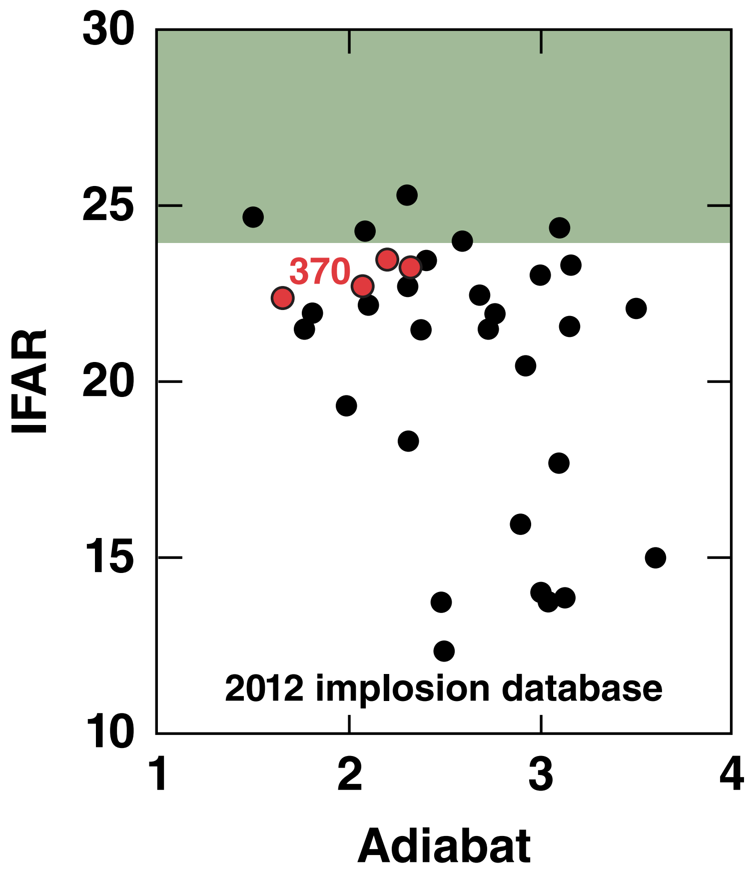
Improving Cryogenic-DT Implosion Performance on OMEGA



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Summary

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

- Experimental flexibility has resulted in a significant performance database for key implosion design parameters
- The yield (Y_n) and ion temperature (T_i) increase with implosion velocity (V_{imp}) up to 3.8×10^7 cm/s (maximum to date)
- The measured $\langle \rho R \rangle_n$ agrees with 1-D predictions for adiabats >2.5
- The ICF Lawson criterion χ is a measure of ignition hydro-equivalence
  - hydro-equivalence to NIF ignition on OMEGA is $\chi = 0.16$
  - cryogenic-DT implosions have reached $\chi = 0.09$
- Performance degradation appears to be caused by outer surface defects created during the DT fill that lead to carbon mix

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Collaborators

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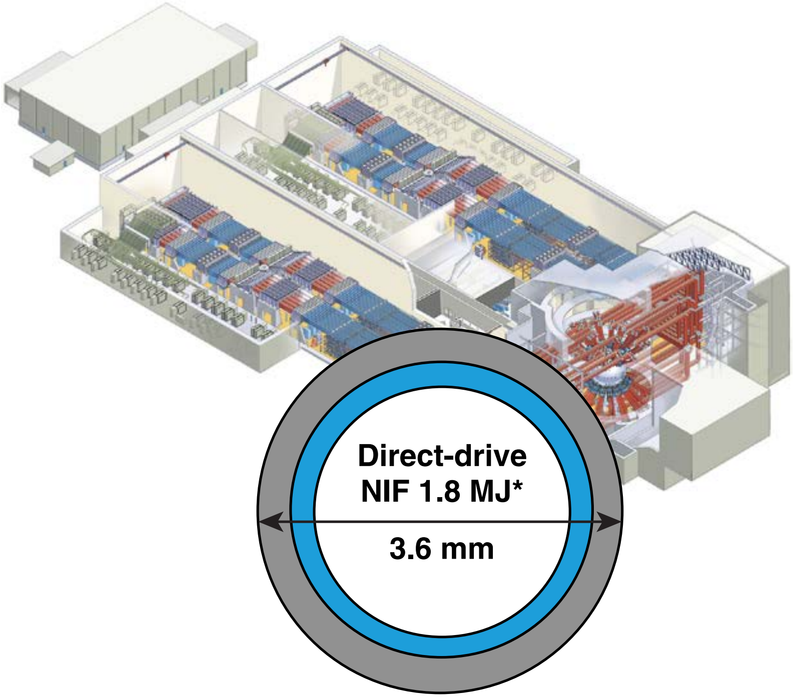
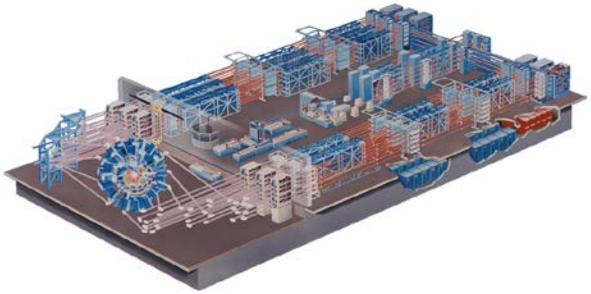
Symmetric direct-drive–ignition designs* can be scaled for hydrodynamic equivalence on OMEGA scale



