in 100 ns**
- **$\beta = 10^{-3}$**



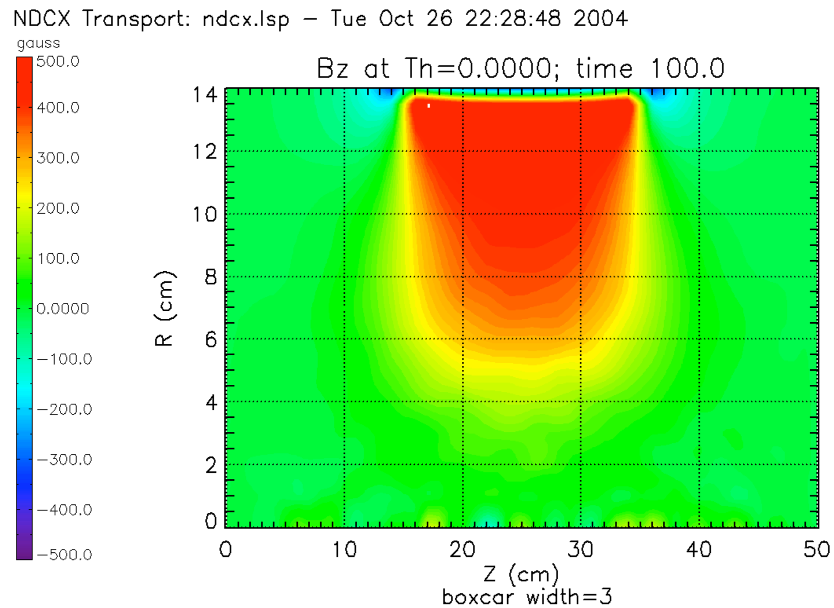
Plasma density at 10 ns

Field for plasma and vacuum cases

field ramps from 50-500 G in first 100 ns

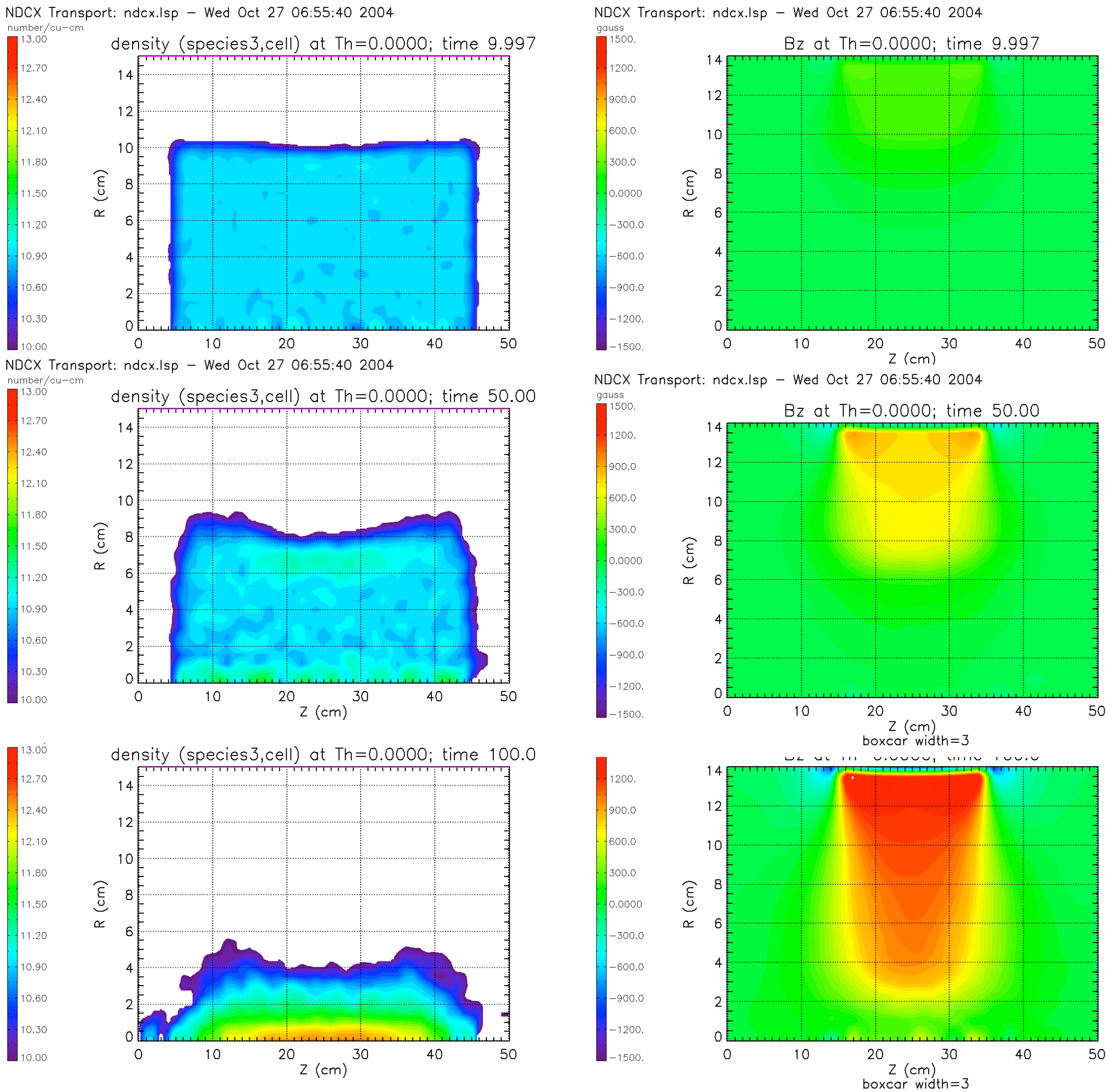


without plasma



with plasma

Low-beta plasma is sqeezed radially



field penetration is small

result is a lumpy mess

correction in plasma may not be possible

What is the effect of a transverse field on the beam?

