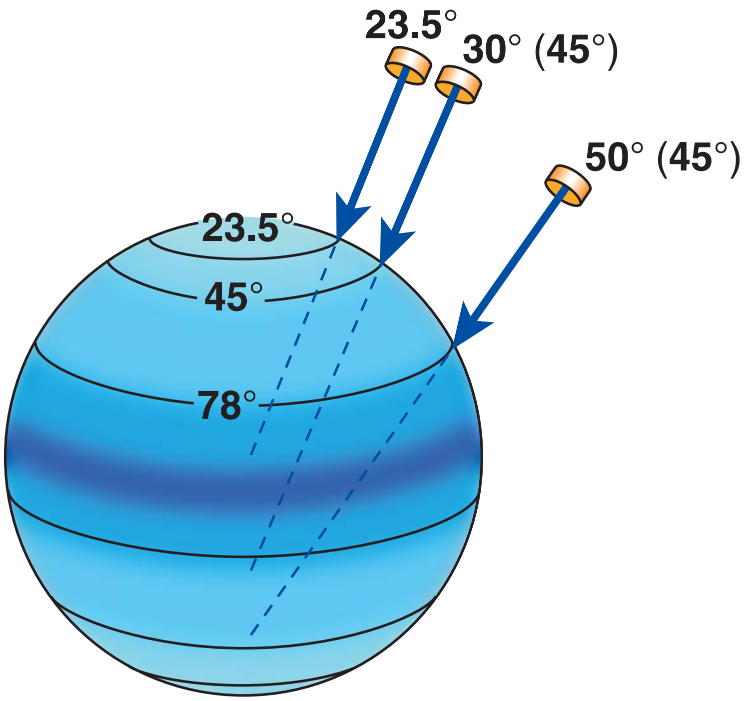
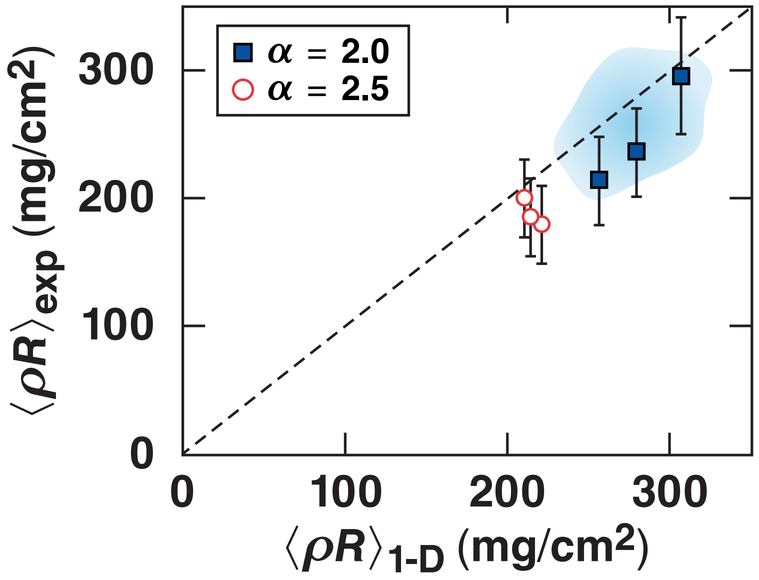
Status of Directly Driven ICF

NIF Polar Drive



OMEGA Experiments



S. Skupsky
University of Rochester
Laboratory for Laser Energetics

NAS/NAE Committee on the
Prospects for IFE Systems
San Ramon, CA
29 January 2011

Summary

Directly-driven ignition designs and IFE designs for the NIF are being validated by high-compression cryogenic experiments on OMEGA

- Target designs are modified and updated based on OMEGA experiments
    - simulations use both *DRACO* (2-D) and *HYDRA* (3-D)
- Detailed modeling of laser–target coupling and heat transport are essential for simulating high-compression experiments on OMEGA
    - experiments are being designed to examine laser–plasma interactions for anticipated NIF conditions
- Low compression Polar Drive (PD) experiments on OMEGA and the NIF are well described by computer simulation
    - high-compression PD experiments are in progress
- The technology for implementing PD on the NIF is being developed at LLE

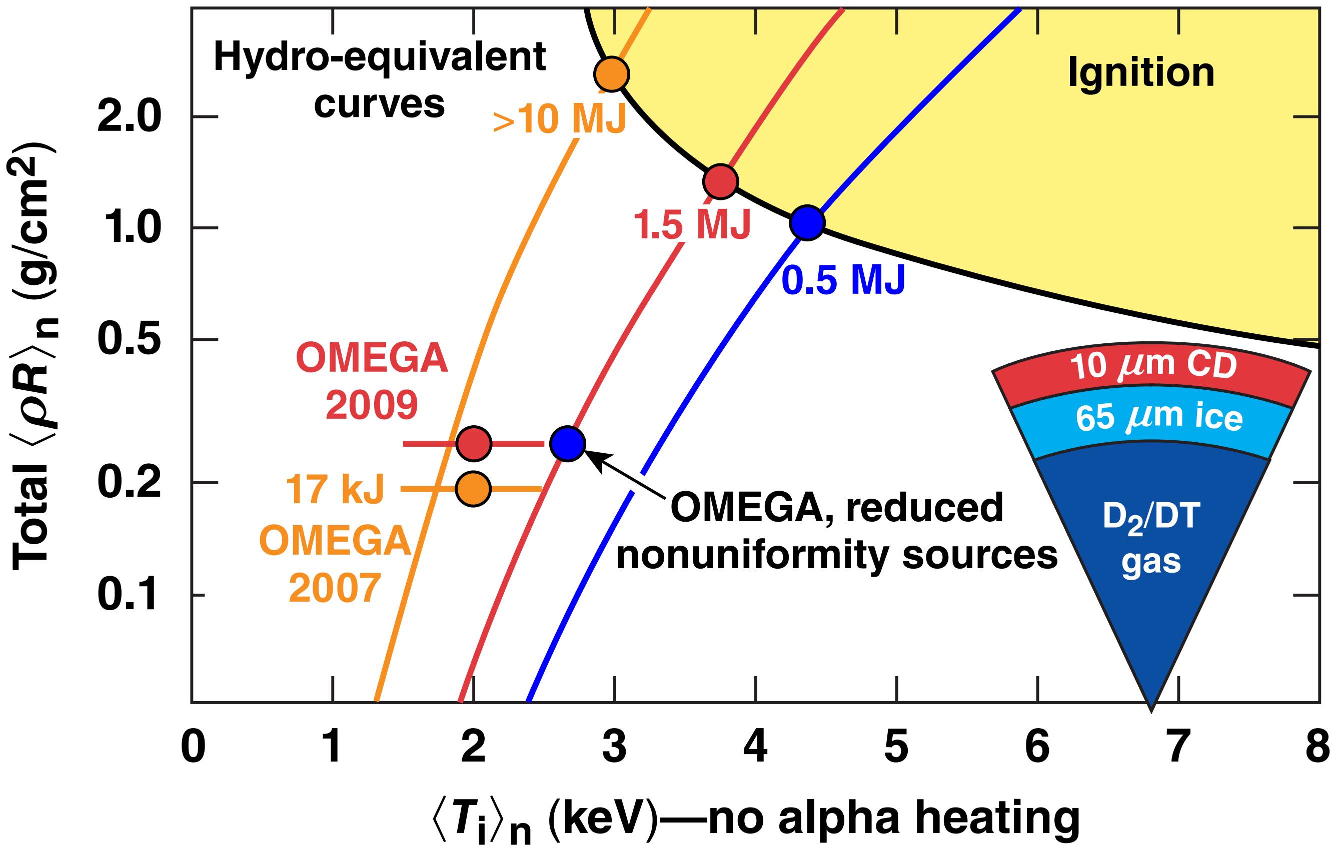
Outline

- High-compression experiments on OMEGA (symmetric drive)
  - physics issues affecting direct-drive ignition

- PD ignition designs for the NIF
  - sensitivity to physics uncertainties
  - technology required for high compression experiments

- Directly-driven IFE concepts using PD irradiation
  - Fast Ignition (FI)
  - Shock Ignition (SI)
  - proof-of-principle experiments on OMEGA

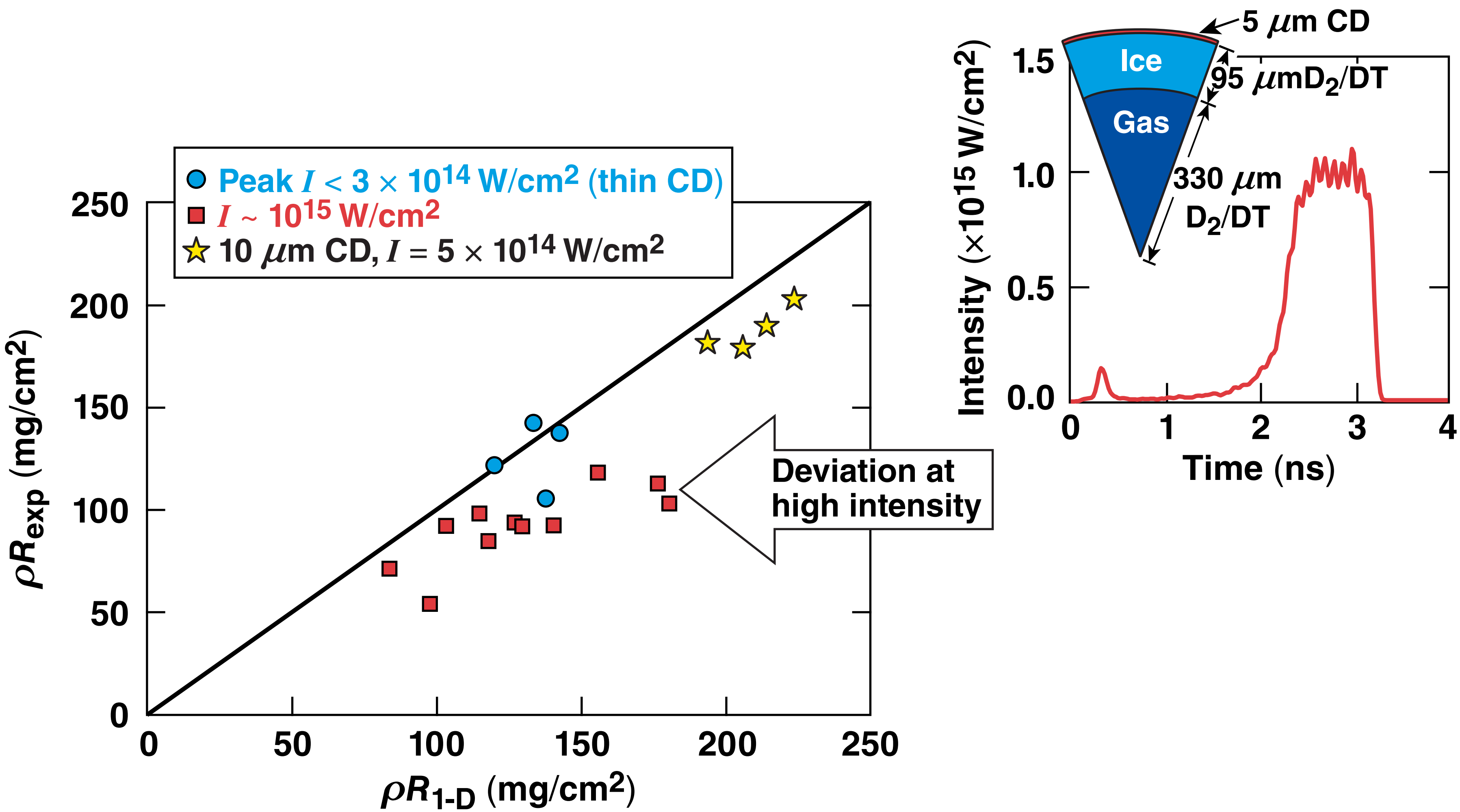
OMEGA is on the path to demonstrate hydro-equivalent ignition at NIF-relevant energies



Compression has been demonstrated. Raising the ion temperature (neutron yield) is the final step.

