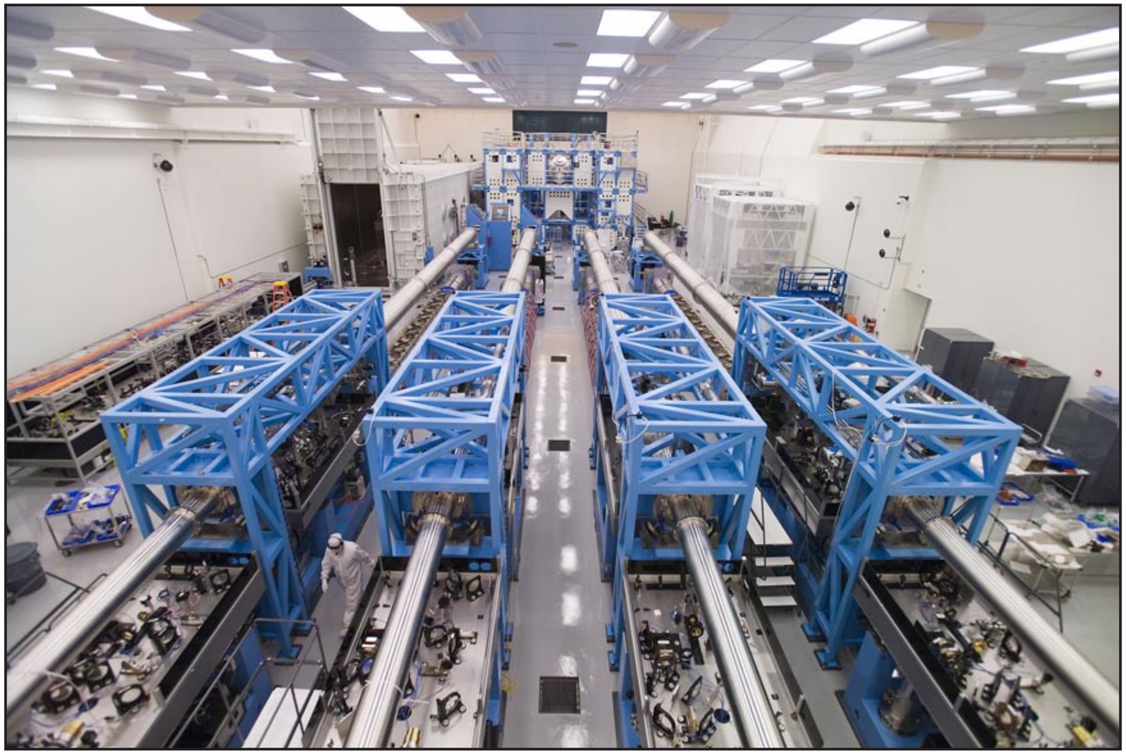
OMEGA Extended Performance Laser System



2008 Annual Meeting of the
American Association for the
Advancement of Science
Boston, MA
14–18 February 2008

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

OMEGA Extended Performance Laser System

R.L. McCrory

Laboratory for Laser Energetics
University of Rochester
250 E. River Rd.
Rochester, NY 14623

rmcc@lle.rochester.edu

Talk Summary

These are exciting times for Inertial Confinement Fusion (ICF) and High Energy Density Physics (HEDP) (see Frontiers in High Energy Density Physics: The X-Games of Contemporary Science. Washington, DC, National Academies Press (2003)). The completion of the National Ignition Facility at Lawrence Livermore National Laboratory in 2009 promises the achievement of fusion ignition in the laboratory. Research carried out on the OMEGA laser system at the University of Rochester's Laboratory for Laser Energetics (UR-LLE) provides the scientific underpinning for this effort.

For the first time, researchers at UR–LLE have succeeded in compressing deuterium to 500 times liquid density, or more than 100 grams per cubic centimeter (g/cc)—five times the density of gold. Deuterium is one of the isotopes driving the fusion engine that powers our sun. It is also one of the most abundant isotopes on earth and is considered a key fuel component for long-term energy independence. The pivotal experiment was performed using the 60-beam, 30-kJ OMEGA laser. A frozen shell of deuterium approximately 1 mm in diameter and less than 0.1 mm thick was imploded by symmetrically irradiating the shell with all 60 beams. The density of the deuterium created at UR-LLE is close to that required for ignition to occur.

The OMEGA Extended Performance (EP) laser system, currently under construction at UR-LLE, will be completed in 2008. This four beam laser system, with both long pulse (~10 ns) ultraviolet beams and high energy petawatt short pulse (1 ps) infrared beams, will significantly extend the ICF and HEDP research opportunities, allowing a wide variety of physics regimes to be explored.

This talk will describe progress in direct drive ICF and high energy density physics opportunities that will be engendered by the completion of the OMEGA EP laser system.

Summary

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.
- The OMEGA Extended Performance (EP) Laser System will
  - be completed in 2008,
  - extend Inertial Confinement Fusion understanding, and
  - allow a wide variety of high-energy-density-physics experiments.

After 35 years, the ICF community is ready to exploit advances in physics understanding and drivers, leading to ignition experiments on the NIF.

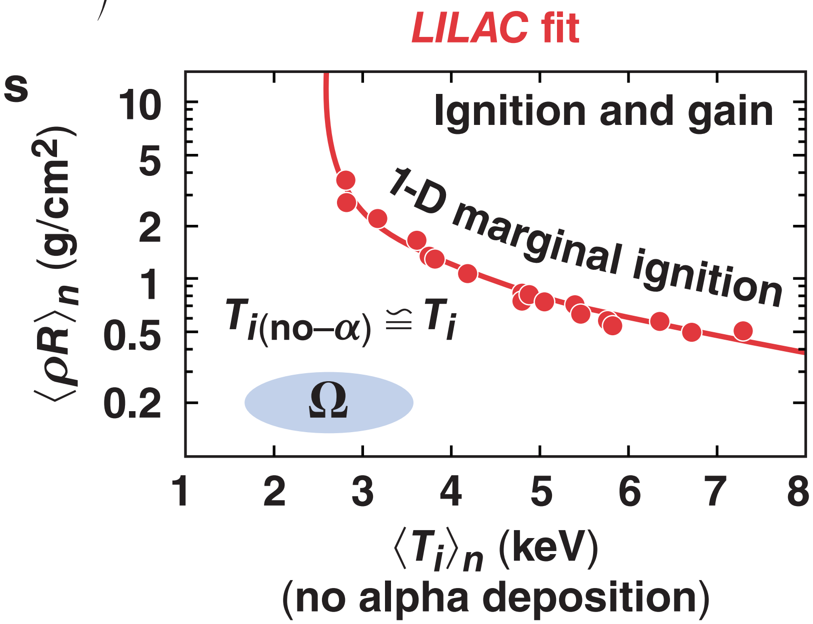
A “Lawson’s criterion” in terms of burn-averaged ρR and T_i shows the requirements for ignition

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

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

- 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.

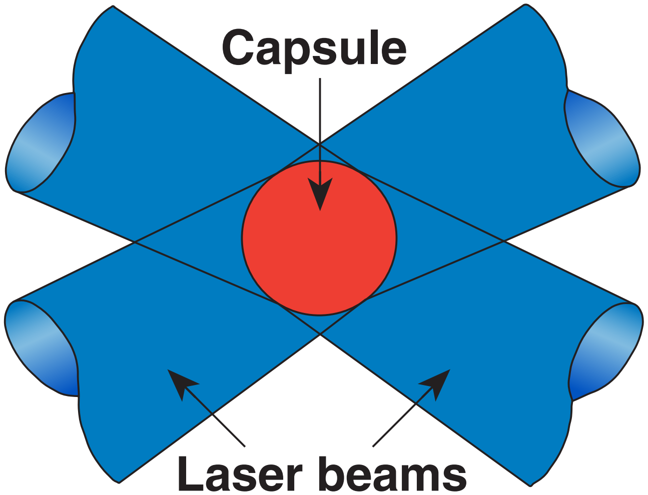
---

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

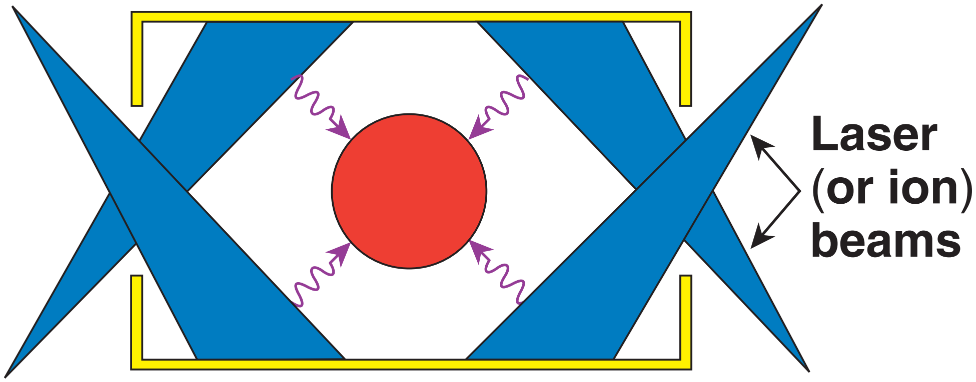
** M. C. Herrmann, M. Tabak, and J. D. Lindl, Nucl. Fusion 41, 99 (2001).

