Perspectives on Inertial Fusion Energy

R. L. McCrory
University Professor
Director and CEO,
Laboratory for Laser Energetics
Vice President and Vice Provost,
University of Rochester

Fusion Power Associates
36th Annual Meeting and Symposium
Washington, DC
16–17 December 2015

Summary

In my opinion, there is no credible inertial fusion energy (IFE) program before ignition and gain is demonstrated in the laboratory

- Growing energy reserves leave CO_2 as the primary motivation for non-carbon-producing energy sources
  - a "carbon tax" will probably be necessary to motivate "carbon-free" energy
  - natural gas is replacing coal plants (gas has 50% of the carbon intensity of coal)
- Without market forces in play, it is now possible to fully explore alternative strategies for IFE—let science take over
- The tri-lab Directors' letter to NNSA Administrator Klotz identifies three viable ignition options (laser indirect drive, laser direct drive, and magnetized targets—all identified in the FY12 Path Forward) and stresses the importance of high yield for science-based Stockpile Stewardship (SBSS)
- Recent success in completing the direct-drive Path Forward milestones is motivation for a multi-institutional national direct-drive program

I2277

In the U.S. there are plans for five new reactors, beyond the five currently under construction

- **Since 2000, annual nuclear power generation has ranged from 754 GWh to 806 GWh**
- **Carbon-neutral (and paid for!) nuclear plants are being shut down at the same rate as they are being constructed**

With no urgency to replace fossil fuels with carbon-neutral solutions, it is possible to properly explore non-LIFE* alternatives for ignition.

I2278

*LIFE: laser inertial fusion engine

The tri-lab Directors' letter to NNSA Administrator Klotz emphasizes the importance of ignition for SBSS and identifies three viable approaches

UR LLE

Lawrence Livermore National Laboratory · Los Alamos National Laboratory · Sandia National Laboratories

January 20, 2015

The Honorable Frank G. Klotz
Under Secretary
National Nuclear Security Administration
United States Department of Energy
Forrestal Building 7A-049
1000 Independence Avenue SW
Washington, DC 20585-3430

Dear Under Secretary Klotz:

The overwhelming majority of the yield of the Nation's nuclear weapons is generated when the conditions within the nuclear explosive package are in the high energy density (HED) state. This requires that proficiency in HED science remains a core technical competency for the Nation's Stockpile Stewardship Program (SSP) for the foreseeable future. As we enter the third decade since the cessation of nuclear testing, the HED program in the United States is at an important juncture where we must reassess the appropriate balance between pursuit of ignition and the other uses of HED research in stewardship. In response, we are developi… approach across the major national HED efforts to ensure the long term …

The NNSA has developed three cutting edge experimental capabilities as… Confinement Fusion (ICF) Program to enable access to HED regimes rel… weapons: the Omega and Omega EP lasers at the University of Rocheste… Energetics, the Z pulsed power facility at Sandia National Laboratories, … Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL). … already enabled critical contributions to the sustainment of the nation's n… more coordinated national HED effort will enhance our ability to sustain… attract a new generation of stockpile stewards, and protect the U.S. undis… in HED science.

With these objectives as guiding principles, we met with key technical le… to discuss the future coordination of our national ICF/HED efforts. A cl… at this meeting that HED science, and more specifically the pursuit of fu… laboratory, is critical for the long-term health of the stockpile stewardshi… December meeting, we committed to work together to bring forward an i… program plan that will enable the long-term sustainment of this essential …

The U.S. nuclear weapons laboratories are fully committed to building a… capabilities that support key NNSA mission drivers:

Under Secretary Klotz 2 January 20, 2015

- Sustaining and modernizing the stockpile
- Qualifying systems and components for new threat environments
- Avoiding technological surprise
- Recruiting, training, testing, and retaining technical staff
- Assessing nuclear designs without a return to nuclear testing

In the absence of new nuclear tests and with the attrition of nuclear test experience, looking forward the nuclear weapons laboratories will need the ability to (1) test nuclear designers in high energy density (HED) experimental design, (2) access material pressure and density regimes that are presently inaccessible to other experimental techniques, (3) generate and utilize thermonuclear burning plasmas, (4) develop commensurate high-fidelity diagnostics and experimental platforms that help to assure our weapons are safe, secure, and effective, and ultimately, (5) create and apply multi-megajoule fusion yields to enable enduring stockpile stewardship.

