

Diagnostic Needs for Inertial Fusion Energy Beyond NIF and OMEGA



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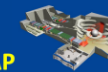
**HIGH POWER LASER
SCIENCE AND ENGINEERING**

REVIEW

Future for inertial-fusion energy in Europe: a roadmap

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**FUTURE FOR
INERTIAL FUSION
ENERGY IN
EUROPE:
A ROADMAP**



HiPER+

*On the prospect of the establishment
of a new European program on
Inertial Fusion Energy (IFE) with the
mission to demonstrate laser-driven
ignition in the direct drive scheme
and to develop pathway technologies
for a commercial fusion reactor.*

Article accepted for publication:
High Power Laser Science and Engineering, 2023

September 2023

12th Annual Meeting – Matter and Technologies, HZDR

THE *HiPER+RF* CDR PROJECT



Enabling Research Project CfP-FSD-AWP26-ENR-01

Conceptual design for a European High Power Laser Fusion Research Facility (*HiPER+RF*)

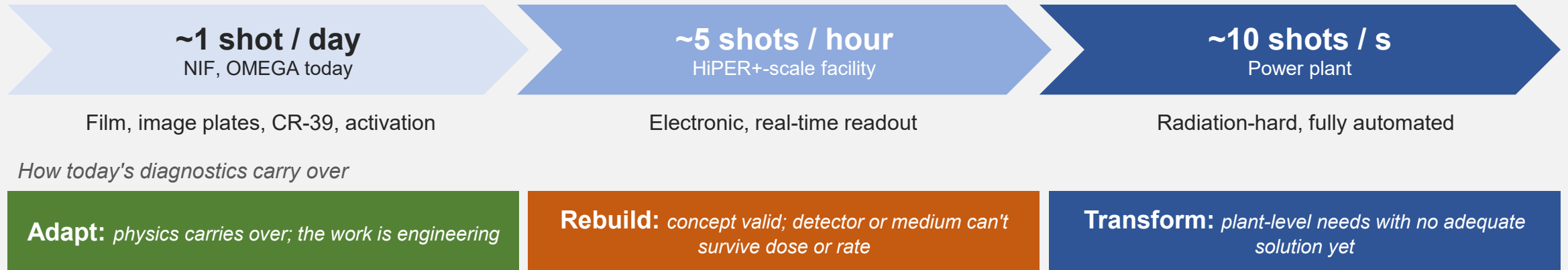
Period 2026-2027
12 countries
30 research groups
146 researchers
Funding 2.4 M€

WP5 --- Laser-Plasma and Nuclear Fusion Diagnostics

Prof. Dr. Marta Fajardo (IST - Pt)
Dr. Massimiliano Sciscio (ENEA - It)
Prof. Dr. T.E. Cowan (HZDR - De)

Executive summary

1) Major innovations in diagnostics will be required to realize laser-driven inertial fusion energy



2) Diagnostics were crucial in achieving ignition on NIF (Laser Indirect Drive)

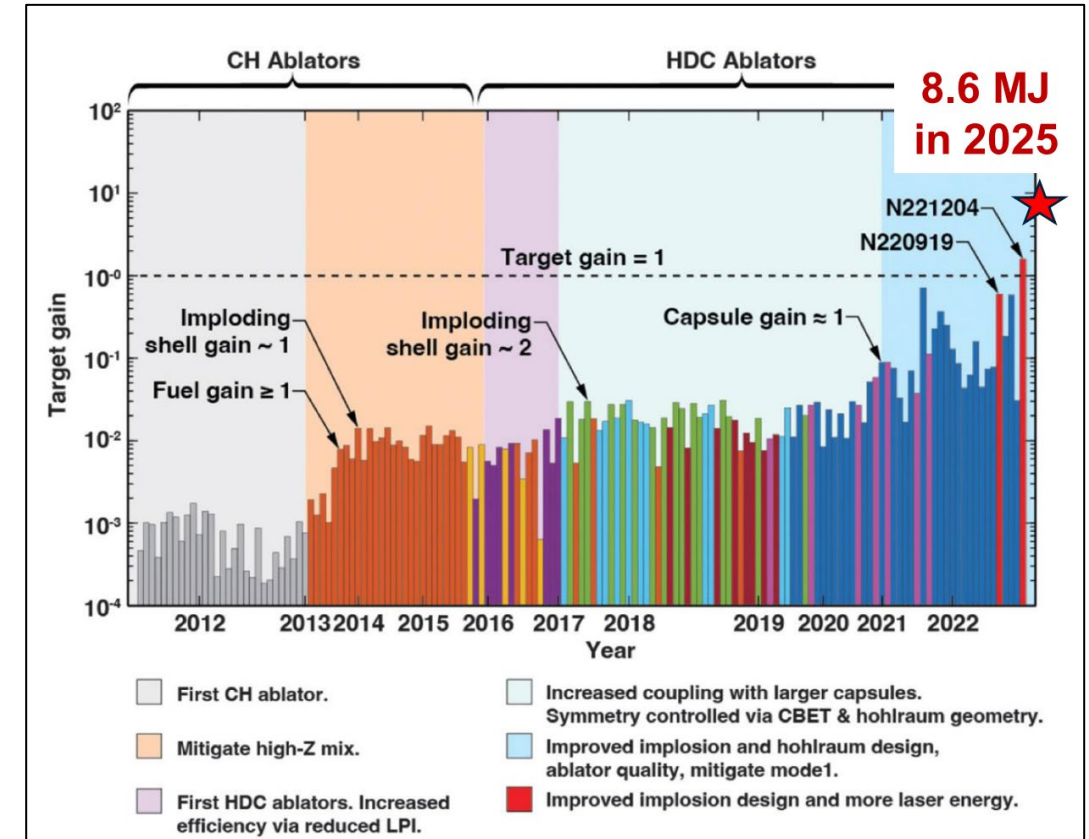
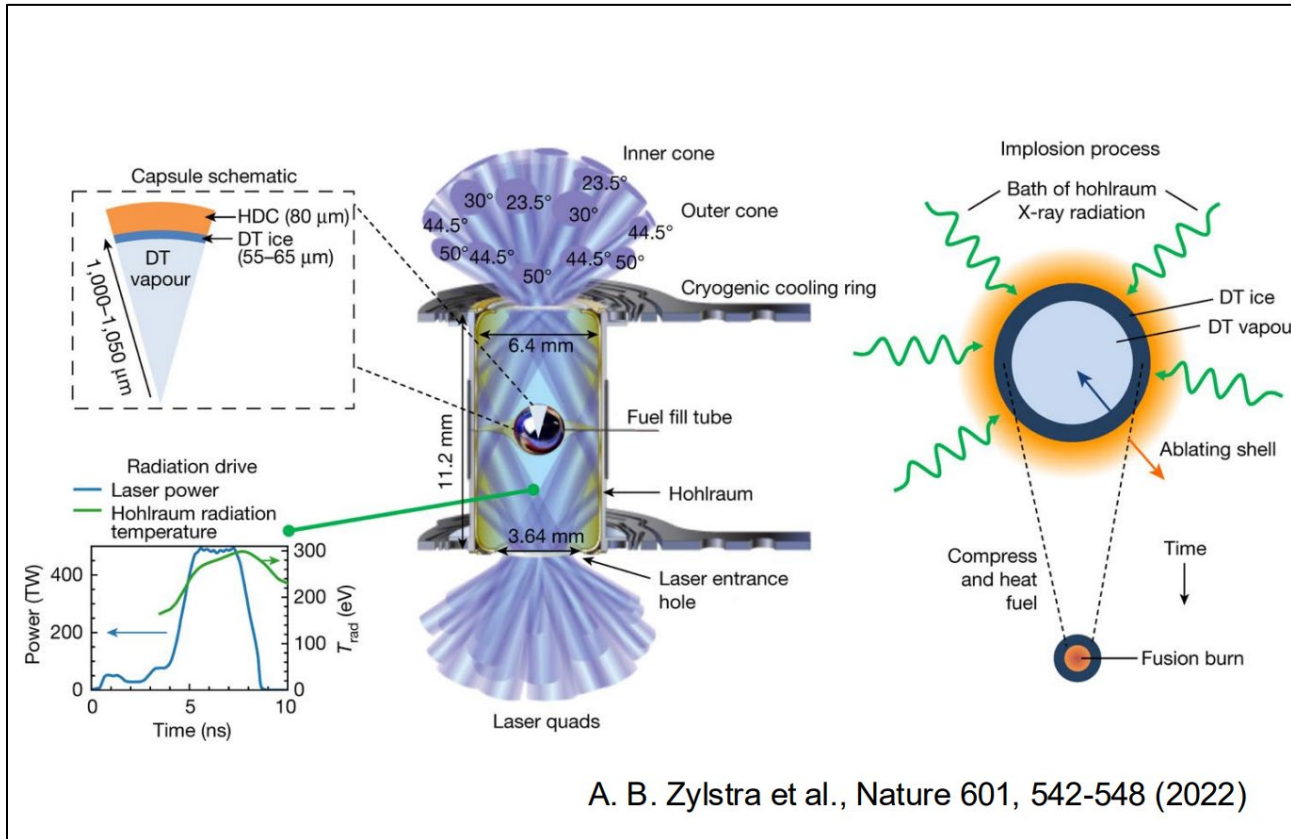
- And the same will be true for new challenges with Laser Direct Drive (from OMEGA to HiPER, and IFE)

3) Main gap: seeing inside the implosion

- Inability to resolve μm -scale hydro instabilities in flight
- Self-emission blinds x-ray backlighters at stagnation and burn

Opportunity Bright coherent x-ray sources (XFEL, compact ICS) could provide the spectral brightness to overcome self-emission and image fuel assembly, mix and burn --> XFEL talk (V. Bouffetier)