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

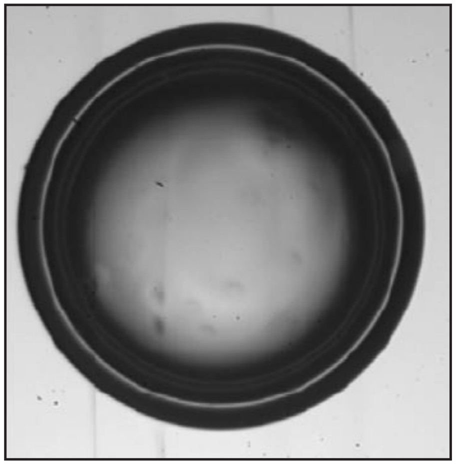
Direct-drive cryogenic implosions provide essential information for ICF physics.

E6426o

Ignition requires smooth cryogenic DT targets

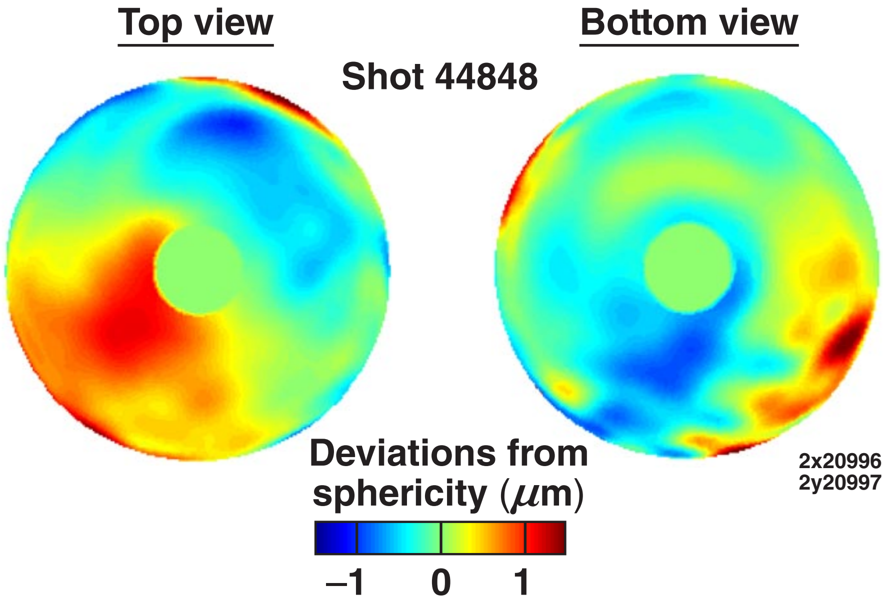
- Thick (>50 μm) DT ice layers are required for ignition.
- β-layered 50:50 DT cryogenic targets have measured ice-roughness nonuniformities <1-μm rms, meeting ignition specifications.

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



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

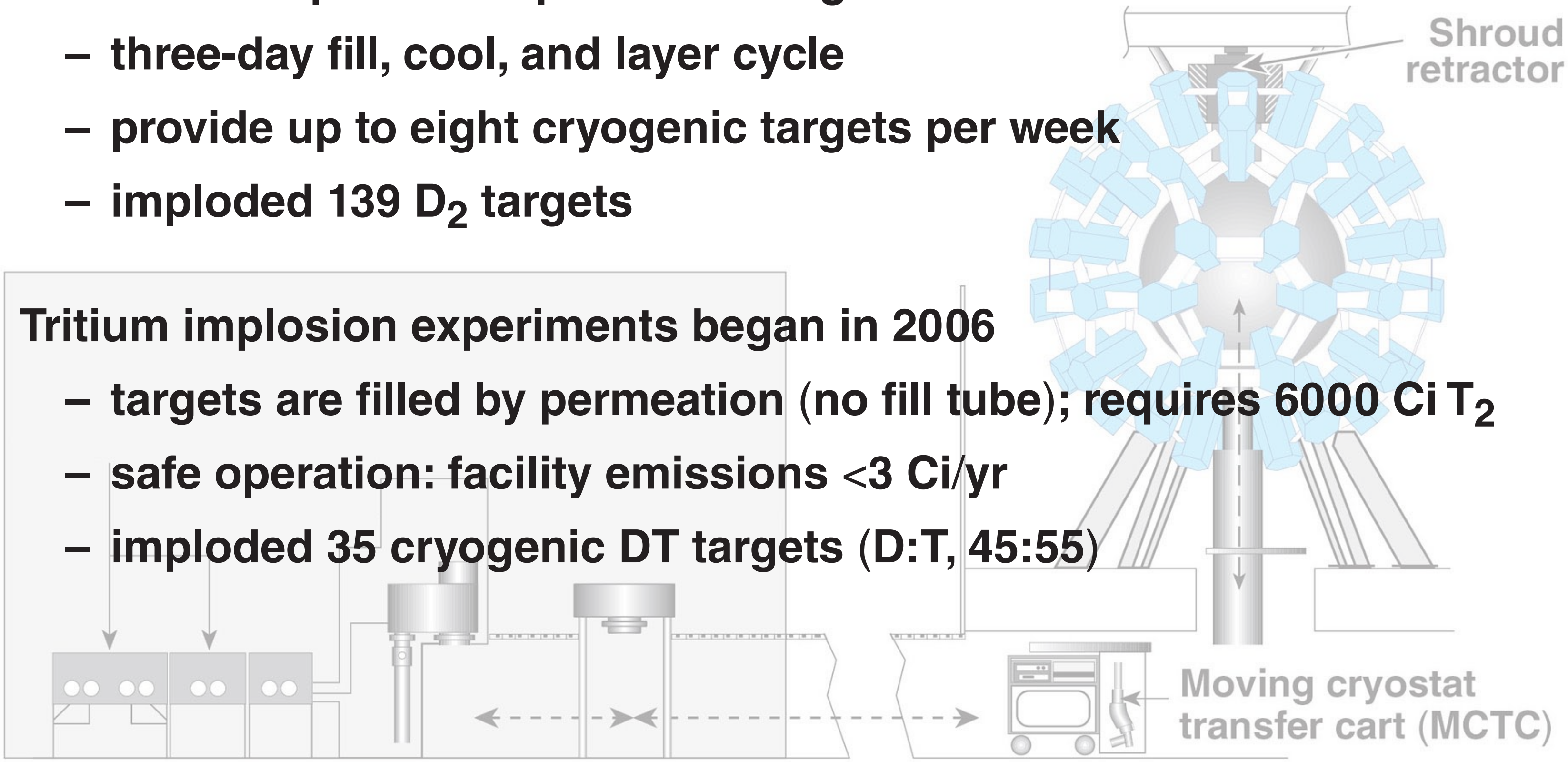
Ice-surface reconstruction showing 0.72-μm rms (48 views)



Multiple views are essential for full characterization.

