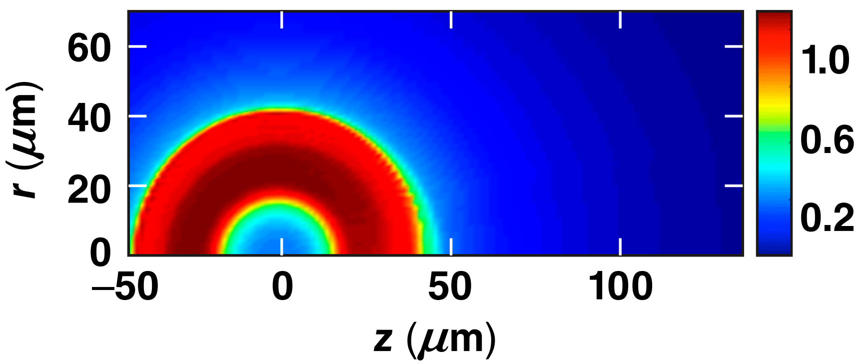
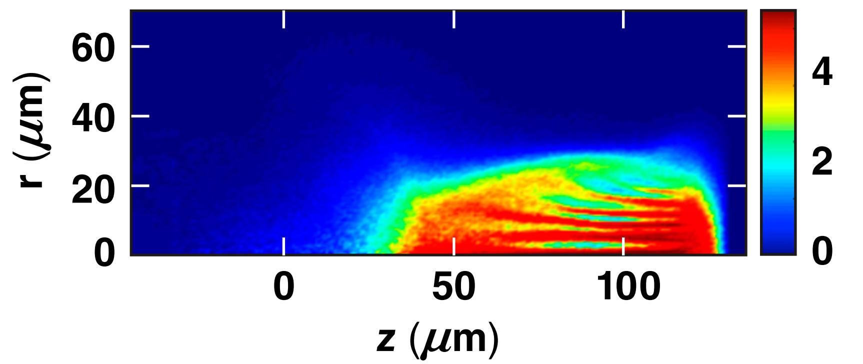
Integrated Simulations of Hot-Electron Transport and Ignition for Direct-Drive, Fast-Ignition Targets

Plasma density ($\times 10^{26}$ cm^{-3})

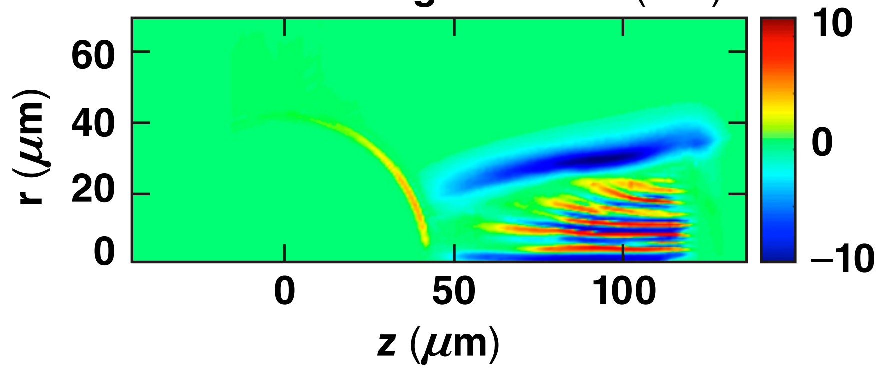


Electron-beam density ($\times 10^{22}$ cm^{-3})



300-kJ fuel assembly
e-beam: Maxwellian, $\langle E \rangle = 2$ MeV
$r_{FWHM} = 30\ \mu$m
opening half angle = 20°
$E_{total} = 43$ kJ

Azimuthal magnetic field (MG)



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Summary

Electron-beam collimation by a self-generated resistive magnetic field increases the coupling efficiency of hot electrons with the target and reduces the energy required for ignition

- The hybrid-PIC code *LSP*[1] and the fluid code *DRACO*[2] have been integrated for simulations of hot-electron transport and ignition for direct-drive, fast-ignition fusion targets
- Integrated simulations show ignition of optimized spherically symmetric targets[3] by a 43-kJ, 2-MeV Maxwellian electron beam.
- Simulations of plastic cone-in-shell targets designed for OMEGA-integrated experiments show heating by up to 1 keV and a neutron yield of 1.6×10^{10}.

[1] D. R. Welch *et al.*, Phys. Plasmas 13, 063105 (2006).
[2] P. B. Radha *et al.*, Phys. Plasmas 12, 056307 (2005).
[3] R. Betti and C. Zhou, Phys. Plasmas 12, 110702 (2005).

TC7788a

Collaborators

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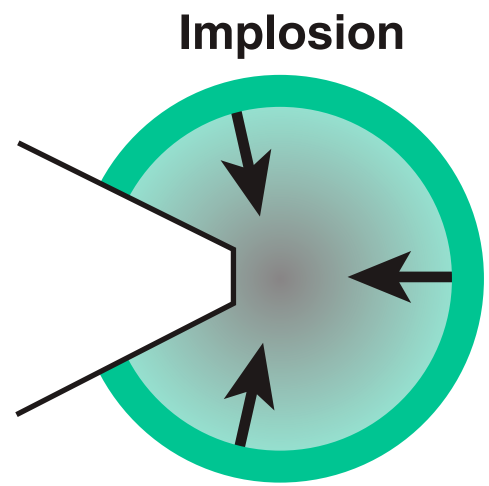
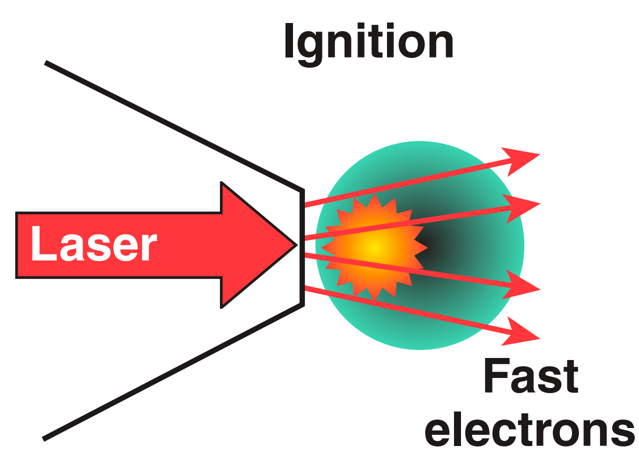
Modeling the entire fast-ignition experiment requires resolving very different spatial and temporal scales and using different types of codes

- A target implosion is simulated using hydrocodes.
- Generation of hot electrons by a petawatt laser pulse interacting with a solid target or coronal plasma is simulated using particle-in-cell (PIC) codes.
- Hot-electron transport to the target core is simulated using hybrid-PIC or Monte Carlo codes.

