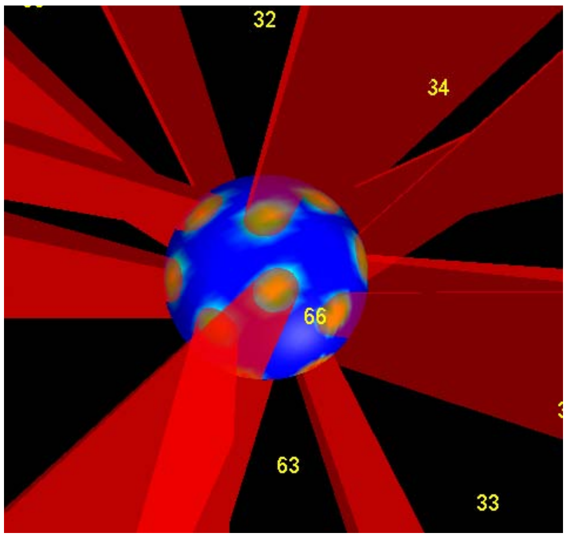
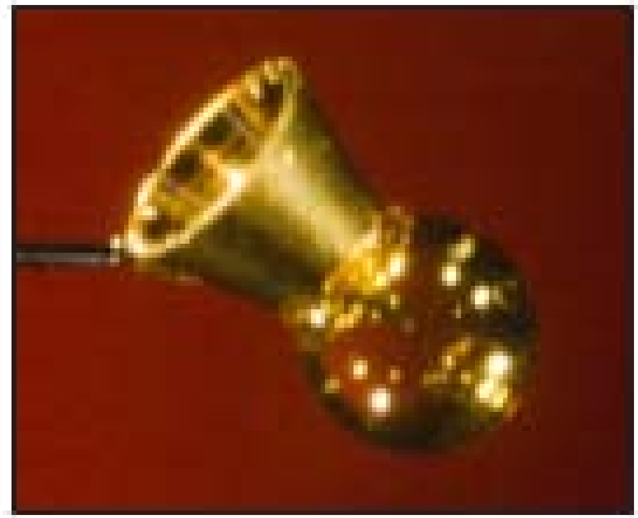
Advanced ignition options for laser ICF





R. Betti

University of Rochester and Princeton Plasma Physics Laboratory

FPA Meeting, Washington DC, December 1-3, 2010

The NIF can explore advanced ignition options

- With day-one hardware, the NIF can explore high-gain shock ignition

  - Polar Shock Ignition (uses half the NIF beams to drive the implosion and the other half to drive the ignitor shock)

- Fast Ignition requires major hardware upgrades: 100kJ-class multi-PW laser [also talk by P. Patel at this meeting]

- Polar Direct Drive requires minor upgrades: multi-FM or 2D-SSD (talk by J. Soures at this meeting)

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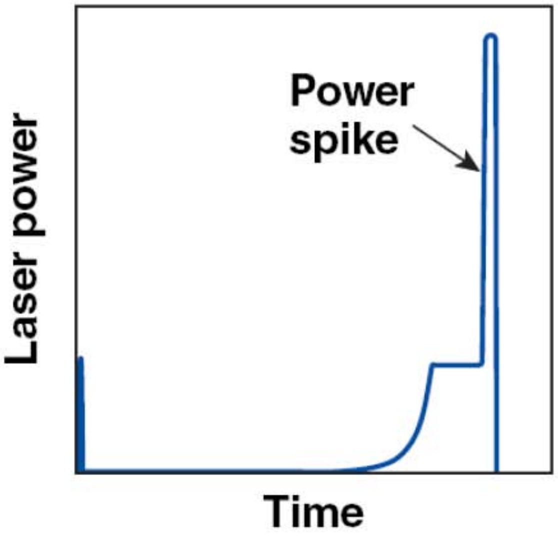
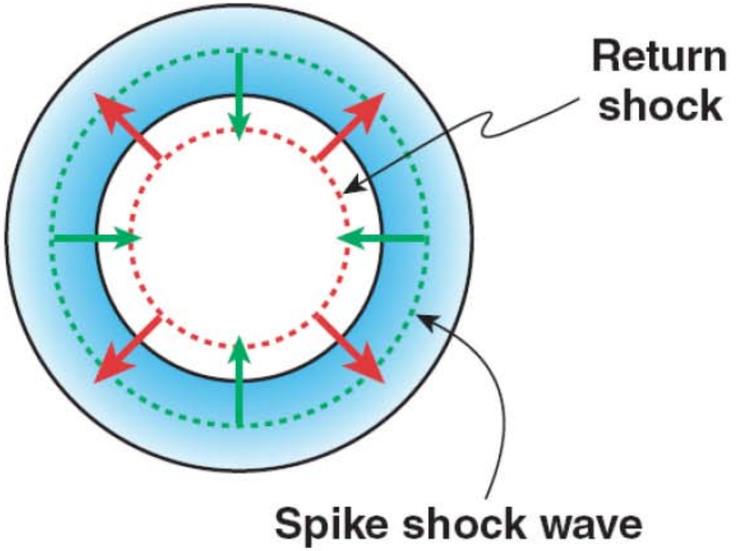
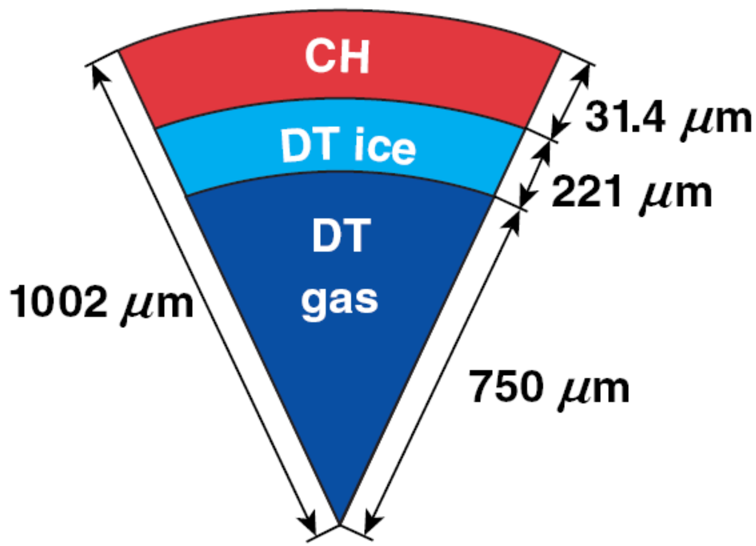
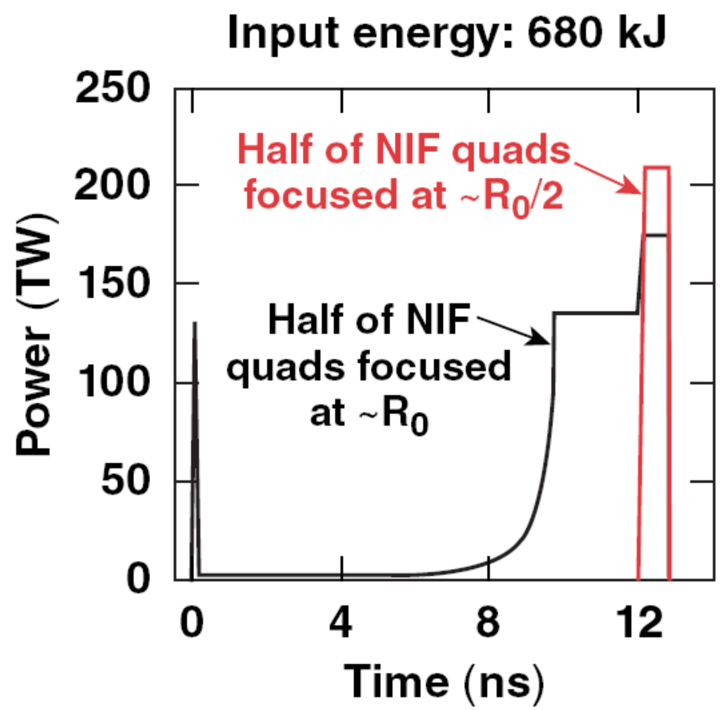
Shock Ignition





A thick plastic-ablator shock-ignition target for the NIF has been designed using existing NIF phase plates





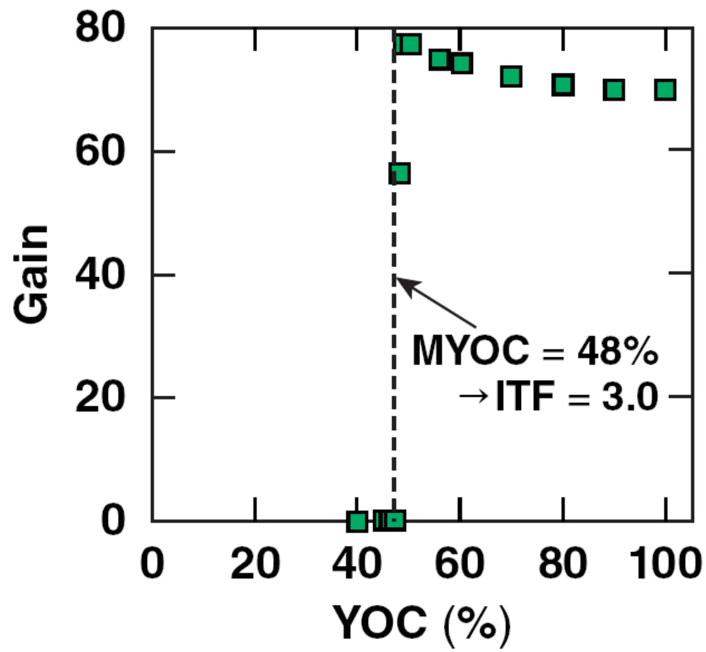
Gain (1-D)	70
ρR (g/cm^2)	2.6
V_{imp} (μm/ns)	300
$IFAR_{2/3}$	30