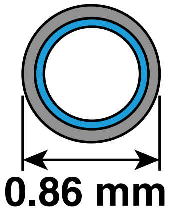
Hydrodynamic scaling

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



Scale 1:70 in energy

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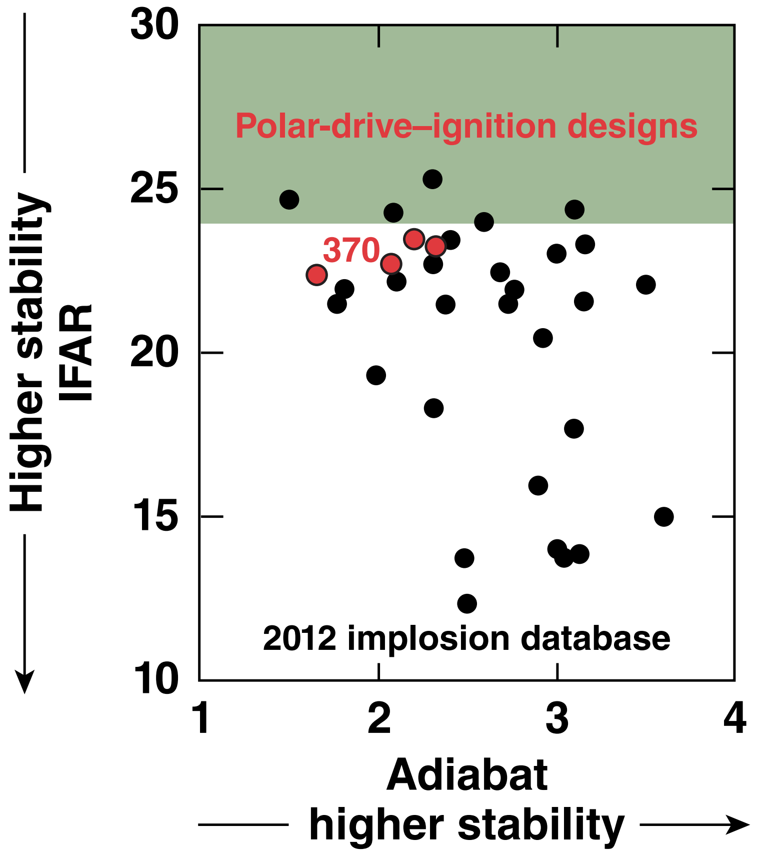
*V. N. Goncharov *et al*., Phys. Rev. Lett. 104, 165001 (2010).

**R. Betti, "Theory of Ignition and Hydro-Equivalence for Inertial Confinement Fusion," presented at the 24th IAEA Fusion Energy Conference, San Diego, CA, 8–13 October 2012.

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.



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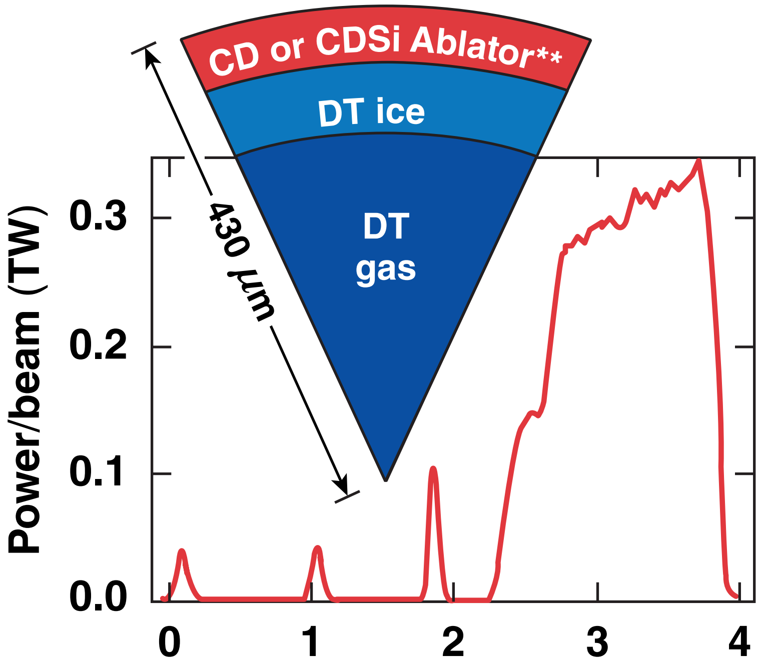
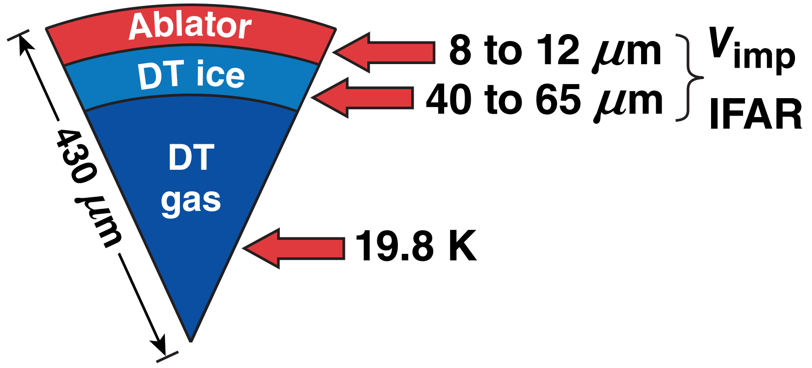
*See T. J. B. Collins, JO4.00010, this conference.

The design space is accessed with a flexible symmetric direct-drive target platform based on a triple-picket drive pulse*



Adiabat is established by picket energies and spacing*

Ranges within past year


Ablator

DT ice

DT gas

430 μm

8 to 12 μm } V_{imp}

40 to 65 μm } IFAR

19.8 K

- 8 μm CD and 45 μm DT, $V_{imp} \sim 4 \times 10^7$ cm/s
- 9 μm CD and 48 μm DT, $V_{imp} \sim 3.5 \times 10^7$ cm/s

OMEGA has the infrastructure to perform more than 50 cryogenic implosions a year.

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*V. N. Goncharov, JO4.00001, this conference.

**G. Fiksel, CO5.00014, this conference.

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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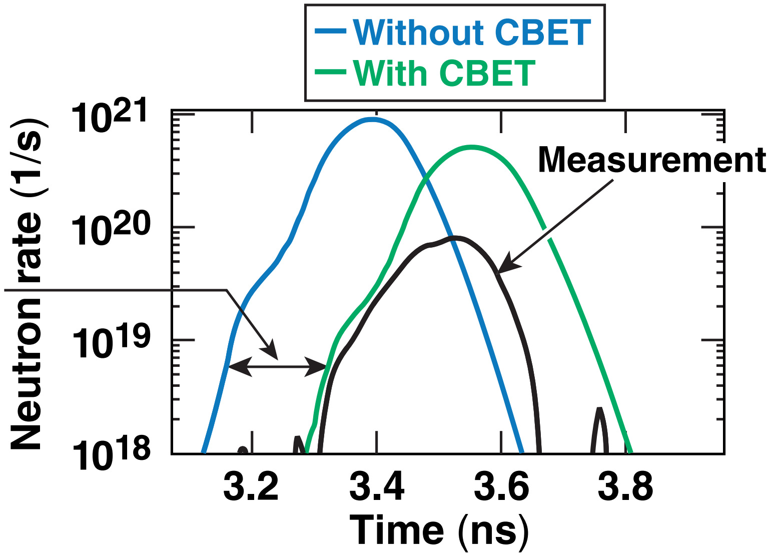
*R. Betti, "Theory of Ignition and Hydro-Equivalence for Inertial Confinement Fusion," presented at the 24th IAEA Fusion Energy Conference, San Diego, CA, 8–13 October 2012.