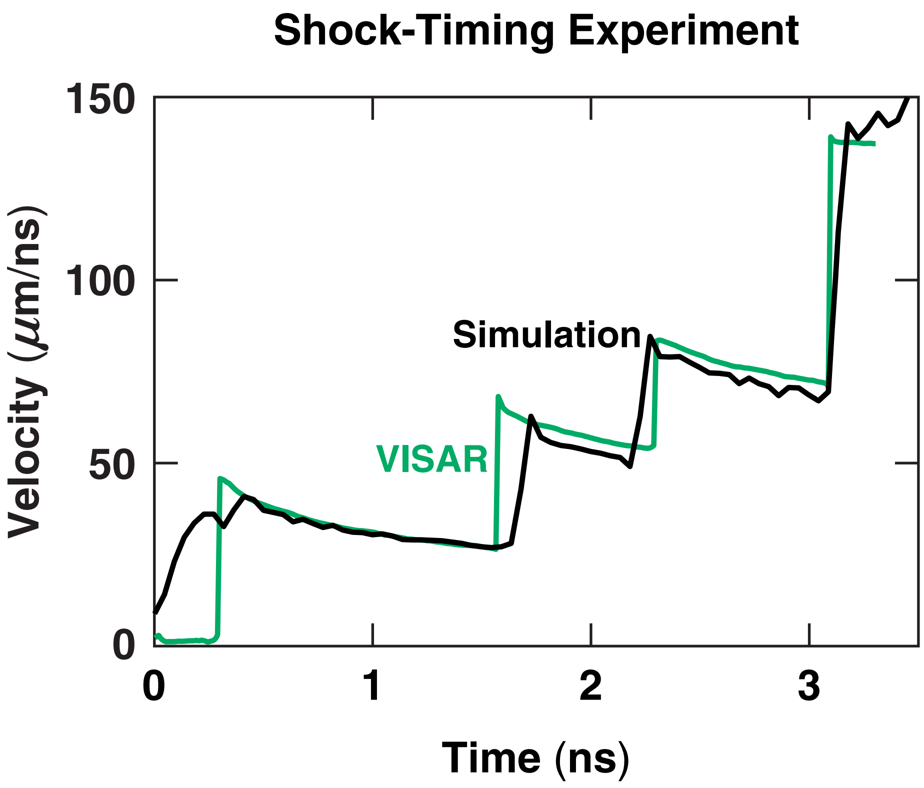
Areal Density

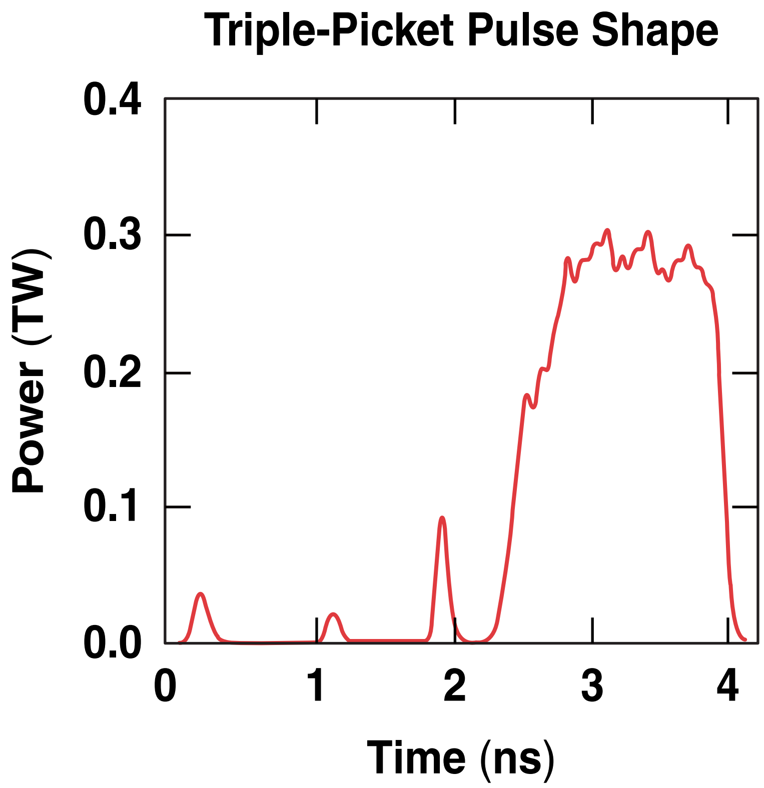
Good agreement between simulation and measured *ρR* is obtained when the two-plasmon decay (TPD) is suppressed



TC8037o

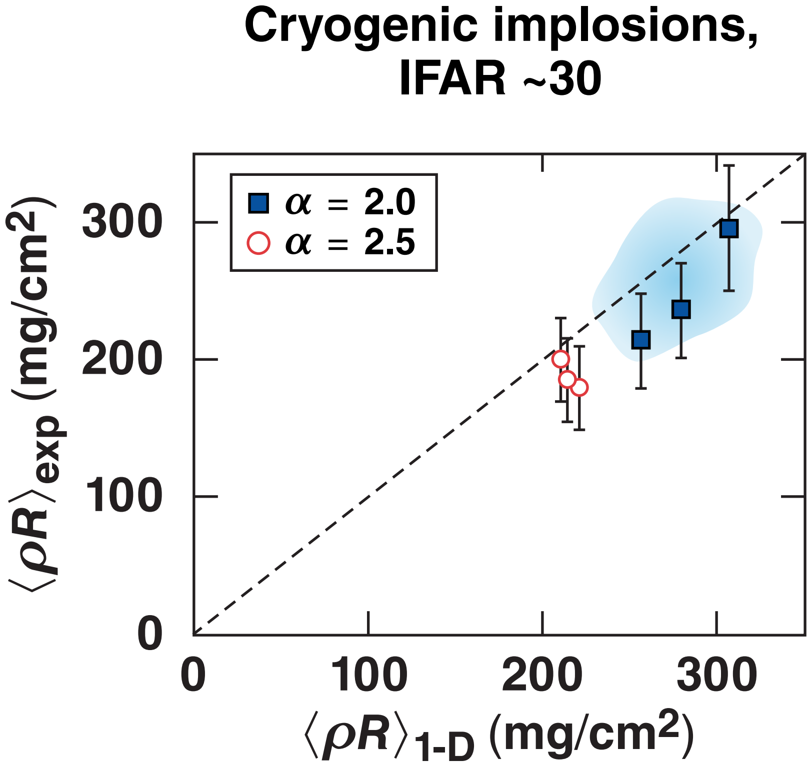
The shock-velocity from shock-timing experiments was successfully reproduced with multiple-picket designs demonstrating adiabat control

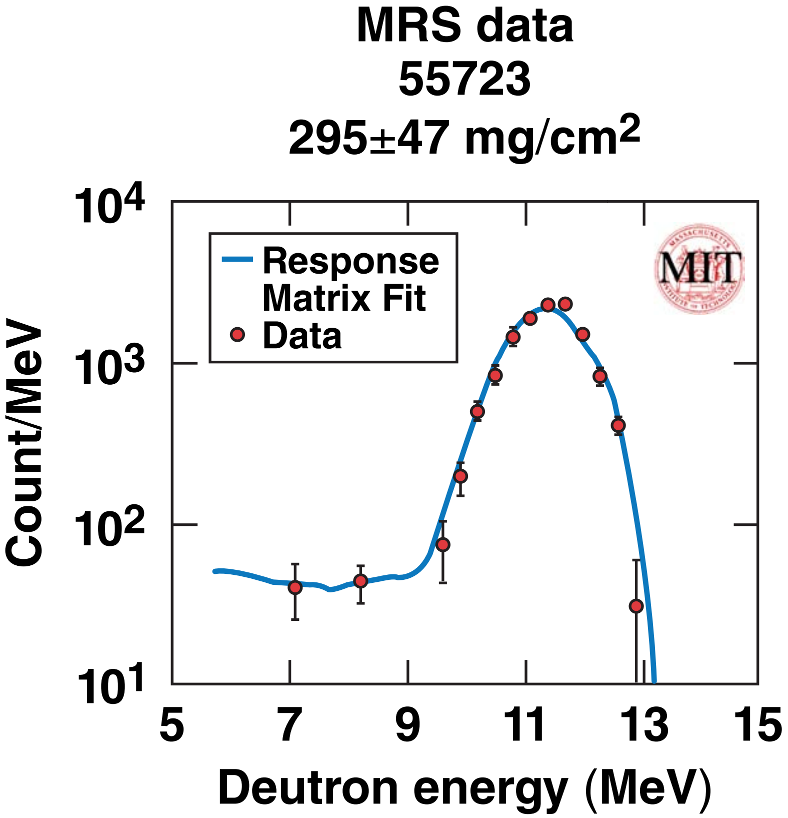

Shock-Timing Experiment


Triple-Picket Pulse Shape

The four shock design is similar to the approach used for x-ray drive.

