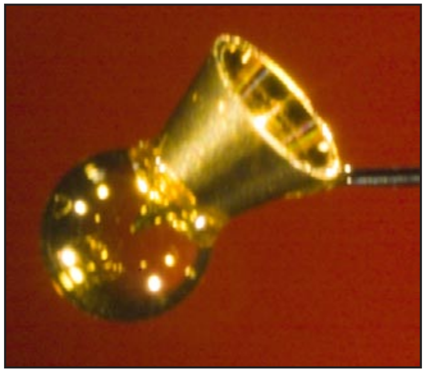
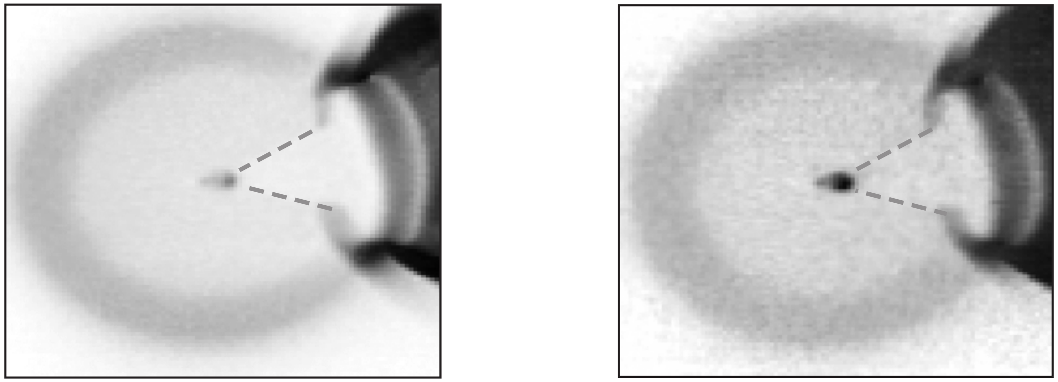
Status of Integrated Fast- and Shock-Ignition Experiments on OMEGA



CD shell	~870-μm diam
Driver energy	~18 kJ
Short pulse	~1.3 kJ
Pulse duration	~10 ps
Focus	~40-μm diam



No short pulse

With short pulse

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Omega Laser Facility
Users' Group Workshop
Rochester, NY
29 April – 1 May 2009

Summary

Fast and shock ignition are investigated on the Omega Laser Facility

- Integrated cone-in-shell fast-ignition experiments with up to 1.3 kJ of short-pulse energy and ~18 kJ of long-pulse energy have begun.
- A significant increase in x-ray emission is measured with the higher OMEGA EP laser energy.
- Neutron measurements are challenging due to a strong x-ray background and mitigation techniques are discussed.
- Experiments with shock-ignition pulses show a 4× improvement in yield and 30% more areal density compared to conventional pulses.
- Shock-ignition experiments with 40 beams for fuel assembly and 20 delayed high-intensity beams show significant coupling of shock- and fast-electron energy into the target.

Two-step ignition processes offer the possibility of higher target gain for a fixed laser energy.

Collaborators

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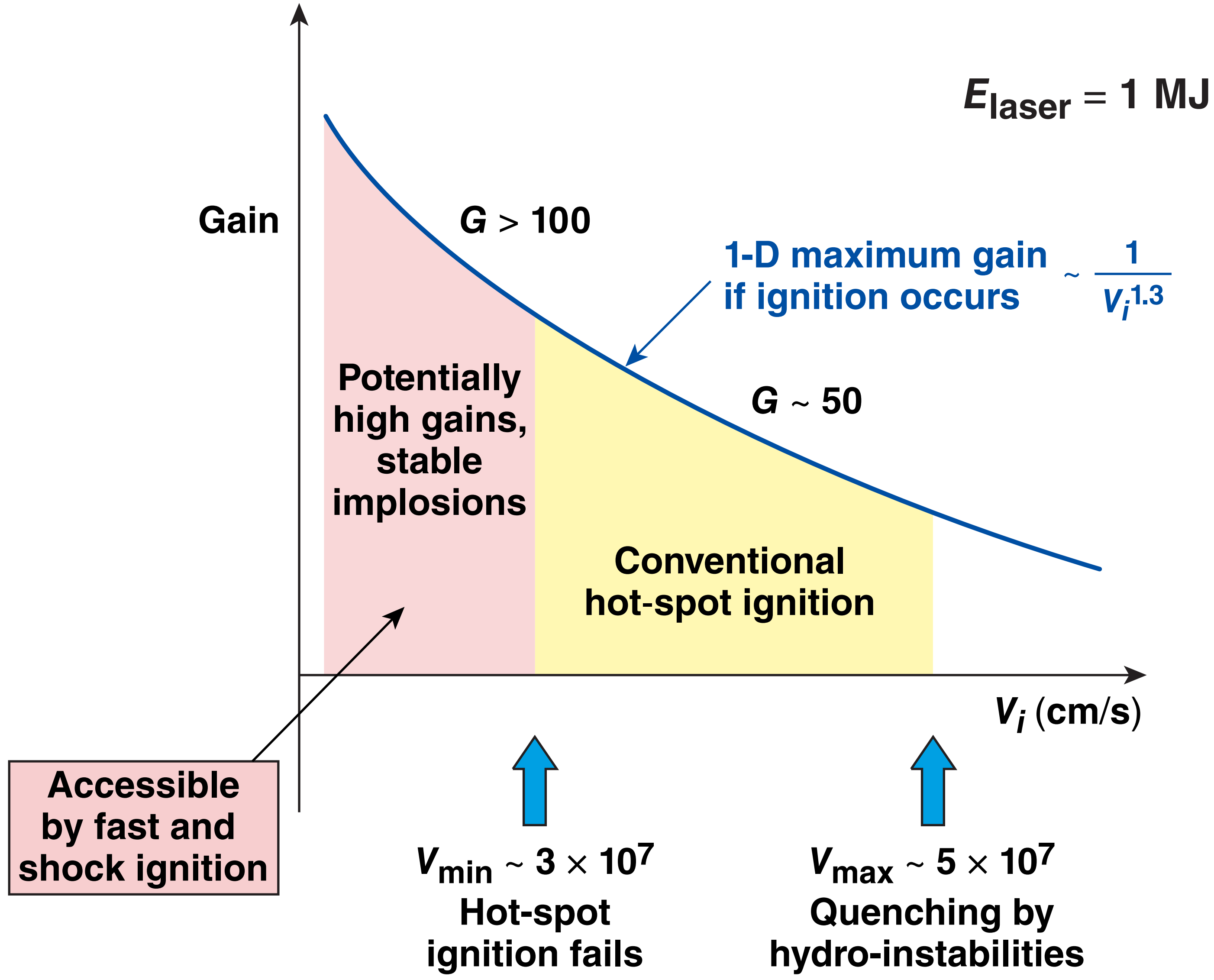
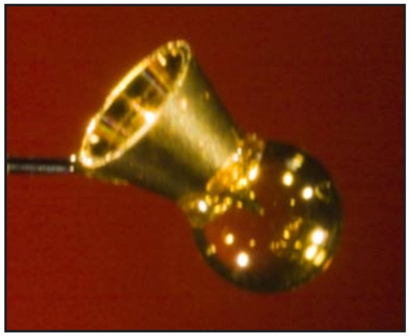
Fast and shock ignition can trigger ignition in massive (slow) targets leading to high gains

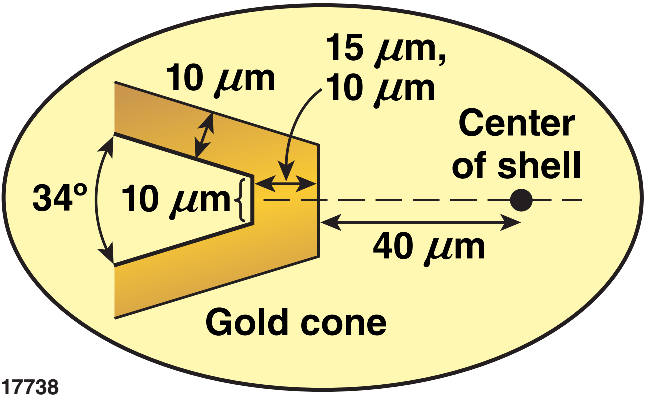


TC7815g

Integrated fast-ignition experiments with re-entrant cone targets have begun at the Omega/Omega EP Laser Facility

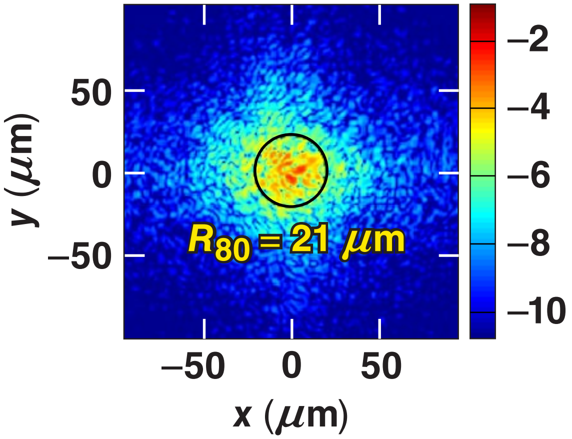


Shell material	CD
Shell diameter	~870 μm
Shell thickness	~40 μm
Shell fill	Empty
Cone material	Gold



