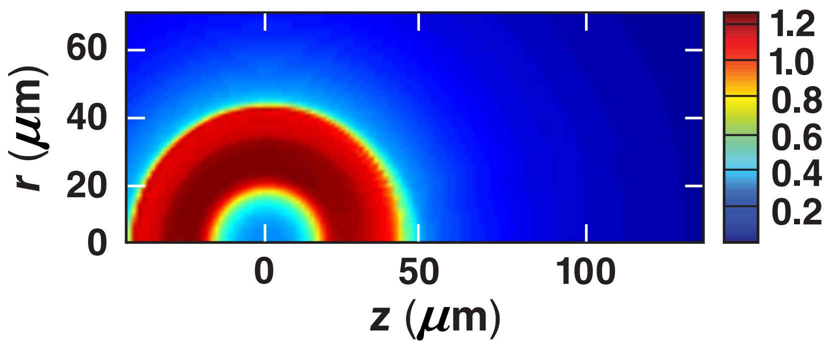
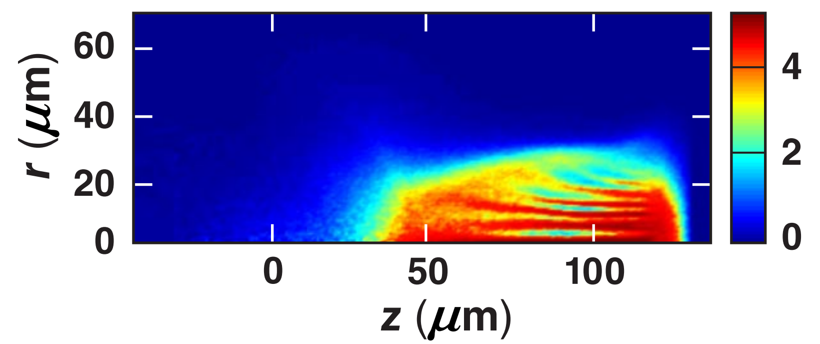
Integrated Simulations of Hot-Electron Transport and Ignition for Direct-Drive, Fast-Ignition Targets

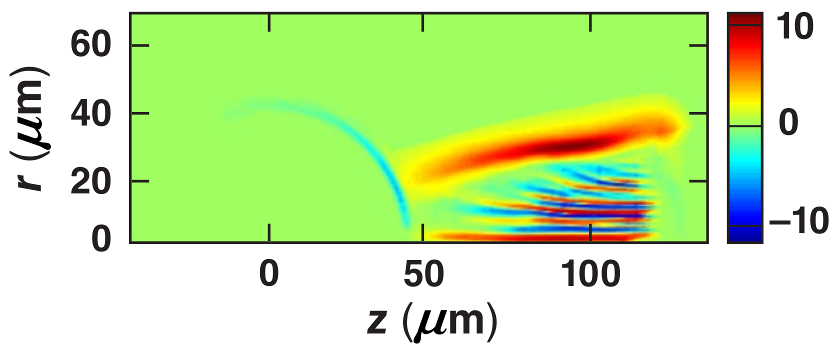
Plasma density ($cm^{-3} \times 10^{26}$)



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



Azimuthal magnetic field (MG)



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Dallas, TX
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Summary

A self-generated resistive magnetic field collimates the hot electrons and increases the coupling efficiency to the target

- 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 a temperature increase of 1 keV and a neutron yield of 4.5×10^9.

Collimation by the resistive magnetic field reduces the energy required for ignition.

[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).

TC7788b

Collaborators

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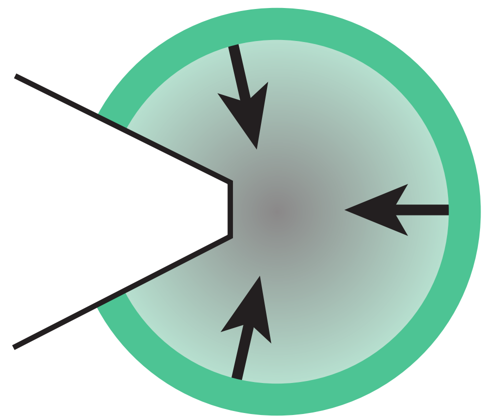
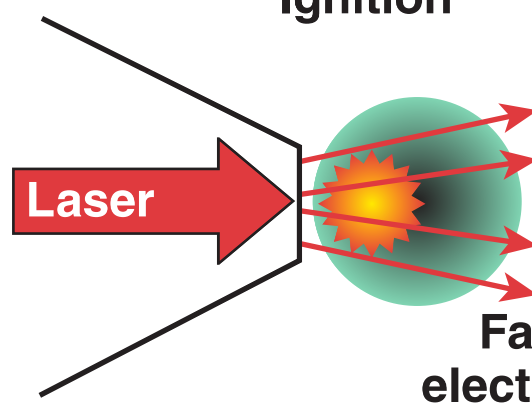
Modeling the entire fast-ignition experiment requires resolving very different spatial and temporal scales and using different types of codes

- 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 the hybrid-PIC code *LSP* to model fast-ignition experiments.

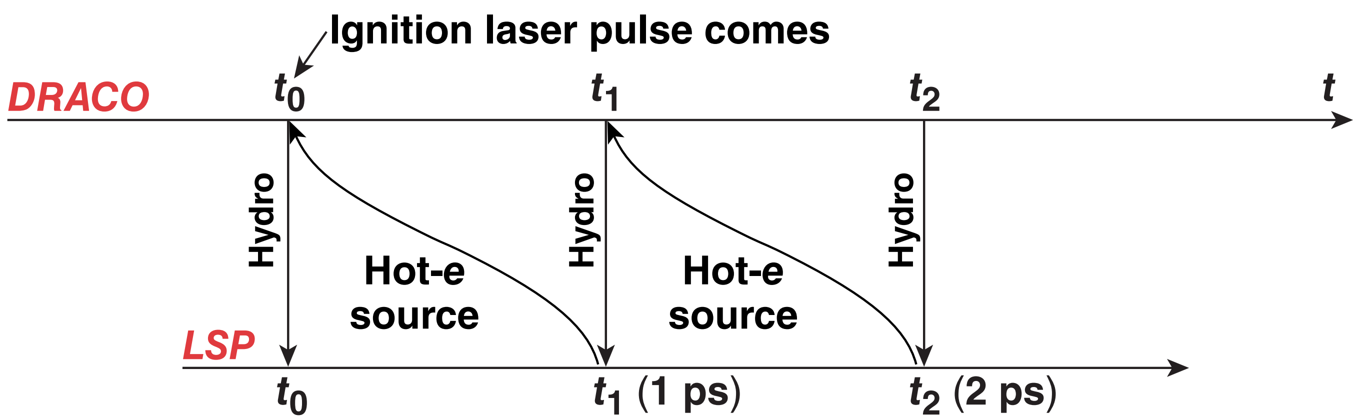




TC8133

LSP simulates the hot-electron transport and energy deposition; *DRACO* simulates the target hydrodynamics and burn

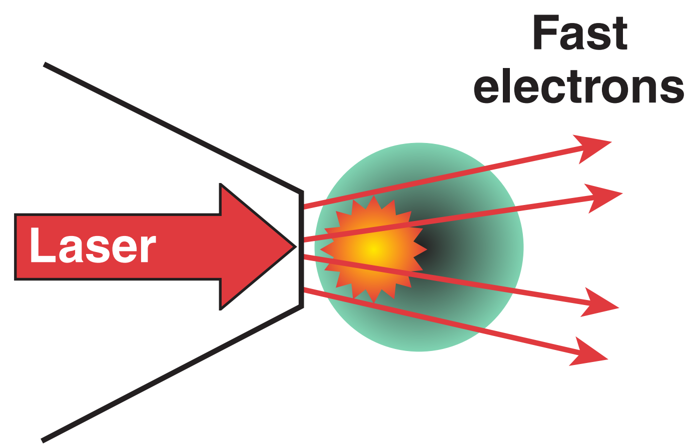
- *DRACO*[1]
  - 2-D cylindrically symmetric hydrodynamic code
  - includes all the necessary physics for ignition and burn of the imploded capsules
- *LSP*[2]
  - 2-D/3-D implicit-hybrid PIC code
  - hybrid fluid-kinetic description for plasma electrons
  - intra- and inter-species collisions based on modified Spitzer rates
  - ideal gas equation of state



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

TC7791c

In *LSP*, hot electrons are promoted from cold plasma electrons with mean energy determined by the ponderomotive scaling[1,2]



$$E_h = mc^2(\gamma_{os} - 1)\sqrt{\gamma_{os} n_c / n_p}, \text{ where } \gamma_{os}^2 = 1 + \frac{I\lambda_\mu^2}{2.8 \times 10^{18}}$$

n_p is the plasma electron density, n_c is the critical density.

