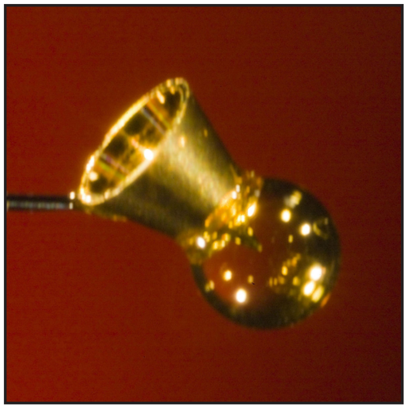
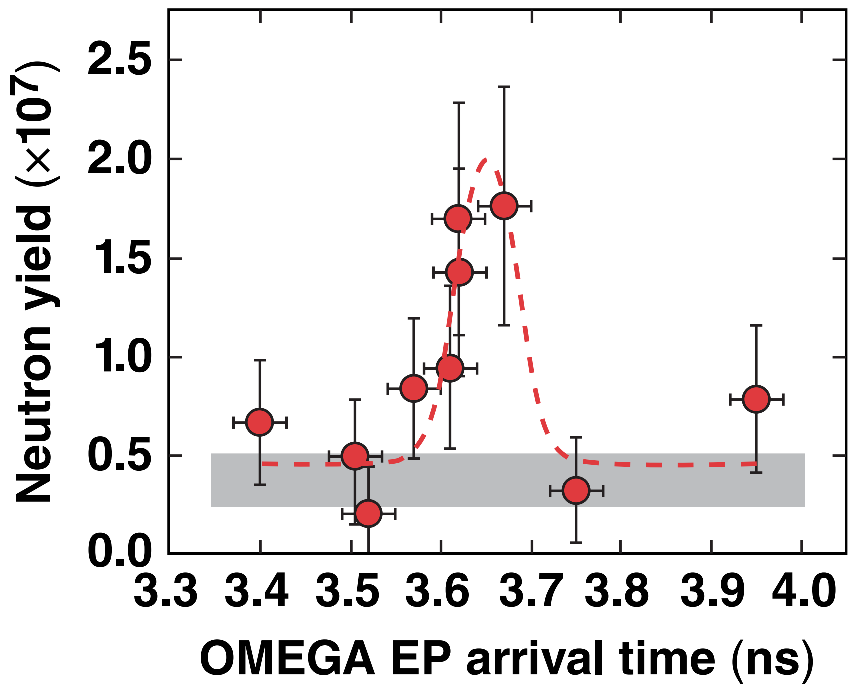
Integrated Fast-Ignition Core-Heating Experiments on OMEGA





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Summary

Integrated fast-ignition experiments study the coupling of fast-electron energy into a compressed core

- The short-pulse laser produced up to $1.4 \pm 0.5 \times 10^7$ additional neutrons with proper beam timing
- Shock-breakout measurements confirm an intact cone tip at peak neutron production
- 20-MeV electrons are measured in the laser-forward direction, suggesting that the pre-plasma plays an important role in the interaction
- *DRACO–LSP* integrated simulations model target implosion and heating
- The inferred ~3.5% laser–to–target-heating coupling should increase with improved OMEGA EP performance

Collaborators

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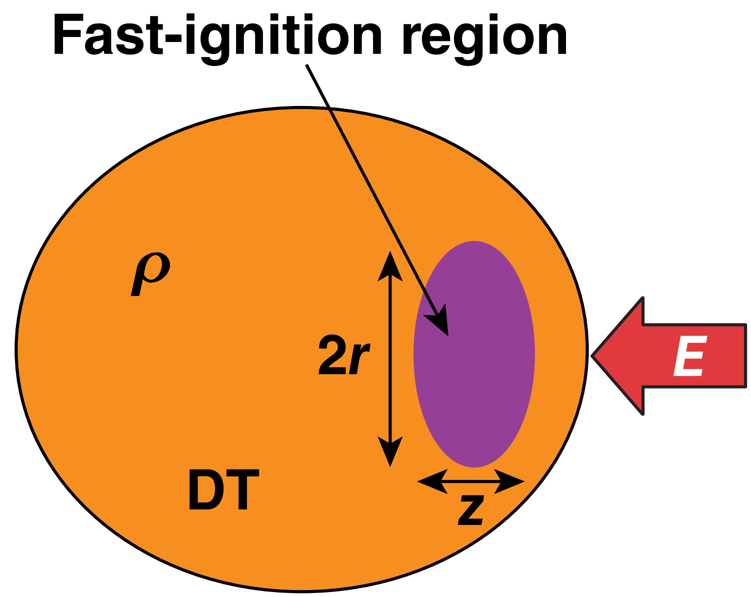
Fast ignition relies on the localized energy deposition of fast electrons in the compressed core

Core conditions for achieving ignition:
$T \sim 10$ keV, $\rho R \sim 1$ g/cm^2, $\rho \sim 500$ g/cm^3
Energy that needs to be delivered to fuel*:
$E_{ign} \sim 20$ to 40 kJ in $\langle E \rangle \sim 1$ to 2 MeV electrons Power ~ several PW $I \sim 10^{20}$ W/cm^2 $t \sim 20$ ps, $r \sim 20$ μm $z \sim 20$ to 40 μm



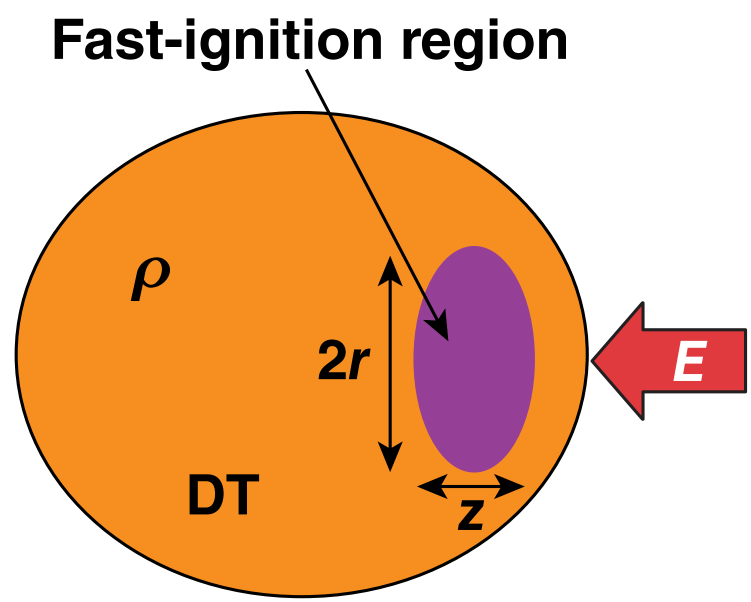
* S. Atzeni *et al*., Phys. Plasmas 15, 056311 (2008); M. Tabak *et al*., Fusion Sci. Technol. 49, 254 (2006); A. A. Solodov *et al*., Phys. Plasmas 15, 112702 (2008).

E17851a

Maximizing the coupling efficiency is a challenge for full-scale fast ignition

Coupling efficiency depends on

- laser conversion to electrons
- energy spectrum of electrons
- collimation of electrons
- cone tip to dense plasma separation
- transport efficiency through the cone and plasma



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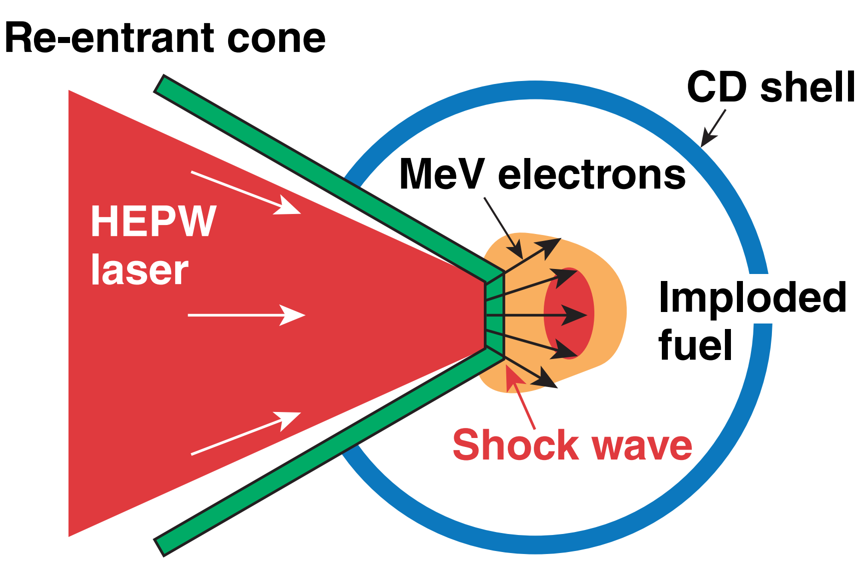
Integrated re-entrant cone fast-ignition experiments allow for studying core heating and electron coupling in compressed shells

