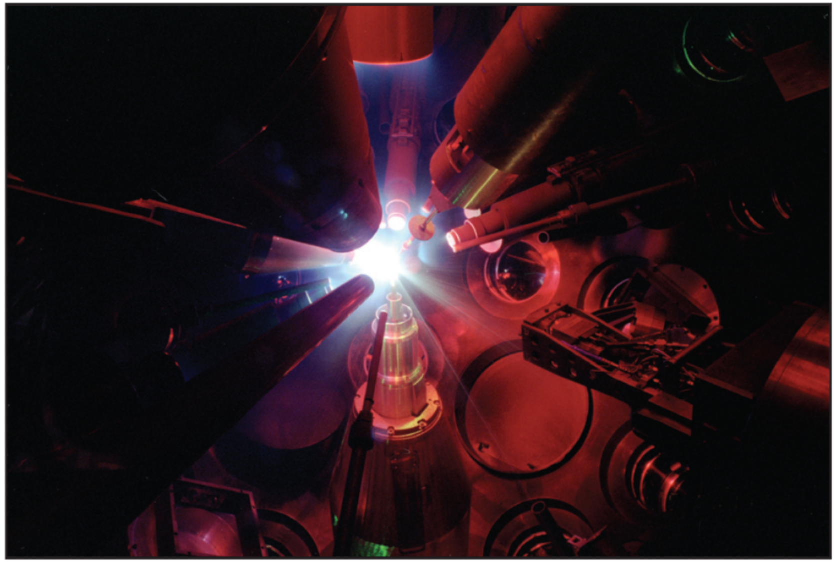
Laser-Direct-Drive (LDD) Inertial Confinement Fusion (ICF)—A Pathway to Ignition



OMEGA: ~ 3.3 m
NIF: ~ 10 m

J. A. Marozas
University of Rochester
Laboratory for Laser Energetics

62nd Annual Meeting of the American Physical Society
Division of Plasma Physics
Tutorial Talk
9–13 November 2020

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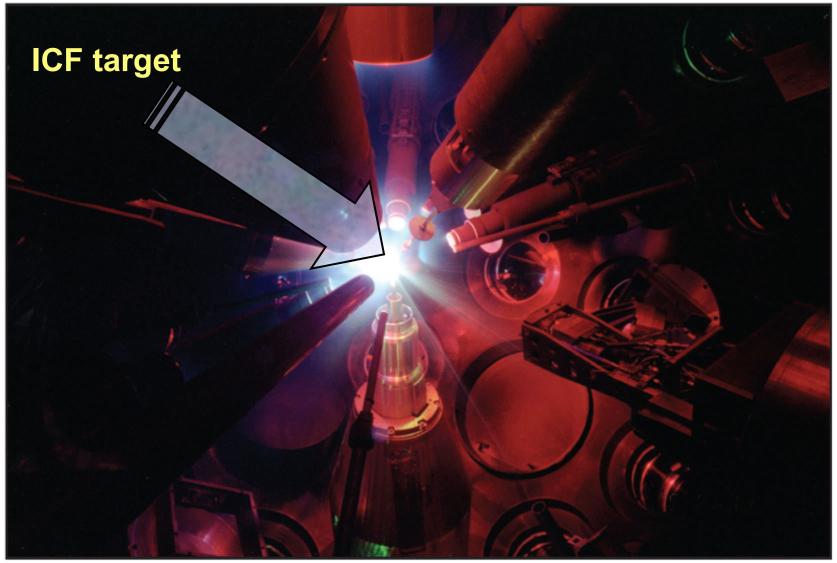

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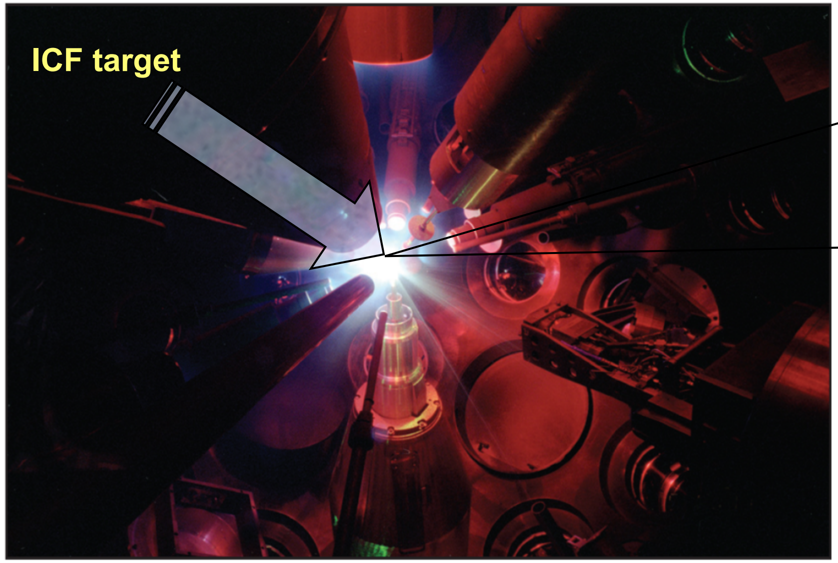

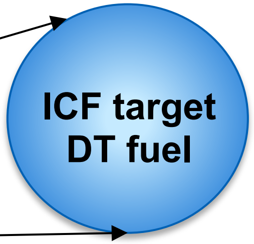

NIF: ~3 mm

OMEGA: ~ 3.3 m
NIF: ~ 10 m

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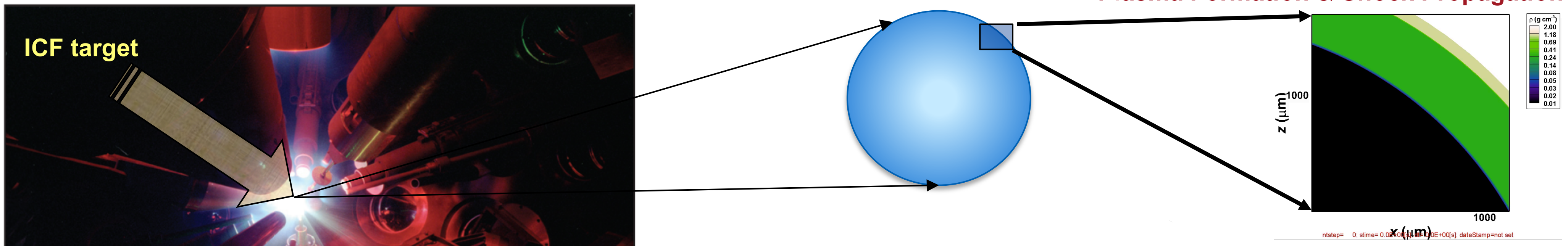
Plasma Formation & Shock Propagation



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NIF: ~ 10 m

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*2-D *DRACO* Imprint Simulations with LLE Ray Trace, performed by T. Collins (2019).

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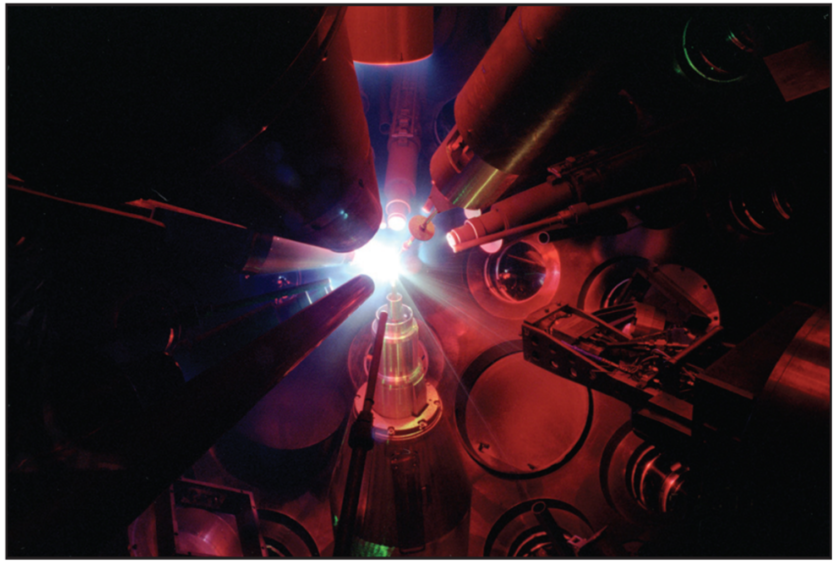

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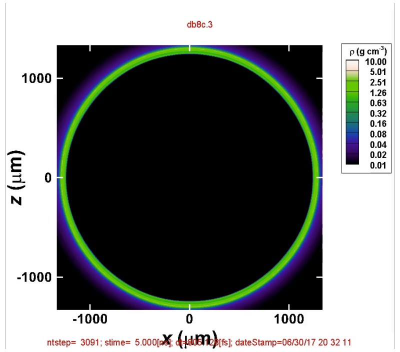
NIF: ~ 10 m



Acceleration

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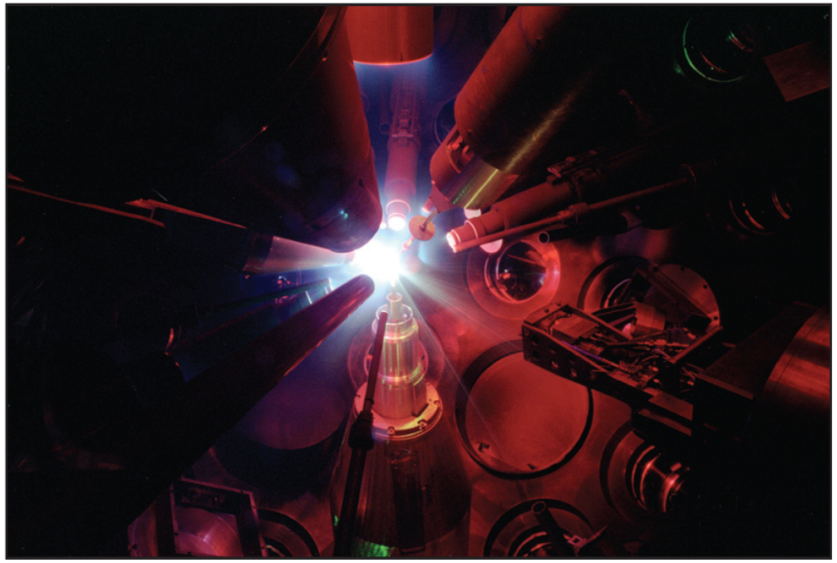

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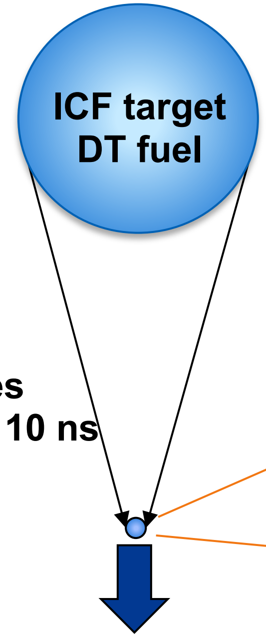
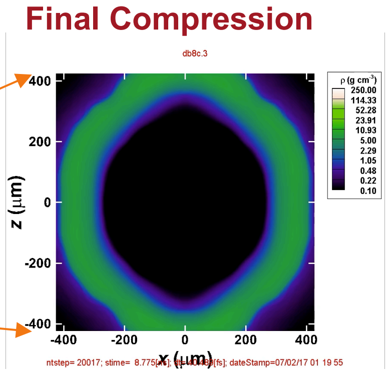


Implodes
>20× in 10 ns



High T_i, pressure and density
➔ DT_n

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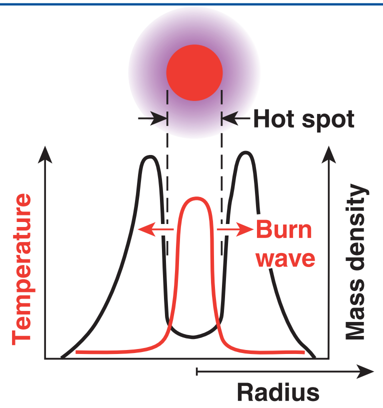
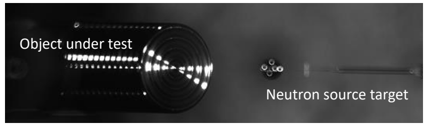
Summary

Laser direct drive (LDD) is making strides along the pathway to ignition

- ICF assembles DT fuel mass with a cold, high-areal-density (ρR) shell and hot central core using a high-speed and low-entropy implosion
  - LDD increases the ignition margin at moderate convergence (20 to 30)* while providing open access to diagnostics and external magnetic fields



- A robust "exploding-pusher" (XP) platform generates a high neutron flux,** albeit at low areal density (ρR)
  - ideal platform to study implosion physics modeling†, NIF improvements, and neutron-survivability device testing



- The pathway incorporates upgrades for energy coupling and symmetry control
  - **short term**: predicted to reach >100-kJ fusion yields at low convergence (~10)
  - **long term**: information gleaned will feed forward into higher-convergence, higher-ρR targets that can ignite

* Relative to Laser Indirect Drive (LID)
** C. B. Yeamans *et al.*, "High Yield Polar Direct Drive Fusion Neutron Sources at the National Ignition Facility," submitted to Nuclear Fusion.
† J. A. Marozas *et al.*, Phys. Rev. Lett. 120, 085001 (2018);
H. D. Whitley *et al.*, Physics Archive, https://arxiv.org/abs/2006.15635 (2020).
ICF: inertial confinement fusion
NIF: National Ignition Facility

Collaborators

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Schafer Corporation

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Los Alamos National Laboratory

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Naval Research Laboratory

G. Rochau, L. Claus, Q. Looker, J. Porter, G. Robertson, and M. Sanchez

Sandia National Laboratories

J. Hares and T. Dymoke-Bradshaw

Kentech Instruments Ltd.

W. J. Garbett

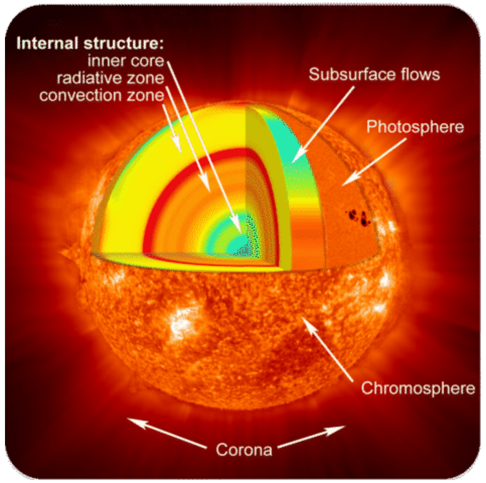
Atomic Weapons Establishment

Laser-direct-drive (LDD) inertial confinement fusion (ICF)— A pathway to ignition

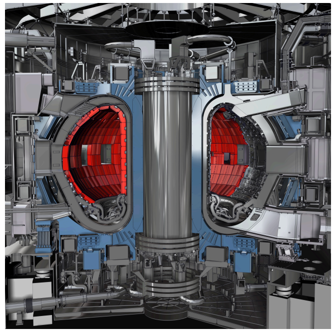
- Fusion: introduction to ICF
  - laser direct drive (LDD)
  - laser indirect drive (LID)
- Simulations and experiments in LDD
- NIF LDD ⇔ polar direct drive (PDD)
  - focus: exploding-pusher (XP) platform
- Future NIF upgrades progressing toward ignition

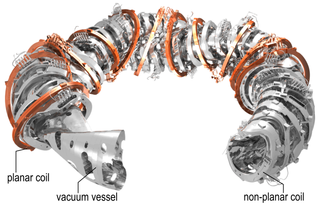
Nuclear fusion is known to occur in three different forms of confinement

Gravity confinement

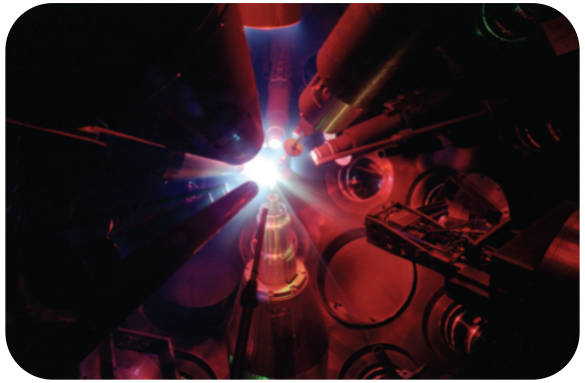


Magnetic confinement

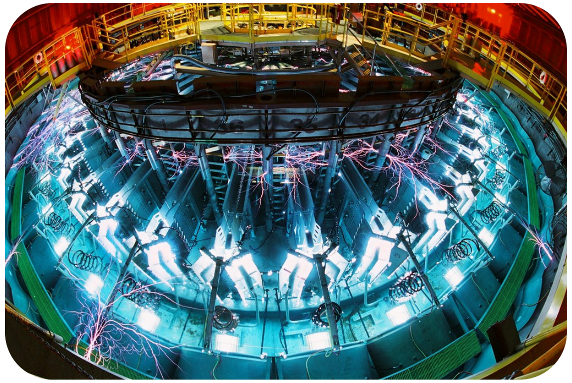




Inertial confinement



- Laser direct drive (LDD)
- Laser indirect drive (LID)
- Laser-magnetic hybrid
  - "MagLIF"
  - polar LDD on NIF
- Shock and fast ignition

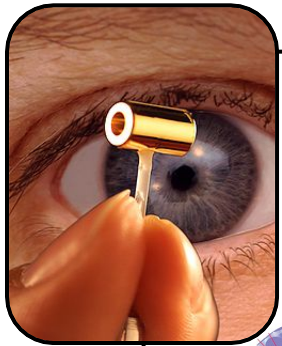


- Magnetic ICF: Pulsed power Z machine

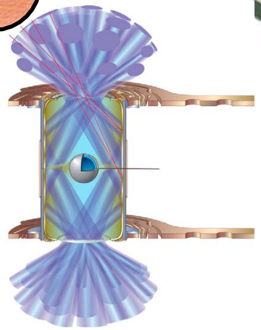
All laboratory approaches, covering a vast range of time and length scales, depend on confinement typically expressed as a "Lawson"-type criterion.

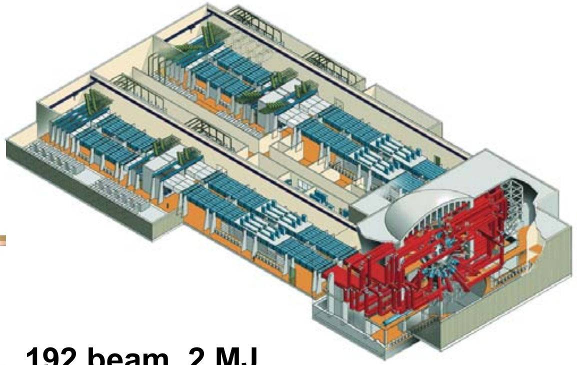
* MagLIF: magnetic liner inertial fusion

Laser-based ICF research is divided into LID and LDD, where the laser source either indirectly or directly ablatively drives a shell containing nuclear fuel



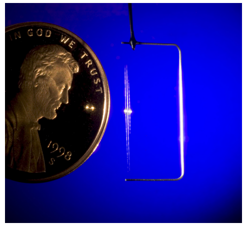
National Ignition Facility (NIF)
Lawrence Livermore National Laboratory

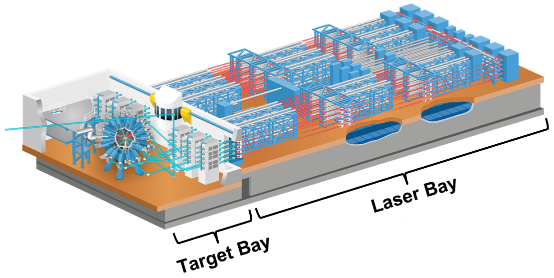




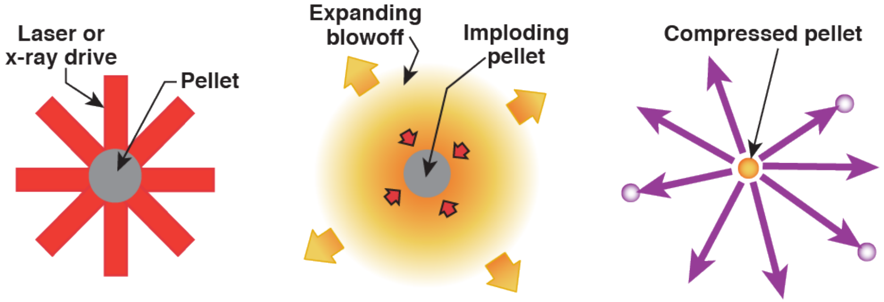
192 beam, 2 MJ

LLE 60-beam
OMEGA Laser System





60 beam, 26 kJ



Implosions are driven by the rocket effect from the blow-off plasmas

Laser ICF is a national multi-laboratory effort spanning decades of research across multiple disciplines

UR LLE

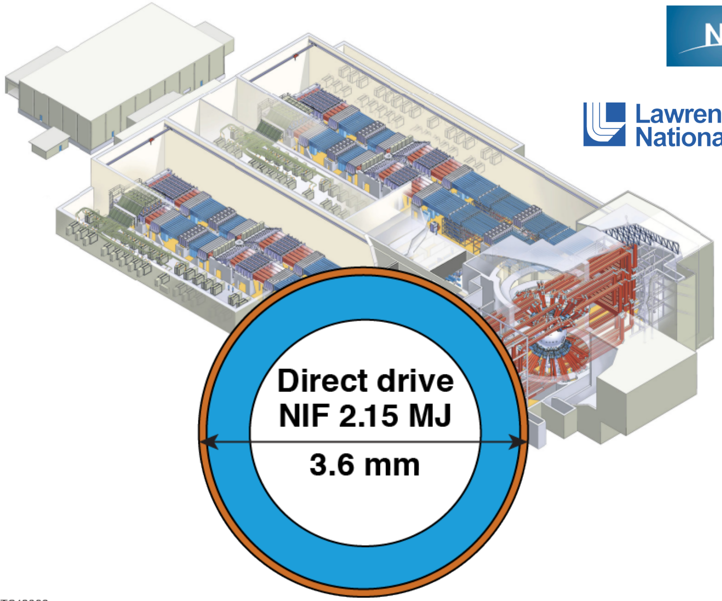
NIF

GENERAL ATOMICS

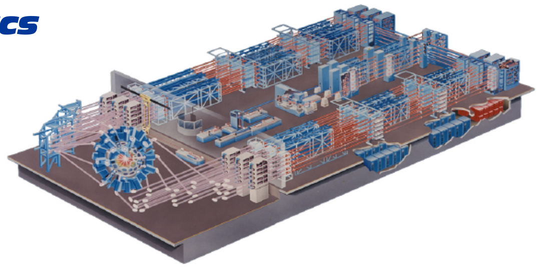
Lawrence Livermore National Laboratory

Massachusetts Institute of Technology

U.S. NAVAL RESEARCH LABORATORY

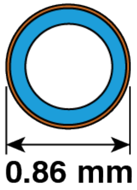


TC13889q

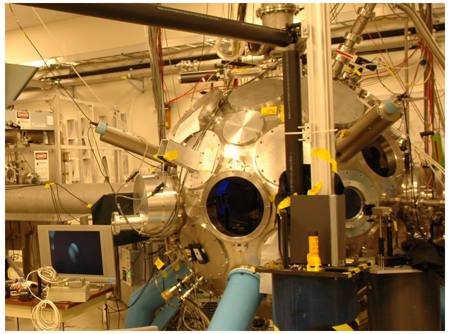


Scale 1:70
in energy

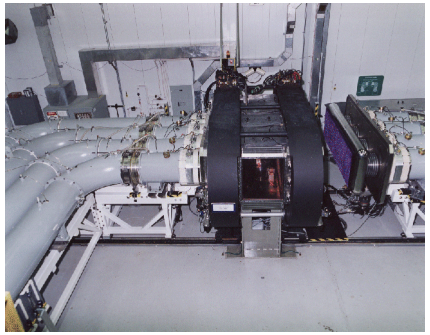
OMEGA 26 kJ



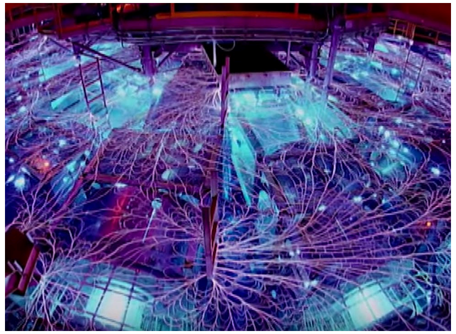
Trident Laser
Los Alamos National Lab



Nike KrF Laser
Naval Research Lab

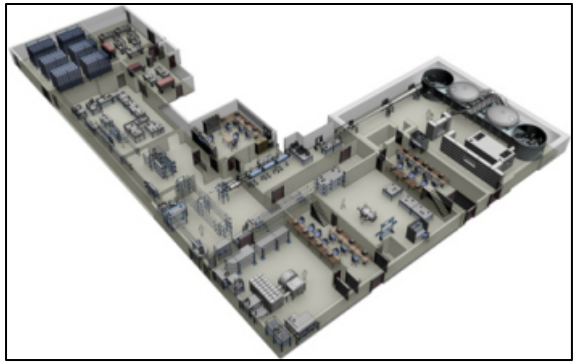


Z-machine
Sandia National Lab

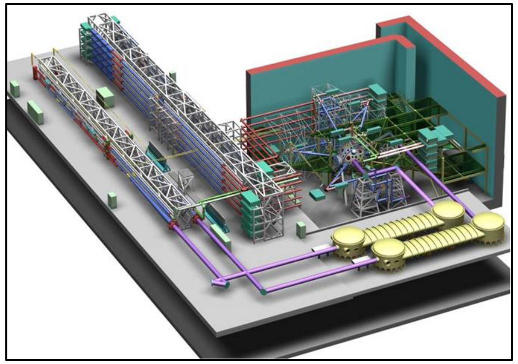


ICF-related research is conducted at a variety of labs across the globe

Vulcan and Vulcan PW Lasers
RAL, UK



Orion Laser
AWE, UK

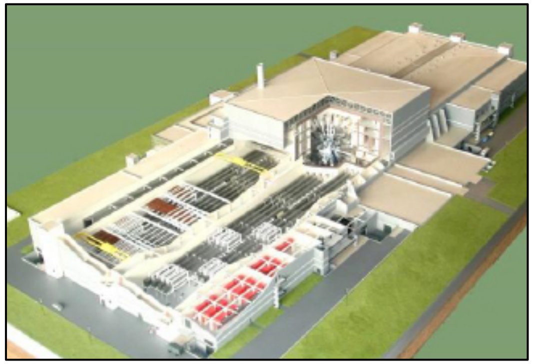


ILE (Osaka
University, Japan)

