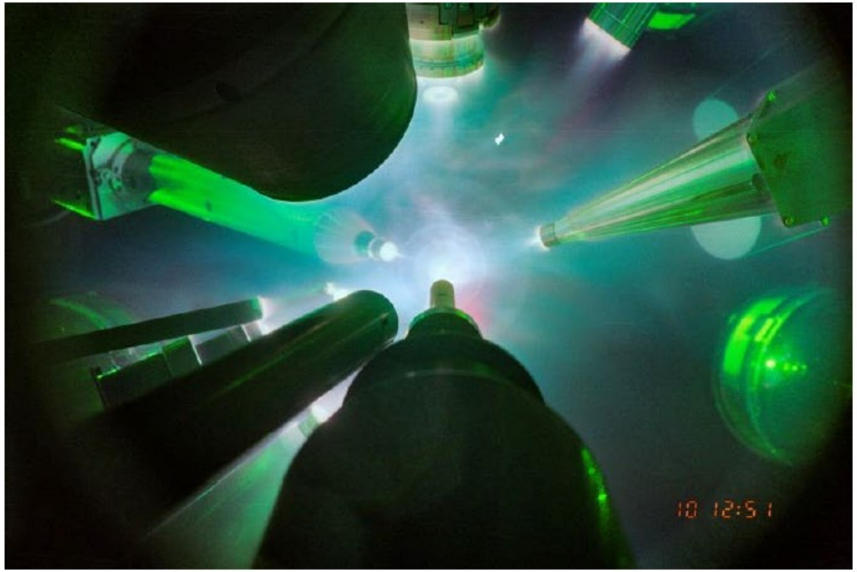
Unraveling Implosion Physics in Inertial Confinement Fusion: Direct-drive Simulations, Experiments, and Physics-Informed Data Science



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Seminar at MIPSE
University of Michigan
Nov 16, 2022

Summary

Progress in direct drive implosion performance is being made through feedback between experiments and codes, and physics-informed data science techniques

- Direct drive applications include studies related to high-energy density plasmas, nuclear astrophysics etc.
- Several approaches in parallel are being pursued in parallel to improve performance in proof-of-principle DT-layered OMEGA implosions (kJ scale)
  - Surrogate implosions, targeted science experiments to guide design of cryogenic implosions and improve simulation predictability
  - Improved tools for postprocessing simulations to identify signatures and potential failure metrics
  - Data driven models incorporating failure metrics to improve performance
- Modern computing is permitting large scale simulations with improved models.

Collaborators

Laboratory for Laser Energetics, University of Rochester

General Atomics, San Diego

Lawrence Livermore National Labs

Plasma Science and Fusion Center, MIT

Los Alamos National Labs

Naval Research Labs, Washington DC

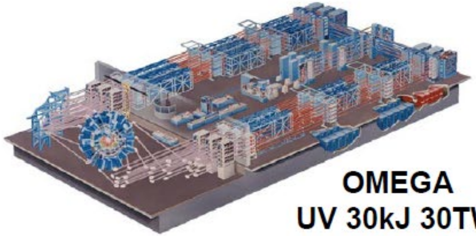
AWE, United Kingdom

University of Bordeaux

Outline

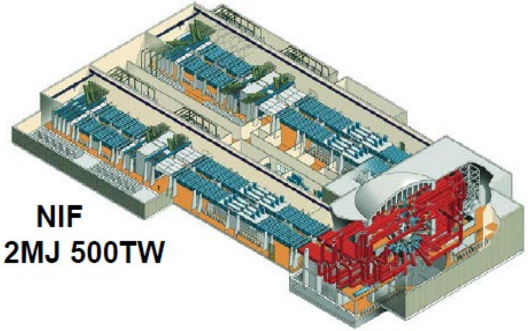
- Direct drive on OMEGA
- Improving implosion performance by improving models
  - 1D physics – e.g. role of cross beam energy transfer and mitigation using laser bandwidth – evidence from the NIF – upgrade to ray-trace models in hydrodynamic simulations
  - multi-D physics – Role of perturbations - modeling and diagnosing nonuniformity
  - Postprocessing tools, new signatures identifying failure mechanisms
- Improving implosion performance using physics informed data-science models
- Scaling to Mega-Joule facilities