- Initial experiments at the Gekko Laser Facility at ILE, Osaka, with cone-in-shell targets were encouraging*



OMEGA experiments allow for
- ~20-kJ drive energy
- ≳1-kJ short-pulse energy
- low-adiabat implosion
- ~17× higher target mass
- cryogenic targets

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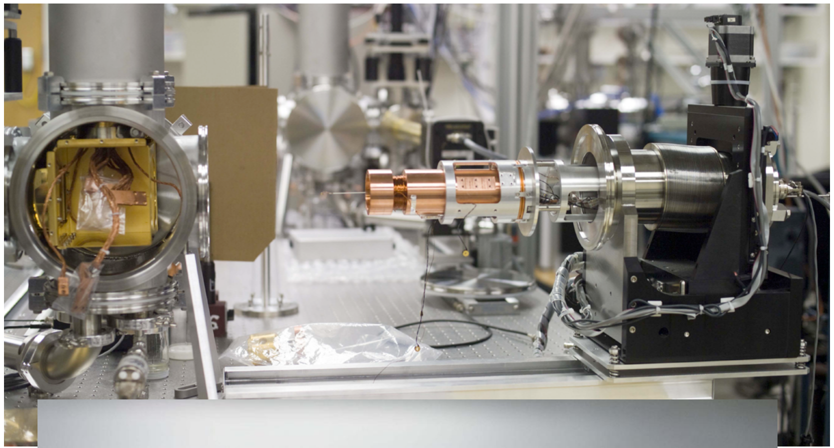
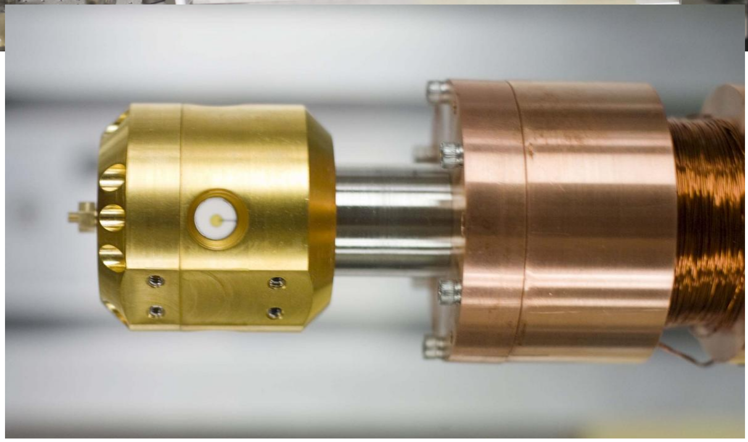
*R. Kodama *et al*., Nature 418, 933 (2002).

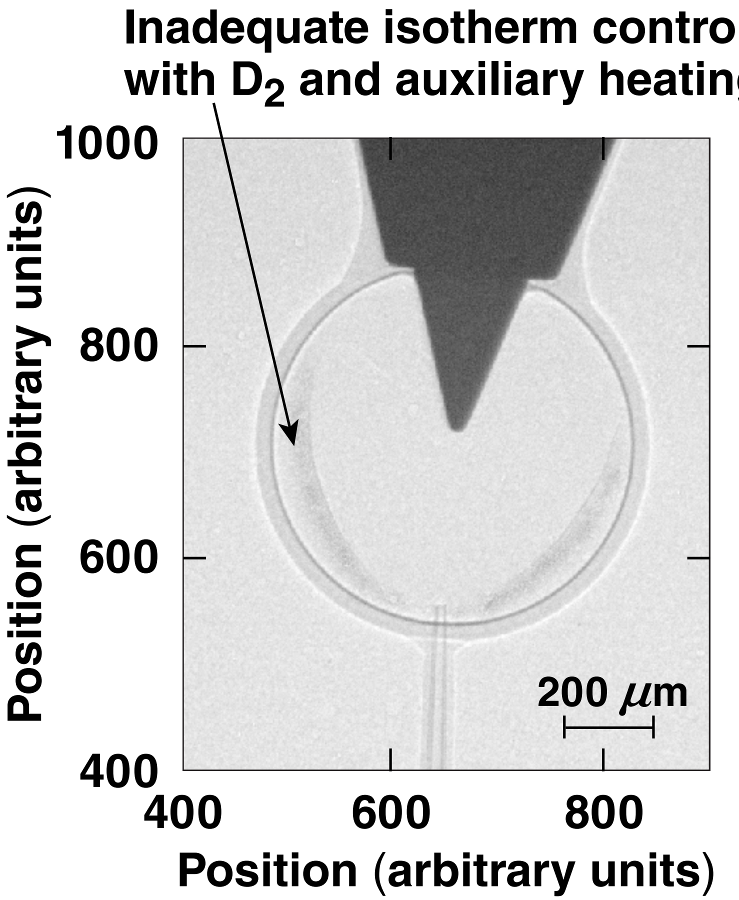
Cryogenic cone-in-shell targets are being developed at LLE

Development of test stand facility is independent of OMEGA operations



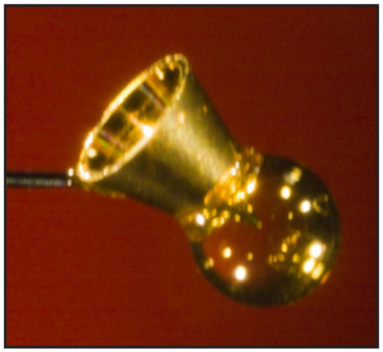


X-ray phase contrast image shows the D_2 ice in a cone-in-shell target

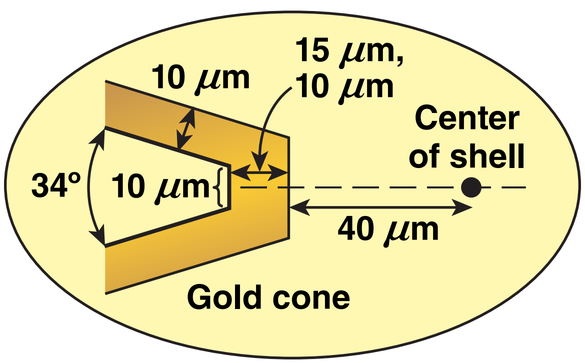


The facility will be DT capable in less than a year, reducing isotherm constraints on fuel layering.

