The National Direct-Drive Program

Ignition hydro-equivalence on OMEGA

26 kJ

1.8 MJ

Verify laser–plasma interaction scaling at the National Ignition Facility

T. C. Sangster
University of Rochester
Laboratory for Laser Energetics

Fusion Power Associates
37th Annual Meeting and Symposium
Washington, DC
13–14 December 2016

Summary

The National Direct-Drive Program will inform a decision on whether to reconfigure the NIF for spherical direct-drive

- Establishing the science basis for direct drive is collaborative and (at present) does not require significant modification of the NIF
  - laser direct drive (LDD) couples more energy into the hot spot [relative to laser indirect drive (LID)], relaxing the ignition requirements on the hot spot
- Direct-drive laser–plasma instabilities (CBET, TPD, and SRS) can be effectively studied at the MJ scale with experiments on the NIF
  - additional distributed scattered-light diagnostics are being added to the NIF
- CBET mitigation using wavelength detuning ($\Delta\lambda$) has been demonstrated on the NIF
- CBET mitigation using “zooming” has been demonstrated on OMEGA
- Polystyrene shells appear to be a promising candidate for high-performance implosions on OMEGA

NIF: National Ignition Facility
CBET: cross-beam energy transfer
TPD: two-plasmon decay
SRS: stimulated Raman scattering

The National Direct-Drive Program has four components

1. Hydro-equivalent implosions on OMEGA
    - the 100-Gbar Campaign will identify knowledge gaps and demonstrate implosion "robustness"
    - intermediate goal of 80 Gbar with reduced requirements
    - focus on improving target quality and laser/diagnostics capabilities
2. Laser–plasma interaction (LPI) control, energy coupling, and imprint mitigation with MJ-scale plasmas on the NIF
    - the MJ direct-drive campaign will address LPI understanding/control and mitigation strategies at the ignition scale
    - polar direct drive on the NIF is now a platform, not an objective
    - LLE is leading the national LPI initiative (with LLNL, LANL, NRL, and SNL)
3. Strategy for the conversion of the NIF to spherical direct drive (SDD)
    - initial look at cost, schedule, and phasing in 2016
    - LLNL and LLE collaboration
4. Robust target designs for a range of performance and applications
    - engage design communities at LLNL, LANL and NRL
    - hot-spot ignition
    - shock ignition
    - alpha heating and gain
    - multiple shells

Spherical illumination is now the baseline approach (*lowest risk*) for LDD ignition on the NIF.

The National Direct-Drive Program includes all of the ICF sites and the HEDP group at MIT

V. N. Goncharov, S. P. Regan, K. S. Anderson, R. Betti, T. R. Boehly, R. Boni, M. J. Bonino,
E. M. Campbell, D. Canning, D. Cao, T. J. B. Collins, R. S. Craxton, A. K. Davis, J. A. Delettrez,
W. R. Donaldson, D. H. Edgell, R. Epstein, C. J. Forrest, D. H. Froula, V. Yu. Glebov, D. R. Harding, S. X. Hu, H. Huang,
I. V. Igumenshchev, R. T. Janezic, D. W. Jacobs-Perkins, J. Katz, R. L. Keck, J. H. Kelly, T. J. Kessler, B. E. Kruschwitz,
J. P. Knauer, T. Z. Kosc, S. J. Loucks, J. A. Marozas, F. J. Marshall, A. V. Maximov, R. L. McCrory, P. W. McKenty,
D. T. Michel, S. F. B. Morse, J. F. Myatt, P. M. Nilson, J. C. Puth, P. B. Radha, B. Rice, M. J. Rosenberg, W. Seka,
W. T. Shmayda, R. W. Short, A. Shvydky, M. J. Shoup III, S. Skupsky, A. A. Solodov, C. Sorce, S. Stagnitto,
C. Stoeckl, W. Theobald, D. Turnbull, J. Ulreich, M. D. Wittman, B. Yaakobi, and J. D. Zuegel
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, P. Bell, D. K. Bradley, D. A. Callahan, A. Carpenter, D. T. Casey, J. Celeste,
M. Dayton, S. N. Dixit, C. S. Goyon, M. Hohenberger, O. A. Hurricane, S. LePape,
L. Masse, P. Michel, J. D. Moody, S. R. Nagel, A. Nikroo, R. Nora, L. Pickworth,
J. E. Ralph, H. G. Rinderknecht, R. P. J. Town, R. J. Wallace, and P. J. Wegner
Lawrence Livermore National Laboratory

M. Farrell, P. Fitzsimmons, A. Greenwood, L. Carlson, T. Hilsabeck, H. Huang, J. D. Kilkenny, N. Rice, and M. Schoff
General Atomics

N. Petta and J. Hund
Schafer Corporation

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

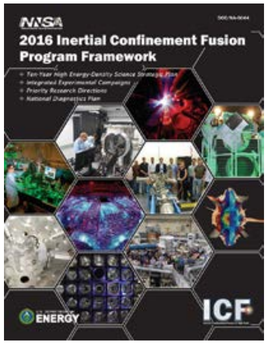
M. J. Schmitt and S. Shu
Los Alamos National Laboratory

G. Rochau, L. Claus, Q. Looker, J. Porter, G. Robertson, and M. Sanchez
Sandia National Laboratory

J. Hares and T. Dymoke-Bradshaw
Kentech Instruments Ltd.

ICF: inertial confinement fusion
HEDP: high-energy-density physics

LLE partners with NNSA laboratories, academia, and industry to establish scientific confidence in all three ignition approaches



