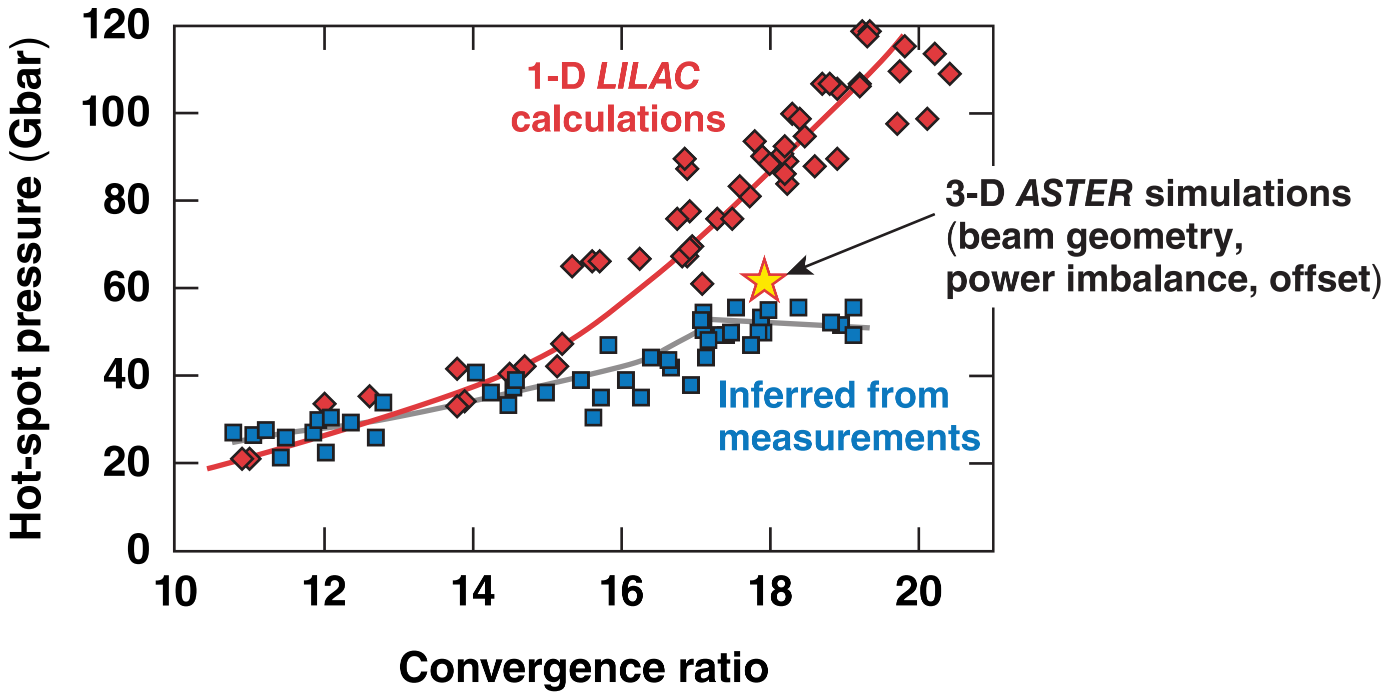
Progress Toward Demonstration of Ignition Hydro-equivalence on OMEGA



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Fusion Power Associates
Pathways and Progress Toward Fusion Power
Washington, DC
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Summary

The National Direct-Drive Inertial Confinement Fusion (ICF) Program* is underway at the Omega Laser facility and at the National Ignition Facility (NIF)

- The 100-Gbar Campaign on OMEGA and the Megajoule Direct-Drive Campaign at the NIF explore physics and technology requirements for laser-direct-drive (LDD) ignition at the MJ scale
  - establish requirements for drive uniformity
  - establish requirements for target uniformity
  - understand and improve laser coupling (wavelength detuning)
  - understand and mitigate the source of hot-electron preheat (mid-Z layers, λ detuning)
  - continue to improve an understanding of LDD physics [1-D implosion campaign, shell release, shock timing, imprint reduction, high-energy-density (HED) material properties]

Detailed measurements and better physics modeling will continue to lead the progress in laser direct drive.

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*V.N. Goncharov *et al.*, Plasma Phys. Control. Fusion 59 014008 (2017)

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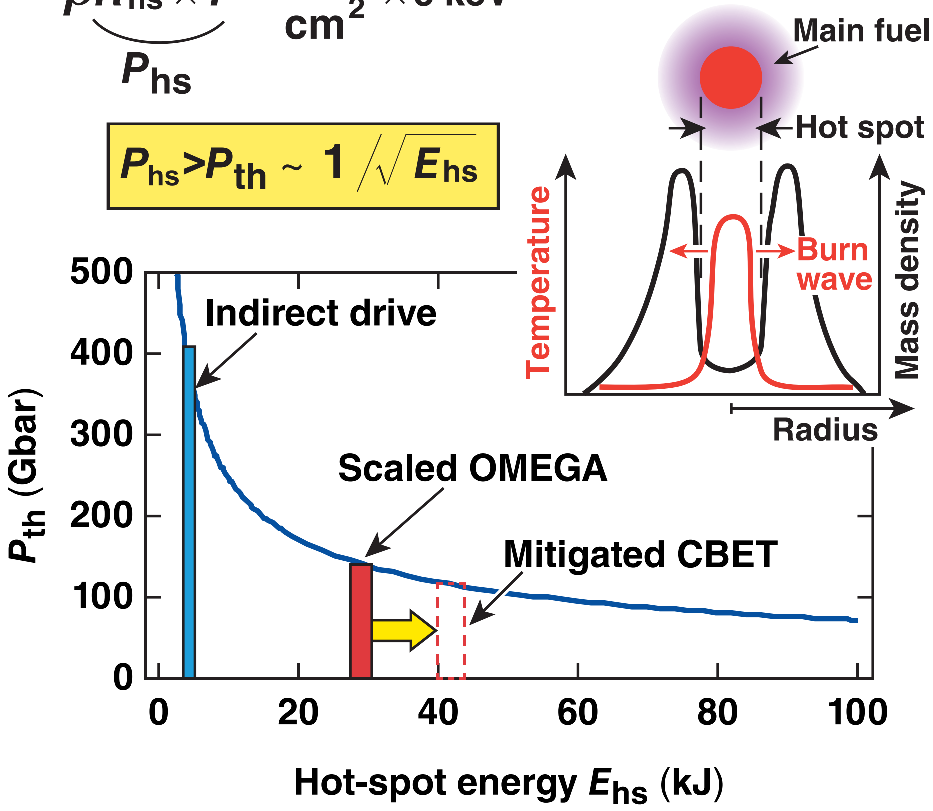
The threshold hot-spot pressure for alpha heating depends on hot-spot internal energy

