Fast Electron Transport in Dense Plasmas in the Context of Fast-Ignition

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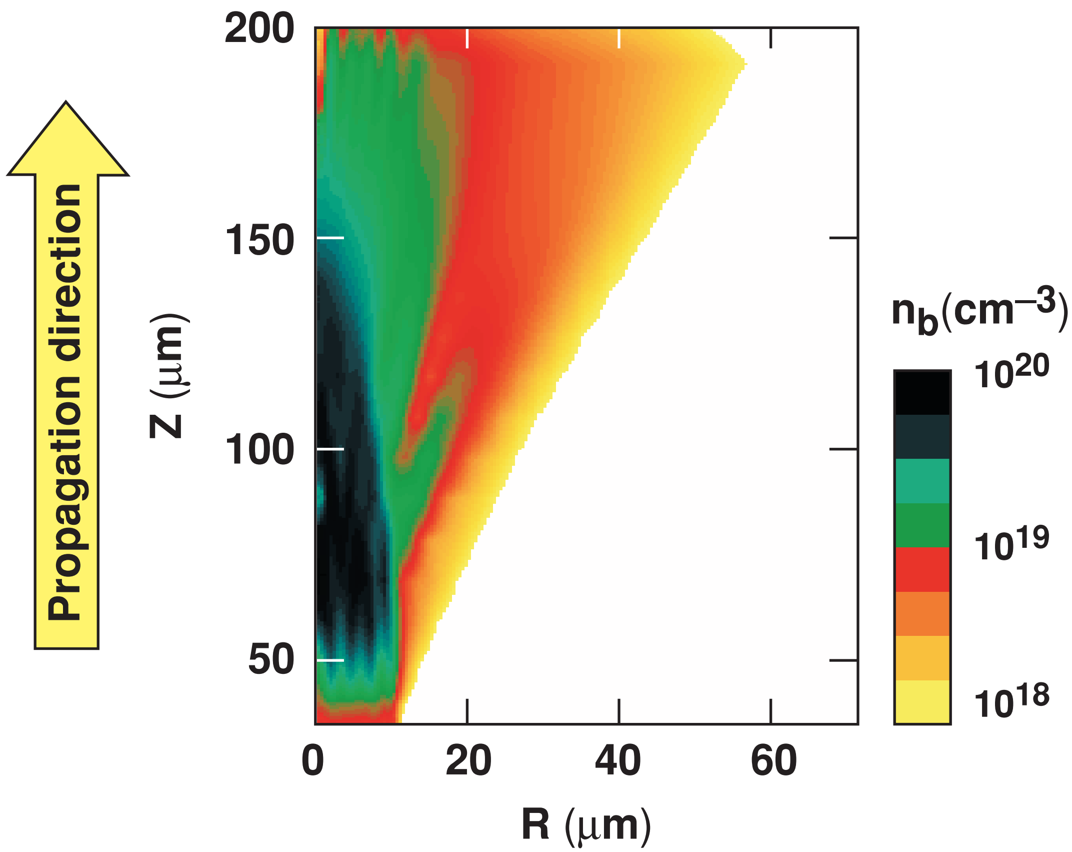

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Summary

The PIC/hybrid approach is a promising technique for the modeling of electron transport in very overdense plasmas