Integrated fast-ignition experiments with re-entrant cone targets were performed at the OMEGA/OMEGA EP Laser Facility



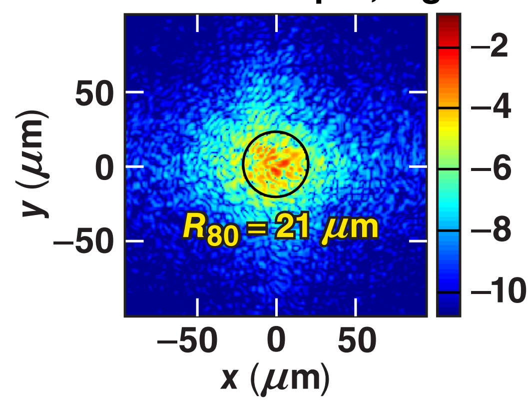
Shell material	CD
Shell diameter	~870 μm
Shell thickness	~40 μm



Implosion

Energy	~20 kJ (54 beams)
Wavelength	351 nm
Pulse shape	Low-adiabat, $\alpha \approx 1.5$
Pulse duration	~3 ns
Implosion velocity	~2 × 10^7 cm/s

OMEGA EP focal spot, log scale*



Heating beam (relative timing varied)

Energy	~1.0 kJ
Wavelength	1053 nm
Pulse duration	~10 ps
Intensity	~1 × 10^{19} W/cm^2

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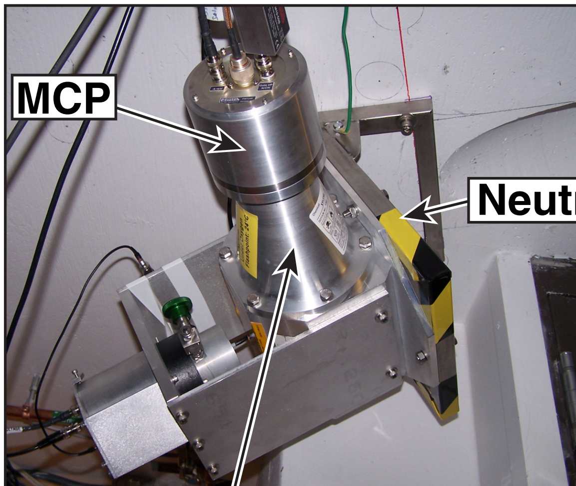
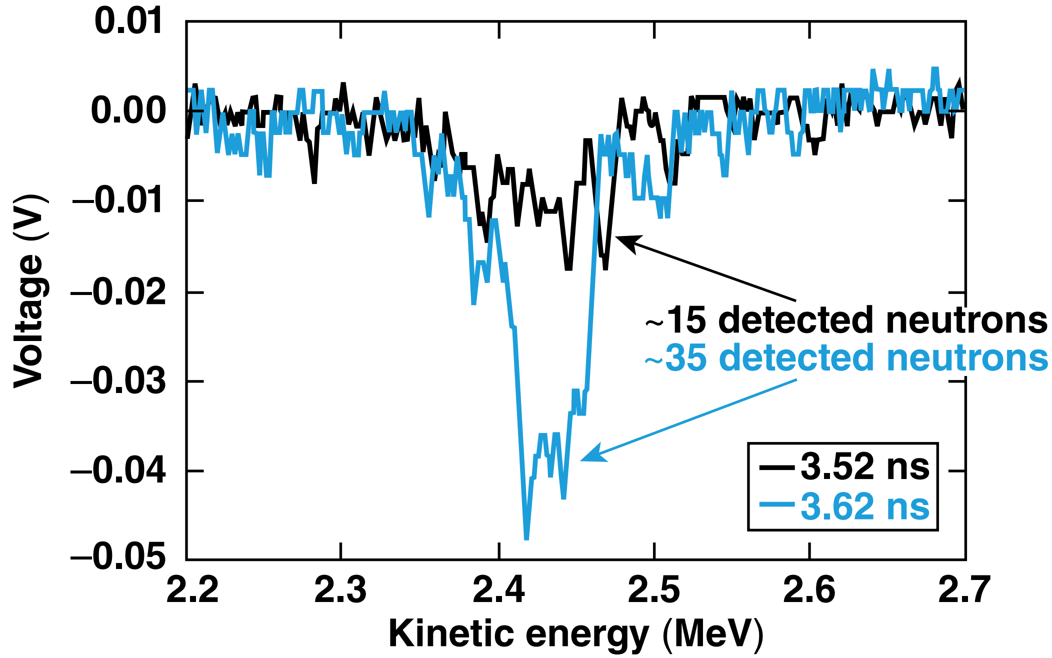
*J. Bromage *et al.*, Opt. Express 21, 16,561 (2008).

A new detector has been developed that reliably measures neutron yields in FI-cone experiments



~3-L volume
Xylene + PPO + bis-MSB + O_2

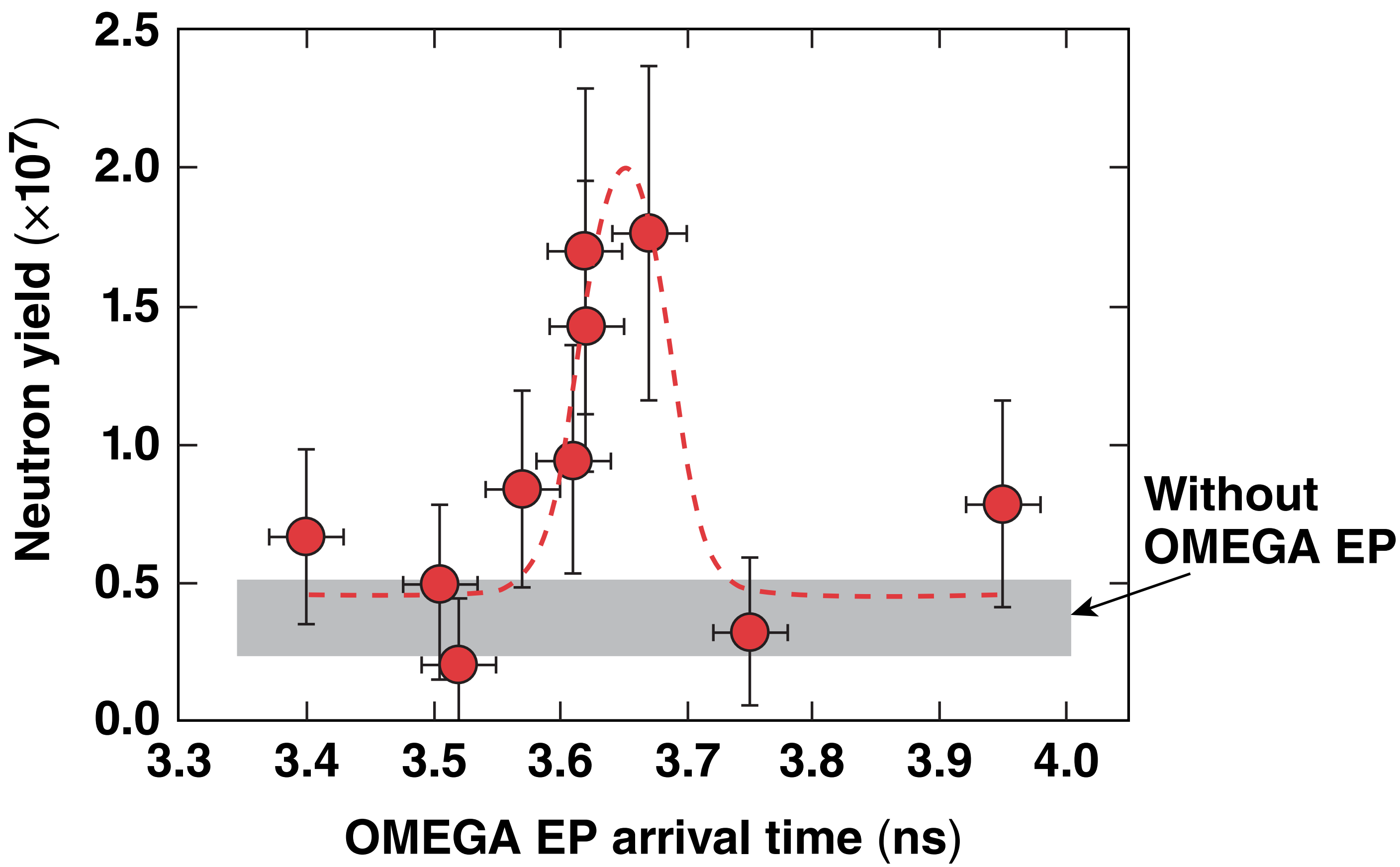


- A liquid scintillator neutron time-of-flight detector* was developed that efficiently suppresses the hard x-ray background
- The 2.45-MeV neutron peak is smeared out because of neutron scattering and a large detector volume (~3.5 liter)
- The total neutron yield was obtained by integration