D. R. Harding, to be published in *IFSA 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.

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

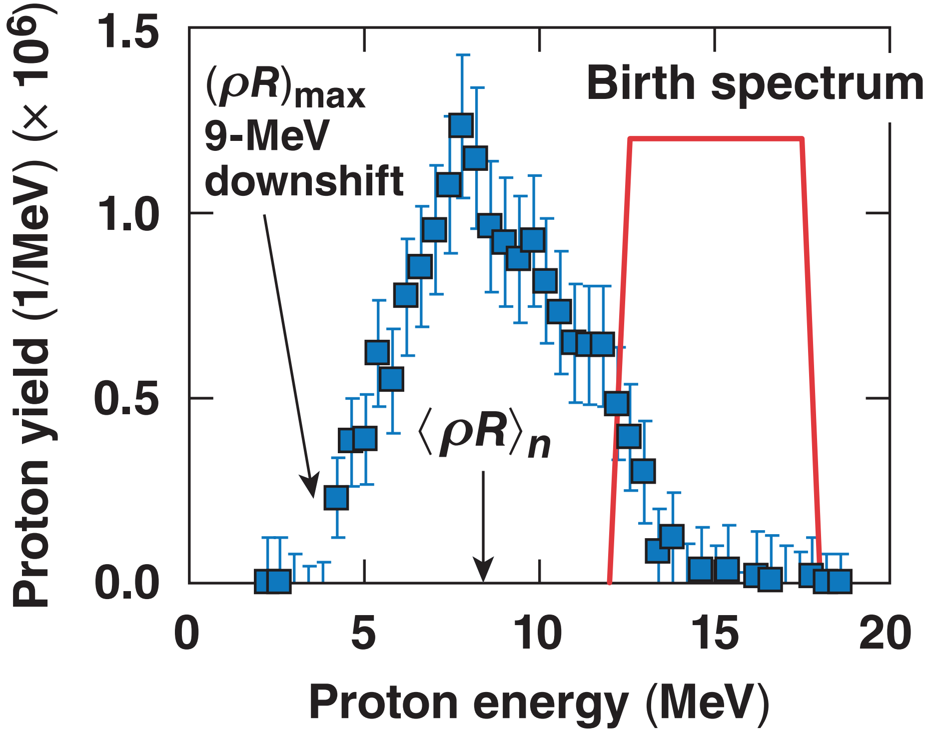
- Precise pulse shaping, including a picket, sets the target on the appropriate adiabat
- Current experiments have demonstrated ignition-relevant areal densities
  - shock timing and strength
  - preheat
  - compressibility
  - hydrodynamic instabilities
- Future experiments will increase the ion temperature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

Understanding cryogenic dynamics is a key to successful ICF ignition.

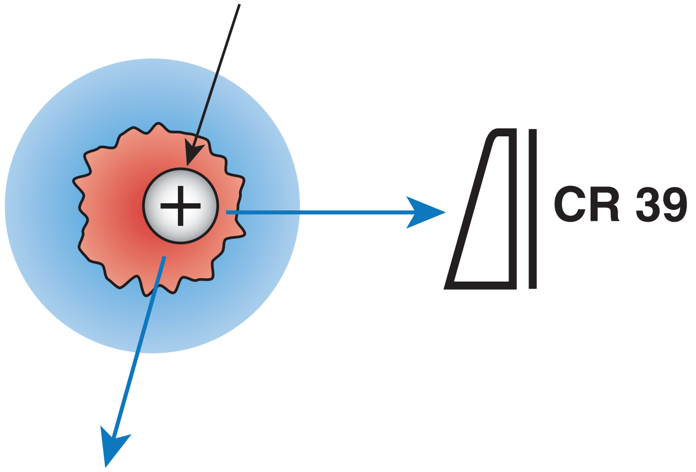
Areal Density

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

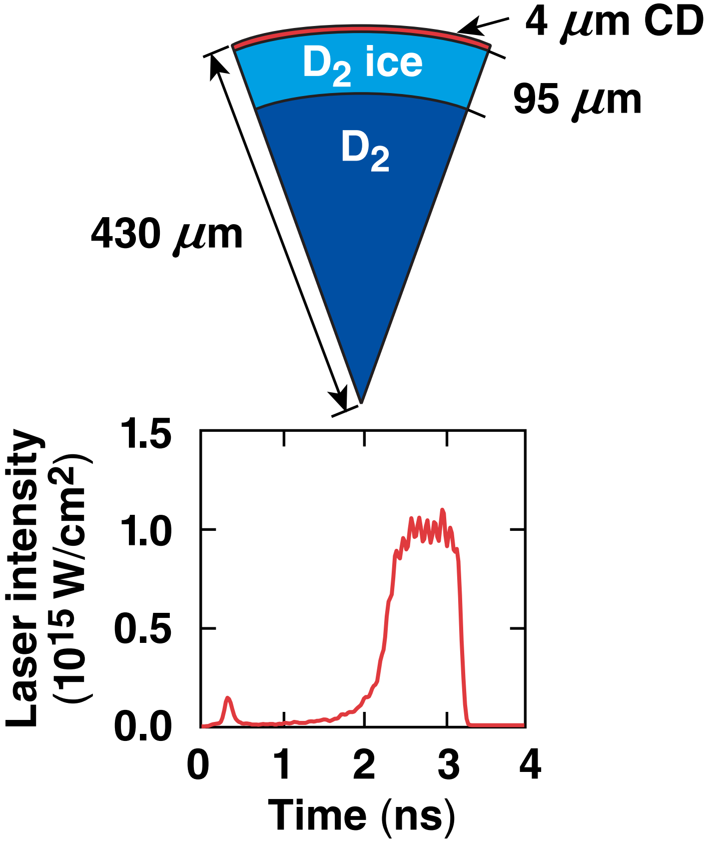
---

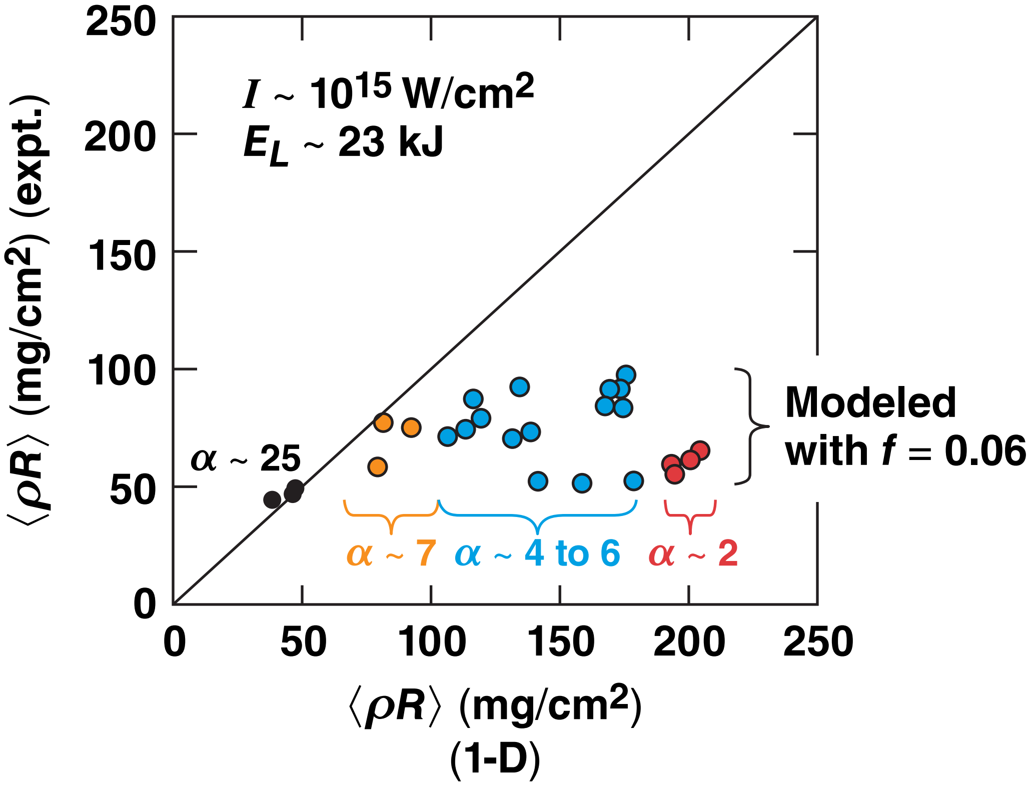
*F. H. Séguin *et al.*, Rev. Sci. Instrum. 74, 975 (2003).

Areal Density

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





Main causes of degradation: shock mistiming and fast-electron preheating

TC7833c

Areal Density

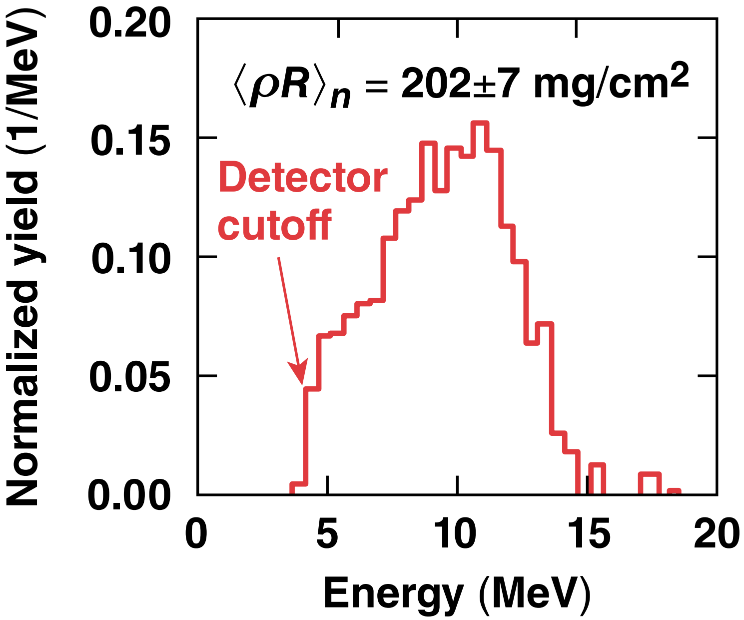
Ignition-relevant areal densities (~200 mg/cm^2) are achieved by accurate shock timing and mitigating fast-electron preheat