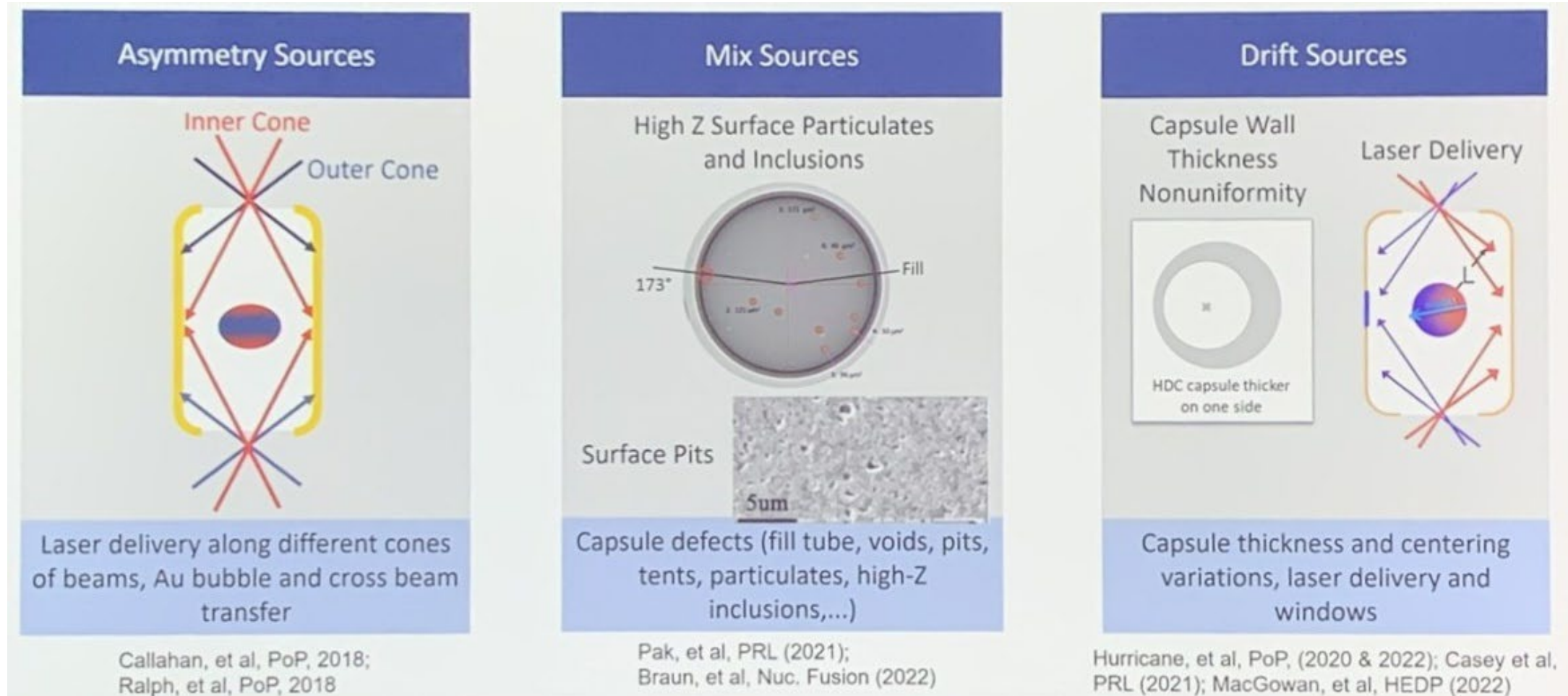
First burning fusion plasma at LLNL National Ignition Facility (Dec 2022)



**Burning Fusion Plasma -->
prospect for Inertial Fusion Energy**

- Achieving ignition took 10 years longer than expected (!)
- To date only 11 shots with Gain > 1
- In "repeats" of ignition shots, up to 10x degradation in fusion yields --> near ideal conditions are required (!)

Principal sources of fusion yield degradation

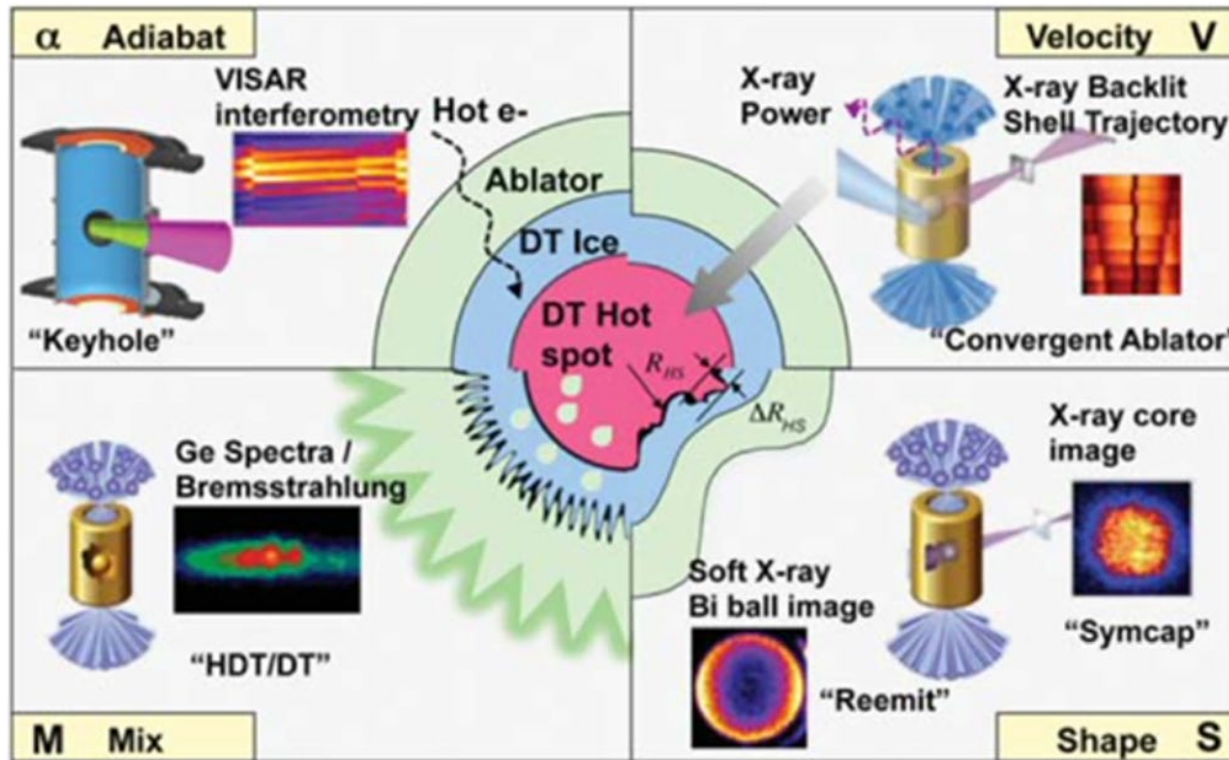


Prolate / oblate shell -> early breakout of hotspot -> expansion cooling -> extinguishes burn wave

µm-scale defects seed hydro instabilities -> mixes ablator material into fuel -> reduces fuel compressibility, increases Bremsstrahlung losses

Residual Kinetic Energy (RKE) in hotspot drift reduces implosion energy available for compression and heating

Crucial role of diagnostics in achieving ignition on the NIF



- Well over 100 diagnostics operate on NIF -- for nuclear, x-ray and optical systems
 - Extensive suite of specialized platforms had to be developed for tuning the ICF implosion parameters
 - Iterative process of discovery, simulation and prediction, characterization, and remediation of deficiencies
 - Diagnostic data to verify or falsify simulations
- known unknowns vs. unknown unknowns

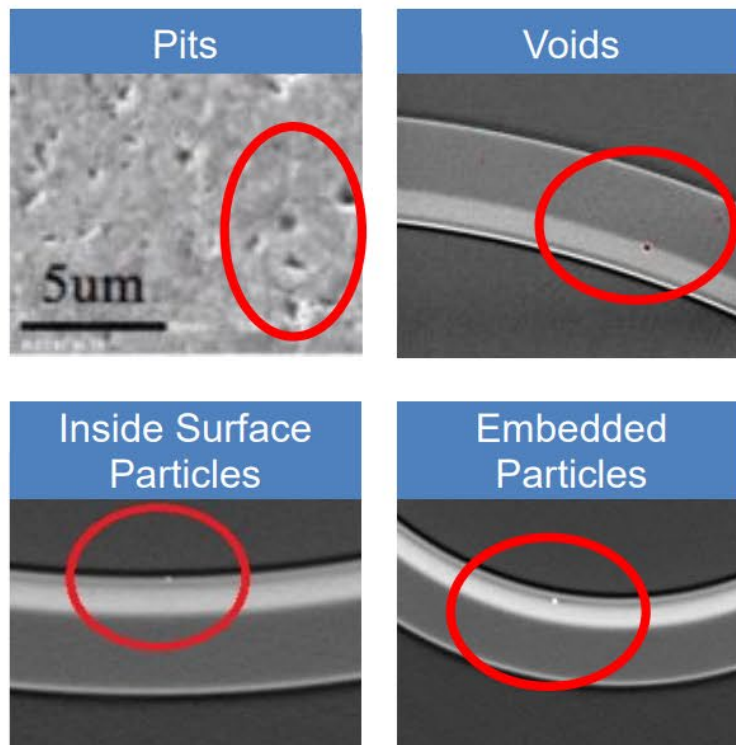
When things go wrong: diagnostics find the surprises

Surprise (NIF)	Found by	Degradation (direct drive)	Needed at several 100 kJ
Drive imbalance, low-mode asymmetry	3D neutron hot-spot shape and motion	$\ell=1$ from mispointing, offset, power imbalance (OMEGA)	Multi-LOS nTOF velocity and T_i ; 3D hot-spot imaging; per-beam metrology
Tent and fill-tube seeds larger than expected	In-flight x-ray radiography; x-ray emission imaging	Illumination mid-modes, imprint (OMEGA: beam/target radius)	In-flight radiography; shell self-emission imaging
Ablator defects, voids, high-Z debris $\rightarrow$ mix	X-ray/neutron yield ratio; bright spots in gated x-ray images; pre-shot tomography	Stability margin: adiabat, in-flight aspect ratio (OMEGA)	Shock timing; mix signatures; x-ray/neutron ratio
Doped-ablator mix into hot spot	Cu/Ge K-shell x-ray spectroscopy	DT fill age, ice quality (OMEGA)	Pre-shot 3D target metrology; fill tracking
		<i>Expected at scale: CBET coupling loss, TPD/SRS hot-electron preheat</i>	<i>Angle-resolved scattered light; time-resolved hard x-ray and $K\alpha$</i>

OMEGA: degradations untangled statistically over hundreds of shots. **Several 100 kJ:** far fewer shots, so each shot must be diagnosable on its own.

