PIC MODELING:
Measuring Ion Beam Current Density in the Presence of a Neutralizing Background Plasma
and
Proton Beam Generation and Propagation from Femtosecond Laser-solid Interactions

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2005 Workshop on Nonlocal, Collisionless Electron Transport in Plasma

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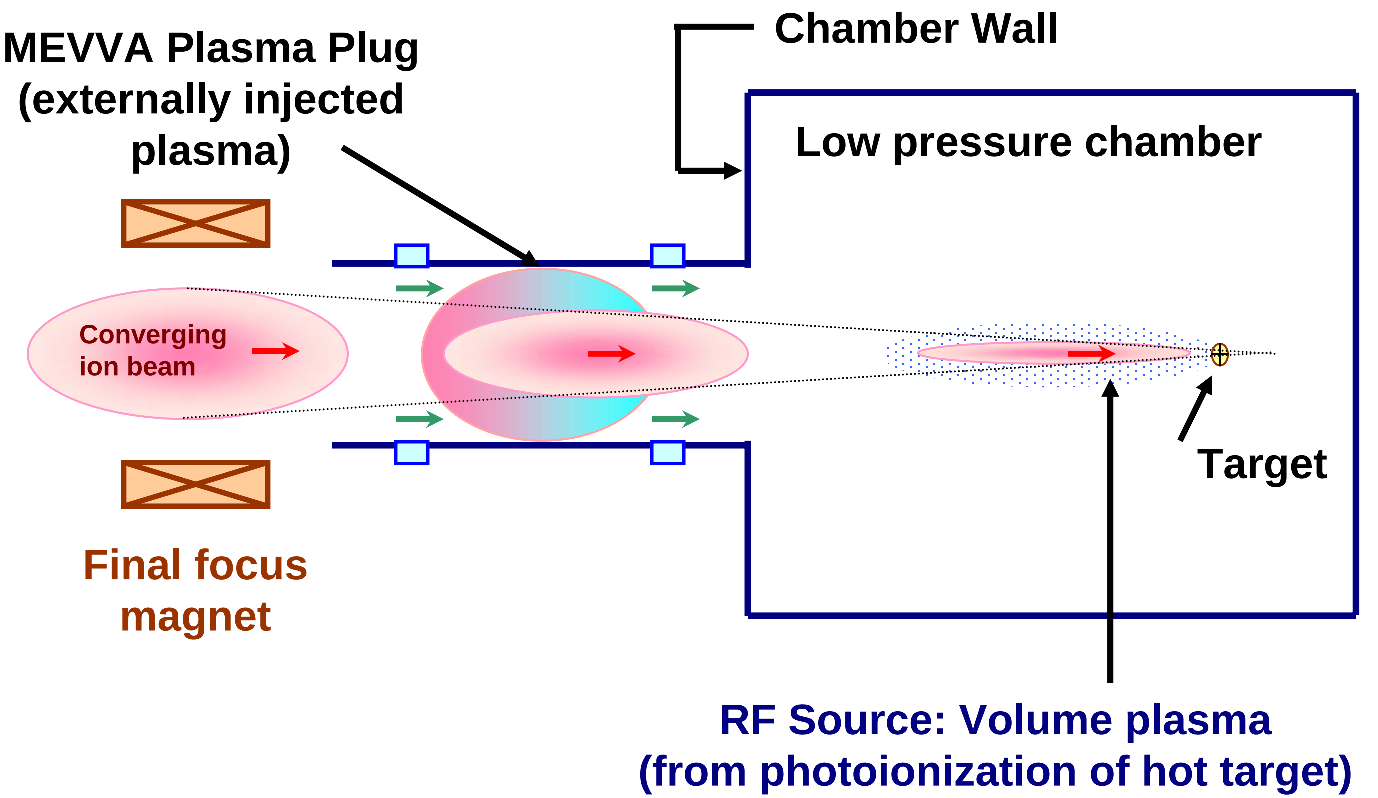
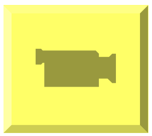
* LSP is a software product of
ATK-Mission Research, Albuquerque, NM 87110

Neutralized Transport Experiment (NTX) at LBNL

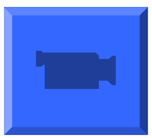


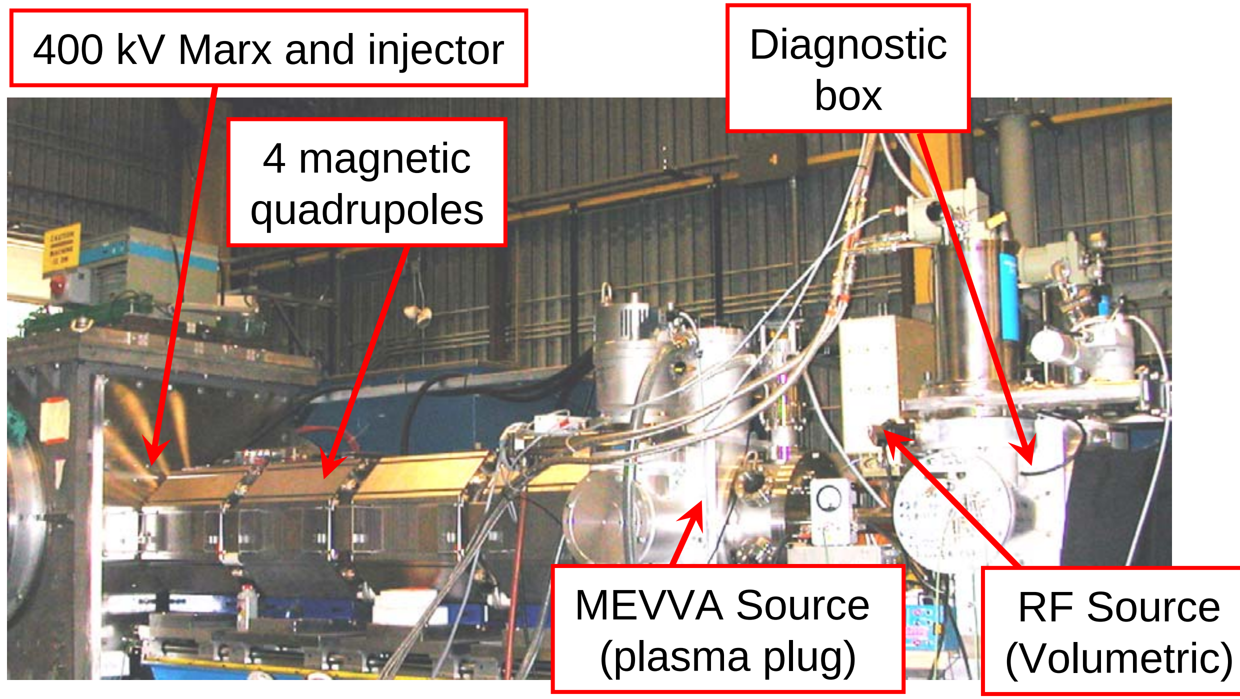
The Neutralized Transport Experiment was a success