It is our view that the U.S. must continue to strive to be the first nation to demonstrate ignition and high yield in the laboratory. This goal is important not only because of its support for the SSP but also to send a strong signal to others regarding our Nation's scientific and technical capabilities. NNSA presently has three credible research approaches to demonstrating laboratory ignition and high fusion yield and addressing the technical challenges outlined above: x-ray drive, direct laser drive, and magnetic drive. Continued leadership in HED science is and will continue to be an essential component of a coordinated and balanced sustainable national nuclear security enterprise. We and our delegates will be meeting regularly in 2015 to ensure progress towards this integrated and coordinated National HED effort, and we look forward to a continuing dialogue with NNSA leadership on the importance of this effort.

Sincerely,

Dr. William H. Goldstein
Director, Lawrence Livermore National Laboratory

Dr. Charles F. McMillan
Director, Los Alamos National Laboratory

Dr. Paul J. Hommert
Director, Sandia National Laboratories

"A clear consensus emerged at this meeting that HED science, and more specifically the pursuit of fusion yield in the laboratory, is critical for the long-term health of the Stockpile Stewardship Program"

"It is our view that the U.S. must continue to strive to be the first nation to demonstrate ignition and high yield in the laboratory"

E24046a

The original vision for the National Ignition Facility (NIF) was to explore all approaches to ignition

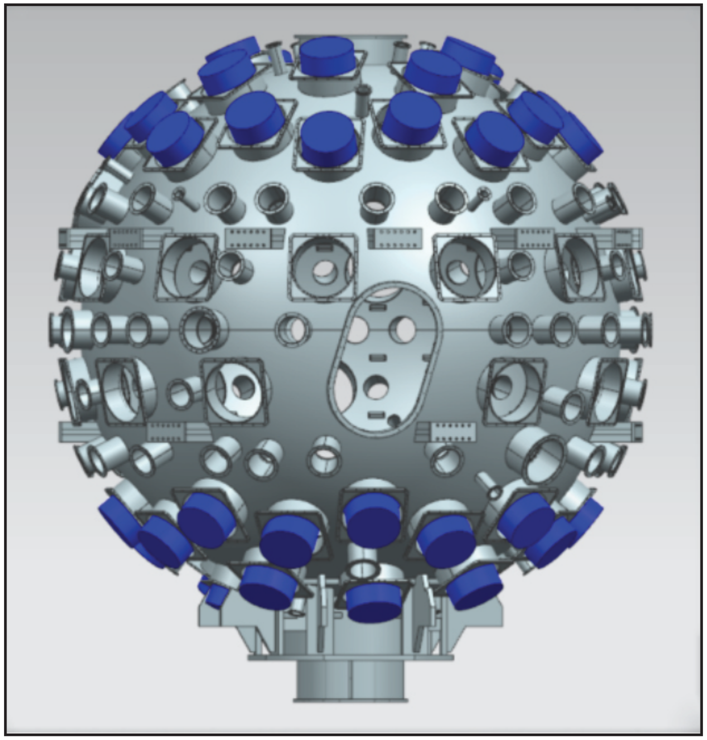
Energy Secretary Bill Richardson addresses the crowd that attended the June 11, 1999, dedication of the National Ignition Facility target chamber.

