## Dr. David H. Crandall

Dr. Crandall is Advisor on National Security and Inertial Fusion to the Under Secretary for Science at the Department of Energy.

His experience includes 16 years of physics research, 28 years of science program management, and 3 years as Chief Scientist for the National Nuclear Security Administration (NNSA). He has led significant scientific programs in plasma physics and Fusion Energy and in nuclear weapon Stockpile Stewardship prior to his current role. He entered the Senior Executive Service in 1987.

Substituting for Dr. Robert McCrory and the Polar Drive team.

Opening comment: This paper is about using direct drive and seeking a good set of parameters for compression of ICF capsules at low enough adiabat, high enough velocity and low enough Rayleigh-Taylor to reach ignition. The paper will illustrate these general comments. NIF is a highly capable facility and the ICF endeavor now has the opportunity to match that physical facility with research basis created by thinkers/doers. ICF has many avenues to be explored and we in the US have facilities (NIF, Omega, Z) to match with the avenues and the people. The exploration paths are flexible (we can change targets rapidly). Our high energy density science community is growing, vigorous and youthful.- that gives me confidence. The associated weapons and science programs do not require ignition to get value from these facilities; the IFE concept does. Fortunately ignition will also be valuable to the weapon scientists at our labs; we will continue to pursue it both for that reason and for the IFE concept. The DOE requires a proven ignition basis for any substantial IFE program. For scientists this is a wonderful time to match capability to challenge in ICF.

Progress Toward Polar-Drive Ignition for the NIF
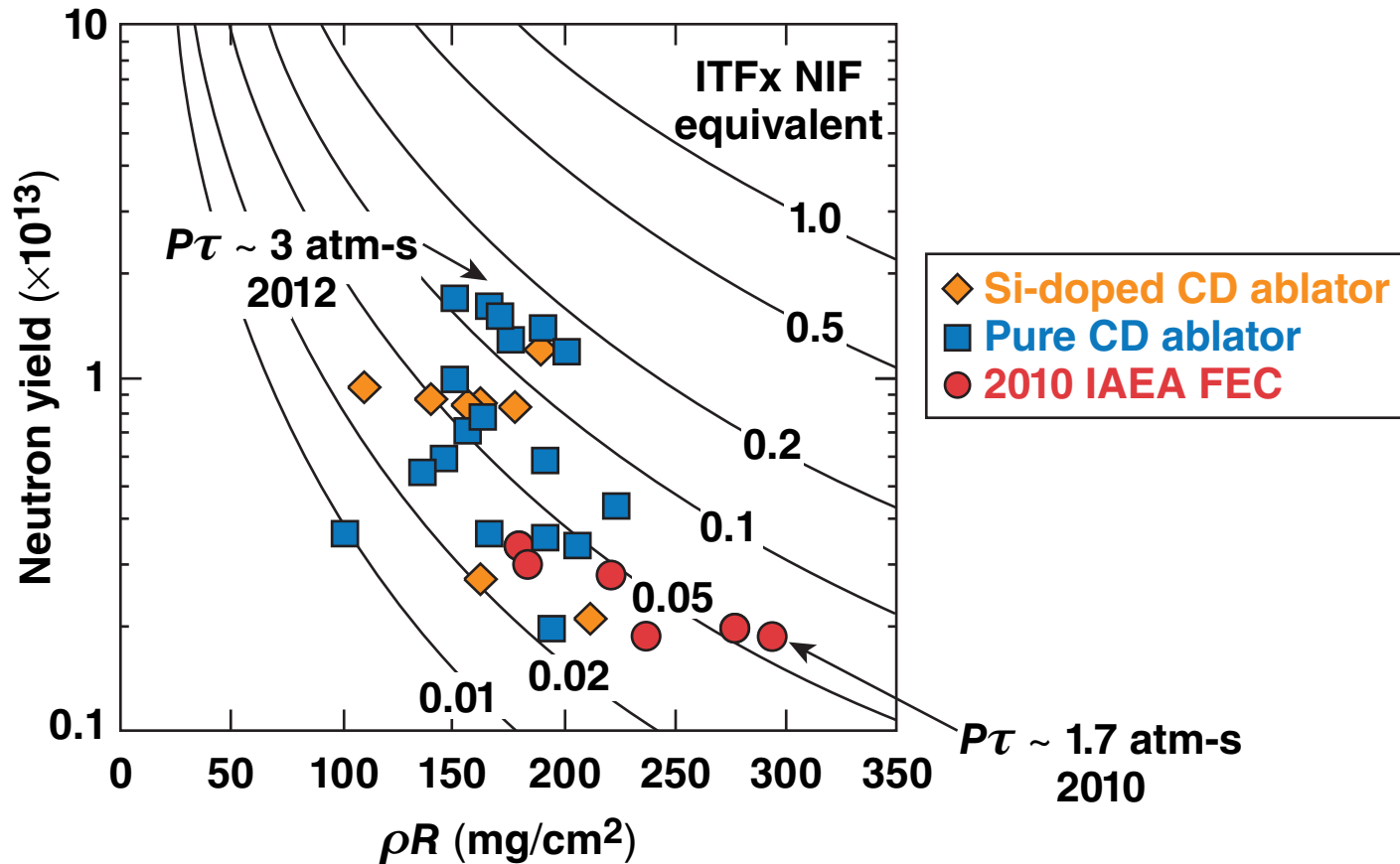
R. L. McCrory
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Professor of Mechanical Engineering
Director, Vice Provost, and Vice President
University of Rochester
Laboratory for Laser Energetics

Summary

Direct-drive inertial confinement fusion (ICF) research has made significant progress since the 2010 IAEA meeting

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- **Polar drive (PD) will allow for direct-drive–ignition experiments at the National Ignition Facility (NIF) in the x-ray-drive beam configuration**

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

- **Performance continues to improve:**
    - **neutron yields exceeding 10^{13} (up to ~20% of clean 1-D simulations)**
        - **ion temperature increased from 2.2 to 3.0 keV**
    - **$P\tau$ increased from 1.7 to 3.0 atm-s**

- **A NIF-scaled experimental ignition threshold factor has increased from 0.05 to 0.15**

- **Progress in developing polar drive is ongoing**
    - **new phase plates will allow polar-drive cryogenic implosions on OMEGA**
    - **Multi-FM beam smoothing has been demonstrated on OMEGA EP**

Initial polar-drive experiments have been carried out on the NIF.