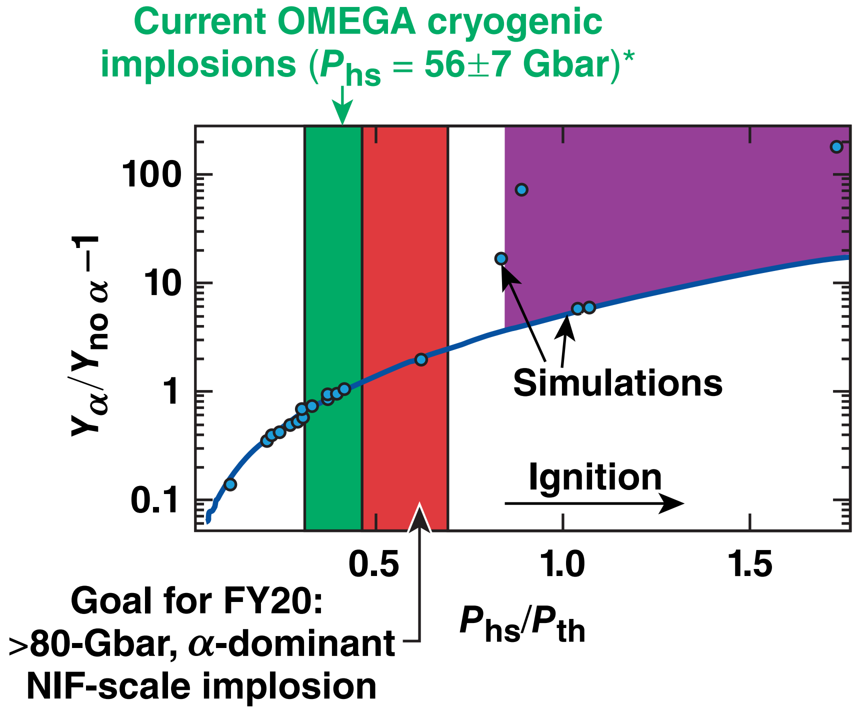
Ignition condition

$$\underbrace{\rho R_{hs} \times T}_{P_{hs}} \sim \frac{\text{mg}}{\text{cm}^2} \times 5\ \text{keV}$$

$$\boxed{P_{hs} > P_{th} \sim 1/\sqrt{E_{hs}}}$$



Yield amplification caused by alpha heating projected to a ~ MJ facility



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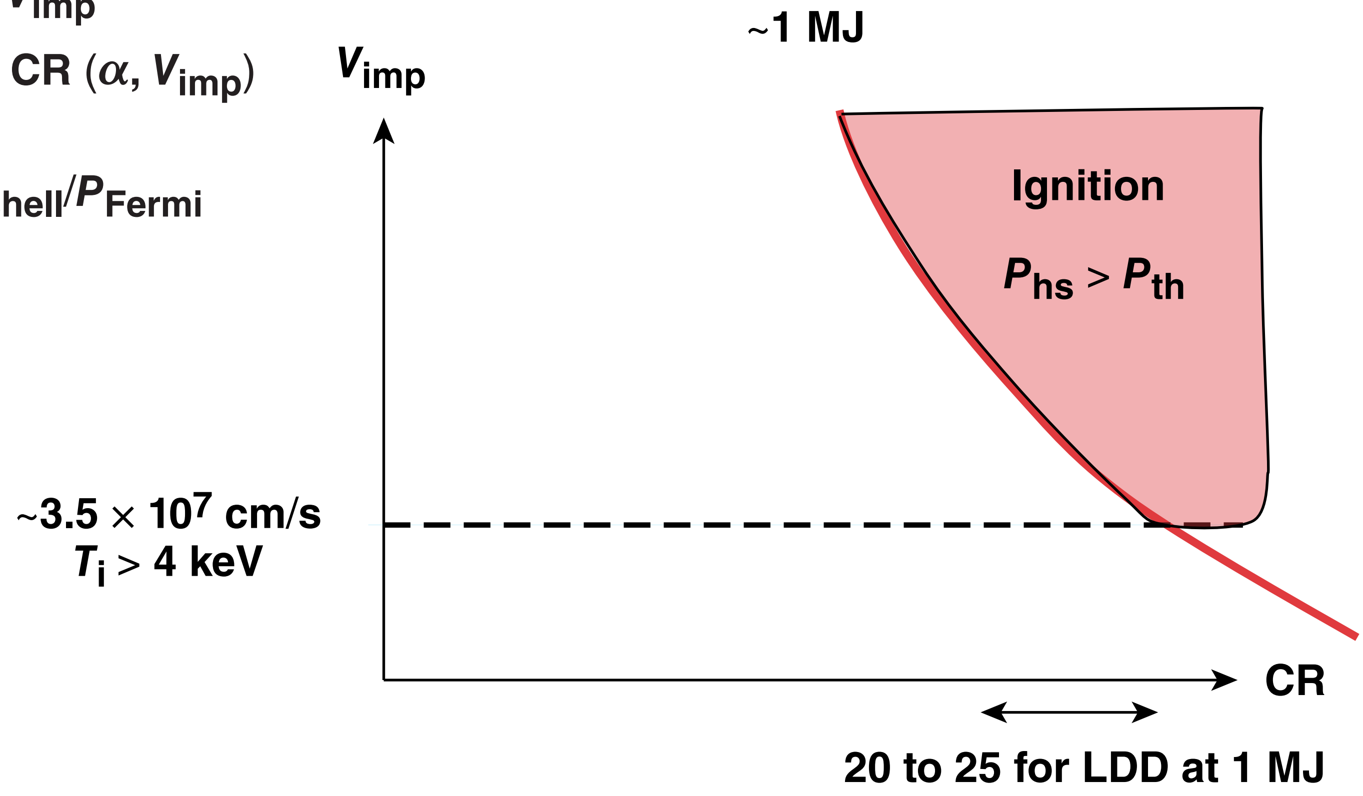
*S. P. Regan *et al.*, Phys. Rev. Lett. 117, 025001 (2016).

