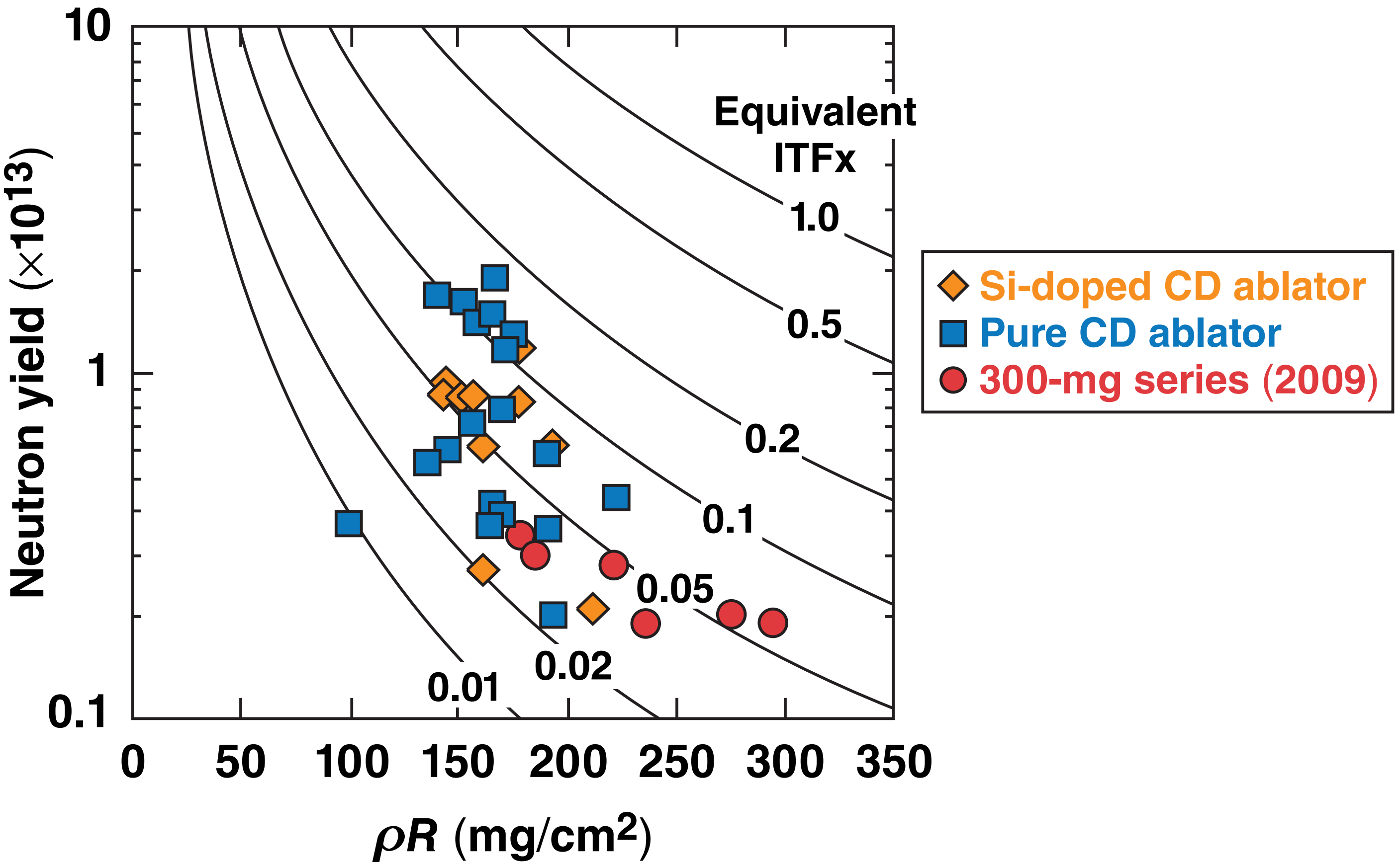
Progress Toward Polar-Drive Ignition for the NIF



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Fusion Power
Associates Meeting
Washington, DC
5–6 December 2012

Summary

Significant progress toward demonstrating direct-drive ignition on the NIF is being made

- Polar drive (PD) will allow for direct-drive–ignition experiments at the National Ignition Facility (NIF) in the x-ray-drive configuration
- OMEGA direct-drive cryogenic target implosions are defining the ignition design space
- Performance continues to improve
  - the yield and ion temperature increase with implosion velocity up to 3.8×10^7 cm/s (maximum to date)
  - the measured areal density agrees with 1-D predictions for adiabats >2.5
  - $P\tau$ increased to ~3.0 atm-s
  - a NIF-scaled experimental ignition threshold factor has increased to ~0.15
- Progress toward developing polar drive is ongoing, including initial NIF PD experiments

LLE is making progress toward demonstrating ignition hydro-equivalent performance on OMEGA.

Collaborators

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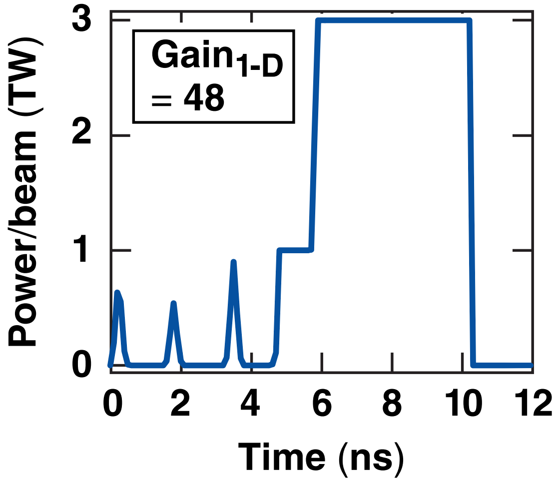
Direct drive is a true alternative to indirect drive

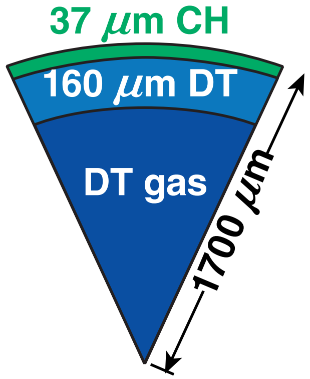
- Direct drive couples more energy to the capsule
  - provides higher margins
- The concept has been validated through decades of research, primarily by LLE on OMEGA, with contributions from NRL
- Shock ignition provides an additional direct-drive option with the possibility of significantly higher gain
  - less validated to date

Direct-drive ICF is a viable ignition alternative for the NIF

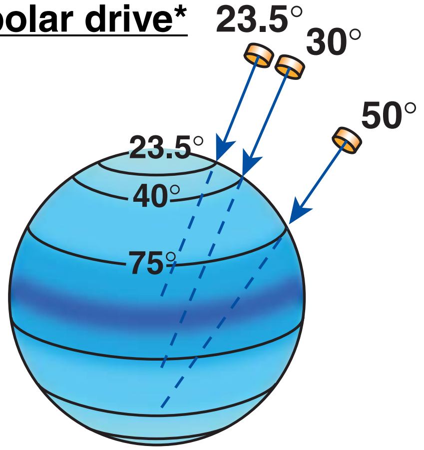
- Direct drive is predicted to couple 7 to 9× more energy to the compressed core than indirect drive
- 2-D simulations predict gains of ~50 on the NIF with symmetric irradiation
- Cryogenic target implosions are studied on OMEGA at ~1/4 of the NIF target scale
  - $R \sim (E_L)^{1/3}$
- LLE is developing polar drive to allow for direct-drive–ignition experiments while the NIF is configured for x-ray drive

Three-picket NIF design





Repointing for polar drive*



2-D simulations predict polar-drive ignition on the NIF when appropriate beam smoothing has been added.