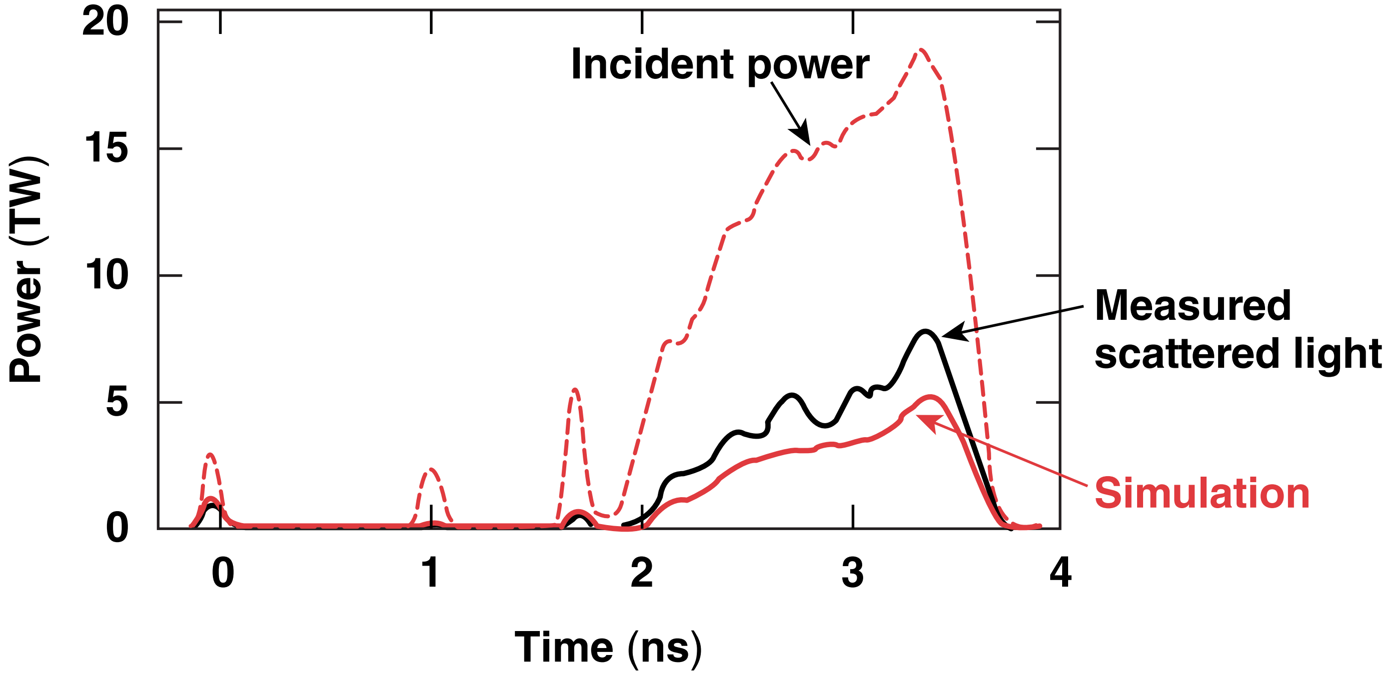
Shock-tuned triple-picket designs demonstrated near 1-D compression up to $\langle \rho R \rangle$~300 mg/cm^2





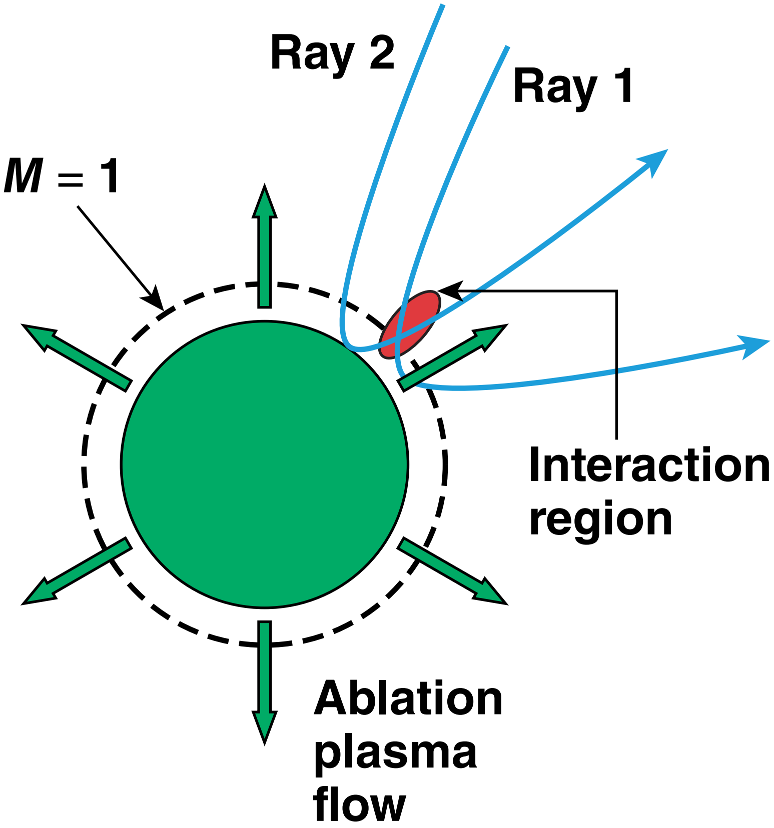
High ρR is achieved by controlling shock heating of the fuel and by reducing preheat from TPD fast electrons.

The scattered-light measurement indicates a loss in laser coupling during the main pulse



Beam-to-beam energy transfer leads to a reduction in laser coupling[1]

The transfer of energy from (1) to (2) is due to SBS before deposition[2]



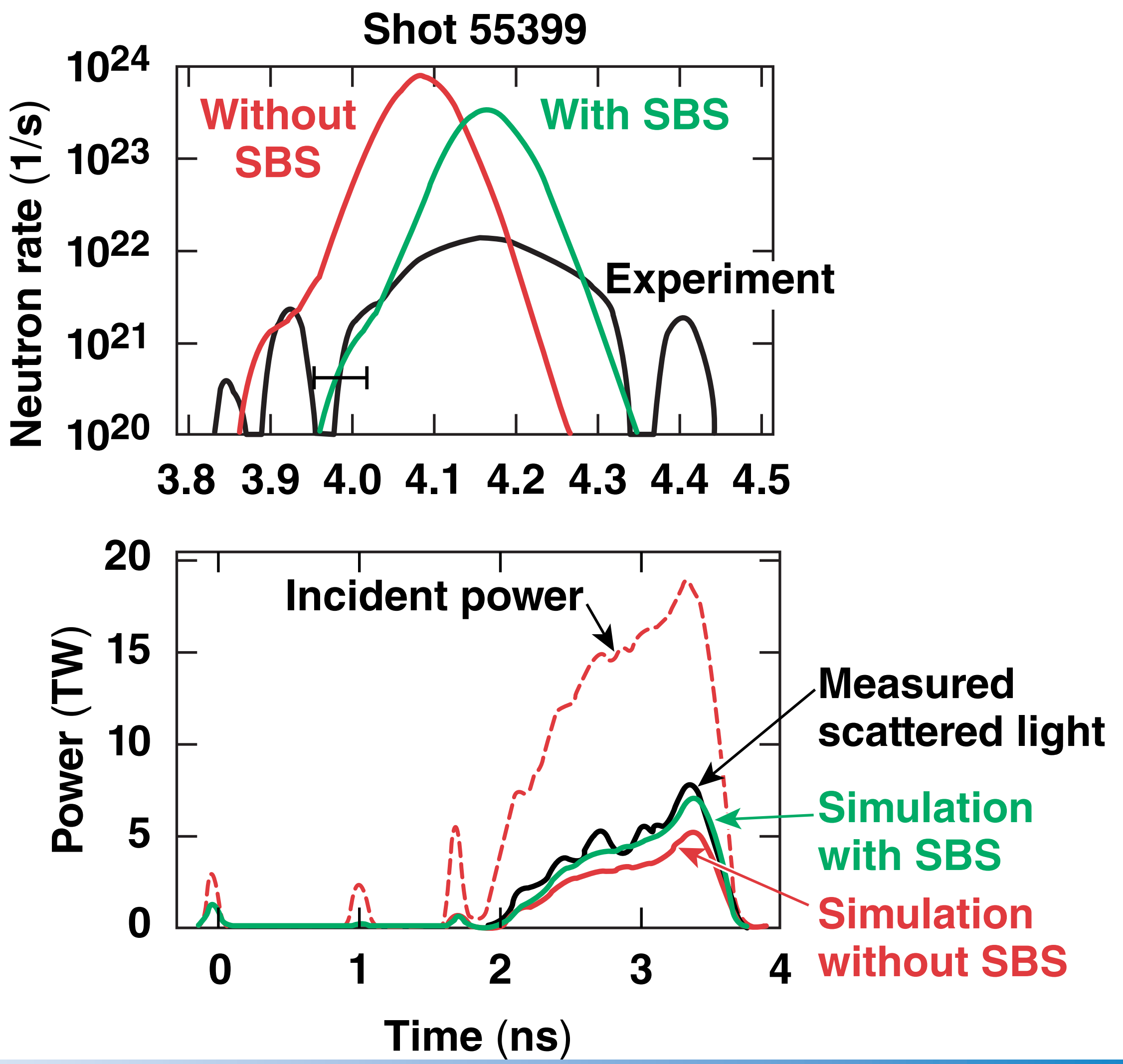
---

[1] I. Igumenshchev *et al.*, "Cross-Beam Energy Transfer in ICF Implosions on OMEGA," submitted to Phys. Plasmas

[2] C. J. Randall, J. R. Albritton, and J. J. Thomson, Phys. Fluidss 24, 1474 (1981).

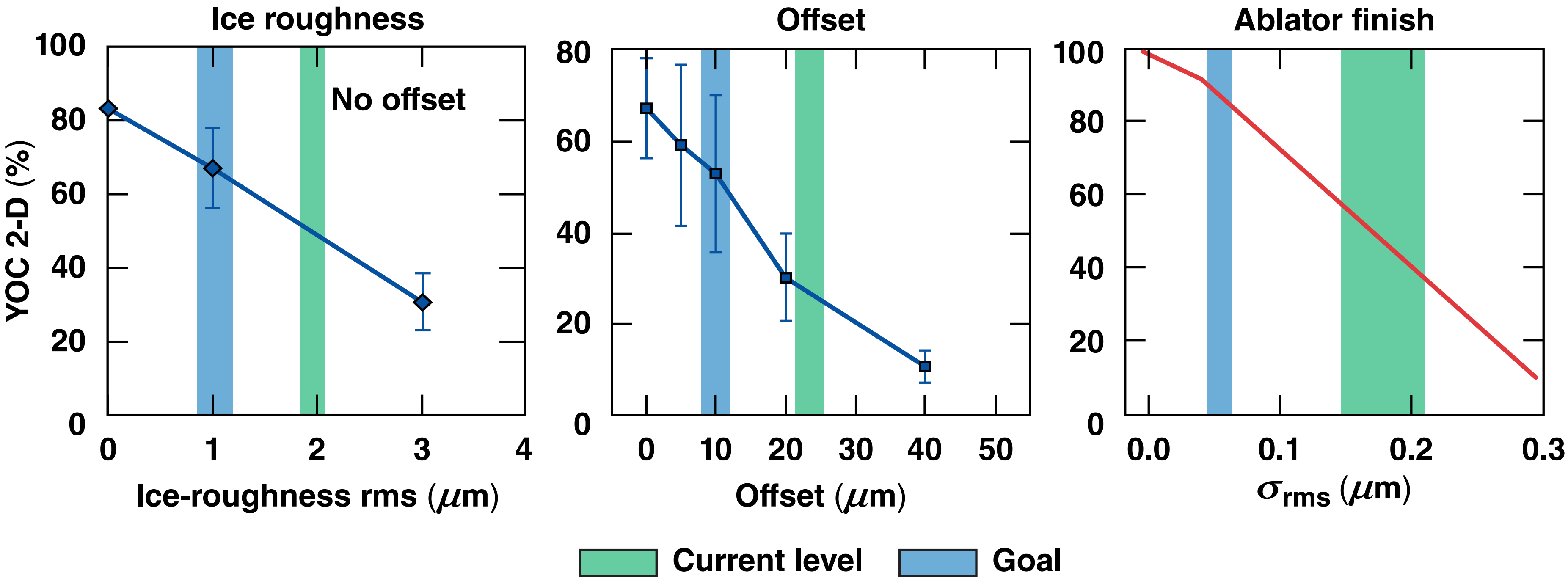
Ion Temperature and Yield: Drive Efficiency