The ignition condition defines an ignition boundary in velocity-convergence ratio (CR) parameter space

Hot-spot self-heating in 1-D is determined by

- **Laser energy E_L and coupling**
- **Implosion velocity V_{imp}**
- **Shell convergence CR (α, V_{imp})**

$$\alpha = P_{shell}/P_{Fermi}$$



Three-dimensional nonuniformity growth limits the achievable conditions at peak compression

Hot-spot self-heating in 1-D is determined by

- Laser energy E_L and coupling
- Implosion velocity V_{imp}
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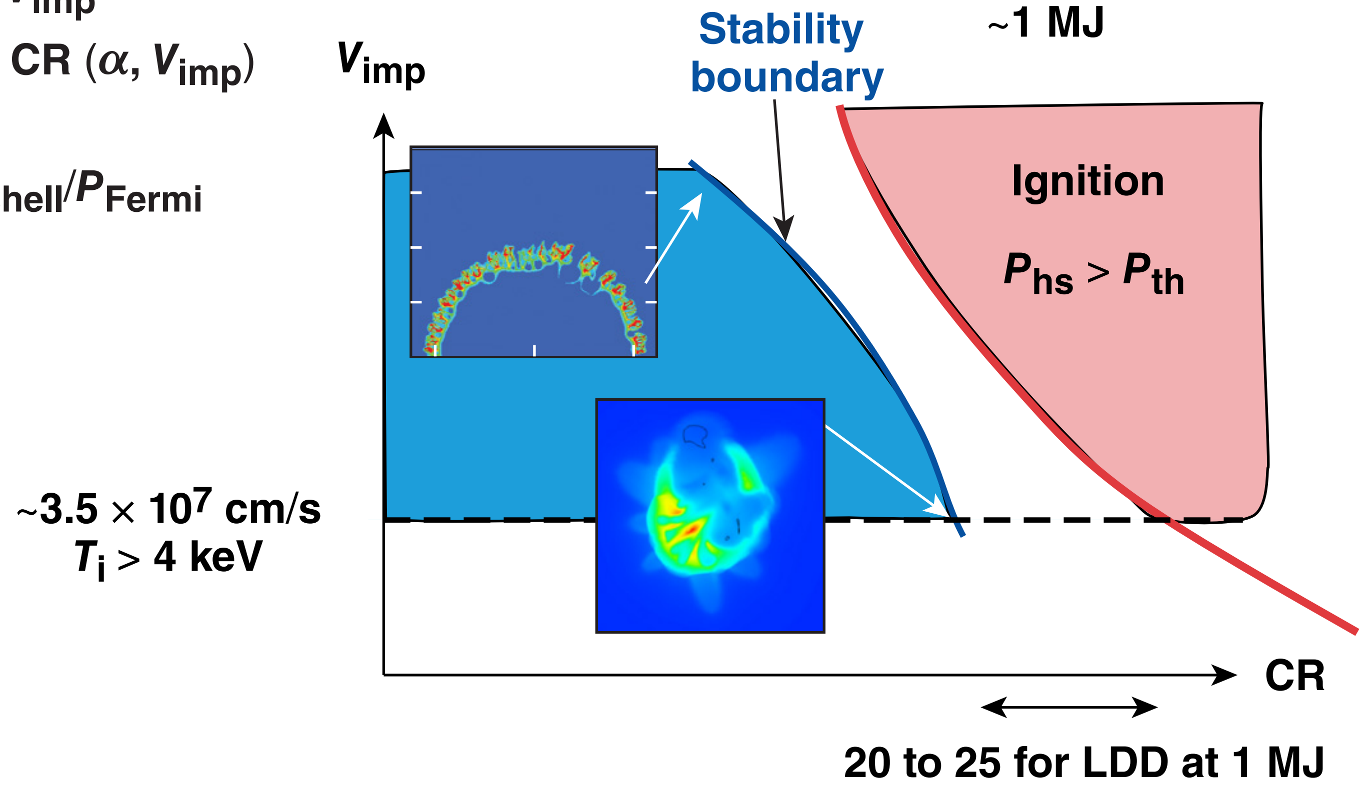


TC14013a

Cryogenic experiments on OMEGA are designed to study ignition hydro-equivalence

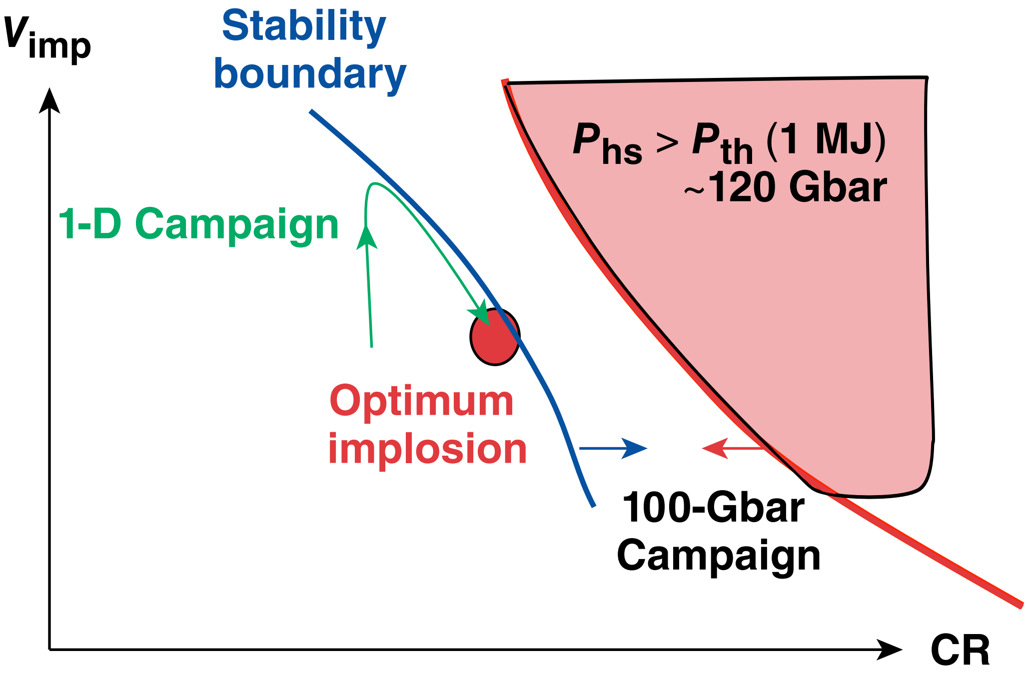
1-D Campaign – R. Betti's talk (part of 100-Gbar Project)