Energy	~18 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

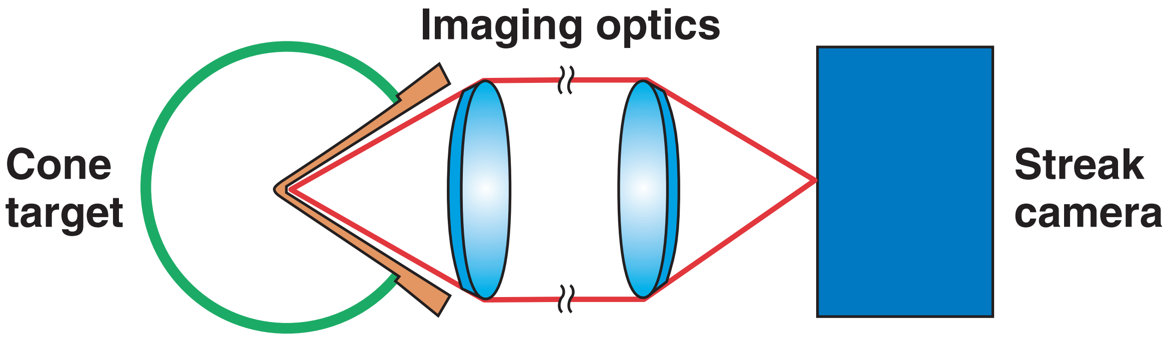
Target focal spot, log scale

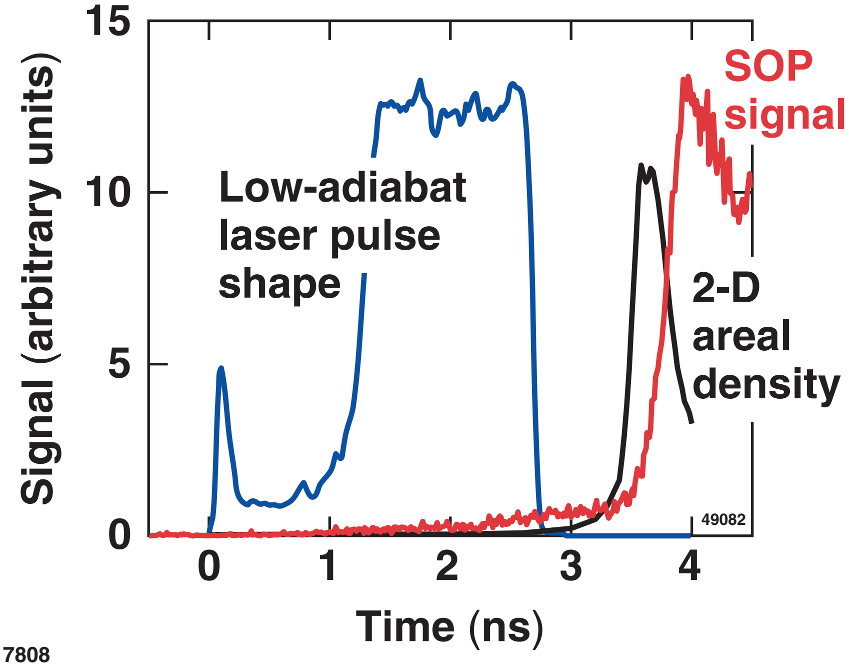


J. Bromage *et al*., Opt. Express 21, 16,561 (2008).

Energy	~1.3 kJ
Wavelength	1053 nm
Pulse duration	~10 ps
Intensity	~1×10^{19} W/cm^2

The cone has to withstand the plasma pressure up to peak compression, ensuring a plasma-free path for the short-pulse beam

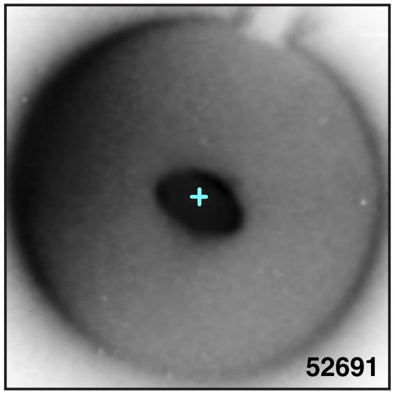




- Streaked optical pyrometer (SOP) measures the breakout through 15-μm-thick cone tip
- Shock breakout at 3.50±0.05 ns is close to peak compression
- Areal density from 2-D hydrocode simulations
- Time of $(\rho R)_{max}$ is close to optimum injection time for fast electrons

Pointing and timing of the short-pulse beam was achieved with ~20-μm and ~50-ps accuracy

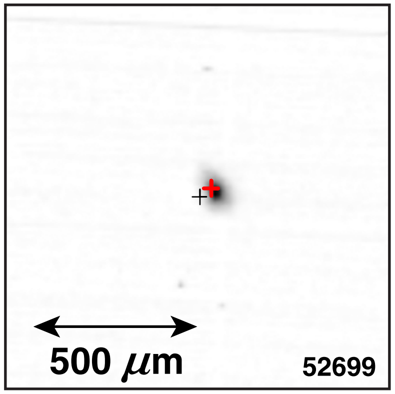
Drive laser only
(18 kJ, spherical shell)



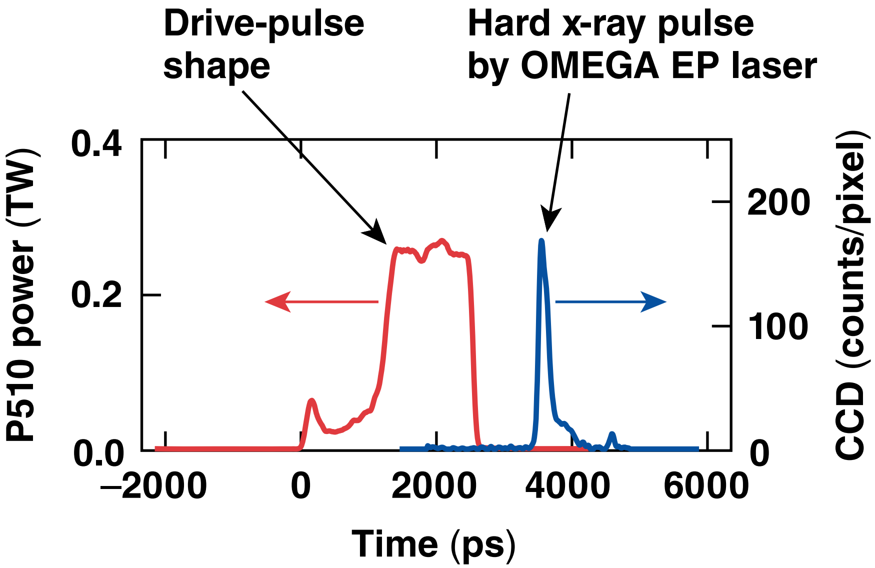
Short pulse only

Black + **target chamber center**

Red + **nominal OMEGA EP pointing**



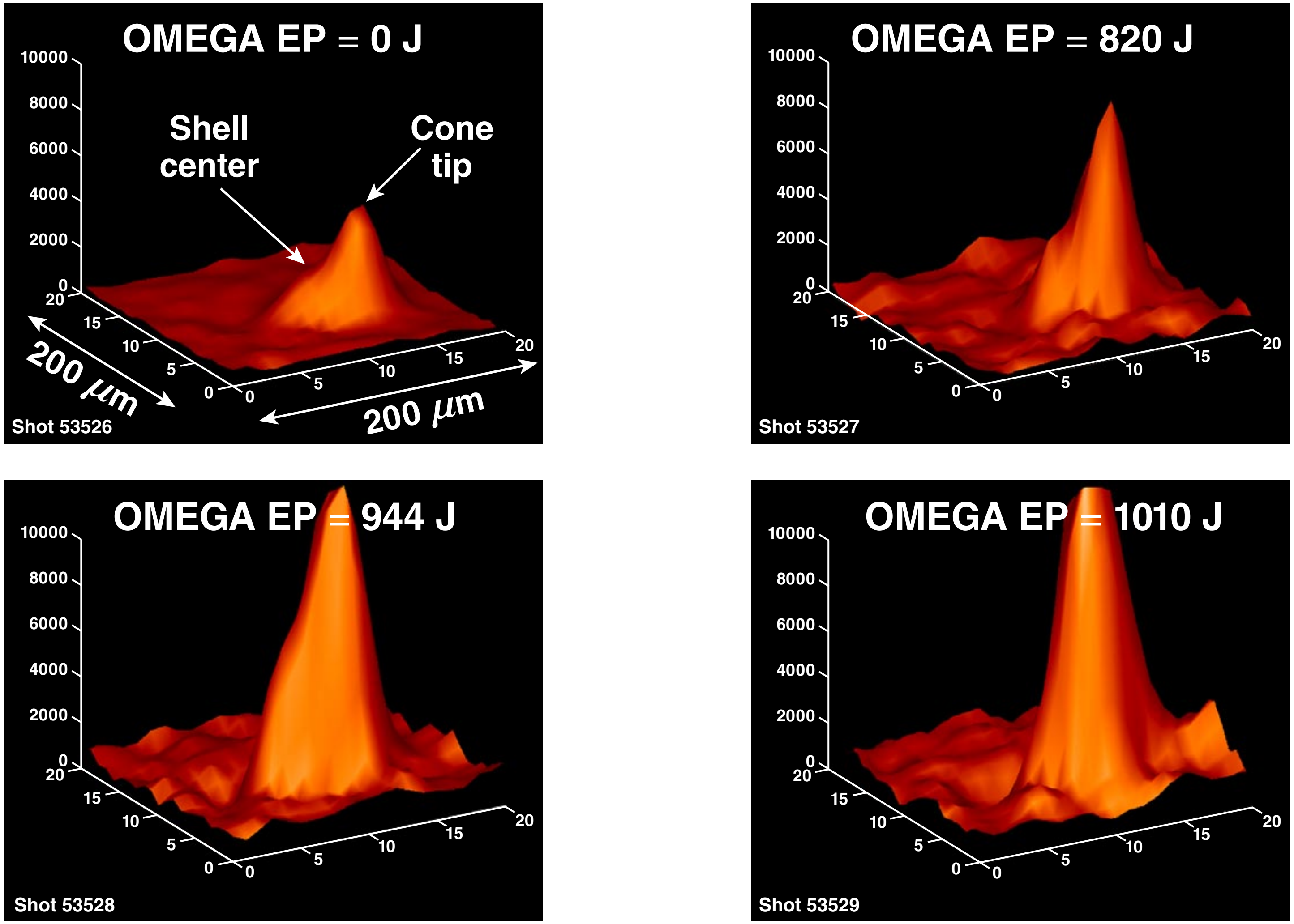
Two orthogonal x-ray pinhole camera views provide the spatial information



