Laser-Driven Inertial Fusion Energy; Direct-Drive Targets Overview

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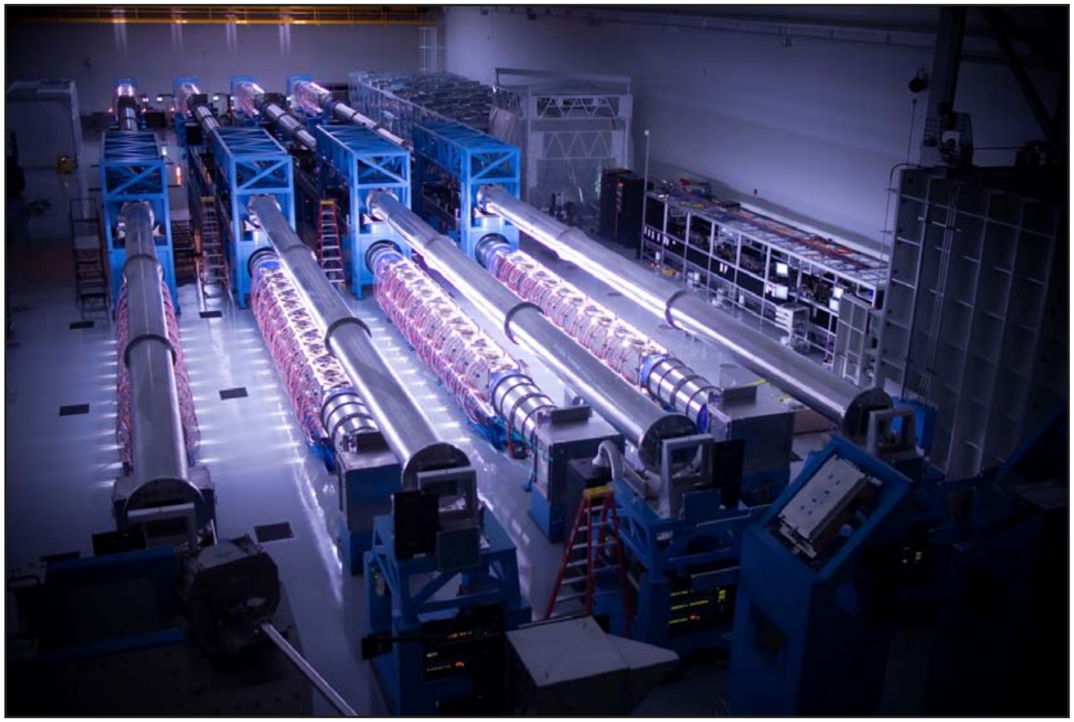

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NAS/NAE Committee on the
Prospects for IFE Systems
San Ramon, CA
29 January 2011

University of Rochester

Summary

LLE is the leader for direct-drive laser-based inertial fusion energy (IFE) concepts

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- Direct-drive based IFE concepts provide a complementary path to IFE relative to indirect-drive—with the potential of higher gains
- The Omega Laser Facility is being used to develop direct-drive IFE concepts—hot spot and shock ignition
- Hot-spot cryogenic implosions have achieved performance comparable to magnetic fusion
- Polar drive was conceived to allow direct-drive concepts to be tested on the NIF without reconfiguration of the beam disposition—current designs predict gains of ~30
- Polar drive could demonstrate ignition on the NIF before 2020
- LLE expertise will be used to develop technologies for glass laser-driven IFE – e.g. "lab-on-a-chip" target manufacture
- LLE and LLNL have partnered to develop the glass laser IFE concept

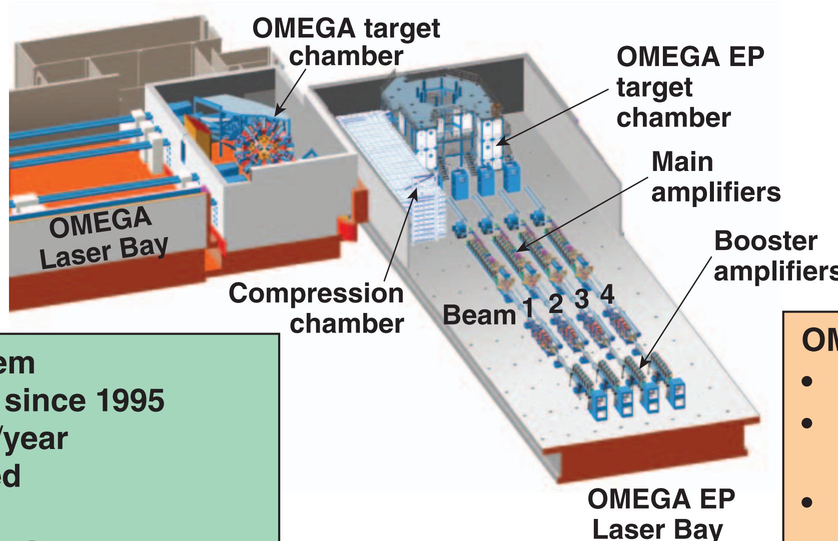
The solid-state laser concept shows great promise for IFE.