TC10125

Collaborators

D.D. Meyerhofer, [1]*, R. Betti[1]*, T.R. Boehly[1], D.T. Casey[2], T.J.B. Collins[1], R.S. Craxton[1], J.A. Delettrez[1], D.H. Edgell[1], R. Epstein, J.A. Frenje[2], D.H. Froula[1], M. Gatu-Johnson[2], Y.Yu. Glebov[1], V.N. Goncharov[1], D.R. Harding[1], M. Hohenberger[1], S.X. Hu[1], I.V. Igumenshchev[1], T.J. Kessler[1], J.P. Knauer[1], C.K. Li[2], J.A. Marozas[1], F.J. Marshall[1], P.W. McKenty[1], D.T. Michel[1], J.F. Myatt[1], P.M. Nilson[1], S.J. Padalino[3], R.D. Petrasso[2], P.B. Radha[1], S.P. Regan[1], T.C. Sangster[1], F.H. Séguin[2], W. Seka[1], R.W. Short[1], A. Shvydky[1], S. Skupsky[1], J.M. Soures[1], C. Stoeckl[1], W. Theobald[1], B. Yaakobi[1], and J.D. Zuegel[1]

[1]Laboratory for Laser Energetics, University of Rochester

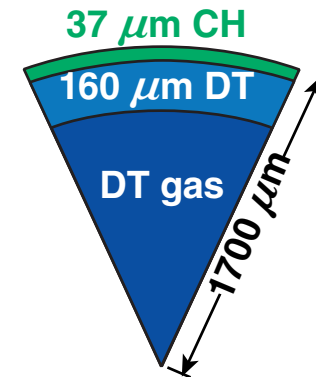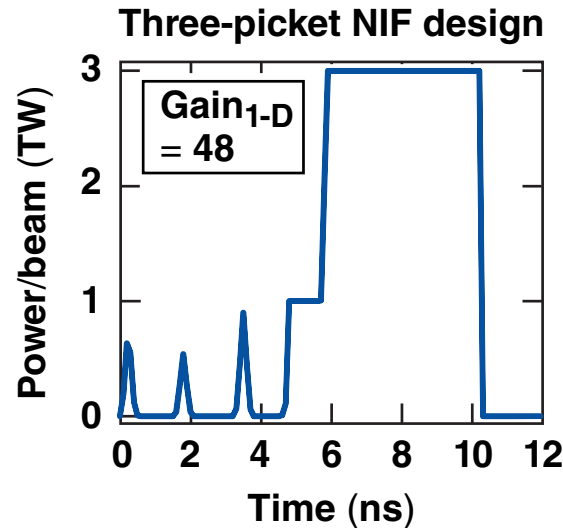[2]Plasma Science Fusion Center, Massachusetts Institute of Technology

[3]State University of New York at Geneseo

*also Depts. of Mechanical Engineering and Physics and Astronomy, University of Rochester
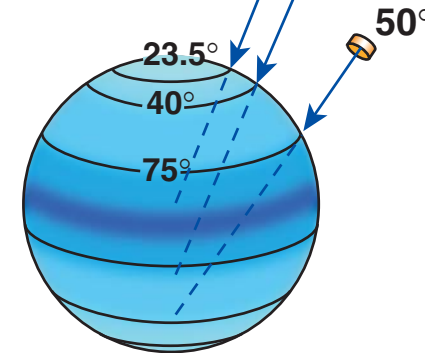
Direct-drive ICF is a viable ignition alternative for the NIF

- **Direct-drive is predicted to couple 7 to 9 times 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 direct-drive–ignition experiments while the NIF is configured for x-ray drive**

Three-picket NIF design

Power/beam (TW) vs Time (ns)

$\text{Gain}_{1\text{-D}} = 48$

37 μm CH
160 μm DT
DT gas
1700 μm

Repointing for polar drive* 23.5° 30° 50°

23.5°
40°
75°

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**

$$\text{IFAR}_{2/3} = R_{2/3}/\triangle_{2/3}$$

  - **IFAR determines of the amplitude of the Rayleigh–Taylor (RT) modulations that disrupt the implosion**

  - **the 1-D minimum energy for ignition, $E_{min} \sim 1/(\text{IFAR})^3$**

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

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

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

OMEGA direct-drive cryogenic target implosions are defining the NIF PD design space
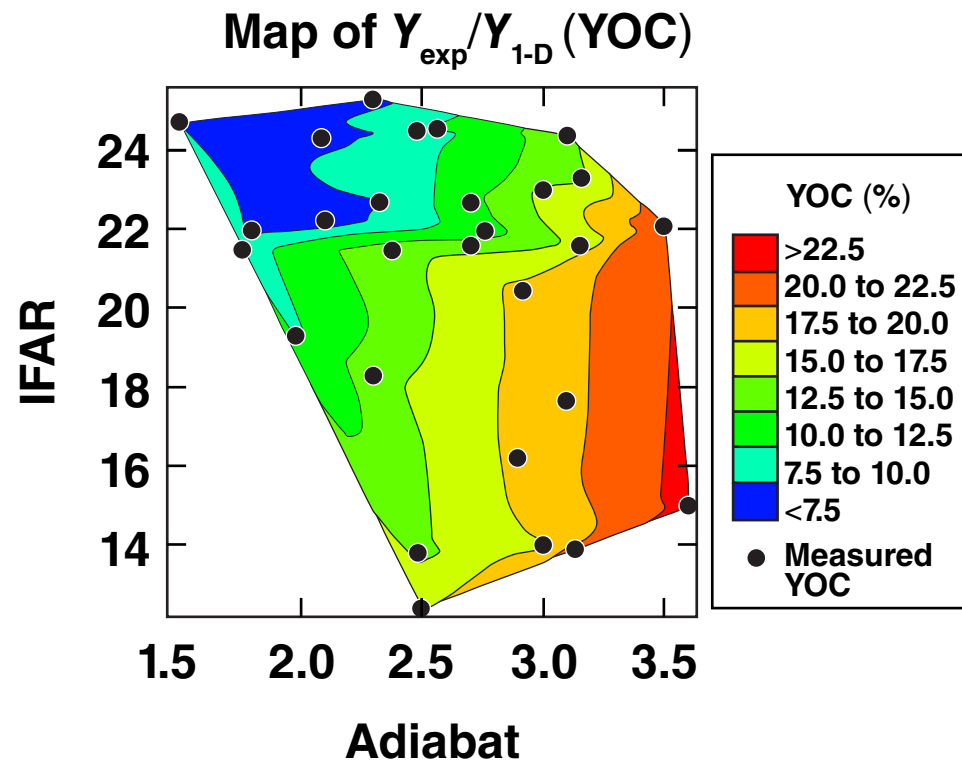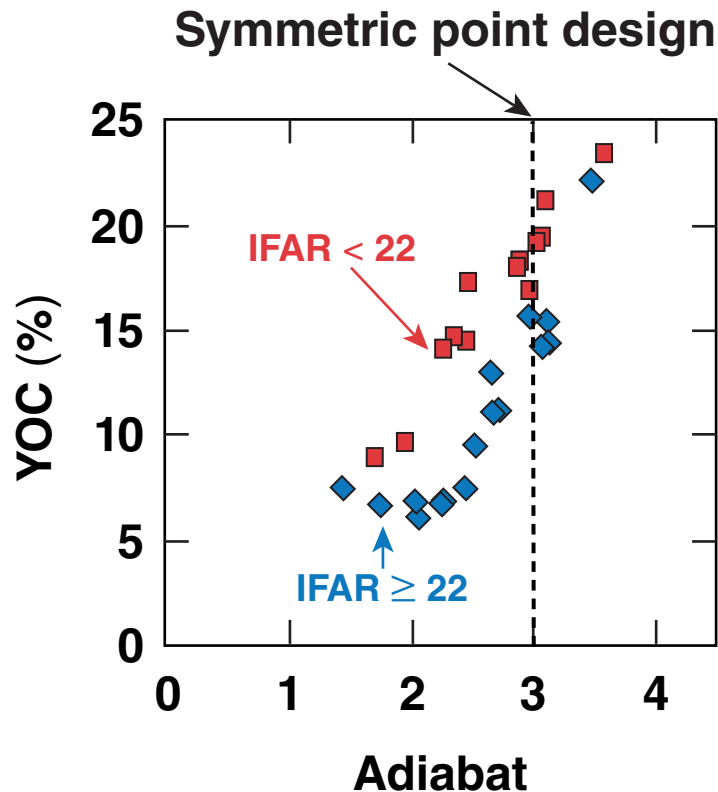
- **The target adiabat is changed with**
  - picket-pulse spacing and heights
  - step on main pulse rise