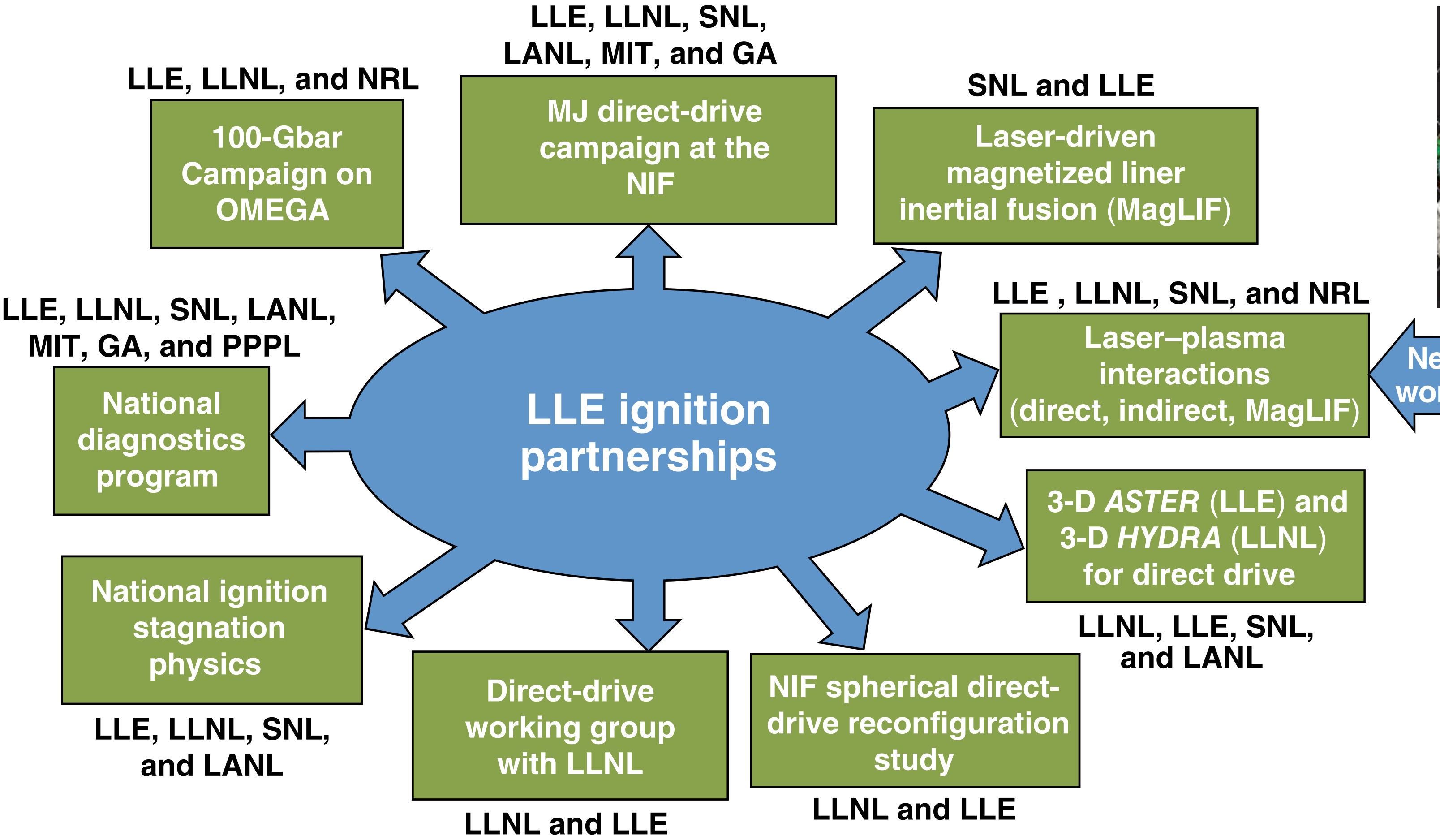
NNSA

2016 Inertial Confinement Fusion Program Framework

- Ten-Year High Energy-Density Science Strategic Plan
- Integrated Experimental Campaigns
- Priority Research Directions
- National Diagnostics Plan

ENERGY

ICF



LLE ignition partnerships

100-Gbar Campaign on OMEGA
LLE, LLNL, and NRL

MJ direct-drive campaign at the NIF
LLE, LLNL, SNL, LANL, MIT, and GA

Laser-driven magnetized liner inertial fusion (MagLIF)
SNL and LLE

Laser–plasma interactions (direct, indirect, MagLIF)
LLE , LLNL, SNL, and NRL
← New national working group

3-D *ASTER* (LLE) and 3-D *HYDRA* (LLNL) for direct drive
LLNL, LLE, SNL, and LANL

NIF spherical direct-drive reconfiguration study
LLNL and LLE

Direct-drive working group with LLNL
LLNL and LLE

National ignition stagnation physics
LLE, LLNL, SNL, and LANL

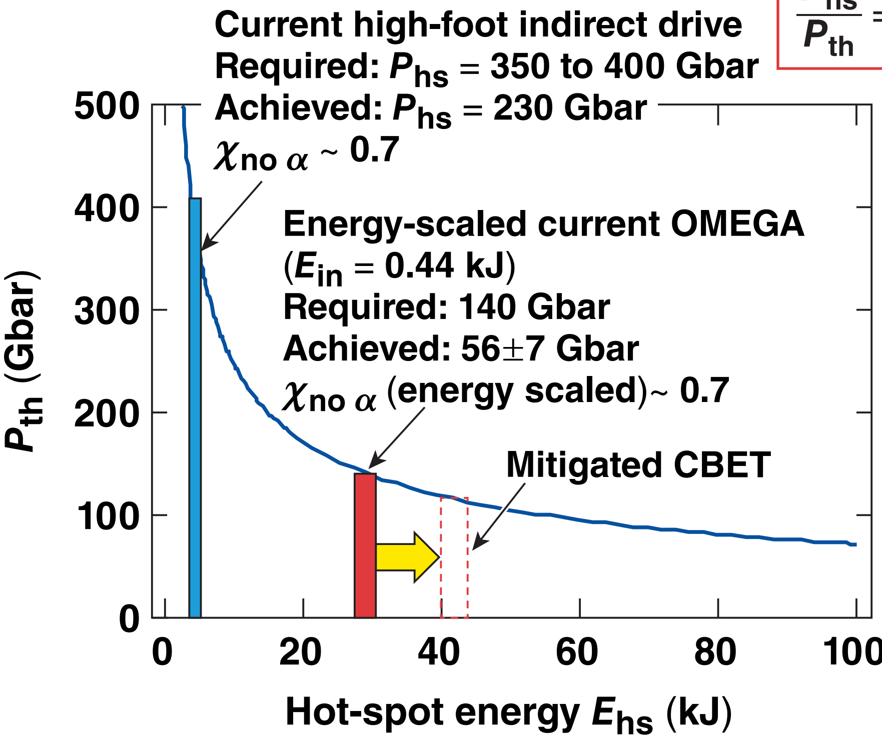
National diagnostics program
LLE, LLNL, SNL, LANL, MIT, GA, and PPPL

LLE is the lead laboratory for laser direct drive.

I2382b

Direct drive couples ~5× more energy into the fuel, reducing the implosion requirements and producing higher yields

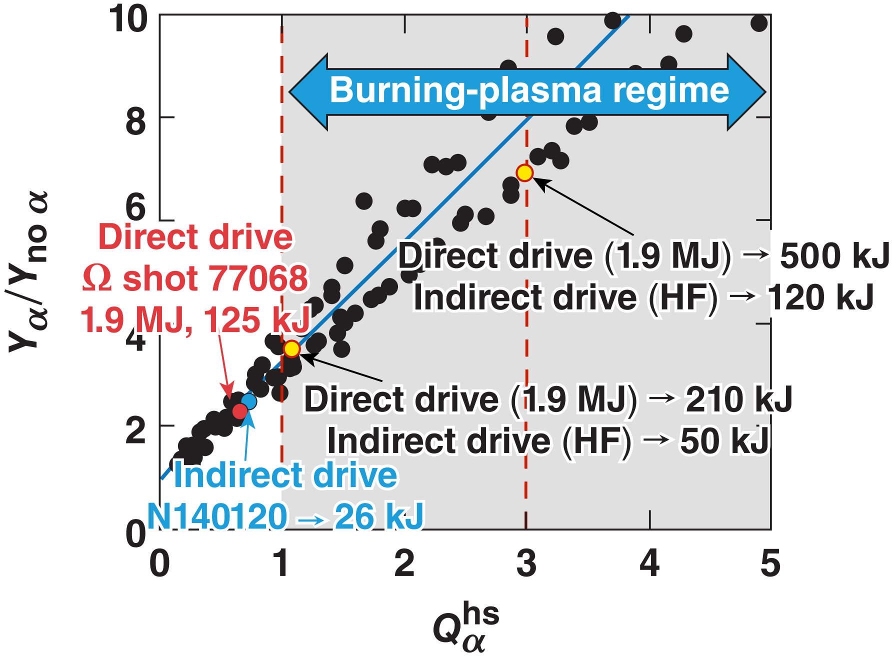
$$\frac{P_{hs}}{P_{th}} = \left(\frac{P_{hs}}{250\ \text{Gbar}}\right)\sqrt{\frac{E_{hs}}{10\ \text{kJ}}} > 1$$



