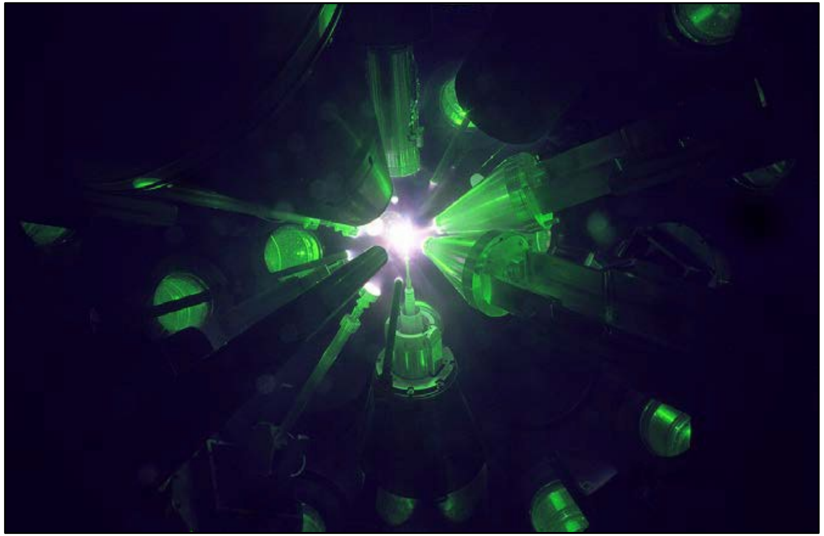
Toward High-yield in Direct-Drive Inertial Confinement Fusion: Laboratory for Laser Energetics (LLE)

OMEGA target chamber during a shot



P. B. Radha
Distinguished Scientist
Laboratory for Laser Energetics
University of Rochester

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Summary

Significant progress towards high yield has been made in direct-drive inertial confinement fusion at LLE

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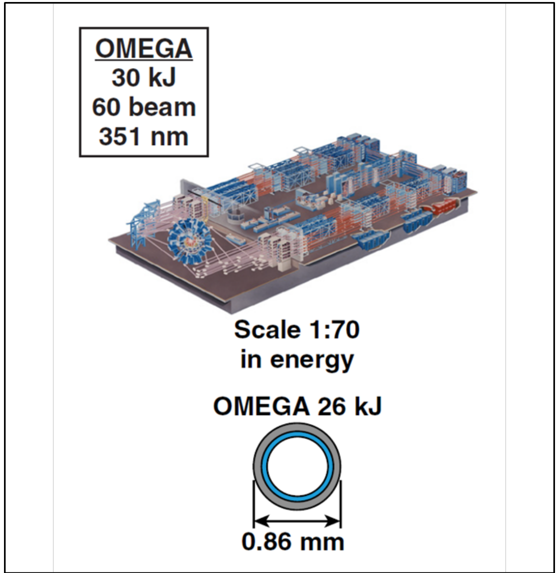
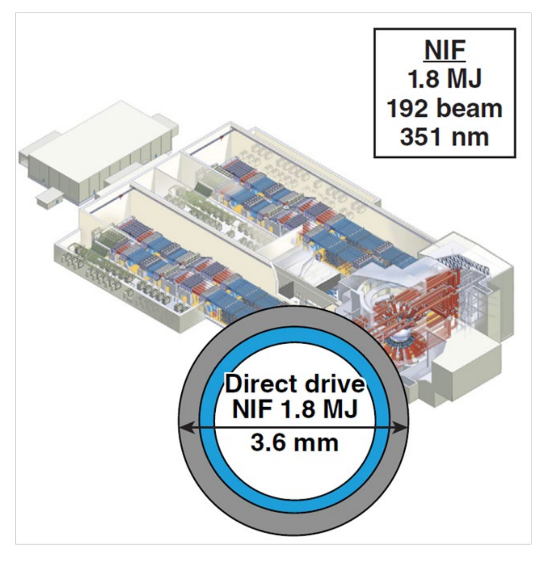
- Direct-drive couples 4-5x more energy into the capsule than indirect drive.
- Research at LLE focuses on making the physics case for direct-drive ignition.
  - The traditional hotspot implosions have resulted in the best performance ever over the last year, with hydrodynamically-scaled yields approaching a burning plasma at 2 MJ.
  - Results from the NIF are being used to validate modeling and identify mitigation strategies for laser-plasma interactions (LPI) that can potentially compromise performance.
- Advanced concepts are also being studied in parallel.
  - Broadband lasers are being explored as options to limit LPI, reduce laser imprint and expand design space.
  - Alternate designs are also being explored that are robust to nonuniformities.

