Simulation of Heavy Ion Beam Propagation

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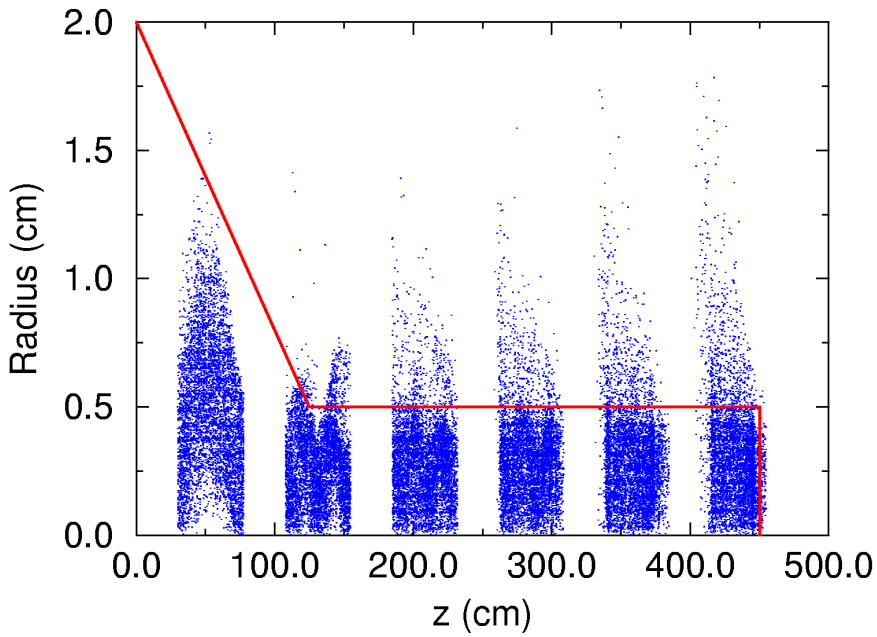
Outline of Talk

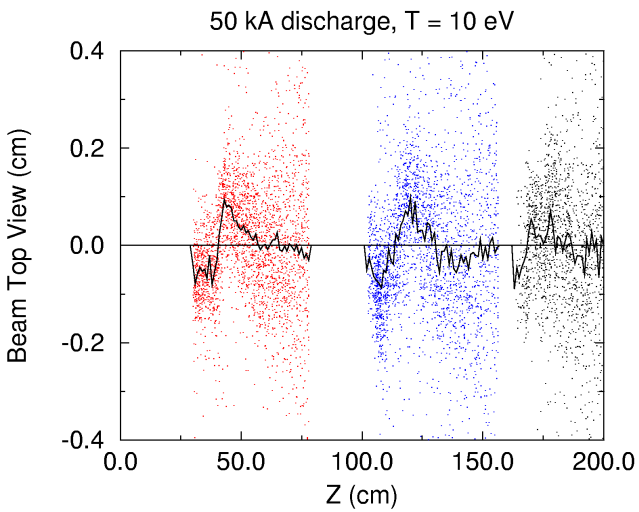
- Assisted-Pinch Transport
  - concept
  - self field evolution
  - transport efficiency
  - stability
- Self-Pinched Transport
  - concept
  - pinch force mechanism
  - propagation window
  - status of 3d modeling
- Transport Issues

IPROP Modeling of Assisted Pinch Transport

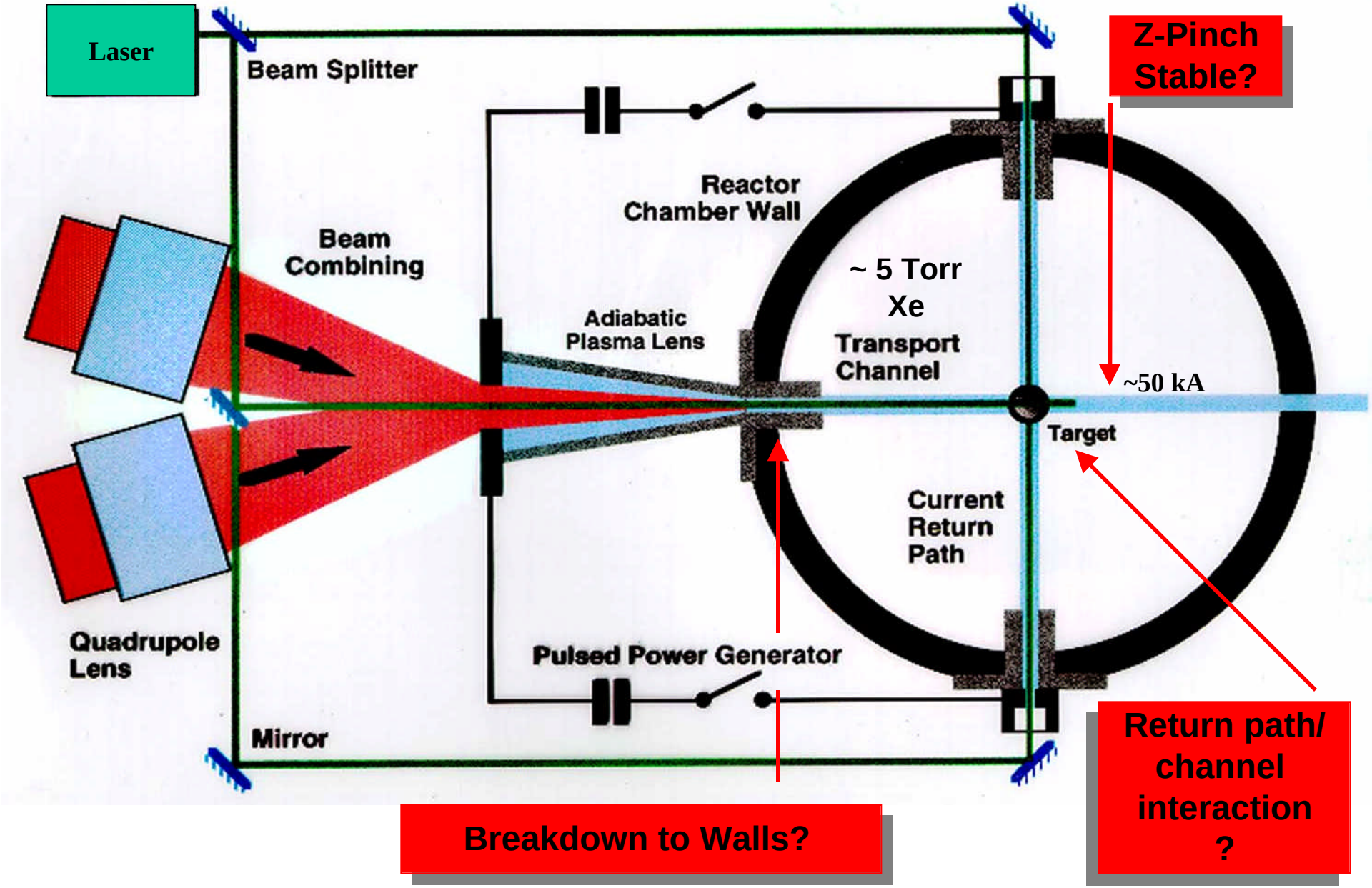
Equilibrium



Stability



Channel transport could ease chamber focus requirements and reduce driver costs



Key physics issues involve the evolution of self fields

- Beam must first be captured at small radius by 50 kA discharge current - adiabatic lens
- 6-MA electrical beam current has potential for huge self fields given finite plasma conductivity
- Strong plasma return current can drive “hose” instability

IPROP* simulates HIF beam interaction with discharge channel in 2 and 3D

- IPROP is a quasi 3D EM hybrid code
- 2 fluid model for the plasma, PIC beam ions
- Extensive models for xenon gas breakdown physics

*D. R. Welch, et al., Phys. Plasmas 1 (1994) 764.

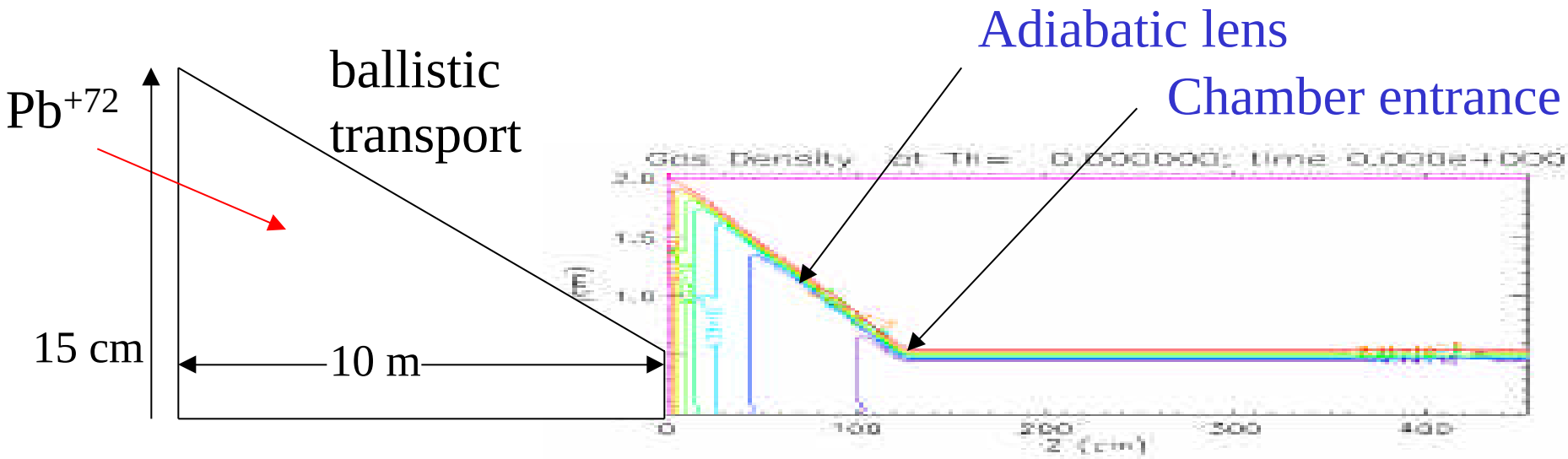
Simulation beam and gas conditions

- 4-GeV, 6 MA Pb^{+72} ions
- 15-cm radius beam is first transported ballistically 10 meters to the discharge. Micro-divergence nominally 1 mrad.
- Discharge initial parameters:

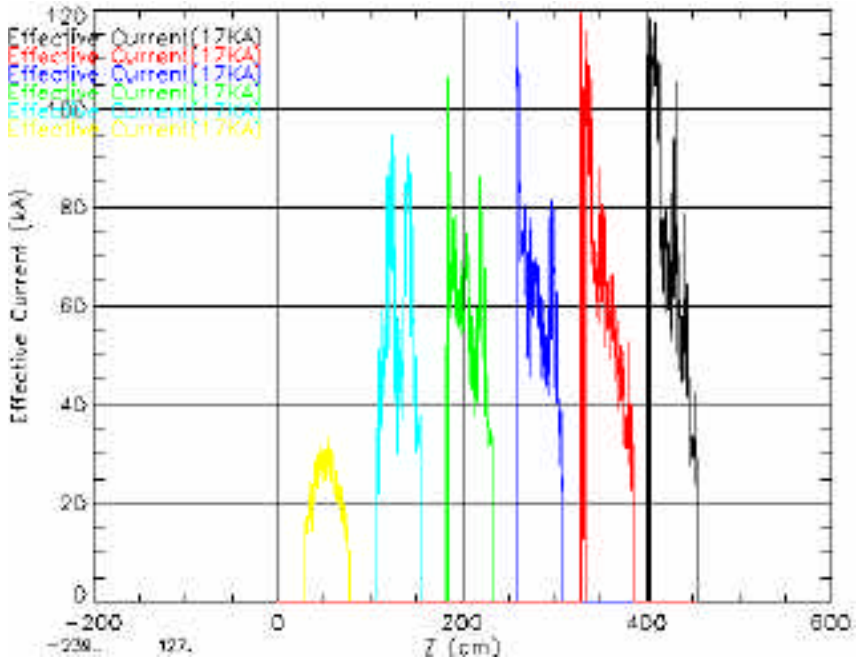
  50-kA current

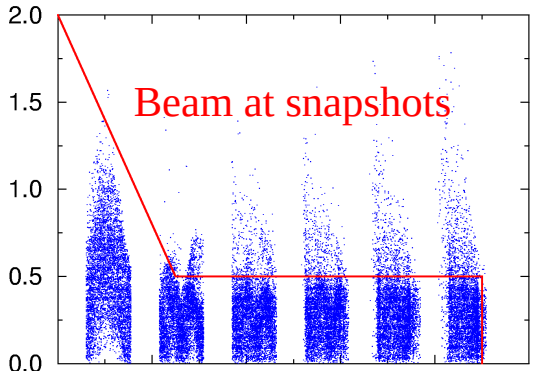
  5-Torr, 3-eV ambient Xe

  Axial position-dependent radius, reduced density (to 0.5 Torr minimum), ionization fraction (0.9 peak). Current density, reduced gas density and ionization fraction have square profiles



Effective current - sum of discharge and self currents - reaches 80 kA

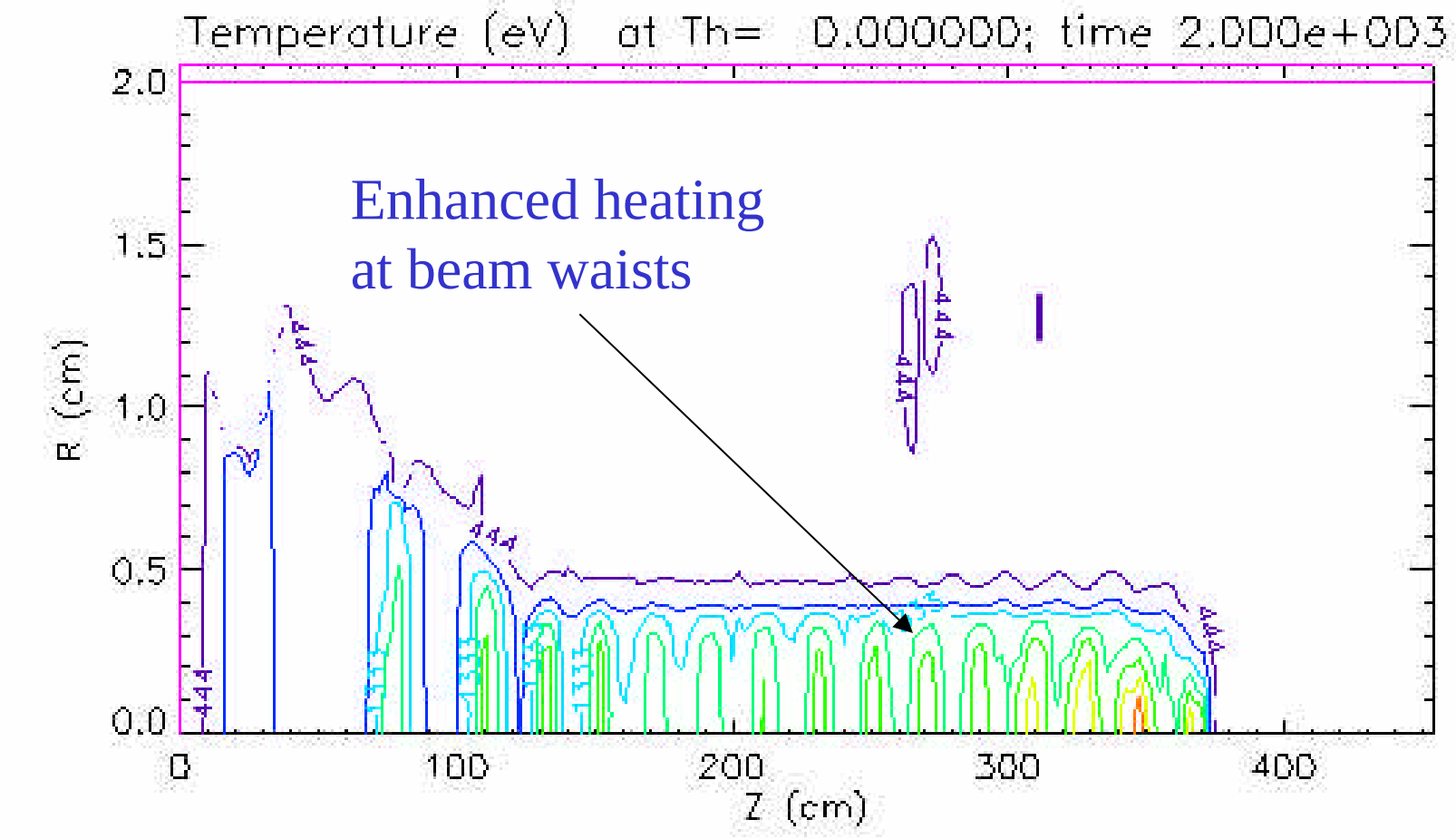




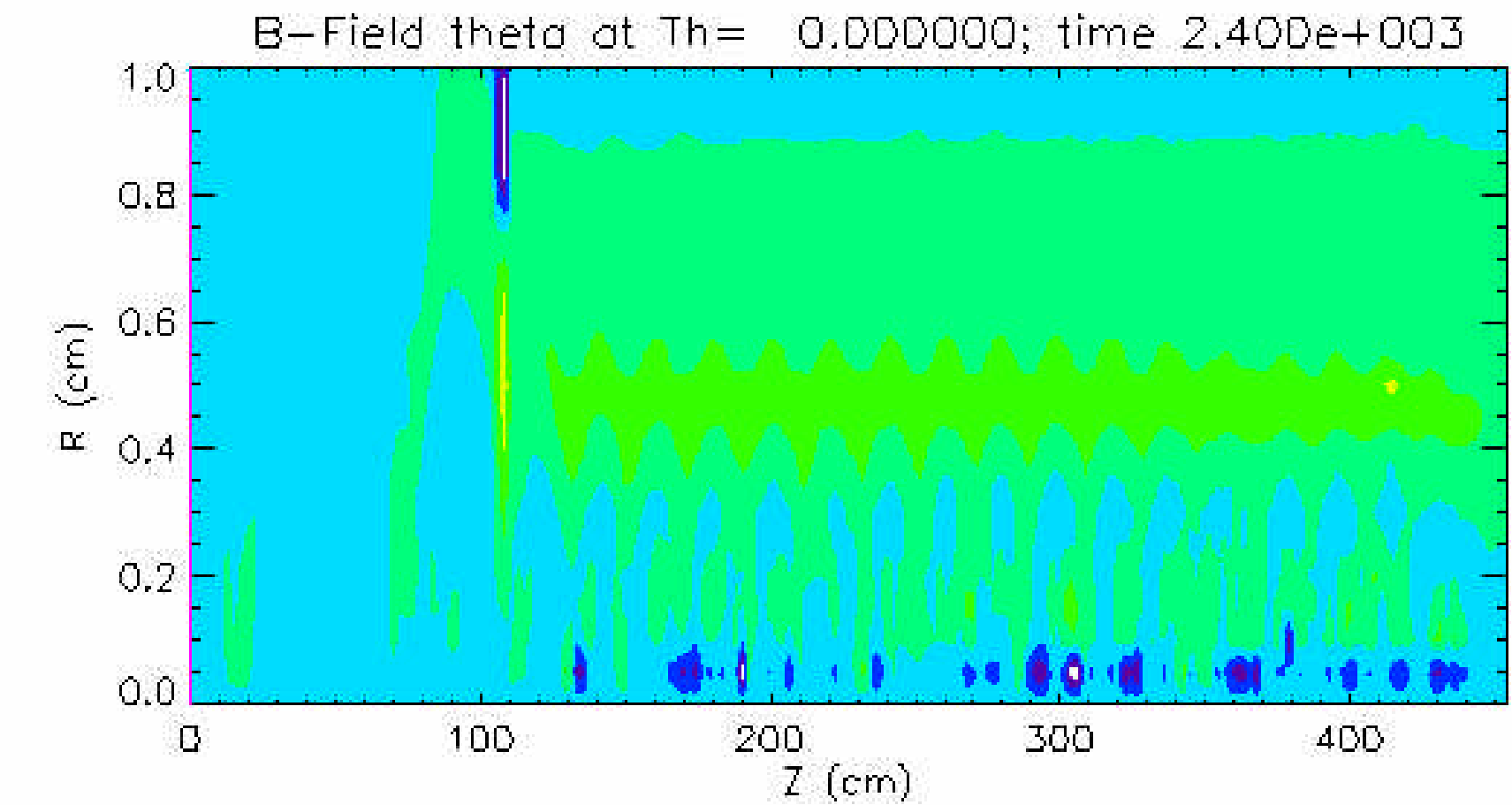
- Results for nominal parameters
- 6 snapshots of effective current
- 2-4 :s plasma return current decay time permits self field growth

Plasma heats ohmicly and from beam impact - decay time increases

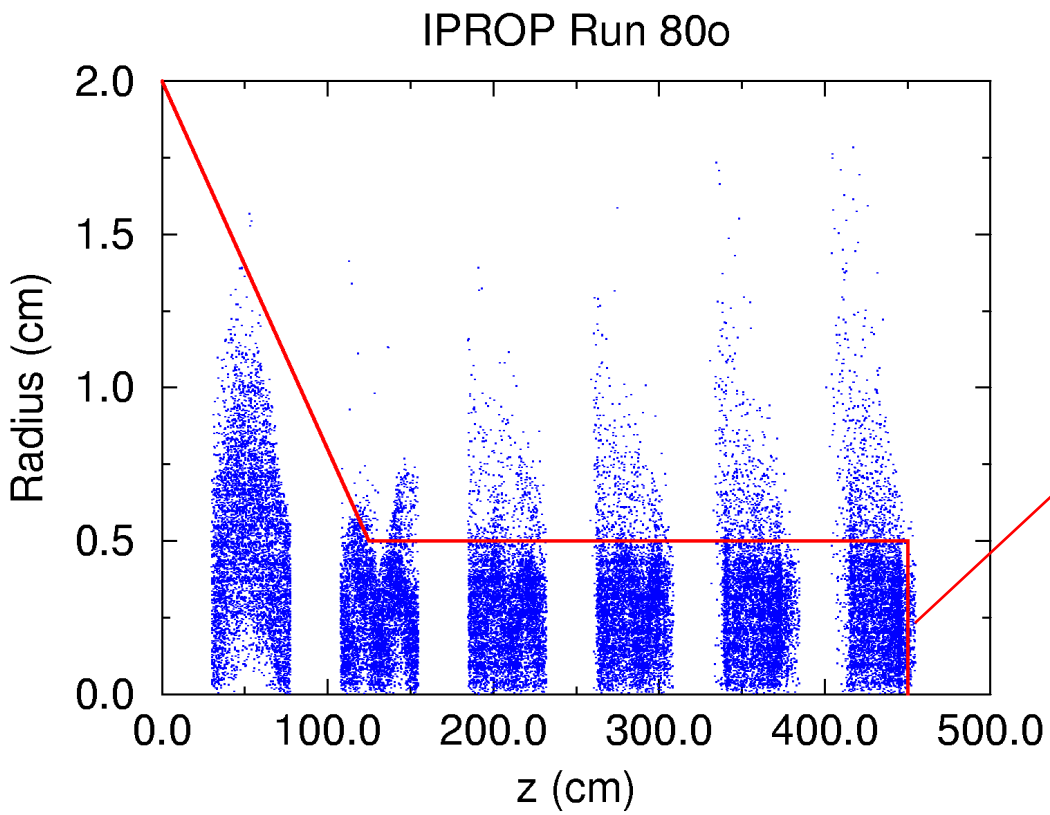
- Red contour is 3.3 keV, beam head at 375 cm
- Enhanced sigma reduces magnitude of B oscillation