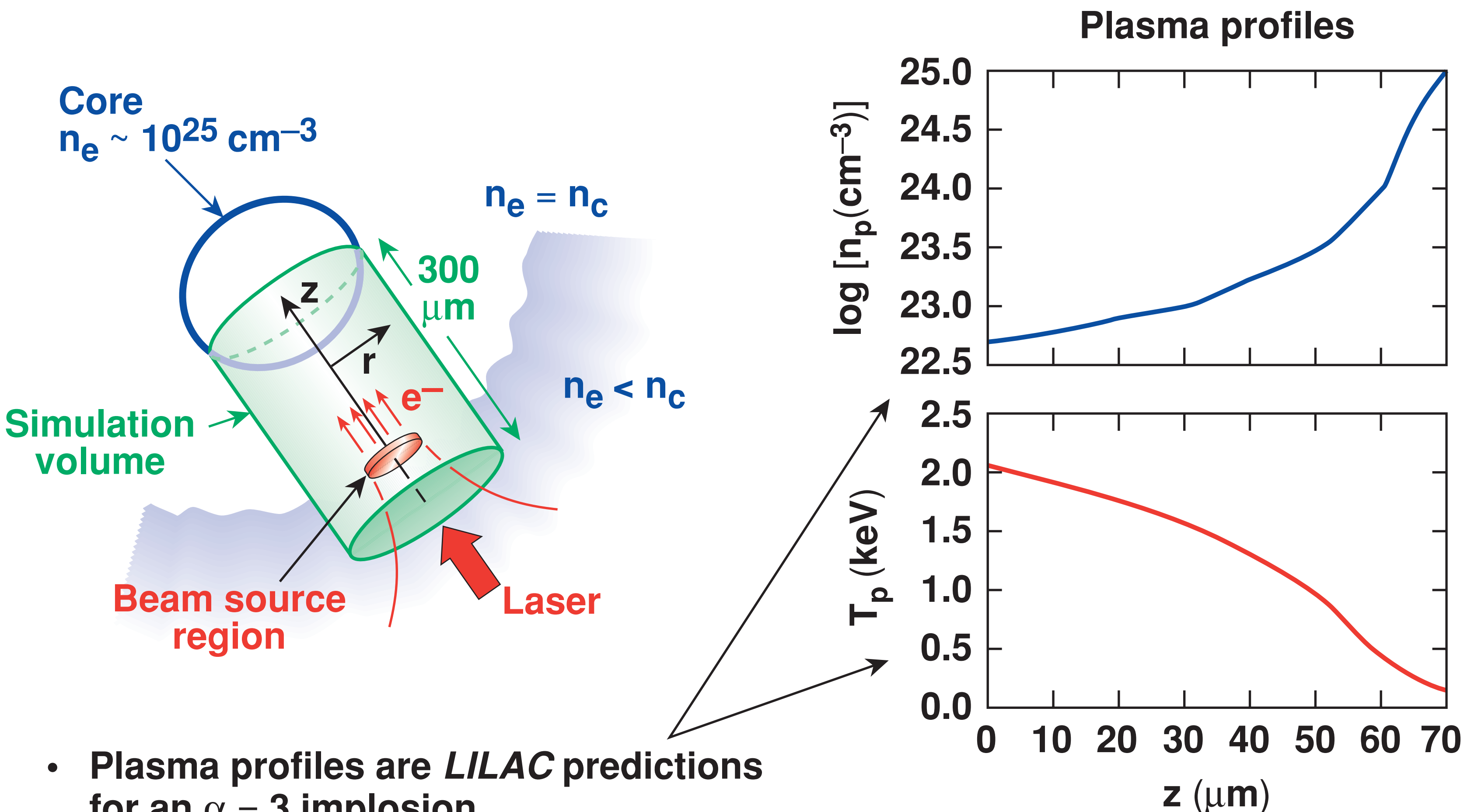
- Two-dimensional simulations of fast (1-MeV) FI electron beams have been made in imploded cryogenic DT fusion targets
  - Relevant to future OMEGA EP fast-ignition experiments
  - Also see talk by J. A. Delettrez
- The electrons do not behave as a "rigid beam."
- The self-generated azimuthal magnetic field collimates the electron beam.
  - The beam radius is smaller than the laser spot at the core.
- We observe filamentation of beam current.
  - Consistent with resistive filamentation (Gremillet *et al.*, 2002)
- Target is heated by the return current.

Outline

- Lsp* simulations of intense electron beam propagation from critical density to the compressed core in cryogenic DT targets
  - 2-D (r-z cylindrical), nonuniform mesh
  - Electromagnetic, implicit algorithm (large time step)
- Hybrid model for dense plasma
  - Plasma resistivity is due to electron–ion collisions.
  - Hot beam electrons collide with plasma electrons.
- Focusing and filamentation of beam current
- Future plans

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

We treat the fast electron transport in a two-dimensional r-z cylindrical geometry, but not the generation mechanism



- Plasma profiles are *LILAC* predictions for an $\alpha = 3$ implosion.