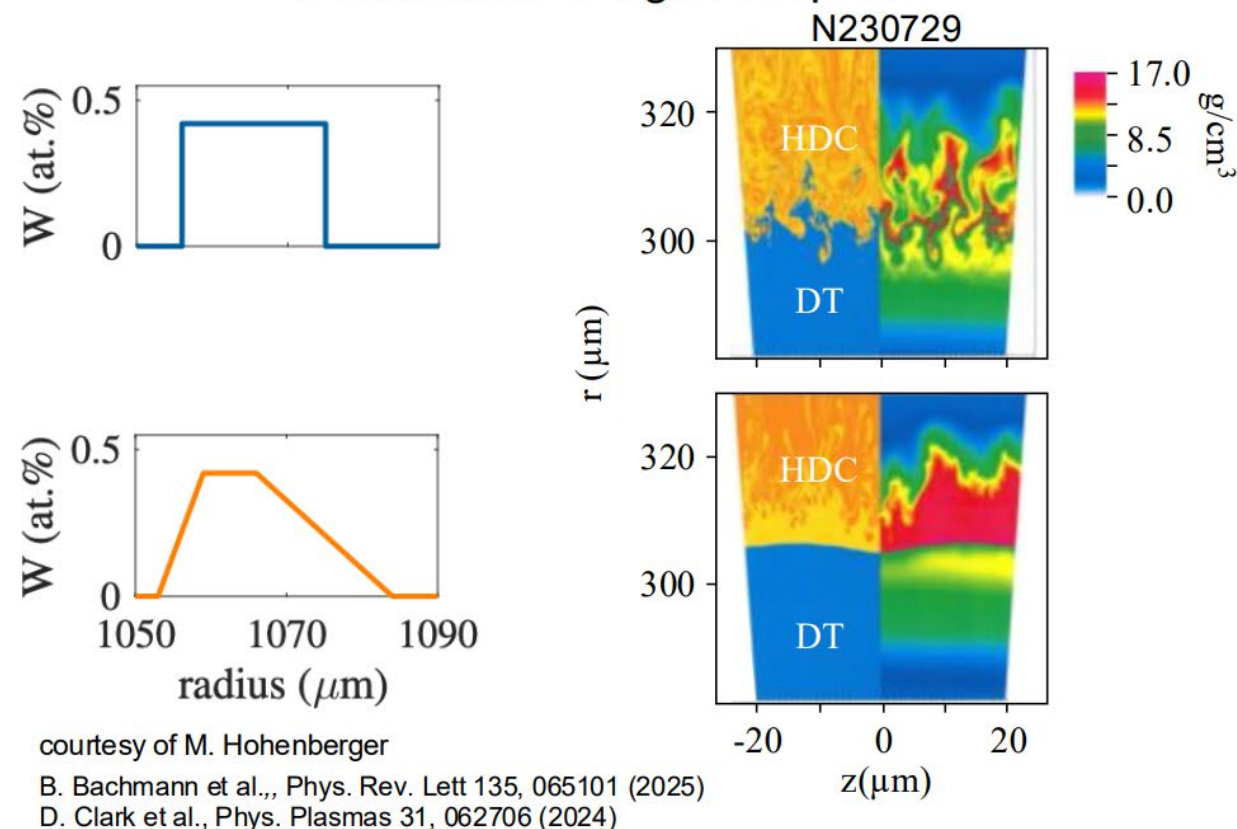
Effect of target quality and dopants in ablator materials

Target quality



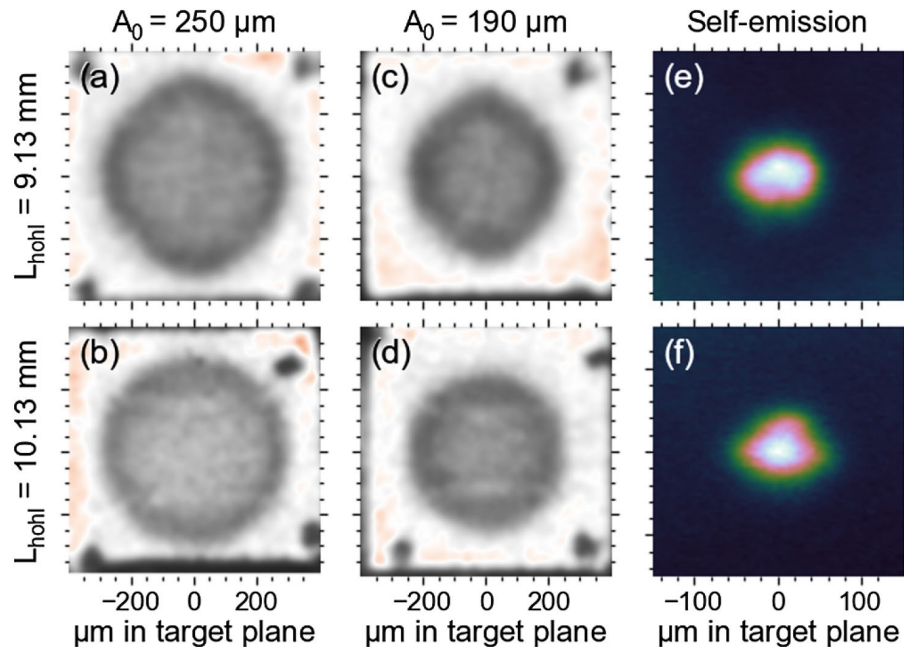
Target optimization and defect developments upon compression

Distribution of high-Z dopants



Investigating high-Z chemistry in low-Z matrix upon dynamic compression

X-ray imaging on NIF



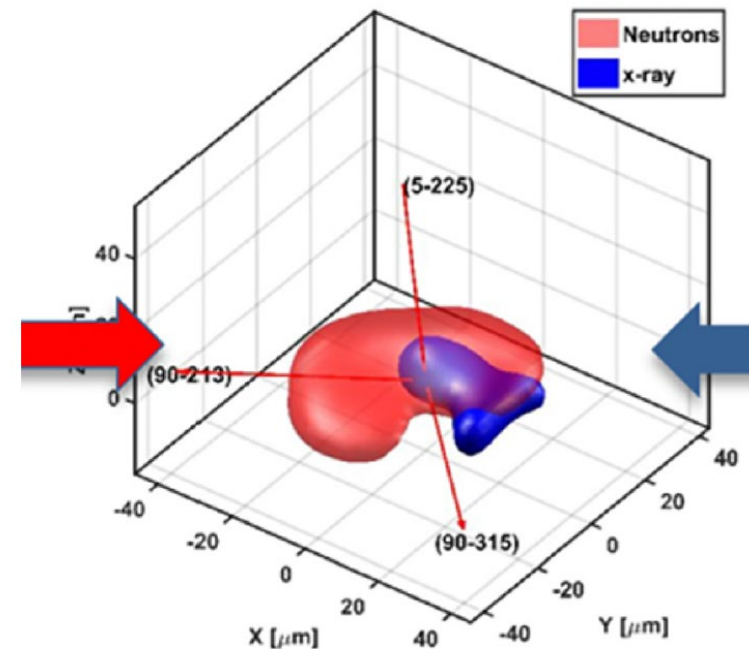
- Laser-heated foil + gated pinhole cameras
- Bragg crystal reflection imager
- 10-40 μm resolution, 35 - 100 ps gating
- X-ray backlighters blinded by self-emission

Rygg, *PRL* 112, 195001 (2014); Hall, *RSI* 90, 013702 (2019)

Hydro instabilities are not resolvable

- X-ray backlighters insufficient to resolve hydrodynamic instabilities at ablation front, fuel-ablator interface, or mix and burn
- Implosion characterization relies on reconstruction of self-emission X-ray (pinhole) and neutron (penumbral) images

3-axis
neutron
images



multiple
line-of-sight
X-ray images

“Mix” of shell material into compressed fuel: increased bremsstrahlung (x-rays) and reduced fusion (neutrons). Cold blue zone shows fill-tube mix.

From single shots to a firing machine

	NIF / OMEGA today	IFE facility
Shot rate	A few shots per day	Shots per hour at a research facility; ~10 Hz at a plant
Recording	Film, image plates, CR-39 and activation samples, recovered by hand	Electronic, read out and cleared between shots
Radiation	One pulse per shot; detectors recover in between	Cumulative dose and damage accumulated over campaigns
Access	Many ports; diagnostics inserted and aligned per shot	Few lines of sight through a blanket
Analysis	Days to weeks of expert interpretation	Automated, before the next shot
Role	Explain the shot	Control the machine

NIF today: ~1,870 image plates scanned 5,265 times in 2024 on obsolete scanners; 200–300 films/yr, high-yield film in short supply; MRS CR-39 etched and scanned offline; radiochemistry collectors lose data to decay before retrieval. *Source: NIF Target Diagnostic 1-pager Summaries, LLNL-PRES-2017572 (Jan 2026).*

Landscape of Inertial Fusion Energy startups

INERTIA Enterprises (USA: \$458 M)

- Indirect Drive, 10 MJ DPSSL



XCIMER Energy Corp (USA: \$200 M)

- Hybrid Indirect Drive, 8-12 MJ KrF excimer (gas)



Focused Energy (DE/USA: \$500 M)

- Direct Drive, 2 MJ DPSSL



Marvel Fusion (DE: \$418 M)

- Hollow-Shell Fast Ignition, 1 MJ DPSSL



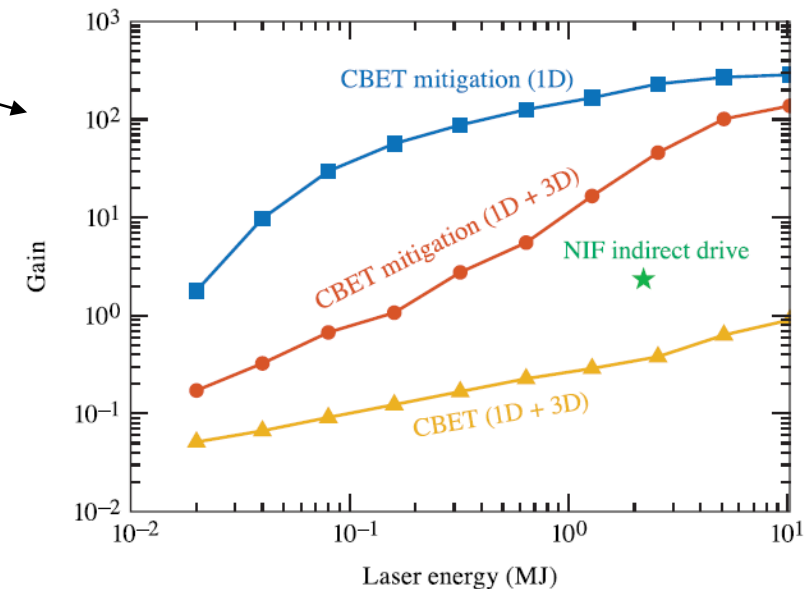
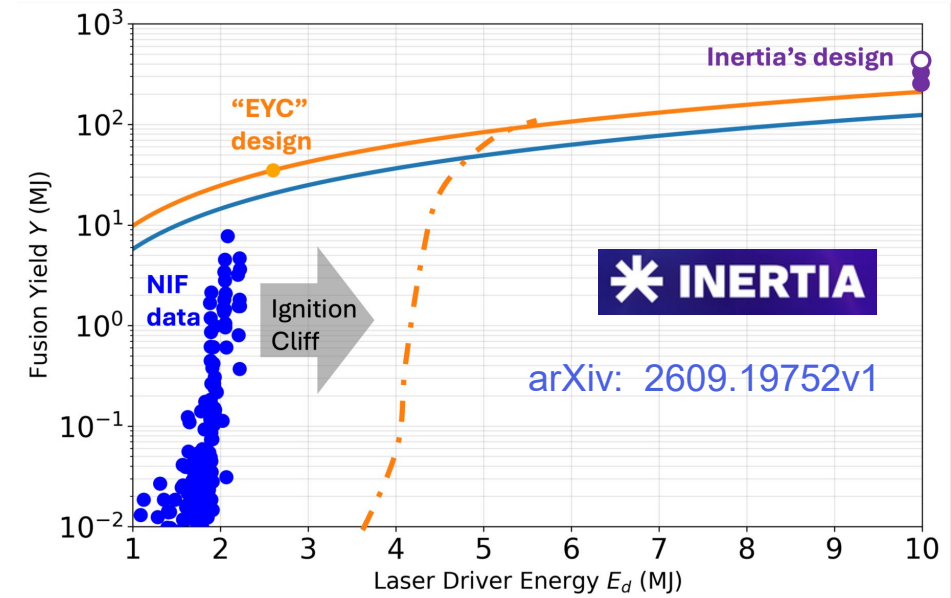
HIPER+ Collaboration (EU)