E19352

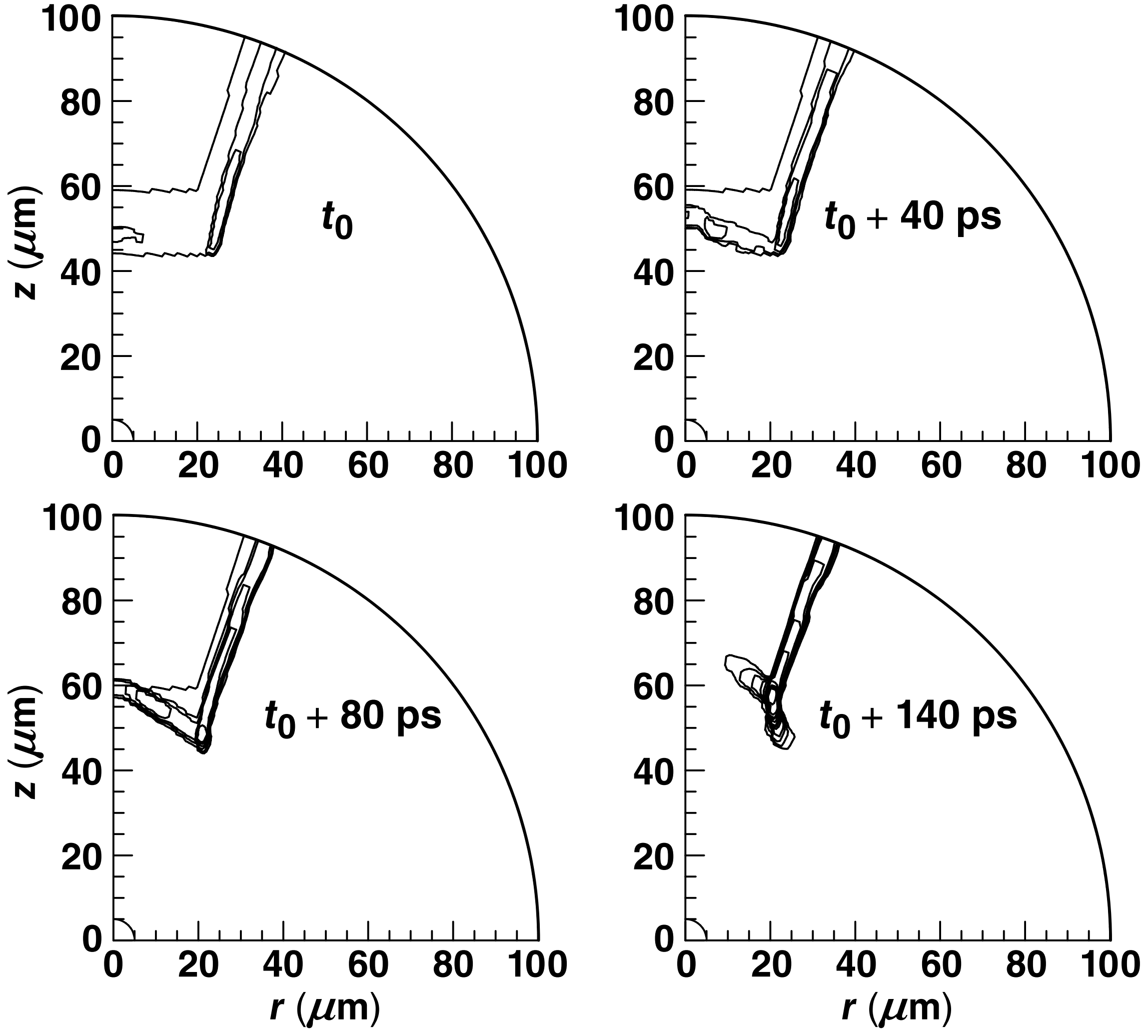
*C. Stoeckl *et al*., "A Gated Liquid-Scintillator-Based Neutron Detector for Fast-Ignitor Experiments and Down-Scattered Neutron Measurements," to be published in Rev. Sci. Instrum.

The neutron yield increased by a factor of 4 with an appropriately timed OMEGA EP beam



$1.4 \pm 0.5 \times 10^7$ additional neutrons were produced with the short-pulse laser.

A strong shock launched by the implosion travels rapidly through the cone tip

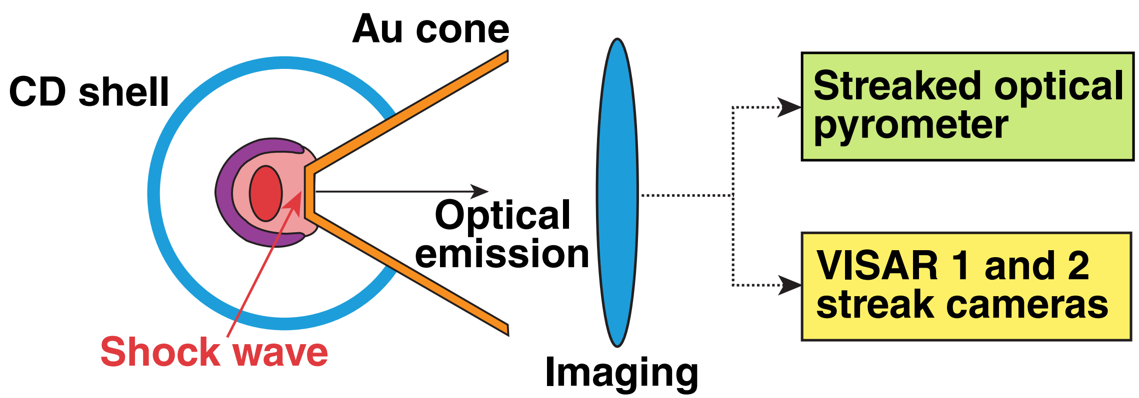


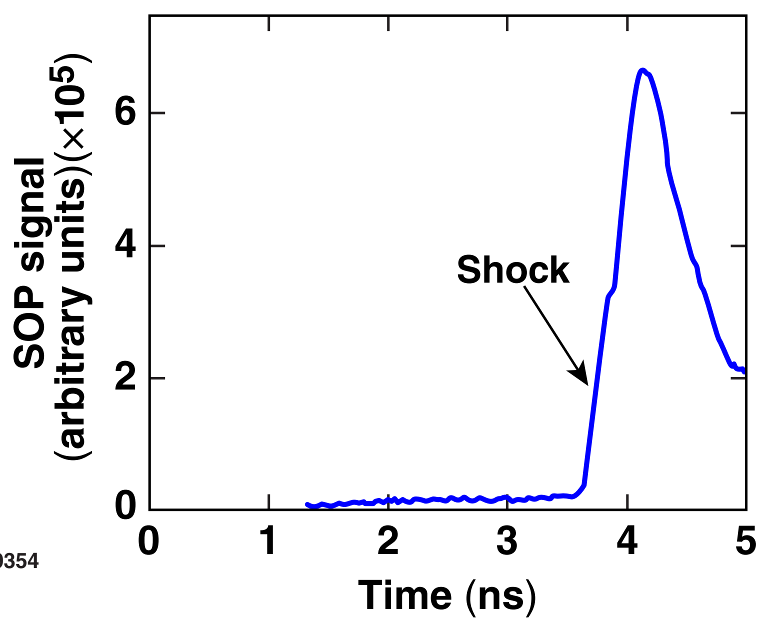
2-D hydrodynamic simulations with the code *SAGE**

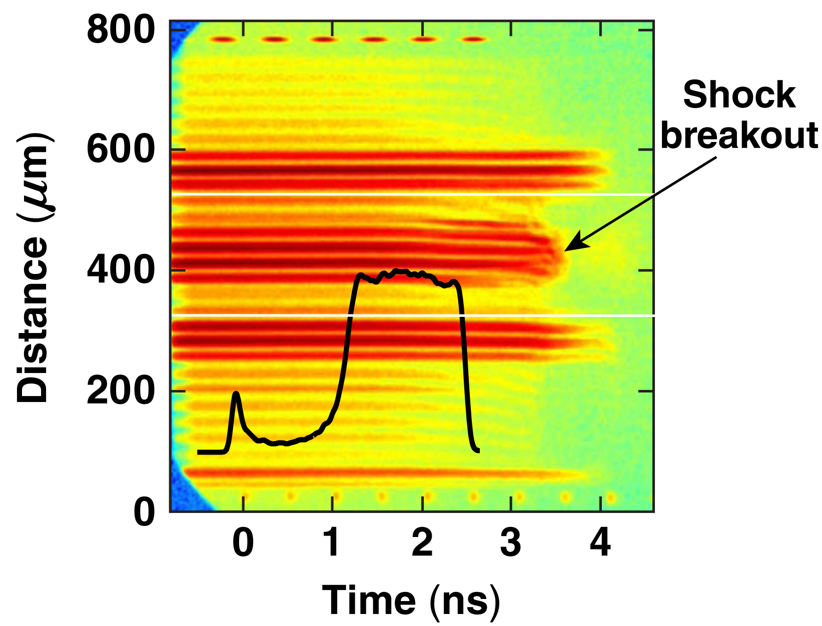
E19356

*R. S. Craxton and R. L. McCrory, J. Appl. Phys. 56, 108 (1984).