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



A 10% change in velocity is a timing shift of 150 ps

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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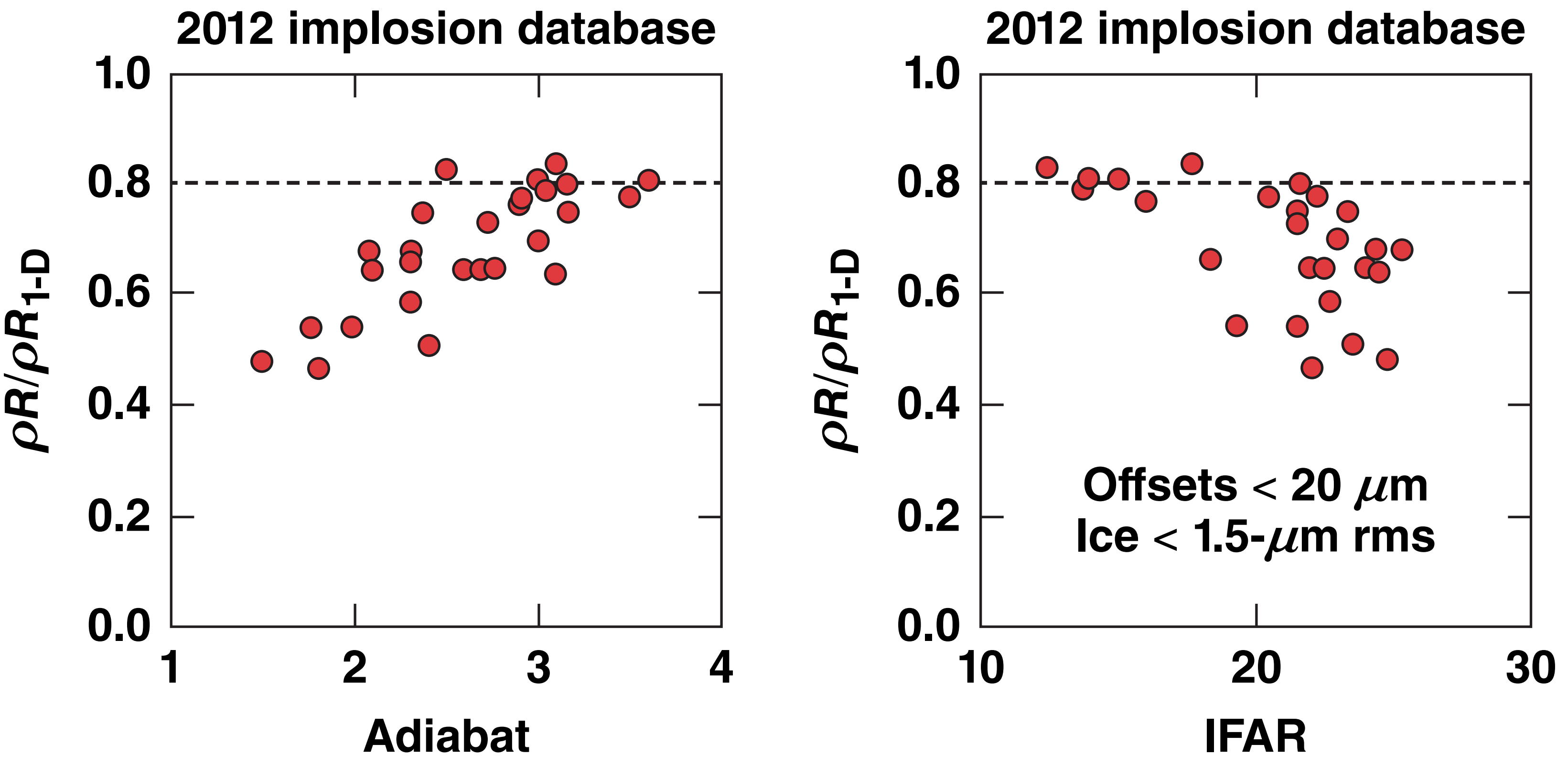
[1] V. N. Goncharov *et al.*, Phys. Plasmas 15, 056310 (2008).
[2] I. V. Igumenshchev *et al.*, Phys. Plasmas 19, 056314 (2012).

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.