When beam-to-beam energy transfer is included, both the bang time and laser absorption are in good agreement with simulations



Reducing target offset, ice roughness, and ablator finish is required to improve neutron yield and T_i

Results of 2-D *DRACO* simulations[1]



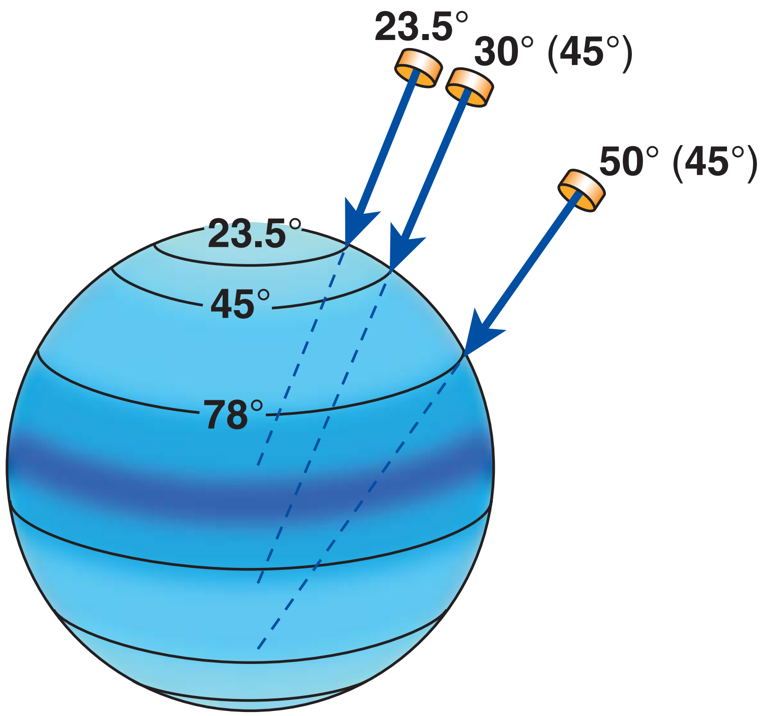
3-D *HYDRA* simulations are in progress that combine the nonuniformities from ice roughness and target offset.

---

[1] S. X. Hu *et al.*, Phys. Plasmas 17, 102706 (2010).

Direct-drive ignition experiments on the NIF will use the Polar Drive (PD) configuration

Repointing for PD*



- Oblique irradiation near the equator is at lower densities ($n = n_{\text{crit}} \times \cos^2\theta_{\text{inc}}$)
  - – reduced absorption
  - – reduced hydro-effciency
  - – lateral heat flow
  - – nonradial beams

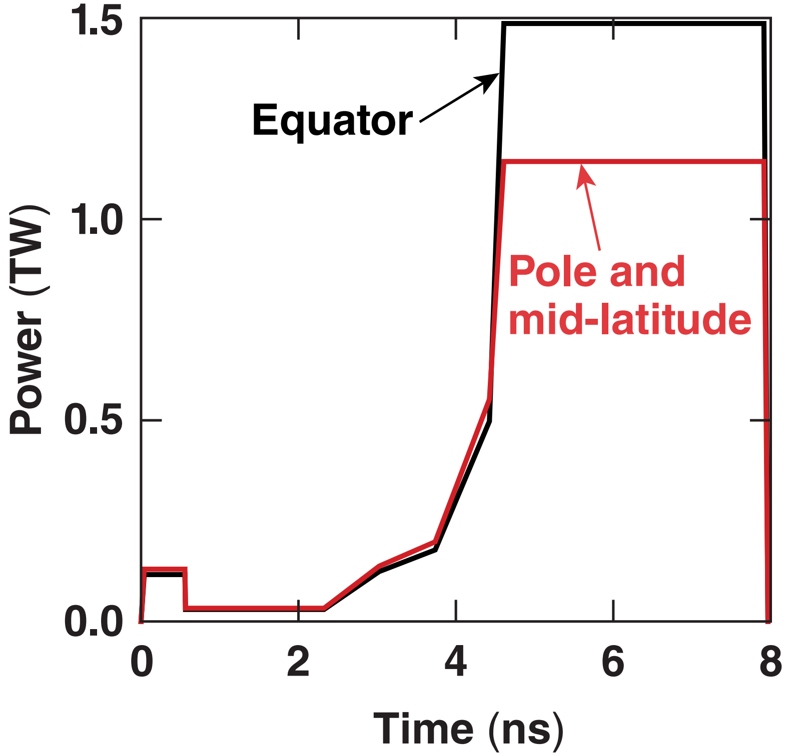
Uniform target drive with PD irradiation requires increased intensity at the equator to compensate for the oblique irradiation.

---

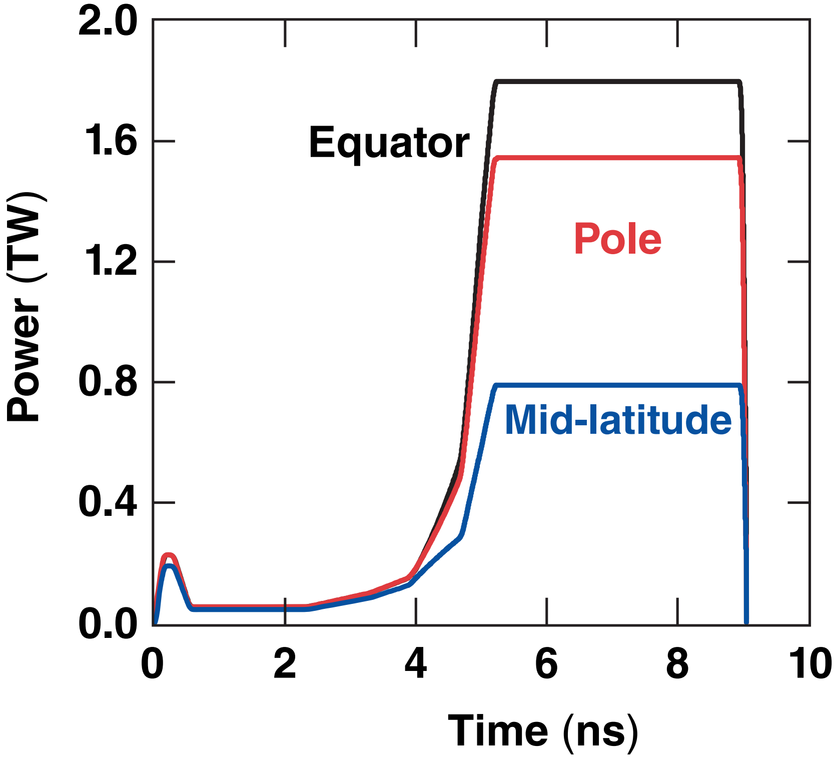
*S. Skupsky *et al*., Phys. Plasmas 11, 2763 (2004).

Target drive for the equatorial beams is very sensitive to the modeling of laser absorption and heat transport