Laboratory for Laser Energetics

Total square footage:
310,000 ft^2

- Faculty equivalent staff: 96
- Professional staff: 178
- Associated faculty: 26
- Contract professionals: 12
- Graduate and undergraduate students: 127

LLE operates two of the world's largest lasers for high-energy-density physics research



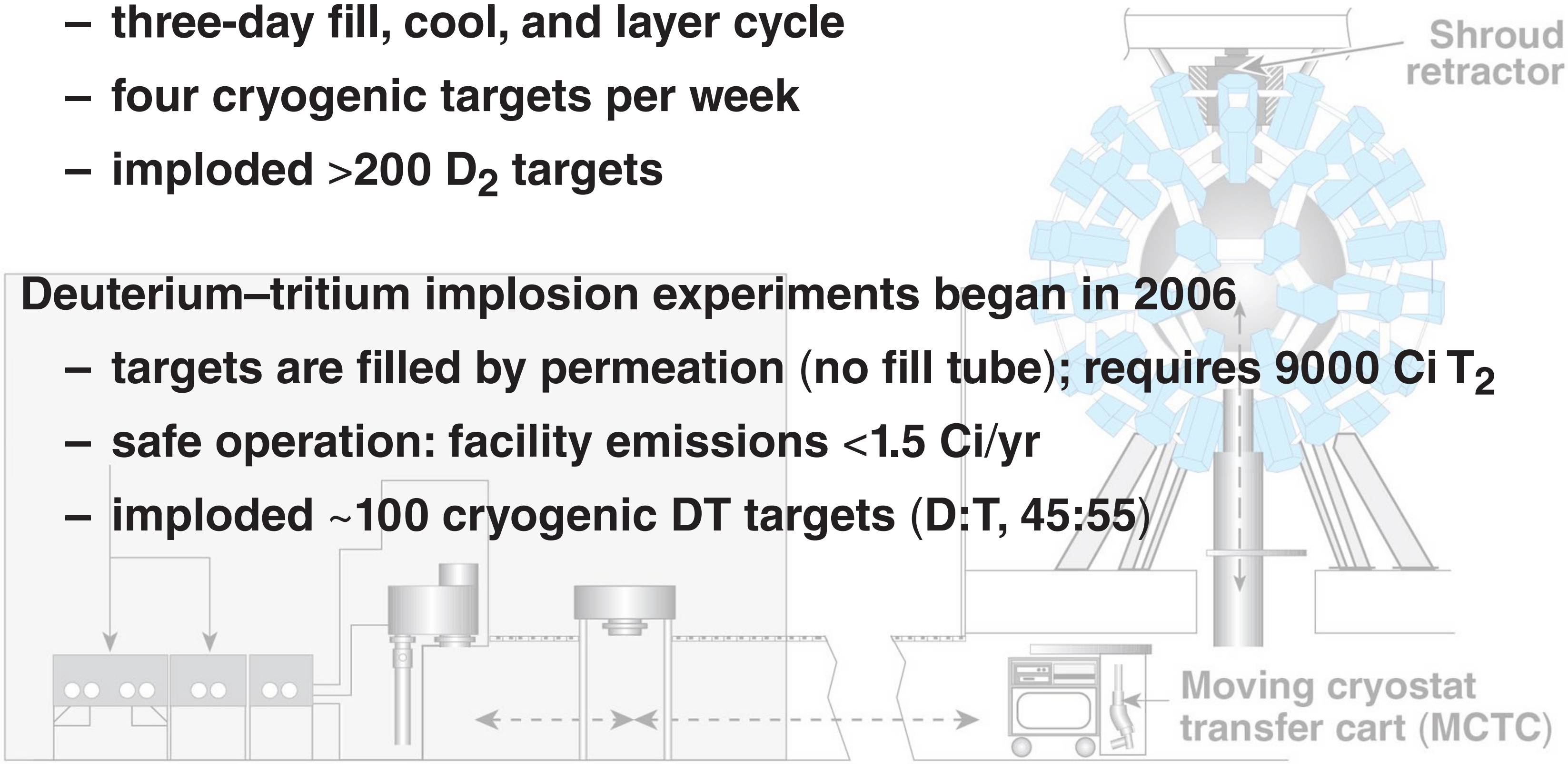
OMEGA Laser System
- Operating at LLE since 1995
- Up to 1500 shots/year
- Fully instrumented
- 60 beams
- >30-kJ UV on target
- 1% to 2% irradiation nonuniformity
- Flexible pulse shaping
- Short shot cycle (1 h)

OMEGA EP Laser System
- Construction complete 25 April 2008
- Adds four NIF-like beamlines; 6.5-kJ UV (10 ns)
- Two beams can be high-energy petawatt
  - 2.6-kJ IR in 10 ps
  - Can propagate to the OMEGA or OMEGA EP target chamber.

