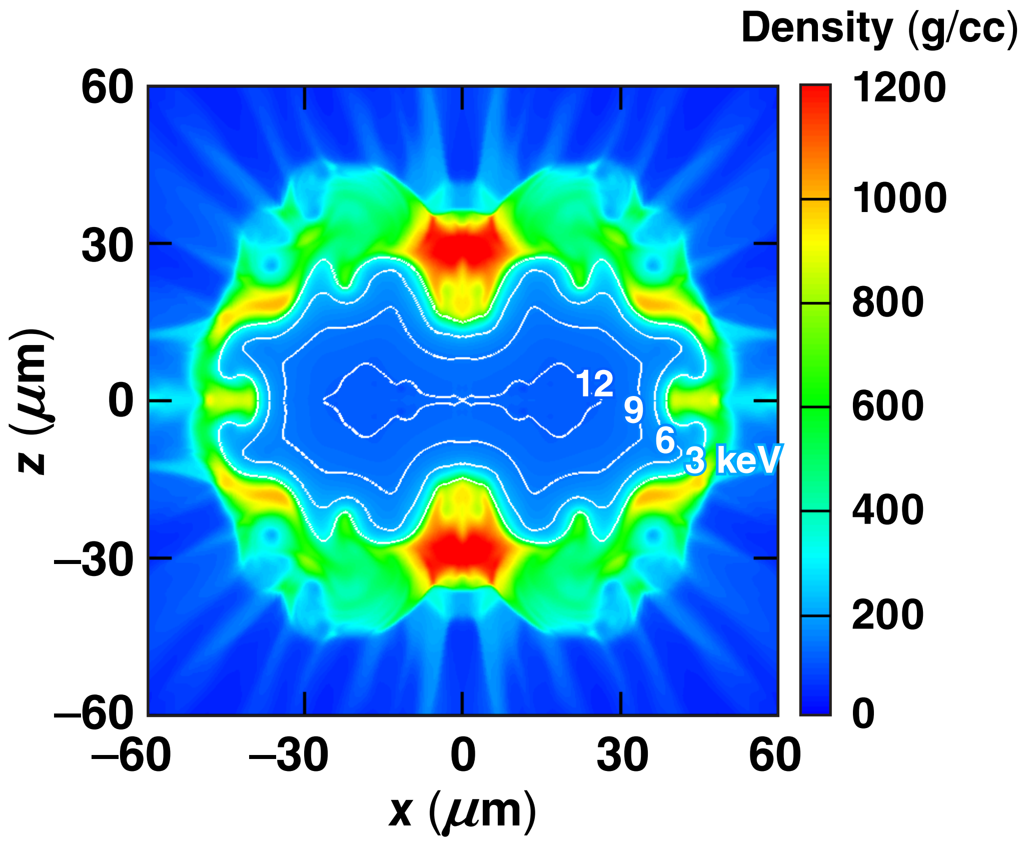
NIF Target Design and OMEGA Experiments for Shock-Ignition Inertial Confinement Fusion



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American Physical Society
Division of Plasma Physics
Providence, RI
29 October–2 November 2012

Summary

Polar-drive shock ignition is a viable path to ignition on the NIF

- Shock-ignition–relevant shocks up to 100 Mbar have been demonstrated on OMEGA in planar geometry in agreement with simulations
- One- and two-dimensional simulations demonstrate that polar-drive shock ignition is robust to various forms of system uncertainty and nonuniformity to levels that exceed NIC IDI specifications
- 1-D target design has an ignition threshold factor (ITF) in 1-D of 4.1
- 2-D polar-drive simulations predict gain of 38 at 750 kJ with all expected levels of non-uniformity

Experiments and simulations are validating shock-ignition physics.

Collaborators

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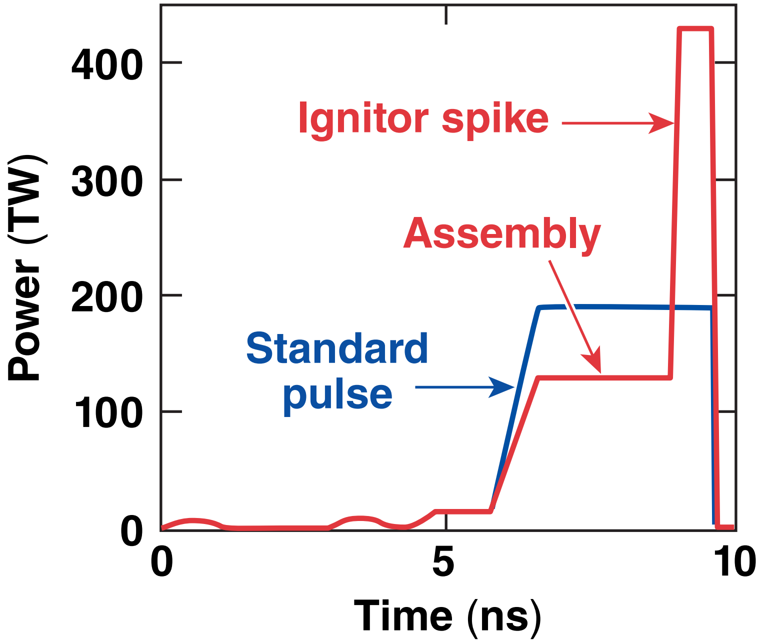
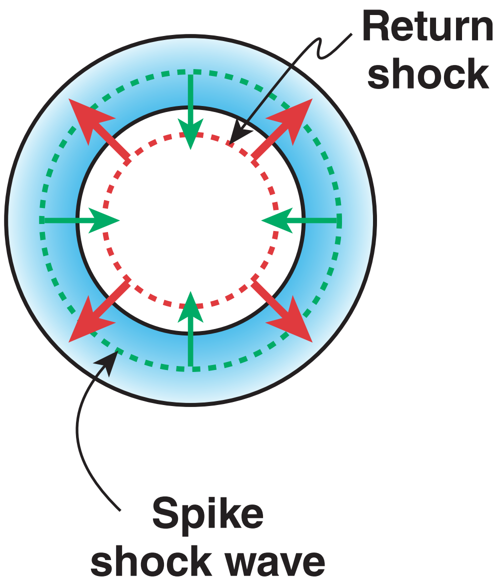
Outline

- Background
- Strong shock generation at laser intensities of mid × 10^{15} W/cm^2
- Laser–plasma interactions in shock ignition
- Simulations and parameter studies for the NIF SI point design

Shock ignition separates the fuel assembly phase from the ignition phase using a single laser system



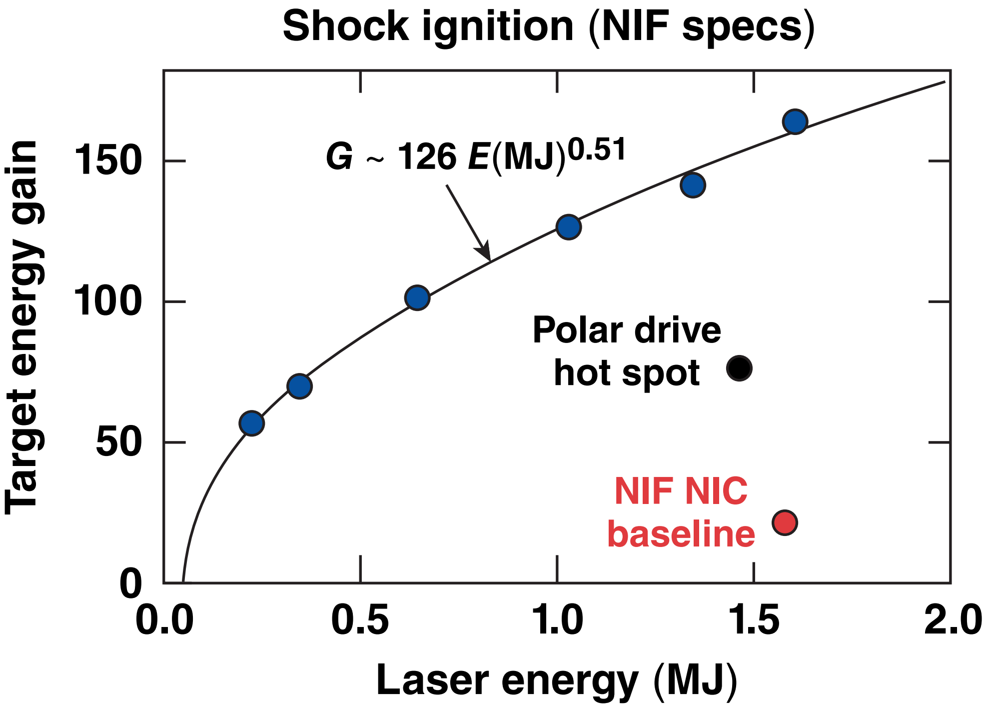


- Low implosion velocities, higher fuel mass lead to higher gains at a fixed laser energy

TC10153

R. Betti *et al.*, Phys. Rev. Lett. 98, 155001 (2007).

Shock ignition lowers the minimum energy required for ignition and allows the potential for high gain at low energies