- Relax α and CR, increase V_{imp} to maximize yield ($Y \sim V_{imp}^{5}\text{CR}^{2}$)
- Increase CR to find optimum implosion (highest P_{hs} or $P\tau$)

100-Gbar Campaign

- Indentify stability boundary and cause (ablator nonuniformity, imprint, power imbalance)
- Indentify P_{th} boundary [implosion physics campaigns: laser–plasma interaction (LPI), materials properties, preheat]
- Improve laser and targets

OMEGA, ~30 kJ V_{imp}, CR, P_{hs}—hydro invariants

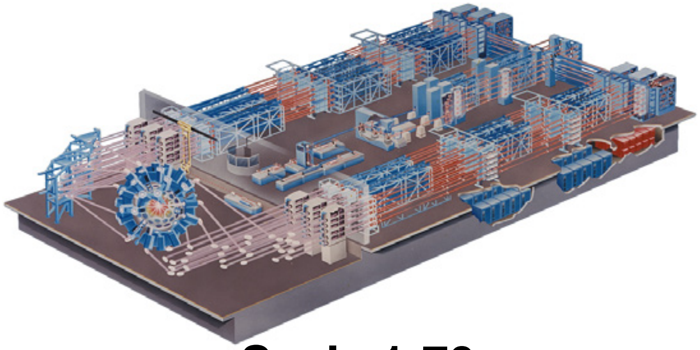


TC14013b

The National Direct-Drive ICF Program includes OMEGA and NIF experiments to study direct-drive target physics

