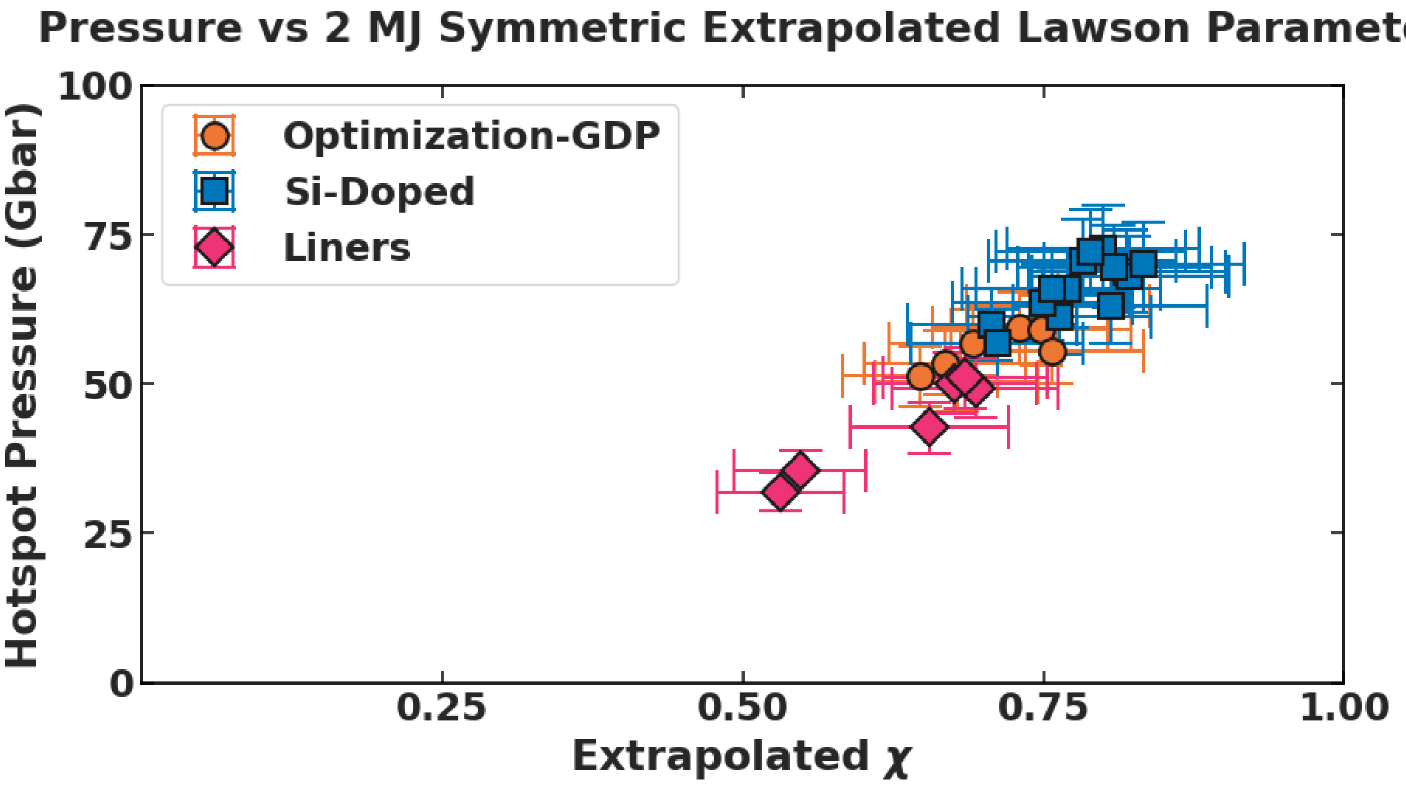
Accomplishments of the 100 Gbar Campaign on OMEGA



S. P. Regan *et al.*
University of Rochester
Laboratory for Laser Energetics

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Division of Plasma Physics
Spokane, WA
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Summary

Understanding and mitigating the degradation mechanisms of Laser Direct Drive (LDD) implosions is the goal of the 100 Gbar Campaign

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R&D of implosion physics of DT cryogenic targets and improvements to lasers, targets, and diagnostics led to:

- ❑ an increase of the stagnation pressure from 50 Gbar to 80 Gbar
- ❑ an increase in the energy-scaled, generalized Lawson criterion*,** from 0.56 to 0.8 to reach burning plasma conditions at NIF scale (1.0 corresponds to ignition)

Multiple paths to hydroequivalent ignition with LDD are being pursued:

- ❑ Statistical modeling with current OMEGA capabilities and target solutions to mitigate LPI and laser imprint
- ❑ Next-generation, broad-bandwidth lasers (OMEGA Next)

Related APS DPP 2022 talks:	
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Williams NI02.00004	Gopalaswamy CO04.00006
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Betti CO04.00004	Edgell UO05.00015

* Betti et al., Physical Review Letters 114, 255003.
** Bose et al., Physical Review E 94, 011201(R).