Current high-foot indirect drive
Required: P_{hs} = 350 to 400 Gbar
Achieved: P_{hs} = 230 Gbar
$\chi_{\text{no}\ \alpha}$ ~ 0.7

Energy-scaled current OMEGA
(E_{in} = 0.44 kJ)
Required: 140 Gbar
Achieved: 56±7 Gbar
$\chi_{\text{no}\ \alpha}$ (energy scaled)~ 0.7

Mitigated CBET



Direct drive
Ω shot 77068
1.9 MJ, 125 kJ

Direct drive (1.9 MJ) → 500 kJ
Indirect drive (HF) → 120 kJ

Direct drive (1.9 MJ) → 210 kJ
Indirect drive (HF) → 50 kJ

Indirect drive
N140120 → 26 kJ

It is important to note that hot-spot pressures achieved with indirect drive far exceed what is needed for direct-drive ignition and gain.

- Hydro scaling of OMEGA experiments extrapolate to an α amplification of ~2* and a yield of ~125 kJ

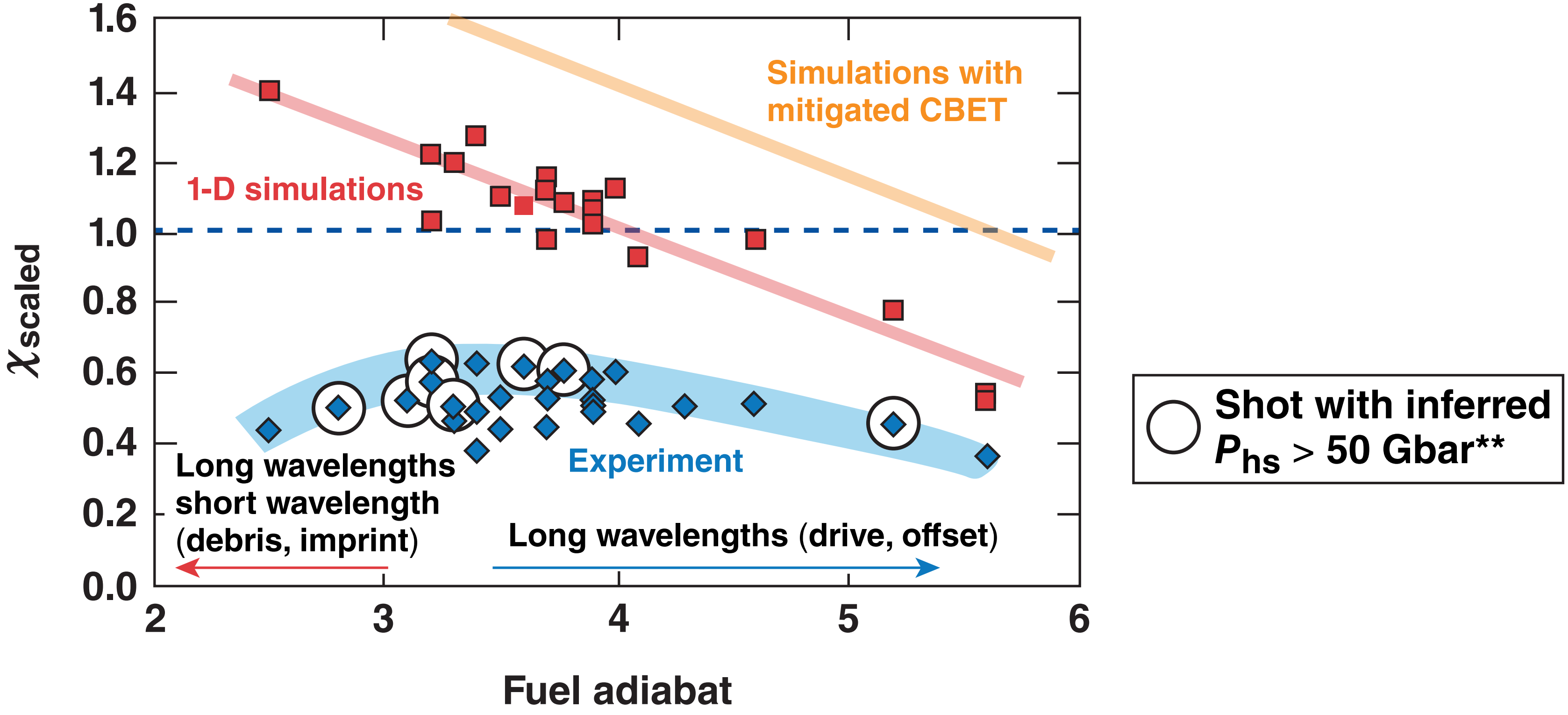
---

*A. Bose *et al.*, Phys. Rev. E 94, 012011(R) (2016).

The data and simulations show where to apply resources; the payoff is the potential for a $\chi_{\text{scaled}} \sim 1$ at an adiabat of 5

Generalized Lawson criterion*

$$\chi_{\text{scaled}} = P\tau/P\tau_{\text{ign}} = \left(\rho R_{\text{no}\,\alpha}\right)^{0.61} \left(0.12\, Y^{16}_{\text{no}\,\alpha} \big/ M^{\text{stag}}_{\text{DT}}\right)^{0.34} \left(E^{\text{NIF}}_{\text{laser}} \big/ E^{\text{OMEGA}}_{\text{laser}}\right)^{0.35}$$

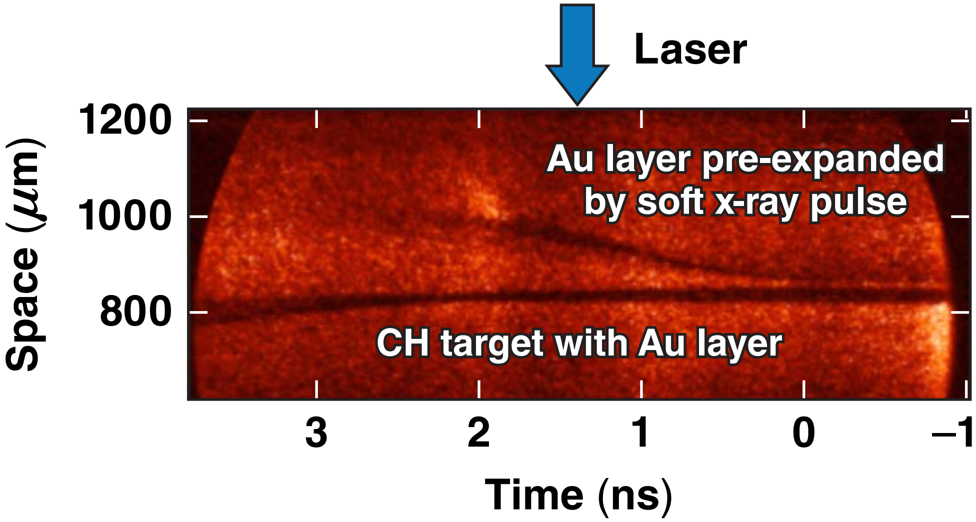


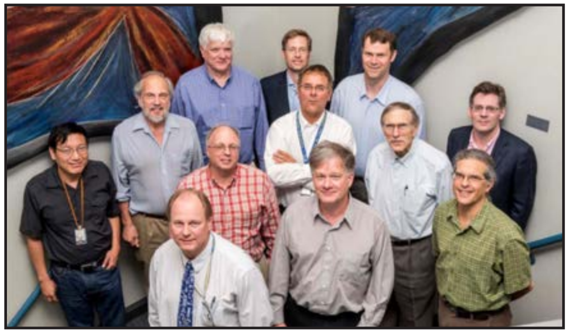
The current layered implosion campaign is exploring "1-D physics".