Direct drive experiments are conducted on OMEGA and the NIF



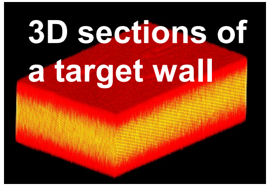
Laser coupling, preheat, imprint, and hydrodynamically scaled implosions



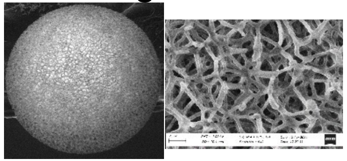
Laser coupling, hydro scaling, preheat, and imprint at the MJ scale

The goal of these experiments is to validate modeling, expand parameter space for target design through mitigation strategies, set requirements for the next-generation laser driver.

Directly driven implosion experiments on OMEGA use the entire spectrum of capabilities

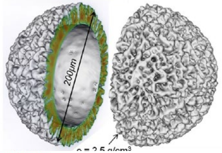


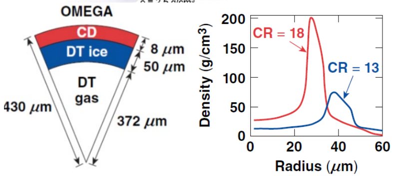
Foam target fabrication



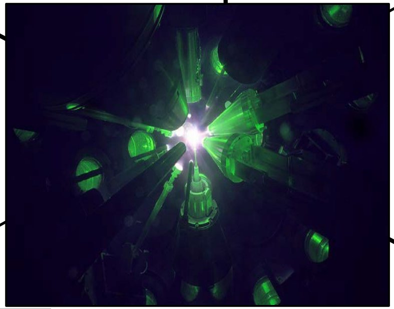
Target manufacture & metrology (partnership with GA)