Collaborators

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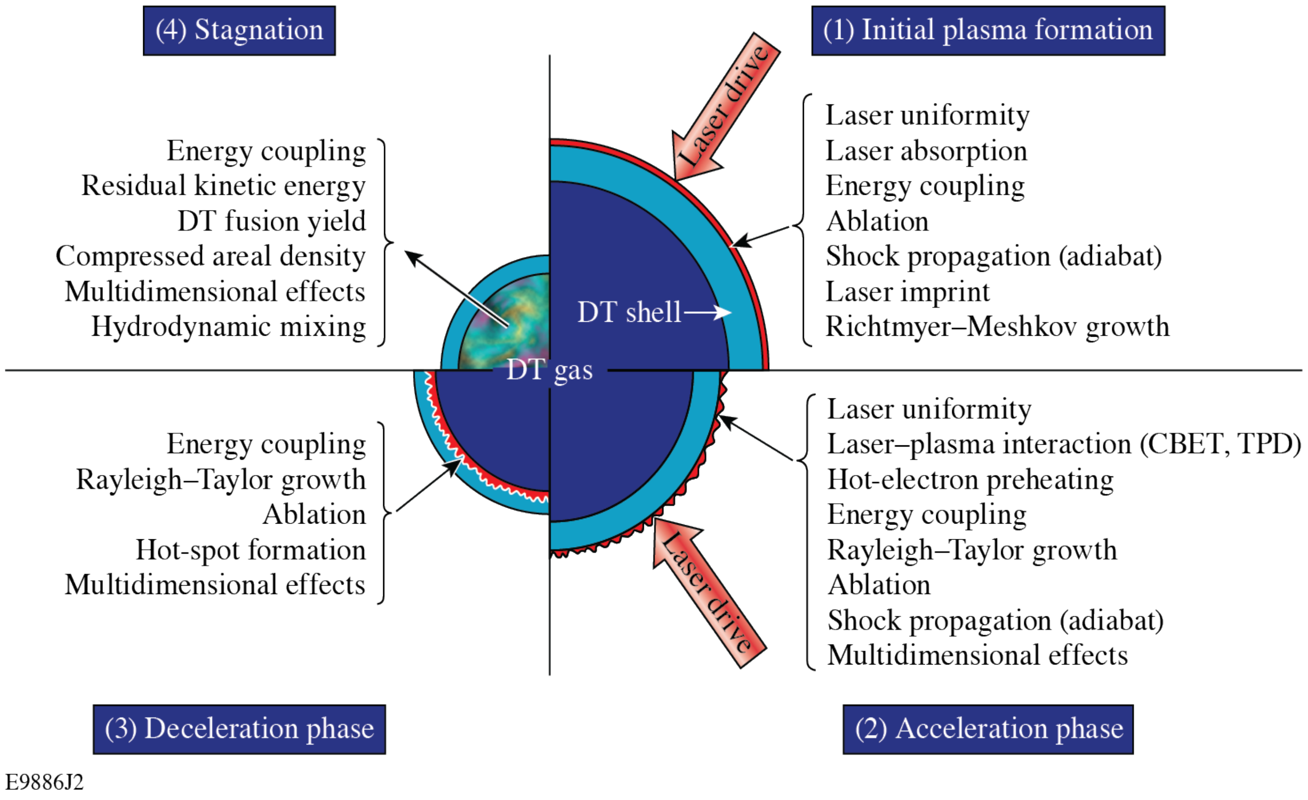
9) Los Alamos National Laboratory, Los Alamos, NM USA

Key physics areas of Laser Direct Drive are studied in the 100 Gbar Campaign*

Laser Direct Drive (LDD) Inertial Confinement Fusion



100 Gbar Campaign accomplishments:

- motivated and drove improvements in laser performance and target fabrication
- spurred innovations in machine learning data analysis techniques
- laser and target solutions to mitigate implosion degradation mechanisms
- 3-D diagnostics to understand implosion symmetry and the flow velocity of the fusing hot-spot plasma
- tunable OMEGA P9 beam for focused Laser Plasma Interaction (LPI) experiments
- next-generation, broad-bandwidth lasers to mitigate LPI and laser imprint

The nominal hot-spot pressure [P_{ign}~$(E_{hs})^{-1/2}$] needed for LDD ignition is ~100 Gbar.*

* V. N. Goncharov et al., "National Direct-Drive Program on OMEGA and the National Ignition Facility," Plasma Phys. Control. Fusion 59 (1), 014008 (2017).
E. M. Campbell et al., "Laser-Direct-Drive Program: Promise, Challenge, and Path Forward," Matter Radiat. Extremes 2 (2), 37–54 (2017).
S. P. Regan et al., "The National Direct-Drive Inertial Confinement Fusion Program," Nucl. Fusion 59 (3), 032007 (2019).

