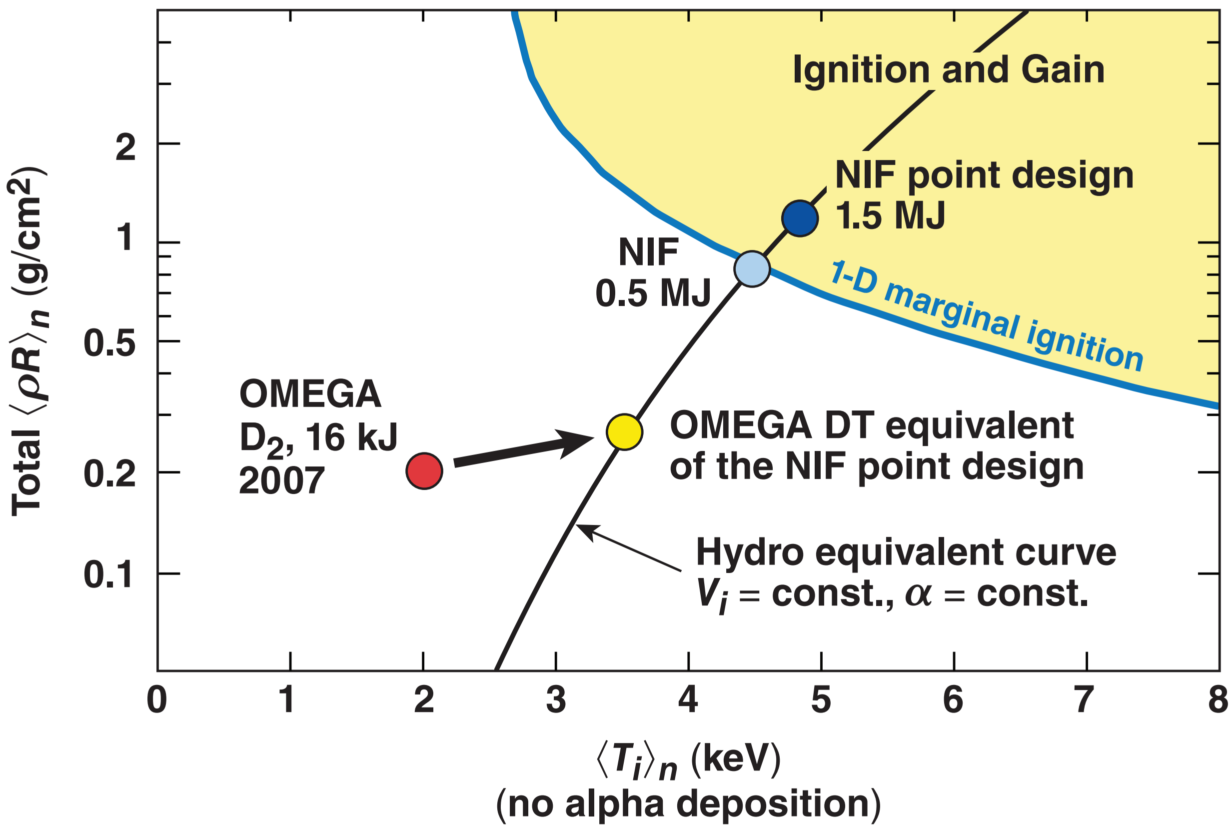
Progress in Direct-Drive Inertial Confinement Fusion Research



R. L. McCrory
University of Rochester
Laboratory for Laser Energetics

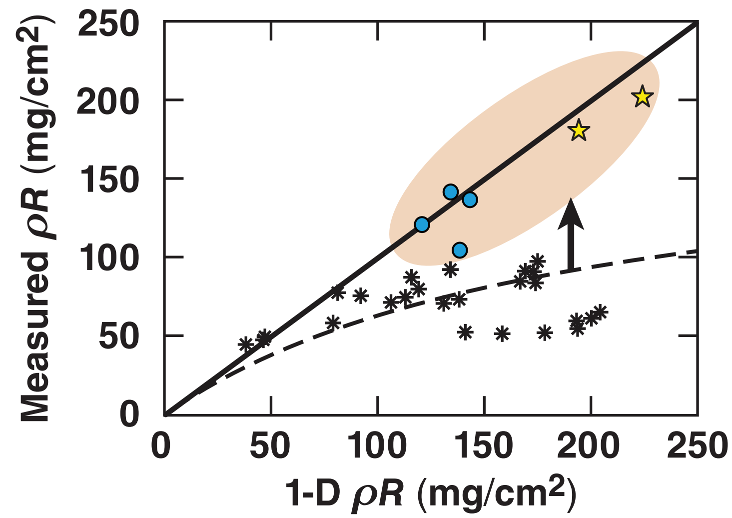
49th Annual Meeting of the
American Physical Society
Division of Plasma Physics
Orlando, FL
12–16 November 2007

Summary

These are exciting times for inertial confinement fusion

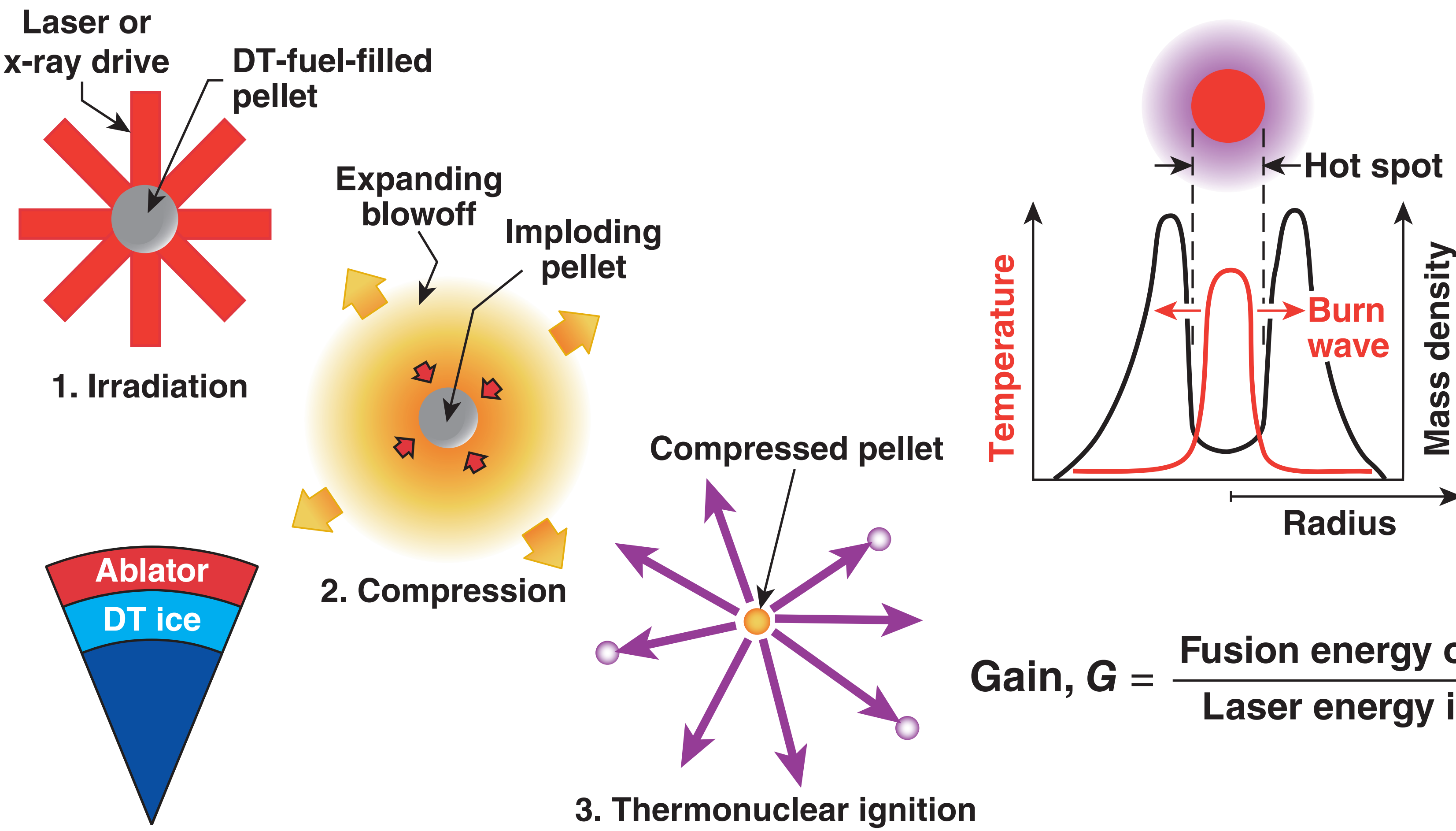
UR LLE

- **Experiments on Nova (previously) and OMEGA are developing the target-physics understanding.**
- **Recent OMEGA experiments have demonstrated ignition-relevant areal densities.**
- **New concepts will extend ignition possibilities.**
- **This talk will review direct-drive ICF progress.***
- **After 35 years, the ICF community is ready to exploit advances in physics understanding and drivers, leading to ignition experiments on the National Ignition Facility (NIF).**



*More ICF, see Lindl (SR1.00001).

Ablation is used to generate the extreme pressures required to compress a fusion capsule to ignition conditions



$$\text{Gain, } G = \frac{\text{Fusion energy out}}{\text{Laser energy in}}$$

"Hot-spot" ignition requires the core temperature to be at least 10 keV and the core fuel areal density to exceed ~300 mg/cm^2.

A "Lawson's criterion" in terms of burn-averaged ρR and T_i shows the requirements for ignition

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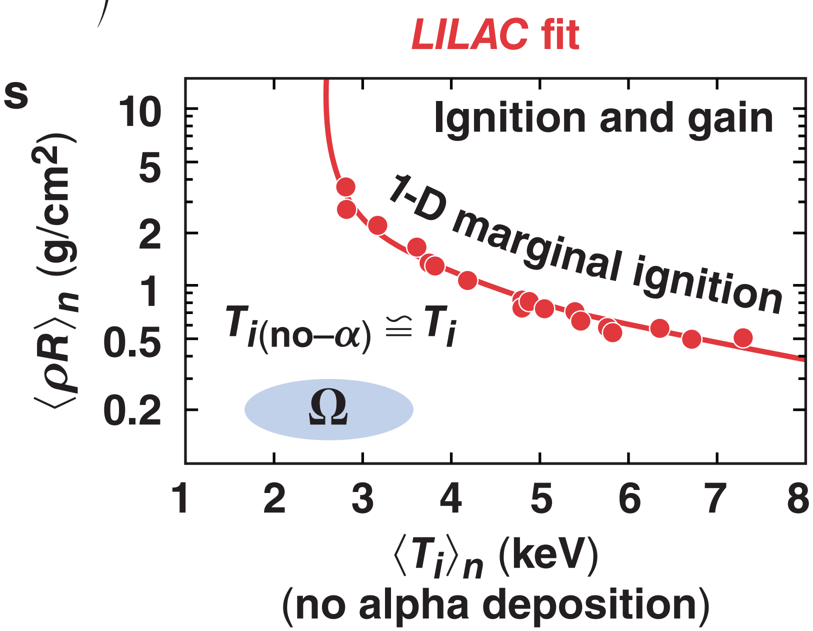
- Simple scaling relations for ignition condition from Zhou *et al.** and Herrmann *et al.***

$$\langle \rho R \rangle_n > 1.3 \left(\frac{4}{\langle T_i \rangle_n (\text{keV})} \right)^{2.4} (\text{g/cm}^2)$$

- Fitting the results of 1-D simulations with Gain = 1 yields an ignition condition that depends on the burn-averaged ρR and ion temperature without alpha deposition.

- For sub-ignited implosions $T_{i(\text{no}-\alpha)} \cong T_i$



Both T_i and ρR can be measured experimentally.

R. Betti and C. Zhou (CO5.00001).

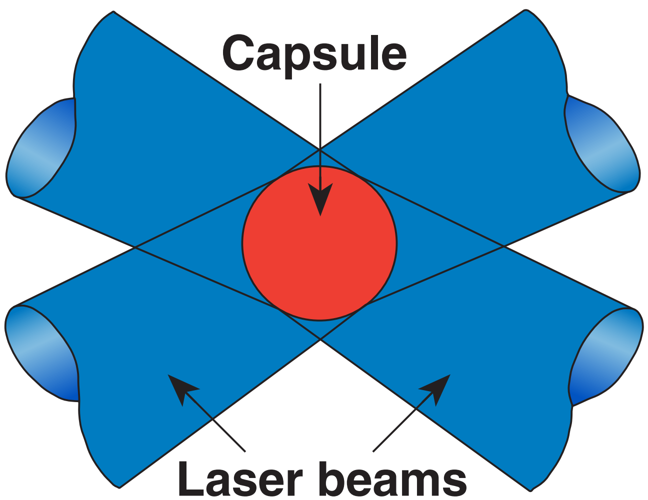
* C. Zhou and R. Betti, Phys. Plasmas 14, 072703 (2007).

** M. C.Herrmann, M. Tabak, and J. D. Lindl, Nucl. Fusion 41, 99 (2001).

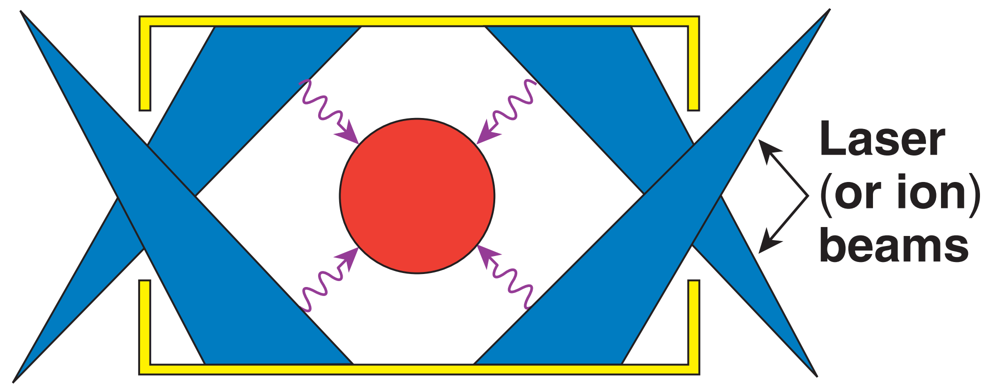
I1770

The fundamental physics of direct- and indirect-drive ICF implosions is the same

Direct-drive target



X-ray-drive target



Hohlraum using a cylindrical high-Z case

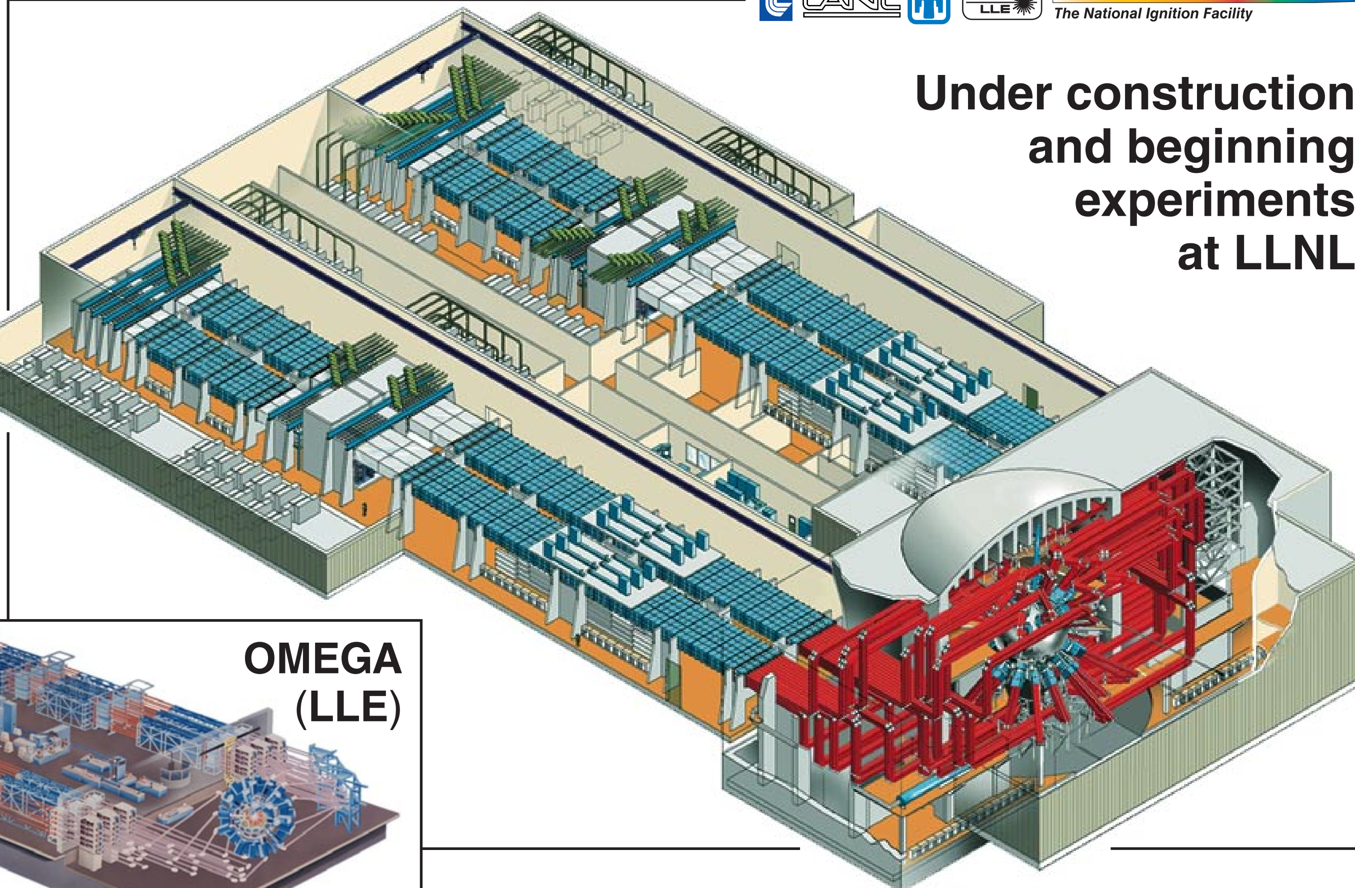
Key physics issues are common to both

- Energy coupling
- Drive uniformity
- Hydrodynamic instabilities
- Compressibility

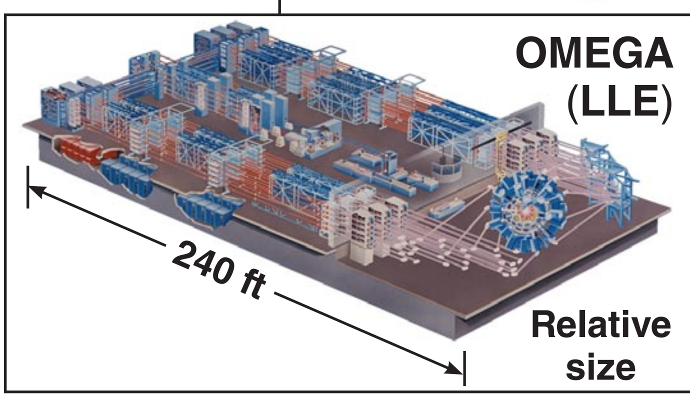
Direct-drive cryogenic implosions provide essential information for ICF physics.