- The OMEGA Users' Group
  - founded in 2008 to facilitate communication among the users, the Omega facility, and the broader scientific community
  - 2nd annual OMEGA Laser Facility Users Group Workshop—held 29–30 April 2010
  - 190 members

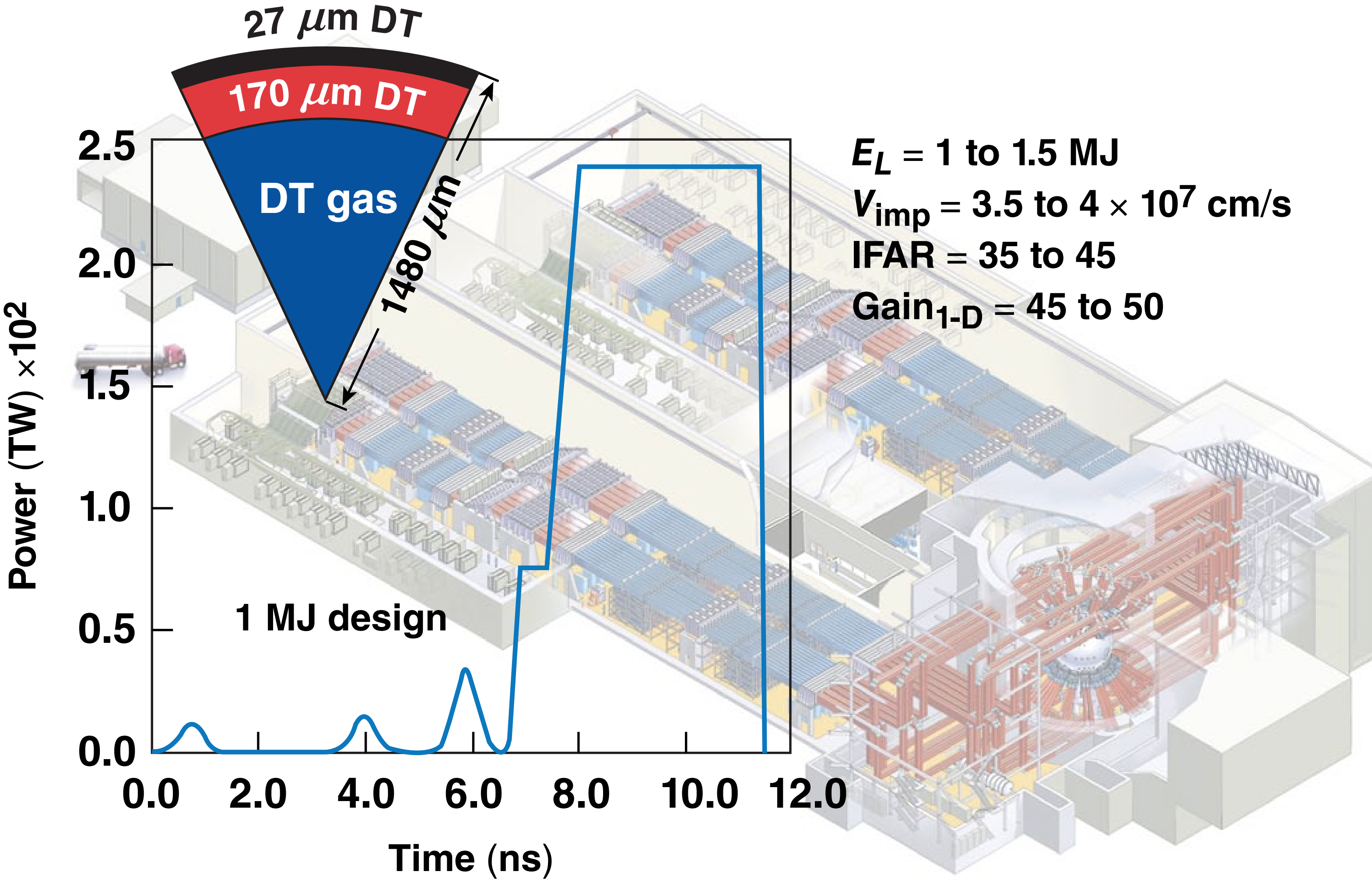
LLE routinely fields smooth cryogenic capsules