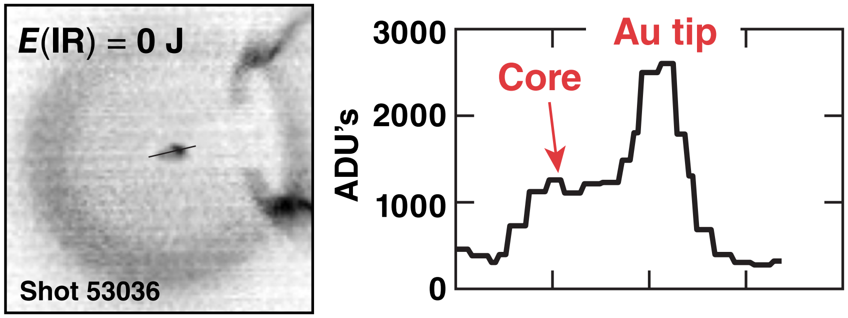
- **The neutron temporal diagnostic operating in hard x-ray mode provides temporal information**
- **Measured time of short-pulse interaction: 3.50±0.05 ns**

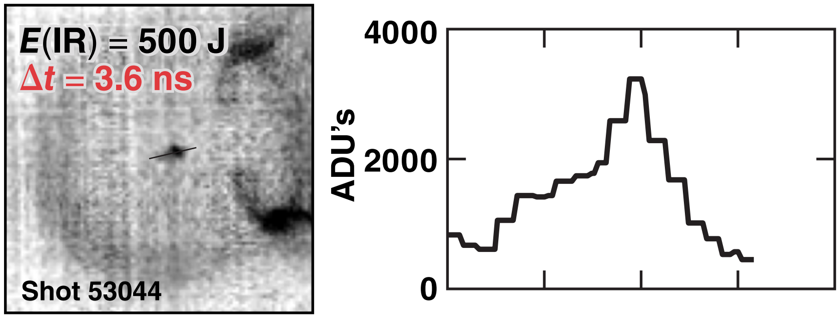
A significant increase in x-ray emission is measured with higher OMEGA EP laser energy

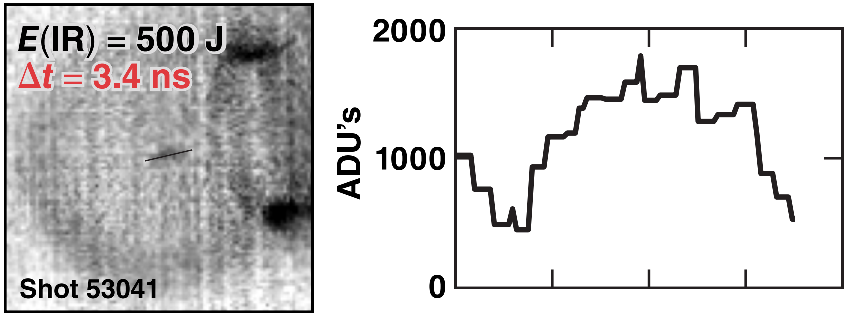
Time-integrated x-ray pinhole images $E_{\mathrm{Ph}} = 2$ to 7 keV, $\Delta t = 3.5$ ns

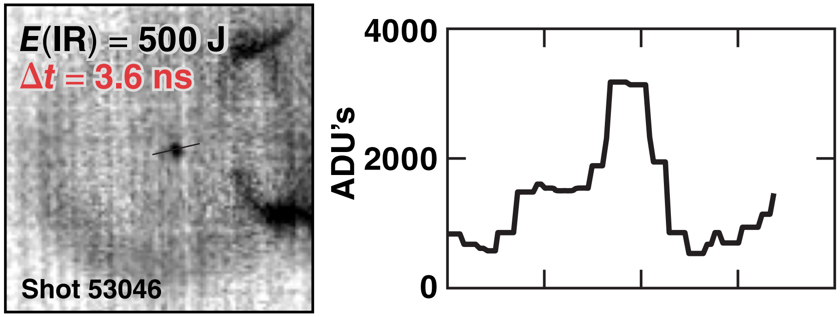


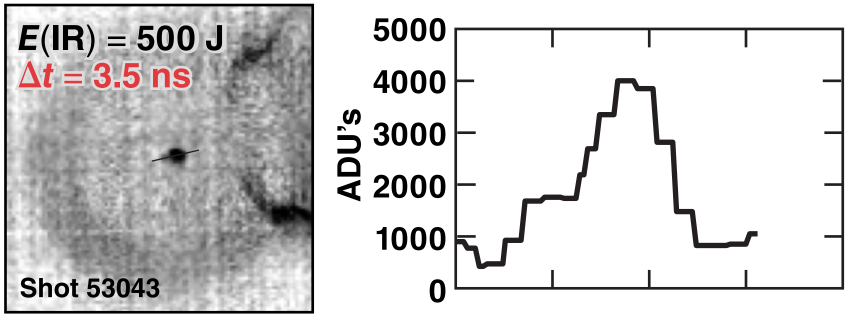
No significant change in x-ray emission was measured for various time delays and 500 J short-pulse energy