3D simulation of laser imprint



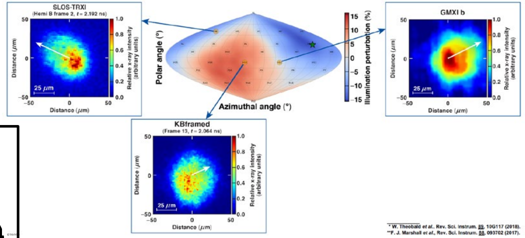


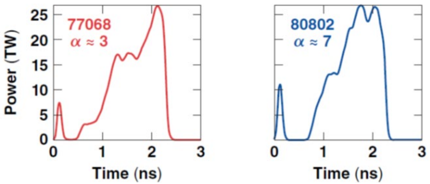
Tritium handling



Target design/physics

3D x-ray tomography



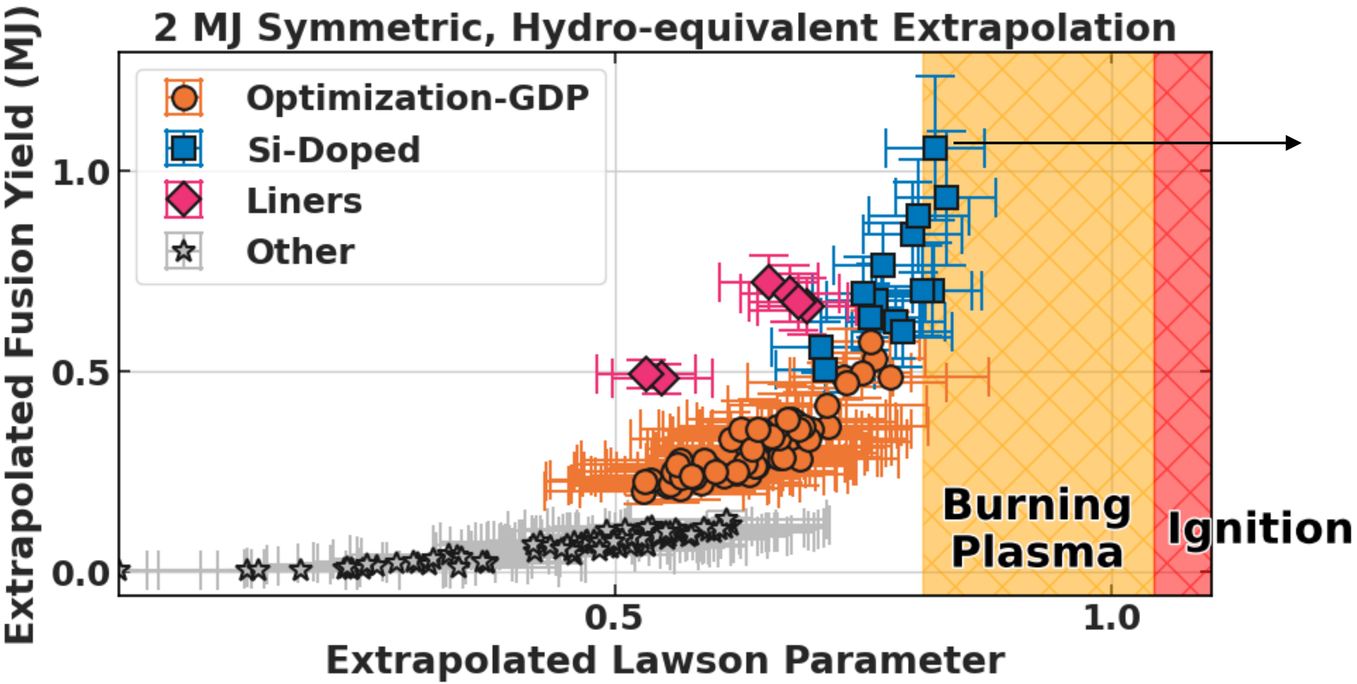


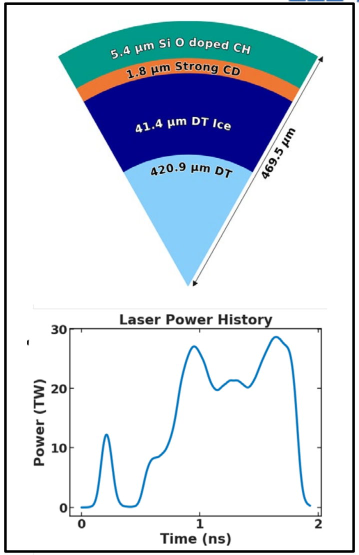
Flexible pulse Shaping

Diagnostics (partnership with MIT/PSFC)

* W. Theobald *et al.*, Rev. Sci. Instrum. 89, 10G117 (2018).
**F. J. Marshall *et al.*, Rev. Sci. Instrum. 88, 093702 (2017).

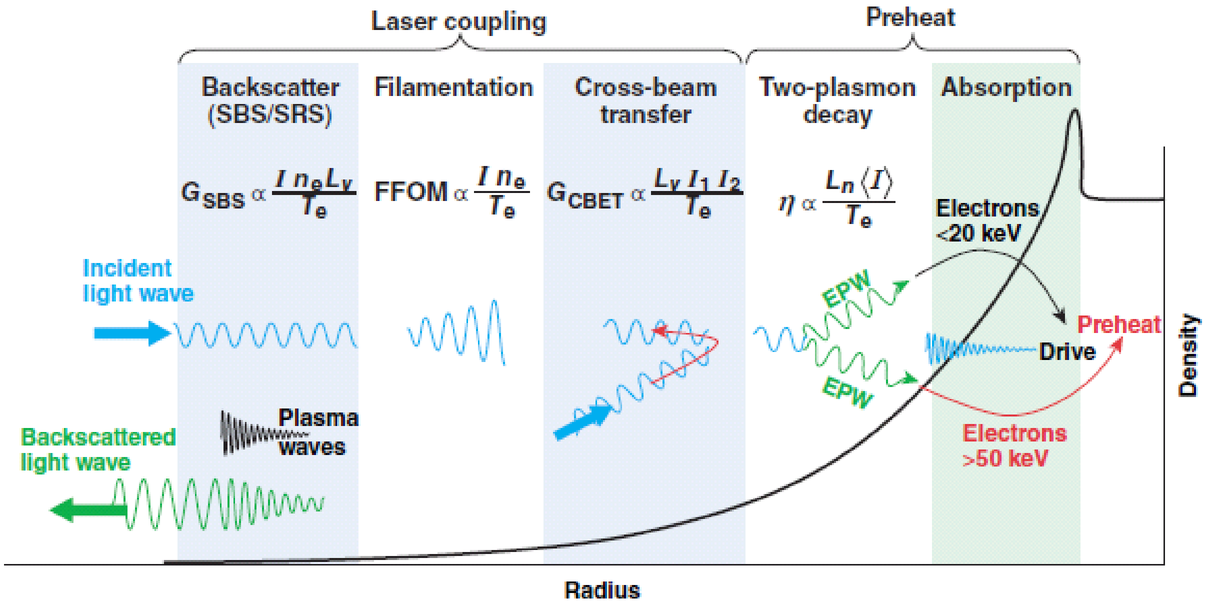
The best performing implosions produce over a megajoule of fusion energy when hydro-equivalently extrapolated to 2 MJ of symmetric drive