- **Deuterium implosion experiments on ignition-scale targets began in 2001**
  - three-day fill, cool, and layer cycle
  - four cryogenic targets per week
  - imploded >200 D_2 targets
- **Deuterium–tritium implosion experiments began in 2006**
  - targets are filled by permeation (no fill tube); requires 9000 Ci T_2
  - safe operation: facility emissions <1.5 Ci/yr
  - imploded ~100 cryogenic DT targets (D:T, 45:55)



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

The symmetric direct-drive NIF ignition design has a 1-D gain of ~50



E_L = 1 to 1.5 MJ

V_{imp} = 3.5 to 4 × 10^7 cm/s

IFAR = 35 to 45

$Gain_{1\text{-}D}$ = 45 to 50

Multiple-picket pulse shapes are being used to drive ignition-scaled cryogenic-DT implosions on OMEGA

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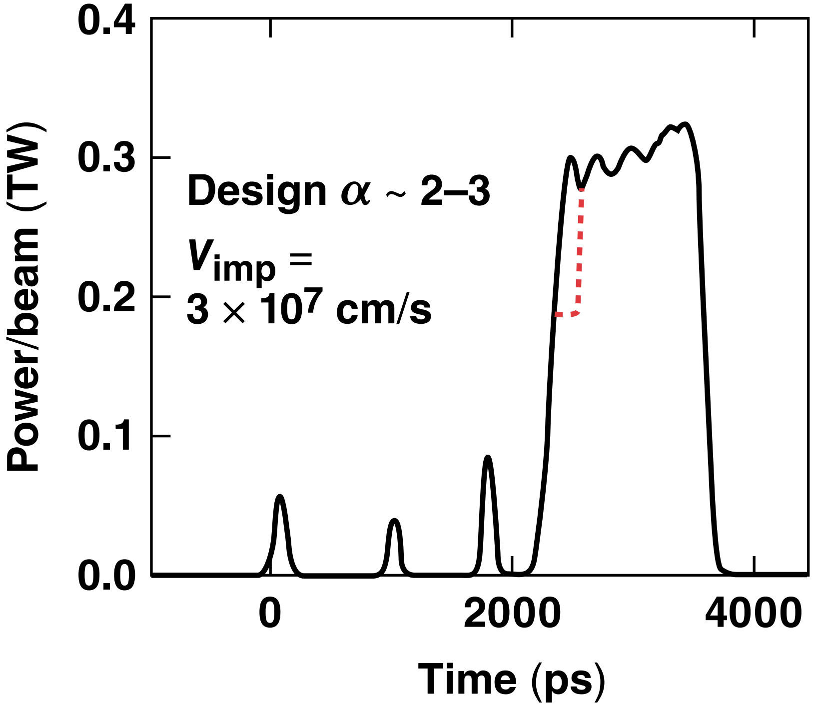
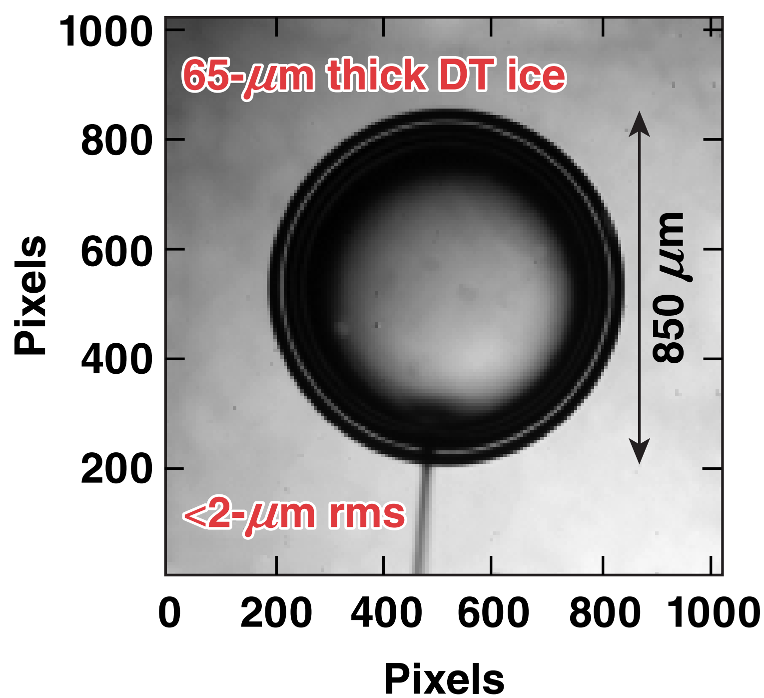
Current drive pulse used to implode cryogenic-DT targets



Shadowgraph of a stalk-mounted cryogenic-DT capsule



Picket energies and relative timing are adjusted to optimize the shock coalescence