- **The IFAR is varied through the**
  - ablator thickness
  - ice thickness

- **The implosion velocity is varied through the**
  - target mass
  - laser intensity

Target design

Ablator

DT ice

D_2/DT gas

430 μm

Power (TW)

Time (ns)
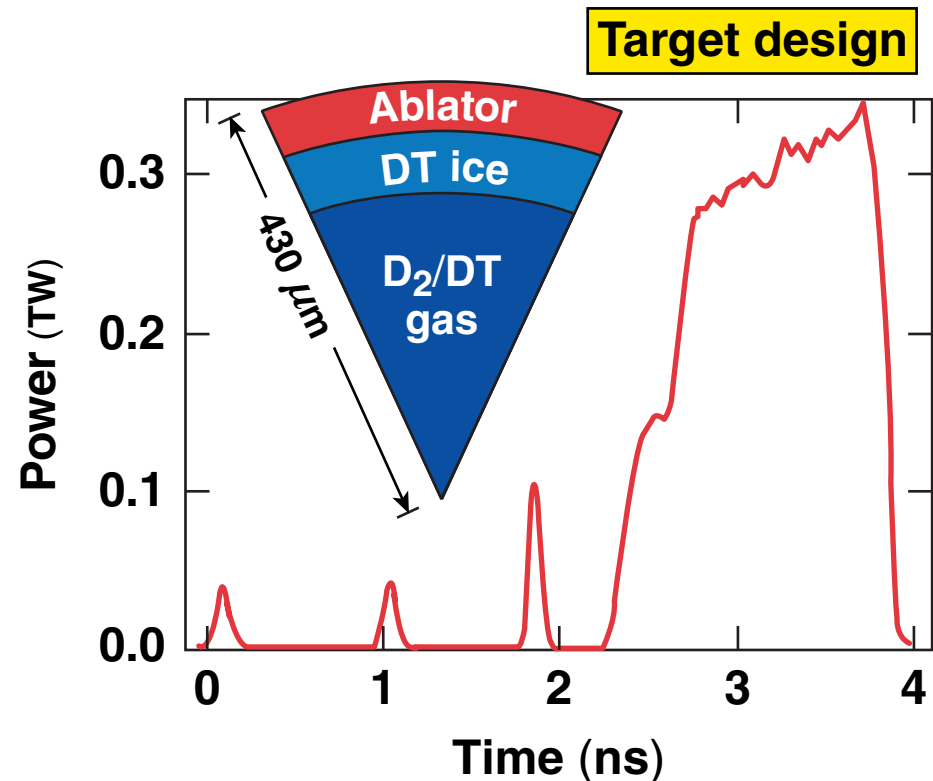
Cryogenic target implosions are validating the physics models used in simulations.

$$P\tau \sim (\rho R)^{0.6} Y_{meas}^{0.34}$$

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

Symmetric point design

Map of Y_{exp}/Y_{1-D} (YOC)

IFAR < 22

IFAR ≥ 22

YOC (%)

Adiabat

IFAR

Adiabat

YOC (%)

>22.5
20.0 to 22.5
17.5 to 20.0
15.0 to 17.5
12.5 to 15.0
10.0 to 12.5
7.5 to 10.0
<7.5

● Measured YOC

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

The areal density is degraded for lower adiabats

Offset <20 μm

$\rho R/\rho R$ (1-D)

Adiabat
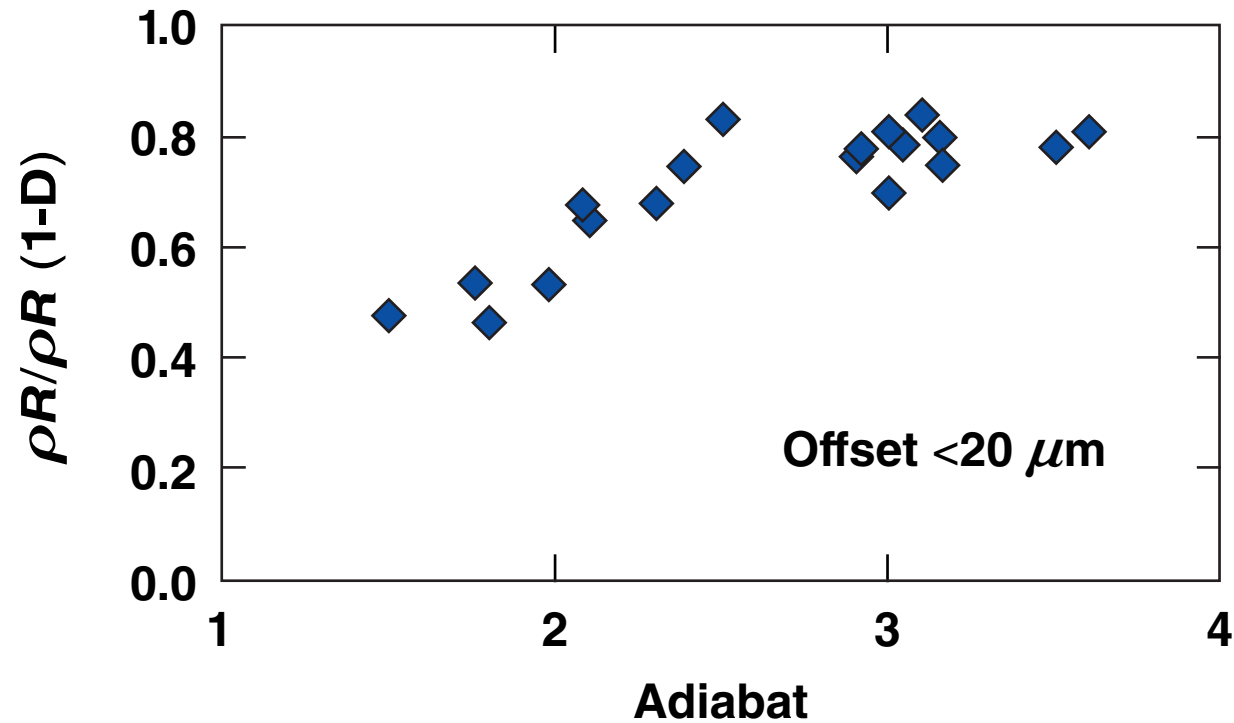
Hydrodynamic scaling suggests less yield degradation due to nonuniformities on NIF

