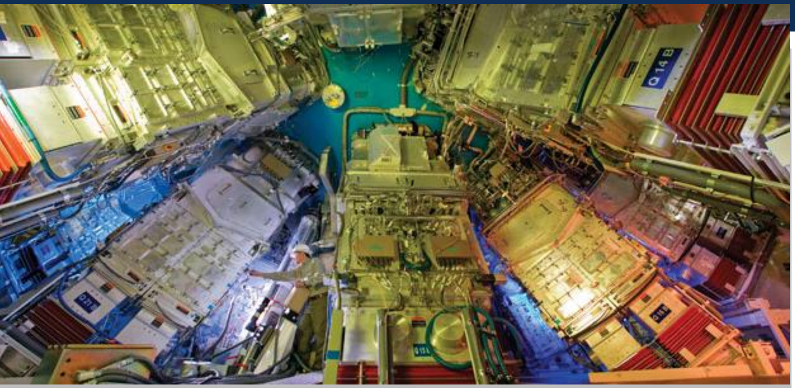
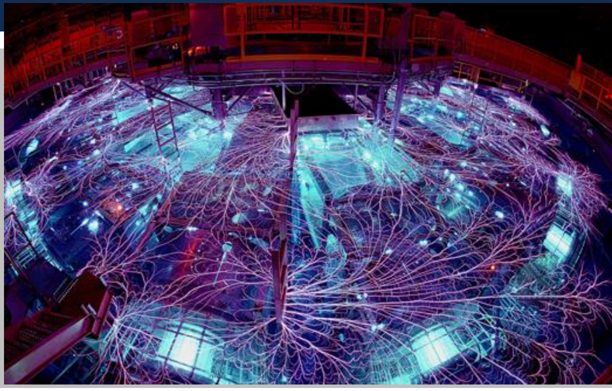
Exceptional service in the national interest

Sandia National Laboratories





A Multi-Dimensional View of the US Inertial Confinement Fusion Program

Gregory A. Rochau

Sandia National Laboratories

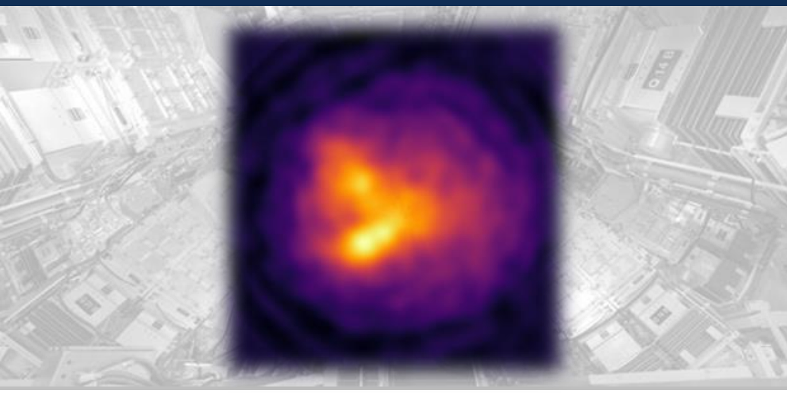
IFSA 2017

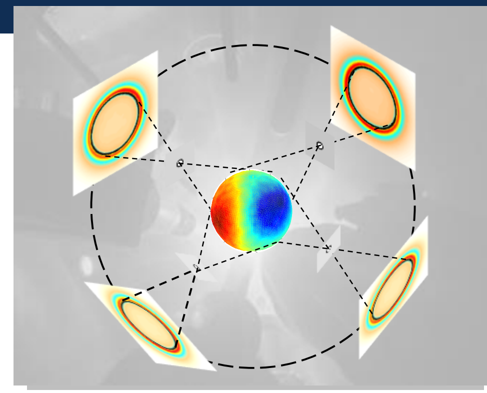
SAND2017-9584 C

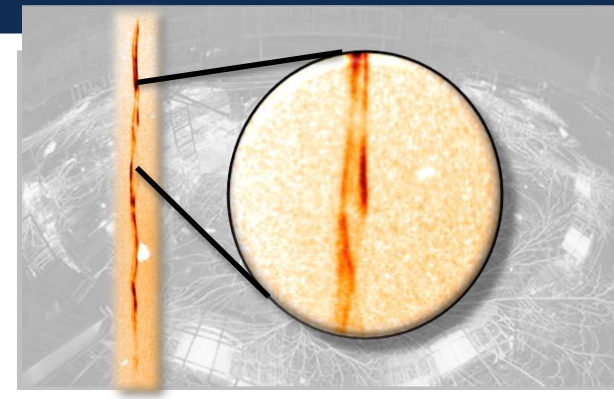
U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.







A Multi-Dimensional View of the US Inertial Confinement Fusion Program

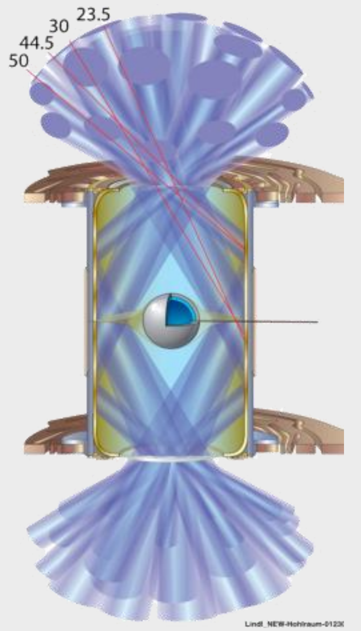
Gregory A. Rochau

Sandia National Laboratories

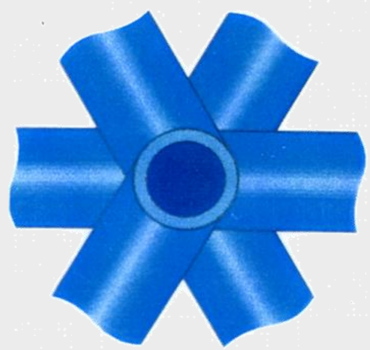
IFSA 2017

The US Inertial Confinement Fusion program is studying three main approaches.

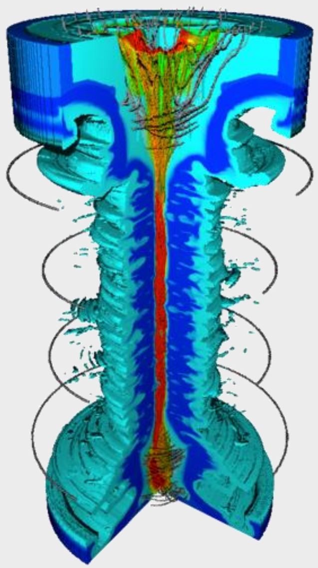
Laser Indirect Drive



Laser Direct Drive



Magnetic Direct Drive

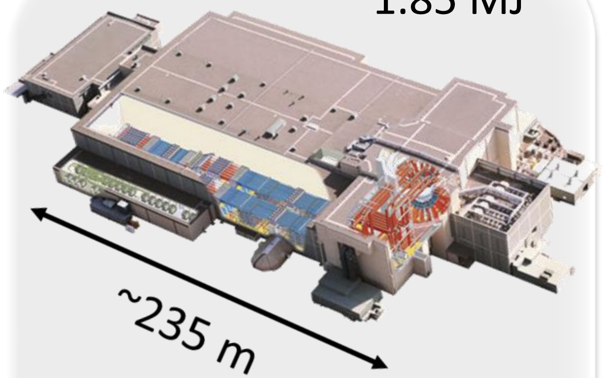


UR LLE
Los Alamos NATIONAL LABORATORY EST. 1943
PPPL
GENERAL ATOMICS
Schafer
National Security Technologies LLC
Vision • Service • Partnership

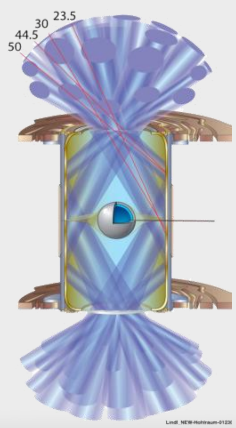
All three major US ICF facilities provide critical data across all the major approaches.

National Ignition Facility

1.85 MJ

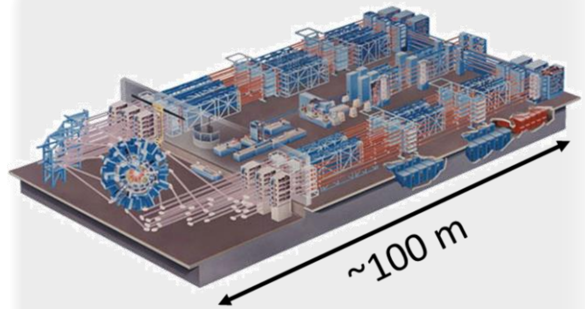


Laser Indirect Drive

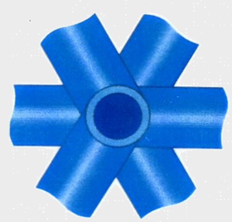


Omega Facility

26 kJ

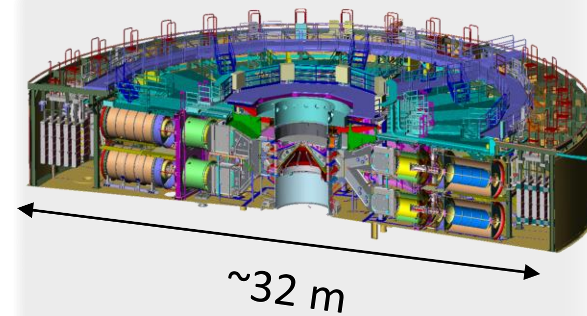


Laser Direct Drive

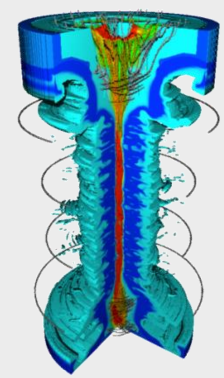


Z Facility

2 MJ



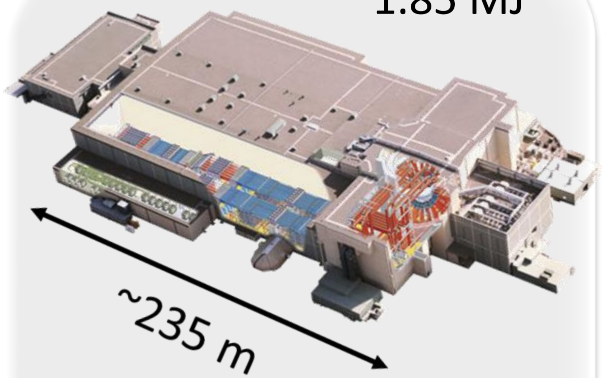
Magnetic Direct Drive



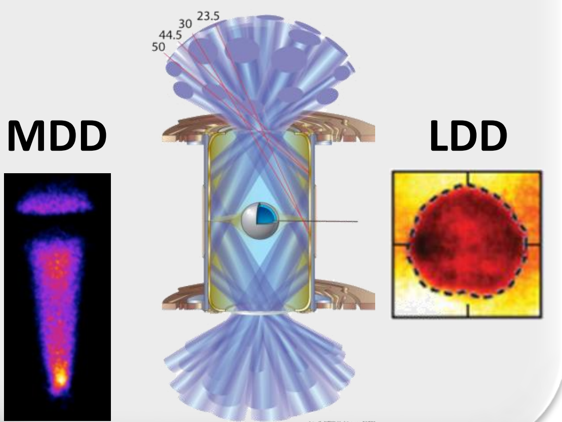
All three major US ICF facilities provide critical data across all the major approaches.

National Ignition Facility

1.85 MJ

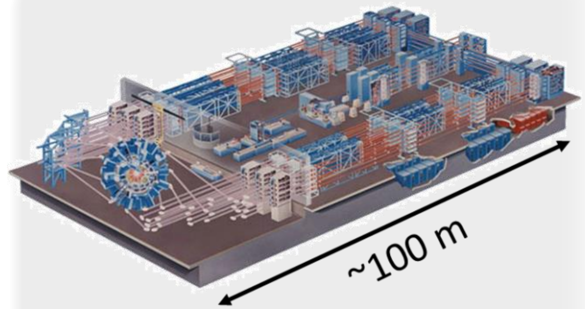


Laser Indirect Drive



Omega Facility

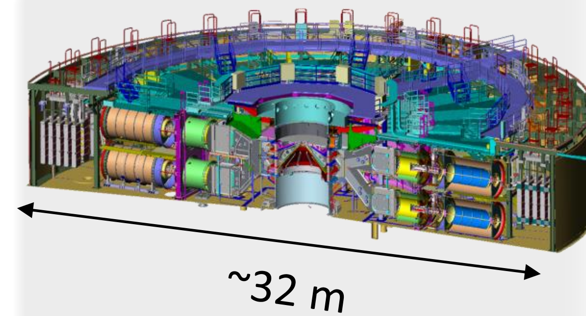
26 kJ



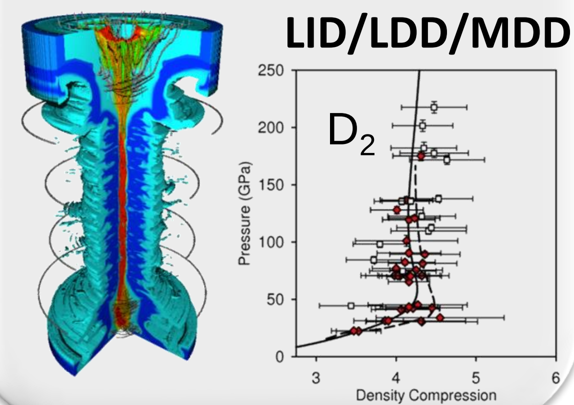
Laser Direct Drive

Z Facility

2 MJ



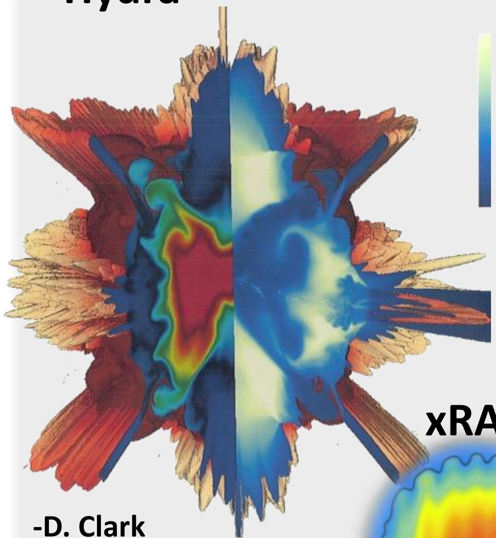
Magnetic Direct Drive



3-D simulations are playing an increasing role in the understanding of complex dynamics and error modes.

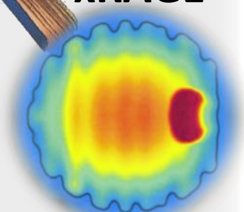
Laser Indirect Drive

Hydra



-D. Clark

xRAGE

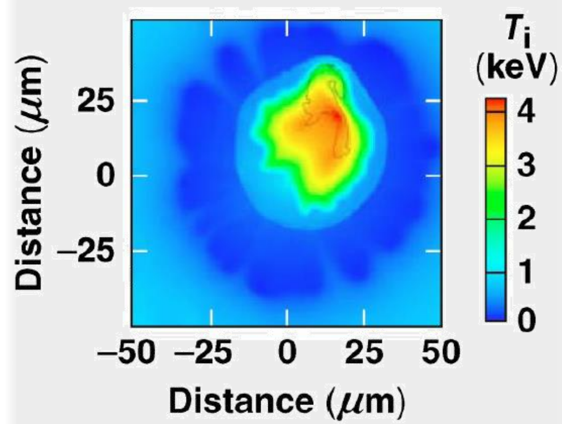


-B. Haines

- Tent/fill-tube effects
- Isolated defects

Laser Direct Drive

ASTER

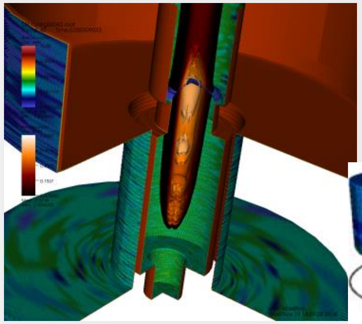


-V. Goncharov

- Capsule displacement
- Beam power balance and pointing errors

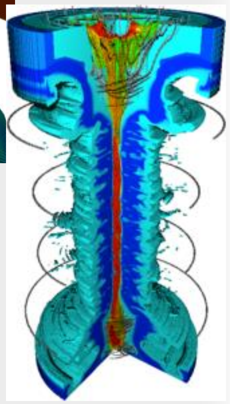
Magnetic Direct Drive

Hydra



-A. Sefkow

Gorgon



-C. Jennings

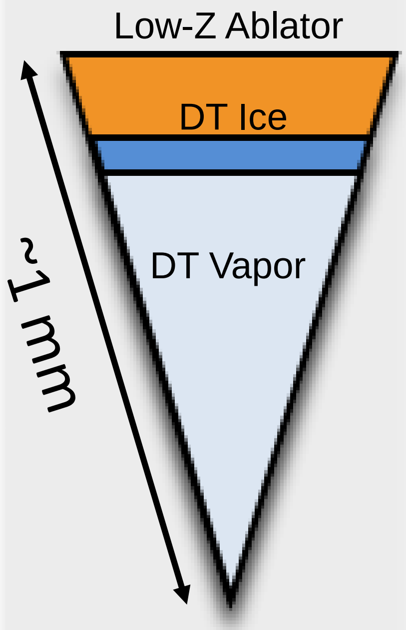
- Helical/Flute modes
- Preheat non-uniformity

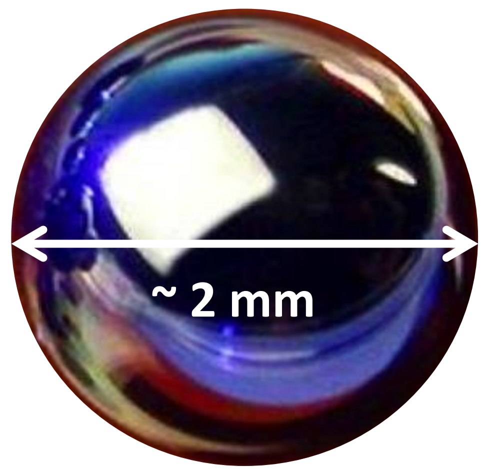
Outline

- **Overview of the major ICF approaches in the US program**
  - 3 major approaches and high-level results
- **Common challenges under investigation**
  - Laser Plasma Interactions
    - CBET understanding and mitigation in Laser Direct Drive
  - Implosion and Stagnation - Morphology and Mix
    - 3-D structure and diagnosis in Laser Indirect Drive and Magnetic Direct Drive
- **Path forward**
  - National Program Goals
  - Transformative Diagnostics
  - Major planned efforts across each approach

ICF is about making a hot, dense plasma and holding it together long enough to create significant fusion yields.