The in-flight aspect ratio and adiabat determine the target stability and areal density

- In-flight aspect ratio (IFAR): Ratio of the implosion radius to the shell thickness at 2/3 of the in-flight radius

$$\mathrm{IFAR}_{2/3} = R_{2/3}/\Delta_{2/3}$$

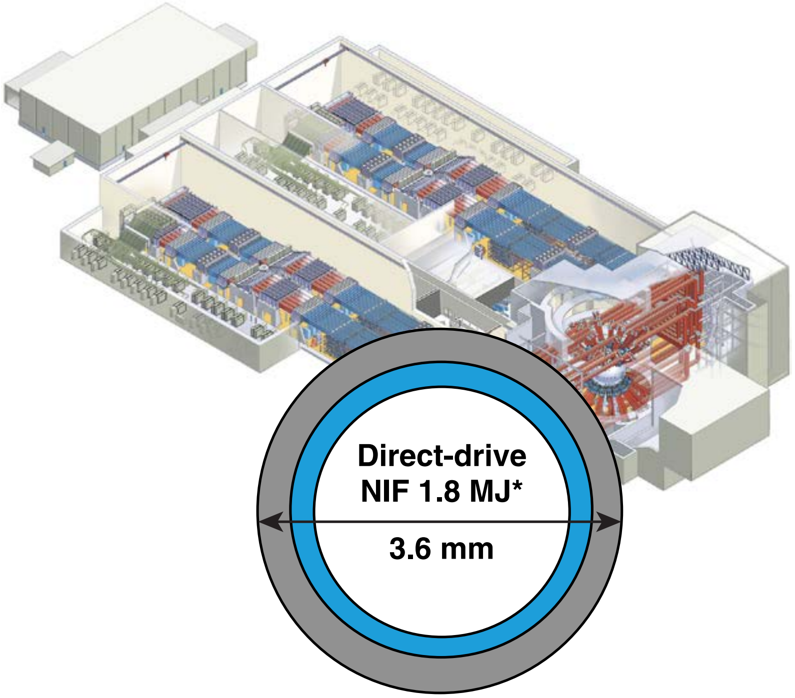
  - IFAR determines of the amplitude of the Rayleigh–Taylor (RT) modulations that disrupt the implosion
  - the 1-D minimum energy for ignition, $E_{\mathrm{min}} \sim 1/(\mathrm{IFAR})^3$

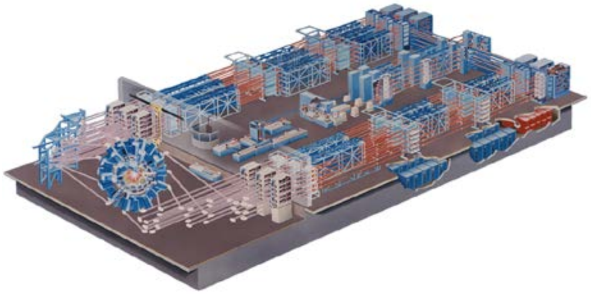
- Adiabat: Mass-averaged adiabat contributing to the stagnation pressure

$$\mathrm{adiabat} = \frac{P}{P_f} = \frac{\mathrm{pressure}\,(\mathrm{Mbar})}{2.2\,\rho\,(\mathrm{g/cm^3})^{5/3}}$$

  - the adiabat determines the target compressibility and the RT growth rate

Symmetric direct-drive–ignition designs* can be scaled for hydrodynamic equivalence on OMEGA scale



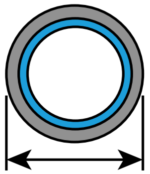


Scale 1:70
in energy

Hydrodynamic scaling

- Capsule radius ~ $E_L^{1/3}$
- Shell thickness Δ ~ $E_L^{1/3}$
- Laser power ~ $E_L^{2/3}$
- Pulse length ~ $E_L^{1/3}$
- Mass fuel ~ E_L

OMEGA 26 kJ



Hydrodynamic similarity is ensured by keeping the implosion velocity, adiabat, and laser intensity the same at the two scales.**

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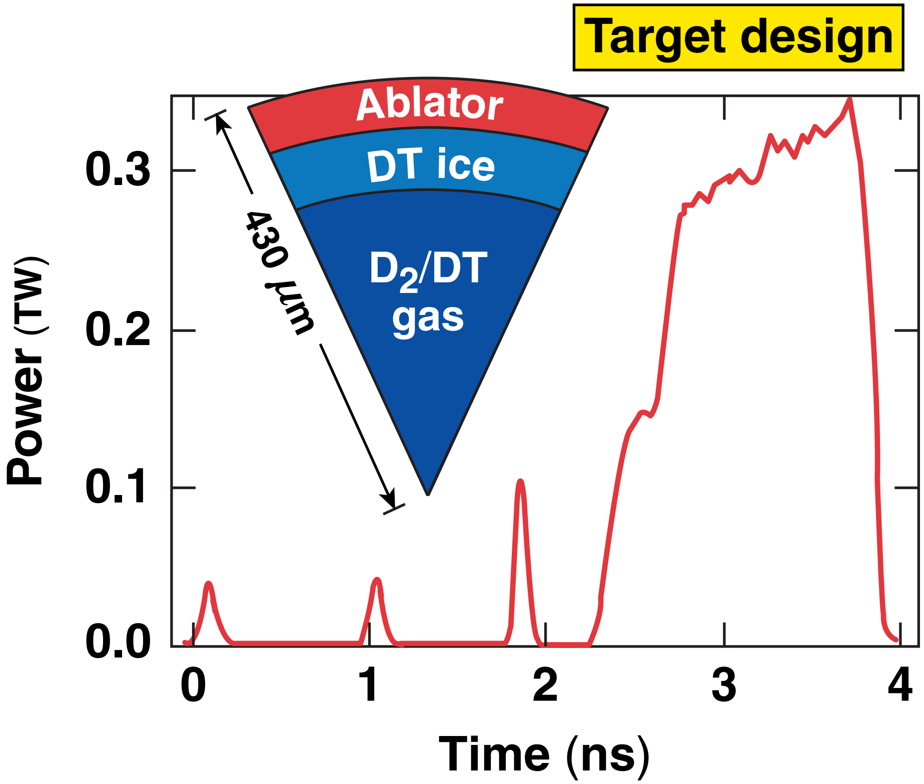
*V. N. Goncharov *et al*., Phys. Rev. Lett. 104, 165001 (2010).