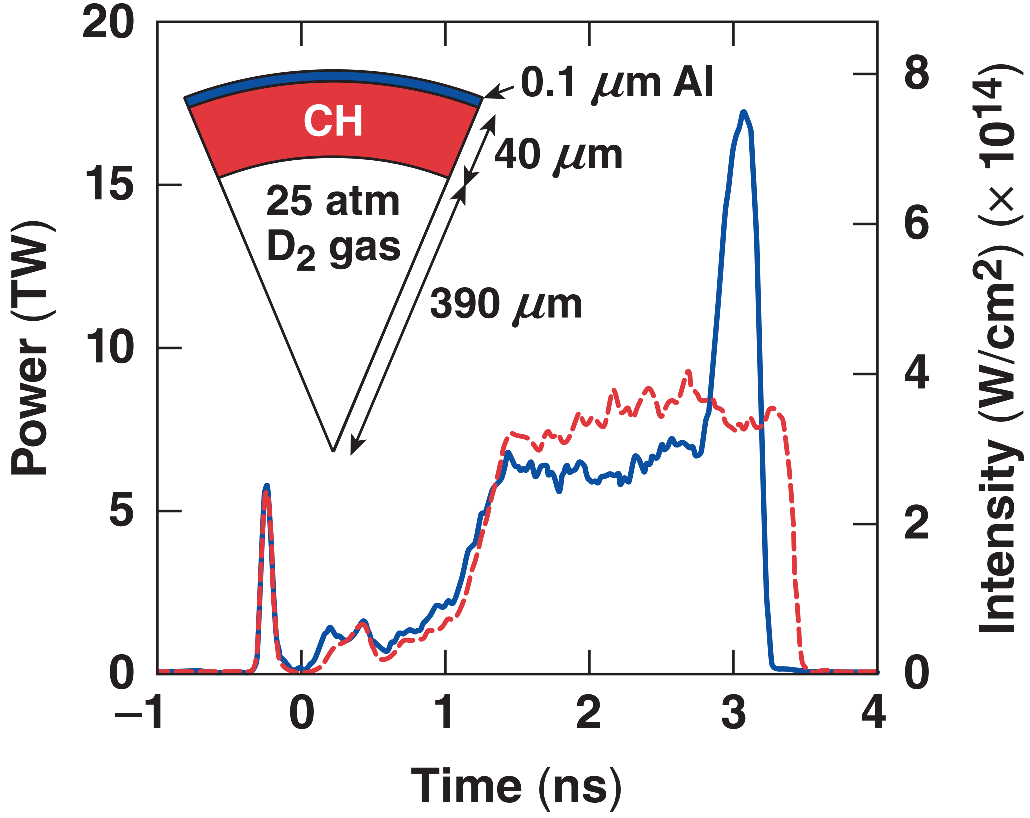


The shock pulse lowers the energy required to ignite a given capsule.

L. J. Perkins *et al.*, Phys. Rev. Lett. 103, 045004 (2009).
See also
X. Ribeyre, *et al.*, Plasma Phys. Control. Fusion 51, 1 (2009),
M. Lafon, *et al.*, Phys. Plasmas 17, 052704 (2010),
A. J. Schmitt, *et al.*, Phys. Plasmas 17, 042701 (2010).

Warm plastic implosions with spike pulse shapes on OMEGA have shown higher neutron yield relative to no-spike pulses of the same energy*

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



$Y_n = 2 \pm 0.2 \times 10^9$

$Y_n = 8 \pm 0.8 \times 10^9$

TC9875a

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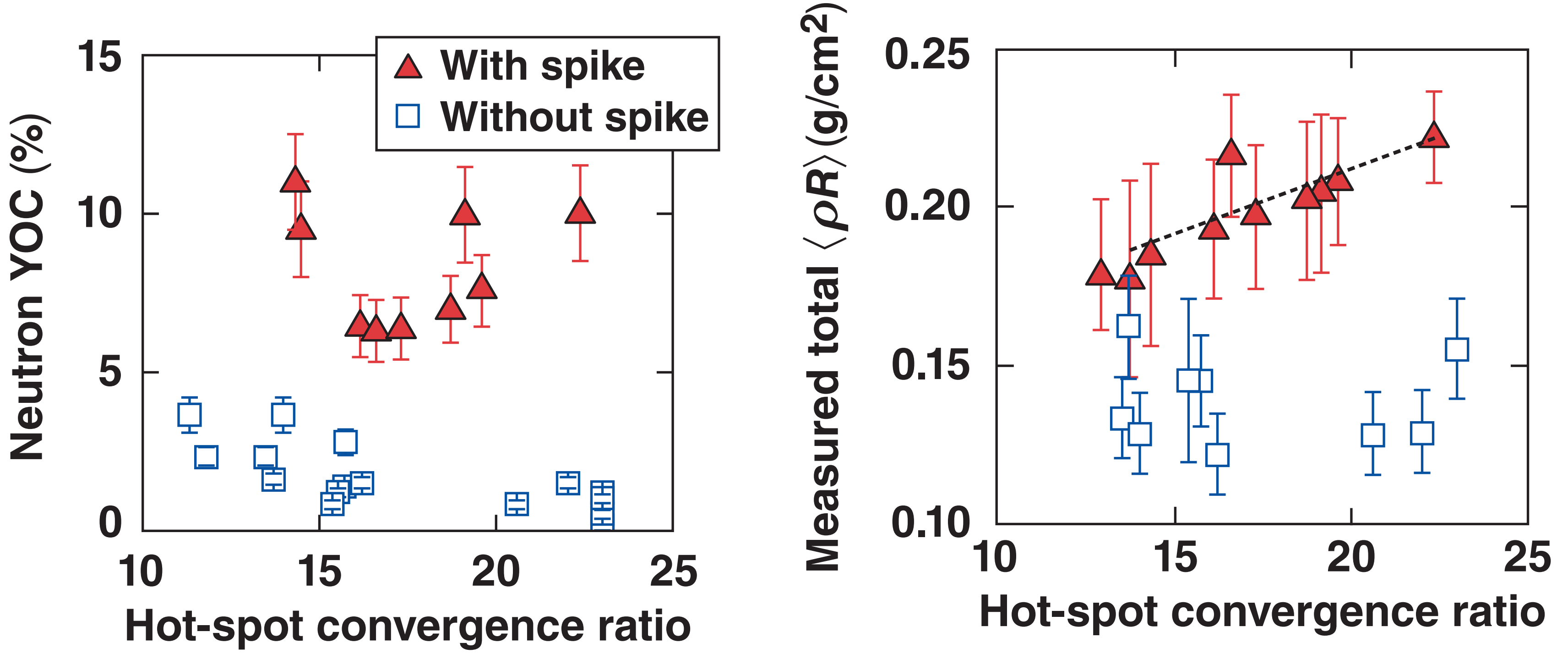
*W. Theobald *et al.*, Phys. Plasmas 15, 056306 (2008).

Higher neutron yield over clean (YOC) and areal density have been achieved in shock ignition implosions

YOC ≡ experimental yield/1-D



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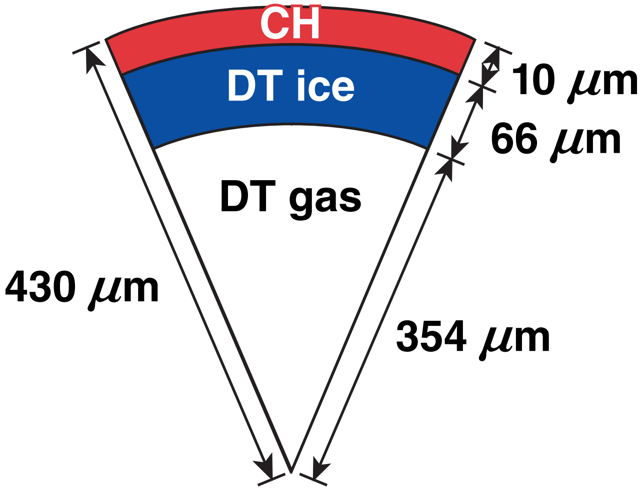
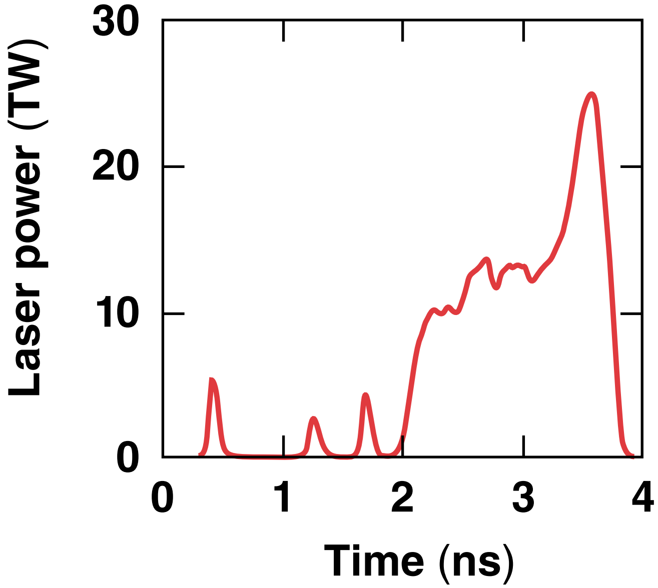
*W. Theobald *et al.*, Phys. Plasmas 15, 056306 (2008).