UR LLE

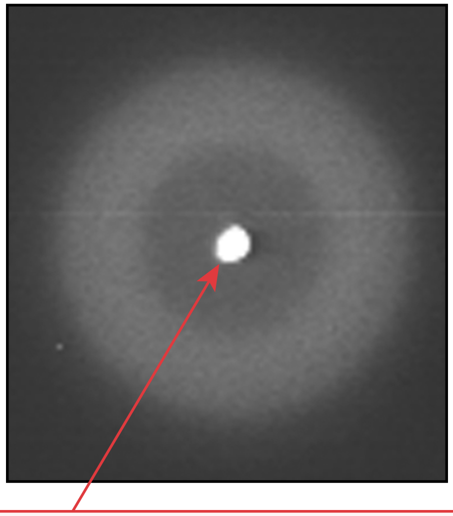
- Target design tuned to be insensitive to the thermal transport model and has low hard x-ray signal.

10-μm CD cryogenic implosion

Secondary D^{3}He proton spectrum



X-ray pinhole camera



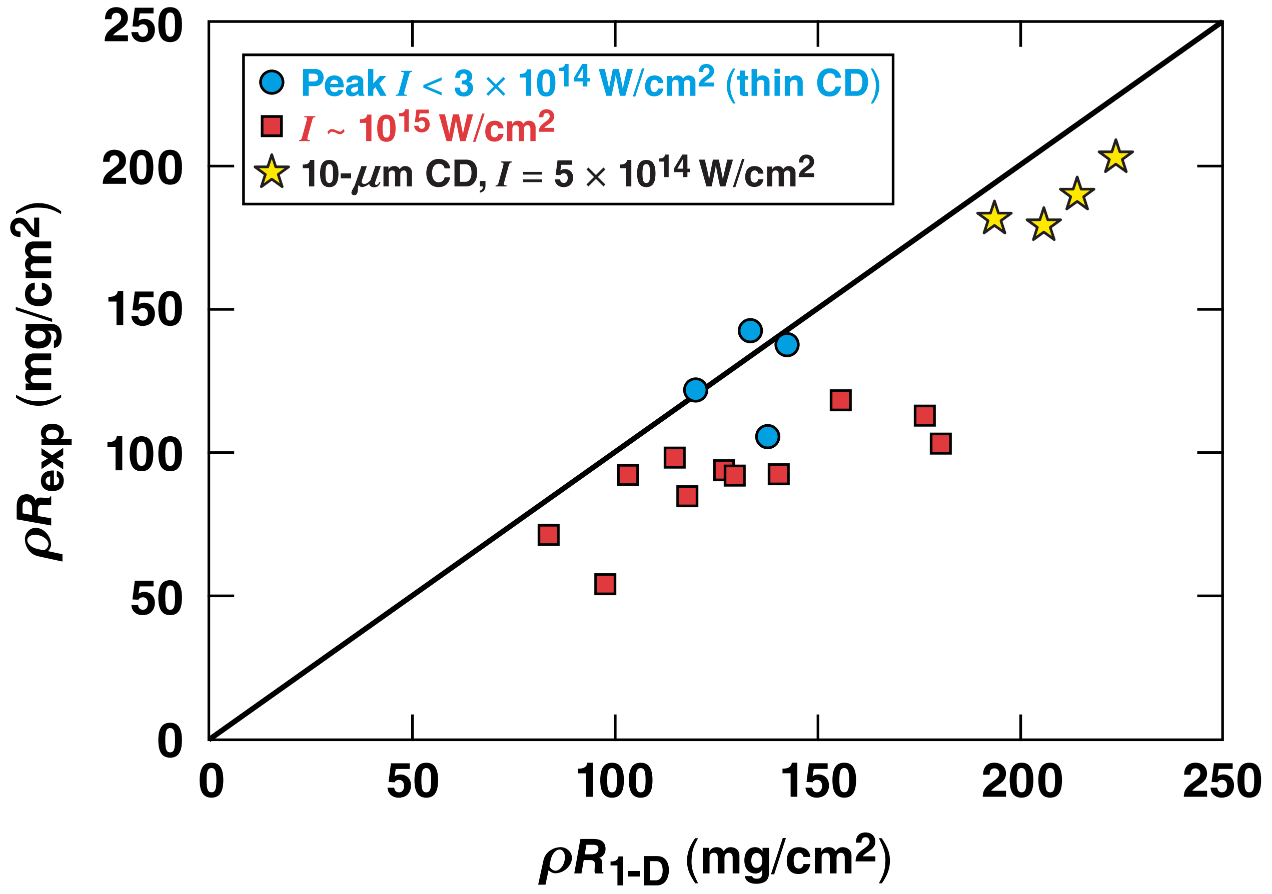
D$_2$ fuel density reaches ~100 g/cc (500× liquid density)

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*., to be published in Phys. Rev. Lett.

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

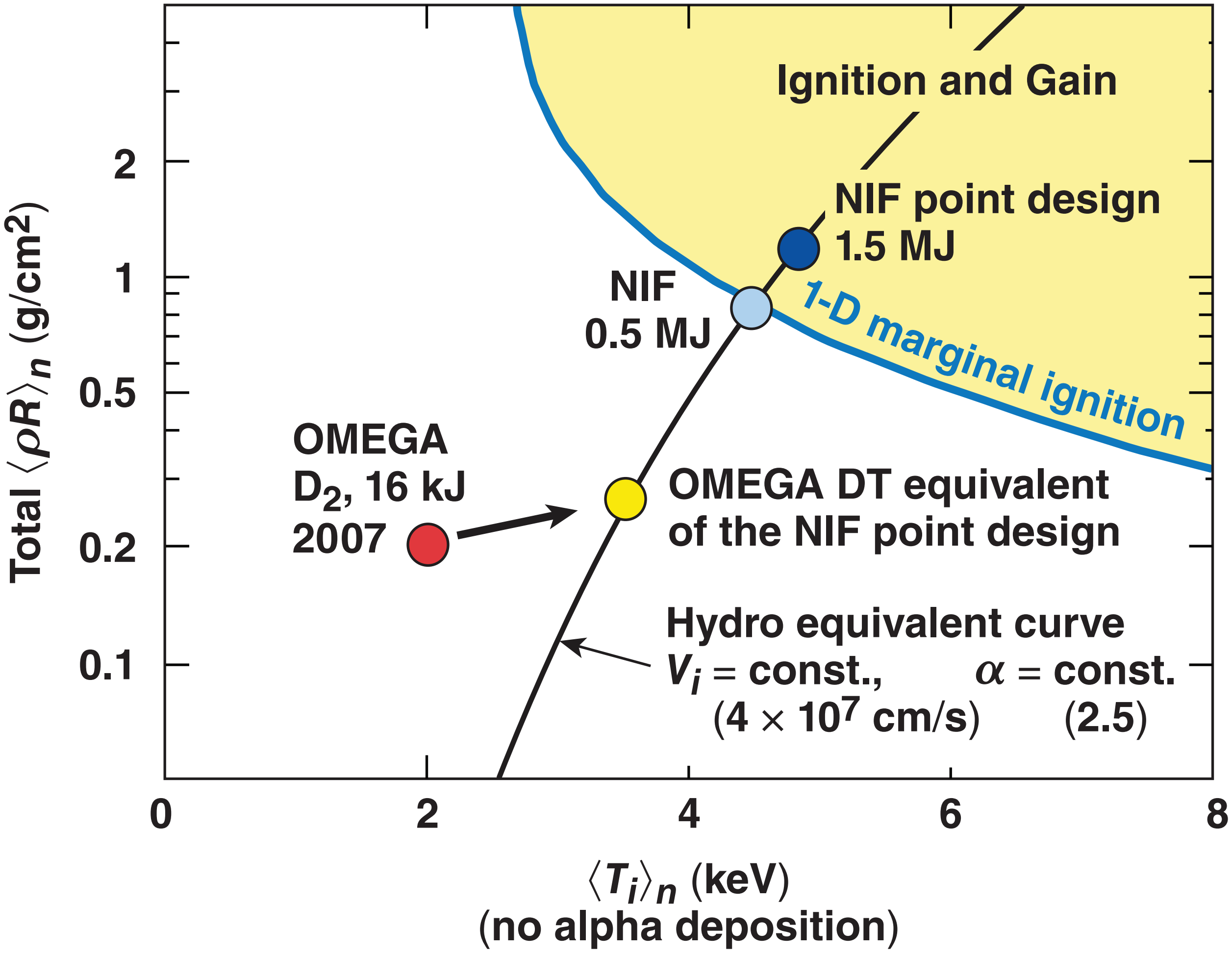
All simulations use nonlocal thermal-transport model