**R. Betti presented at the 24th IAEA Fusion Energy Conference, San Diego, CA, 8–13 October 2012.

OMEGA direct-drive cryogenic target implosions are defining the NIF PD design space

- The target adiabat is changed with
  - picket-pulse spacing and heights
  - step on main pulse rise
- The IFAR is varied through the
  - ablator thickness
  - ice thickness
- The implosion velocity is varied through the
  - target mass
  - laser intensity



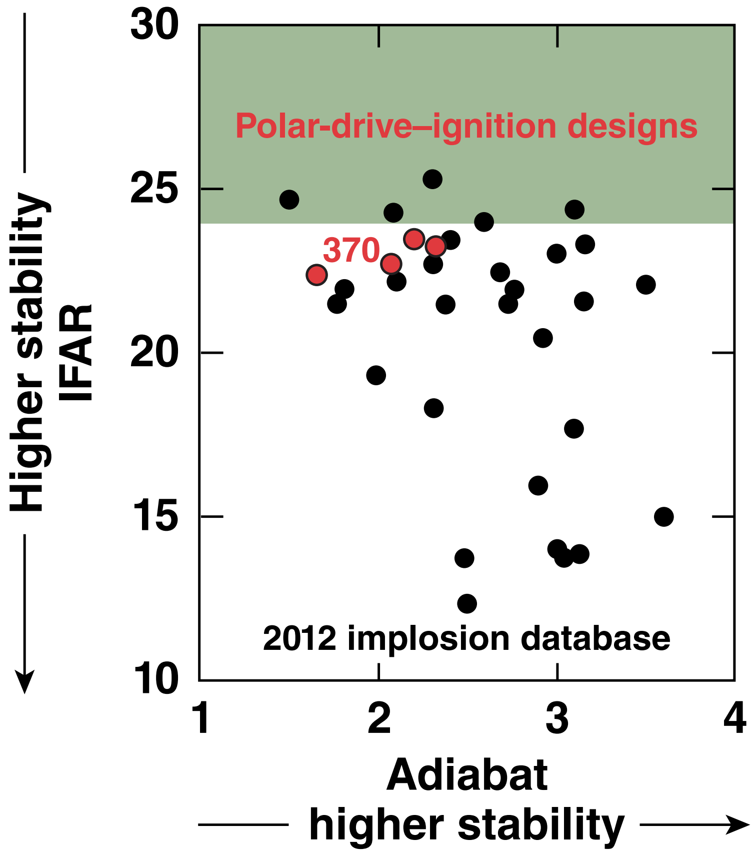
Cryogenic target implosions are validating the physics models used in simulations. $P\tau \sim (\rho R)^{0.6} Y_{\text{meas}}^{0.34}$

TC10127

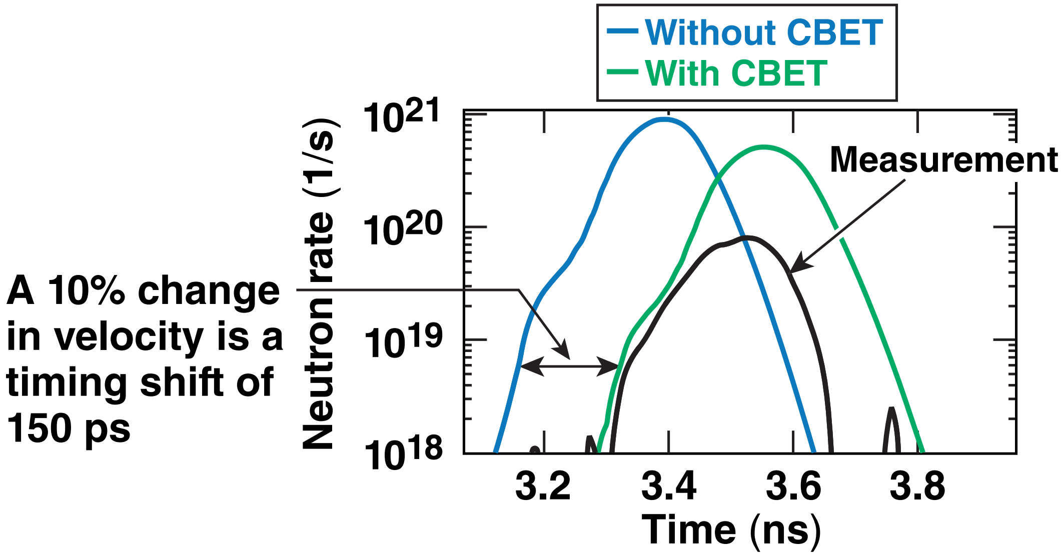
OMEGA cryogenic-DT implosions can access the design space for ignition on the NIF

- The primary design parameters in the radiation–hydrodynamic models are
  - laser intensity: $I_L \sim 0.8$ to 1×10^{15} W/cm^2
  - shell velocity at the end of acceleration: $V_{imp} \sim 2.5$ to 3.8×10^7 cm/s
  - mass-averaged adiabat contributing to the stagnation pressure: $\alpha \sim 1.5$ to 4.0, where $\alpha = P/P_f = P/2.2\ \rho^{5/3}$
  - in-flight aspect ratio: IFAR ~ 10 to 25, where $R/\Delta r$ is evaluated at 2/3 the initial radius

Our database includes only physics quality shots.



The (1-D) predicted implosion velocity is confirmed by the measured burn history



To match the data, the 1-D design code *LILAC* incorporates nonlocal thermal transport[1] and a stimulated Brillouin scattering (SBS) model[2] to account for cross-beam energy transfer (CBET).

The observed shift in the 1-D bang time shows the importance of including the CBET model in the design code.

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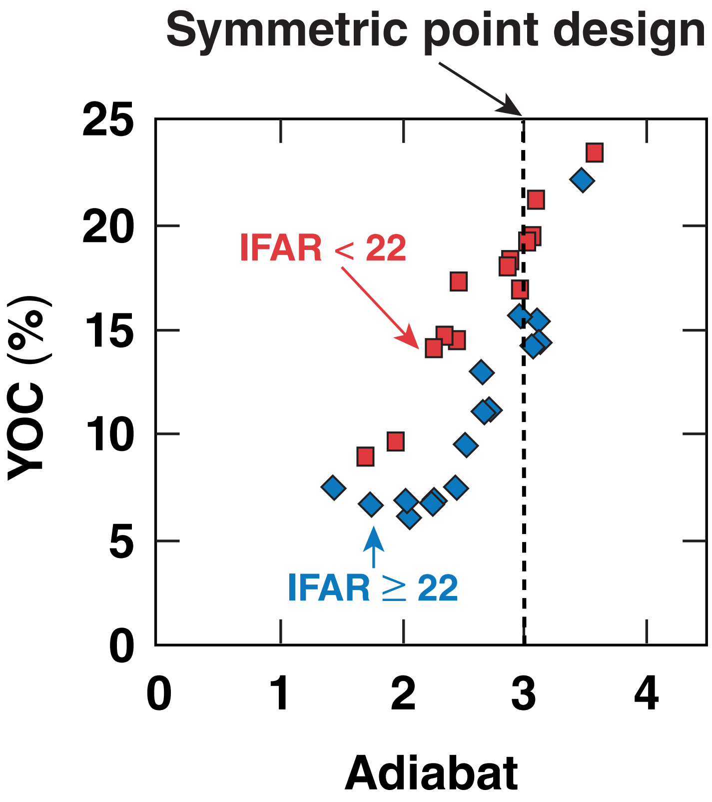
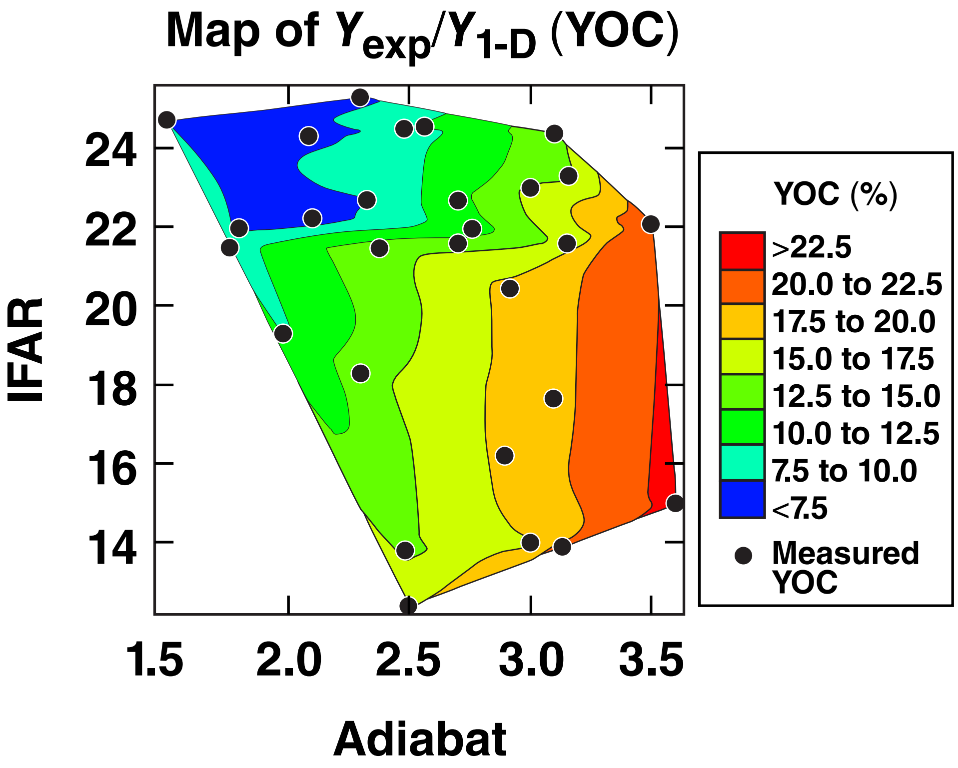
[1] V. N. Goncharov *et al.*, Phys. Plasmas 15, 056310 (2008).