Cryogenic experiments* with spike pulses have achieved excellent performance relative to 1-D simulations





Adiabat	3.5
Neutron yield (experimental)	5.6×10^{12}
YOC (%)	33
ρR (mg/cm^2)	200

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*R. Nora *et al.*, Bull. Am. Phys. Soc. 56, 327 (2011).

Outline

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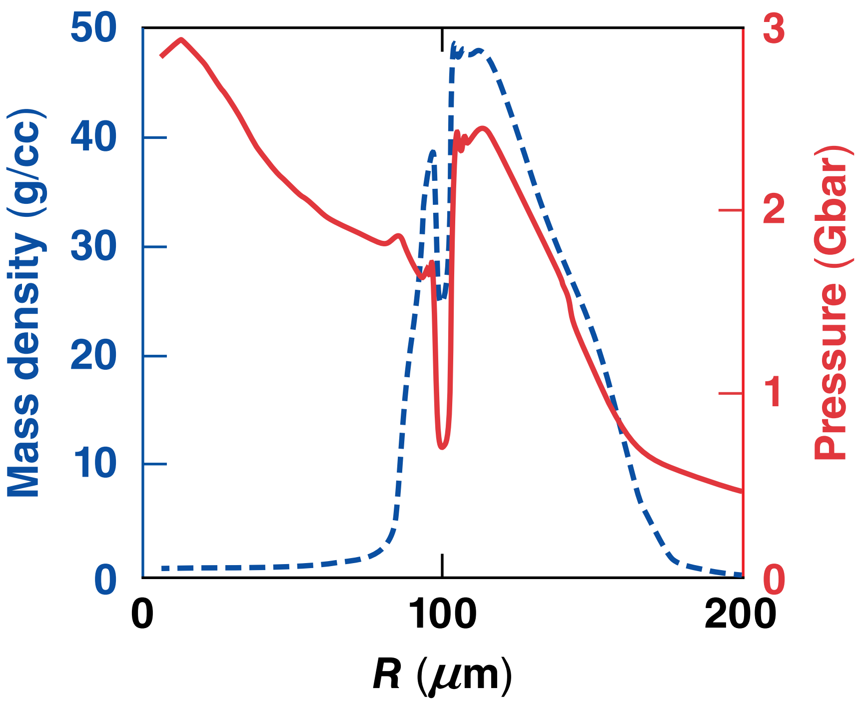
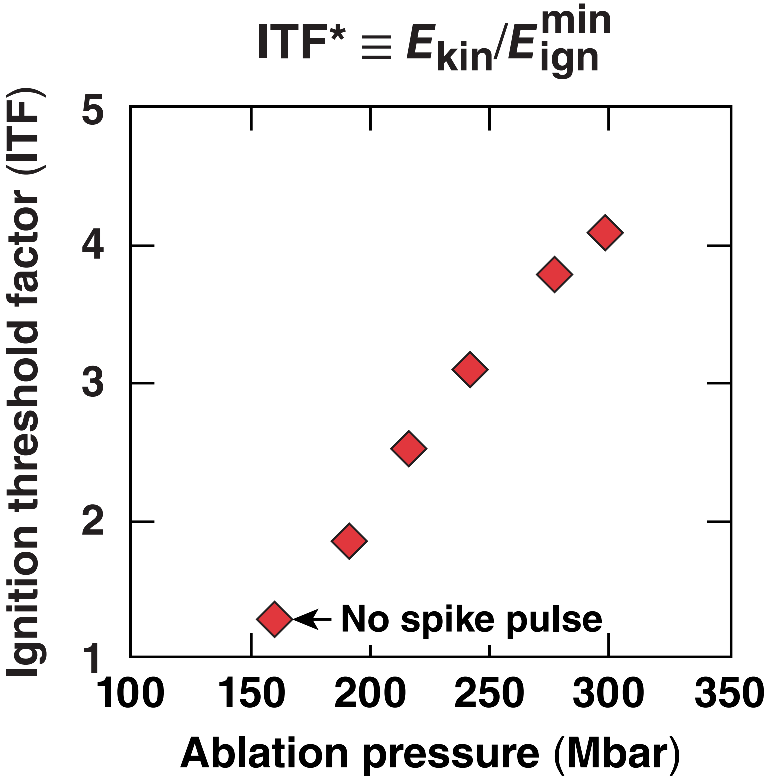
Shock ignition requires the spike pulse to generate a spherically symmetric shock of 100's of Mbars



Convergent shock launched at 300 Mbar reaches 2.5 Gbar at shock collision



ITF* $\equiv E_{\text{kin}}/E_{\text{ign}}^{\text{min}}$

Implosion margin (ITF) increases with the addition of the spike shock.

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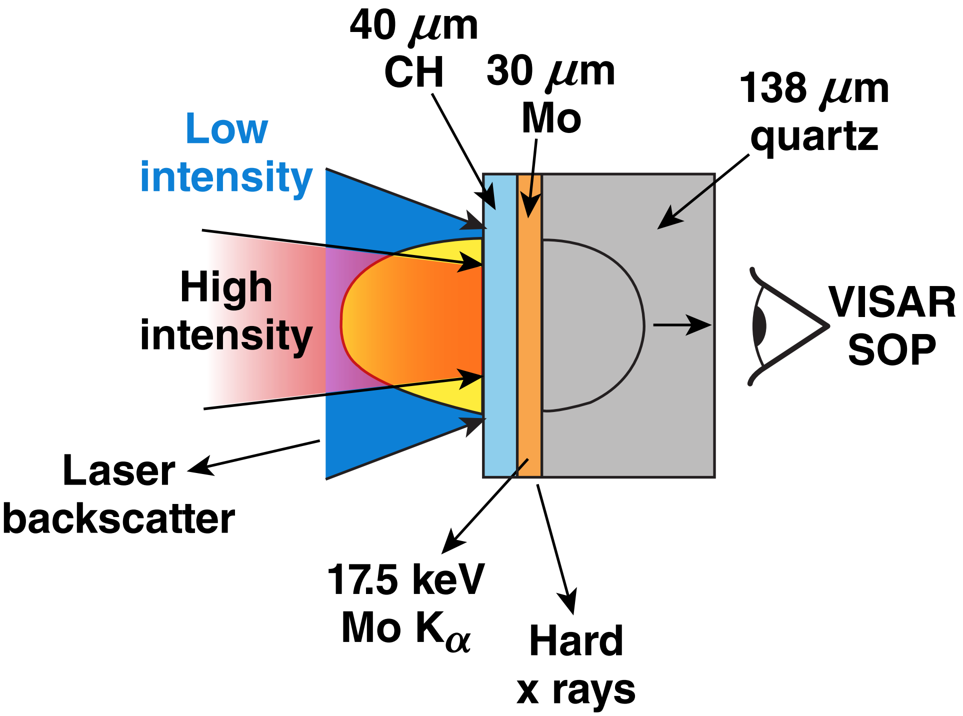
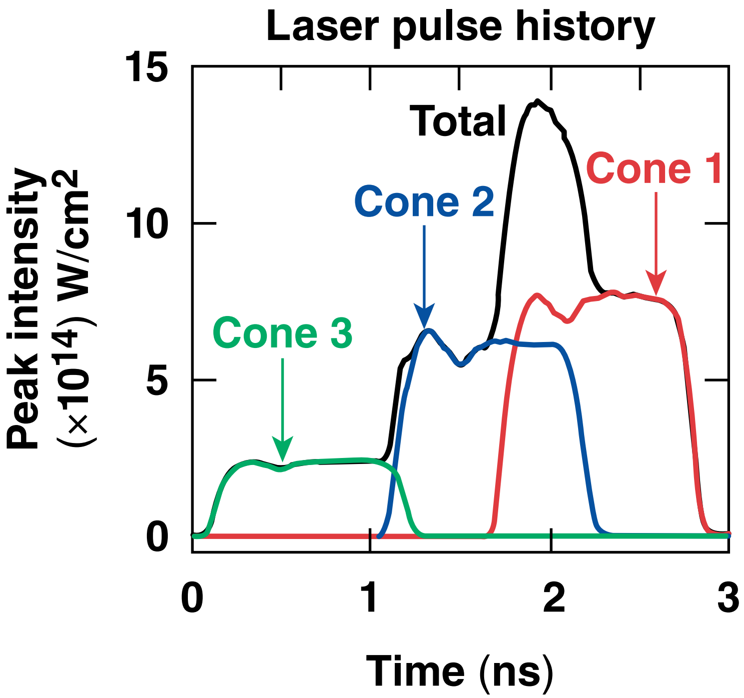
*P. Y. Chang, *et al.*, Phys. Rev. Lett. 104, 135002 (2010),
D. S. Clark, *et al.*, Phys. Plasmas 15, 056305 (2008),
B. K. Spears, *et al.*, Phys. Plasmas 19, 056316 (2012).