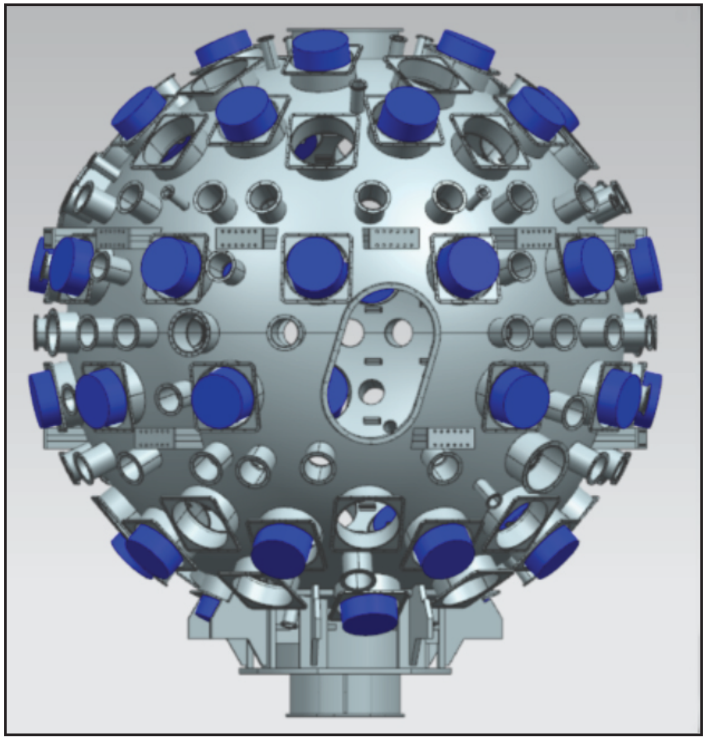
The reconfiguration of the NIF for direct drive should be viewed as an option for the long-term strategy for the facility (and MagLIF*-relevant experiments soon!)

*MagLIF: magnetized liner inertial fusion

E22810

A joint LLNL/LLE* working group will assess the cost and schedule (including a phased approach) for symmetric direct drive on the NIF in FY16





Direct-drive–specific laser capabilities (i.e., beam smoothing, power balance) will be addressed in subsequent studies.

*LLNL: Lawrence Livermore National Laboratory;
LLE: Laboratory for Laser Energetics;
other laboratories will participate as observers

I2280

The direct-drive Path Forward was very successful—the FY15 Review was completed in August 2015

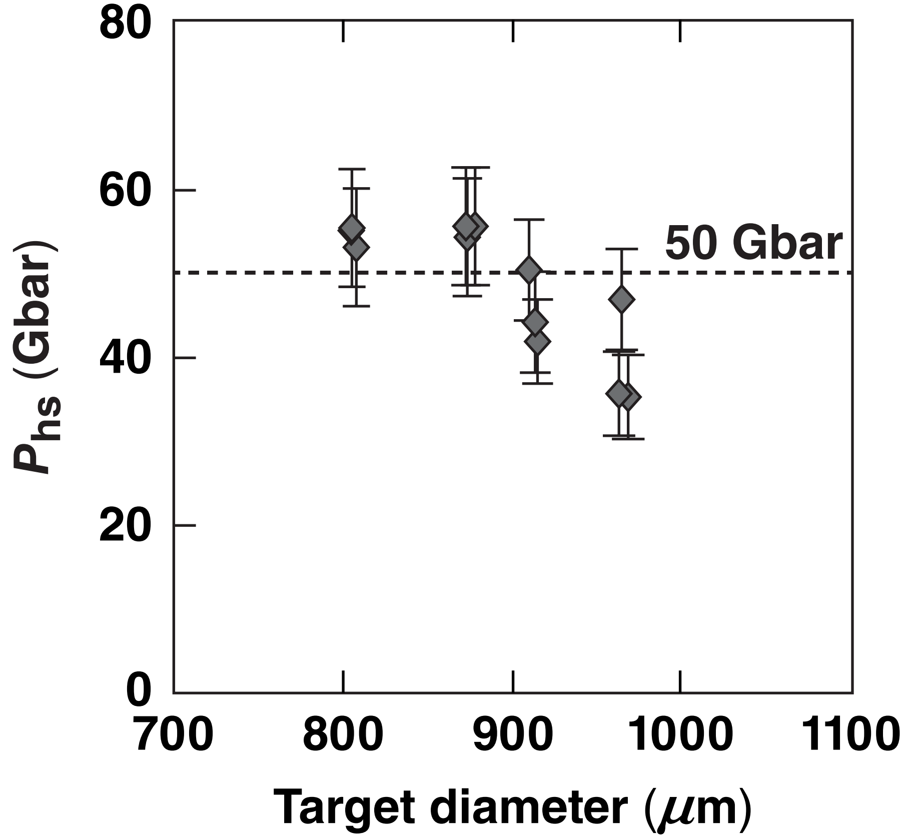
UR LLE

- Increased the routine hot-spot pressure in OMEGA cryogenic DT implosions to >50 Gbar*
- Experimentally established symmetry control and developed a test-bed on the NIF for long-scale laser–plasma instability (LPI) model validation**
- Experimentally demonstrated the predicted single-beam smoothing using 1-D multi-FM smoothing by spectral dispersion (SSD) (an inexpensive option for NIF)
- Identified and developed glancing angle deposition (GLAD)-coated optics as the primary option for single-beam polarization smoothing on the NIF
- Established the Laser Path Forward Working Group that led to the qualification of direct-drive phase plates and the installation of multi-FM SSD on a NIF quad (the first imprint test is scheduled for January 2016)