- proposing [academic](#) Direct Drive facility, 2 MJ DPSSL



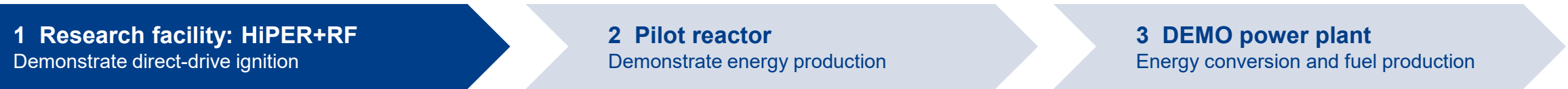
Paradigms for IFE

1. Scale-up of NIF Indirect Drive to **overwhelm** non-ideal targets and laser conditions (Inertia, XCIMER)
 - laser energy to 10 MJ, at 10 Hz rep-rate
 - need cheap, high-rep targets (\$100k to \$1)
 - new mfg techniques with commodity materials
2. Direct Drive at 2 MJ - 5x more efficient than ID under ideal conditions (Focused Energy, HiPER+)
 - additional physics challenges
 - similar target challenges
3. Advanced fast ignitor concepts with 100 kJ-class short-pulse lasers (Marvel Fusion)
 - relaxed compression, less hydro instabilities
 - additional physics challenges: relativistic plasmas to **overwhelm** non-ideal target conditions



E31159J1

HiPER+: Europe's direct-drive path to fusion energy



HiPER+ roadmap: three successive steps over about thirty years

Physics baseline

- Direct-drive shock ignition
- Fast and magnetized ignition assessed as alternatives
- Goal: ignition, then scale to high gain, $Q \geq 100$

Laser driver

- Diode-pumped solid-state lasers, 7–15% wall-plug efficiency
- ≥ 10 shots/hr, with multi-Hz potential
- MJ class; first step at a few 100 kJ

LPI and imprint control

- Broadband pulses
- Second-harmonic (2ω) option, which also eases optics damage
- Advanced beam smoothing

Targets and diagnostics

- Mass-produced cryogenic targets, injected and tracked at ~ 1 Hz
- Radiation-hard, real-time, EMP-resilient diagnostics (WP5)

Status: EUROfusion Enabling Research project HiPER+RF (2026–27) prepares the conceptual design of an open, civilian direct-drive facility: 146 researchers, 30 groups, 12 countries. Next step: ESFRI roadmap; facility possibly realized by ~ 2035 .

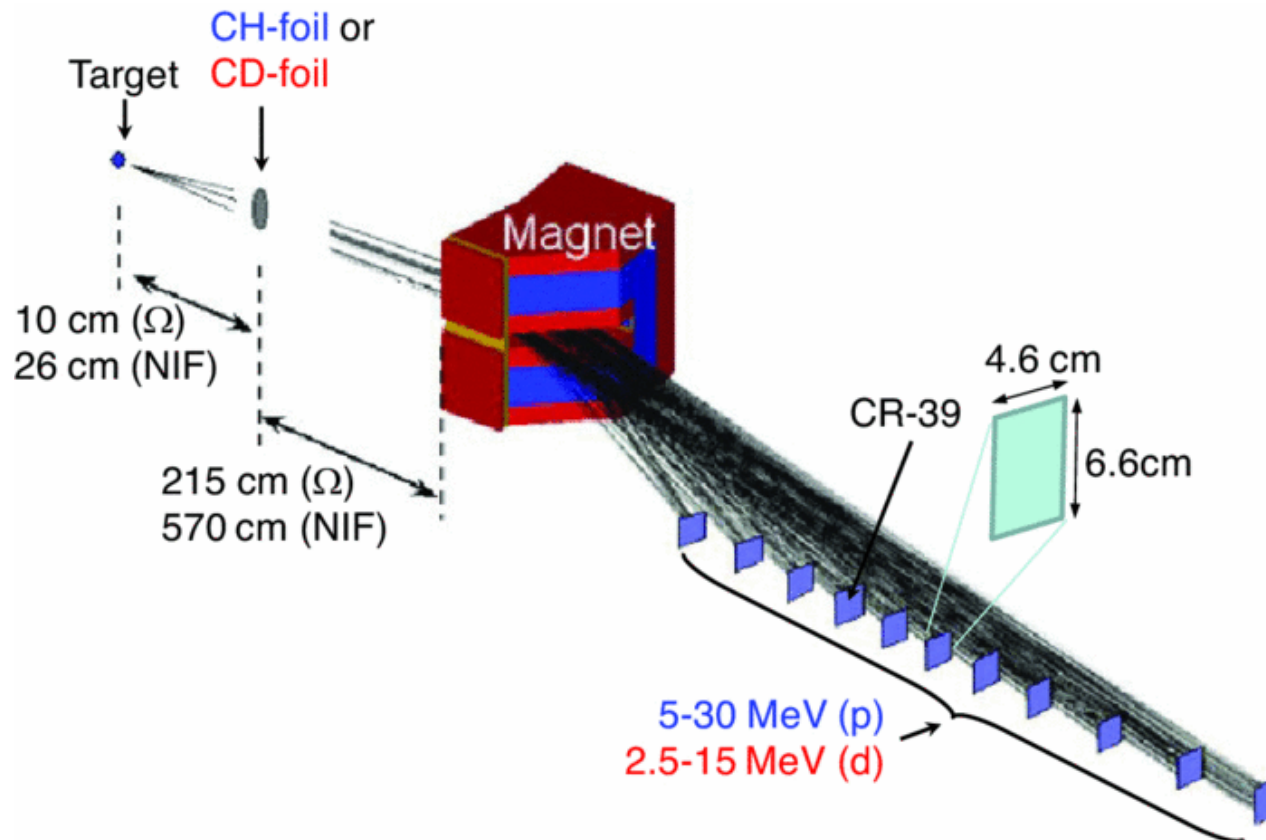
Sources: Batani et al., High Power Laser Sci. Eng. 11, e83 (2023), doi:10.1017/hpl.2023.80; HiPER+RF project presentation, EUROfusion ENR CfP-FSD-AWP26-ENR-01 (Dec 2025); D. Batani, ELI Laser-Induced Fusion meeting (Nov 2023).

What defines implosion quality, and how it is measured

Quantity	Measured today by	At HiPER+ and beyond
Hot-spot shape and size (P2, P4, Mode-1)	Primary neutron and x-ray self-emission imaging, several lines of sight	Fewer views; detectors must clear between shots
Cold-fuel pR and asymmetry	DSR from nTOF on 5 lines of sight (pR asymmetry) and MRS; down-scattered neutron imaging; activation detectors	nTOF DSR carries over (Adapt), but detectors must recover fast after the primary pulse; down-scattered signal ~1–3% of primary; activation must be replaced
Ablator pR, remaining shell, mix	4.4 MeV carbon γ : reaction history (routine) and first images; narrowband x-ray mix imaging	γ flux $\sim 10^{-3}$ of neutron flux: counts-starved ♦
Burn history, bang time, burn width	Gamma reaction history (bang time to ~ 30 ps); neutron temporal diagnostics	Picosecond resolution of burn onset needed ♦
Hot-spot drift (RKE), ion temperature	nTOF on 5 collimated lines of sight: energy shift $\rightarrow$ velocity vector, width $\rightarrow T_i$; the 5th view cut velocity uncertainty from 20–40 to <10 km/s	Detectors Adapt, but ≥ 5 well-spread views are needed: each is a port through the blanket
Alpha heating	Yield amplification; alpha knock-on neutron tail	New capability ♦

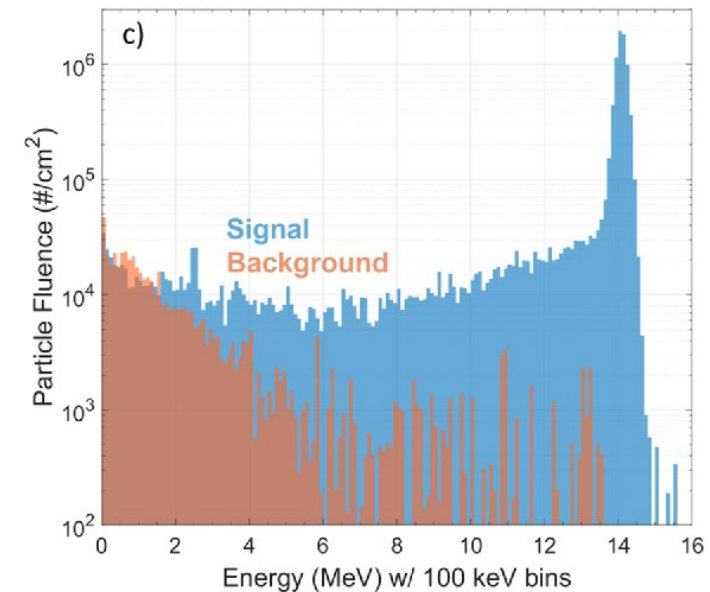
Shaded rows: the nuclear imaging measurements, detailed on the Rebuild slide. ♦ capability gap even on single NIF shots. Sources on the Rebuild slide and Moore et al., Nucl. Fusion 64, 106041 (2024); 5-LOS nTOF suite, OSTI 1631917.