Particle movie



Density movie





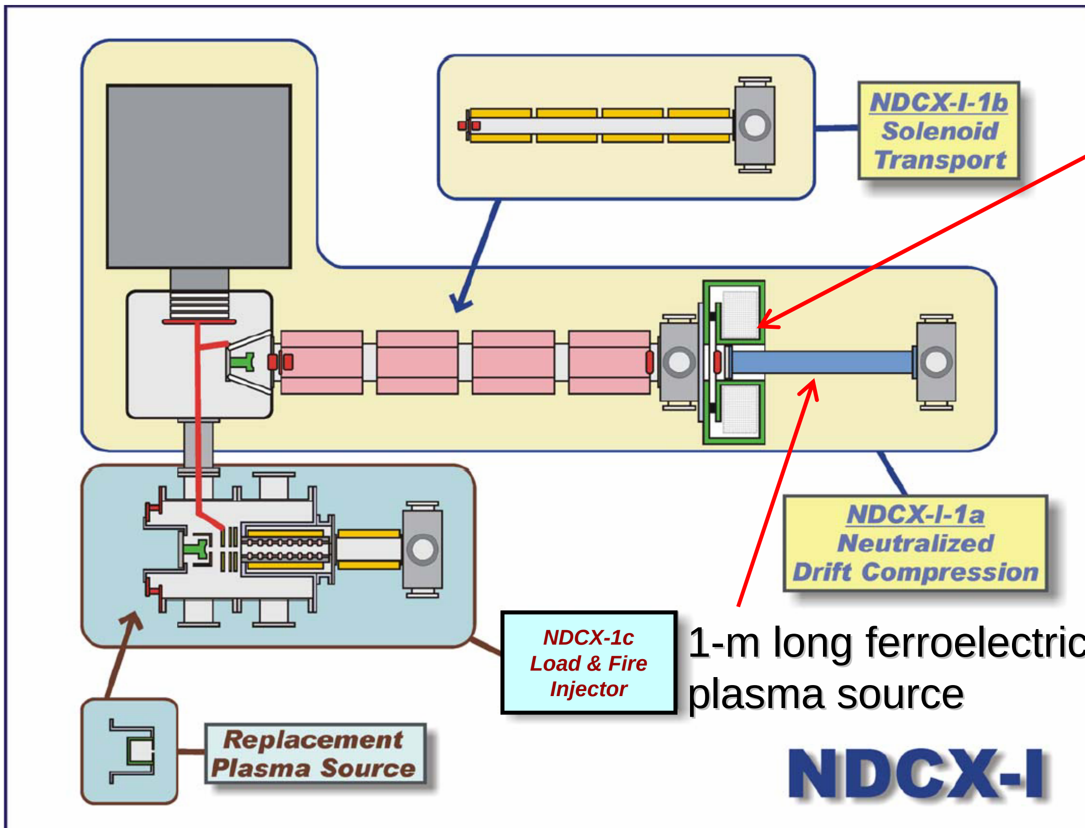
Non-neutralized transport

Effect of plasma plug on spot size

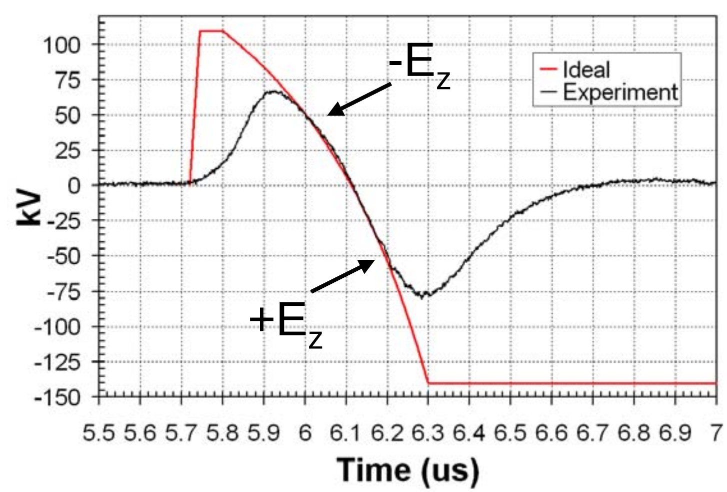
Effect of plasma plug and volume plasma on spot size

The next steps: to investigate more heavy ion beam transport issues

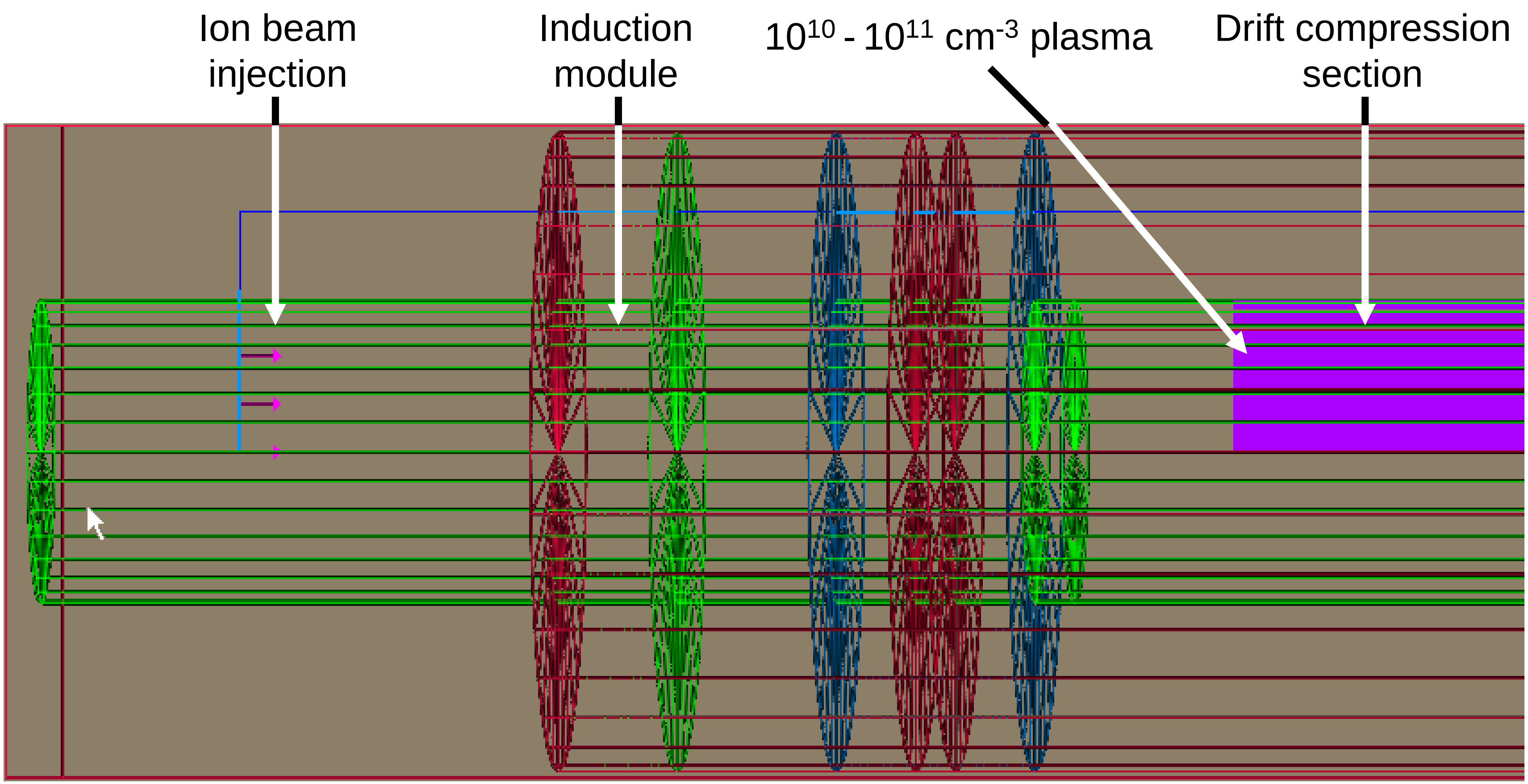
- The upgrade of NTX is the Neutralized Drift Compression Experiment-1 (NDCX-1)
- Issues to be addressed:
  1. Fundamental limits of longitudinal compression
  2. Control of emittance growth from source to target
  3. Determine architecture of integrated system by testing small systems individually
- NDCX-1 will provide the knowledge to design and construct NDCX-2



Single-gap linear induction accelerator (induces pulsed E(t) along axis of beam), also called the “tiltcore” because it imposes a head-to-tail velocity tilt on the passing ion beam



K^+ ion beam injection with E_b = 300 keV and interaction with a 50% velocity tilt ($\Delta v/v_{max}$ = ½)



Particle movie

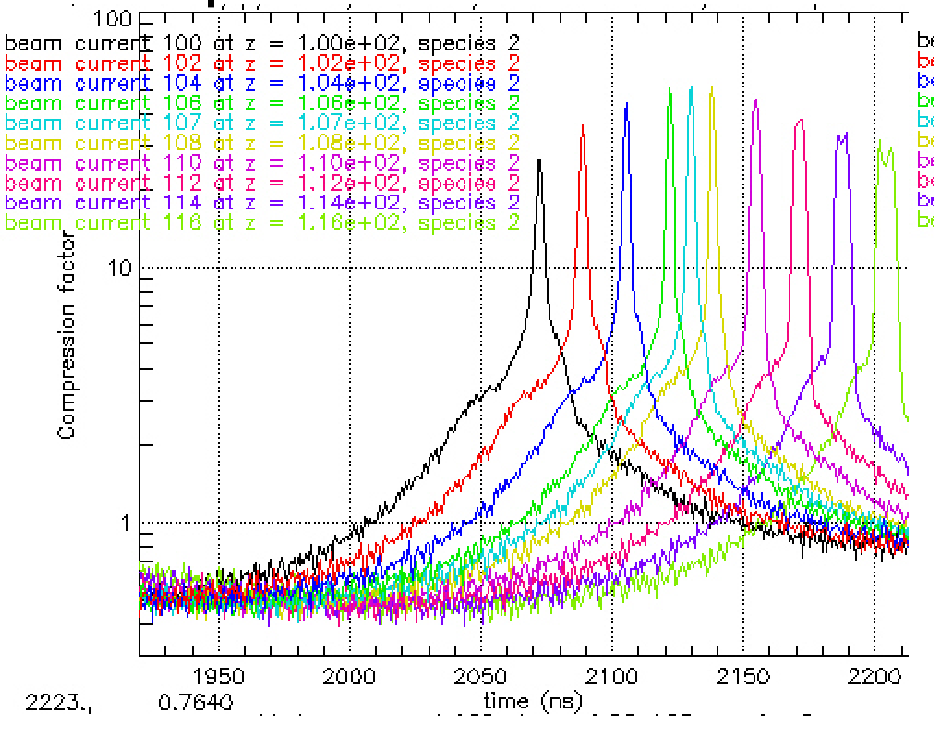
Density movie

Density movie (Simultaneous)