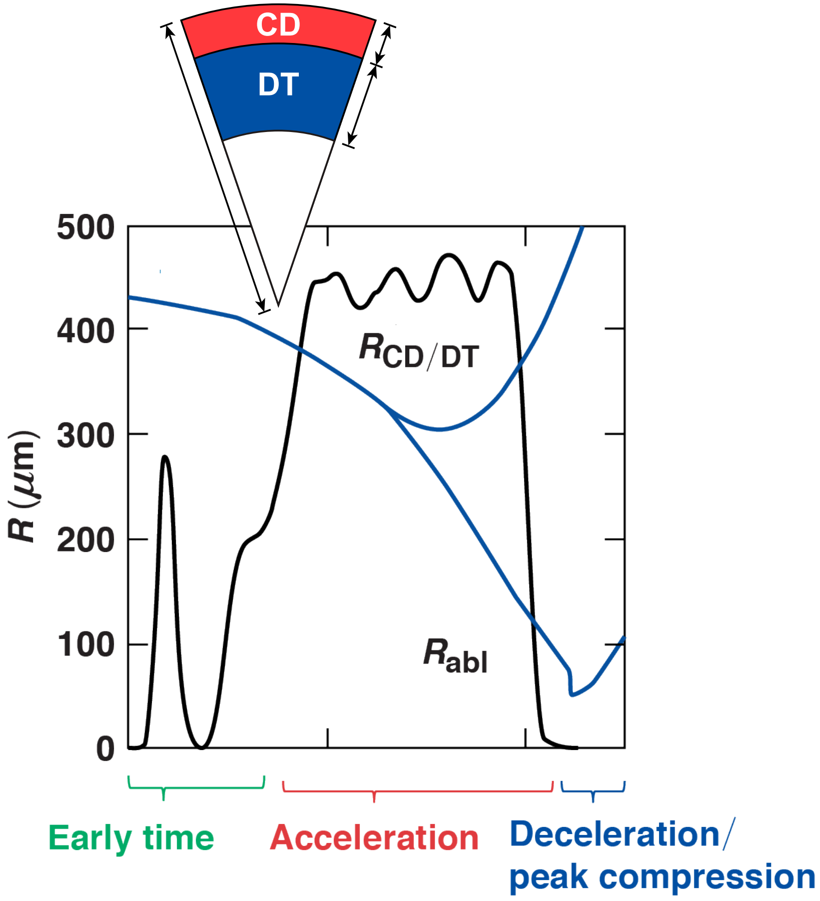
Shenguang II Laser
(SIOM, Shanghai, China)

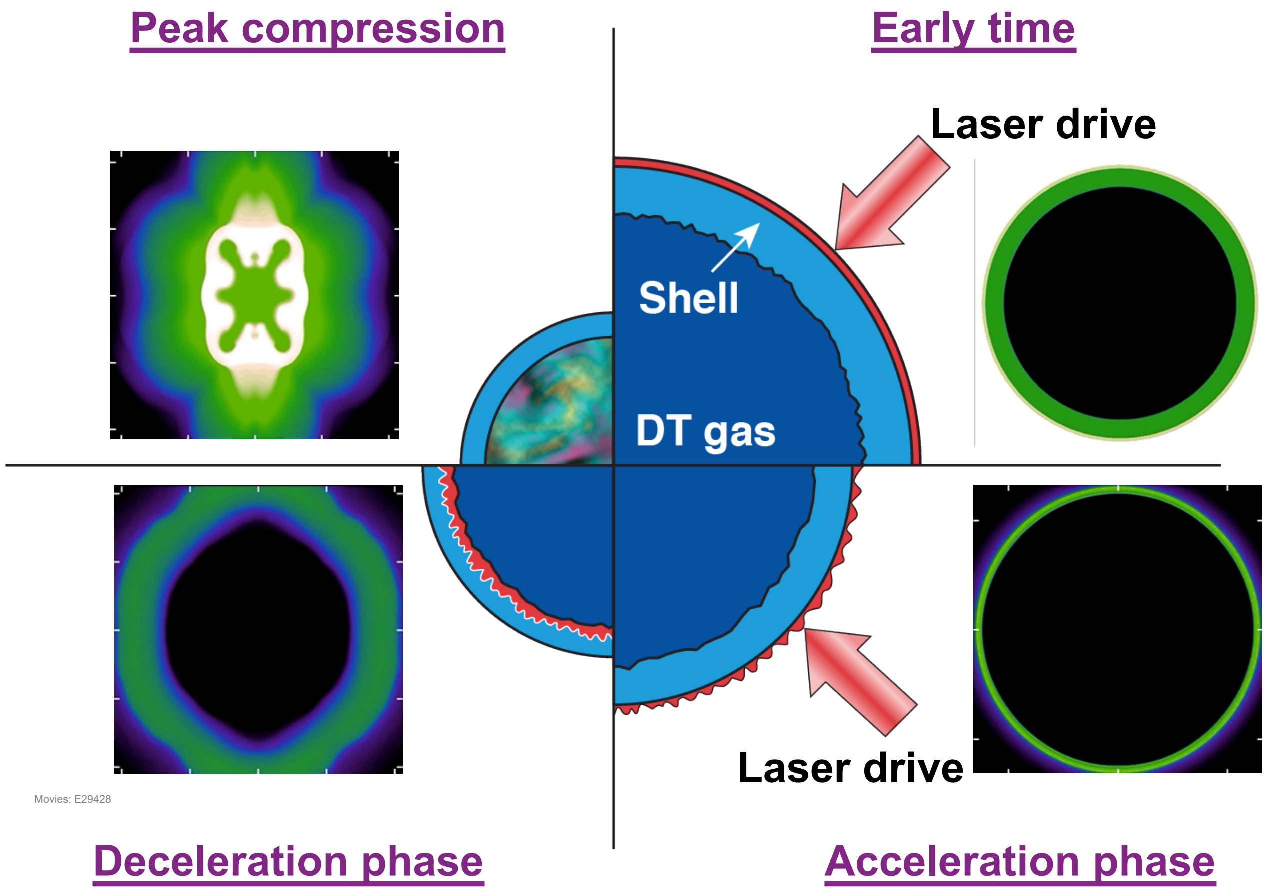
LULI 2000 Laser
LULI, France

Laser Mégajoule (LMJ in progress)
CEA-CESTA, France



LDD ICF implosions are divided into four phases





*2-D *DRACO* Imprint Simulations with LLE Ray Trace, performed by T. Collins (2019).

The ablatively driven shell increases the internal pressure and heat via compression, causing fusion reactions

- The *Lawson criterion* defines a simple condition required for ignition:

  (fusion products power density) × (containment time) > (plasma energy density)

  For 50-50 DT plasma: $n^2/4\,\langle\sigma v\rangle Q\tau > 3nk_\mathrm{B}T$

  Solving for $n\tau$:* $n\tau > \frac{12k_\mathrm{B}T}{\langle\sigma v\rangle Q} \approx 10^{14}\text{:}\,10^{15}\left[\mathrm{s/cm^3}\right]$

- Containment time can be approximated by disassembly time; i.e., related to the ion sound speed traversal across the fuel assembly as:

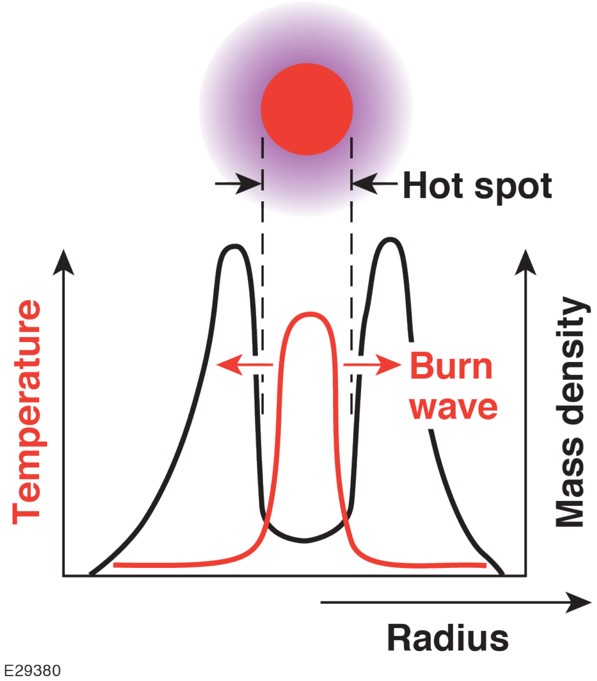
$$\langle\tau\rangle \cong \frac{R_\mathrm{f}}{4c_\mathrm{s}}, n \equiv \rho/m \Rightarrow n\tau \cong \frac{\rho R_\mathrm{f}}{4\langle M_\mathrm{i}\rangle c_\mathrm{s}}$$

$\rho R_\mathrm{f} \gtrsim$ 1 [g/cm²] for efficient burn, i.e., large gains

*Q_{DT} = 17.6 MeV

The ablatively driven shell increases the internal pressure and heat via compression, causing fusion reactions

- A sufficiently compressed shell density provides inertial confinement, leading to ignition amplified by alpha heating



Gain, $G = \dfrac{\text{Fusion energy out}}{\text{Laser energy in}}$

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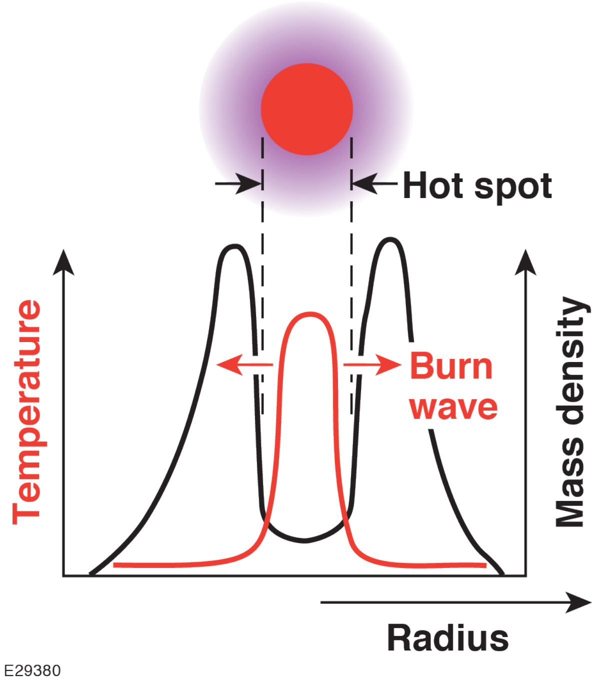

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$\rho R_{\mathrm{f}} \gtrsim 1$ [g/cm²] for efficient burn, i.e., large gains

The areal density, ρR, can be expanded to express other important ignition criteria

$$P_{\mathrm{hs}} > 250\ \mathrm{Gbar}\left(\frac{E_{\mathrm{hs}}}{10\ \mathrm{kJ}}\right)^{-1/2} = P_{\mathrm{th}}$$

*Q_{DT} = 17.6 MeV

Maximizing hydroefficiency is key for successful ICF implosions

- Hydroefficiency $\eta_H = E_k/E_L$

$$\boxed{\eta_H \sim \frac{p_{abl} V_{imp}}{I}}$$

$$p_{abl} = f_{abs}\, I^{\frac{2}{3}}$$

To maximize hydroefficiency

Maximize laser coupling

- Mitigate LPI losses
- Use mid-*Z* ablator (balance between κ_B and radiation losses)

Increase implosion velocity

- Reduce shell mass

Reduce laser intensity

- Good for LPI but stability is a concern
- Advantage in multi-shell designs

Stability must be addressed:

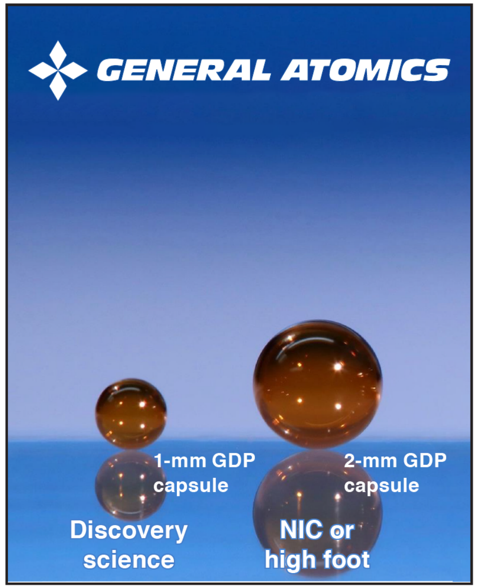
$$\text{IFAR} \equiv R/\Delta R \sim v_{imp}^2 / p_{abl}^{2/5}\ \alpha^{3/5}$$

While working on mitigating the deleterious effects of LPI, the LDD program on the NIF and OMEGA leverages on v_{imp} and adiabat to maximize the performance.

LPI: laser–plasma instability
IFAR: in-flight aspect ratio

Target designs are an essential aspect of laser ICF experimental design

- **Targets are made from a variety of materials and sizes; designs affect coupling, preheat, and stability**
  - **laser coupling depends on *A*/*Z*: $p_{\mathrm{abl}} \sim I^{2/3}(A/Z)^{1/3}$**
  - **higher *Z* materials can drive up the coronal temperature, disrupting laser-induced plasma instabilities**
- **Advanced target development includes graded dopants, thin shell 'balloons', 3-D printed foams to multiple shells of varying density, and others**



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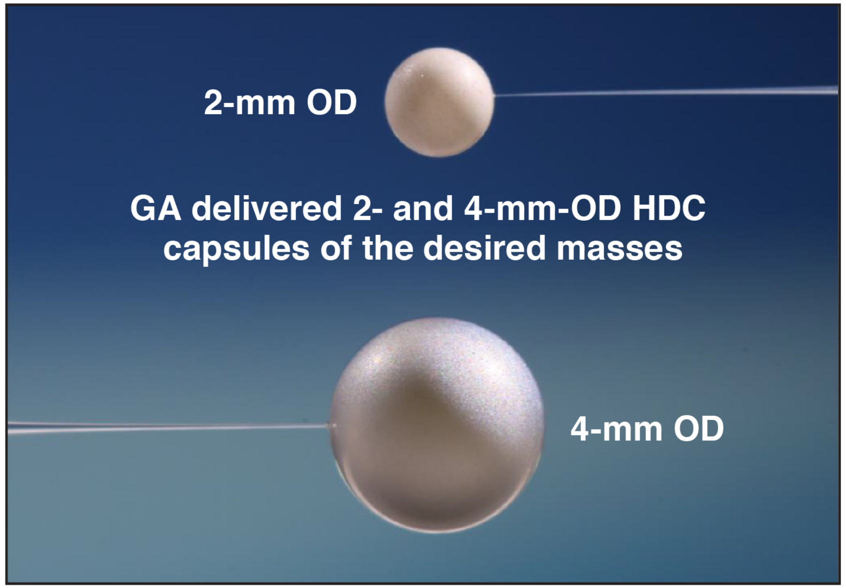
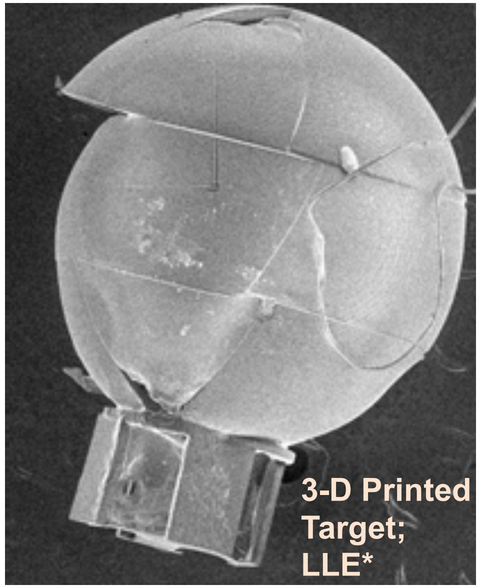
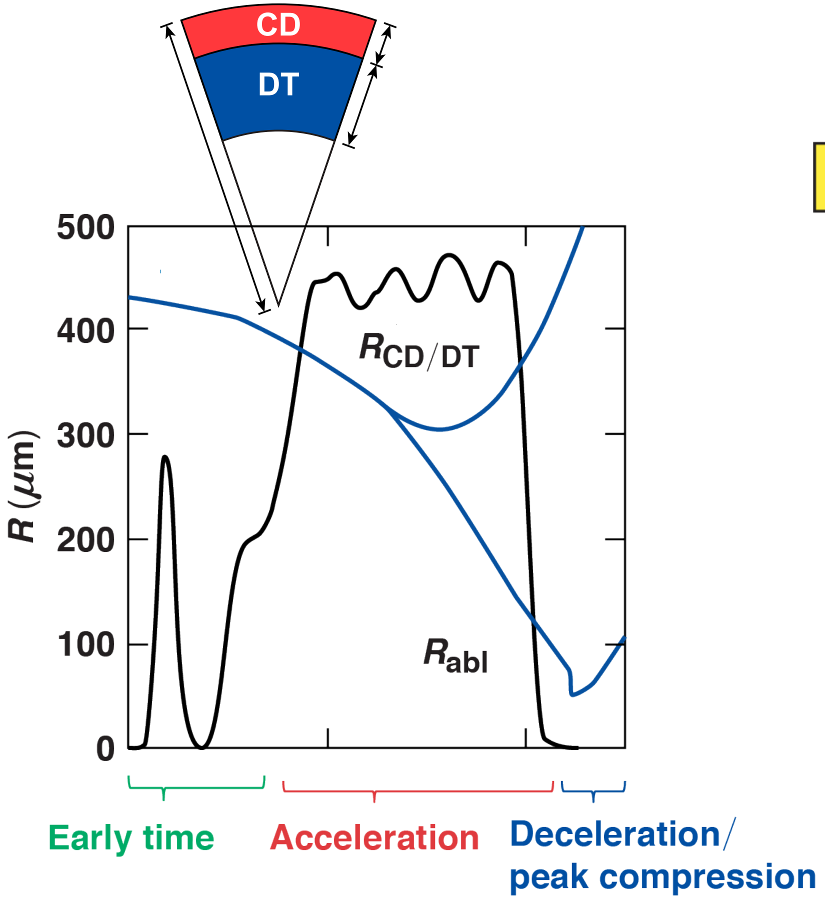


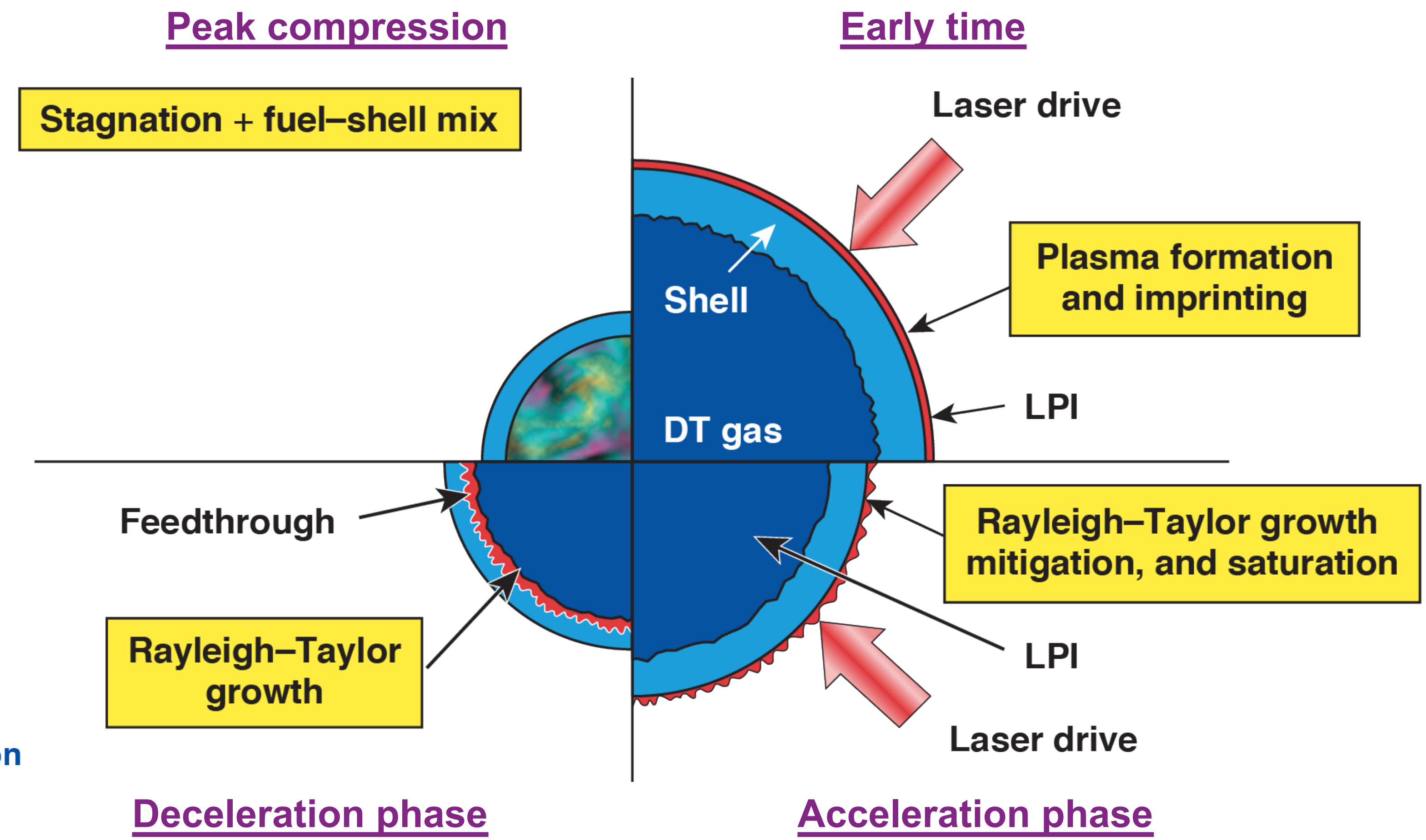


NIC: National Ignition Campaign HDC: high-density carbon

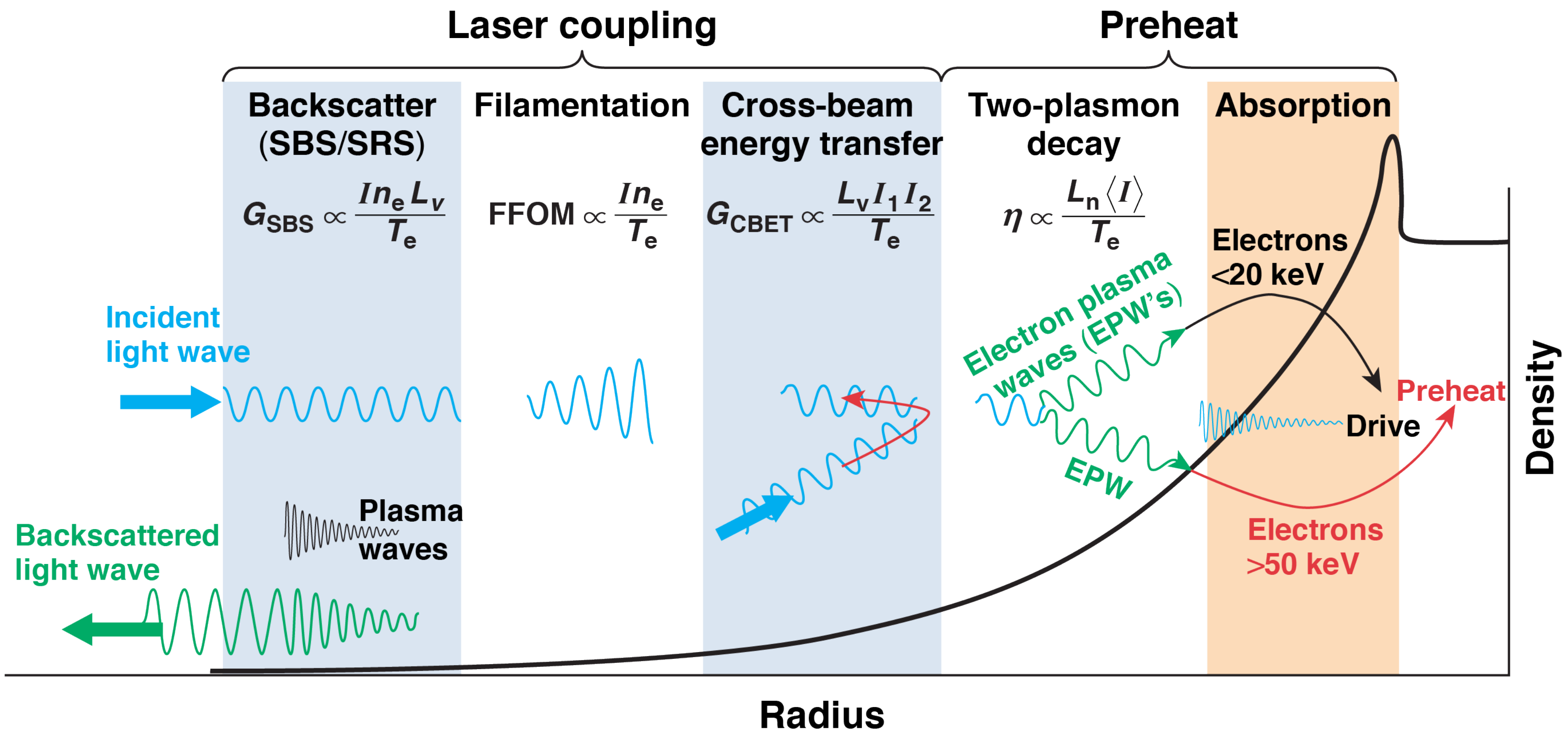
* D. Harding, et al., LLE

Many processes interplay throughout the ICF implosion: some contribute to ignition, while some conspire to prevent ignition





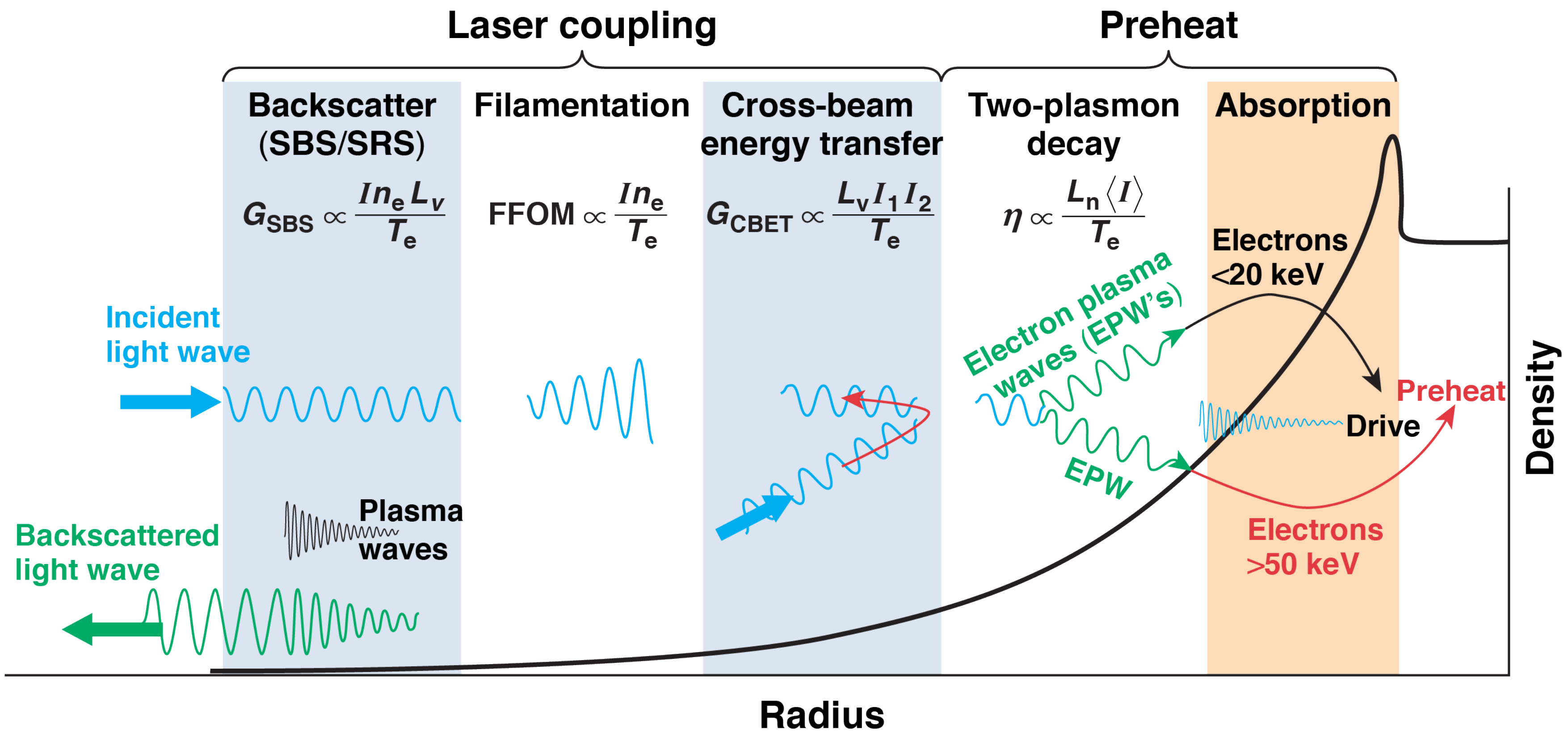
The LPI effects that limit LDD performance occur in distinct regions within the coronal plasma during laser deposition