MRS: Magnetic Recoil Spectrometer



- Principal instrument for neutron characterization
- measure recoil D (or H) from CH or CD foil
- CR-39 (gamma, n blind) - recovery & etching
- DT yield -- $Y[13-15 \text{ MeV}]$
- Tion -- DT ion temperature: fwhm of 14 MeV peak
- Fuel pR from neutron down-scatter ratio (DSR)

$$\text{DSR} = Y[10-12 \text{ MeV}] / Y[13-15 \text{ MeV}]$$
- Alpha knock-on: $Y[15-20 \text{ MeV}]$
- RKE -- shift of 14 MeV peak



Where today's diagnostics land

Adapt

Physics carries over; re-engineer standoff, shielding, debris protection, recording

- nTOF on ≥ 5 lines of sight (yield, T_i , DSR/pR, drift)
- VISAR / SOP shock timing
- Optical LPI: backscatter, calorimetry, Thomson scattering
- Hot-electron hard x-ray diagnostics
- Gamma reaction history (bang time, carbon pR)
- Driver diagnostics

Rebuild

Concept valid; detector or recording medium cannot survive dose or shot rate

- **Neutron imaging: primary and down-scattered** ♦
- **Gamma imaging: remaining carbon ablator** ♦
- Gated x-ray imaging (MCP)
- Backlit and Compton radiography
- Narrowband crystal imaging (mix)
- Film, image plates, CR-39 $\rightarrow$ electronic sensors (MRS; time-resolved MRSt on hold)
- Activation, radiochemistry $\rightarrow$ new principle (decay- and retrieval-limited)
- Burn history, time-resolved n-spectroscopy, AKN ♦

Transform

Plant-level needs with no adequate solution yet

- 100% target inspection and in-flight tracking
- Shot-by-shot registration of nuclear images
- Real-time analysis and reconstruction
- Minimal survivable sensor suite behind the blanket
- Symmetry control from few lines of sight
- Tritium, fuel-cycle and chamber monitoring

Radiation hardness & repetition rate

Rule of thumb: Adapt $\approx$ optical or long standoff; Rebuild $\approx$ near-chamber detectors or recovered media. ♦ *capability gap even on single NIF shots*

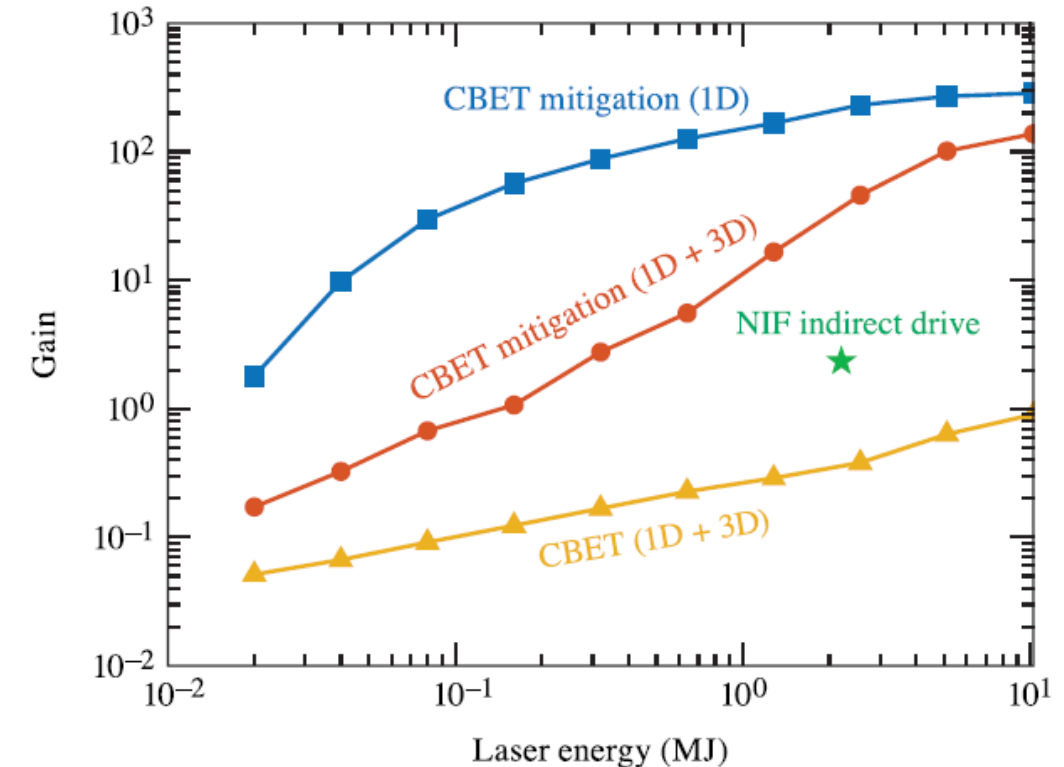
Adapt: the physics carries over

- **nTOF on long, shielded lines**: fusion yield, ion temperature, down-scattered ratio "DSR" (pR)
- **VISAR / SOP**: relayed optically out of the chamber; protect final optics from debris
- **Optical LPI diagnostics**: backscatter, scattered-light calorimetry, Thomson scattering, scaled from OMEGA to open direct-drive geometry
- **Hot-electron x-rays and gamma reaction history**: electronic detectors at standoff
- **The work is engineering**: standoff, shielding, debris protection, electronic recording

Adapt

Rebuild

Transform



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At HiPER+-scale laser energies, CBET mitigation changes predicted gain by one to two orders of magnitude, so LPI must be measured quantitatively.

D.H. Froula et al., Phys. Plasmas 32, 052713 (2025); R.K. Follett et al., Phys. Plasmas 32, 042705 (2025)

Rebuild, in depth: neutron and gamma imaging

Adapt

Rebuild

Transform

Three images, three questions

Primary n, 14 MeV	Where is the hot spot? 3 near-orthogonal views on NIF; $\sim 10\ \mu\text{m}$ after reconstruction
Down-scattered n, 6–12 MeV	Where is the cold fuel? $\sim 1\text{--}3\%$ of primary; separated by time of flight at 28 m; fewer views
Carbon γ, 4.4 MeV	Where is the ablator? First images at NIF; ablator is optically thin, so every carbon nucleus can contribute

Together: symmetry and mix mapped in the burning plasma itself, where x-ray backlighters are blinded

What breaks at HiPER+ and beyond

- **Statistics:** γ flux $\sim 10^{-3}$ of neutrons; lower yield per shot means accumulating over shots, which needs reproducible implosions
- **Registration:** even at NIF, views are not registered to each other or to chamber coordinates; with injected targets, every shot must be registered
- **Detectors:** dim down-scattered signal right after a bright primary pulse needs fast, bright scintillators; add afterglow, damage, clearing between shots
- **Reconstruction:** iterative, with human intervention; must become automated and fast

Proposal for direct drive: in CH or wetted-foam targets, carbon- γ imaging could map where foam carbon ends up at burn

Transform: the diagnostic philosophy changes

Adapt

Rebuild

Transform

Targets

100% inspection at Hz rates; fuel-layer quality in transit; in-flight tracking and beam engagement

Control

Real-time analysis with AI/ML, digital twins and synthetic diagnostics; feedback before the next shot

Survival

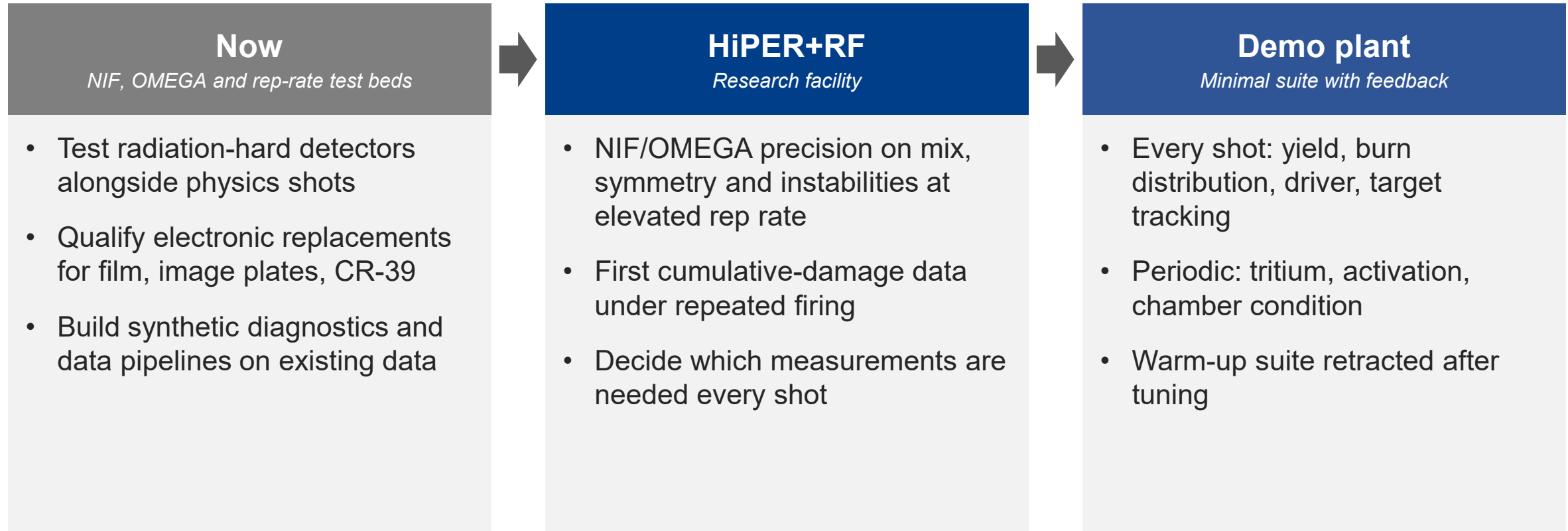
A minimal sensor suite behind the blanket; lifetime models from cumulative-damage data

Operations

Tritium accountancy, fuel cycle and chamber monitoring; symmetry inferred statistically across shots

Warm-up suite: full diagnostics to reach the operating point, then retracted to limit exposure

A development path



Mirrors the BRN two-step approach: needs at a burning-plasma research facility, then a downselect for a first pilot plant

Summary

Adapt

Optical and long-standoff diagnostics carry over; the work is engineering.

Rebuild

Near-chamber detectors and recovered media must be replaced by radiation-hard, fast, electronic detectors. Start testing now.