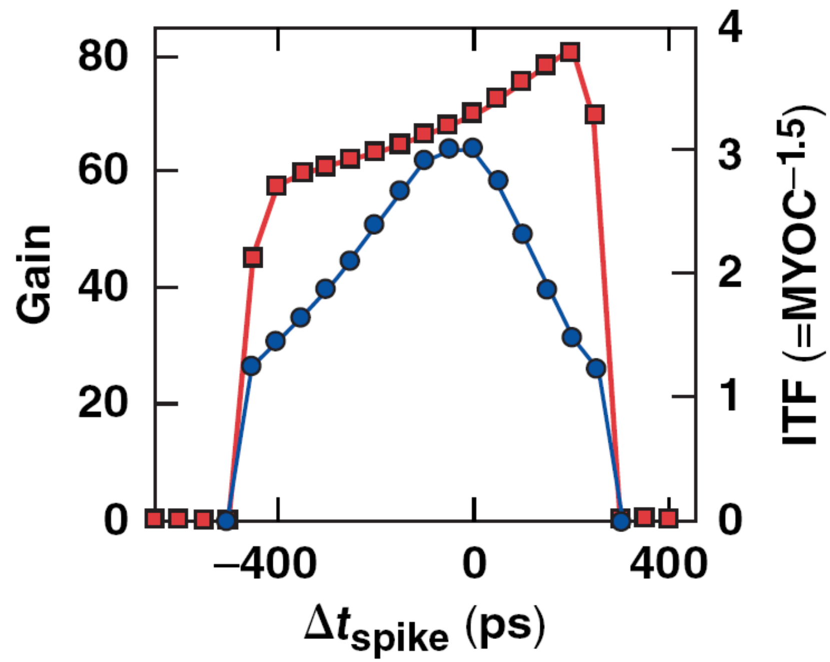
$$IFAR_{2/3} = \frac{R}{\Delta R} \text{ at } R = \frac{2}{3} R_0$$

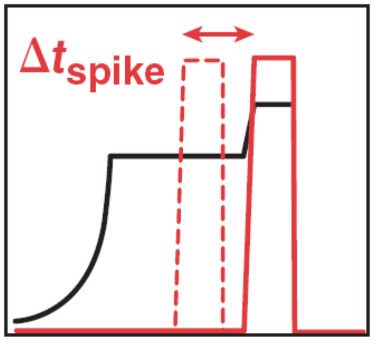
1-D beam profiles approximate polar drive.*

TC9109

Plastic-ablator shock-ignition targets are robust to shock timing and reduced clean volumes





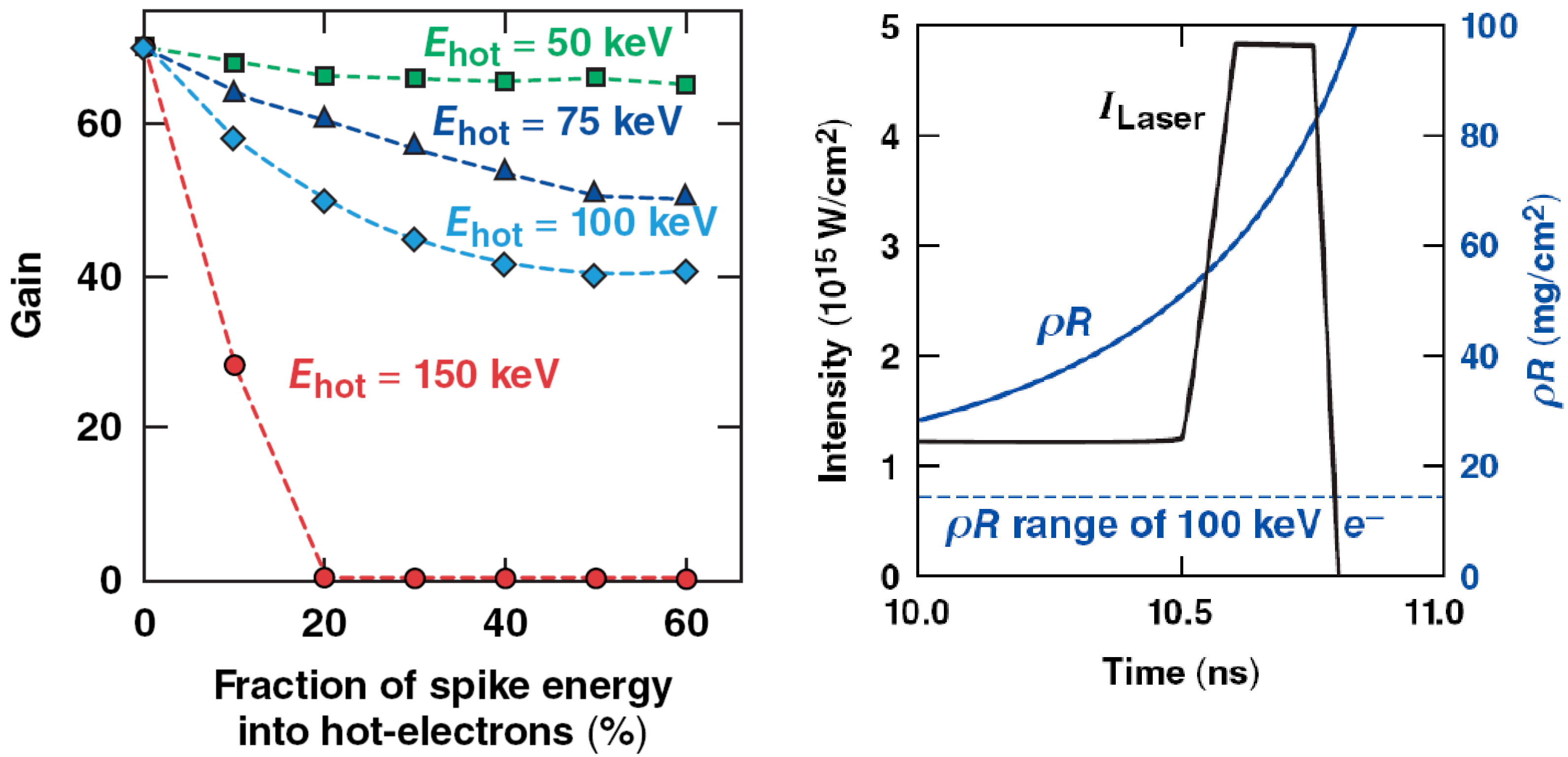


ITF for indirect-drive point design* is ~5.3 (MYOC = 33%) at 1 MJ.

*J. Lindl, presented to the JASON Review Committee Study #JSR-09-330, San Diego, CA, 14–16 January 2009.

TC9110

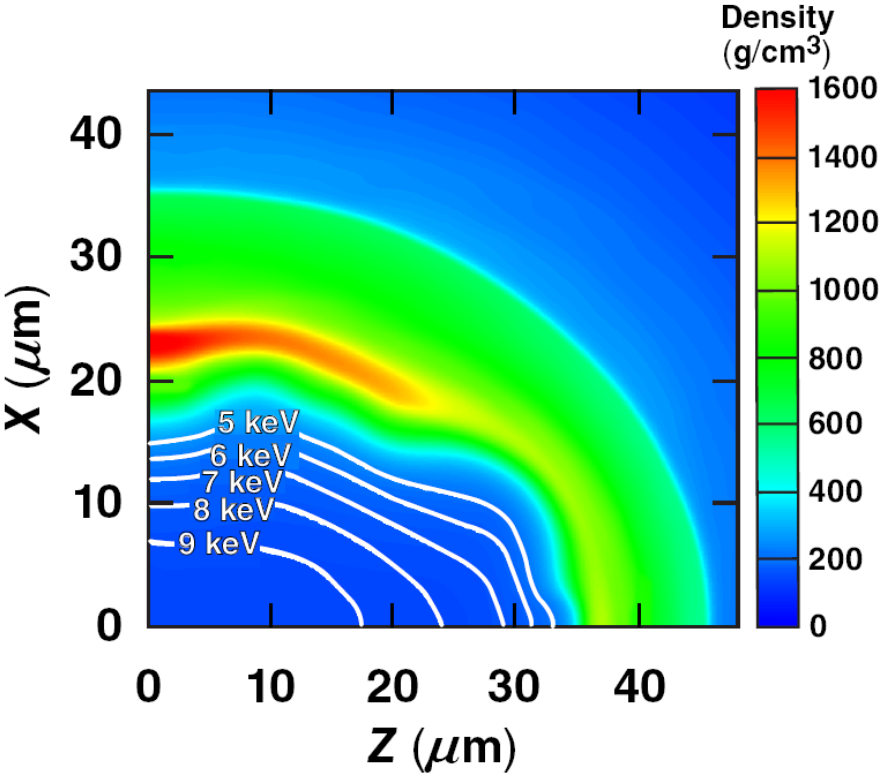
The plastic-ablator SI design is robust to hot electrons up to 100 keV at 60% of laser energy during the spike pulse



TC9111

Symmetric 2-D *DRACO* simulations performed with similar targets indicate robustness to ice roughness >3.5-μm rms