from MHD, electron equation of motion is basically E x B

$$\underset{\sim}{E} + \underset{\sim}{v}_e \times \underset{\sim}{B} \approx 0$$

for perfect current neutralization,

$$v_e = v_b \frac{n_b}{n_e}$$

the induced transverse electron field for applied B_y is then

$$E_x \approx v_b \frac{n_b}{n_p} B_y$$

this electric force acts to oppose v_b B_y

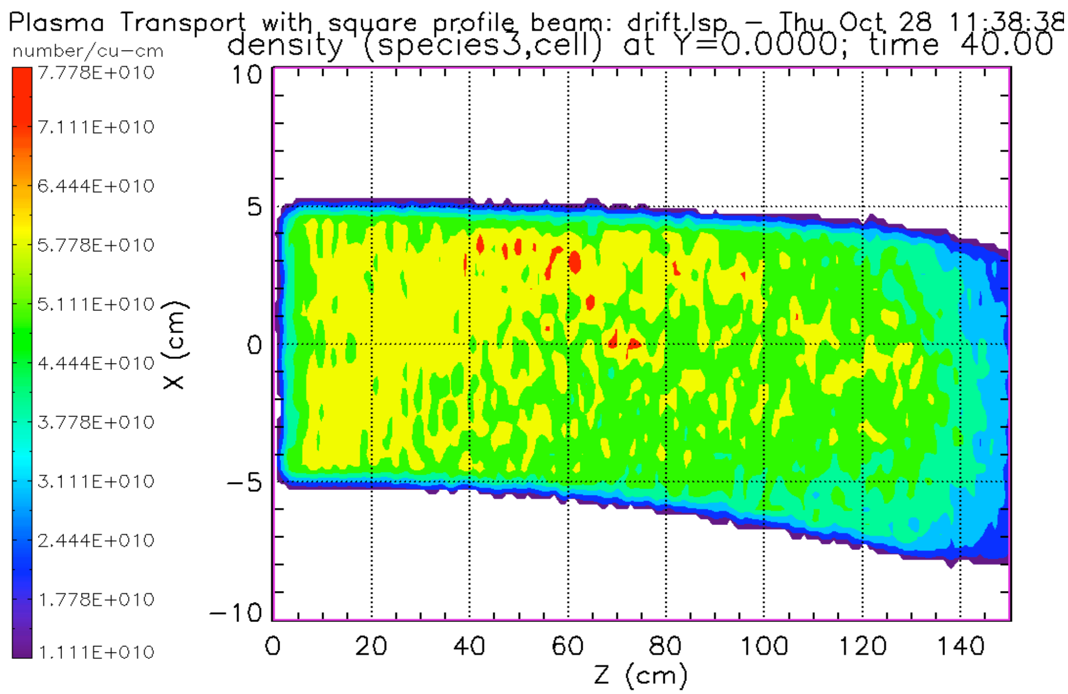
force is reduced from that of applied field by the ratio of densities