We have integrated the hydrocode *DRACO* and hybrid-PIC code *LSP* to model the fast-ignition experiment.



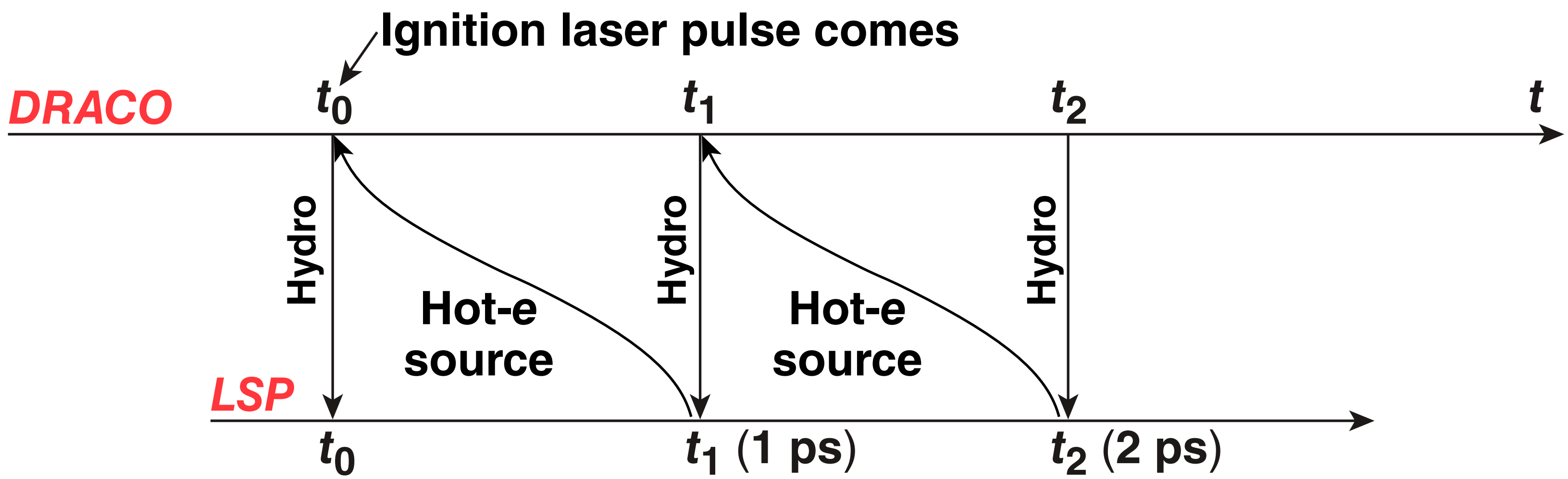


TC8133

LSP simulates the hot-electron transport and energy deposition, and *DRACO* is used to simulate the target hydrodynamics and burn

- *DRACO*
  - 2-D cylindrically symmetric hydrodynamic code
  - includes all the necessary physics required to simulate ignition and burn of the imploded capsules
- *LSP*
  - 2-D/3-D implicit-hybrid PIC code
  - implicit solution for the electromagnetic fields and implicit particle push
  - hybrid fluid-kinetic description for plasma electrons with dynamic reallocation
  - intra- and interspecies collisions based on Spitzer rates (have been corrected to include relativistic effects)
  - uses ideal gas equation of state

LSP generates a hot-electron source term in the temperature equation solved by *DRACO*