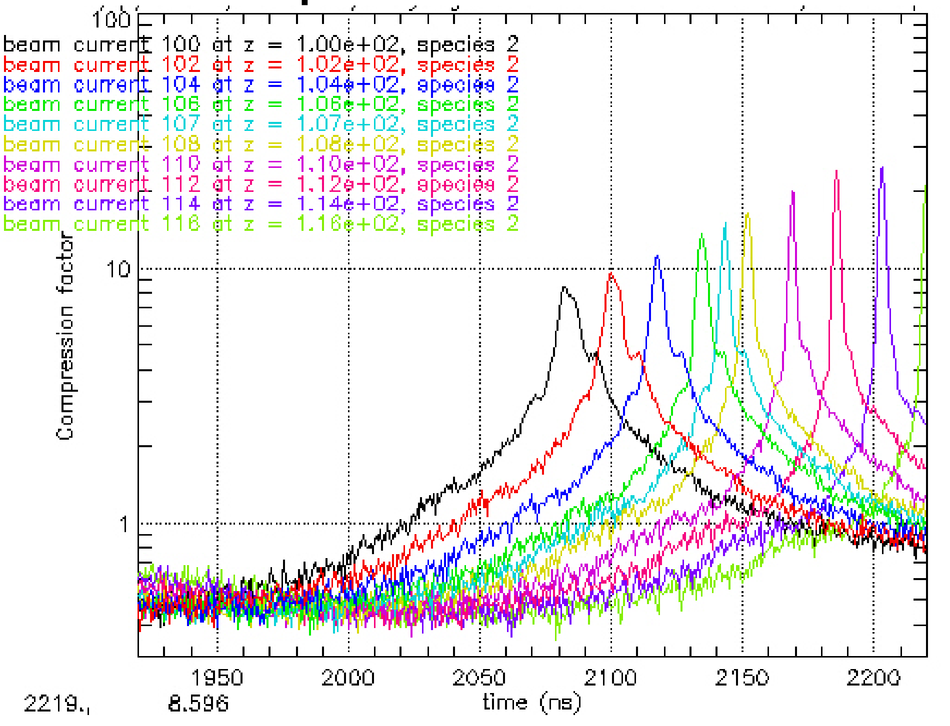
Density movie without plasma

- J_{beam} initial: < 0.1 mA cm^{-2} final: > 1 A cm^{-2}
- n_{beam} initial: 10^6 – 10^7 cm^{-3} final: 10^{10} – 10^{11} cm^{-3}
- Transverse focusing initial: > 2 cm final: < 2 mm rms radius
- Longitudinal focusing initial: 100's of ns final: < 5 ns pulse width
- E_{beam} 250 – 350 keV
- Power on target 10^5 – 10^6 W
- Intensity on target 10^{10} – 10^{11} W m^{-2}

With plasma:

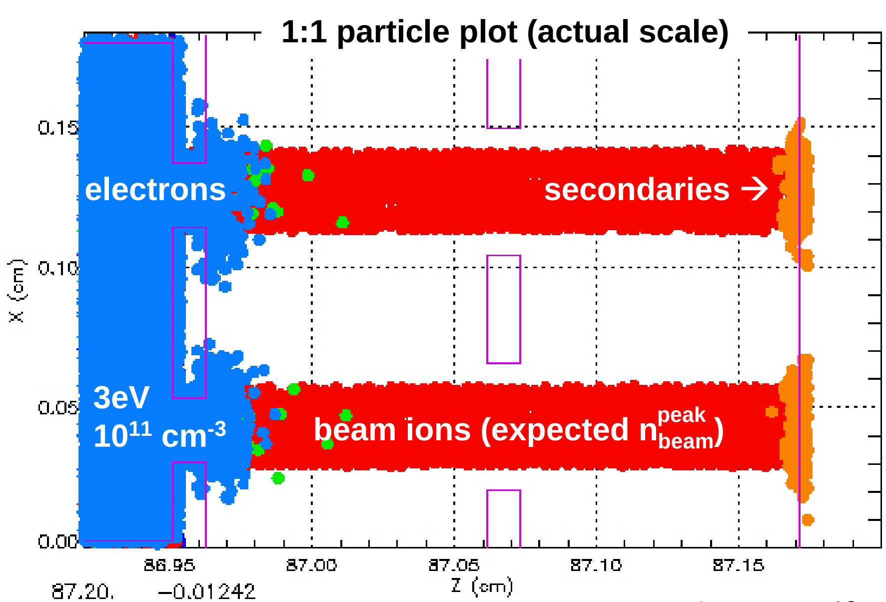


Without plasma:



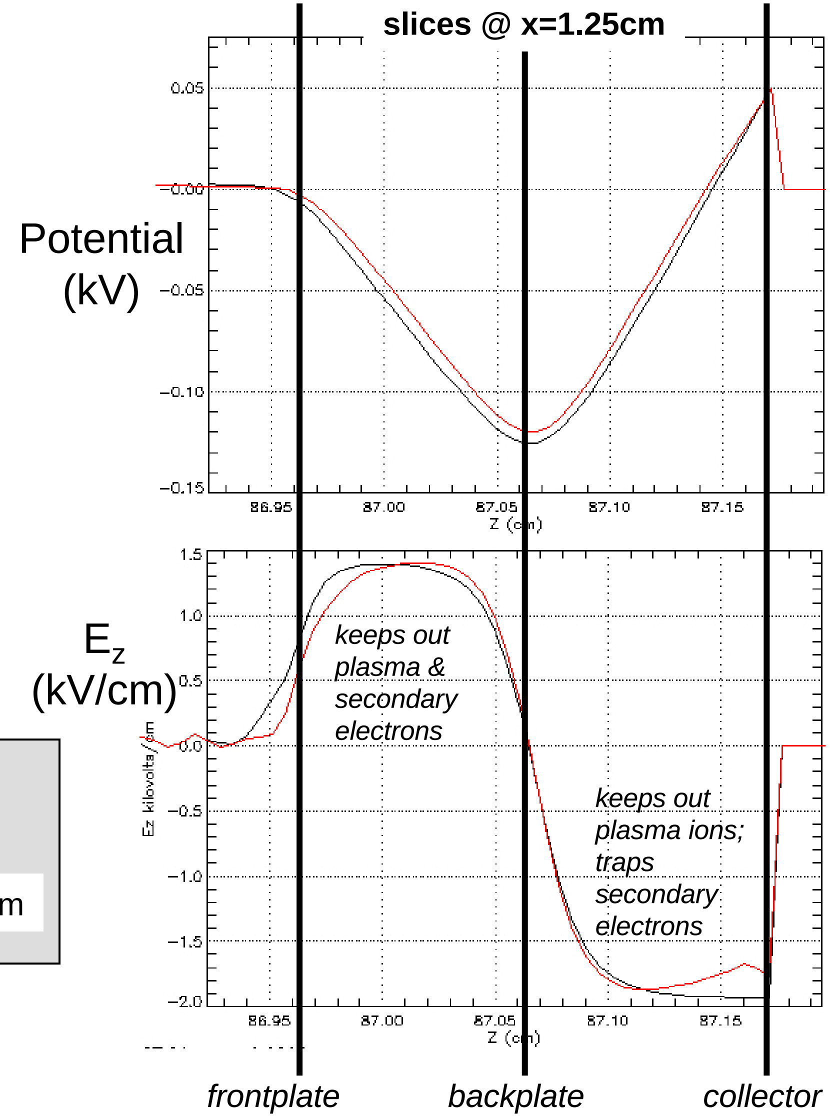
Also, can't transversely focus without plasma!

LSP predicts good characteristics for pinhole Faraday cup with 1 mm gaps



Frontplate hole diameter = 0.009" :

~1.8 λ_D (3eV, 10^{10} cm^{-3})
~5.6 λ_D (3eV, 10^{11} cm^{-3})



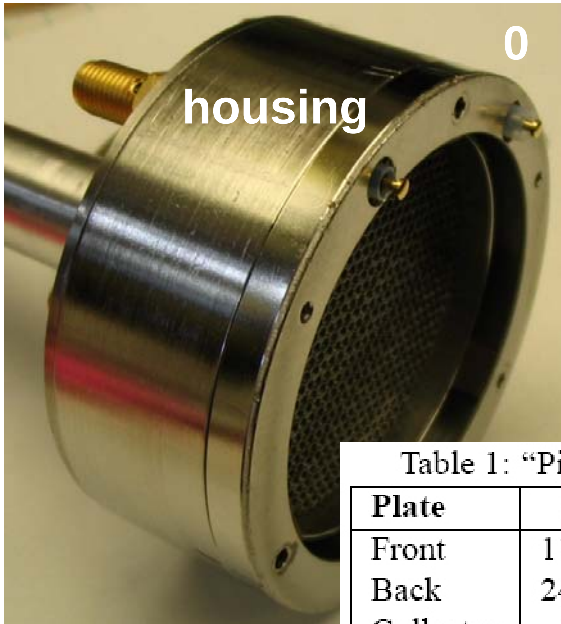
Calculations suggest no concern for ionizing desorbed gas from plates:

P_{gas} ~ 10 - 100 mTorr (too low) | V_{drop}^{max} = 200 V | λ_{mfp} >> 2 mm

Particle movie of pinhole cup in operation

Black: no beam present
Red: expected n_{beam}^{peak} present

The assembly of the pinhole Faraday cup for measuring $I_{beam}(t)$



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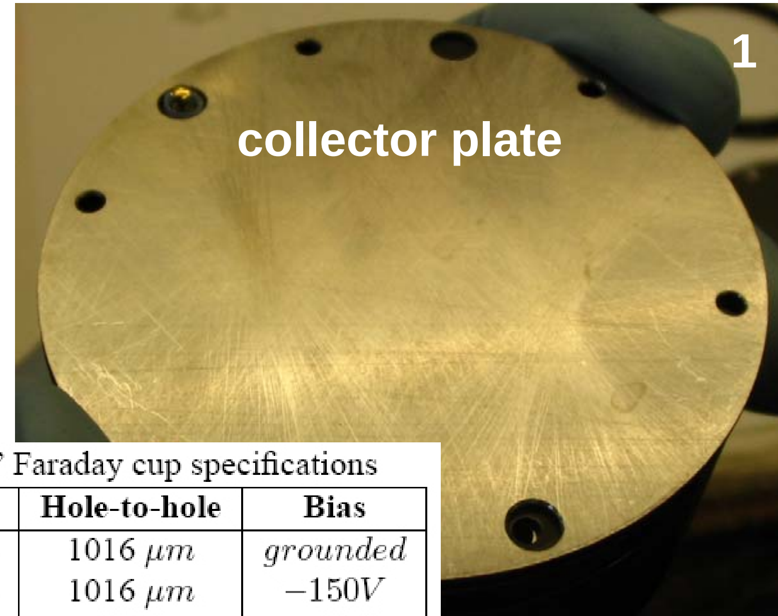
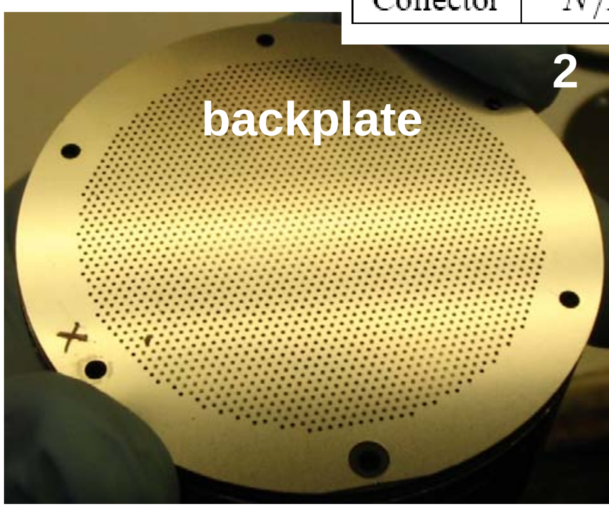