TC14523a

SBS: stimulated Brillouin scattering
SRS: stimulated Raman scattering
CBET: cross-beam energy transfer

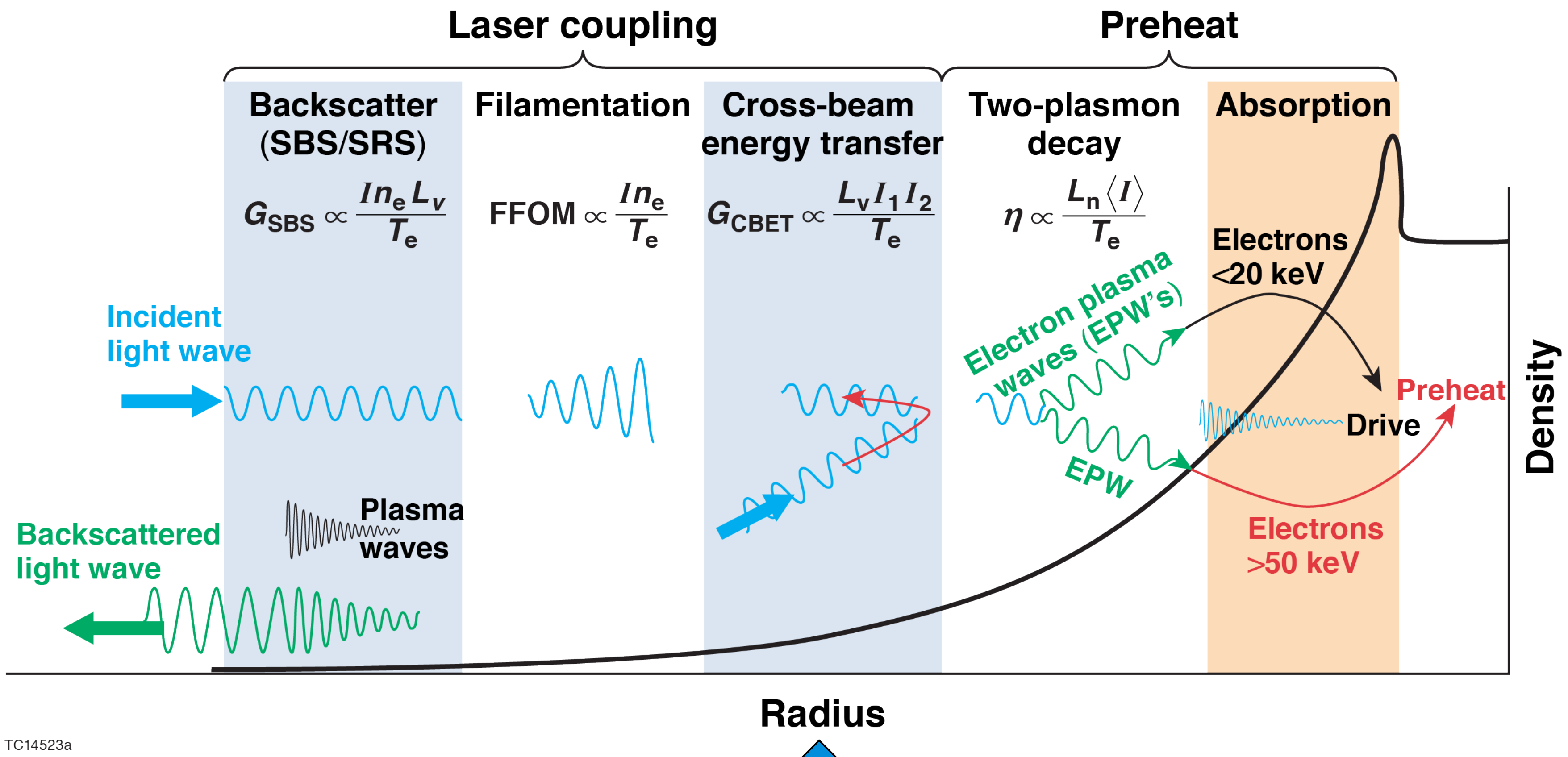
The LPI effects that limit LDD performance occur in distinct regions within the coronal plasma during laser deposition



TC14523a

The CBET LPI effect severely limits energy absorption by 20 to 40%

The LPI effects that limit LDD performance occur in distinct regions within the coronal plasma during laser deposition



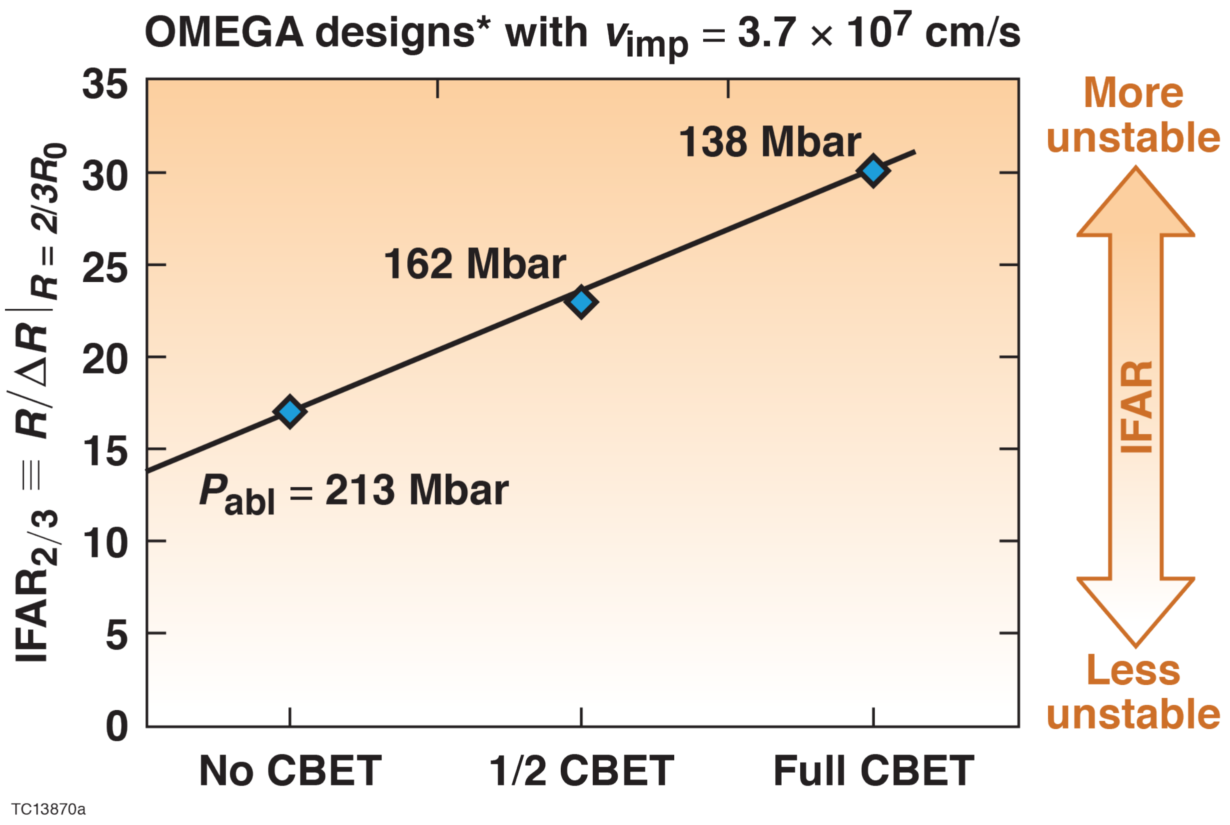
Other LPI effects (SRS on the NIF and TPD on OMEGA) can be a source of hot electrons that preheat the fuel.

The CBET LPI effect severely limits energy absorption by 20 to 40%

TPD: two-plasmon decay

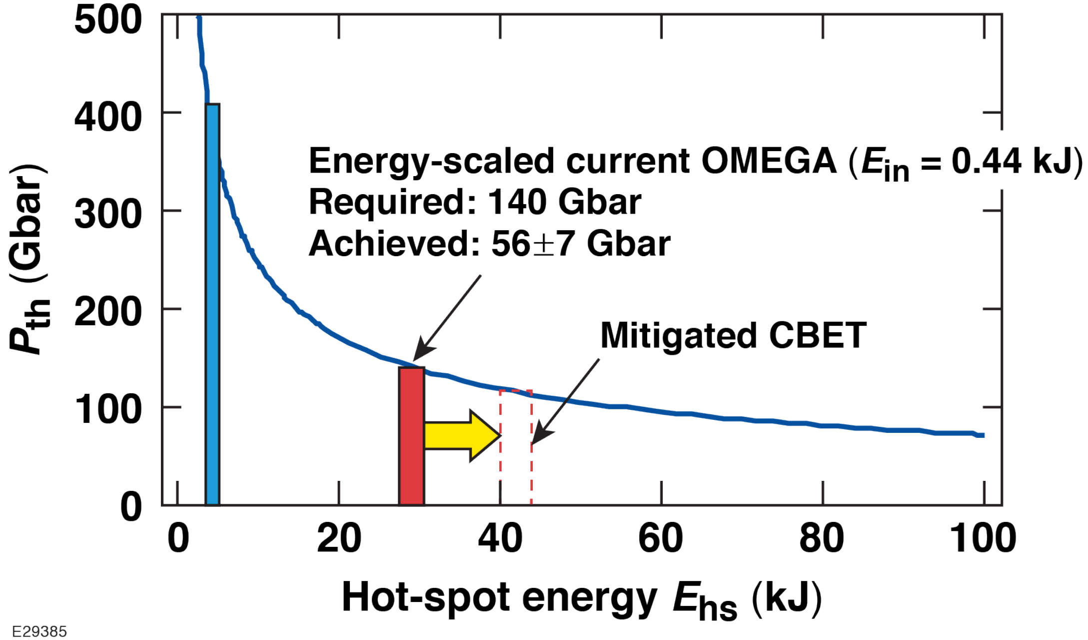
Mitigating CBET is important for high-yield, robust implosions

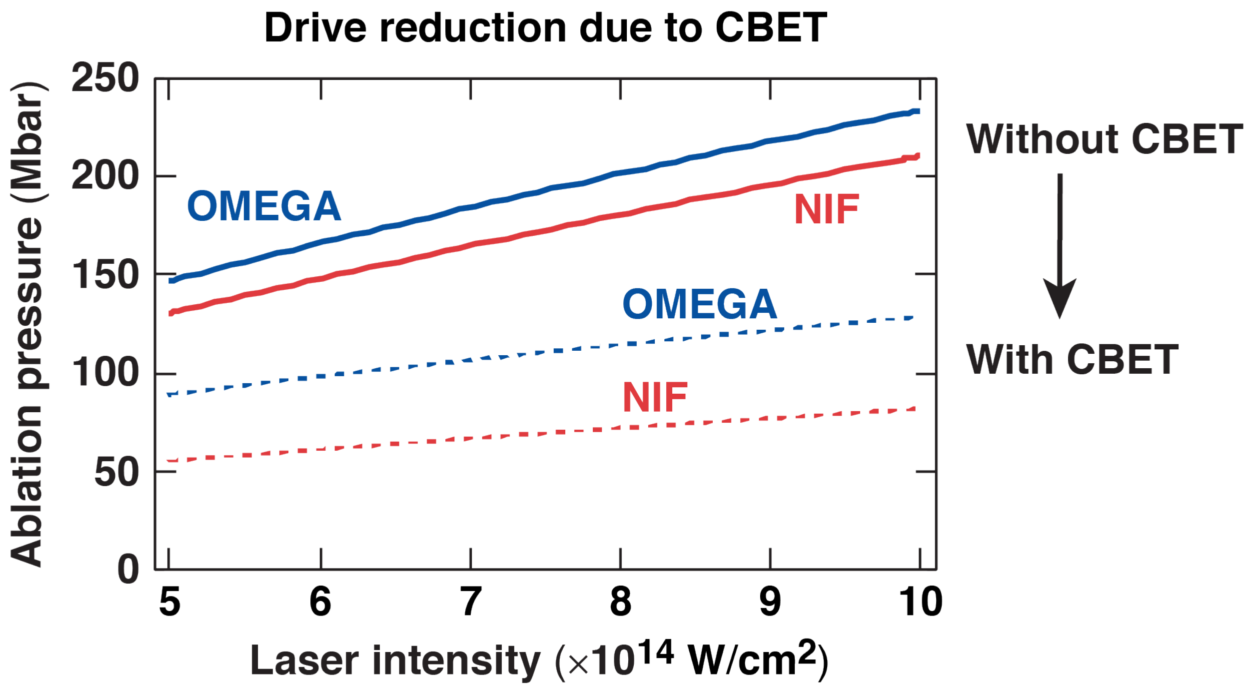
- Compensating for CBET losses by thinning the shell compromises its integrity
- CBET mitigation is the best option



* V. N. Goncharov *et al.*, Phys. Plasmas 21, 05615 (2014).
IFAR: in-flight aspect ratio

Recovering CBET losses results in increased fuel mass, robustness to instability growth, ablation pressure, and hot-spot energy

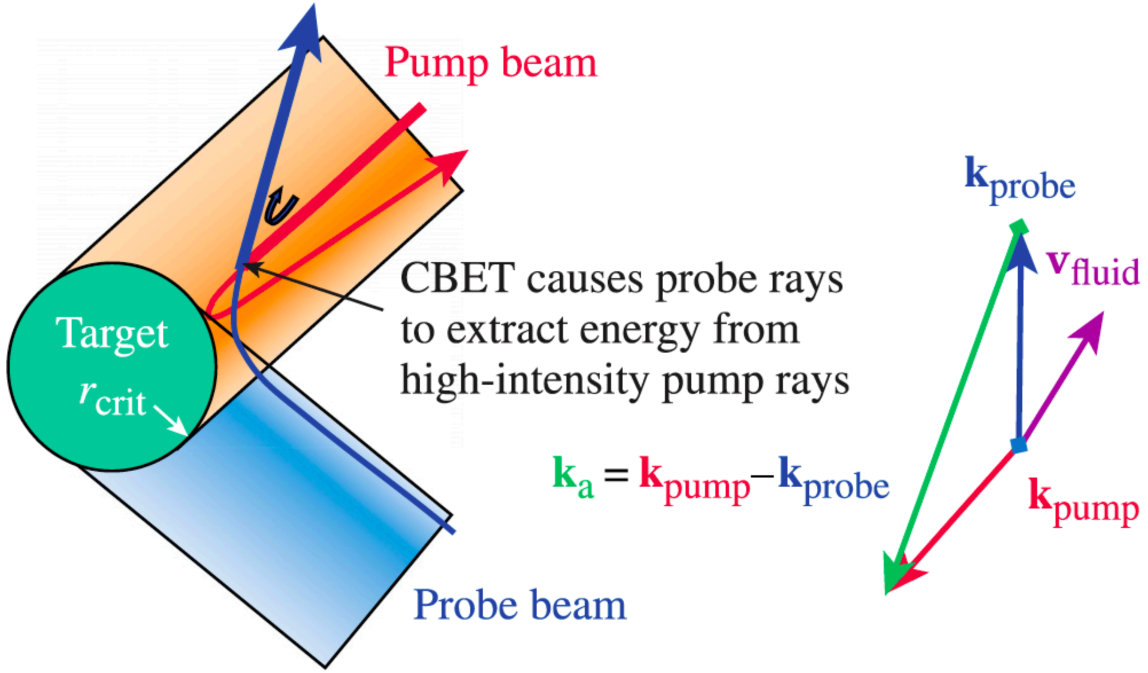




E29385

CBET losses are included in the modeling to agree with multiple experimental measures

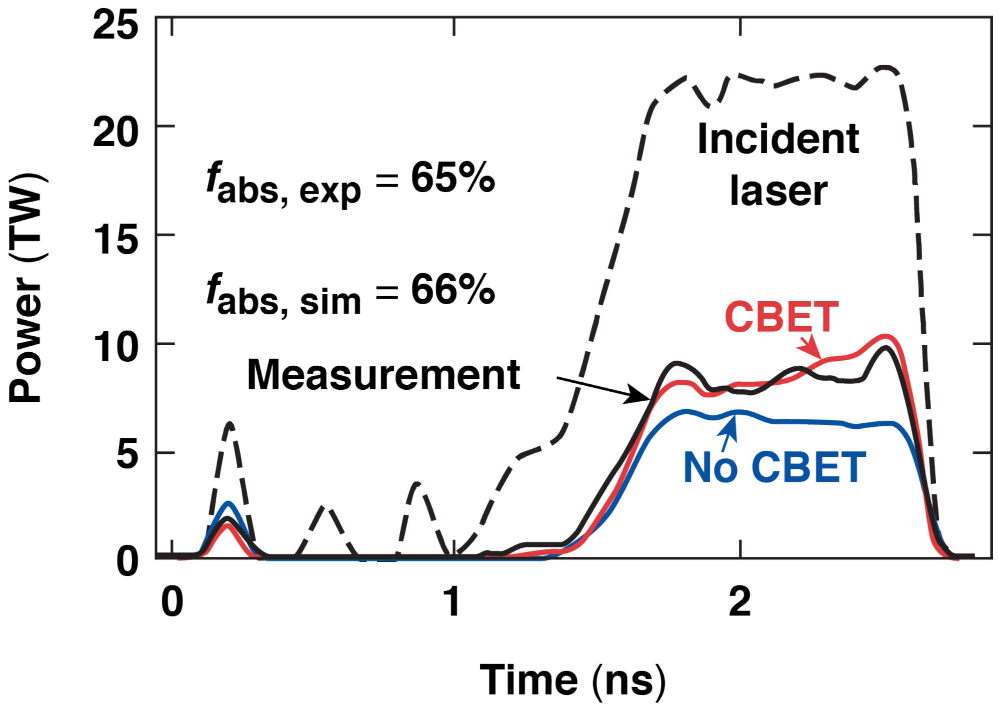
The backscatter mode occurs for opposing beams



TC13869J1

- The outbound ray always gains energy regardless of color $\left(\Delta\lambda_0 < \left|\pm 20\ \text{Å UV}\right|\right)$
- Leads to shell nonuniformity; mitigation can correct

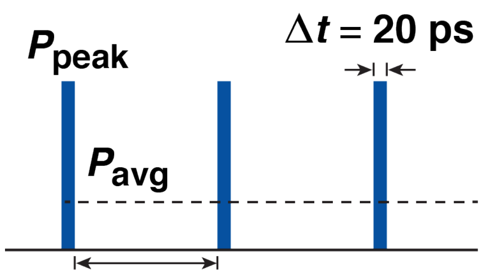
OMEGA experiment and simulation



- Measurement constraints: scattered light, shell trajectory, bang time, and shock timing

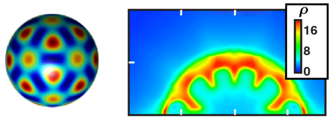
Laser–energy coupling loss caused by CBET can be mitigated in different domains that can be combined; temporal, spatial, and spectral

- **Temporal domain**
  - multiplexing the beams reduces interaction

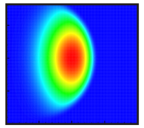


  - STUD* pulses

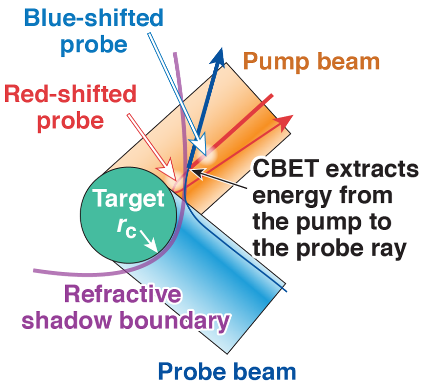
- **Spatial domain** (reduce interaction volume)
  - dynamic spot shape
  - spots smaller than target (e.g., R_{75})†



  - spot-masking apodization (SMA)



- **Spectral domain**
  - wavelength detuning; $\Delta\lambda_0$



  - wide bandwidth within each beam (e.g., SRRS‡)
    - lower intensity per band and incoherence disrupts growth

* STUD: spike trains of uneven duration and delay; B. Afeyan and S. Hüller, EPJ Web Conf. 59, 05009 (2013).
†S. P. Regan *et al.*, Phys. Rev. Lett. 117, 025001 (2016); 059903(E) (2016).
‡ SRRS: stimulated rotational Raman scattering; J. Weaver *et al.*, "Spectral and Far-Field Broadening due to Stimulated Rotational Raman Scattering Driven by the Nike Krypton Fluoride Laser," to be published in Applied Optics.

Laser-direct-drive (LDD) inertial confinement fusion (ICF)— A pathway to ignition

UR LLE

- Fusion: introduction to ICF
  - LID and LDD
- **Simulations and experiments**
- NIF LDD ⇔ polar direct drive (PDD)
  - focus: exploding-pusher (XP) platform
- Future NIF upgrades progressing toward ignition

Simulations from a variety of codes emulate experimental diagnostic measurements

Computational tools for direct drive and the ICF/HEDP community

Models EM fields, polarization, and speckle (but not other effects)

LPI codes

- LPSE: laser plasma simulation environment (LLE)
- *OSIRIS* (PIC) (UCLA + U of R)

Models EOS, radiation, fusion and burn, EOS, thermal conduction, fluid flow, nonlocal electron transport, select LPI processes (CBET)

Hydrocodes

- 1-D *LILAC* (LLE)
- 2-D *DRACO, DEC2D, SAGE* (LLE); FAST2D (NRL)
- 3-D *ASTER, DEC3D* (LLE); FAST3D (NRL)
- 3-D *HYDRA* (LLNL + LLE)

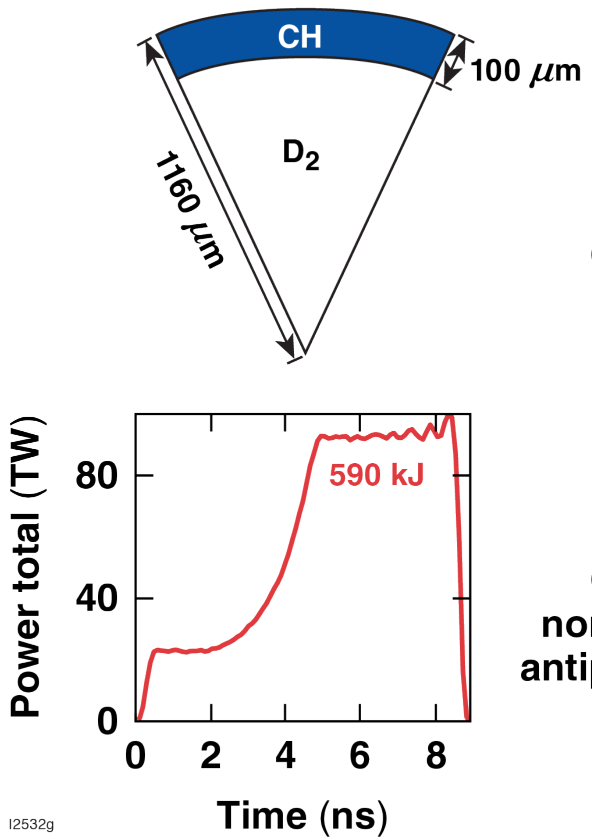
Quantum/statistical mechanical modeling of EOS

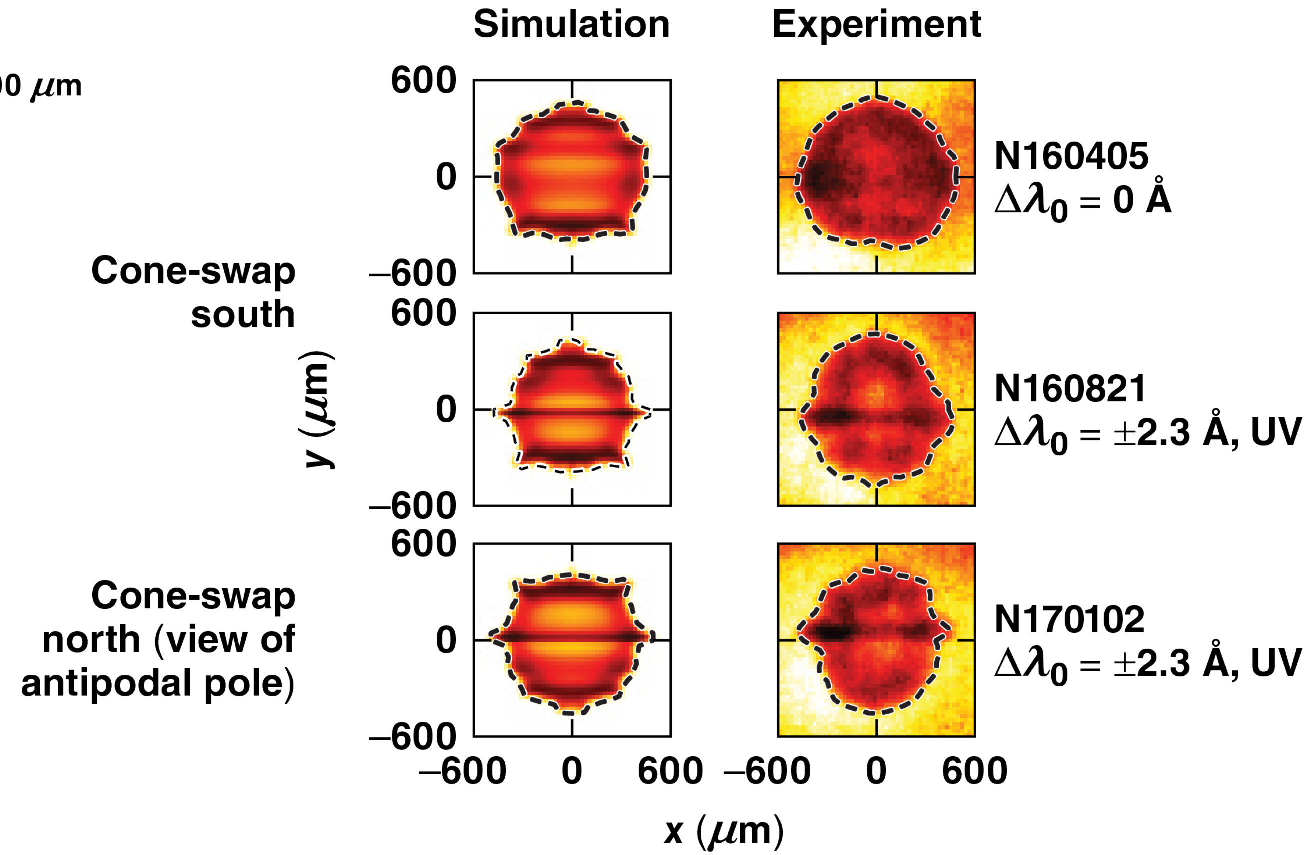
HEDP codes

- QMD (VASP)
- PIMC (path integral Monte Carlo) (LLE)

HEDP: high-energy-density physics
EM: electromagnetic
PIC: particle in cell
EOS: equation of state

Multi-physics radiation-hydrodynamics simulations with *DRACO* mimic experimental data