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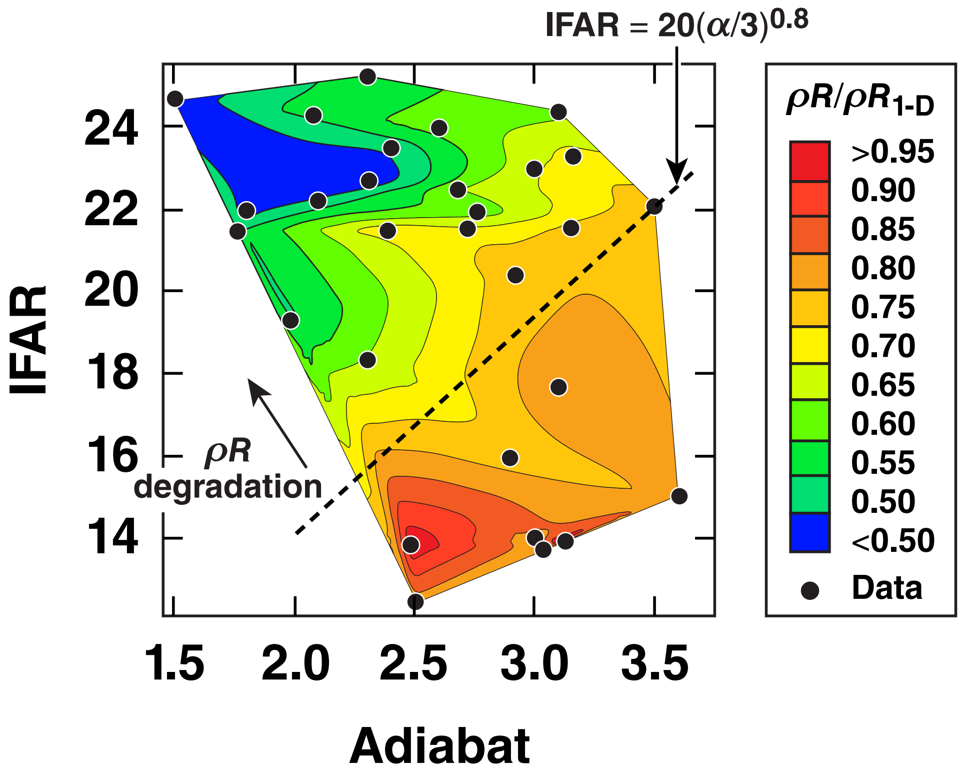
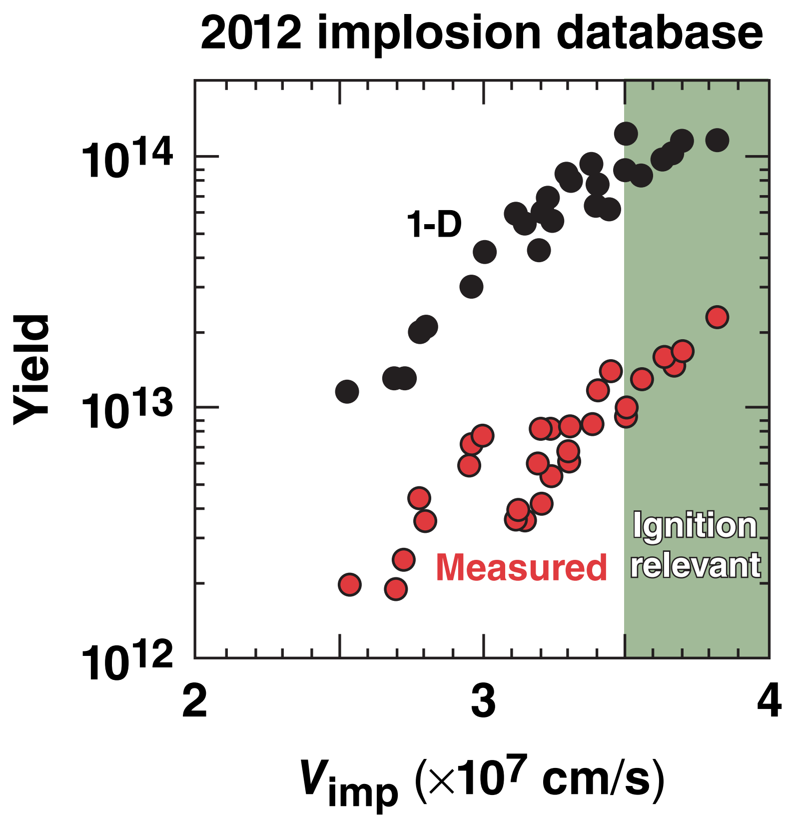
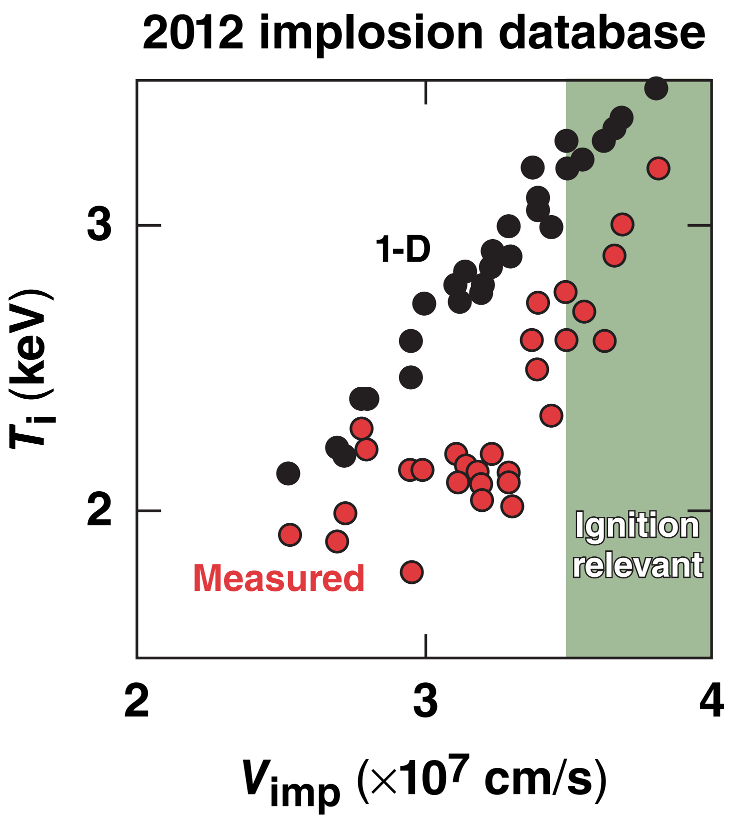
The shell integrity is compromised for IFAR > 20 $(\alpha/3)^{0.8}$