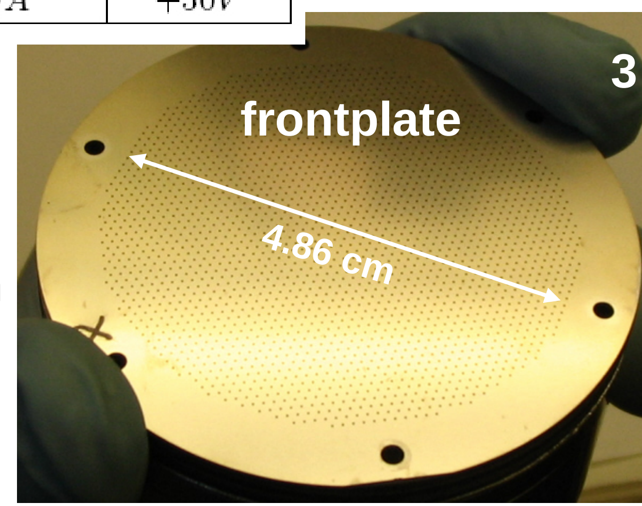
Table 1: "Pinhole" Faraday cup specifications

Plate	r_{hole}	Hole-to-hole	Bias
Front	$114\ \mu m$	$1016\ \mu m$	*grounded*
Back	$241\ \mu m$	$1016\ \mu m$	$-150V$
Collector	N/A	N/A	$+50V$

+ 1mm

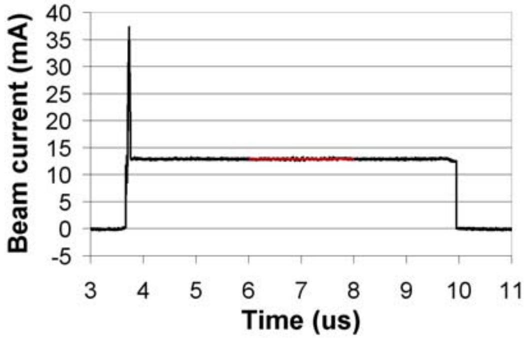


+ 1mm

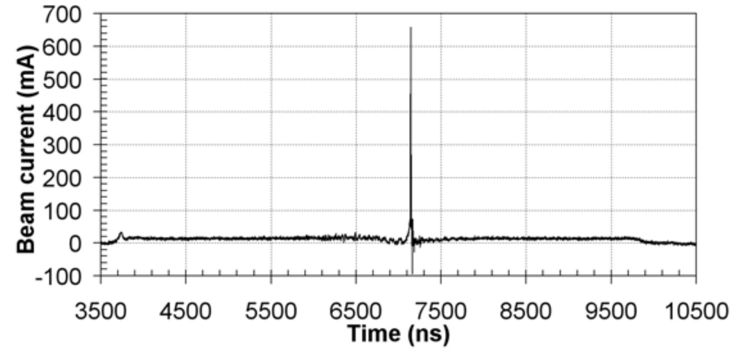


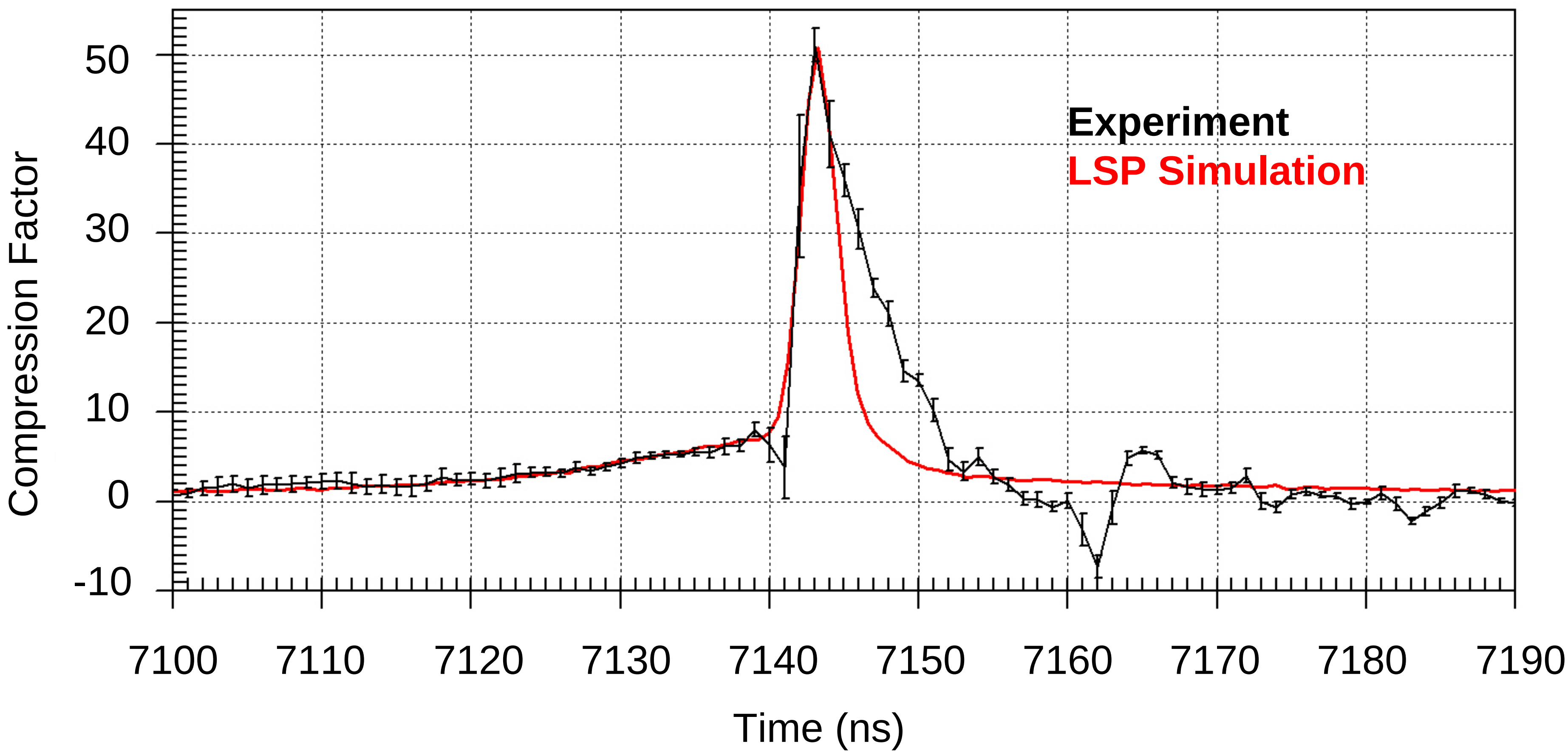
The diagnostic for measuring $J_{beam}(x,y,z,t)$ will be similar, but smaller* and moveable**

Without velocity tilt:

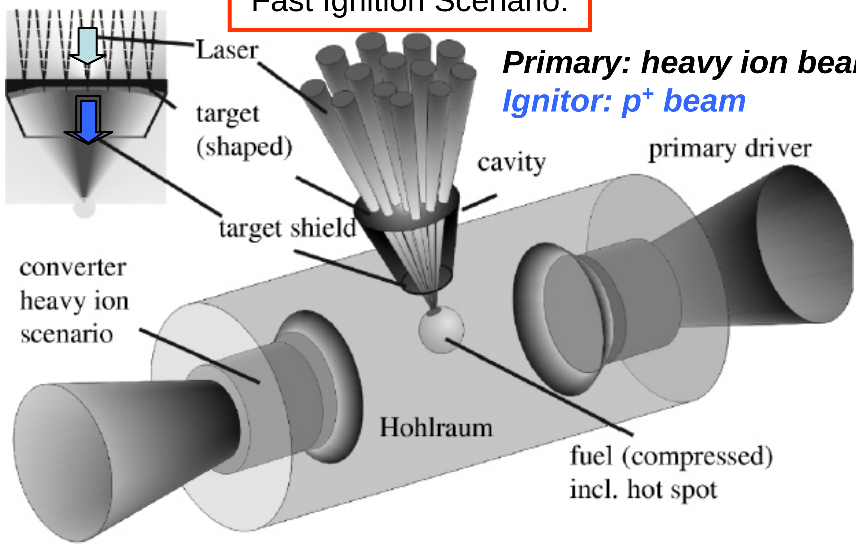


With velocity tilt:





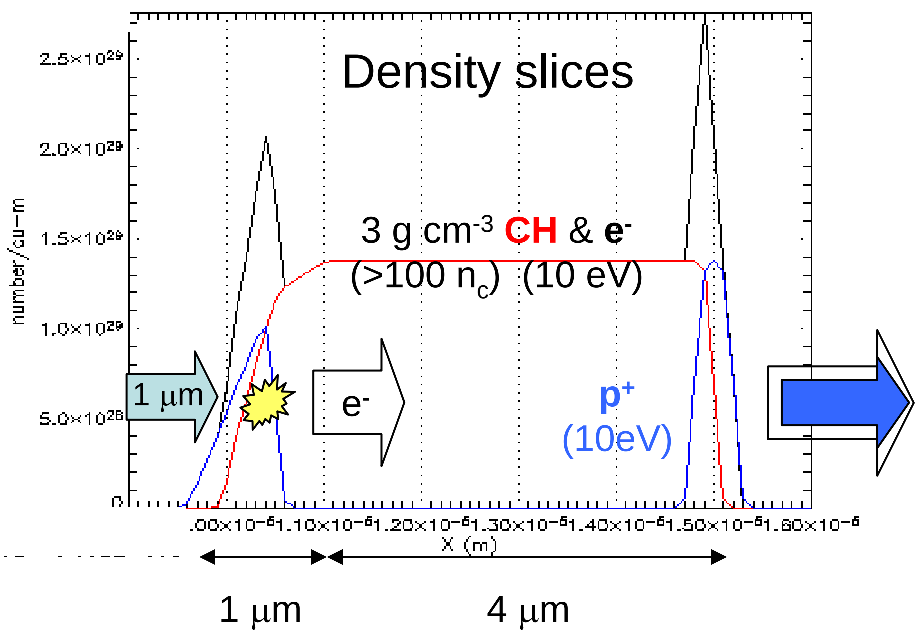
Fast Ignition Scenario:



Proton beam generation mechanism:

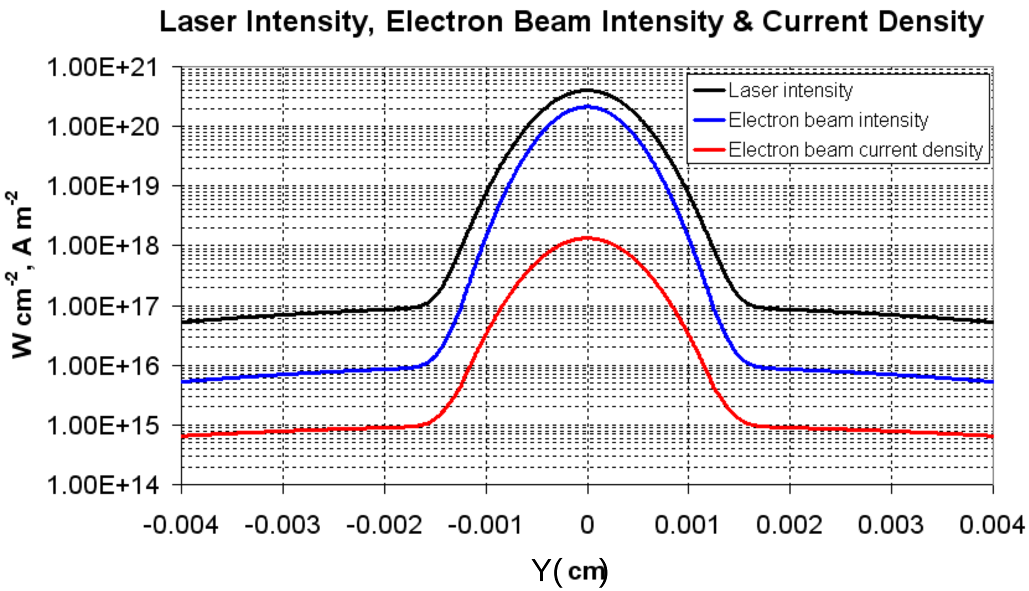
(1) an ultra-intense, short-pulse laser is focused onto a solid-density, thin foil with H contaminants on its backside;
(2) the laser pulse encounters n_c plasma, some power is absorbed into relativistic e^-s;
(3) the e^-s pass through the thin foil, creating a sheath;
(4) the sheath's **E** field inhibits further loss of e^-s from the target and field ionizes the H on the back of the foil; and
(5) the p^+ beam is accelerated by the sheath, <u>with an accompanying hot electron cloud</u>, up to 10s of MeV over 10s of μms in < 10 ps.

(*Applications*: ion implantation, radiography, ion source injectors, thin solid object imaging, medical tomography, and fast ignition)



The p^+ beam must then pass through a target shield and propagate a large distance (~3mm) through a background hohlraum plasma containing large (> 1 MG) **B** fields.

Laser-produced p⁺ beam propagation: PIC simulation parameters

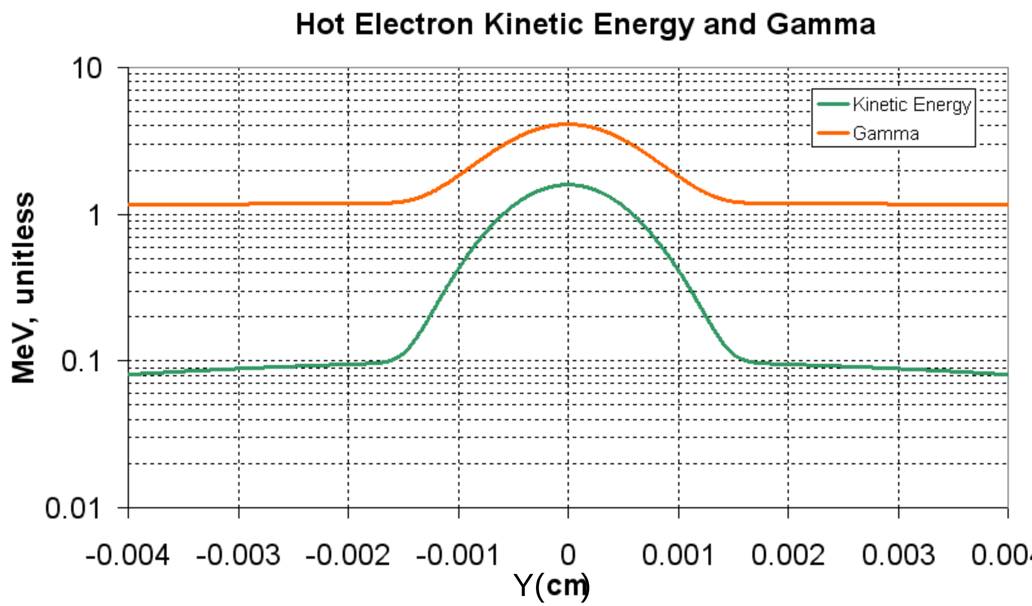


Laser: 13J (40 fs pulse)
Electron beam: 5½ J (40%)