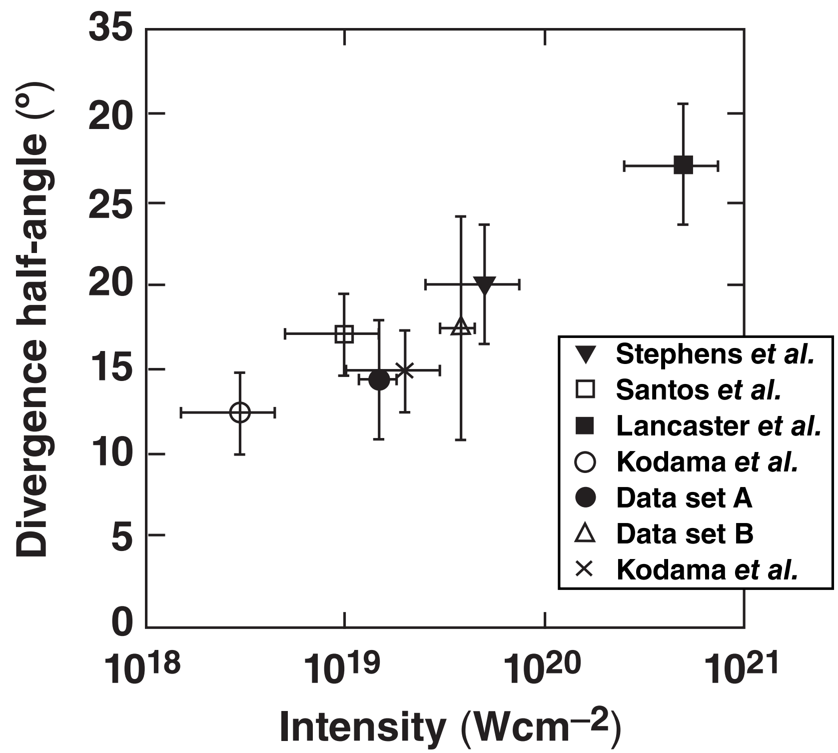
[1] B. Chrisman, Y. Sentoku, and A. J. Kemp, Phys. Plasmas 15, 056309 (2008).
[2] S. C. Wilks and W. L. Kruer, IEEE J. Quantum Electron. 33, 1954 (1997).

TC8247

Previous solid-target experiments[1] suggested that a collimation of hot electrons occurs at low laser intensities and energies only

- Collimation was observed in plastic- and glass-target experiments with $I \sim 10^{19}$ W/cm^2, $E \sim 10$ J (Refs. 1–3).

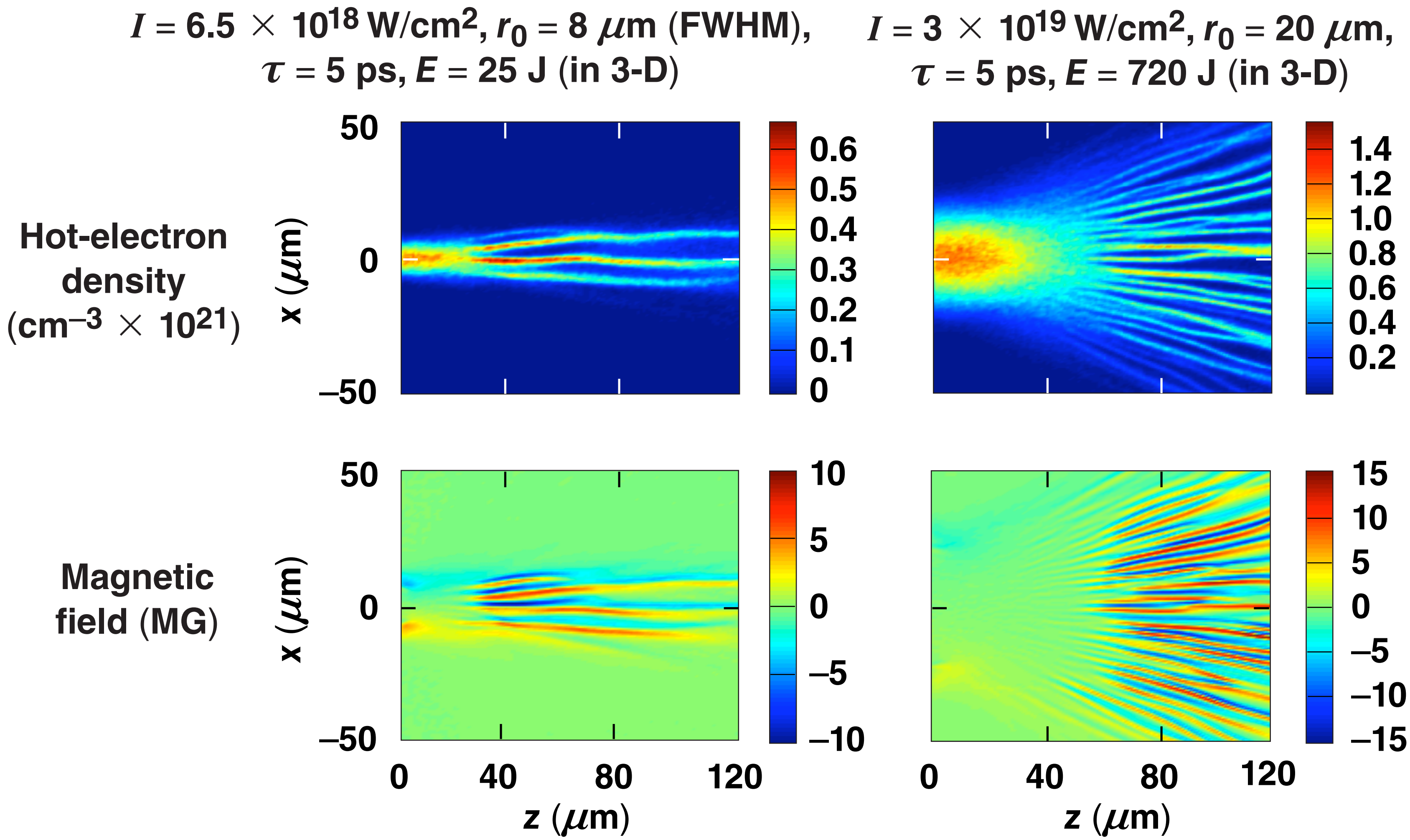
- Later experiments using Al, Cu, and plastic targets and more energetic laser pulses showed the electron divergence angle increased with laser intensity.[4]



[1]Tatarakis *et al*., Phys. Rev. Lett. 81, 999 (1998).
[2]Borghesi *et al*., Phys. Rev. Lett. 83, 4309 (1999).
[3]Gremillet *et al*., Phys. Rev. Lett. 83, 5015(1999).
[4]J. S. Green *et al*., Phys. Rev. Lett. 100, 015003 (2008), and references therein.

TC8306

LSP simulations showed increasing divergence angles with intensity and energy for planar plastic targets



Planar geometry, Maxwellian electrons, ⟨E⟩ from ponderomotive scaling, angular divergence of 30° (half angle).