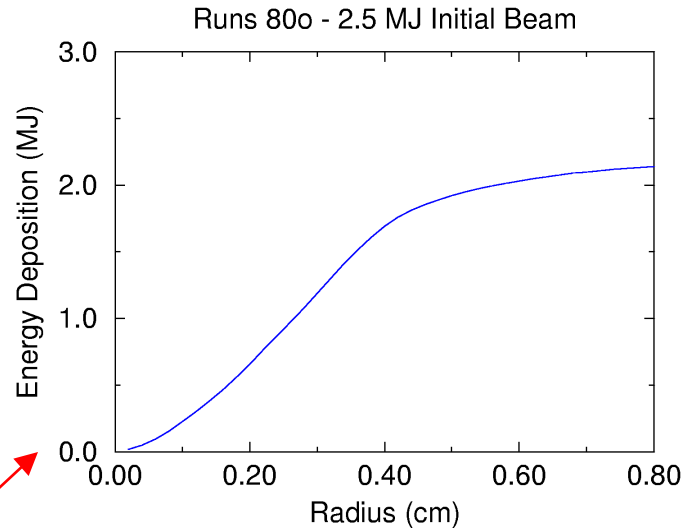


Beam oscillations imprinted on self magnetic fields



Beam halo growth from interaction with varying $B_2(z)$





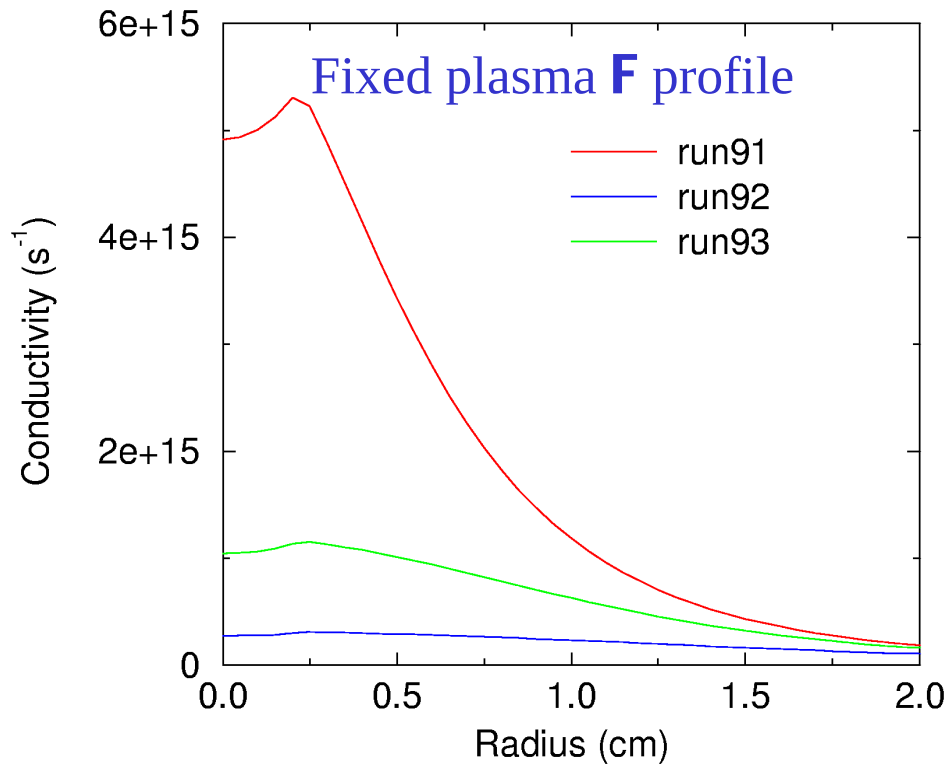
- 87% of beam transported over 4.5-m length
- 3.5-mm RMS radius

Finite conductivity results in some self field growth, beam loss

- Plasma current decay time scales as **F** r^2, reaches 2-4 **:**s (enough to permit 20-30 kA self field for 8 ns beam)
- Inductive fields rise with net current, reducing beam energy
- Oscillating beam imprints oscillating magnetic well
- Ions interact with changing B fields and heat
- Despite above effects, 87% beam energy transported, 3.5-mm RMS radius.

IPROP simulations of assisted-pinch hose instability

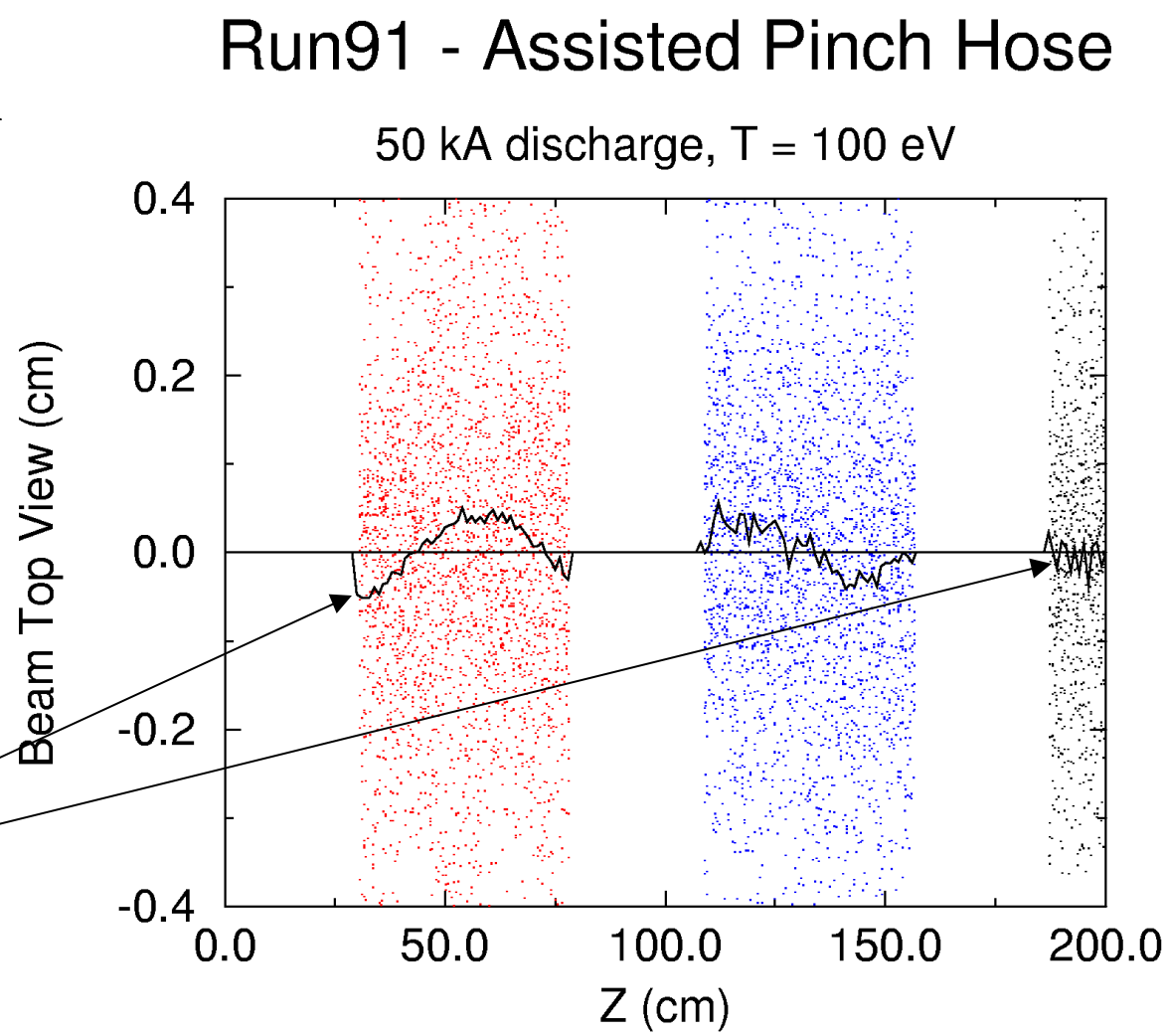
- IPROP is run with 2 azimuthal Fourier modes, m=0,1
- Beam is injected offset from channel 0.5 mm
- Conductivity profile is held fixed by initializing a singly ionized plasma with a gaussian radial profile



- Run91 - 100 eV plasma and 50 kA discharge
- Run92 - 10 eV plasma and 50 kA discharge
- Run93 - 30 eV plasma and 12.5 kA discharge

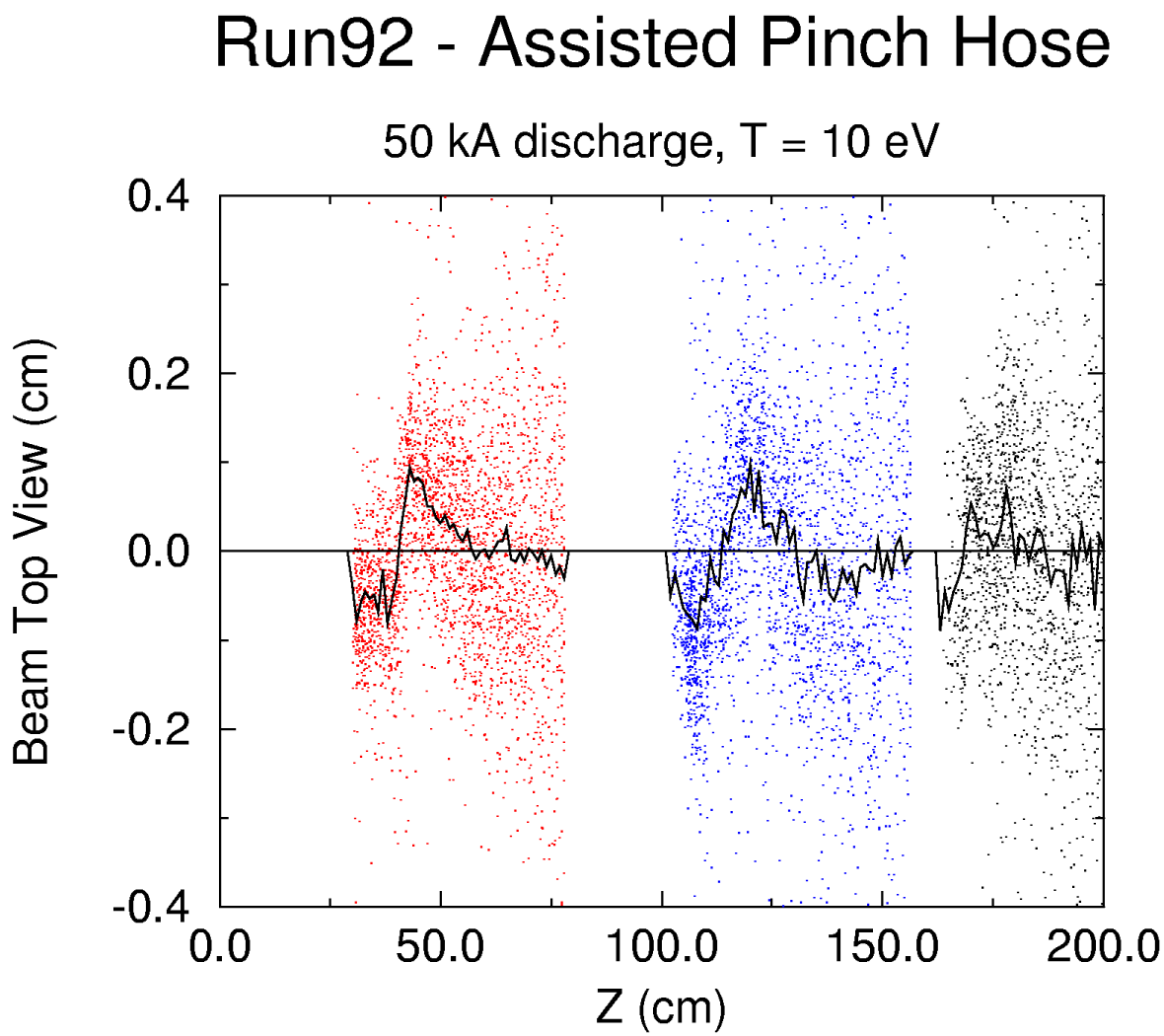
Nominal conductivity simulation shows no evidence of hose