How good is this model?

LSP *x-y* simulation shows transverse field is close to prediction

parameters:

- **N_b= 7x10^{10} cm^{-3} , 220 MeV, Ne^{+1} beam 10-cm across**
- **3x10^{11} cm^{-3} plasma (1-cm skin depth)**
- **uniform B_y = 2000 G deflects beam down**

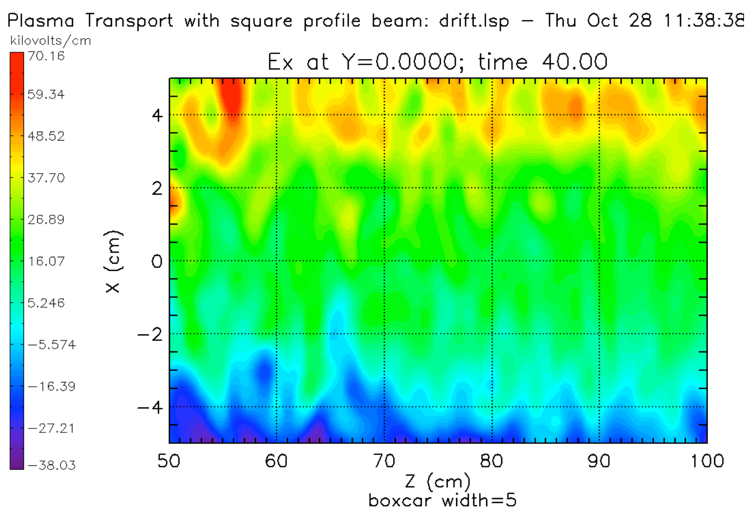


Current neutralization is not complete in bend

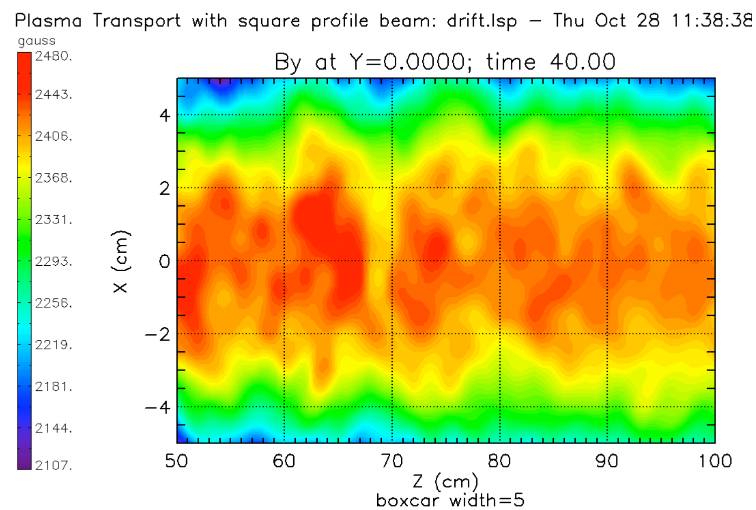
theory predicts roughly 20 kV/cm - roughly that calculated within beam

self-B_y is also calculated of order 400 G

net self-Lorentz force is small except at beam edge (skin depth effect)