Two primary laser driven approaches are being studied in the US

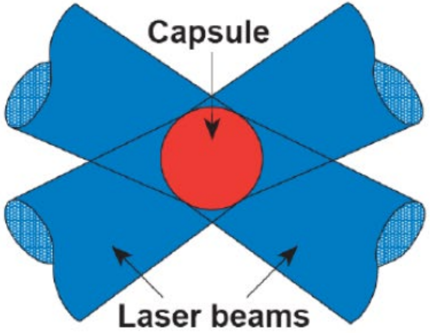


OMEGA
UV 30kJ 30TW

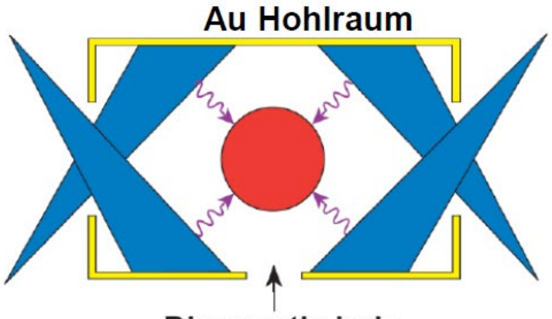
NIF
UV 2MJ 500TW



Direct-drive target



Indirect-drive target



Review papers/books

Lindl et al, Review National Ignition Campaign, Phys. Plasmas 2014

Craxton et al, Review of Direct Drive Phys. Plasmas 2015

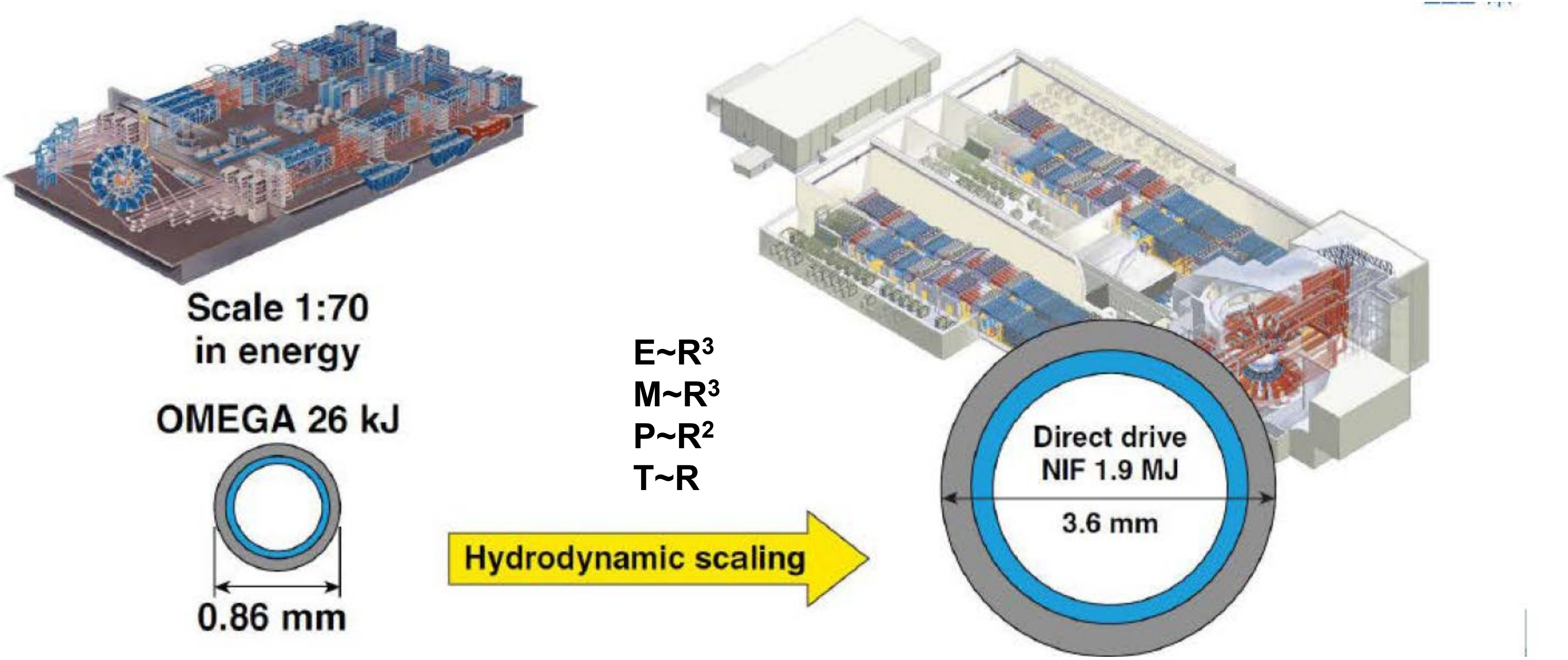
Betti & Hurricane, ICF via Lasers Nature Physics, 2016