The shock breakout into the cone was simultaneously measured with a streaked optical pyrometer and a velocity interferometer







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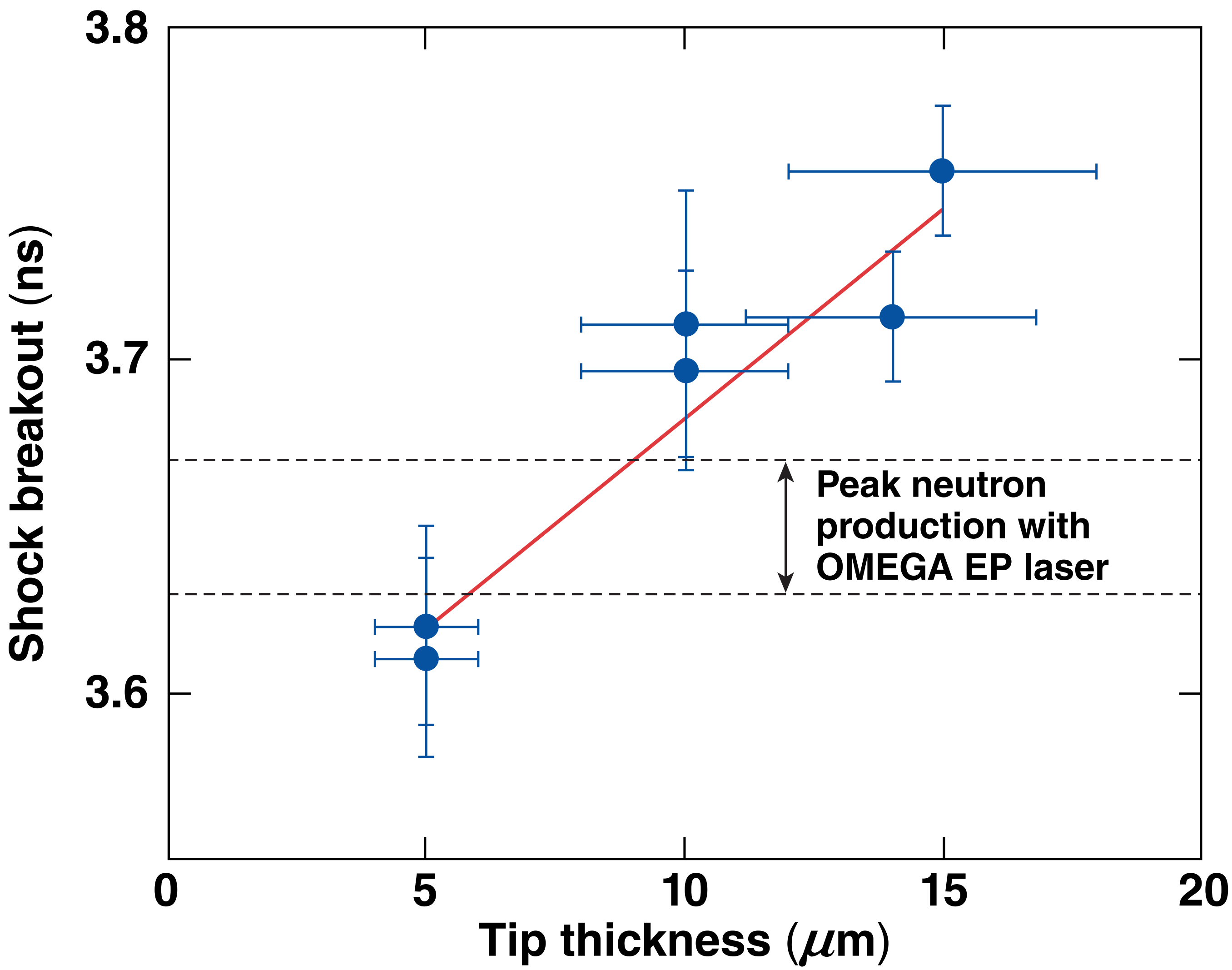
Shock-breakout measurements confirm an intact cone tip at peak neutron production



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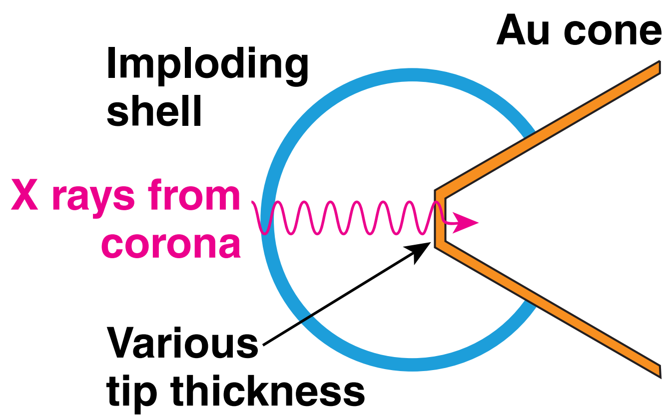
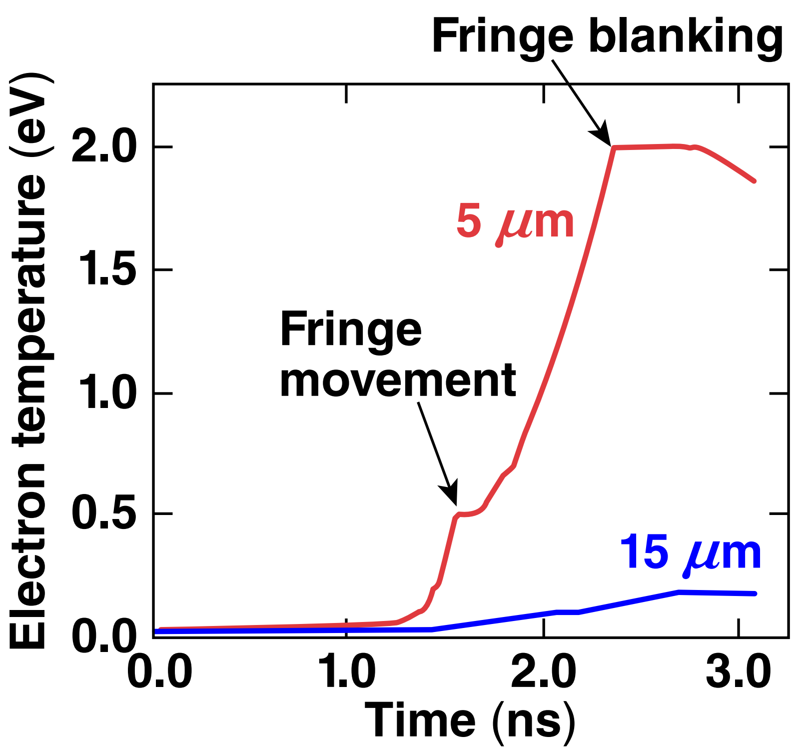
X-ray radiation from the coronal plasma can preheat the cone tip

- The inner surface of the thin tip reaches a temperature of 2 eV, enough to vaporize and ionize it
- *LILAC* modeled the radiation transport through 5- and 15-μm-thick gold walls