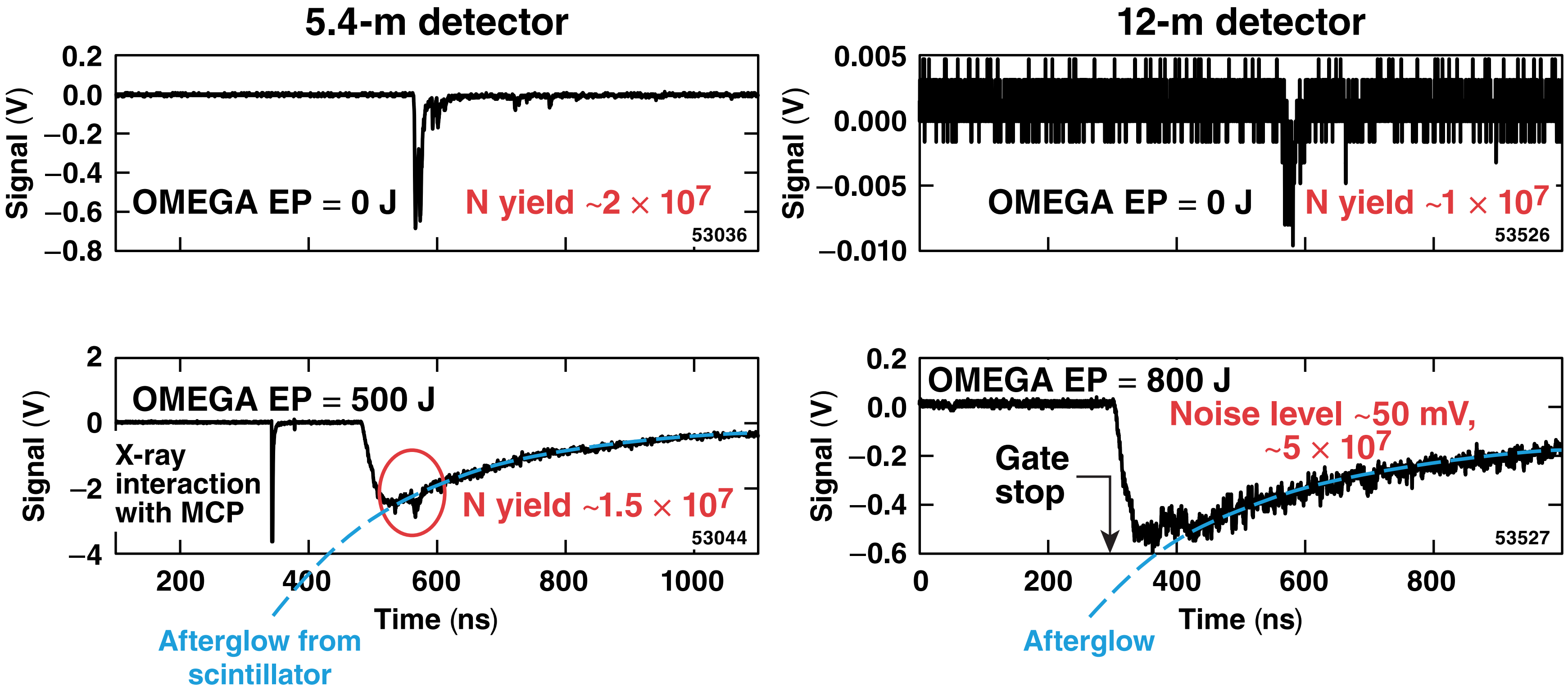






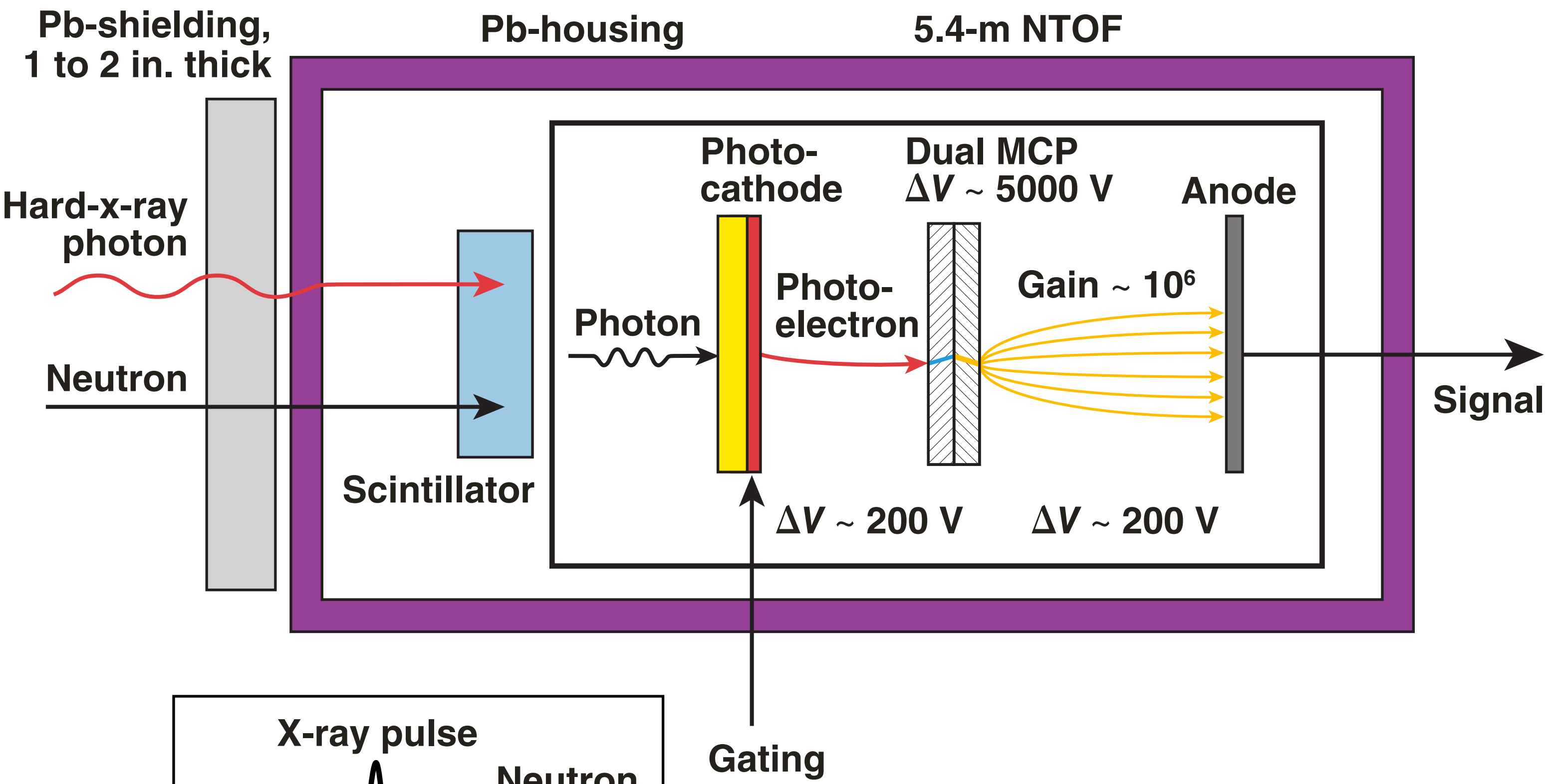
- **X-ray pinhole images (1 × 1-mm regions, 2 to 7 keV)**
- **Shell peak compression and shock breakout inside cone is at ~3.5 ns**

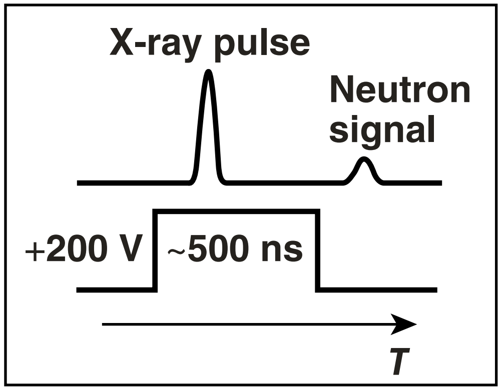
Neutron measurements are challenging in fast-ignition integrated experiments because of a strong x-ray background



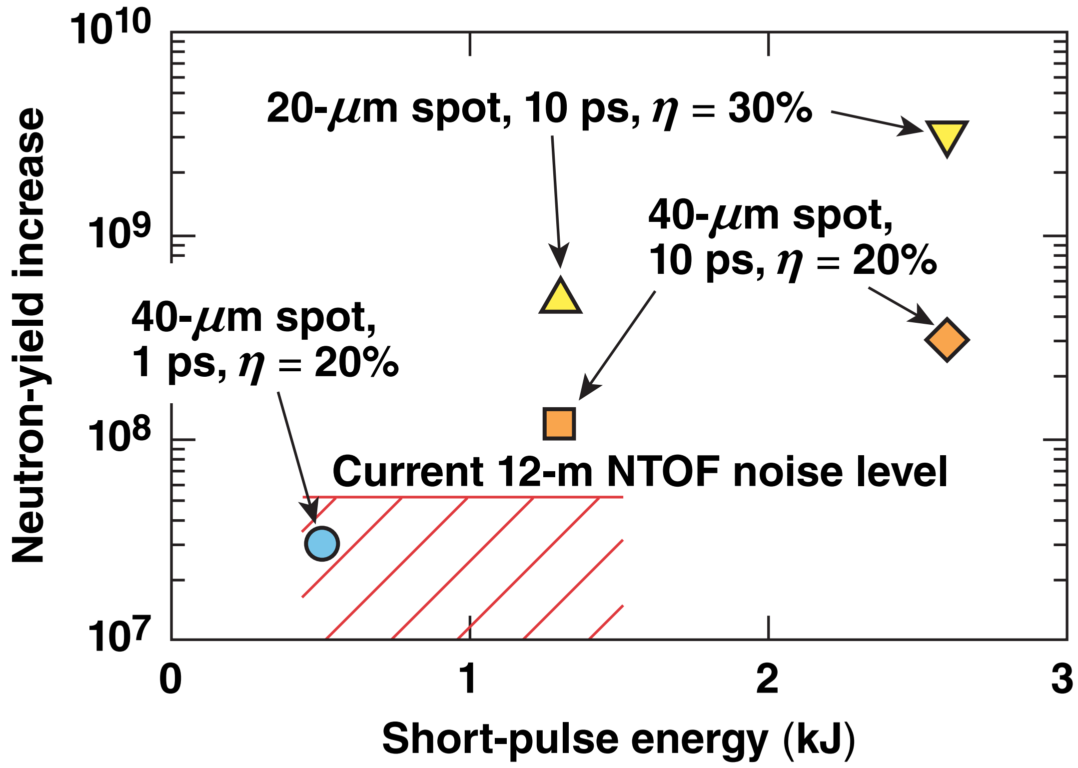
Fast electrons streaming through the high-Z cone material produce a significant γ pulse that overwhelms the neutron time-of-flight diagnostics for $E > 500$ J.