Defect-Free Spherical Capsule

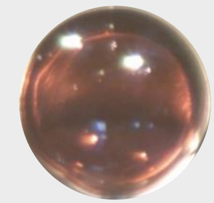




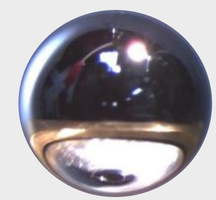
Kline - Tues. 8:30

Capsule Ablators

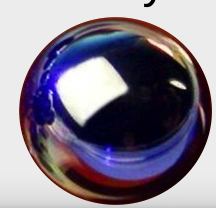
CH



Beryllium

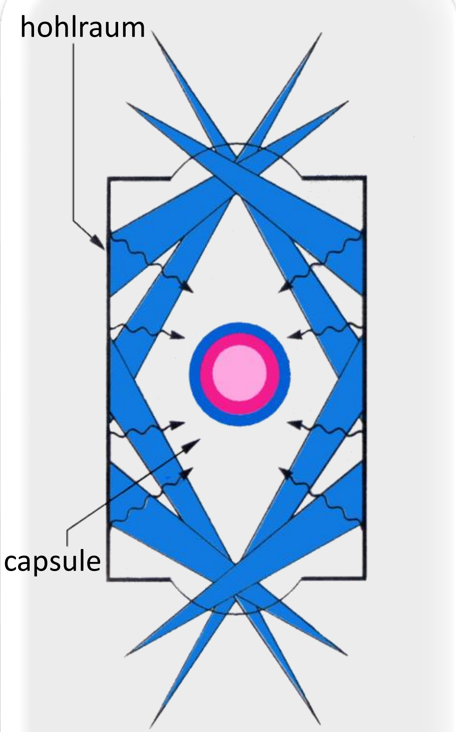


High Density Carbon



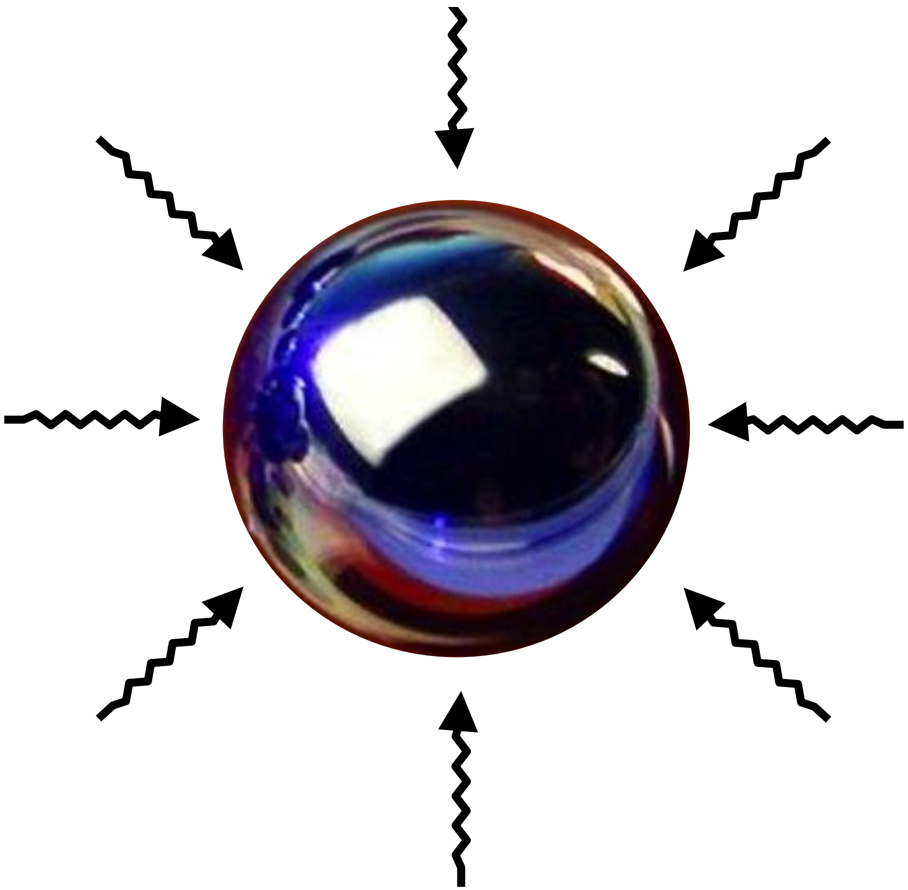
ICF is about making a hot, dense plasma and holding it together long enough to create significant fusion yields.

Laser Indirect Drive (LID)

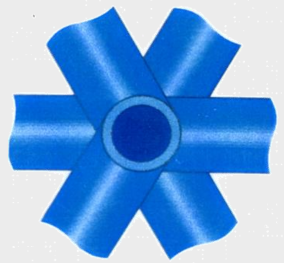


1.9 MJ on NIF

Symmetric Radiation Drive



Laser Direct Drive (LDD)



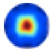
26 kJ on OMEGA

ICF is about making a hot, dense plasma and holding it together long enough to create significant fusion yields.

High Convergence Implosion

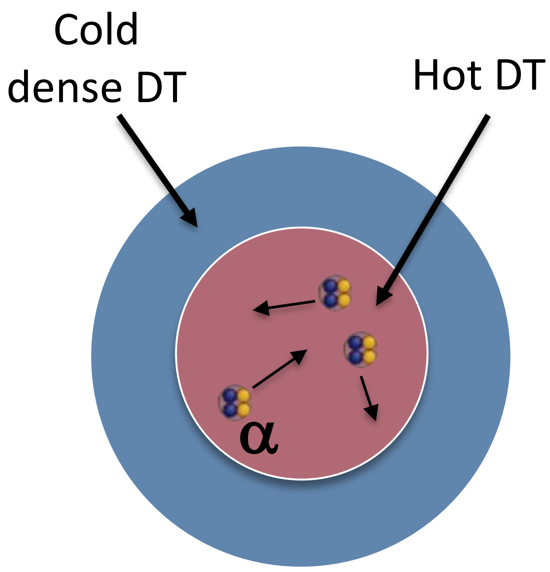
Convergence Ratio (CR) ~20-35

Volume compression 8,000-35,000



ICF is about making a hot, dense plasma and holding it together long enough to create significant fusion yields.

Hot spot surrounded by cold fuel



$$T > 4\,\mathrm{keV}$$

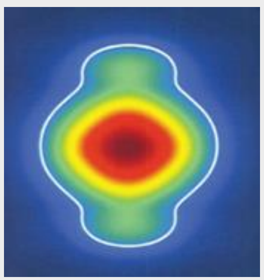
$$\rho R > 0.3\,\mathrm{g/cm^2}$$

ICF is about making a hot, dense plasma and holding it together long enough to create significant fusion yields.

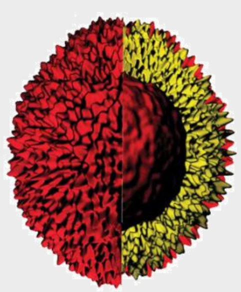
Hot spot surrounded by cold fuel

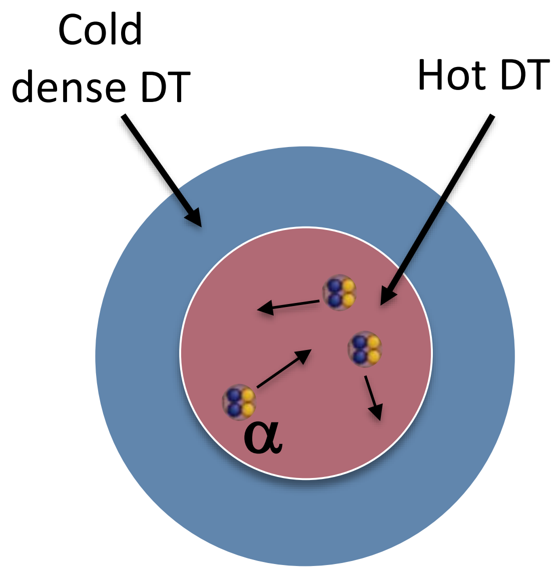
High Quality

Good Shape



Low mix



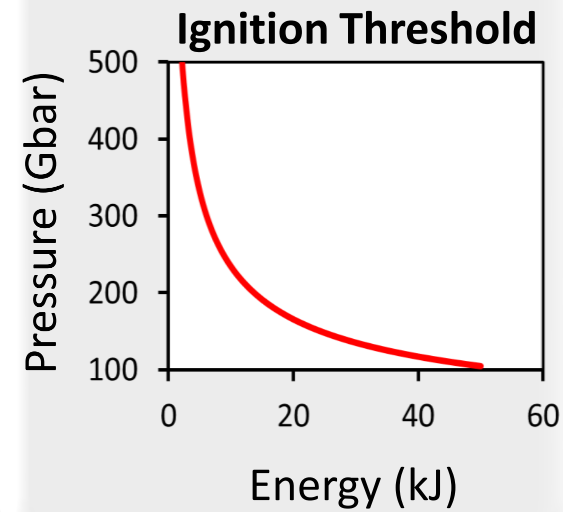


$$T > 4\,\mathrm{keV}$$

$$\rho R > 0.3\,\mathrm{g/cm^2}$$

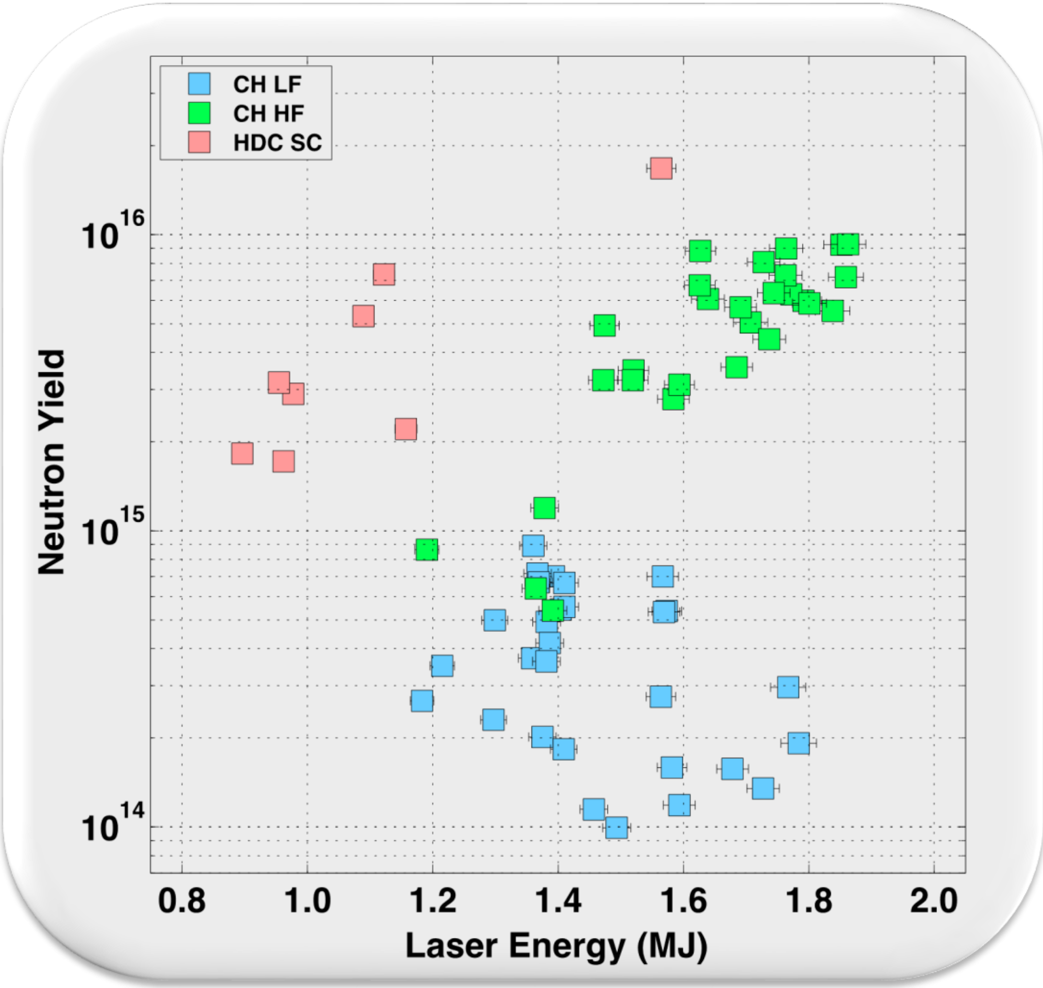
High Energy

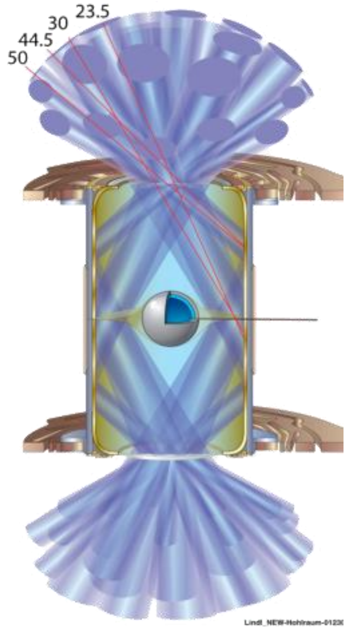
$$E \propto mT \propto \frac{(\rho R)^3 T^3}{P^2}$$



LID implosions have produced significant yield with alpha heating and continue to improve symmetry and efficiency.

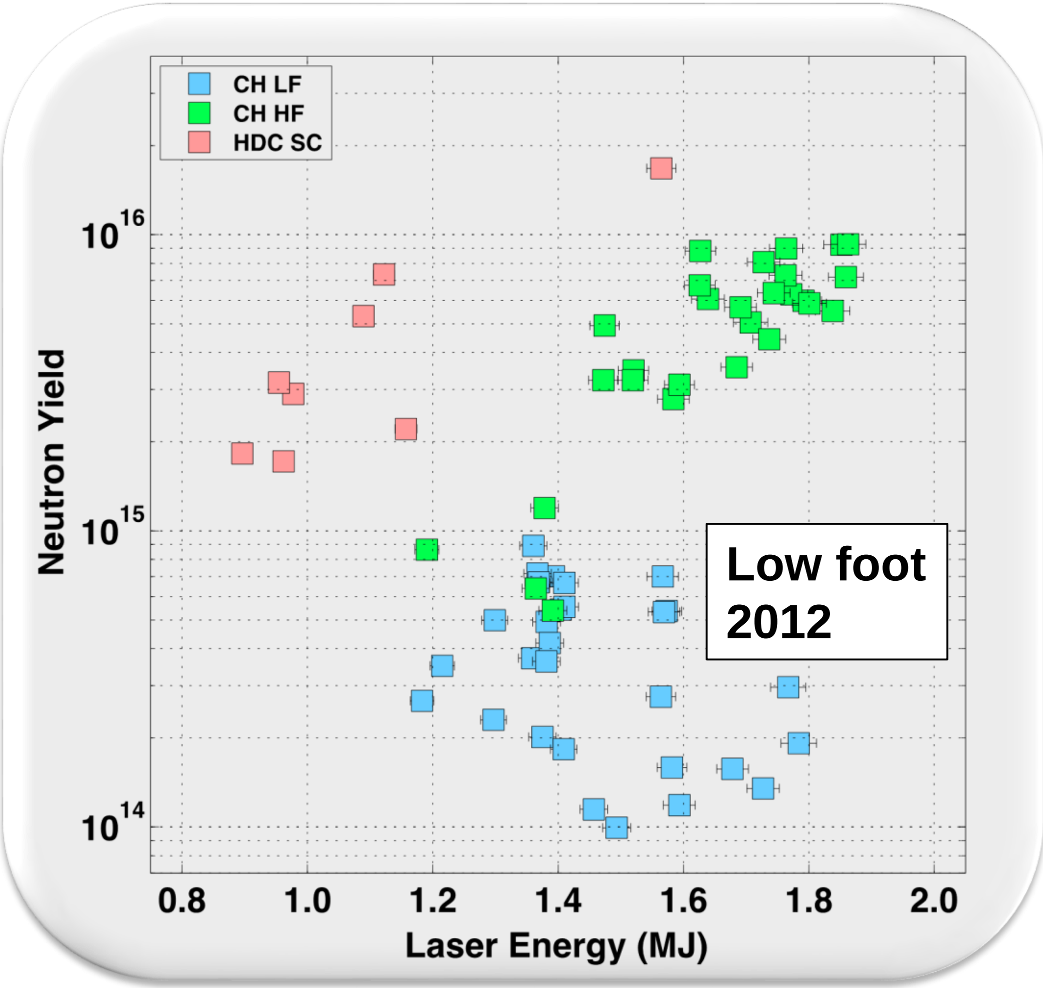
Yield vs. Laser Energy on NIF





LID implosions have produced significant yield with alpha heating and continue to improve symmetry and efficiency.