E6426o

The 1.8-MJ National Ignition Facility (NIF) will demonstrate ICF ignition and modest energy gain



Under construction and beginning experiments at LLNL



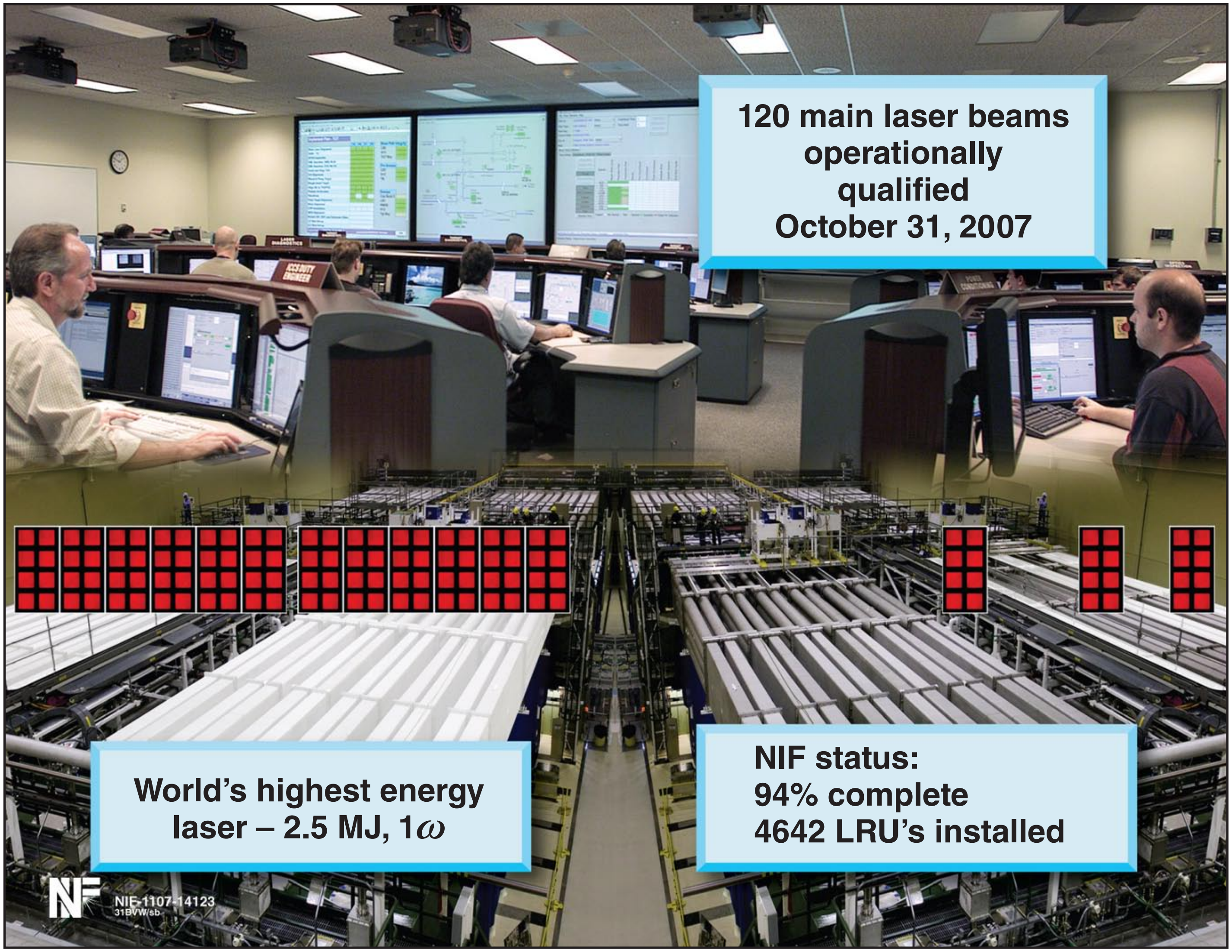
OMEGA (LLE)

Relative size

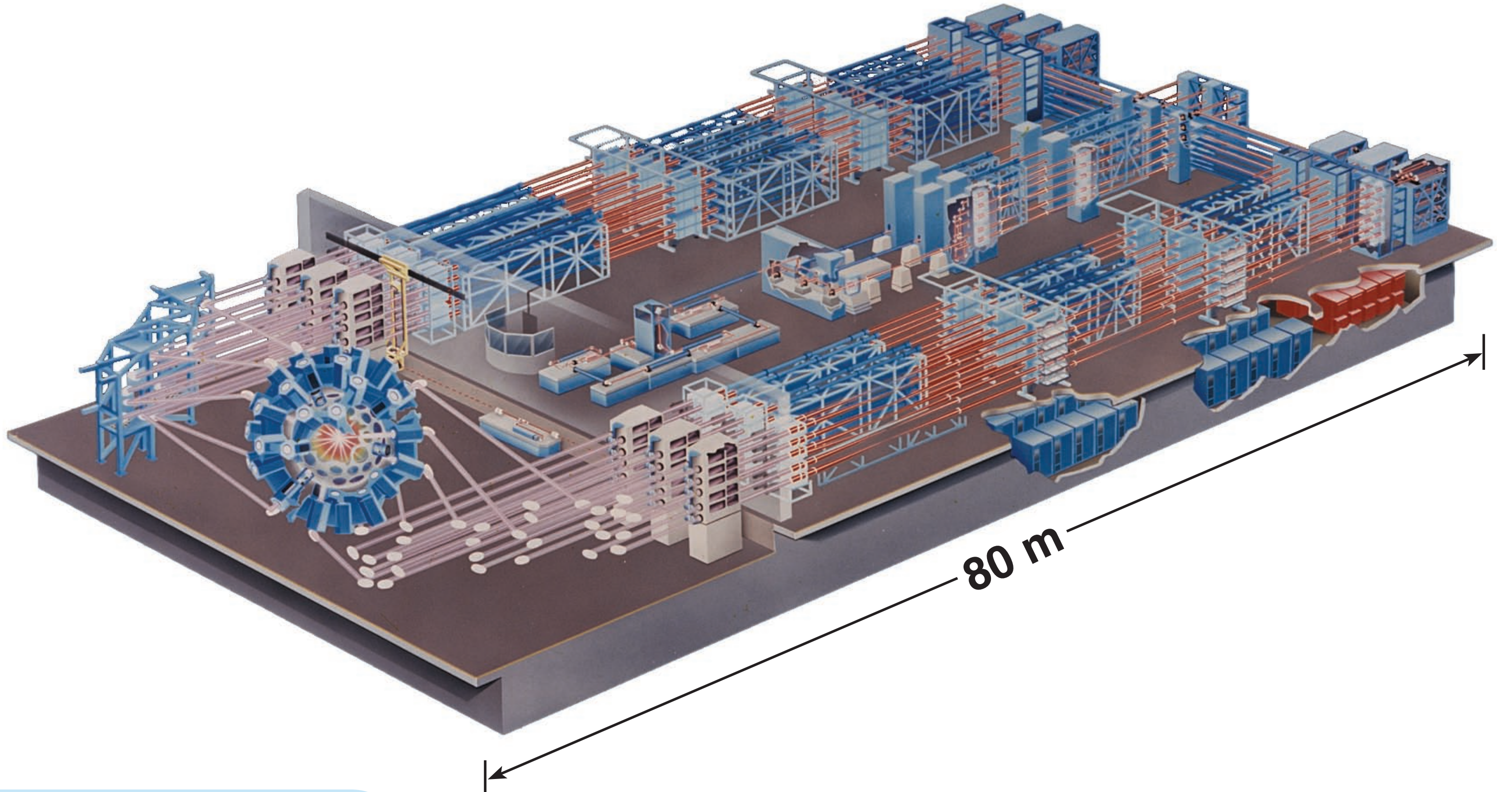
OMEGA experiments are integral to an ignition demonstration on the NIF.

TC4680m

The NIF is on track for completion in FY09



The OMEGA laser is designed to achieve high irradiation uniformity with flexible pulse-shaping capability



Fully instrumented

Successfully operated for 10 years

1500 target shots/year

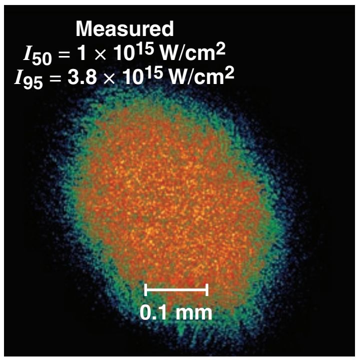
- 60 beams
- ~30-kJ UV on target
- 1% to 2% irradiation nonuniformity
- Flexible pulse shaping
- Short shot cycle (1 h)

TC2998s

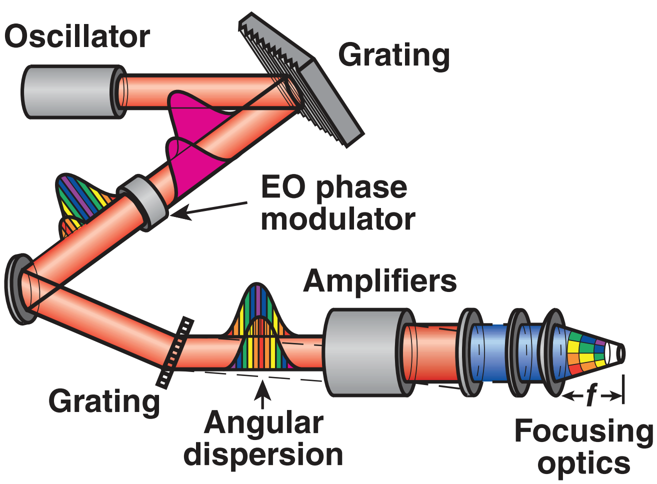
Laser-beam smoothing is critical to ICF ignition

Phase Plates[1]

Measured far field of an OMEGA indirect-drive phase plate



Smoothing by Spectral Dispersion[2]



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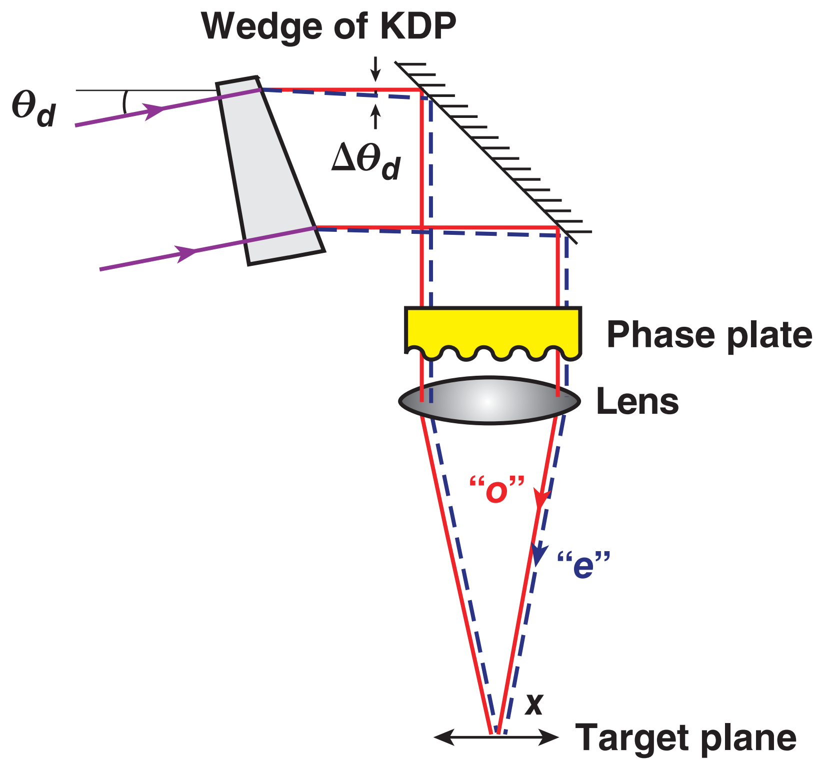
Polarization Smoothing[3]

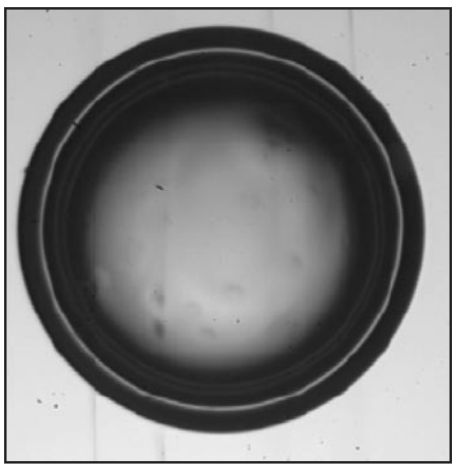


[1] Y. Kato *et al.*, Phys. Rev. Lett. 53, 1057 (1984); Y. Lin, T. J. Kessler, and G. N. Lawrence, Opt. Lett. 20, 764 (1995).
[2] S. Skupsky *et al.*, J. Appl. Phys. 66, 3456 (1989).
[3] T. R. Boehly *et al.*, J. Appl. Phys. 85, 3444 (1999).

Ignition requires smooth cryogenic DT targets

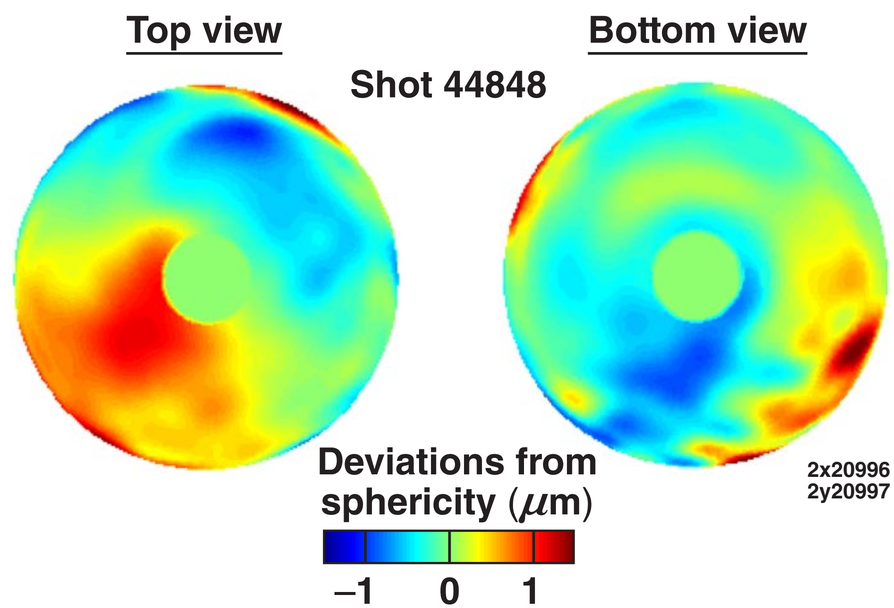
- Thick (>50 μm) DT ice layers are required for ignition.
- β-layered 50:50 DT cryogenic targets have measured ice-roughness nonuniformities <1-μm rms, meeting ignition specifications.

Shadowgraph image of a cryogenic DT target (~100-μm-thick layer)



Ice-surface roughness: 0.47-μm rms in a single view

Ice-surface reconstruction showing 0.72-μm rms (48 views)



Multiple views are essential for full characterization.

D. R. Harding (YO5.00001).
D. R. Harding, to be published in *IFSA 2007*.

About 80% of the DT capsules created to date have produced layers with sub-1-μm rms roughness

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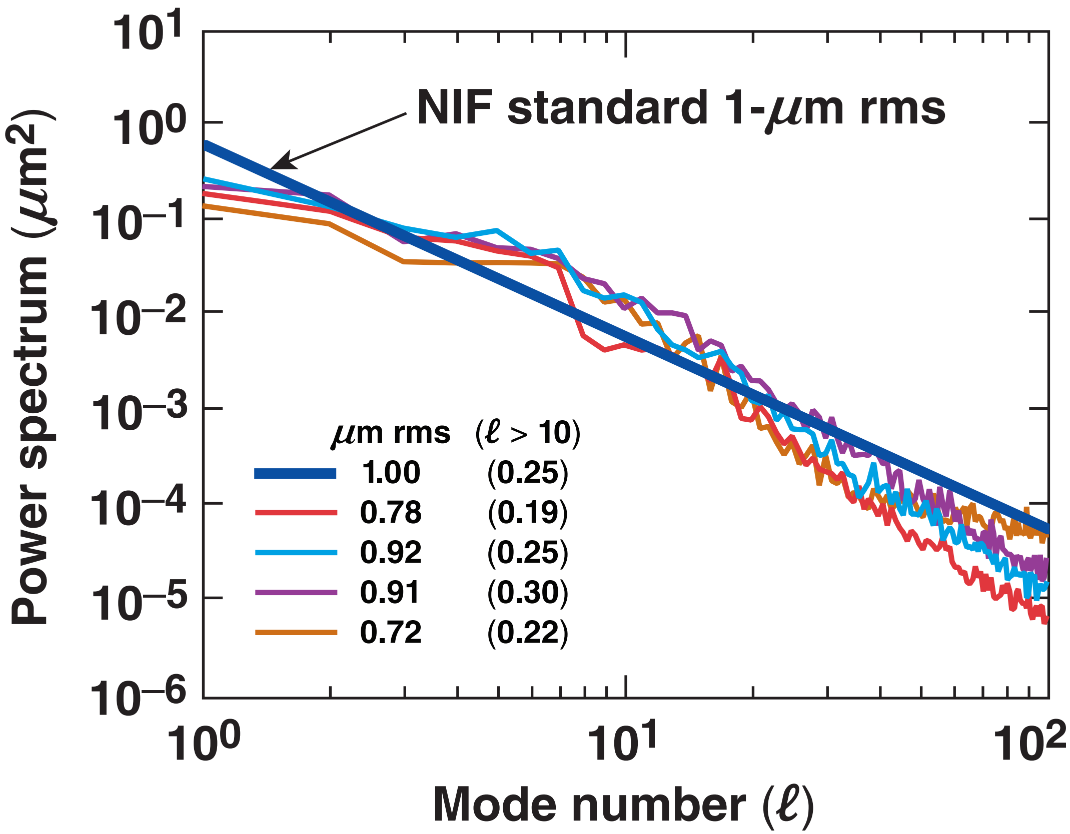


- High-mode (ℓ > 20) roughness is minimal for "single-crystal" layers
- Low-mode roughness (ℓ < 6) is due to asymmetries in the triple-point isotherm
- Mid-mode roughness (6 < ℓ < 20) is likely related to outer-surface features (glue for silks)
- The best layers are achieved at the triple point

DT layer quality meets ignition requirements.