The neutron detectors are strongly affected by the hard-x-ray background





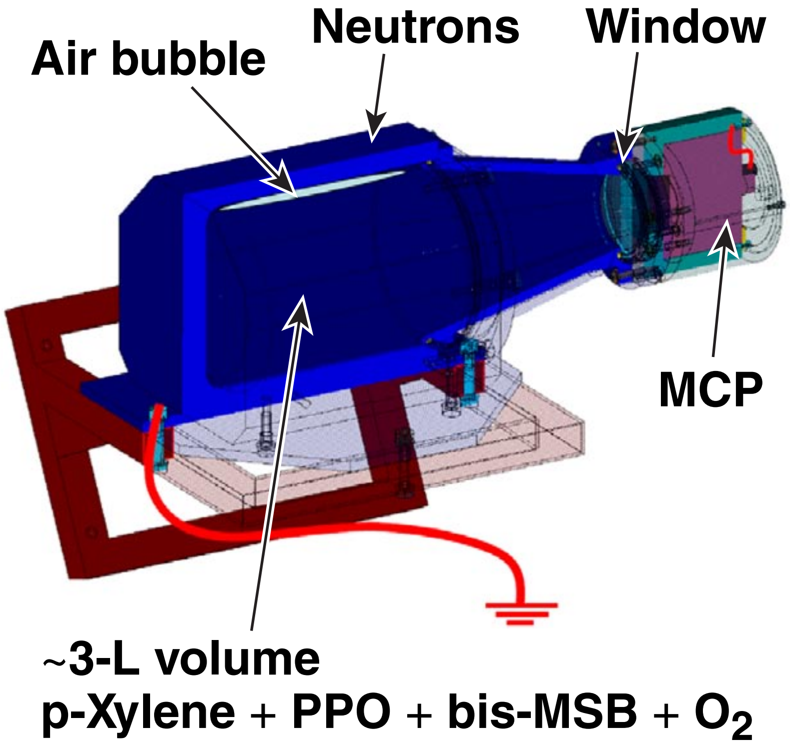
Integrated 2-D hydrodynamic *DRACO*/*LSP* simulations were performed for various experimental conditions



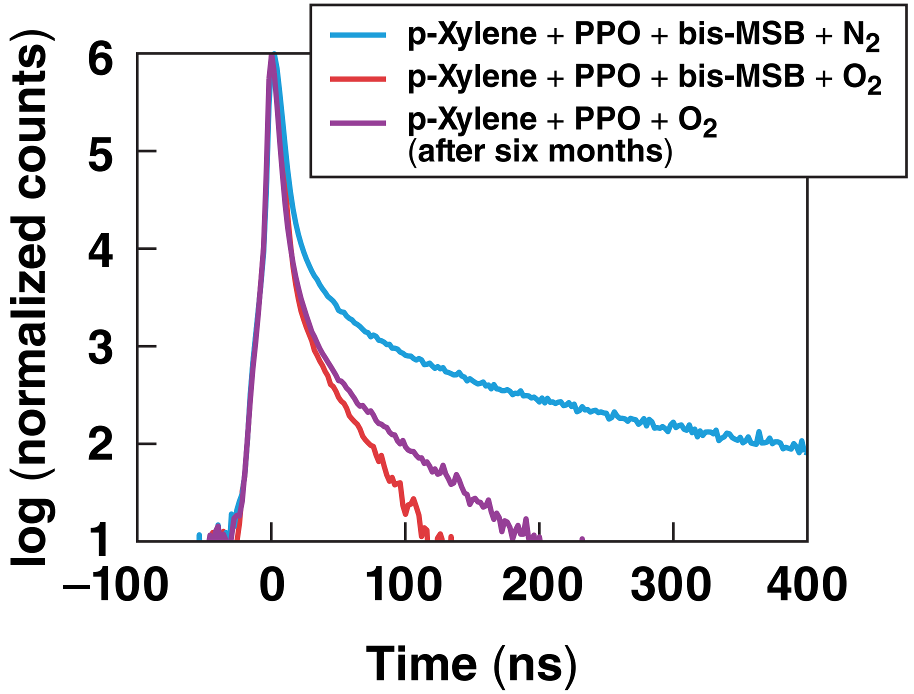
- 20° half-divergence angle of electron beam
- Calculations do not account for transport through cone wall
- 15-μm gold wall thickness will have significant effect on energy transport
- The expected n yields below 1 kJ are in the range of the current noise level of 12-m NTOF

A liquid scintillator neutron time-of-flight detector is being developed to suppress the x-ray background induced fluorescence

Liquid scintillators with a molecular O_2 quenching agent have a fast decay time and are promising detectors to measure the D_2 neutron yield



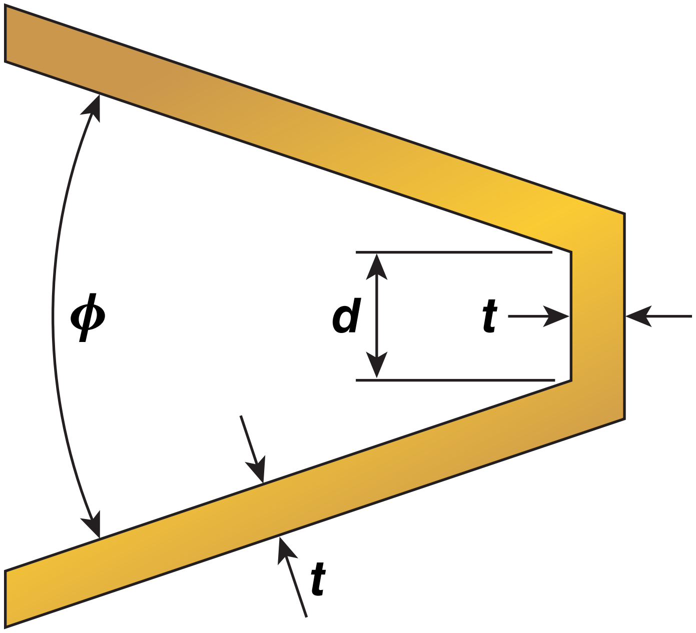
~3-L volume
p-Xylene + PPO + bis-MSB + O_2



Courtesy of Ronald Lauck, PTB (Physikalisch Technische Bundesanstalt, Braunschweig, Germany).

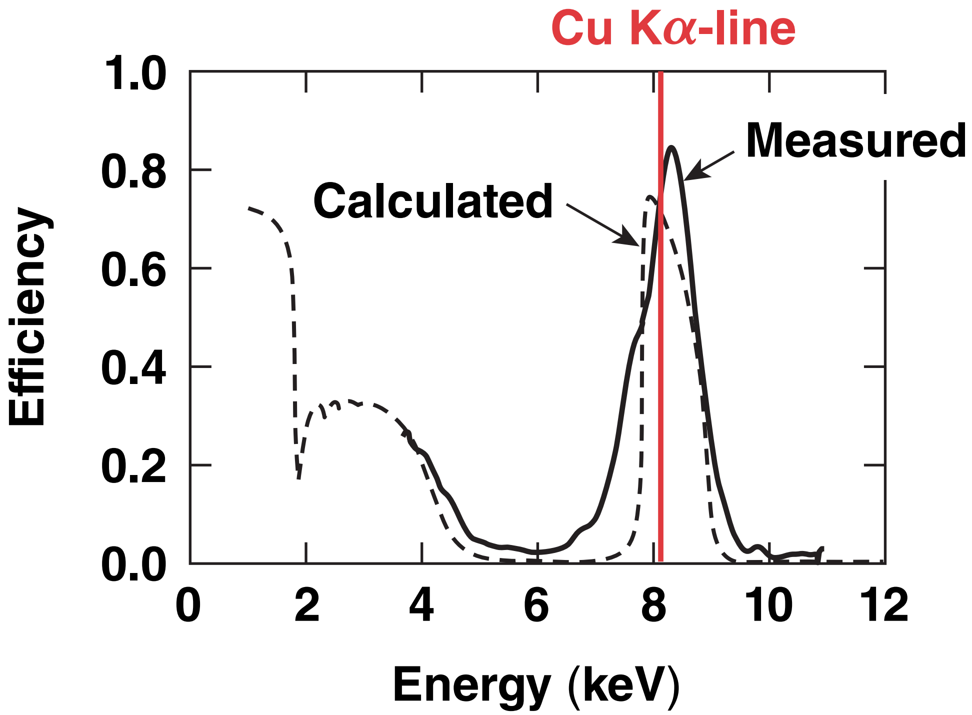
Copper cone targets will be tested in future experiments

- Reduced x-ray bremsstrahlung emission
- Improved fast-electron energy transport through cone wall for lower-*Z* elements

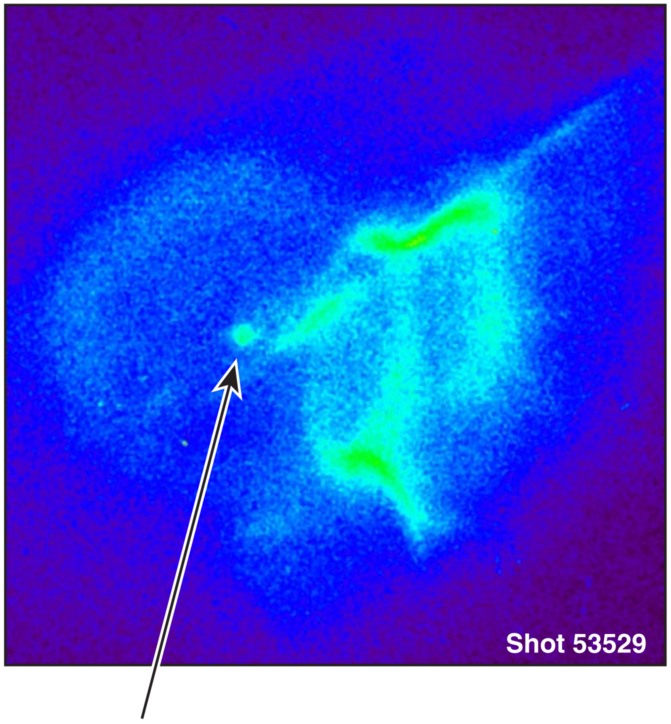


Cone type	*t* (μm) wall thickness	*d* (μm) tip diameter	Φ (°) full cone angle
I	20	20	34
II	25	40	40
III	30	60	46

A Kirkpatrick–Baez x-ray microscope with a WB_4C multilayer mirror will image the Cu K-shell emission