*S. P. Regan *et al*. "Demonstration of 50-Gbar Hot-Spot Pressure and Reduction of Cross-Beam Energy Transfer for Direct-Drive Layered Deuterium-Tritium Implosions on OMEGA," submitted to Physical Review Letters.
**M. Hohenberger *et al*., Phys. Plasmas 22, 056308 (2015).

I2281

The main FY12 Path Forward direct-drive milestone was the demonstration of P_{hs} > 50 Gbar on OMEGA*

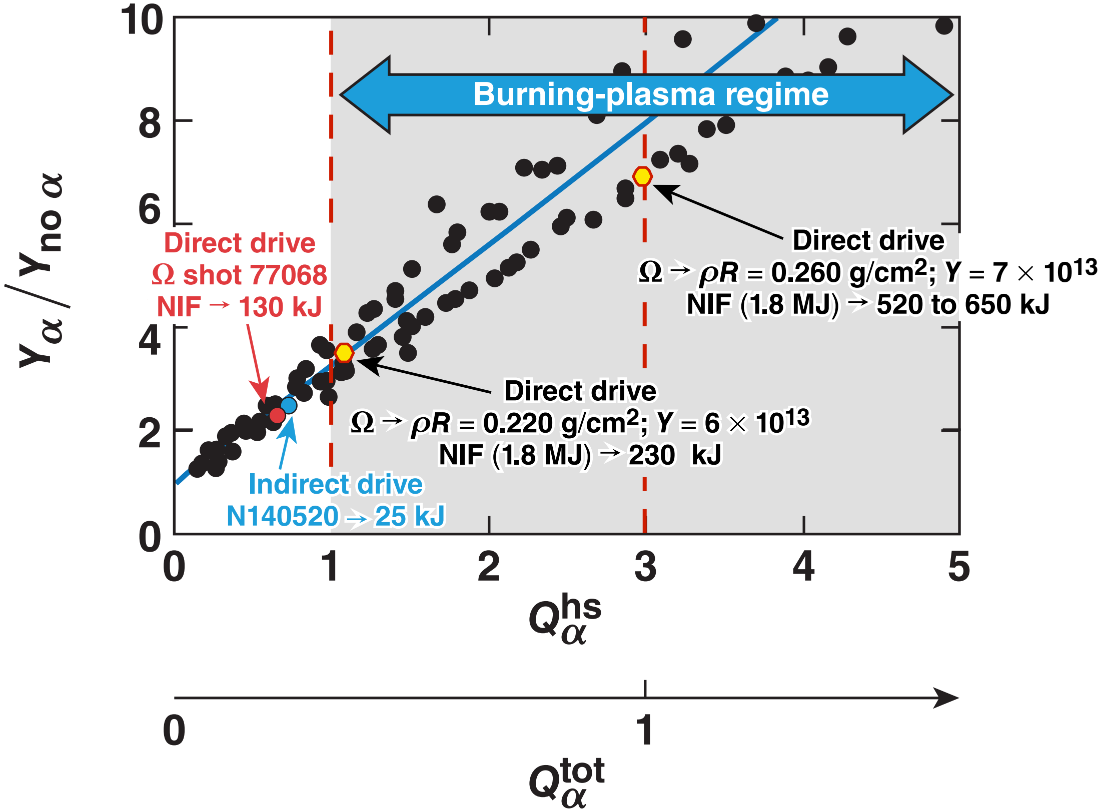


The 50-Gbar campaign was based on a target diameter scan to study the mitigation of cross-beam energy transfer (CBET) with a fixed-beam profile.

*S. P. Regan *et al*. "Demonstration of 50-Gbar Hot-Spot Pressure and Reduction of Cross-Beam Energy Transfer for Direct-Drive Layered Deuterium-Tritium Implosions on OMEGA," submitted to Physical Review Letters.