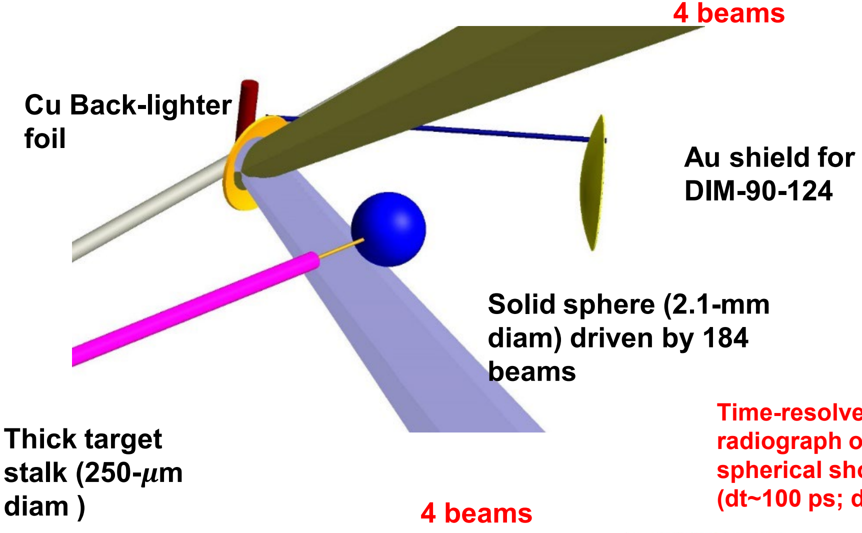
V. Gopalaswamy et al., APS (2022).

Scaling from the k-Joule scale (OMEGA) to higher energies (necessary for IFE) requires modeling of various laser-plasma interaction processes

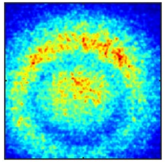


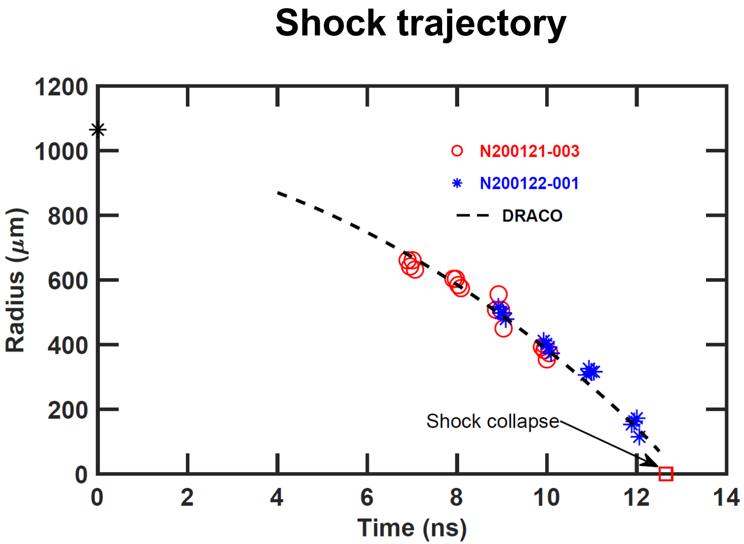
Two primary areas of concern: laser-target coupling and fast-electron preheat

State-of-the-art models predict accurately the energy coupling diagnosed with shock-trajectory measurements at the NIF (Mega-Joule) scale