E_x field after 40 ns



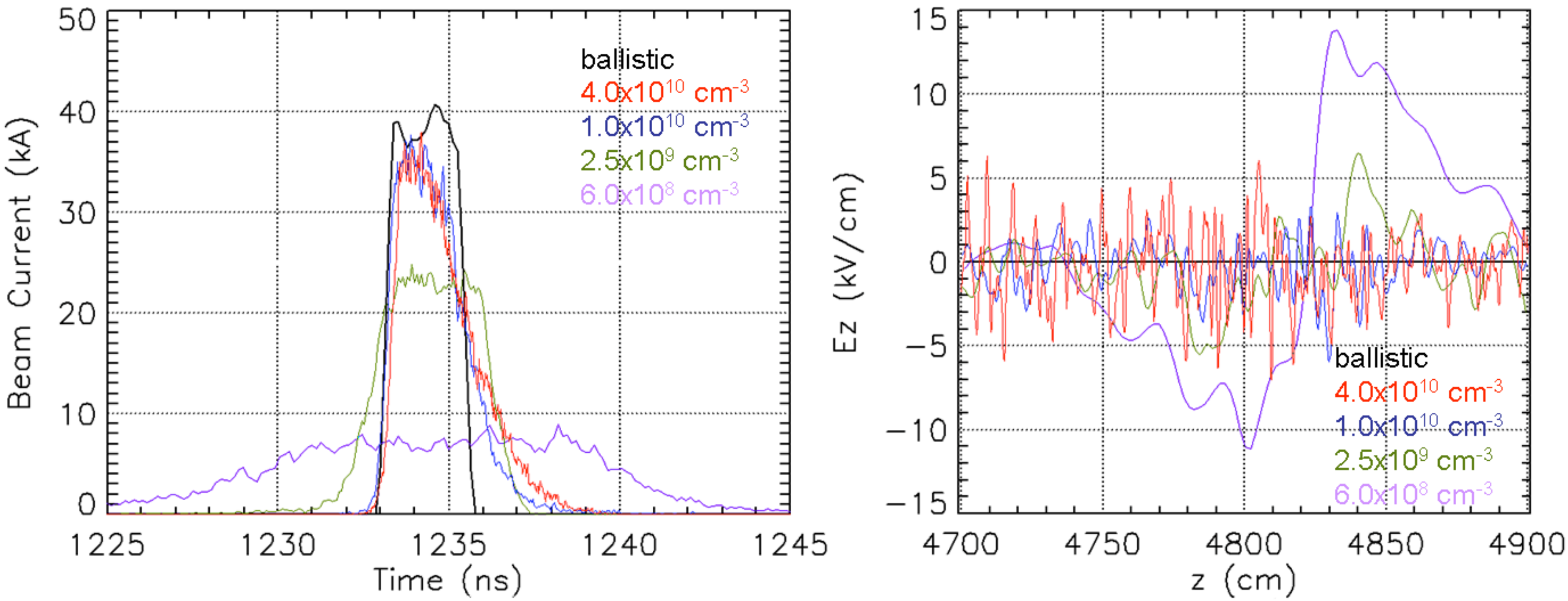
B_y field after 40 ns (self + applied)

net self-force is weak, so static transverse magnetic field may be OK

How does plasma density affect compression?