- Fixed 5 microsecond decay time - **consistent with 2D breakdown calculations**
- 100 eV plasma temperature
- 50 kA discharge
- offsets damp



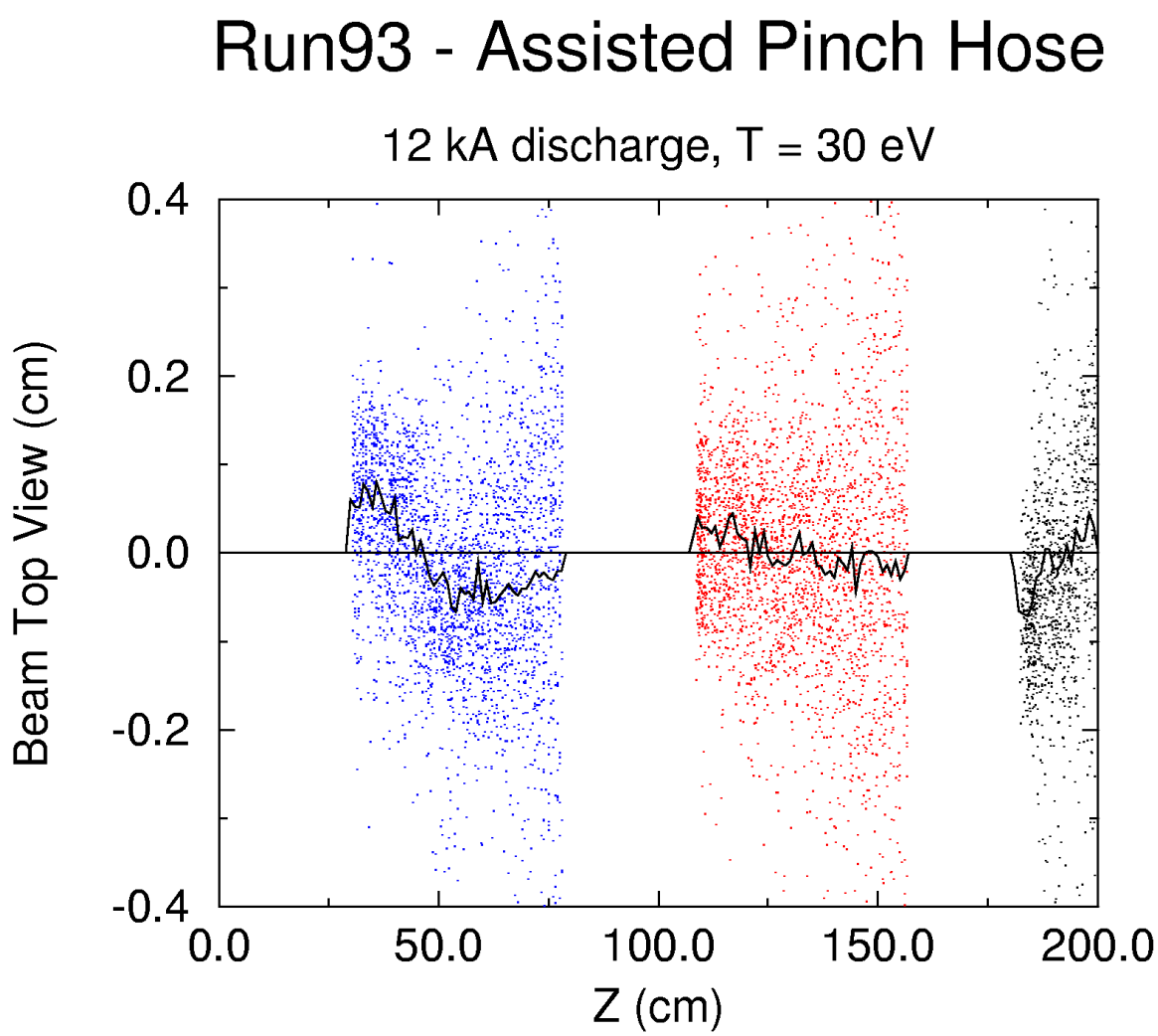
Highly resistive case - less than an e-fold growth

- 10-eV temperature,
- 50 kA discharge
- Large net currents, beam pinches
- Weak hose growth that damps rapidly



Low discharge current, medium conductivity case

- 30 eV temperature, 12.5-kA channel
- Hose again is very weak



Simulations suggest weak assisted pinch hose

	$I_{d\ \ dp} / (I_{b\ \ b}) > 1$*	*IPROP result*
run91	5	rock stable
run92	0.4	weak instability
run93	0.26	weak instability

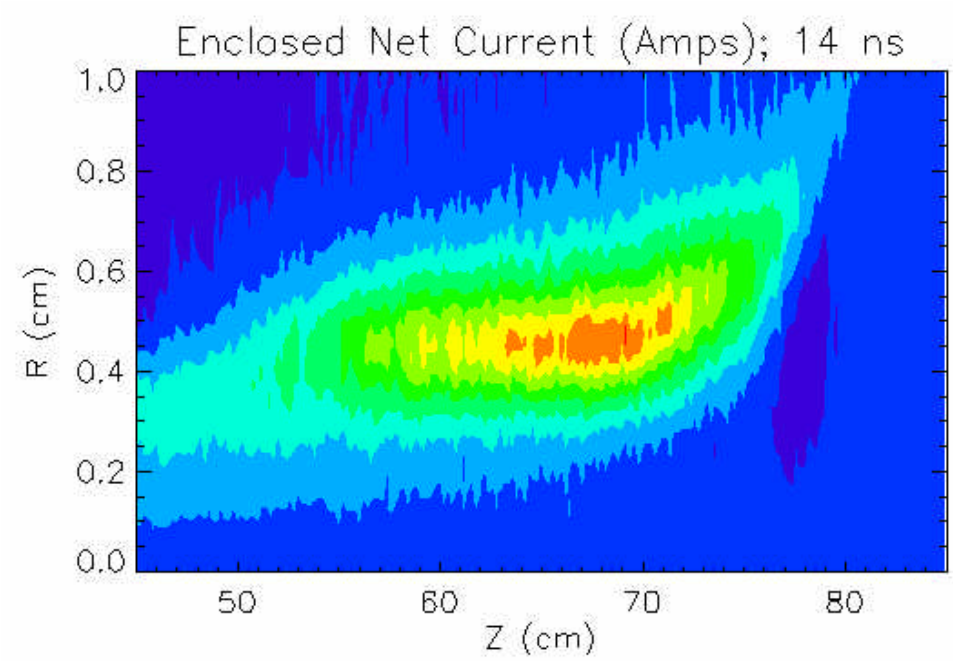
- Hose instability does not appear to be an issue for assisted pinch
- Neglected effects of beam scattering, ionization should be stabilizing

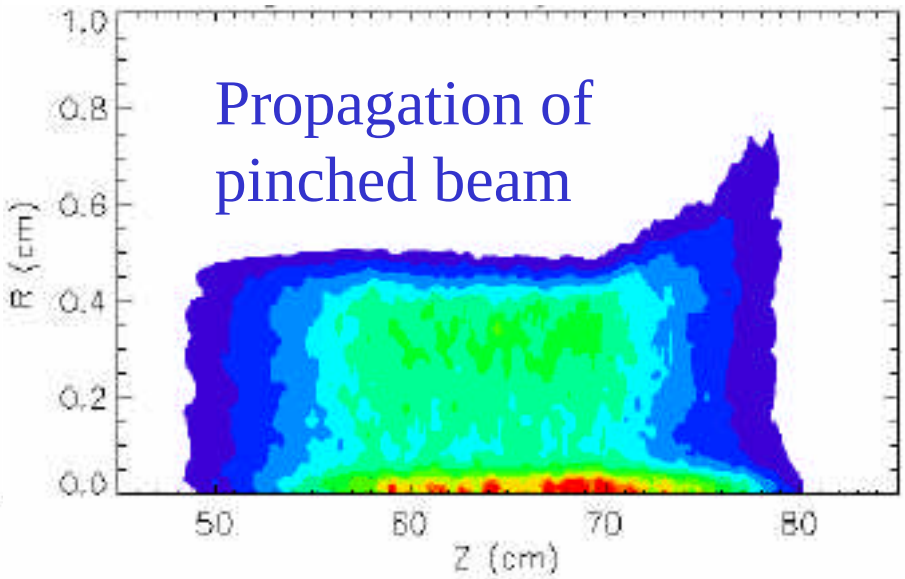
* Ed Lee's stability condition from Pinch Transport Workshop, 2001

Optimization of beam transport - work in progress

- Self-field strength limits energy transport efficiency and spot size
- 87% transport and 3.5 mm RMS spot size calculated over 4.5-m transport
- Weak self-hose instability calculated
- Need to develop technique for hollowing beam profile to better match recent target designs