TC8307

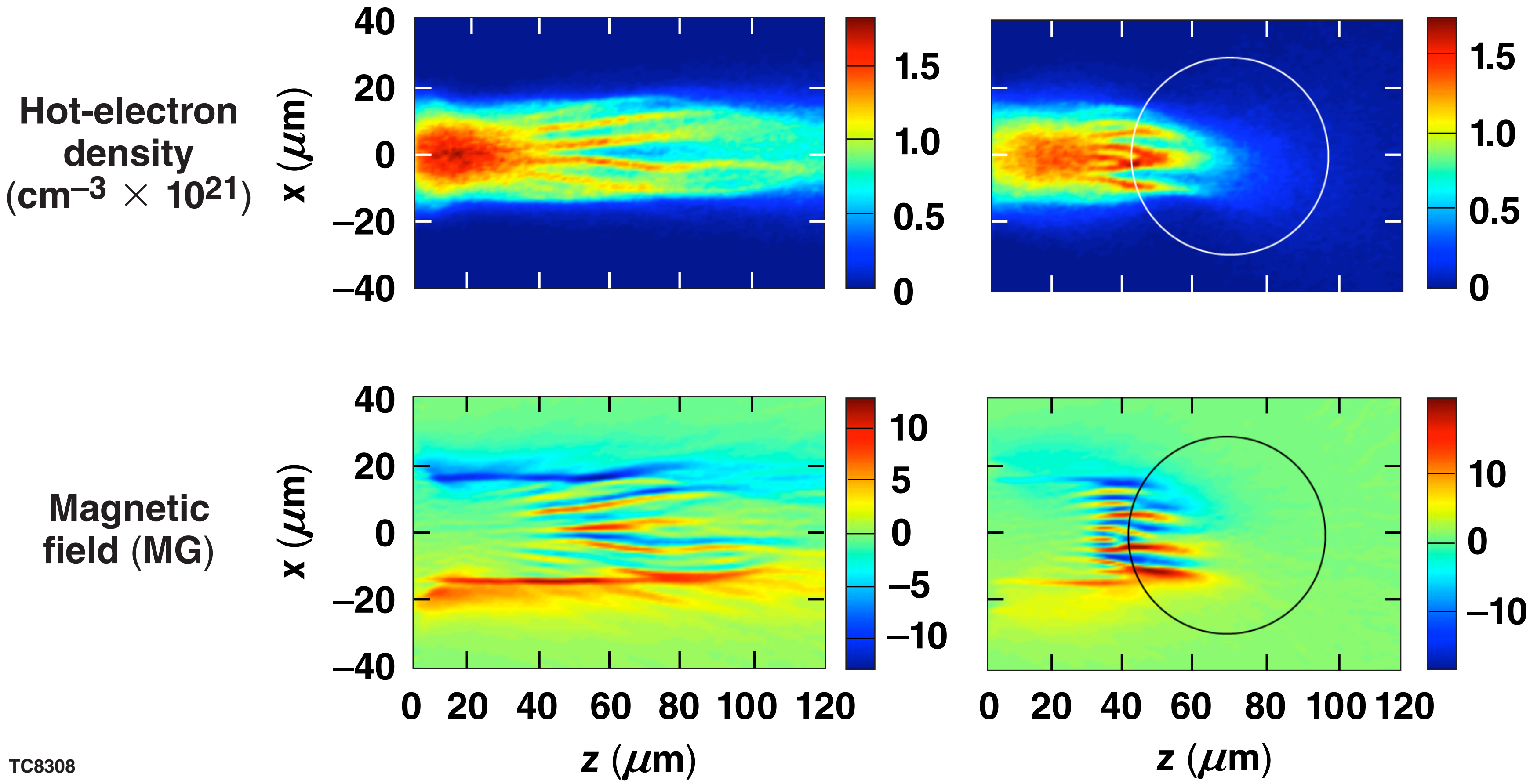
Magnetic hot-electron collimation is observed with *LSP* simulations for compressed plastic targets

UR LLE

$I = 3 \times 10^{19}$ W/cm^2, $r_0 = 20$ μm, $\tau = 5$ ps, $E = 720$ J
initial divergence half-angle = 30°

CH density = 10× solid density

$\rho = 100\ \rho_{solid} \times \exp(-\{[z(\mu m)-70]^2 + x(\mu m)^2\}/33^2)$



TC8308

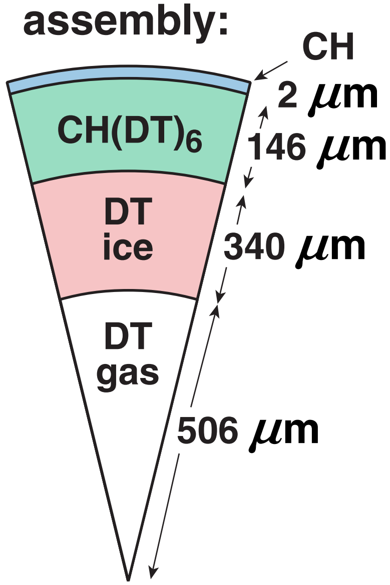
An imploded optimized fast-ignition target[1] is heated by a 2-MeV, 30-μm-FWHM electron beam in the integrated simulation[2]

UR LLE

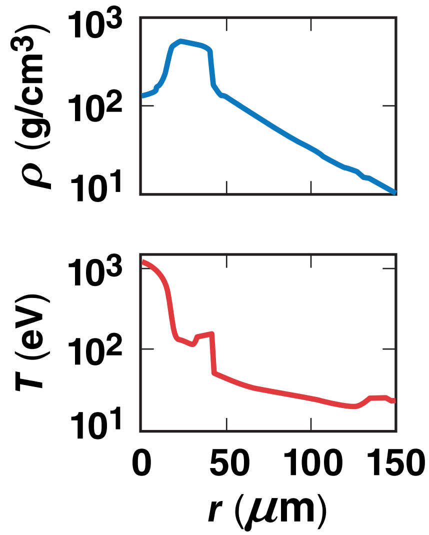
Gaussian, relativistic-Maxwellian e-beam

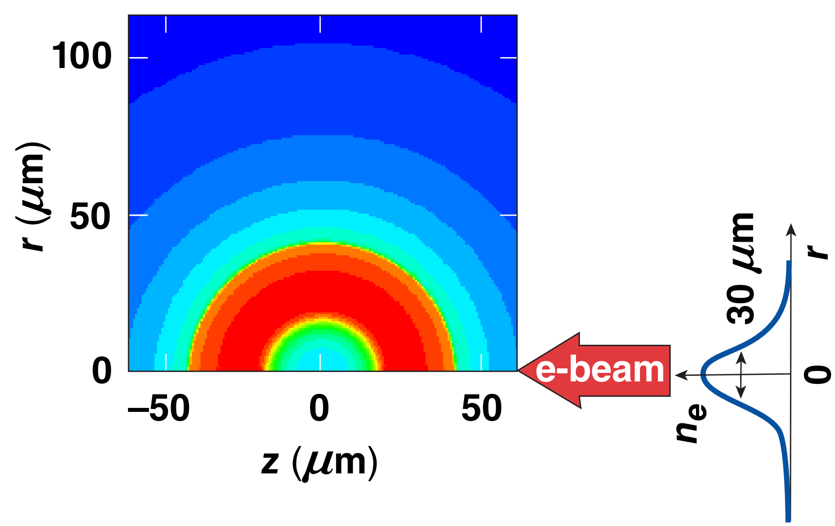
FWHM	30 μm
Duration	10 ps
$\langle E_e \rangle$	2 MeV
Divergence half-angle	20° to 40°
Distance to the target	125 μm

300 kJ fuel assembly:



Compressed target density and temperature:



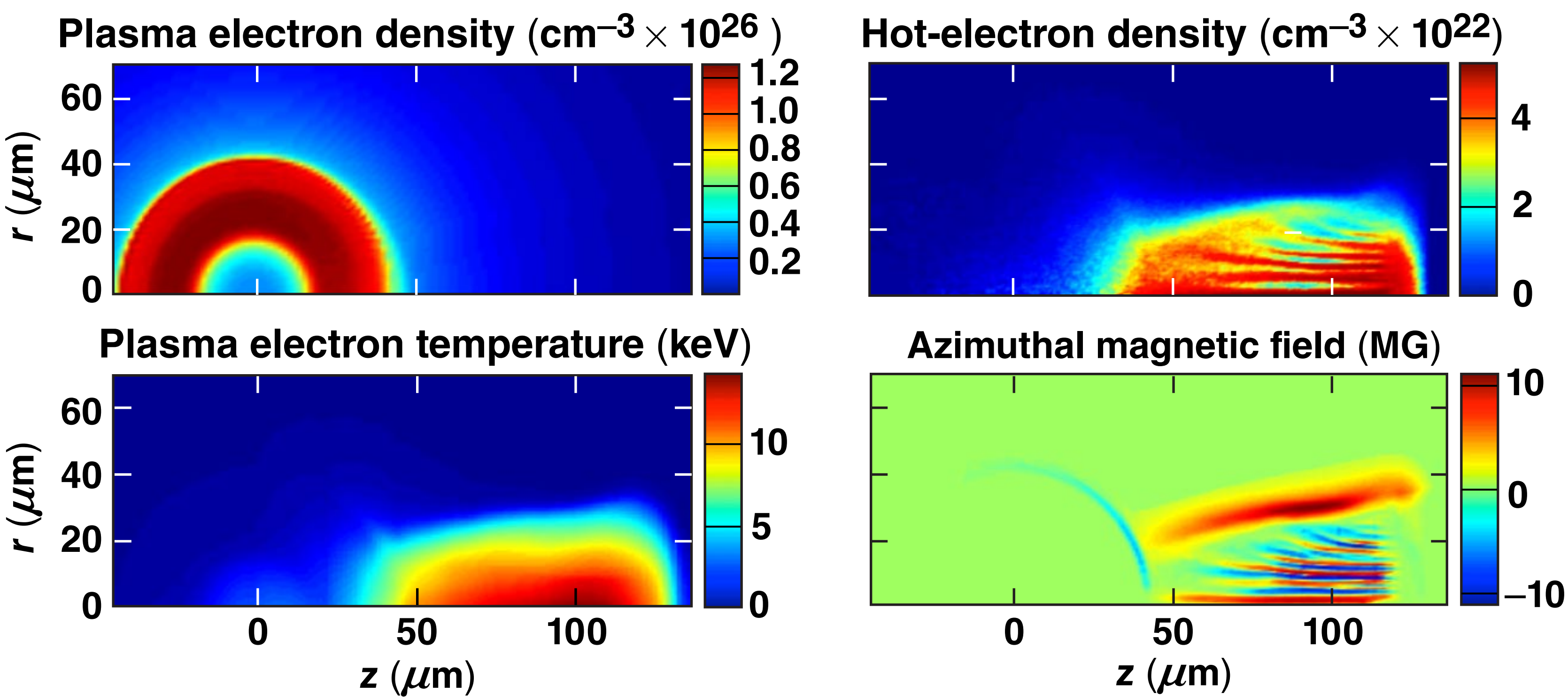


[1] R. Betti and C. Zhou, Phys. Plasmas 12, 110702 (2005).
[2] A. A. Solodov *et al*., Phys. Plasmas 15, 112702 (2008).

TC7792e

The integrated simulation shows electron-beam collimation by the self-generated resistive magnetic field, resistive filamentation,[1,2] and ignition by a 43-kJ e-beam

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

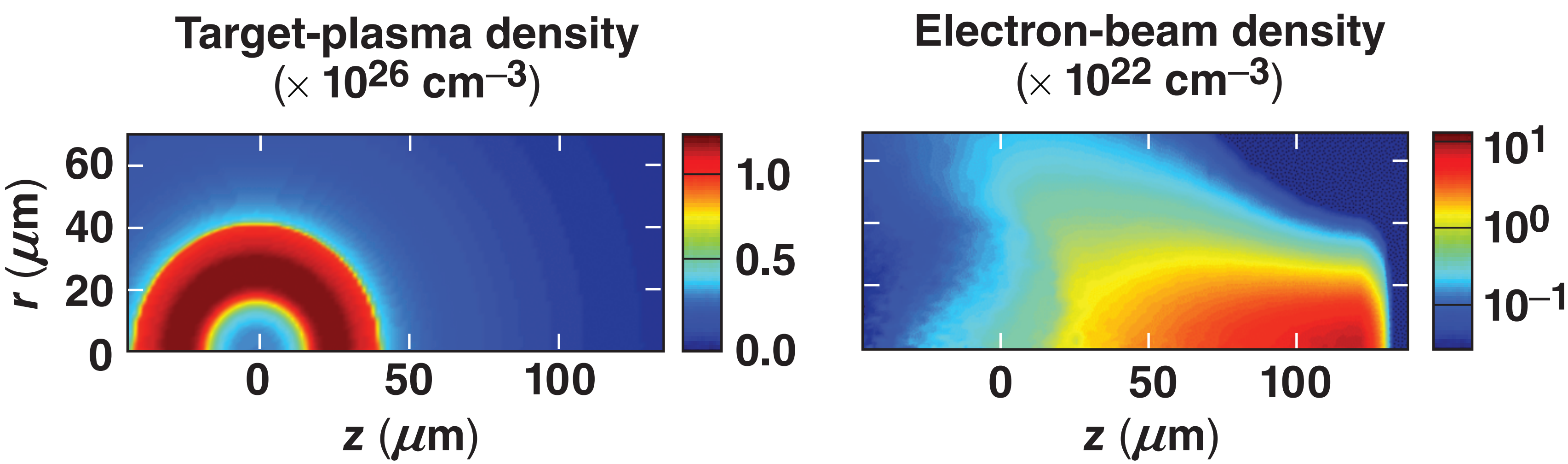


Initial divergance half-angle = 20°

[1] L. Gremillet *et al.*, Phys. Plasmas 9, 914 (2002).
[2] J. J. Honrubia and J. Meyer-ter-Vehn, Nucl. Fusion 46, L25 (2006); Journal of Physics 112, 022055 (2008).

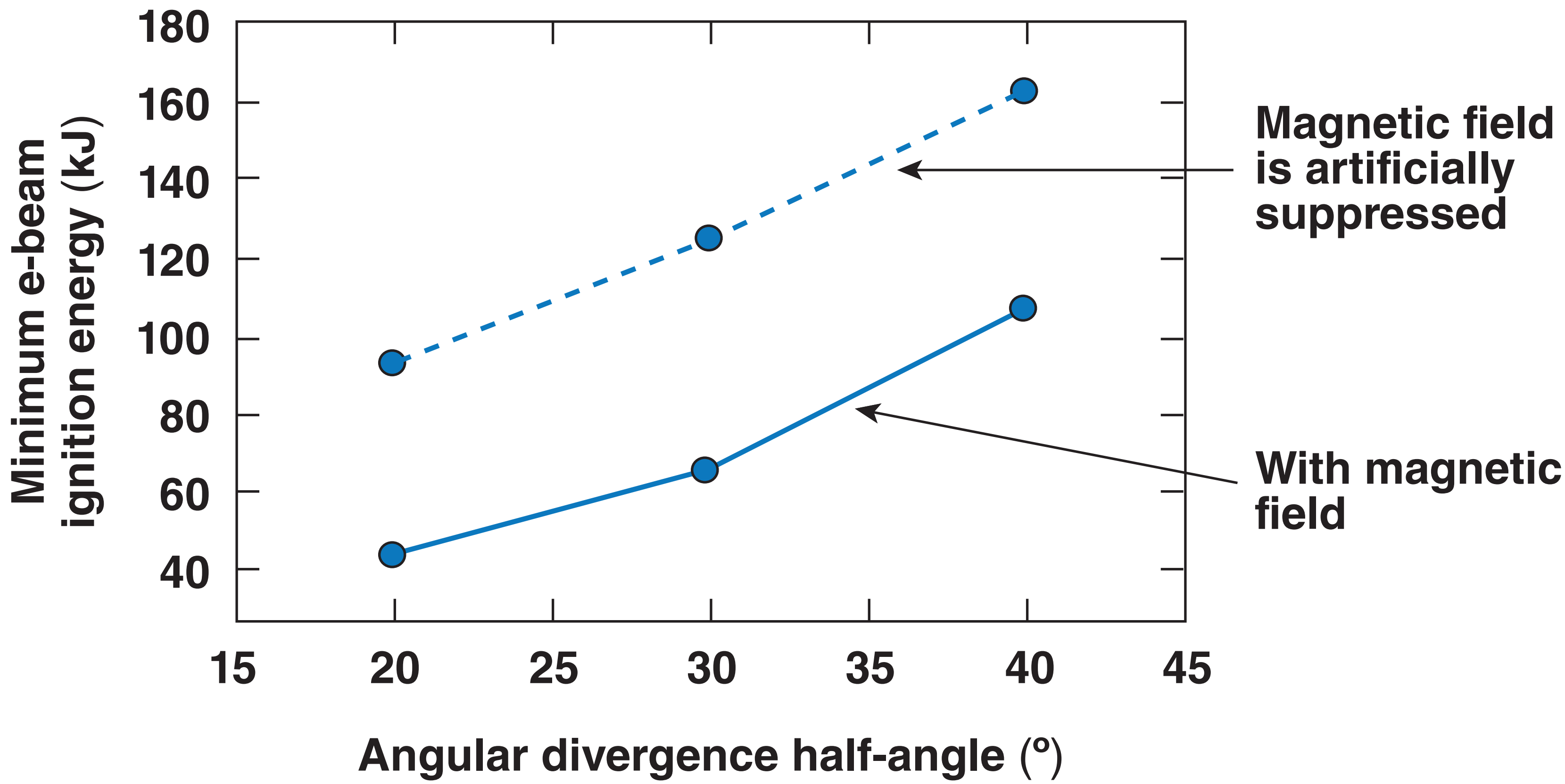
TC7793f

A simulation with the magnetic field artificially suppressed predicts a minimum hot-electron energy for ignition of 92 kJ for the same electron-beam properties