OMEGA implosion performance is assessed through yield and areal density measurements; the inference of a normalized Lawson parameter is hydrodynamically scaled to ~2 MJ of symmetric illumination with same absorption fraction as OMEGA

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- **Lawson parameter for ICF***

Measured with nuclear diagnostics

$$\chi_{3D} = \frac{nT\tau}{[nT\tau]_{ign}} \approx \left\langle \rho R_{g/cm^2} \right\rangle_{3D}^{0.61} \left(\frac{0.12 Yield_{16}}{M_{DTstag}^{mg}} \right)^{0.34}$$

LDD (2 MJ, SDD): 0.12 - 0.16 MJ coupled to imploding shell

- **Hydrodynamic scaling****

$$\chi \sim P\tau \sim \tau \sim R \sim E_L^{1/3}$$

- **Scaled ignition**

$$\chi_{MJ} \equiv \chi_{OMEGA} \left(\frac{E_L(MJ)}{E_{Laser}^{OMEGA}} \right)^{1/3} \Rightarrow 1$$

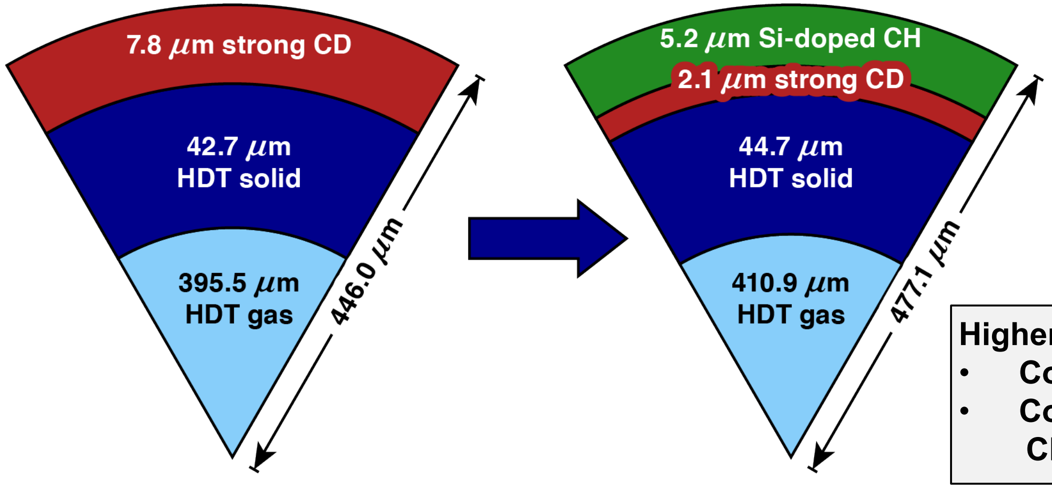
For ignition

About 4.2x for 2MJ

Hydroequivalent ignition: χ=1 at ≈ 2MJ

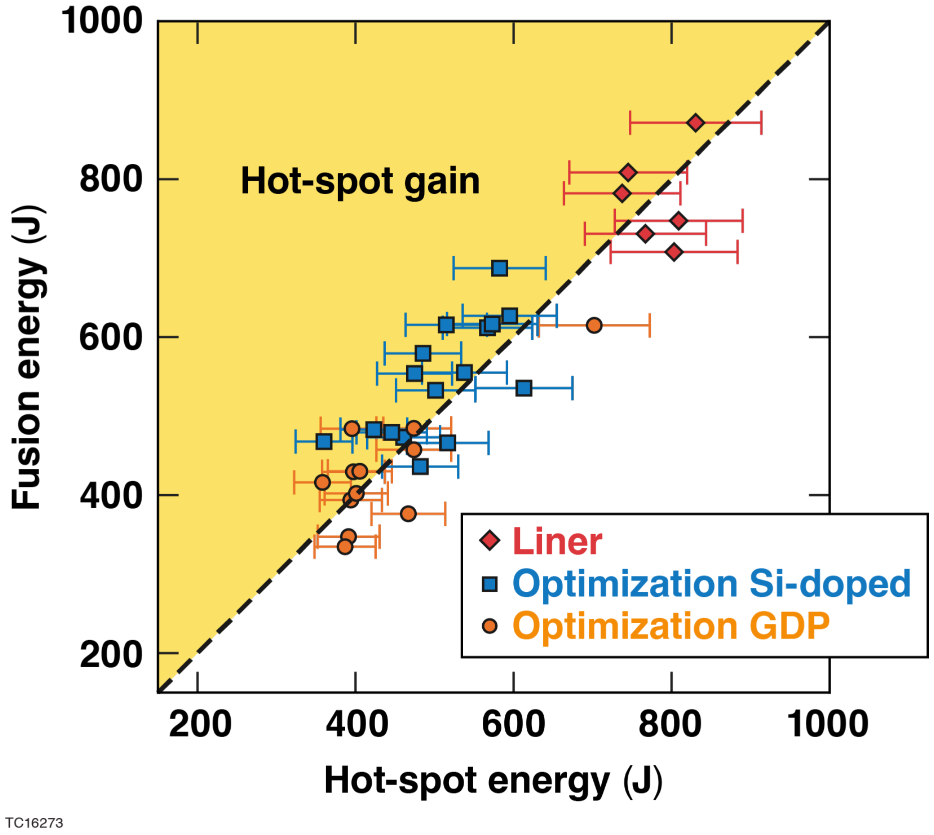
* Betti et al., Physical Review Letters 114, 255003.
** Bose et al., Physical Review E 94, 011201(R).