---

*R. Betti *et al*., Phys. Rev. Lett. 114, 255003 (2015);
A. Bose *et al*., Phys. Rev. Lett. E 94, 011201(R) (2016).
**S. P. Regan *et al*., Phys. Rev. Lett. 117, 025001 (2016).

NRL is leading an investigation to understand and mitigate short-wavelength imprint in LDD





NRL and LLE are collaborating on CBET mitigation strategies

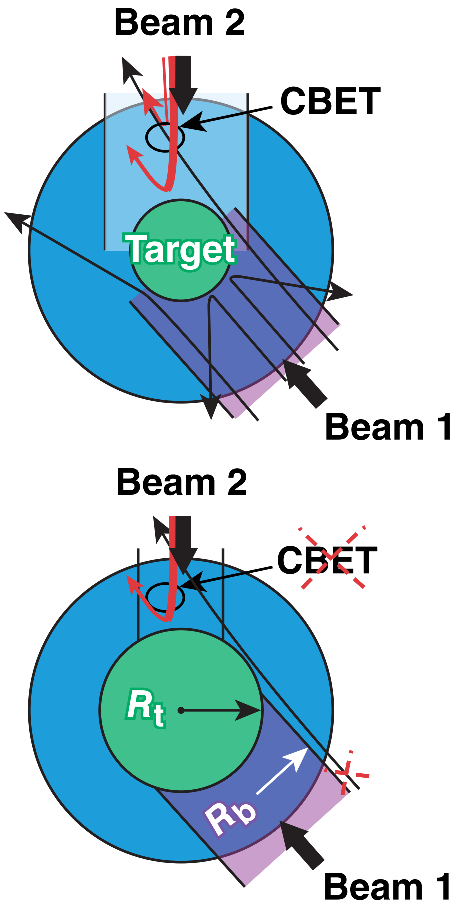
Face-on radiography (OMEGA EP) shows RT amplified imprint without Au layer.

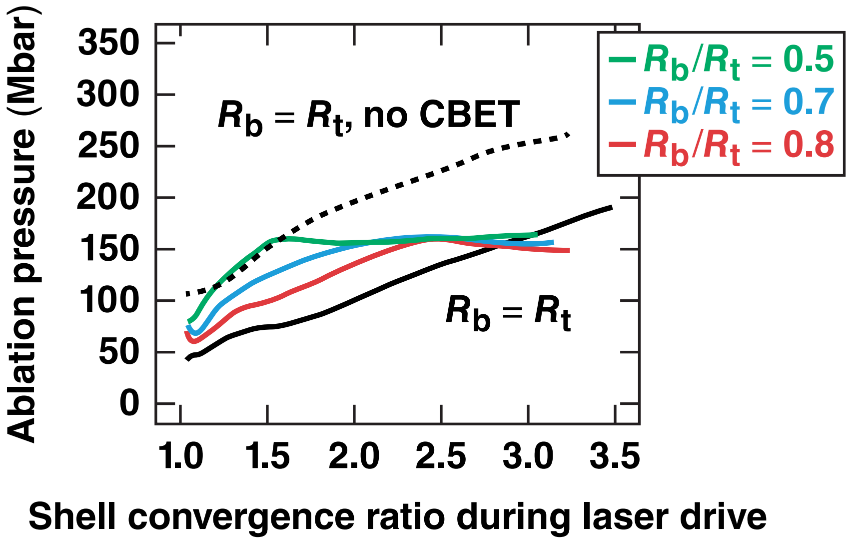
Radiographs with a pre-expanded Au layer show no measureable imprint.