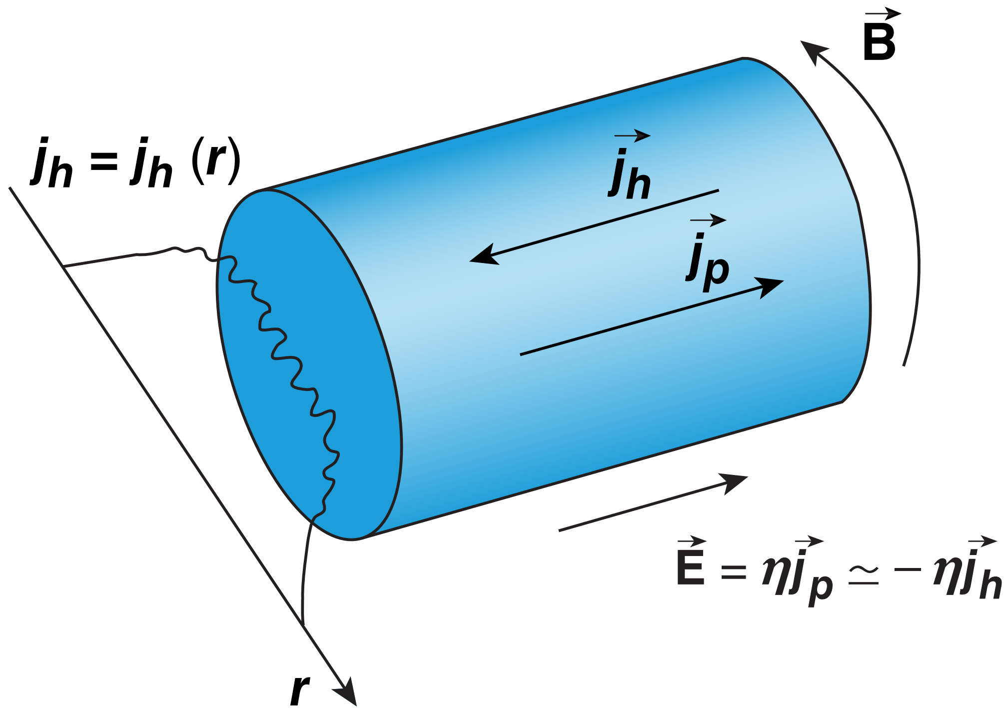
Beam collimation by the resistive magnetic field reduces the energy required for ignition.

The minimum energy required for ignition increases with the initial beam divergence angle



TC8245

Theoretical models of electron-beam collimation and resistive filamentation have been developed[1,2]



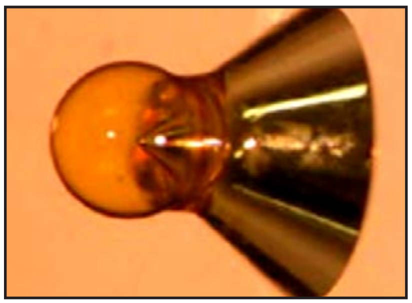
$$\frac{\partial B_\varphi}{\partial t} \sim \frac{\partial E_z}{\partial r}$$

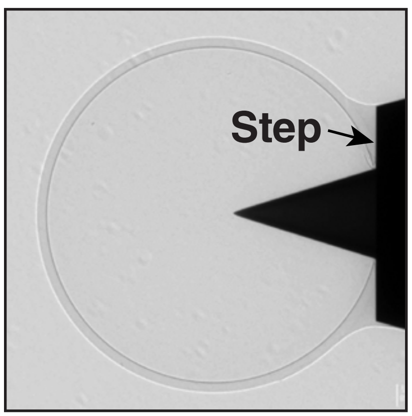
$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}$$

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

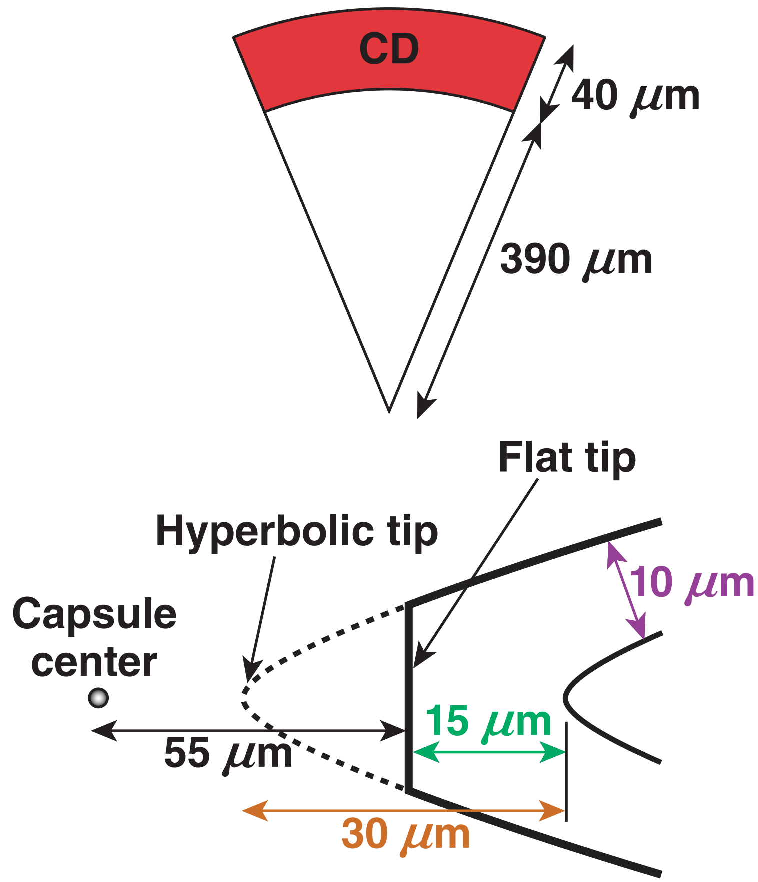
TC8246

Integrated OMEGA experiments using low-adiabat implosions of plastic cone-in-shell targets* and PW heating pulses from OMEGA EP have begun