OMEGA cryo implosions with Si-doped shells have recently been implemented to increase laser coupling and mitigate hot electrons



Higher $\langle Z \rangle$ increases
- Collisional Absorption
- Coronal Temperature → CBET, TPD mitigation

	CD (Shot 99922)	CHSi (Shots 102154/ 102162/10177)
Experimental yield	1.6×10^{14}	2.0 to 2.25×10^{14}
HXRD (pC)	195±24	53±16
Absorption fraction	66% (LILAC) 59±5% (experiment)	73% (LILAC) 69±5% (experiment)

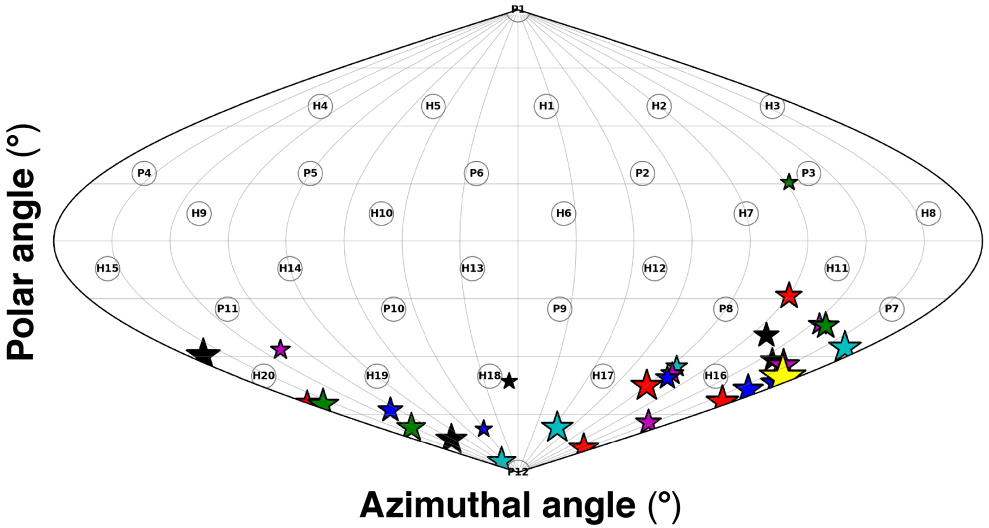


Williams NI02.00004
Farmakis CO04.00003
Gopalaswamy CO04.00006
Churnetski CO04.00007

Target solutions with Si-doped targets to mitigate LPI led to the highest yields to date.

With improved beam pointing, beam-to-beam energy/power imbalance, inaccuracies in target positioning, and laser–plasma interactions‡ are the leading causes for the hot-spot flow*,**,†

Hot-spot flow velocity for DT cryogenic target implosions



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Hot-spot flow velocity:
- 30 to 150 km/s
- average direction (θ,ϕ) = (142°,171°)

Heuer BO04.00008
Kunimune BO04.00011
Churnetski CO04.00007
Edgell UO05.00015

ℓ-mode amplitudes of drive asymmetry♯

ℓ mode	Beam pointing (worst)**	Beam pointing (typical)	Energy / power imbalance (typical)	Target positioning (typical)	LPI effects‡
1	~5%	~1-1.5%	~0.5-1%	~0.5%	~0.4%

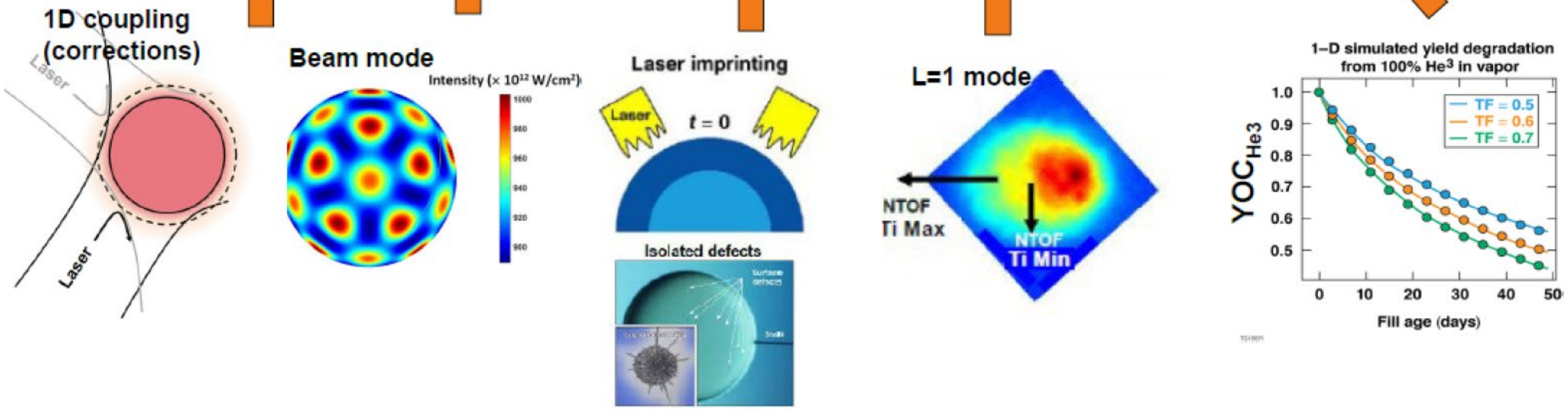
Maximum acceptable amplitude for low-mode drive asymmetry is now included in the beam-pointing specification.