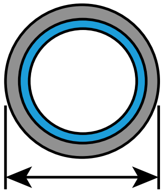
OMEGA
30 kJ
60 beam
351 nm

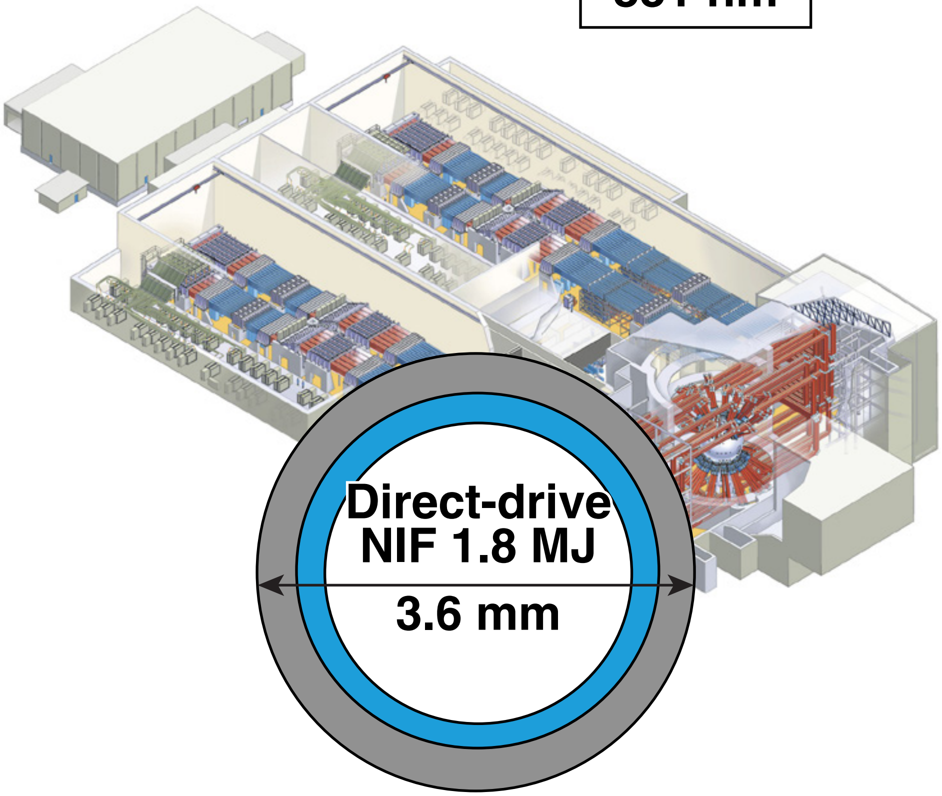
NIF
1.8 MJ
192 beam
351 nm



Scale 1:70 in energy

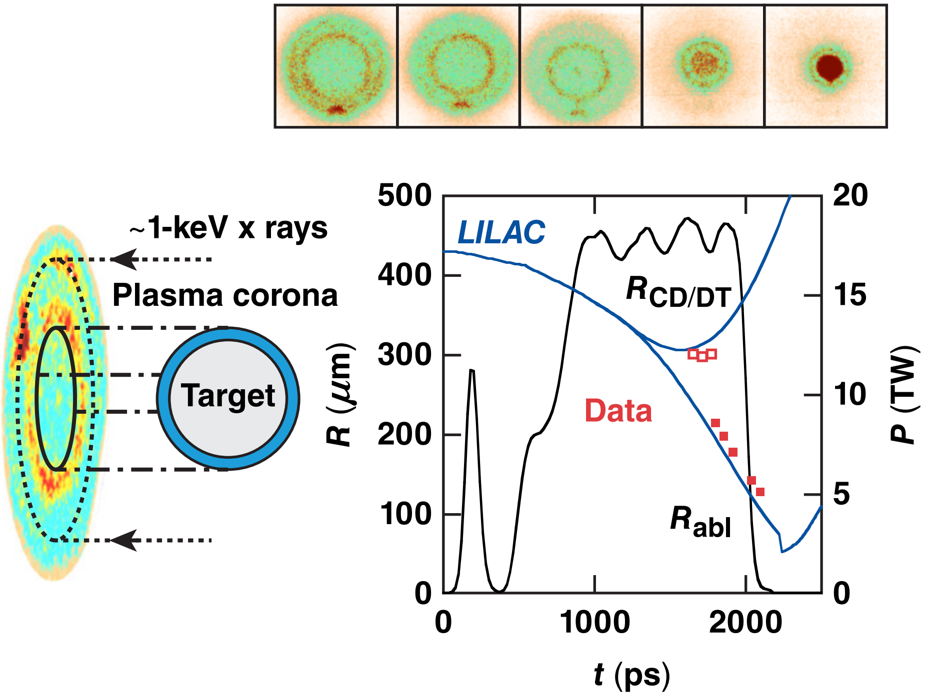
OMEGA 26 kJ



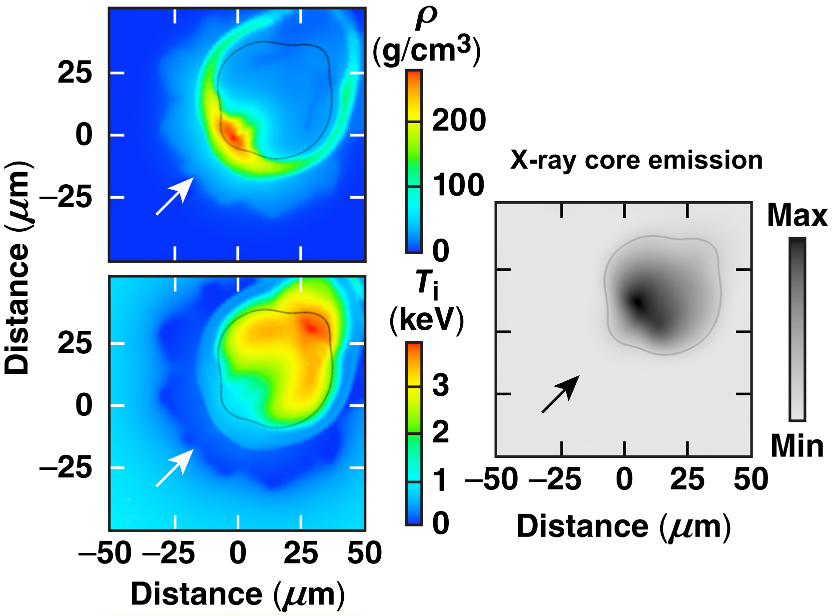


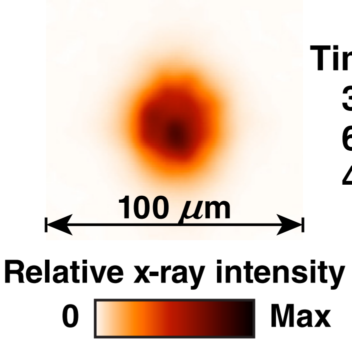
Shell velocity and shell convergence are inferred using self-emission and core-emission imaging

Self-emission imaging of inflight shell**



Core x-ray imaging*





Time-resolved KBFramed*
- 30-ps temporal resolution
- 6-μm spatial resolution
- 4- to 8-keV photon-energy range

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

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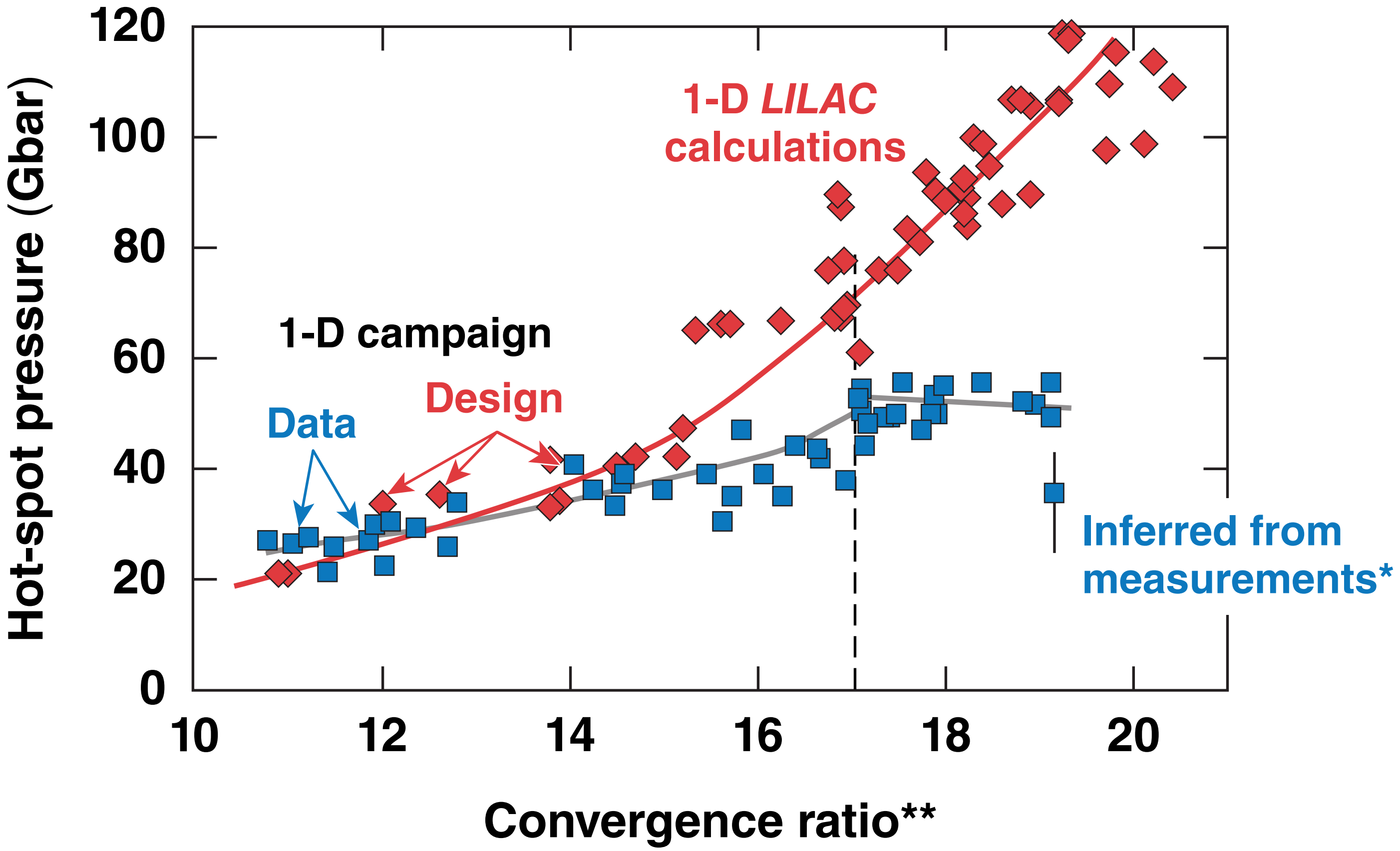
*F. J. Marshall *et al.*, Rev. Sci. Instrum. 88, 093702 (2017).