- **Fusion reactions occur in the clean volume (red)**
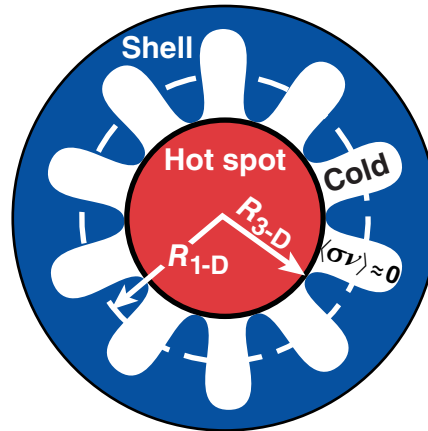
$$YOC = \frac{Y_n^{3\text{-}D}}{Y_n^{1\text{-}D}} \approx \left(\frac{R_{3\text{-}D}}{R_{1\text{-}D}}\right)^3$$

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

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

| RT spike amplitude | Initial seed | Growth factor | Hydro-equivalency |

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

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

TC8660a

Implosion performance can be parameterized by an ignition threshold factor and the Lawson criterion

- **Betti _et al._* derived an ICF Lawson criterion for ICF implosions based on measurable quantities**

$$P\tau\,(\text{atm-s}) \sim 27 \left\langle \rho R\,(\text{g/cm}^2) \right\rangle_n^{0.61} \left[\frac{0.24\, Y_{exp}^{16}}{M(\text{g})_{DT}} \right]^{0.34} \left[\frac{4.7}{\left\langle T\,(\text{keV}) \right\rangle_n} \right]^{0.8}$$

- **LLNL derived an Experimental Ignition Threshold Factor (ITFx)[†]**

    - **ITFx (ID) = $(Y/3.2 \times 10^{15}) \times (DSR/0.07)^{2.3}$,
    where $\rho R\,(\text{g/cm}^2) = 21 \times DSR\,(\%)$**

    - **ITFx = 1 corresponds to a 50% likelihood of ignition**

    - **ITFx $\sim (P\tau)^3$**

- **This formula can be scaled to OMEGA (Ω) energies***

    - **ITFx (NIF equivalent) = ITFx $(ID_\Omega) \times (E_{NIF}/E_\Omega)^{1.28} \times (M_{fuel\ NIF}/M_{fuel\ \Omega})$**

        $$\times YOC_{NIF}/YOC_\Omega$$

    - **$E_{NIF} = 1.8$ MJ, $E_\Omega = 25$ kJ, $M_{fuel\ NIF} = 0.17$ g, $M_{fuel\ \Omega} = 0.02$ g**

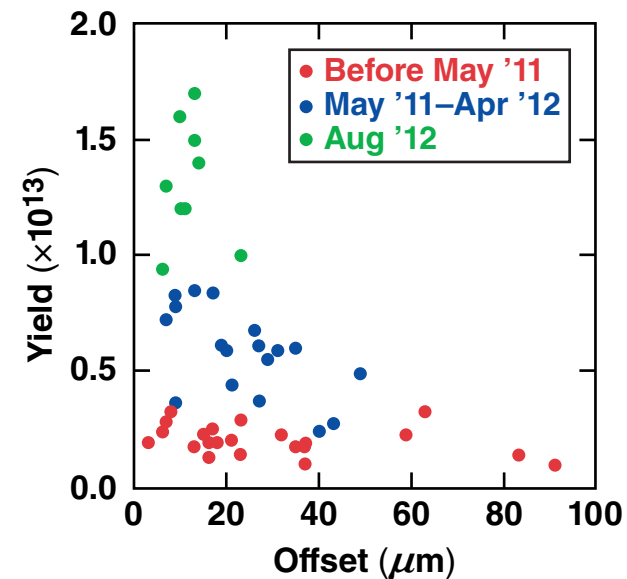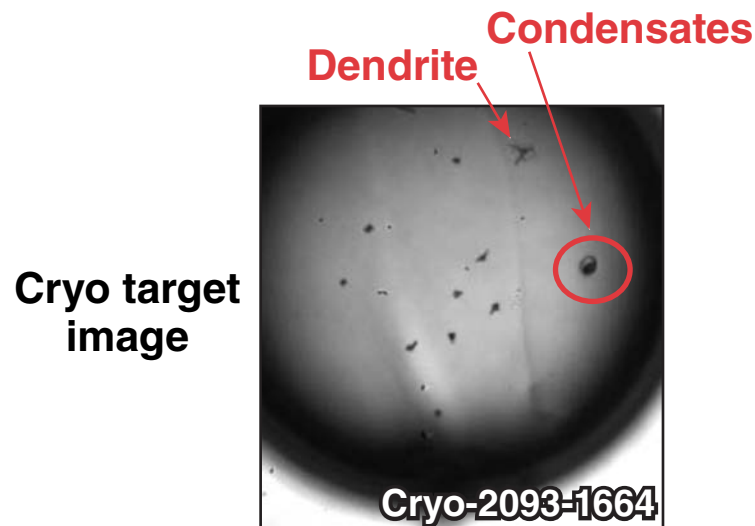† S. W. Haan _et al._, Phys. Plasmas **18**, 051001 (2011).
* C.D. Zhou and R. Betti, Phys. Plasmas **15**, 102707 (2008); R. Betti _et al._,
Bull. Am. Phys. Soc. **54**, 219 (2009); R. Betti _et al._, this conference.