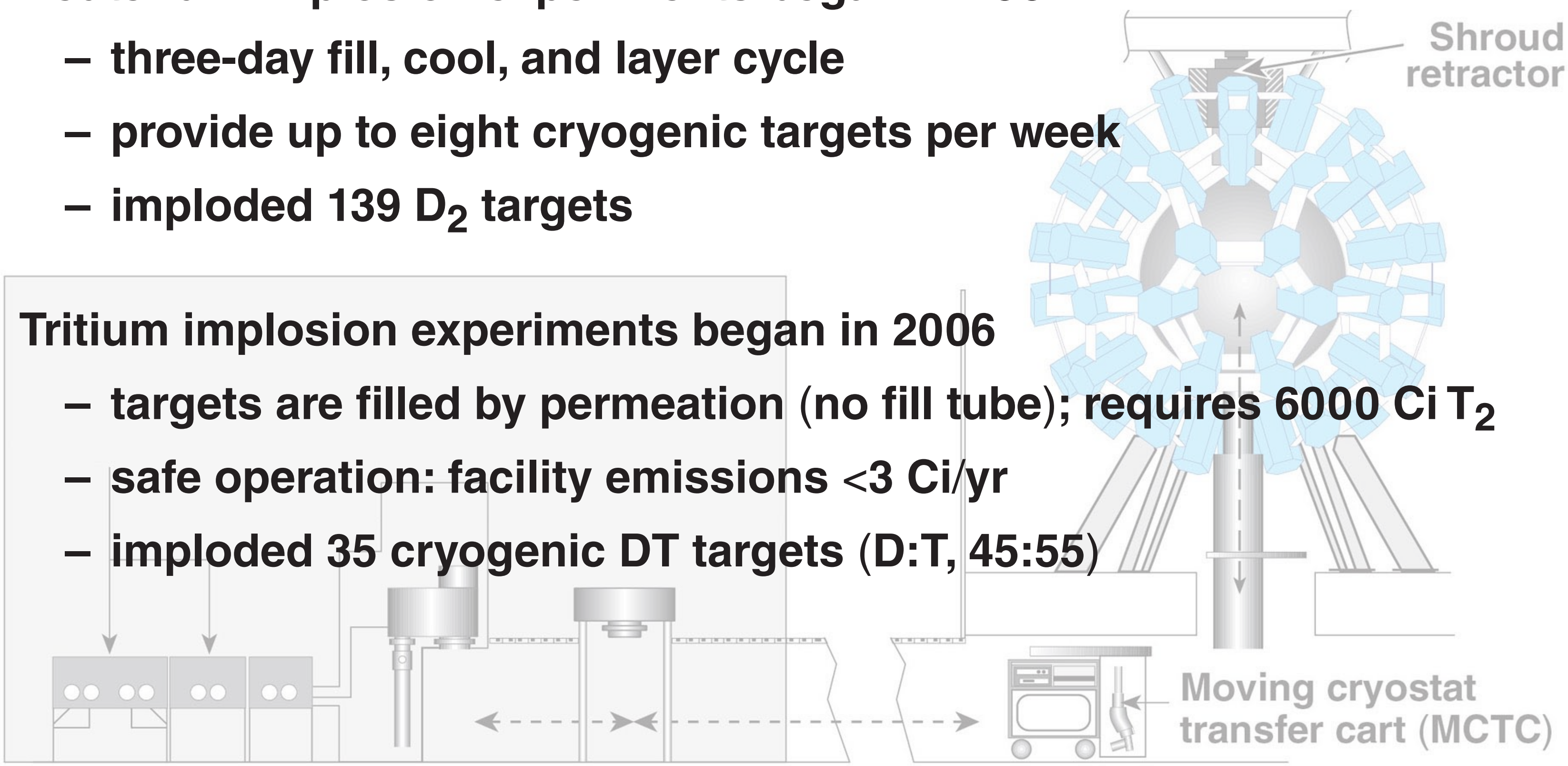
E15043d

T. C. Sangster *et al*., Phys. Plasmas 14, 058101 (2007).

LLE has learned how to reliably field cryogenic capsules

- Deuterium implosion experiments began in 2001
  - three-day fill, cool, and layer cycle
  - provide up to eight cryogenic targets per week
  - imploded 139 D_2 targets

- Tritium implosion experiments began in 2006
  - targets are filled by permeation (no fill tube); requires 6000 Ci T_2
  - safe operation: facility emissions <3 Ci/yr
  - imploded 35 cryogenic DT targets (D:T, 45:55)



Improvements in the ice-layer quality and target position have proceeded in parallel with implosion experiments.

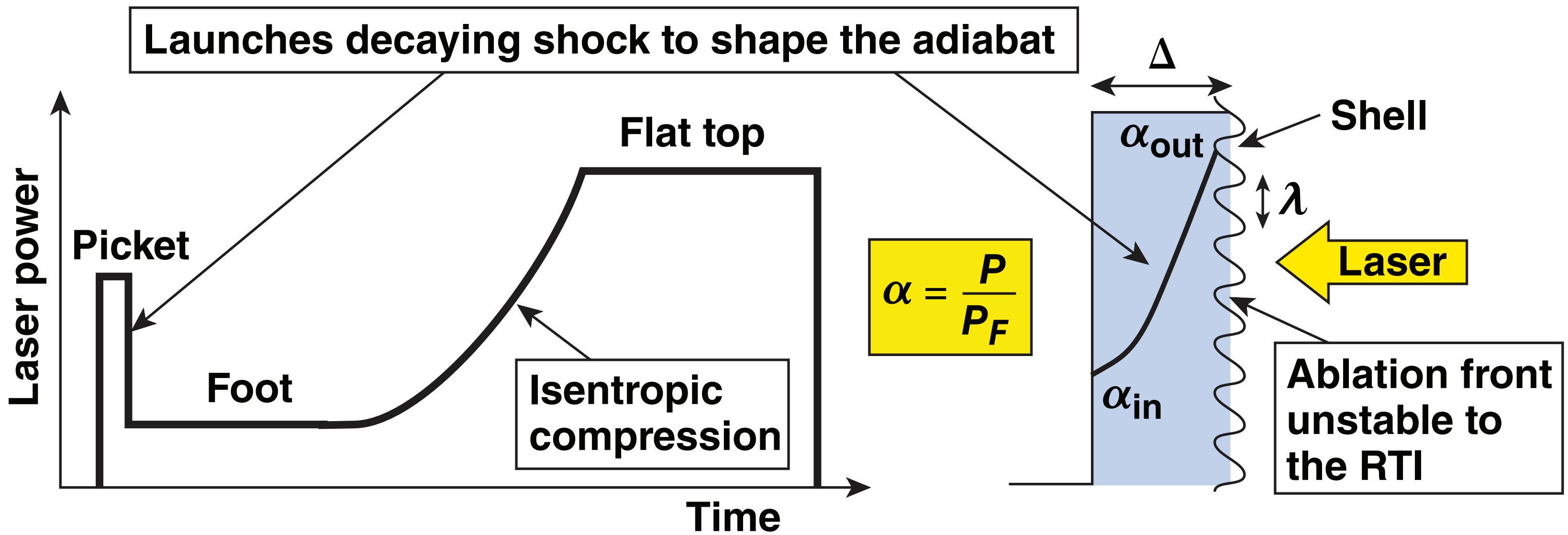
T2364a

The fuel areal density and hot-spot ion temperature determine ignition performance

- **Areal density (ρR)**
  - shock timing and strength
  - preheat
  - compressibility
  - hydrodynamic instabilities
- **Ion temperature (T_i)**
  - implosion velocity
  - hydrodynamic instabilities
  - absorption/drive coupling

Our strategy is to first increase ρR and then T_i

The laser power is tailored to drive the target on a low fuel adiabat, including adiabat shaping*



- High outer α reduces the RTI growth rates through higher ablation velocity

$$\gamma_{RTI} = 0.9\sqrt{kg} - 3kV_a{}^{\dagger} \quad k = 2\pi/\lambda \quad V_a \sim \alpha_{out}^{0.6}$$

- High $\langle\alpha\rangle$ increases the shell thickness and reduces feedthrough, $\Delta \sim \langle\alpha\rangle^{0.6}$
- Low inner α reduces the shell kinetic energy required for ignition, $E_{ign} \sim \alpha_{in}^{1.8\ddagger}$

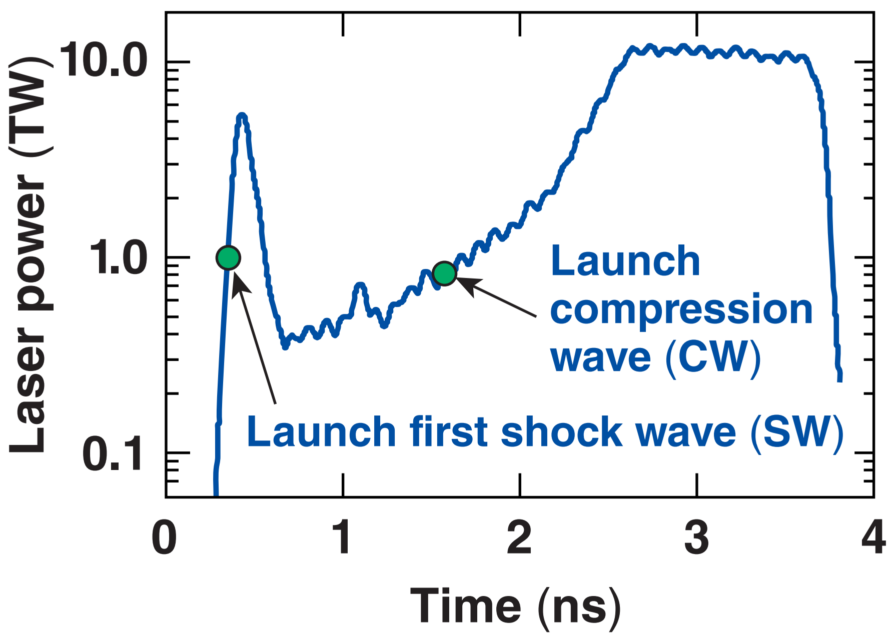
ICF ignition targets have α_{in} ~ 1 to 3, α_{out} ~ 3 to 6, and α_{avg} ~ 2 to 3.

*V. N. Goncharov *et al*., Phys. Plasmas 10, 1906 (2003).
†H. Takabe *et al*., Phys. Fluids 28, 3676 (1985).
‡W. K. Levedahl and J. D. Lindl, Nucl. Fusion 37, 165 (1997).

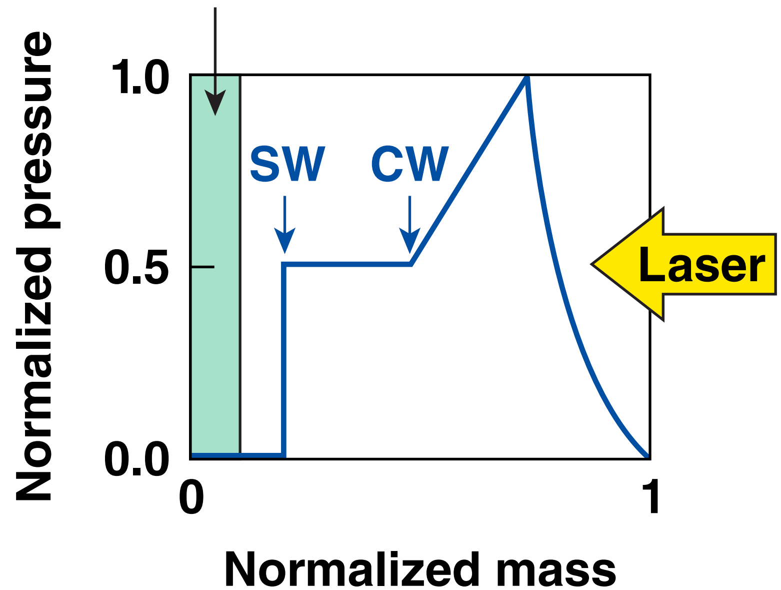
Shock Timing

The shock and isentropic compression must be precisely timed to reach the areal density required for ignition

- Accurate shock and compression wave timing sets the proper α_{in}, $\rho R \sim \alpha_{in}^{-0.6}$



CW and SW must coalesce near the inner edge of the shell



$$\frac{\Delta t_{shock}}{t_{shock}} < 5\%,\ t_{shock} \sim E_p^{-1/2} \Rightarrow \boxed{\frac{\Delta E_p}{E_p} < 10\%}$$

(E_p is the picket energy)

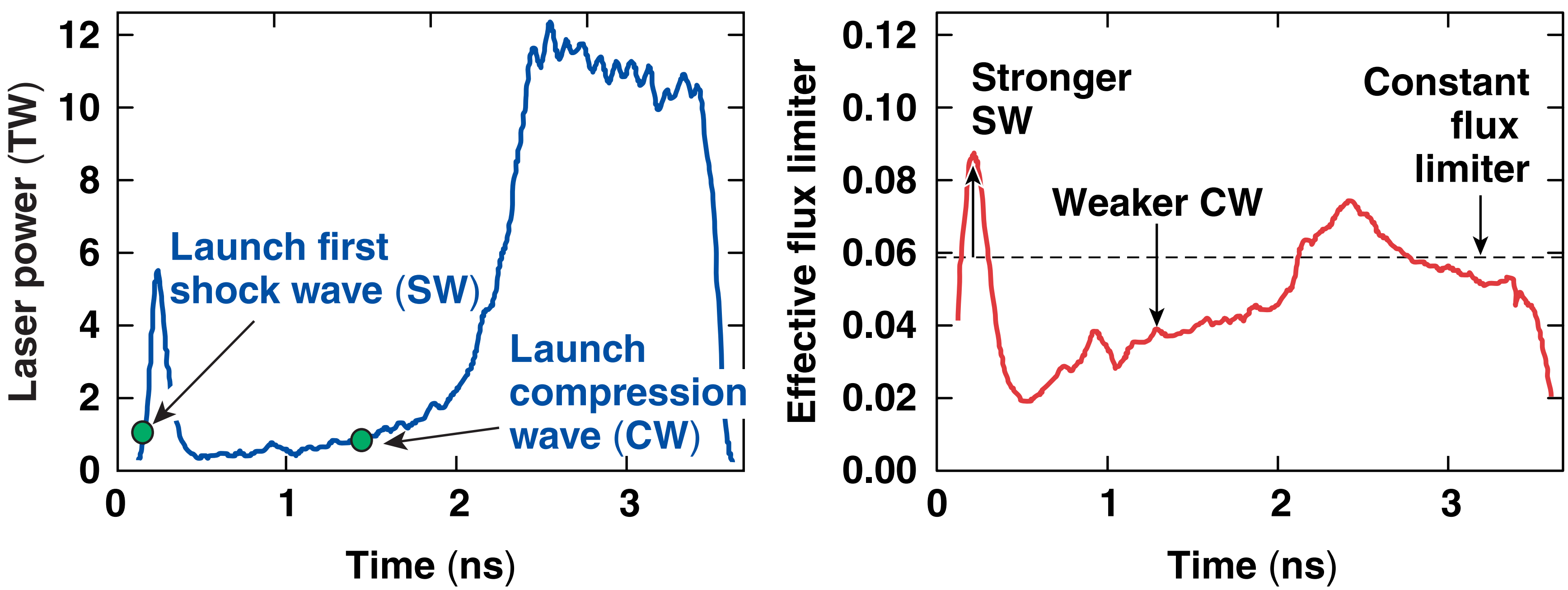
TC7809b

V. N. Goncharov (GI1.00001).

Shock Timing

A nonlocal model is required to correctly predict electron thermal transport

- Flux limiter: $q = \min \begin{cases} -\kappa \nabla T \\ f\, n_e m_e v_{th}^3 \end{cases}$ *f:* flux limiter
- Previously, f = const. (~0.06) was used based on heuristic and experimental observations $f_{eff} = \dfrac{q_{nl}}{n_e m_e v_{th}^3}$



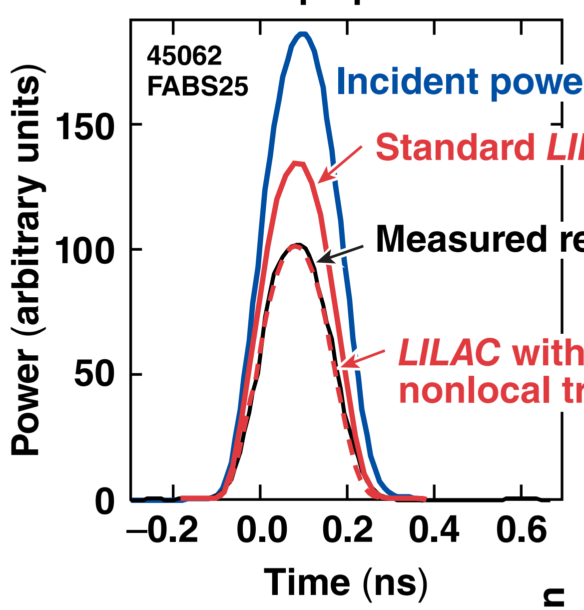
- A more accurate model based on the solution of the Fokker–Planck equation predicts a time-dependent flux limiter.

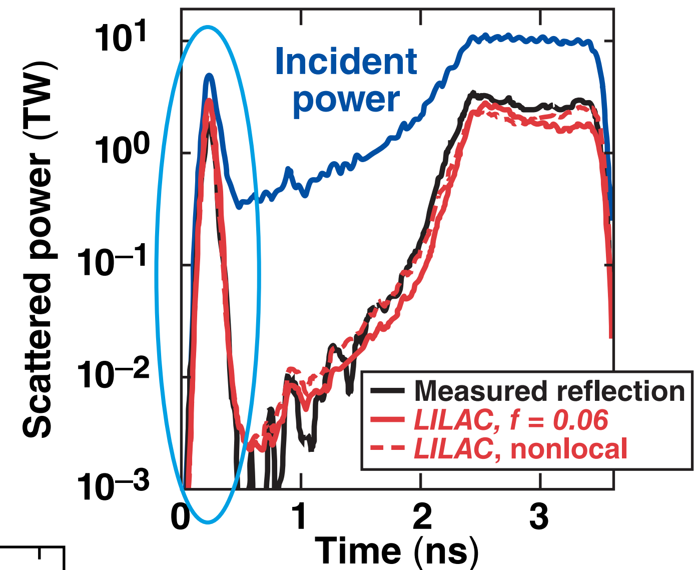
TC7863a

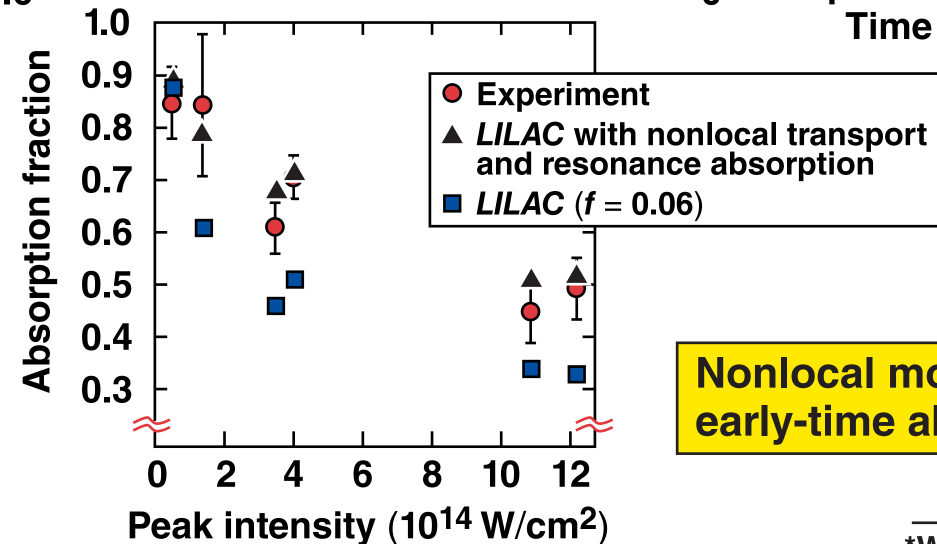
Shock Timing

Accurate modeling of electron thermal transport is crucial for shock timing and setting the shell adiabat

200-ps pulses







Nonlocal model explains early-time absorption

E15979a

*W. Seka (GI1.00003).