[2] I. V. Igumenshchev *et al.*, Phys. Plasmas 19, 056314 (2012).

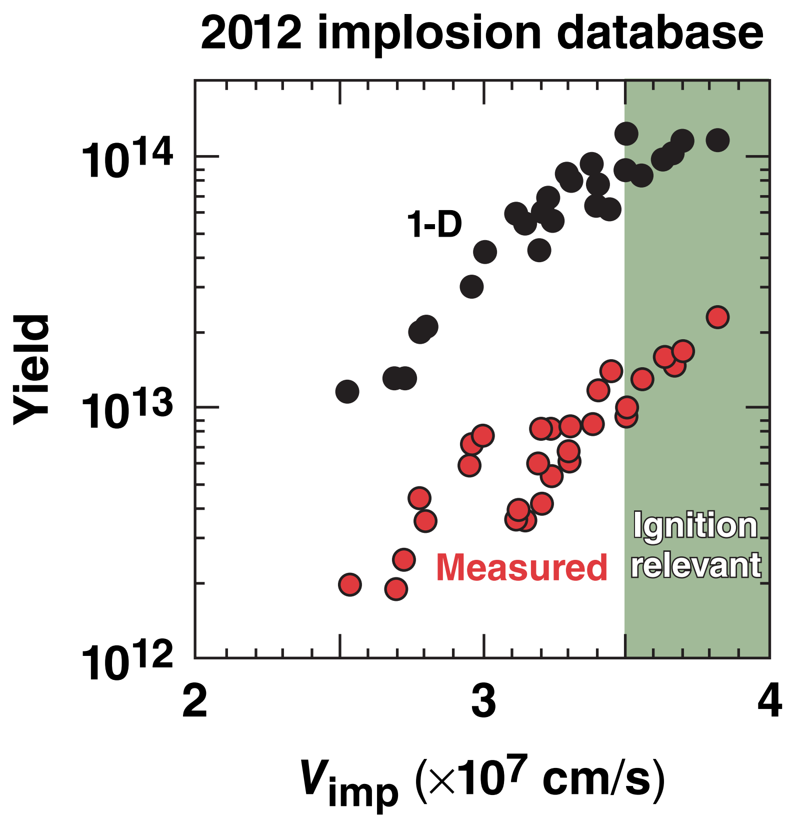
Cryogenic target performance is parameterized by the ratio of the neutron yield to that predicted by 1-D simulations [yield over clean (YOC)]