* O. M. Mannion *et al*., Nucl. Instrum. Methods Phys. Res. A 964, 163774 (2020).
** O. M. Mannion *et al*., Phys. Plasmas 28, 042701 (2021).
† O. M. Mannion *et al*., Rev. Sci. Instrum. 92, 033529 (2021).
‡ D. H. Edgell *et al*., Phys. Rev. Lett. 127, 075001 (2021).
‡ A. Colaitis et al., "3D Simulations Capture the Persistent Low-Mode Asymmetries Evident in Laser-Direct-Drive Implosions on OMEGA," submitted to PRL.
♯ W. Theobald *et al*., "Report on the status of OMEGA laser-beam pointing and its effects on laser drive uniformity," Laboratory for Laser Energetics (2021).

Each degradation mechanism affecting the fusion yield has been quantified by statistical mapping to the experimental data*,**

CBET/1D physics? | Beam mode | Short wavelengths | $\ell=1$ | T-decay

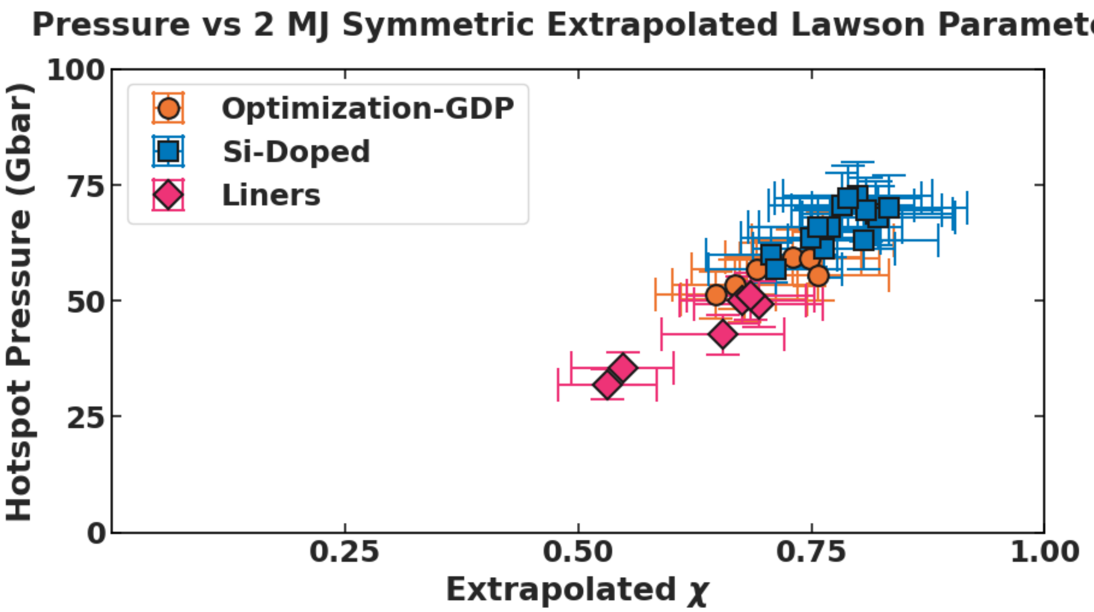
$$YOC \sim \left(\frac{Rb}{Rt}\right)^{b_1} e^{-(b_2+b_3\alpha+b_4 CR)\sigma_{rms}^{b_5}} \left(\frac{\alpha_F^{b_6}}{IFAR}\right)^{b_7,b_8} Max\left[\left(\frac{T_{max}}{b_9 T_{min}}\right),1\right]^{b_{10}} YOC_{He3}^{b_{11}}$$