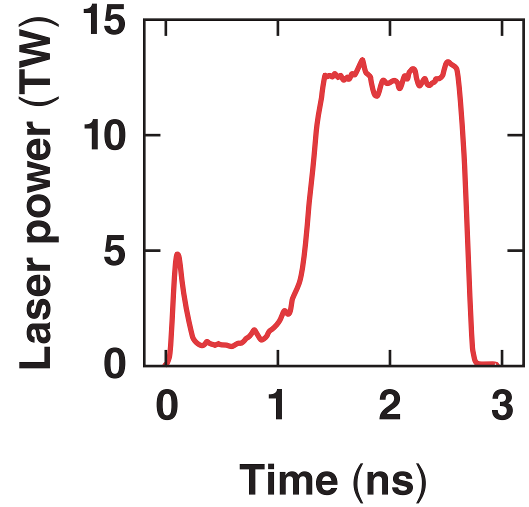


Radiograph of target



Fuel Assembly

E_L = 19.7 kJ



$Y_n = 2 \times 10^7$ for implosion without OMEGA EP beam

OMEGA EP: 2.6 kJ in 10 ps

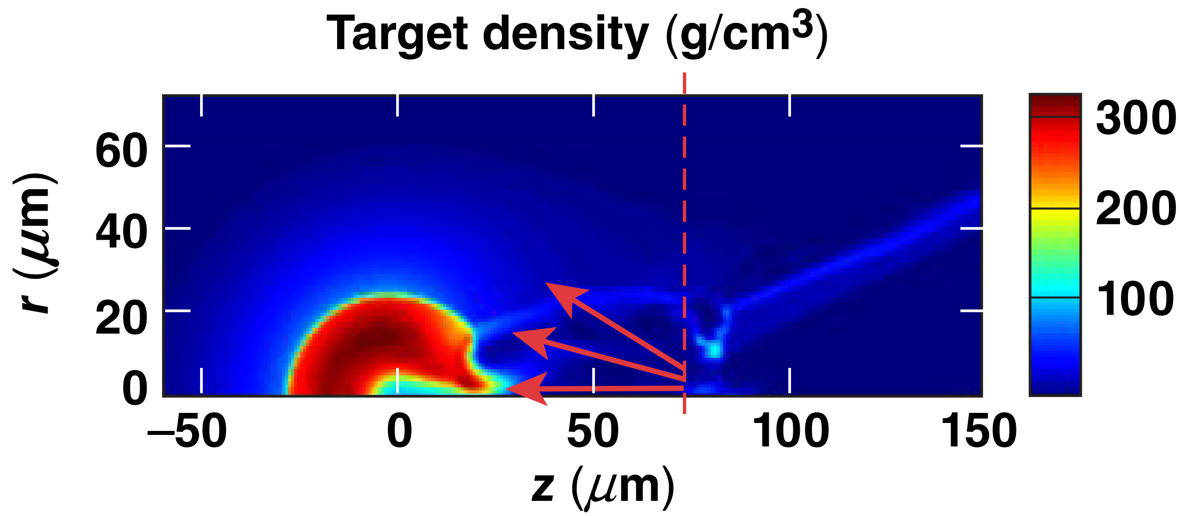
TC8134a

*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*
- Electrons injected at maximum areal density

Plastic shell:
$\rho R \sim 0.7$ g/cm^2



Gaussian (in *r*),
relativistic-Maxwellian e-beam

FWHM	20 µm
Duration	10 ps
$\langle E_e \rangle$	1.2 to 2.4 MeV
Divergence half-angle	20° to 60°

Laser pulse

Intensity	5.4×10^{19} W/cm^2
Energy	2.6 kJ
Conv. to hot-e	0.3

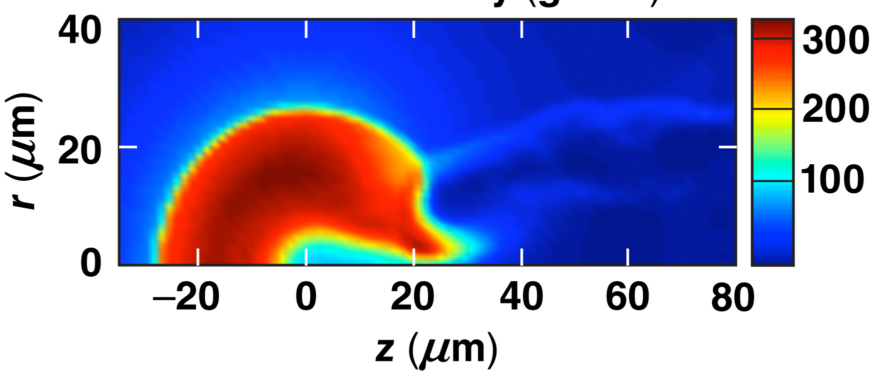
TC8135a

*K. S. Anderson (C04.00005).

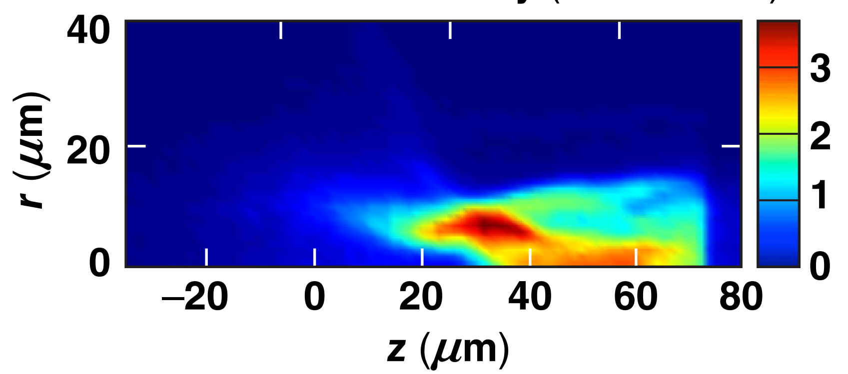
Hot electrons are collimated by the resistive magnetic field in the OMEGA integrated simulation

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

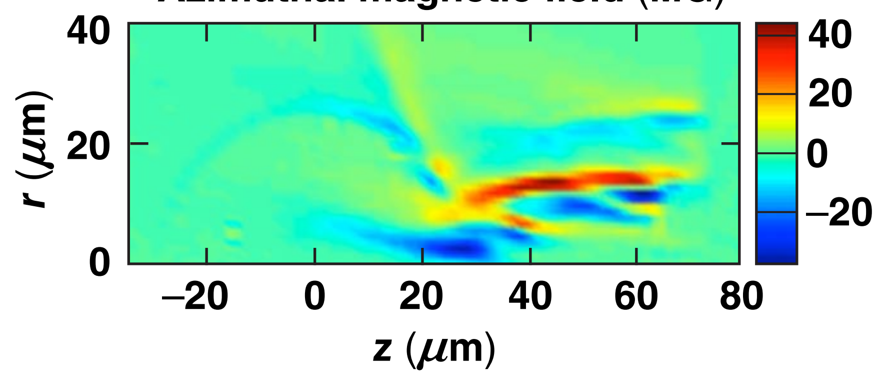
Plasma density (g/cm^3)



Electron-beam density (×10^{21} cm^{-3})



Azimuthal magnetic field (MG)

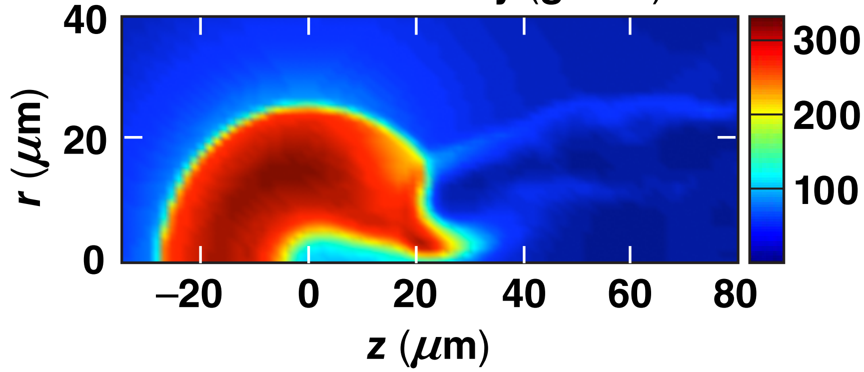


$\langle E_h \rangle$ = 2 MeV
Angular divergence = 20° (half angle)

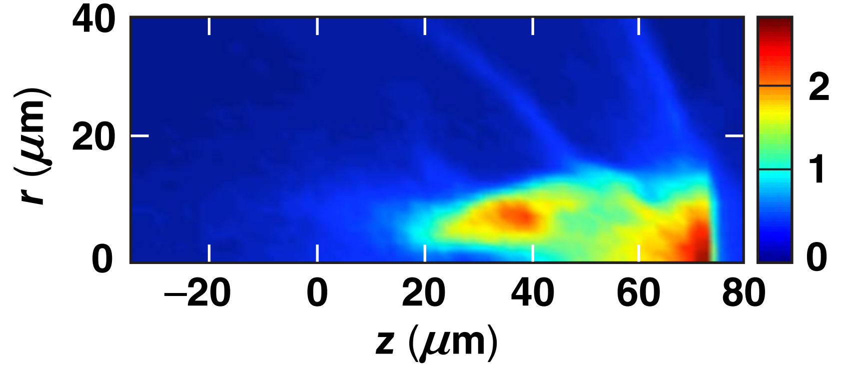
Hot electrons are collimated for an angular spread as high as 60° half angle in the OMEGA integrated simulation