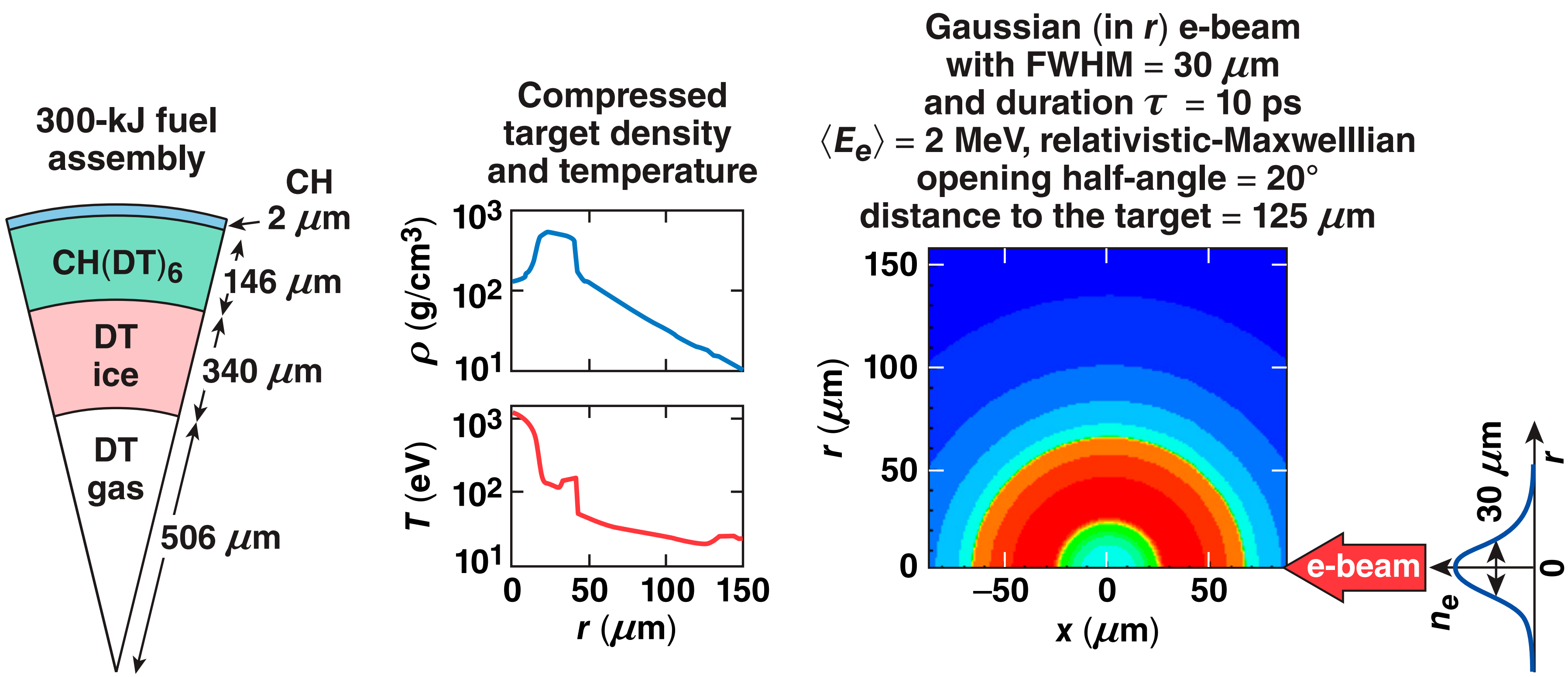


- *LSP* generates the time history of hot-electron-energy deposition in plasma for *DRACO*.
- Hydrodynamic profiles in *LSP*: electron and ion temperatures, densities, and velocities are periodically updated according to *DRACO* results (fluid species). Electromagnetic fields and hot-electron distributions (kinetic species) are not changed.
- In *LSP*, hot electrons are promoted from background electrons with a mean energy predicted by PIC simulations*.

TC7791b

*B. Chrisman, Y. Sentoku, and A. J. Kemp, Phys. Plasmas 15, 056309 (2008).

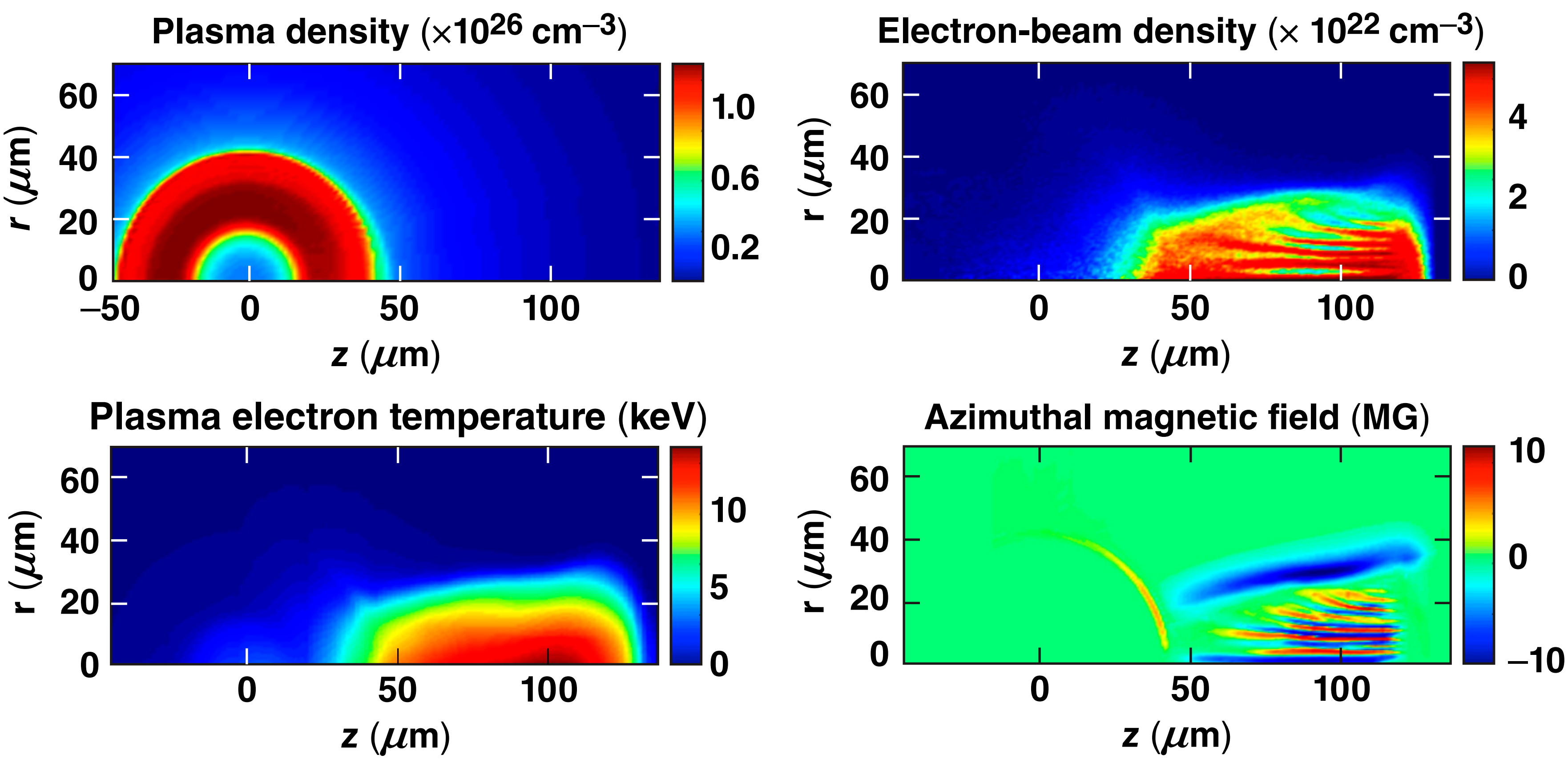
In the integrated simulation, an imploded optimized fast-ignition target* is heated by a 2-MeV, FWHM = 30-μm electron beam



*R. Betti and C. Zhou, Phys. Plasmas 12, 110702 (2005).