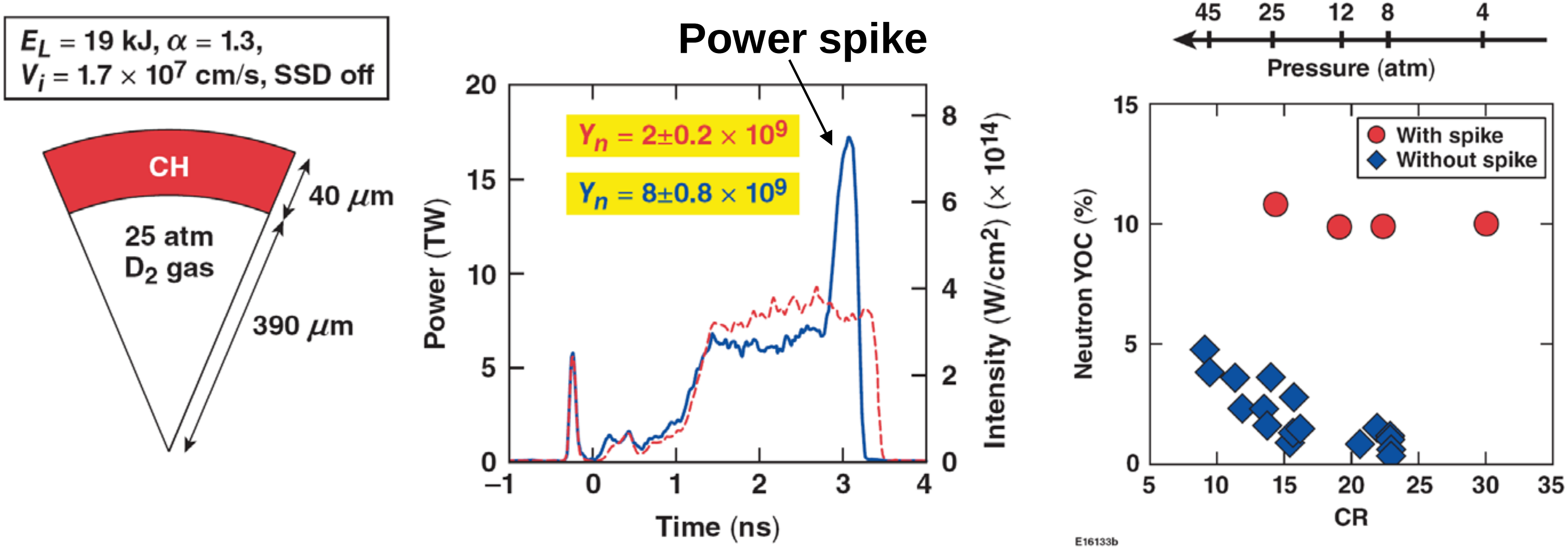
- Symmetric laser irradiation
- *DRACO* simulations with 3.5-μm-rms roughness in modes ℓ = 2 to 50
- Target ignites with full gain
- Upper limit on robustness to ice modes not yet explored
- Other nonuniformity studies to follow (imprint, target offset, polar drive, etc.)



A Schmitt (NRL) has also developed robust sub-MJ high-gain designs for KrF

TC9112

Shock-ignition experiments on OMEGA have shown improved performance when a shock launching power spike is added at the end of the laser pulse

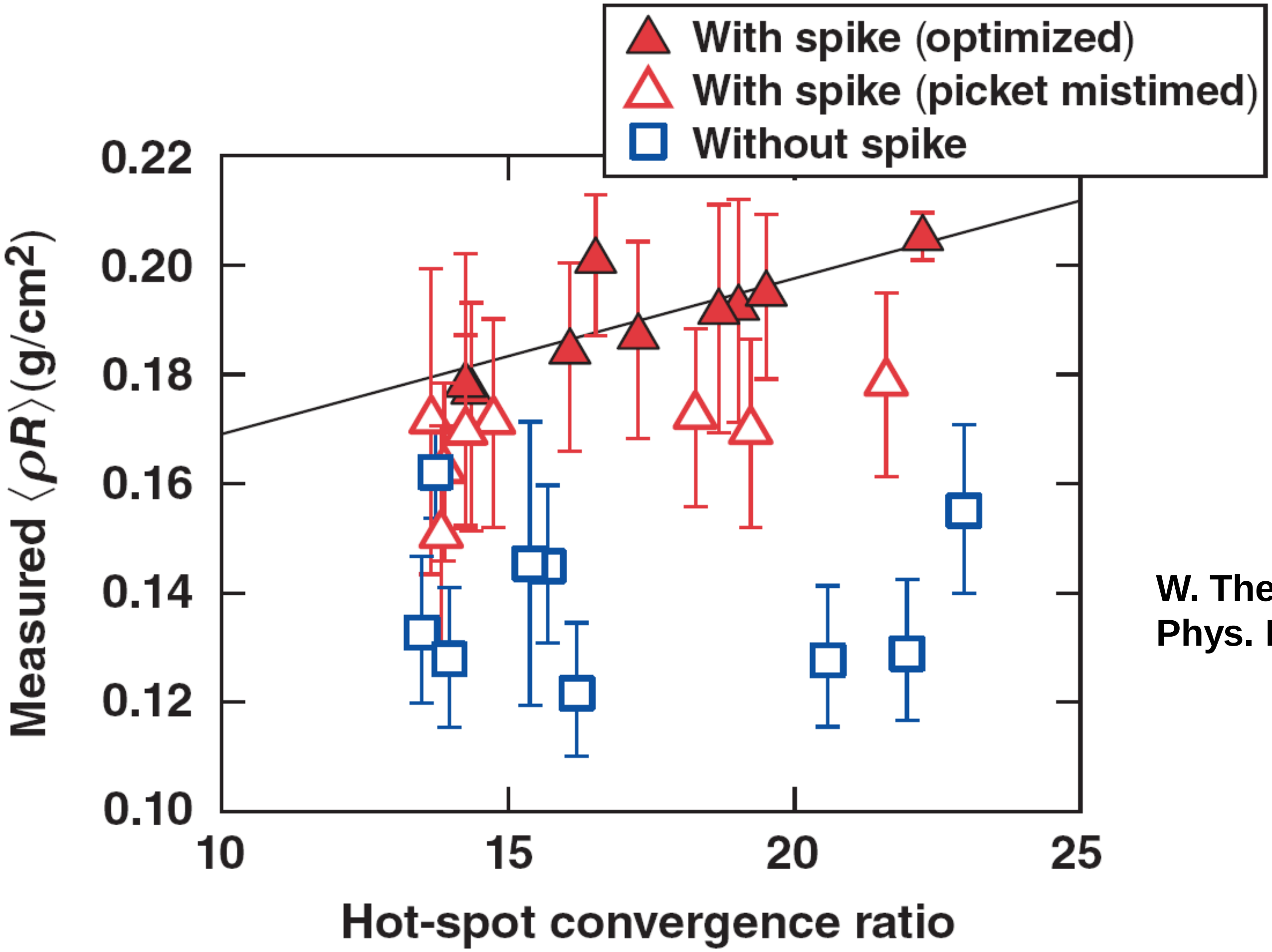


The neutron yield increases considerably when a shock is launched at the end of the pulse.

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

W. Theobald,et al Phys. Plasmas (2008)

Higher ⟨ρR⟩ exceeding = 0.2 g/cm^2 where measured in implosions with late spike

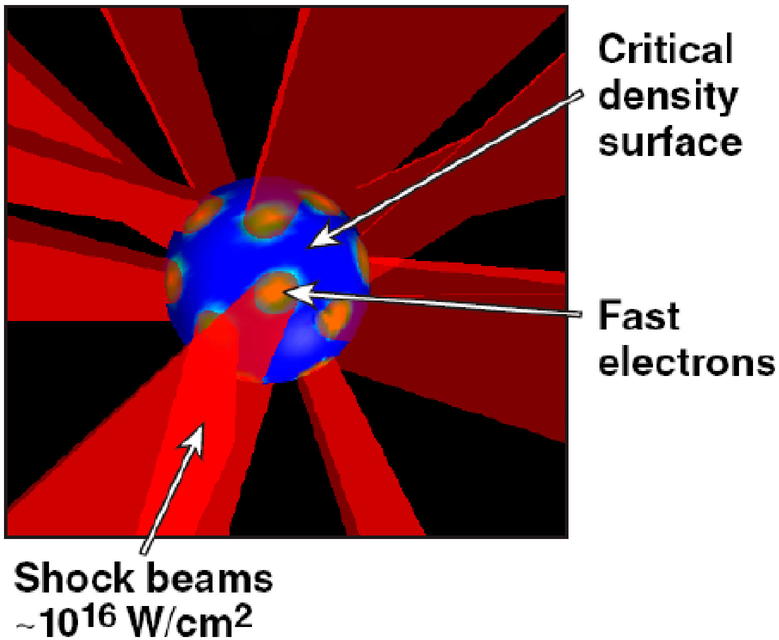


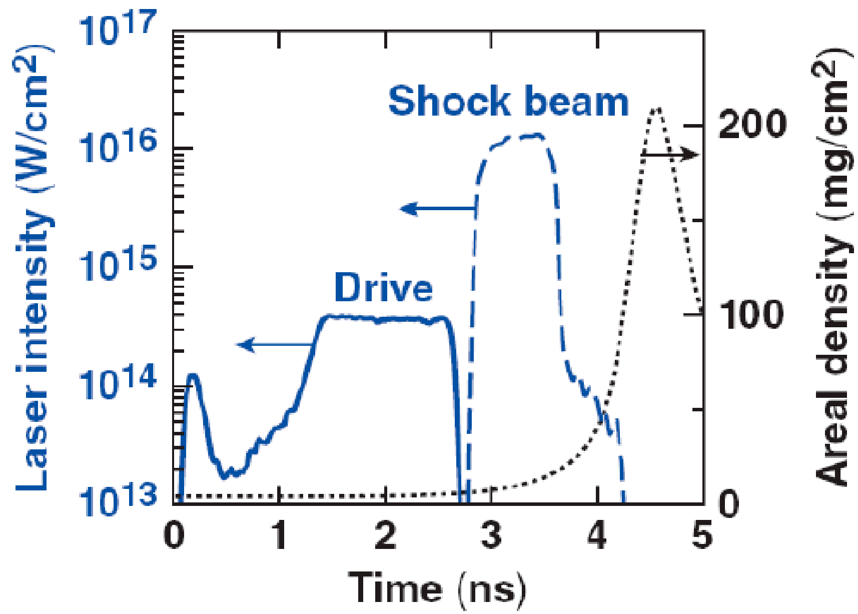
W. Theobald,et al
Phys. Plasmas (2008)

The shock-ignition pulse-shape implosions show an improved performance with respect to compression and neutron yields.