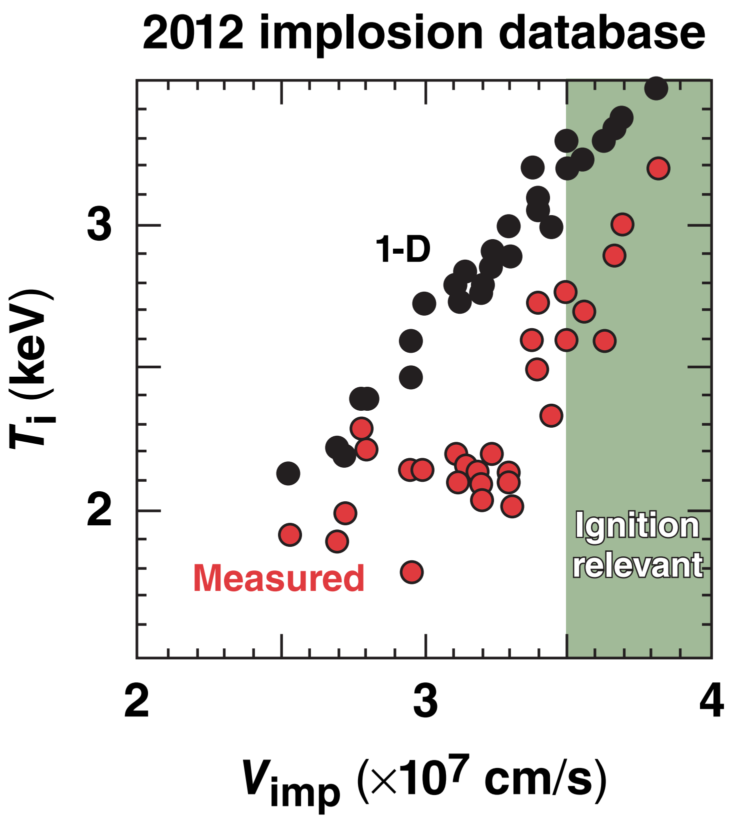




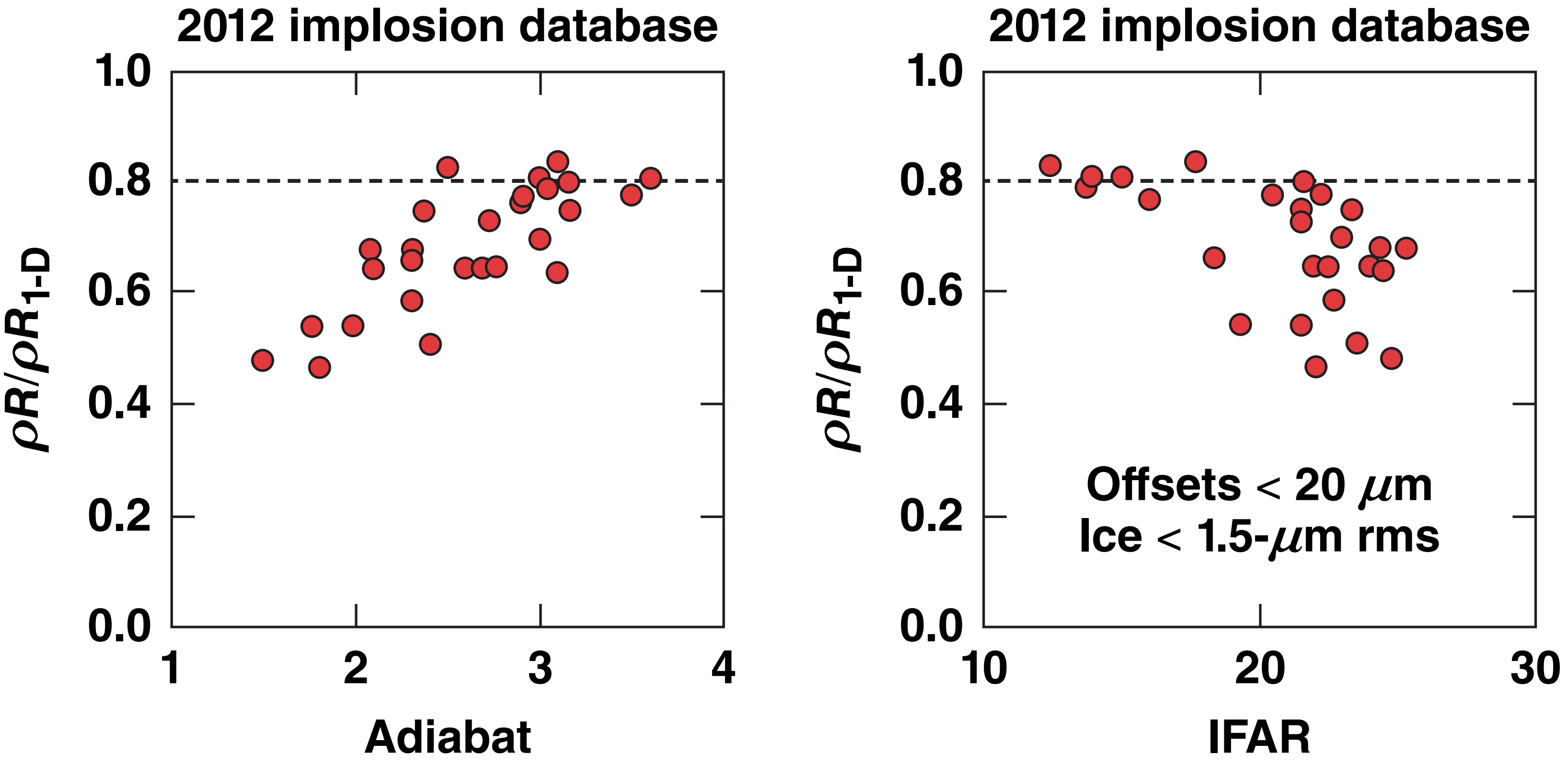
The 1-D simulations include all of the known physics with no adjustable "knobs."

The neutron yield and ion temperature increase with implosion velocity





The measured ρR performance is ~1-D for adiabats > 2.5 and IFAR < 20



Note: For most points, the measured ρR is an average inferred from two independent measurements.

The ICF Lawson criterion can be used to connect the design parameters to observables

- Lawson criterion is defined as $\chi = P\tau/P\tau_{\mathrm{ign}} > 1$
- A measurable form* of χ is:

  $\chi \sim (\rho R)^{0.61} \times (0.24\ Y_n/M_{\mathrm{fuel}})^{0.34}$, where ρR is in g/cm^2, Y_n is in units of 10^{16}, and M_{fuel} is in mg
- A value of $\chi = 0.16$ is needed to demonstrate hydro-equivalent ignition performance on OMEGA*
- This corresponds to a ρR of ~300 mg/cm^2 and a yield of $\sim 4 \times 10^{13}$
- The best implosions on OMEGA to date give a value of $\chi = 0.09$, where $\rho R \sim 160$ mg/cm^2 and $Y \sim 2.1 \times 10^{13}$

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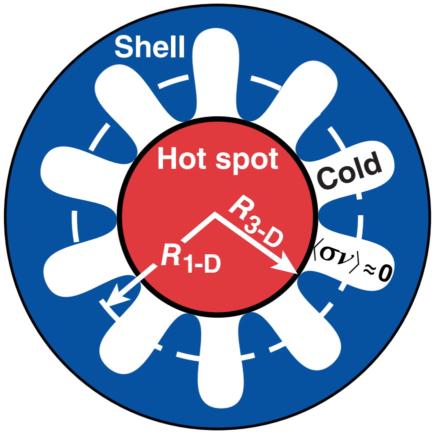
*R. Betti presented at the 24th IAEA Fusion Energy Conference, San Diego, CA, 8–13 October 2012.

Hydrodynamic scaling suggests less yield degradation due to nonuniformities on NIF

- Fusion reactions occur in the clean volume (red)



$$\text{YOC} = \frac{Y_n^{3\text{-D}}}{Y_n^{1\text{-D}}} \approx \left(\frac{R_{3\text{-D}}}{R_{1\text{-D}}}\right)^3$$

- The required YOC on OMEGA is difficult to estimate. Use simple clean volume analysis:

$$R_{3\text{-D}} = R_{1\text{-D}} - \Delta R_{\text{RT}} \qquad \Delta R_{\text{RT}} \sim \sigma_0 G_{\text{RT}} \qquad G_{\text{RT}}^{\text{NIF}} \approx G_{\text{RT}}^{\Omega}$$

RT spike amplitude

Initial seed

Growth factor

Hydro-equivalency

$$\text{YOC}^{\text{NIF}} \approx \left[1 - \frac{\sigma_0^{\text{NIF}}}{\sigma_0^{\Omega}}\left(\frac{E_L^{\Omega}}{E_L^{\text{NIF}}}\right)^{1/3}\left(1 - \left(\text{YOC}^{\Omega}\right)^{1/3}\right)\right]^3$$

YOC's are expected to be higher on the NIF because of a significantly larger clean volume fraction.

Implosion performance can be parameterized by an ignition threshold factor

- LLNL derived an Experimental Ignition Threshold Factor (ITFx)
  - ITFx (ID) = $(Y/3.2 \times 10^{15}) \times (\mathrm{DSR}/0.07)^{2.3}$, where ρR (g/cm^2) = 21× DSR (%)
  - ITFx = 1 corresponds to a 50% likelihood of ignition
  - ITFx ~ $(P\tau)^3$
- This formula can be scaled to OMEGA (Ω) energies*
  - ITFx (NIF equivalent) = ITFx $(\mathrm{ID}_\Omega) \times (E_{\mathrm{NIF}}/E_\Omega)^{1.28} \times (M_{\mathrm{fuel\ NIF}}/M_{\mathrm{fuel}\ \Omega})$ $\times\ \mathrm{YOC}_{\mathrm{NIF}}/\mathrm{YOC}_\Omega$
  - E_{NIF} = 1.8 MJ, E_Ω = 25 kJ, $M_{\mathrm{fuel\ NIF}}$ = 0.17 g, $M_{\mathrm{fuel}\ \Omega}$ = 0.02 g