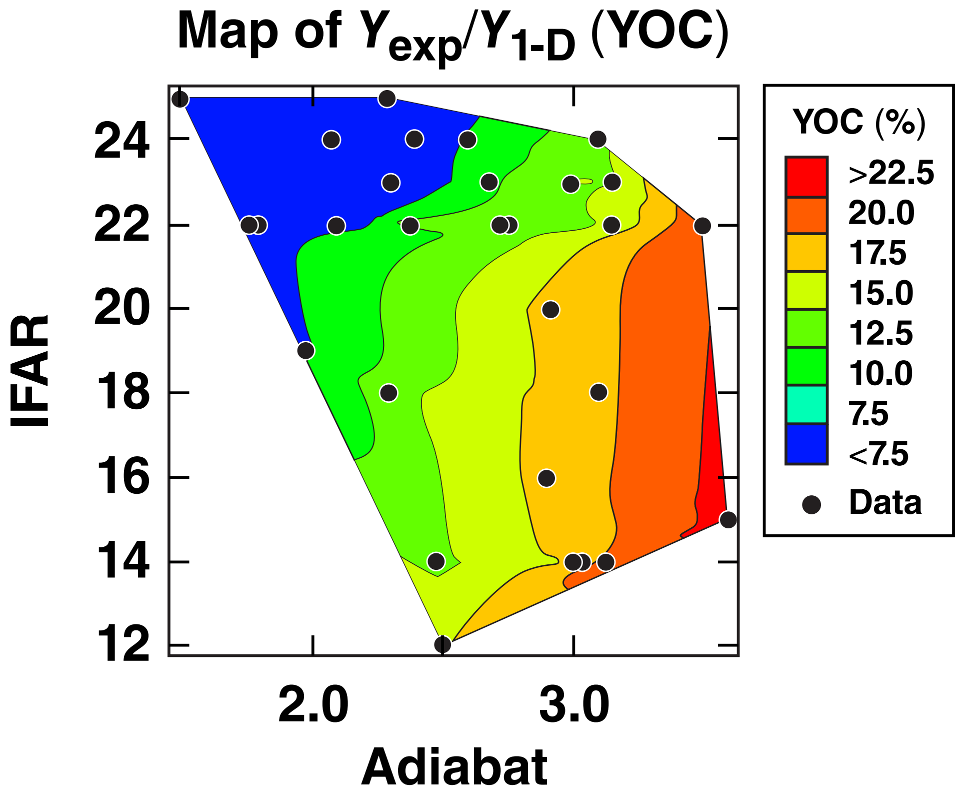


The neutron yield and ion temperature increase as expected with implosion velocity