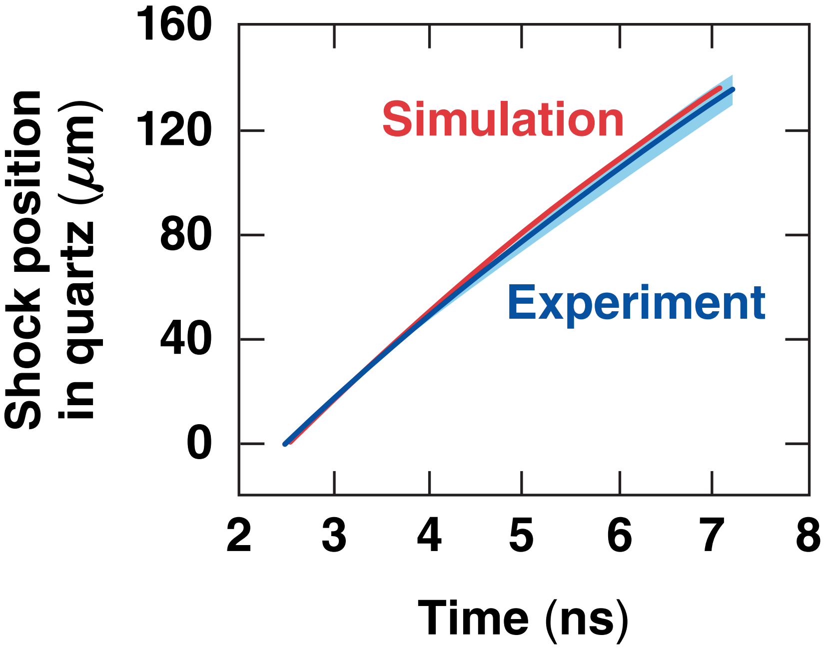
Planar experiments have validated the simulated shock pressures generated by high-intensity laser pulses in a long-scale-length plasma

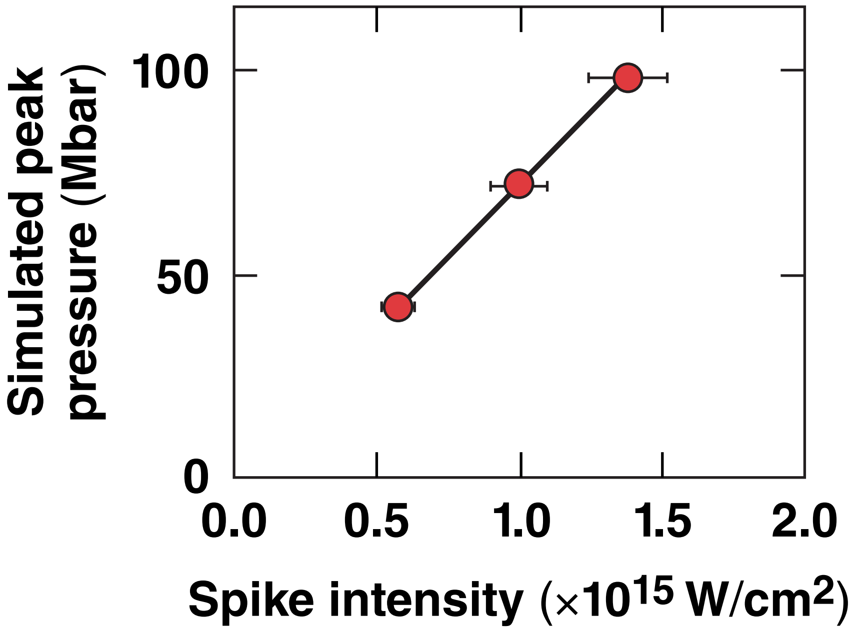




M. Hohenberger, GO5.00001, this conference.
M. Hohenberger *et al.*, "Shock-Ignition Experiments with Planar Targets on OMEGA," submitted to Physical Review Letters.

Trajectories of high-pressure shocks driven at intensities up to ~1.5 × 10^{15} W/cm^2 are in good agreement with simulation





Up to 100 Mbar shock pressures are inferred.

M. Hohenberger, GO5.00001, this conference.

M. Hohenberger *et al.*, "Shock-Ignition Experiments with Planar Targets on OMEGA," submitted to Physical Review Letters.

Outline

- Background
- Strong shock generation at laser intensities of mid × 10^{15} W/cm^2
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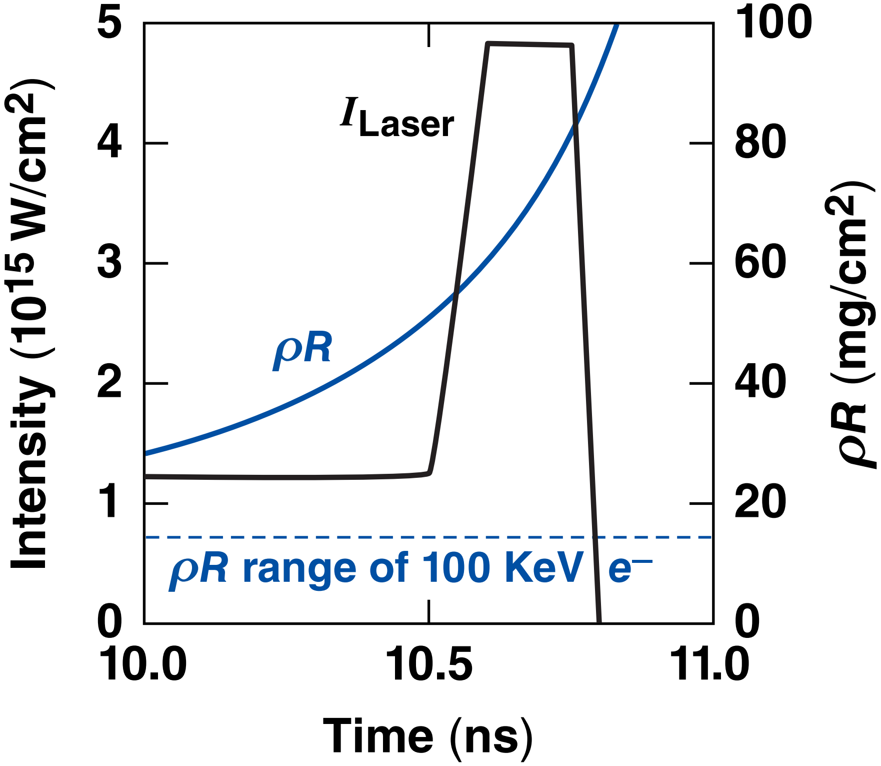
- Simulations and parameter studies for the NIF SI point design

Hot-electron generation and capsule preheat must be well-characterized and controlled

- Hot electrons at moderate temperatures and conversion efficiencies during the spike may improve margin*
- Preheat during the main drive can raise the shell adiabat, ruining compression

Shock-ignition target with 350-kJ total energy



At moderate hot-electron energy, electrons are stopped in the ablator, increasing the shock pressure during the spike pulse.

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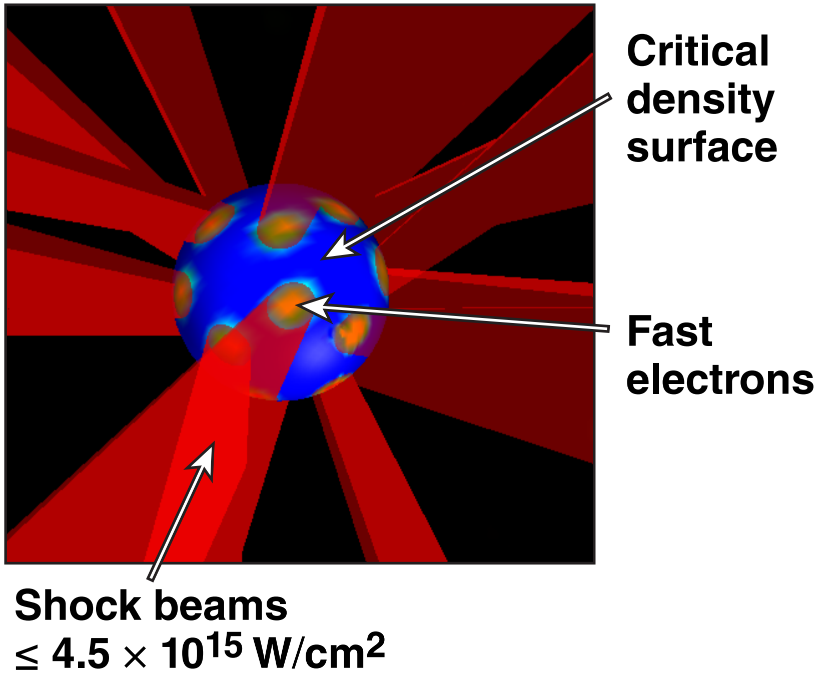
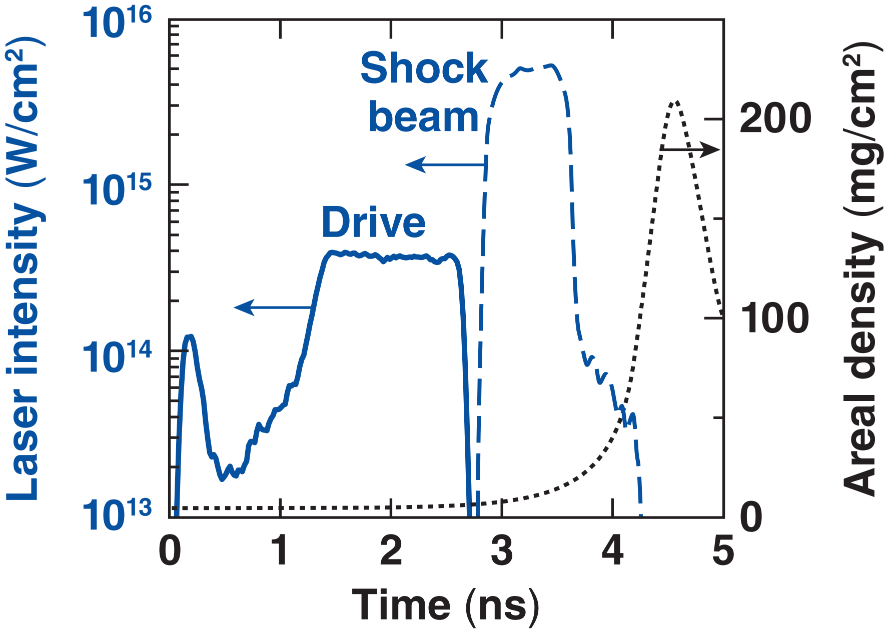
*R. Betti *et al.*, J. Phys., Conf. Ser. 112, 022024 (2008).