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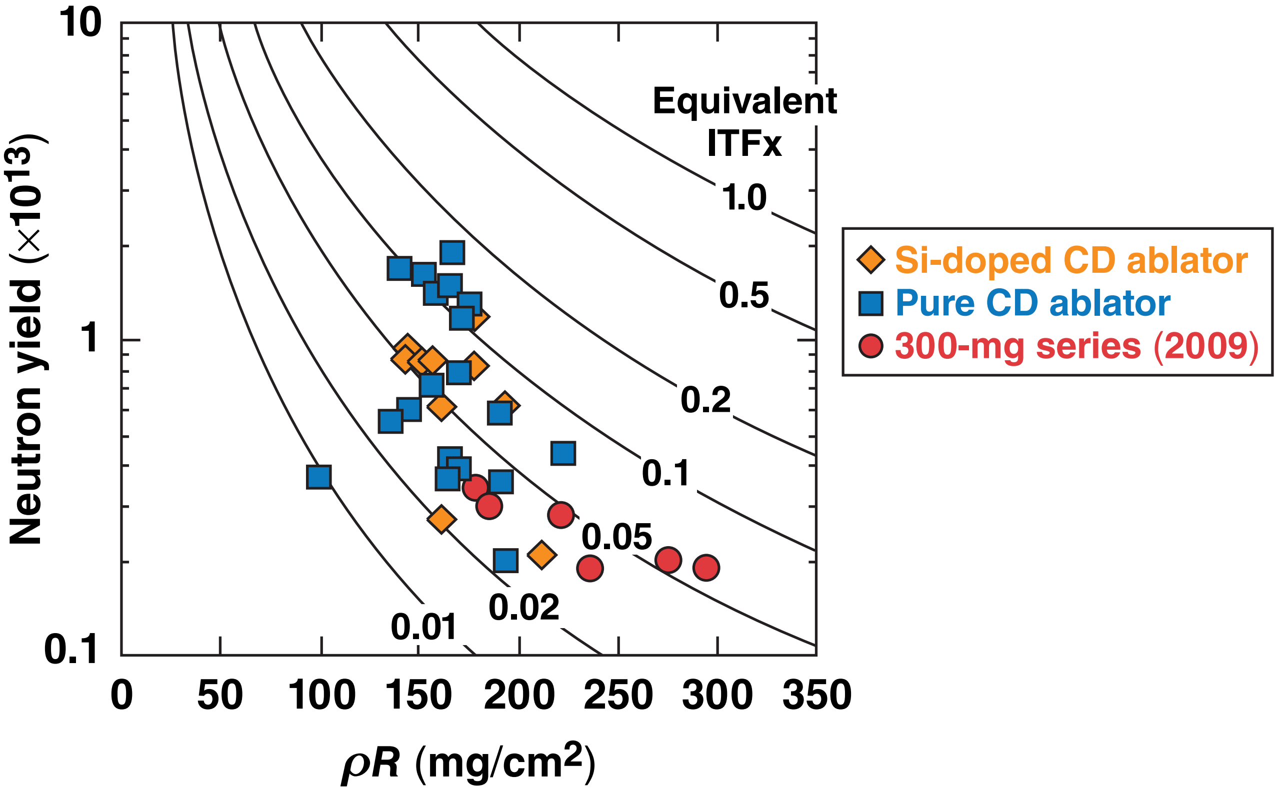
† S. W. Haan *et al.*, Phys. Plasmas 18, 051001 (2011).

* C.D. Zhou and R. Betti, Phys. Plasmas 15, 102707 (2008); R. Betti *et al.*, Bull. Am. Phys. Soc. 54, 219 (2009).

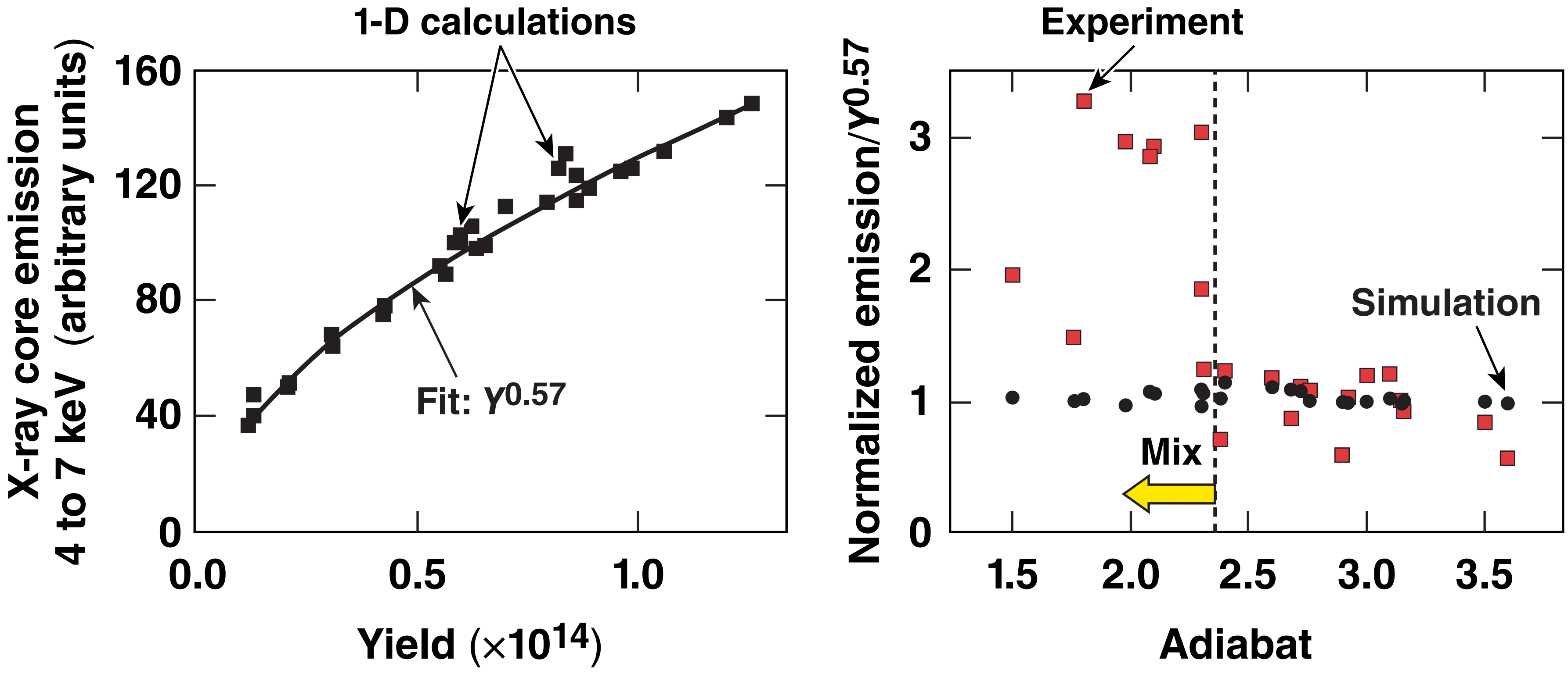
The OMEGA ITFx hydro-scaled to the energy available on the NIF exceeds 0.1

$$\text{ITFx (NIF Equiv)} = 4050 * (Y/3.2 \times 10^{15}) \times (\rho R/1.5\ \text{g/cm}^2)^{2.3}$$



Performance is independent of the ablator indicating that imprint is not (yet) the dominant perturbation source.