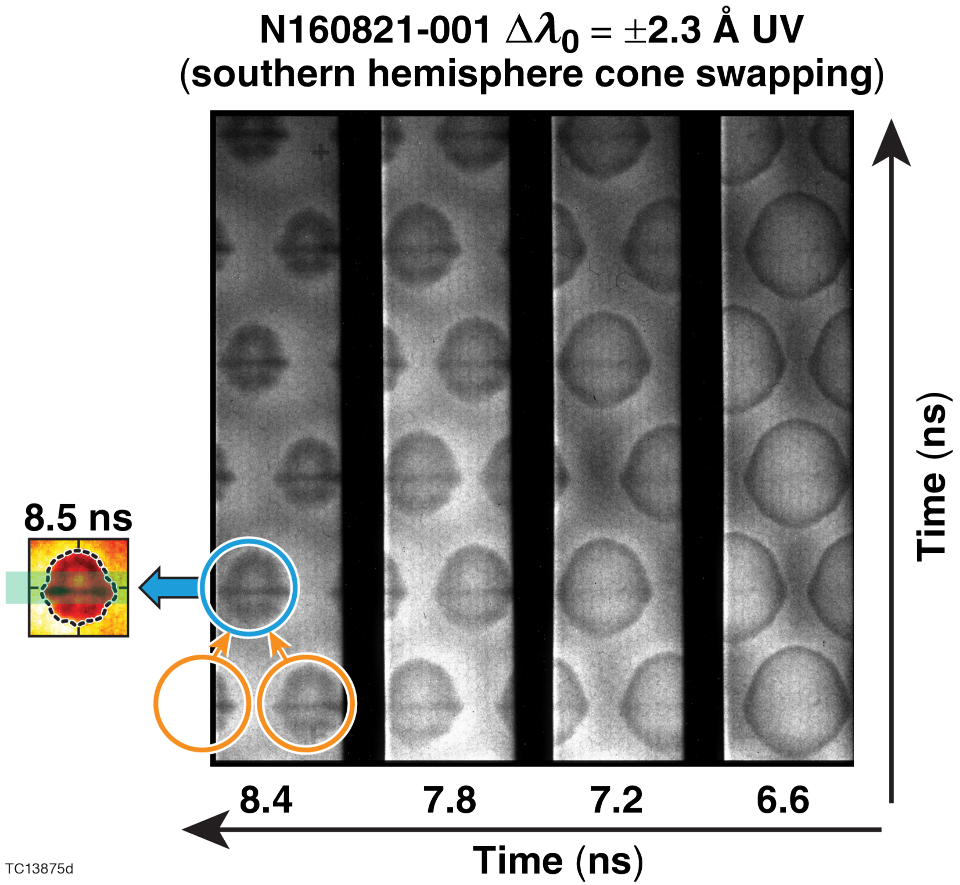




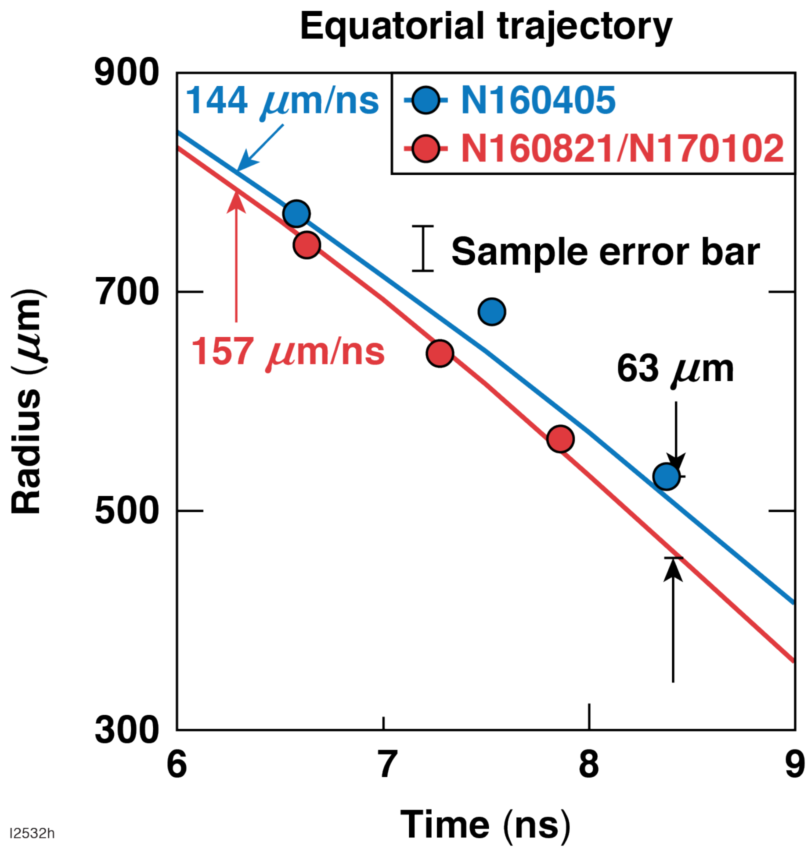
The extreme contortions required (described later) to reconfigure the NIF to evaluate the first detuning experiments resulted in the severe distortions.*

* J. A. Marozas *et al.*, Phys. Rev. Lett. 120, 085001 (2018).

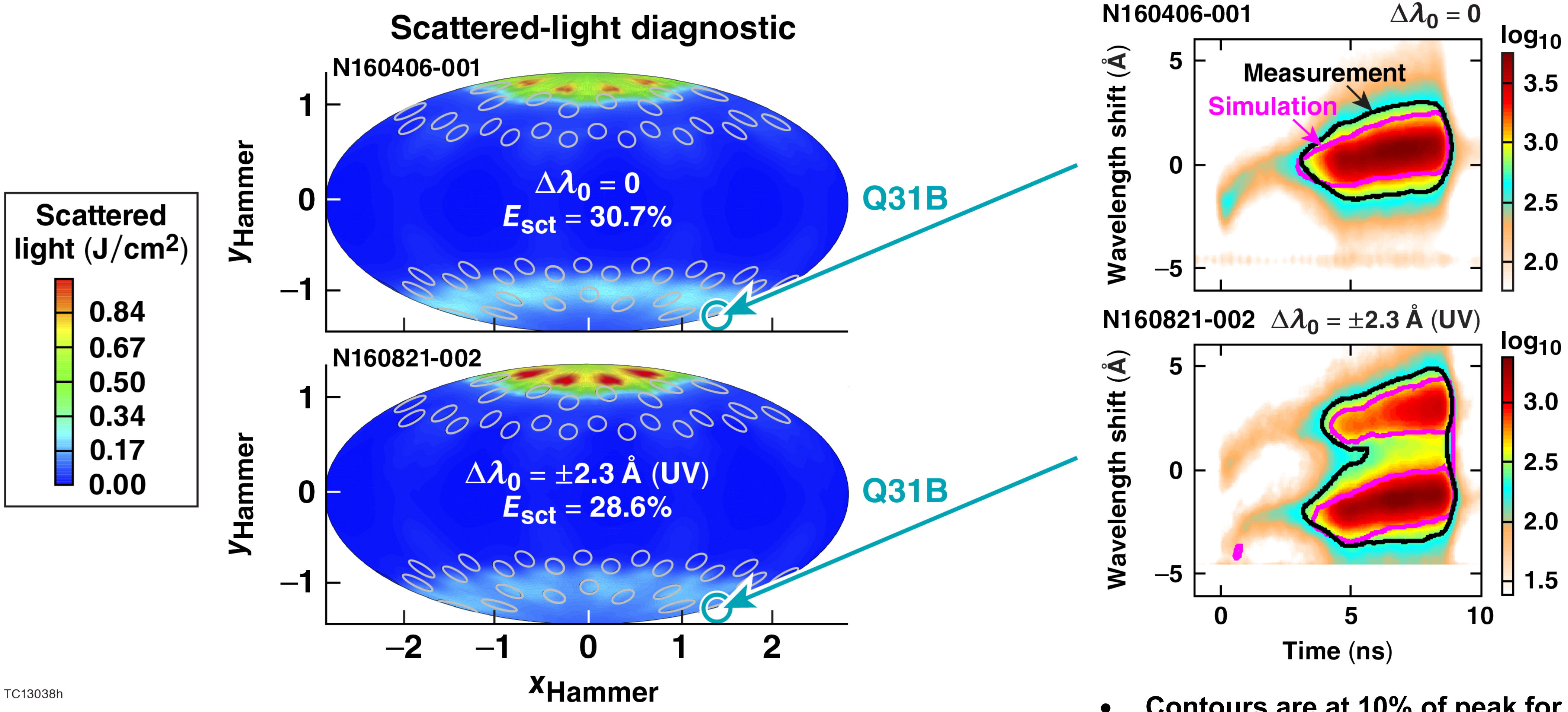
Gated backlit radiographs (experimental or simulated) are used to infer the shell trajectory



- A trajectory is then inferred by plotting the surface-weighted radial average



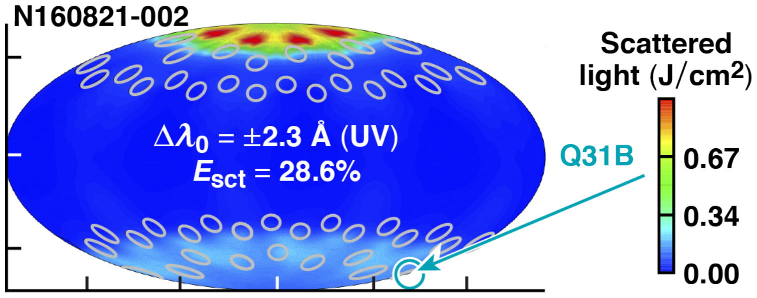
Scattered-light measurements can be used to diagnose wavelength detuning CBET mitigation



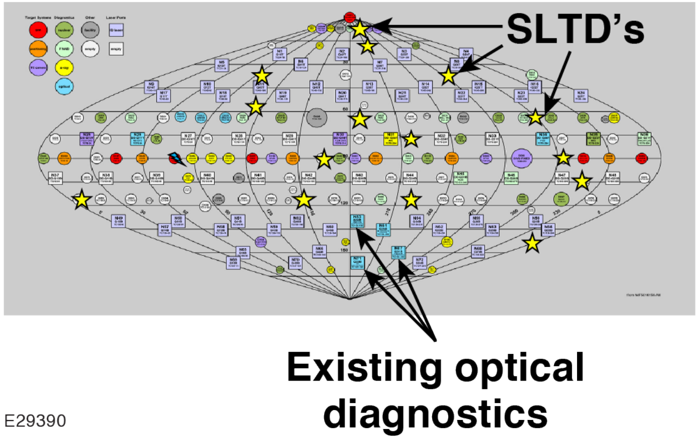
- Contours are at 10% of peak for measurement and simulation

The scattered-light time-history diagnostic (SLTD) will diagnose SBS, SRS, and $\omega/2$ emission at 15 locations around the NIF chamber

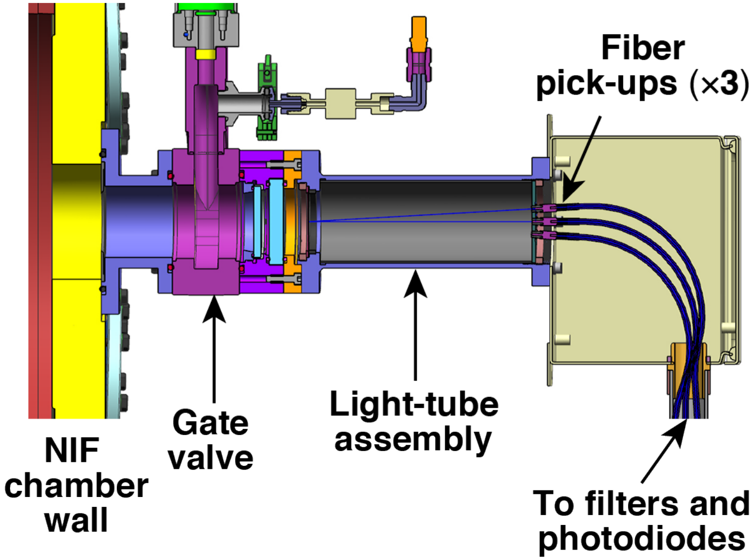
PDD implosion simulated scattered light



NIF chamber map



SLTD prototype schematic



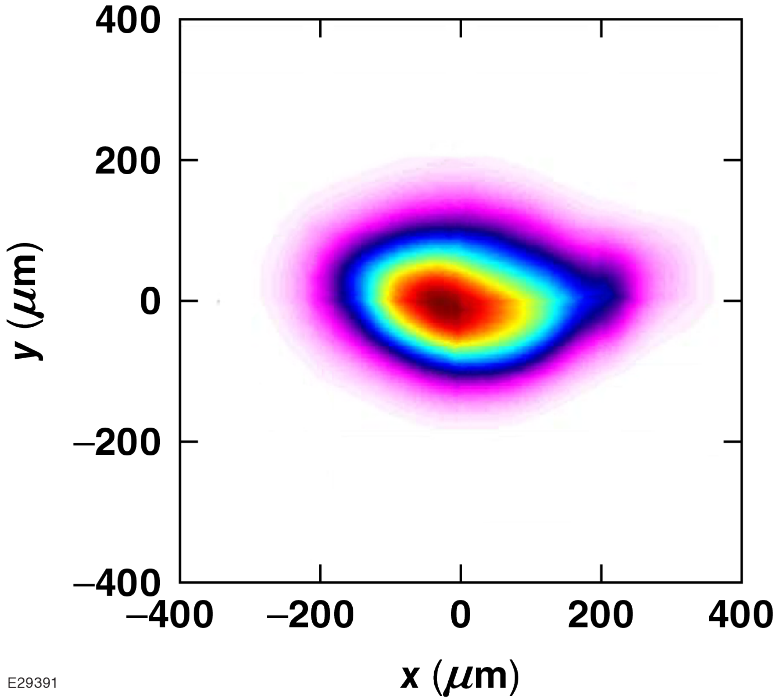
SLTD schedule	
1 SLTD unit	April 2018
6 SLTD units	August 2019
11 SLTD units	January 2021
15 SLTD units	Late 2021

The SLTD suite will constrain modeling of scattered-light spatial distribution and facilitate inference of total scattered light in direct-drive and other NIF experiments.

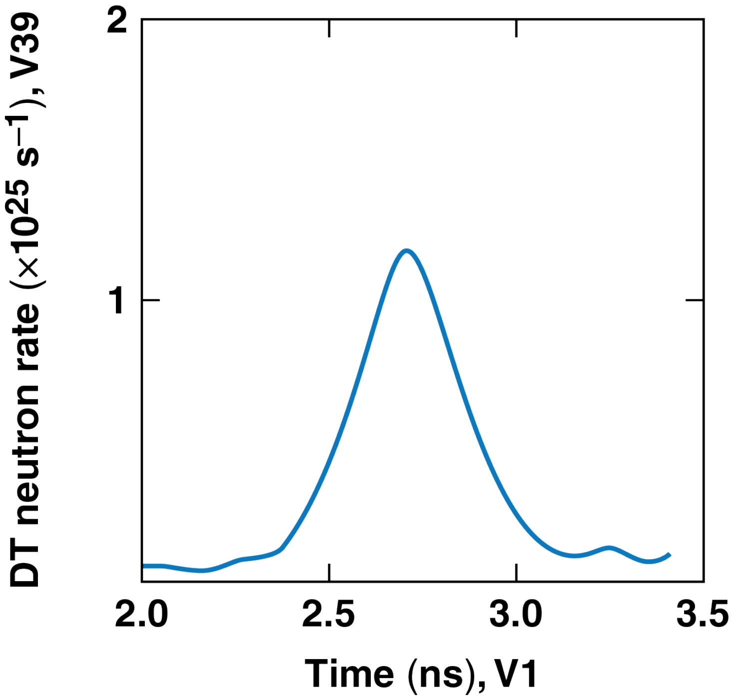
E29390

Many other diagnostics exist, like neutron imaging and reaction rates, which are measured and can be compared to simulations

Experimental equatorial neutron images*



Gamma rays from the DT reactions infer the neutron production rates



* P. Volegov, Los Alamos National Laboratory, private communication (2019).

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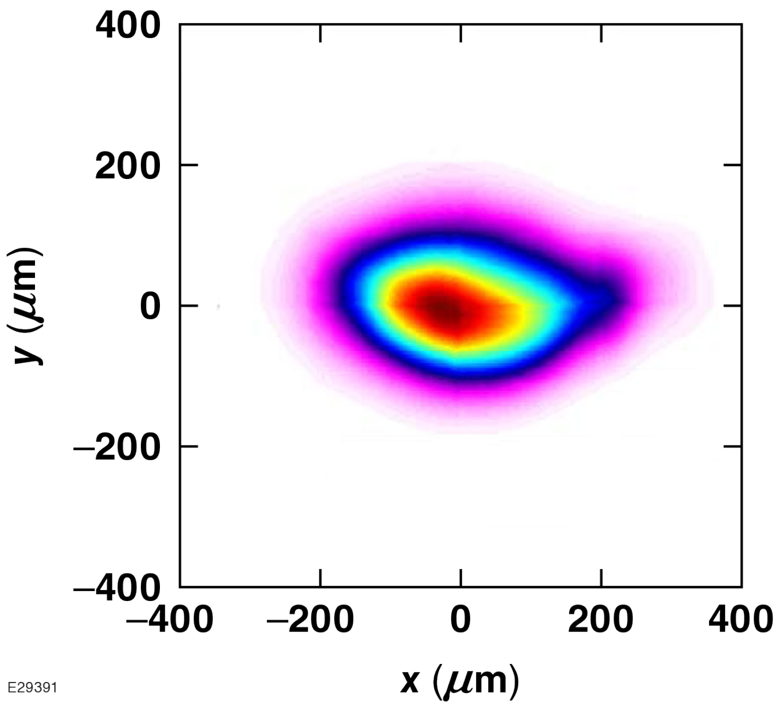
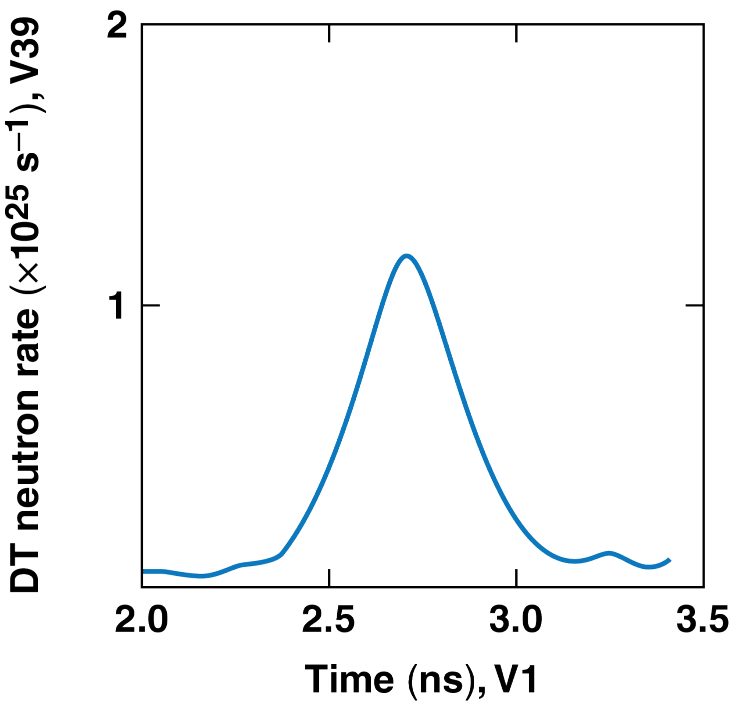


E29391

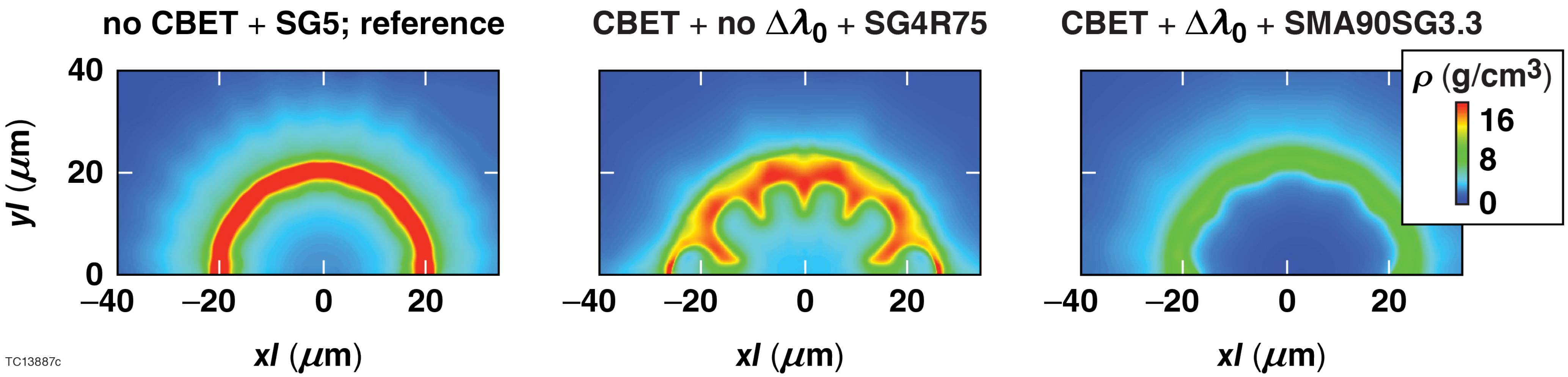
Gamma rays from the DT reactions infer the neutron production rates



Next, moving on to discuss using simulations as a predictive tool to design and diagnose shots…

* P. Volegov, Los Alamos National Laboratory, private communication (2019).

Mitigating CBET with wavelength detuning* restores energy coupling without compromising uniformity, while spatial mitigation can impart strong modulation

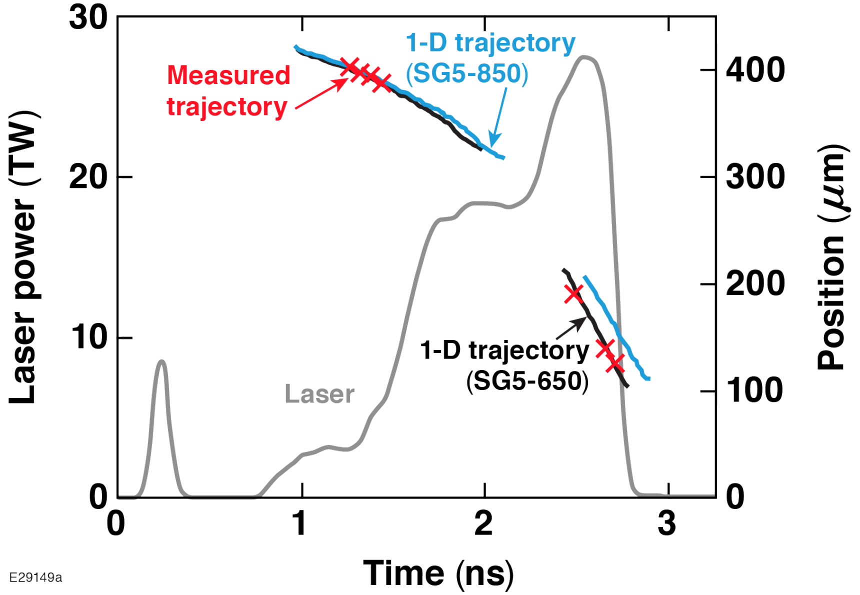


Spot-shape name	Description
SG5	Super-Gaussian exponent SG = 5, $e^{-\lvert r/r_0 \rvert^{sg}}$
SG4R75	Super-Gaussian SG = 4, with smaller 75% radius
SMA90SG3.3	Super-Gaussian SG = 3.3, with SMA at 90%

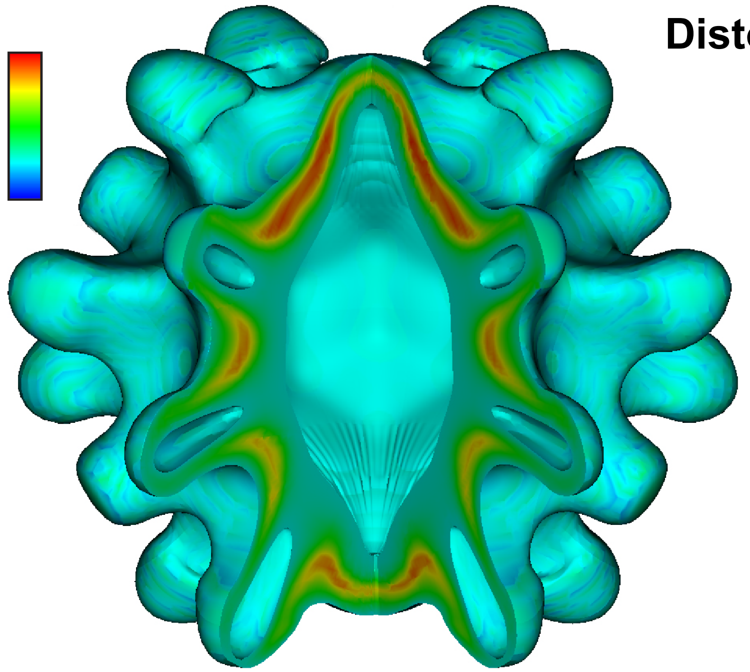
*Potential detuning on OMEGA

Smaller laser beams enhance laser coupling but lead to significant shell and core distortions

***R_{75}* target with SG5, full 3-D ray trace with inverse-point-projection isodensity contour at 0.8 g/cm^3, plotted at 250 ps after bang time**



E29149a



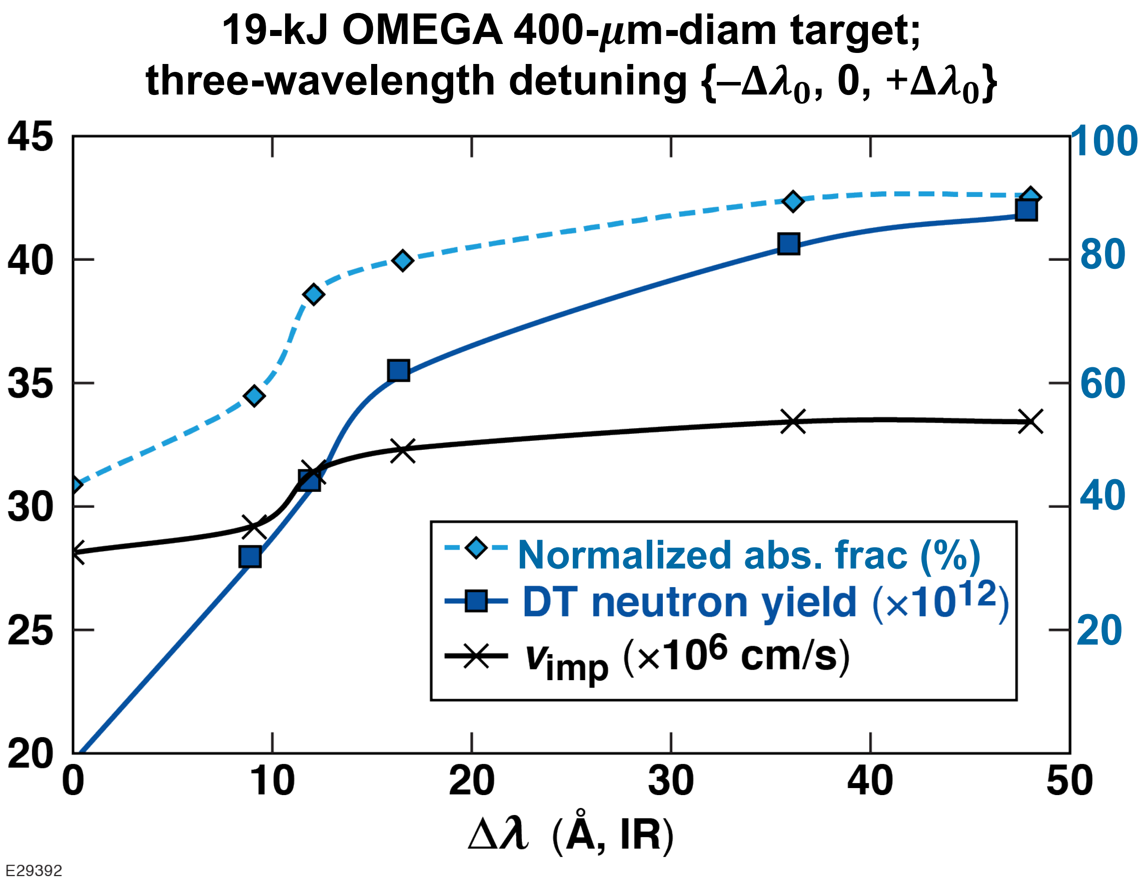
Distortions from beam ports (ℓ = 10)

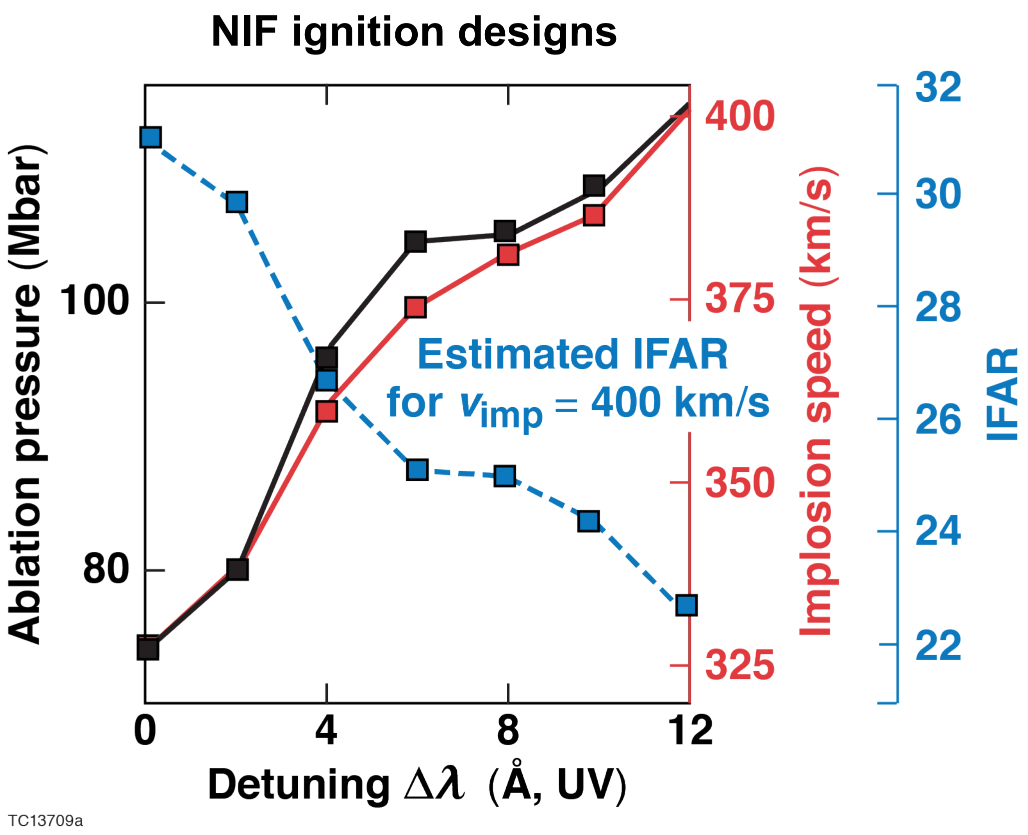
- **3-D simulations do not reproduce the 1-D predicted 25% increase in yield due to better coupling because of enhanced hot-spot distortions**
- **Hot-electron preheat reduces experimental yield further**

A new LLE ray-tracing package implemented into *HYDRA* makes it possible to assess the effects of 3-D distortions on the target performance.