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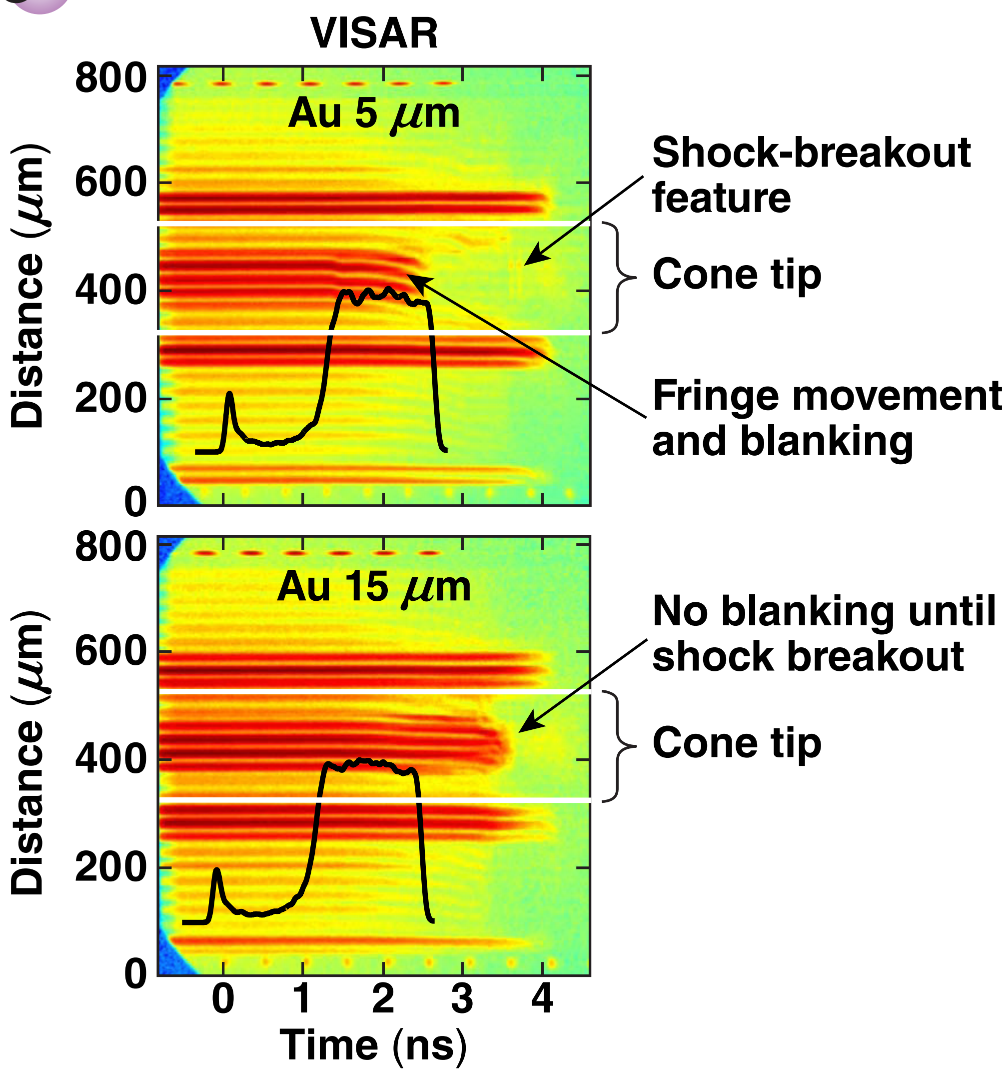
X-ray radiation from the implosion corona affects the inner cone wall for a thin cone tip



The inner cone wall is affected by x-ray preheat

The inner cone wall is well preserved until shock breakout

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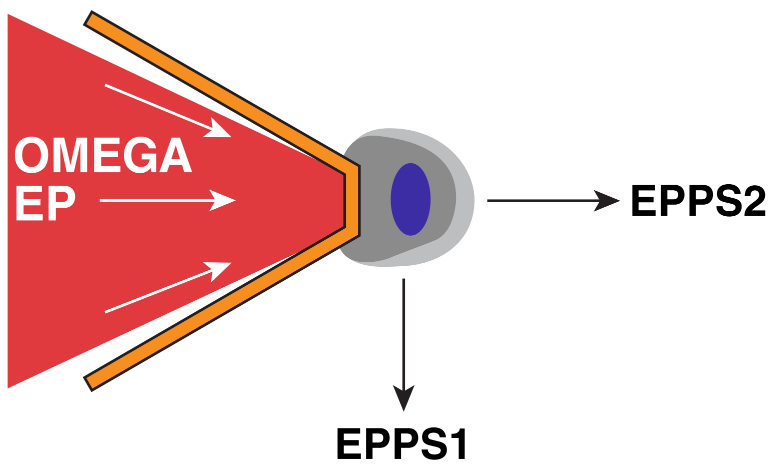
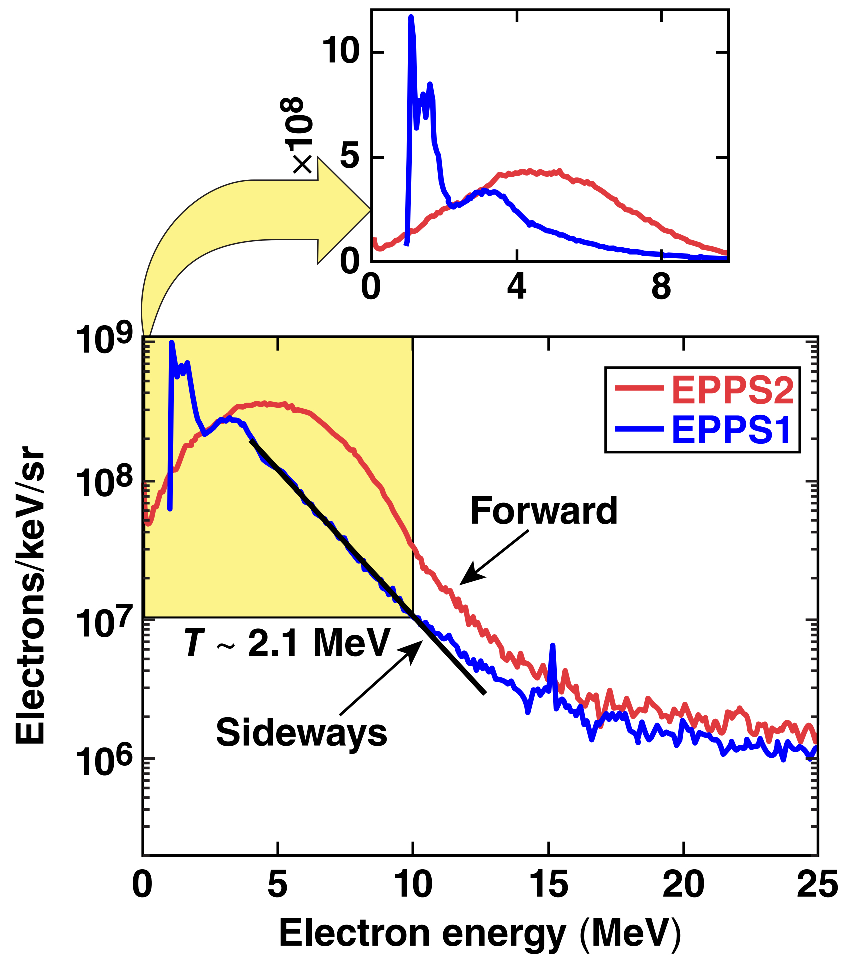
Radiation transport through cone wall is important for thinner-walled targets.