Integrated simulation shows electron beam collimation by the self-generated resistive magnetic field and resistive filamentation[1,2]

Snapshots at t = 8 ps after the beginning of the e-beam



Total e-beam energy = 43 kJ, angular divergence = 20°

TC7793c

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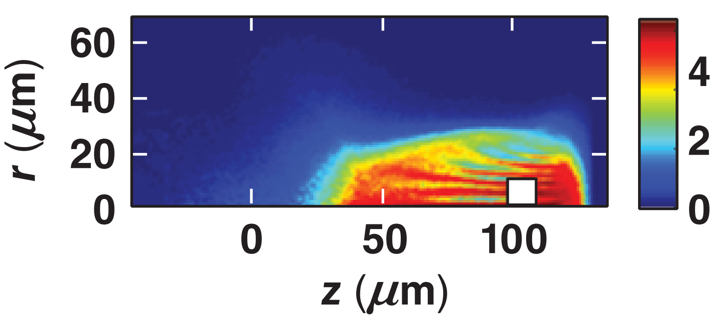
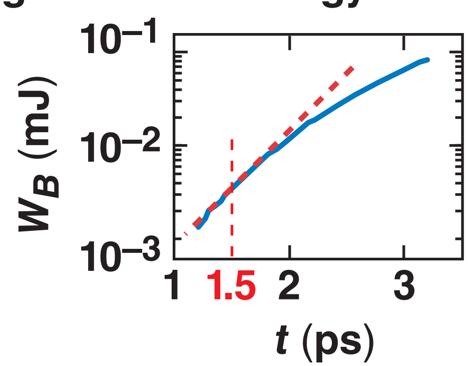
[1] L. Gremillet *et al.*, Phys. Plasmas 9, 941 (2002).

[2] J. J. Honrubia and J. Meyer-ter-Vehn, Nucl. Fusion 46, L25 (2006).

Beam collimation and resistive filamentation in *LSP* simulations are in agreement with theoretical predictions[1,2,3]

- *LSP* reproduces correctly the analytic magnetic field for a rigid Gaussian electron beam[3]
- The resistive filamentation instability growth rate in the simulations is in agreement with Ref. 1





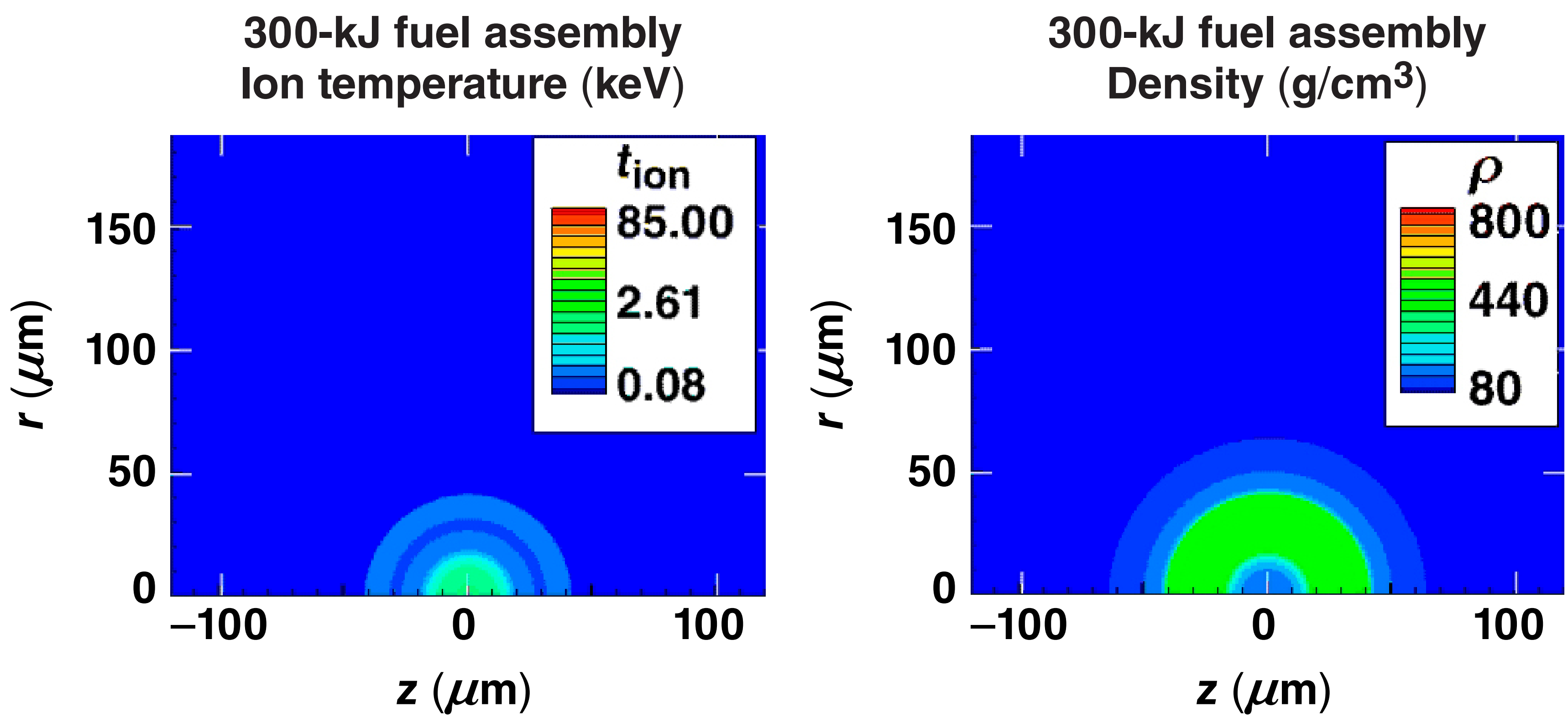
$\Gamma^{\mathrm{sim}} = 1.4 \times 10^{12}\ \mathrm{s}^{-1}$

$$\Gamma^{\mathrm{theory}} = \frac{2}{\tau_d \gamma_b}\left(\frac{\beta_b}{\beta_b^{\mathrm{th}}}\right)^2, \text{ where } \tau_d = \mu_0 c^2 / \left(\eta \omega_b^2\right);\ \Gamma^{\mathrm{theory}} \approx 1.7 \times 10^{12}\ \mathrm{s}^{-1} \text{ at } t = 1.5 \text{ ps}$$

[1]L. Gremillet *et al*., Phys. Plasmas 9, 914 (2002).
[2]A. R. Bell and R. J. Kingham, Phys. Rev. Lett. 91, 035003 (2003).
[3]J. R. Davies, Phys. Rev. E 68, 056404 (2003).