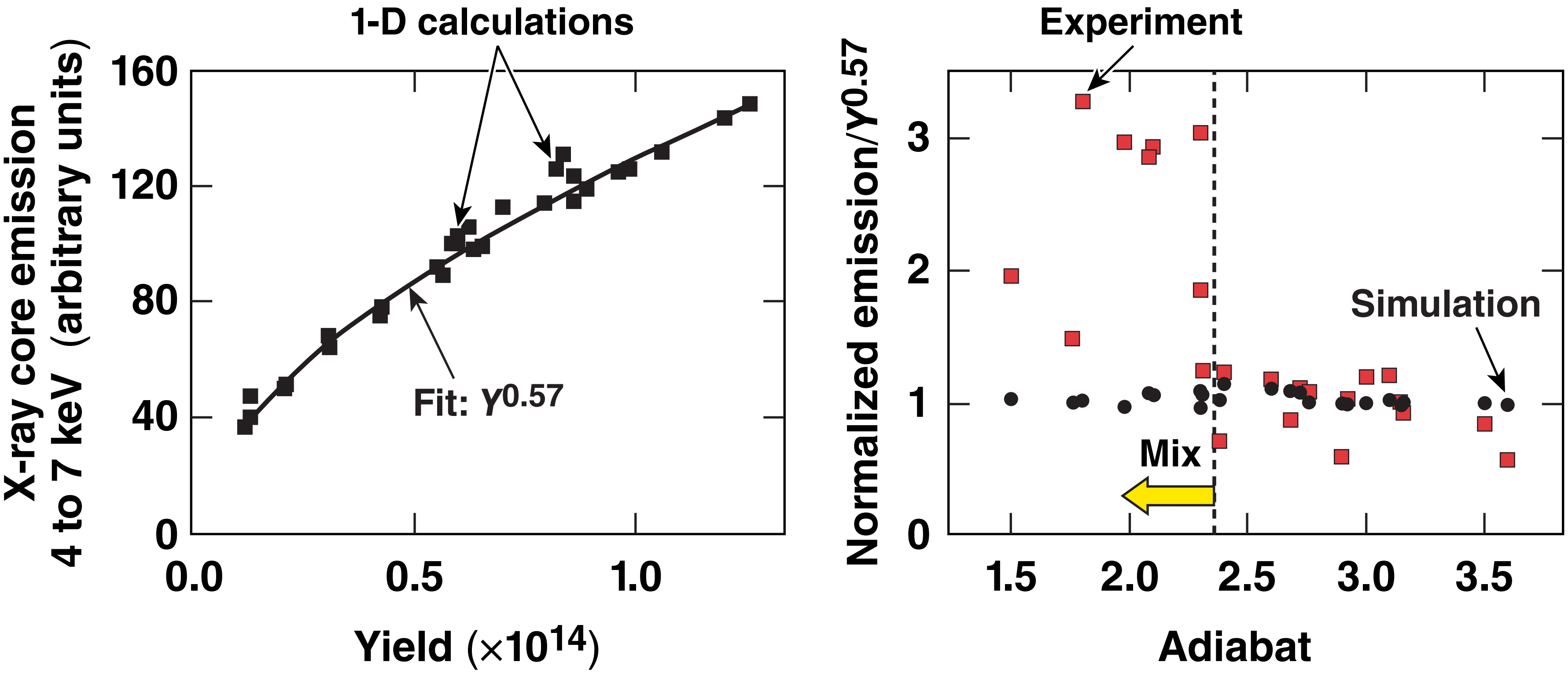




Yield depends primarily on the adiabat for values of IFAR < 22



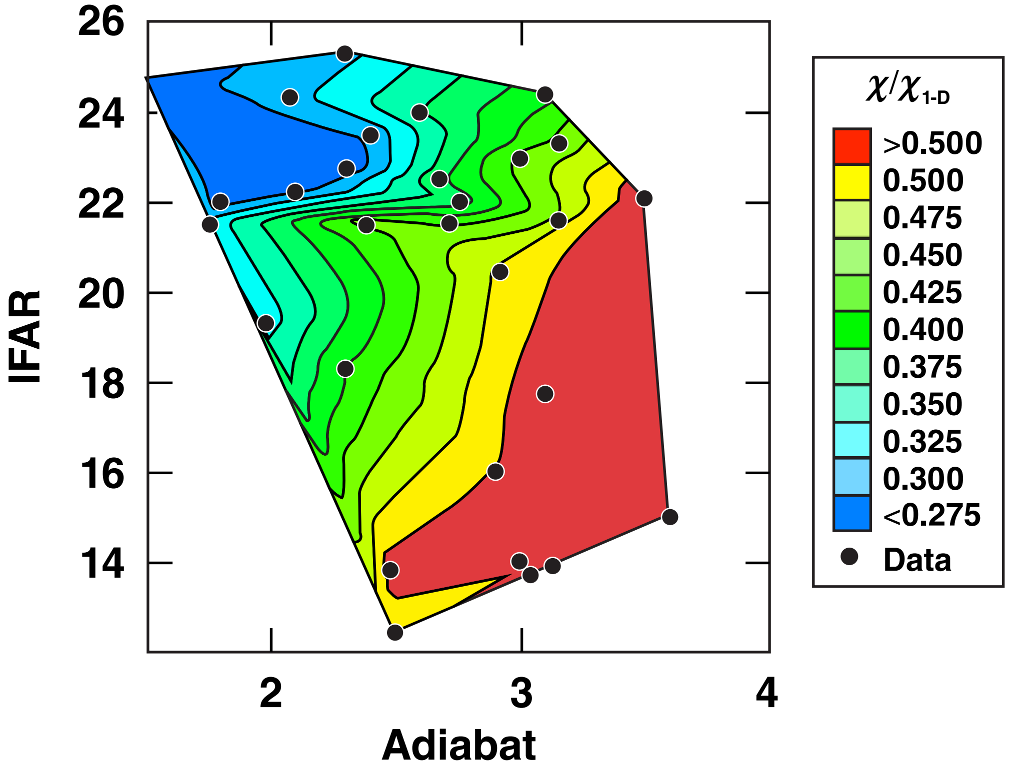
Core x-ray emission suggests that target performance degradation is caused by ablator carbon mix in the core



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

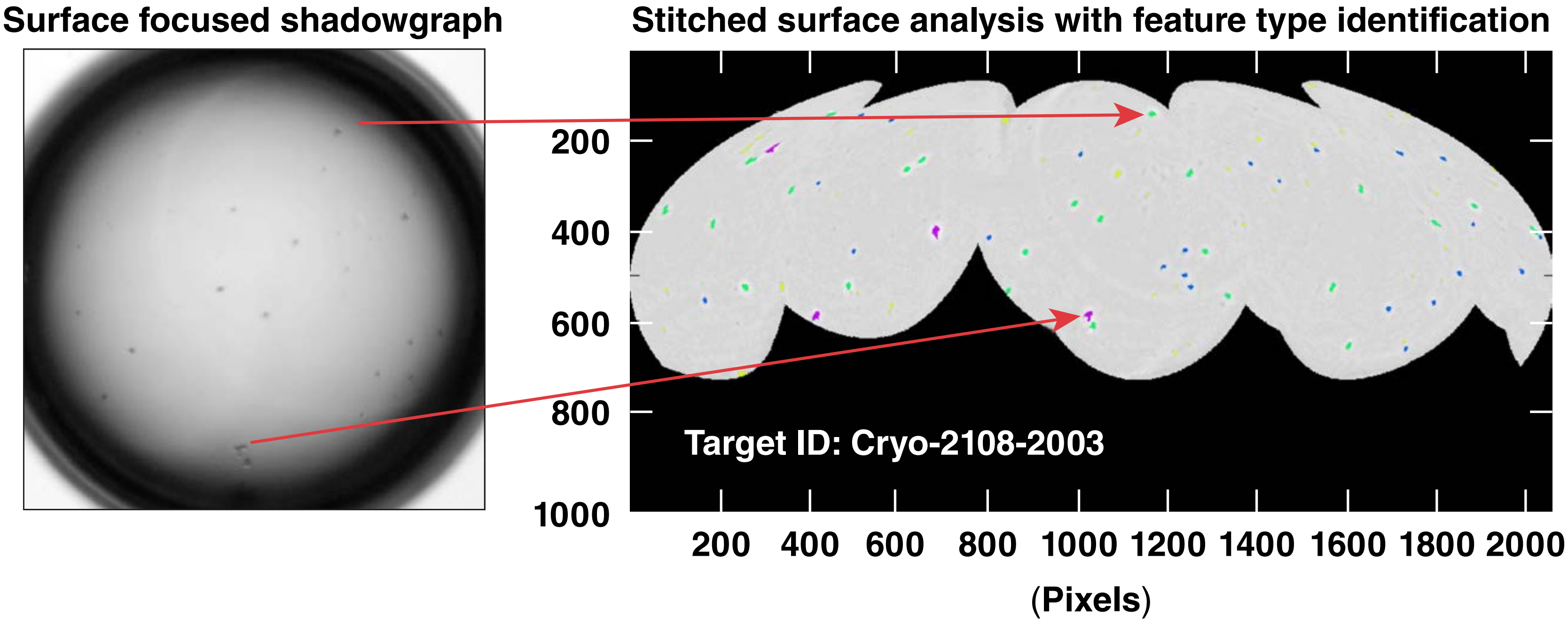
The peak values of $\chi/\chi_{\text{1-D}}$ occur for values of IFAR and α that do not scale to ignition at 1.8 MJ

$$\chi \sim (\rho R)^{0.61} \times (0.24\ Y_n/M_{\text{fuel}})^{0.34}$$



Isolated surface defects would explain the χ degradation.