The fuel areal density and hot-spot ion temperature determine the compression performance of ICF targets

UR LLE

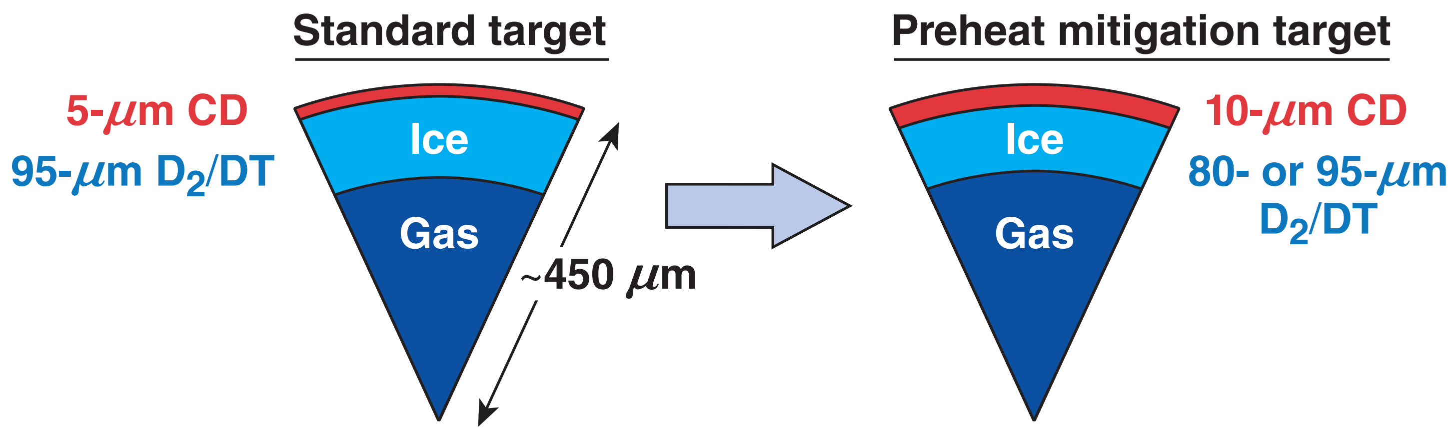
- Precise pulse shaping, including a picket, sets the target on the appropriate adiabat
- Current experiments have demonstrated ignition-relevant areal densities
  - shock timing and strength
  - preheat
  - compressibility
  - hydrodynamic instabilities
- Future experiments will increase the ion temperature
  - implosion velocity
  - hydrodynamic instabilities
  - absorption/drive coupling

Understanding cryogenic dynamics is a key to successful ICF ignition.

Areal Density

Implosions demonstrate compression of cryogenic fuel to ignition-relevant areal densities

- Cryogenic targets are energy scaled from NIF ignition designs
- Target designs are being refined based upon these experiments



- A systematic experimental scan of fuel adiabat and drive intensities has been conducted

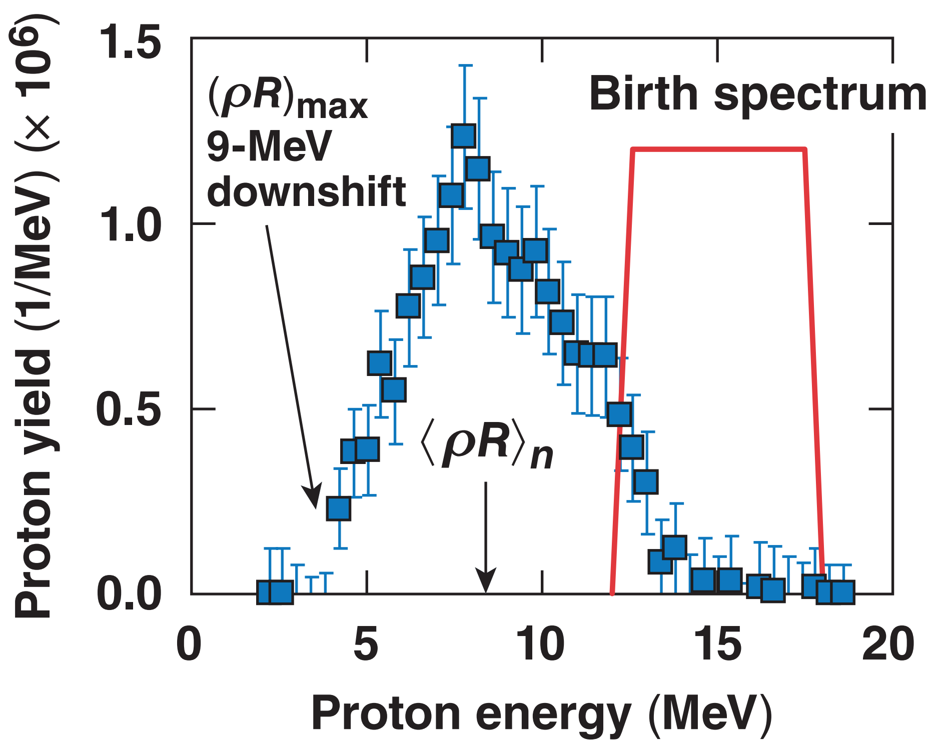
ρR:
- $2 < \alpha < 10$; α = fuel pressure/Fermi-degenerate pressure
- $I_L = 0.25$ to 1.5×10^{15} W/cm^2

T_i:
- $V_{imp} = 2.5$ to 4.0×10^7 cm/s
- In-flight aspect ratio: 30 to 50
- Number of perturbation e-folds ~5 to 7

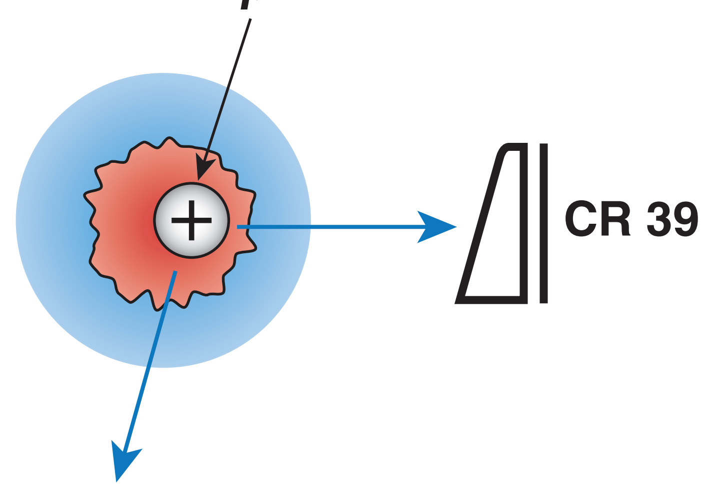
T2365a

Downshifted secondary proton spectra measure* the compressed fuel areal density

Warm plastic shell example
Shot 48674, E_L = 18 kJ, D_2 8.3 atm



$D + D \rightarrow {}^3He + n$
${}^3He + D \rightarrow p + {}^4He$



~9-MeV downshift

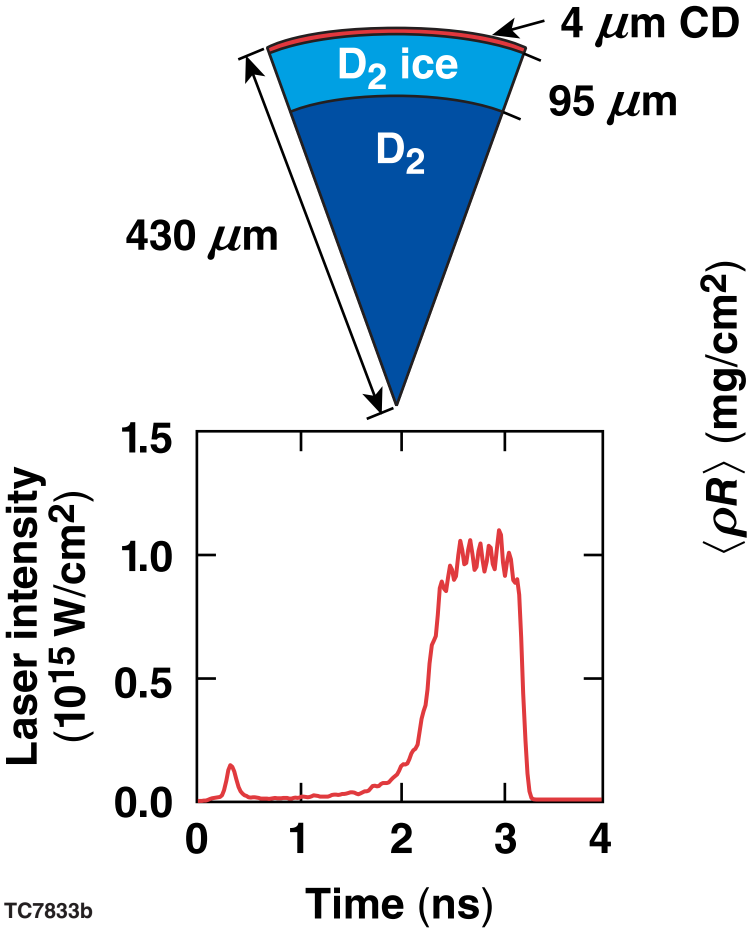
$(\rho R)_{max} > 0.3\ g/cm^2$
$\langle \rho R \rangle_n = 0.2\ g/cm^2$

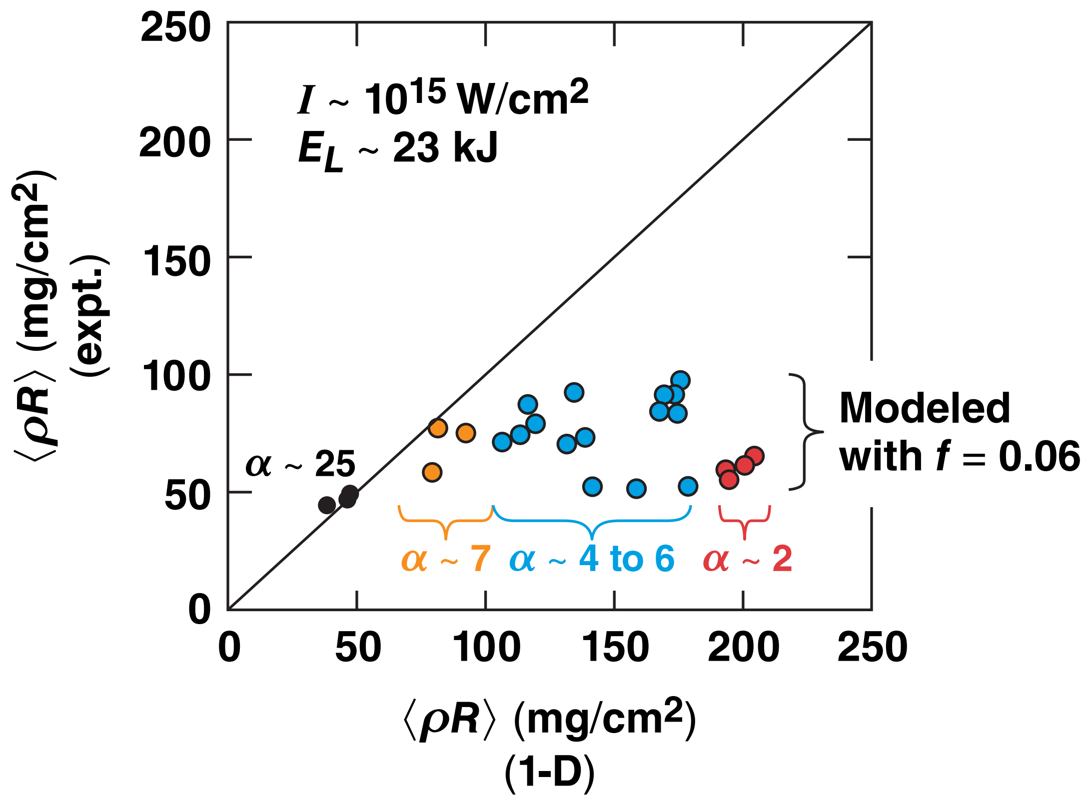
E16134a

*F. H. Séguin *et al*., Rev. Sci. Instrum. 74, 975 (2003).

A severe degradation of ρR, up to 40% of 1-D predictions, was observed in high-intensity mid- and low-adiabat cryogenic implosions on OMEGA

- Thick targets minimize hydro-instabilities: in-flight aspect ratio ~ 30





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Areal Density

The nonlocal thermal-transport model improves the agreement between 1-D simulation and experimental areal densities

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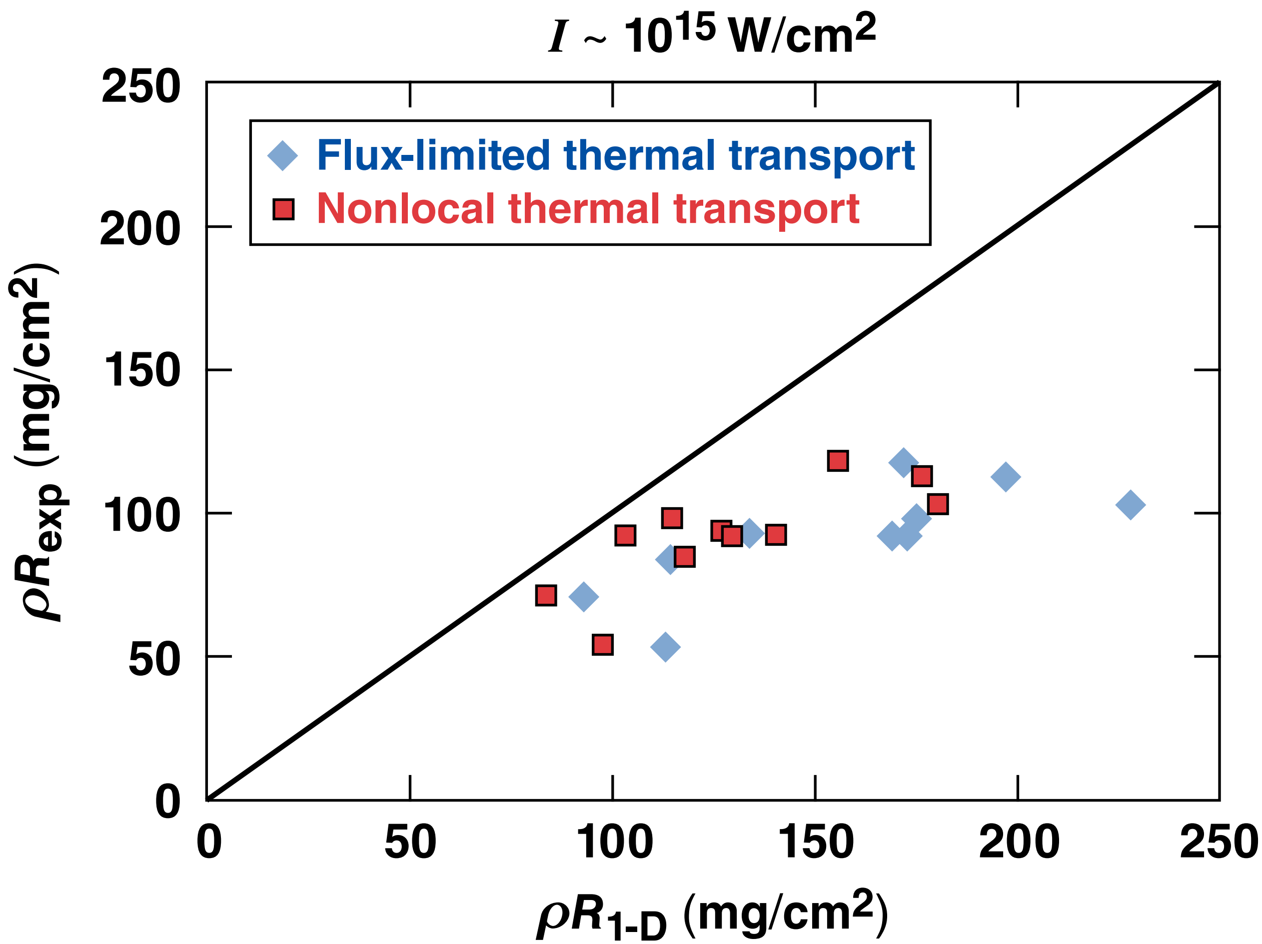


- The measured areal densities remain somewhat lower than 1-D simulations with nonlocal heat conduction.

I1786

Preheat

The remaining discrepancies between measured and simulated areal density may be due to hot-electron preheat

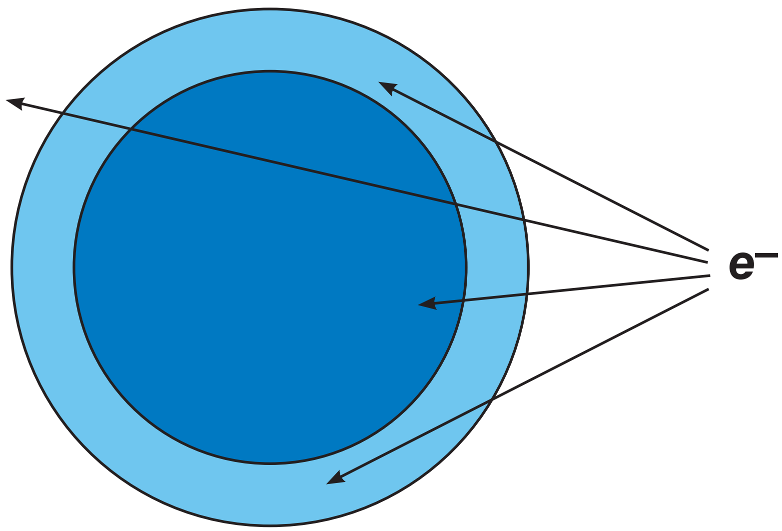
- There are two plausible explanations for the reduction of the experimental areal density relative to the 1-D simulations
  - preheat by hot electrons generated by the two-plasmon-decay instability (discussed next)
  - measured nuclear burn histories can be different from 1-D simulations due to hydrodynamic instabilities*
    - protons may sample lower areal densities
    - a similar effect has been seen in warm plastic-target implosions
    - statistics need to be improved to measure this in cryogenic implosions

I1787

*P. B. Radha *et al*., Bull. Am. Phys. Soc. 51, 104 (2006).