E16136

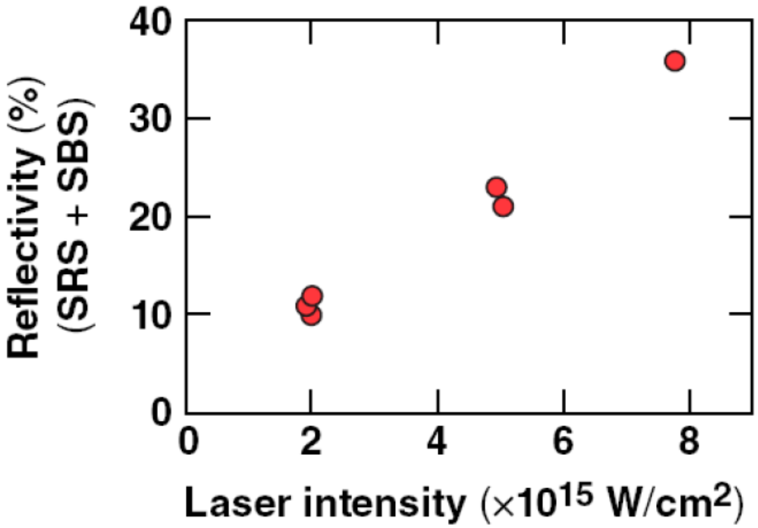
60 OMEGA beams were split into 40 low-intensity drive beams and 20 tightly focused beams to study LPI in shock ignition

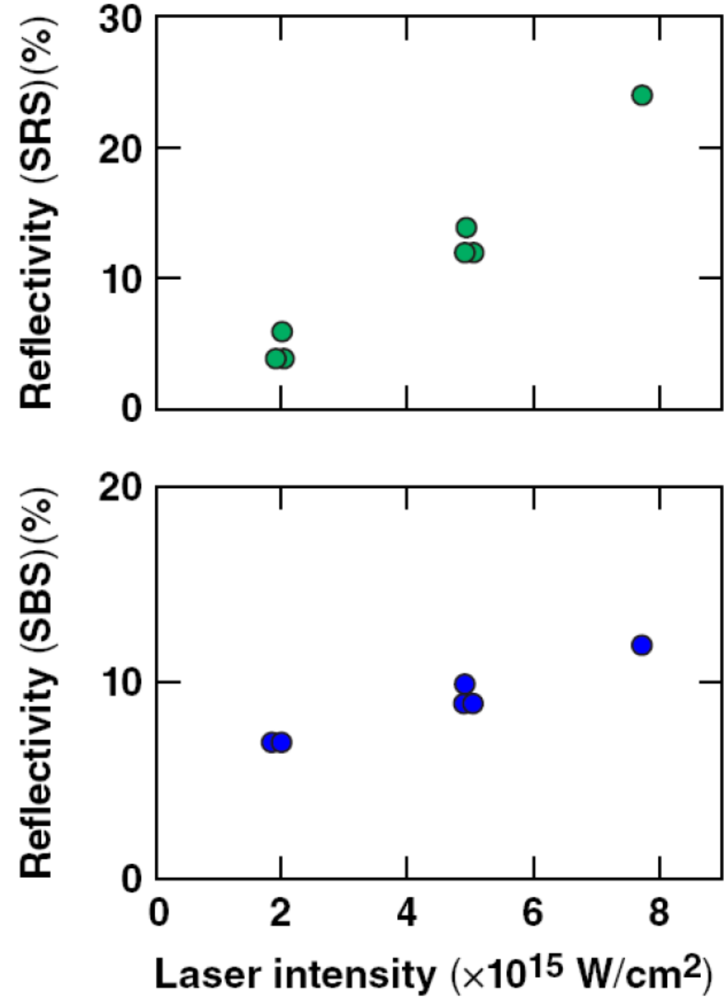




- Density scale length ~200 μm
- The delay and intensity of the tightly focused beams were varied
- Laser backscattering and hot-electron generation were studied

Up to 35% of the shock-beam laser energy is lost due to backscatter

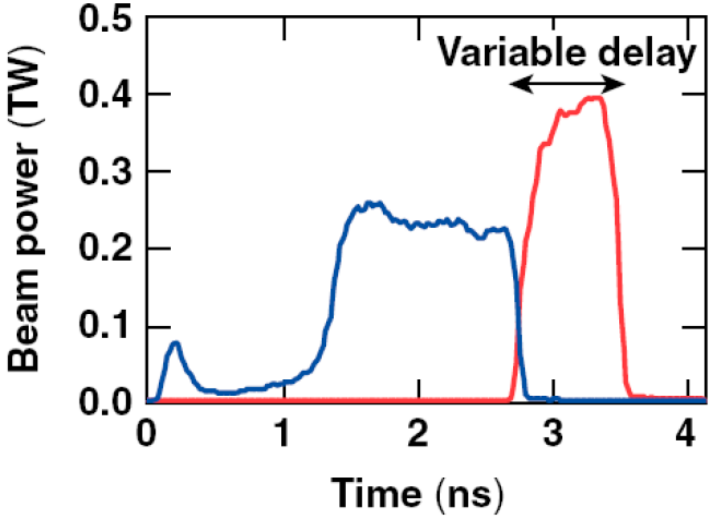


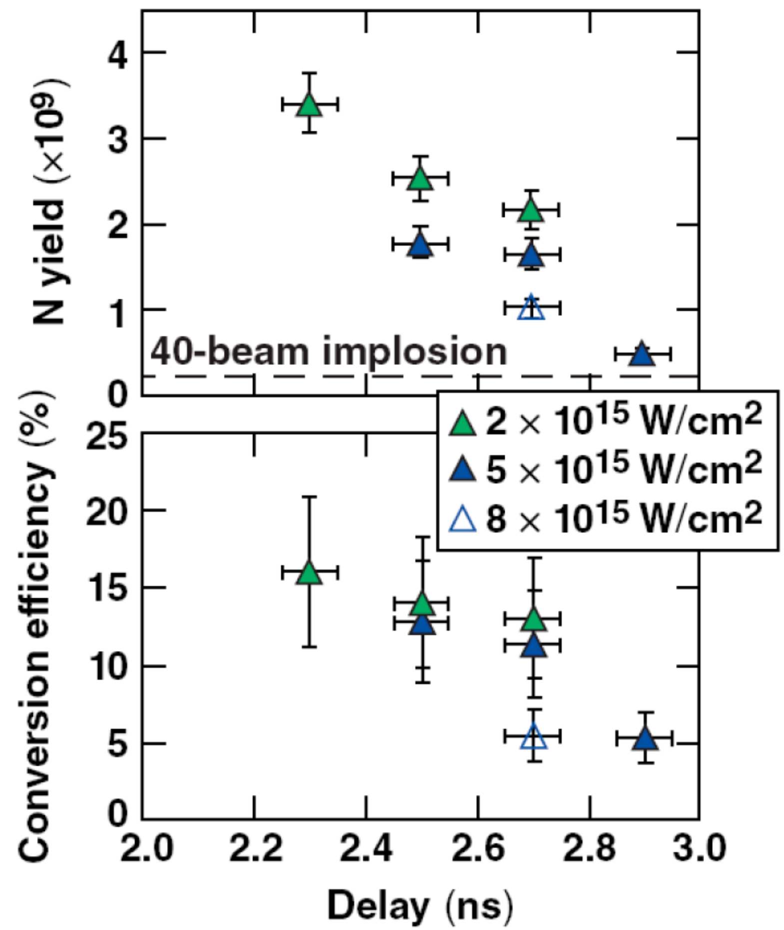


- No measurable signal of the 3/2 harmonic
- SRS dominates back reflection at highest intensity
- SBS reflection is relatively stable at ~10%

E18435

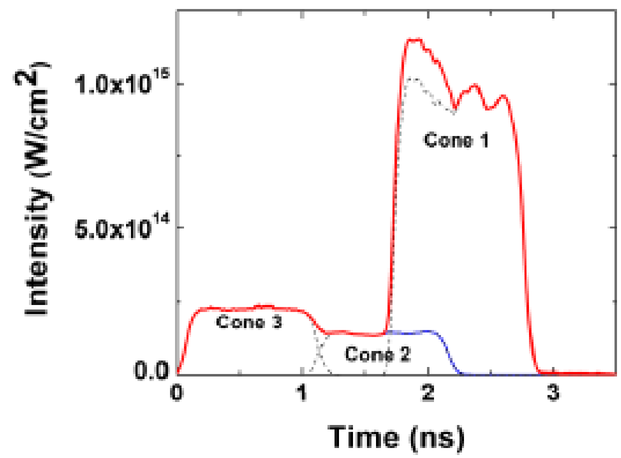
Up to 16% of the shock-beam energy is converted into hot electrons of 45-keV temperature

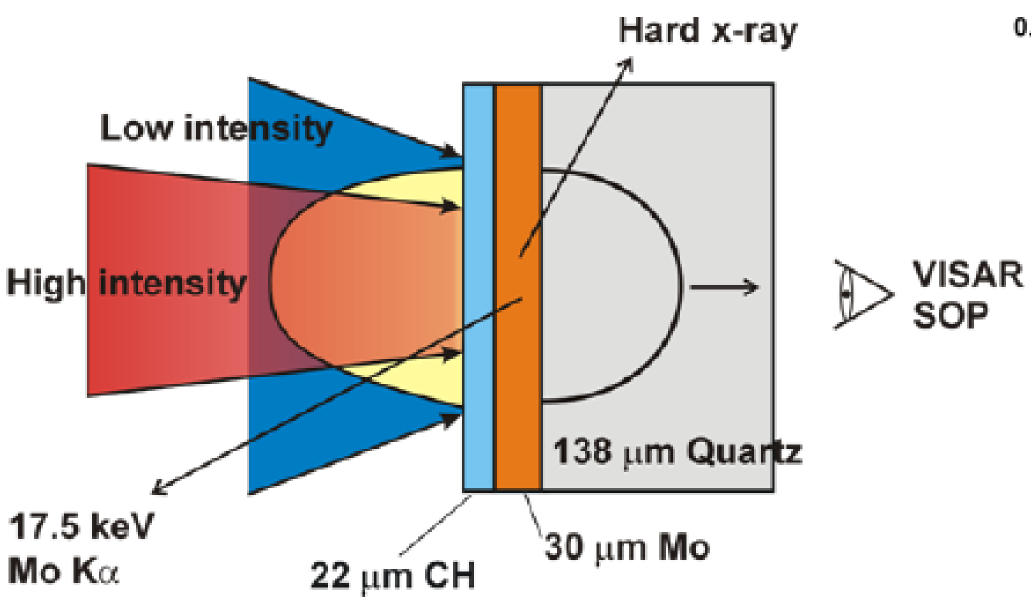




A laser-plasma interaction experiment was performed in planar geometry with overlapping beams