Spherical implosions were performed on OMEGA using 40 beams to compress and 20 tightly focused beams to shock the target

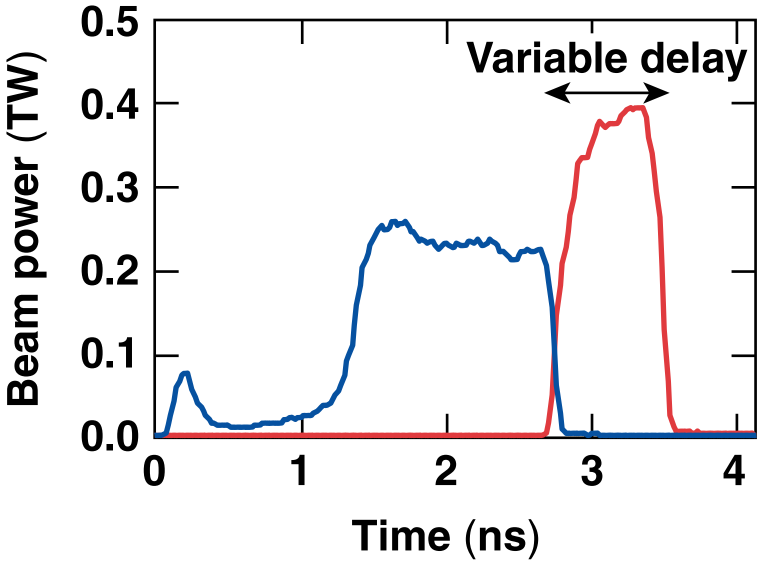




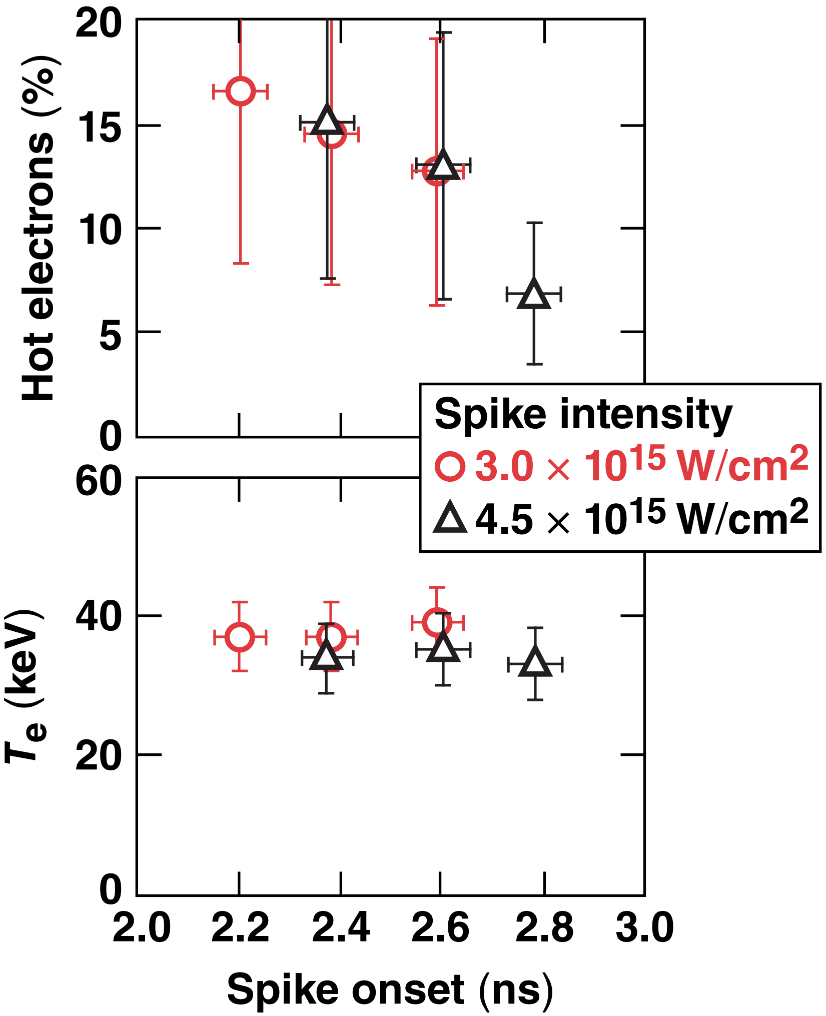
- The delay and intensity of the tightly focused beams are varied

W. Theobald *et al.*, Phys. Plasmas 19, 102706 (2012).

Up to 16% of the shock-beam energy is converted into 40-keV hot electrons



- Hot electrons are from stimulated Raman scattering
- No two-plasmon decay hard x-ray signal is measured



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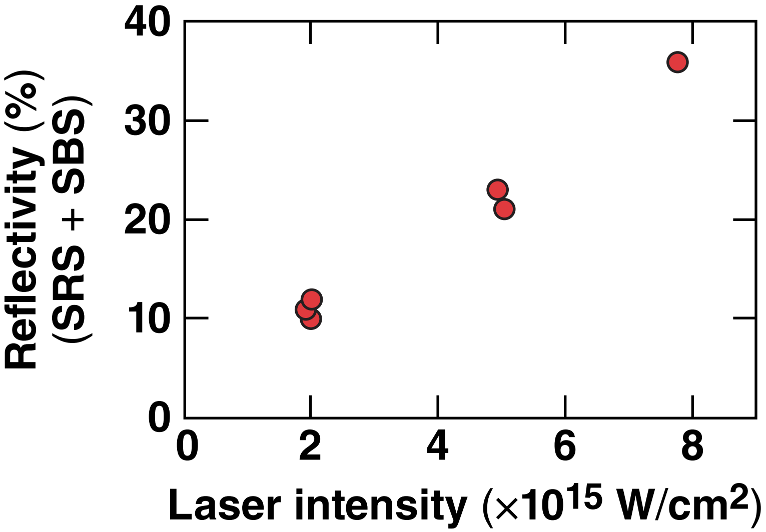
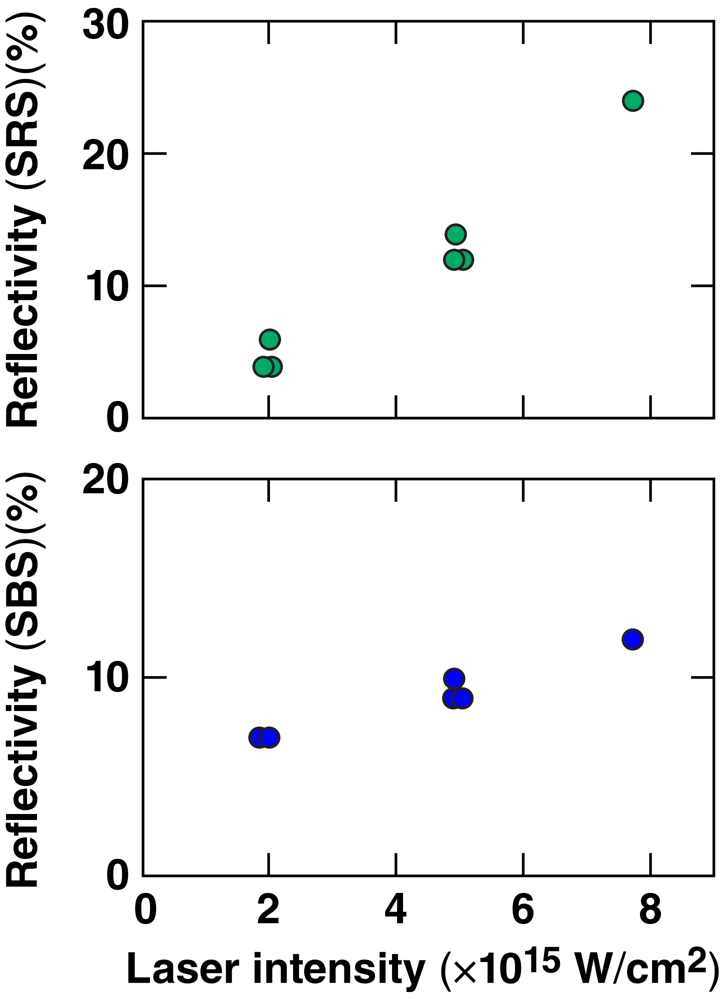
Nora, BO4.00002, this conference.