Preheat

Hot-electron preheat generated by laser–plasma interactions can significantly degrade the final areal density



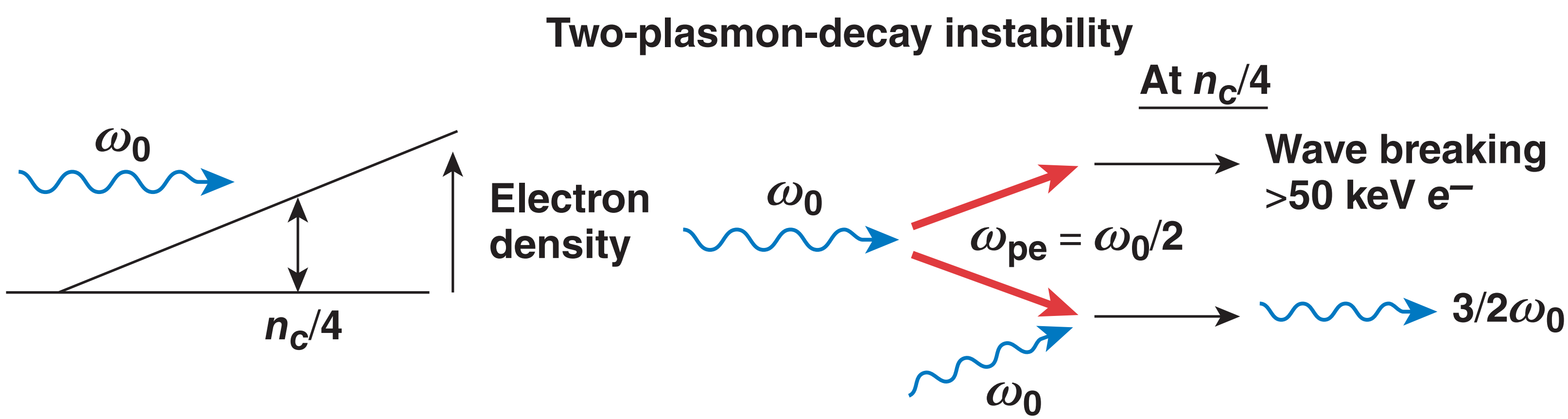
$$p \sim \alpha \rho^{5/3}$$

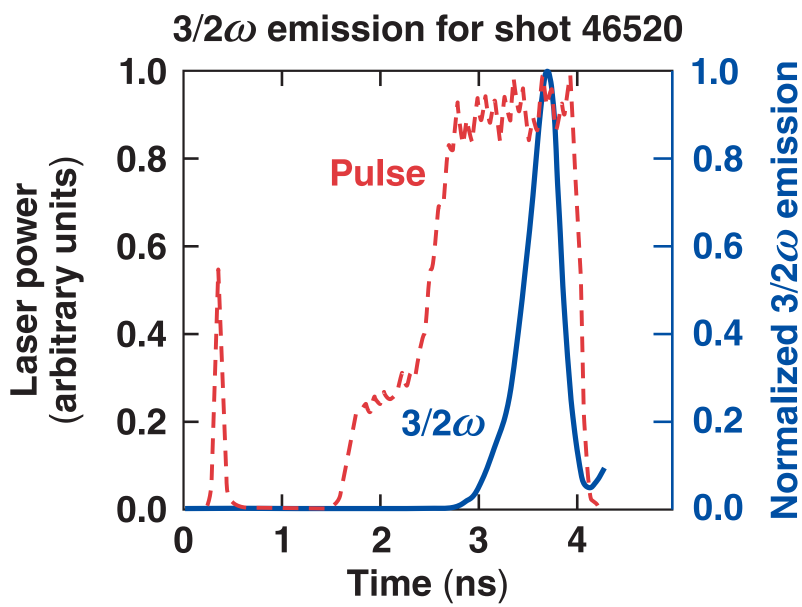
$$\rho R \sim \alpha^{-0.6} \Rightarrow \rho R = \frac{\rho R_0}{\left[\left(T_0 + \Delta T_{shell}\right)/T_0\right]}$$

- Low-α designs T_0 ~ 20 eV
- 20% ρR reduction for ΔT_{shell} ~ 6 eV
- For OMEGA experiments, $E_{preheat}$ ~ 10 to 20 J (~0.1% of laser energy)

TC7812a

3/2ω light and hard x rays* indicate the presence of the two-plasmon-decay instability





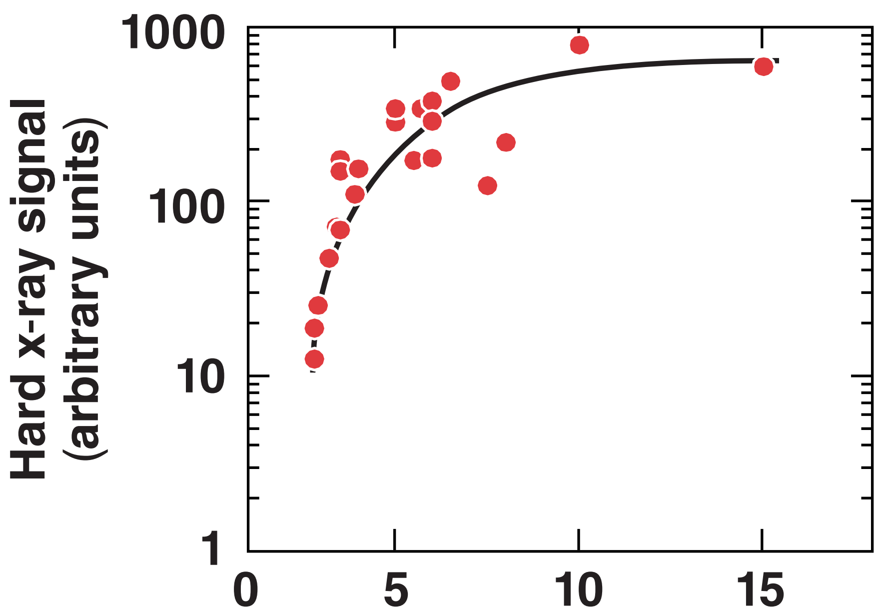
TC7848a

*C. Stoeckl *et al.*, Rev. Sci. Instrum. 72, 1197 (2001).

Preheat

Preheating by hot electrons from the two-plasmon-decay instability is a candidate for additional cryo ρR degradation

Measured hard x-ray signal*



- $I_{\text{th},2\omega_p} \approx 2 \times 10^{14} \dfrac{T(\text{keV})}{L_n(100\ \mu\text{m})}\ \text{W/cm}^2$ **
- Measured $T_{\text{hot}} > 50$ keV – electron range is greater than the D_2 thickness

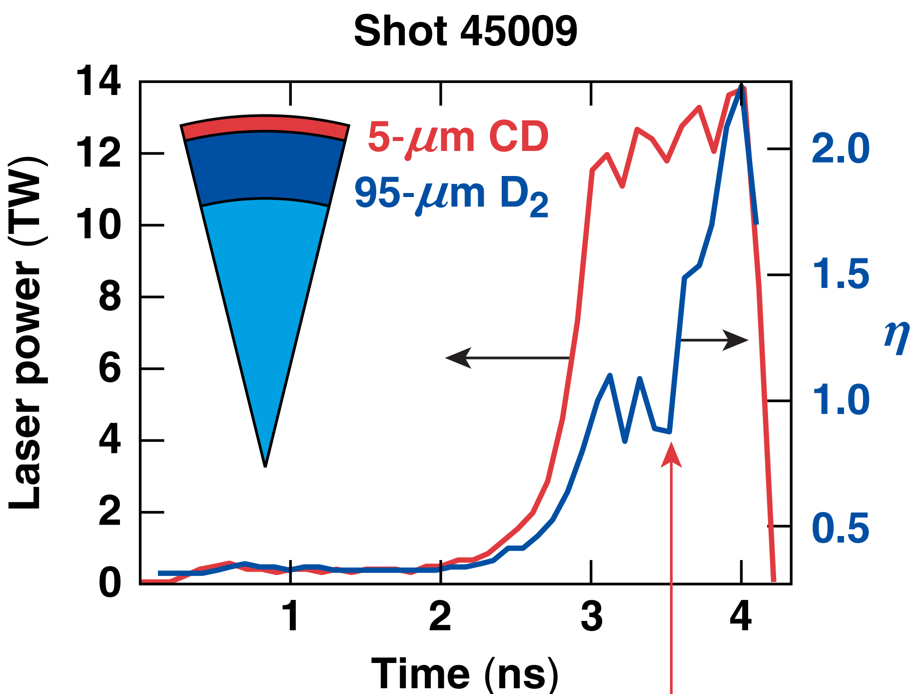
*B. Yaakobi *et al.,* Phys. Plasmas 12, 062703 (2005).
*C. Stoeckl *et al.* Phys. Rev. Lett. 90, 235002 (2003).
**A. Simon *et al.*, Phys. Fluids 26, 3107 (1983).

TC7835c

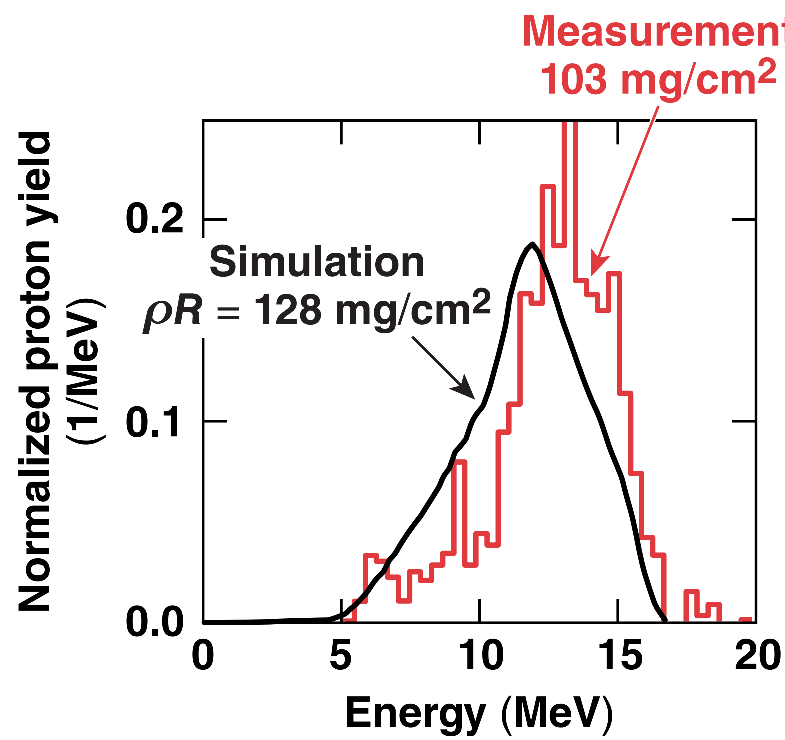
Preheat

The two-plasmon-decay threshold is exceeded when the laser burns into the D_2 fuel

- Above-threshold parameter* for 2 ω_p instability $\eta = \frac{I_{14} L_{\mu m}}{230\, T_{keV}}$
- Instability develops when $\eta > 1$



CD burnthrough:
Absorption is reduced; therefore
T is reduced and *I* is increased



V. N. Goncharov (GI1.00001).

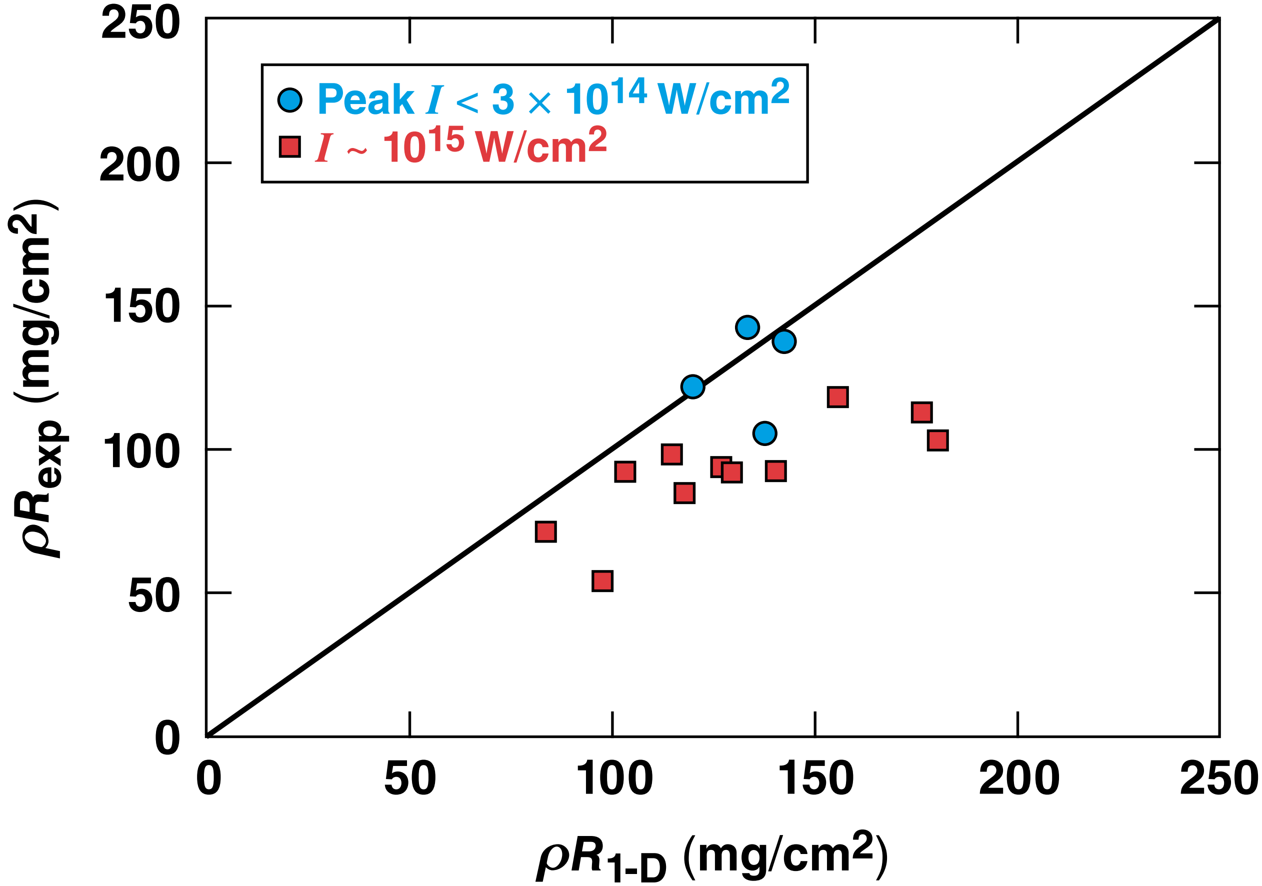
* A. Simon *et al.*, Phys. Fluids 26, 3107 (1983).

TC7866a

Preheat

An improved agreement between simulated and measured ρR is observed for low intensity implosions*

All simulations use nonlocal thermal-transport model



*V. A. Smalyuk *et al*., Anomalous Absorption (2007); and to be published in Phys. Rev. Lett.
D. Shvarts *et al*., Anomalous Absorption and IFSA (2007).

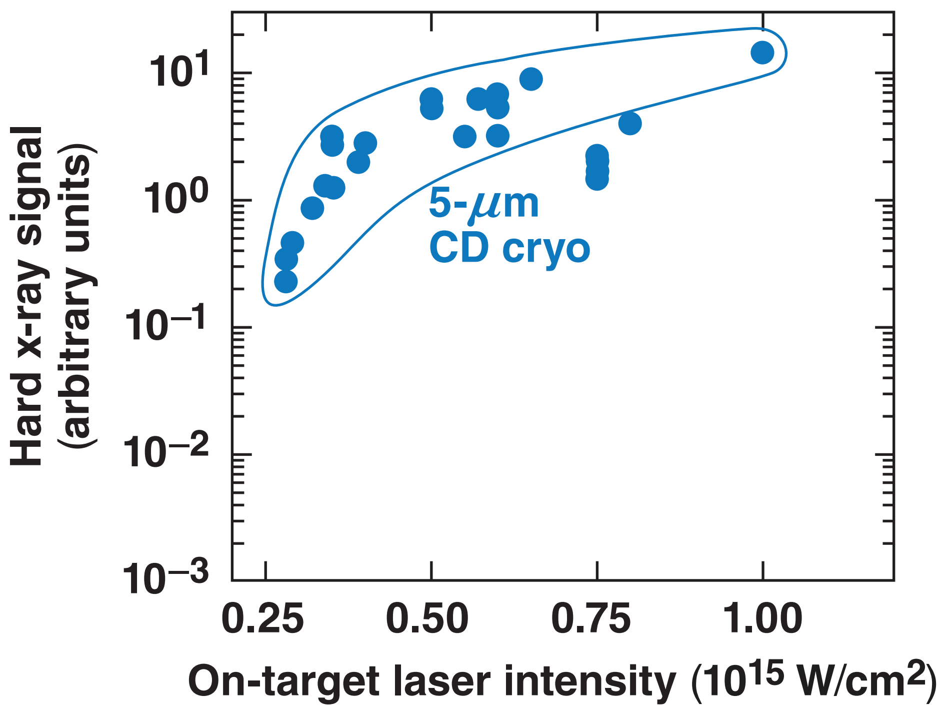
TC8037c

Preheat

Hard x rays due to energetic electrons from the two-plasmon-decay instability increases rapidly with laser intensity

UR LLE

- Hard x-ray signals produced by bremsstrahlung radiation from fast electrons may indicate preheating*



T2367a

*V. A. Smalyuk *et al.*, to be published in Phys. Rev. Lett.

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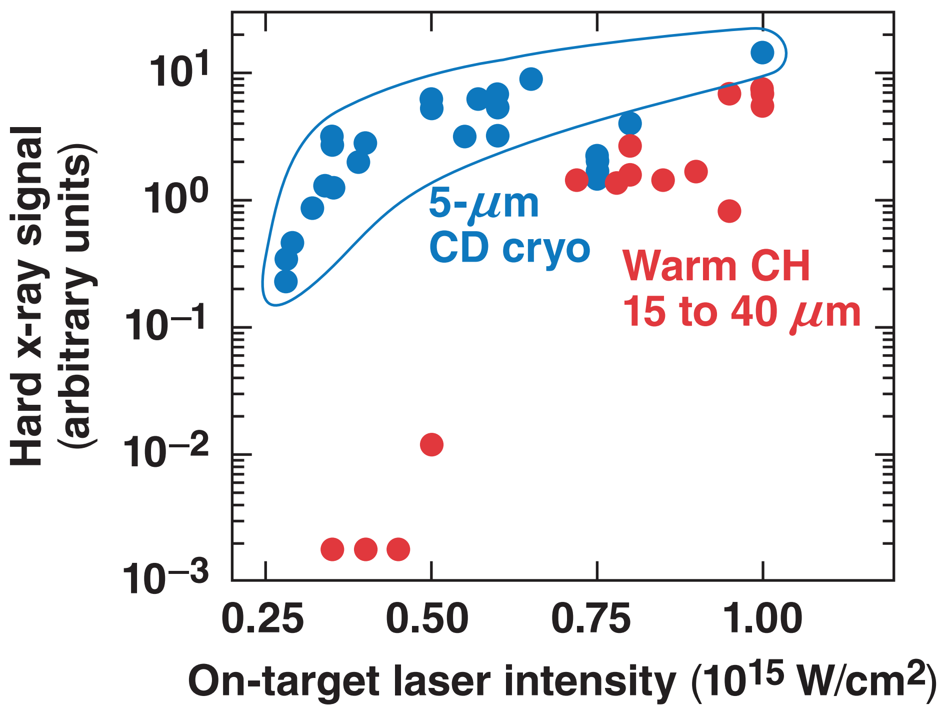

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*V. A. Smalyuk *et al.*, to be published in Phys. Rev. Lett.

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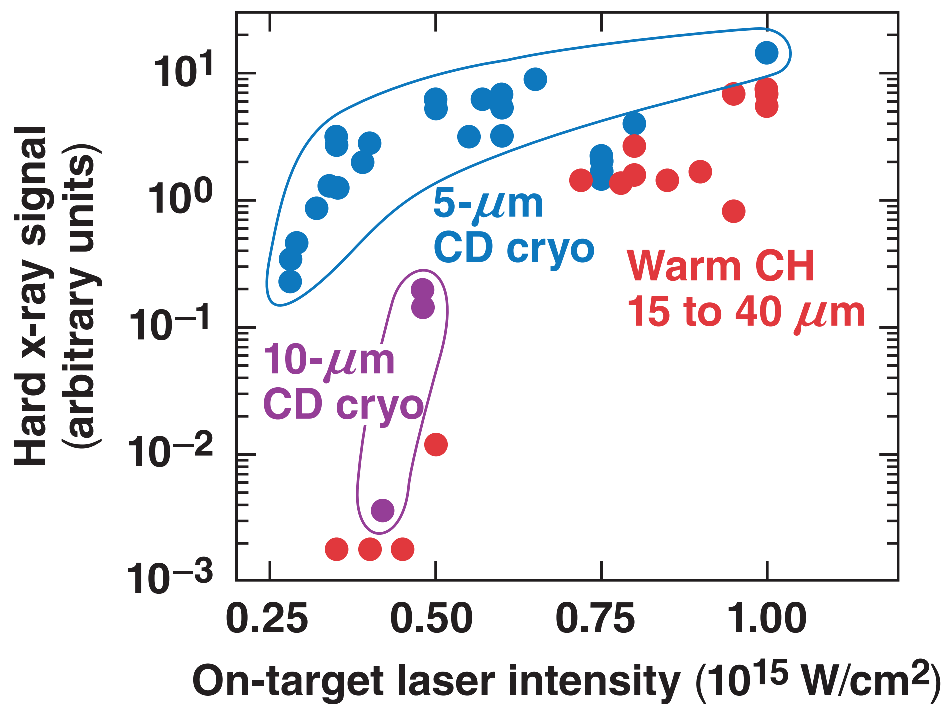


Hard x rays from energetic electrons are reduced by increasing the CD thickness.