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The measured areal density in triple-picket cryogenic implosions is larger than 88% of the 1-D predicted value[1]

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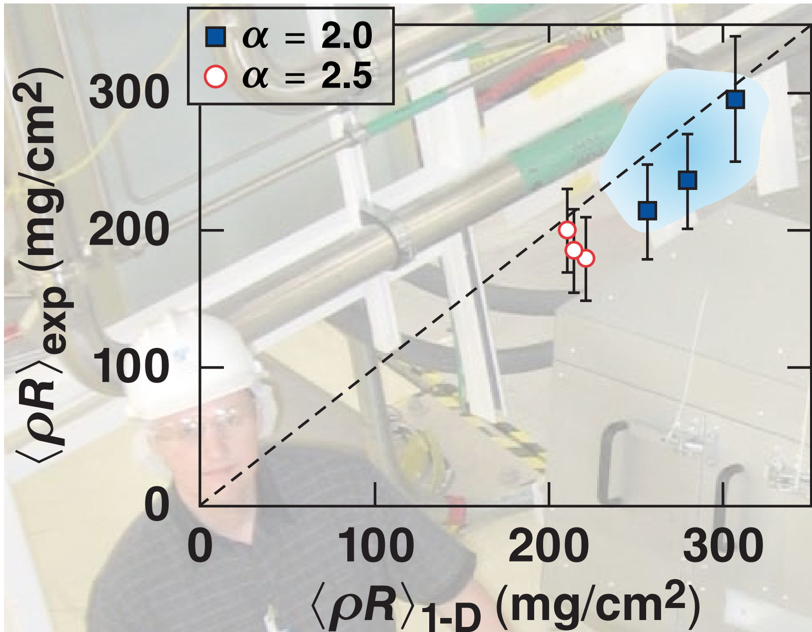
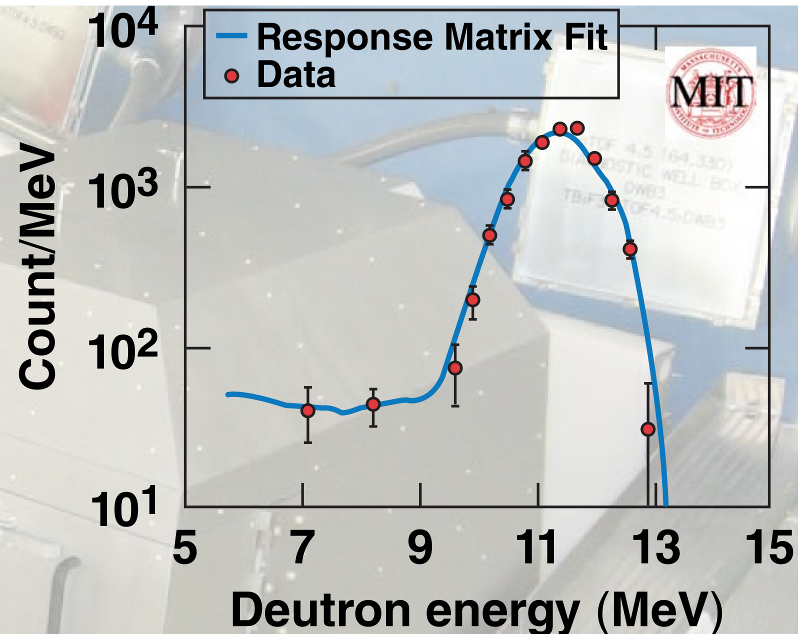
Cryogenic implosions, IFAR ~30



MRS data
55723
295±47 mg/cm^2



The areal-density measurements confirm accuracy of shock tuning and shell stability to short-wavelength perturbations.

[1]V. N. Goncharov *et al.*, Phys. Rev. Lett., 104, 165001 (2010).

The product $P\tau$ can be related to the measurable parameters ρR, T, and neutron yield

$$P\tau\,(\text{atm}\cdot\text{s}) \approx 8\left(\rho R_{\text{g/cm}^2}\, T_{\text{keV}}\right)^{0.8} \text{YOC}^{0.4}$$

$$\text{YOC} = \frac{\text{measured neutron yield}}{\text{1-D predicted neutron yield}}$$

- Measure ρR (magnetic recoil spectrometer)
- Measure T (neutron time of flight)
- Measure neutron yield (scintillators)
- Compute 1-D neutron yield (1-D code)

$$\chi = \left(\rho R_{\text{g/cm}^2}\right)^{0.8} \left(\frac{T_{\text{keV}}}{4.7}\right)^{1.6} \text{YOC}^{0.4}$$