M. M. Marinak *et al.*, Phys. Plasmas 8, 2275 (2001).
3-D *HYDRA* Simulations with LLE Ray Trace, performed by K. S. Anderson (2019).

OMEGA and NIF simulation results show a large improvement for large detuning ranges greater than $\Delta\lambda_0$ 18A, IR





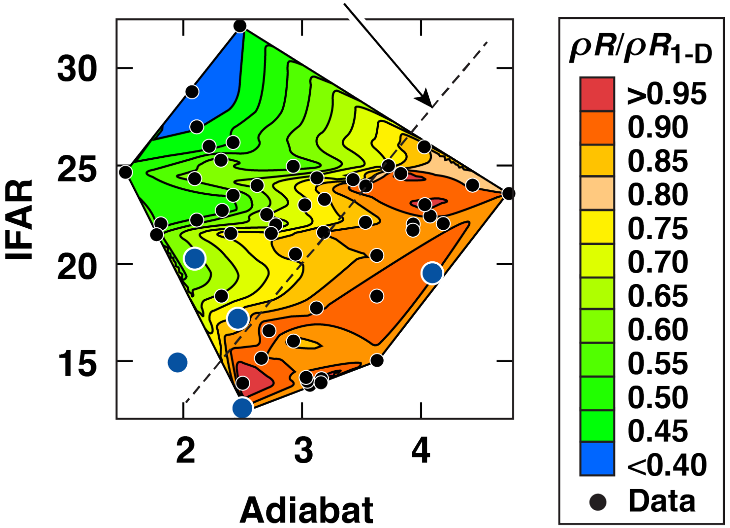
OMEGA and the NIF show similar trends for detuning ranges exceeding ±18 Å, IR (±6 Å, UV).

* T. J. B. Collins and J. A. Marozas, Phys. Plasmas 25, 072706 (2018).

Simulations are employed to study the effect of imprint on target performance

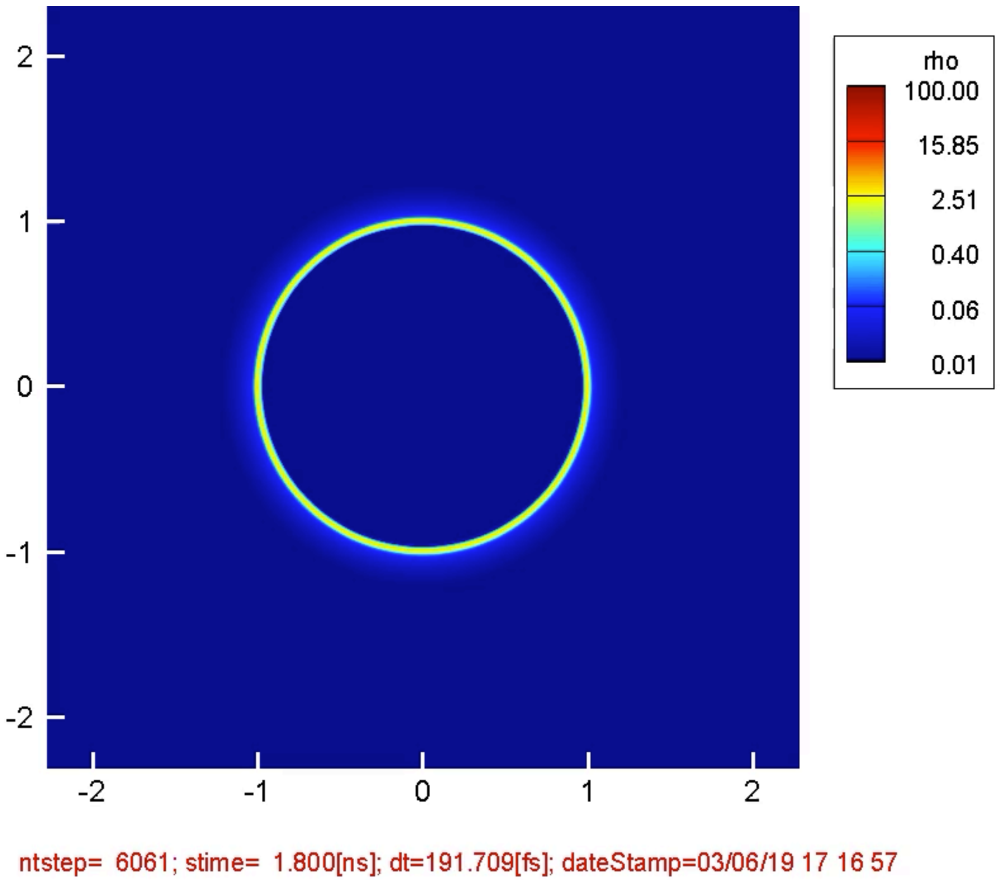
- Imprint has a strong impact on target performance
  - Compromises the shell integrity and lowers density and temperature and increases surface area
- Laser smoothing techniques mitigate imprint
- Simulations help gauge the laser smoothing requirements and guide target designs

Stability boundary $IFAR_S = 20\ (\alpha/3)^{1.1}$



TC12040d

Imprint simulation* follows the shell in flight



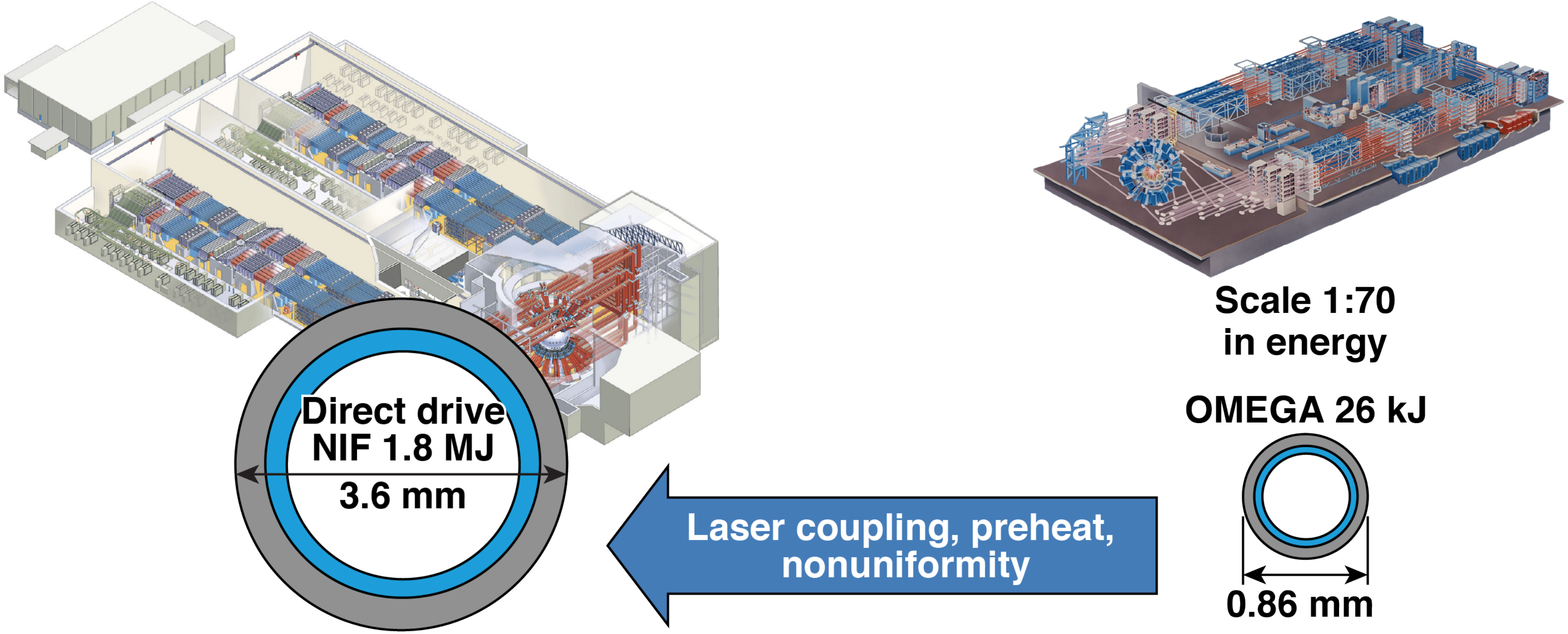
*2-D *DRACO* Imprint Simulations with LLE Ray Trace, performed by T. Collins (2019).

Laser-direct-drive (LDD) inertial confinement fusion (ICF)—A pathway to ignition

UR LLE

- Fusion: introduction to ICF
  - LID and LDD
- Simulations and experiments
- NIF LDD ⇔ polar direct drive (PDD)
  - focus: exploding-pusher (XP) platform
- Future NIF upgrades progressing toward ignition

NIF experiments offer the opportunity to study direct-drive physics (LPI, coupling) at the MJ scale

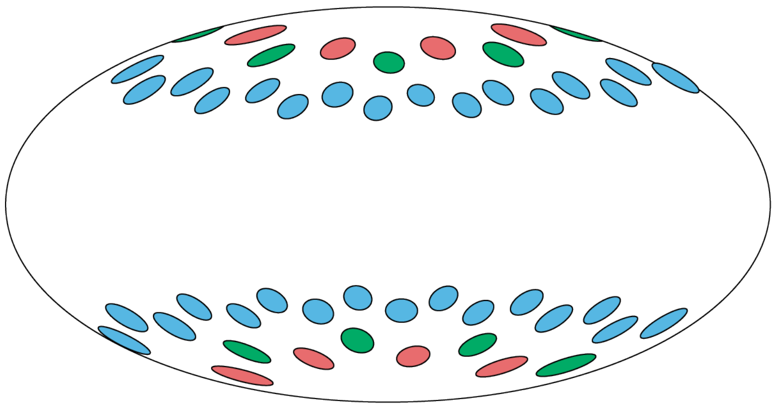


TC13889r

- Existing NIF hardware (phase plates, indirect-drive smoothing) is used
- Beam geometry is the axisymmetric indirect-drive beam geometry
- Improvements in diagnostics (i.e., scattered light) are required

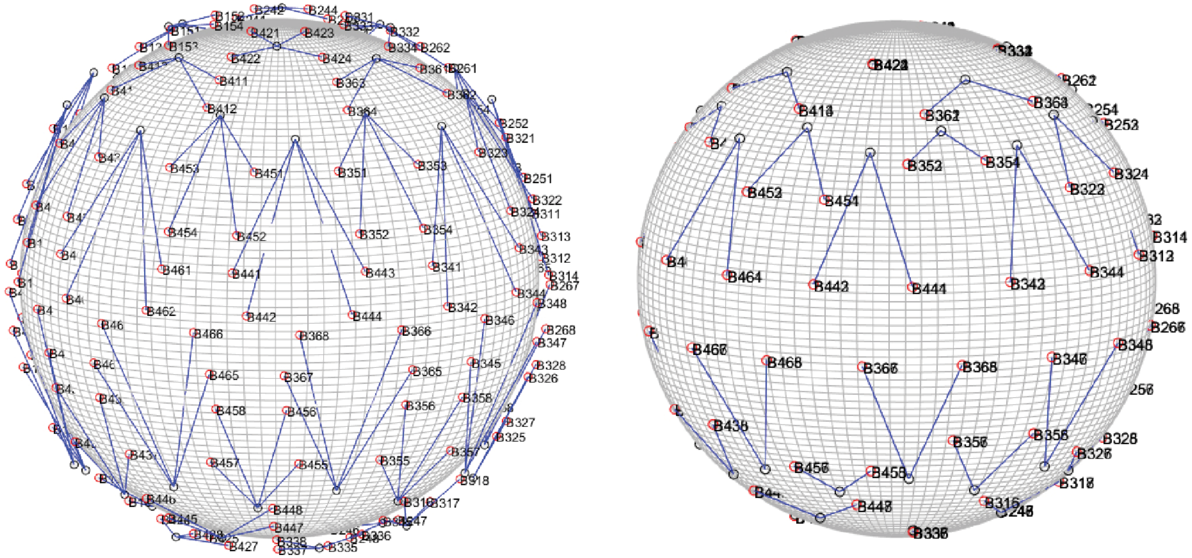
The NIF beams must be repointed for direct-drive experiments owing to its clustered polar port arrangement; referred to as polar direct drive (PDD)

LID port-color arrangement



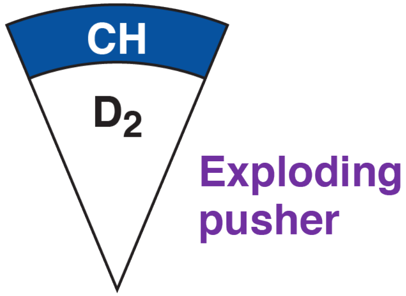
TC15447

LDD-PDD port repointing designs

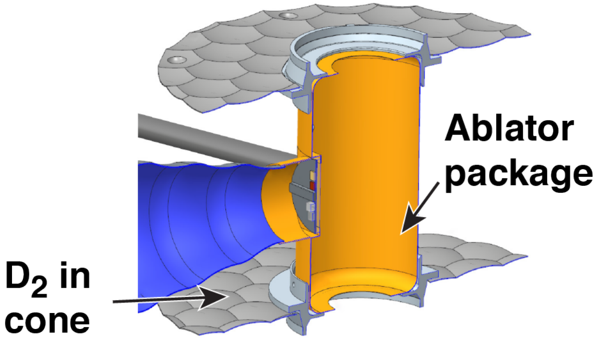


The NIF LDD experiments employ the PDD configuration to perform a variety of physics investigations

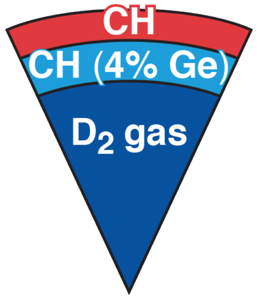
Energy coupling and PDD symmetry



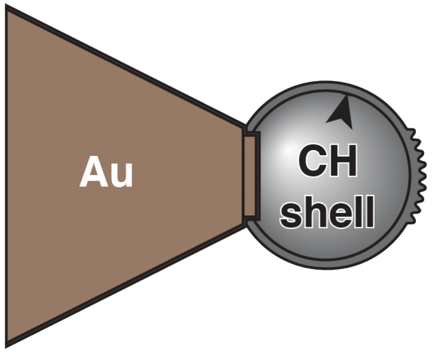
Microphysics



LPI: Hot electron preheat,* etc.



Laser imprint



E29389

* A, Solodov *et al.*, BO09.00012, this conference. --- BO09: ICF Laser Direct Drive

The XP platform has a long history dating back to the early days of ICF, circa 1970's

- Thin-shelled glass microballoons filled with DT gas were shot with an intense, short laser burst
  - the laser energy rapidly heats the electrons
    - preheats the DT electrons (reduces convergence, low ρR)
    - causes ~1/2 the shell-mass to explosively ablate (high stability)
  - the imploding inner ~1/2 -shell acts as a piston, driving a strong inward shock (high speeds)
    - heats the ions to thermonuclear temperatures, producing fusion reactions
  - the exploding outer shell and imploding/compressing inner shell led to these targets being called exploding pushers

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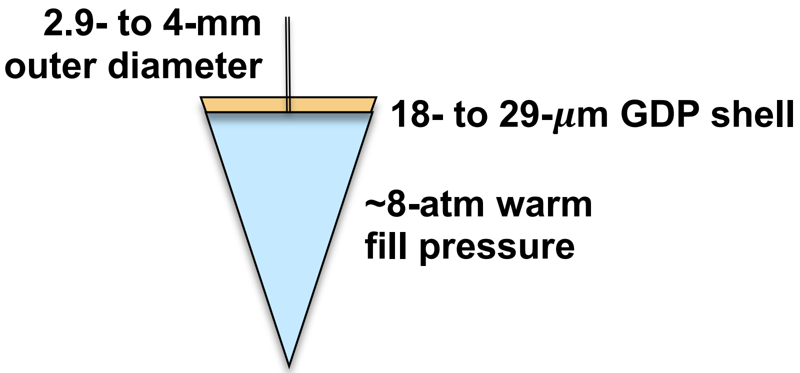
Current XP experiments use similar concepts, scaled to higher energy and similar aspect ratio targets but leveraging shaped pulses to drive the remaining shell during compression, further increasing the DT_n yield.

A large-diameter NIF-PDD XP design was developed to provide a large-volume uniform, plasma for heat-flow measurements, and provides a robust platform for high yield generation

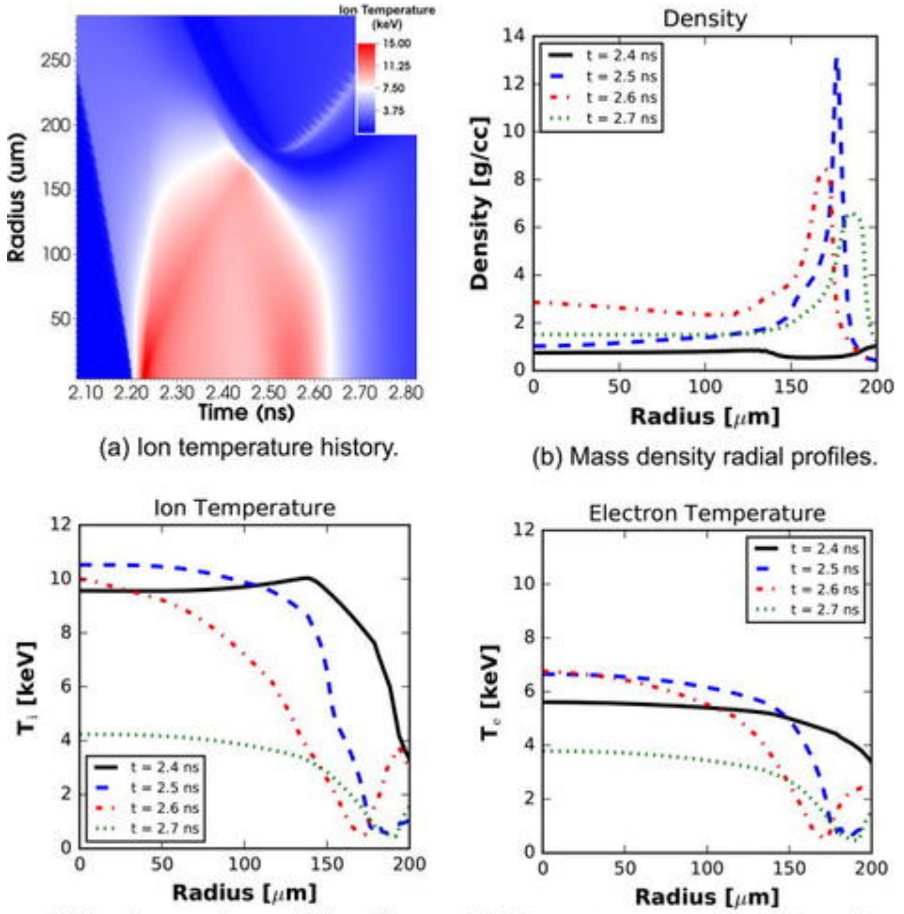
- **Heat flow experiments, Ellison *et al.****

NIF polar-direct-drive XP (PDXP) capsule



- **The design provided the baseline for neutron source development experiments****

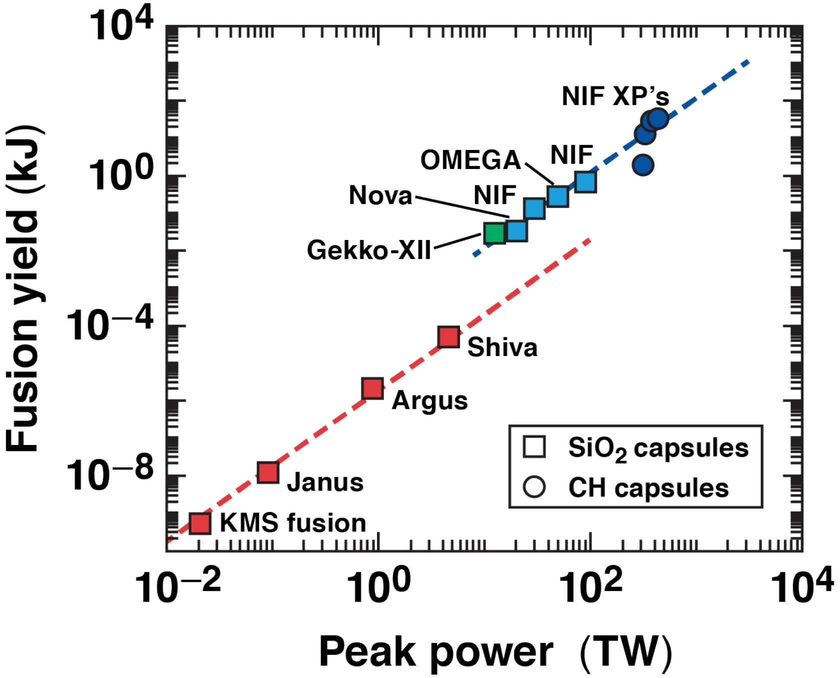
- **The design is also used in nucleosynthesis experiments†**

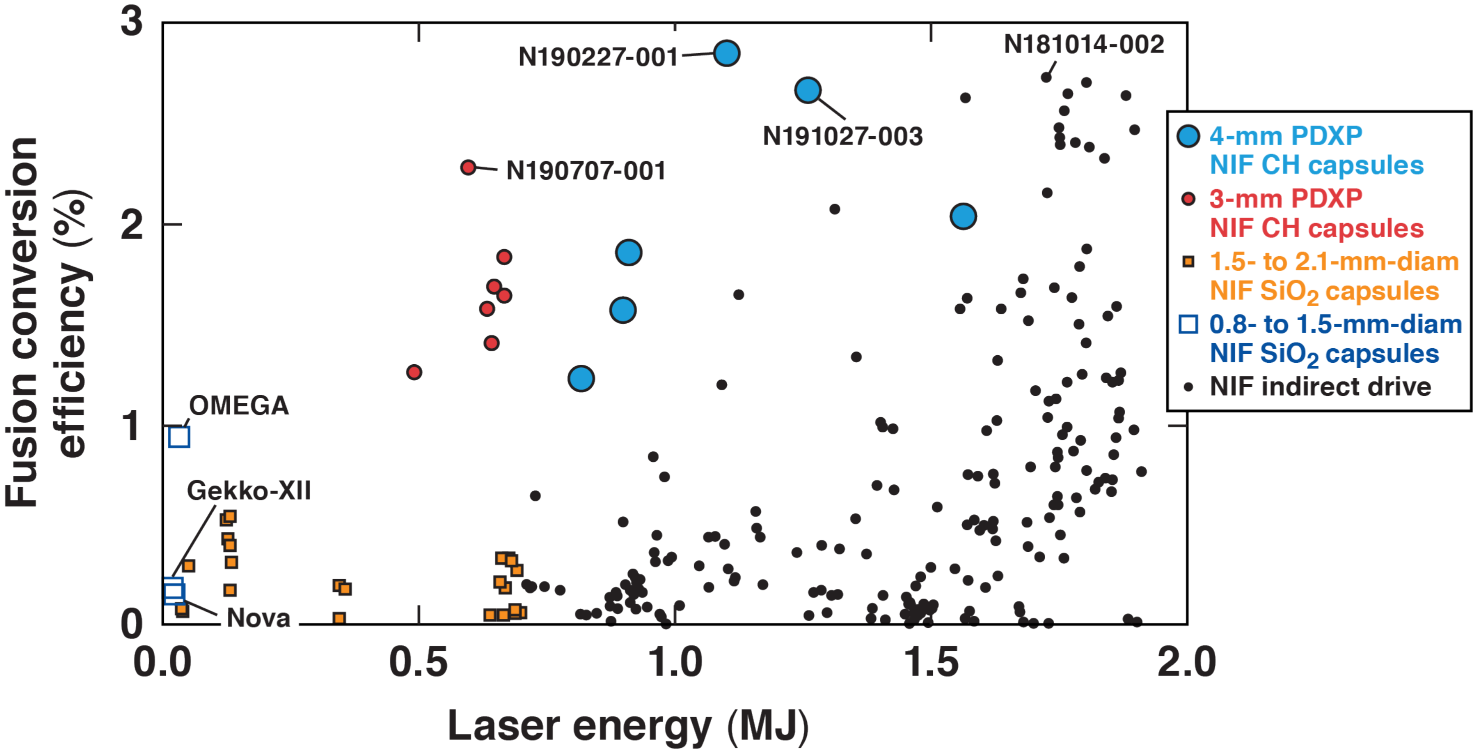


(a) Ion temperature history. (b) Mass density radial profiles. (c) Ion temperature radial profiles. (d) Electron temperature radial profiles.