E25882

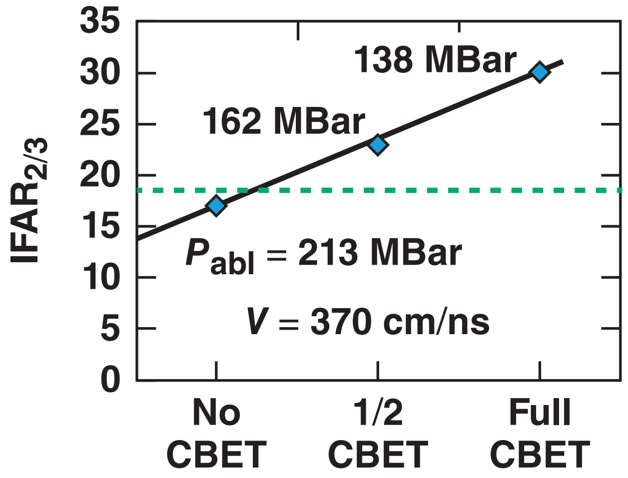
RT: Rayleigh–Taylor

The primary limiting physics for LDD is CBET



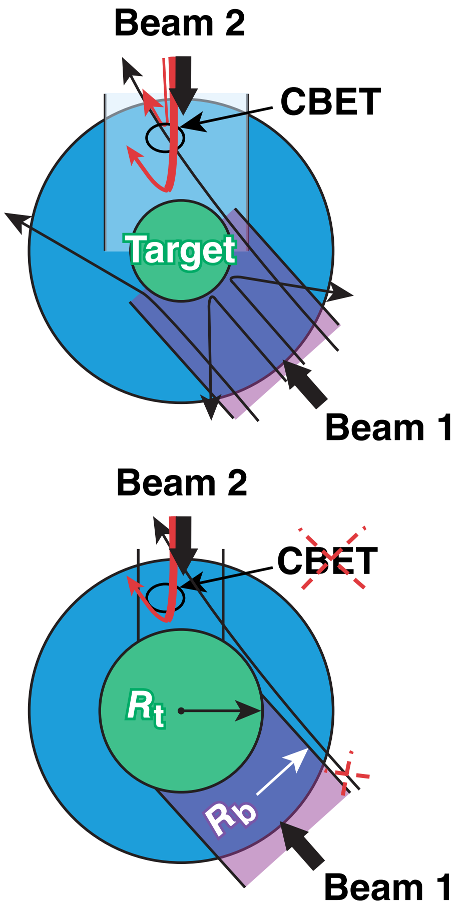


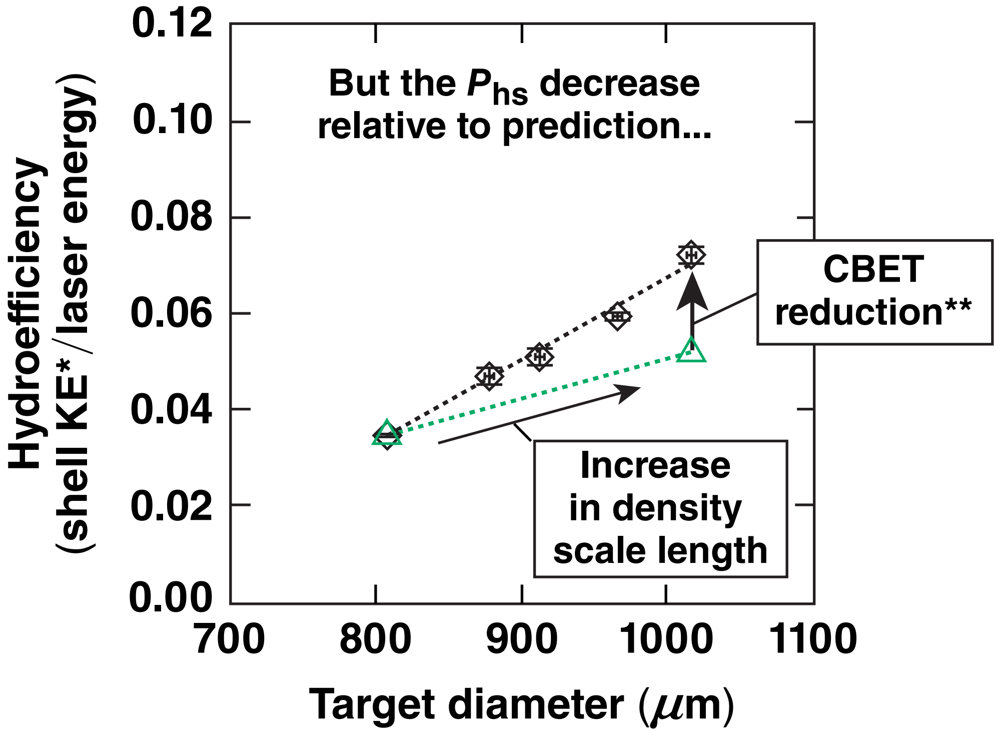
OMEGA designs* with $V_{imp} = 3.7 \times 10^7$ cm/s



Reducing the light over the horizon (zooming) is an effective way to mitigate CBET ($R_b/R_t < 1$).

Improved laser coupling was demonstrated by reducing R_b/R_t (larger out diameter shells from GA)





A 61st beam for OMEGA is being developed to study the details of beam-to-beam CBET.

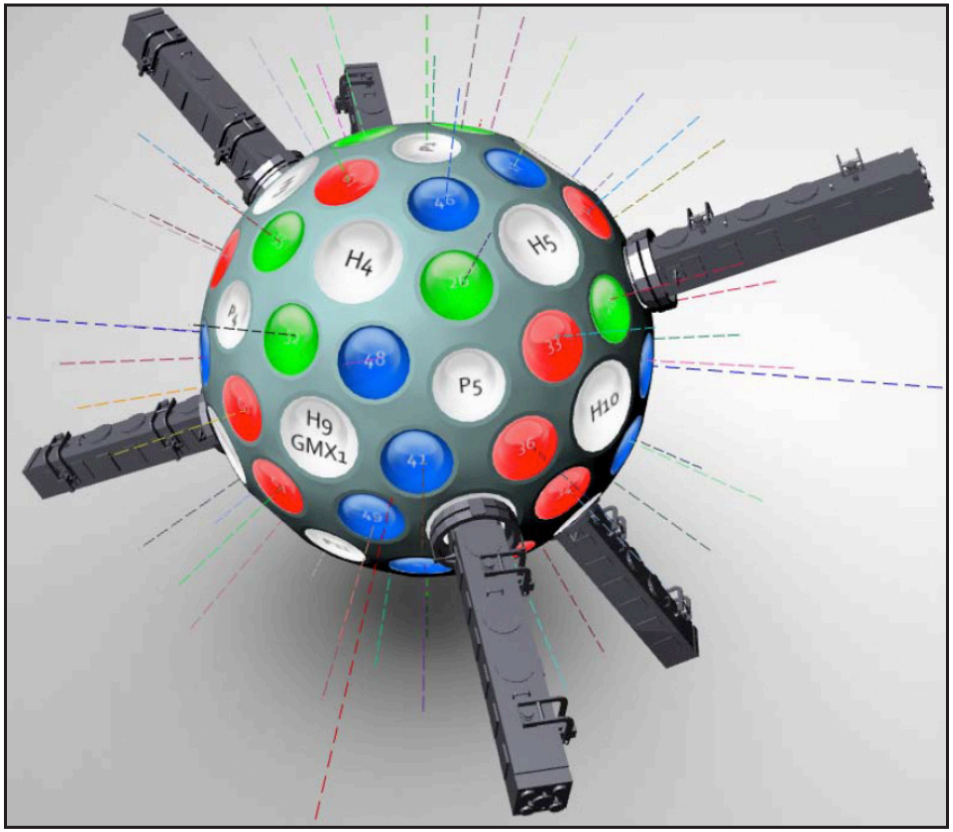
---

*I. V. Igumenshchev *et al.*, Phys. Plasmas 17, 122708 (2010); D. H. Froula *et al.*, Phys. Rev. Lett. 108, 125003 (2012);

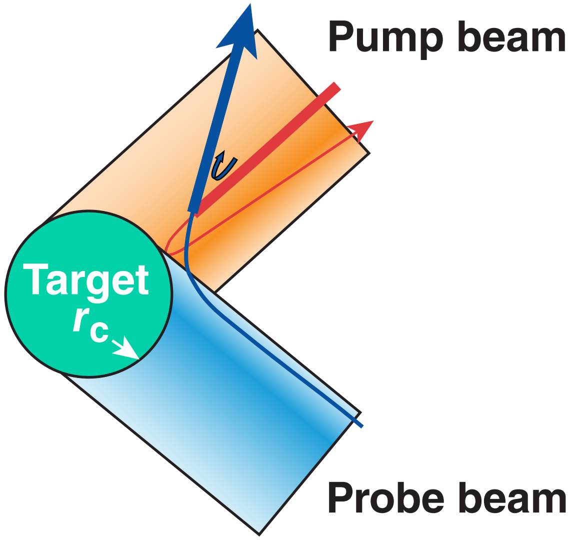
**S. P. Regan *et al.*, "Energy Coupling and Hot-Spot Pressure in Direct-Drive Layered Deuterium-Tritium Implosions on OMEGA," to be submitted to Physics of Plasmas.