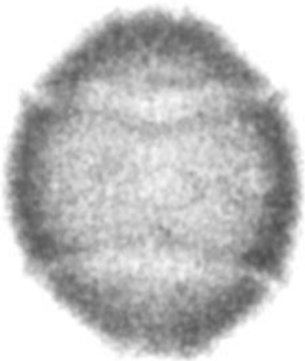
Yield vs. Laser Energy on NIF



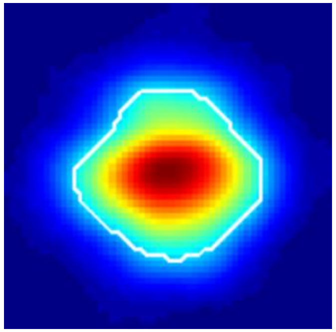
Low-foot

- Hydro-instability, mix, 3-D shape, Hohlraum LPI

Backlit Radiograph

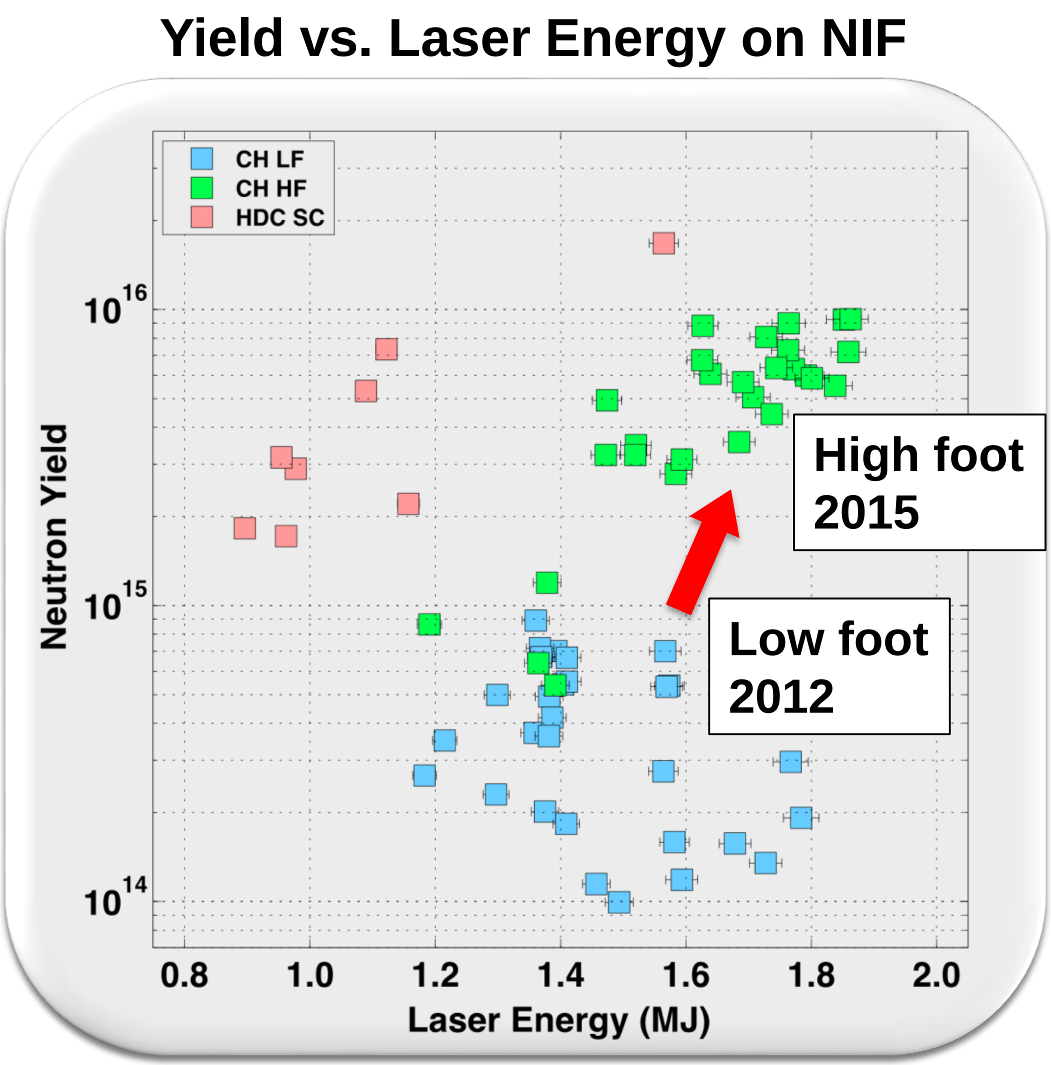


X-ray Self-Emission



Low-foot
α ~1.5

LID implosions have produced significant yield with alpha heating and continue to improve symmetry and efficiency.

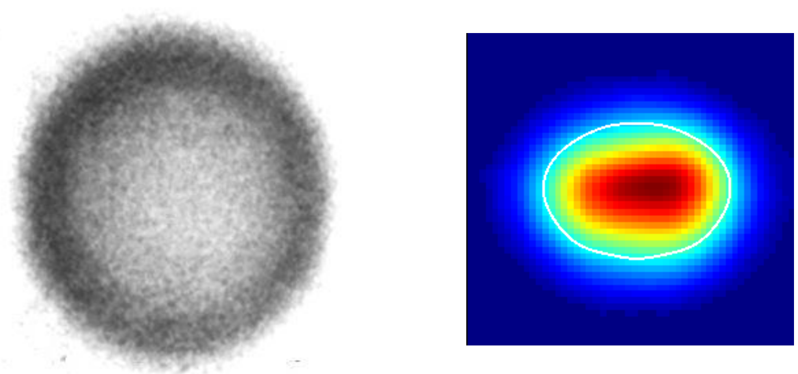


Low-foot

- Hydro-instability, mix, 3-D shape, Hohlraum LPI

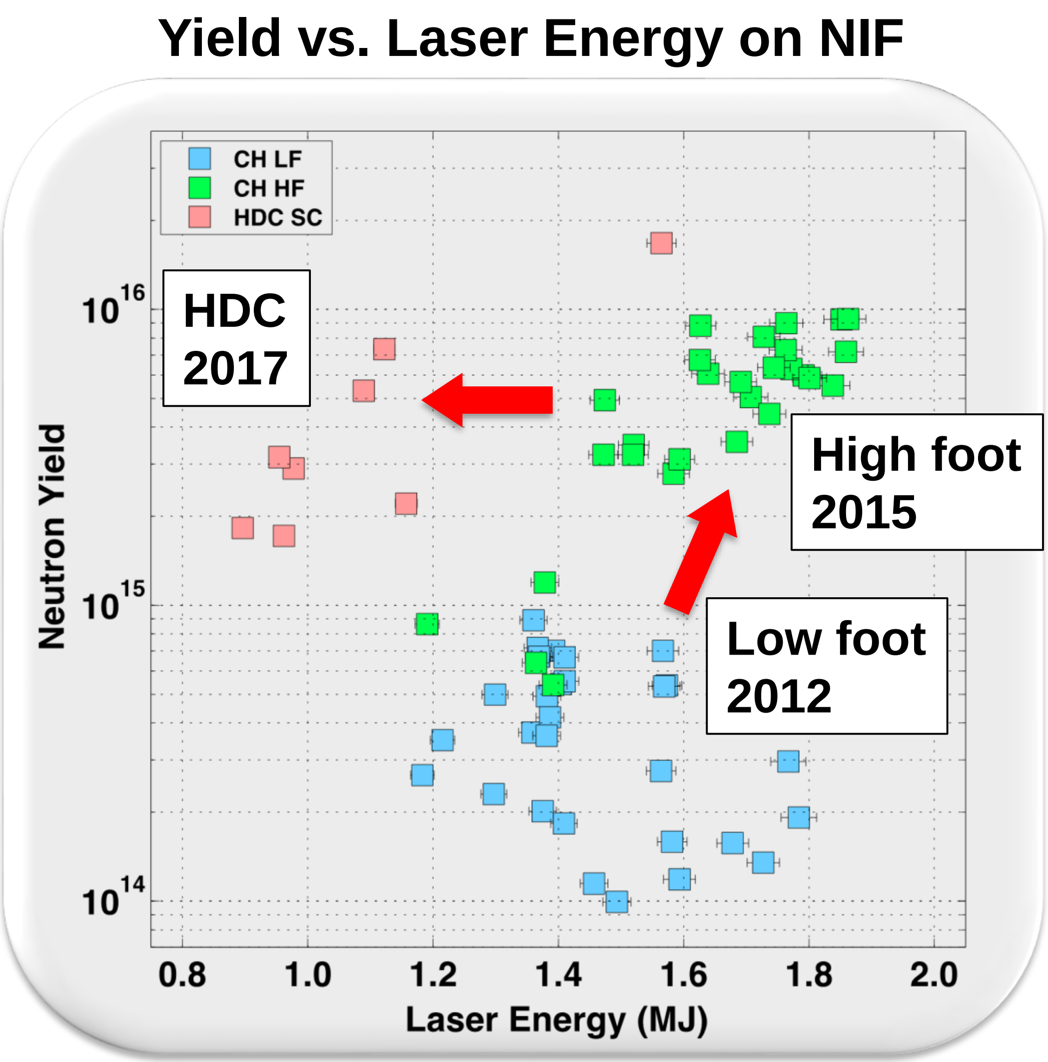
High-foot

- Reduced hydro-instability and mix, but 3-D shape still an issue



High-foot
α ~2.5

LID implosions have produced significant yield with alpha heating and continue to improve symmetry and efficiency.



Low-foot

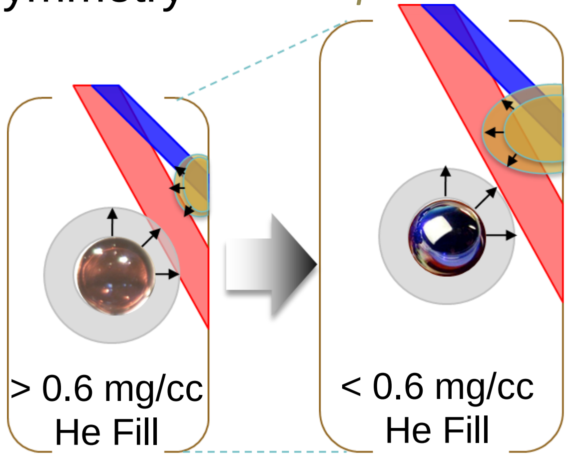
- Hydro-instability, mix, 3-D shape, Hohlraum LPI

High-foot

- Reduced hydro-instability and mix, but 3-D shape still an issue

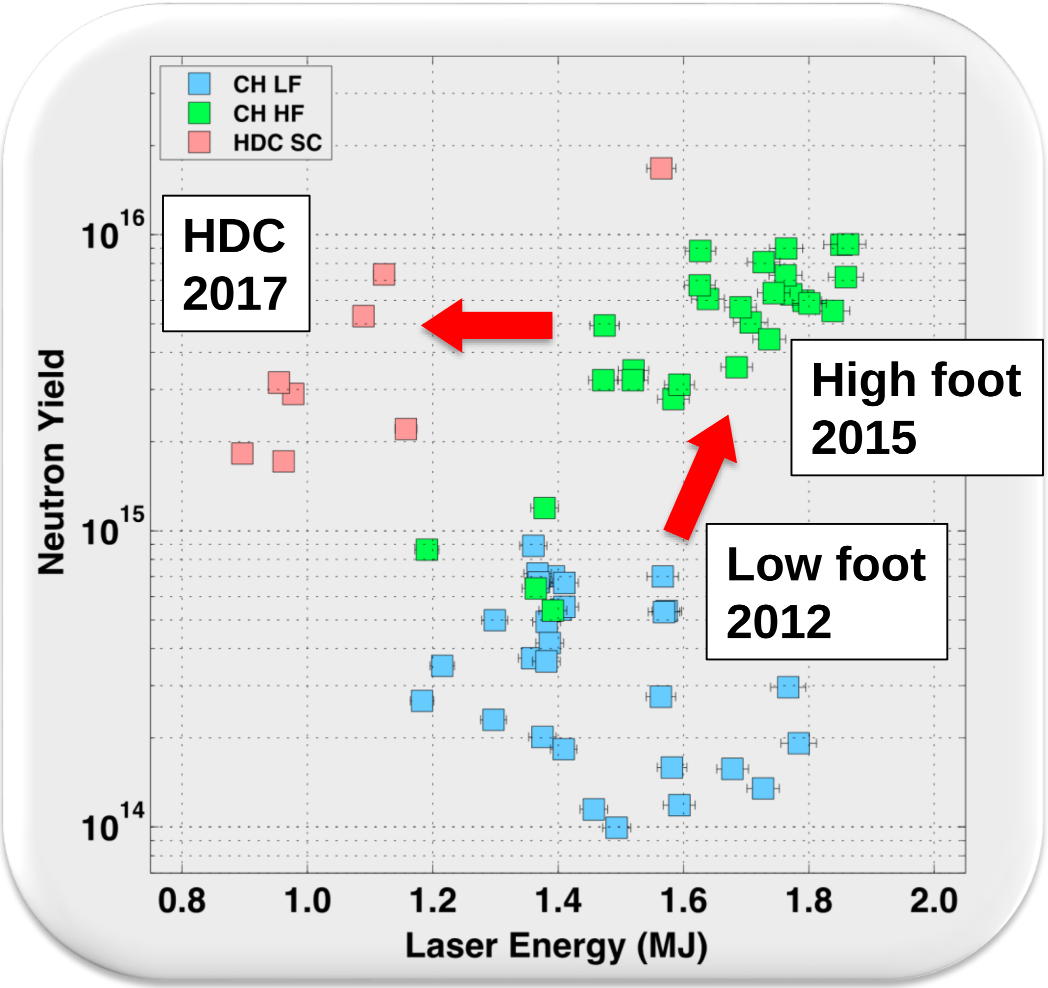
High Density Carbon (HDC)

- Improved efficiency and symmetry *Le Pape - Mon. 1:30*



LID implosions have produced significant yield with alpha heating and continue to improve symmetry and efficiency.

Yield vs. Laser Energy on NIF



Low-foot

- Hydro-instability, mix, 3-D shape, Hohlraum LPI

High-foot

- Reduced hydro-instability and mix, but 3-D shape still an issue

High Density Carbon (HDC)

- Improved efficiency and symmetry

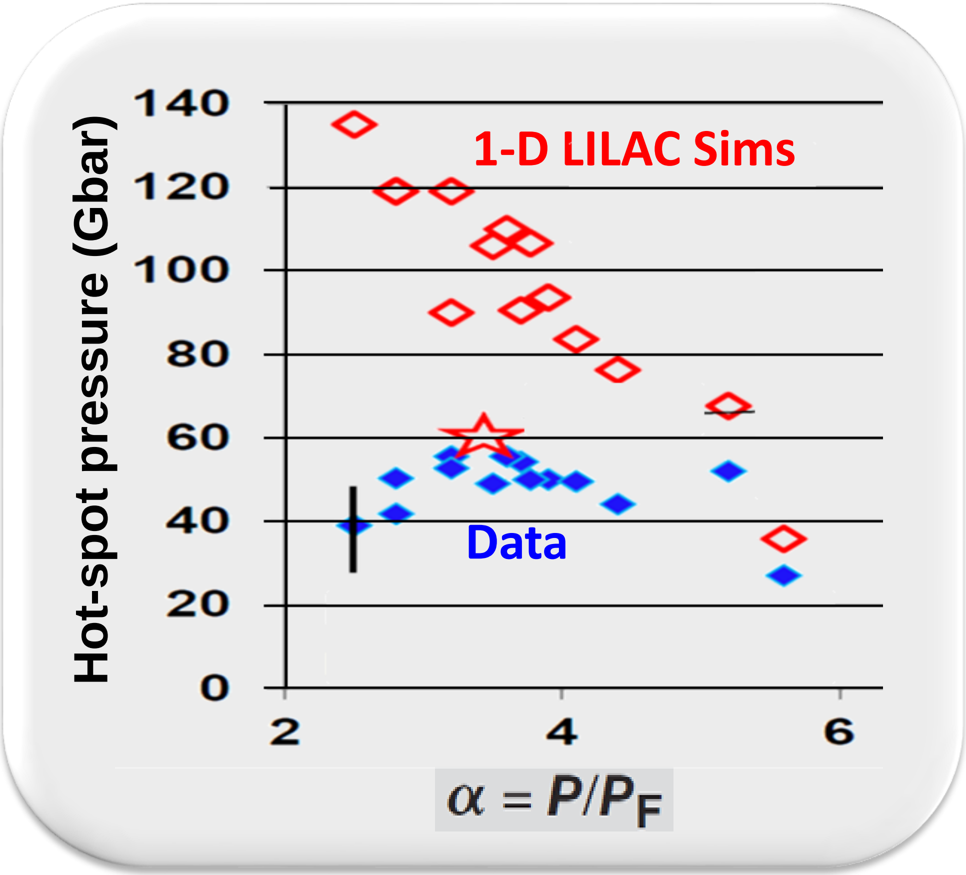
Wetted Foams *Olson – Tues. 1:30*

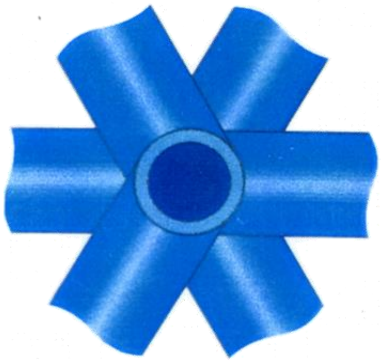
- Control CR w/ vapor pressure

Double Shells *Wilson – Fri. 11:00*

Cryo-layered LDD implosions on OMEGA achieve pressures > 50 Gbar, but deviate from 1-D simulations at low-adiabat

Stagnation Pressure vs. Fuel Adiabat on OMEGA

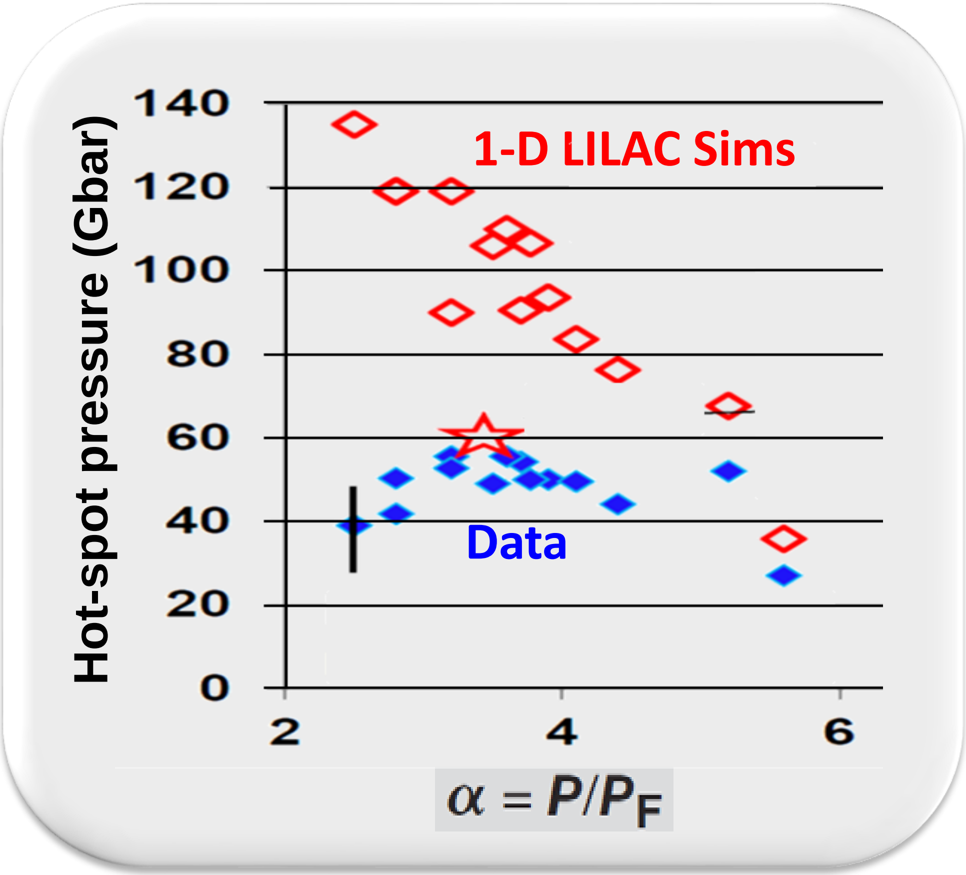




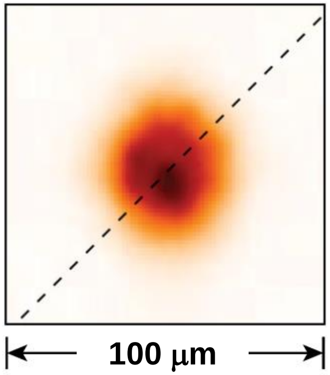
Regan et al., PRL 117 (2016)

Cryo-layered LDD implosions on OMEGA achieve pressures > 50 Gbar, but deviate from 1-D simulations at low-adiabat

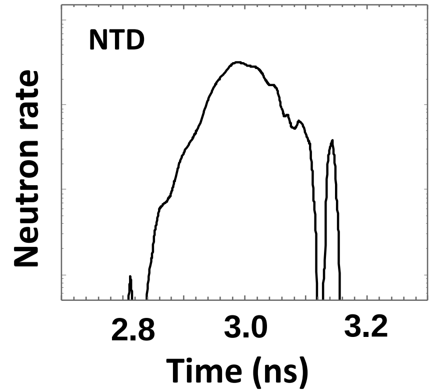
Stagnation Pressure vs. Fuel Adiabat on OMEGA



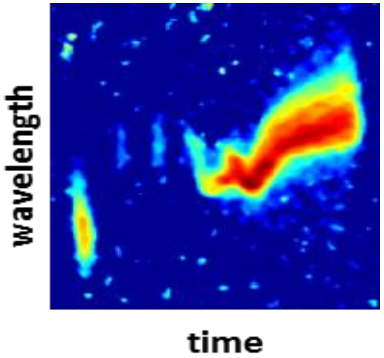
Hot-spot Imaging
16-channel KB!