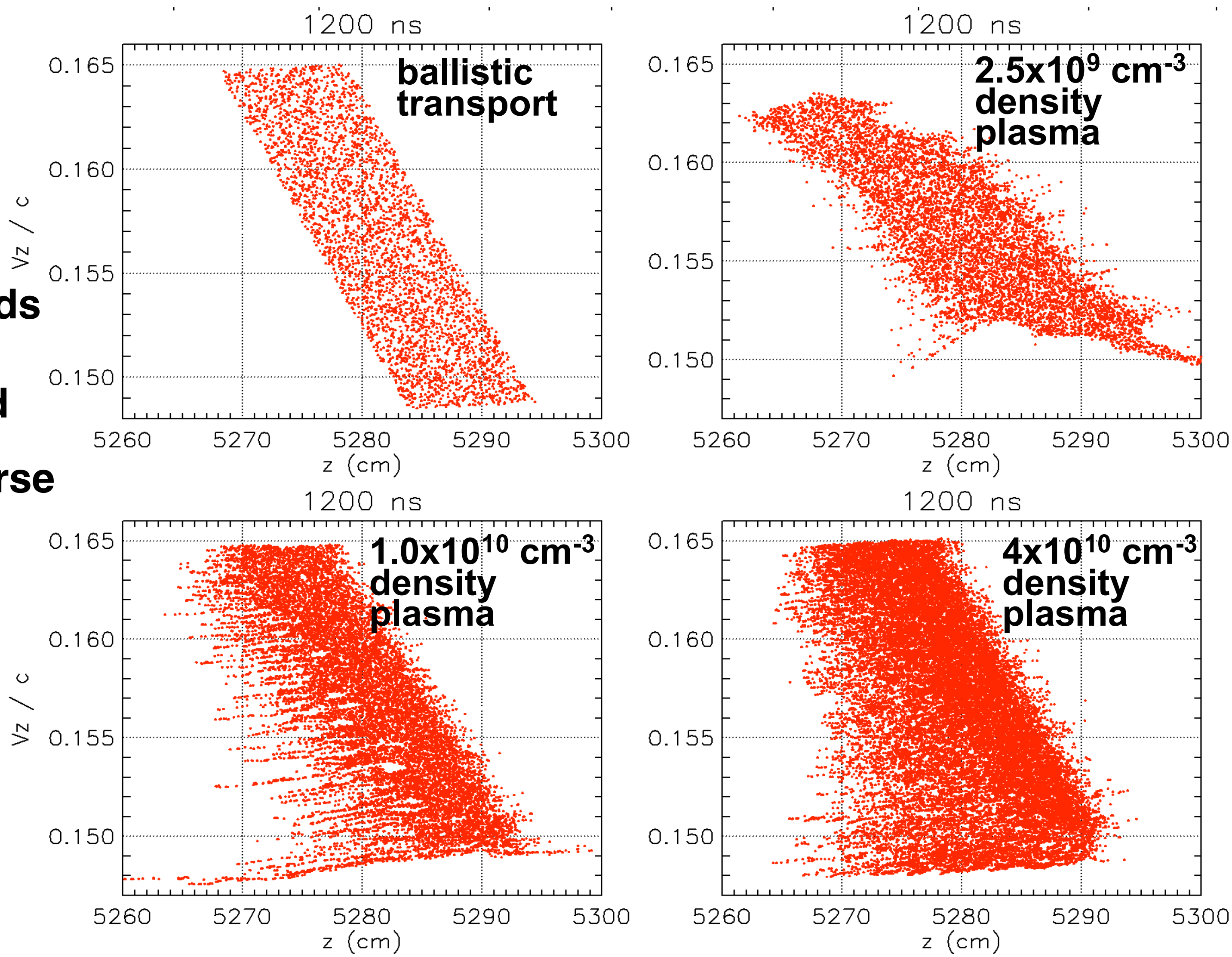
longitudinal compression approaches ballistic for large n_p/n_b parameters:

- **780-A, 110-ns, 20-cm Ne^{+1} beam with *L* = 5450 cm**
- **10% head-to-tail velocity tilt with 0.1% random v_z variation**
- **$n_b = 10^9$ cm^{-3} ; $n_p = 6x10^8 - 4x10^{10}$ cm^{-3}, T_0 = 3 eV**
- **$\Delta z = 0.5\ c\beta / \omega_p$, $\Delta t = 1/5\omega_p$ for all simulations resolves 2-stream**



What does two-stream do to the beam phase space?