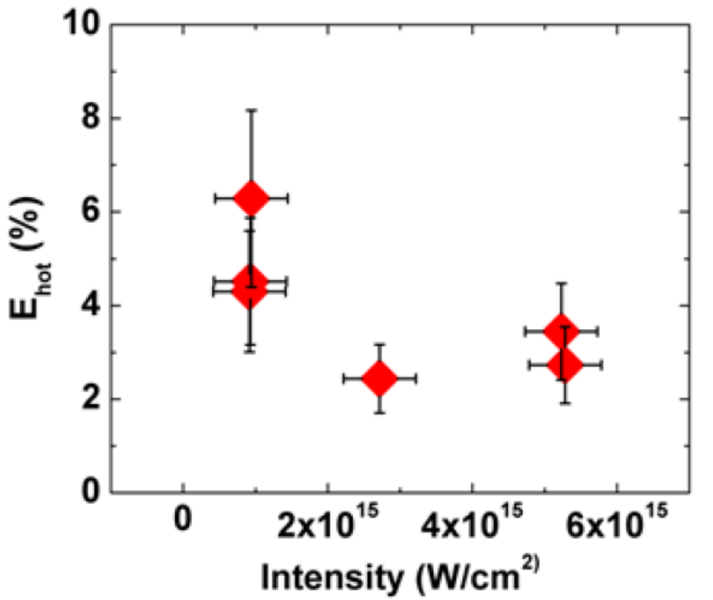
- Pre-plasma: ~2 × 10^{14} W/cm^2
- Shock: ~1 - 6 × 10^{15} W/cm^2
- Density scale length: ~500 μm



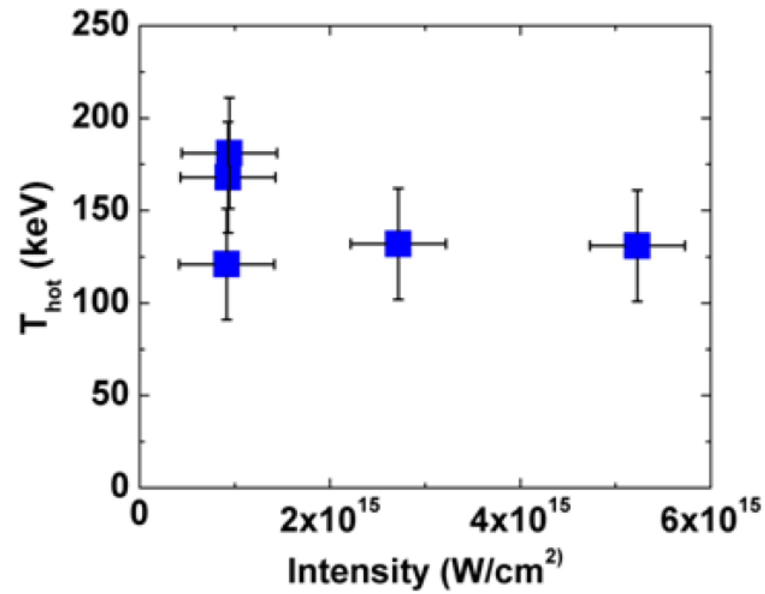


Up to 6% of the high intensity laser energy is converted into hot electrons

Hot electron energy fraction versus intensity

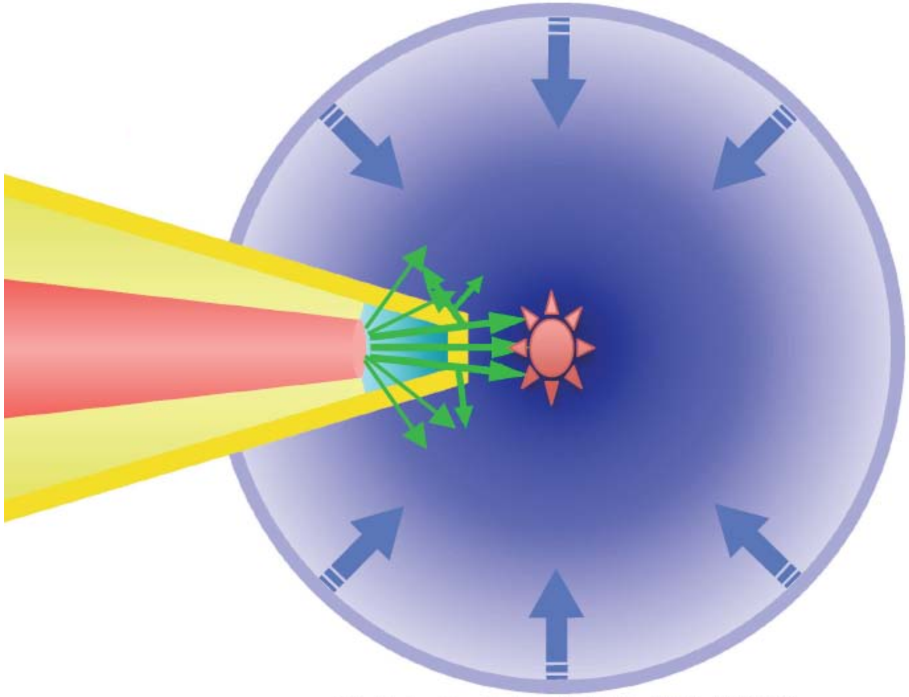


Hot electron temperature versus intensity



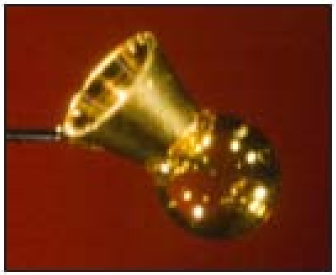
- The measured hot electron temperature is a factor ~3 higher compared to spherical target experiment

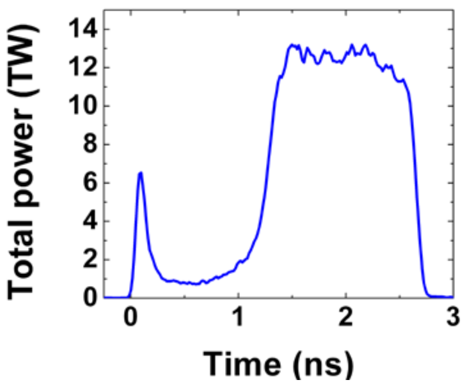
Fast Ignition

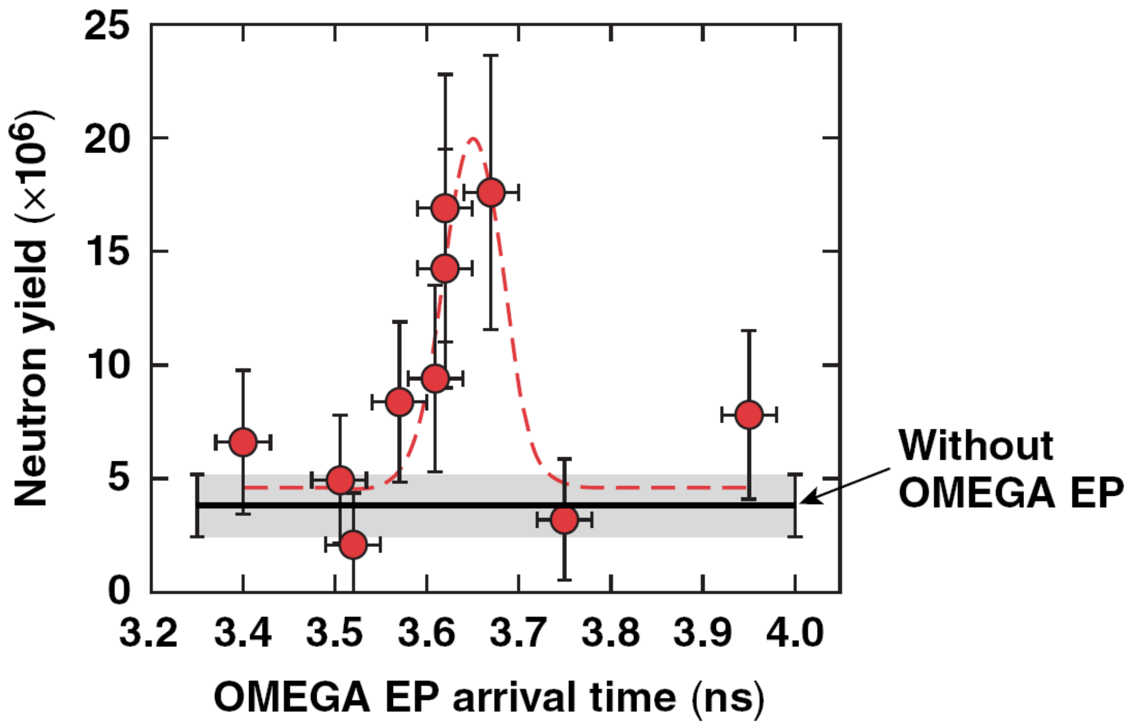


M. Tabak et al., PoP 1, 626 (1994)
S Atzeni et al., PPCF 51, 015016 (2009)

Fast electron heating is observed in fast ignition integrated experiments on OMEGA