TC8045a

Ignition is triggered by a 43-kJ e-beam in the integrated simulation



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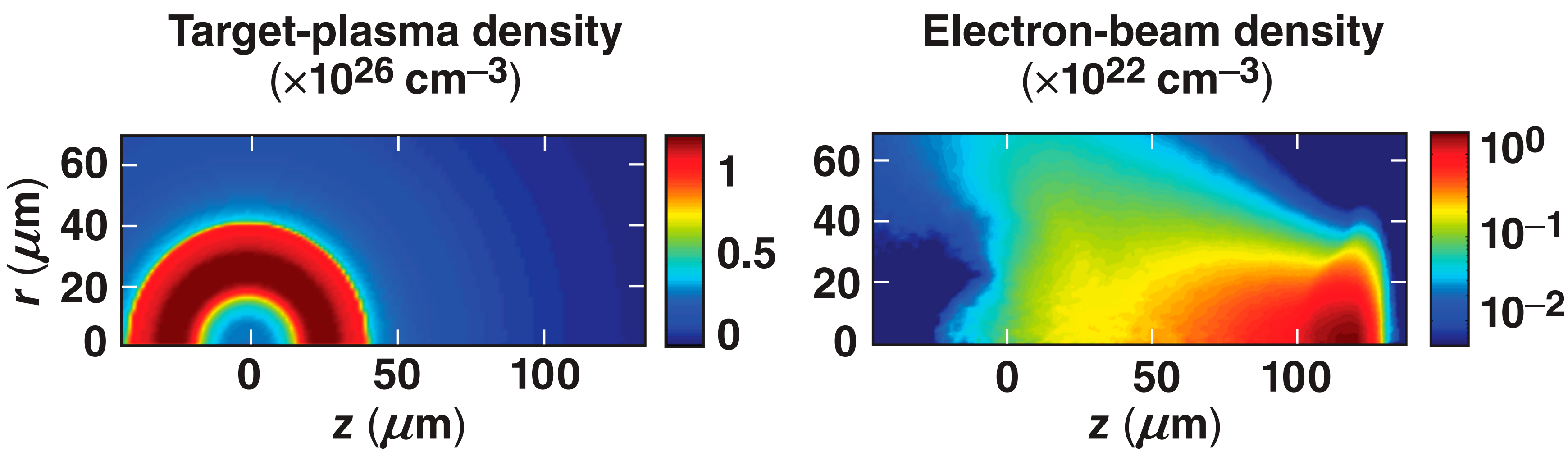
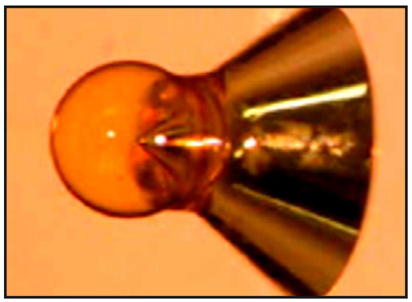
Simulation with the magnetic field artificially suppressed predicts a minimum energy for ignition of 96 kJ for the same e-beam properties

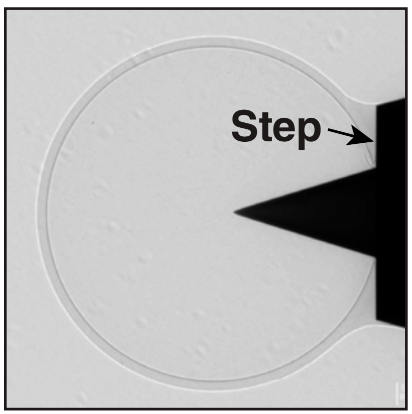


Beam collimation by the resistive magnetic field reduces the energy required for ignition.

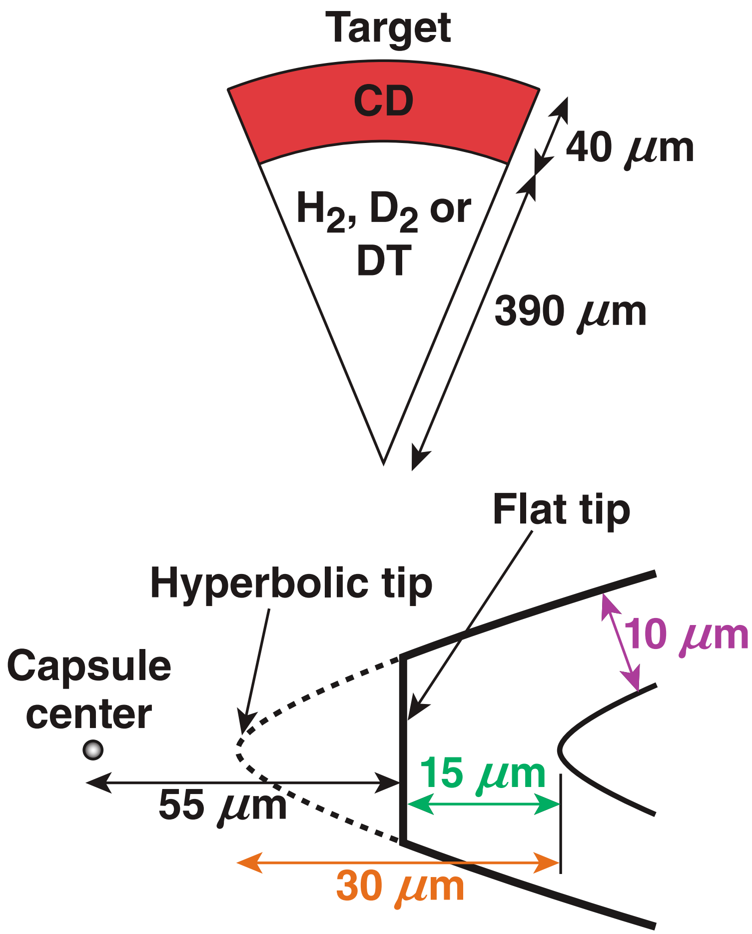
TC8046a

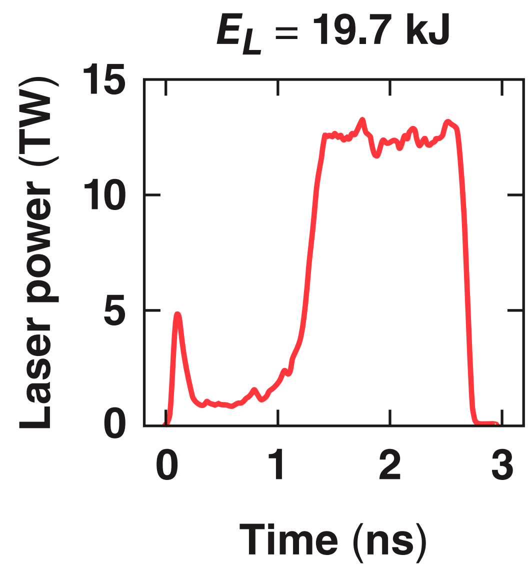
Integrated OMEGA experiments using low-adiabat implosions of plastic cone-in-shell targets* and PW heating pulses from OMEGA EP will be performed soon