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

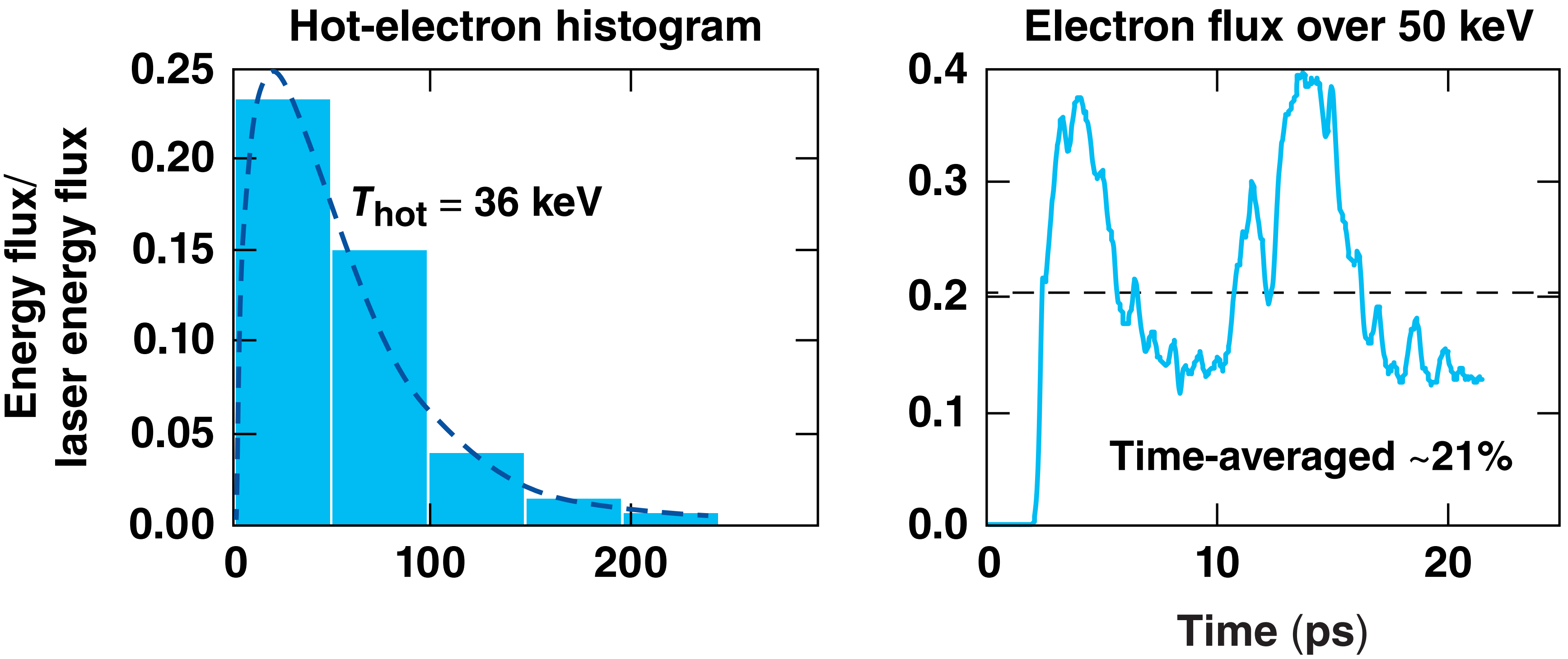




- No measurable signal of the 3/2 harmonic
- SRS dominates back reflection at highest intensity
- SBS reflection is relatively stable at ~10%

C. Stoeckl *et al*., Bull. Am. Phys. Soc. 54, 265 (2009).
W. Theobald *et al*., Plasma Phys. Control. Fusion 51, 124052 (2009).

Two-dimensional particle-in-cell simulations predict similar hot-electron temperature and conversion efficiency



R. Yan, CP8.00093, this conference.

Outline

- Background
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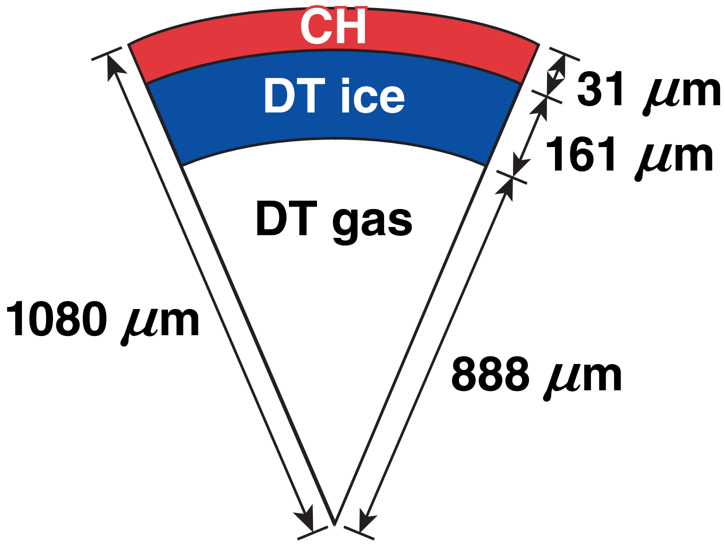
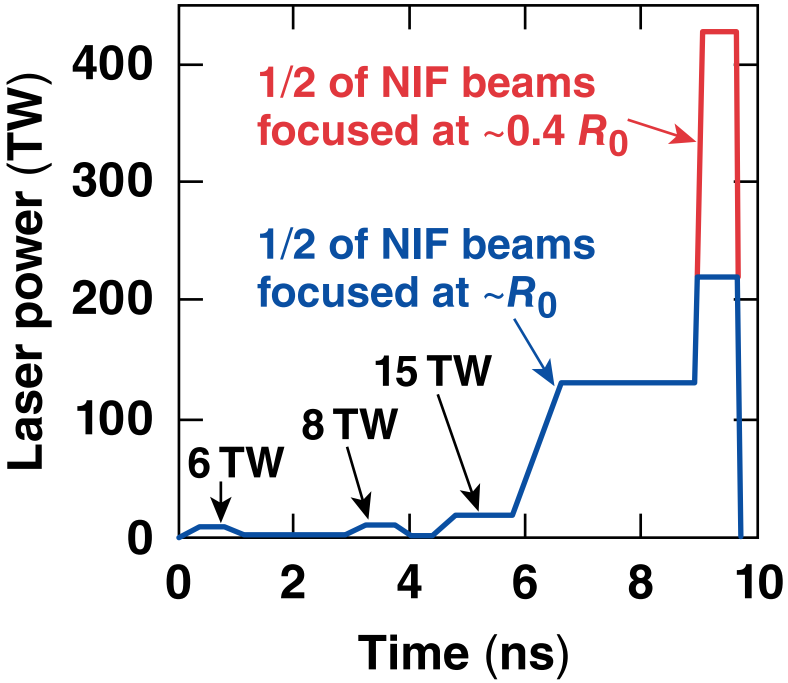
- **Simulations and parameter studies for the NIF SI point design**

A two-picket shock-ignition pulse has been designed for the NIF at 700 kJ



Gain (1-D)	58
ρR (g/cm^2)	1.6
V_{imp} (μm/ns)	305
$IFAR_{2/3}$	22
Average adiabat	1.8
ITF	4.1

Design pulse = 700 kJ



Peak power is 85% of demonstrated NIF performance.

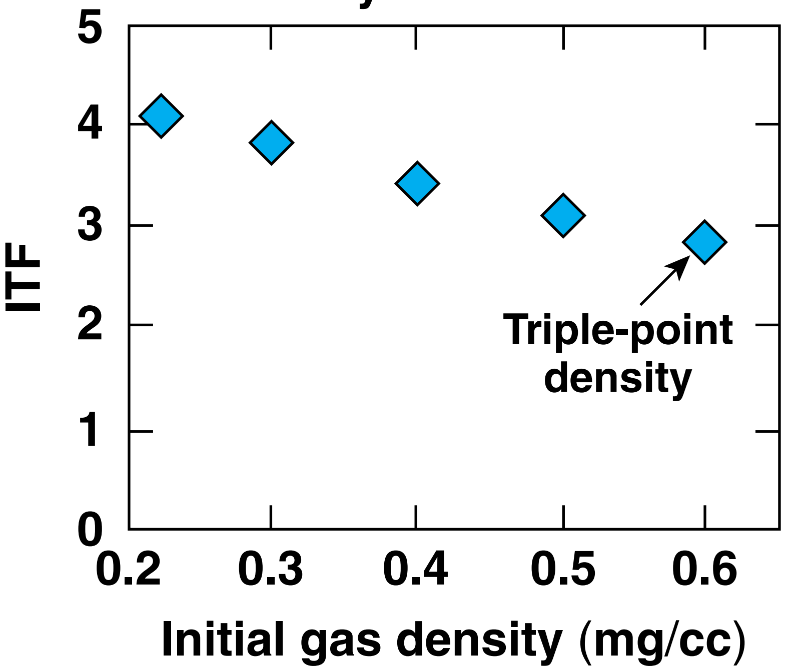
Simulations indicate the target is robust to 1-D uncertainties