The measured hot-electron temperature is several MeV and is significantly higher than expected from ponderomotive scaling



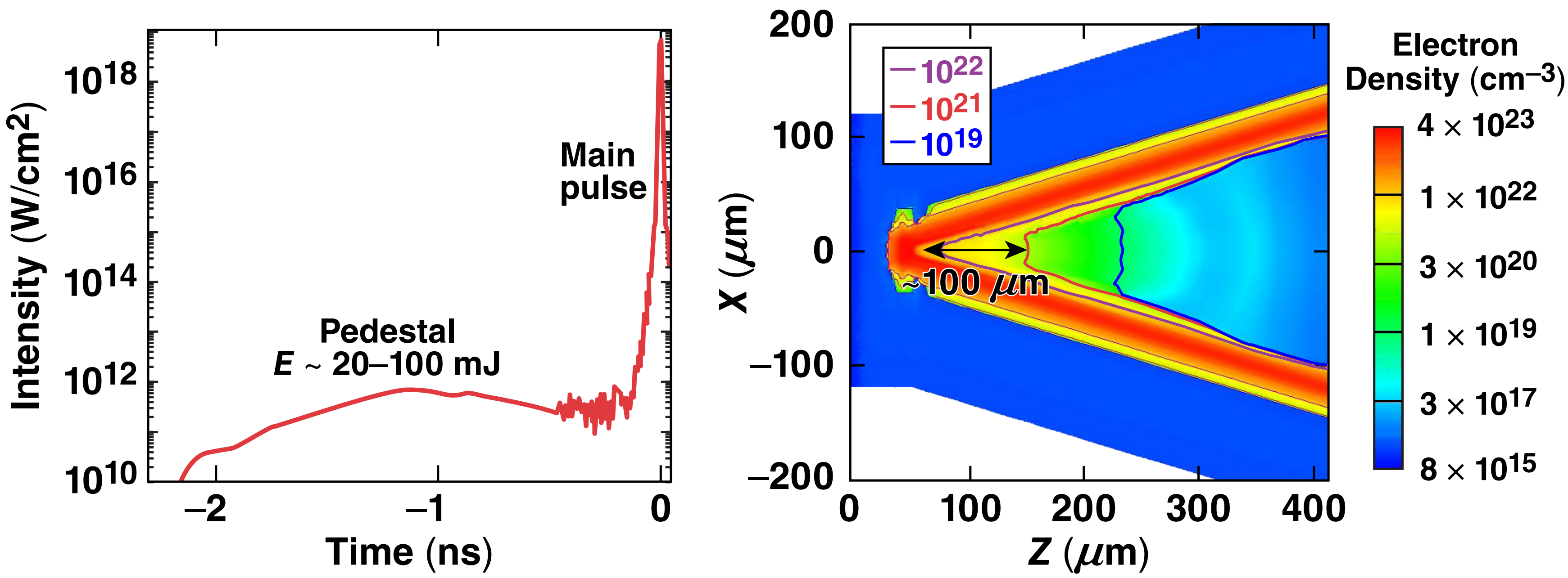


- Ponderomotive scaling predicts ~0.3 MeV
- More electrons below 2 MeV were measured sideways

E19359

Higher electron energies may be caused by cone filling by a pre-plasma

2-D hydrodynamic simulations* predict plasma filling in the cone because of a laser pre-pulse



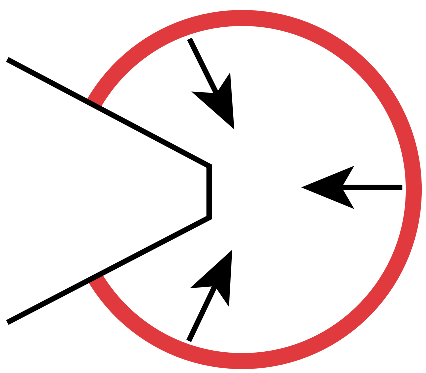
- The IR critical density contour moved ~100 μm away from the surface of the inner cone tip
- Self-focusing in pre-plasma and OMEGA EP beam nonuniformities might explain the observed hard-electron spectrum

E19360

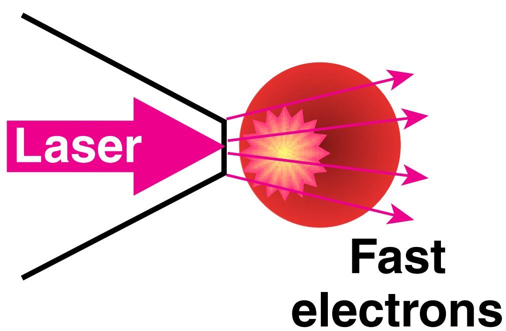
*HYDRA simulations: M. M. Marinak et al., Phys. Plasmas 3, 2070 (1996).

Hydrocode *DRACO*[1] and hybrid-PIC code *LSP*[2] were coupled to simulate integrated fast-ignition experiments[3]

Implosion



Coupling



DRACO

- Simulates the implosion in 2-D cylindrically symmetric geometry
- Calculates the neutron yield

LSP

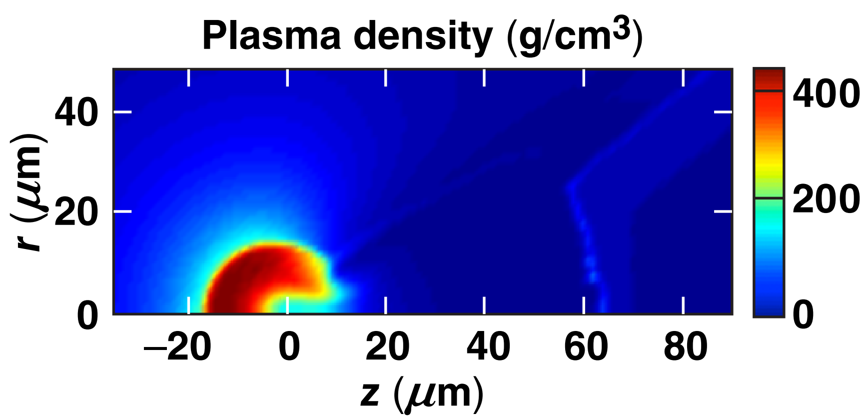
- 2-D/3-D implicit hybrid-PIC code that calculates the target heating by fast electrons
- Coupled to the hydrodynamic code *DRACO* during the short-pulse interaction
- Ponderomotive scaling

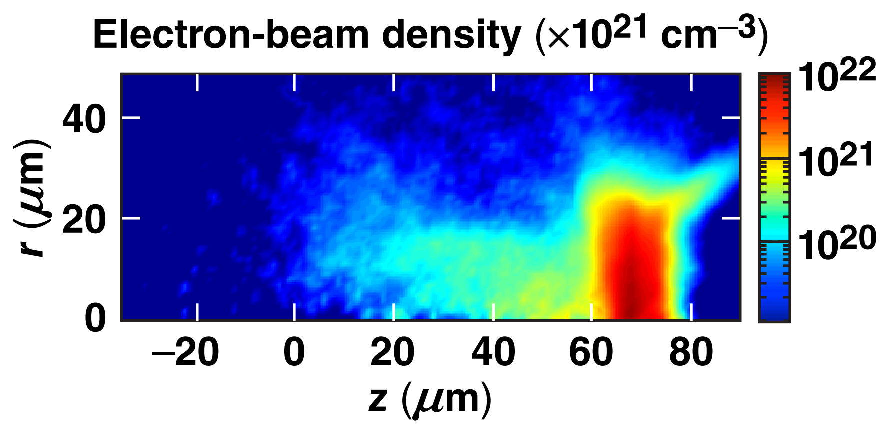
[1] P. B. Radha *et al*., Phys. Plasmas 12, 056307 (2005).
[2] D. R. Welch *et al*., Phys. Plasmas 13, 063105 (2006).
[3] A. A. Solodov *et al*., Phys. Plasmas 16, 056309 (2009).

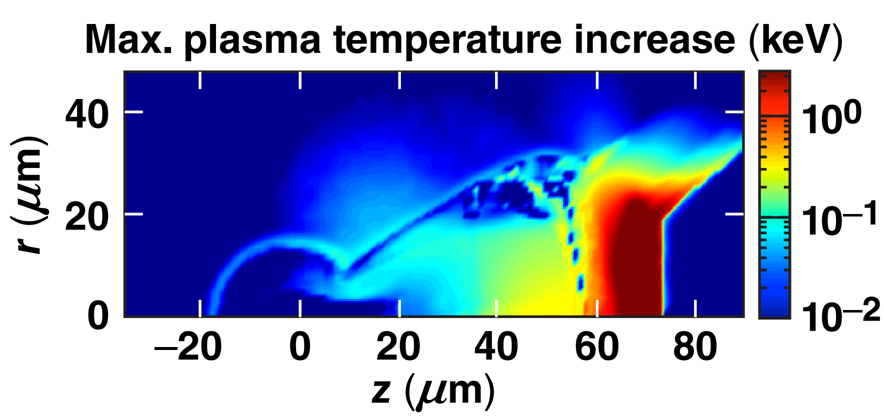
E19361

Integrated *DRACO–LSP* simulations show that low-energy electrons do not efficiently couple into the core