The most-likely source of seeds for ablator mix in the core is the outer surface target quality post-fill*



- Up to 100 isolated defects with total area up to 15,000 μm^2 (1%)
- Optical identification suggests defect thickness >1 μm (but not measured directly)
- Source traced to organics (CH_x), N_2, and CO_2 in the DT fuel supply (i.e., *defects are frozen gas on the surface of the capsule*)

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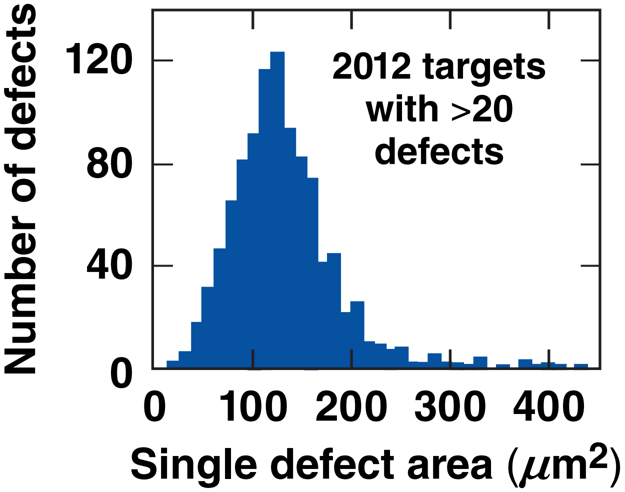
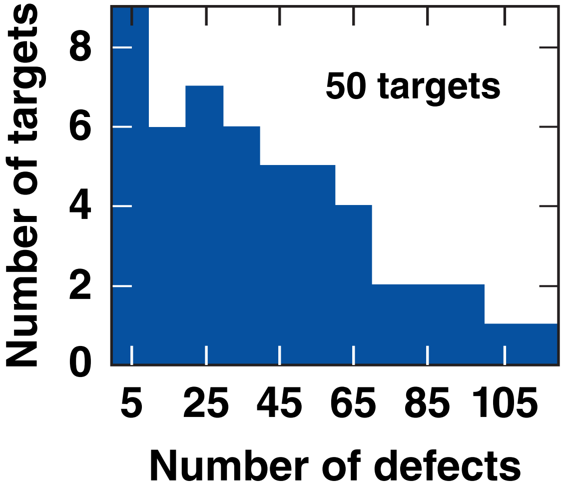
*See I. V. Igumenshchev, JO4.00002, this conference.

The defect size distribution suggests most of the defects will contribute to mix at ignition α and V_{imp}



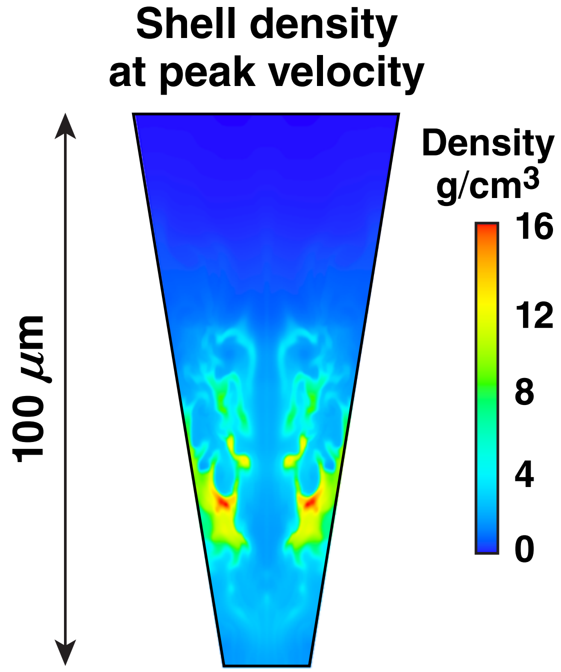


- Two mitigation processes are under development:
  - – a PdAg filter to pass only hydrogen (organics continue to accumulate) January 2013
  - – an isotope separation unit to periodically purify the DT gas (eliminate contaminants)

Simulations suggest that the defect area should be <50 μm^2 with heights of <0.5 μm.

Using the measured defect distribution, 2-D simulations account for the observed performance degradation*

2-D simulation with single isolated defect and reflecting boundary conditions



Shot 66999	Y_n ($\times 10^{13}$)	ρR (mg/cm^2)	T_i (keV)
1-D (NL + CBET)	7.9	238	3.1
2-D defect	1.8	151	2.7
Measured	1.2	175	2.5

TC10253b

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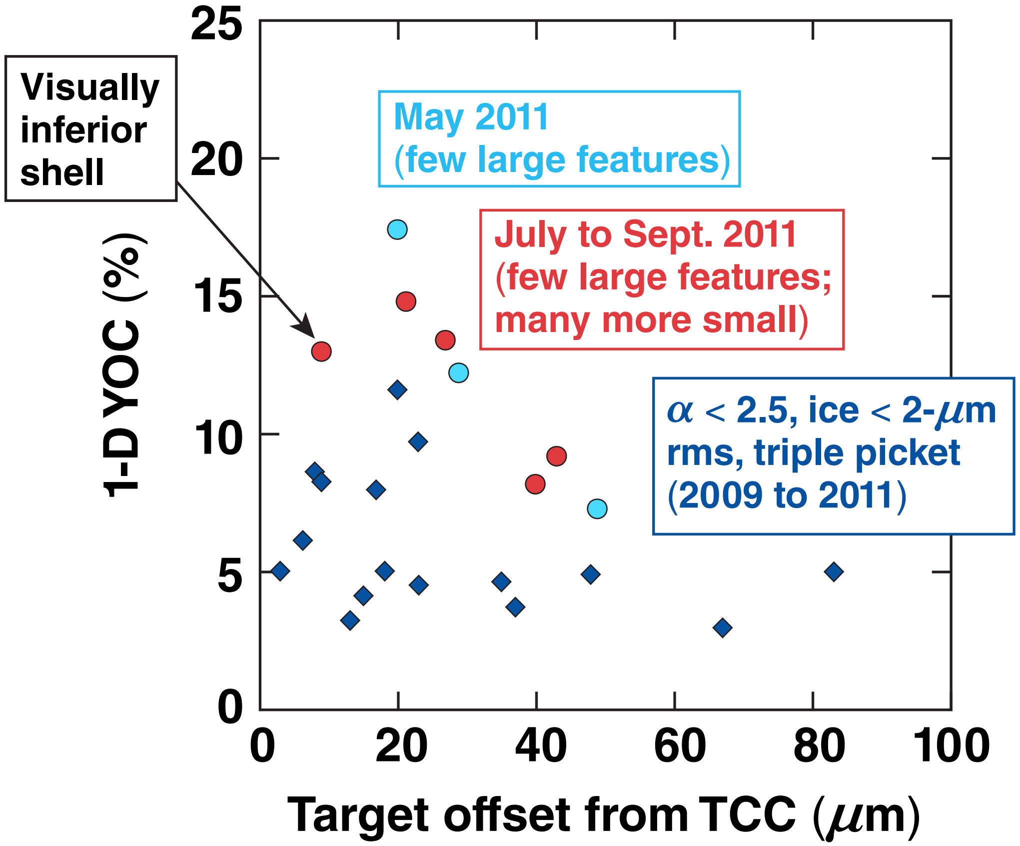
*See I. V. Igumenshchev, JO4.00002, this conference.