The inferred hot-spot pressure increases with convergence up to CR = 17



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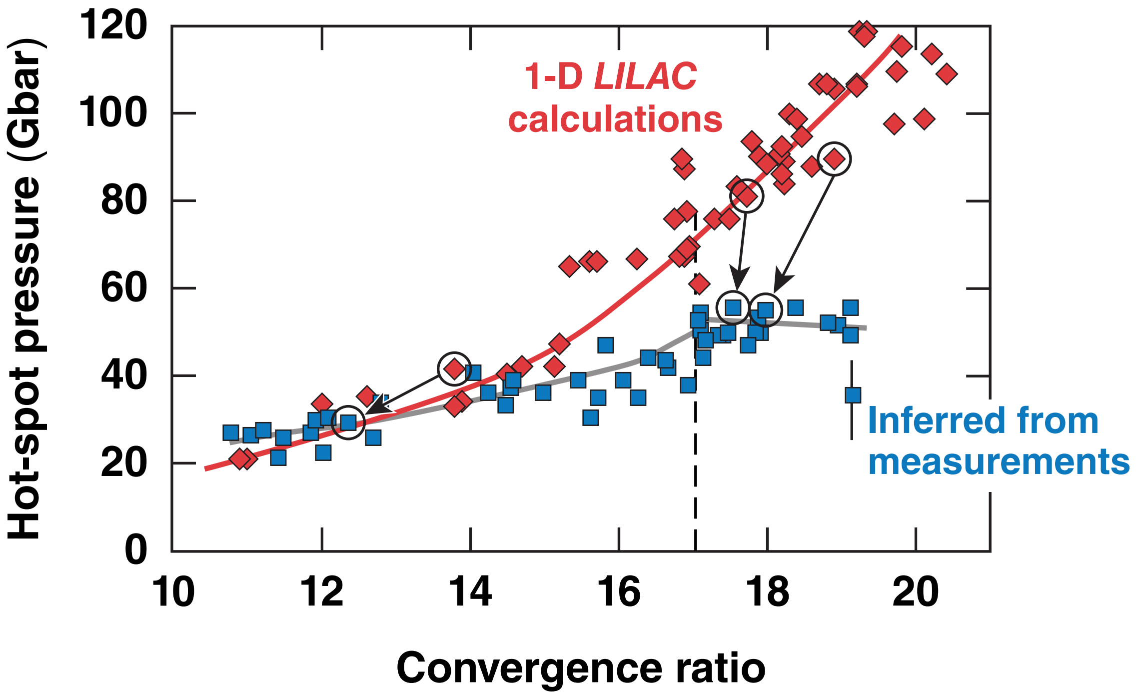
*S. P. Regan *et al.*, Phys. Rev. Lett. 117, 025001 (2016).

**CR = $R_{0,\text{inner}}/R_{17}$, R_{17} is calculated or measured radius of 17% contour of peak hot-spot x-ray emission at bang time.

TC14016

Two categories of the performance degradation are identified



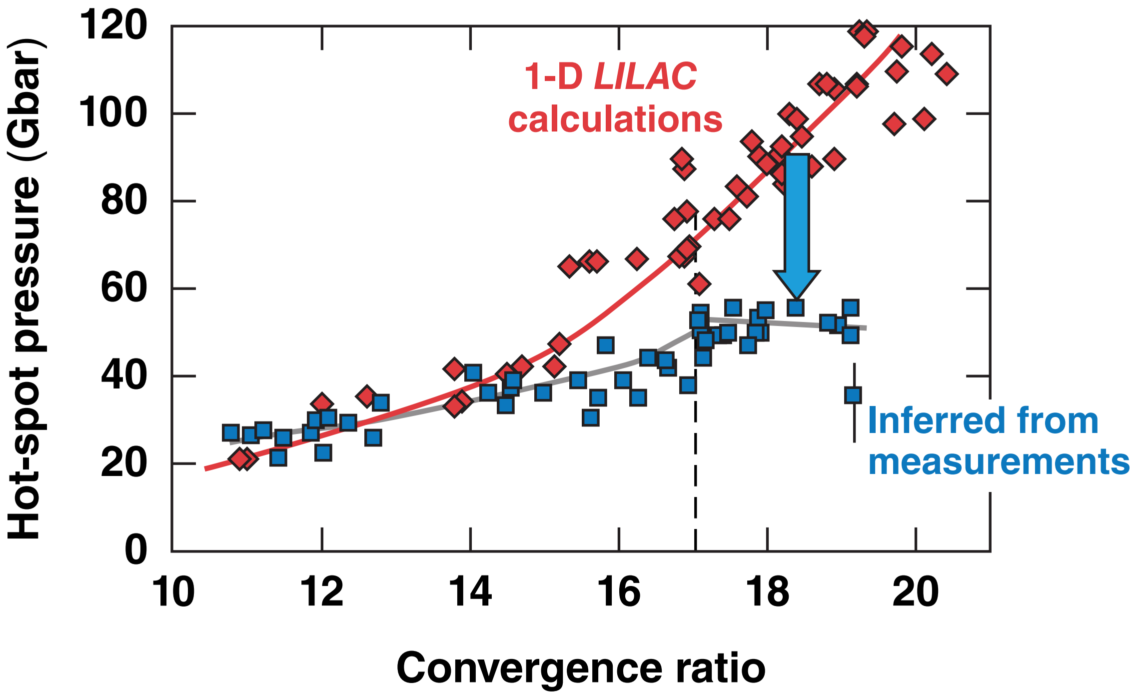
I. Designs overpredict the inferred convergence