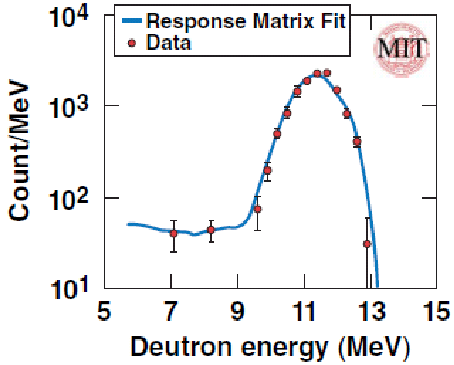
Neutron Temporal History



Scattered Laser Spectrum



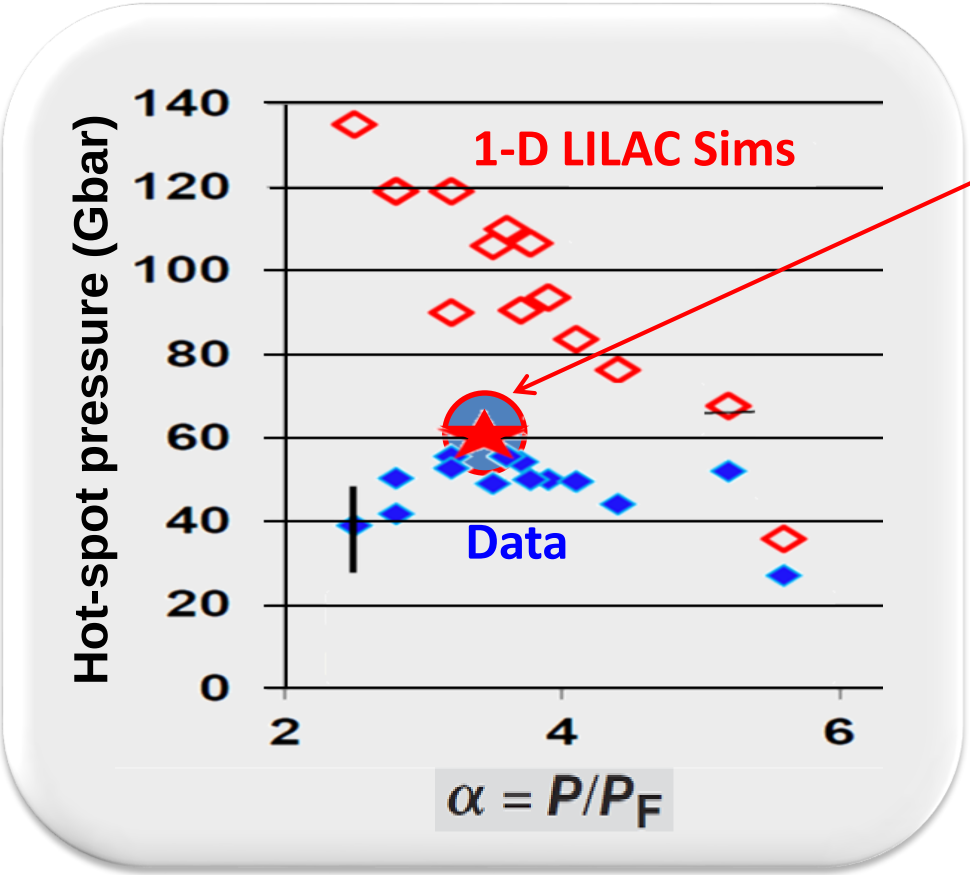
Neutron Spectrum



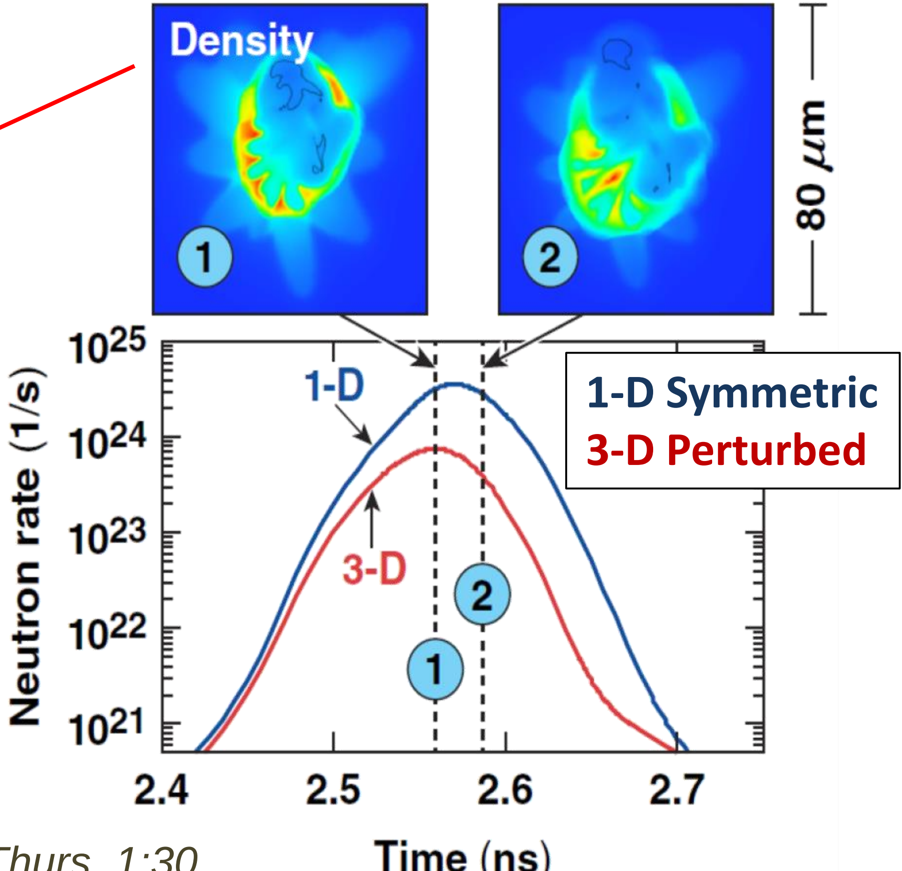
Regan et al., PRL 117 (2016)

A better understanding of the 3-D implosion reveals the limiting factors to achieving ignition-scale pressures in LDD

Stagnation Pressure vs. Fuel Adiabat on OMEGA



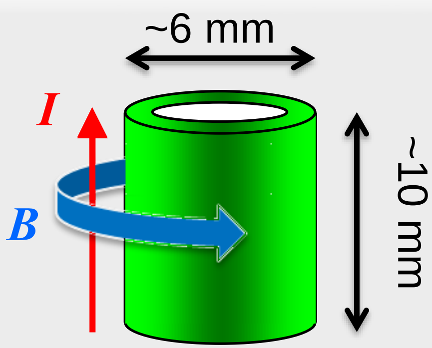
3-D ASTER simulations show effect of errors in beam pointing, power balance, and capsule placement



Goncharov –Thurs. 1:30

Magnetic direct drive provides an alternative way to do ICF using an axial B-field to reduce ρr requirements

Magnetic Direct Drive (MDD)



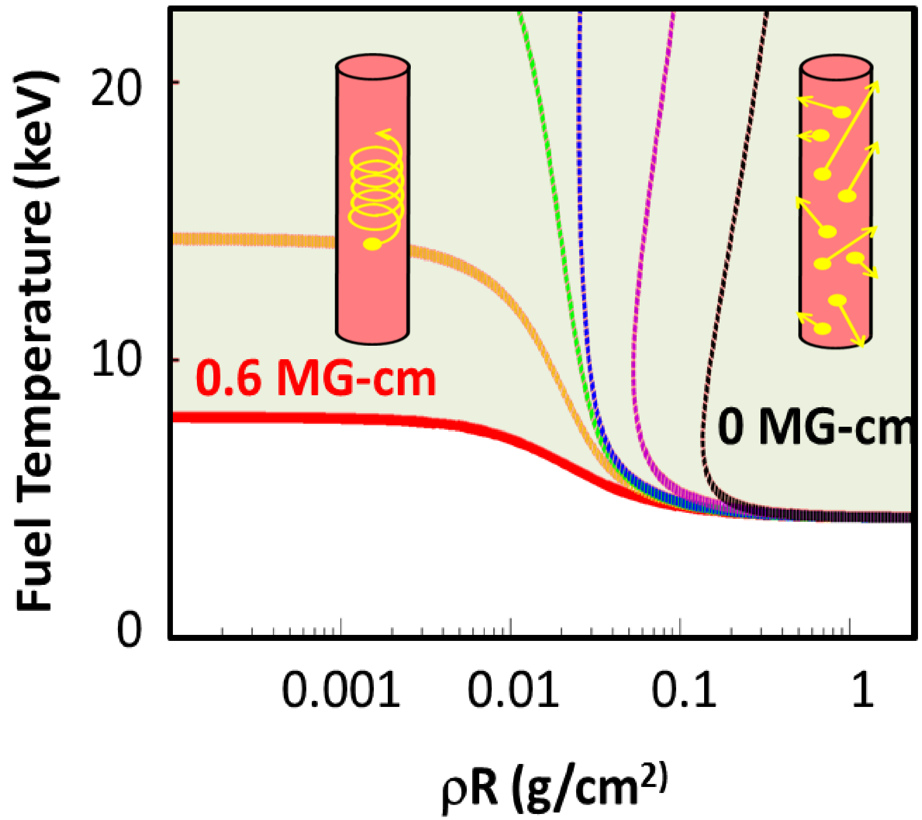
Drive Pressure

$$P = \frac{B^2}{8\pi} = 105\left(\frac{I_{MA}/26}{R_{mm}}\right)^2 \text{ Mbar}$$

- Cylindrical convergence
  - Harder to achieve high ρr
- Thick liners (~500 μm)
  - Harder to achieve high velocity

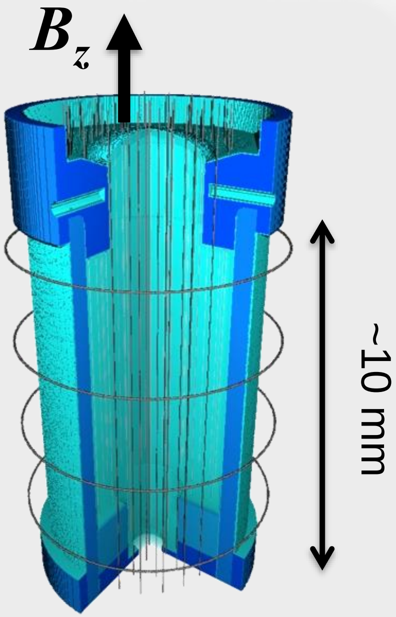
Imposing an axial B-field relaxes ρr requirements

Curves of self-heating from DT fusion alphas



The US is studying a form of magnetic direct drive called Magnetized Liner Inertial Fusion (MagLIF).

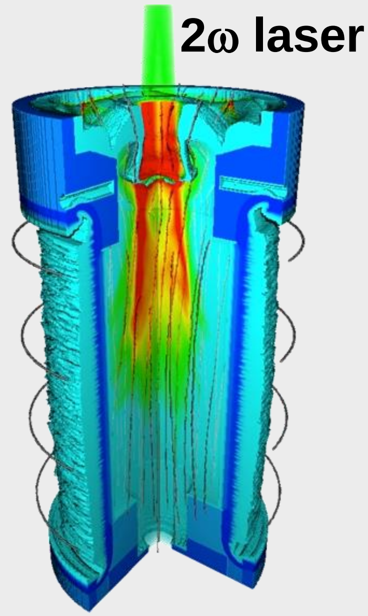
Pre-Magnetize



Beryllium liner

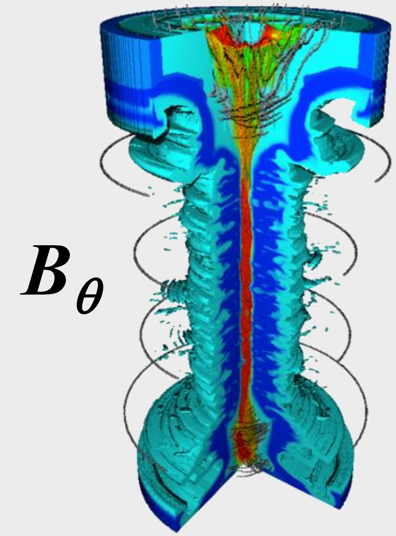
- B_z = 10-30 T
- Inhibit e^- conduction
- Confine α's

Preheat



- Laser Energy = 1-4 kJ
- T_0 ~ 100's eV
- Reduce required implosion velocity

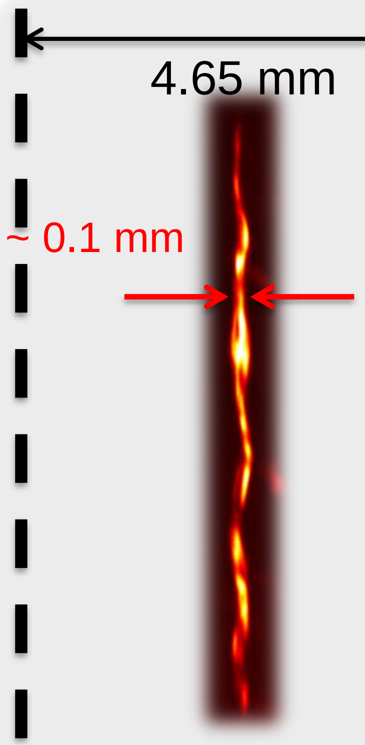
Compress



- CR ~ 35
- ρR ~ 0.003 g/cm^2
- P ~ 5 Gbar
- BR ~ 0.5 MG-cm

MagLIF experiments on Z have demonstrated the key features of magnetized inertial fusion.

High Convergence Implosion



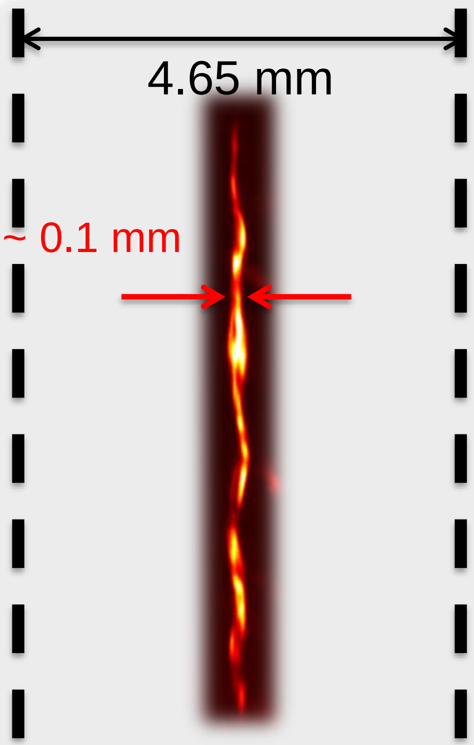
6+9 keV Emission Image

CR > 40

Gomez et al., PRL 113 (2014); Schmit et al., PRL 113 (2014); Hahn et al., RSI 85 (2014)

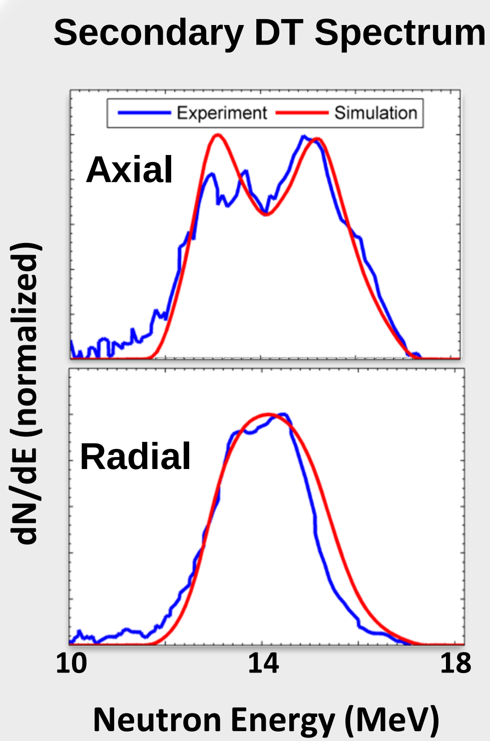
MagLIF experiments on Z have demonstrated the key features of magnetized inertial fusion.

High Convergence Implosion



6+9 keV Emission Image
CR > 40

B-field Flux Compression

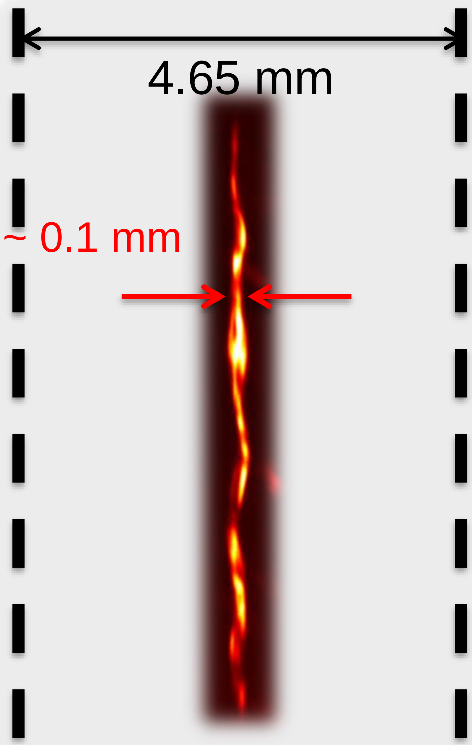


DT Secondary Spectra
BR > 0.35 MG-cm

Gomez et al., PRL 113 (2014); Schmit et al., PRL 113 (2014); Hahn et al., RSI 85 (2014)

MagLIF experiments on Z have demonstrated the key features of magnetized inertial fusion.