E24751b

At 1.9 MJ, current OMEGA implosions would achieve the same α heating as x-ray drive but with higher yields*

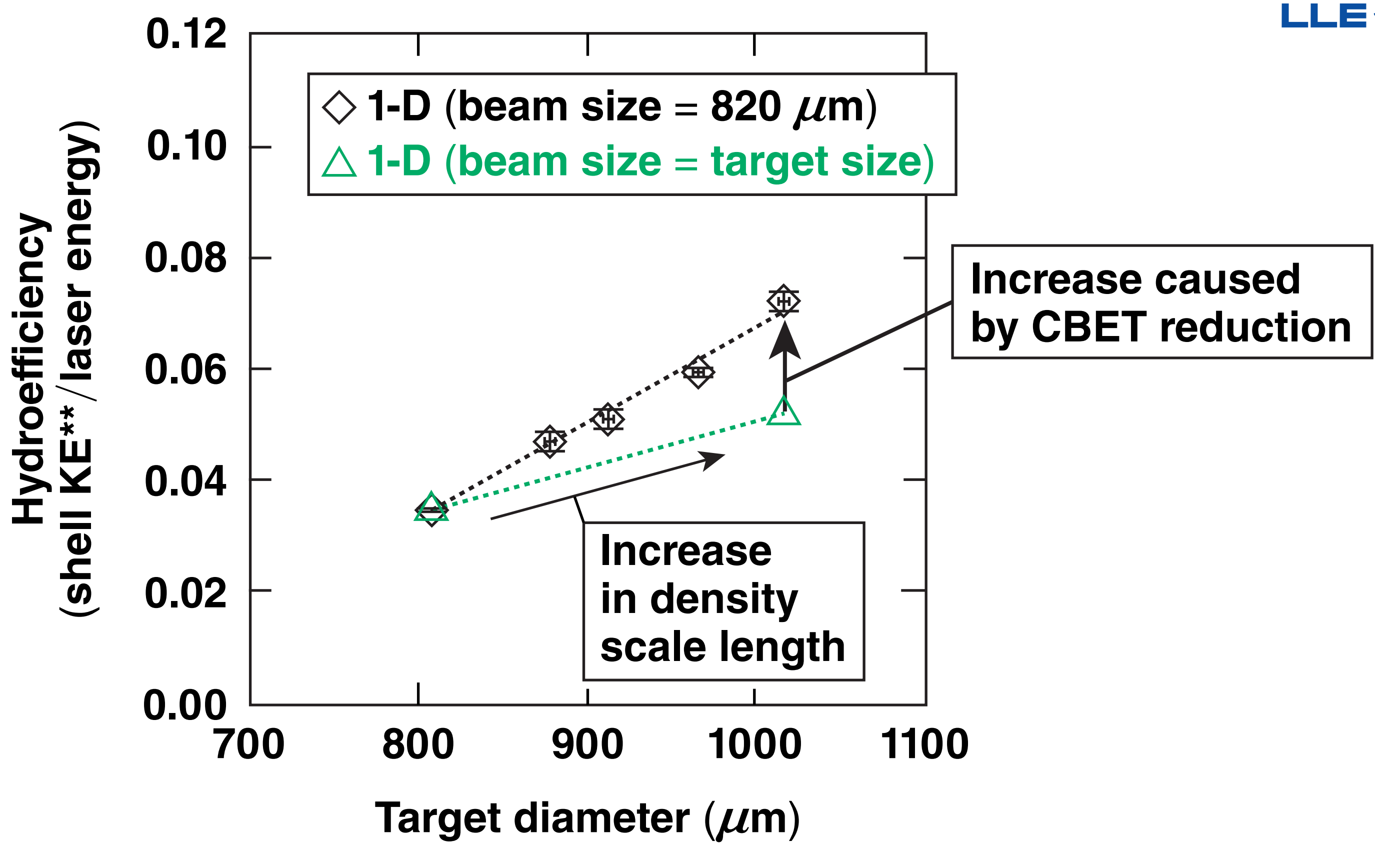


The hydro scaling from OMEGA to the NIF assumes the LPI scales similarly and motivates the LPI emphasis of the LLE–NIF experiments.