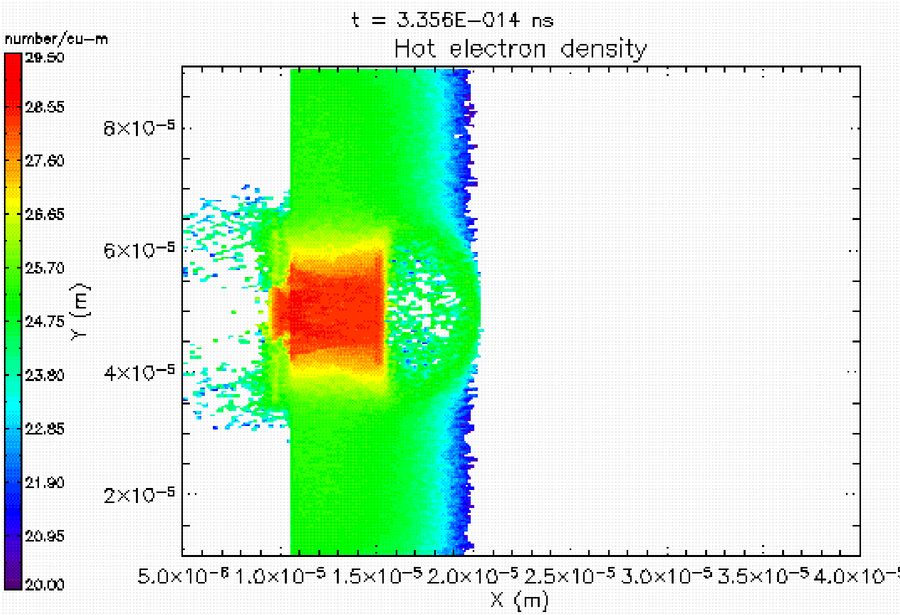
Hot e^-

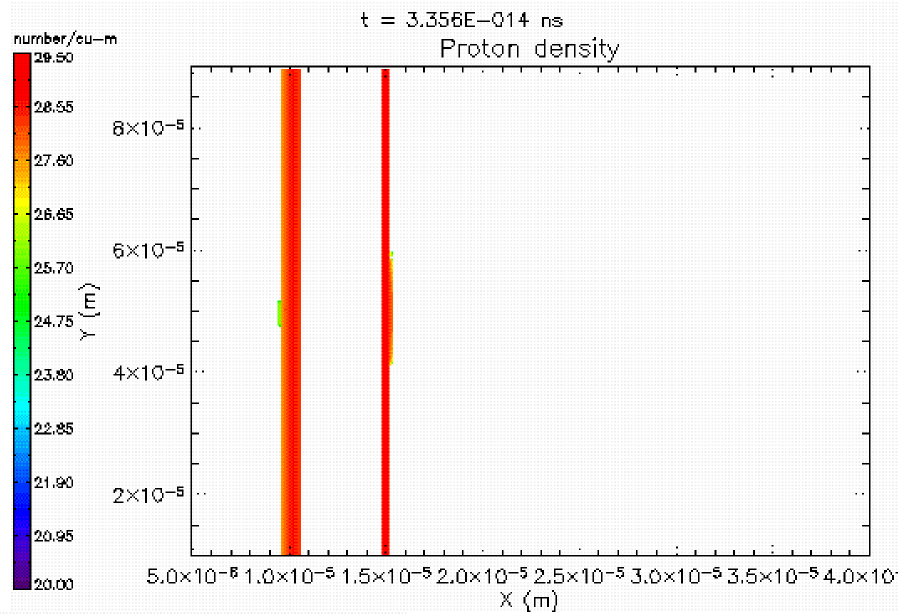
E_x

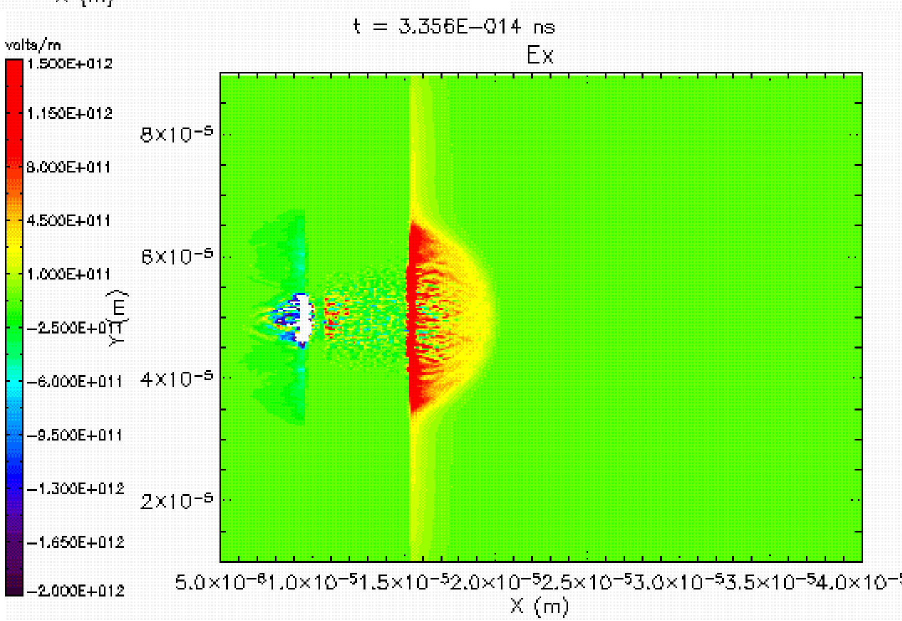
p^+



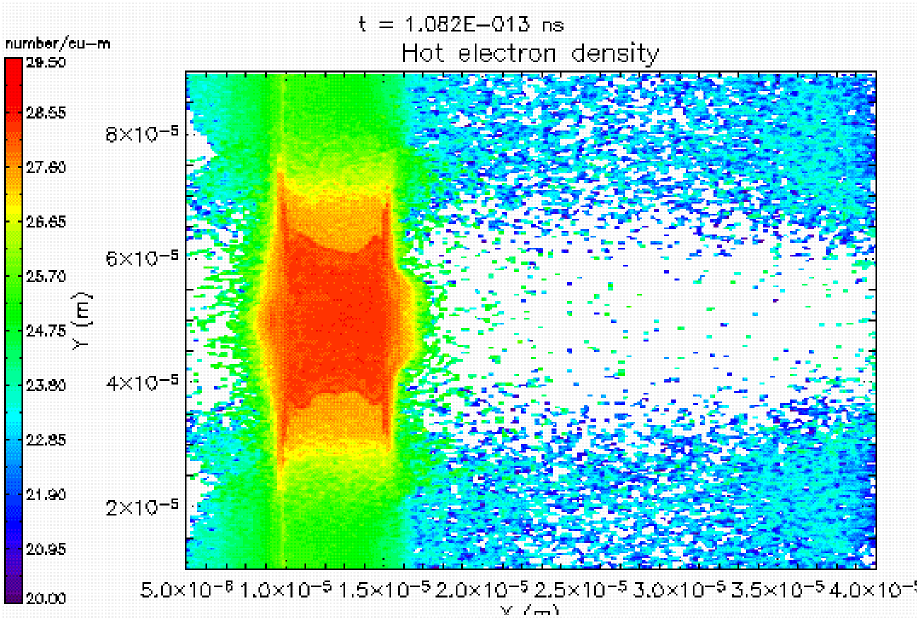
Laser-produced p⁺ beam propagation PIC simulation (Slide 1)

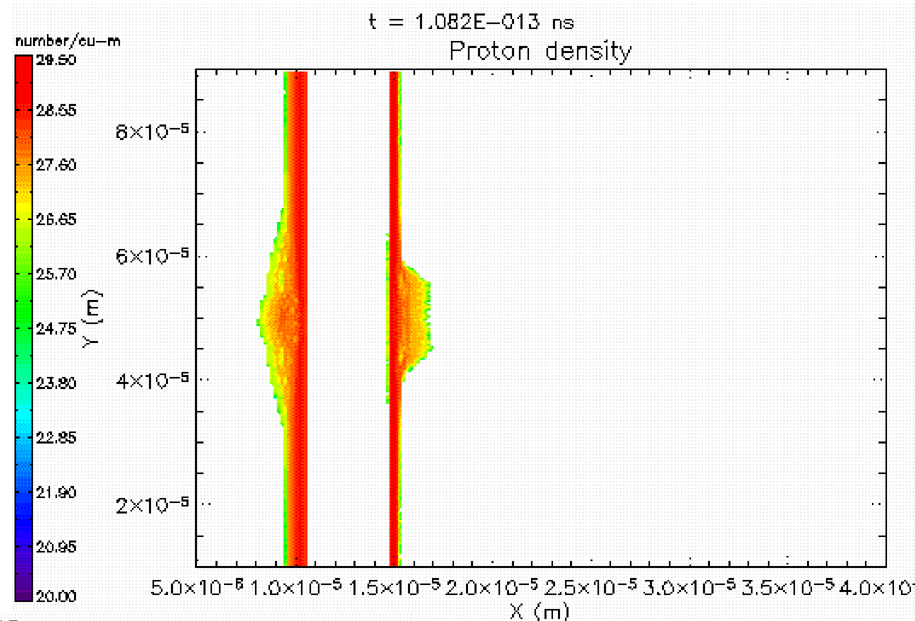


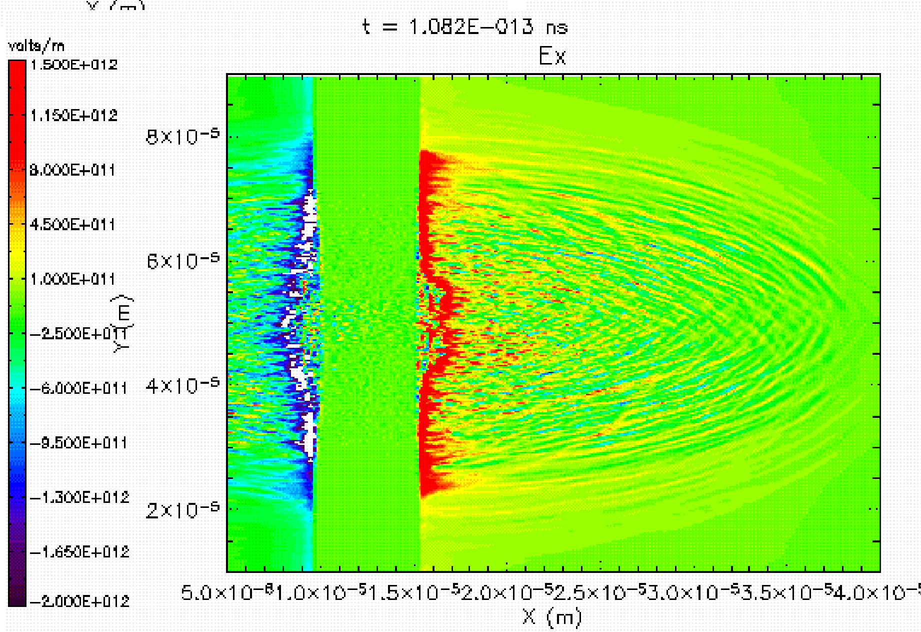




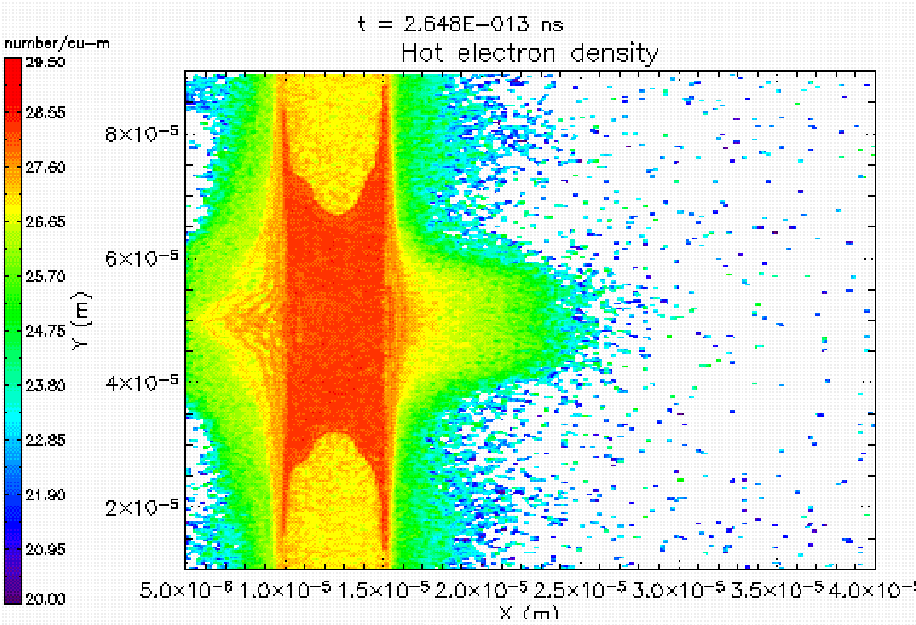
Laser-produced p^+ beam propagation PIC simulation (Slide 2)