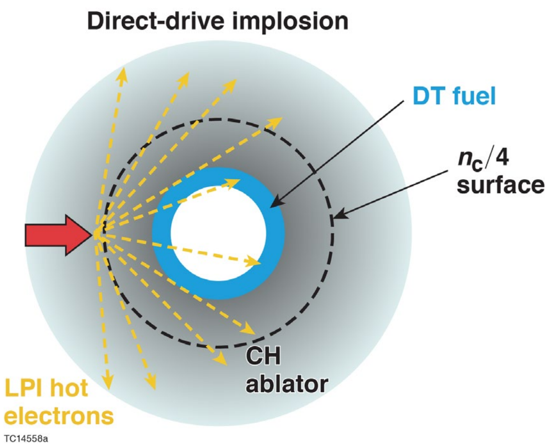


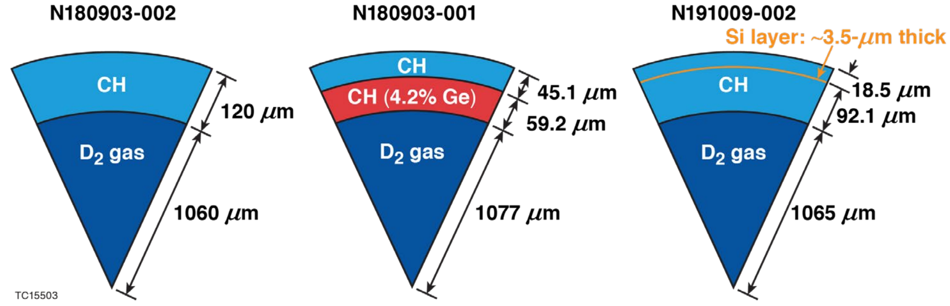
Time-resolved X-ray radiograph of spherical shock wave (dt~100 ps; dx~30 μm)



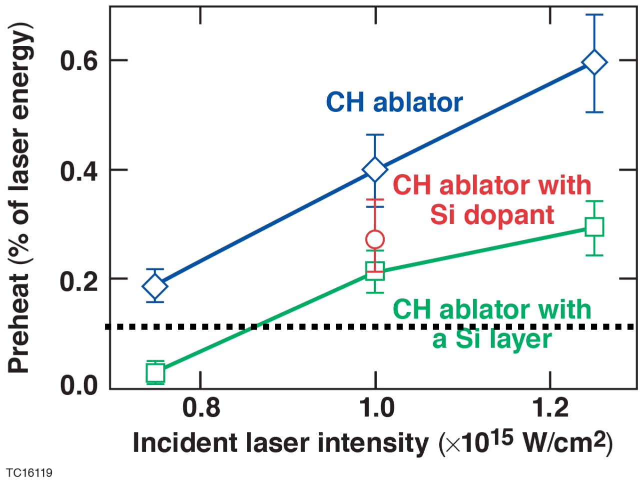


Preheat of the converging shell from coronal electrons has been quantified on the NIF; shell dopants are effective at mitigating preheat are effective even at the Mega-Joule scale





Hot-electron energy deposition in an unablated shell



This encouraging result suggests that direct-drive can result in high yields at the Mega-Joule scale.

A. Solodov et al., Phys. Plasmas (2022)

LPI modeling predicts that $\Delta\omega/\omega > 1\%$ bandwidth increases laser coupling, leading to more massive and hydrodynamically robust LDD implosions