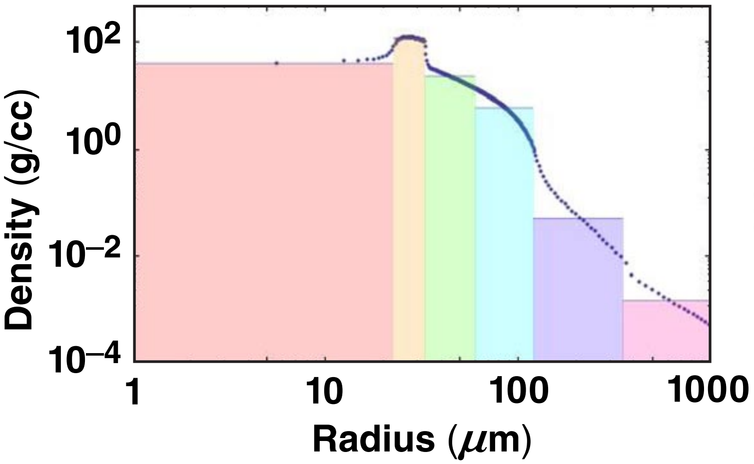
KB image from gold cone target and broadband mirror

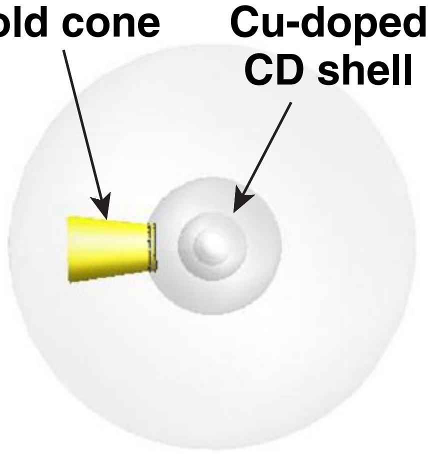


Core and cone tip heated with OMEGA EP beam (1 kJ, 10 ps)

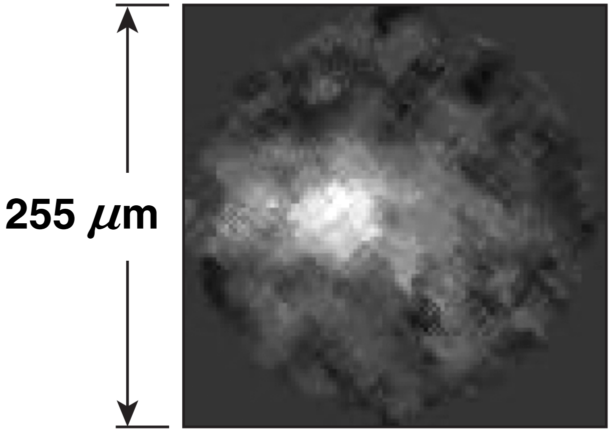
F. J. Marshall and G. R. Benett, Rev. Sci. Instrum. 70, 617 (1999).

Kα emission from Cu-doped CH shells will be used to infer fast-electron heating

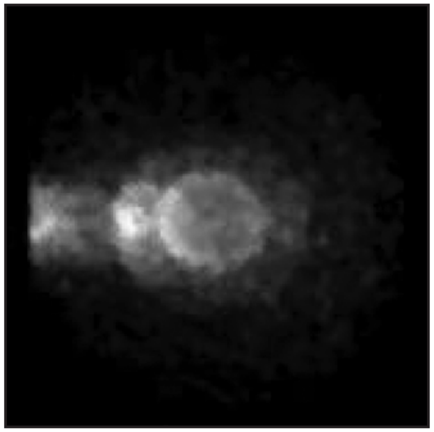




- ITS Monte Carlo code simulations by A. MacKinnon and D. Hey assuming 1% atomic Cu in 40 μm CH shell
- Predicted good signal level for KB instrument

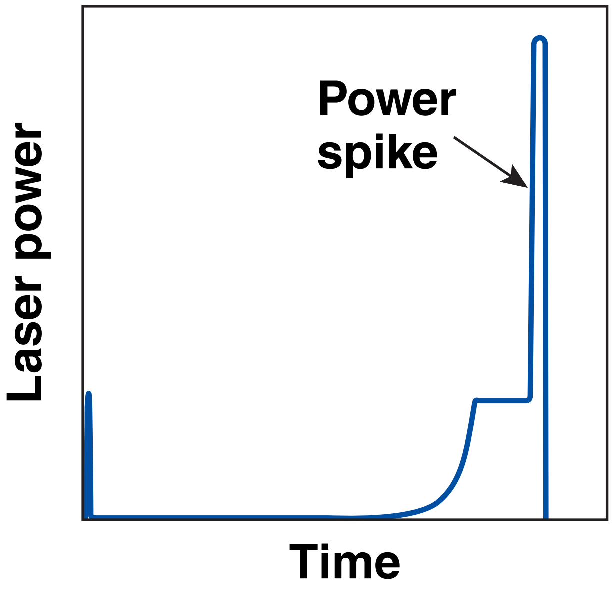


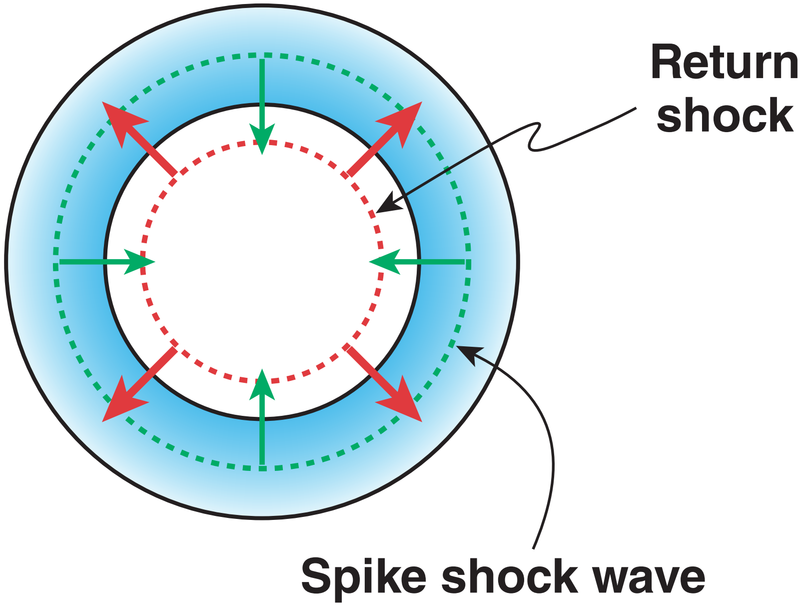
Ross-pair pinhole image subtraction at 8 keV



KB microscope at 8 keV

Shock ignition relies on a shaped laser pulse with a trailing high-intensity spike



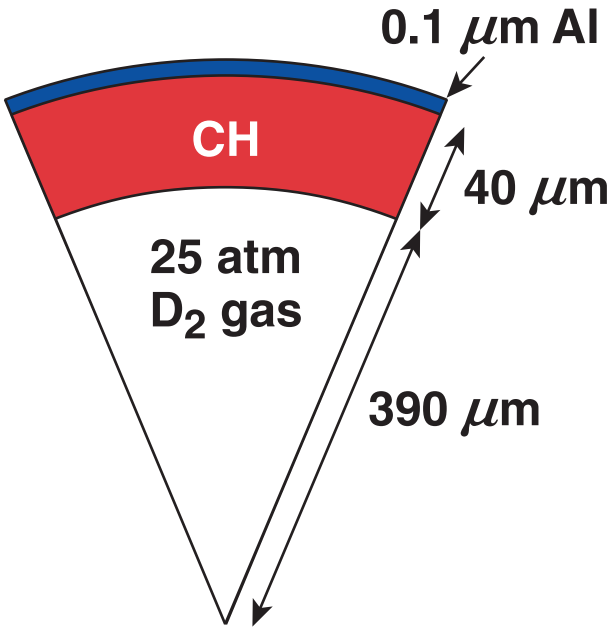


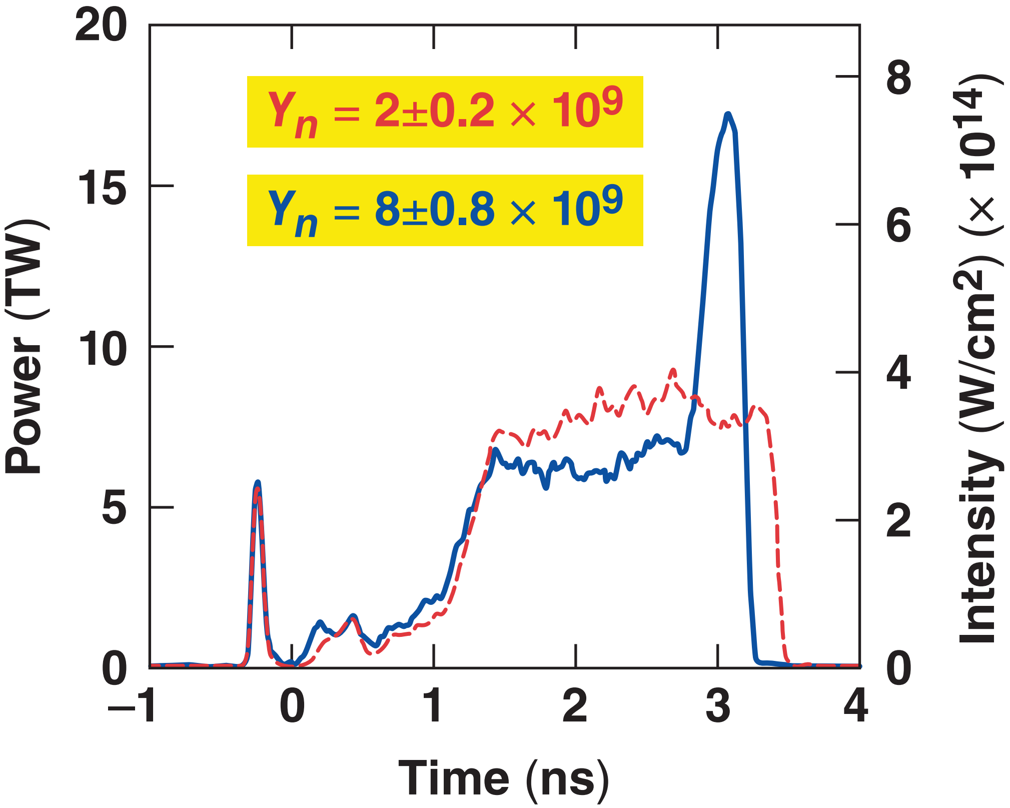
The ignitor shock wave significantly increases its strength as it propagates through the converging shell.