Path to T_i

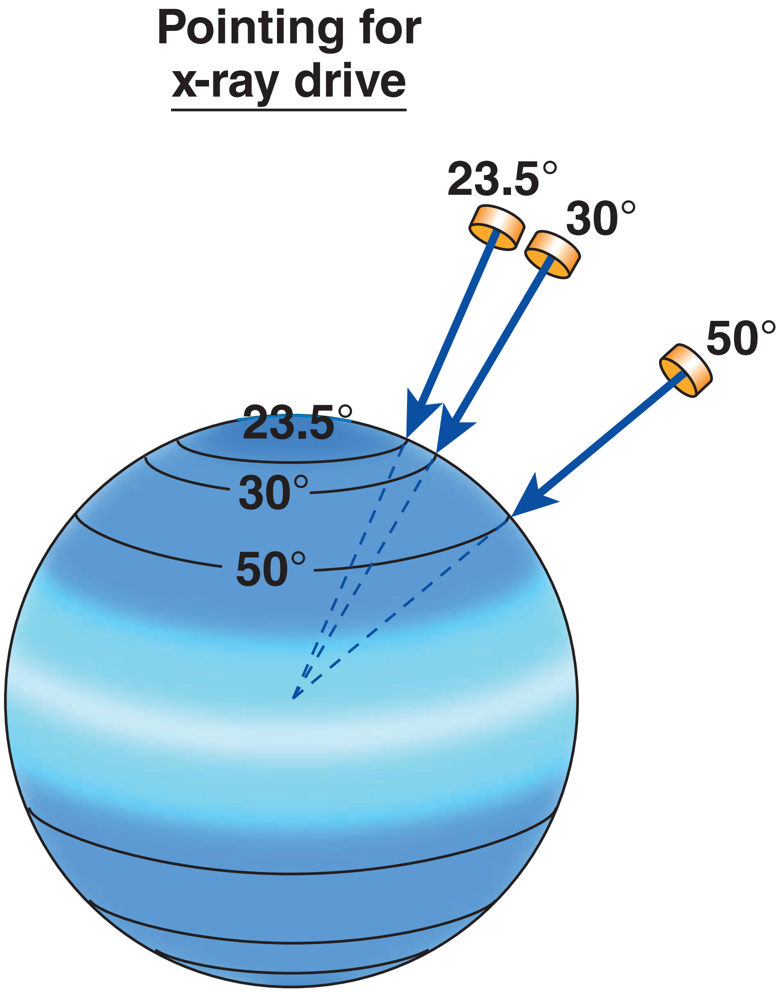
Direct-drive research is on a path to ignition on the NIF

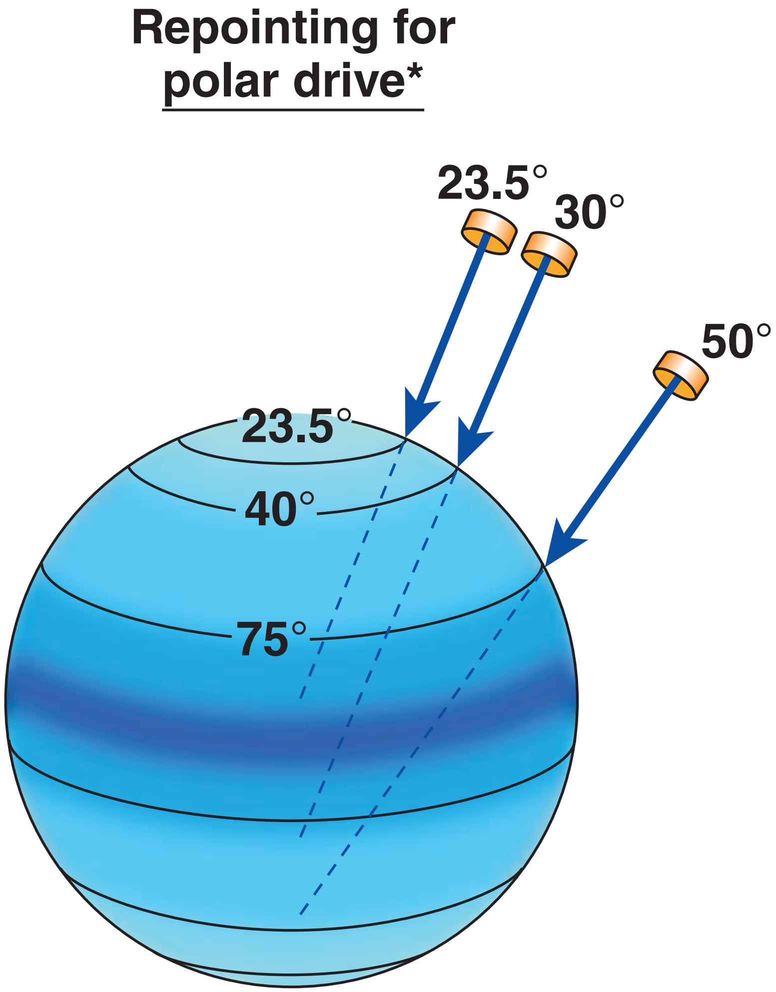
- Ignition-relevant areal densities have been achieved
- The next step is to increase T_i



Polar Drive

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



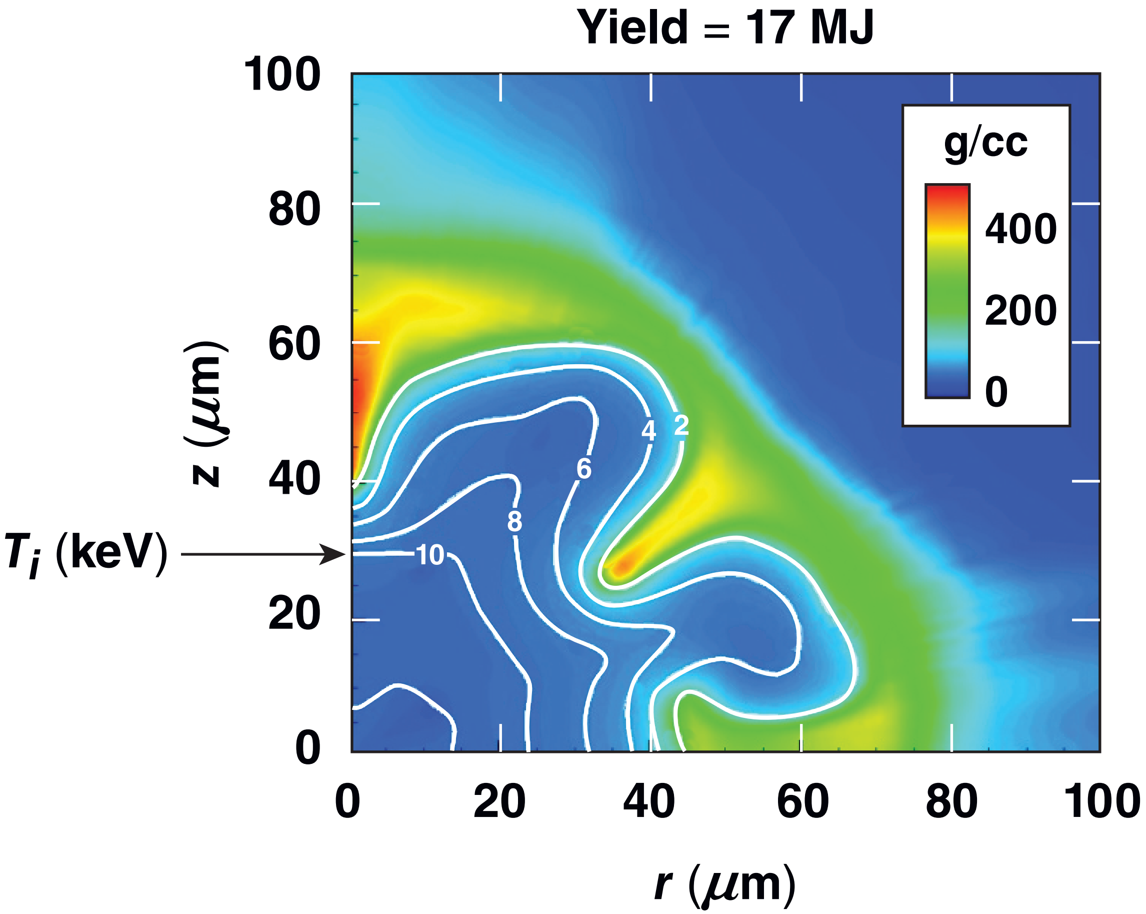


---

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

Polar Drive

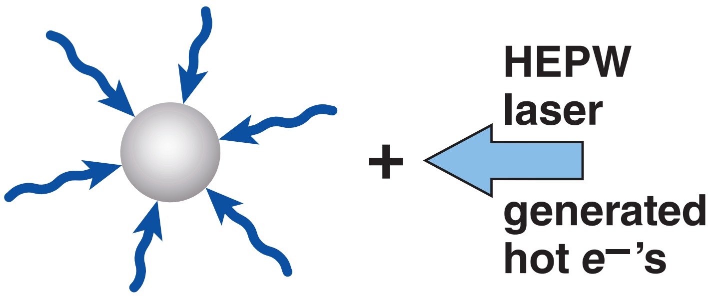
The polar-drive point design achieves a yield of 17 MJ with all current levels of NIF nonuniformities included in the calculation