* C. L. Ellison *et al.*, Phys. Plasmas 25, 072710 (2018).
** C. B. Yeamans *et al.*, "High Yield Polar Direct Drive Fusion Neutron Sources at the National Ignition Facility," submitted to Nuclear Fusion.
† M. Gatu Johnson *et al.*, Phys. Plasmas 25, 056303 (2018).

XP targets on the NIF are being employed to study laser–energy coupling and implosion dynamics in an effort to push toward high yields to prepare the pathway toward ignition



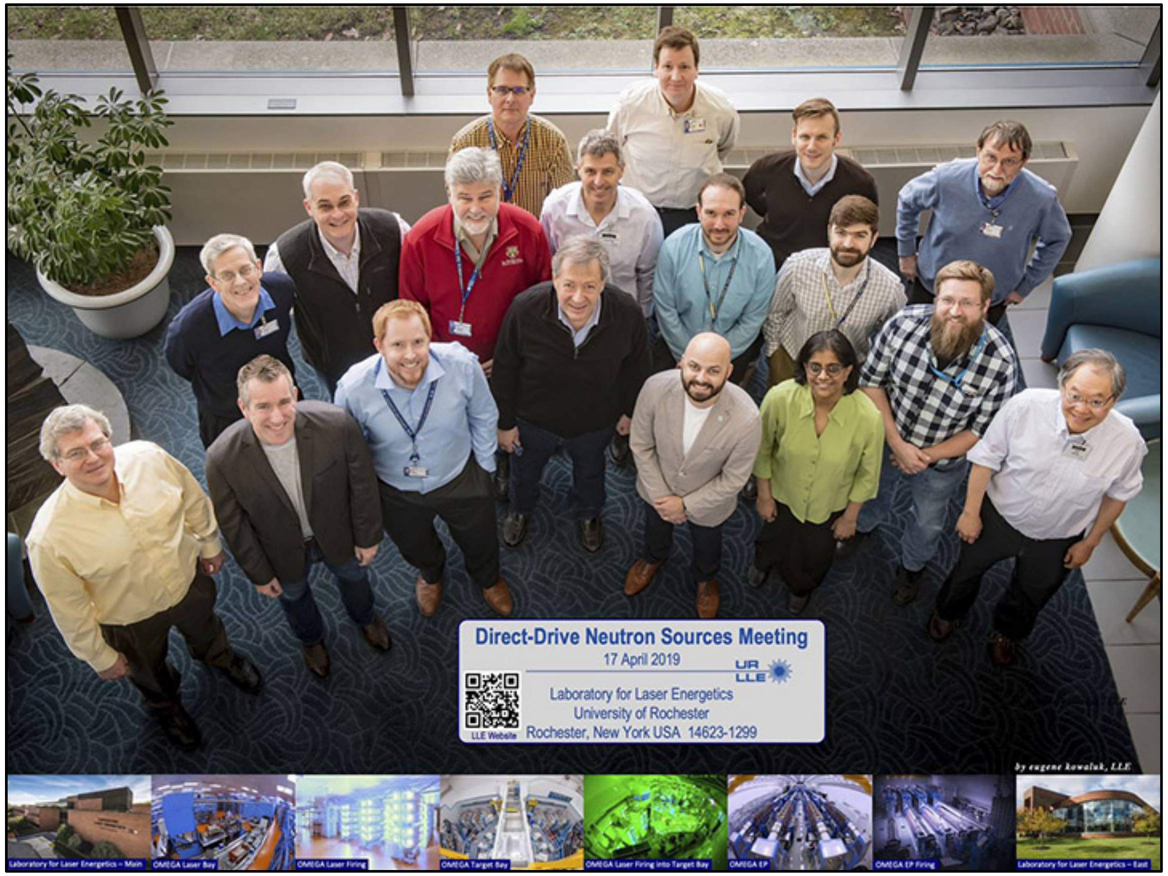


E29393

XP targets can achieve large DT_n yields owing to their high implosion speed ~700 to 900 μm/ns, but their high electron preheat, low convergence and low ρR all prevent a propagating burn wave, i.e,. ignition.

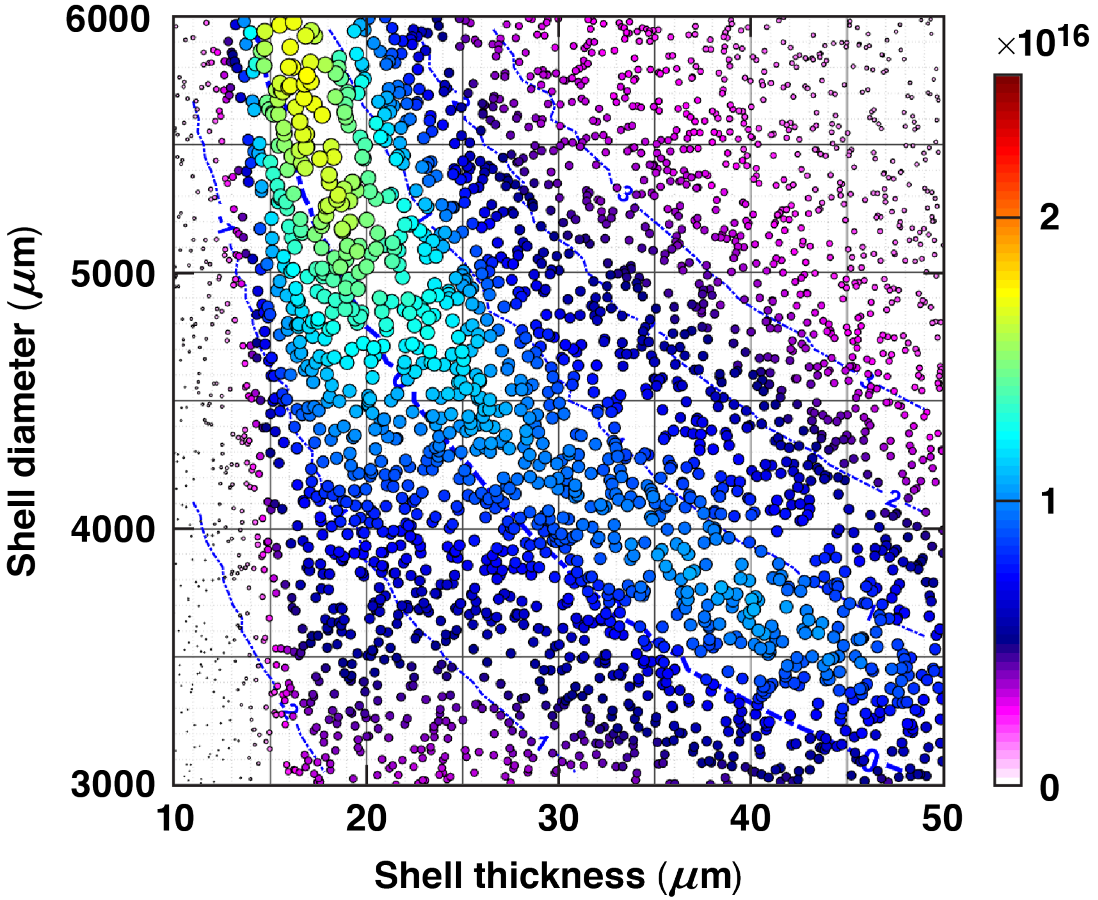
XP's are robust to nonuniformity, making them an ideal candidate to study LDD ICF physics while NIF improves laser requirements for high-convergence LDD targets

- **The XP platform offers a wide range of study**
  - **implosion physics, laser–energy coupling, LPI mitigation, shell-morphology dynamics, high-yield neutron flux, neutron-survivability tests**
  - **evaluation of future CBET mitigation, PDD spot profiles, advancing code physics modeling, e.g., laser-energy coupling, heat conduction**
- **XP's remain robust to nonuniformity due to rapid thermal heating of the shell, resulting in high implosion speeds exceeding >700 μm/ns**
- **The XP platform allows useful LDD experiments on the NIF while laser enhancements are made to prepare for high convergence**

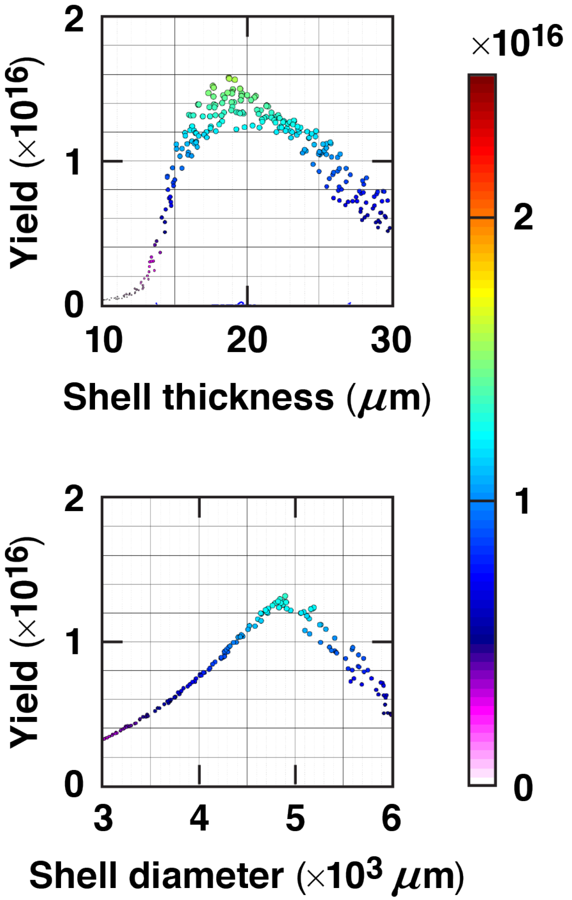


Neutron Sources Working Group; A collaboration between LLNL and LLE.

A massive number of 1-D simulations are used to optimize XP target designs with the aid of machine learning*



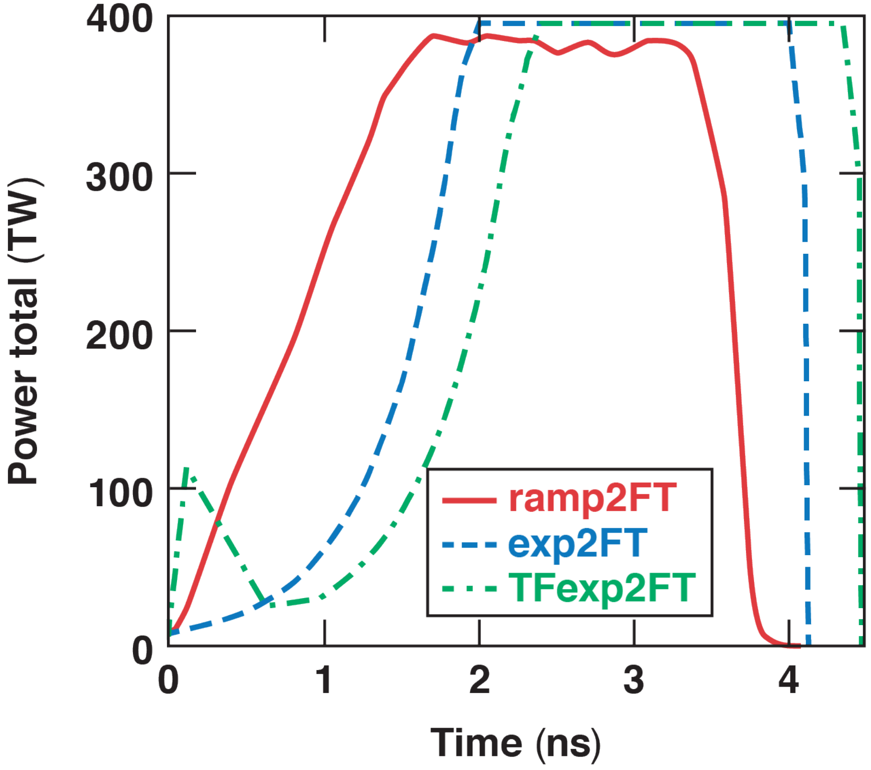
E29401



* E. Kemp; ARES simulations; LLNL-NIF

A variety of pulse shapes and contoured shells are being studied on the XP platform

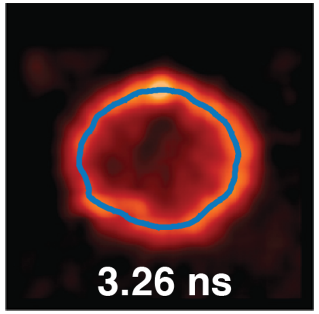
Pulse shapes



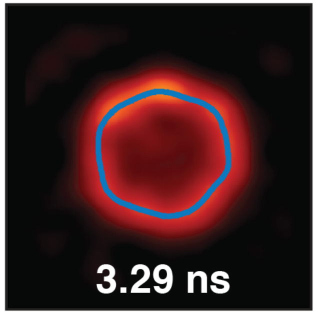
TC15444

Contoured shells have been explored on OMEGA and the NIF* to improve in-flight shell uniformity

OMEGA shots



Without contour

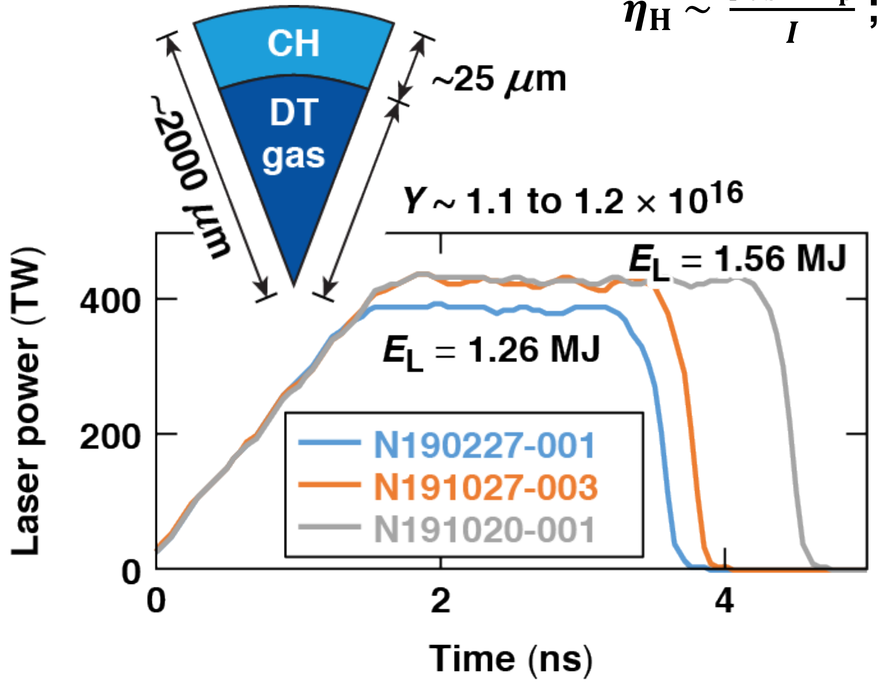


With contour

* P. W. McKenty *et al.*, GO09.00008, this conference. --- GO09: ICF Alternative Technologies

High v_{imp} PDD warm implosions on the NIF couple up to E_k = 100 kJ and E_{hs} = 30 kJ, producing $Y > 1 \times 10^{16}$

$$\eta_H \sim \frac{p_{abl} v_{imp}}{I}\ ;\ \mathrm{IFAR} \sim v_{imp}^2 / p_{abl}^{2/5}\ \alpha^{3/5}$$



E29180a

- High α and v_{imp} to maximize hydroefficiency and stability
- v_{imp} > 800 km/s
- CR ~ 8 to 10
- Incident drive intensity I = 8 to 9 × 10^{14} W/cm^2
- Hot-electron preheat does not affect performance (α is too high)

Saturation of the performance at $Y = 10^{16}$ is likely caused by limited implosion symmetry. The path forward includes symmetry improvements.

The LLE 2-D radiation-hydrodynamics code *DRACO* has proven reliable in predicting performance metrics for XP targets.

Experiments by C. Yeamans (LLNL)
CR: convergence ratio

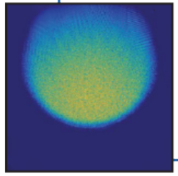
Laser-direct-drive (LDD) inertial confinement fusion (ICF)—A pathway to ignition

- Fusion: introduction to ICF
  - LID and LDD
- Simulations and experiments
- NIF LDD ⇔ polar direct drive (PDD)
  - focus: exploding-pusher (XP) platform
- **Future NIF upgrades progressing toward ignition**

NIF facility enhancements are required to perform CR > 15 PDD experiments

Symmetry and coupling

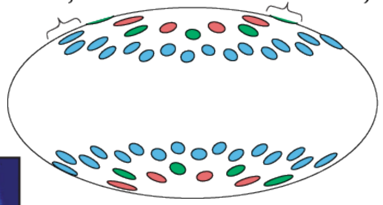
XP:



Port-color arrangement

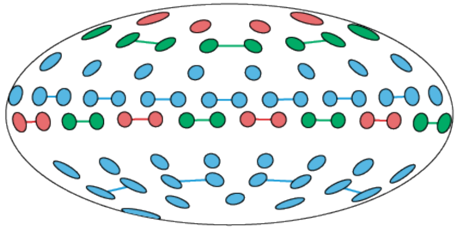
Outer cones, λ_3 Inner cones, $\{\lambda_1, \lambda_2\}$

θ = 45°, 50° θ = 23°, 30°



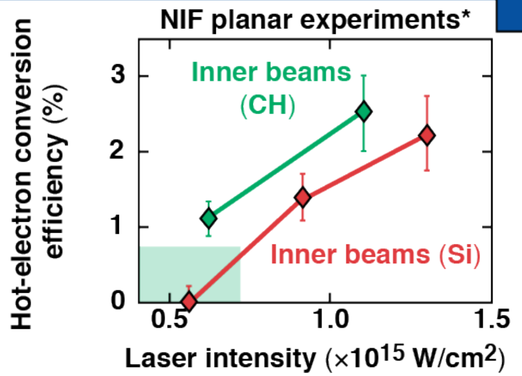
Current

Flexible color-to-port mapping

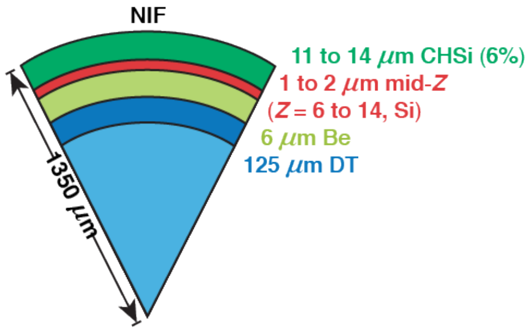


Required to reduce CBET

Preheat



Target solution**



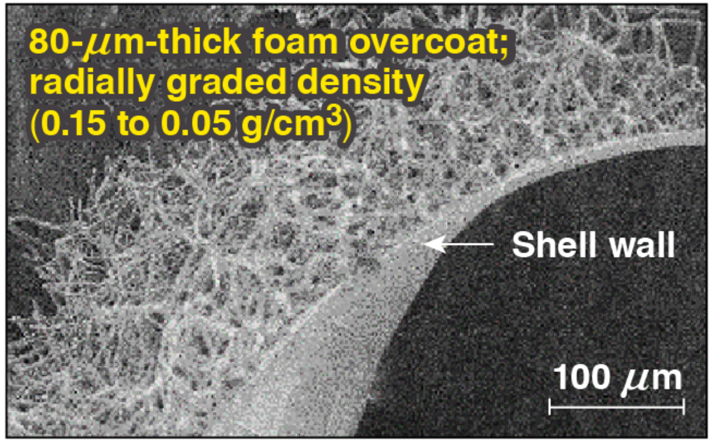
E29182a

Imprint mitigation

Multi-FM/2-D SSD + Target solution

LLE effort

Printed polymer shell with a randomized foam structure on the outer surface for imprint reduction

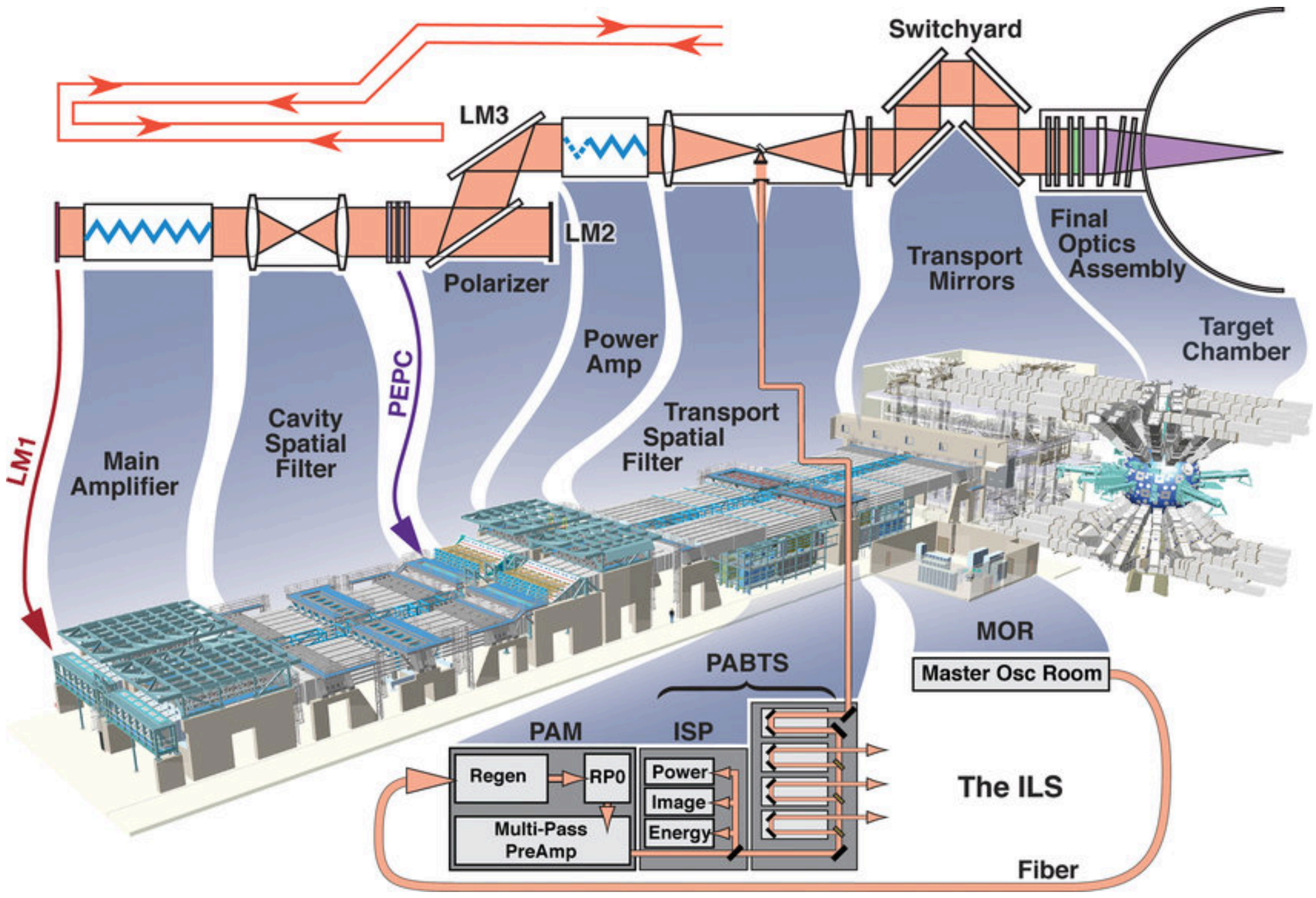


Experiments are underway to understand acceptable laser-target parameter space.

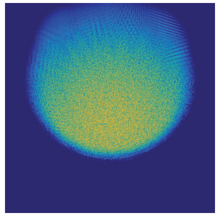
* A. A. Solodov *et al.*, Phys. Plasmas 27, 052706 (2020).
** V. N. Goncharov *et al.*, Phys. Plasmas 21, 056315 (2014).