Core x-ray emission suggests that target performance degradation is caused by ablator carbon mix in the core

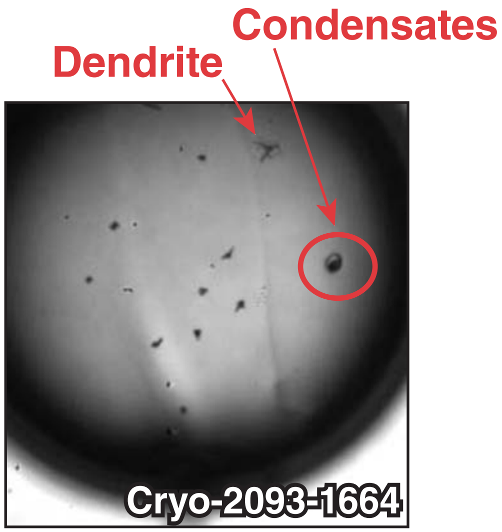


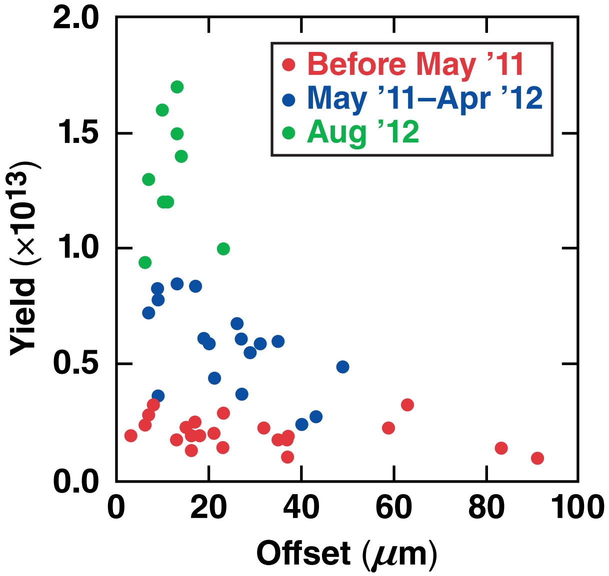
By raising the adiabat, the shell is stabilized, and mix is reduced even at high implosion velocities.

Further improvements in cryogenic target performance are expected over the next year

- Isolated surface debris on the target appear to be limiting the implosion performance
  - a significant engineering effort is underway to remove the defects
  - a 2011 shot series showed improved YOC when fewer defects were present

Cryo target image





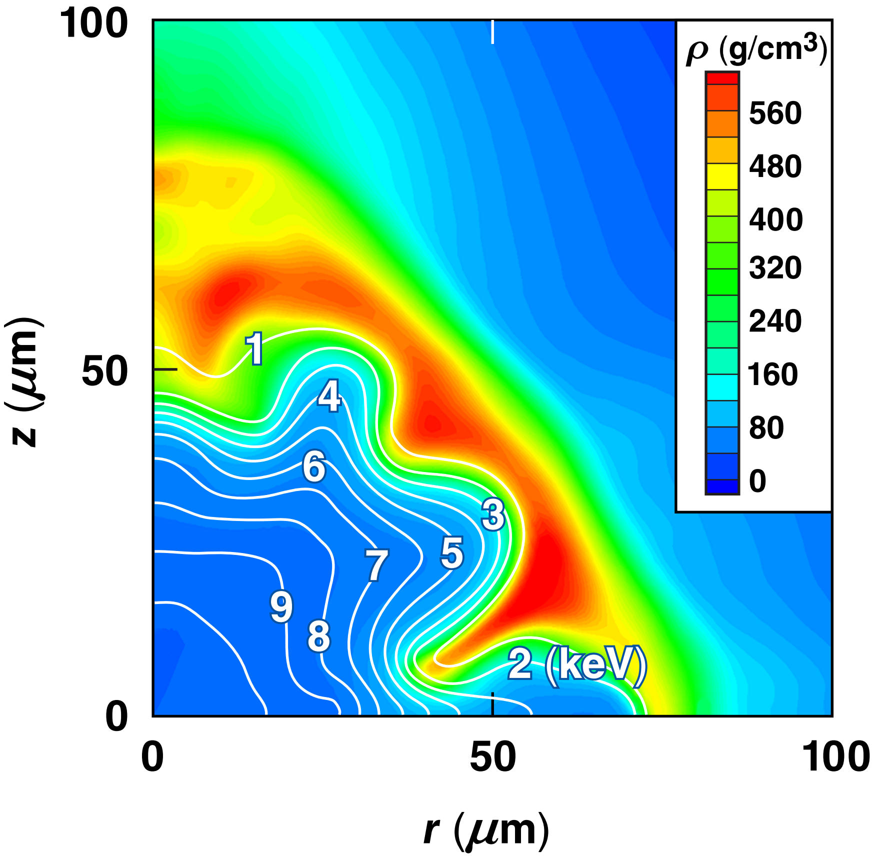
- The effects of cross-beam energy transfer are being understood
- Doping the outer part of the ablator with Si or Ge will reduce imprinting and RT growth

LLE is working to demonstrate ignition hydro-equivalent performance in 2013

- Eliminating the isolated target surface defects will mean
  - lower-adiabat implosions (higher ρR) with improved shell stability
  - higher-velocity/IFAR implosions at lower adiabats
  - imprint and stalk become the dominant perturbation sources
- While CBET does not restrict access to the design space on OMEGA, mitigation would provide more stability across the design space
  - thicker shells could be driven to the same V_{imp} with the same laser energy
  - mitigation may be necessary to achieve hydro-equivalent performance (should know within a year)

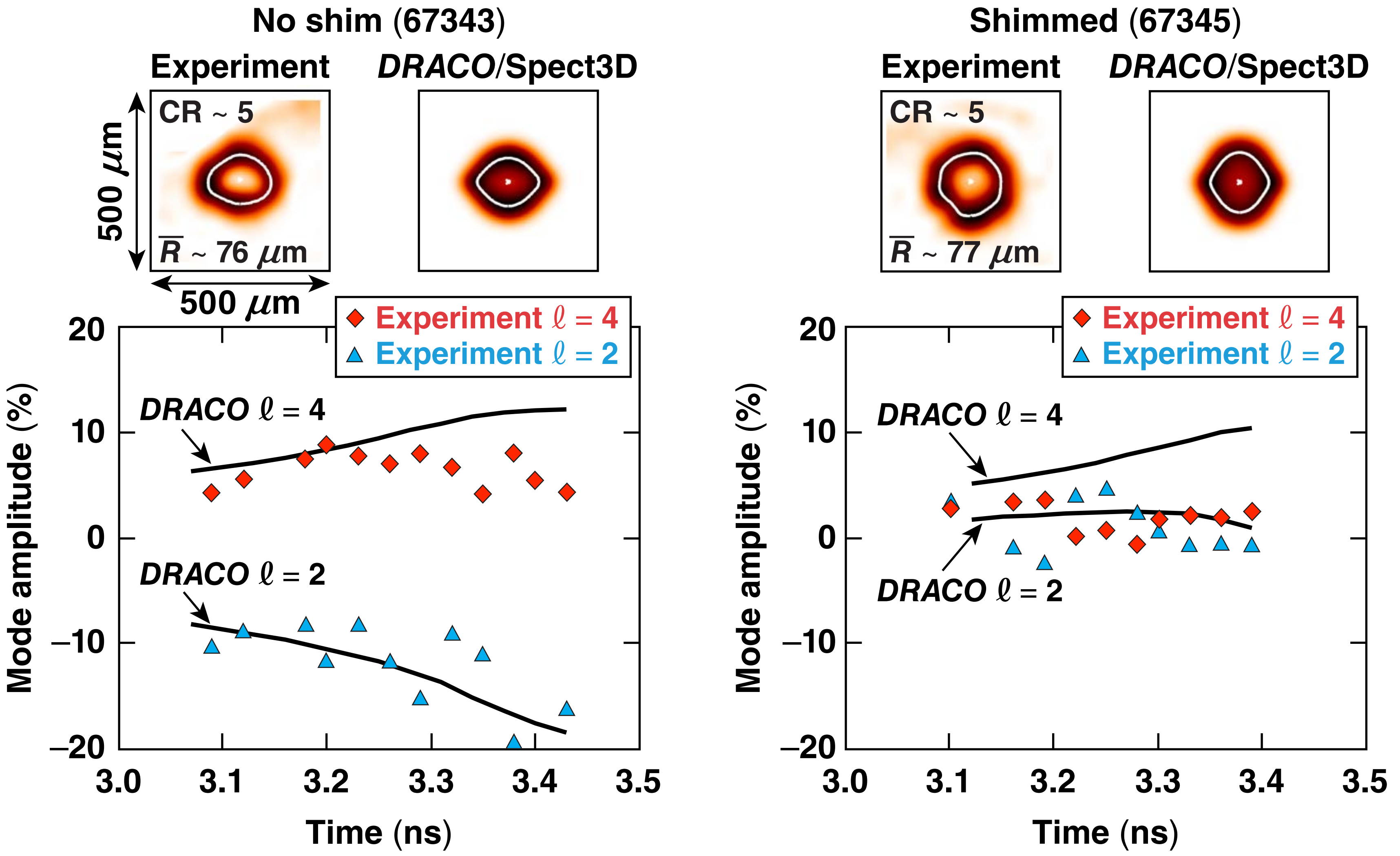
Improvements to the NIF PD target design have reduced the IFAR and implosion velocity