- Two pulse shapes are required for fux-limiter > 0.065

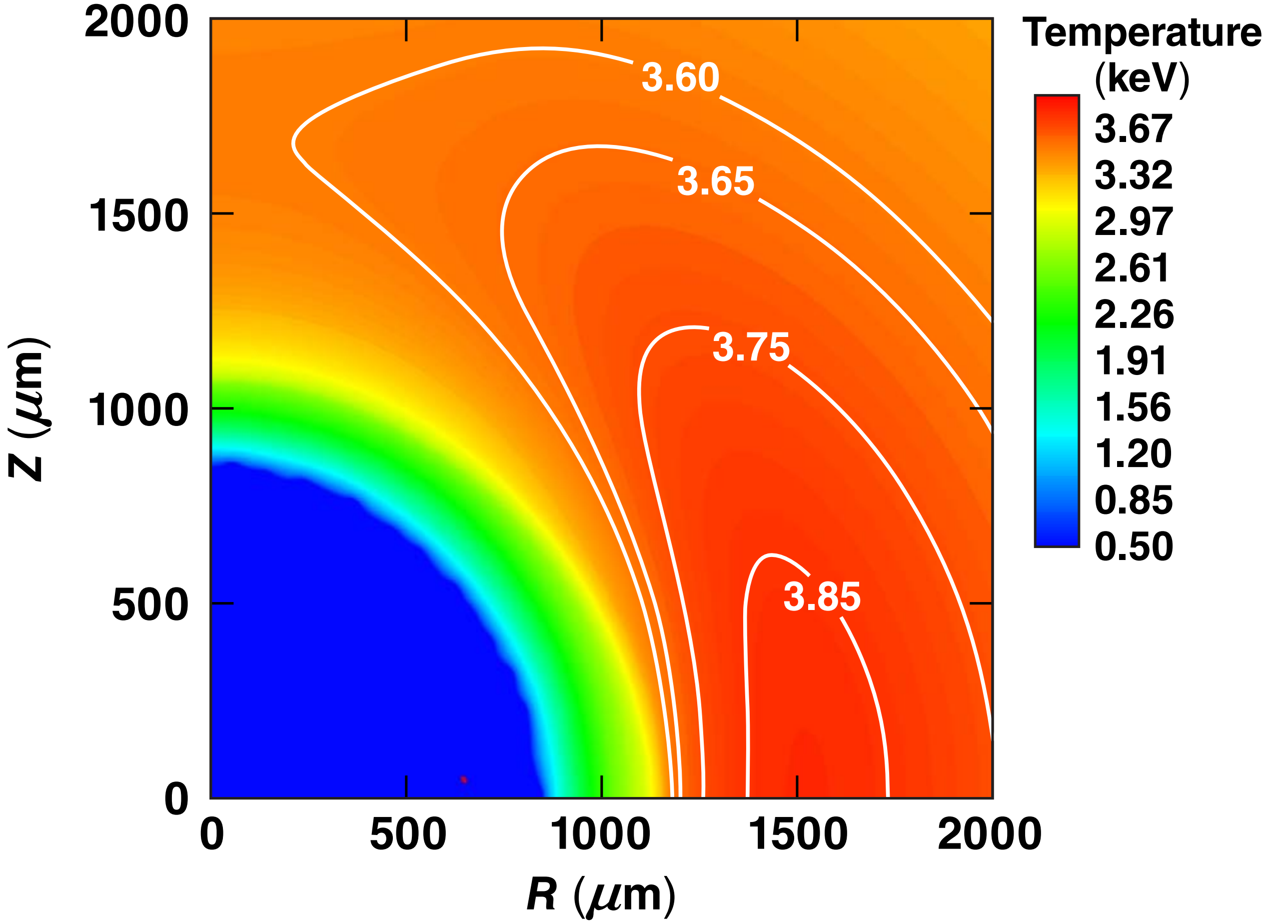


- Three pulse shapes are required for fux-limiter = 0.06



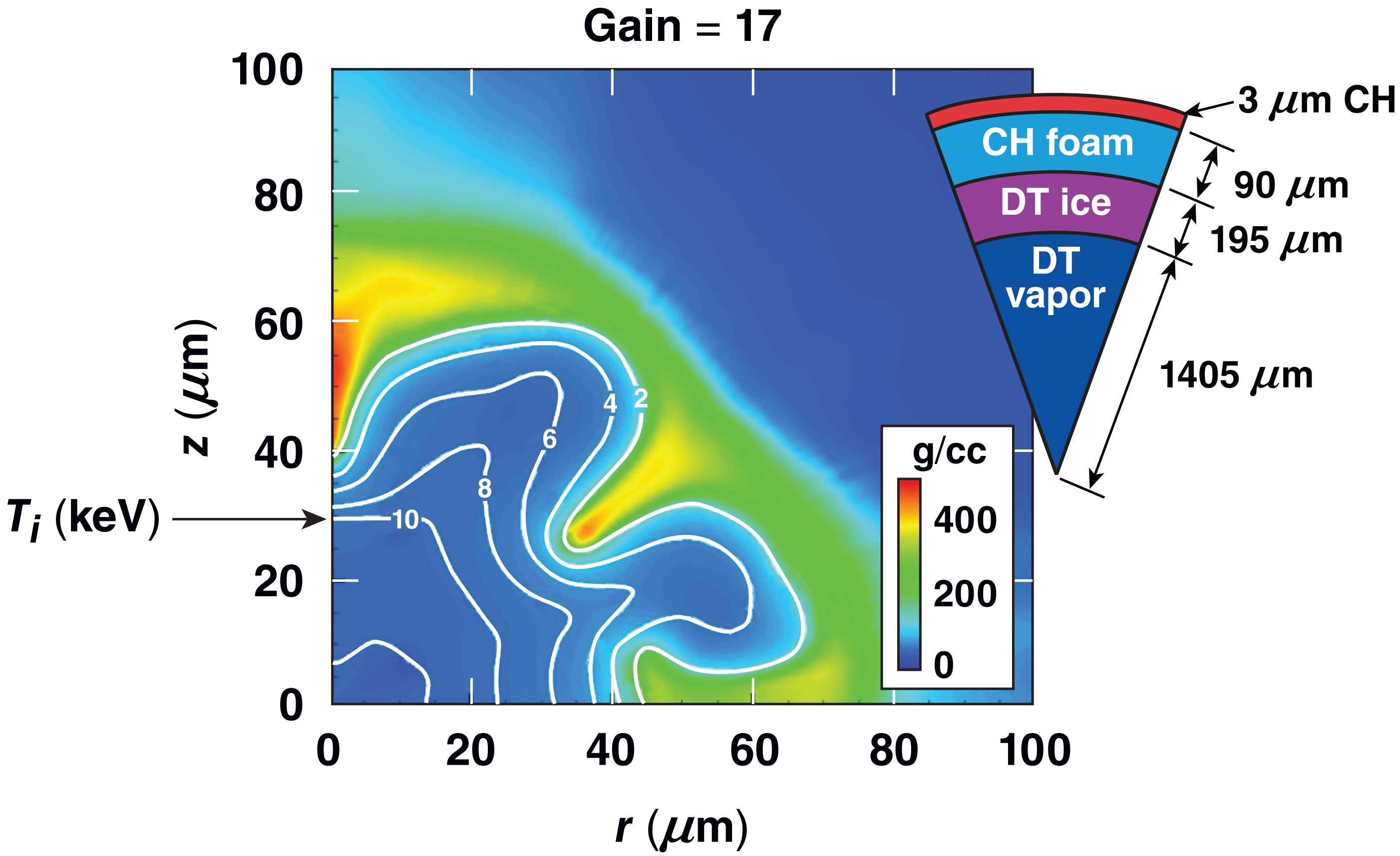
For all transport models examined, it has been possible to retune the target to achieve ignition.

Polar drive will produce large lateral temperature gradients in the corona that depend on details of heat-transport modeling



A nonlocal heat transport model for 2-D simulations is being developed.

The polar-drive point design achieves a gain of 17 with all current levels of NIF nonuniformities included in the calculation ($f = 0.06$, and no LPI)



Point design from January 2007. Upgraded designs are in progress.

Recent NIF PD designs achieve a gain of 35

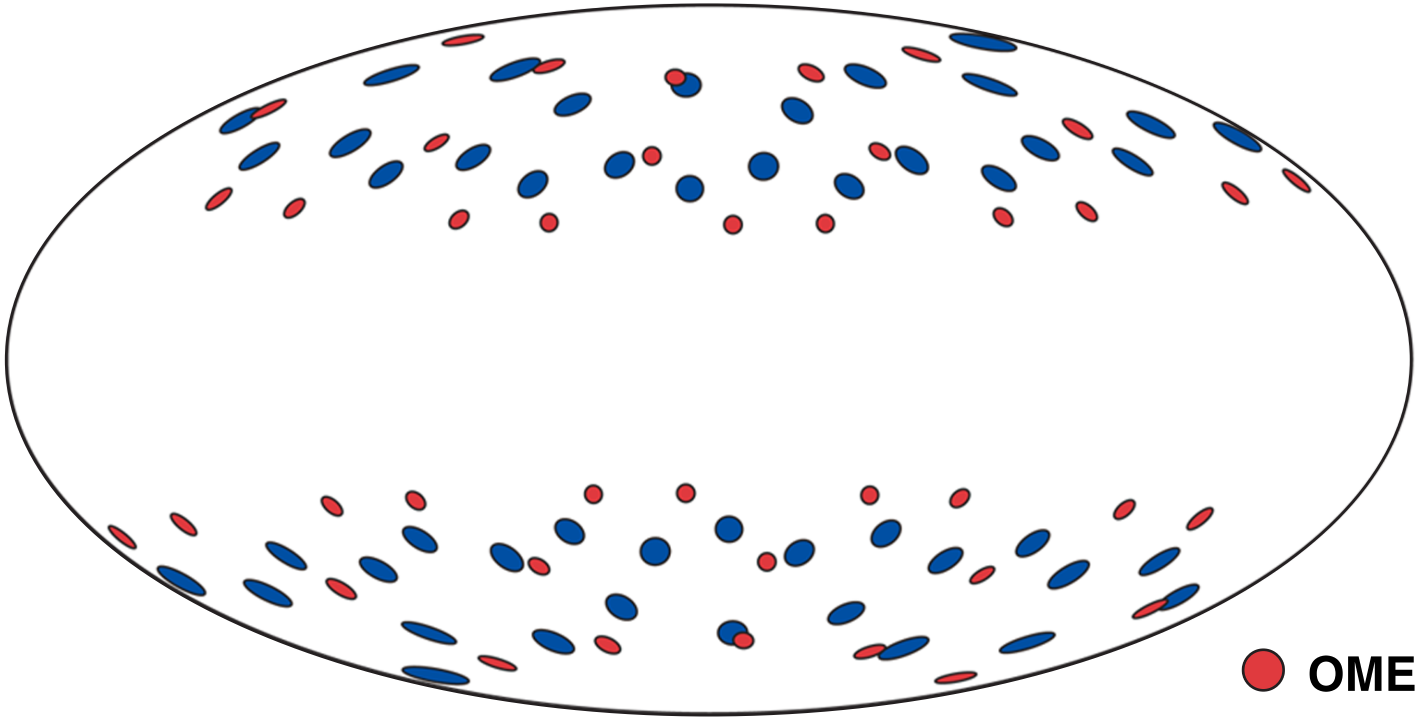
- The laser intensity at the equator is reduced by using “shimmed” targets
  - initial results show that reducing the target thickness at the equator by 18 μm (relative to the pole) can reduce the intensity required to drive the equator by ~20%
- Triple-picket designs are being used, based on OMEGA experiments
- Both plastic and wetted-foam ablators are being examined
  - wetted-foam targets offer greater stability
  - plastic ablators have a higher threshold for the onset of the two-plasmon decay (TPD) instability

LPI physics will be added as determined by OMEGA and NIF experiments.