E16323c

CH shells have been imploded on OMEGA to test the performance of shock-ignition pulse shapes

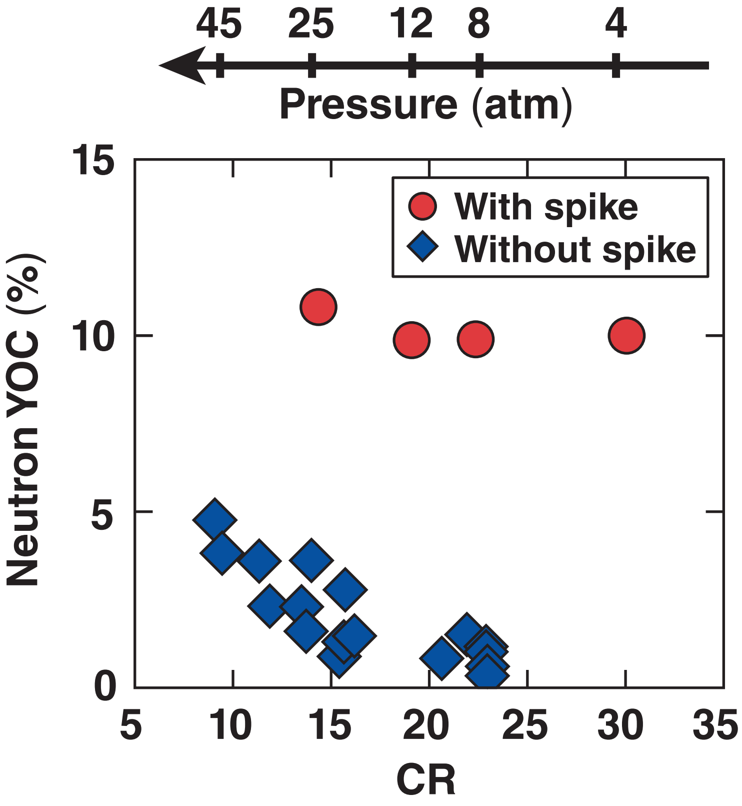
$E_L = 19$ kJ, $\alpha = 1.3$,
$V_i = 1.7 \times 10^7$ cm/s, SSD off

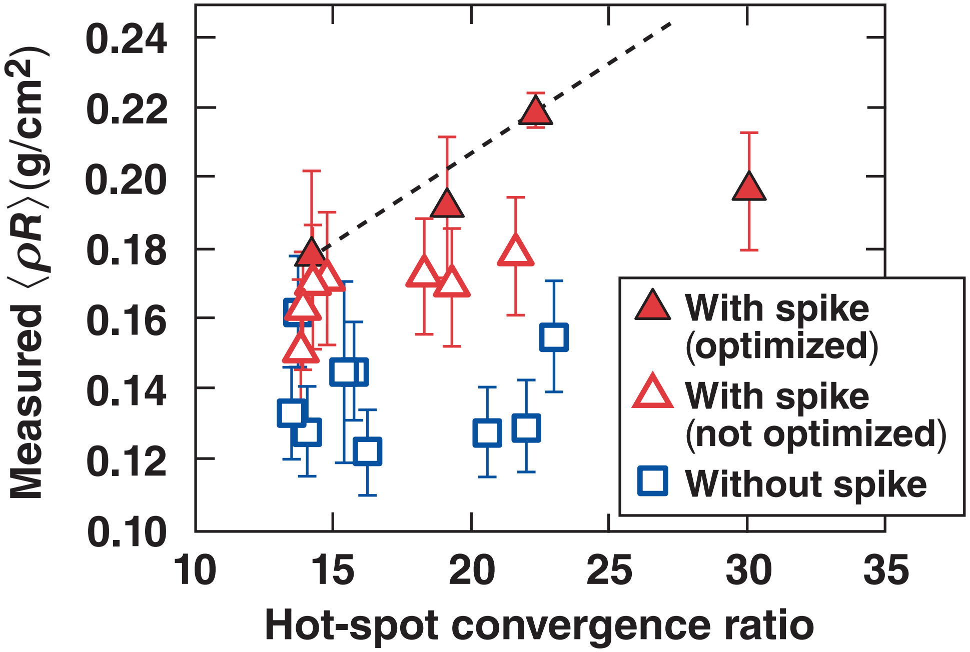




The neutron yield increases considerably when a shock is launched at the end of the pulse.

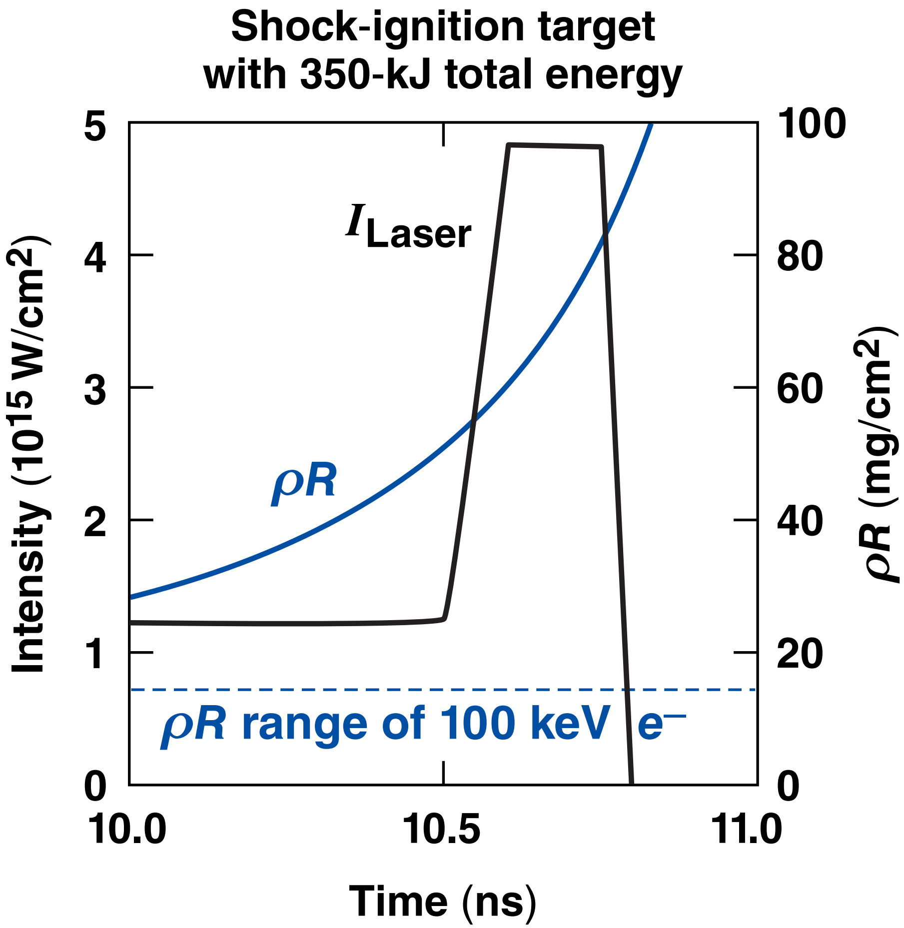
The shock-ignition pulse-shape implosions show improved areal densities and neutron yields