- too low a density results in space charge spreading
- saturation of two-stream growth leads to **tolerable** momentum spread
- impact on transverse dynamics being investigated



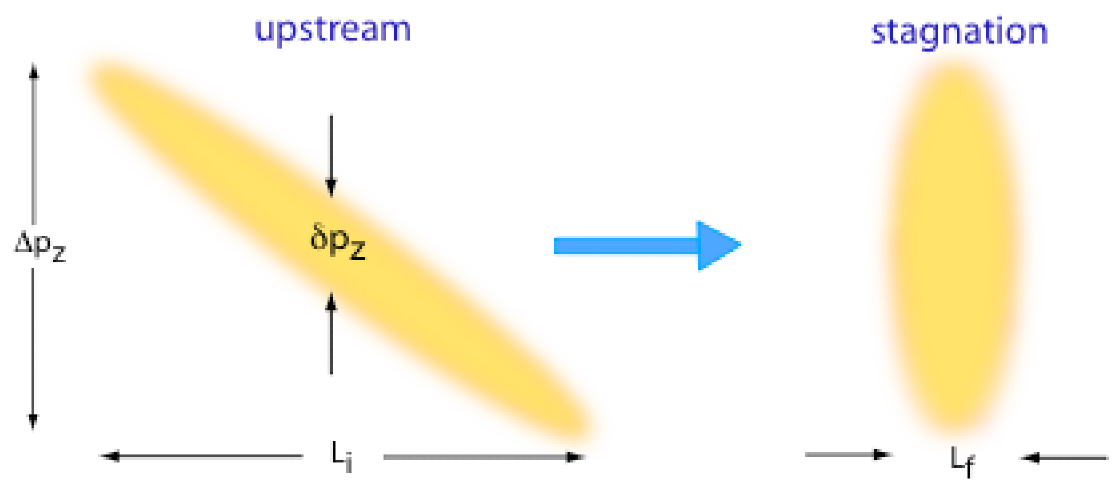
What constrains the initial beam temperature?

best case assumes ballistic compression

- **no scattering, stripping, or energy loss**
- **assume uniform momentum spread δp_z**

for a given compression ratio L_i / L_f and head-to-tail momentum tilt Δp_z

$$L_i / L_f = \Delta p_z / \delta p_z$$



for 100:1 compression and $\Delta p_z / p_z = 0.1$, $\delta p_z / p_z$ must be 0.001 or less

for 20 MeV beam, longitudinal temperature must be less than 40 keV

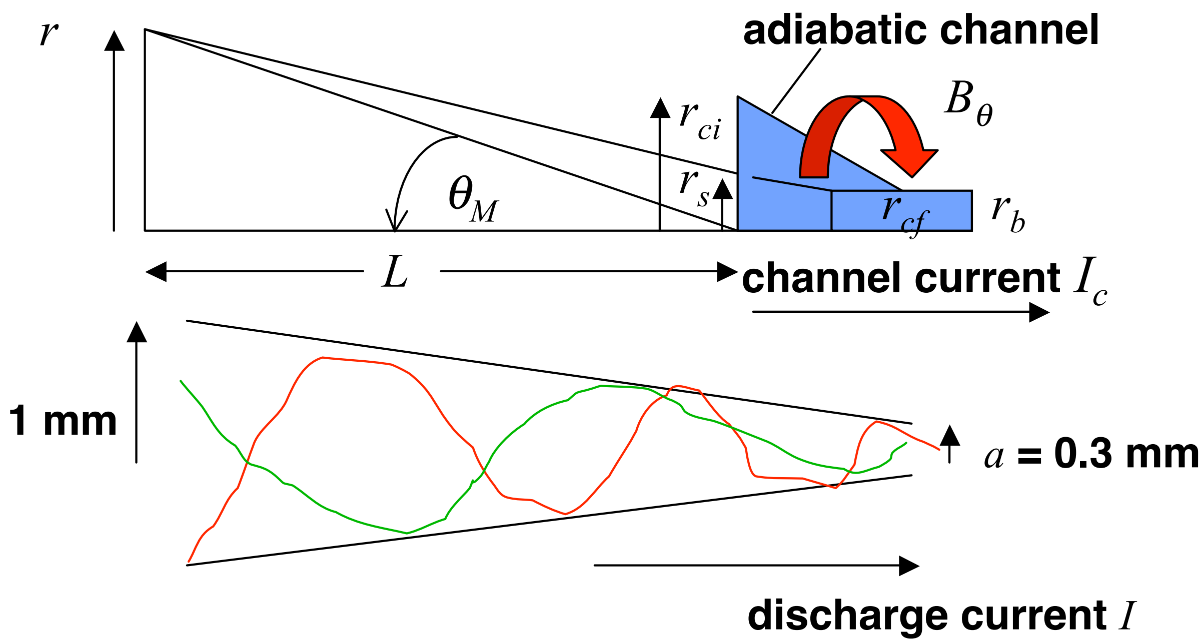
Seems possible!