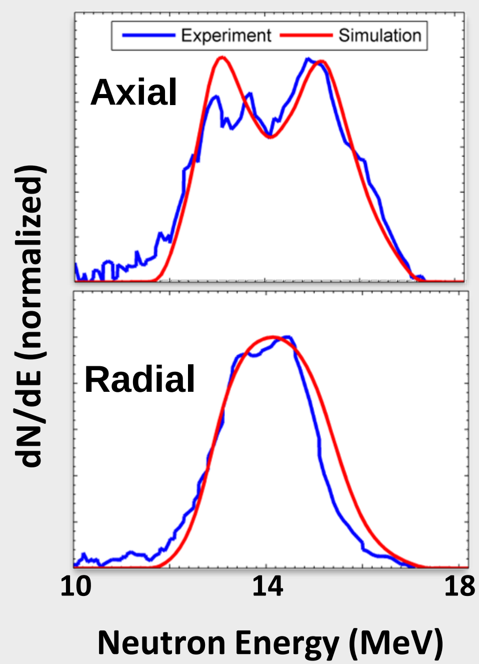
High Convergence Implosion



<u>6+9 keV Emission Image</u>

CR > 40

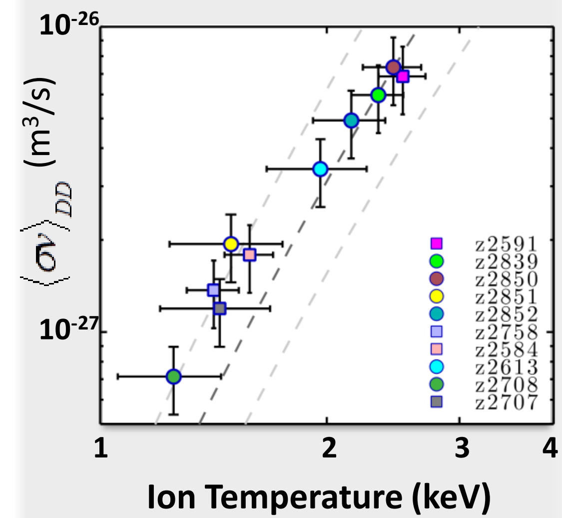
B-field Flux Compression



<u>DT Secondary Spectra</u>

BR > 0.35 MG-cm

Thermonuclear Neutrons



$$\mathrm{Y}_{\mathrm{DD}} = \frac{1}{2} n_{\mathrm{D}}^2 \langle \sigma v \rangle_{\mathrm{DD}} V \tau$$

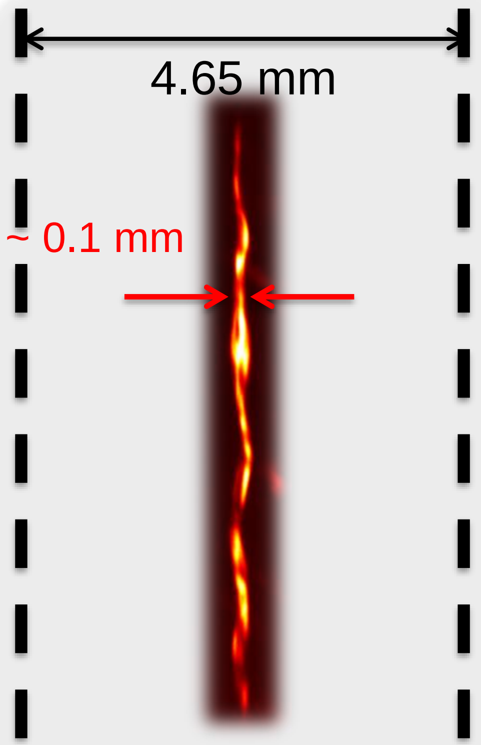
<u>Yield, Volume, Duration</u>

Consistent with DD reactivity

Gomez et al., PRL 113 (2014); Schmit et al., PRL 113 (2014); Hahn et al., RSI 85 (2014)

MagLIF experiments on Z have demonstrated the key features of magnetized inertial fusion.

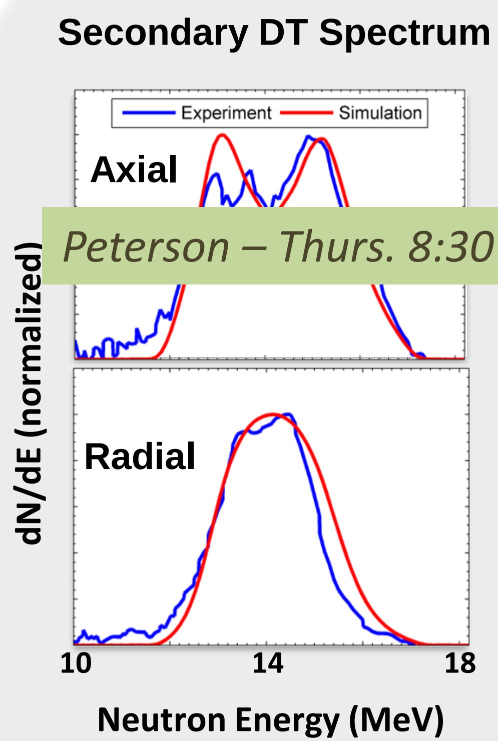
High Convergence Implosion



6+9 keV Emission Image

CR > 40

B-field Flux Compression

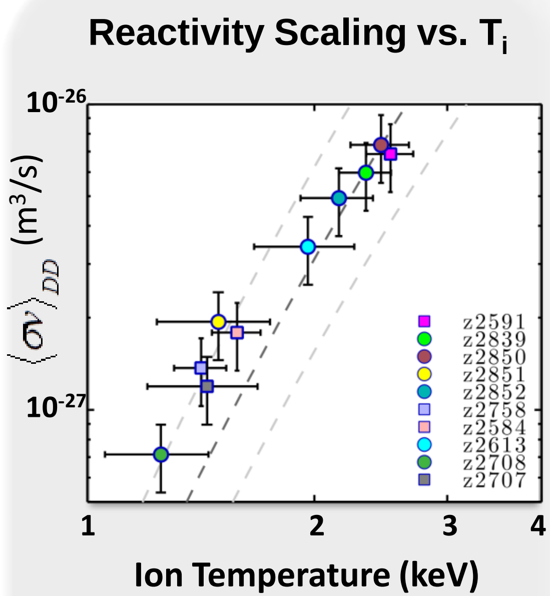


Peterson – Thurs. 8:30

DT Secondary Spectra

BR > 0.35 MG-cm

Thermonuclear Neutrons



$$Y_{DD} = \frac{1}{2} n_D^2 \langle \sigma v \rangle_{DD} V \tau$$

Yield, Volume, Duration

Consistent with DD reactivity

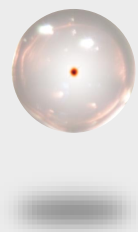
Gomez et al., PRL 113 (2014); Schmit et al., PRL 113 (2014); Hahn et al., RSI 85 (2014)

Present US facilities drive the three major ICF approaches at much different spatial and energy scales

Laser Indirect Drive On NIF

E_{driver} ~ 1.8 MJ
P_{HS} ~ 300 Gbar
R_{HS} ~ 30 um
Y_{DT} ~ 2E16

Laser Direct Drive On OMEGA



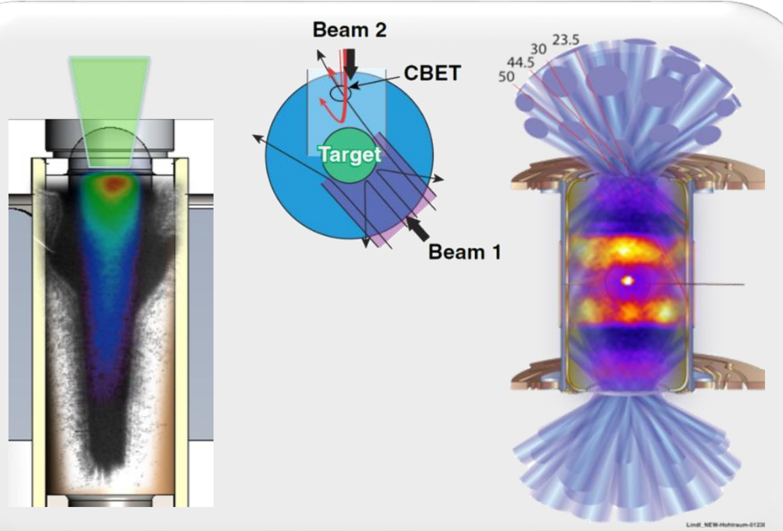
E_{driver} ~ 26 kJ
P_{HS} ~ 55 Gbar
R_{HS} ~ 20 um
Y_{DT} ~ 5E13

MagLIF On Z

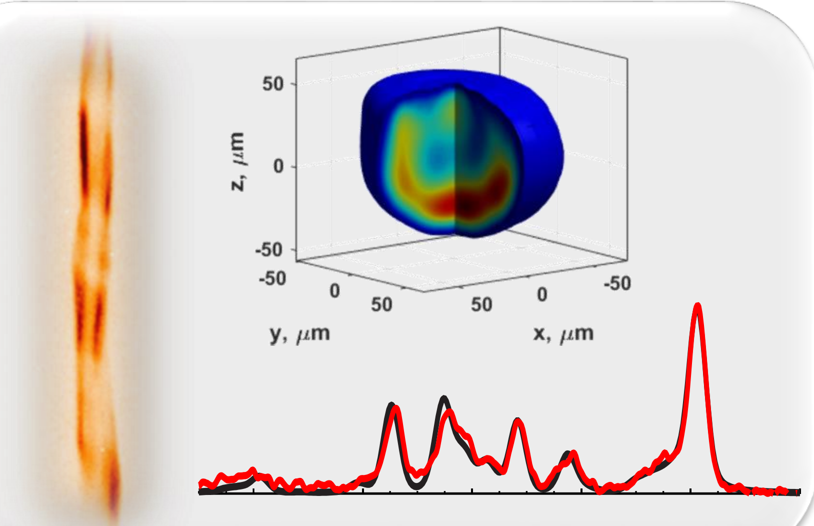
E_{driver} ~ 2 MJ
P_{HS} ~ 1 Gbar
R_{HS} ~ 100 um
L_{HS} ~ 10 mm
Y_{DD} ~ 4E12

Despite the differences in the approaches, there are many common challenges being addressed by the US program.

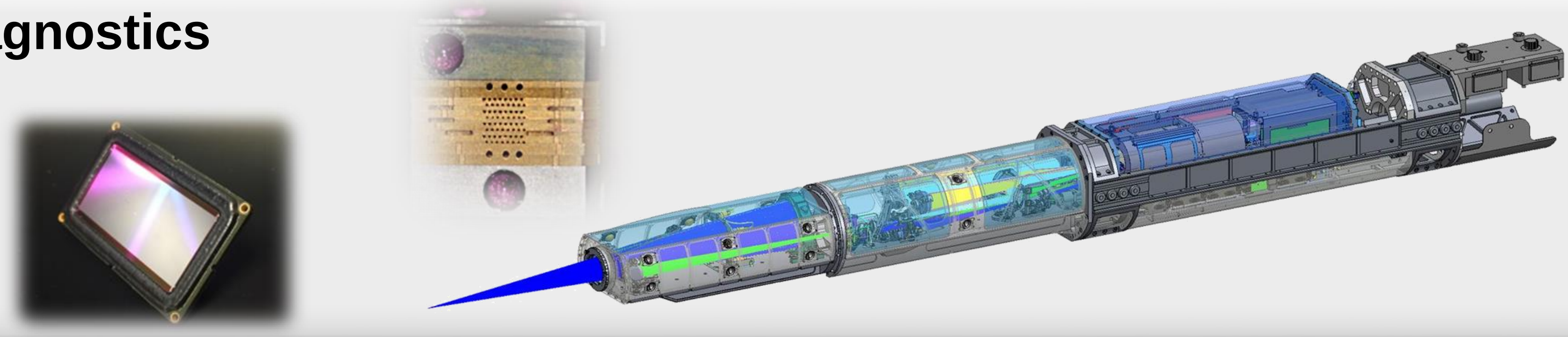
Laser Plasma Interactions



Implosion & Stagnation Physics



Diagnostics



Despite the differences in the approaches, there are many common challenges being addressed by the US program.

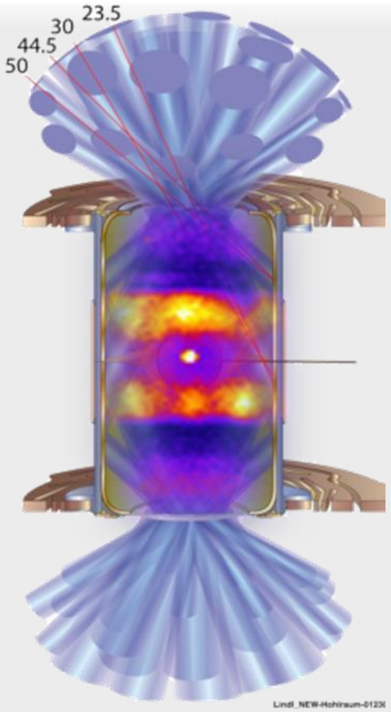
Laser Plasma Interactions

Implosion & Stagnation Physics

Diagnostics

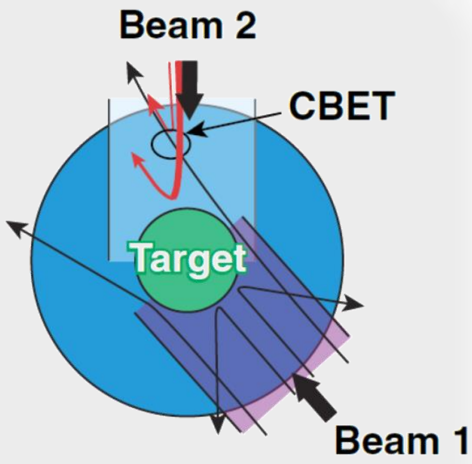
Controlling (or avoiding) laser plasma instabilities is key to the future success of most ICF approaches.

Laser Indirect Drive



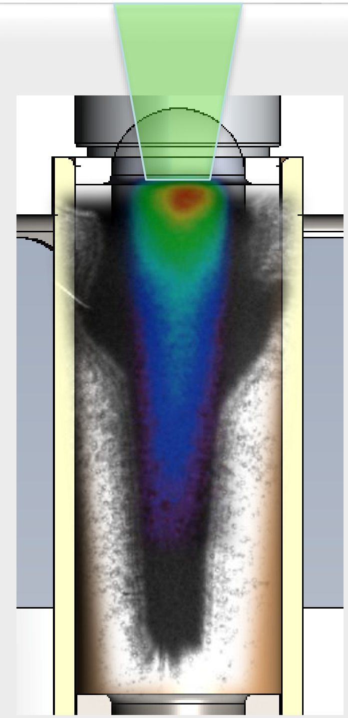
- Inner beam propagation and hohlraum interaction
- Affects energy balance and symmetry control

Laser Direct Drive



- Drive beam absorption and interaction
- Affects hot spot energy and symmetry control

Magnetic Direct Drive

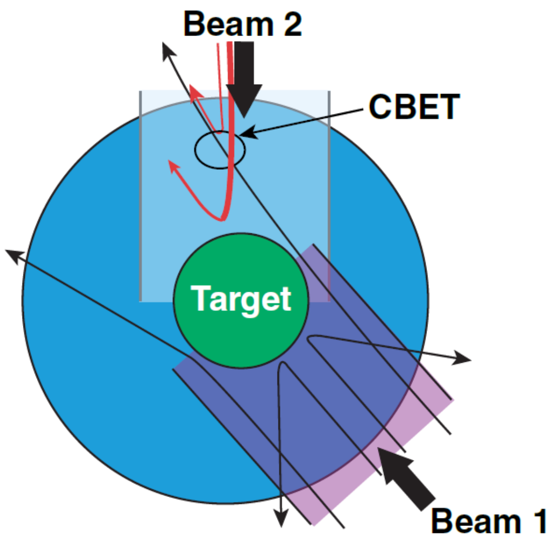


- Preheat beam absorption and propagation
- Affects preheat energy and early-time mix

In LDD, crossed-beam energy transfer (CBET) reduces the drive pressure and resulting hot-spot conditions.

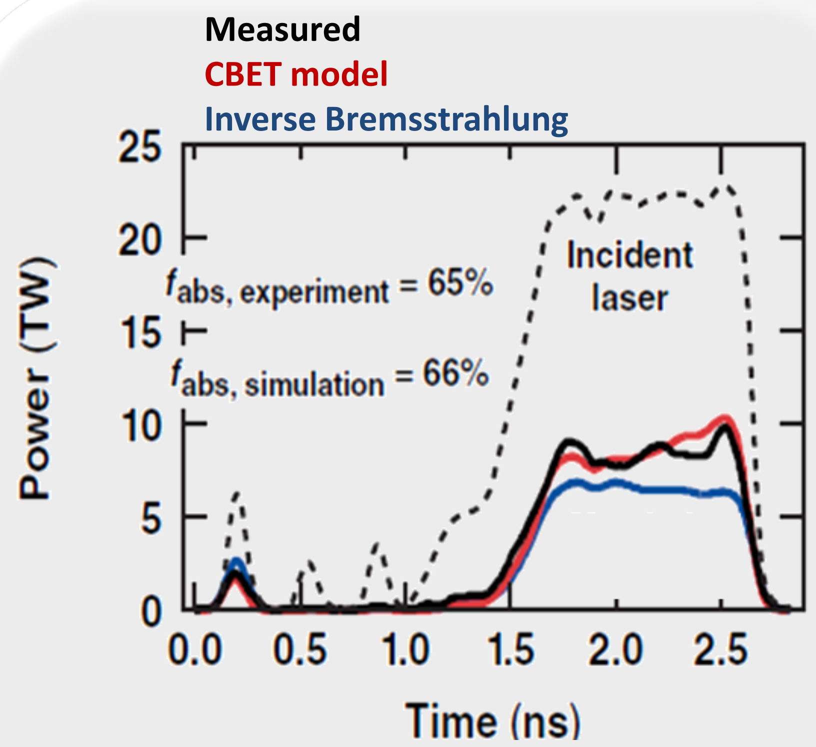
CBET reduces the ablation pressure

by transferring laser energy from incoming rays to outgoing rays



$$P_{HS} \propto P_{abl}\left(\mathrm{R}/\Delta\mathrm{R}\right)^{5/3}$$

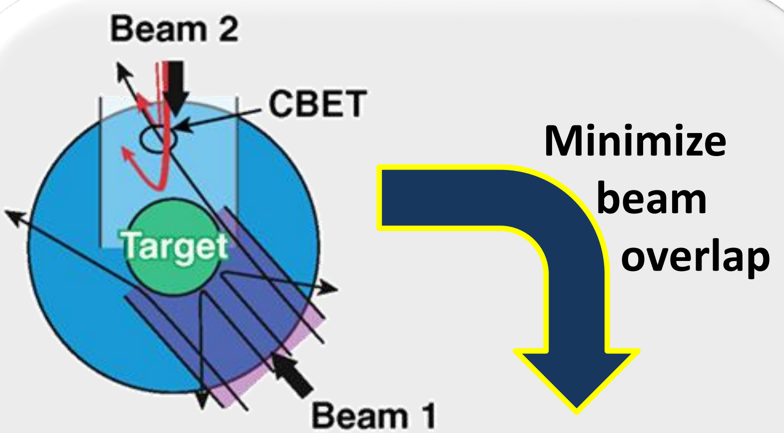
Measured/Simulated Scattered Light Power