Radiograph of target





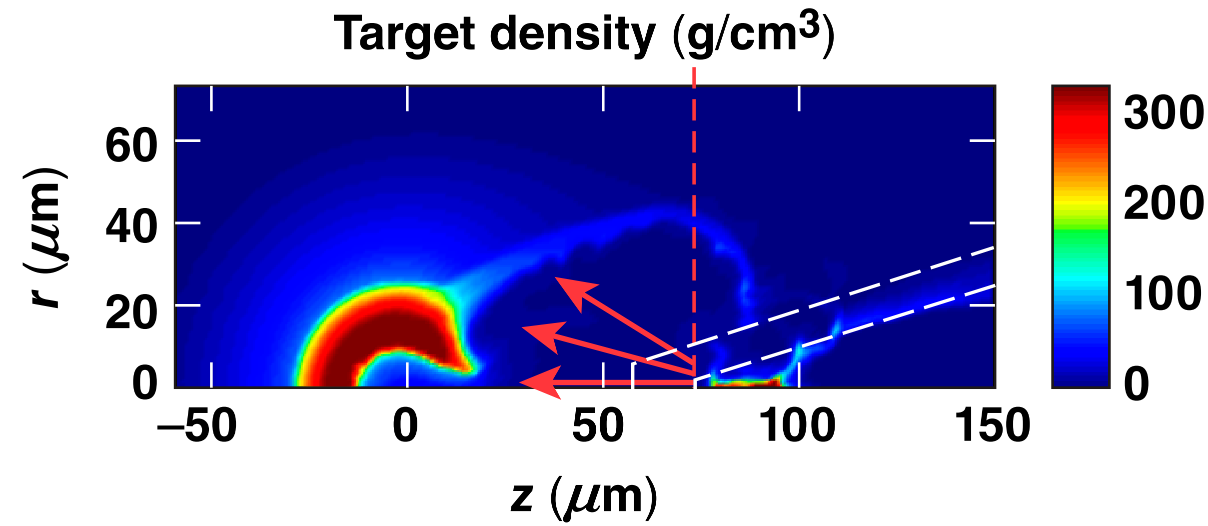
TC8134

*C. Stoeckl *et al.*, Phys. Plasmas 14, 112702 (2007).

We have performed simulations of target heating for integrated OMEGA experiments

- Hydrodynamic simulations of cone-in-shell target implosions predict areal densities sufficient to stop MeV electrons*

Plastic shell:
$\rho R \sim 0.45$ g/cm^2



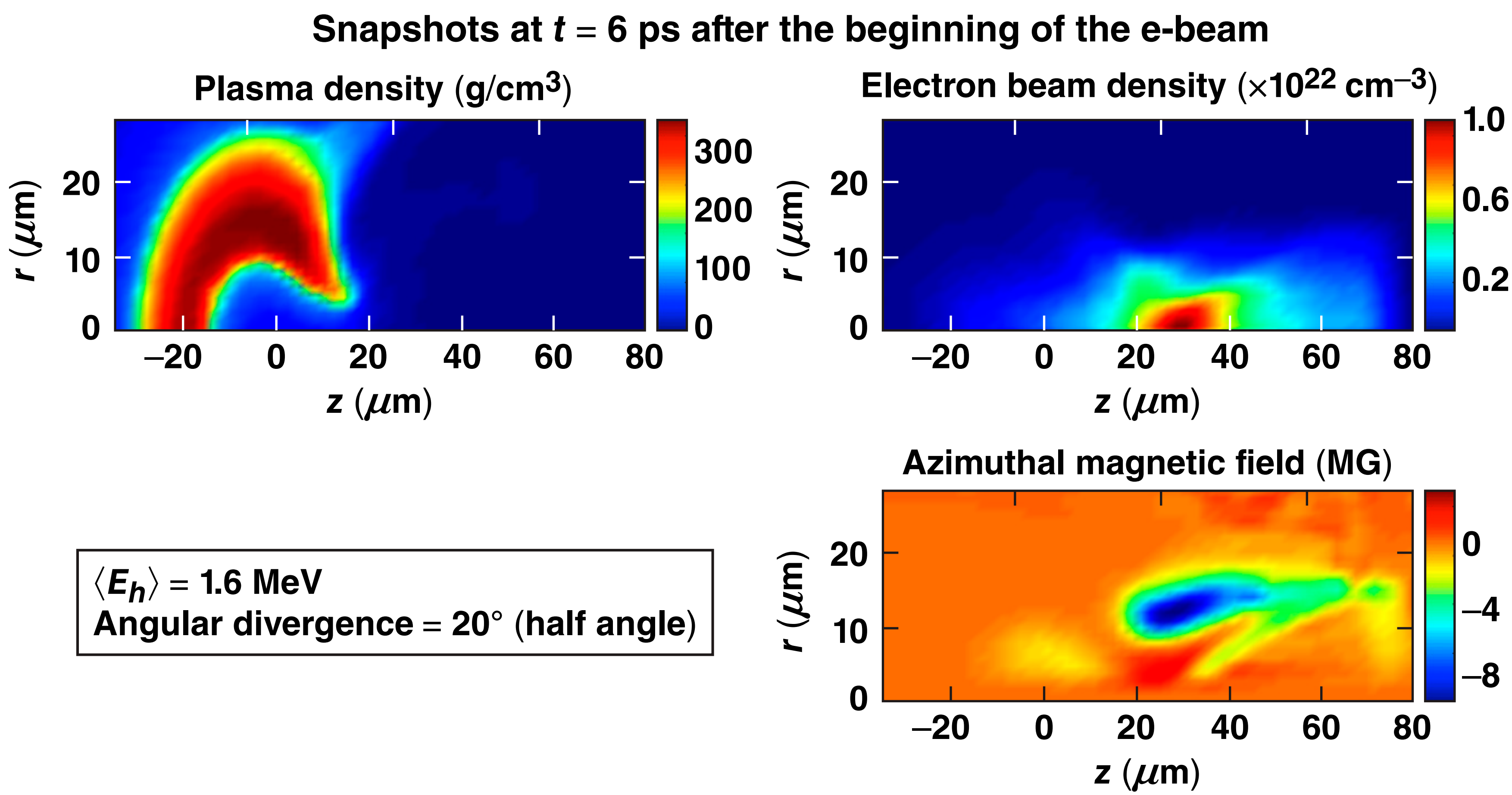
e-beam: Gaussian, spot size = 20 μm (FWHM), duration = 10 ps
angular spread = 20° to 60° (half angle)
Maxwellian energy spectrum with $\langle E_h \rangle$ = 1.2 to 2 MeV

Laser pulse: $I_0 = 5.4 \times 10^{19}$ W/cm^2, E_ℓ = 2.6 kJ
conversion efficiency to hot electrons = 0.3

TC8135

*K. S. Anderson *et al*., Bull. Am. Phys. Soc. 52, 283 (2007).