Electron-beam parameters are relevant to future fast-ignition studies on OMEGA EP

- An electron beam is generated by promotion from background over a 20-μm spot with a pulse duration of 10 ps.
- FI-relevant parameters are chosen for the beam source

$$n_b = 2 \times 10^{20}\, \eta_{eff} \frac{I}{10^{19}\,\mathrm{Wcm^{-2}}} \frac{1\,\mathrm{MeV}}{\varepsilon_b}\,\mathrm{cm^{-3}}$$

- Unlike simulations in near-critical plasmas, the beam is "weak" in the sense that $n_b/n_e << 1$

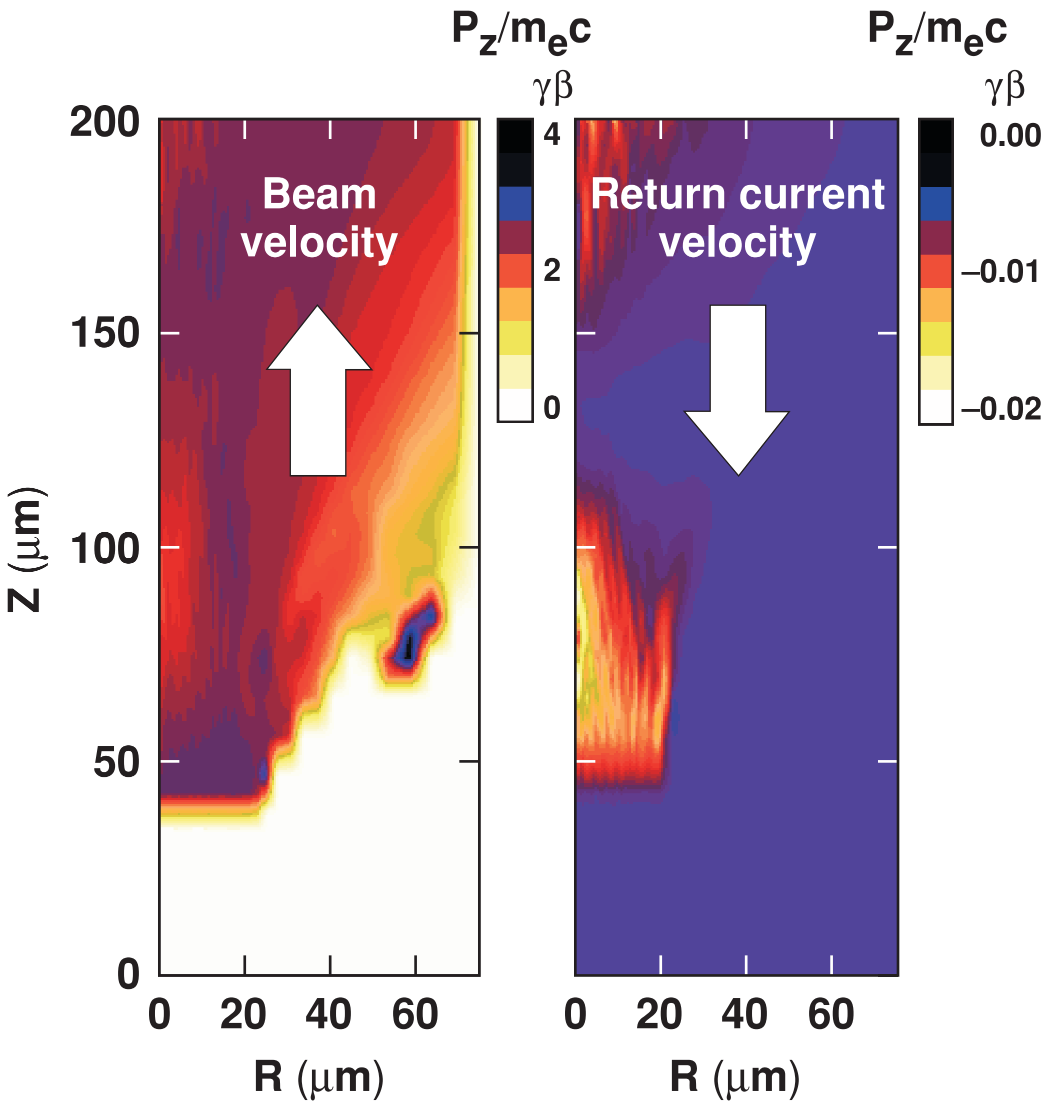
$$I_b = 30\, \eta_{eff} \frac{I}{10^{19}\,\mathrm{Wcm^{-2}}} \frac{A_{spot}}{300\,\mu\mathrm{m}^2} \left(\frac{1\,\mathrm{MeV}}{\varepsilon_b}\right) \mathrm{MA}$$

$$I_A = 17\gamma\beta\ \mathrm{kA} << I_b$$

- Self-generated fields are therefore important for transport.