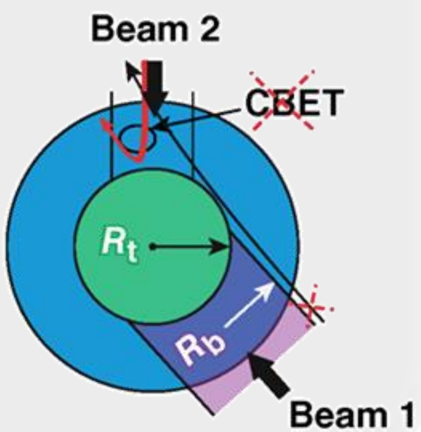


- CBET increases the total scattered light by >10%

CBET mitigation is being studied in the spatial and spectral domain

Spatial Domain

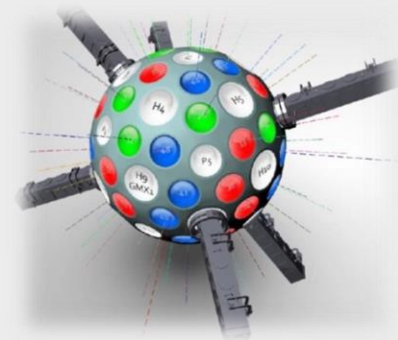




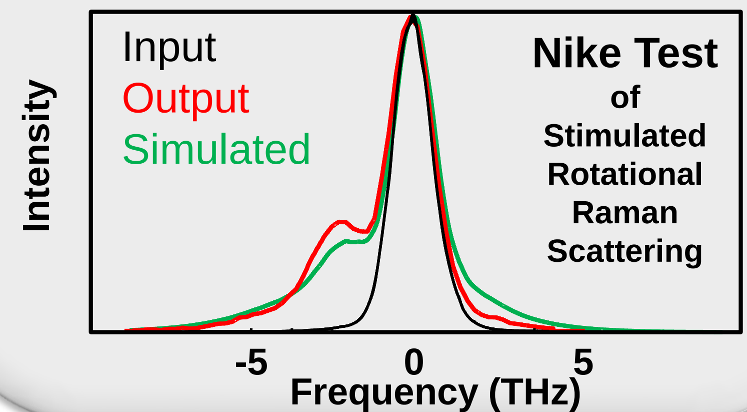
- Reduce beam size relative to target size
- Modify beam shape to reduce energy over the horizon

Spectral Domain

Change color of adjacent beams



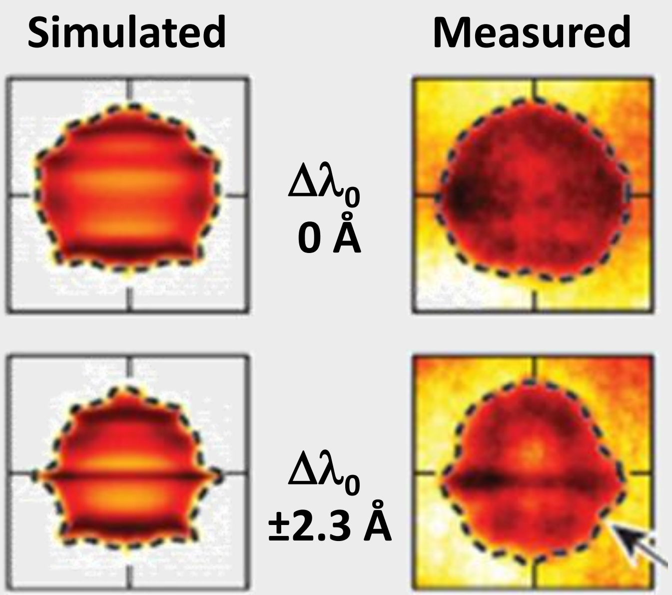
Increase the laser bandwidth



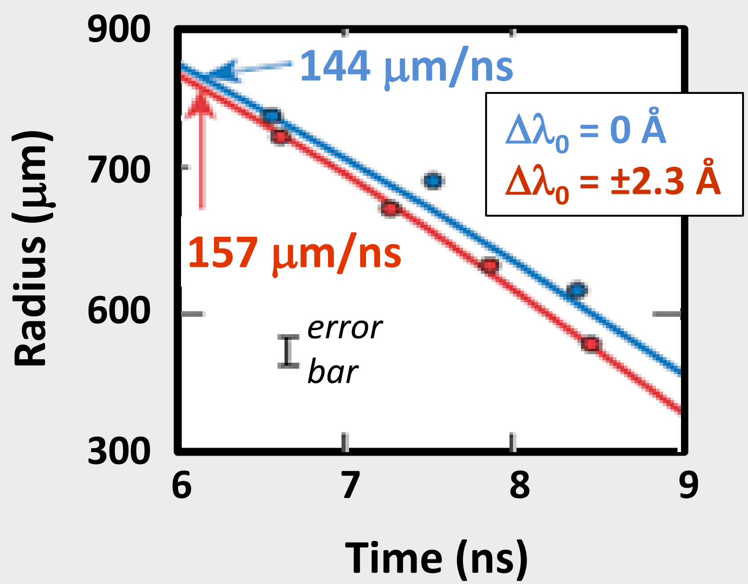
Igumenshchev et al., POP 17 (2010); Froula et al., PRL 108 (2012); Regan et al., POP (2016)

Proof-of-principle LDD experiments have demonstrated CBET mitigation with wavelength detuning on the NIF.

Detuning changes the implosion shape



Detuning increases the measured implosion velocity



There are also common challenges in achieving a predictable and controlled implosion and stagnation.

Engineering Features

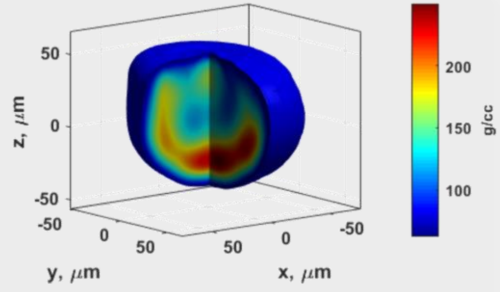
LID

LDD

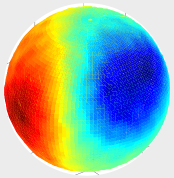
MDD

3-D Morphology

LID



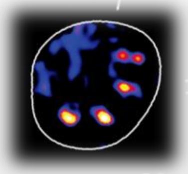
LDD



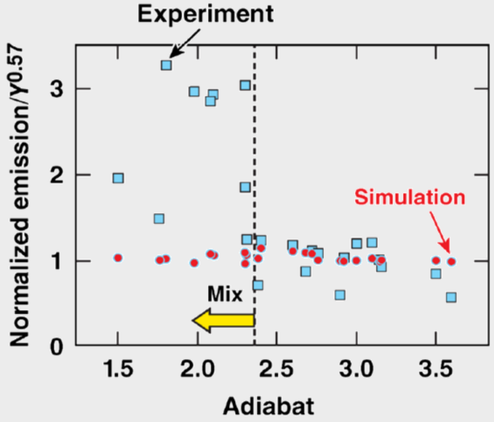
MDD

Ablator/Liner Mix

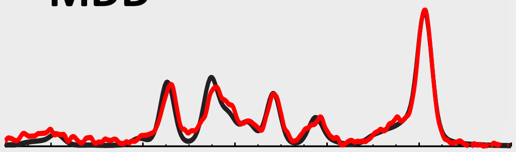
LID



LDD

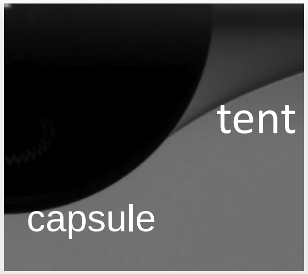


MDD

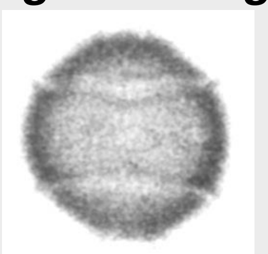


Non-ideal target features can lead to a complex stagnation that impacts conditions and confinement.

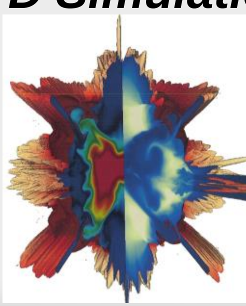
Capsule 'Tent'

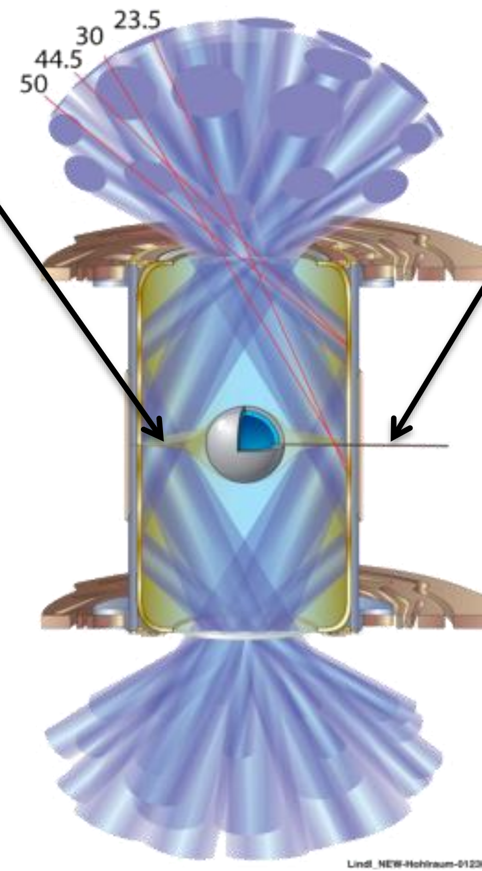


In-Flight Radiograph

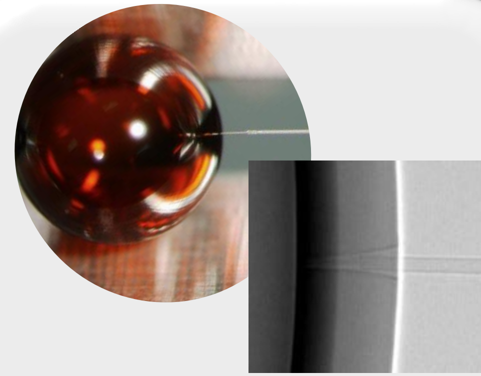


3-D Simulation

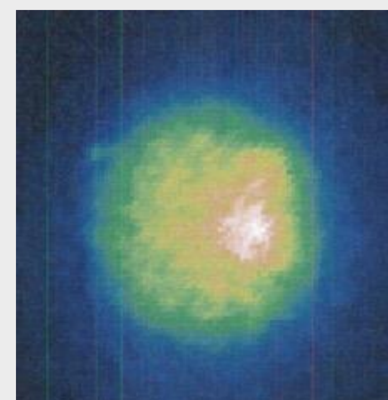




Fill Tube



X-ray Imaging

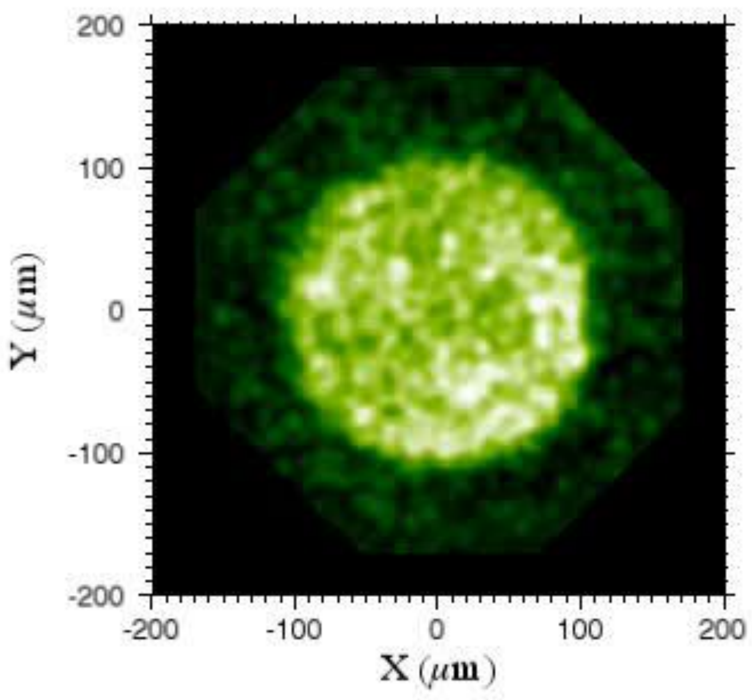


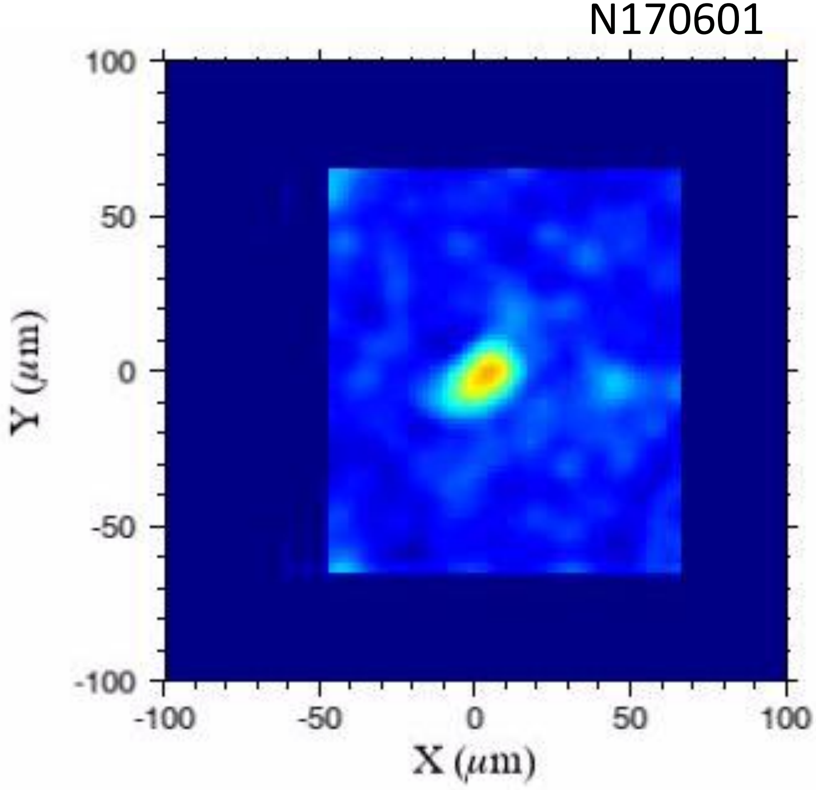
Pickworth – Wed. 11:00

HDC implosions in LID are less sensitive to the 'tent', and evidence of the fill tube is now more pronounced.

MacPhee - Wed. 8:30

X-ray movies from HDC implosions

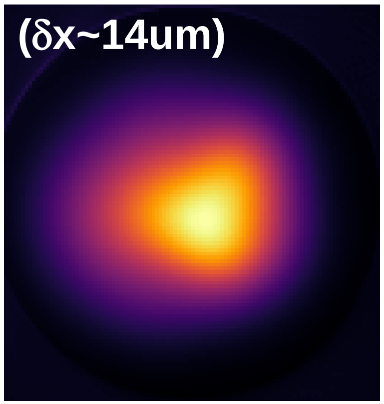




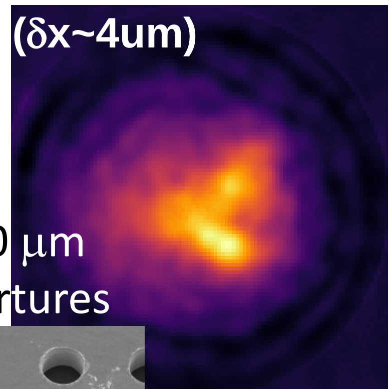
Is this resolution sufficient?

New measurements using penumbral apertures dramatically improve the view of the hot-spot structure

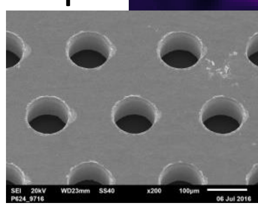
Pinhole Image



Penumbral Image

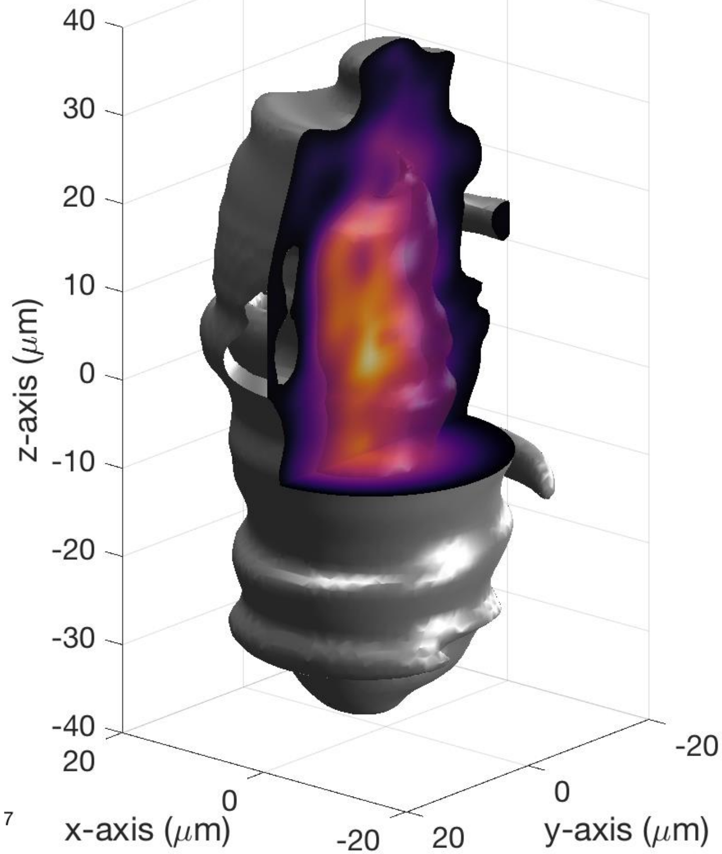


100 μm apertures



Multi-LOS 3-D Reconstruction

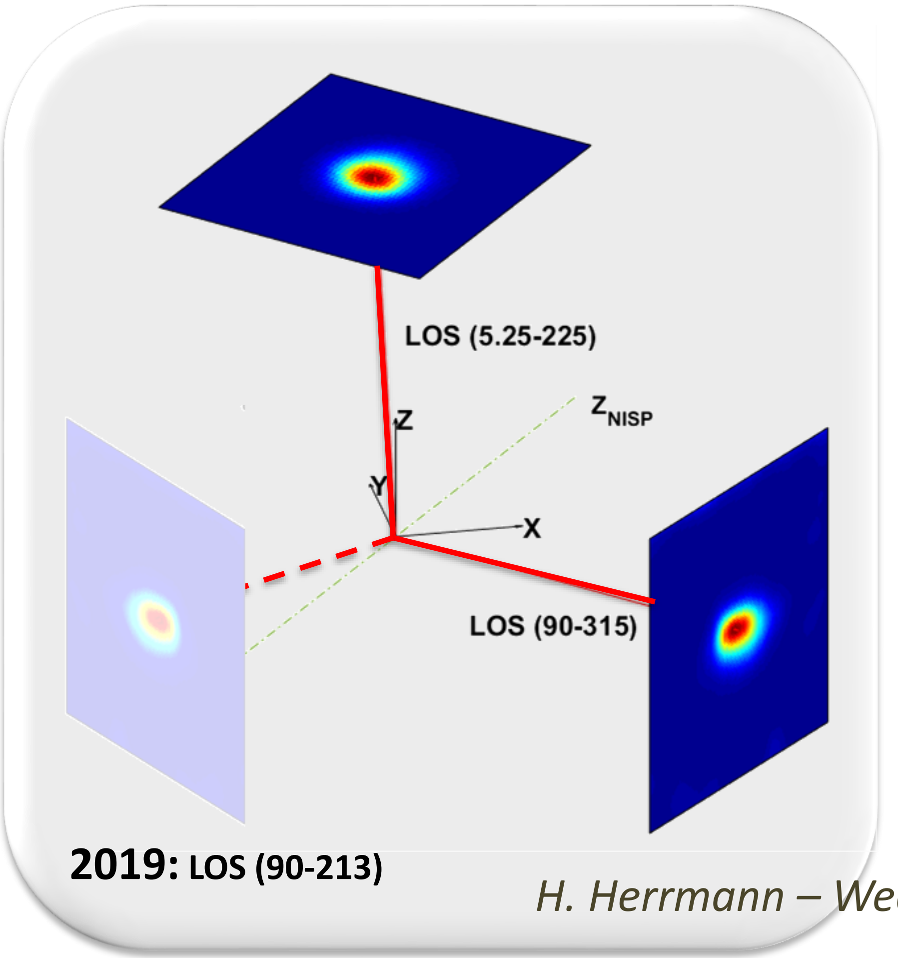
Patel – Wed. 11:00



- More 3D structure than previously observable
- Need to understand impact on performance, and identify sources (fill tube, dust, microstructure, etc.)
- Next steps include inferring 3D plasma conditions (T_e, mix), and fast time-resolution

Orthogonal neutron imaging on NIF provides new information on the 3-D asymmetry of the fusing fuel.