The data shown at the 2011 APS meeting confirms that target performance improved with fewer large defects



- The average number of large defects (>140 μm^2) prior to May 2011 was 35 (range from 15 to 63; but sample of only five targets)
- The average number of large defects during May to September 2011 was five (range from 1 to 12)
- Comparable numbers of large defects today (2 to 15 in recent targets)

The initial mitigation step likely eliminated surface particulates rather than gas contaminants.

OMEGA implosion performance can be parameterized by the experimental ignition threshold factor (ITFx)

- The LLNL derived ITFx is given by*
  - ITFx (ID) = $(Y/3.2 \times 10^{15}) \times (\mathrm{DSR}/0.07)^{2.3}$, where DSR (%) = $\rho R(\mathrm{g/cm^2})/21$
- This can be scaled for NIF-equivalent symmetric drive using the relations
  - $\rho R \sim E_L 1/3$ and $Y/M_{\mathrm{fuel}} \sim E_L{}^{0.51}$ and accounting for differences in the perturbation amplitudes
- The NIF-equivalent symmetric-drive ITFx is then**
  - ITFx (NIF equivalent) = $\mathrm{ITFx}(\Omega) \times \left(E_L^{\mathrm{NIF}} / E_L^{\Omega}\right) 1.28 \times \left(M_{\mathrm{NIF}} / M_{\Omega}\right) * \mathrm{YOC_{NIF}} / \mathrm{YOC_{\Omega}}$
  - For $M_{\mathrm{NIF}} = 0.17$ gm, $\mathrm{M}_{\Omega} = 0.02$ gm, $E_L^{\mathrm{NIF}} = 1.8$ MJ, $E_L^{\Omega} = 0.025$ MJ, $\mathrm{YOC_{NIF}} = 50\%$, and $\mathrm{YOC_{\Omega}} = 25\%$

ITFx (NIF Equiv) = 4050 * ITFx (Ω)

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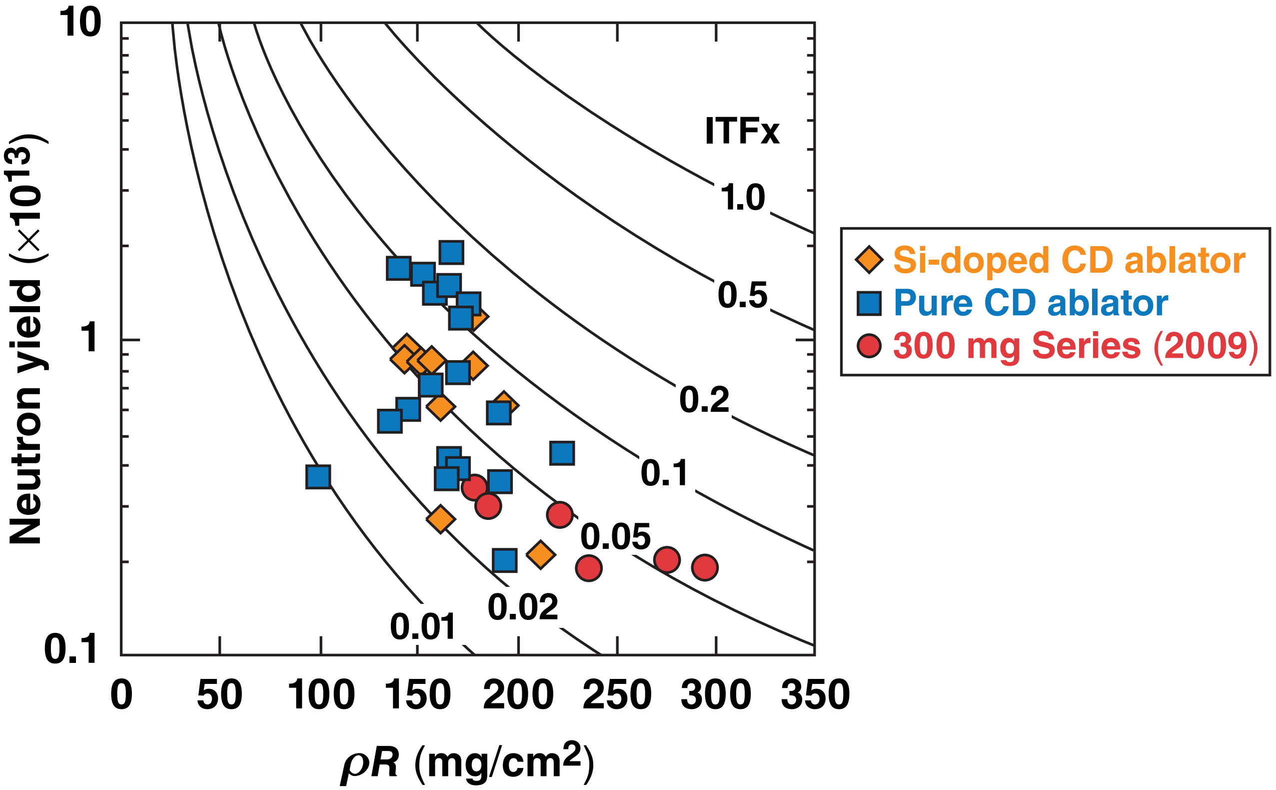
*S. W. Haan *et al*., Phys. Plasmas 18, 051001 (2011).

**R. Betti, "Theory of Ignition and Hydro-Equivalence for Inertial Confinement Fusion," presented at the 24th IAEA Fusion Energy Conference, San Diego, CA, 8–13 October 2012.

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

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



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

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*See G. Fiksel, CO5.00014, this conference.

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)

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*D. H. Edgell, UO5.00001, this conference.
J. A. Marozas, UO5.00003, this conference.

Summary/Conclusions

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