Wavelength detuning may be the most effective way to mitigate CBET ($R_b/R_t = 1$ at early time)

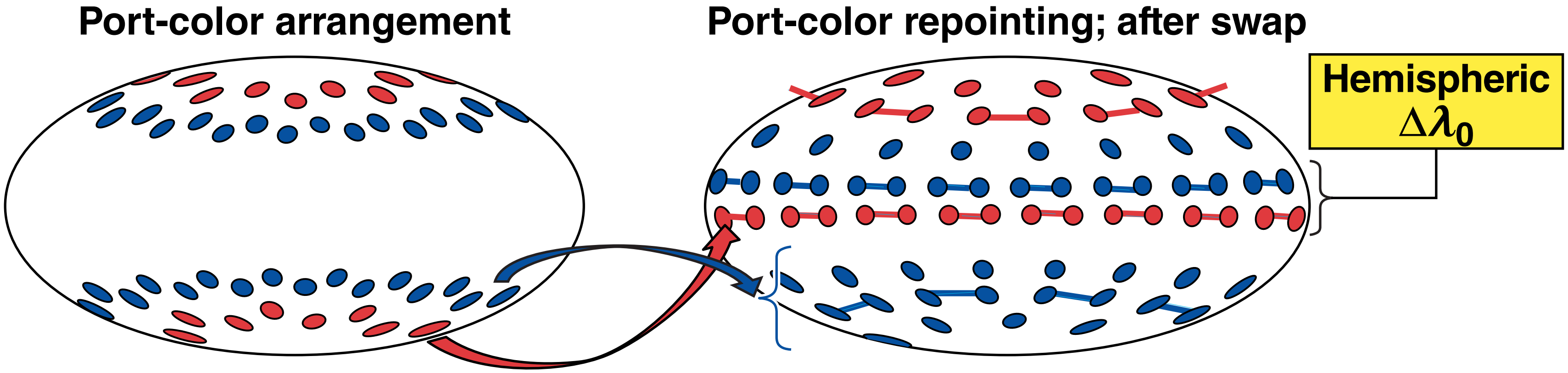
Three separate wavelengths could be mapped onto a target using the “three legs” of OMEGA



Recent NIF implosion experiments tested CBET mitigation using wavelength $\Delta\lambda$ across the equator

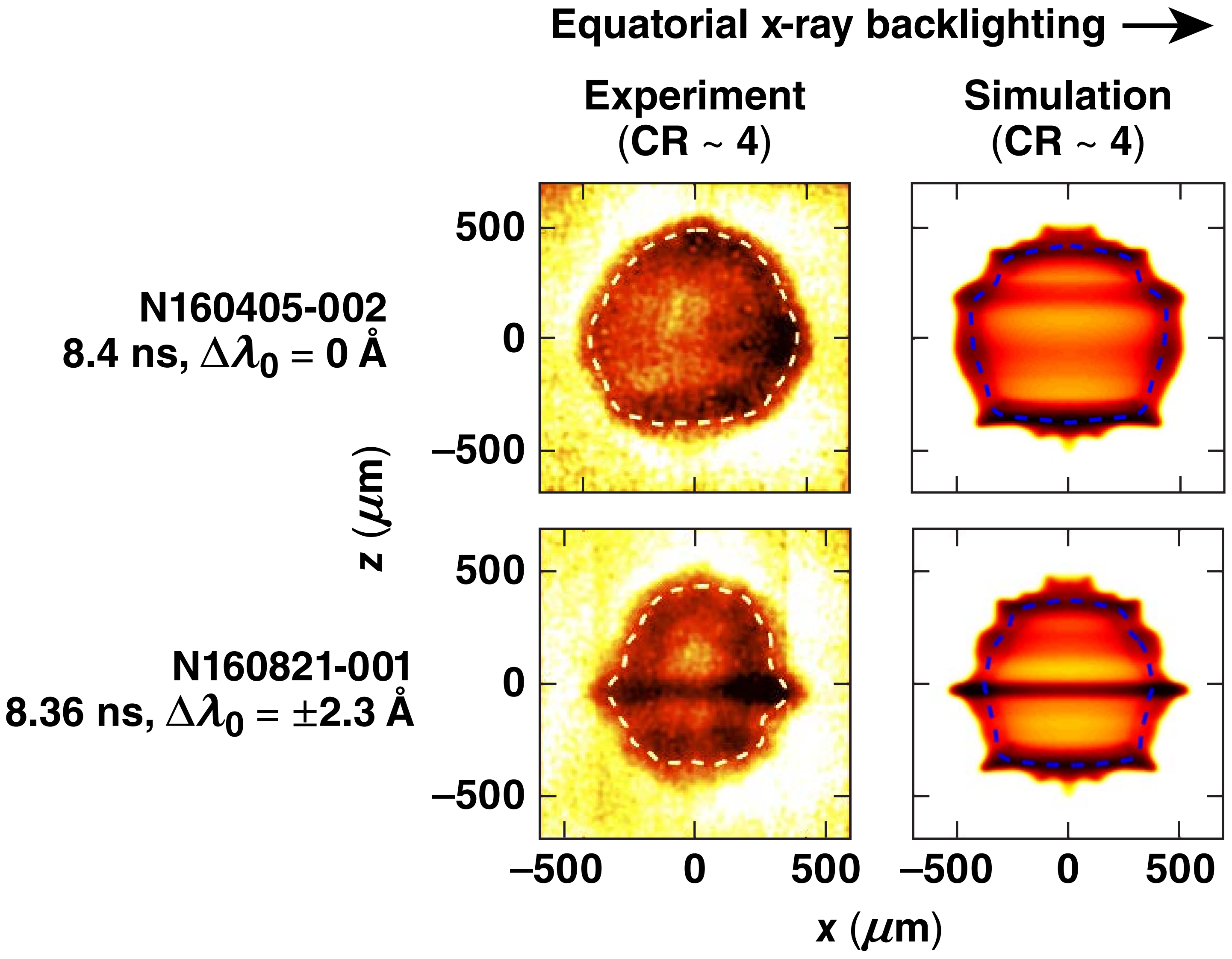


- NIF currently supports $\Delta\lambda$ between inner and outer quads so equatorial $\Delta\lambda$ can only be achieved with beam repointing



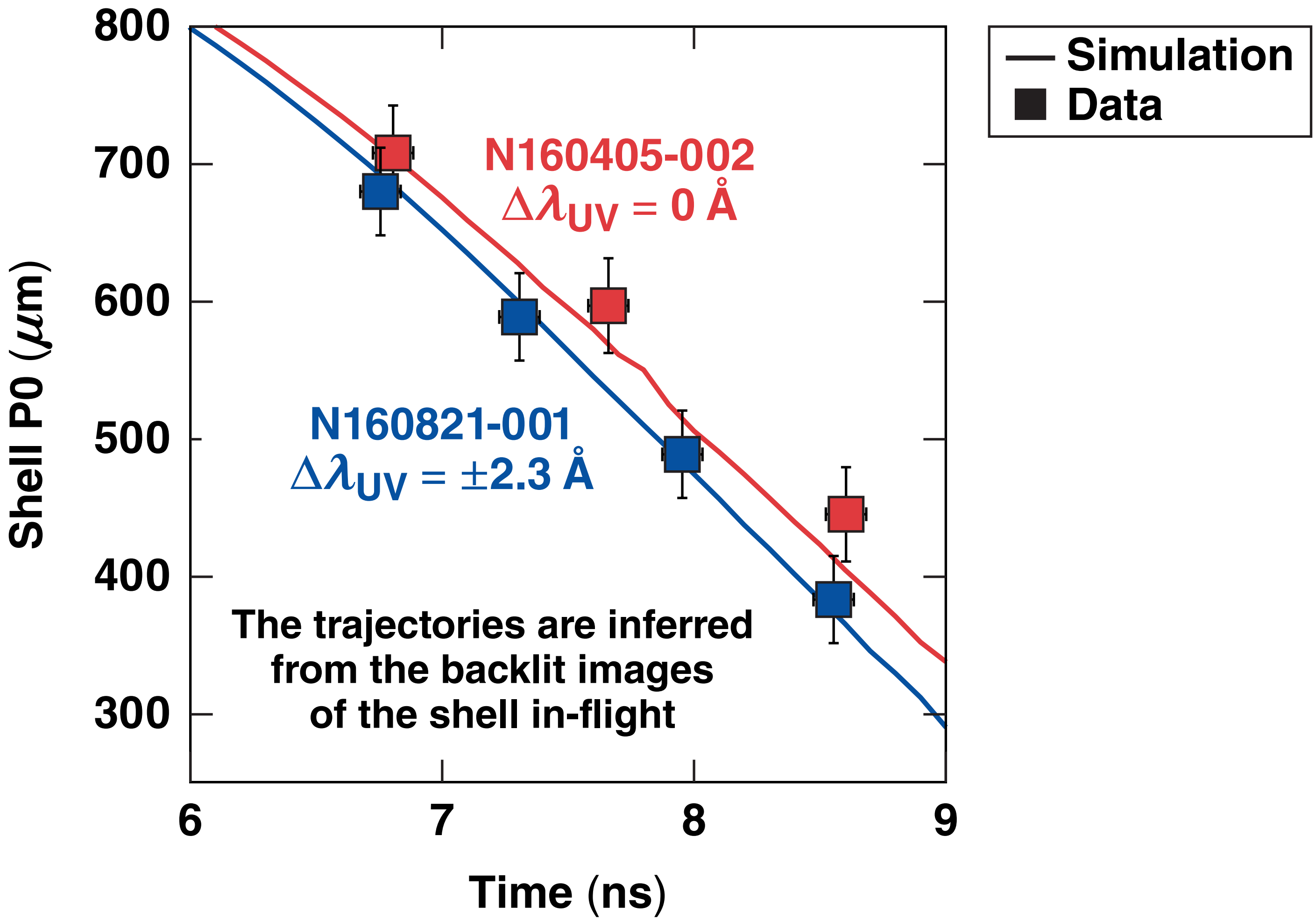
This CBET mitigation strategy today can only be tested on the NIF.