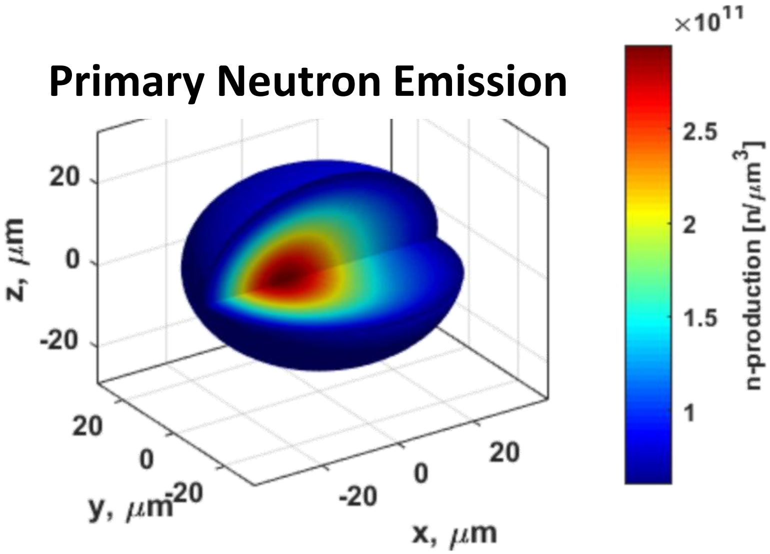
Stagnation is now imaged from the Equator and Pole



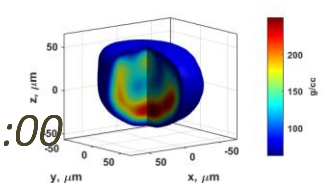
2019: LOS (90-213)

H. Herrmann – Wed. 11:00

Primary Neutron Emission

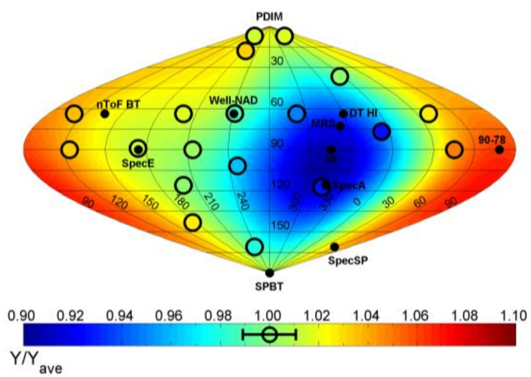


Inferred Density

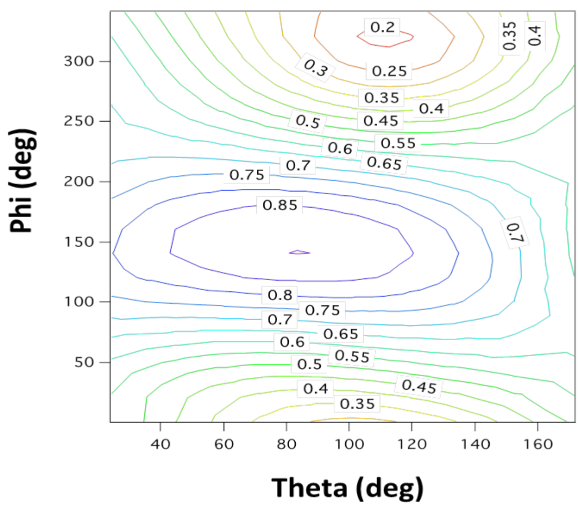


A new methodology for interpreting neutron yield asymmetry provides information on the 3-D evolution of LID implosions

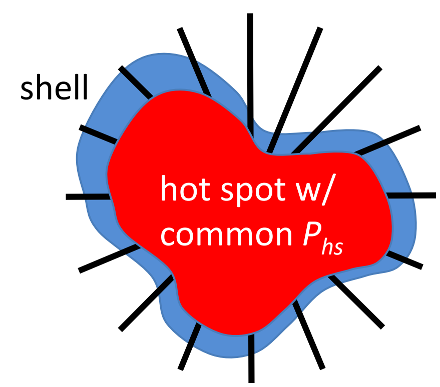
Neutron Yield Asymmetry Data



ρR Asymmetry Inference



Analytic Model of Dynamic Shell Evolution



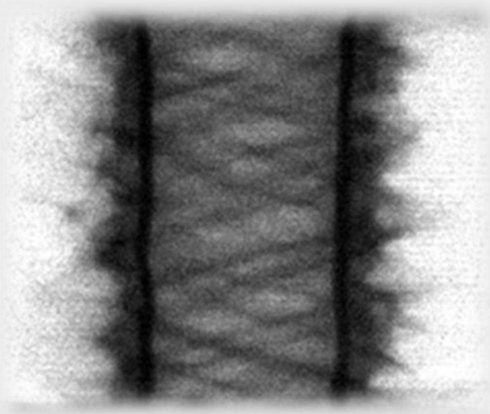
- Small variations in implosion velocity can lead to large variations in cold fuel rho-r

Springer – Thurs. 8:30

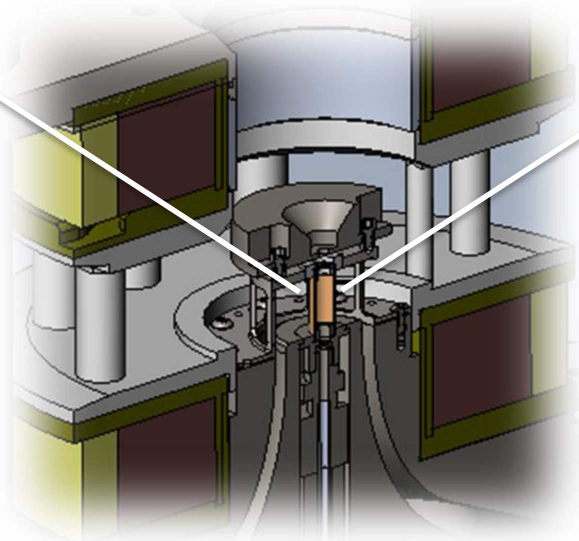
In MagLIF, the applied B-field induces 3-D liner features that imprint on the stagnation column at CR > 40.

Backlit Radiographs

B_z = 7 T



No B_z



Helmholtz Coil Provides Axial Magnetic Field (B_z)

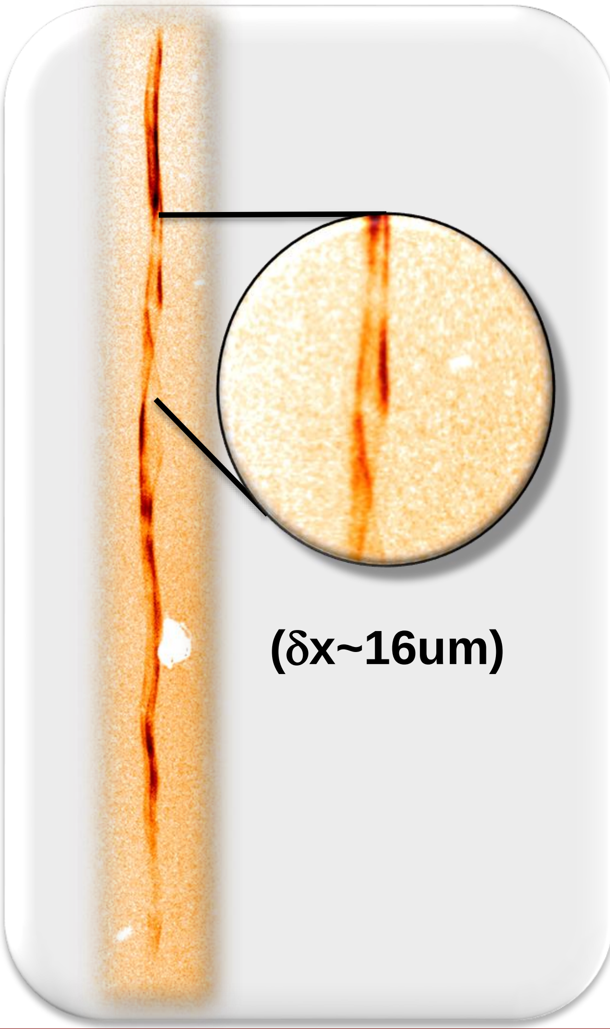
- Thermal insulation
- Trap fusion particles

X-ray Self Emission

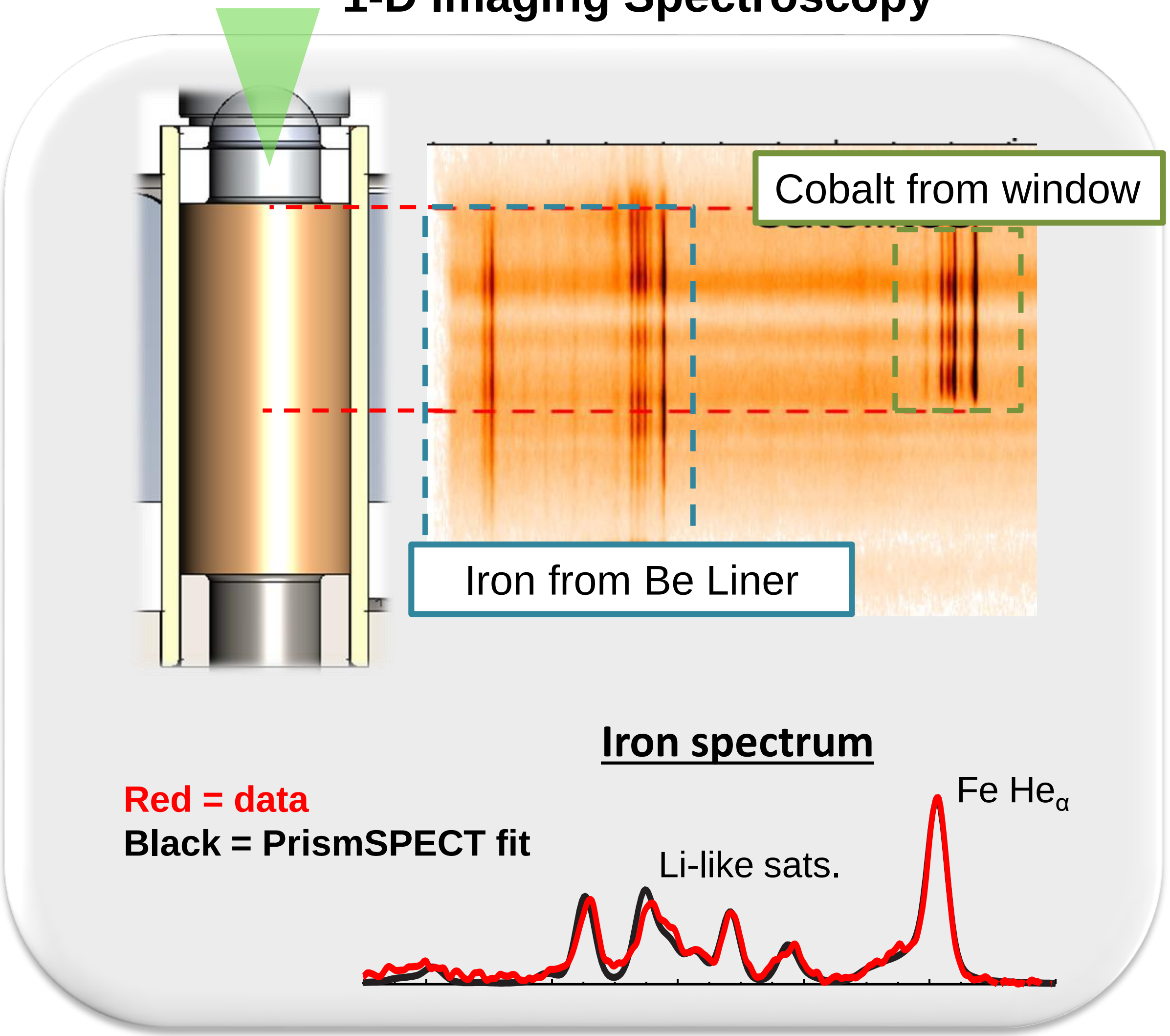
B_z = 15 T **No B_z**

New high resolution diagnostics are providing important insight into the MagLIF stagnation morphology and mix

2-D Monochromatic Imaging



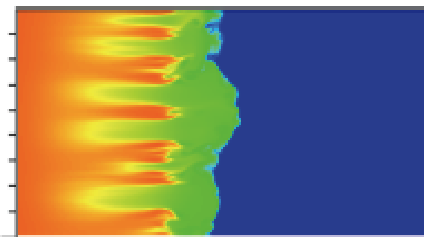
1-D Imaging Spectroscopy



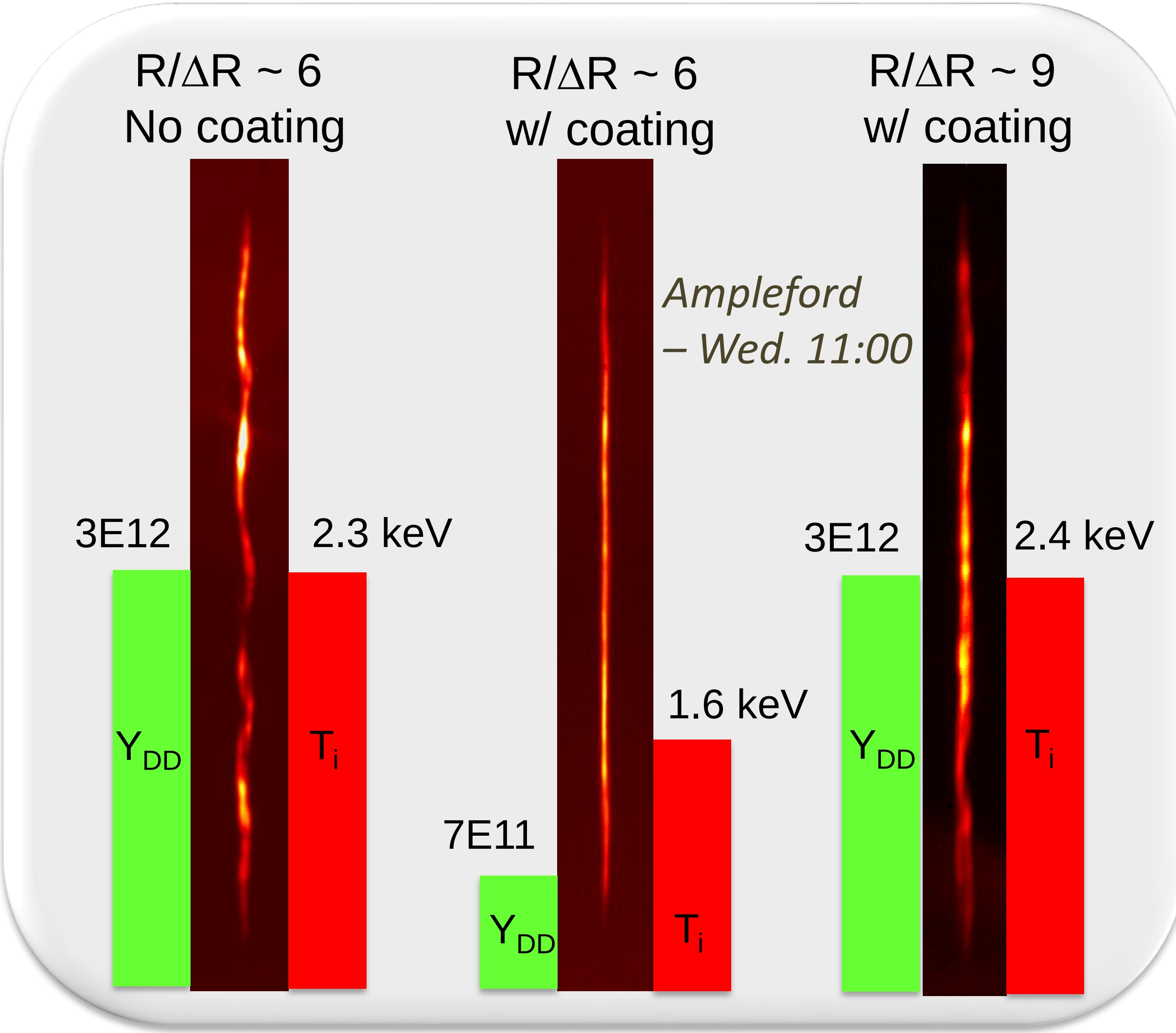
Dielectric liner coatings improve the stagnation shape but require a thinner liner to recover performance