OMEGA ITFx scaled to NIF has increased to ~0.15
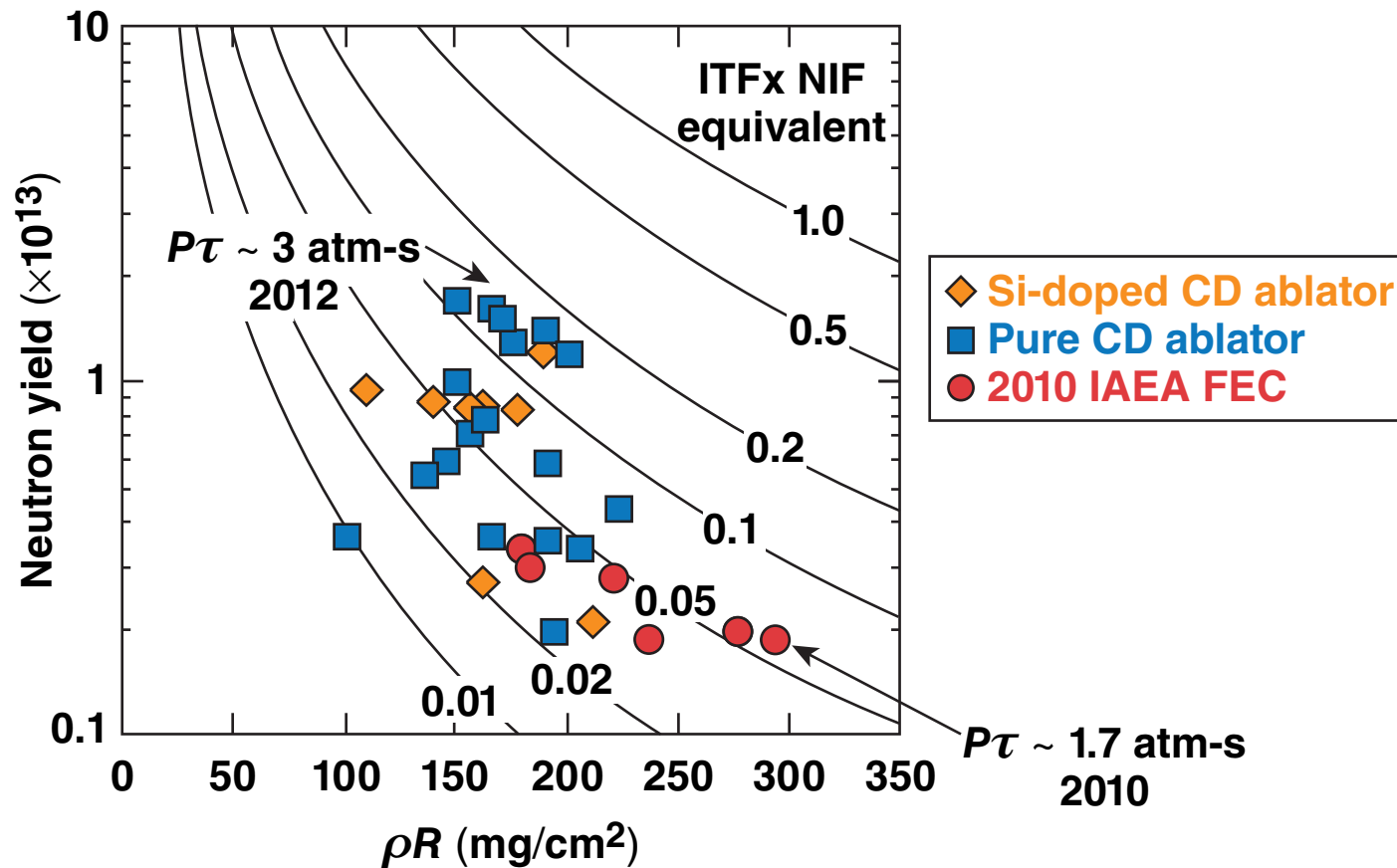
Further improvements in cryogenic target performance are expected over the next year

- **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

Cryo-2093-1664

Dendrite

Condensates

Yield ($\times 10^{13}$)

Offset (μm)

- Before May '11
- May '11–Apr '12
- Aug '12

- **The effects of crossed-beam energy transfer are being understood**

- **Doping the outer part of the ablator with Si or Ge will reduce imprinting and Rayleigh–Taylor (RT) growth**
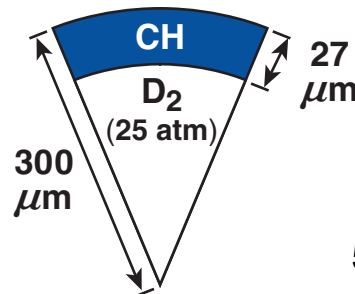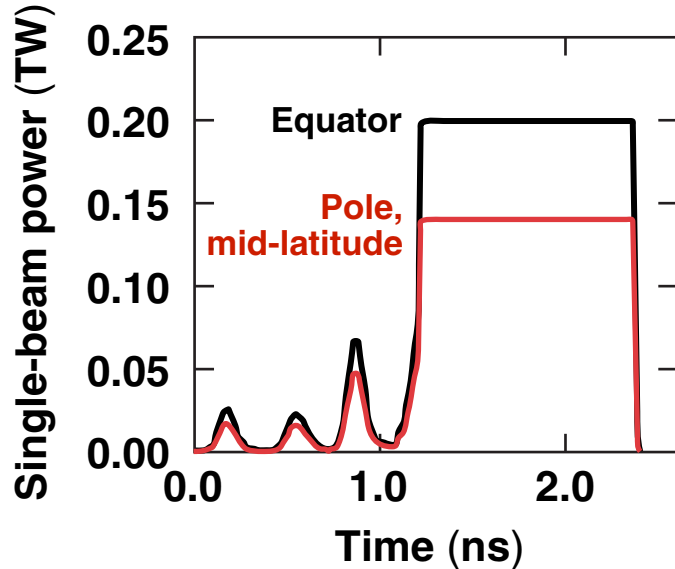
TC10132

High-Z doping of the plastic ablator reduces imprinting and the Rayleigh–Taylor (RT) growth

- High-Z doping inhibits the RT instability through:

  - increased ablation velocity caused by a higher absorption

  - smoothing of the plasma pressure gradients

  - imprint reduction by increasing the standoff distance between the ablation front and the critical surface
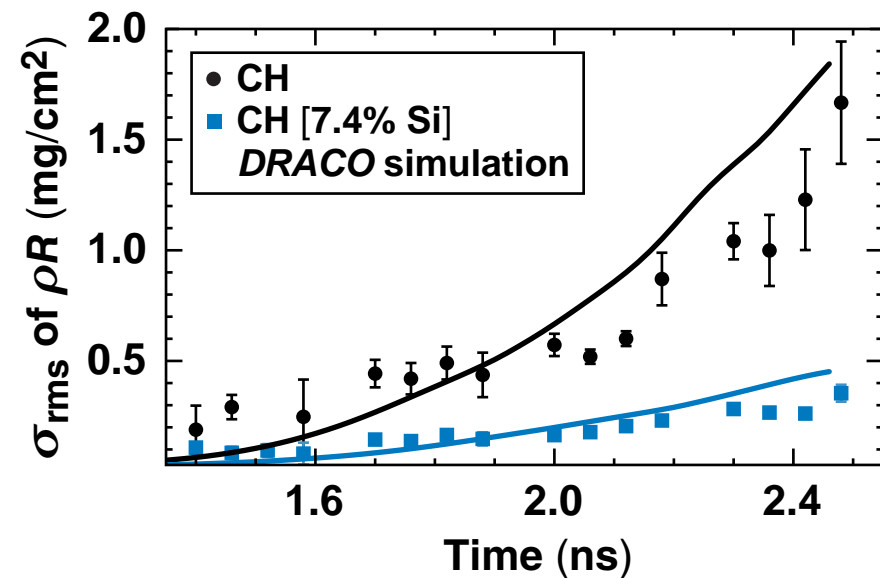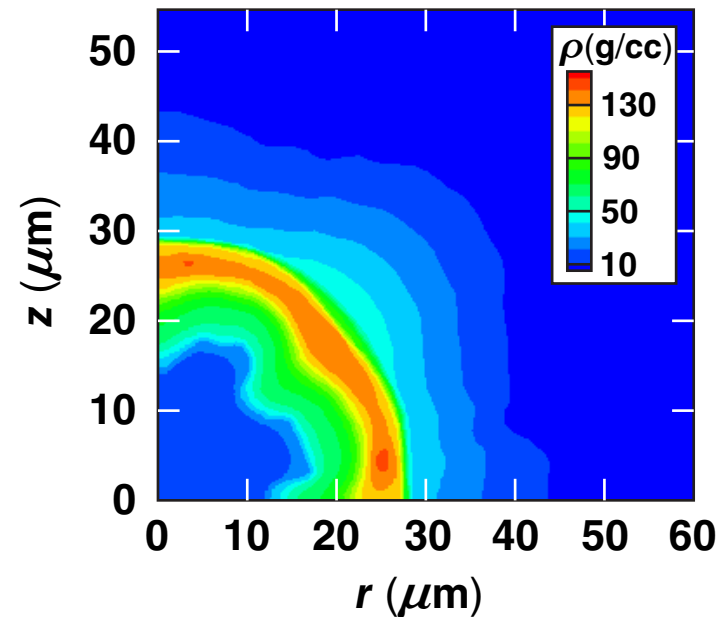

The growth rate is reduced by a factor of 1.5 and the modulation amplitude is reduced by a factor of 4.

*S. X. Hu *et al.*, Phys. Rev. Lett. <u>108</u>, 195003 (2012);
G. Fiksel *et al.*, Phys. Plasmas <u>19</u>, 062704 (2012).

Cryogenic polar-drive–implosion experiments will begin on OMEGA in 2013—new phase plates are being made

Single-beam power (TW) vs Time (ns)

Equator

Pole, mid-latitude

CH

D_2 (25 atm)

27 μm

300 μm

Density contours at peak neutron production

Ring 1, 15 μm, Ring 2, 10 μm, Ring 3, 120 μm

ρ(g/cc)
130
90
50
10

z (μm)

r (μm)

OMEGA far-field spot shapes

Pole and mid-latitude rings

Equatorial ring

1.0
0.7
0.3
0.0

y (μm)

x (μm)

x (μm)
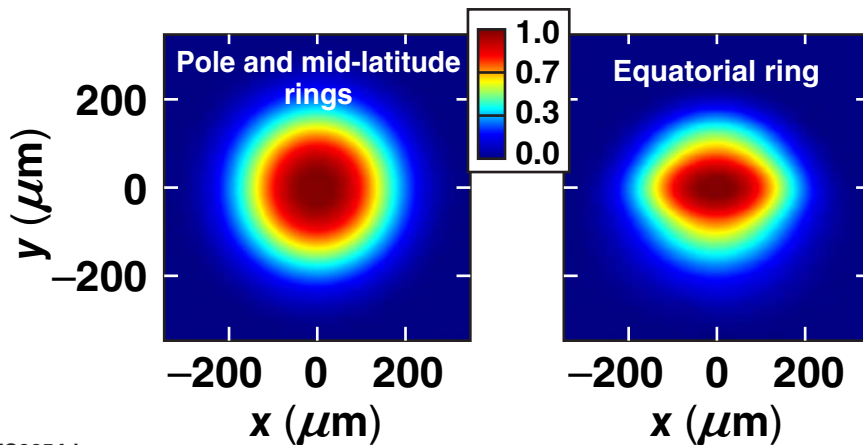
Yield ratio (PD/symmetric) = 65%
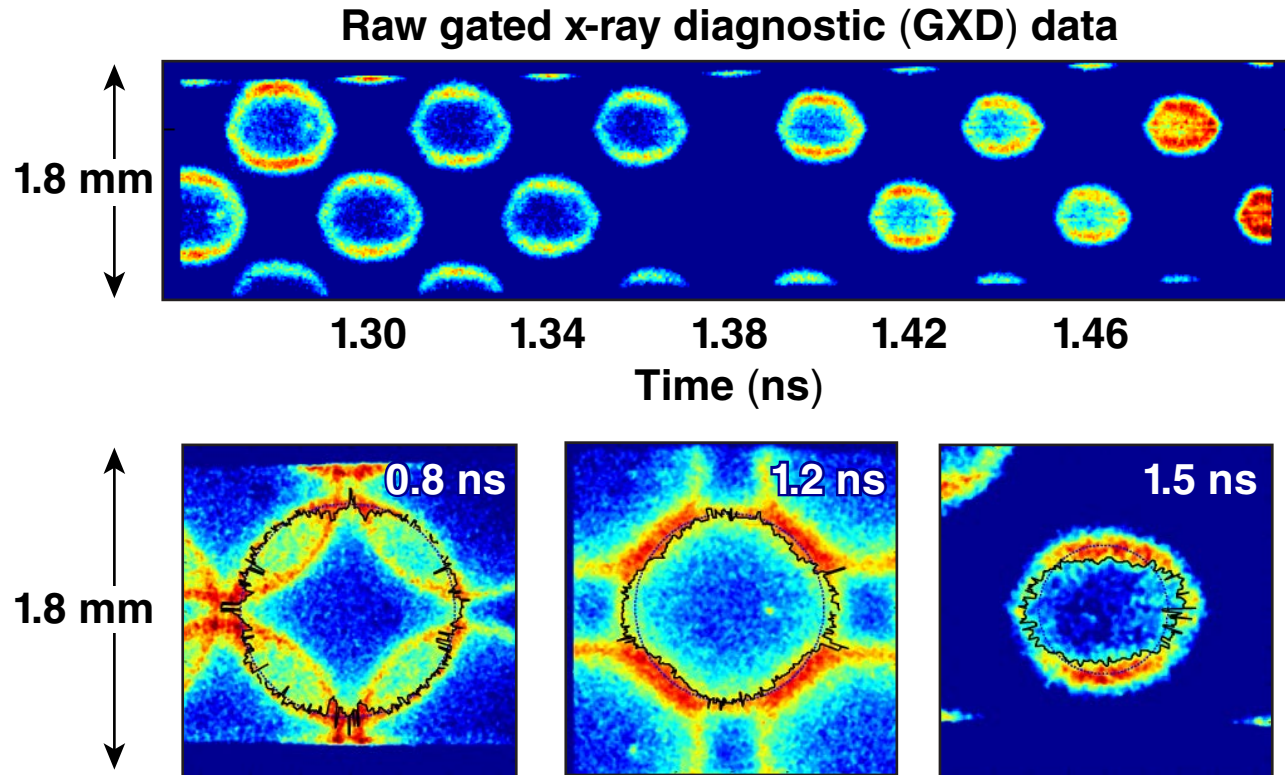**BT (symmetric) − BT (PD) = −20 ps**