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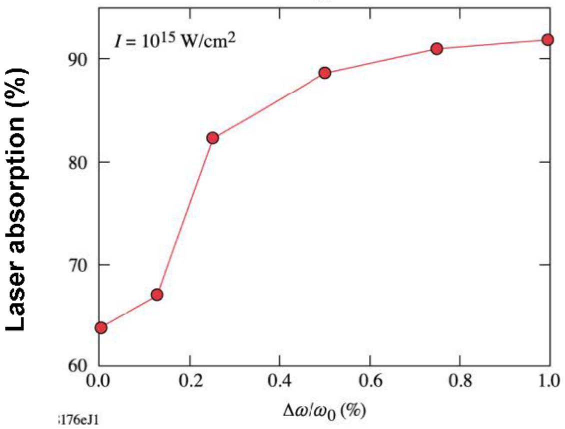
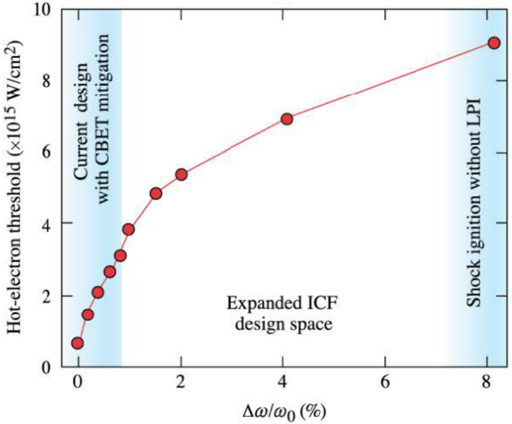
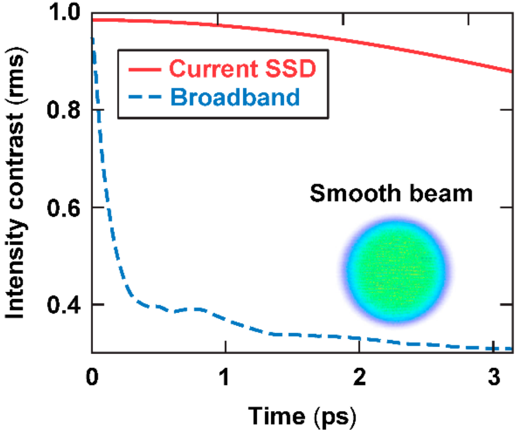
Crossed-beam energy transfer (Increased drive pressure)



Two-plasmon decay (Hot-electron mitigation)



Improved imprint (<1-ps asymptotic smoothing)



Increasing $\Delta\omega/\omega$ > 0.5% will allow stable implosions on OMEGA (IFAR = 15)

Increasing $\Delta\omega/\omega$ > 1% will mitigate both CBET and hot electrons

Improved imprint will expand the direct-drive design space by increasing the hydrostability threshold

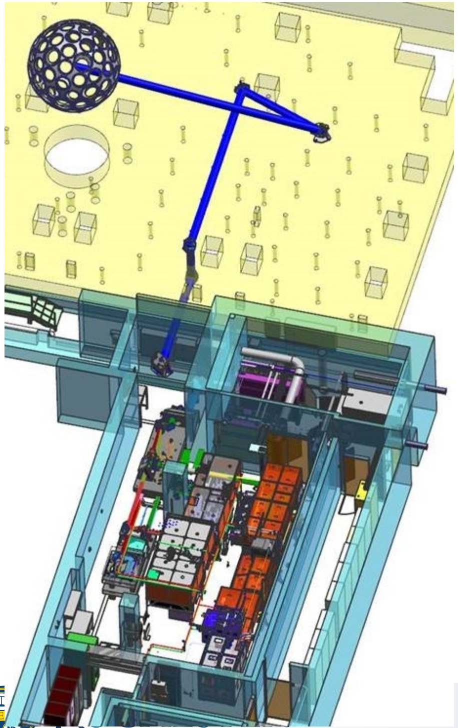
LLE is exploring higher-bandwidth driver concepts ($\Delta\omega/\omega > 3\%$) to expand the ignition parameter space for future MJ-class facilities

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

ROCHESTER

LLE is developing a broadband laser to set the requirements for the next generation of drivers with the goal of mitigating laser plasma interactions and laser imprint

FLUX system to the OMEGA Target Chamber

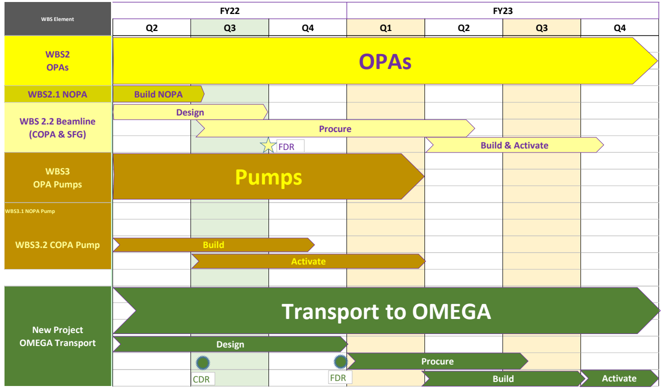


The Fourth-generation Laser for Ultra-broadband eXperiments (FLUX) will be used to validate broadband LPI modeling and set future driver requirements

FLUX Laser Requirements

Physics requirement	Specification
Central wavelength	351 nm (3ω)
Fractional bandwidth $\Delta\omega/\omega_0$	0 to 1.5%
Pulse duration/shape	1.5 ns/flat in time
Energy	150 J
On-target power	0.1 TW
Far-field size	Focusable to 100 μm (with distributed phase plates)
On-target intensity	10^{15} W/cm^2