*R. Betti *et al.*, presented at the Ninth International Conference on Inertial Fusion Sciences and Applications (IFSA 2015), Seattle, WA, 20–25 September 2015 (Paper Tu.P.2);
A. Bose *et al.*, "Fusion Yield Extrapolation to Higher Laser Energies for Direct-Drive Inertial Fusion Including the Effect of Alpha Heating," submitted to Physical Review Letters.

TC12302c

The hydroefficiency increased (as predicted) by ~40% when CBET was reduced with the larger targets*



The compelling scaling and physics understanding from the 50-Gbar campaign motivated the creation of a National Direct-Drive Program.

*S. P. Regan *et al*. "Demonstration of 50-Gbar Hot-Spot Pressure and Reduction of Cross-Beam Energy Transfer for Direct-Drive Layered Deuterium-Tritium Implosions on OMEGA," submitted to Physical Review Letters.

**KE: kinetic energy

E24751c

The National Direct-Drive Program has four elements

- Demonstrate ignition hydro-equivalent implosions on OMEGA—the 100 Gbar campaign
  - this includes a near-term subcampaign to validate 1-D physics on OMEGA
- Demonstrate understanding and control of LPI's, energy coupling, and imprint mitigation at the MJ plasma scale on the NIF
  - multiple platforms have been established over the past two years
- Develop the strategy for the conversion of the NIF to symmetric direct-drive
  - the initial goal is the cost and schedule of beam and infrastructure relocation by the end of FY16
- Develop robust target designs for a range of performances

The National Direct-Drive strategy involves multiple institutions.

I2282

National Direct-Drive Program collaborators (multi-institutional effort)

UR LLE

R. Betti, T. R. Boehly, M. J. Bonino, E. M. Campbell, D. Cao, T. J. B. Collins, R. S. Craxton, A. K. Davis, D. H. Edgell, R. Epstein, C. J. Forrest, D. H. Froula, V. Yu. Glebov, V. N. Goncharov, D. R. Harding, M. Hohenberger, S. X. Hu, I. V. Igumenshchev, R. L. Keck, T. J. Kessler, J. P. Knauer, J. A. Marozas, F. J. Marshall, R. L. McCrory, P. W. McKenty, D. T. Michel, J. F. Myatt, P. B. Radha, B. Rice, M. Rosenberg, T. C. Sangster, W. Seka, W. T. Shmayda, A. Shvydky, M. J. Shoup III, A. A. Solodov, C. Stoeckl, J. Ulreich, J. D. Zuegel, and B. Yaakobi

University of Rochester
Laboratory for Laser Energetics

J. A. Frenje, M. Gatu Johnson, R. D. Petrasso, H. Sio, and B. Lahmann

Plasma Science and Fusion Center, MIT

M. A. Barrios, D. Callahan, D. T. Casey, S. N. Dixit, C. Goyon, O. A. Hurricane, S. LePape, L. Masse, P. Michel, J. D. Moody, A. Nikroo, R. Nora, J. E. Ralph, H. G. Rinderknecht, R. P. J. Town, D. P. Turnbull, R. J. Wallace, and P. J. Wegner