Cause:

- Inadequate 1-D physics models (microphysics, HED, LPI)
- In-flight shell breakup and mass injection into vapor region (surface debris, imprint, engineering features)
- Preheat (hot-electron, radiation)—not significant on OMEGA

TC14016a

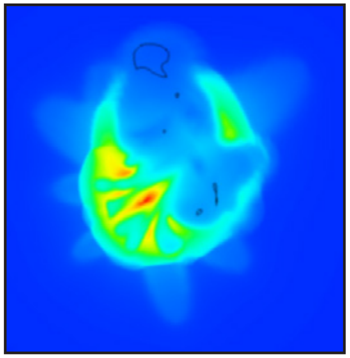
Two categories of the performance degradation are identified



II. For the same convergence, the inferred pressure is reduced for CR > 14

Cause:

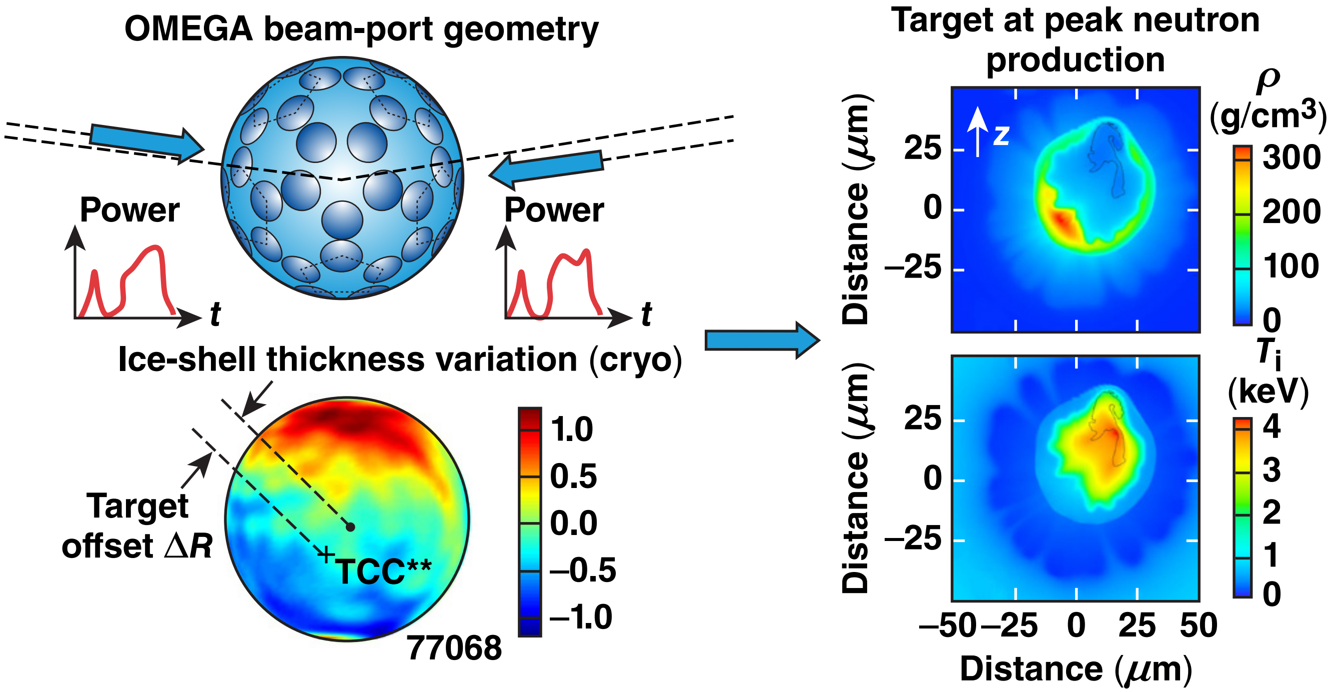
- Long-wavelength ($\ell < 5$) shell-mass modulations at peak compression



TC14016b

Three-dimensional simulations show that the present level of illumination asymmetry is sufficient to match the observed pressure reduction

3-D *ASTER simulations including power imbalance, target offset, ice roughness, and mispointing**



$$\frac{Y_{3\text{-D}}}{Y_{\text{symmetric}}} = 40\%$$

$$\frac{P_{3\text{-D}}}{P_{\text{symmetric}}} = 64\%$$

One of the main goals of the 100-Gbar Campaign is to quantify on-target intensity imbalance and improve it to 1% rms.