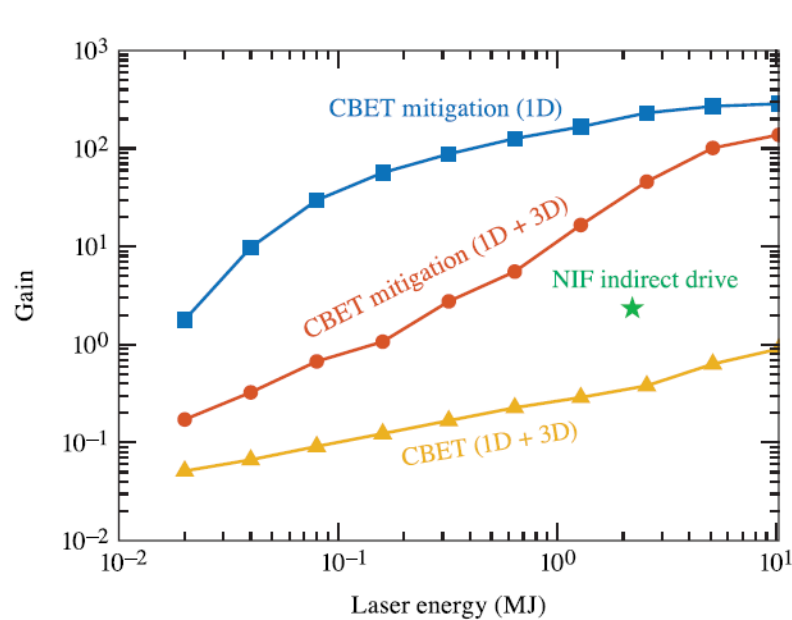
Transform

At a plant, diagnostics control the machine rather than explain the shot. Target metrology and real-time feedback have no adequate solution yet.

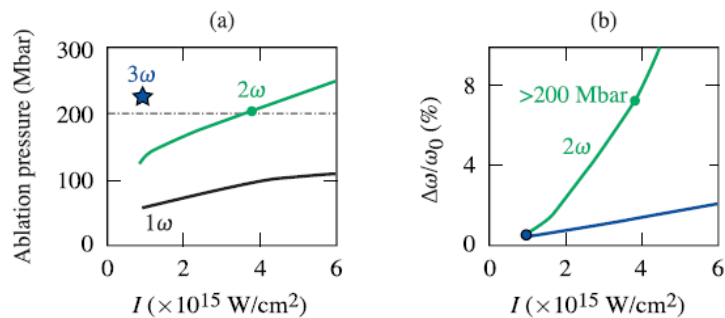
HiPER+RF is where precision diagnostics and plant-like conditions first meet: the place to make the Rebuild column real.

BACKUP SLIDES

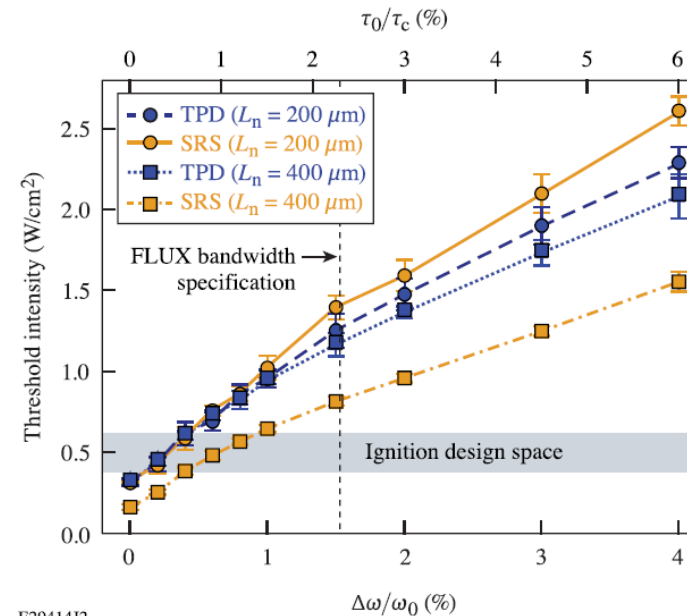
From NIF ignition towards IFE – Direct Drive scaling from OMEGA



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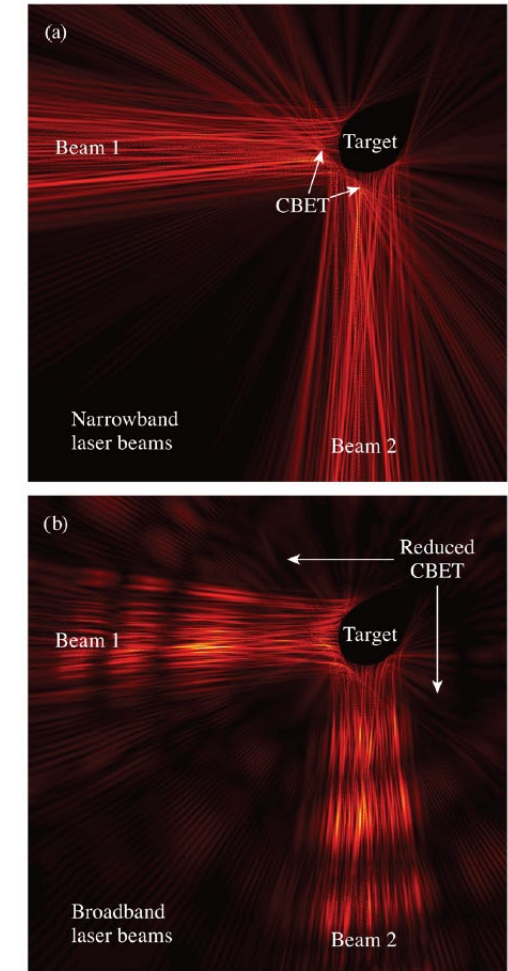


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E29414J2

- More efficient laser coupling possible, if no CBET
- Suppression of CBET and LPI (SRS, SBS, TPD) with laser bandwidth
- Laser imprint mitigation (smoothing) required to suppress seed of high-mode instabilities



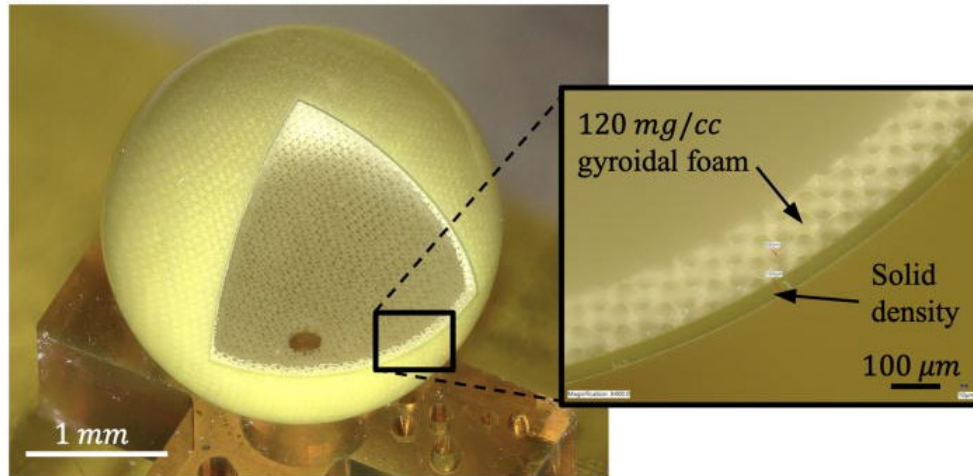
E31095J1

D.H. Froula, et al., Phys. Plasmas **32**, 052713 (2025) doi: 10.1063/5.0261155

R.K. Follett, et al, Phys. Plasmas **32**, 042705 (2025) doi: 10.1063/5.0253853

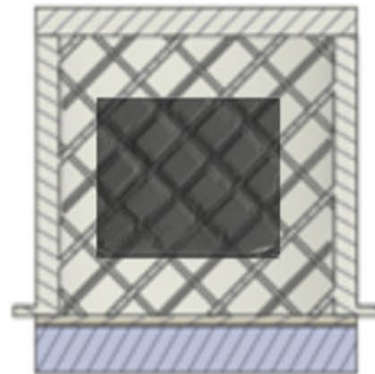
High rep-rate IFE targets: 3D printing of wetted-foam capsules

(b) All 2PP capsule with octant slice

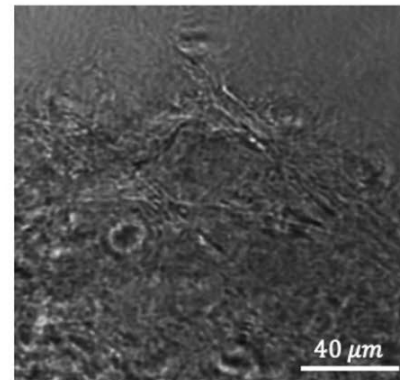


- Additive mfg: TPP (two-photon polymerization)
- Liquid DT wets into inner foam layer by capillary action
- Mutually supportive shell and foam: thinner shell, lower density
- Physics design freedom from 3D geometry
- Fast and flexible fabrication with low materials cost
- **BUT: strong disruption of laser-driven shocks (LCLS)**

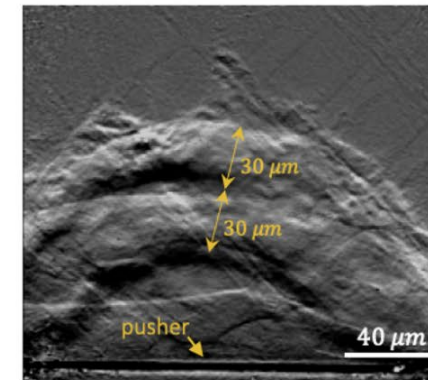
a. Talbot-XPCI cold target
overlapping TPP lattice drawing
 $\rho_0 = 35 \text{ mg/cm}^3$ tilted lattice



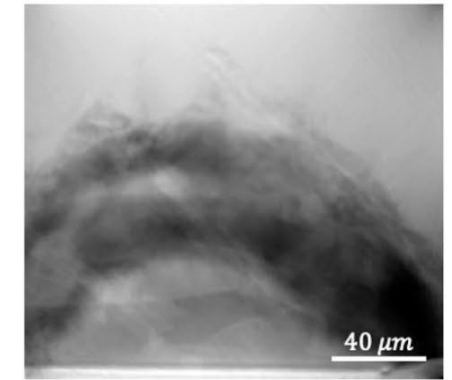
b. Transmission (normalized)
 $\rho_0 = 35 \text{ mg/cm}^3$ tilted lattice
 $t = 21 \text{ ns}$



c. Talbot-XPCI: Y-gradient
 $\rho_0 = 35 \text{ mg/cm}^3$ tilted lattice
 $t = 21 \text{ ns}$