Simulation of high-compression experiments requires enhanced modeling of laser–plasma physics

- To calculate preheat from two-plasmon decay (TPD), a model for the nonlinear evolution and saturation of plasma waves is being developed, in collaboration with Don DuBois *et al*. (LANL)
  - fast-electron generation is being added to the model
- Competition between TPD and SBS is being investigated, both theoretically and experimentally
- A model for cross-beam energy transfer (CBET) is being developed to more-accurately model the timing of target implosion
- A model for 2-D nonlocal heat transport is being developed in collaboration with Greg Moses (U. Wisconsin) to more-accurately model both lateral and radial energy transport from the target corona to the ablation surface

The NIF Polar–Drive configuration with 48 quads can be approximated by repointing 40 beams of OMEGA

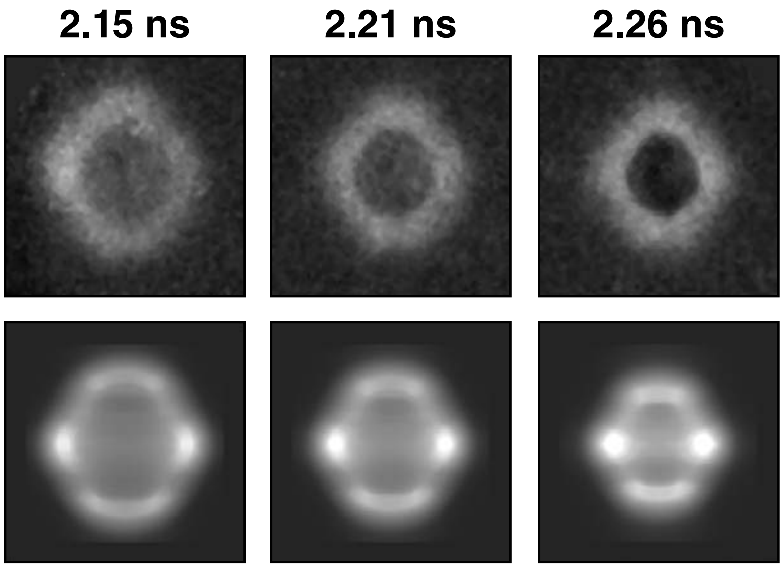


🟥 OMEGA beam

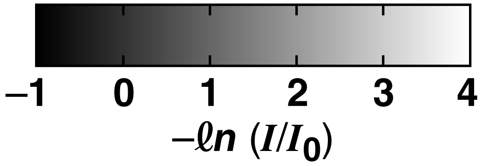
🟦 NIF ID quad

The observed shell perturbations are well reproduced by *DRACO* 2-D simulations for low convergence (~10) PD experiments on OMEGA

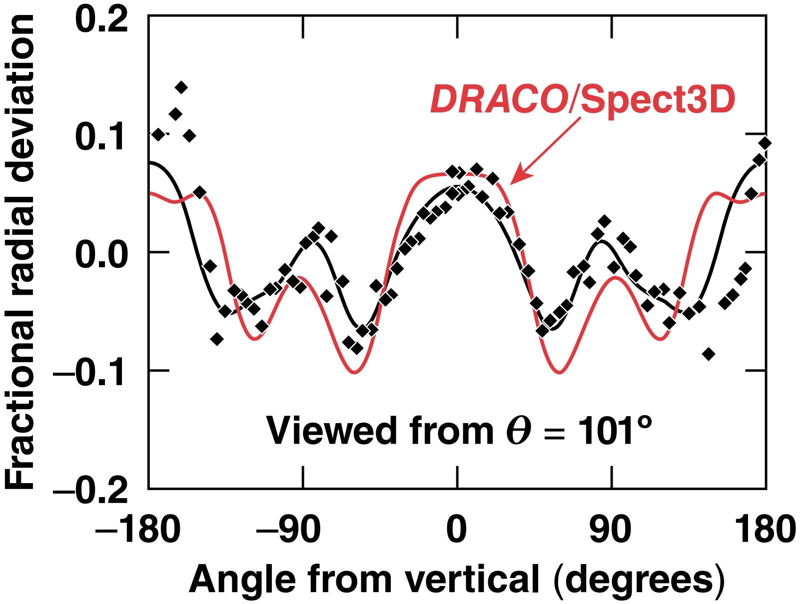
OMEGA shot 49331, PD implosion
Framed x-ray radiographs,
2.5 to 4-keV backllighter



***DRACO*/Spect3D simulation**
400 × 400 μm regions



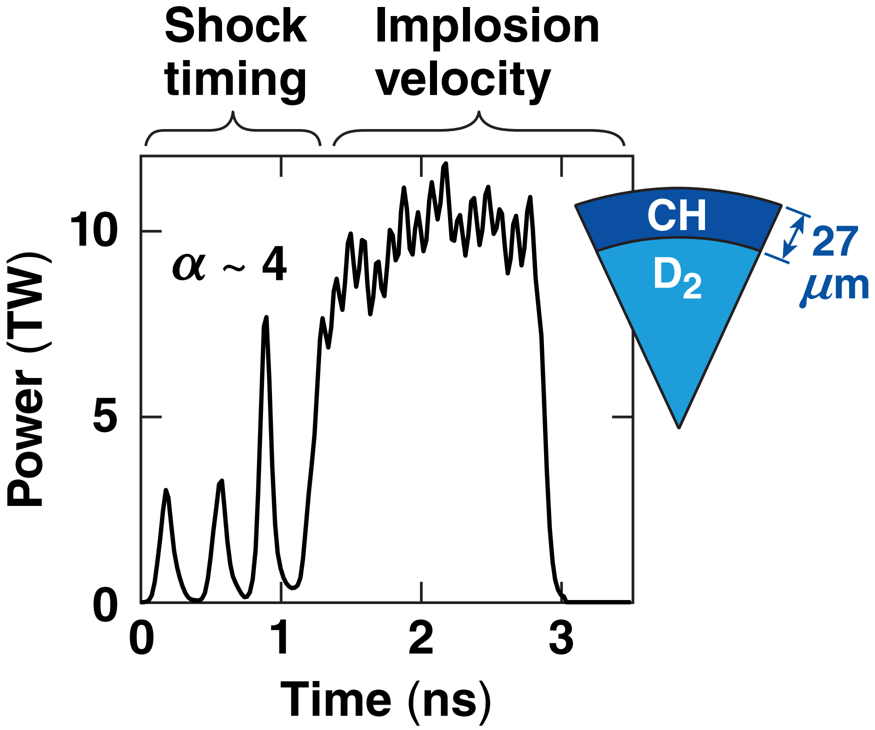
Shell shape compared to simulation (t = 2.21 ns)



F. J. Marshall *et al*., J. Phys. IV France 133, 153 (2006).

High-compression PD experiments, scheduled for FY11, will examine laser–plasma coupling for the very oblique irradiation near the equator

- Details of laser coupling will affect
  - – shock timing
  - – implosion velocity
  - – bang time
  - – scattered light
  - – implosion symmetry



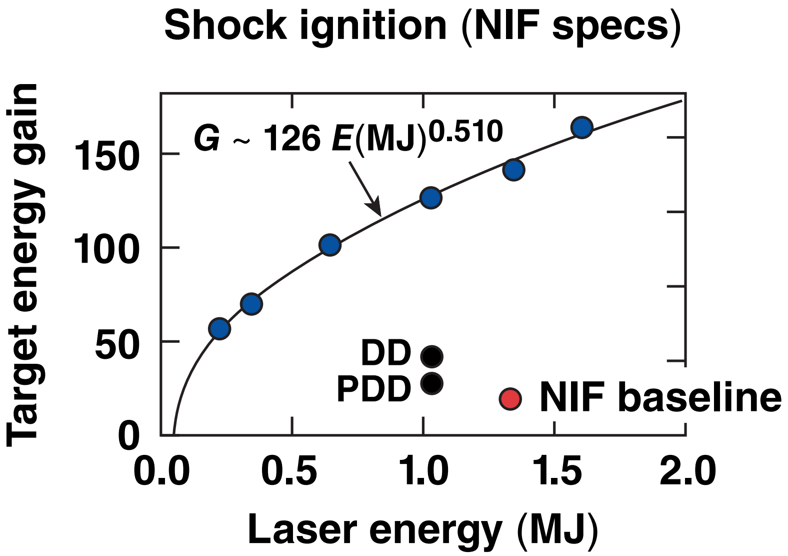
Initial high-compression PD experiments will use warm (non-cryogenic) targets with a triple-picket pulse shape: $\rho R \sim 150$ mg/cm^2 is predicted.

Directly-driven ignition experiments on the NIF will require the addition of some new optics and new beam-smoothing technology

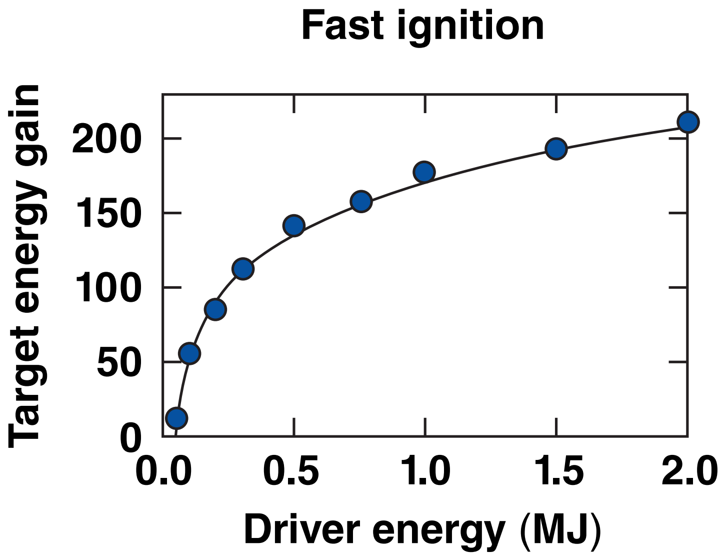
- New phase plates to control the spot shape on target
- Birefringent wedges for polarization smoothing
- Smoothing by Spectral Dispersion (SSD)
  - a multi-frequency approach with spectral dispersion in only one direction will provide adequate smoothing and will fit within existing PAMS
- Target-insertion device

The required optics and hardware are being designed at LLE, maintaining close contact with NIF personnel, to ensure that all components are consistent with NIF specs.

If successful, fast and shock ignition will open the path to high gain ICF (gain ~ 150) for ~1-MJ IFE laser drivers