Implosion

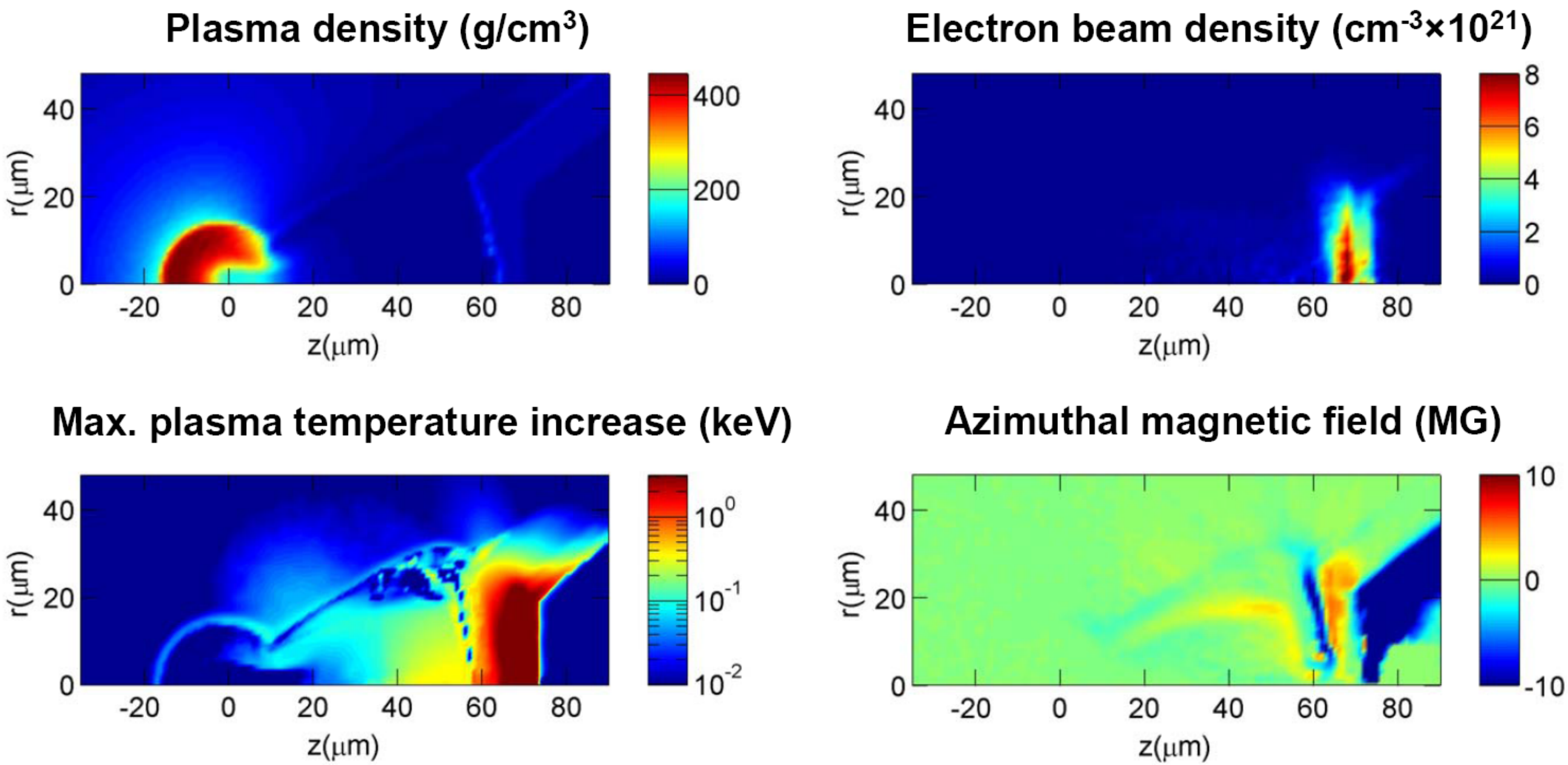
Energy	~18 kJ (54 beams)
Wavelength	351 nm
Pulse shape	Low-adiabat, $\alpha \approx 1.5$
Pulse duration	~3 ns
Implosion velocity	~2×10^7 cm/s

Heating beam

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

Low-energy electrons do not heat the core in integrated DRACO-LSP simulation

- Simulation for 10ps, 1kJ, R_{80}=27μm, 20% EP energy converted into fast electrons. Injection before peak ρR
- n_{hot} and B are shown at the peak of the laser pulse

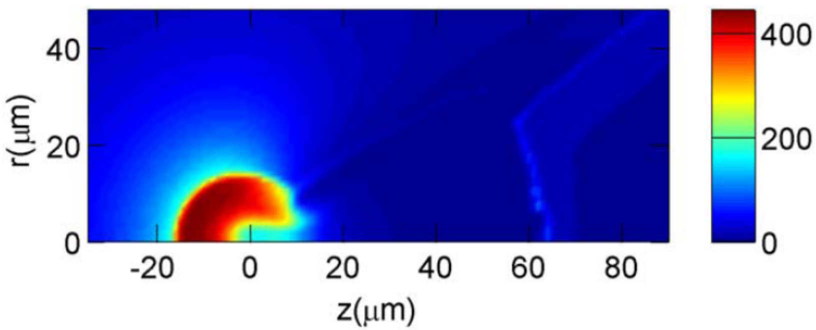


The simulations predict an improved fast electron coupling at higher laser intensity

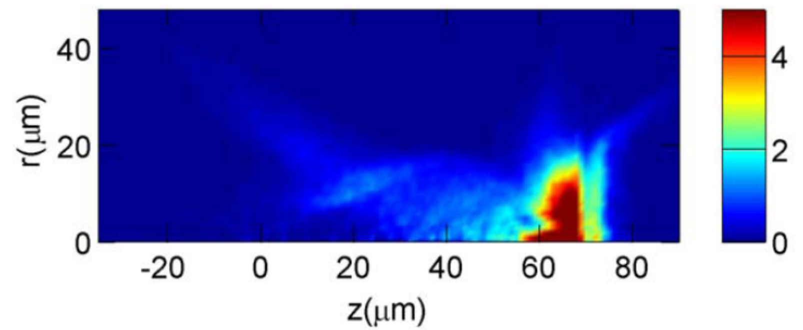
Simulation for 10ps, 2.6kJ, R_{80}=15µm. Injection before peak ρR

- CE (>100 g/cm³) improves from 0.6% to 2.4%
- CE (>10 g/cm³) slightly improves from 5% to 6%

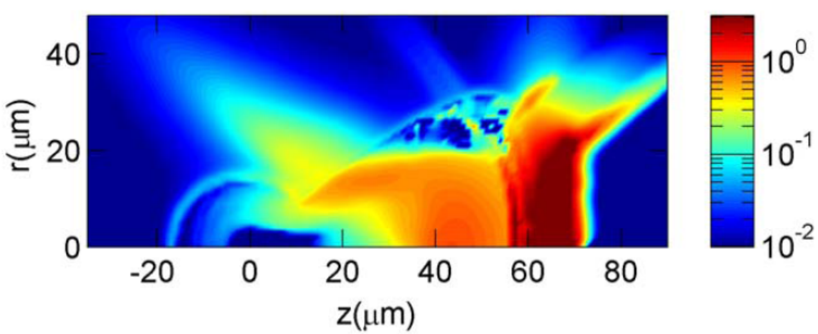
Plasma density (g/cm³)



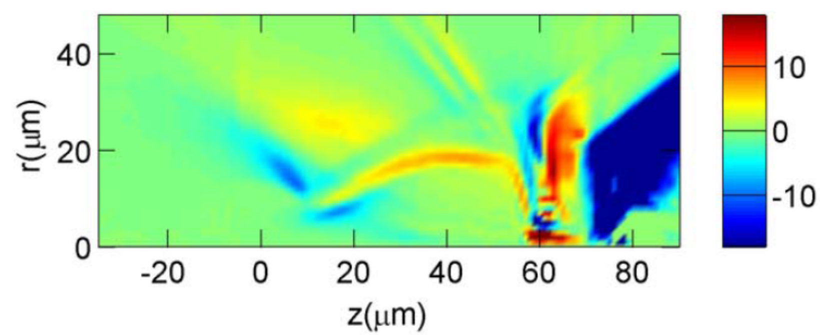
Electron beam density (cm⁻³×10²¹)



Max. plasma temperature increase (keV)



Azimuthal magnetic field (MG)



About 60 researchers participated to the 9th FSC meeting at LLNL—a special two-day topical meeting was devoted to assess electron divergence in fast ignition