FM: frequency modulation
SSD: smoothing by spectral dispersion

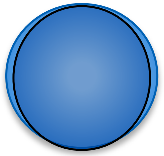
The XP platform will evaluate optimal pulse shape, spot-shapes (DPP), contoured shells, flexible color-to-port mapping (fC2Pm), and larger color separation ($\Delta\lambda_0$ detuning)



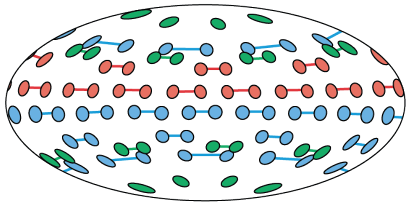
PDD-DPP



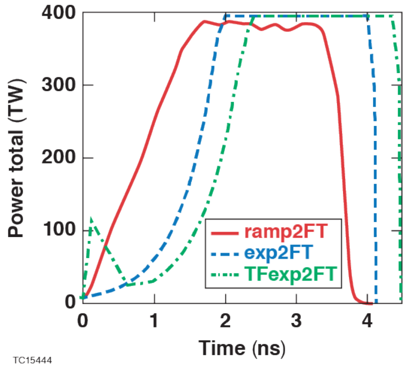
Contoured shell



fC2Pm with large $\Delta\lambda_0$

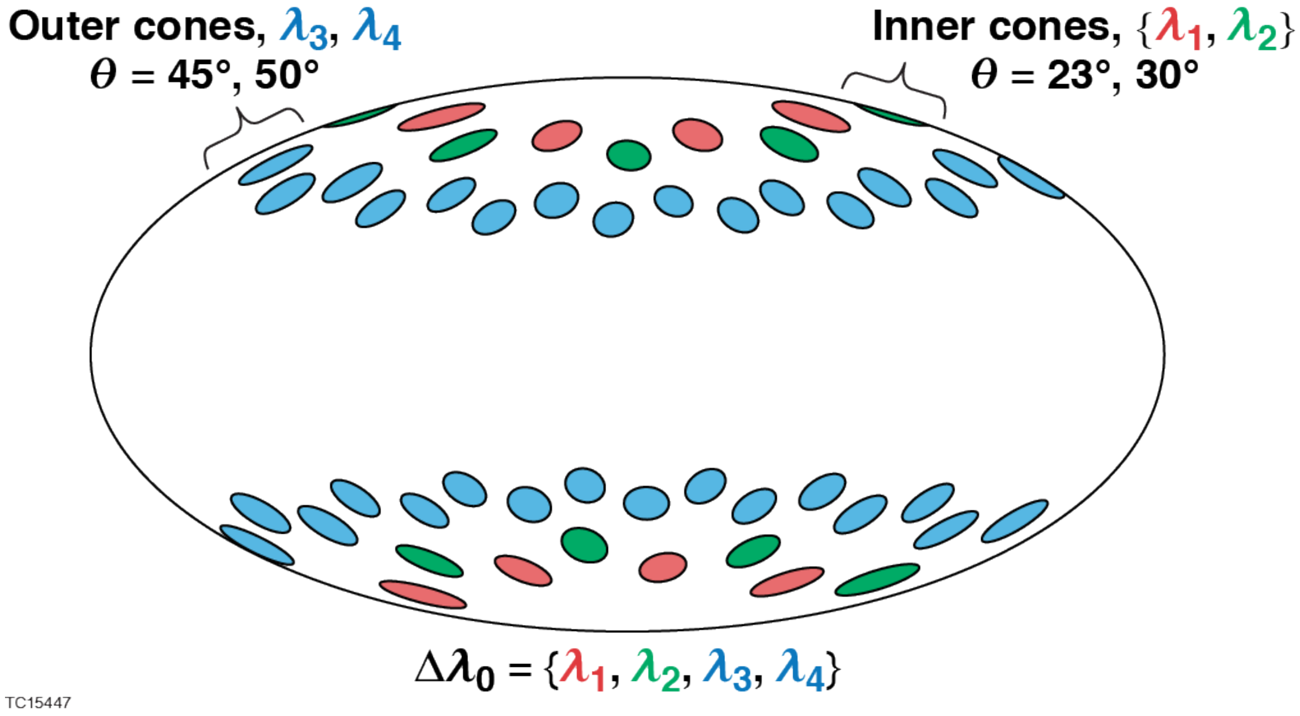


Pulse shapes

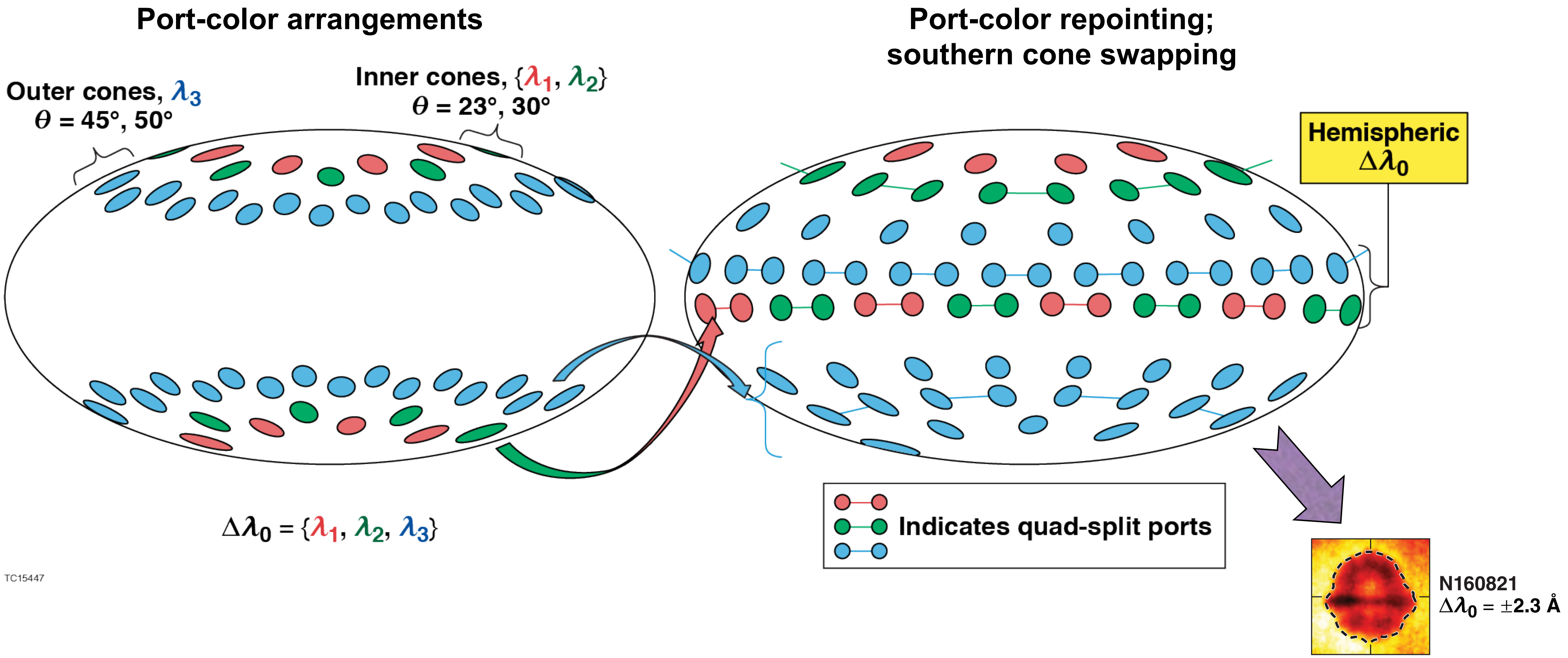


The NIF LID four-color laser sources are currently fixed into a symmetric pattern

LID port-color arrangement



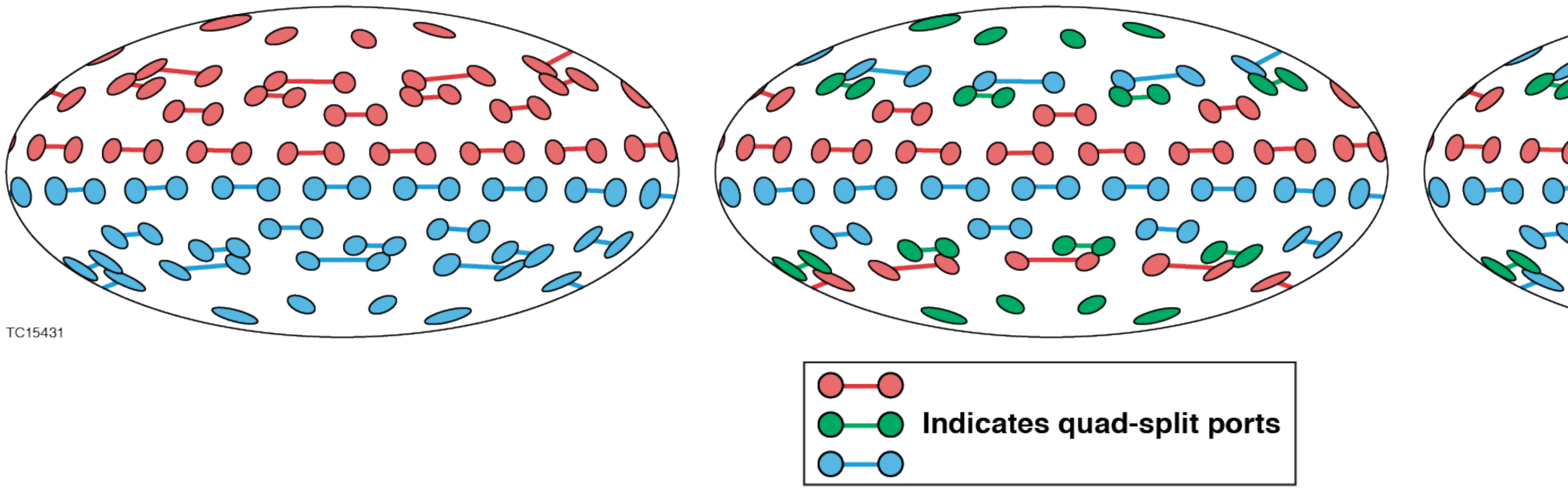
Early NIF PDD experiments employing wavelength detuning to study CBET mitigation used extreme repointing to induce a hemispheric color change

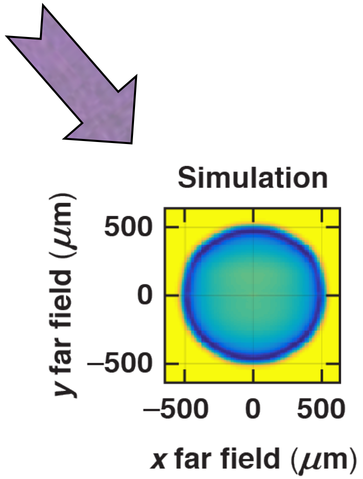


* J. A. Marozas *et al.*, Phys. Rev. Lett. 120, 085001 (2018).

The NIF fiber-optic front end will be updated to flexibly remap the four-color sources to a variety of port configurations to help mitigate CBET

Flexible color-to-port mapping (fC2Pm) with large $\Delta\lambda_0$

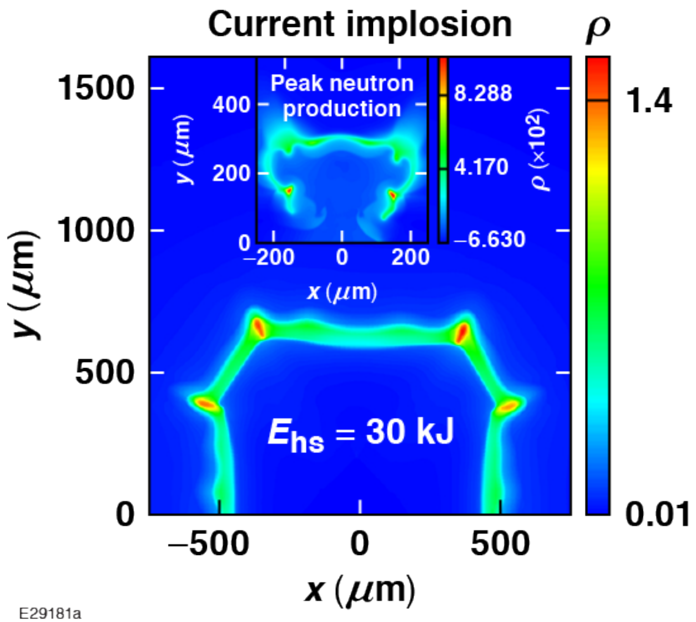




The new front-end remapping eliminates the need for extreme repointing to induce a hemispheric color change.

The performance of current implosions can be improved by better symmetry control and enhanced laser coupling

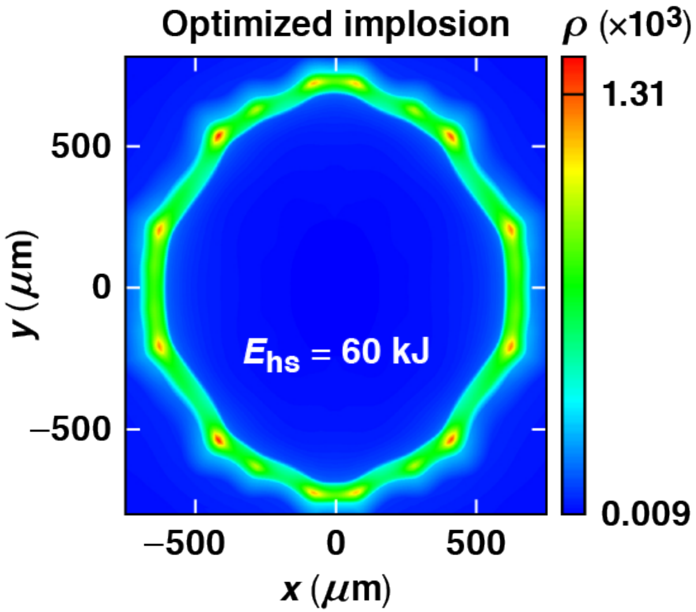
- **CBET mitigation strategies** – smaller SMA spots, $\Delta\lambda = \pm 6$ Å ➡ $E_k = 100 \rightarrow 120$ kJ
- **Symmetry control strategies** – pulse shaping, repointing, PDD phase plates ➡ $E_{hs}/E_k = 30\% \rightarrow 50\%$



DRACO **simulations**

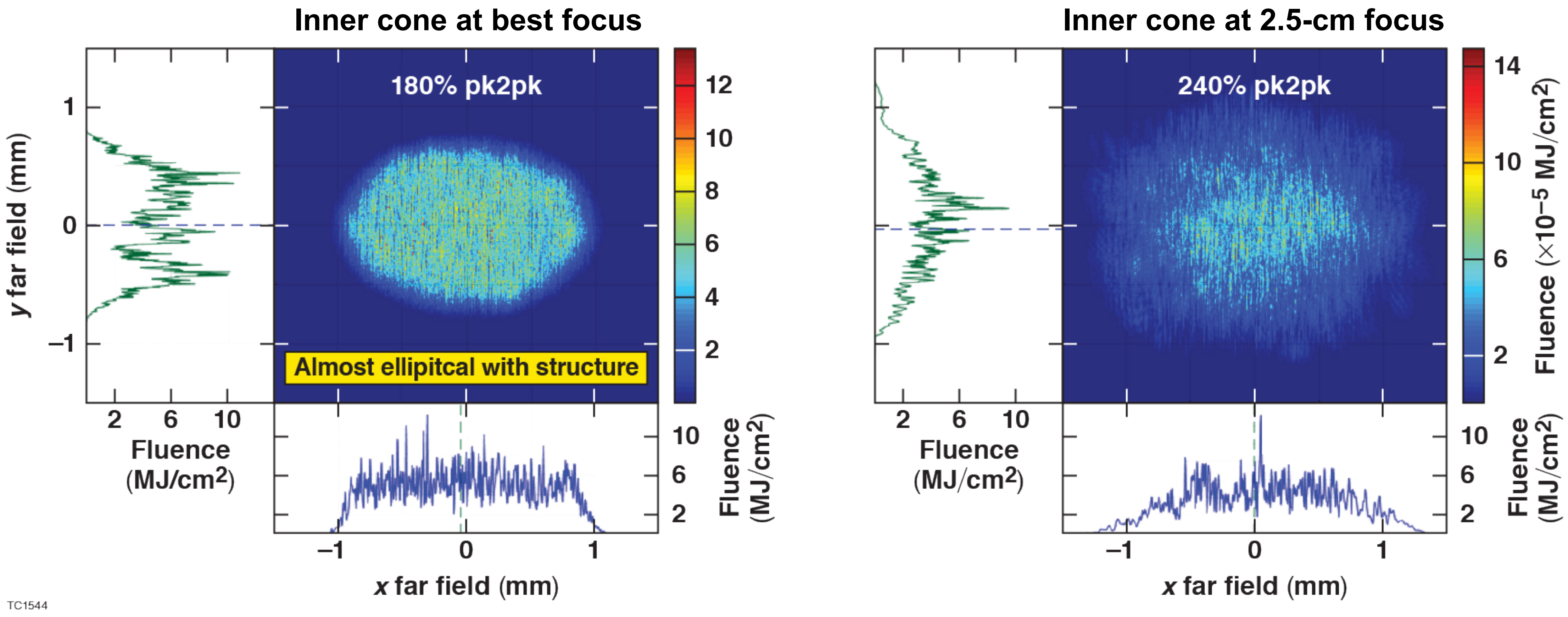
Shot	Y_{DT} (10^{15})		T_i (keV)		t_{bang} (ns)	
	Exp.	Sim.	Exp.	Sim.	Exp.	Sim.
N181014	3.5	3.9	6.3	8.6	5.5	4.9
N190224	6.0	7.0	7.7	10.3	4.9	4.4
N190227	11.1	11.2	9.0	9.7	4.2	4.2

100-kJ goal ➡

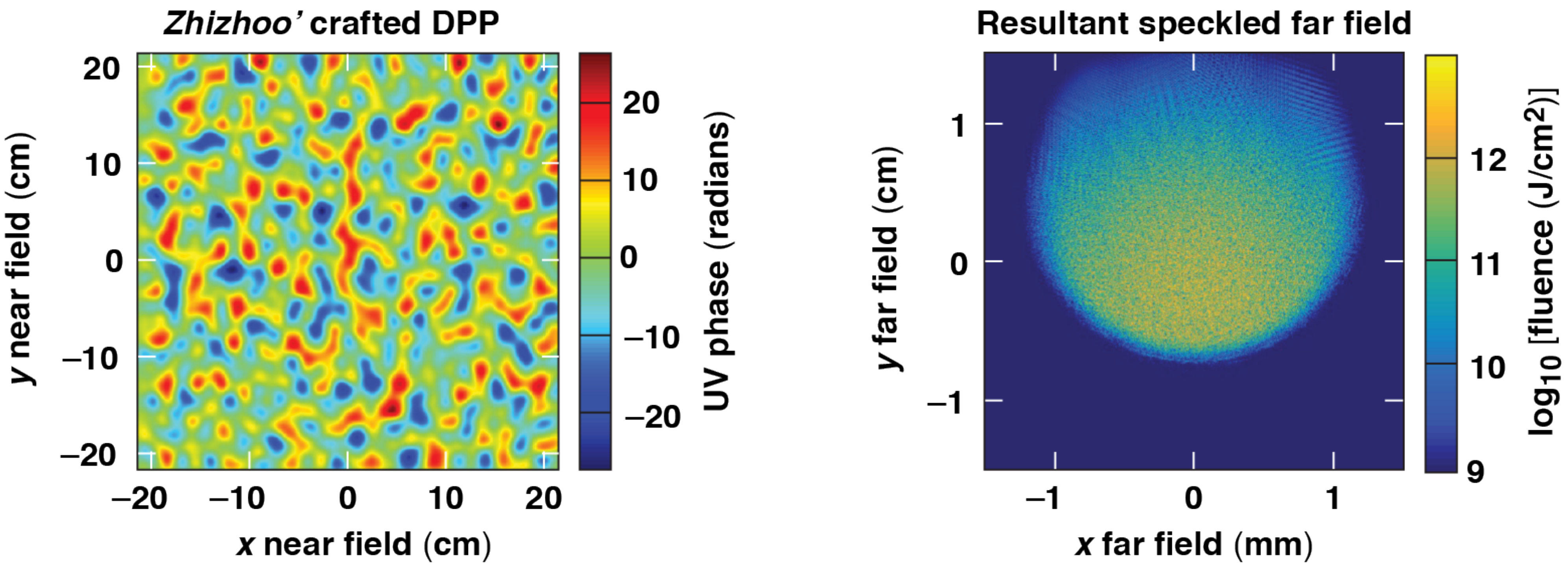


E29181a

The NIF current phase plates produce spots that do not meet the full requirements for high-convergence LDD targets or optimized PDD symmetry on the NIF



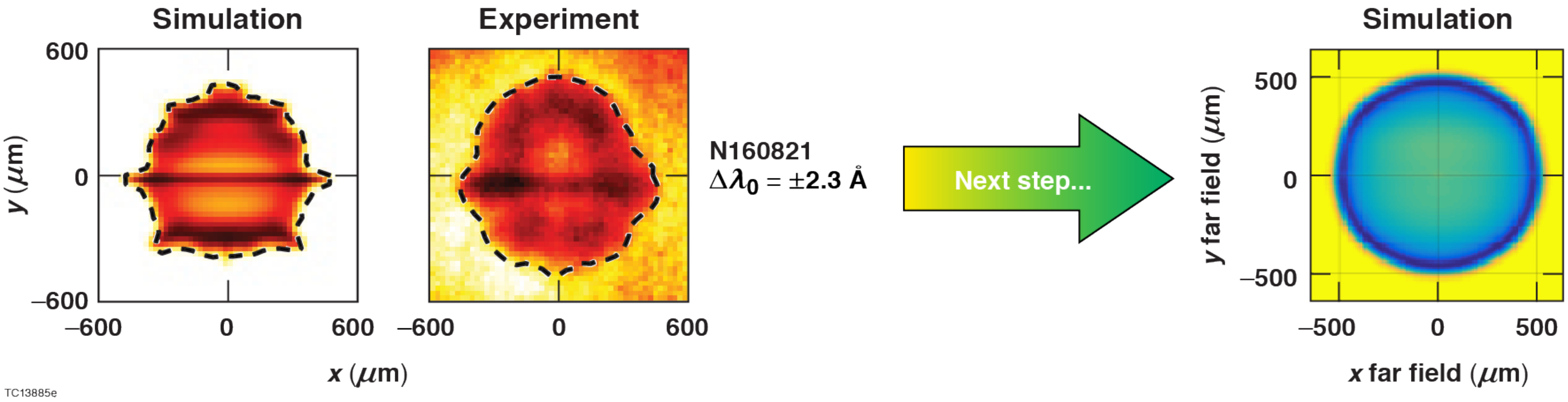
Physical optics devices known as phase plates are used to shape the far-field spot on target by manipulating the near-field phase front



TC12346a

The design code *Zhizhoo'* can produce far-field spots compatible with PDD on the NIF across a wide range of target diameters: 3 to 6mm

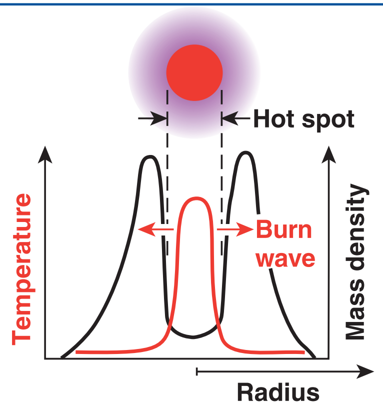
Application of both large wavelength detuning, fC2Pm, and optimized PDD spot shapes promises large returns for high-convergence PDD experiments on the NIF

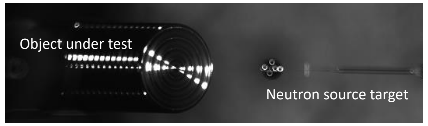


Low convergence XP: ➔ >100kJ yield
High Convergence: alpha burner, ignition

Laser direct drive (LDD) is making strides along the pathway to ignition

- ICF assembles DT fuel mass with a cold, high-areal-density (ρR) shell and hot central core using a high-speed and low-entropy implosion
  - LDD increases the ignition margin at moderate convergence (20 to 30)* while providing open access to diagnostics and external magnetic fields
- A robust "exploding-pusher" (XP) platform generates a high neutron flux,** albeit at low areal density (ρR)
  - ideal platform to study implosion physics modeling†, NIF improvements, and neutron-survivability device testing
- The pathway incorporates upgrades for energy coupling and symmetry control
  - short term: predicted to reach >100-kJ fusion yields at low convergence (~10)
  - long term: information gleaned will feed forward into higher-convergence, higher-ρR targets that can ignite





* Relative to Laser Indirect Drive (LID)
** C. B. Yeamans *et al.*, "High Yield Polar Direct Drive Fusion Neutron Sources at the National Ignition Facility," submitted to Nuclear Fusion.
† J. A. Marozas *et al.*, Phys. Rev. Lett. 120, 085001 (2018);
H. D. Whitley *et al.*, Physics Archive, https://arxiv.org/abs/2006.15635 (2020).
ICF: inertial confinement fusion
NIF: National Ignition Facility

Backup

The DT-plasma fuel assembly areal density (ρR) is a key ICF performance parameter

- The Lawson criterion defines a simple condition required for ignition:
  - ignition: (fusion products power density) $\times$ (containment-time) $>$ (plasma energy density)

for 50-50 DT plasma: $\frac{n^2}{4}\langle\sigma v\rangle Q\tau > 3nk_{\mathrm{B}}T$

solving for $n\tau$:* $n\tau > \frac{12k_{\mathrm{B}}T}{\langle\sigma v\rangle Q} \approx 10^{14}\text{:}\,10^{15}\left[\mathrm{s/cm^3}\right]$ **Lawson Criterion**

- Containment time can be approximated by disassembly time; i.e., related to the ion sound speed traversal across the fuel assembly as

$$\langle\tau\rangle \cong \frac{R_{\mathrm{f}}}{4c_{\mathrm{s}}},\ n \equiv \rho/m \Rightarrow \mathrm{n\tau} \cong \frac{\rho R_{\mathrm{f}}}{4\langle M_i\rangle c_{\mathrm{s}}}$$

$\rho R_{\mathrm{f}} \gtrsim 3\ \left[\mathrm{g/cm^2}\right]$ for efficient burn, i.e., large gains

The areal-density, ρR, can be expanded to express other important ignition criteria…

* $Q_{DT} = 17.6\ \mathrm{MeV}$

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UR LLE

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$\rho R_\mathrm{f} \gtrsim 3\ \left[\mathrm{g/cm^2}\right]$ for efficient burn, i.e., large gains

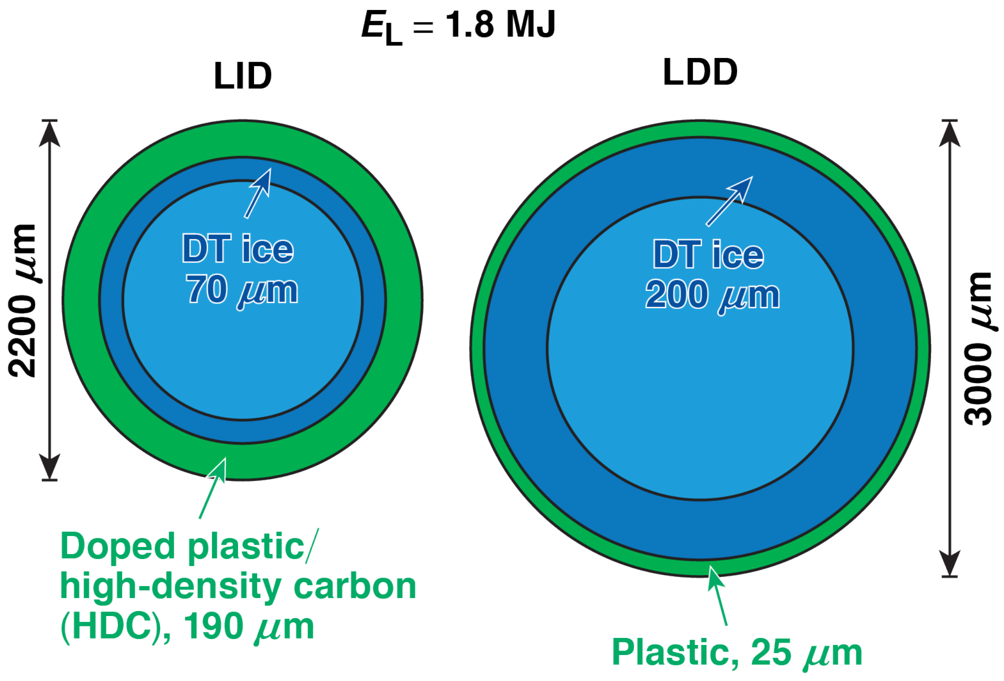
$$\rho R \sim \frac{\left(P_\mathrm{abl}^2/I\right)^{1/3} E_\mathrm{L}^{1/3}}{\sqrt{\alpha}}$$

The areal-density, ρR, can be expanded to express other important ignition criteria…

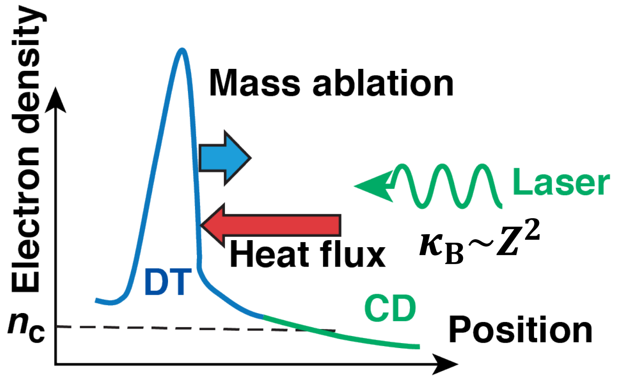
$$P_\mathrm{hs} > 250\ \mathrm{Gbar}\left(\frac{E_\mathrm{hs}}{10\ \mathrm{kJ}}\right)^{-1/2} = P_\mathrm{th}$$

* $Q_\mathrm{DT} = 17.6\ \mathrm{MeV}$

LDD couples more energy to the hot spot compared to LID, which means more fuel mass and thinner ablators



Thinner plastic maximizes drive efficiency



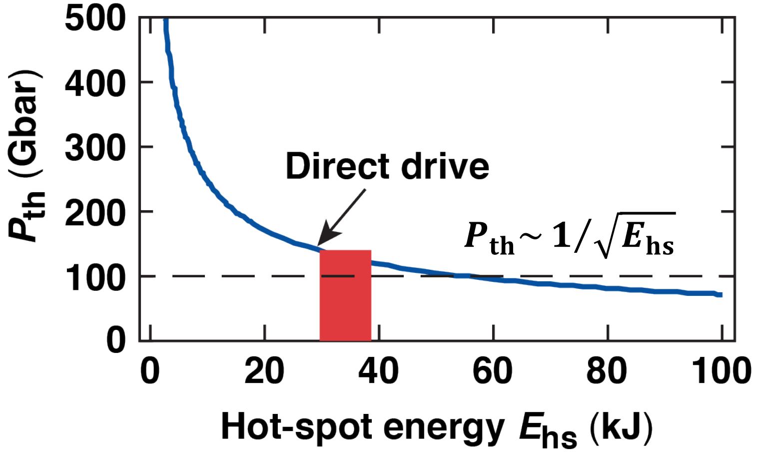
Atomic number

$$m_{abl} \sim I^{1/3}\left(\frac{A}{Z}\right)^{2/3}$$

$$p_{abl} \sim I^{2/3}\left(\frac{A}{Z}\right)^{1/3}$$

Ion charge

Threshold hot-spot pressure for ignition



E29127a

LDD ignition: CR > 22, P_{hs} > 120 Gbar, P_{hs} > 350 Gbar has already been demonstrated in LID implosions.