L. J. Perkins *et al*., Phys. Rev. Lett. 103, 045004 (2009).

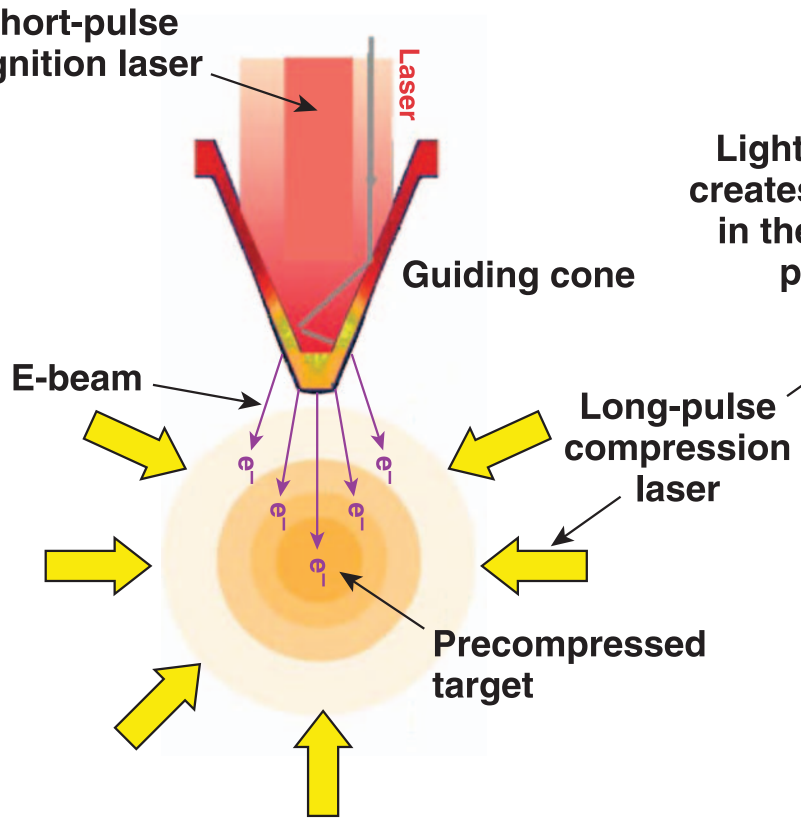


R. Betti *et al*., Phys. Plasmas 13, 100703 (2006).

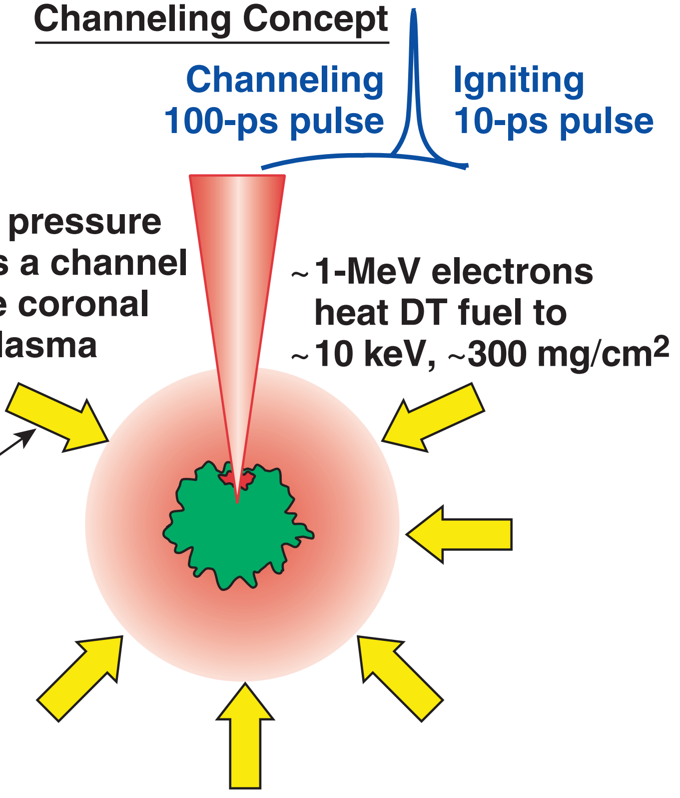
Both concepts can use Polar Drive to compress the target.

Fast ignition uses an electron beam produced by a high-intensity short-pulse laser to ignite a pre-compressed target

Cone-Focused Concept



Channeling Concept

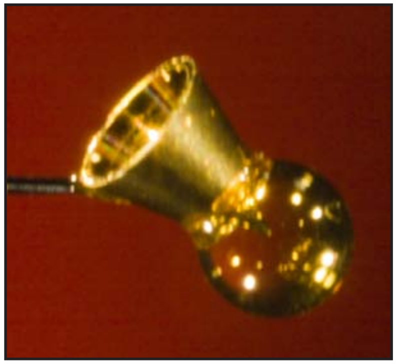


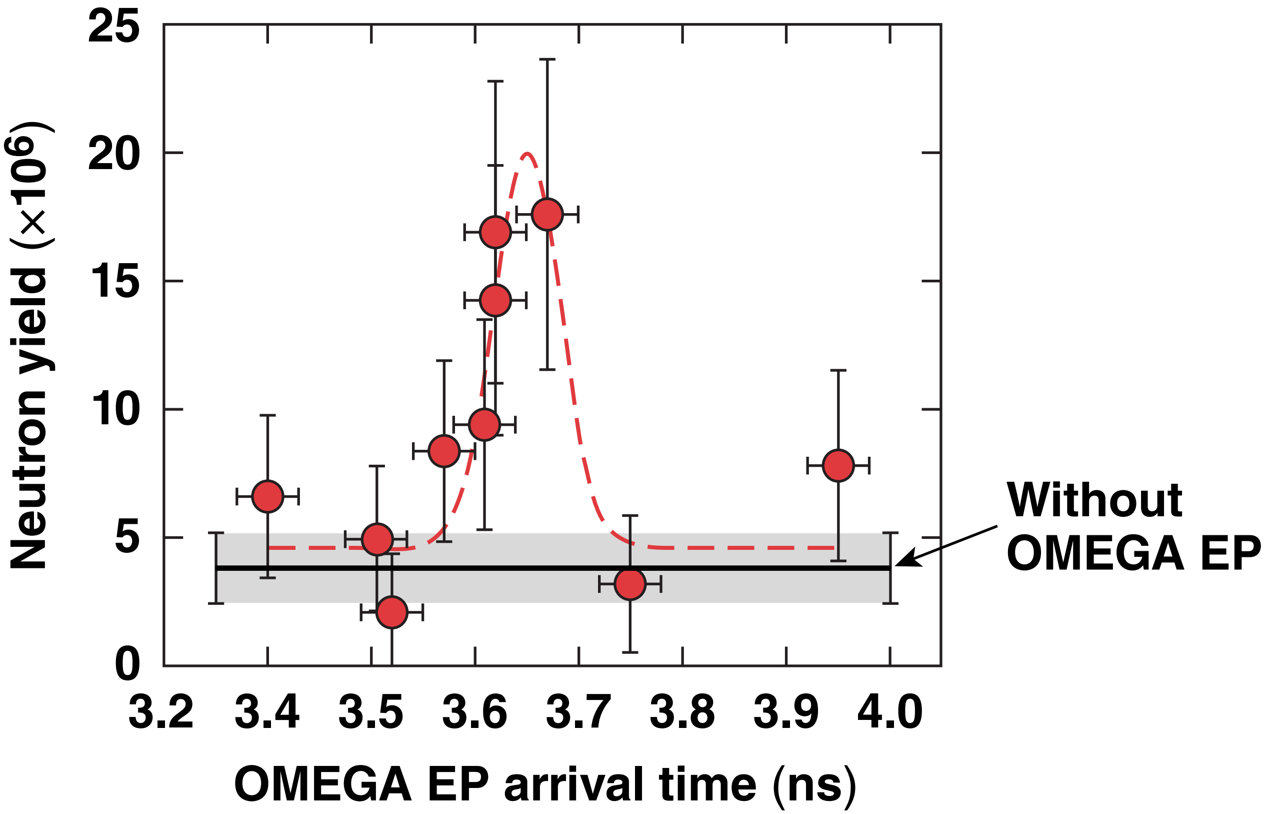
This concept is being investigated using the OMEGA EP laser to generate high-intensity irradiation.

M Tabak *et al.*, Phys. Plasmas 1, 1626 (1994).

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

Cone-in-shell target

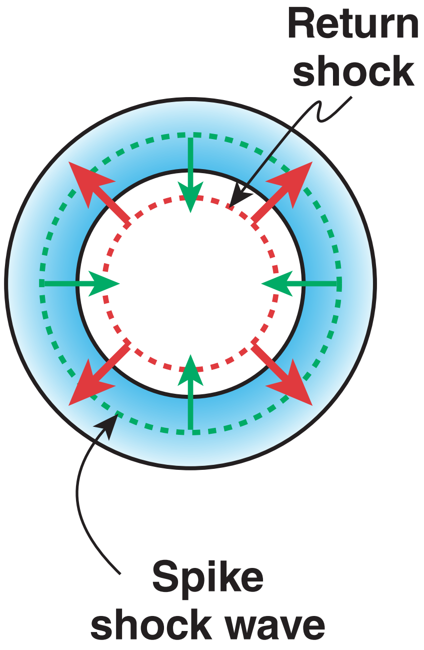


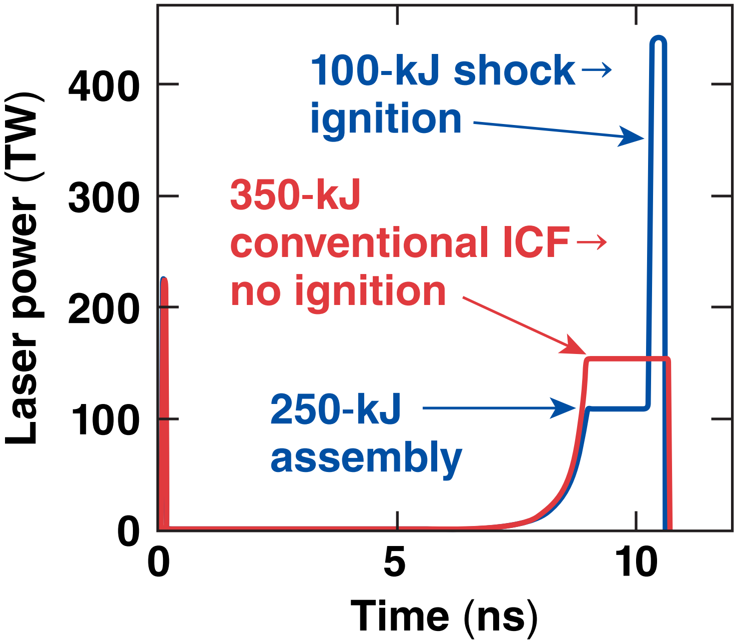


Without OMEGA EP

Shock ignition uses a late, strong shock to ignite the central hot spot of an imploded shell

Polar Drive is used to compress the target, but at a lower velocity than required for central ignition



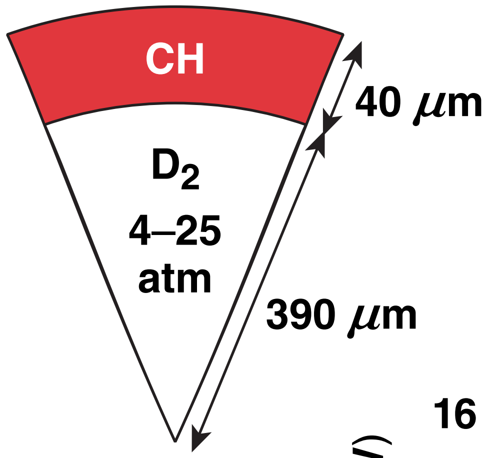


The late spike in laser power drives a ~400-Mb shock. Upon convergence, the shock pressure reaches ~5 Gb (at the collision time), and achieves ignition temperatures.