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

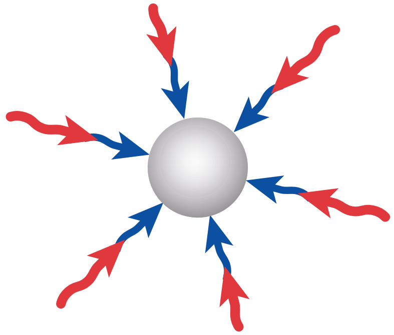
- In the current hot-spot ignition, the driver provides both compression (ρR) and heating (T_i).
- Both fast ignition and shock ignition use a second drive to provide heating (T_i).

Fast Ignition



Compression

Shock Ignition



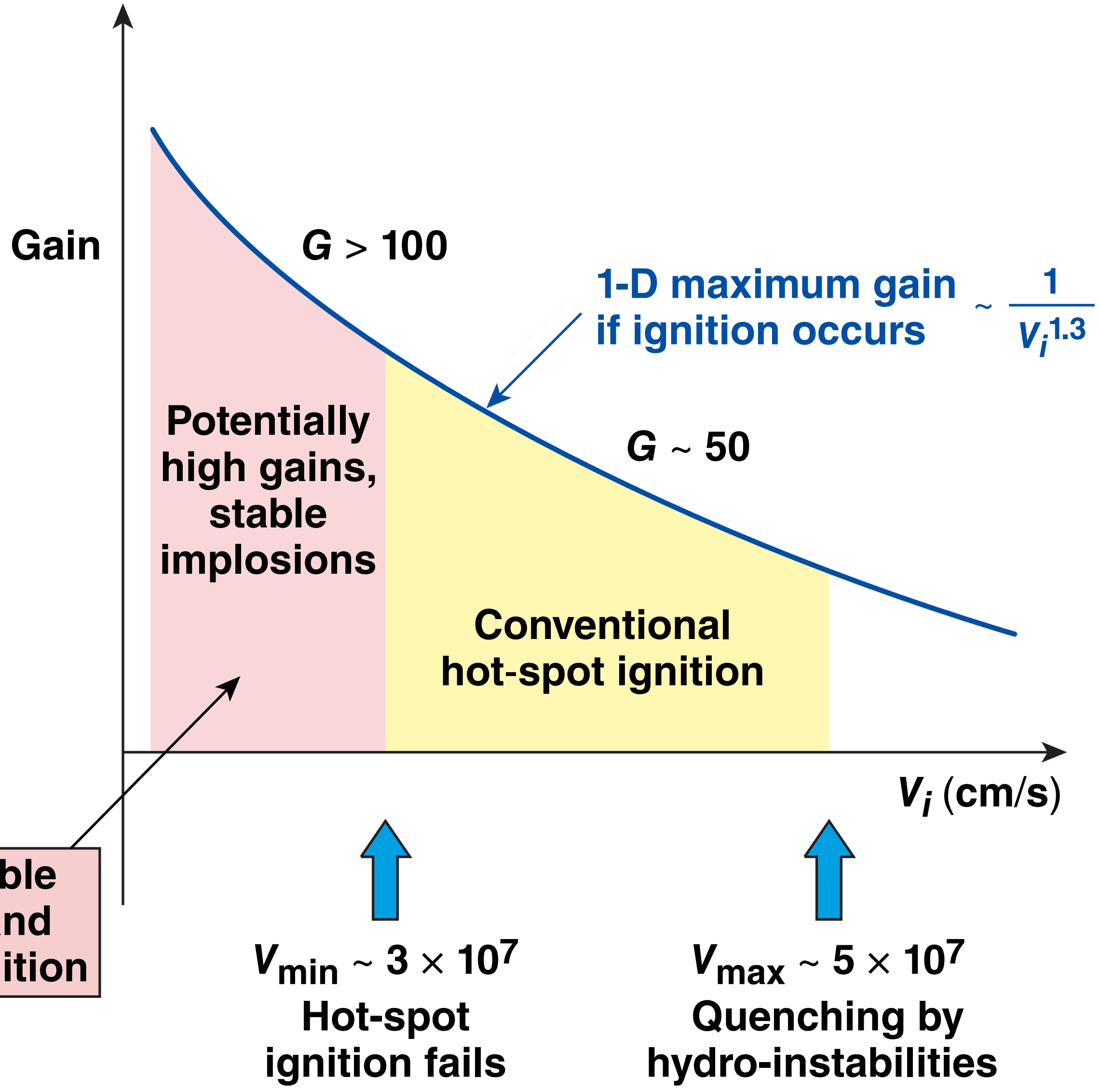
Compression + shock pulse

- 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



Accessible by fast and shock ignition

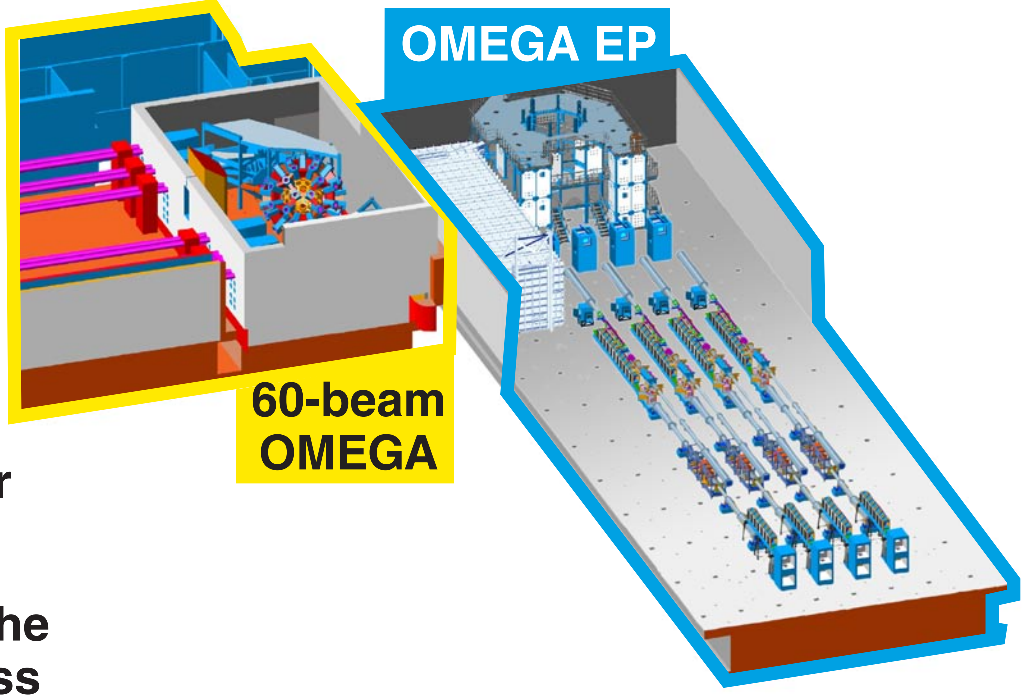
$V_{min} \sim 3 \times 10^7$
Hot-spot ignition fails

$V_{max} \sim 5 \times 10^7$
Quenching by hydro-instabilities

TC7815b

The Extended-Performance (EP) addition to OMEGA has five primary missions

1. Extend HED research capabilities with high-energy and high-brightness backlighting
2. Perform integrated advanced-ignition experiments
3. Develop advanced backlighter techniques for HED physics
4. Provide a staging facility for the NIF to improve its effectiveness
5. Conduct ultrahigh-intensity laser–matter interactions research



OMEGA EP will be completed in Q3 FY08.