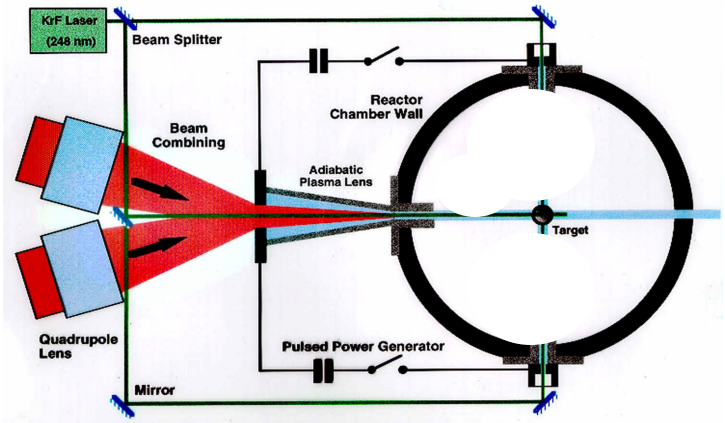
LSP Modeling of Self-Pinched Transport

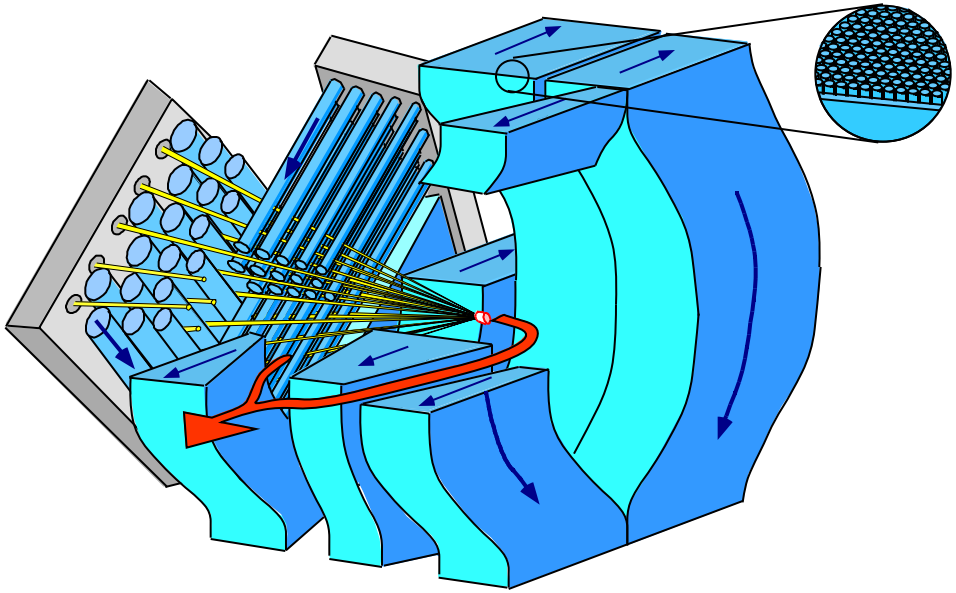




2 possible scenarios for self pinched transport

- Beams combined into 2 as in assisted pinch
  - large currents have potential for instability without discharge channel
- Use 100-200 beams with 1-4 kA per beam (as in Neutralized Ballistic Transport)
  - requires more beam ports, beams overlap near target

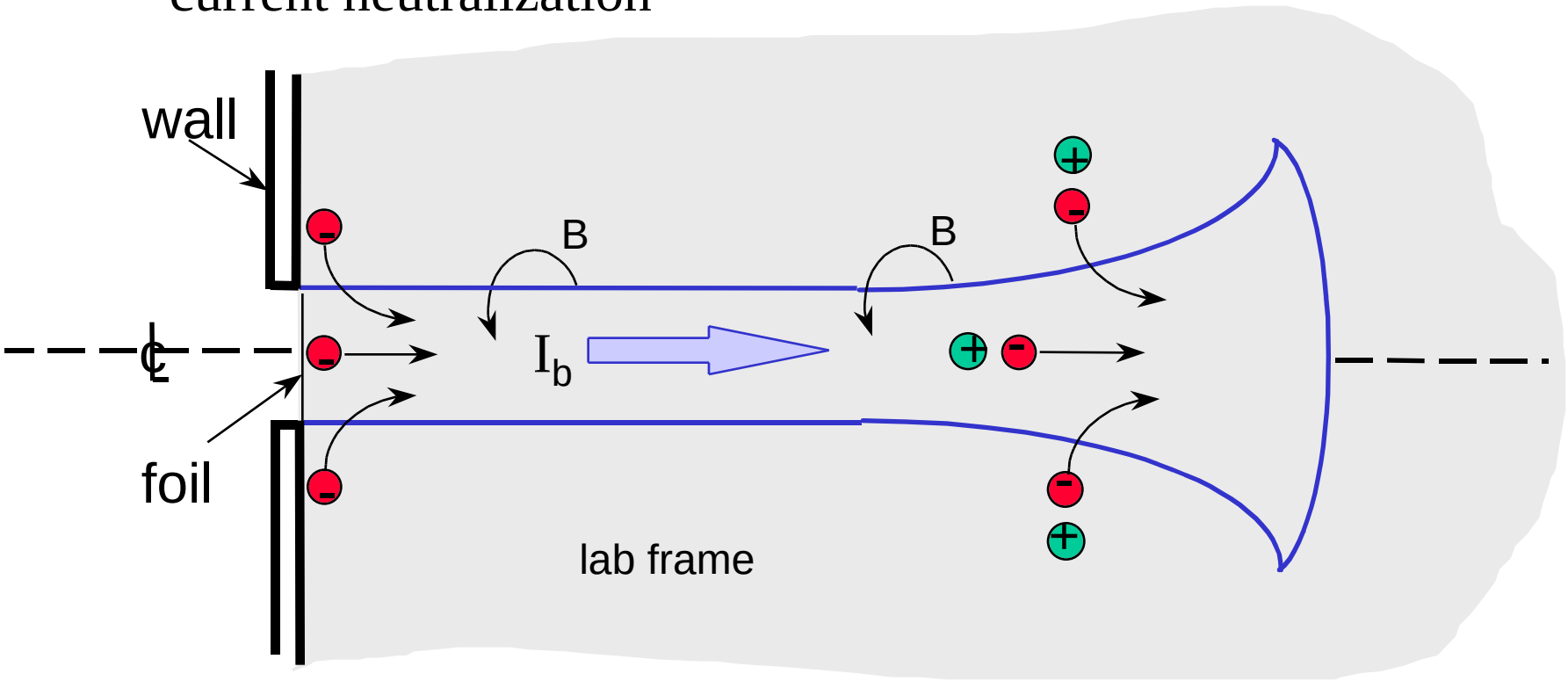




Graphic provided by P. Peterson, UCB

Self-pinched transport relies on limited beam impact ionization in a low pressure gas

- Ionization electrons provide good charge but imperfect current neutralization

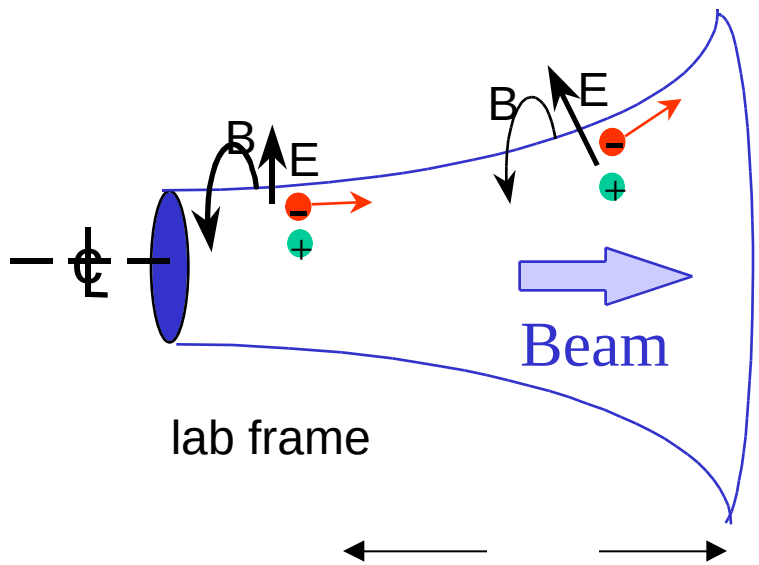


$$I_{net} \;?\; \theta^2 I_A \quad \text{where} \quad I_A = \frac{m_b c^3}{eZ}\beta\gamma \quad \text{and} \quad \theta = v_b / v_{bz}$$

Self-pinched transport is predicted to occur at an intermediate gas pressure

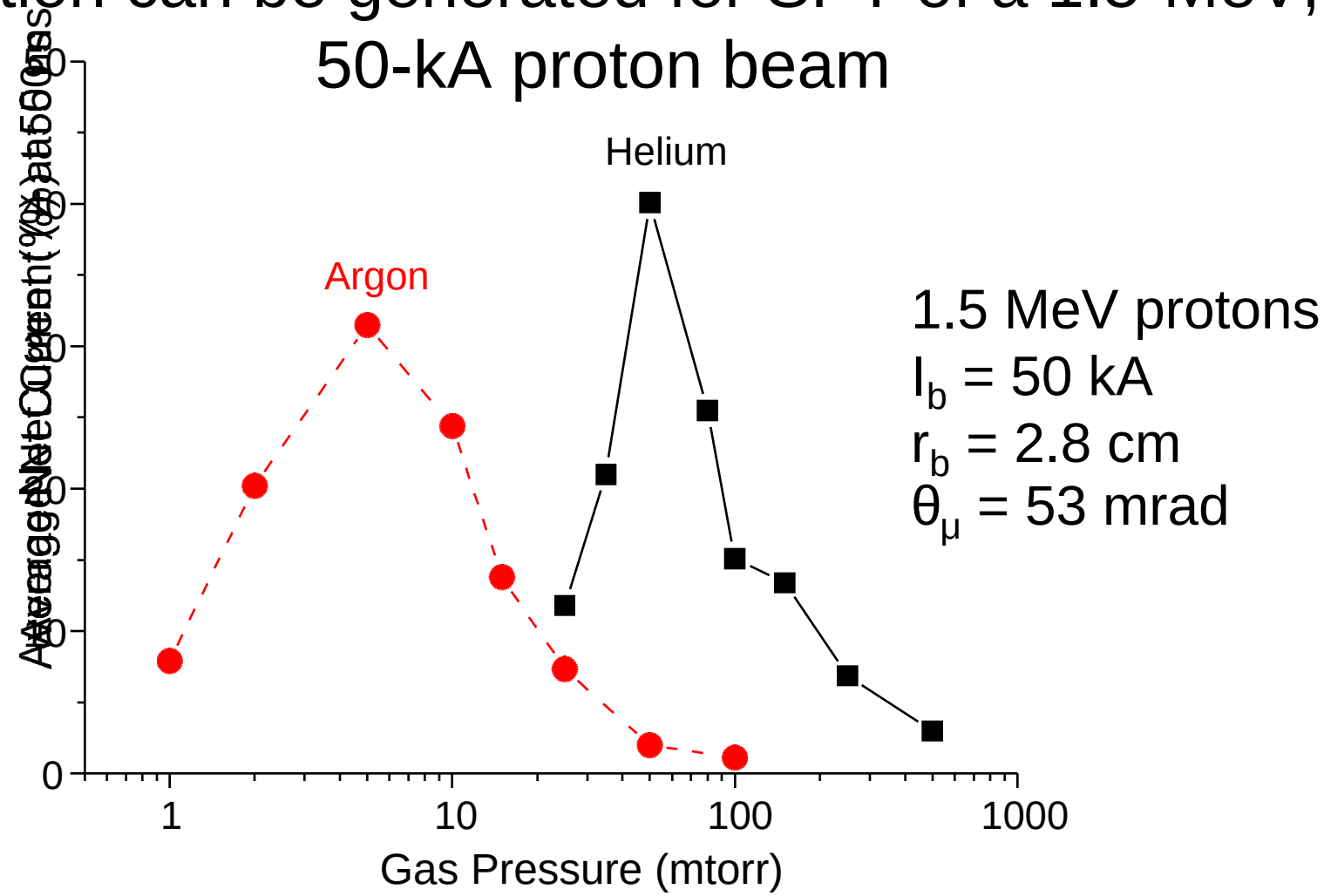
- Maximum pinch force occurs when beam-impact ionizes a plasma density roughly that of the beam on time-scale of beam density rise time, $/v_b$
- Optimized for: $R = \quad n_g/4Z = 1^*$
- Trumpet shape and non-local secondary ionization help supply neutralization without $v_e = v_b$

Electron orbits are mainly ExB



*D.R. Welch and C.L. Olson, Fus. Eng. and Des. **32-33**, 477 (1996).