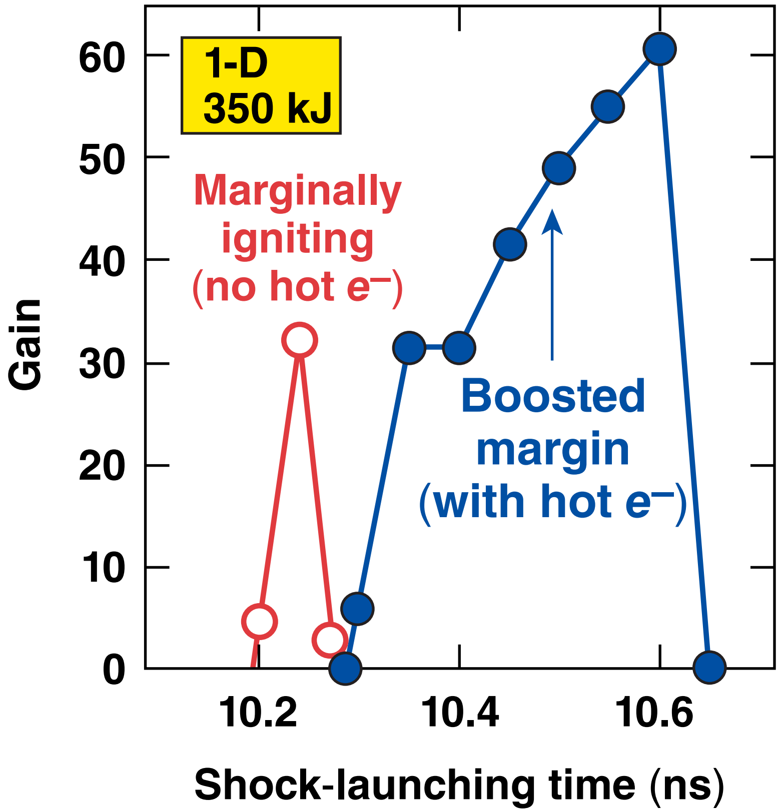




- **The measured-to-calculated neutron-yield ratios are close to 10% for a hot-spot convergence ratio of 30.**

Laser–plasma interaction during the spike pulse and hot-electron generation are important issues for shock ignition



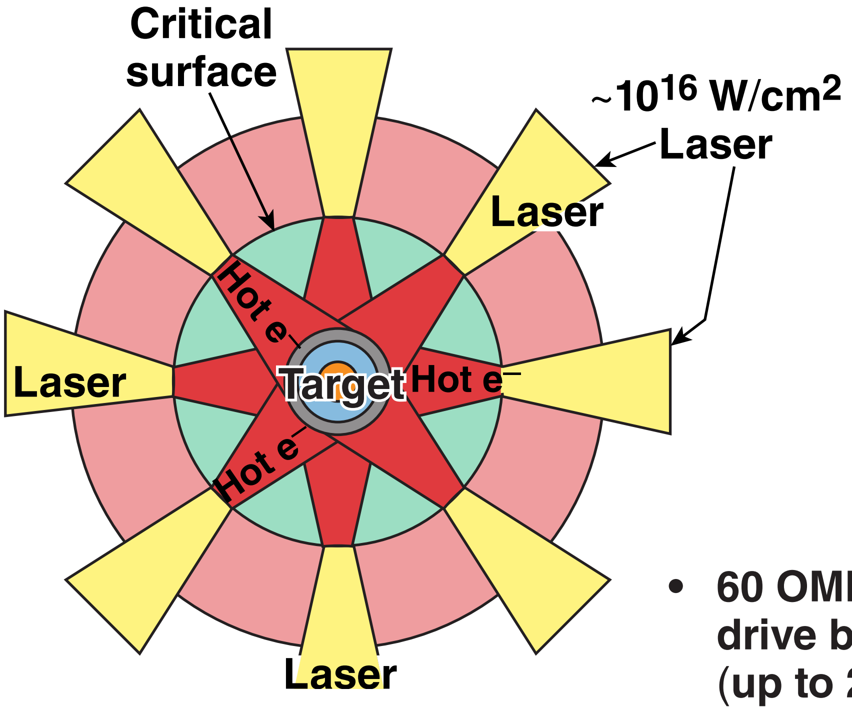


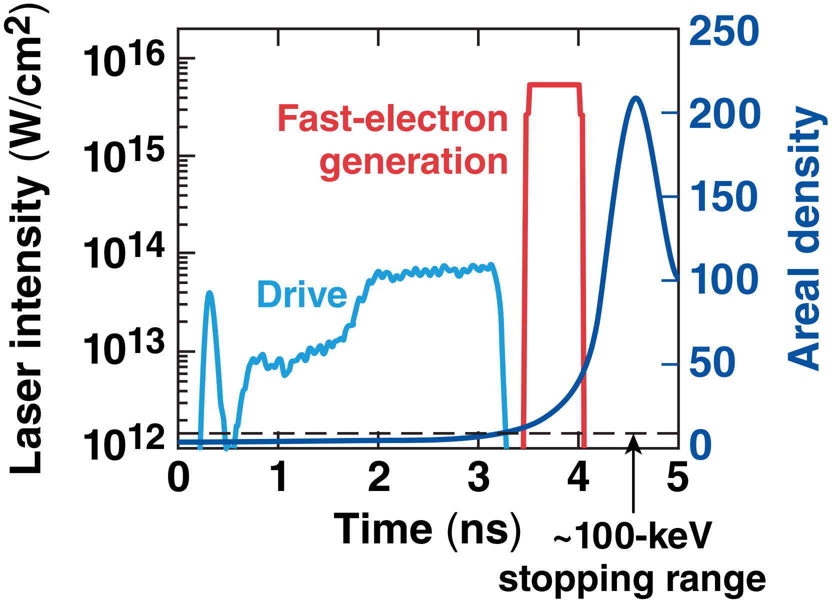
Hot e^- with Maxwellian T_{hot} = 150 keV, E_{hot} = 17% of spike energy, treated using a multigroup diffusion model*

TC7870c

**LILAC* simulations by C. D. Zhou and R. Betti

Hot-electron generation and laser–plasma instabilities are studied at ignition-relevant spike intensities

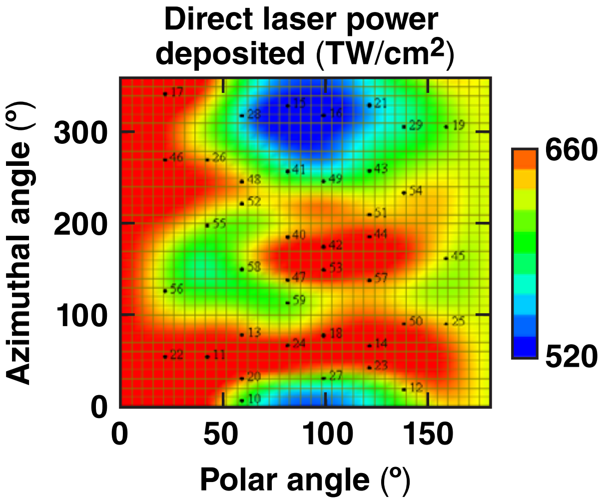




- 60 OMEGA beams are split into 40 low-intensity drive beams and 20 tightly focused, delayed beams (up to 2×10^{16} W/cm^2)
- Hydrodynamic performance and laser backscattering are studied
- Preliminary results are moderate $T_{hot} \sim 45$ keV, ~10% conversion efficiency $E_{spike} \rightarrow E_{hot}$, ~20% backscattering at 5×10^{15} W/cm^2 (SRS + SBS)

A significant coupling of high-intensity-pulse energy into the capsule is measured, despite a large target-illumination nonuniformity

Calculated 40-beam drive power



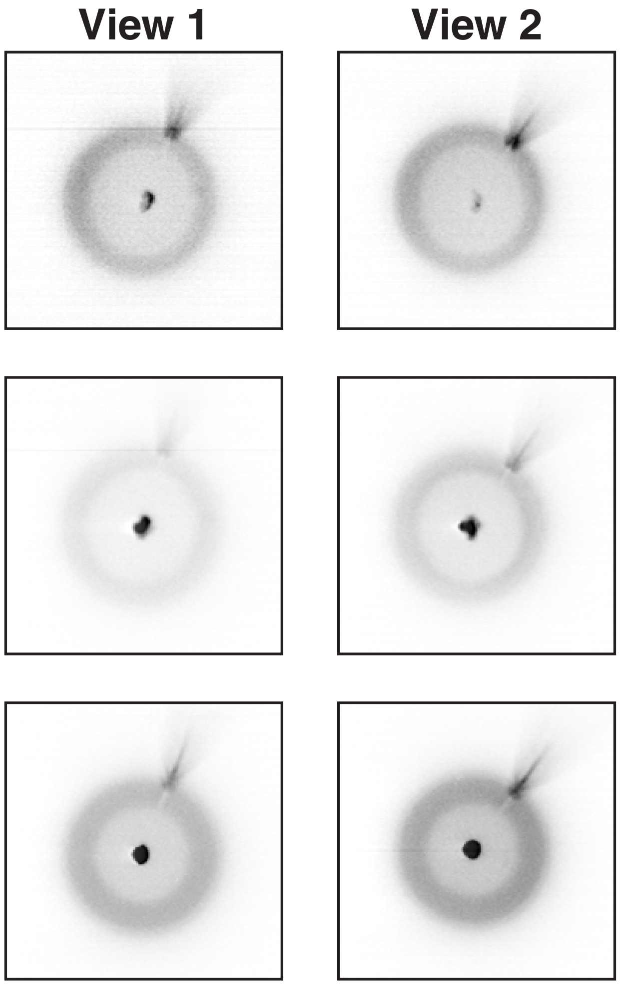
- ~10% power imbalance in current experiment
- Repointing the beams will reduce power imbalance to 2%, similar to spherical 60-beam illumination conditions

X-ray pinhole images

40 beam, 13.7 kJ
nonuniform ill.
N yield: ~2 × 10^8
Shot 52480

40 + 20 beam,
13.6 + 4.8 kJ = 18.4 kJ
nonuniform ill.
N yield: 3.7 × 10^9
Shot 52490

60 beam, 20.8 kJ
uniform ill.
N yield: 1.3 × 10^{10}
Shot 49068



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