Lawrence Livermore National Laboratory

M. Farrell, A. Greenwood, T. Hilsabeck, D. Hoover, J. D. Kilkenny, and N. Rice

General Atomics

J. Hund

Schafer Corporation

S. P. Obenschain, J. W. Bates, M. Karasik, A. J. Schmitt, and J. Weaver

Naval Research Laboratory

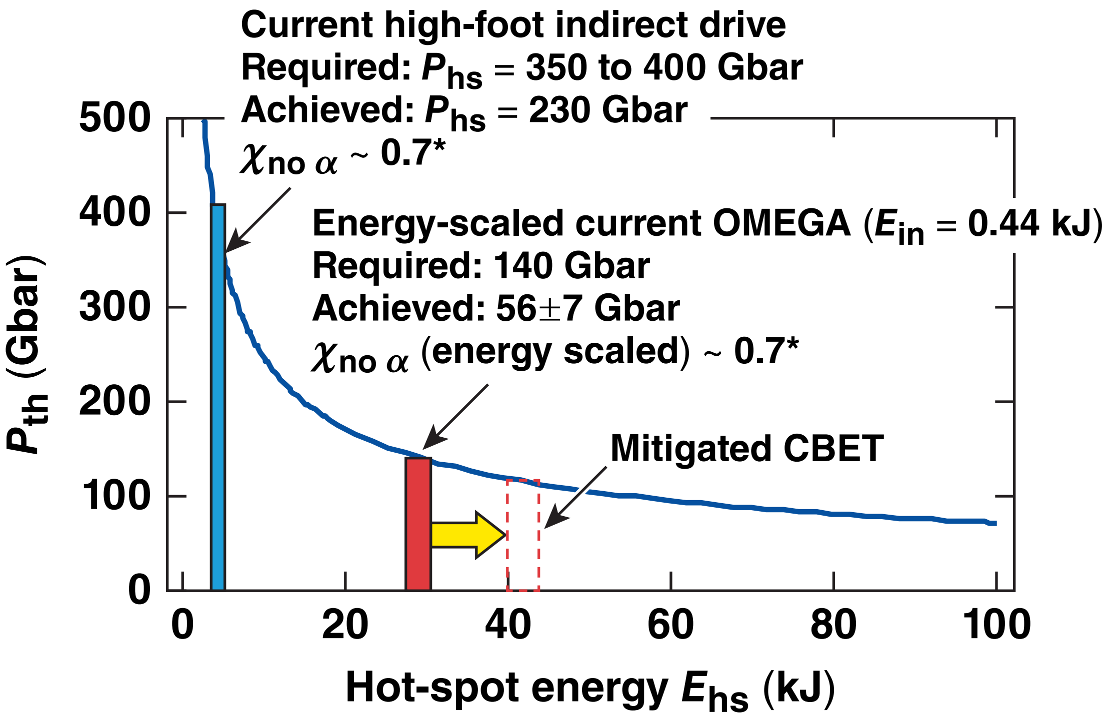
M. J. Schmitt

Los Alamos National Laboratory

...and more in the future

I2283

100 Gbar is very close to the threshold pressure for ignition with 40 kJ coupled to the hot spot



- Pressure threshold for ignition

$$P_{th} \sim 1/\sqrt{E_{hs}}$$

- Generalized Lawson criterion**

$$\chi = P\tau/P\tau_{ign} = (\rho R)^{0.61}\,(0.24\,Y^{16}/M)^{0.34}$$

$$\chi_{OMEGA} \rightarrow \chi_{NIF} \sim E^{0.37}$$

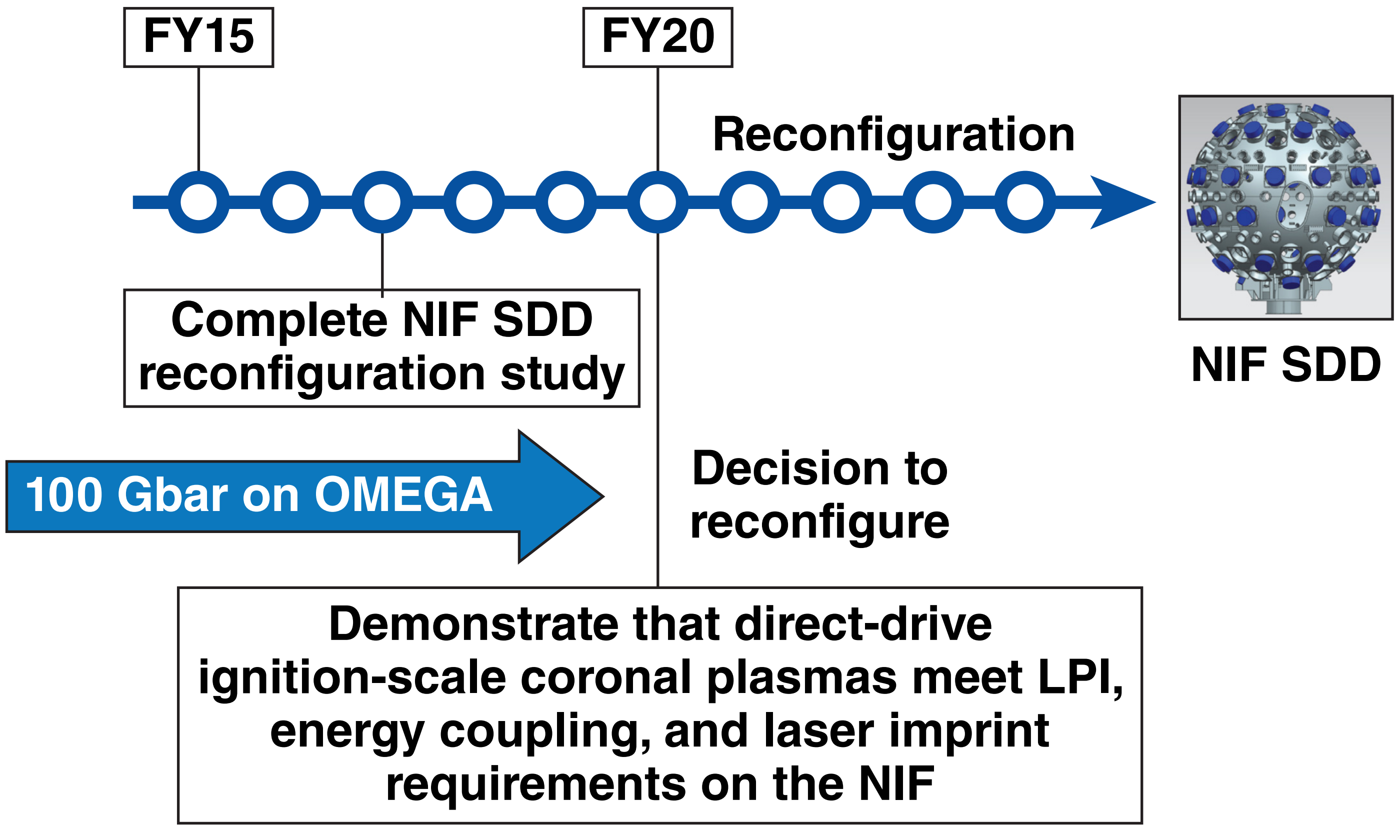
Direct-drive ignition: CR† > 22 and P_{hs} > 120 Gbar.
X-ray-drive ignition: CR = 30 to 40 and P_{hs} > 350 Gbar.

*R. Betti *et al.*, Phys. Rev. Lett. 114, 255003 (2015);
A. R. Christopherson *et al.*, presented at 57th Annual Meeting of the APS Division of Plasma Physics, Savannah, GA, 16–20 November 2015 (Paper CI3.00006) (invited).
**R. Betti *et al.*, Phys. Plasmas 17, 058102 (2010).

†CR: convergence ratio

TC12311h

Demonstration of 100 Gbar on OMEGA is essential for consideration of direct drive on the NIF in the 2020 time frame



Spherical direct drive (SDD) on the NIF builds on the hydro-scaling and LPI understanding from OMEGA.

I2284

LLE is collaborating with SNL* on the development of the pulsed-power–based MagLIF ignition option

- MagLIF is one of three viable options for laboratory fusion *and may be the best path for high fusion yields in the laboratory*