TC6227

The plasma supplies a compensating return current so that the fast electron current is "magnetically neutralized"



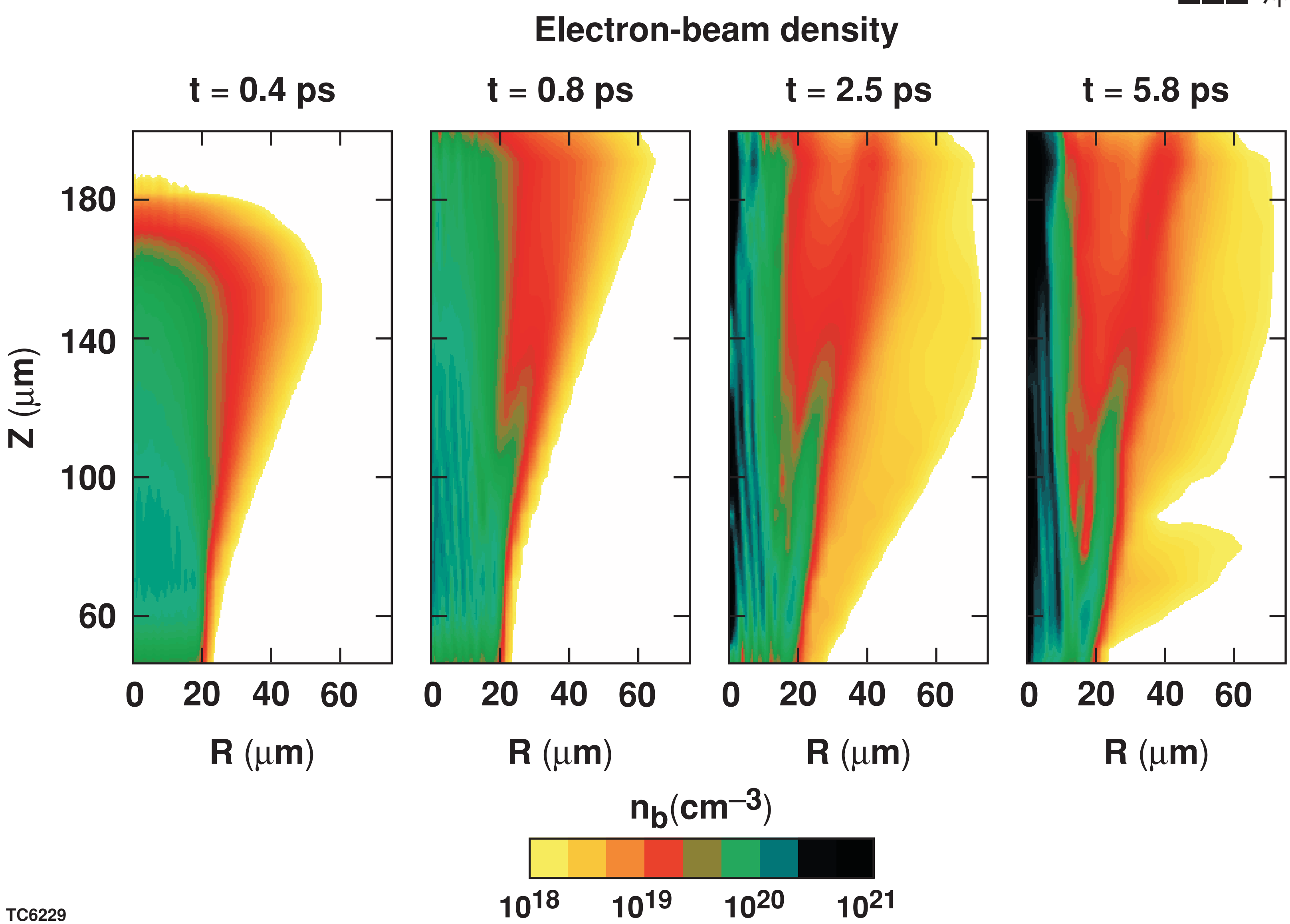
- **A compensating return-current is set up by induction.**
- **The time for decay of the r-c is long due to the high conductivity of hot plasma:**