TC9654d

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
  $36 \to 30$

- 2-D gain ~70, with PD illumination only

- 2-D simulations with full NIF nonuniformities are underway; expect a gain of ~30
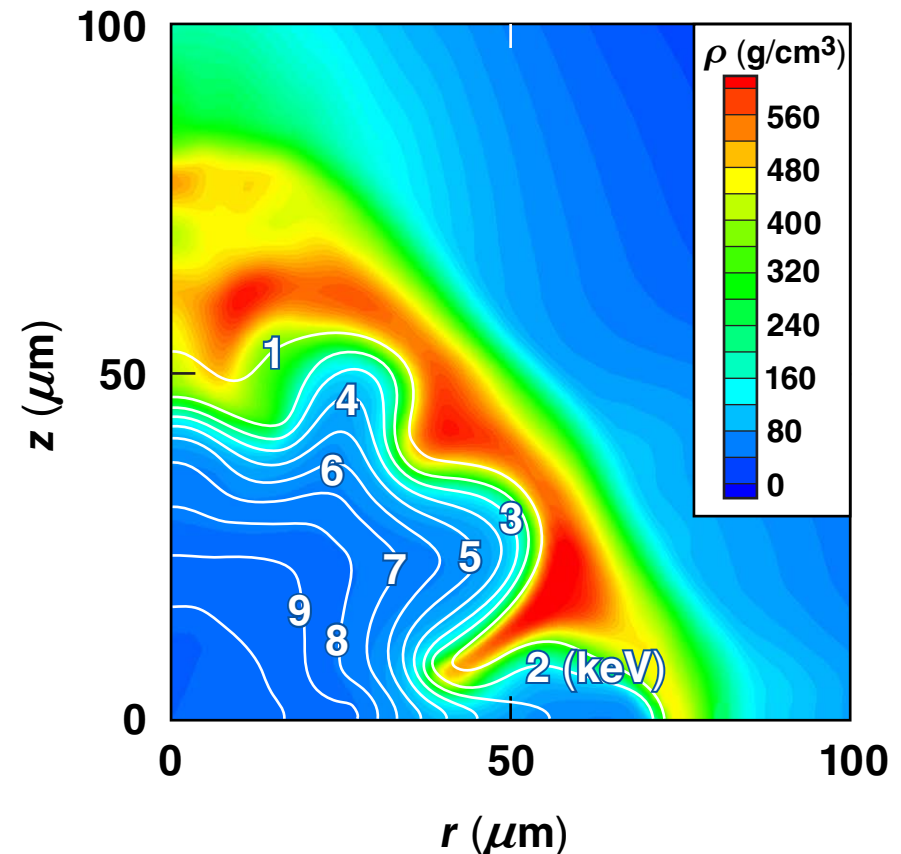
LLE is using NIF polar-drive diagnostic commissioning shots to tune the symmetry

Raw gated x-ray diagnostic (GXD) data

1.8 mm

1.30   1.34   1.38   1.42   1.46

Time (ns)

1.8 mm

0.8 ns   1.2 ns   1.5 ns

- **The shell trajectory can be determined by properly setting the GXD filtration**