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

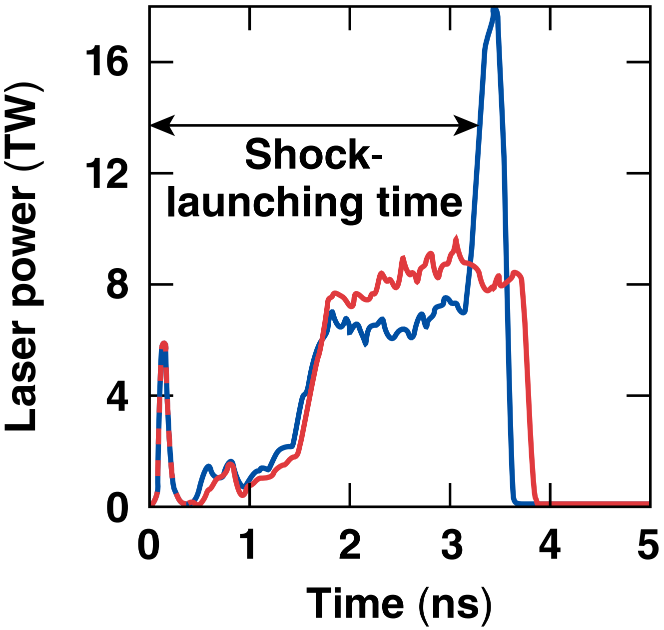
Initial shock-ignition research on OMEGA is encouraging

Warm target

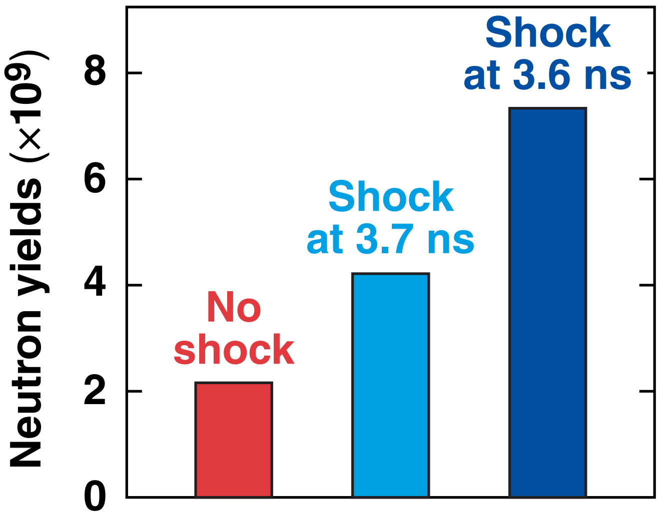


E_L = 17 to 18 kJ
α = 1.3

Pulse shape with and without shock spike

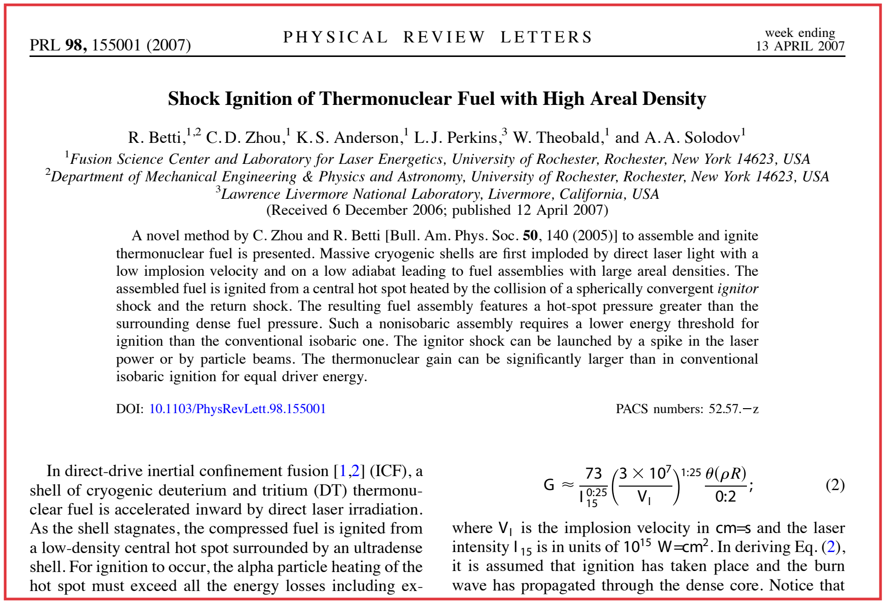


25-atm D_2



The neutron yield increases considerably when a shock is launched at the end of the pulse. ρR increases by ~50%.

Shock ignition as a path to IFE has generated considerable interest in the ICF community


PRL **98,** 155001 (2007) PHYSICAL REVIEW LETTERS week ending 13 APRIL 2007

Shock Ignition of Thermonuclear Fuel with High Areal Density

R. Betti,[1,2] C.D. Zhou,[1] K.S. Anderson,[1] L.J. Perkins,[3] W. Theobald,[1] and A.A. Solodov[1]

[1]*Fusion Science Center and Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA*
[2]*Department of Mechanical Engineering & Physics and Astronomy, University of Rochester, Rochester, New York 14623, USA*
[3]*Lawrence Livermore National Laboratory, Livermore, California, USA*
(Received 6 December 2006; published 12 April 2007)

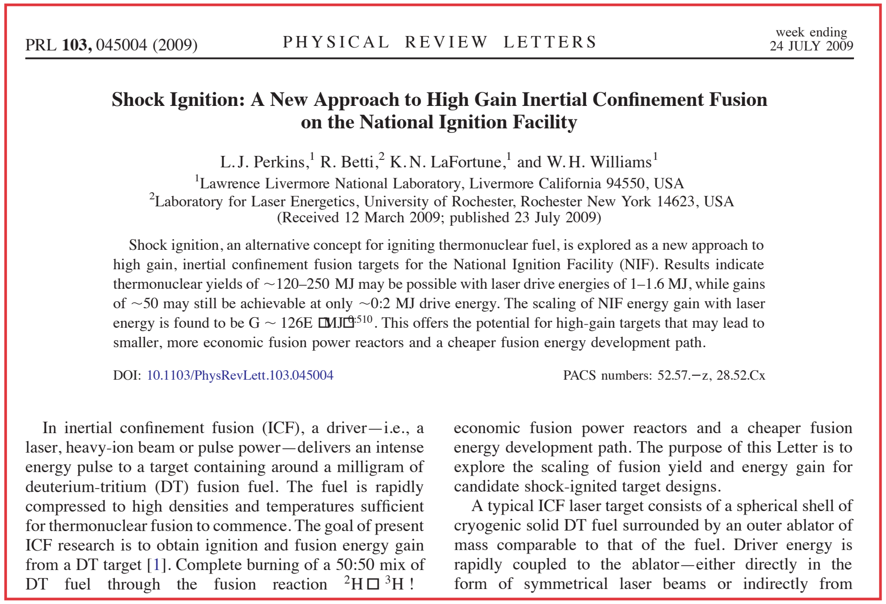
A novel method by C. Zhou and R. Betti [Bull. Am. Phys. Soc. **50**, 140 (2005)] to assemble and ignite thermonuclear fuel is presented. Massive cryogenic shells are first imploded by direct laser light with a low implosion velocity and on a low adiabat leading to fuel assemblies with large areal densities. The assembled fuel is ignited from a central hot spot heated by the collision of a spherically convergent *ignitor* shock and the return shock. The resulting fuel assembly features a hot-spot pressure greater than the surrounding dense fuel pressure. Such a nonisobaric assembly requires a lower energy threshold for ignition than the conventional isobaric one. The ignitor shock can be launched by a spike in the laser power or by particle beams. The thermonuclear gain can be significantly larger than in conventional isobaric ignition for equal driver energy.

DOI: 10.1103/PhysRevLett.98.155001 PACS numbers: 52.57.−z

In direct-drive inertial confinement fusion [1,2] (ICF), a shell of cryogenic deuterium and tritium (DT) thermonuclear fuel is accelerated inward by direct laser irradiation. As the shell stagnates, the compressed fuel is ignited from a low-density central hot spot surrounded by an ultradense shell. For ignition to occur, the alpha particle heating of the hot spot must exceed all the energy losses including ex-

$$G \approx \frac{73}{I_{15}^{0:25}}\left(\frac{3\times 10^7}{V_I}\right)^{1:25}\frac{\theta(\rho R)}{0:2}; \qquad (2)$$

where V_I is the implosion velocity in cm=s and the laser intensity I_{15} is in units of 10^{15} W=cm^2. In deriving Eq. (2), it is assumed that ignition has taken place and the burn wave has propagated through the dense core. Notice that


PRL **103,** 045004 (2009) PHYSICAL REVIEW LETTERS week ending 24 JULY 2009

Shock Ignition: A New Approach to High Gain Inertial Confinement Fusion on the National Ignition Facility

L.J. Perkins,[1] R. Betti,[2] K.N. LaFortune,[1] and W.H. Williams[1]

[1]Lawrence Livermore National Laboratory, Livermore California 94550, USA
[2]Laboratory for Laser Energetics, University of Rochester, Rochester New York 14623, USA
(Received 12 March 2009; published 23 July 2009)

Shock ignition, an alternative concept for igniting thermonuclear fuel, is explored as a new approach to high gain, inertial confinement fusion targets for the National Ignition Facility (NIF). Results indicate thermonuclear yields of ∼120–250 MJ may be possible with laser drive energies of 1–1.6 MJ, while gains of ∼50 may still be achievable at only ∼0:2 MJ drive energy. The scaling of NIF energy gain with laser energy is found to be $G \sim 126E$ □MJ□$^{0:510}$. This offers the potential for high-gain targets that may lead to smaller, more economic fusion power reactors and a cheaper fusion energy development path.

DOI: 10.1103/PhysRevLett.103.045004 PACS numbers: 52.57.−z, 28.52.Cx

In inertial confinement fusion (ICF), a driver—i.e., a laser, heavy-ion beam or pulse power—delivers an intense energy pulse to a target containing around a milligram of deuterium-tritium (DT) fusion fuel. The fuel is rapidly compressed to high densities and temperatures sufficient for thermonuclear fusion to commence. The goal of present ICF research is to obtain ignition and fusion energy gain from a DT target [1]. Complete burning of a 50:50 mix of DT fuel through the fusion reaction ^{2}H□ ^{3}H !

economic fusion power reactors and a cheaper fusion energy development path. The purpose of this Letter is to explore the scaling of fusion yield and energy gain for candidate shock-ignited target designs.

A typical ICF laser target consists of a spherical shell of cryogenic solid DT fuel surrounded by an outer ablator of mass comparable to that of the fuel. Driver energy is rapidly coupled to the ablator—either directly in the form of symmetrical laser beams or indirectly from

International Workshop in ICF Shock Ignition:
Facility Strategies, Target Design and Experimental Planning

March 8–10 2011
University of Rochester
Rochester, NY 14623

Summary/Conclusions

Directly-driven ignition designs and IFE designs for the NIF are being validated by high-compression cryogenic experiments on OMEGA

- Target designs are modified and updated based on OMEGA experiments
  - simulations use both *DRACO* (2-D) and *HYDRA* (3-D)
- Detailed modeling of laser–target coupling and heat transport are essential for simulating high-compression experiments on OMEGA
  - experiments are being designed to examine laser–plasma interactions for anticipated NIF conditions
- Low compression Polar Drive (PD) experiments on OMEGA and the NIF are well described by computer simulation
  - high-compression PD experiments are in progress
- The technology for implementing PD on the NIF is being developed at LLE