The predicted mass accumulation in the radiographs at the equator indicates CBET mitigation as predicted



E25876

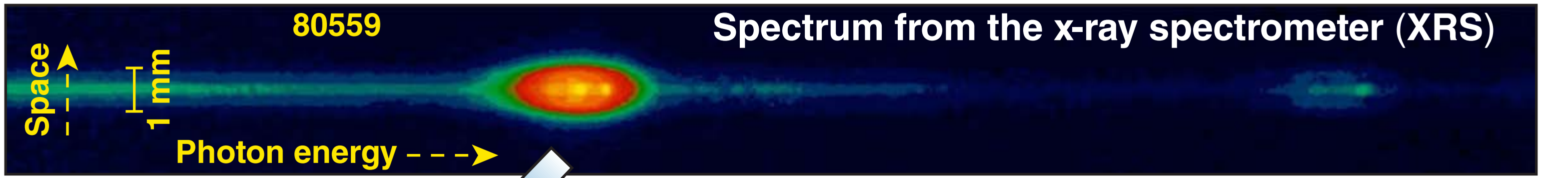
The measured shell trajectory shows the predicted coupling improvement with $\Delta\lambda$ = ±2.3 Å

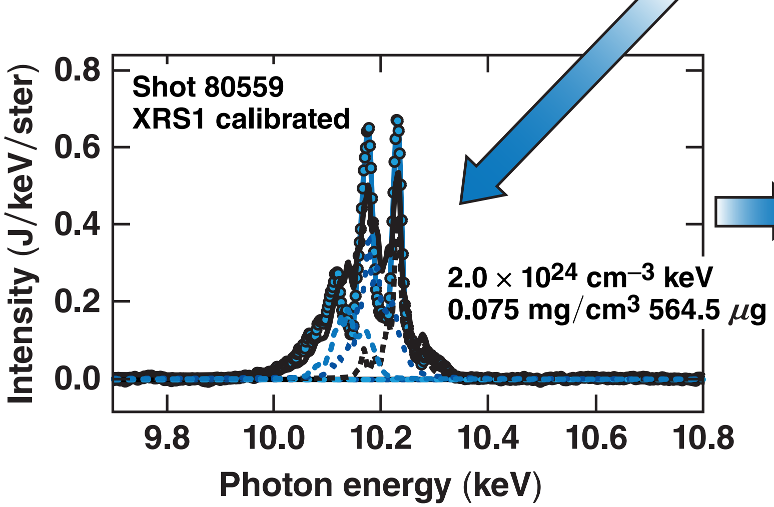


The trajectories are inferred from the backlit images of the shell in-flight

E25877

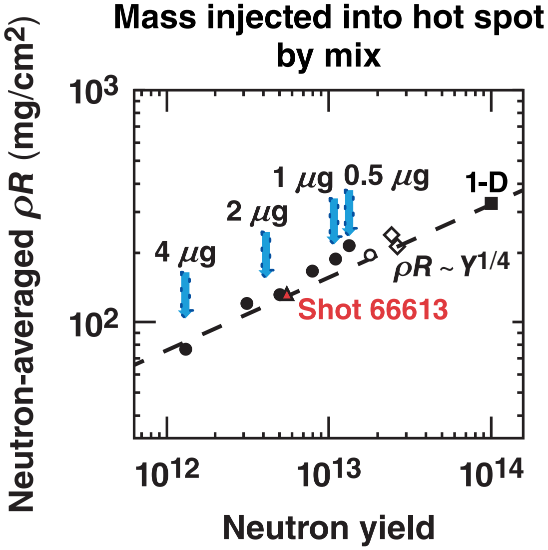
Mass injected into the hot spot in recent Ge-doped ablator-layered DT implosions is consistent with prediction*





Preliminary fit: 0.6 μg of ablator is mixed into the hot spot

Mass injected into hot spot by mix



Relative to non-doped implosions:

- Yield is lower by ~2×
- Absolute core emission is ~2× higher
- T_i is significantly lower
- Bang time is ~50 ps earlier
- Core size is significantly larger
- Burn duration is longer

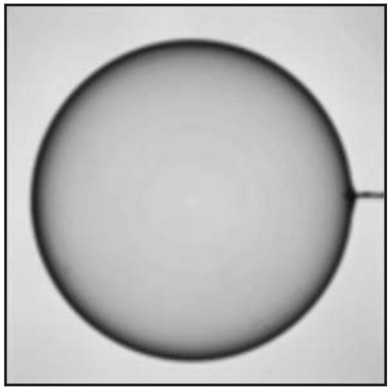
These new results (further) motivate improvements to the capsule surface quality!

---

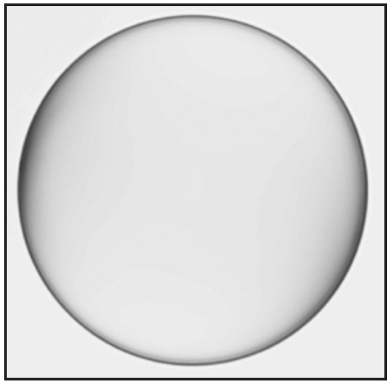
*I. V. Igumenshchev *et al.*, Phys. Plasmas 20, 082703 (2013).