What about plasma lenses?

adiabatic plasma lenses offer important advantages

- tenfold increase in final beam intensity
- larger momentum acceptance than magnetic lenses
- predictable beam dynamics

$$\left(\frac{\varepsilon}{a}\right)^2 = 2\frac{I}{I_A}$$



key issue is technology of building small lens

Several final focusing options considered for BB-TWA

final tilt imposed by last helix segment

30-cm pulse implies a short drift compression section (few m)

Q at output ~ 2×10^{-3} @ 20 MeV

options:

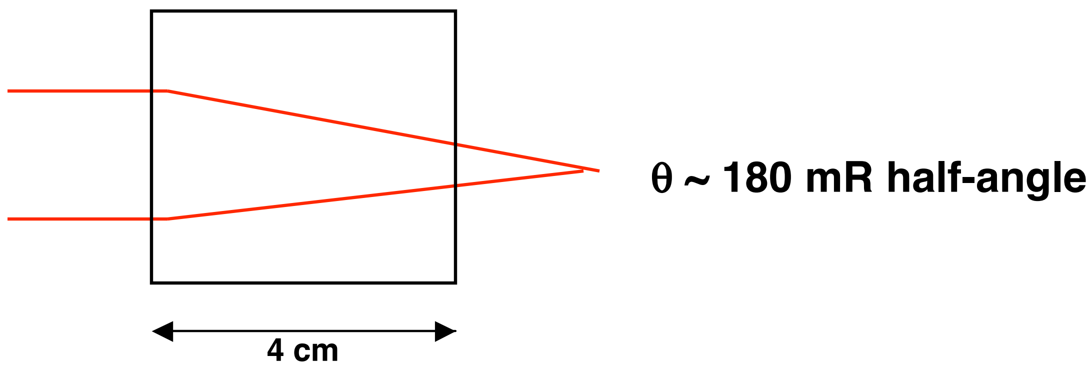
Helix -> Strong Sol's -> Dipole -> Strip to +7 -> 1 T NDC -> 15 T Sol -> Tgt
(match from ~ 3 cm to ~ 1 cm radius for NDC)

Helix -> Dipole -> Opt. Strip -> Graded Sol NDC -> 15 T Sol -> Tgt
(beam radius reduced gradually during NDC, no match section)

Helix -> Graded Sol -> 15 T Sol -> Tgt
(plasma builds up along line, gradually)

MAP He+ diode final focus

- He^{+1} 6 MeV 1.0 ns
- 6.0 J into 1 cm spot
- ΔV negligible
- short solenoid lens:
  B = 2.0 T
  L = 0.04 m



- Focal Length = 5.5 cm
- $\varepsilon = 1.8 \times 10^{-4}$ mR (assumed)
- r_s = 1.0 mm