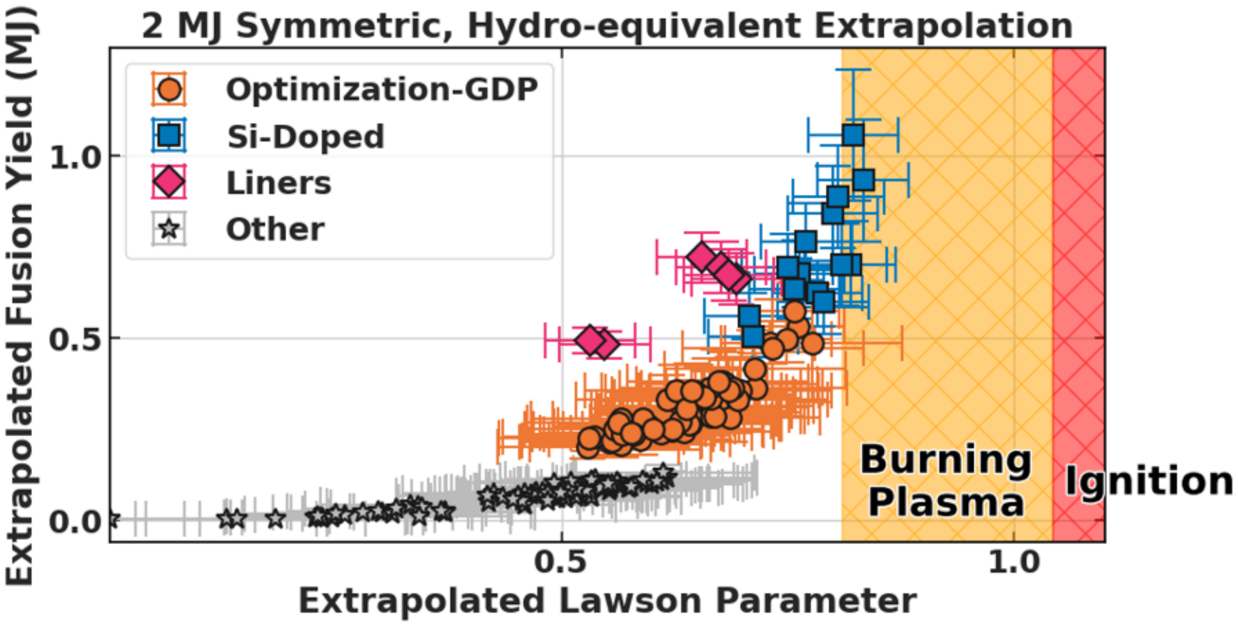


The 100 Gbar Campaign spurred innovations in machine learning data analysis techniques for LDD DT cryogenic implosions.

*V. Gopalaswamy *et al.*, "Tripled Yield in Direct–Drive Laser Fusion Through Statistical Modelling," *Nature* 565 (7741), 581-586 (2019).
**A. Lees *et al.*, "Experimentally Inferred Fusion Yeld Dependencies of OMEGA Inertial Confinement Fusion Implosions," Phys. Rev Lett. 127, 105001 (2021).

R&D of implosion physics of DT cryogenic targets and improvements to lasers, targets, and diagnostics improved LDD performance





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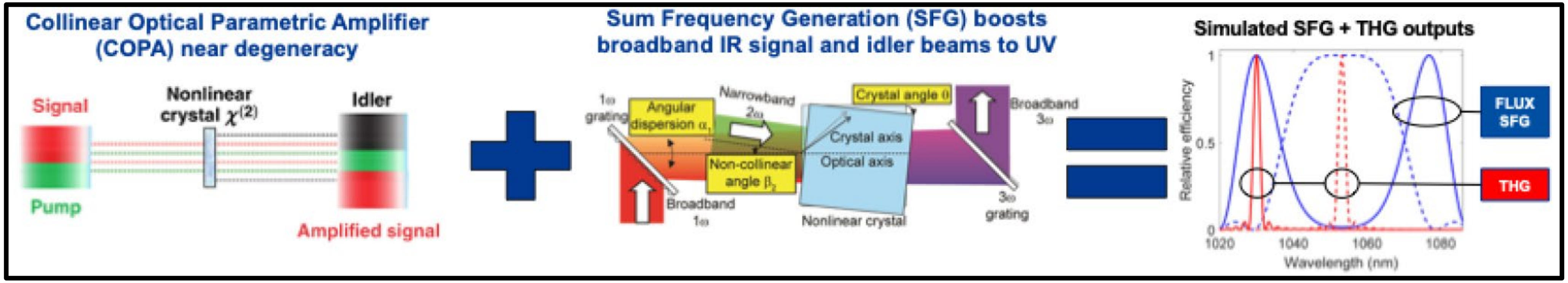
** Bose et al., Physical Review E 94, 011201(R).

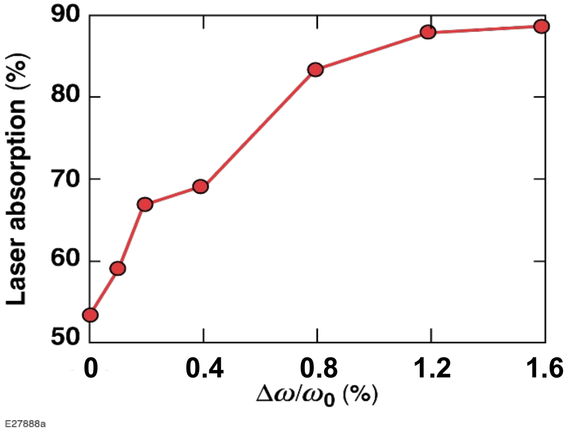
Broad-bandwidth, direct-drive lasers can mitigate laser-plasma instabilities (LPI) and couple higher intensities to ICF capsules*

FLUX**
(350 nm, 10-15 THz)



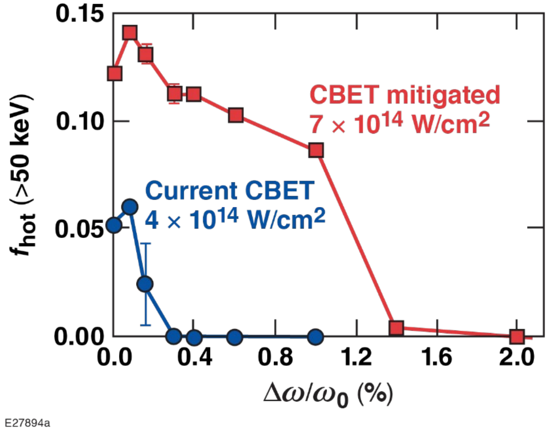
Cross-Beam Energy Transfer (Increased Drive Pressure)