- A new 1.5-MJ NIF PD target design has enhanced stability
  - implosion velocity
    4.3 × 10^7 cm/s → 3.7 × 10^7 cm/s
  - in-flight aspect ratio
    36 → 30
- 2-D gain ~70, with PD illumination only
- 2-D simulations with full NIF nonuniformities are underway; expect a gain of ~30



Improved symmetry has been demonstrated with shimmed shells

0 μm, 120 μm, 140 μm

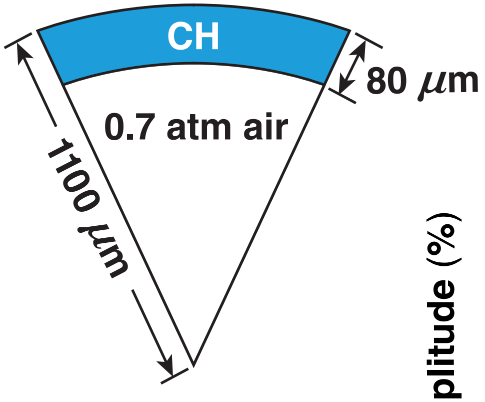


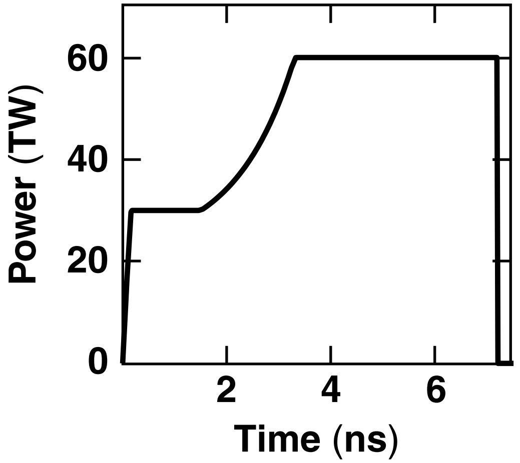
Early NIF experiments will address key issues for PD ignition

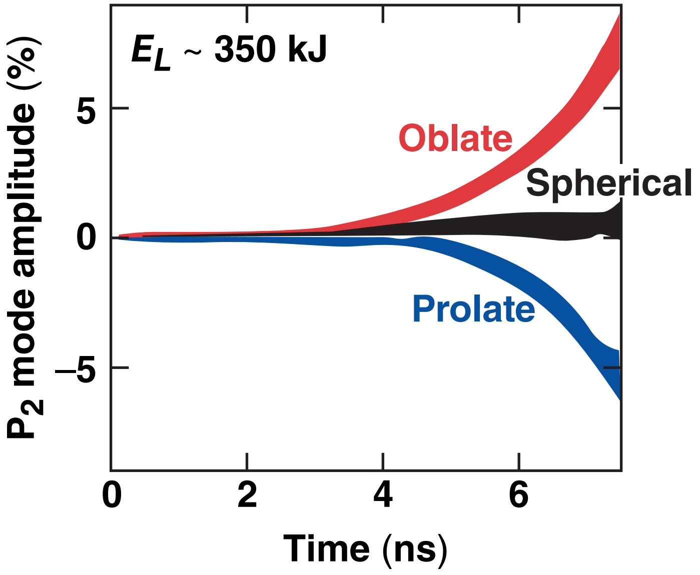
- The goal is to
  - demonstrate drive uniformity
  - measure laser coupling
  - identify and address laser–plasma interactions
    - longer coronal density scale lengths in NIF implosions may result in larger effects of cross-beam energy transfer[1] and fast-electron preheat from two-plasmon decay[2]
- These experiments will use the existing NIF configuration (phase plates and beam smoothing)
- The designs use a combination of beam defocus, repointing, and independent ring pulse shapes to achieve the required symmetry
- The first shot will be performed this month

The primary goal of early NIF experiments is to predictably change implosion symmetry

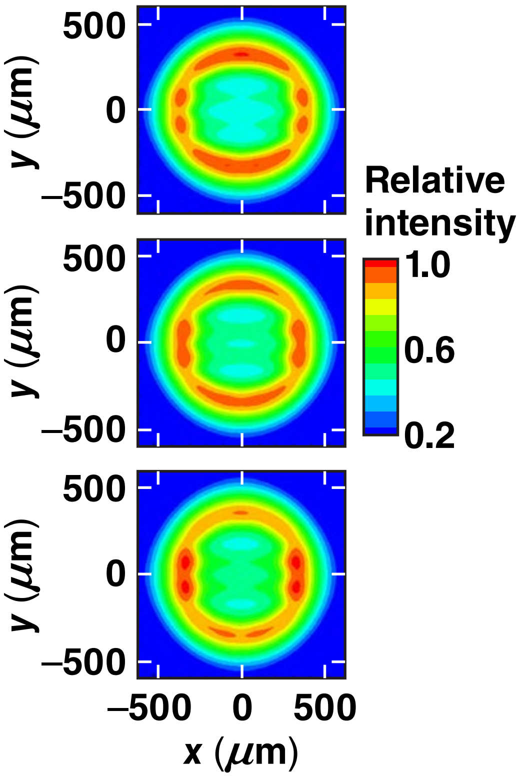
- **Implosion symmetry is varied by changing ring energies**







Simulated x-ray self-emission images* ($h\nu \gtrsim 2$ keV)



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*D. T. Michel *et al.*, Rev. Sci. Instrum. 83, 10E530 (2012).

Substantial IFE technology development will be required after the demonstration of ignition

- Fusion researchers have too often made claims about energy production that are not supported by demonstrated technology
- Any energy demonstration must be cost effective and reliable
- The path to a prototype power plant demonstration is longer and slower than most fusion researchers would like
- An aggressive technology program is required after the demonstration of ignition

The community must not “over-promise.”

Summary/Conclusions

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