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

Plasma density (g/cm^3)



Electron-beam density (×10^{21} cm^{-3})



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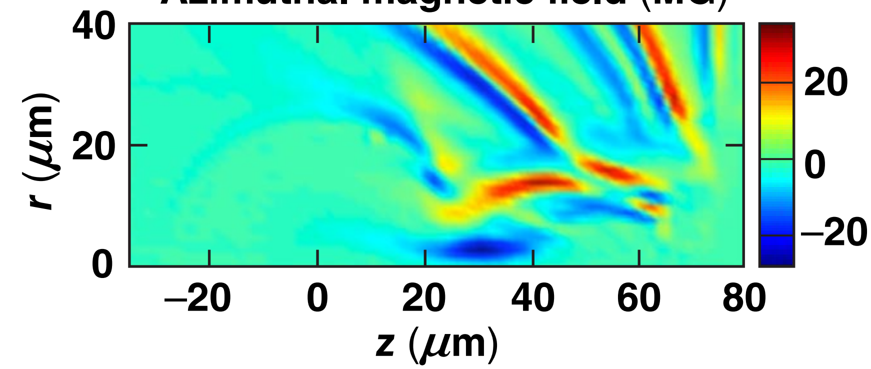
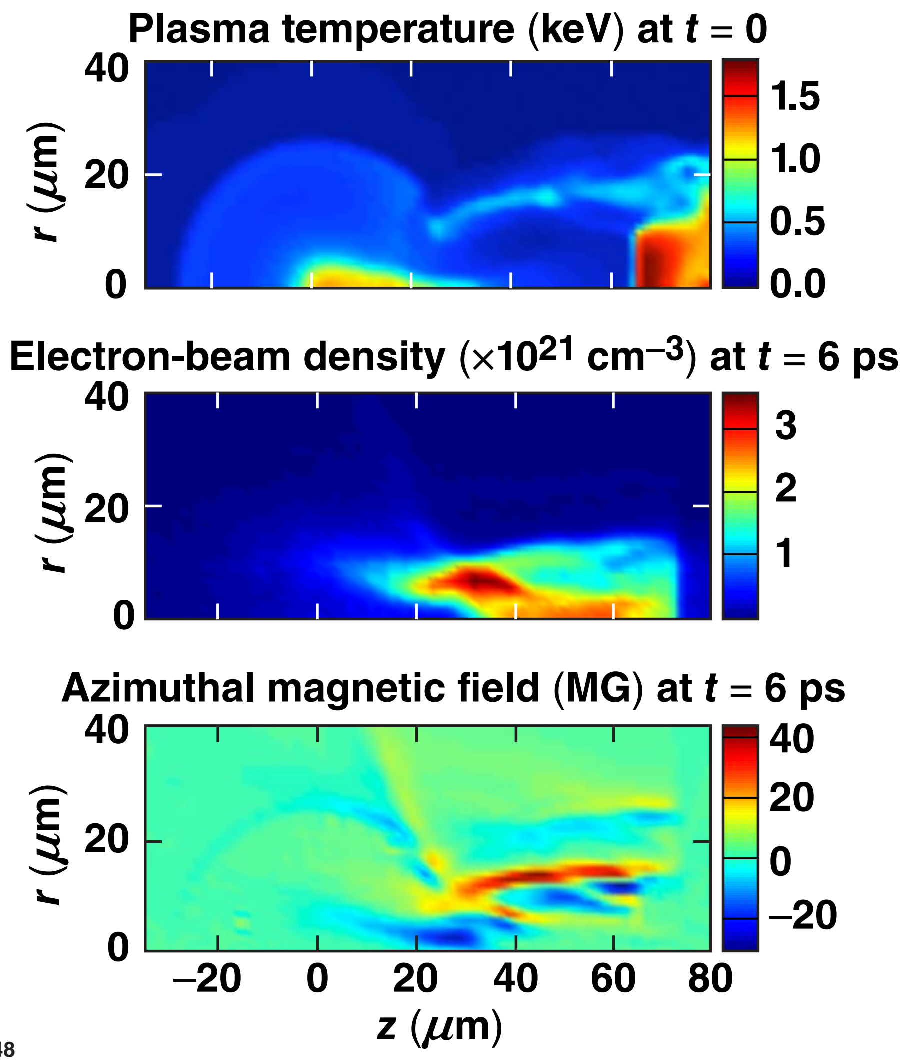


$\langle E_h \rangle$ = 2 MeV
Angular divergence = 60° (half-angle)

Close to the core, hot electrons are deflected by the resistive magnetic field generated in the escaping hot-spot gas



$$\frac{\partial \underline{\mathbf{B}}}{\partial t} = -\nabla \times \underline{\mathbf{E}},\ \underline{\mathbf{E}} \approx -\eta \underline{\mathbf{j}}_h,$$

- **Spitzer resistivity:**

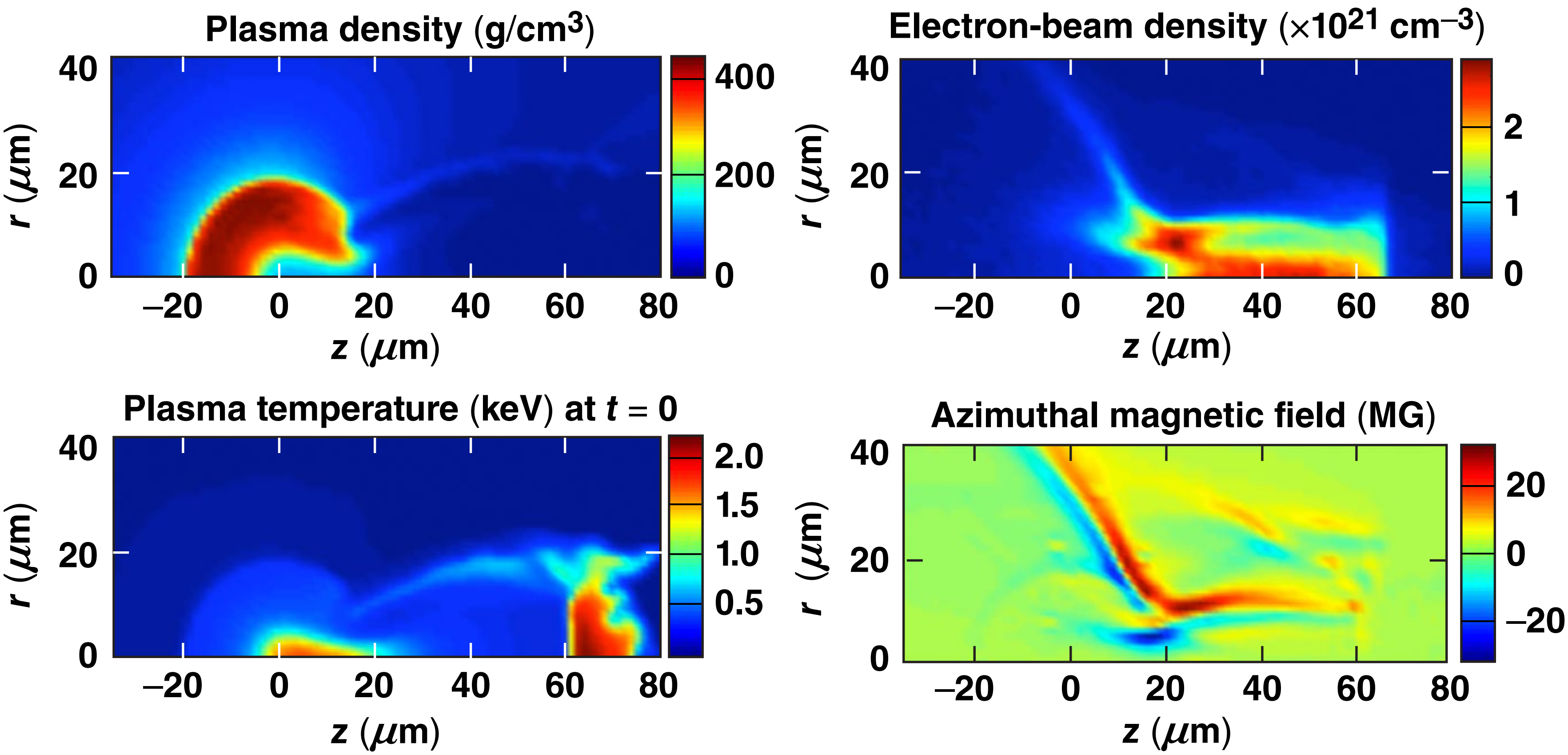
$$\eta = \eta_0 \left(\frac{T_0}{T}\right)^{3/2}.$$