Robust to mistiming of shocks in the ±100-ps range

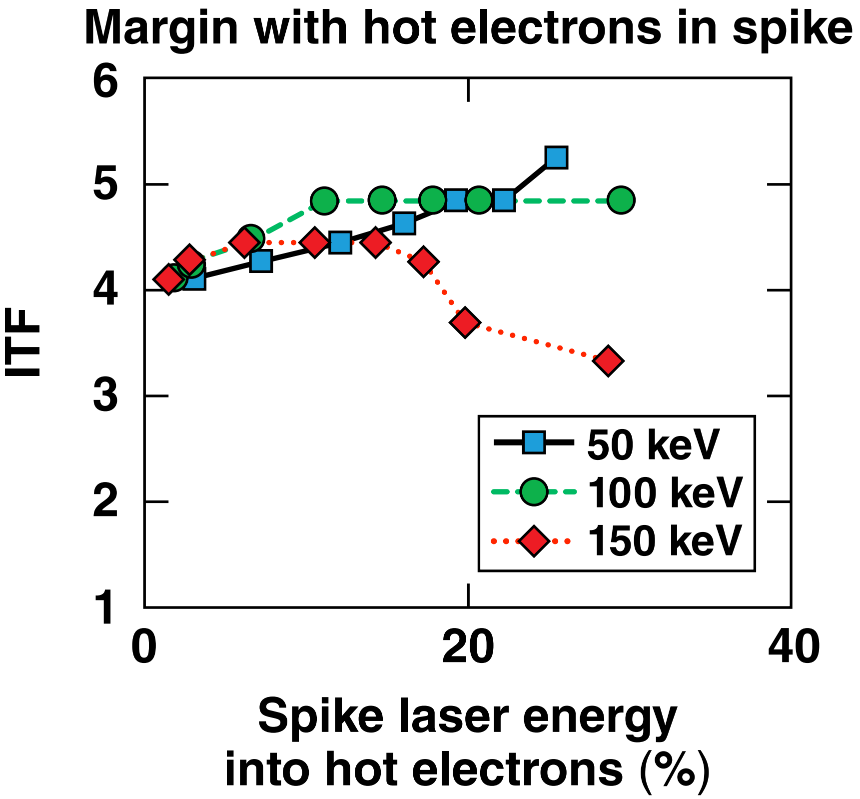
ITF*	Δt = –100 ps	Δt = +100 ps
Picket 2	3.5	4.0
Foot pulse	4.3	2.6
Main drive	3.3	4.4
Spike pulse	4.1	4.1

*ITF of design with no mistiming = 4.1

The target ignites at triple-point density with ITF 2.8



One-dimensional simulations predict the target is robust to laser-spike-generated hot electrons up to 150 keV

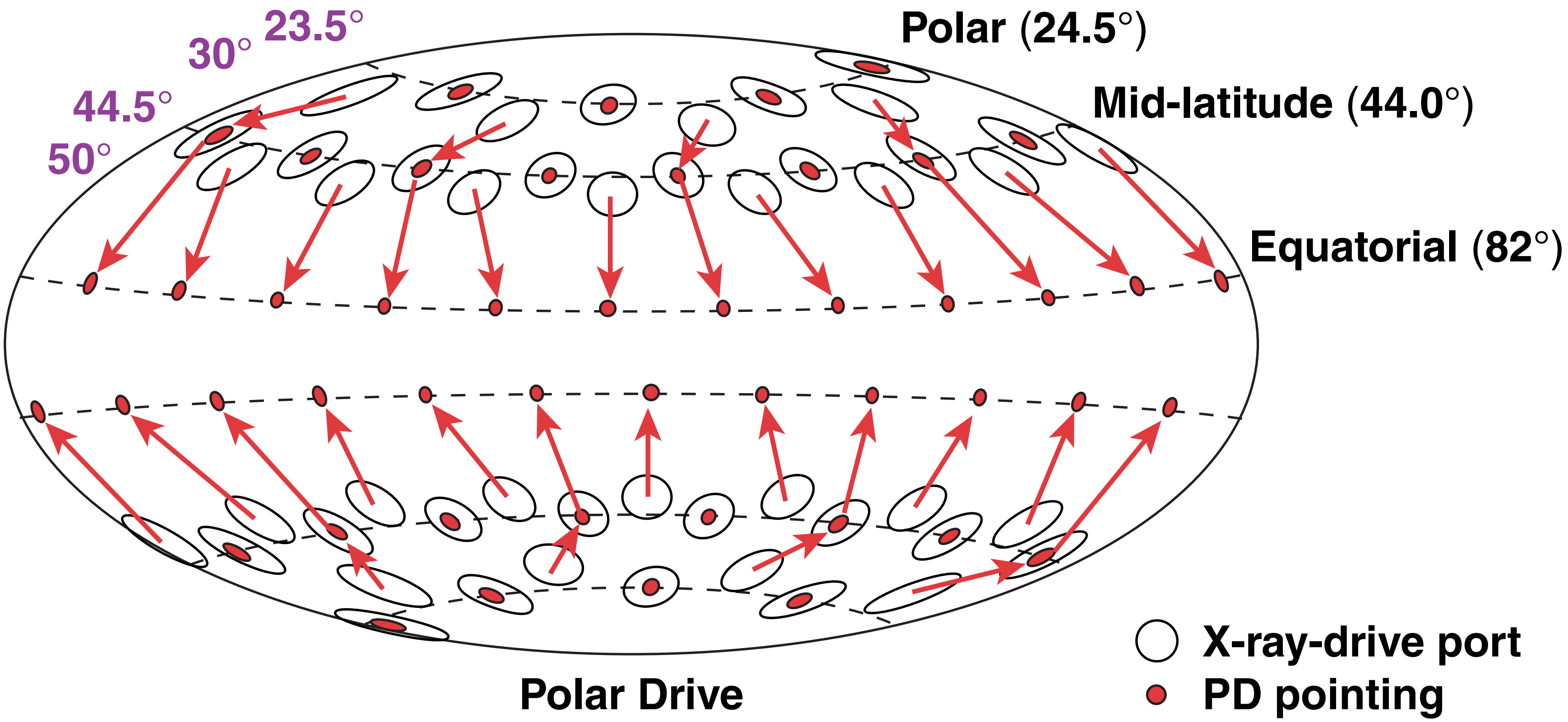


Hot electrons below 100 keV may increase the ignition margin.

Initial polar-drive pointing schemes use split-quads, two beams from each quad for the main drive, two beams for the shock pulse

Port angles:

Illumination regions:



A full-quad repointing shows ignition—further refinement is underway.

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*S. Skupsky et al., Phys. Plasmas 11, 2763 (2004).

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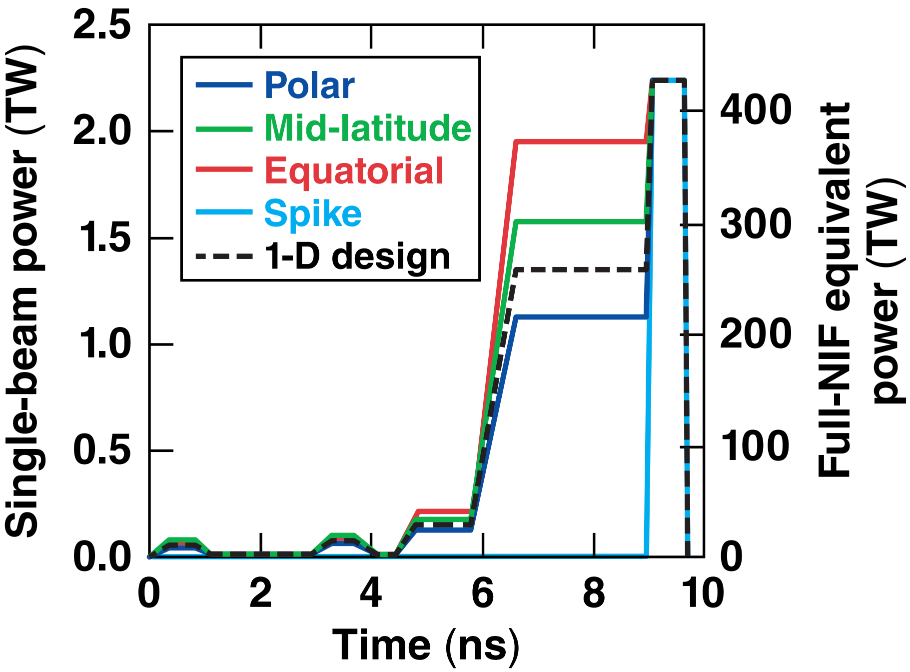
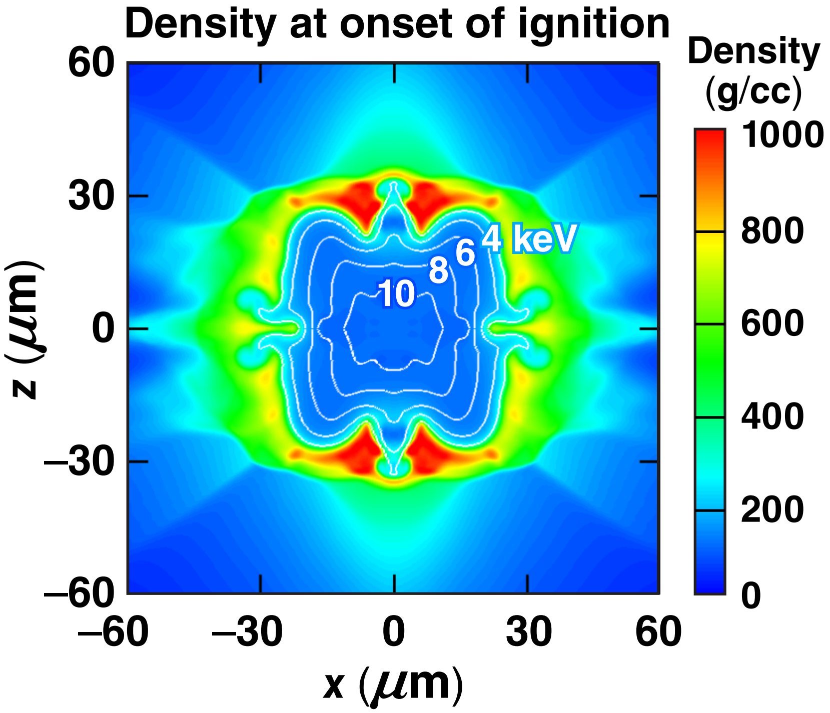
The two-picket shock-ignition point design gives a gain of 52 in split-quad polar drive at 750 kJ