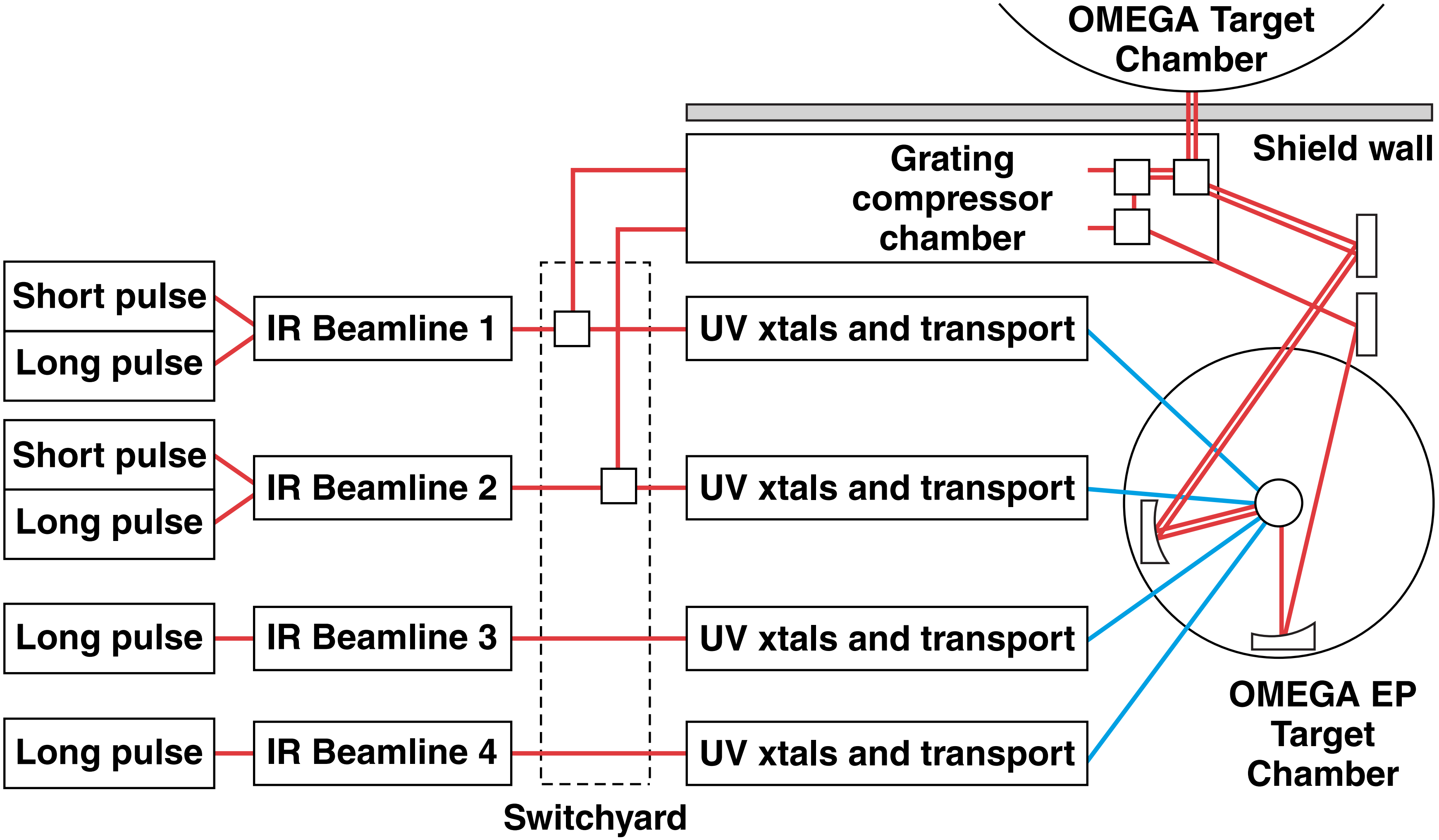
OMEGA EP will achieve its missions using a variety of on-target intensities and pulse durations

Performance capabilities	Short-pulse beam 1		Short-pulse beam 2		Long-pulse beams 1–4	
Target chamber	Ω or EP		Ω or EP		EP	
Pulse width	1–10 ps	10–100 ps	1–80 ps	80–100 ps	1 ns	10 ns
Energy on target (kJ)	1–2.6 (grating limited)	2.6	0.03–2.6 (combiner limited)	2.6	2.5	6.5
Intensity (W/cm^2)	3×10^{20}	8×10^{19}	2×10^{18}		3×10^{16}	8×10^{15}
Focusing (diam)	>80% in 20 μm		>80% in 40 μm		>80% in 100 μm	
Wavelength (nm)	1053		1053		351	

G5546cc

OMEGA EP

The OMEGA EP architecture is based on multi-configurable beam paths

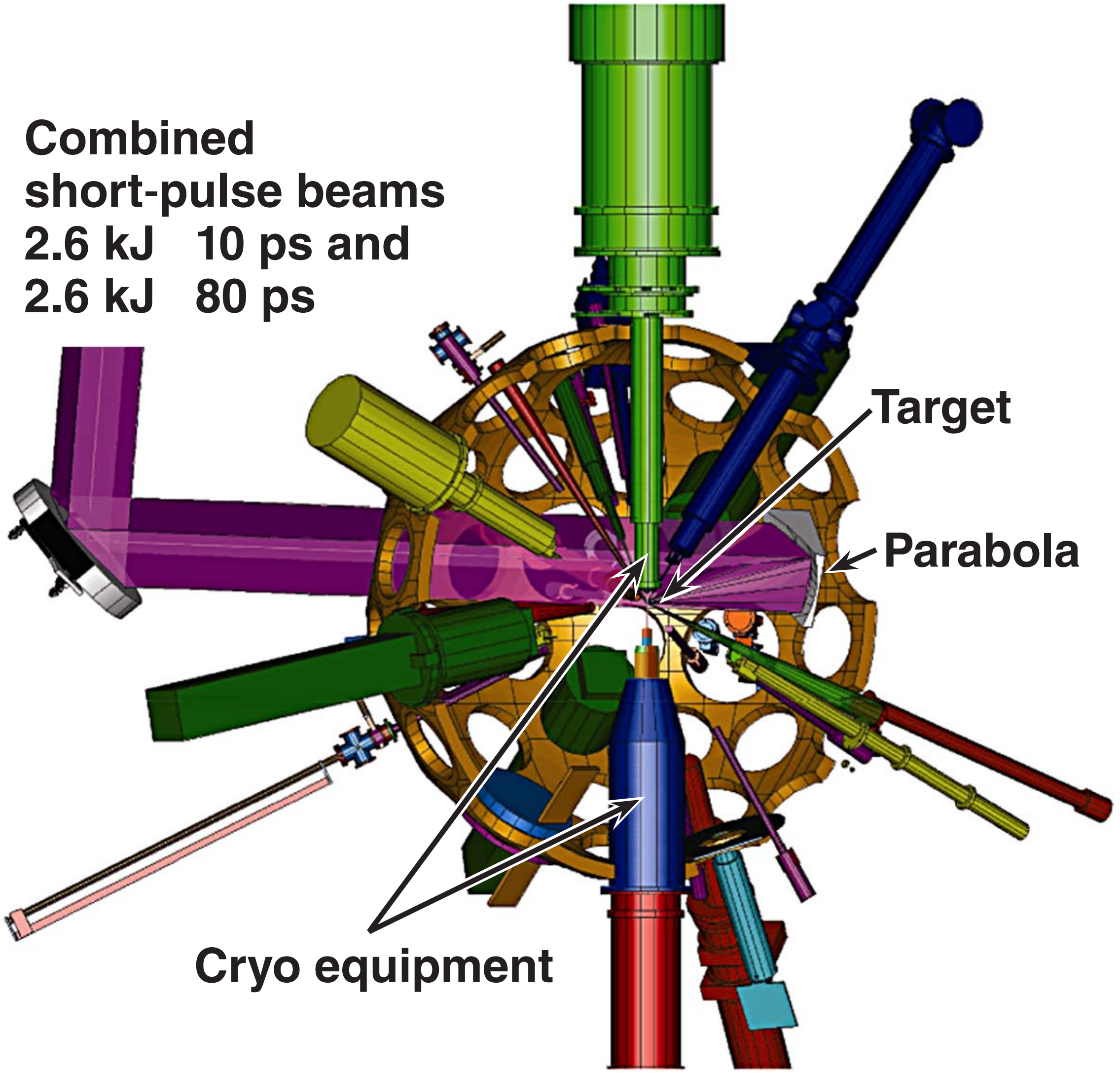


G7791c

OMEGA EP

The beams from OMEGA EP will be focused with a 23° *f*/2 off-axis parabola inside the OMEGA target chamber