Follett *et al.*, PRL **120**, 135005 (2018)

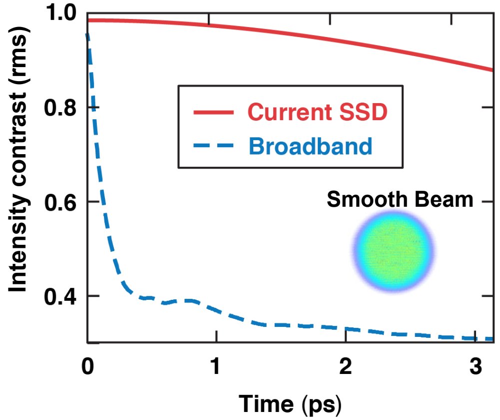


Hot-Electron Mitigation (n_{cr} / 4 ignition intensities)

Follett *et al.*, Phys. Plasmas **26**, 062111 (2019)



Imprint Mitigation (ps asymptotic smoothing)



Marozas CO04.00015

LPI and laser imprint experiments with the FLUX beamline are being planned for FY24.

FLUX: Fourth Generation Laser for Ultrabroad Experiments
SSD: Smoothing by Spectral Dispersion

* R. Follett *et al.*, Phys. Plasmas 28, 032103 (2021)

**C. Dorrer, E. M. Hill, J. D. Zuegel, *Opt. Express* 28, 451–471 (2020).
C. Dorrer et al., *Opt. Express* 29, 16135-16152 (2021).

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* Betti et al., Physical Review Letters 114, 255003.
** Bose et al., Physical Review E 94, 011201(R).

Future research directions

- Determine limit of energy scaled, generalized Lawson criterion on OMEGA
  - Characterize DT cryogenic targets with Coherent Anti-Stokes Raman Spectroscopy (CARS)
  - Demonstrate foam overcoats reduce laser imprint
  - Statistical modeling with current OMEGA capabilities and target solutions to mitigate LPI and laser imprint
  - Develop 4π average ρR diagnostic and optimize ρR using statistical modeling
  - 3-D Reconstruction of Implosion including multi-dimensional simulations
  - Achieve higher compression implosions (lower adiabat)
  - Increase energy-scaled, generalized Lawson criterion from 0.8 to 1.0
  - Fill-tube target
- Broad bandwidth experiments for LPI and laser imprint using FLUX laser beamline
  - Foundational R&D for OMEGA Next

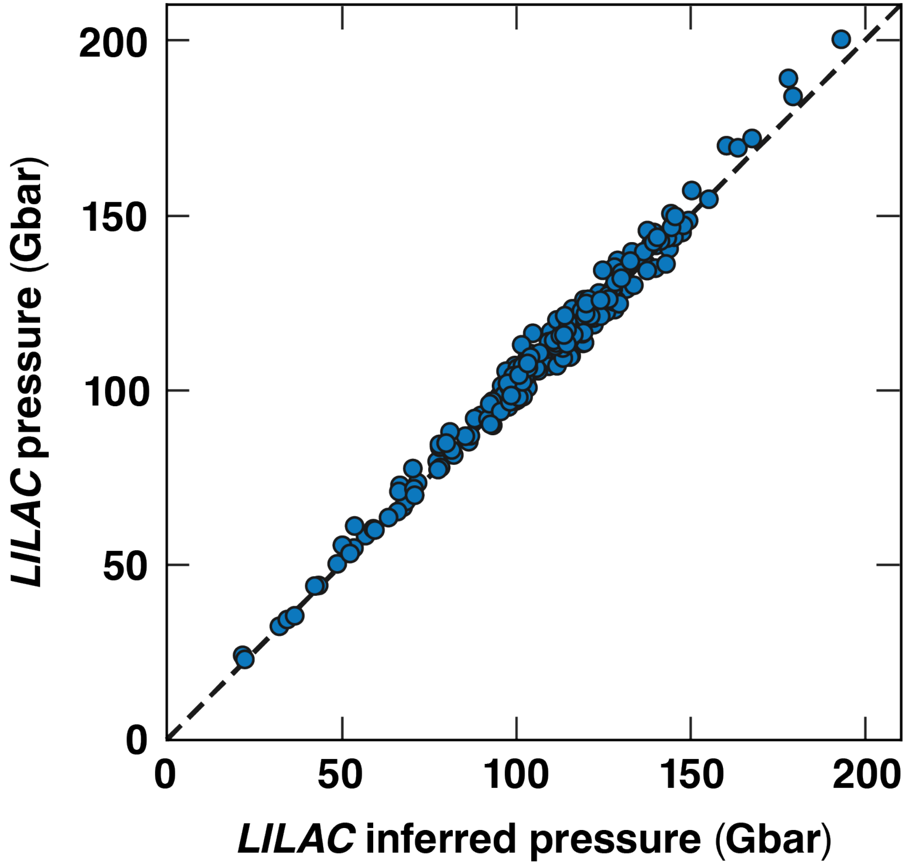
Other performance metrics: hot-spot pressures and energies can be inferred using measurements from neutron and x-ray diagnostics*,**