T2367a

*V. A. Smalyuk *et al.*, to be published in Phys. Rev. Lett.

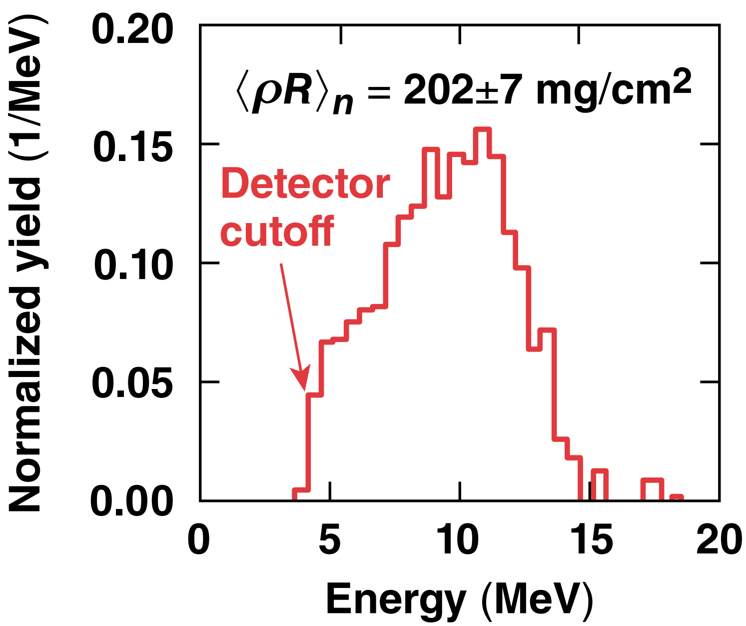
Areal Density

Ignition-relevant areal densities (~200 mg/cm^2) are achieved by accurate shock timing and mitigating fast-electron preheat

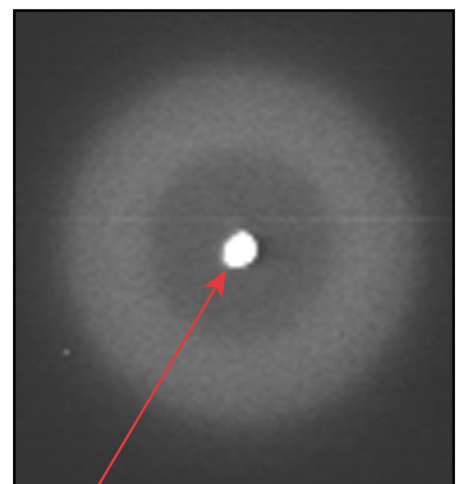
- Target design tuned to be insensitive to the thermal transport model and has low hard x-ray signal.

10-μm CD cryogenic implosion

Secondary D^{3}He proton spectrum



X-ray pinhole camera



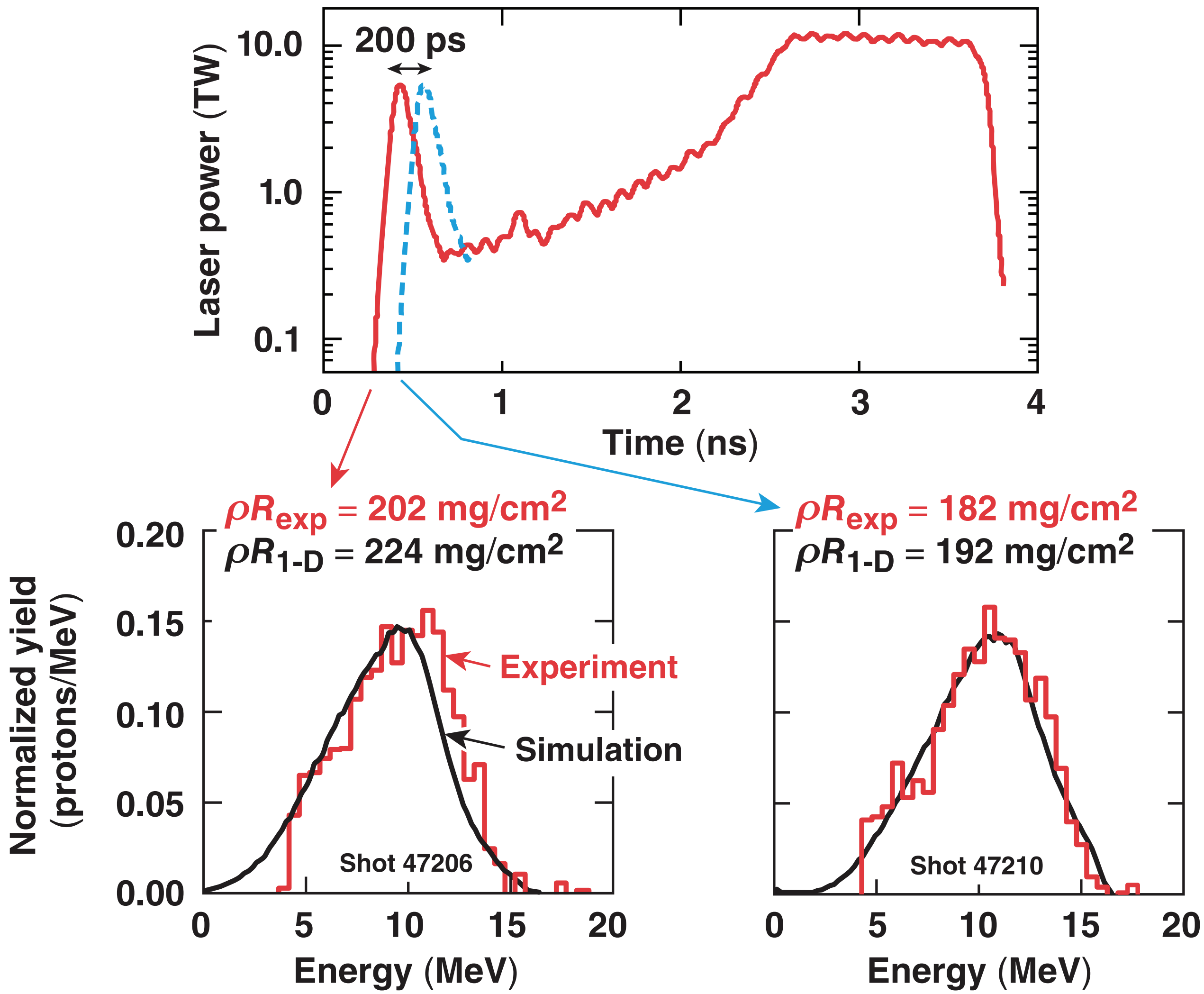
D$_2$ fuel density reaches ~100 g/cc (500× liquid density)

These are, by far, the highest areal densities measured in ignition-relevant laboratory implosions—very important for direct- and indirect-drive ignition.

T. C. Sangster *et al.*, (JO3.00001) and to be published in Phys. Rev. Lett.

Areal Density

Predictive capability for the shock timing is validated by adjusting picket timing



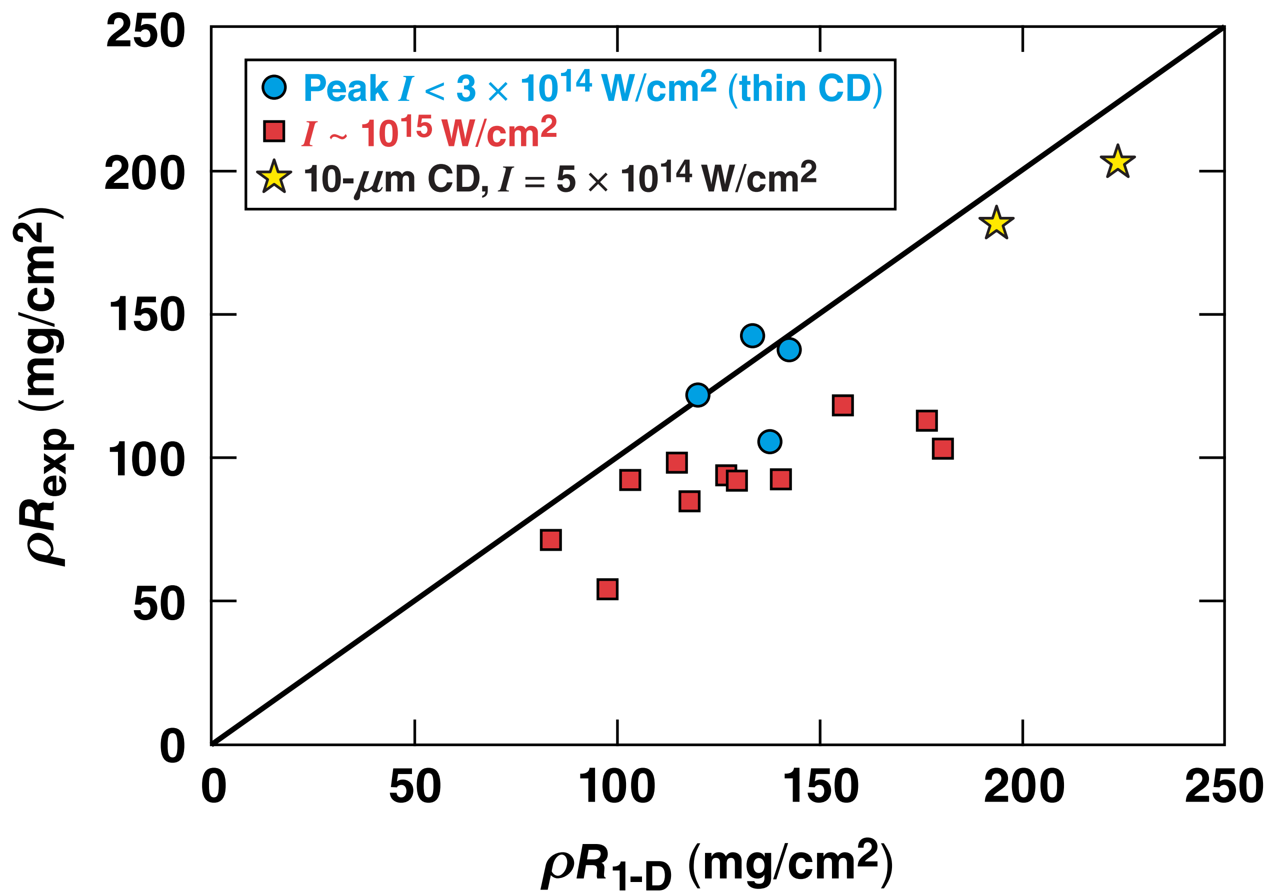
T2368a

V. N. Goncharov (GI1.00001).

Areal Density

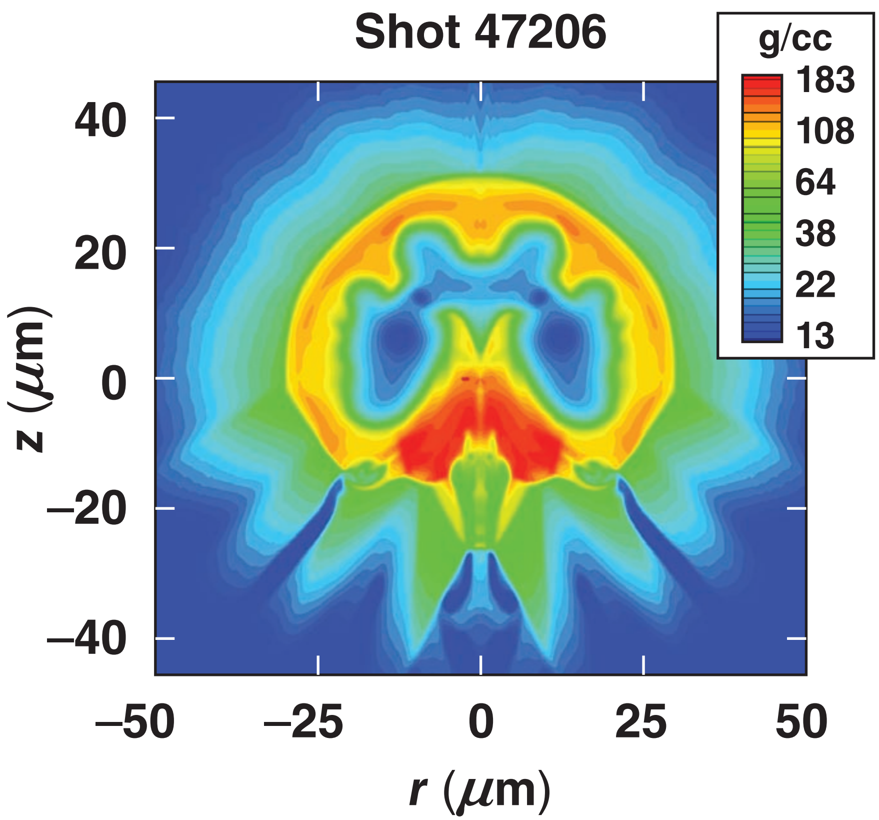
Good agreement between simulated and measured ρR is observed for implosions with low hard x-ray signals

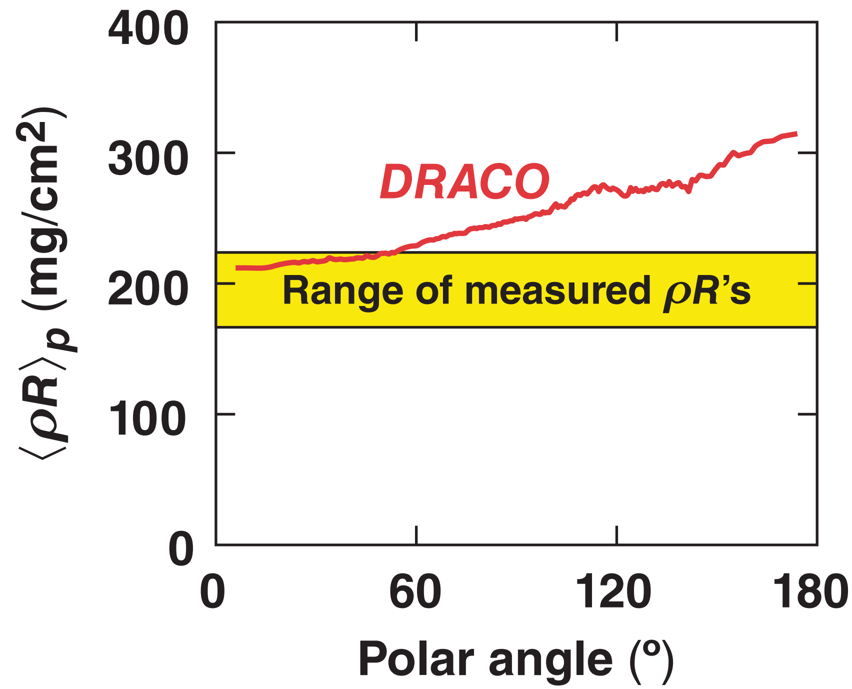
All simulations use nonlocal thermal-transport model



TC8037d

2-D *DRACO* simulations of cryogenic high-ρR shots confirm experimentally observed areal densities





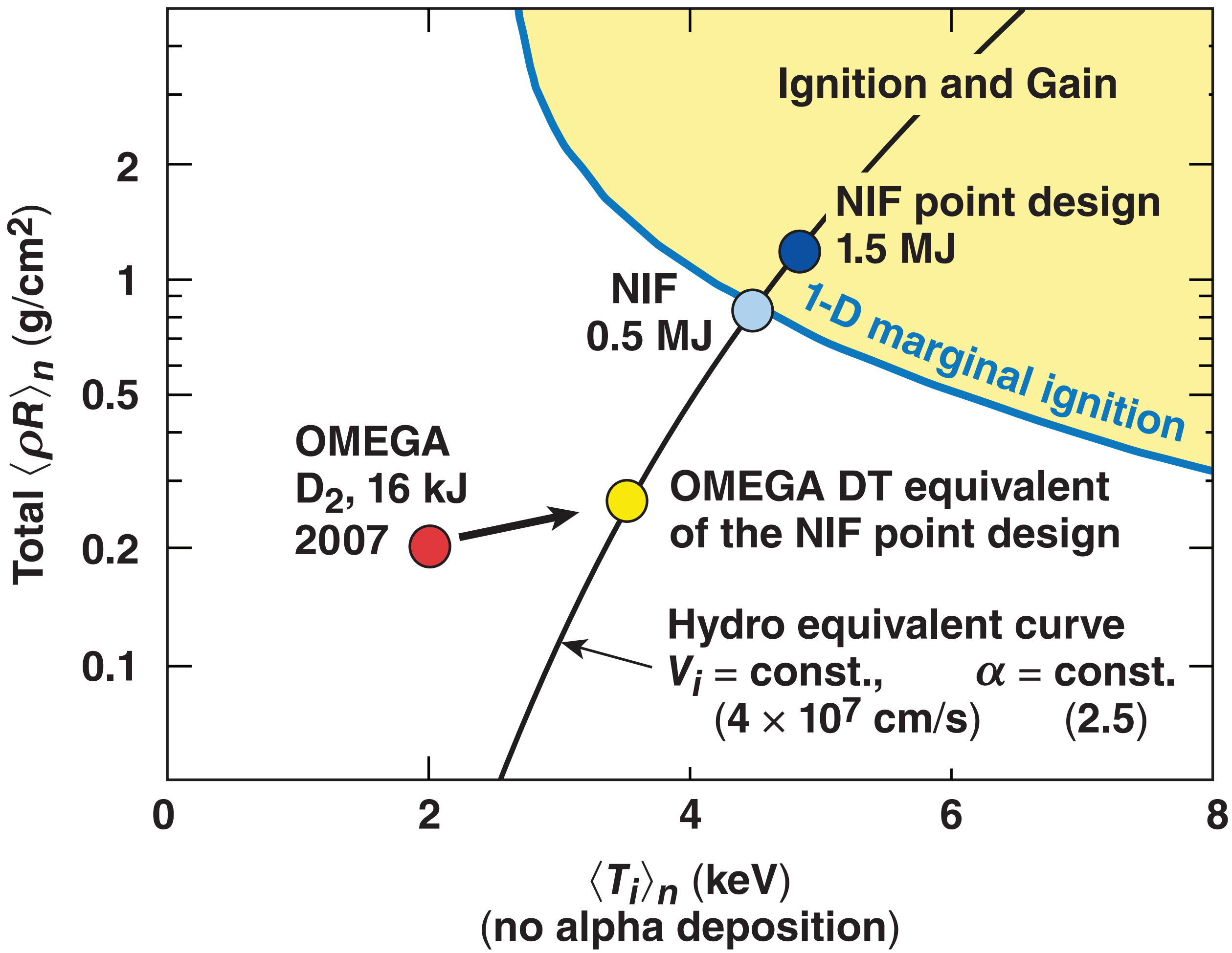
- Target offset from target chamber center by 20 μm

- Observed yield is one third of 2-D prediction

Path to T_i

Direct-drive research is on a path to ignition on the NIF

- Ignition-relevant areal densities have been achieved
- The next step is to increase T_i