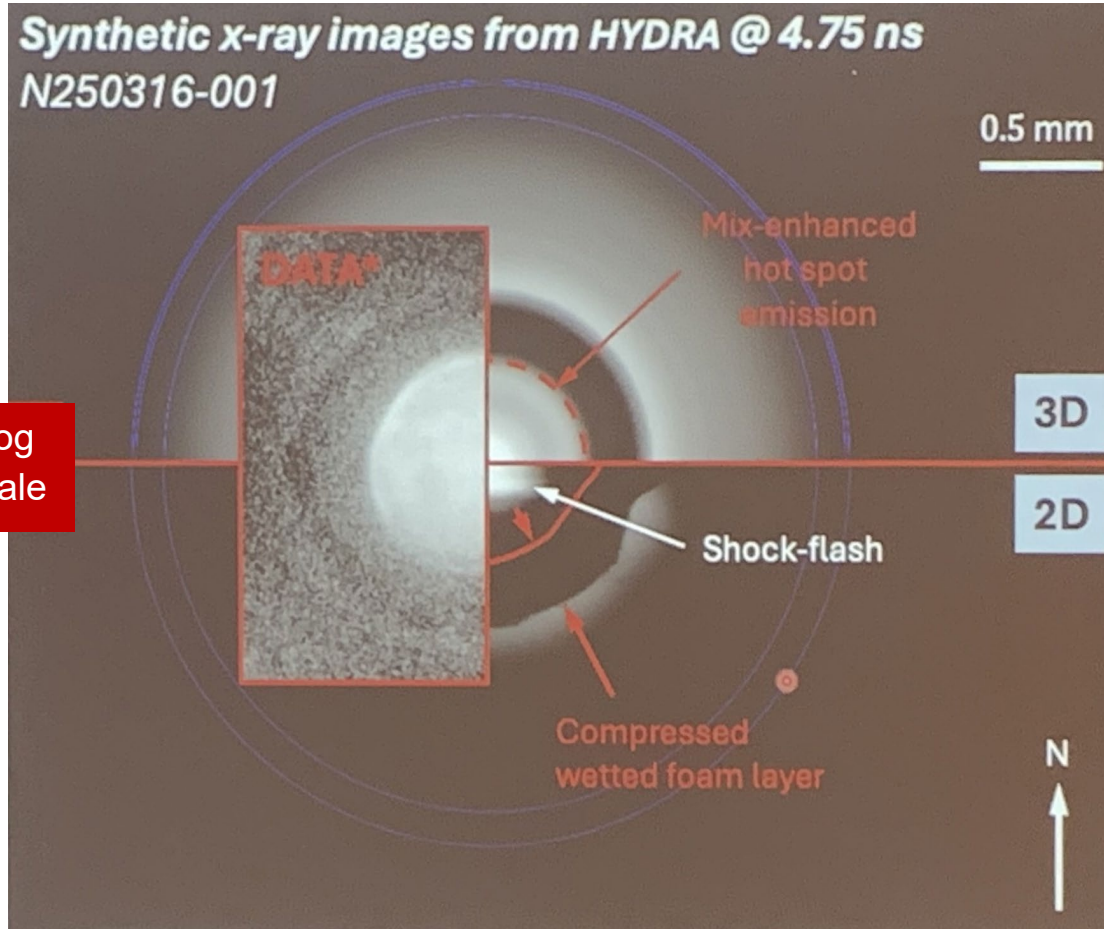


d. Talbot-XPCI: Phase Integrated
 $\rho_0 = 35 \text{ mg/cm}^3$ tilted lattice
 $t = 21 \text{ ns}$

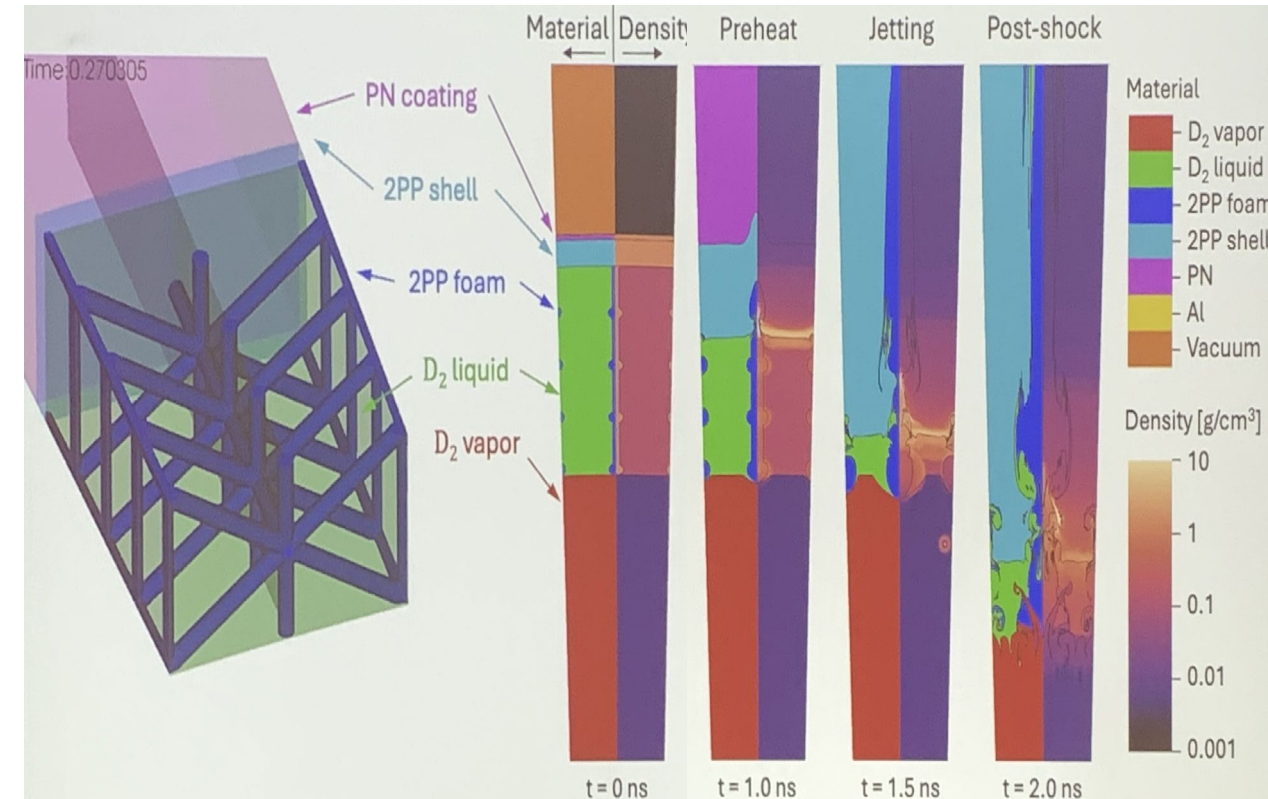


Wetted Foam (DD) performance on NIF (polar direct drive)

G.E. Kemp et al, Phys Plasmas 32, 022702 (2025), doi: 10.1063/5.0233748



3D HYDRA models suggest 2PP foam struts imprint on shell, shredding the capsule prior to shock breakout



Foam micro-structure seeds significant Richtmyer-Meshkov shear instabilities, turbulent mix, electron heating --> *significant research required for wetted foam qualification for direct drive IFE*

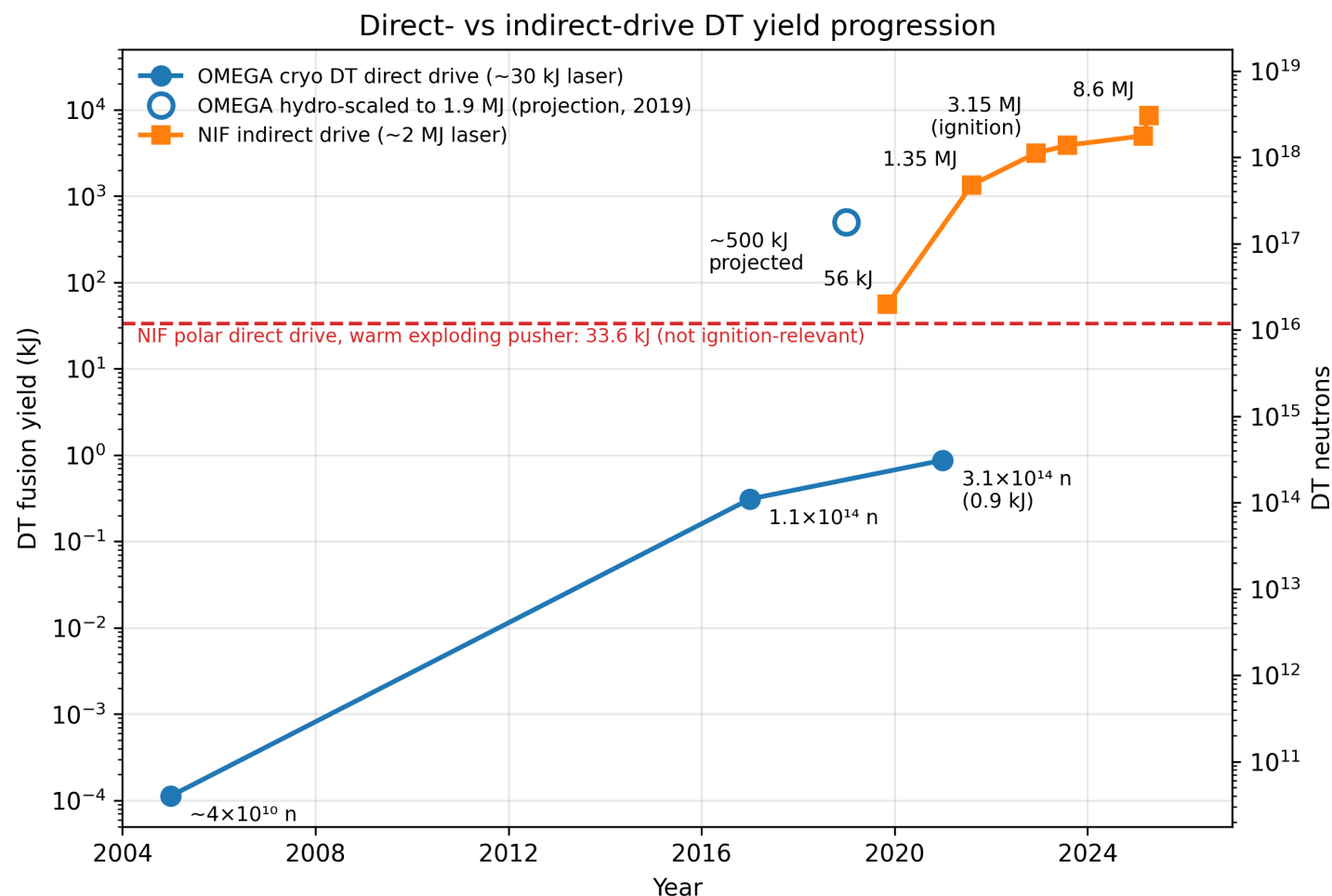
Backup: neutron fluence per shot

DT yield per shot	Neutrons	Fluence at 1 m	Fluence at 5 m
1 MJ	3.5×10^{17}	$2.8 \times 10^{12} \text{ n/cm}^2$	$1.1 \times 10^{11} \text{ n/cm}^2$
10 MJ	3.5×10^{18}	$2.8 \times 10^{13} \text{ n/cm}^2$	$1.1 \times 10^{12} \text{ n/cm}^2$
100 MJ	3.5×10^{19}	$2.8 \times 10^{14} \text{ n/cm}^2$	$1.1 \times 10^{13} \text{ n/cm}^2$
100 MJ at 10 Hz, one day	3.1×10^{25}	$2.4 \times 10^{20} \text{ n/cm}^2$	$9.8 \times 10^{18} \text{ n/cm}^2$

17.6 MeV per DT reaction $\rightarrow 3.55 \times 10^{17}$ neutrons per MJ of yield. Isotropic point source, 14.1 MeV neutrons, no shielding or scattering: an upper-bound geometric estimate.