A new fill-tube-based cryogenic target insertion system is being developed for 100-Gbar experiments in 2020

- Capsule surface cleanliness cannot be maintained with the current cryogenic permeation fill system
- CH shell dose (T β-decay) is estimated to approach 200 Mrad (methane is recovered after the fill)
- Layers and non-CH ablators for LPI mitigation and hydro efficiency are not compatible with permeation filling
- The new fill-tube–based system is being developed with single-sided shroud retraction (NIF SDD requirement)
- New metrology methods for submicron-surface particulate is being developed with GA



OMEGA target supported by a 10-μm fill tube (GA)

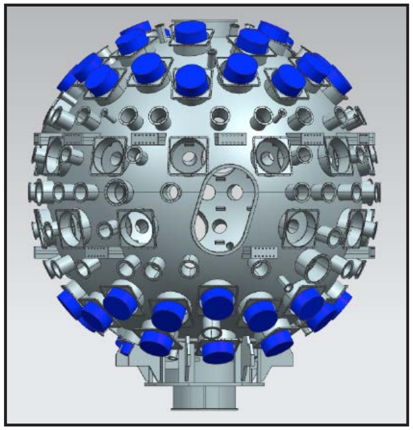


The surface quality of recent polystyrene shells may meet specification for 100-Gbar implosions

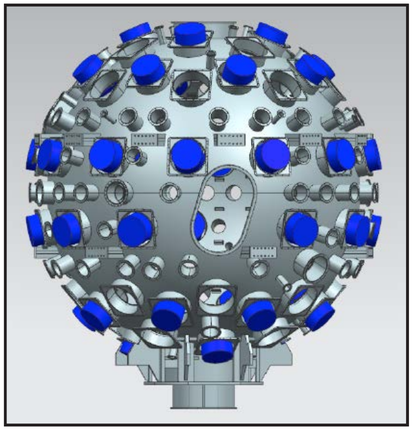
E24574

In FY16, a working group developed an estimate of the effort and cost needed to reconfigure the NIF for spherical drive

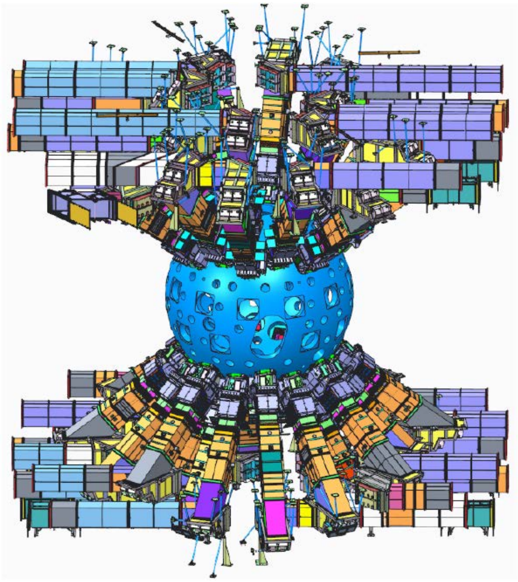
Indirect drive

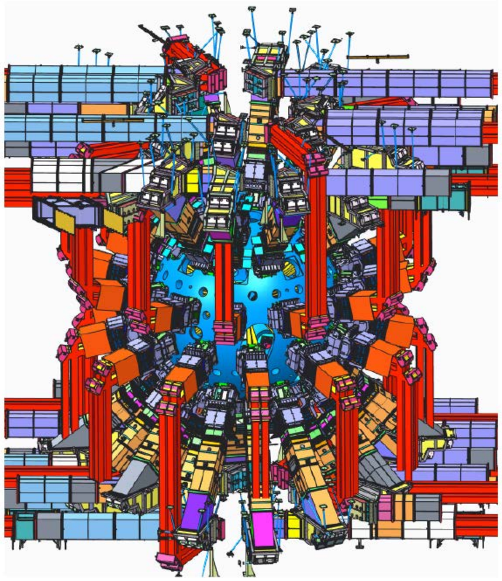


Spherical drive



The preliminary cost and schedule estimate was within the current operating envelope of the facility.





CAD models from the spherical direct-drive reconfiguration working group

E25879

In FY16, a working group developed an estimate of the effort and cost needed to reconfigure the NIF for spherical drive

Indirect drive

Spherical drive

The preliminary cost and

E25879a

Summary/Conclusions

The National Direct-Drive Program will inform a decision on whether to reconfigure the NIF for spherical direct-drive

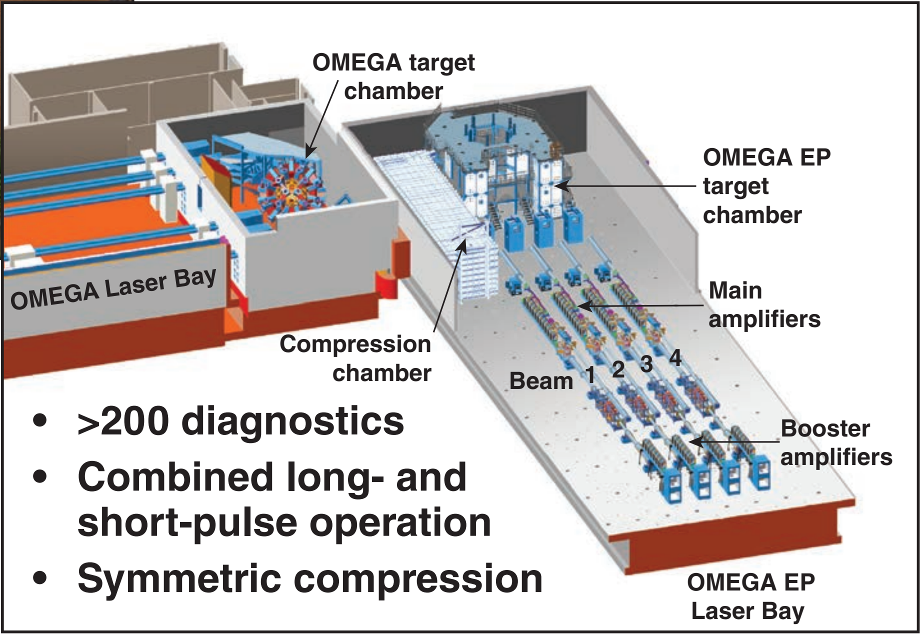
- Establishing the science basis for direct drive is collaborative and (at present) does not require significant modification of the NIF
  - laser direct drive (LDD) couples more energy into the hot spot [relative to laser indirect drive (LID)], relaxing the ignition requirements on the hot spot
- Direct-drive laser–plasma instabilities (CBET, TPD, and SRS) can be effectively studied at the MJ scale with experiments on the NIF
  - additional distributed scattered-light diagnostics are being added to the NIF
- CBET mitigation using wavelength detuning ($\Delta\lambda$) has been demonstrated on the NIF
- CBET mitigation using “zooming” has been demonstrated on OMEGA
- Polystyrene shells appear to be a promising candidate for high-performance implosions on OMEGA

NIF: National Ignition Facility
CBET: cross-beam energy transfer
TPD: two-plasmon decay
SRS: stimulated Raman scattering

The two HEDP laser systems at LLE provide ~2100 shots per year for the Stockpile Stewardship Program and Fundamental Science

The LLE lasers provide 80% of the ICF/HEDP experiments for 13% of the ICF program budget.

- **Faculty equivalent staff: 115**
- **Professional staff: 168**
- **Associated faculty: 22**
- **Contract professionals: 8**
- **Graduate and undergraduate students: 129**



- **>200 diagnostics**
- **Combined long- and short-pulse operation**
- **Symmetric compression**

External users perform 60% of the experiments on these facilities.

E19929z