$$\tau_d = 4\pi\sigma\, r_b^2/c^2 > 1\,\text{ns}$$

- **Plasma velocity is much smaller than beam velocity because the beam is weak.**
- **Filaments are evident.**

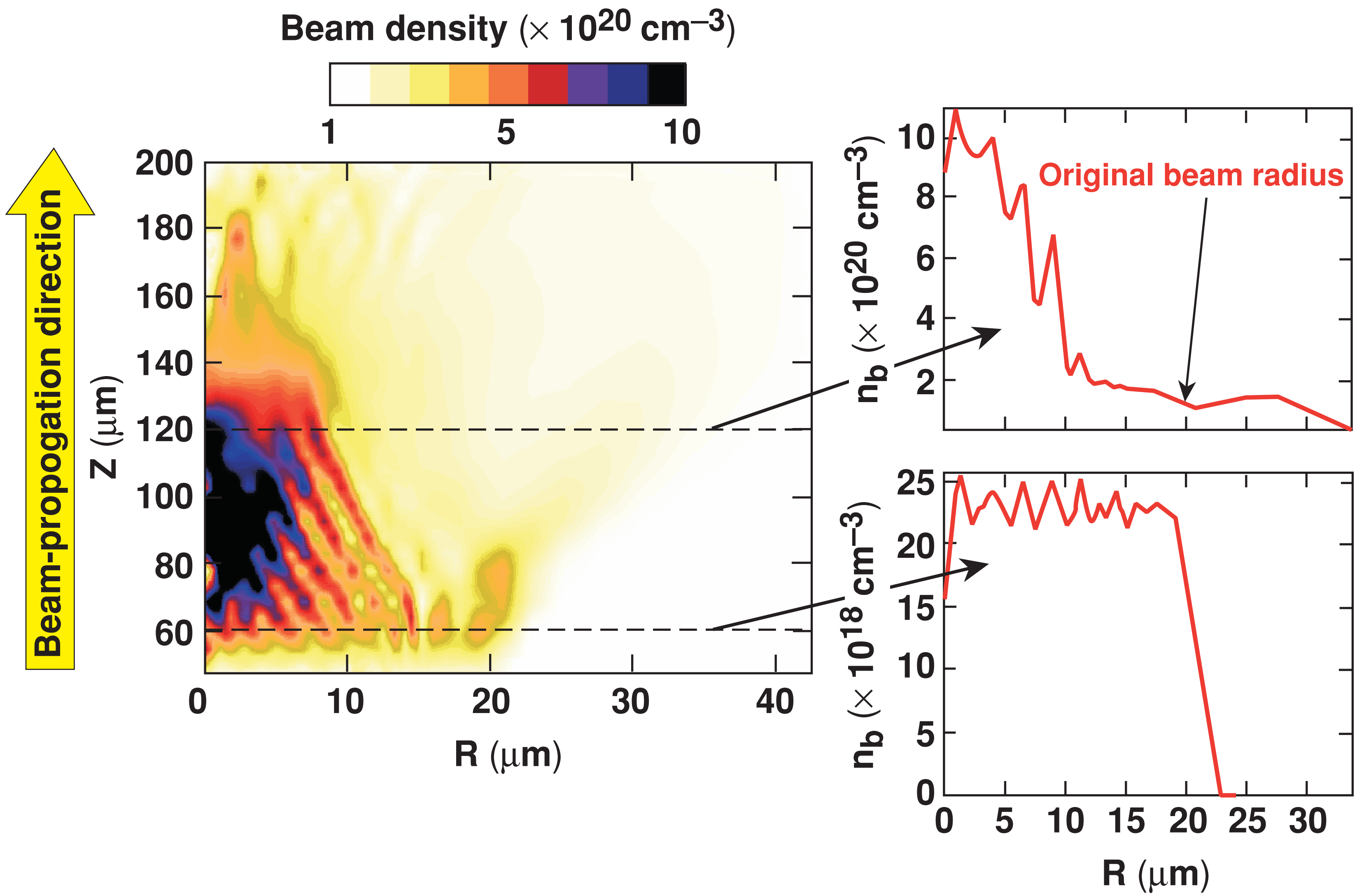
TC6228

The electron beam breaks into filaments and contracts radially



TC6229

Despite the filamentation, the beam is collimated



TC6230

Although the current is compensated, the residual magnetic fields are strong enough to pinch the beam

- A longitudinal resistive electric field is set up with the same radial profile as the beam current density:

$$E_z \sim \frac{j_b}{\sigma} \sim 10^6 \text{statvolt}/\text{cm}$$