Simulations indicated that a large net current fraction can be generated for SPT of a 1.5-MeV, 50-kA proton beam



Consistent with results observed in SPT experiment on Gamble II at NRL (Ottinger et al., Phys. of Plasmas **7**, 346, 2000)

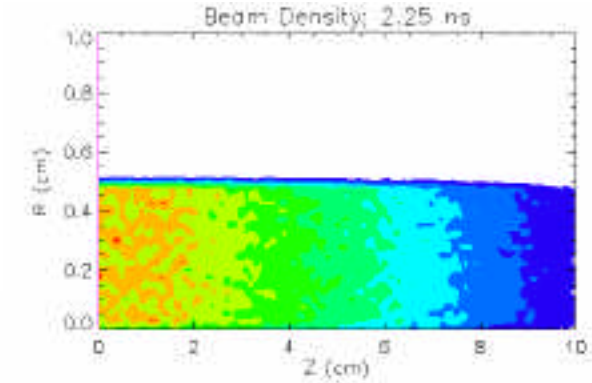
Identify pinched transport gas/plasma constraints for HIF chamber transport

- New LSP* code calculations
- 10-kA, 4-GeV Pb^+ beam, 2-ns rise in current
- **J** = 2 ns trumpet-shaped beam envelope:
  - 1-cm max radius falling to .5 cm in 2 ns
- 3-300-mtorr FLiBe pressure (R = .1-10)
- Normalized plasma density $N = n_p/n_b$=0-1
  - $n_b = 1.3 \times 10^{13}$ cm^{-3}
- Beam impact ionization only (ignore avalanche)

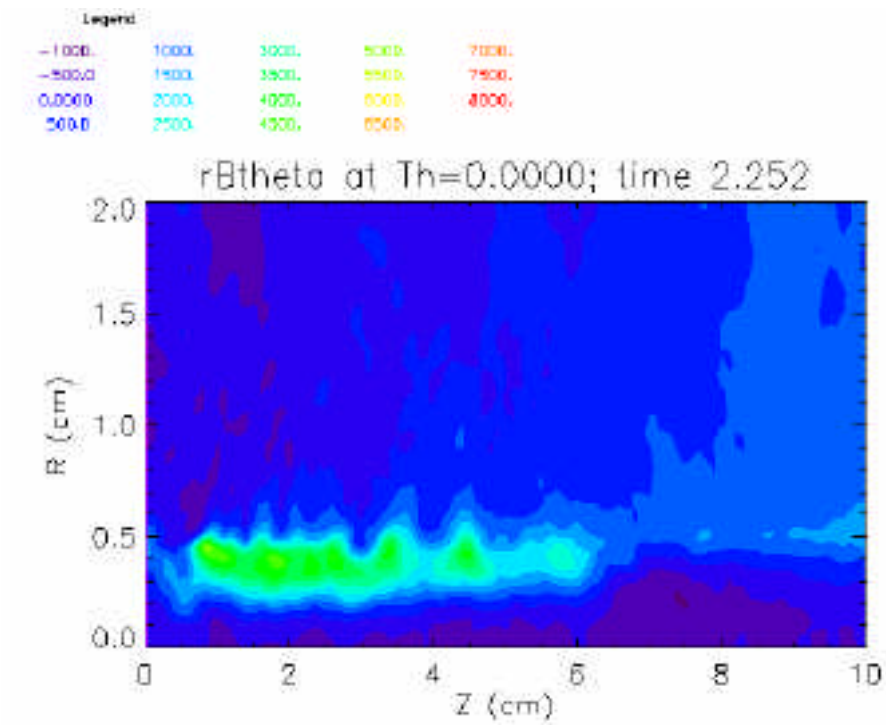
* Welch, et al., Nucl. Instrum. Meth. Phys. Res. A **464**, 134 (2001).

Weak net force for pencil beam in gas

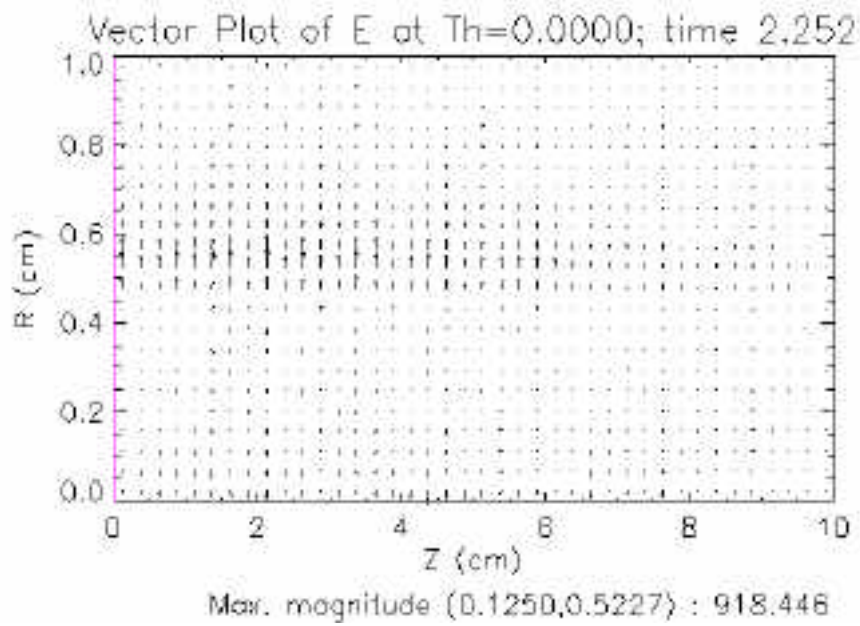
- Significant fields limited to beam edge (skin depth effect)



beam density



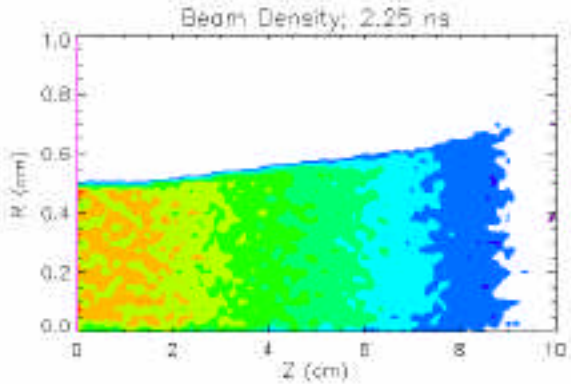
Constant enclosed net current

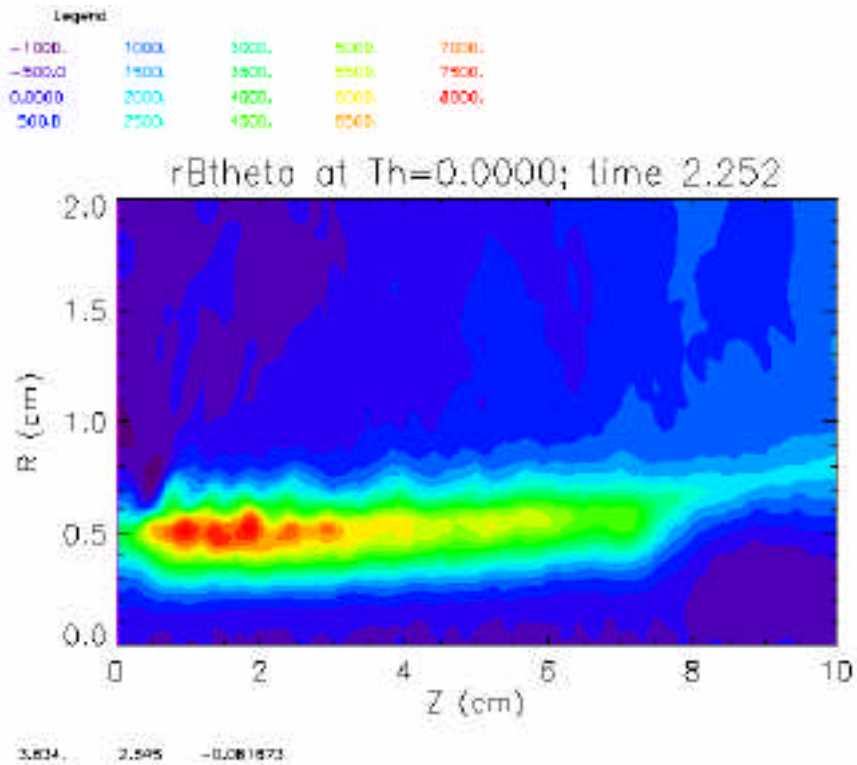


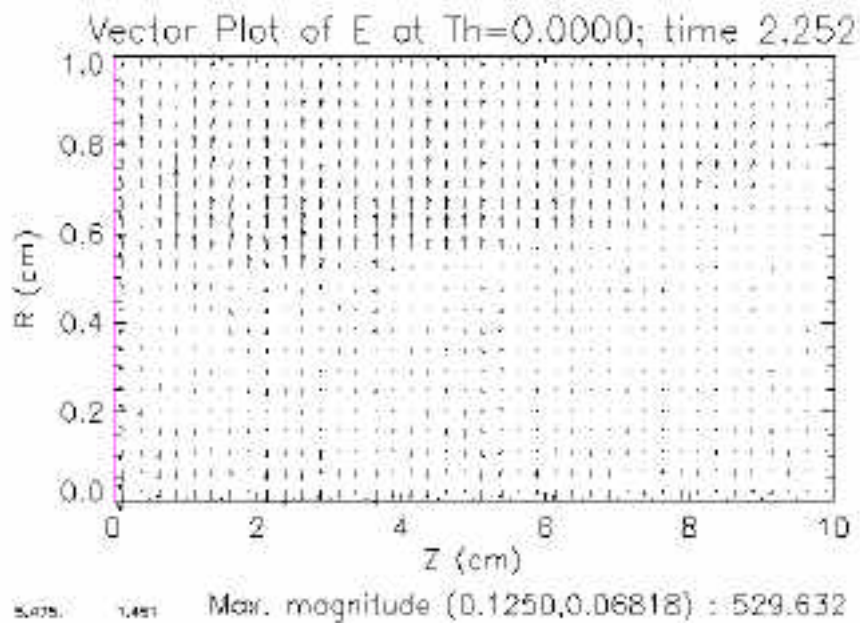
Electric fields, 918 kV/cm max

Trumpet beam shape enlarges net-current sheath

- Large net current with trumpet
- Sheath thickness defined in low density beam front