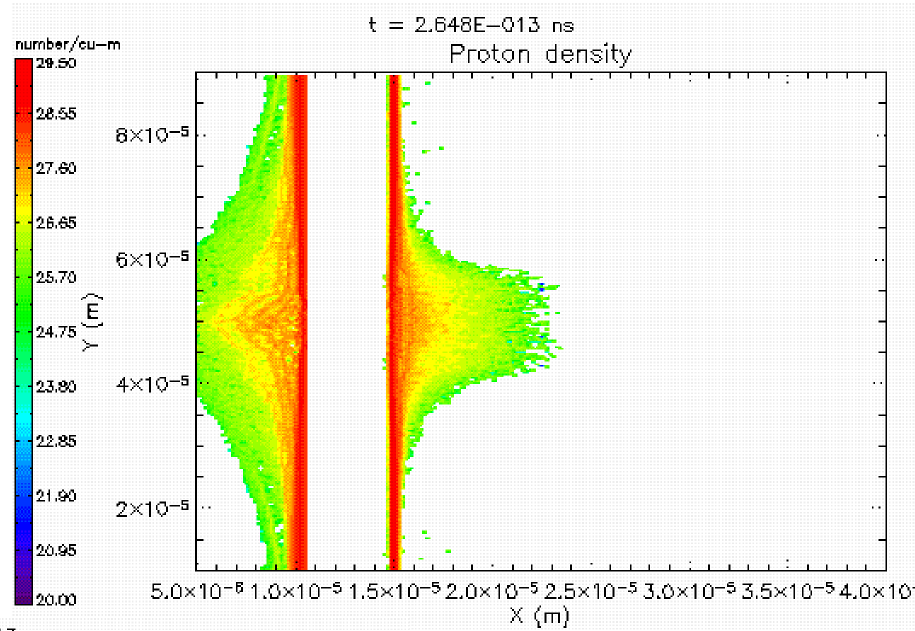


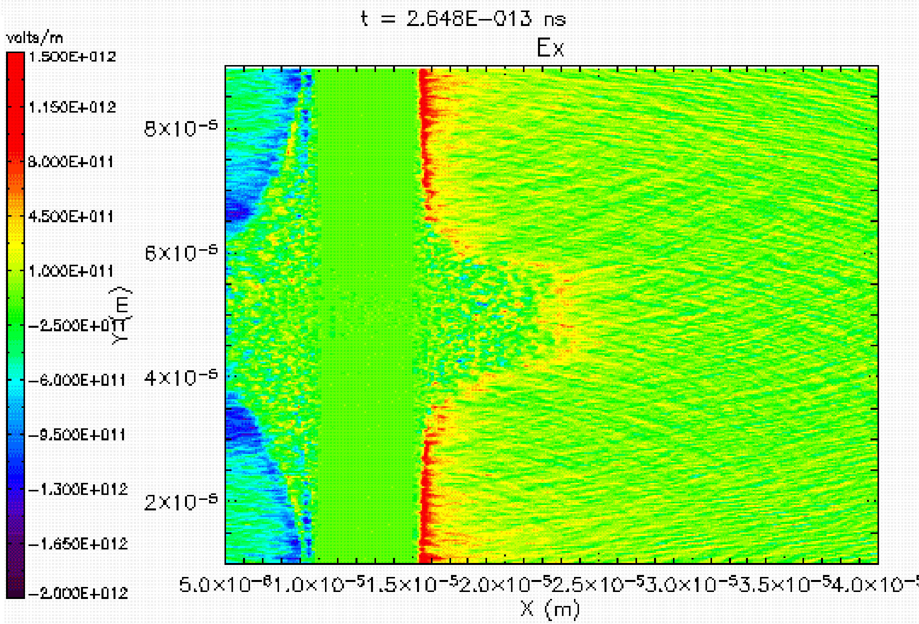




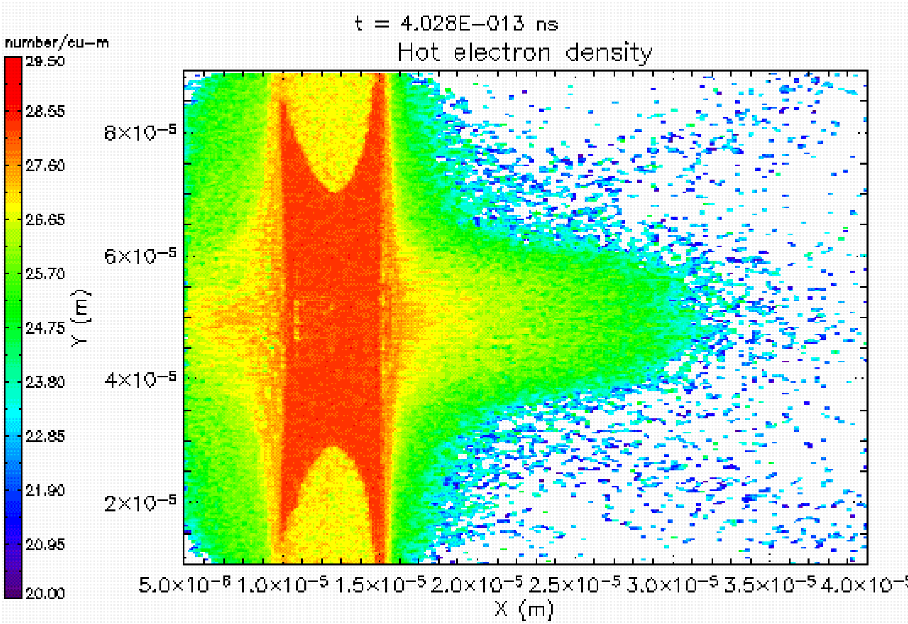
Laser-produced p^+ beam propagation PIC simulation (Slide 3)