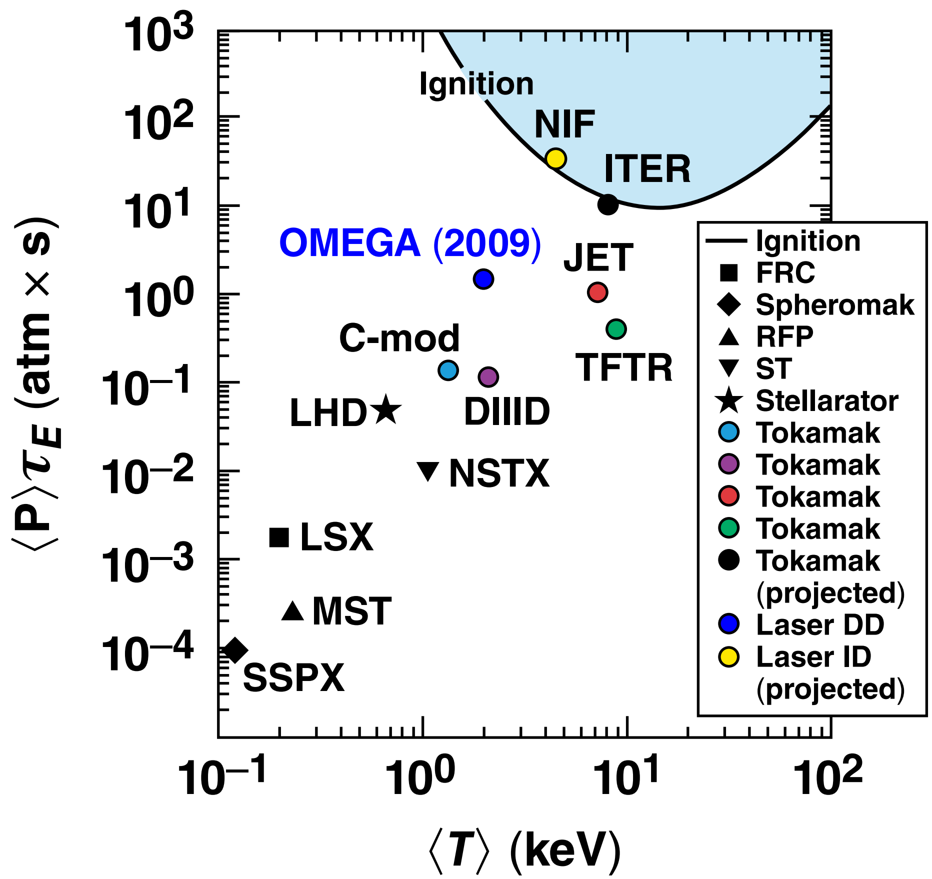
← Overall ignition parameter

$\chi > 1$ ← Required for ignition

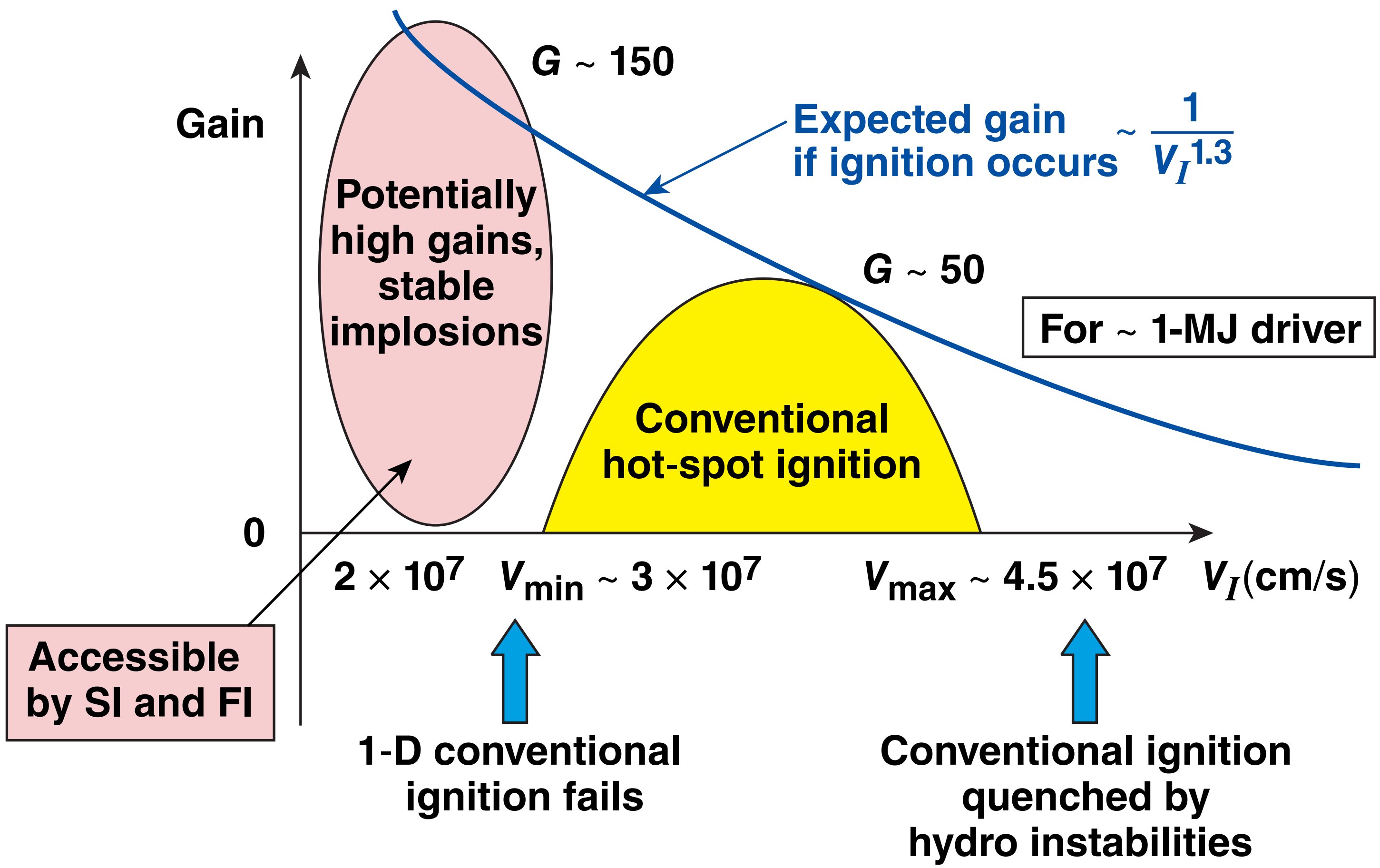
P. Y. Chang *et al.*, Phys. Rev. Lett. 104, 135002 (2010).
R. Betti *et al.*, Phys. Plasmas 17, 058102 (2010).

OMEGA cryogenic implosions have achieved a Lawson criterion, $P\tau > 1$ atm-s

- On OMEGA, ignition-equivalent performance requires
  - $\langle T \rangle \sim 3.4$ keV
  - $P\tau \sim 2.6$ atm-s
- Cryogenic implosions to date
  - $\rho R = 0.3$ g/cm^2, $\langle T \rangle = 2$ keV
  - YOC = 5% ~ 10% give
  - $P\tau \geq 1$ atm-s, $\chi = 0.08$
- For comparison, the Joint European Tokamak has produced
  - $P\tau \sim 1$ atm-s



Advanced ICF concepts such as shock ignition (SI) or fast ignition (FI) provide alternatives for laser IFE