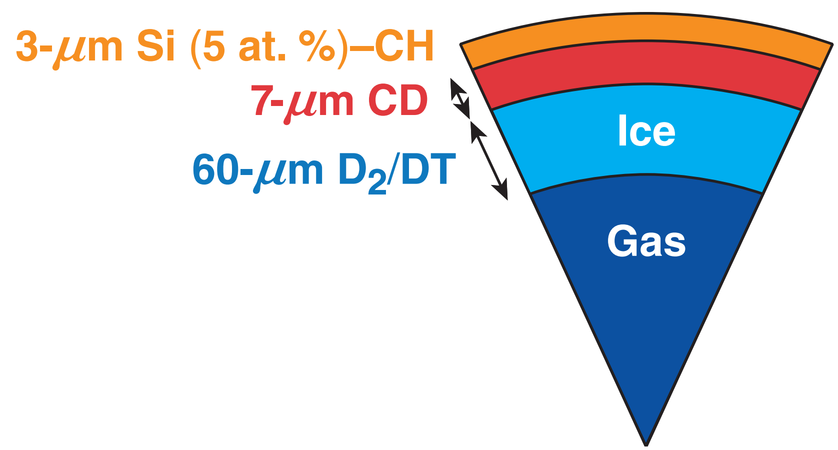
I1772

R. Betti (CO5.00001).

Path to T_i

Future experiments will increase the ion temperature while mitigating preheat and hydro-instabilities

- T_i increases with implosion velocity, $T_i \sim V_{imp}^{1.3}$
- Increase the implosion velocity to 4×10^7 cm/s
  - – thinner ice layer (60-μm D_2)
  - – higher intensity
  - – re-time shock waves with the nonlocal model
- Doped ablators (Si and Ge) can minimize energetic electron preheat and Rayleigh–Taylor growth rate

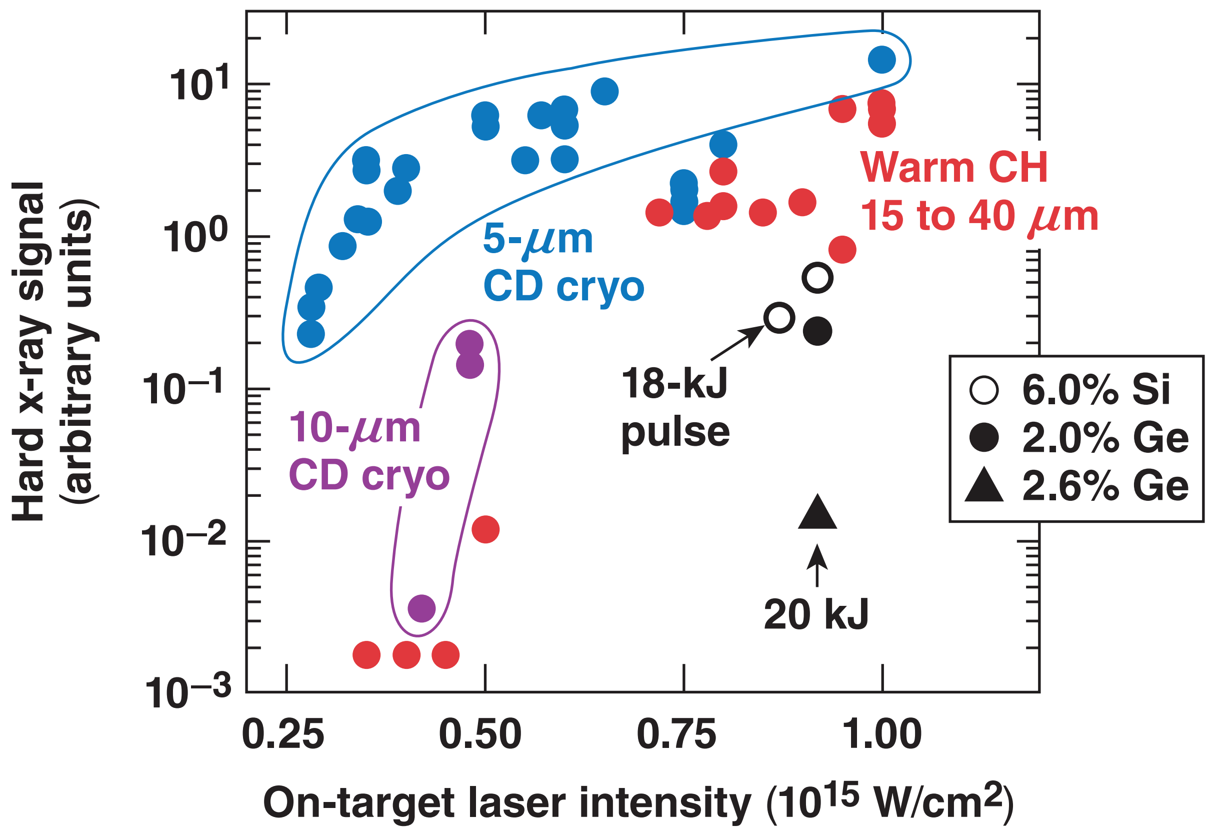


T2371a

Path to T_i

Initial experiments with high-Z doped plastic shells show reduced hard x-ray production

- High-Z dopants reduce hot-electron generation



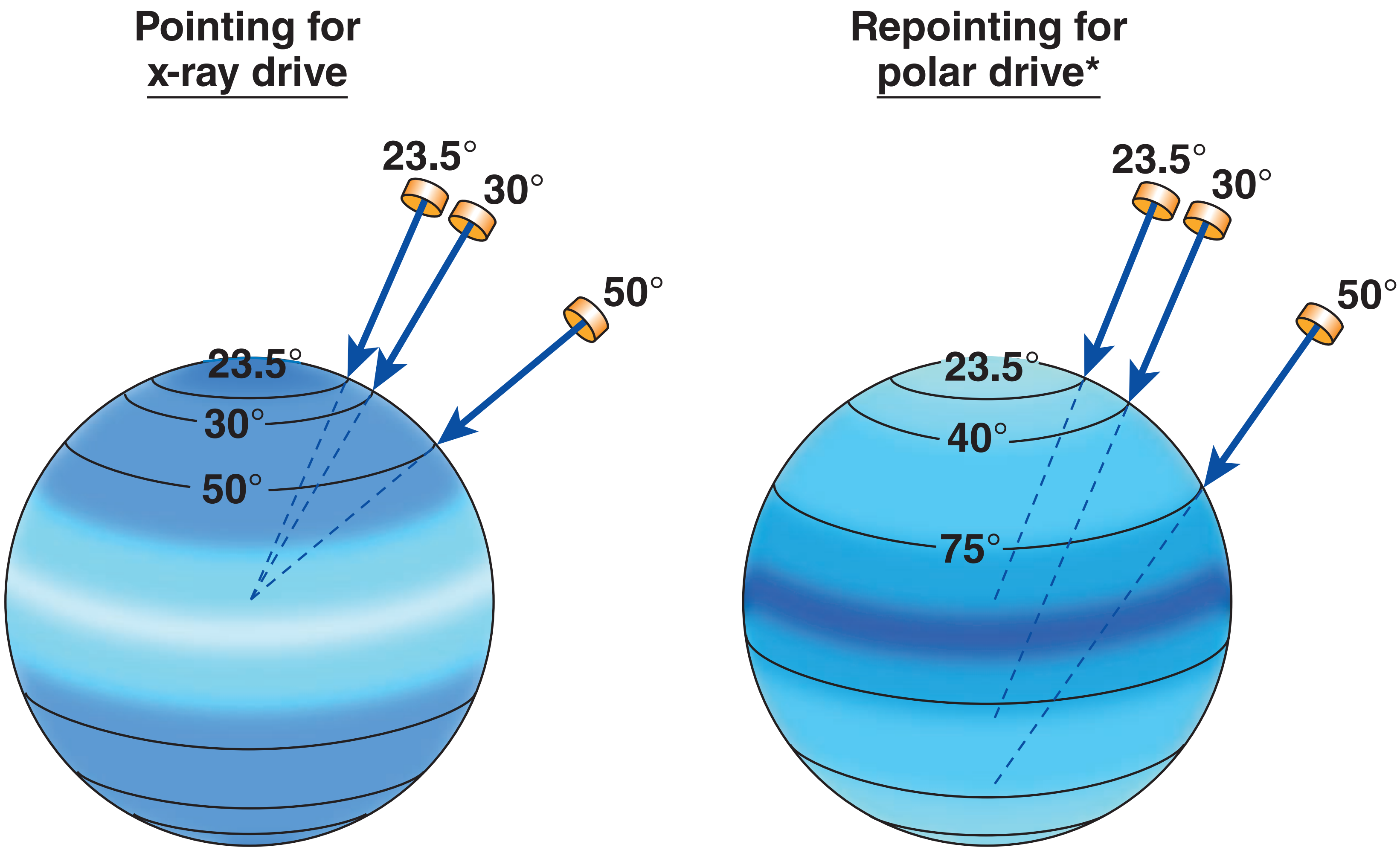
- High-Z dopants reduce Rayleigh–Taylor growth rates*

*P. B. Radha (JO3.00002).
J. P. Knauer (PO6.00010).

TC7813c

Polar Drive

Direct drive can achieve ignition conditions while NIF is in the x-ray-drive configuration

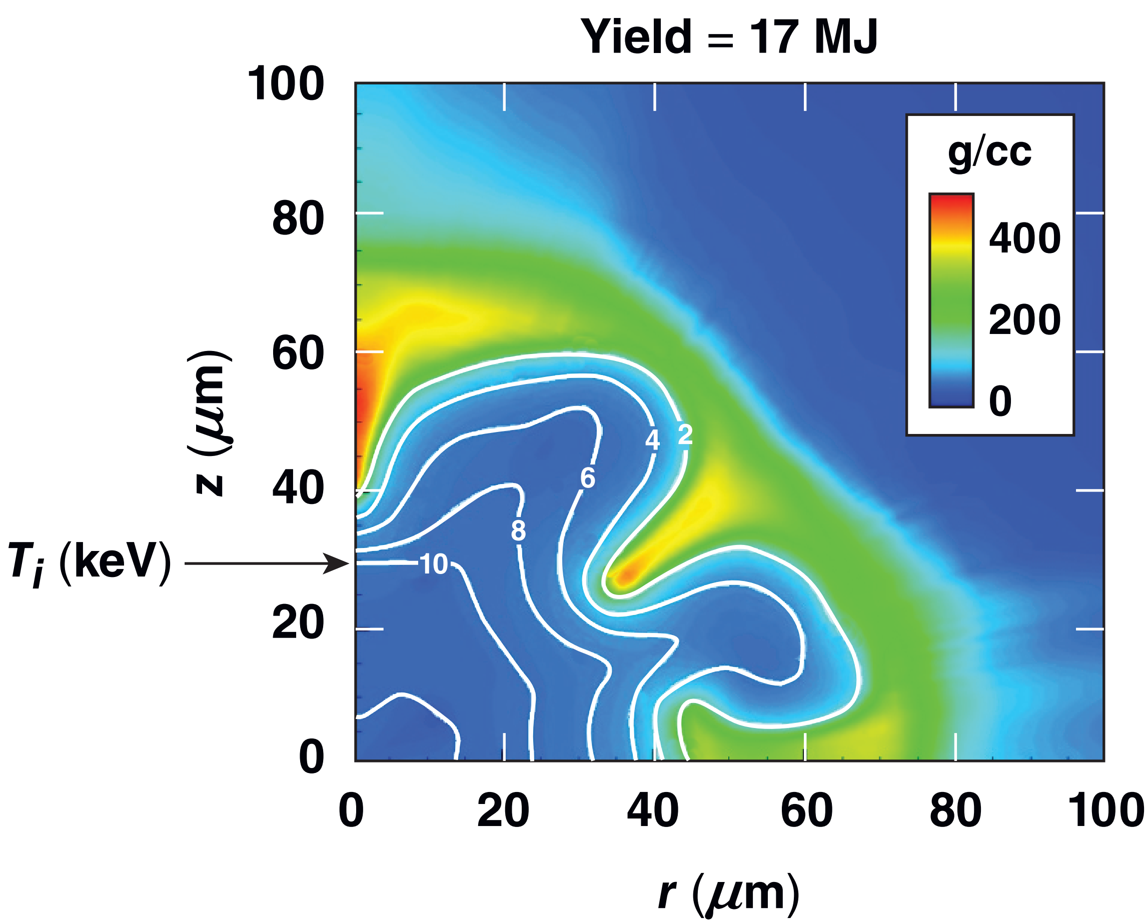


TC6300c

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

Polar Drive

The polar-drive point design achieves a yield of 17 MJ with all current levels of NIF nonuniformities included in the calculation

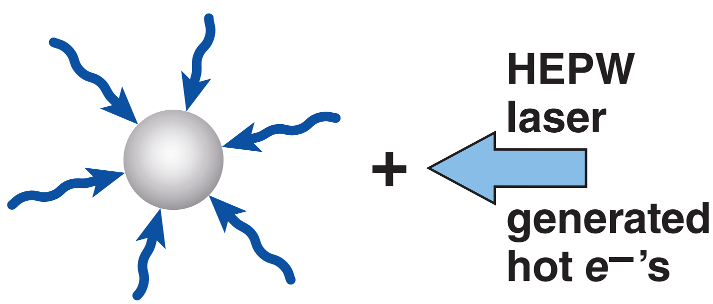


TC7741b

New ignition concepts separate compression (ρR) and heating (T_i)—two-step ignition

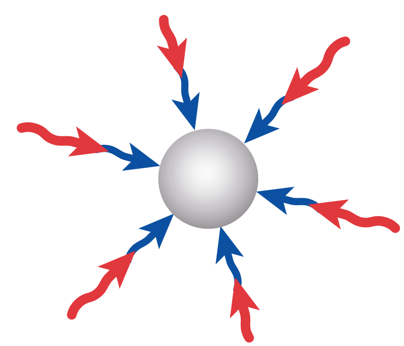
- In the current hot-spot ignition, the driver provides both compression (ρR) and heating (T_i).
- Both fast ignition and shock ignition use a second drive to provide heating (T_i).

Fast Ignition



Compression

Shock Ignition



Compression + shock pulse

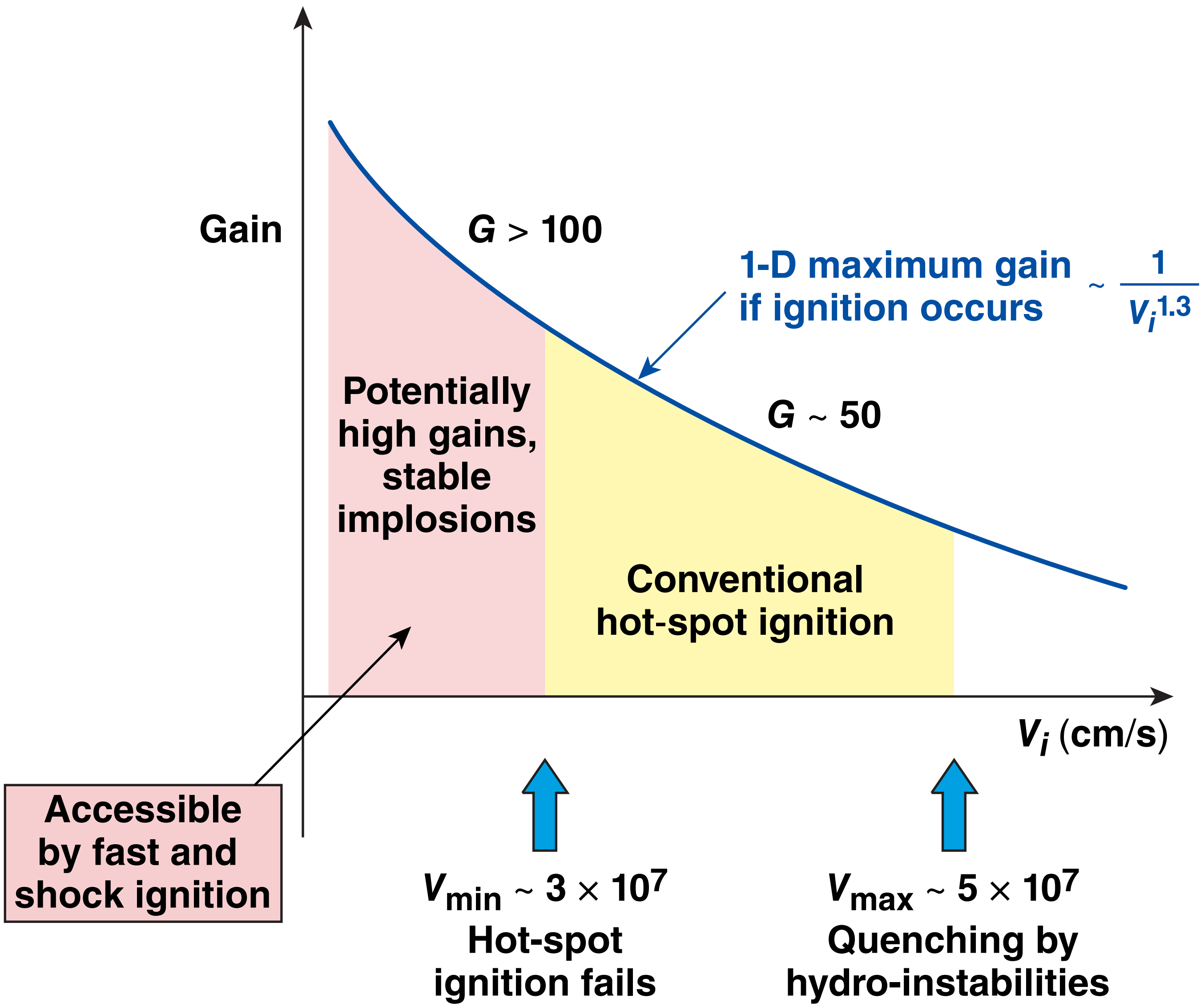
- Measured cryogenic target areal densities are relevant to these schemes.

Two-step ignition offers lower driver energies with the possibility of higher gain.

Advanced Concepts

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

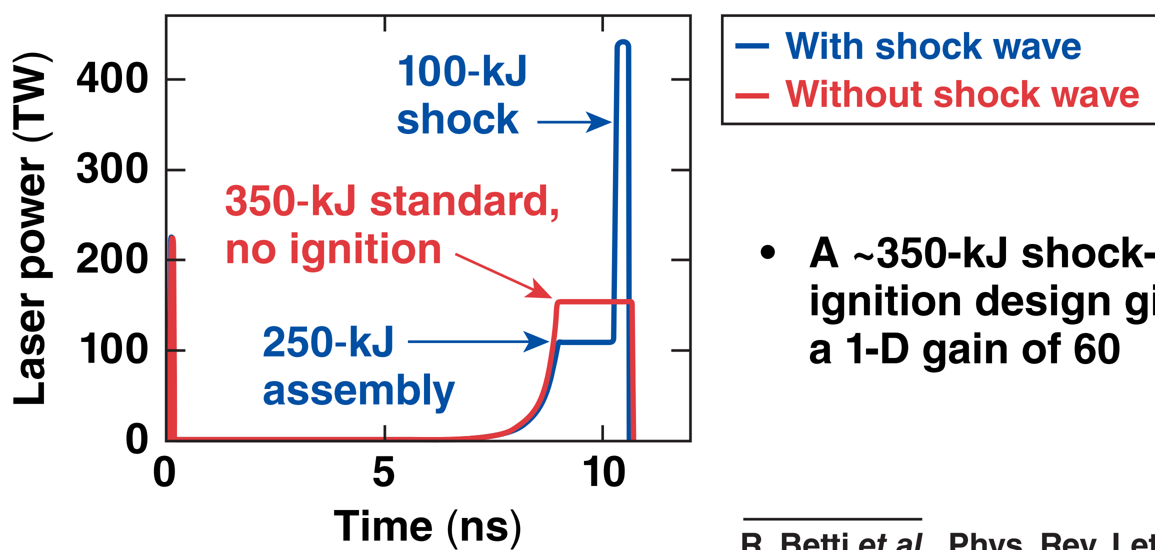
UR LLE



TC7815b

Launching a spherically convergent shock wave at the end of the laser pulse can trigger ignition at lower driver energies

- Low-velocity implosions can be shock-ignited to yield moderately high gains (~50 to 70) at relatively low UV driver energies (~400 to 500 kJ).
- 2-D simulations indicate that shock ignition survives the detrimental effects of laser imprinting for UV driver energies in the 500-kJ range.
- Implosion experiments on thick CH shells filled with 4- to 25-atm D_2 show that pulse shapes with shock spikes give higher neutron yields and higher areal densities than standard pulse shapes.