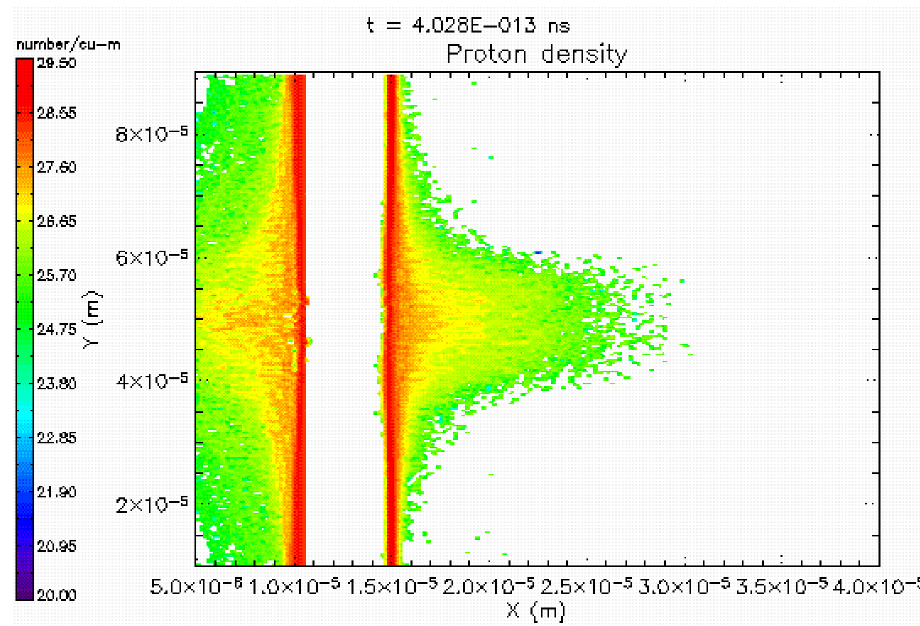


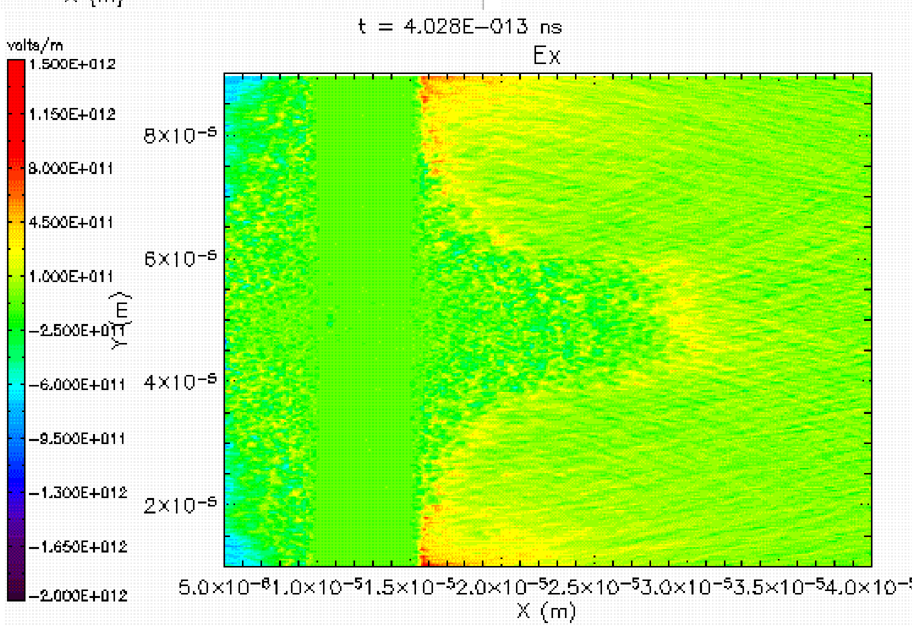


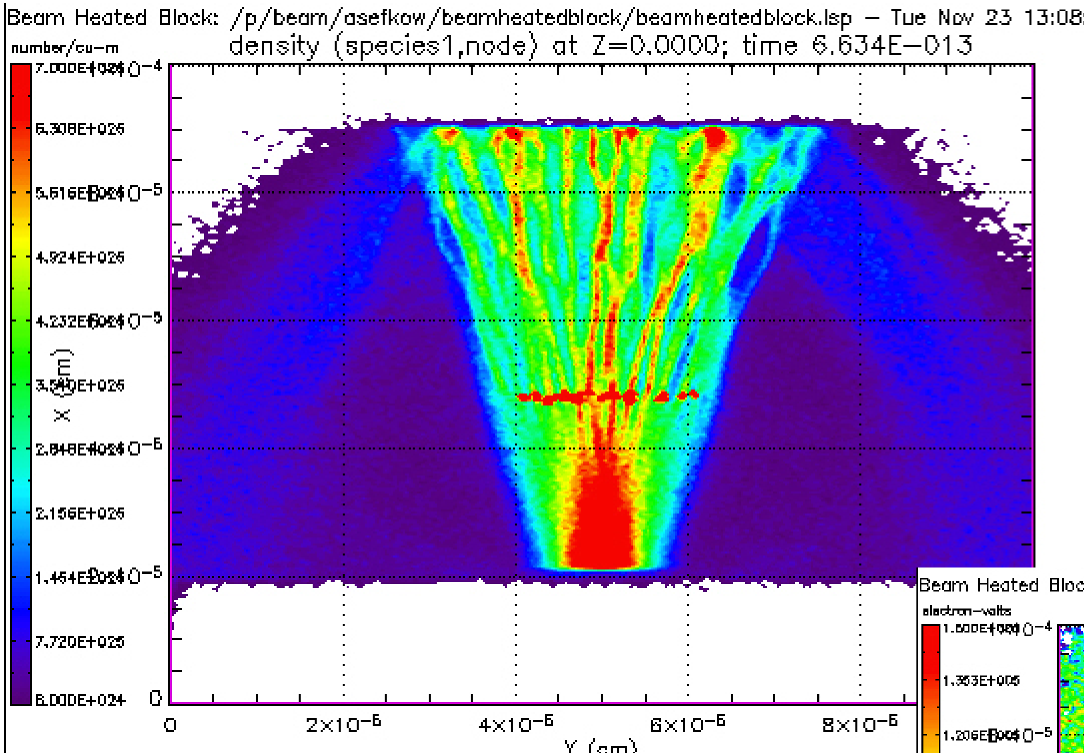


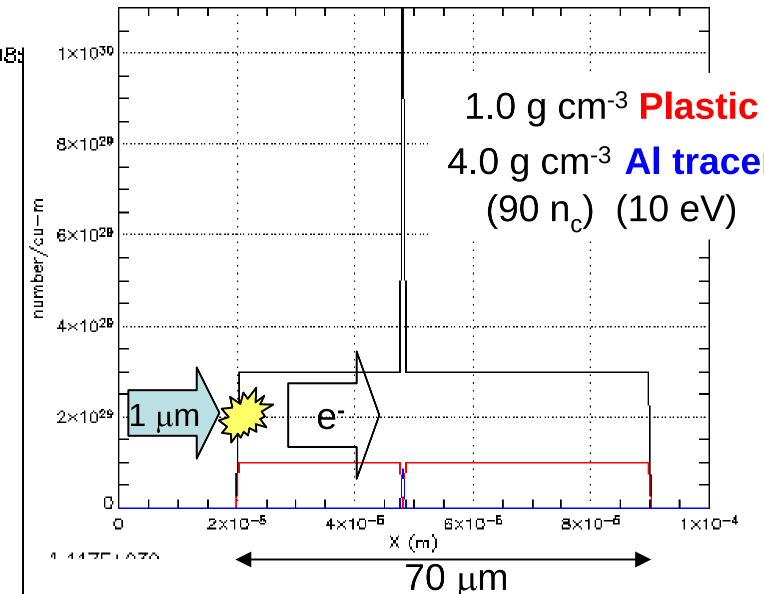
Laser-produced p+ beam propagation PIC simulation (Slide 4)

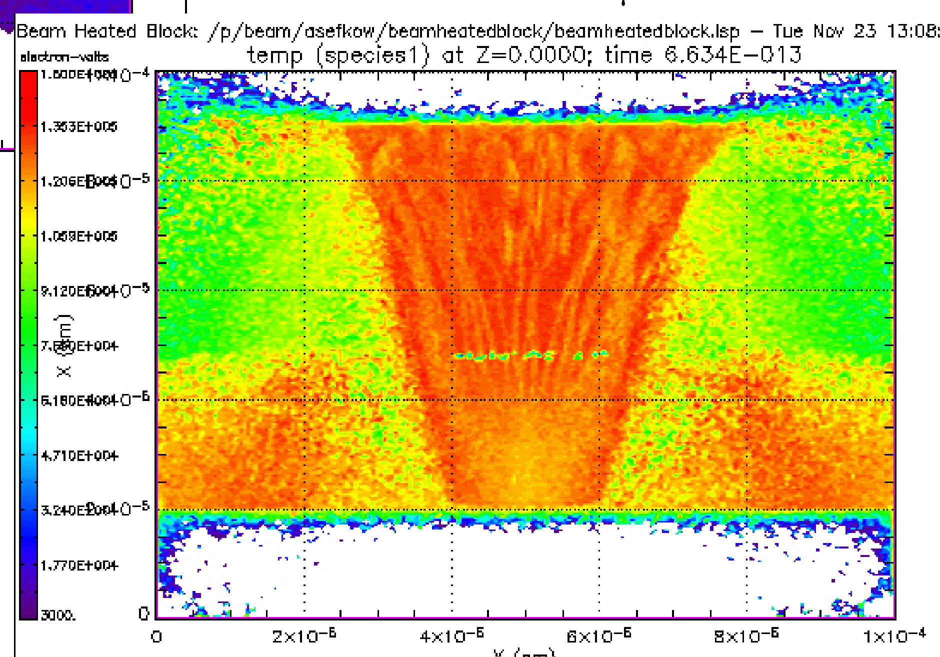












Lower mass density,
Thicker solid targets

Filamentation
(70 μm, 1 g cm^{-3})

1) Cold fluid species (background e^-s): perfect gas EOS and Spitzer transport coeff's

2) LSP uses flux-limited thermal conduction for fluid species

3) Return current is resistive & described by fluid equations

4) Plasma resistivity due to electron-ion collisions, plasma heated by I^2 R losses of r-c

5) Hot beam electrons collide with cold plasma (fluid) electrons

6) Focusing/filamentation of beam current, self-fields important for transport

7) Fast e^- current magnetically neutralized by plasma return current (induction), decay is long due to high conductivity of hot plasma

8) { 1E29 m^{-3}, 10eV } → λ_d = 75E-15 m, ω_{pe} = 1.8E16 s-1, c/ω_{pe} = 0.17E-7 m

9) Transverse resistive filamentation ~ fs scale (depends on beam temperature)

10) Ionization ~ 1 fs, Collisions & Radiation ~ 10fs, Ions ~ 100fs

11) Finite collisionality between cold e^- r-c and plasma ions gives resistive filamentation and emittance growth

12) Coulomb collisions between charged particles treated using Spitzer collision rates

*Slide from D. R. Welch (ATK-Mission Research)

Long simulations can compromise energy conservation of kinetic particles

LSP uses a PIC fluid electron description: pushing particles with ensemble velocity and a pressure gradient term is added to the equation of motion.

Fluid electron internal energy:

$$\frac{3}{2} n_e \frac{dT_e}{dt} = -n_e T_e \nabla \cdot \mathbf{v}_e + \sum_j \frac{2 m_e n_e}{m_j \tau_{je}} \left(T_j - T_e \right) + \nabla \cdot \kappa \nabla T_e + Q_e - n_e \frac{dE_{ie}}{dt},$$

pdV | thermalization | conduction | ohmic | inelastic losses

$$m_e n_e \frac{du_e}{dt} = -\nabla p_e - \nu_{ei} \gamma_e m_e n_e (v_e - v_i),$$