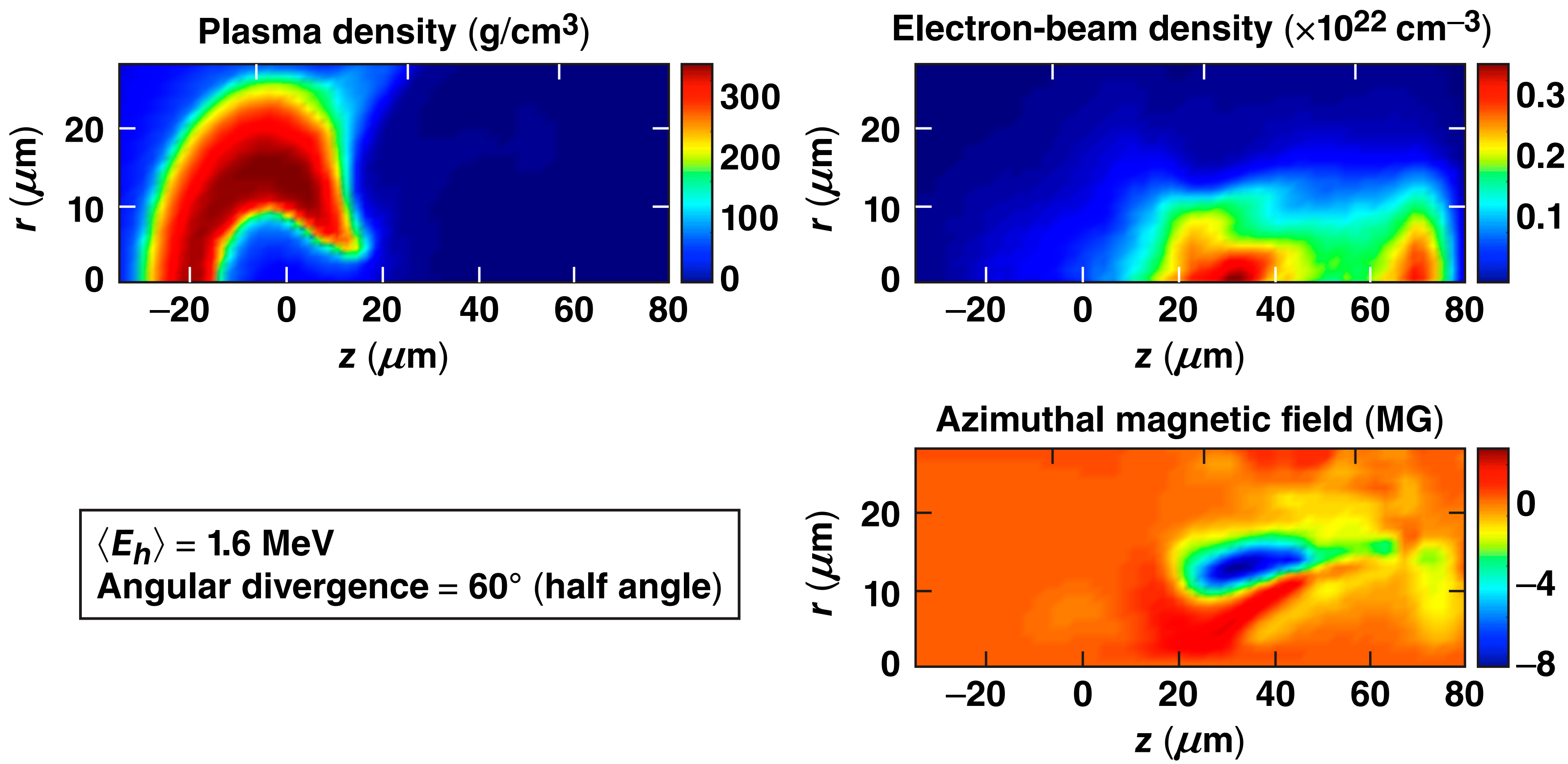
Hot electrons are collimated by the resistive magnetic field in the integrated simulation



$\langle E_h \rangle$ = 1.6 MeV
Angular divergence = 20° (half angle)

Hot electrons are collimated for an angular spread as high as 60°

Snapshots at t = 6 ps after the beginning of the e-beam



$\langle E_h \rangle$ = 1.6 MeV
Angular divergence = 60° (half angle)

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The hot electrons deposit 25% to 75% of their energy on target