Atzeni et al, Review of Shock Ignition Nuclear Fusion 2014

Tabak et al, Review of Fast Ignition Phys. Plasmas 2005

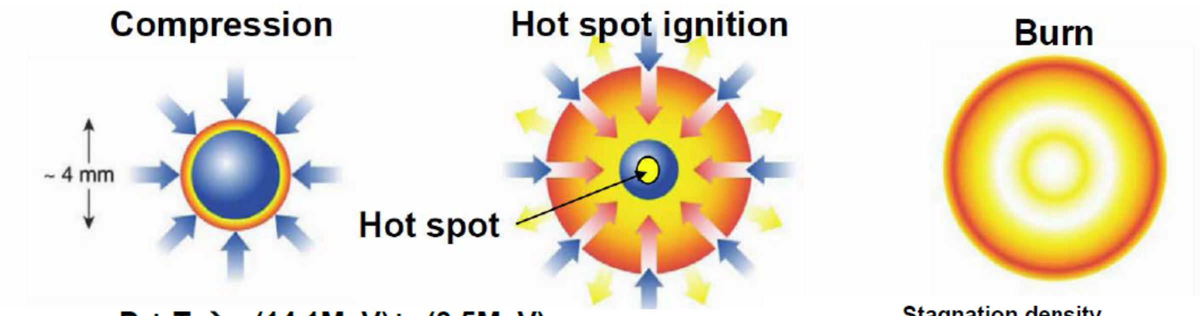
Atzeni & Meyer-ter-vehn "Physics of Inertial Fusion" 2005

OMEGA implosion studies are based on hydrodynamic scaling between OMEGA and an ignition facility like the National Ignition Facility



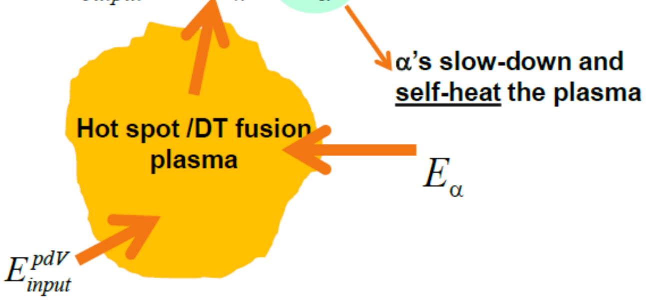
$E \sim R^3$
$M \sim R^3$
$P \sim R^2$
$T \sim R$