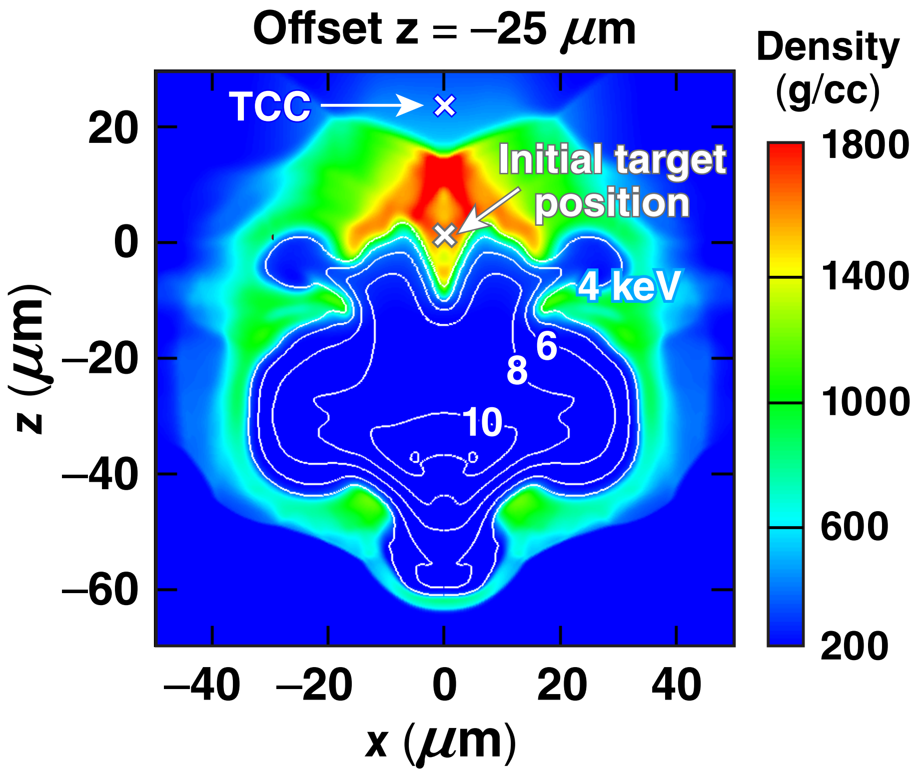




The polar-drive SI design can tolerate high levels of 2-D nonuniformities

Ignites in polar drive with

- 5× NIF-spec inner ice roughness
- 5× NIF-spec outer surface roughness in modes 2 to 50
- 10% rms beam-to-beam power imbalance
- 100-ps rms beam-to-beam mistiming
- 100-μm rms beam mispointing
- Expected level of imprint with Multi-FM*-SSD in modes 2 to 100
- Target offset up 25 μm



Ignites with gain 38 with all expected levels of non-uniformity and system uncertainty.

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*LLE Review Quarterly Report 114, 73, LLE Document No. DOE/NA/28302-826 (2008). A. Shvydky, JO4.00009, this conference.

Planned and proposed experiments on OMEGA and the NIF will continue to explore shock ignition physics

- OMEGA cryogenic and polar-drive SI experiments
- OMEGA spherical strong-shock experiments to quantify shock strength in spherical geometry up to 5 × 10^{15} W/cm^2
- Mid-Z ablator (glass, silicon, etc.) implosions on OMEGA for imprint reduction and TPD mitigation during the main drive*
- NIF day-one-hardware shot proposal for near-term polar-drive uniformity testing†

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*Lafon, JO4.00003, this conference.
Betti, JO4.00005, this conference.
Myatt, TO5.00005, this conference.

†L. J. Perkins *et al.*, Lawrence Livermore National Laboratory, Livermore, CA, Report UCRL-TR-432811 (2010).

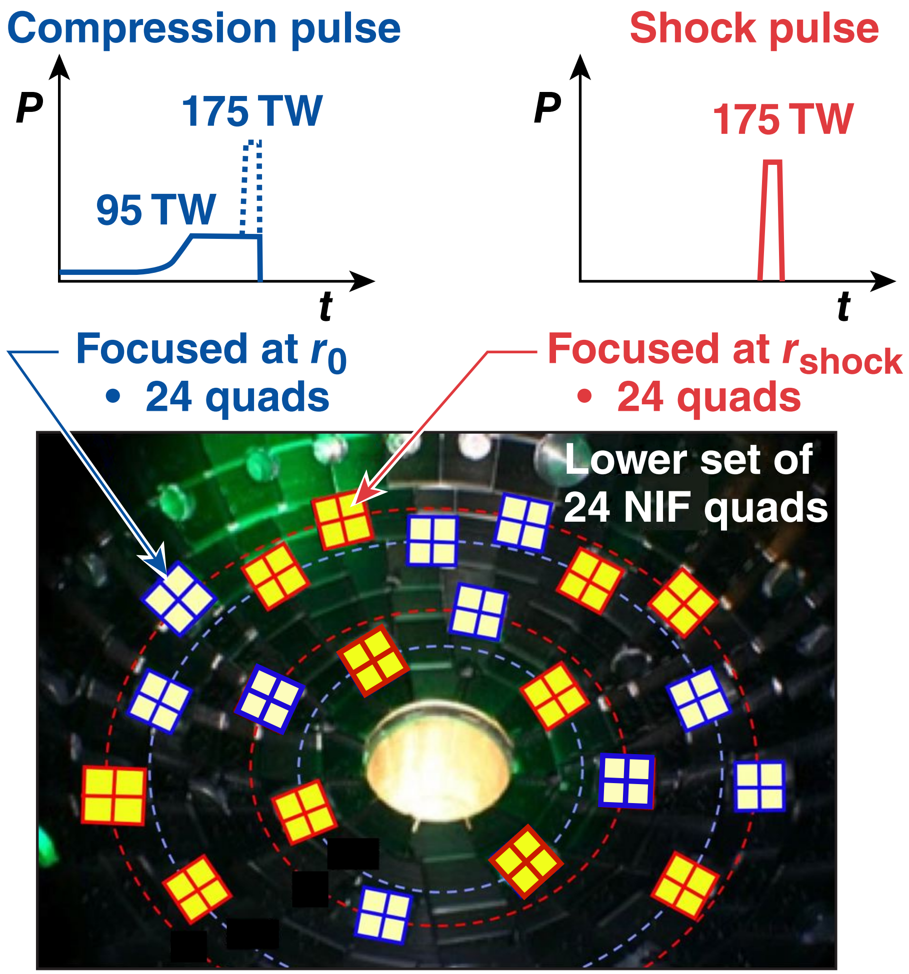
Polar-drive shock ignition is a viable path to ignition on the NIF

- Shock-ignition–relevant shocks up to 100 Mbar have been demonstrated on OMEGA in planar geometry in agreement with simulations
- One- and two-dimensional simulations demonstrate that polar-drive shock ignition is robust to various forms of system uncertainty and nonuniformity to levels that exceed NIC IDI specifications
- 1-D target design has an ignition threshold factor (ITF) in 1-D of 4.1
- 2-D polar-drive simulations predict gain of 38 at 750 kJ with all expected levels of non-uniformity

Experiments and simulations are validating shock-ignition physics.

24–24 polar drive

The main drive beams, two from each quad, are repointed to three regions per hemisphere on the target



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Focused at r_0
- 24 quads

Focused at r_{shock}
- 24 quads

Main drive beams

Port angle	Repointing angle
30.0	25.0
44.5	59.0
50.0	85.0

- No repointing on spike beams
- Requires custom phase plates

R. S. Craxton *et al.*, Bull. Am. Phys. Soc. 55, 26 (2010).

In 24–24 polar-drive configuration, the shock-ignition point design gives gain 51