Electrothermal Instability can be mitigated using epoxy coatings

No Coating



50 μm coating



Outline

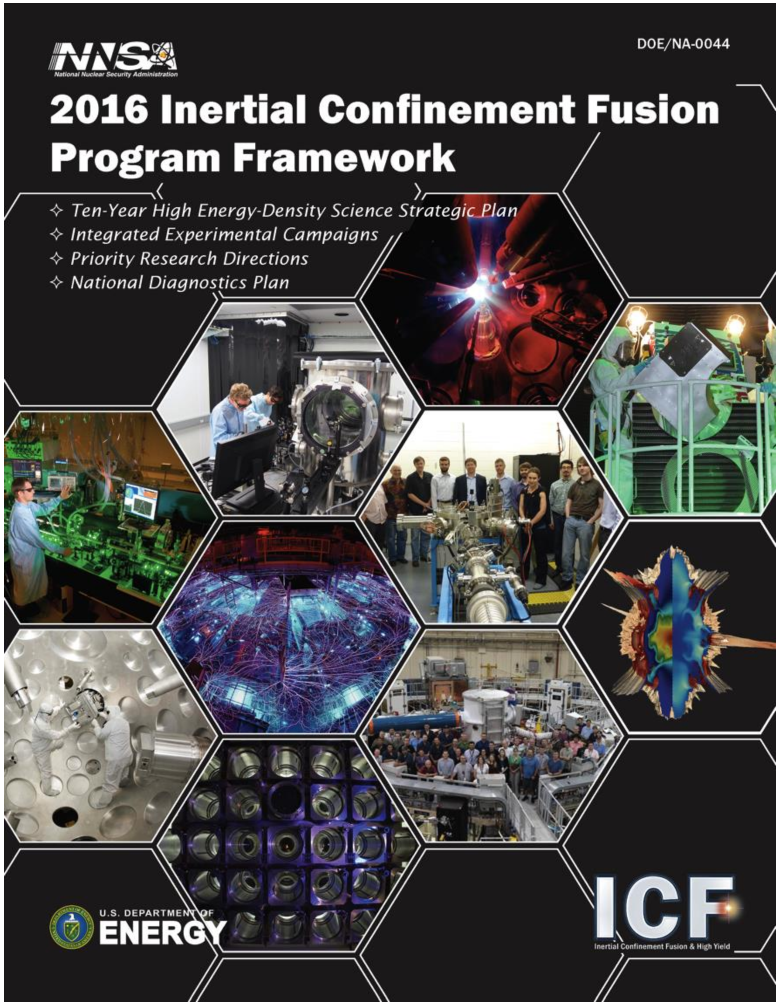
- Overview of the major ICF approaches in the US program
  - 3 major approaches and high-level results
- Common challenges under investigation
  - Laser Plasma Interactions
    - CBET understanding and mitigation in Laser Direct Drive
  - Implosion and Stagnation - Morphology and Mix
    - 3-D structure and diagnosis in Laser Indirect Drive and Magnetic Direct Drive
- **Path forward**
  - National Program Goals
  - Transformative Diagnostics
  - Major planned efforts across each approach

The goal of the US ICF program is to achieve multi-MJ fusion yields.

US National Program Goal: Determine the efficacy of reaching ignition on the NIF and of achieving credible physics scaling to multi-megajoule fusion yields for each of the three major ICF approaches

Organized around four framework elements:

- 10-year strategic plan for High Energy Density Science
- Integrated Experimental Campaigns
- Priority Research Directions (focused science)
- Transformative Diagnostics

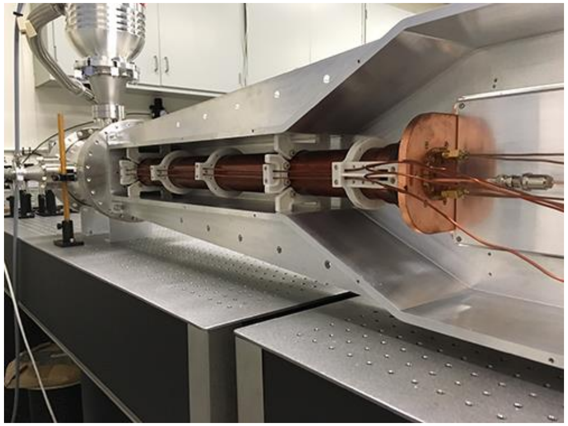


Search 'ICF Framework NNSA' on Google

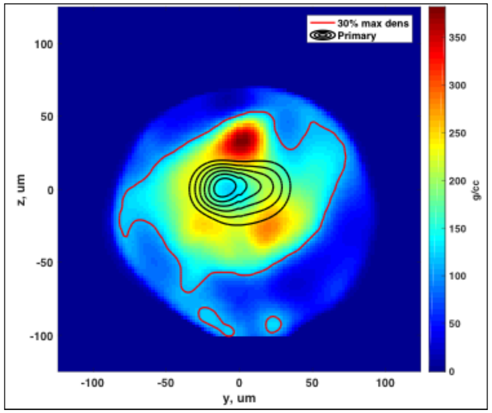
A US National effort to develop transformative diagnostics will provide new capability for assessing the details of ICF plasmas

Transformative Diagnostic	New capability
Single LOS (SLOS) imager	Imaging and spectroscopy with <20 ps temporal resolution along a single line-of-sight
UV Optical Thomson Scattering	Localized plasma conditions and turbulence in hohlraums
3D n/γ imaging	3D shape of burning and cold compressed fuel
Gamma Spectroscopy	Fusion burn history and shell rho-r
Time resolved n spectrum	Time evolution of the fusion burn temperature
High Resolution X-ray Spectroscopy	Time evolution of electron density, temperature, and mix in the hot fuel

SLOS (new invention)



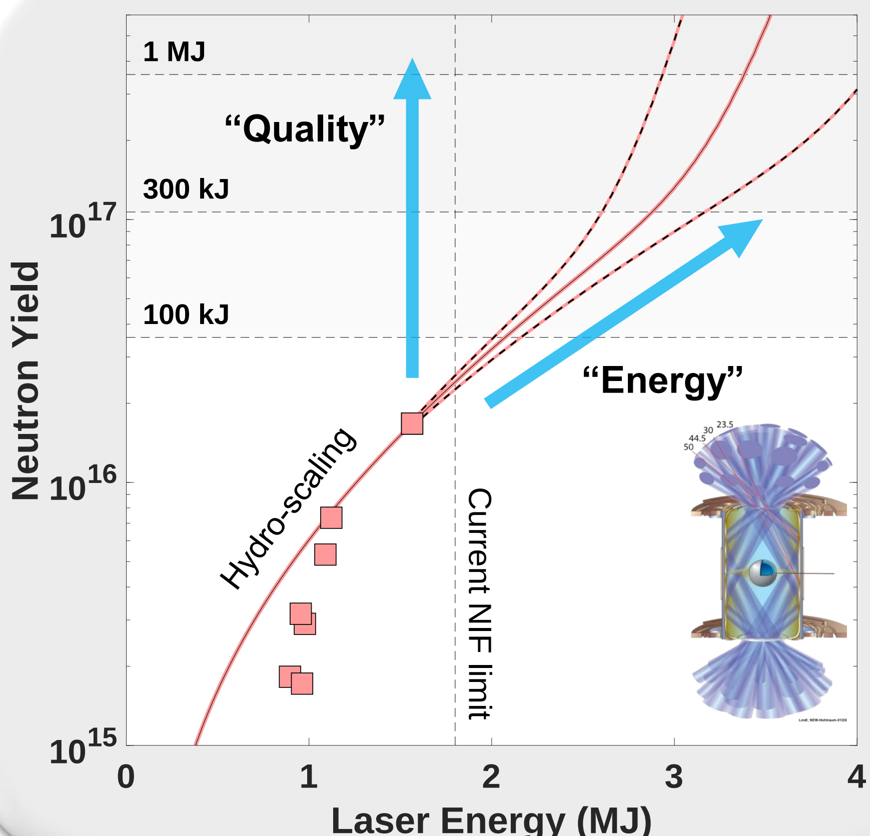
Density of compressed DT from neutron image



Diagnostics I – Wed. 11 AM – Sangster, Chen, Hilsabeck, Herrmann
Diagnostics II – Thurs. 4:30 PM – Bradley
Diagnostics III – Fri. 1:30 PM – Ross

LID efforts will focus on improving implosion quality and assessing if additional energy is needed for MJ yields

HDC Implosion Data



Can ignition be achieved on NIF?

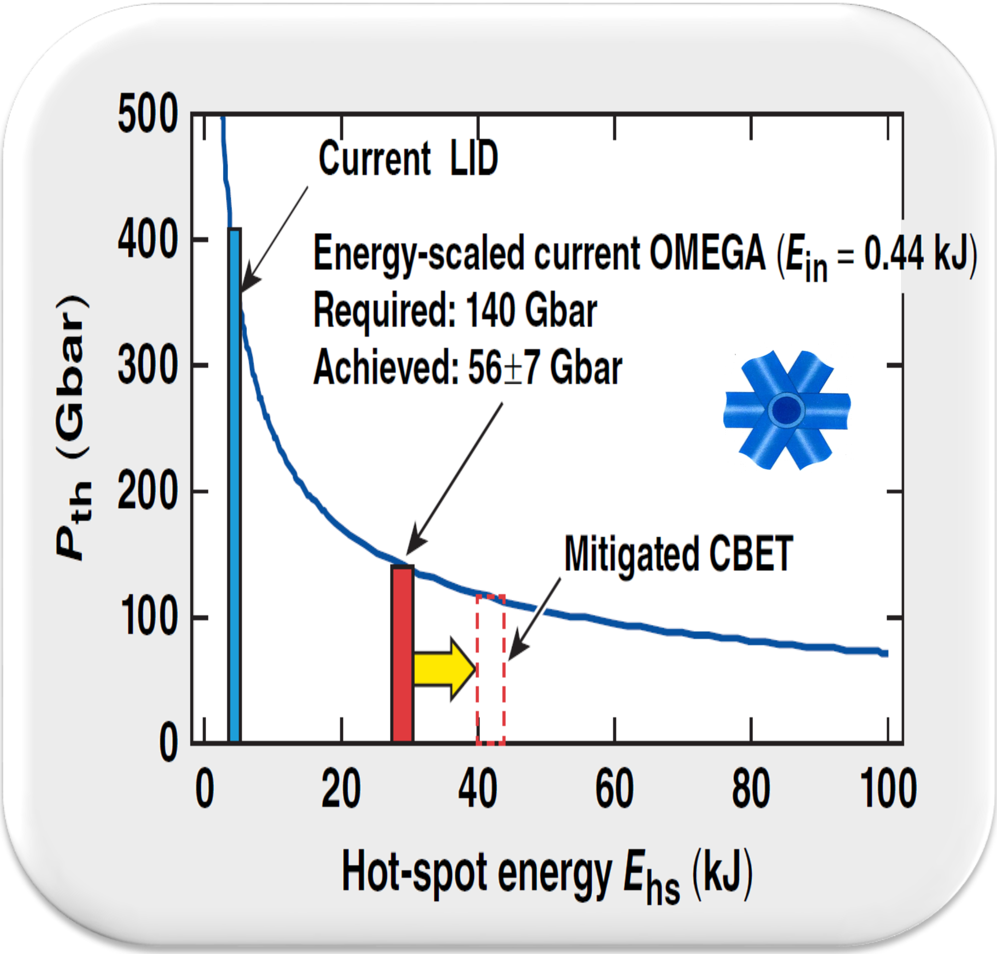
—improving implosion **"quality"** by using better measurements and models to identify degradation mechanisms and finding ways to remove or work around them

If not, what is the credible scaling to ignition

—determining how much more **"energy/power"** is needed, through extrapolation from measured performance using experimentally validated models

LDD efforts will follow the National Direct Drive Program plans to demonstrate a credible scaling to ignition

Ignition Pressure vs. Hot Spot Energy



100 Gbar Campaign on OMEGA

- Demonstrate 80-100 Gbar in ignition-scaled designs on OMEGA

Regan – Fri. 2:40

MJ Direct Drive Campaign on NIF

- Demonstrate understanding and control of LPI at the 1.8 MJ scale

Bahukutumbi – Tues. 1:30

1-D Campaign on OMEGA

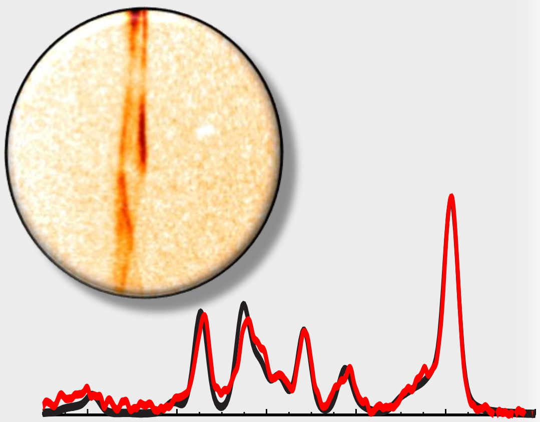
- Test understanding in low-convergence implosions

Betti – Mon. 1:30

MagLIF efforts are focused on improved performance at lower convergence by increasing capability in each phase.

Implosion & Stagnation

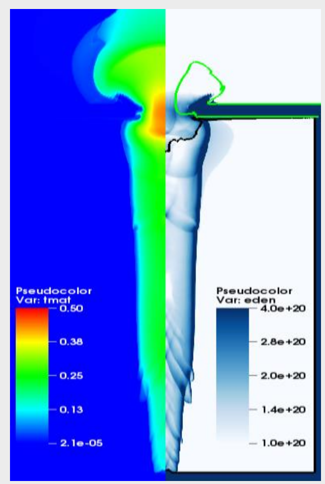
- Decrease CR to ~35 for a less structured and more repeatable stagnation.



- Achieve >10 kJ DT yield on Z with T > 4 keV and BR > 0.5 MG-cm

Laser Preheat

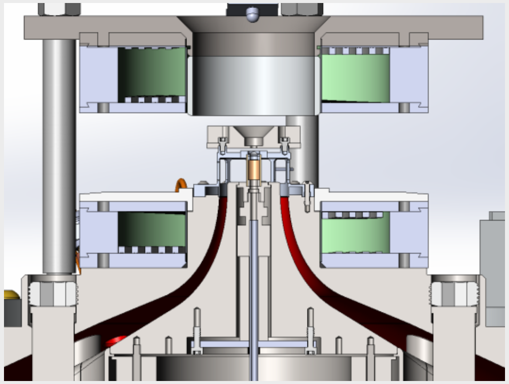
- Develop methods and validated models for more efficient laser preheat.



- Achieve >2 kJ preheat w/ minimal laser-induced mix

Power Flow

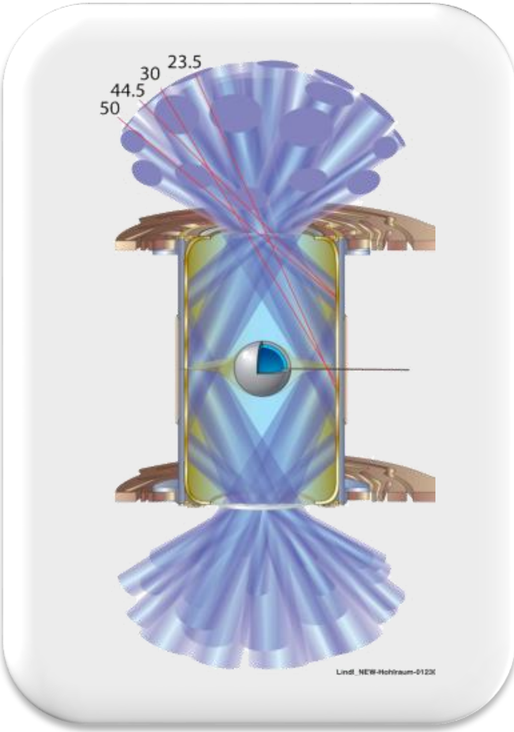
- Develop platforms and validated models for more efficient power flow compatible with High B_z



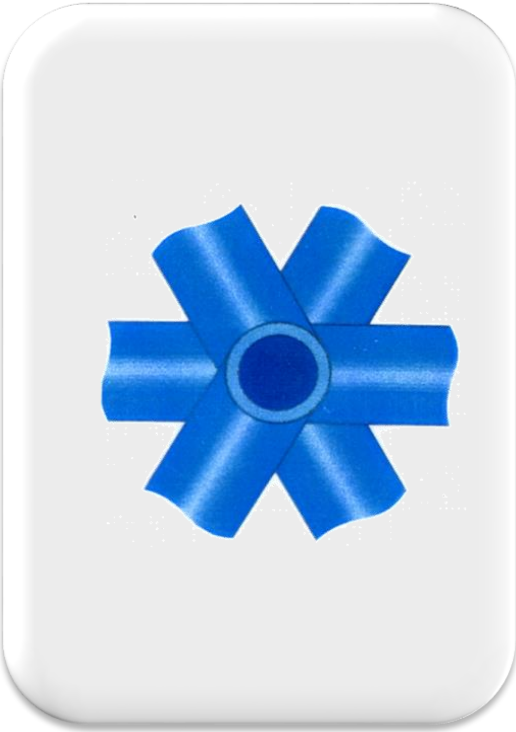
- Achieve >20 MA peak current w/ $B_z \sim 25$ T

The US Inertial Confinement Fusion program is studying three main approaches.

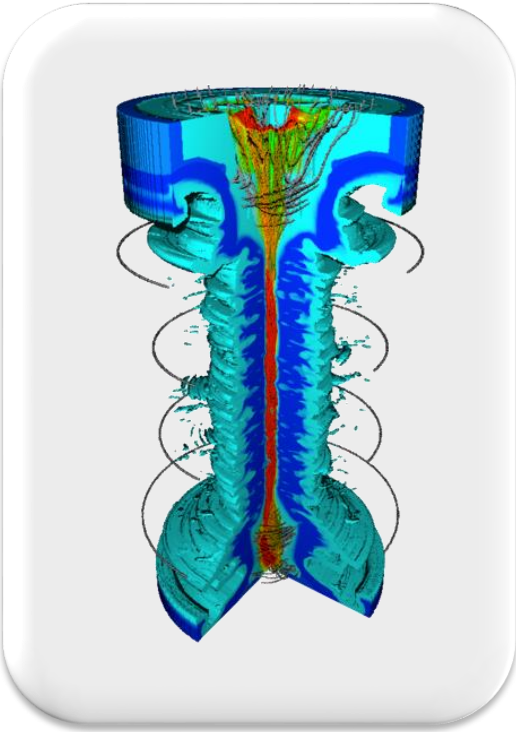
Laser Indirect Drive



Laser Direct Drive



Magnetic Direct Drive



UR LLE

Los Alamos NATIONAL LABORATORY EST.1943

PPPL

GENERAL ATOMICS

Schafer

National Security Technologies LLC
Vision • Service • Partnership

Thank you to the US National ICF Community

<u>Special thanks in putting this together</u>

Prav Patel, Radha Bahukutumbi, John Edwards, Joe Kilkenny, Craig Sangster, Mike Campbell, Valeri Goncharov, Dan Sinars, Kyle Peterson, Matt Gomez