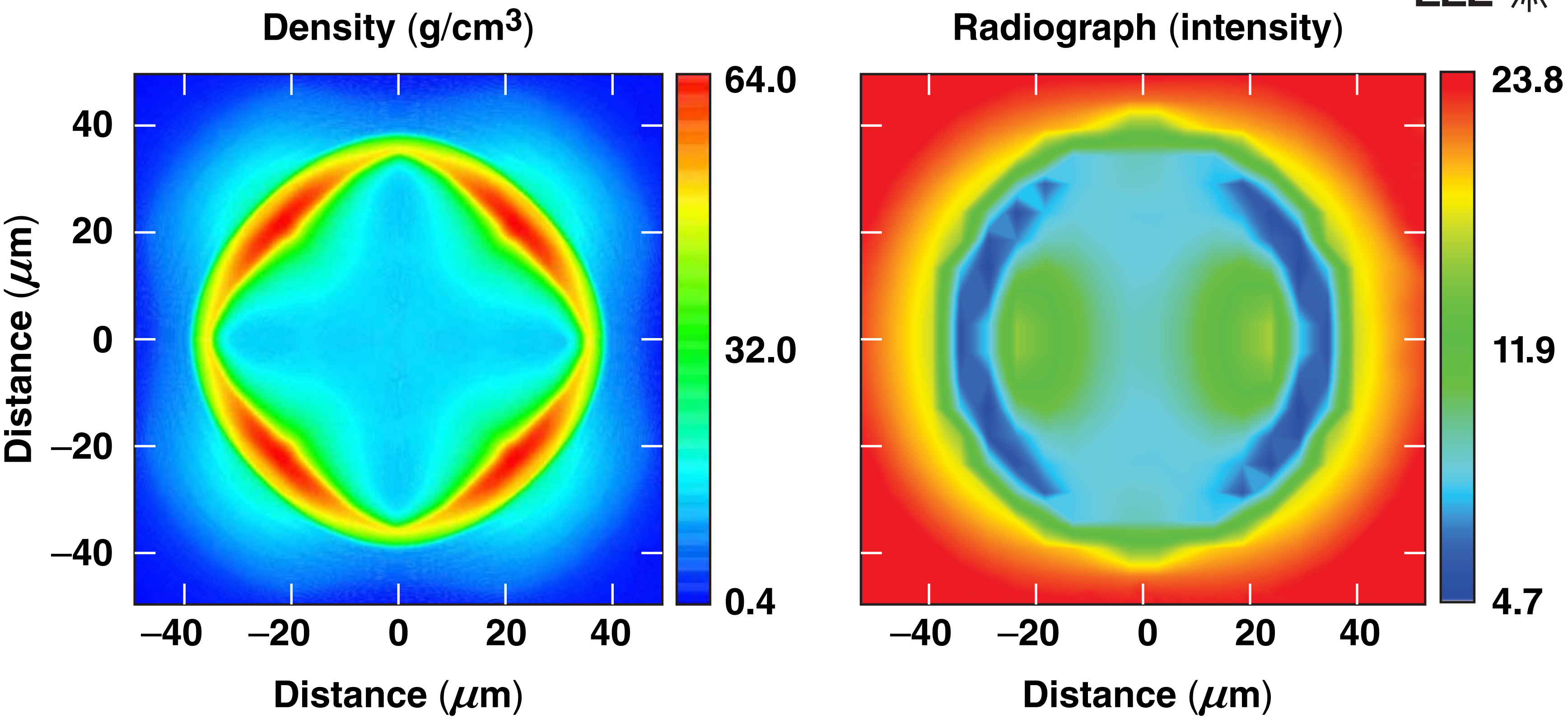
- A fast-focusing optic is necessary to meet the 20-μm-diam focal-spot requirement.
- The size of the target chamber port limits the input beam size.
- The beam path has to stay clear of the cryogenic target handling equipment.



Combined short-pulse beams
2.6 kJ 10 ps and
2.6 kJ 80 ps

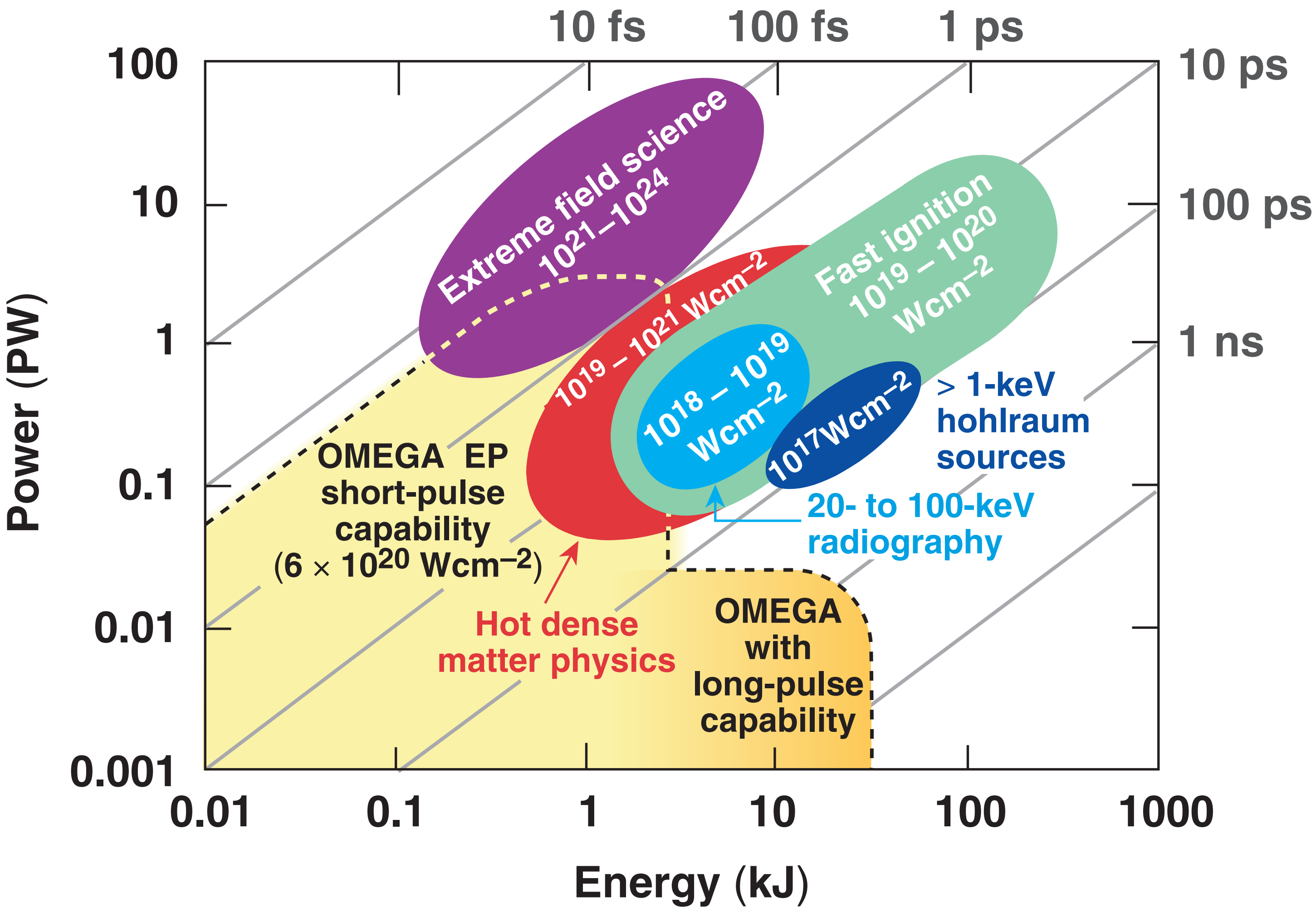
E13316c

A backlighter spectral brightness of ~60 μJ/eV/ps/Sr in the 2-keV spectral range is required for imaging cryogenic targets



- Simulations predict a self-emission of 8 μJ/eV/ps/Sr in the 2-keV range.
- Current cryogenic experiments show a self-emission of ~2 μJ/eV/ps/Sr.
- The simulation assumes, for the backlighter, a 3-keV Planckian spectrum filtered in the 2- to 2.2-keV spectral range.

The OMEGA/OMEGA EP Laser System will allow a large high-energy-density-physics parameter space to be explored



- Many target shots are required to fully develop these capabilities.

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.
- The OMEGA Extended Performance (EP) Laser System will
  - be completed in 2008,
  - extend Inertial Confinement Fusion understanding, and
  - allow a wide variety of high-energy-density-physics experiments.

After 35 years, the ICF community is ready to exploit advances in physics understanding and drivers, leading to ignition experiments on the NIF.