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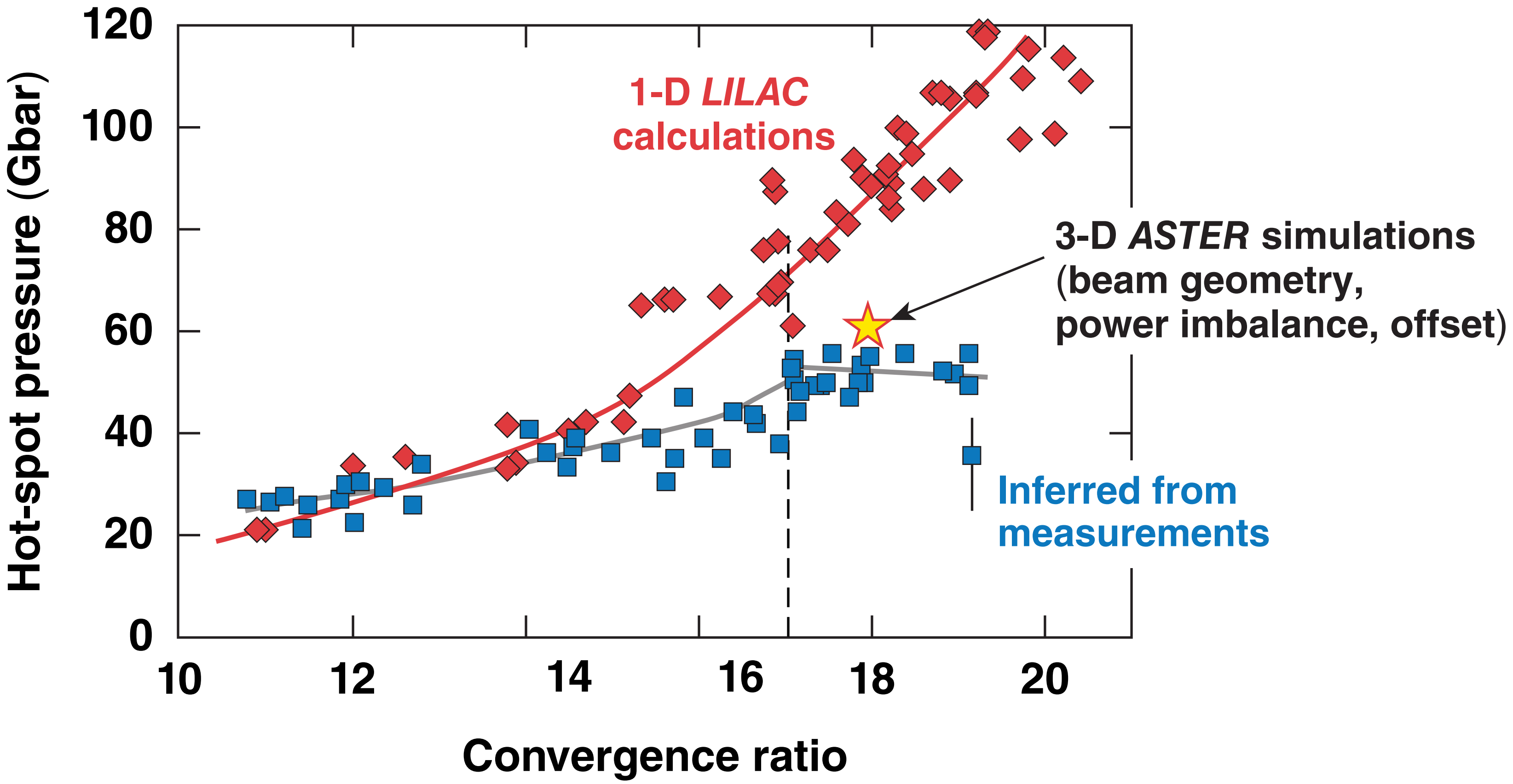
*I. V. Igumenshchev *et al.*, Phys. Plasmas 23, 052702 (2016).
**TCC: target chamber center

TC14018

Three-dimensional simulations show that the present level of illumination asymmetry is sufficient to match the observed pressure reduction



TC14016c

The 100-Gbar and Megajoule Campaigns are developed to address the physics uncertainties and quantify effect of nonuniformity

I. Designs overpredict the inferred convergence

Inadequate physics models

HED physics campaigns

- materials properties behind shocks
- first-principle EOS, opacity, conductivities

Understanding LPI/coupling

- 61st tunable beam on OMEGA
- computational tools (*LPSE*, PIC)

Short-scale growth

Imprint campaigns

- accurate imprint characterization (OHRV)
- mitigation (high *Z*, foams)

Target debris

- fill-tube project
- target characterization

Preheat

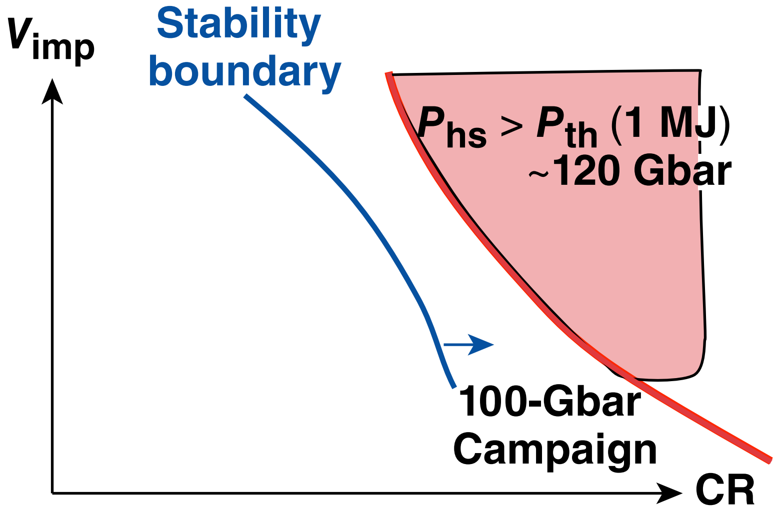
Hot-electron campaign

- hard x-ray emission from inner layers
- competition between SRS and TPD (Megajoule NIF campaign)

EOS: equation of state
PIC: particle-in-cell
OHRV: OMEGA high-resolution velocimeter
SRS: stimulated Raman scattering
TPD: two-plasmon decay

Increasing laser coupling is required for reaching ignition-relevant hot-spot conditions

- Cross-beam energy transfer (CBET) in LDD reduces drive pressure by 40% on OMEGA and by 60% on the NIF
- $P_{hs} \sim P_{abl}$ IFAR$^{5/3}$ (in-flight aspect ratio)
- Current level of imprint and target debris limit IFAR to ~22 (CR = 19) for $\alpha \sim 4$ and to ~10 (CR = 15) for $\alpha \sim 2$ on OMEGA implosions—reduction in adiabat does not lead to higher convergence in current experiments



CBET is reduced by

- reducing laser beam relative to target size*— Q4FY18 on OMEGA
- wavelength separation between different beams*,** ($\Delta\lambda > 6$ Å UV)—part of Megajoule Campaign on the NIF
- introducing bandwidth in each beam

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*I. Igumenshchev et al., Phys. Plasmas 19, 056314 (2012)
** J. Marozas et al., PRL, accepted for publication (2017)

TC14021

LLE is engaging the community in addressing the grand challenge physics questions of ICF implosions

- A set of high-priority physics questions is being formed and distributed through the ICF and high-energy-density-physics (HEDP) communities

I. Start-up phase and early shock transit	Category
A. Understanding of early-time imprint growth	Hydro Atomic physics
B. Understanding the dynamics of phase transition behind multiple shocks	HEDP Hydro
C. Materials property gradients throughout multiple materials in the shell behind decaying shocks	HEDP Hydro
D. Interaction of multiple shocks with material rarefaction/rarefaction in convergent geometry	HEDP

TC14022

Summary/Conclusions

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Detailed measurements and better physics modeling will continue to lead the progress in laser direct drive.

TC14012