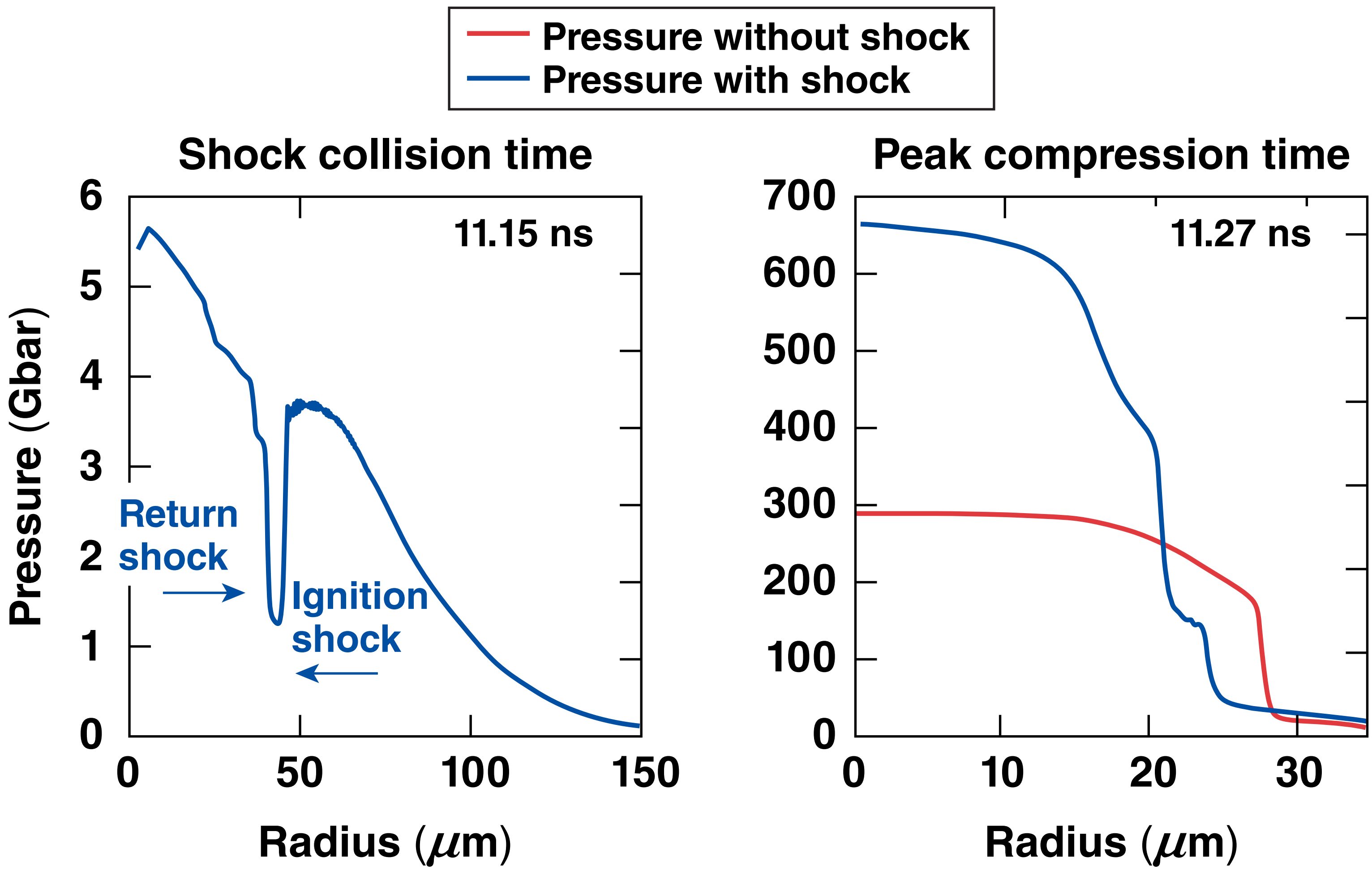
- A ~350-kJ shock-ignition design gives a 1-D gain of 60

TC7830a

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

Advanced Concepts

Shock-ignition pulse shapes lead to higher compression and more favorable ignition conditions



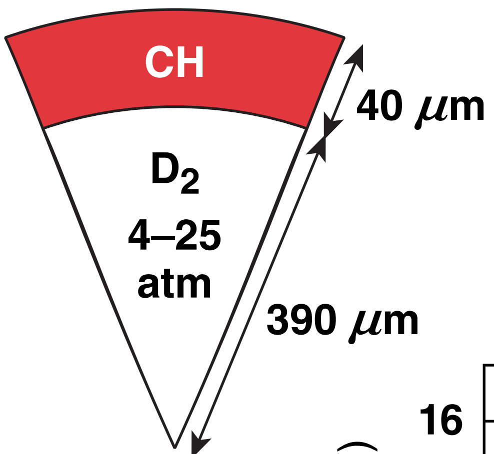
Marginal shock ignition (with λ_L = 0.35 μm) requires 350 kJ. Hydro-equivalent conventional ignition requires 1.3 MJ.

TC7868a

Advanced Concepts

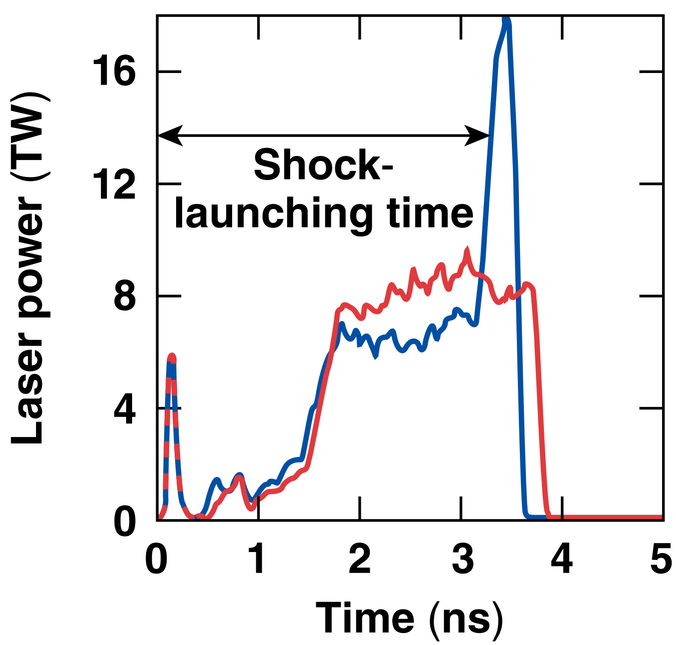
Initial shock-ignition research on OMEGA is encouraging

Warm target

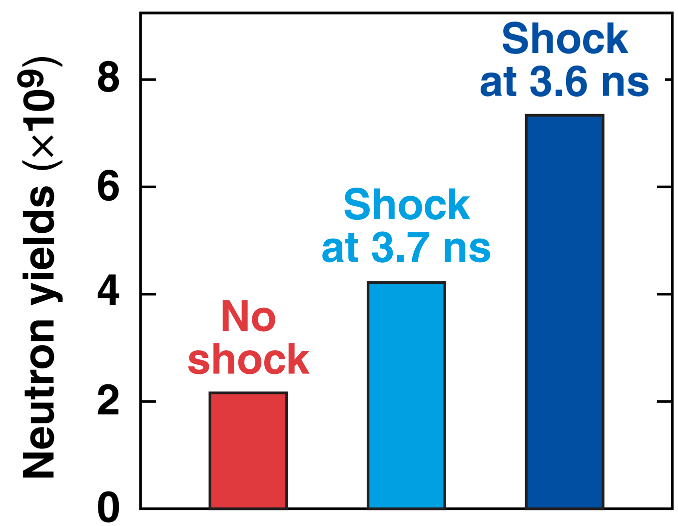


E_L = 17 to 18 kJ
α = 1.3

Pulse shape with and without shock spike



25-atm D_2



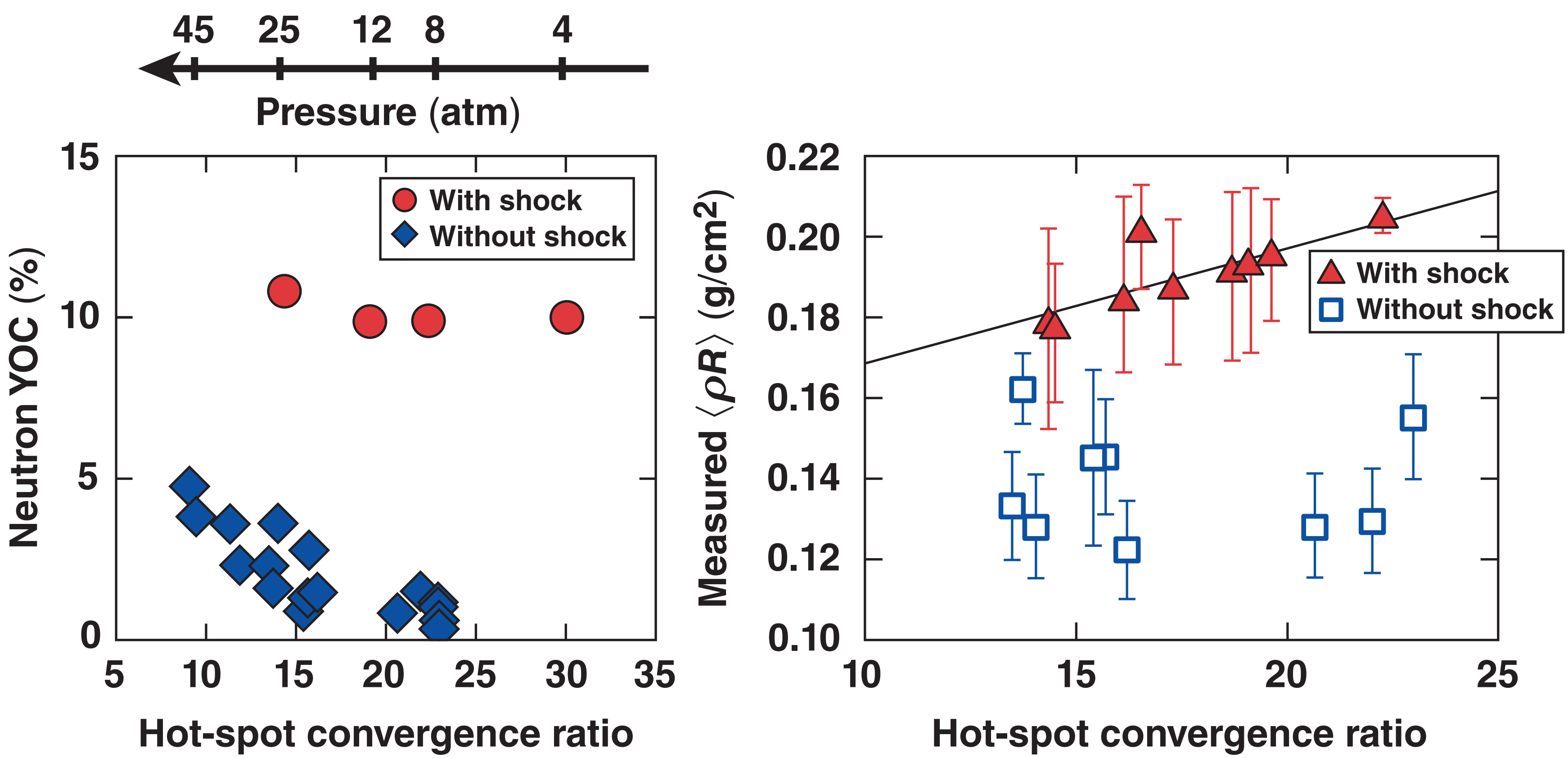
The neutron yield increases considerably when a shock is launched at the end of the pulse.

TC7824a

W. Theobald (GI1.00002).

Advanced Concepts

Plastic-shell implosions with a shock-ignition pulse shape show larger yield and higher compressibility



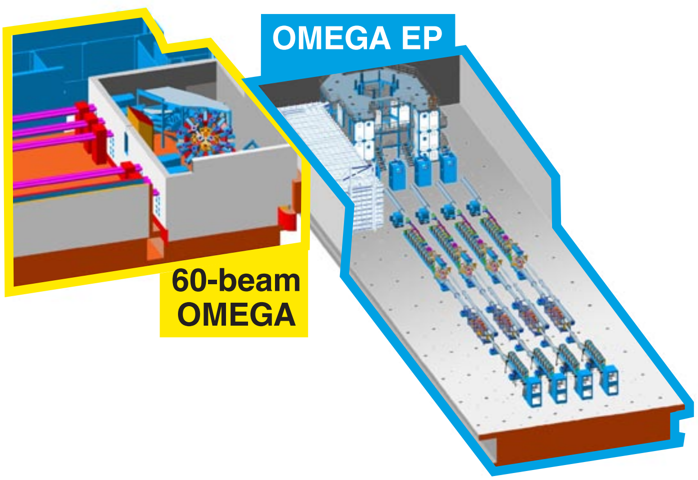
- YOC is the measured yield divided by the 1-D predicted yield.
- Hot-spot convergence ratio: ratio of the original target radius to the compressed hot-spot radius.

E16133a

High-energy petawatt lasers will extend ignition capabilities

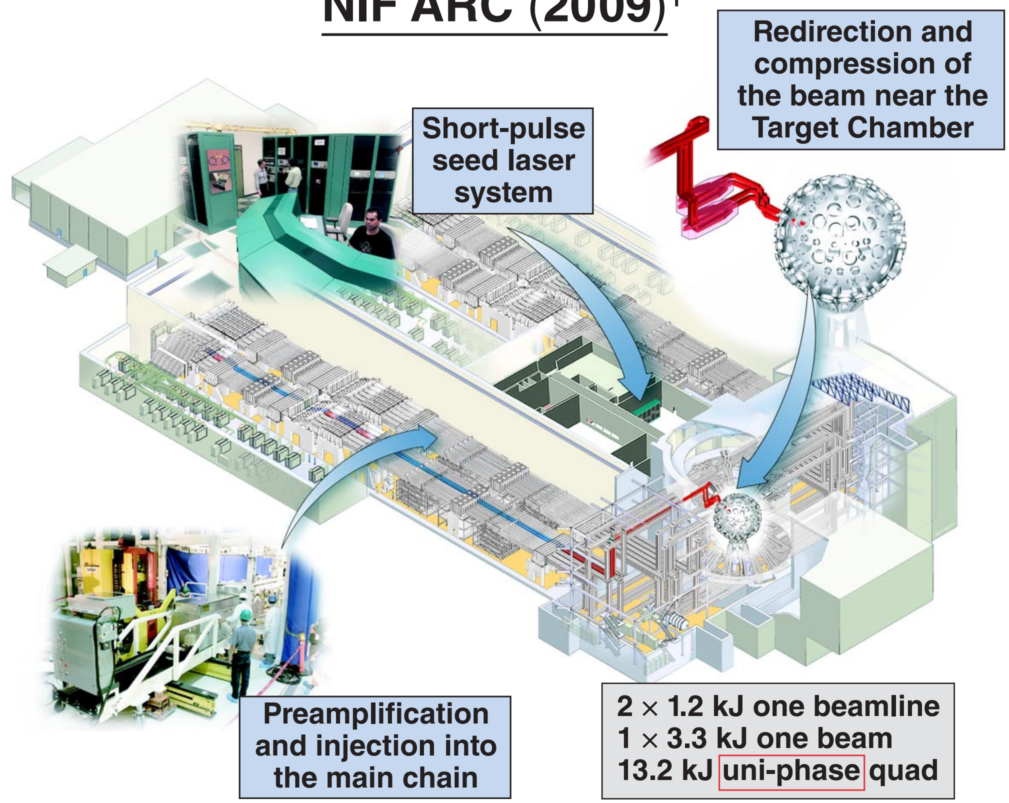
- Backlighting of target implosions
- Fast ignition (reviewed by M. Key APS/DPP 06)

OMEGA EP (2008)*



2 HEPW beamlines
2.6 kJ_{IR} each in 10 ps

NIF ARC (2009)†

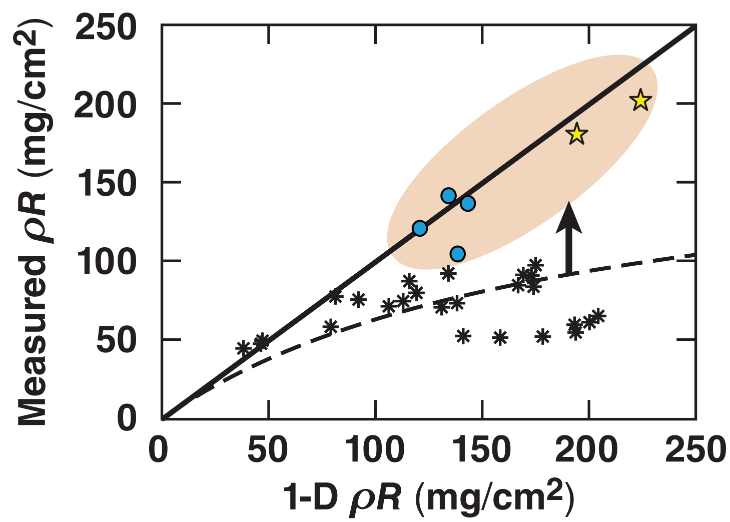


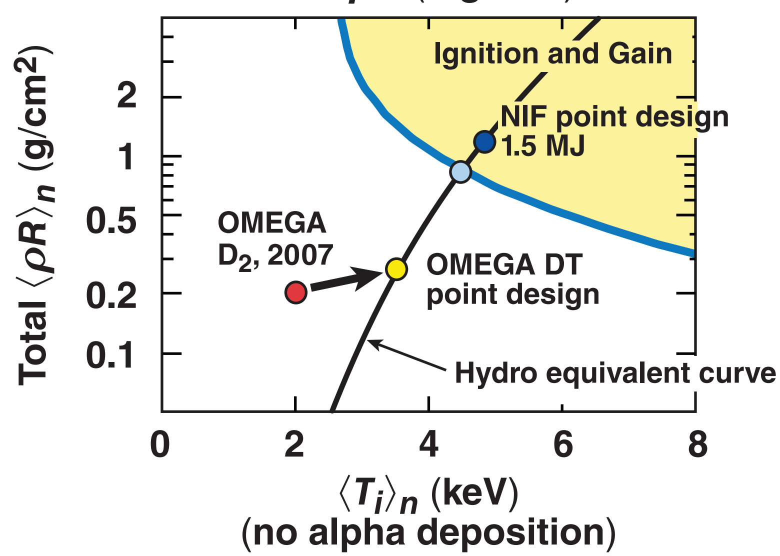
*D. D. Meyerhofer (TO6.00001).
†M. Key, ECLIM (2006).

Summary/Conclusions

These are exciting times for inertial confinement fusion

- Experiments on Nova (previously) and OMEGA are developing the target-physics understanding.
- Recent OMEGA experiments have demonstrated ignition-relevant areal densities.
- New concepts will extend ignition possibilities.
- This talk reviewed direct-drive ICF progress.*
- After 35 years, the ICF community is ready to exploit advances in physics understanding and drivers, leading to ignition experiments on the National Ignition Facility (NIF).





The achievement of ICF ignition will change the fusion landscape.

I1768a

*More ICF, see Lindl (SR1.00001).