$\langle E_h \rangle = 2$ MeV,
angular divergence = 20°
(half angle)

TC8248

Hot electrons can miss the target if they are injected 60 ps earlier than at maximum areal density

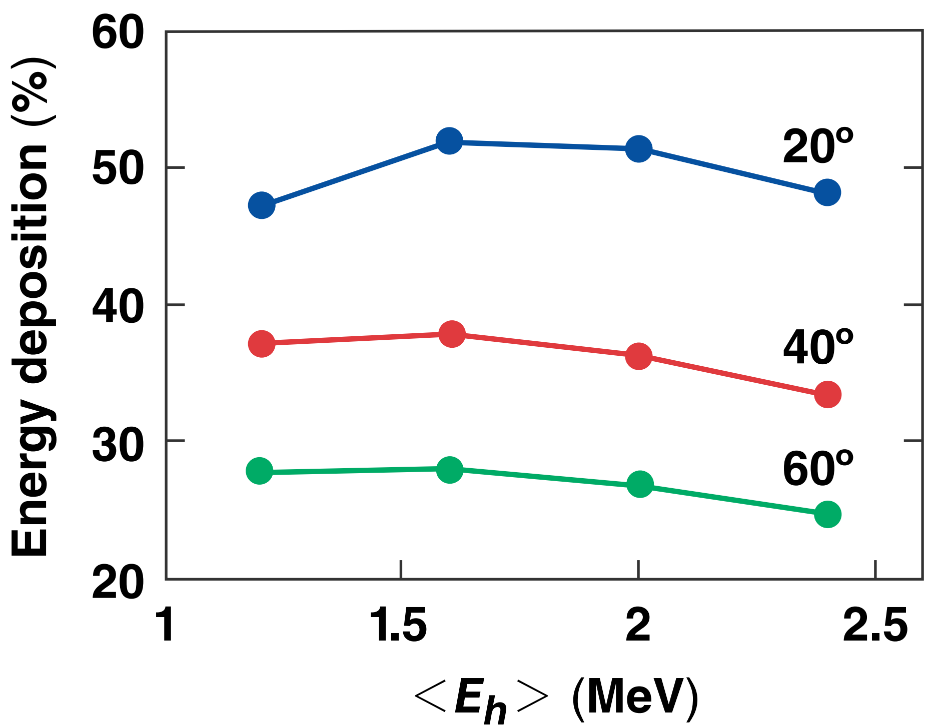
Snapshots at t = 6 ps after the beginning of the e-beam



$\langle E_h \rangle$ = 2 MeV
Angular divergence = 20° (half angle)

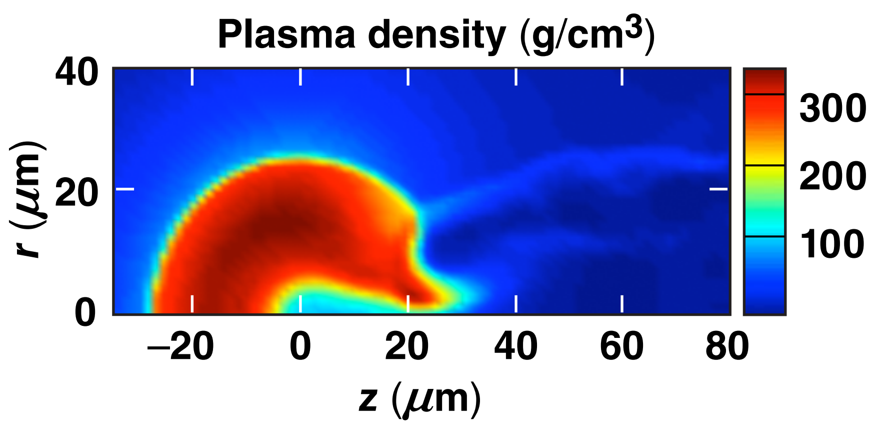
TC8249

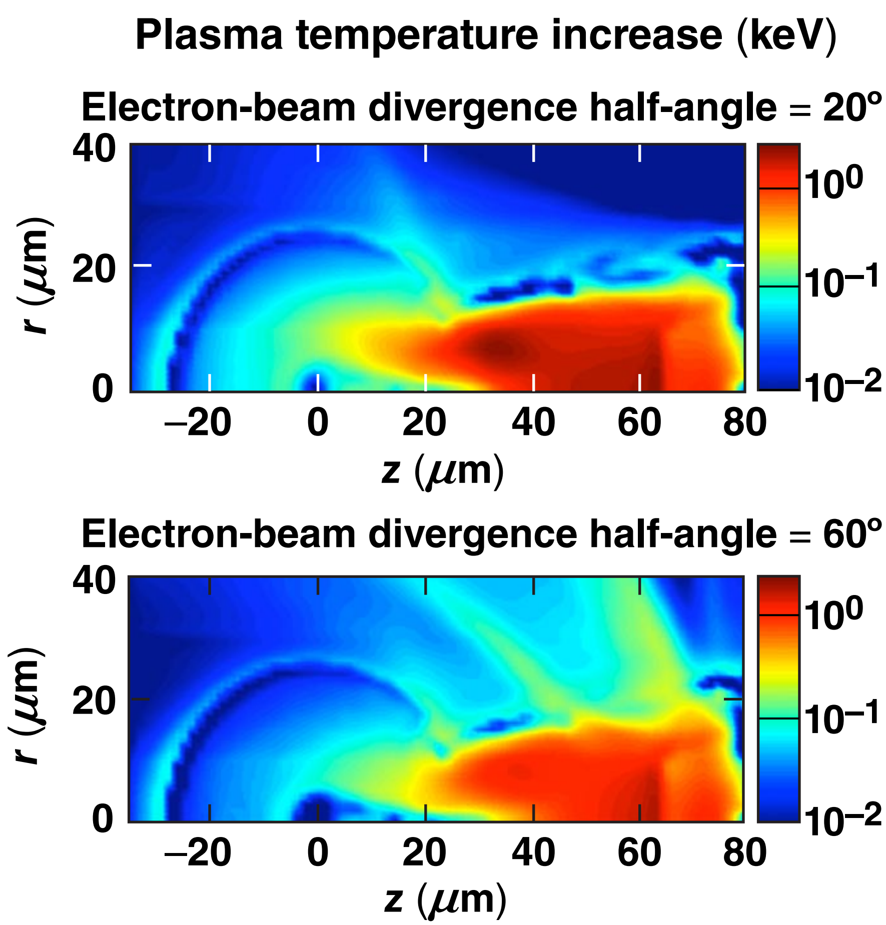
The hot electrons deposit 25% to 55% of their energy in the dense core (ρ > 80 g/cm^3)



TC8250

Hot electrons heat up the target by up to 1 keV





Mean hot-electron energy
$\langle E_h \rangle = 2$ MeV

Neutron yield increases from 1.6×10^9 to 4.5×10^9 due to hot electrons for 20° half-angle.

TC8251

Hot-electron transport through the cone must be addressed

UR LLE

- *LSP* can simulate the hot-electron transport through the cone, provided ionization of the high-*Z* cone material is modeled properly (using QEOS[1]).
- Hot-electron beams can spread out in the cone due to scattering by high-*Z* ions.
- Tens to hundreds megagauss resistive magnetic fields are expected because of a high collisionality of the return current.
- In such fields, the Alfvén limit can be reached for the filaments or for the whole beam.
- Magnetic fields at plasma discontinuities (inner cone surface or cone–plasma interface) can cause a surface transport and/or trapping of hot electrons.
- Extended regions of pre-plasma inside the cone increase the thickness of the high-*Z* material through which the hot electrons propagate.

[1]R. M. More *et al*., Phys. Fluids 31, 3059 (1988).

Summary/Conclusions

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[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).

TC7788b