- Advances in pulsed power science, engineering, and technology have led to unique and consequential contributions to SBSS, making MagLIF a compelling option today
- LLE will provide scientific and technical assistance to SNL on MagLIF laser preheating experiments at all facilities (Z, NIF, and Omega)
- SNL has already published results** from laser preheating experiments on OMEGA EP

*A. Harvey-Thompson *et al*., "Experimental Platform for Laser Preheating for MagLIF," to be published in Physics of Plasmas.

**SNL: Sandia National Laboratories

I2285

In my opinion, there is no credible inertial fusion energy (IFE) program before ignition and gain is demonstrated in the laboratory

UR LLE

- Growing energy reserves leave CO_2 as the primary motivation for non-carbon-producing energy sources
  - a "carbon tax" will probably be necessary to motivate "carbon-free" energy
  - natural gas is replacing coal plants (gas has 50% of the carbon intensity of coal)
- Without market forces in play, it is now possible to fully explore alternative strategies for IFE—let science take over
- The tri-lab Directors' letter to NNSA Administrator Klotz identifies three viable ignition options (laser indirect drive, laser direct drive, and magnetized targets—all identified in the FY12 Path Forward) and stresses the importance of high yield for science-based Stockpile Stewardship (SBSS)
- Recent success in completing the direct-drive Path Forward milestones is motivation for a multi-institutional national direct-drive program

I2277