- **The PD exploding-pusher glass shell becomes oblate well before bang time**

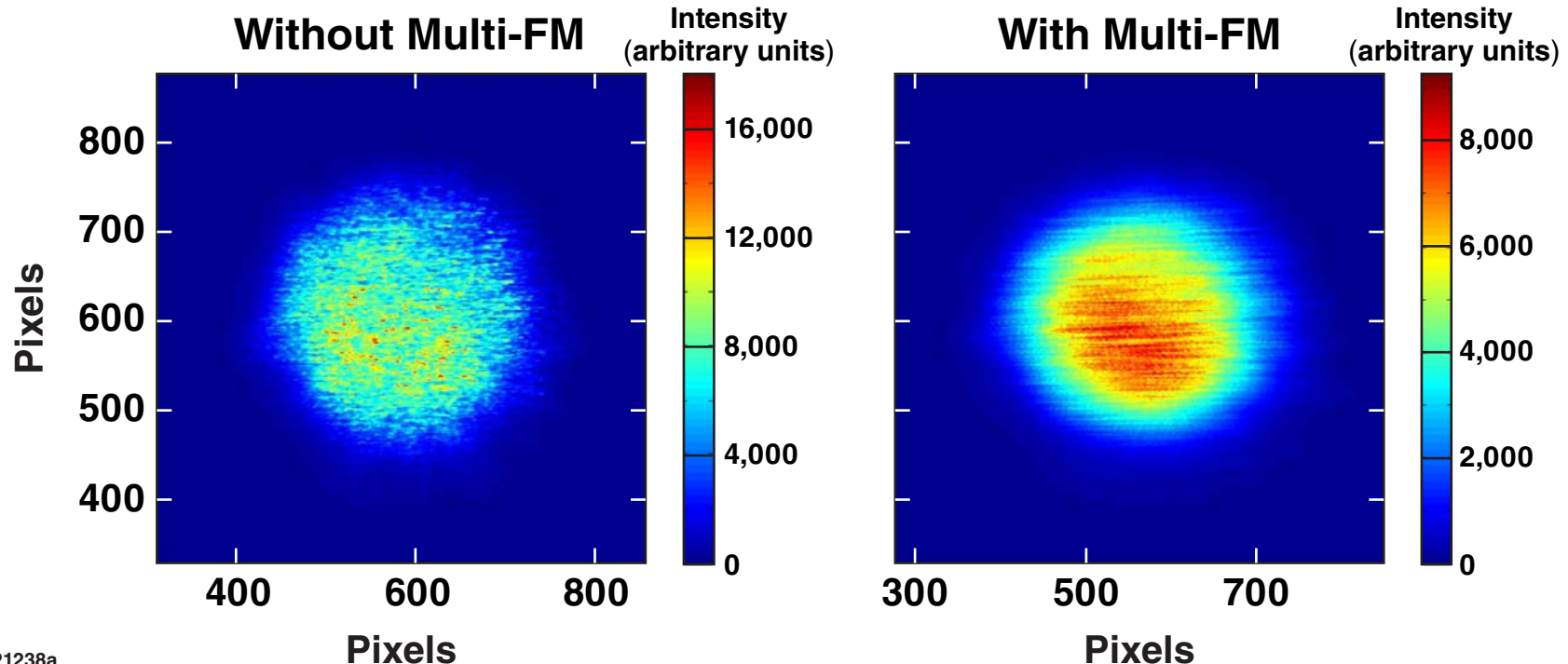# Implementing PD requires five changes on the NIF for an ignition demonstration

1 Add Multi-FM fiber front end and combine with existing system

3 **4** New PD phase plates (2ω) and polarization plates (3ω) in final optics assembly

2 Add new SSD grating to 48 preamplifier modules (PAM's)

5 New PD ignition target insertion cryostat (PD-ITIC)
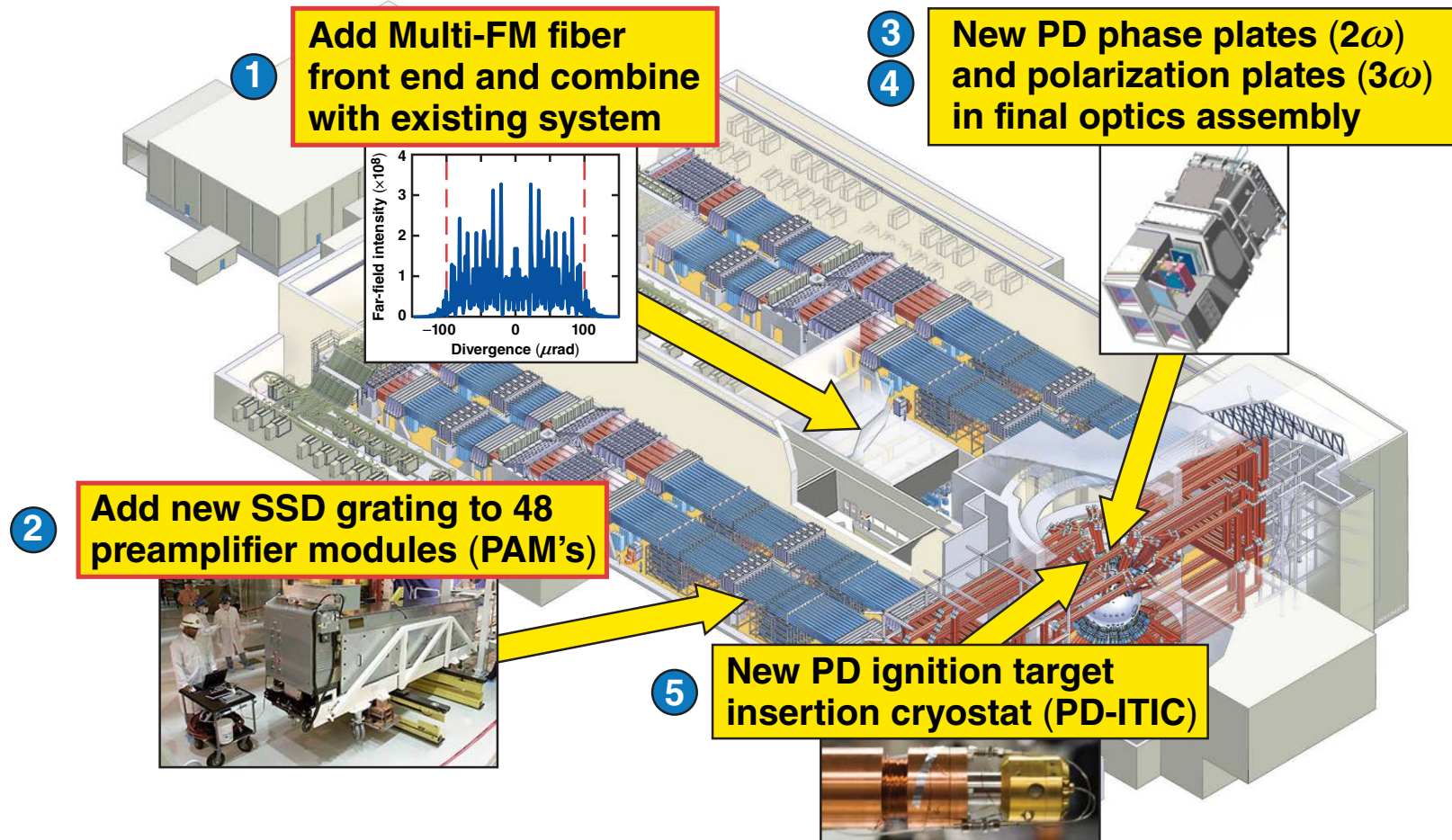
Laser technology required for polar-drive ignition on the NIF is being using a NIF PAM demonstrated on OMEGA EP.

E19668g

Multi-FM smoothing by spectral dispersion (SSD) has been activated on an OMEGA EP beamline

- Equivalent-target-plane images, without and with Multi-FM SSD, show expected smoothing
  - 100-ps laser pulse
  - spatial magnification being measured, ~1-mm-diam spot

- Imprint measurements have been made and are being analyzed

Without Multi-FM

With Multi-FM

E21238a

Direct-drive inertial confinement fusion (ICF) research has made significant progress since the 2010 IAEA meeting

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LLE

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