- This electric field is not curl-free and generates a magnetic field according to Faraday's law:

$$B_\phi \sim \frac{\tau c E_z}{r_b} \sim 1\text{ MG}$$

- For equilibrium (Bennett) Lorentz force balances transverse pressure:

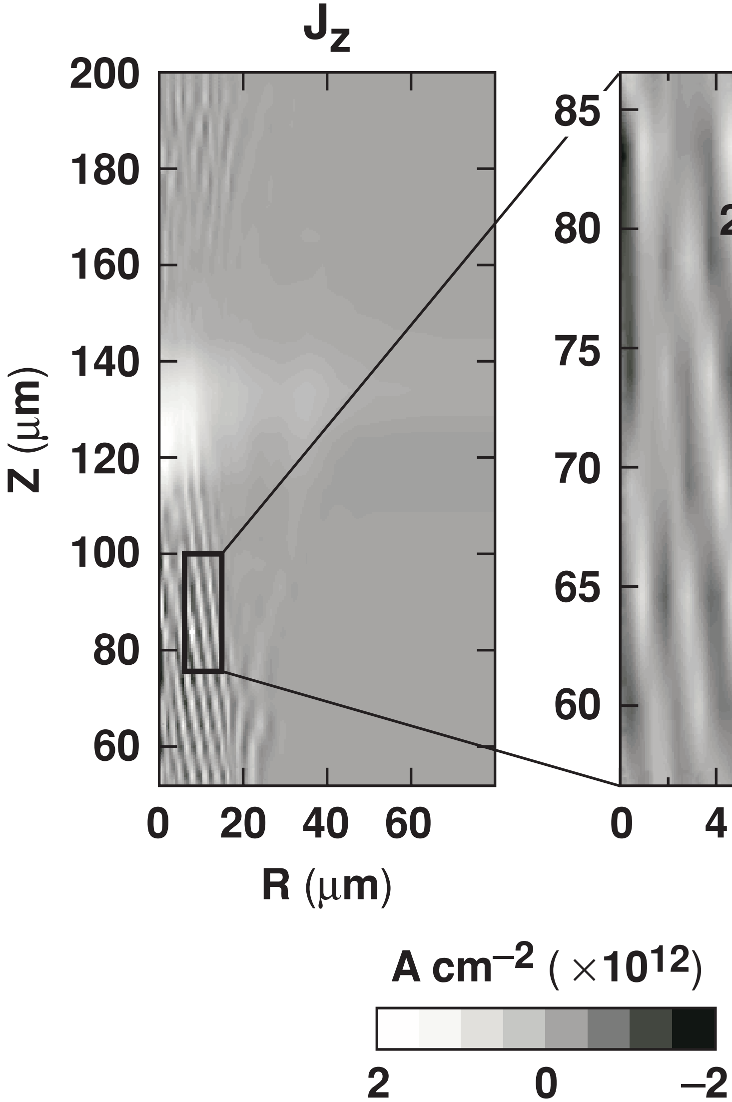
$$\frac{T_b}{r_b} = e\frac{v_z}{c}B_\phi,\; T_{b,r} = \int d\vec{p}\, p_r v_r F_b$$

- Lorentz force exceeds pressure for reasonable beam temperatures:

$$T_{b,r} > 0.5\text{ MeV} \longleftarrow \text{comparable to directed energy}$$

TC6231

The observed transverse perturbations in current density are consistent with resistive filamentation