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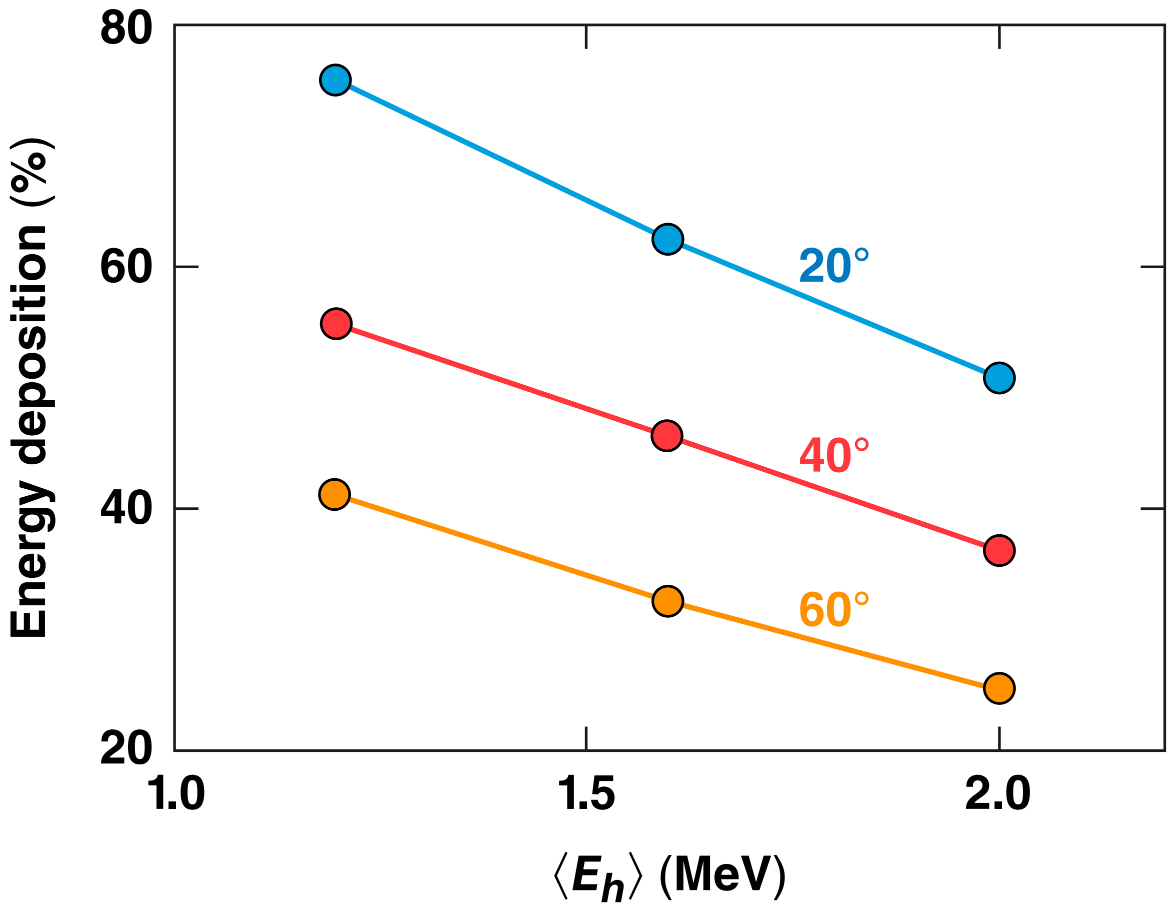

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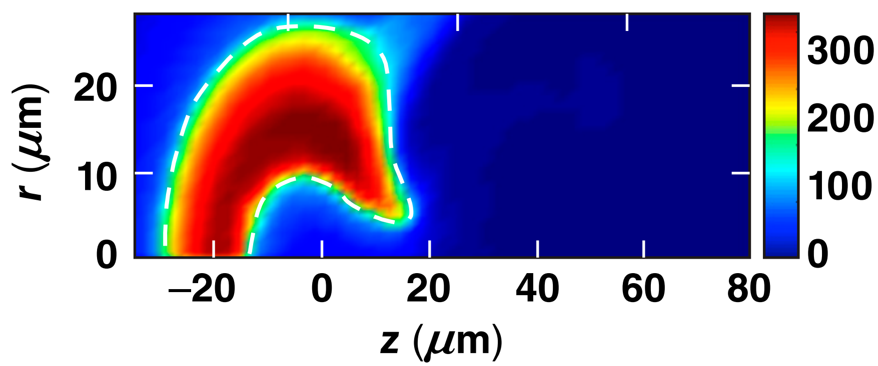
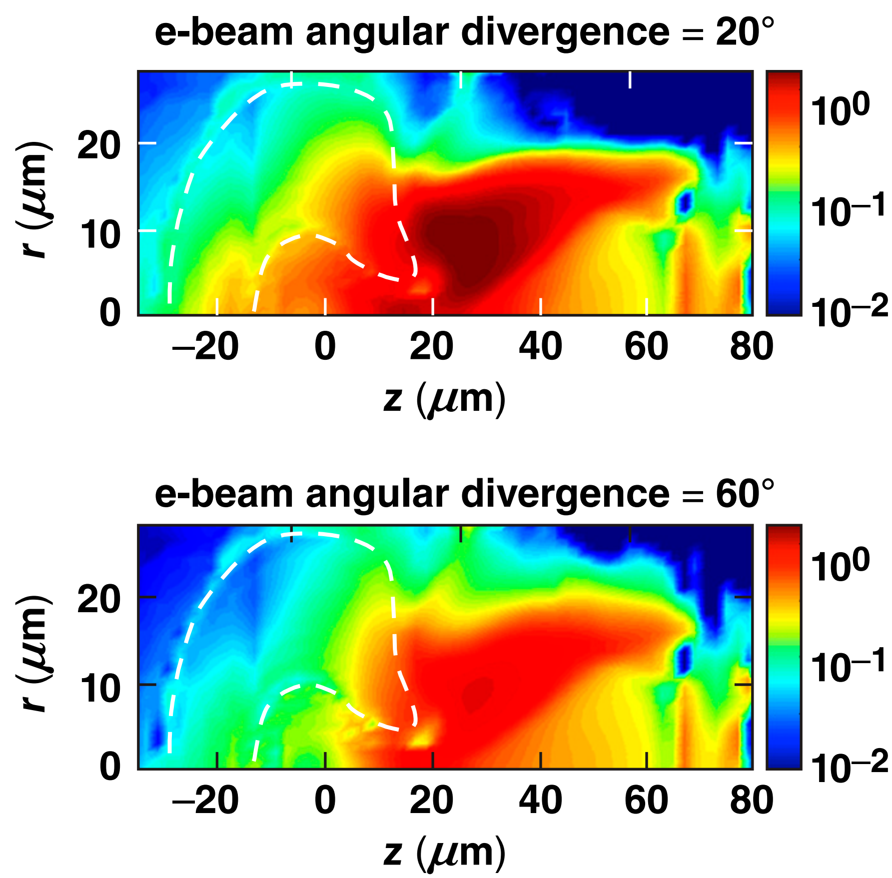
Hot electrons heat up the target by 1 keV (maximum)

Plasma density (g/cm^3)



Plasma temperature increase (keV)



Mean hot-electron energy
$\langle E_h \rangle = 1.2$ MeV

Neutron yield increases from 3×10^9 to 1.6×10^{10} due to hot electrons

Summary/Conclusions

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