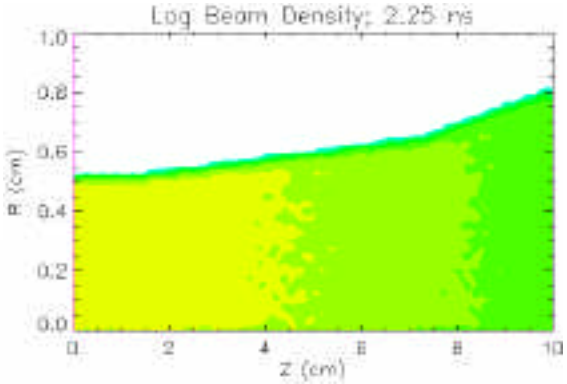


Constant enclosed net current

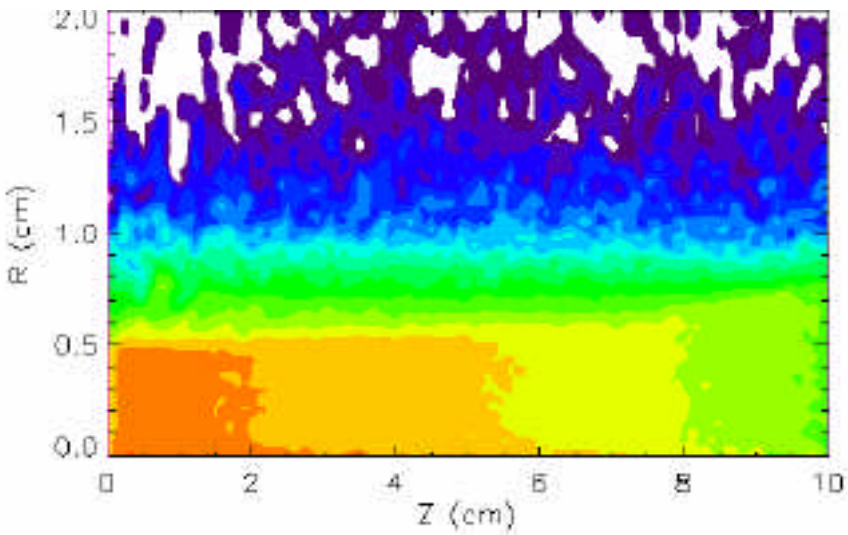
Electric fields, 529 kV/cm max

Electron density follows trumpet shape

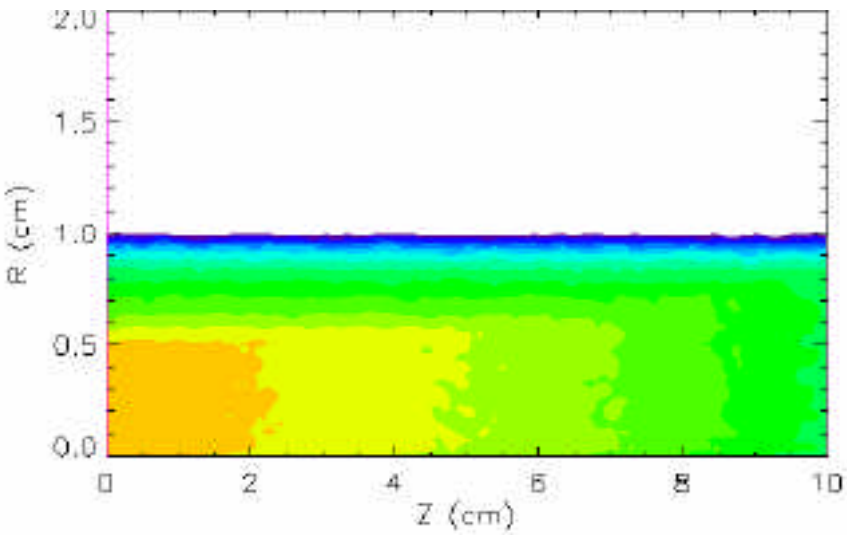
- Ion density indicates ionization position



Log beam density



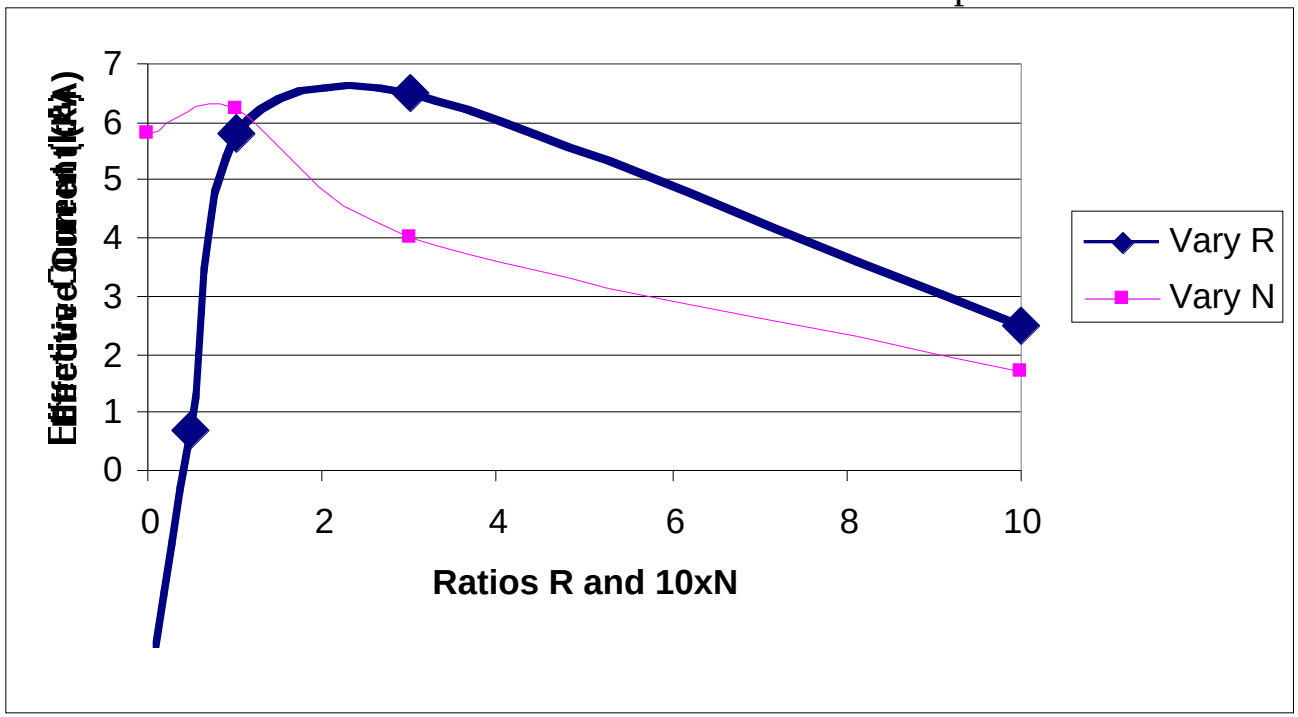
Log electron density



Log plasma ion density

LSP calculates strength of pinch force sensitive to gas, plasma densities

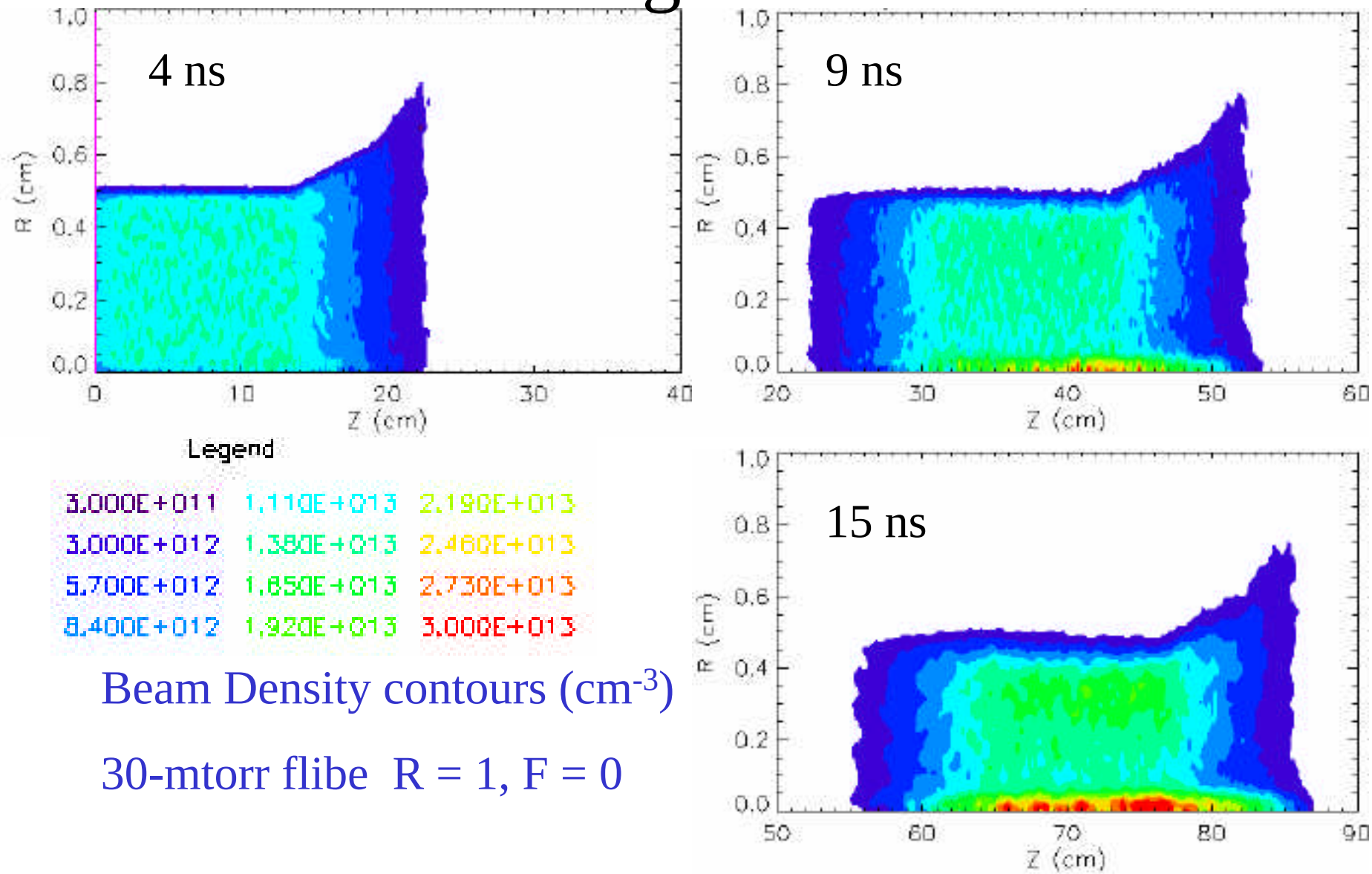
- Normalized gas density, $R = \mathbf{JF}\ n_g/4Z$
- Normalized plasma density (R=1), $N = n_p / n_b$



Pinch force optimized near R = 1-2, constrains chamber pressure

Falls off N > 0.1, pinch may weaken near target due to photo-ionization

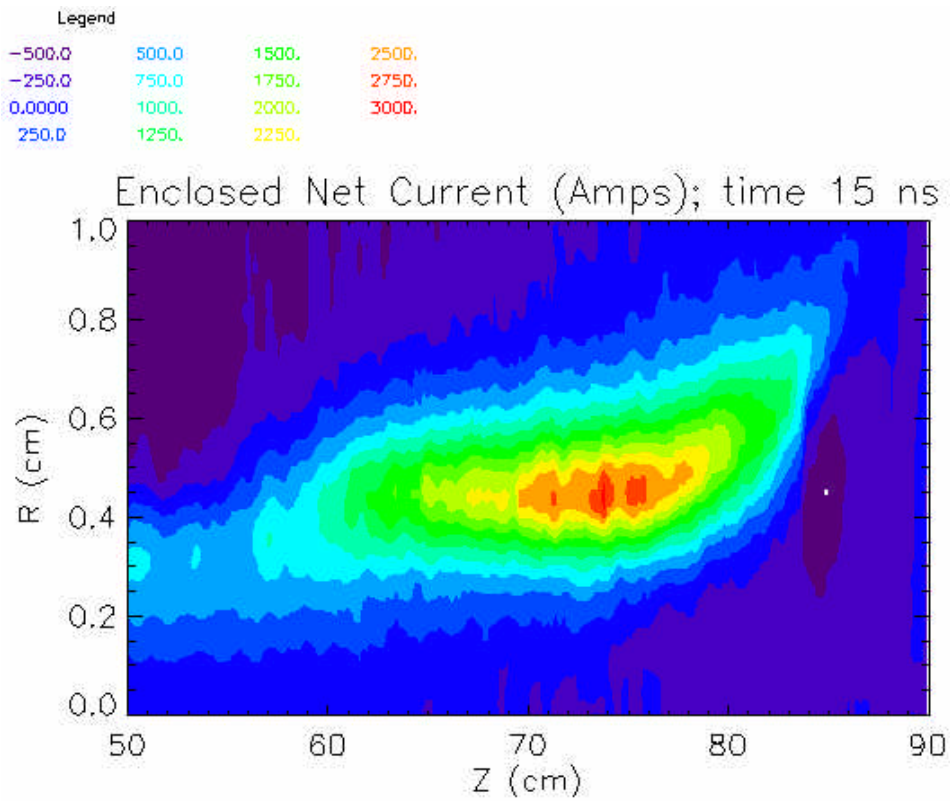
Beam maintains pinch after detaching from wall