- Scale for collisionless Weibel (c/ω_{pe}) is not resolved.
- Transverse resistive filamentation has the most-unstable wave number k_{perp}.
  - according to Gremillet *et al.*, Phys. Plasmas (2002)

$$k_{perp} \sim \frac{\omega_{pb}}{c} \sim \frac{2\pi}{2\,\mu m}$$

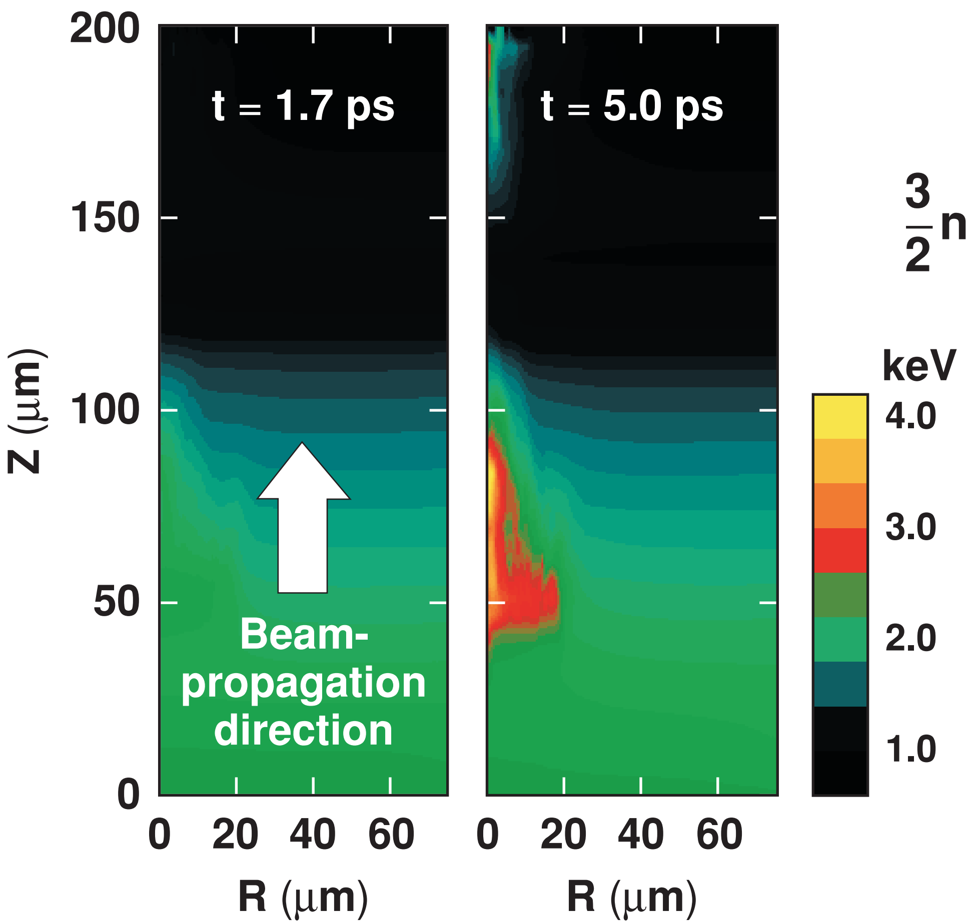
$$\gamma \sim 0.1\omega_{pb} = 1/18\ \text{fs}$$

$$18\ \text{fs} \ll \tau_{laser} = 10\ \text{ps}$$

TC6232

The plasma is heated by the I^2R losses of the return current

Plasma electron temperature (keV)



Return current heating

$$\frac{3}{2} n_p \frac{\partial T_p}{\partial t} = \nabla \bullet \left(\kappa \nabla T_p\right) + \frac{j_p^2}{\sigma_p} + \frac{3}{2}\frac{n_b T_b}{\tau_{pb}}$$

Collisional heating

RC heating is nonlinear:

$$\sigma = \frac{5.5 \times 10^{17}}{(\lambda / 10) Z} T_e^{3/2} (\text{keV})\ s^{-1}$$

Summary/Conclusions

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- The energy deposition needs to be quantified and checked.
- The simulations will be repeated in three-dimensions.