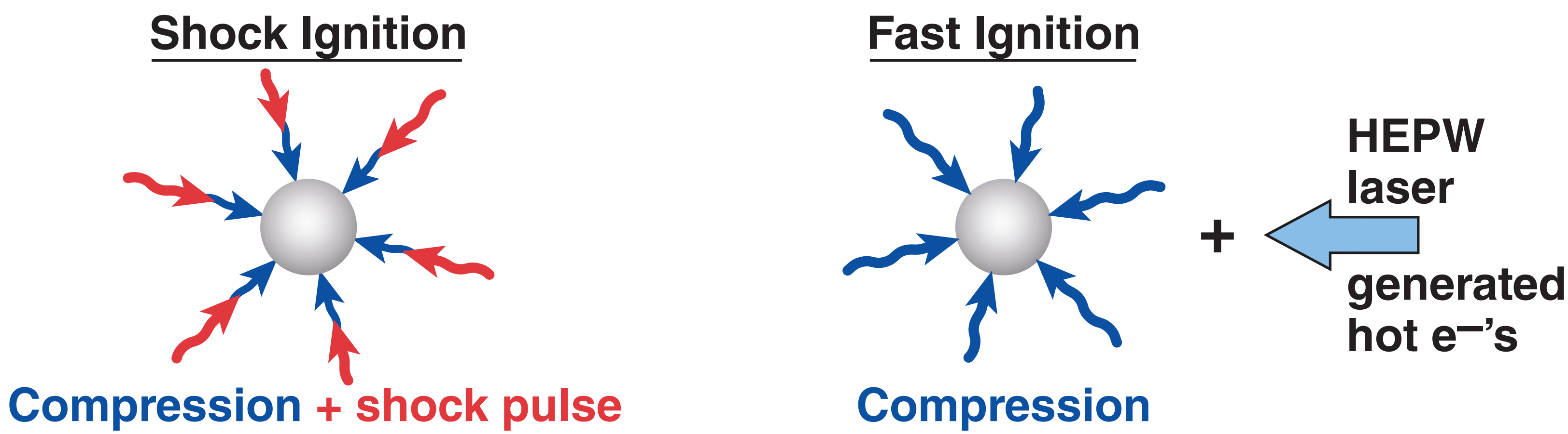


R. L. McCrory *et al.*, Phys. Plasmas 15, 055503 (2008).

TC7815q

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

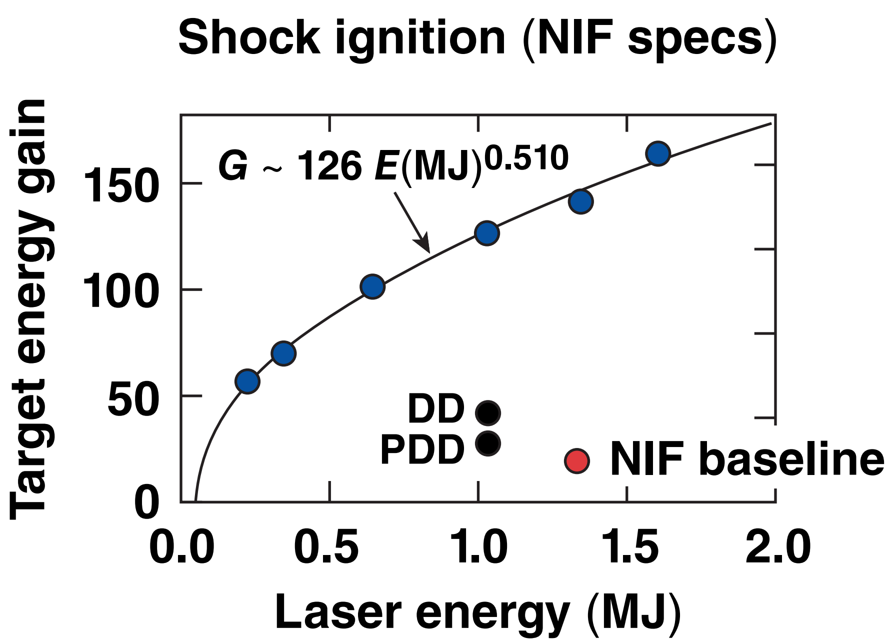
- In the current hot-spot ignition, the driver provides both compression (ρR) and heating (T_i)
- Both shock ignition and fast ignition use a second drive to provide heating (T_i)
- Not as developed as conventional ICF

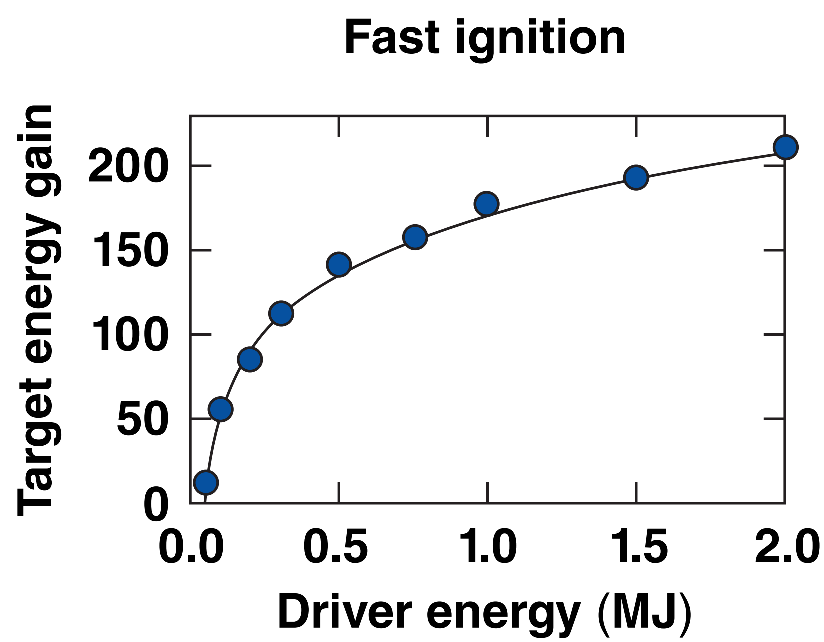


Two-step ignition offers lower driver energies with the possibility of higher gain.

R. L. McCrory, Phys. Plasmas 15, 055503 (2008).

If successful, shock and fast 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).

LLE's IFE-related efforts and path forward follow

- Status of Directly Driven ICF – S. Skupsky
- Technology for Polar-Drive Ignition on the NIF – J. Zuegel
- Technologies for Mass Producing IFE Targets – J. Zuegel
- IFE Path Forward – R. L. McCrory