FSC

UR LLE

UR Fusion Science Center

NIF iLSA

FUSION SCIENCE CENTER MEETING
ON ELECTRON DIVERGENCE IN FAST IGNITION

AUGUST 5-6, 2010

LAWRENCE LIVERMORE NATIONAL LABORATORY

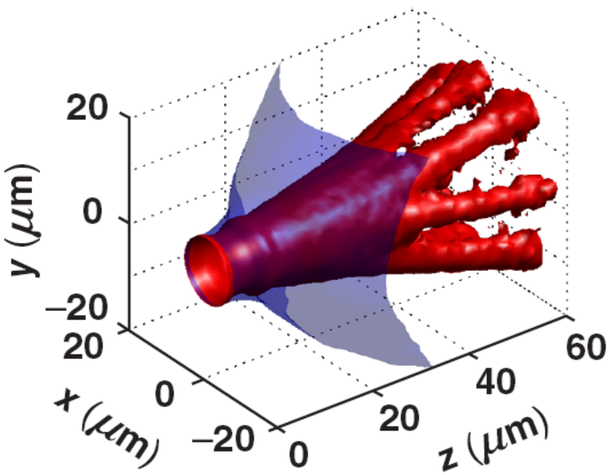
SUMMARY AND CONCLUSIONS

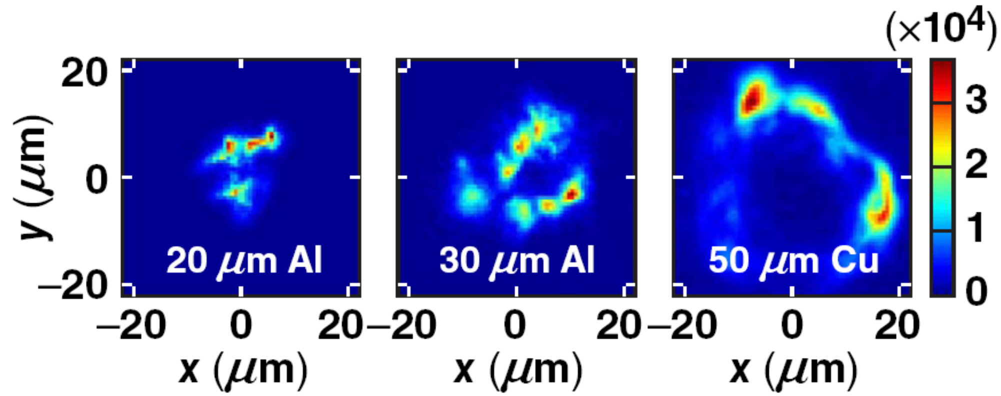
by

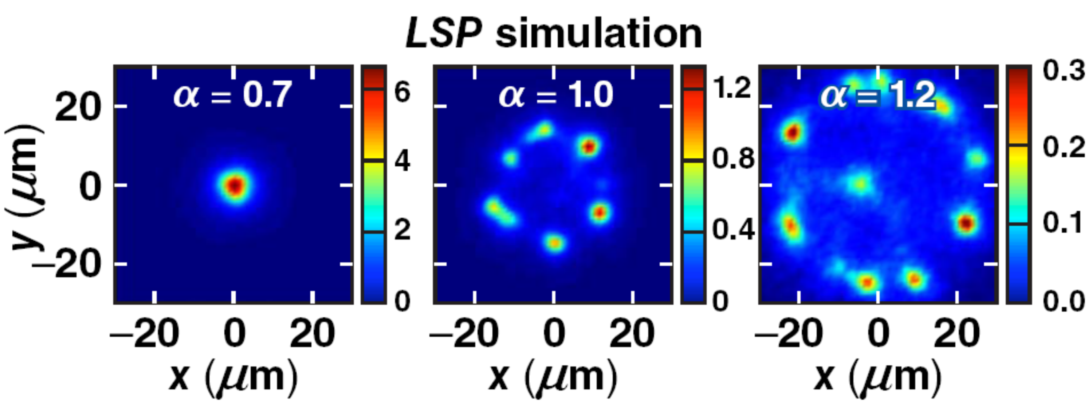
R. Betti

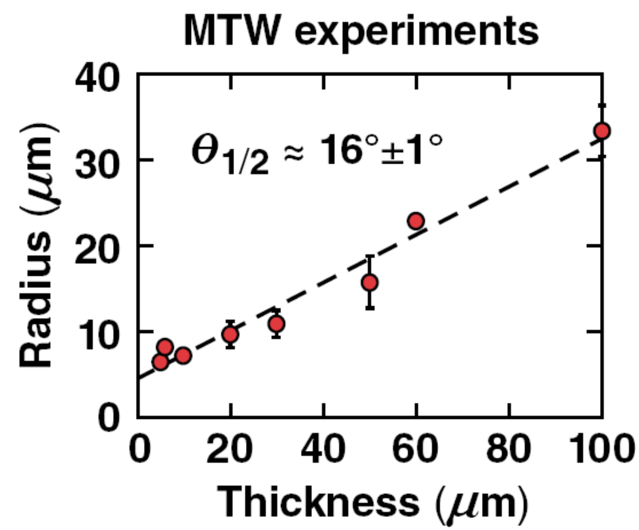
The meeting produced a final report available on the FSC website.

Experiments on MTW and *LSP* simulations study fast-electron divergence and magnetic collimation





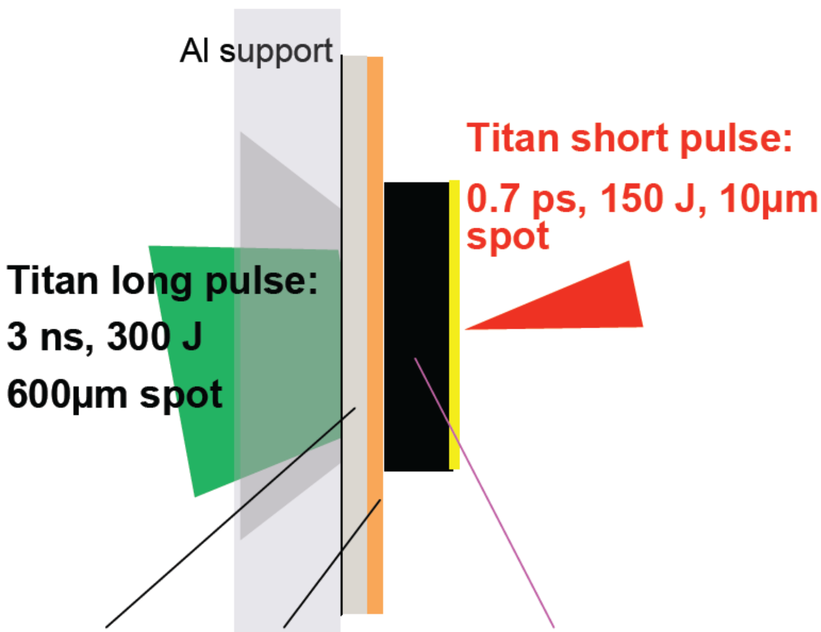




Various type of targets were used to compare fast electrons transport in partially and fully driven, un-driven foams and cold CH

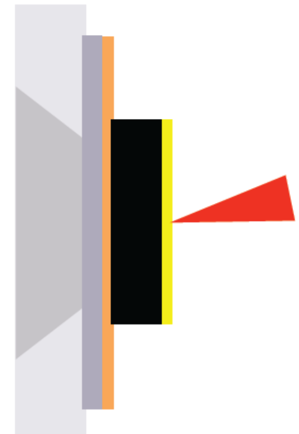
Foam package targets for hot transport

(with various SP and LP timing delays)



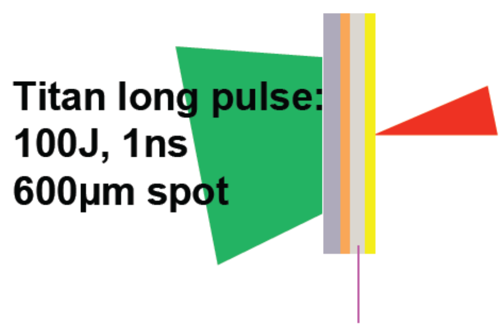
25 µm CH / 5 µm Cu tracer/ 139 µm CRF foam

($r_{initial}$=150 mg/cc) / 4 µm Au



20 µm Al/5 Cu/138 CRF/3.9 Au

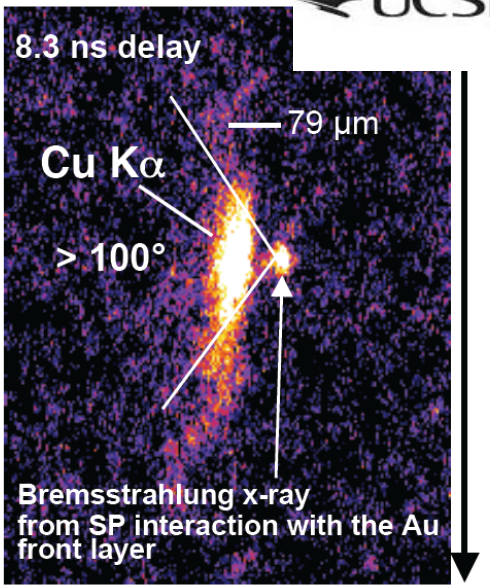
CH insulator as transport layer

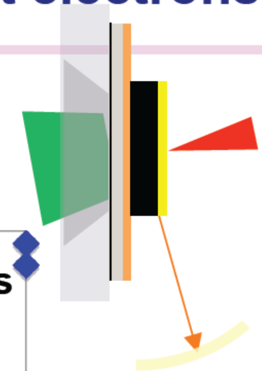


20 µm Al/5 Cu/15 CH/3.9 Au

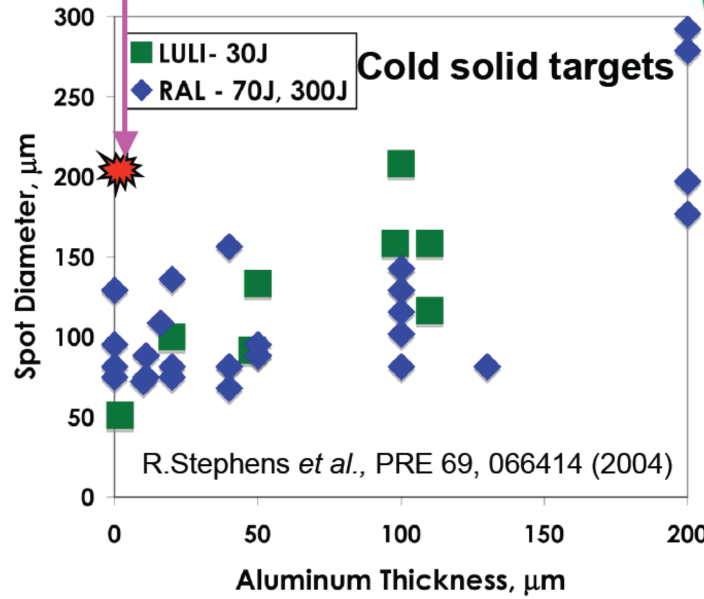
Large extended Cu Ka spot was consistently observed in WDM targets suggesting a large angular spread of fast electrons