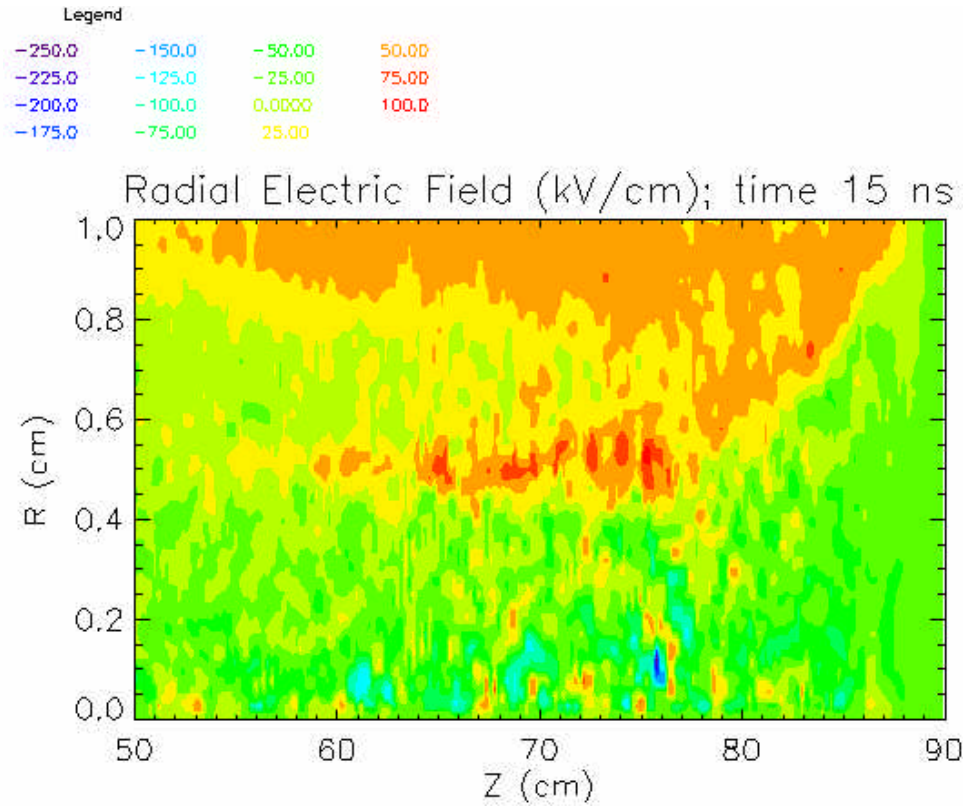


Beam Density contours (cm^{-3})

30-mtorr flibe R = 1, F = 0

Pinch force stabilizes at 3 kA in meter long simulation

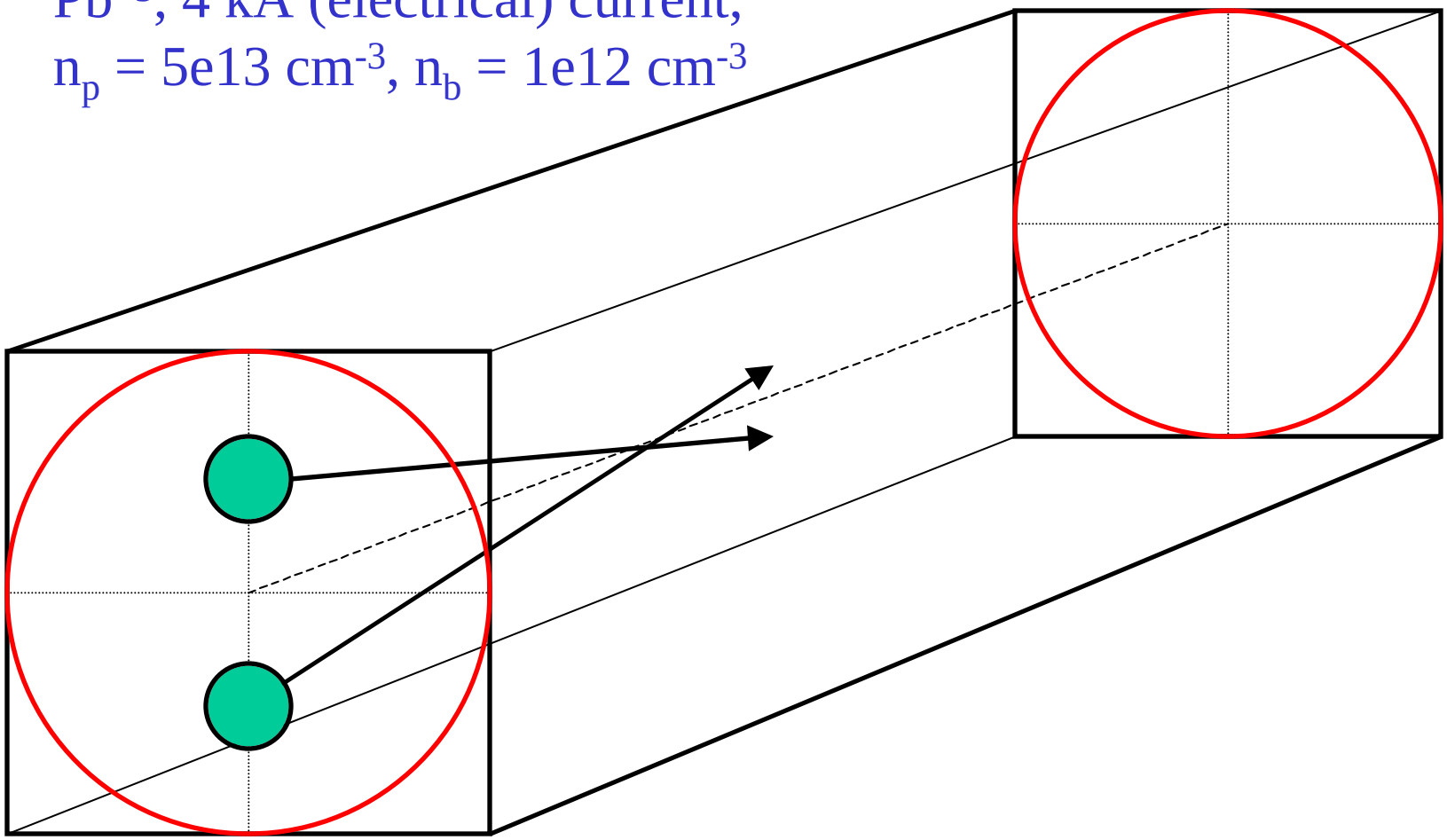




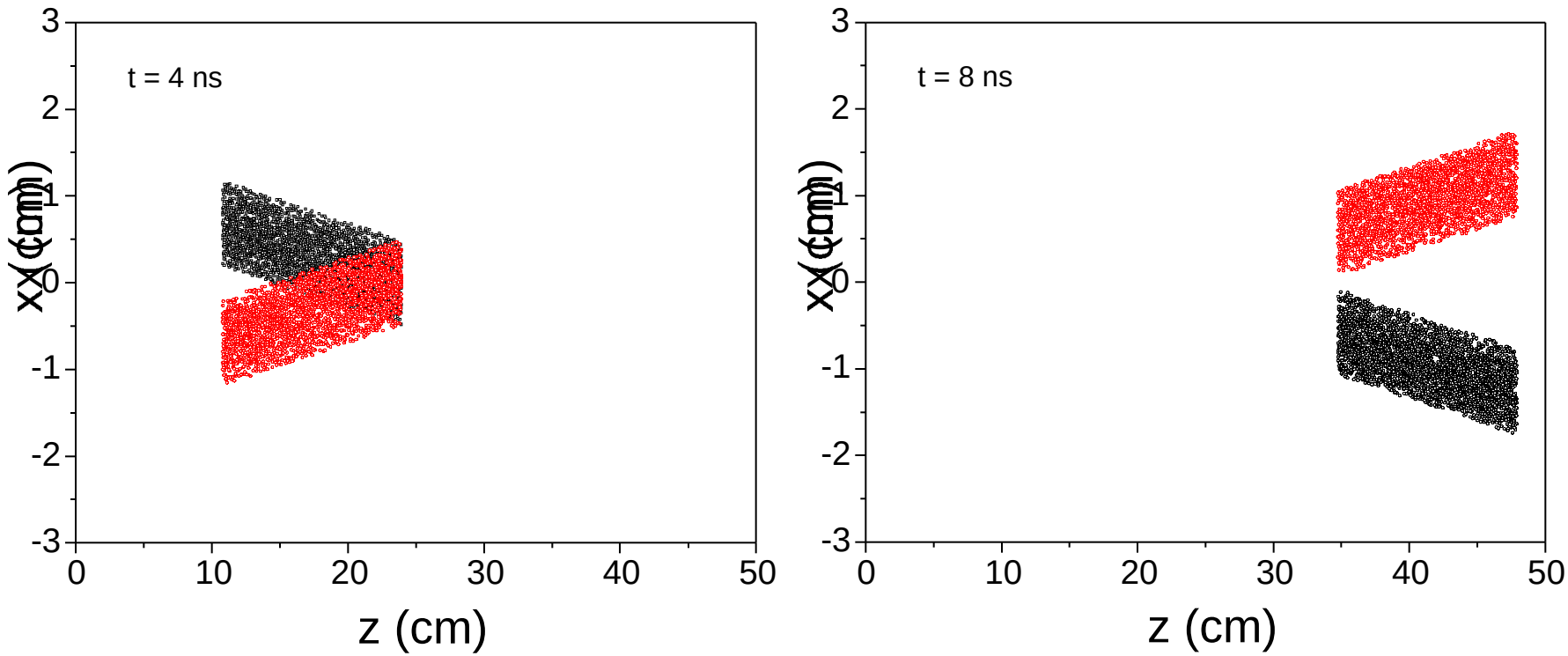
- Pinch force is still sufficient for confinement
- Electric fields are small, < 100 kV/cm

Two-beam interaction in 3-D LSP simulation geometry

Pb^{+5}, 4 kA (electrical) current,
n_p = 5e13 cm^{-3}, n_b = 1e12 cm^{-3}



No observed deflection for these 2 weak beams in N=10 plasma



- Need to examine higher currents, ionization and lower plasma densities

Research in self-pinched transport for HIF beams has just begun

- Confirmed the SPT mechanism for HIF beams
  - constraints of gas pressure and plasma density
- Pinch is sustained after detachment from wall
- Simulation of 3d beam-beam interaction underway
- Many issues remain:
  - Detailed beam-gas interaction (such as beam stripping)
  - Beam losses from inductive fields, trumpet formation
  - m=1 (hose) stability, beam-beam interactions
  - Steering and capturing beam
  - Channel expansion from *JxB* force