Two critical parameters for ignition are hot-spot pressure and internal energy

From the Lawson Criterion:*

$$(\rho R)_{\mathrm{hs}} \times T_{\mathrm{i}} > 0.3\ \mathrm{g/cm^2} \times 5\ \mathrm{keV}$$

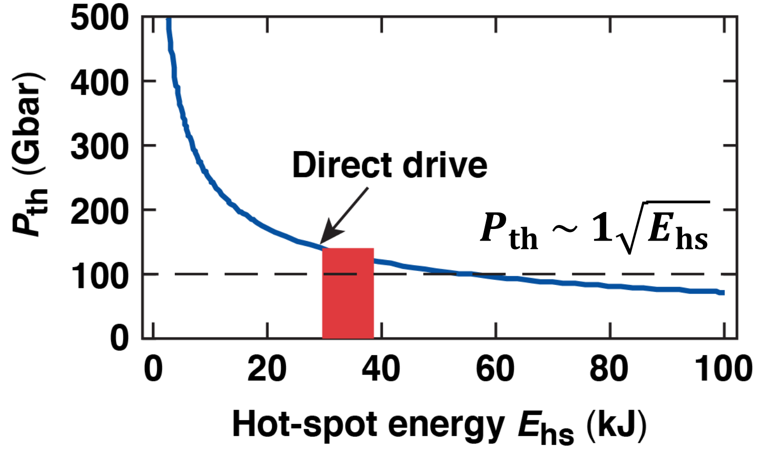
$$P_{\mathrm{DT}} = 2\rho T/2.5m_{\mathrm{p}}$$

$$P_{\mathrm{hs}} = 100\ \mathrm{Gbar}\left(\frac{100\ \mu\mathrm{m}}{R_{\mathrm{hs}}}\right)$$

$$E_{\mathrm{hs}} = 3/2\ P_{\mathrm{hs}} V_{\mathrm{hs}}$$

$$P_{\mathrm{hs}} > 250\ \mathrm{Gbar}\left(\frac{E_{\mathrm{hs}}}{10\ \mathrm{kJ}}\right)^{-1/2} = P_{\mathrm{th}}$$

Threshold hot-spot pressure for ignition



E29127b

To burn the main fuel: Gain > 1, ρR > g/cm^2

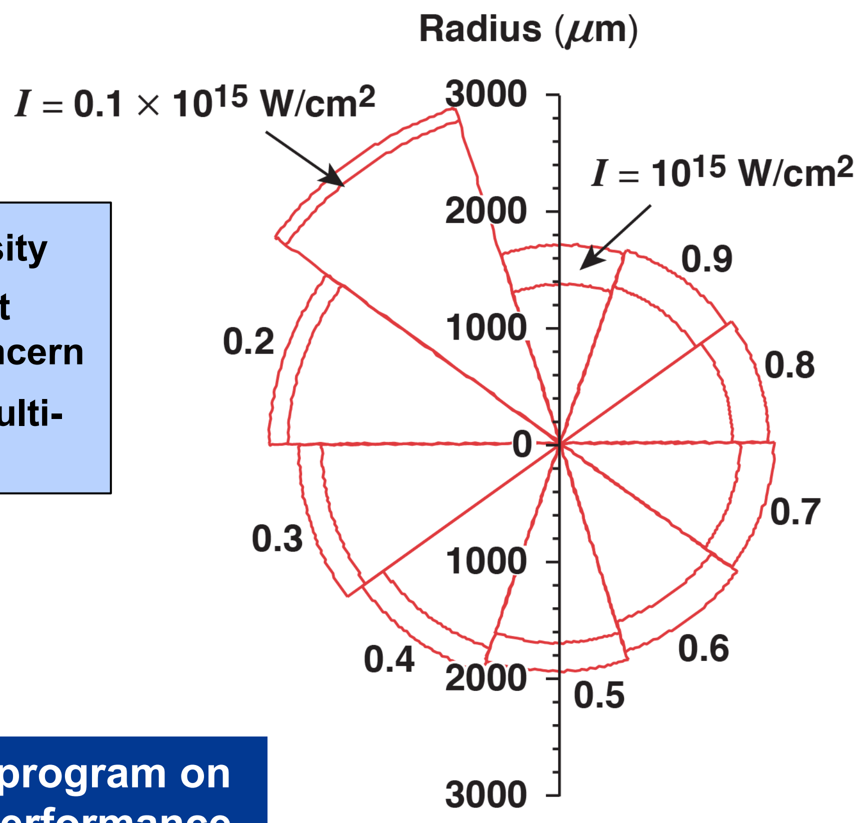
$$\rho R \sim \frac{\left(P_{\mathrm{abl}}^2/I\right)^{1/3} E_{\mathrm{L}}^{1/3}}{\sqrt{\alpha}}$$

* R. Betti *et al.*, Phys. Plasmas 17, 058102 (2010).

Maximizing hydroefficiency is key for successful ICF implosions

Hydroefficiency $\eta_H = E_k/E_L$ $\quad$ $\boxed{\eta_H \sim \frac{p_{abl} v_{imp}}{I}}$ $\quad$ $p_{abl} \sim f_{abs} I^{\frac{2}{3}}$

Shell aspect ratio increases as I decreases (same V_{imp})



To maximize hydroefficiency

Maximize laser coupling
- Mitigate LPI losses
- Use mid-Z ablator (balance between κ_B and radiation losses)

Increase implosion velocity
- Reduce shell mass

Reduce laser intensity
- Good for LPI but stability is a concern
- Advantage in multi-shell designs

Stability must be addressed:

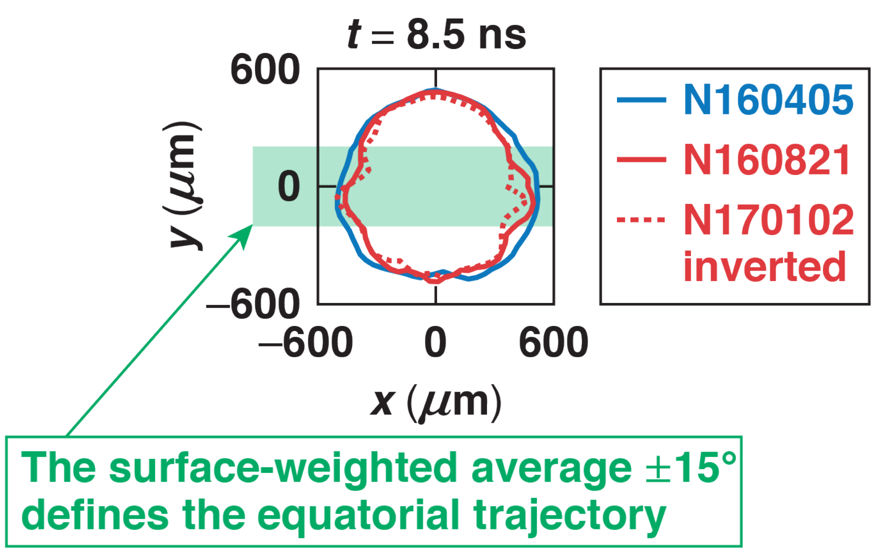
$$\boxed{\mathrm{IFAR} = \frac{R}{\Delta R} \sim v_{imp}^2 / p_{abl}^{\frac{2}{5}} \alpha^{\frac{3}{5}}}$$

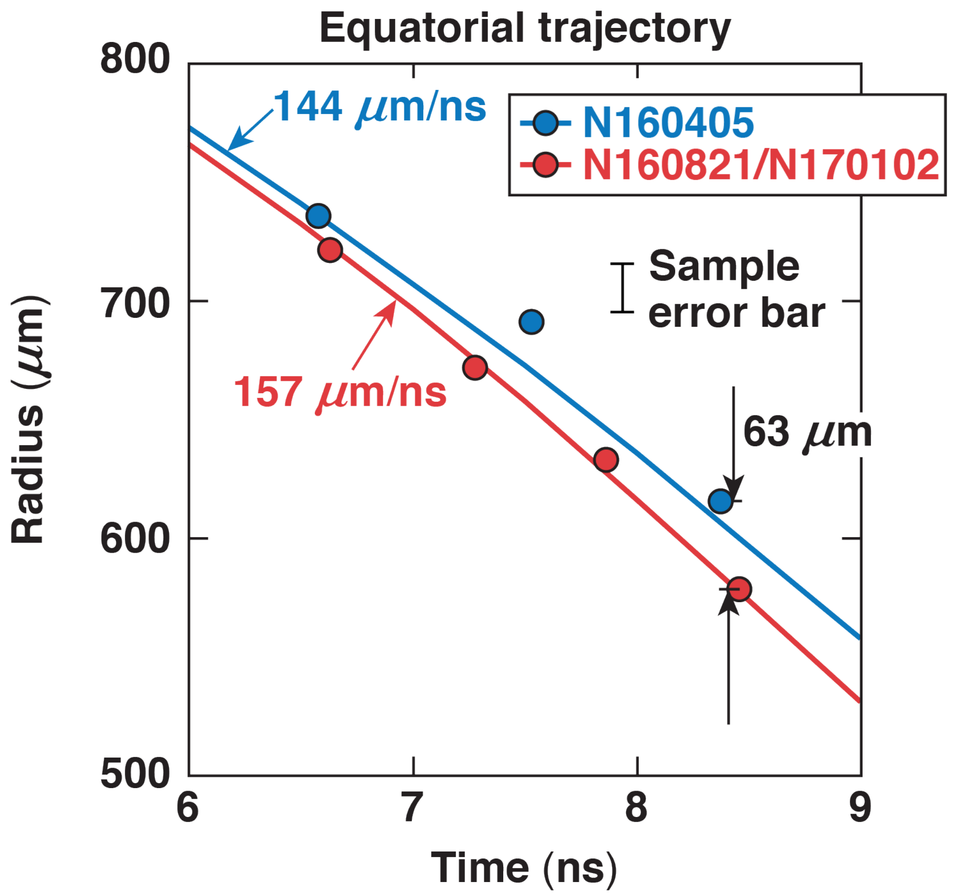
While working on mitigating the deleterious effects of LPI, the LDD program on the NIF and OMEGA leverages on v_{imp} and adiabat to maximize the performance.

LPI: laser--plasma instability
IFAR: in-flight aspect ratio

Improved equatorial coupling from wavelength detuning is inferred from gated radiographs

- **The predicted and measured trajectories* show the expected faster implosion speeds near the equator**



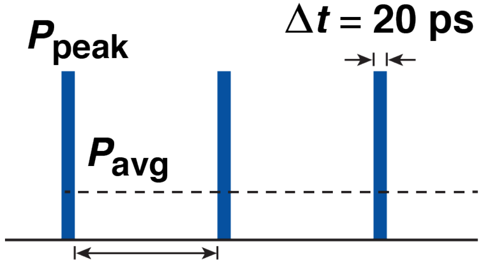


TC13351b

* Analysis by D. Turnbull

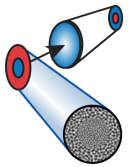
Laser energy coupling loss caused by CBET can be mitigated in different domains that can be combined; temporal, spatial, and spectral

- **Temporal domain**
  - multiplexing the beams reduces interaction

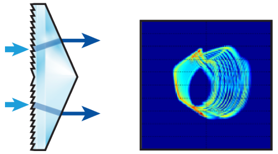


  - STUD* pulses

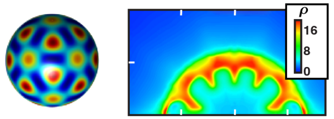
- **Spatial domain** (reduce interaction volume)
  - dynamic spot shape
    - two stage**



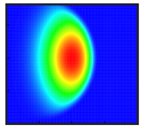
    - Graxicon***



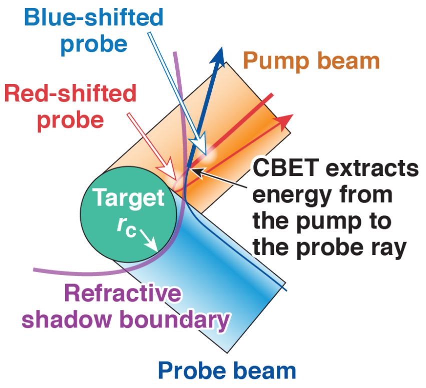
    - KrF lasers (NRL)
  - spots smaller than target (e.g., R_{75})†



  - spot-masking apodization (SMA)



- **Spatial domain**
  - wavelength detuning; $D\omega_0$



  - wide bandwidth within each beam (e.g., SRRS‡)
  - lower intensity per band and incoherence disrupts growth

* STUD: spike trains of uneven duration and delay; B. Afeyan and S. Hüller, EPJ Web Conf. 59, 05009 (2013).

** D. H. Froula *et al.*, Phys. Plasmas 20, 082704 (2013).
*** T. J. Kessler and H. Huang, presented at the Ninth International Conference on Inertial Fusion Sciences and Applications (IFSA 2015), Seattle, WA, 20–25 September 2015 (Abstract Mo.Po.61).
† S. P. Regan *et al.*, Phys. Rev. Lett. 117, 025001 (2016); 059903(E) (2016).
‡ SRRS: stimulated rotational Raman scattering; J. Weaver *et al.*, "Spectral and Far-Field Broadening due to Stimulated Rotational Raman Scattering Driven by the Nike Krypton Fluoride Laser," to be published in Applied Optics.

The XP platform has a long history dating back to the early days of ICF, circa 1970's

- **Thin-shelled glass microballoons filled with DT gas were shot with an intense short laser burst**

A THEORETICAL INTERPRETATION OF
EXPLODING PUSHER LASER FUSION EXPERIMENTS

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ABSTRACT. The implosion of neon-filled glass microballoons has been examined via numerical simulations using a one-dimensional Lagrangian hydrodynamic code. Comparison has been made to experiments performed on a four-beam neodymium glass laser system using an array of diagnostics including X-ray pinhole

Exploding pusher performance – A theoretical model

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A simple model of "exploding-pusher" laser fusion targets is presented. The peak ion temperature is calculated by assuming that the ion heating mechanism is a shock followed by isentropic compression. The compression is calculated by conservation of mass and reasonable assumptions on the density profile at peak compression time. The neutron yield predictions of this model agree over a broad range of parameter space with those of complex one-dimensional numerical simulation, which in two dimensions have tracked experimentally measured yields quite accurately.

I. INTRODUCTION

Exploding pusher targets[1] have been the most common targets of early laser fusion experiments, and are the first targets to be shot on the 25 TW SHIVA laser system at Lawrence Livermore Laboratory. Typically, they consist of a glass microballoon filled with deuterium-tritium (DT) gas. For SHIVA, typical dimensions are radius 200 μ, thickness 2 μ, and DT fill 2 mg/cc, conduction and by expansion.

Whereas the high-compression, isentropic implosion targets are sensitive to electron preheat and to Rayleigh Taylor instability, exploding pushers, by virtue of their rapid thermal wave early heating and by their nonablative implosion dynamics, are not sensitive to the aforementioned problems. On the other hand, the preheat levels of these targets and exploding pusher

A NIF XP*

How do they work?...

* M. J. Rosenberg *et al*., Phys. Plasmas 21, 122712 (2014).

The XP platform has a long history dating back to the early days of ICF, circa 1970's

- Thin-shelled glass microballoons filled with DT gas were shot with an intense short laser burst
  - the laser energy rapidly heats the electrons, driving an inward heat wave into the shell and DT gas preheating the DT electrons (reduces convergence, low ρR)
    - the thermal wave heats the shell ions (strong coupling) but not the DT ions (weak coupling)
    - the rapid deposition causes ~1/2 the shell mass to explosively ablate (high stability)
  - the imploding inner 1/2-shell acts as a piston driving a strong inward shock (high speeds)
    - this shock wave principally heats the ions
    - the inner shell continues to move inward behind the shock front, compressing the post-shock DT gas, further heating the ions to thermonuclear temperatures, producing fusion reactions
    - the shock and compression cause $T_i \gg T_e$, while the weak coupling preserves the imbalance
  - the exploding outer shell and imploding/compressing inner shell led to these targets being called exploding pushers
  - eventually the thermal pressure builds and the return shock impacts the shell, both halting compression
    - fusion reactions continue until the DT is cooled by thermal conduction and expansion
- Current XP experiments use similar concepts but with larger targets with similar aspect ratios and shaped pulses that continue to drive the remaining shell during compression, further increasing the DT_n yield

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    - the exploding outer-shell and imploding/compressing inner-shell led to these targets being called exploding pushers

Current XP experiments use similar concepts scaled to higher energy and similar aspect ratio targets, but leveraging shaped pulses to drive the remaining shell during compression, further increasing the DT_n yield.

The LLE 2-D radiation-hydrodynamics code *DRACO* has proven reliable in predicting performance metrics for XP targets

Shot	Y_{DT} (10^{15})		T_i (keV)		t_{bang} (ns)		t_{burn} (ps)	
	Exp.	Sim.	Exp.	Sim.	Exp.	Sim.	Exp.	Sim.
N181014	3.56	3.87	6.30	8.59	5.52	4.92	618	320
N190224	5.97	6.97	7.65	10.29	4.88	4.41	502	322
N190227	11.1	11.2	8.94	9.65	4.22	4.25	452	300
N190317	5.01	4.83	7.37	8.20	4.58	4.38	607	402
N190707	4.81	4.94	11.14	12.0	2.71	2.84	311	202

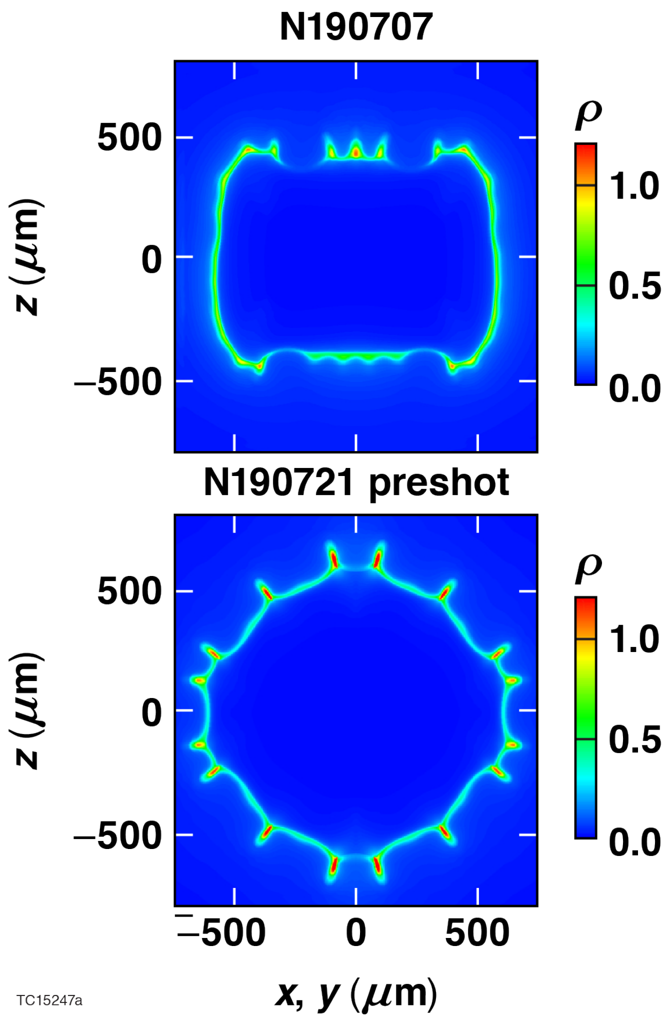
- **NIF experiments will help further code validation/verification to provide a means to design targets, reaching >100-kJ DT fusion yields at low convergence (~10)**
- **The XP platform allows the study of some required NIF improvements to achieve high-convergence implosions such as CBET mitigation and far-field spot profile, as well as our modeling of heat conduction***

* H. D. Whitley *et al.*, Physics Archive, https://arxiv.org/abs/2006.15635 (2020).

Upcoming XP experiments on the NIF hope to increase neutron yield using improved pulse shapes and pointings based on 2-D simulations that include necessary physics

Elements of the new design

- Dual shocks improve yield while remaining high adiabat and predominantly "shock yield"
- The pulse shape improves separation of shell from shock, improving yield
- Steep main pulse rise improves coupling
- Simpler quad splitting improves power imbalance
- Repointing and pulse shapes yield rounder implosions
- Extensible
  - large targets with optimized DPP's >100 kJ



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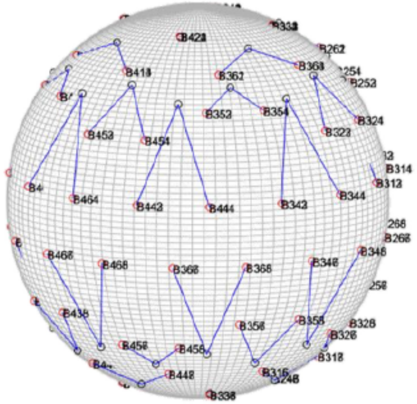
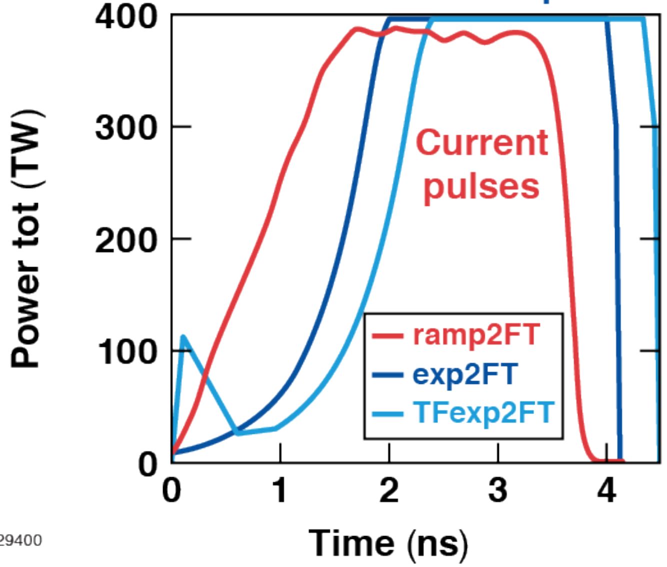
Better symmetry control and enhanced coupling is predicted to triple the yield in warm PDD implosions on the NIF

UR LLE

E_L = 1.1 MJ	Puls-shape	P_{max} (TW)	Abs (%)	Y_{DT} ($\times10^{16}$)	Notes
Current (N190227)	ramp2FT	385	81	1.1	Has severe shell distortion
New pointing	ramp2FT	385	80	1.5	Improved shell morphology, increases yield
New pointing and pulse = *A*	exp2FT	445	80	1.9	Improved shape and speed
A and $\Delta\lambda = \pm3$ Å with fC2Pm*	exp2FT	445	83	1.9	Marginal improvement
A and $\Delta\lambda = \pm4.5$ Å with fC2Pm	exp2FT	445	89	3.2	Better coupling
A and $\Delta\lambda = \pm6$ Å with fC2Pm	exp2FT	445	91	>3.2	Can be optimized better

Target shimming to improve symmetry was successfully tested on the NIF this year.





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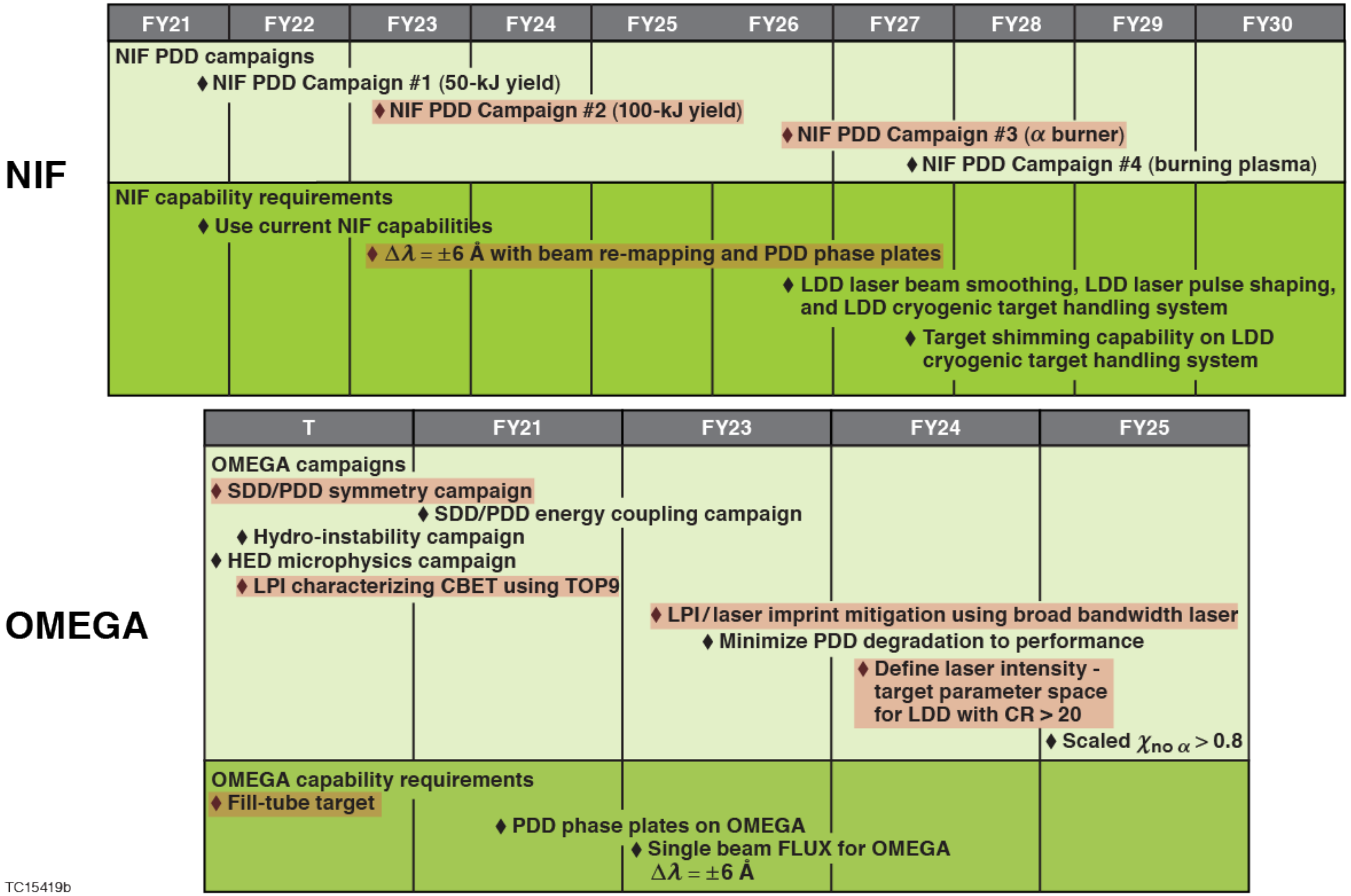
The top-level five-year LDD R&D plans for OMEGA



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Items highlighted in this talk

SDD: spherical direct drive
HED: high-energy density