- Generate constraints on P_{hs} and E_{hs} using

$$Y = f_D f_T \int dt \int_0^{R_{hs}} d^3r \frac{P_i^2}{T_i^2} \langle \sigma v \rangle$$

- $T_i \neq T_e$
- $T(t,r) \rightarrow T_0 \hat{T}_{1D}(r)$ and $P(t,r) \rightarrow P_0 \hat{P}_{1D}\,(r)$
- Process applied to LILAC simulations using synthetic neutron and x-ray diagnostics to ensure bang time profiles are reproduced by this method

LILAC Pressure vs. LILAC Inferred Pressure



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*Williams NI02.00004

**Cerjan, Springer, and Sepke , Physics of Plasmas 20, 056319 (2013).
Regan, Goncharov, Igumenshchev et al., Phys. Rev. Lett. 117, 025001 (2016).

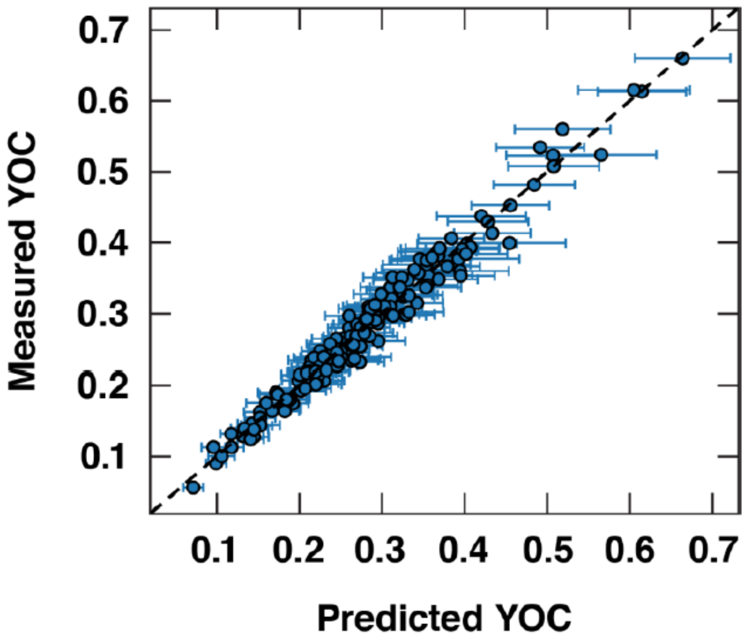
After a global fit of data to simulations using relevant dimensional analysis, the dependence of each degradation mechanism can be visualized by taking out all others*

$$YOC^{\text{exp}} \approx \prod_{j=1-n} YOC_j$$

$$\mathbf{YOC}^{\text{exp}} \sim \alpha^{\varepsilon} T_{\text{rel}}^{\omega} \hat{T}_c^{\eta} \theta_T^{\delta} \theta_D^{\nu} \xi_{\text{He}}^{\phi} \hat{R}_T^{\mu} \left(R_b/R_t\right)^{\gamma}$$

$$YOC_j^{\text{exp}} \approx \frac{YOC_{\text{exp}}}{\prod_{i \neq j} YOC_i}$$

Global fit



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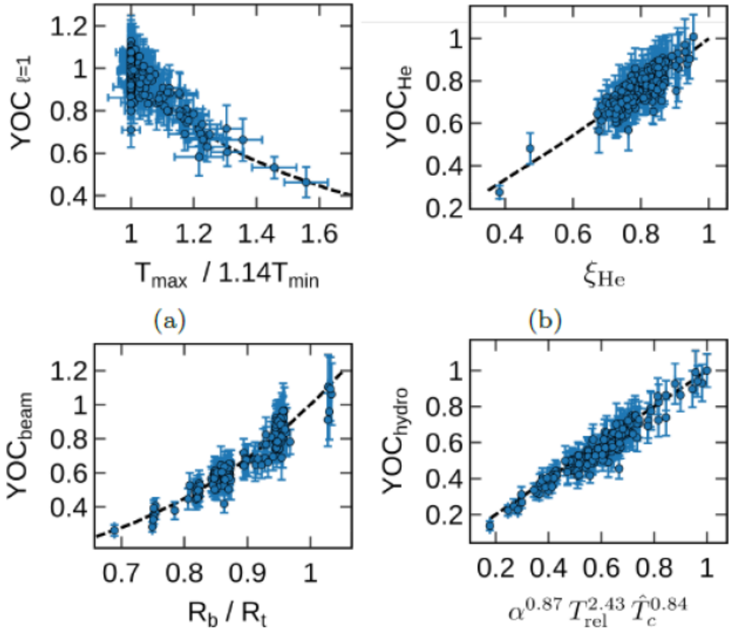
Individual dependencies



*A. Lees *et al.*, “Experimentally Inferred Fusion Yeld Dependencies of OMEGA Inertial Confinement Fusion Implosions,” Phys. Rev Lett. 127, 105001 (2021).