Compare with displacement-damage tolerances of the detector technologies in the Rebuild column.

Backup: Direct- vs indirect-drive DT yield history



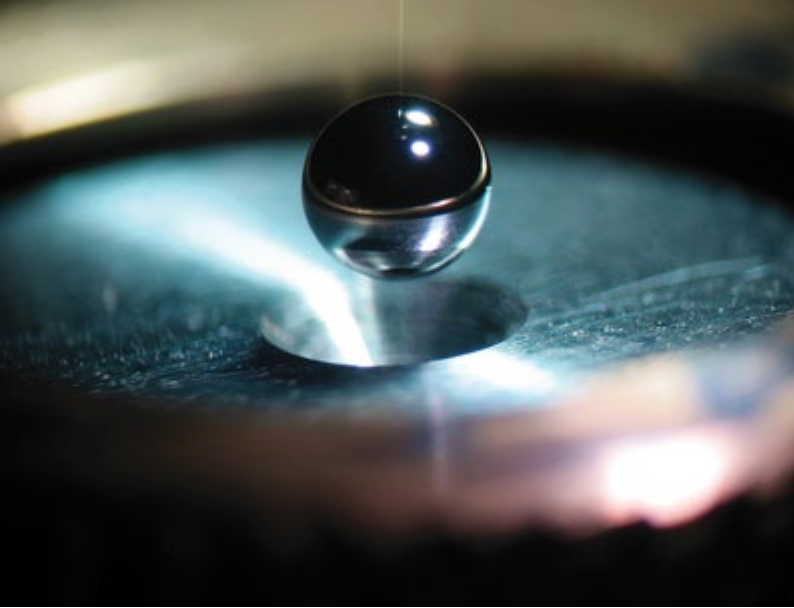
Records only, not all shots. NIF 2021 point plotted mid-year. Neutron→kJ conversion assumes 17.6 MeV per DT reaction.

- Measured cryo direct drive stops at ~1 kJ (OMEGA, 30 kJ laser)
- Hydro-scaled to 1.9 MJ: ~500 kJ projected, never tested
- NIF polar drive reached 33.6 kJ, but with warm exploding pushers, not ignition-relevant
- **No cryogenic direct-drive implosion above OMEGA scale yet → the several-100 kJ step is untested territory**

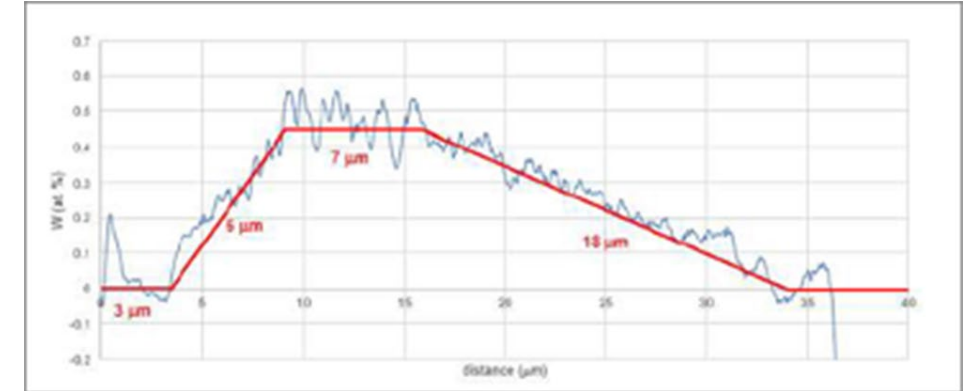
Summary Table of Priority Diagnostic Areas (compiled from DOE BRN)

Priority Area	Key Diagnostics Needed
Gain-limiting physics	Sub-100ps burn history, AKN spectrometry, gamma-ray spectrometers
Alpha heating & burn propagation	Time-resolved nToF, temporally resolved X-ray & neutron imaging
Mix & asymmetry	Narrowband crystal imaging (DCBI), 3D shell radiography, multi-LOS pR
Direct drive / LPI	Backscatter diagnostics, hot-electron calorimetry, CBET quantification
Target metrology	Automated inspection, in-flight imaging, Hz-rate quality assurance
Radiation hardening	Rad-hard electronics, cumulative damage testing, fiber/optic survivability
High-rep-rate / FPP	Real-time AI/ML analysis, minimal sensor suite, 10 Hz feedback loops

<https://str.llnl.gov/str-julyaugust-2025/future-ignition>

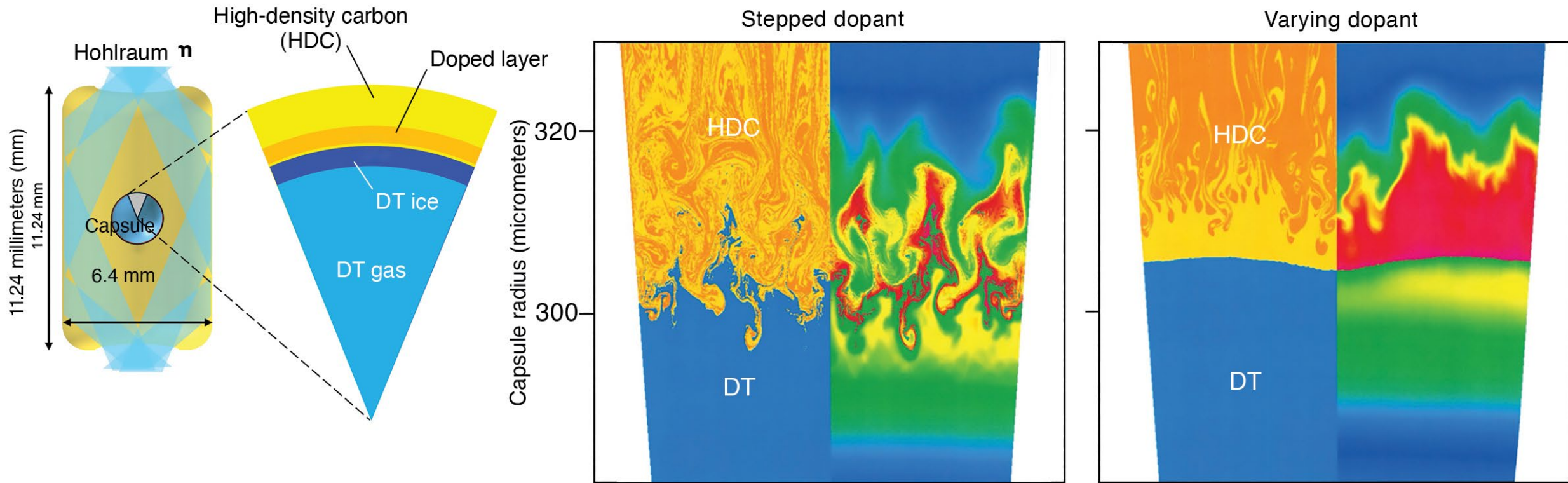


The NIF target capsule measures approximately 2 millimeters in diameter and is filled with frozen deuterium–tritium (DT) fuel. Capsules can be composed of plastic, high-density carbon (HDC, diamond), or beryllium.

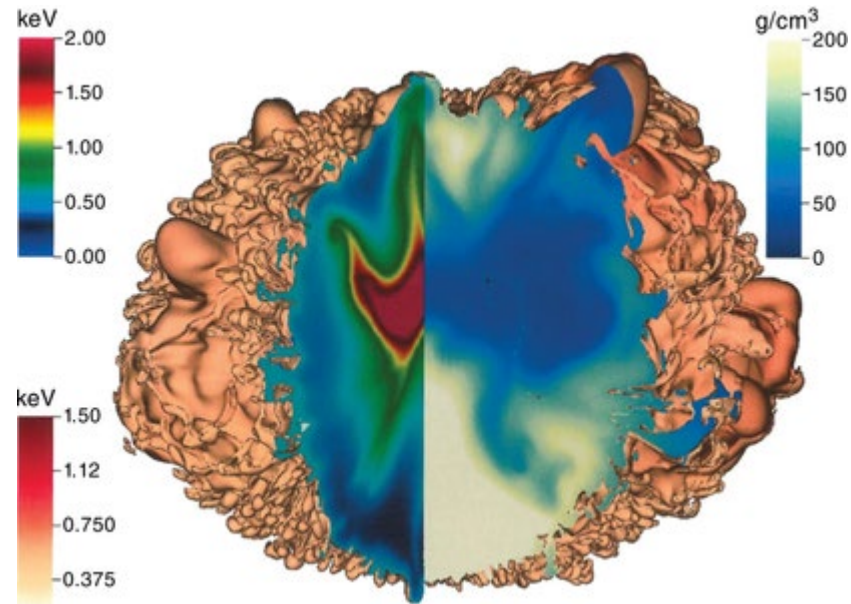


<https://lmf.llnl.gov/news/target-breakthrough-enabled-fusion-record-nif>

<https://str.llnl.gov/str-julyaugust-2025/future-ignition>



To control high-energy x-ray preheating, researchers vary doping schemes in target capsules, affecting mixing levels between the DT fuel and the HDC ablator material as the shell implodes. The target capsule inside the hohlraum has several layers, as depicted in the multicolored capsule slice (left, inset): DT gas (light blue), DT ice (dark blue), tungsten-doped layer (orange), HDC shell (yellow). Experiments with a 0.45 atomic percent tungsten-doped layer offset by 5 micrometers from the shell's inner surface yielded significant mixing along the capsule radius between the DT fuel and the ablator material (middle) as the shell imploded. However, experiments in which a continuously varying dopant profile was used reduced fuel–ablator mixing (right), as predicted in these HYDRA simulations. Mixing is indicated from higher levels (red) down to lower levels (blue).



A cutaway HYDRA simulation shows capsule details and asymmetry in shot N170601, five years before ignition. On the right half of the cutaway, density levels are indicated in grams per cubic centimeter (g/cm³; top, right). On the left half of the cutaway, x-ray energy levels are indicated in kiloelectronvolts (keV) for the capsule interior (top, left). X-ray energy levels for the exterior are indicated in keV (bottom, left).