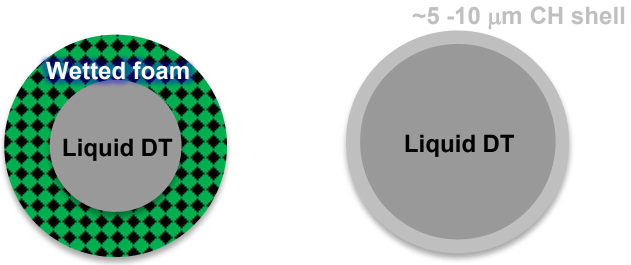
FLUX Top-level Schedule

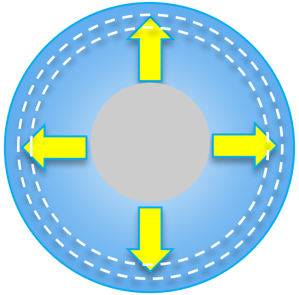


FLUX will be available in 2024 for experiments.

The dynamic shell design offers several advantages over a conventional layered target design, consistent with IFE needs

- Target simplicity
- Fuel uniformity
- Control of density in central region





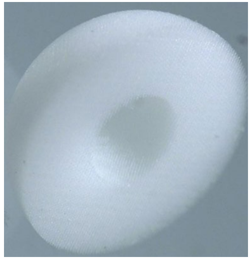
The stronger blast wave leads to lower central density

The shell and hot-spot convergence ratio can be controlled by varying central density.

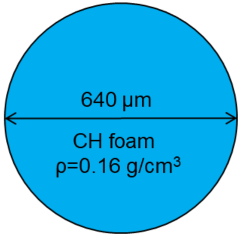
V. Goncharov et al., PRL (2019).

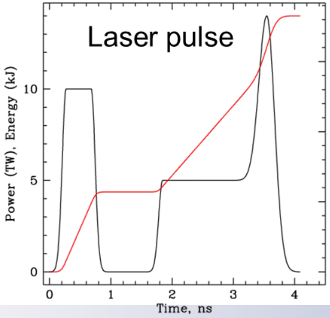
OMEGA experiments have successfully demonstrated proof-of-principle shell formation through multiple shocks

Advancements in additive manufacturing technology enabled GA and LLE to produce targets for wetted foam ignition designs

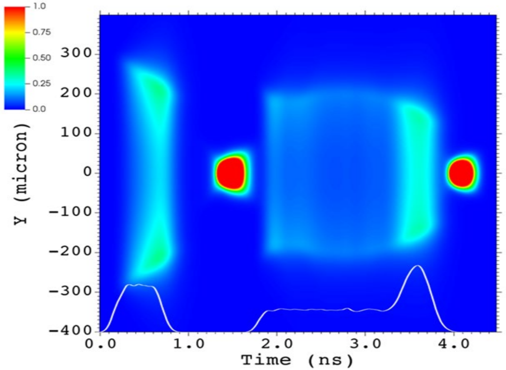


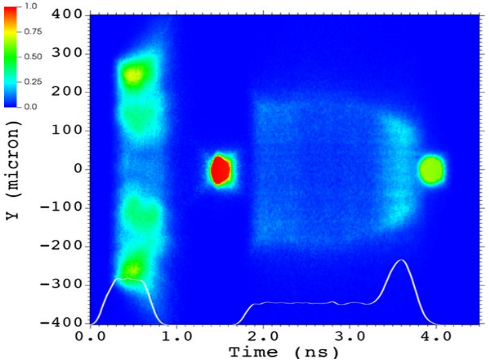
Proof-of-principle LBS experiment on OMEGA (Aug 9, 2022)





Streak imaging of target self-emission





Funded by the ARPA-E BETHE program

Summary/Conclusion

Significant progress towards high yield has been made in direct-drive inertial confinement fusion at LLE

- **Direct-drive couples 4-5x more energy into the capsule than indirect drive.**
- **Research at LLE focuses on making the physics case for direct-drive ignition.**
  - **The traditional hotspot implosions have resulted in the best performance ever over the last year, with hydrodynamically-scaled yields approaching a burning plasma at 2 MJ.**
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Extra slides

A multi-variate regression model is used to identify dependencies on implosion parameters