- Simulation for 10 ps, 1 kJ, R_{80} = 27 μm, injection before peak ρR
- Laser-target coupling efficiency (>10 g/cm^3): 3.5%
- Laser-target coupling efficiency (>100 g/cm^3): 0.4%







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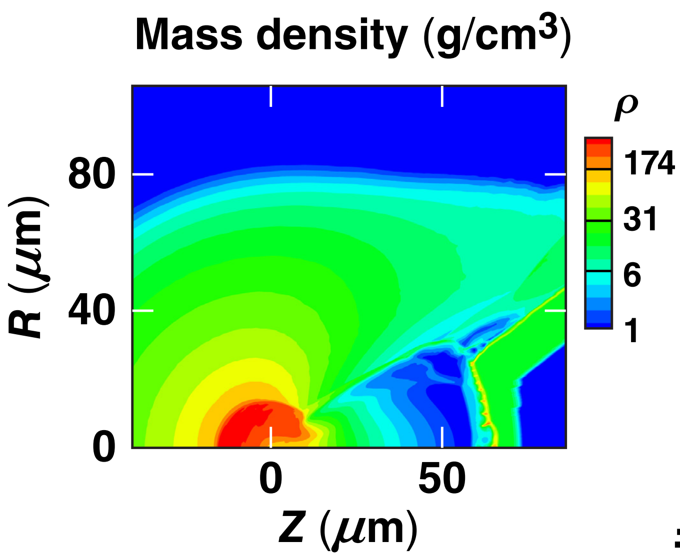
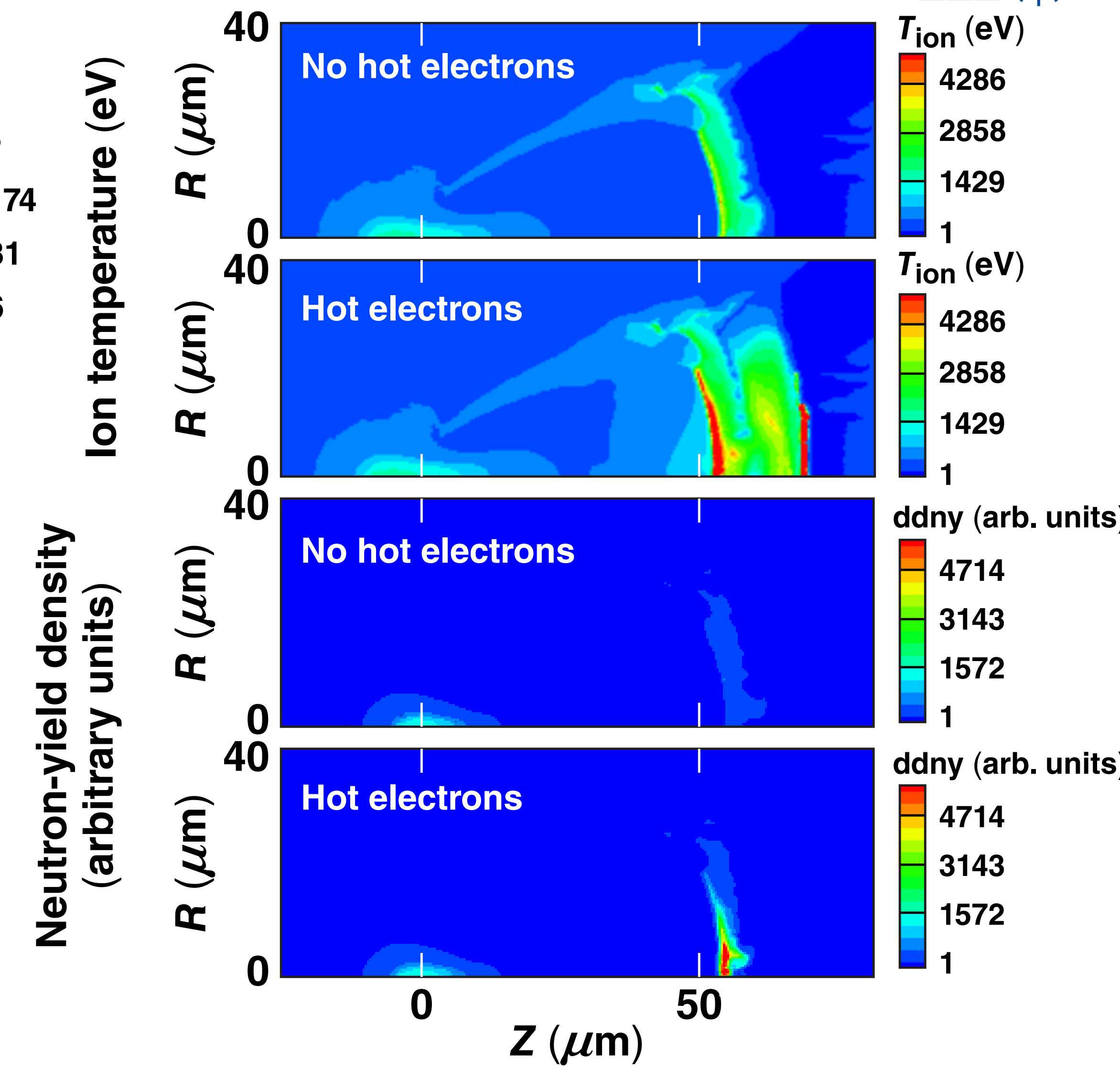
With simple ponderomotive scaling, most neutron-yield increase comes from the shocked region directly behind the cone tip





- More heating in the core is expected with a hotter electron distribution

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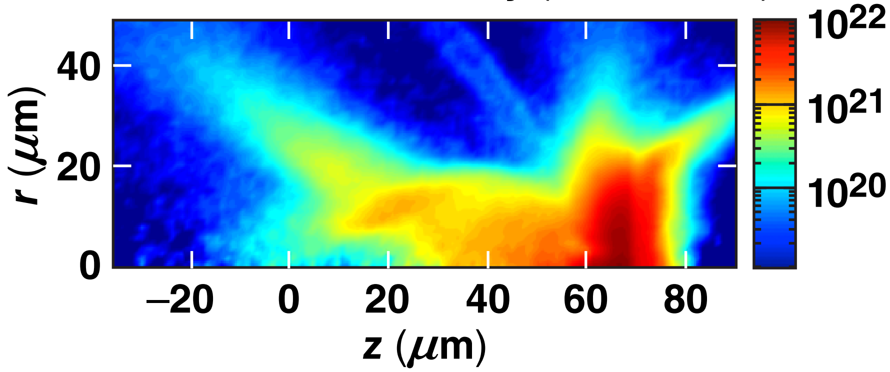
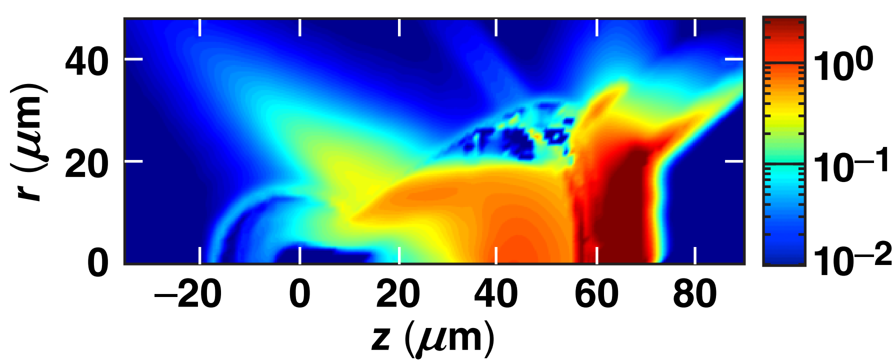
The simulations predict an improved fast-electron coupling at higher laser intensity

Simulation for improved OMEGA EP laser conditions: 10 ps, 2.6 kJ, R_{80} = 15 μm

Electron-beam density ($\times 10^{21}$ cm^{-3})



Max. plasma temperature increase (keV)



- Coupling efficiency (>100 g/cm^3) improves from 0.4% to 1.6%
- Coupling efficiency (>10 g/cm^3) improves from 3.5% to 4.5%
- Predicted neutron yield is ~1.1×10^8

Summary/Conclusions

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