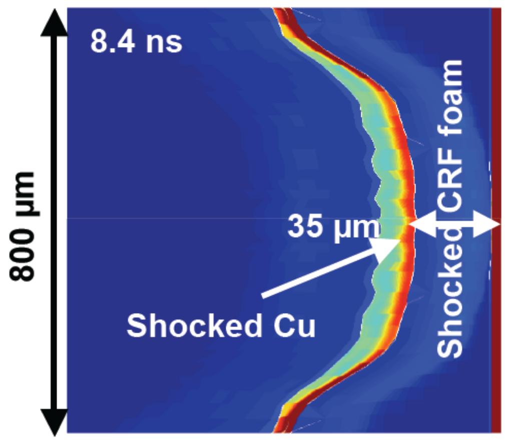
FSC UCSD GENERAL ATOMICS OHIO STATE UNIVERSITY College of Mathematical and Physical Sciences





New results from WDM experiments





- 2X larger Kα spot in WDM case compared to the cold solid targets results
- Such large extended Kα spot was neither observed in un-driven and partially driven (at 3 ns delay case) foam targets, nor in CH insulator targets

The NIF can explore advanced ignition options

- With day-one hardware, the NIF can explore high-gain shock ignition

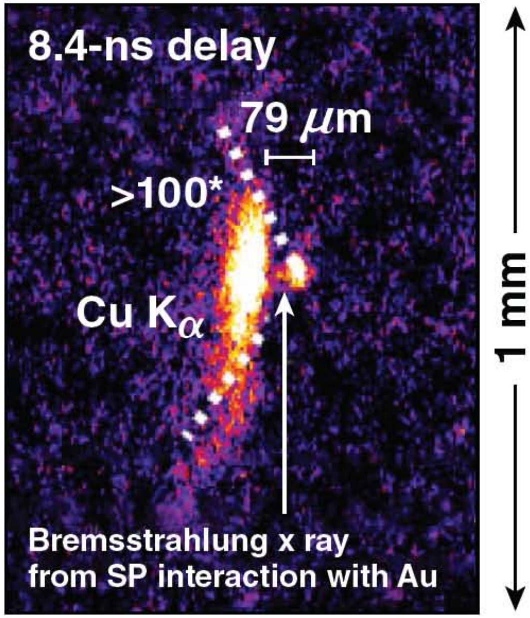
  - Polar Shock Ignition (uses half the NIF beams to drive the implosion and the other half to drive the ignitor shock)

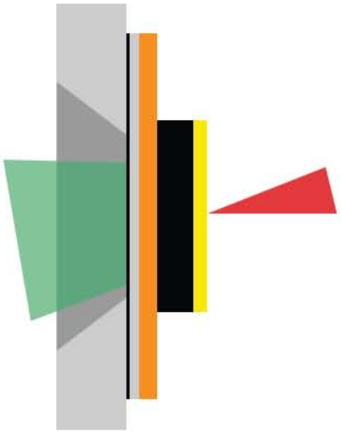
- Fast Ignition requires major hardware upgrades: 100kJ-class multi-PW laser
  [also talk by P. Patel at this meeting]

- Polar Direct Drive requires minor upgrades: multi-FM or 2D-SSD
  (talk by J. Soures at this meeting)

Back-up slides

Fast-electron transport in WDM is investigated in a set of experiments on Titan using foam targets





A large angular spread (>90) has been inferred from the size of the Cu K_α emission spot.

About 3% of the electron-beam energy is deposited in the core region with ρ>100 g/cm^3

FSC UR LLE

Energy deposition

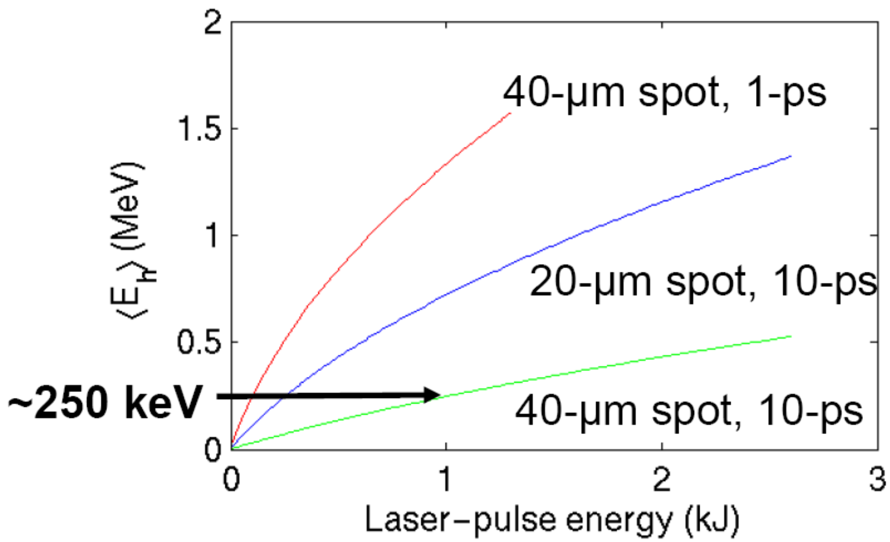
	Fraction of e-beam energy	Fraction of laser energy
Deposition in gold	52%	10%
Deposition in plastic with ρ>10 g/cm^3	25%	5%
Deposition in plastic with ρ>100 g/cm^3	3%	0.6 %

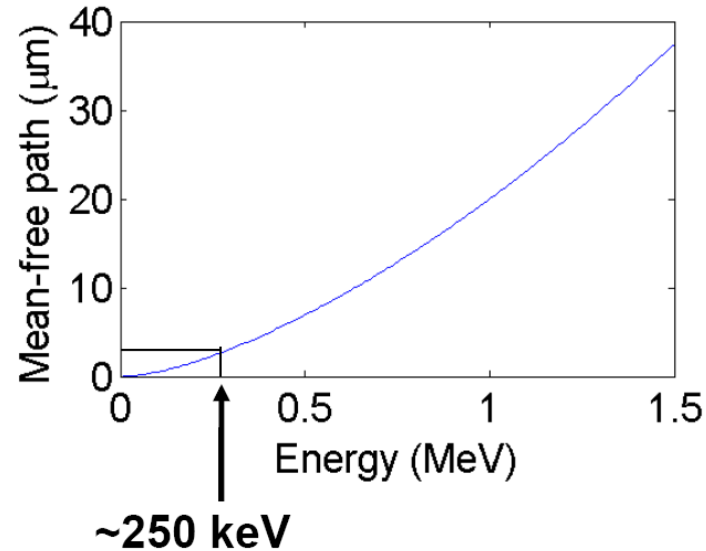
Neutron yield increase

Neutron yield without hot electrons	6.6×10^8
Neutron yield with hot electrons	7.4×10^8
Neutron yield increase	8×10^7
Neutron yield increase in the region with ρ>100 g/cm^3	1.6×10^7

The hot-electron energy can be too low for a good penetration through the Au cone tip

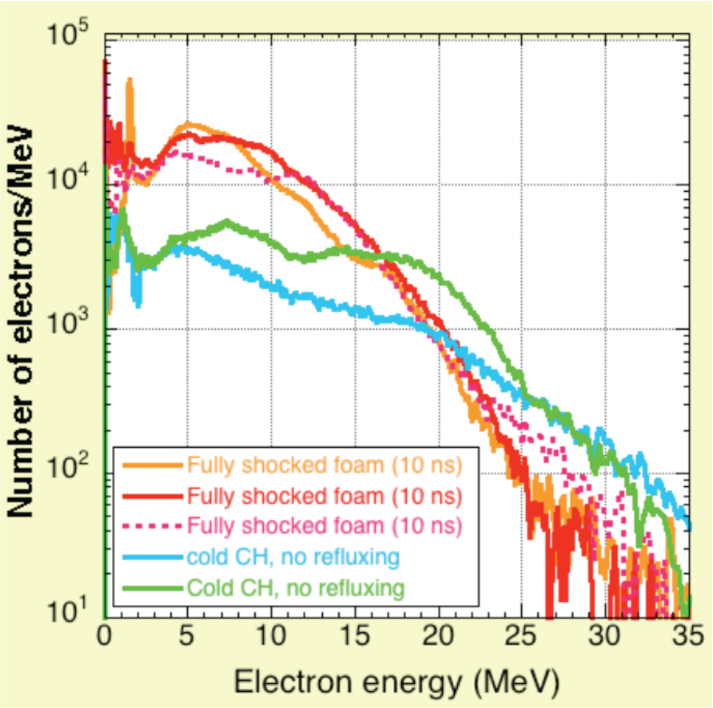
Mean hot-electron energy assuming ponderomotive scaling (averaged within FWHM of the spatial and temporal distribution for a Gaussian pulse)

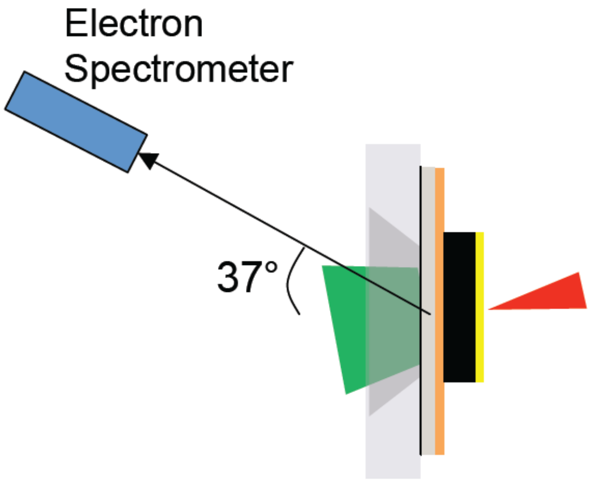




- **Mean-free path of 250 keV electrons is a few µm and is smaller than the cone wall thickness**
- **Higher laser intensities are required**

5X more electrons were emitted sideway in WDM compared to CH insulator case





- **Significant increase in the number of escaped electrons from the side is consistent with large angular spread of electrons in WDM**