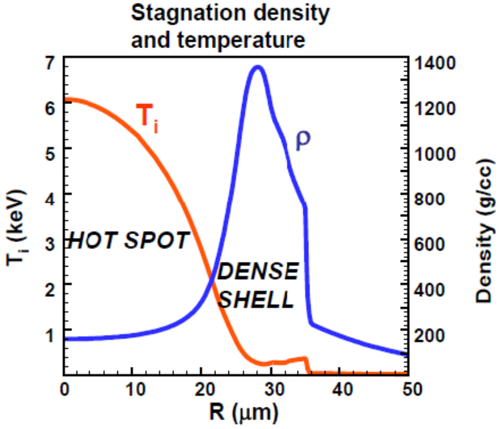
The aim is drive implosions to develop conditions for a robust hotspot and propagating burn



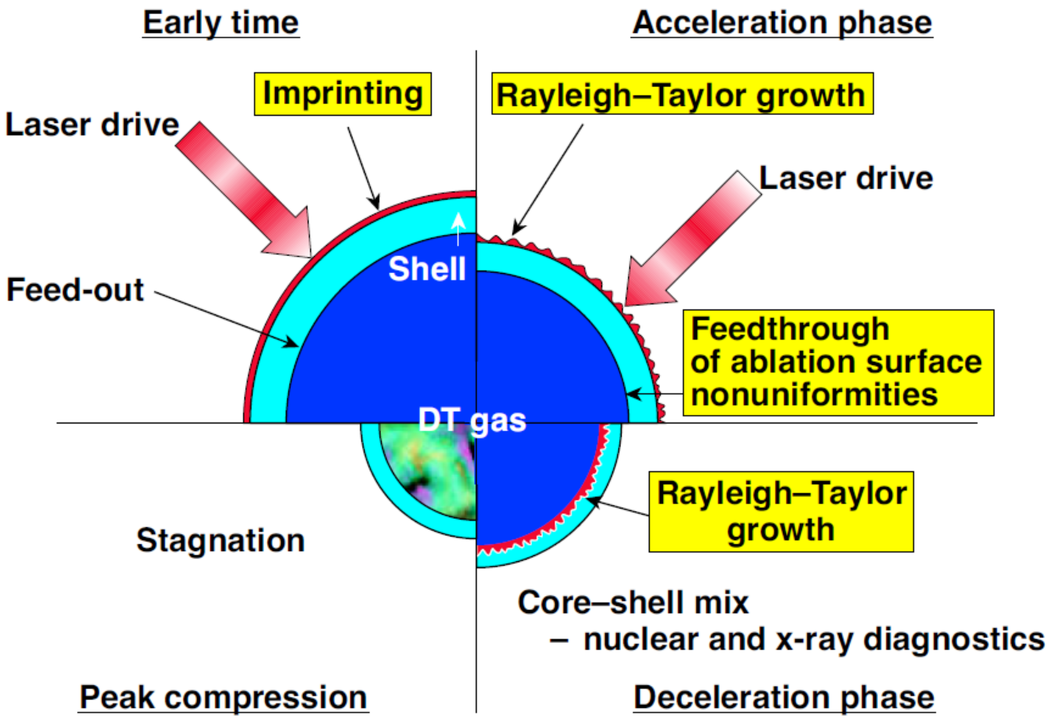
D + T → n(14.1MeV)+α(3.5MeV)

$$E^{nuclear}_{output} = E_n + E_\alpha$$

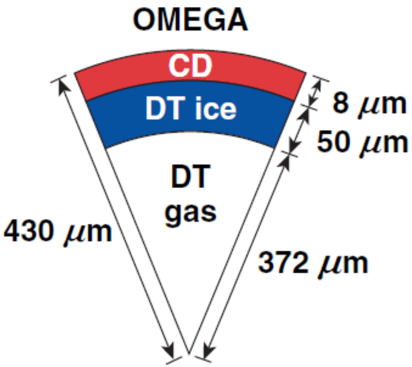




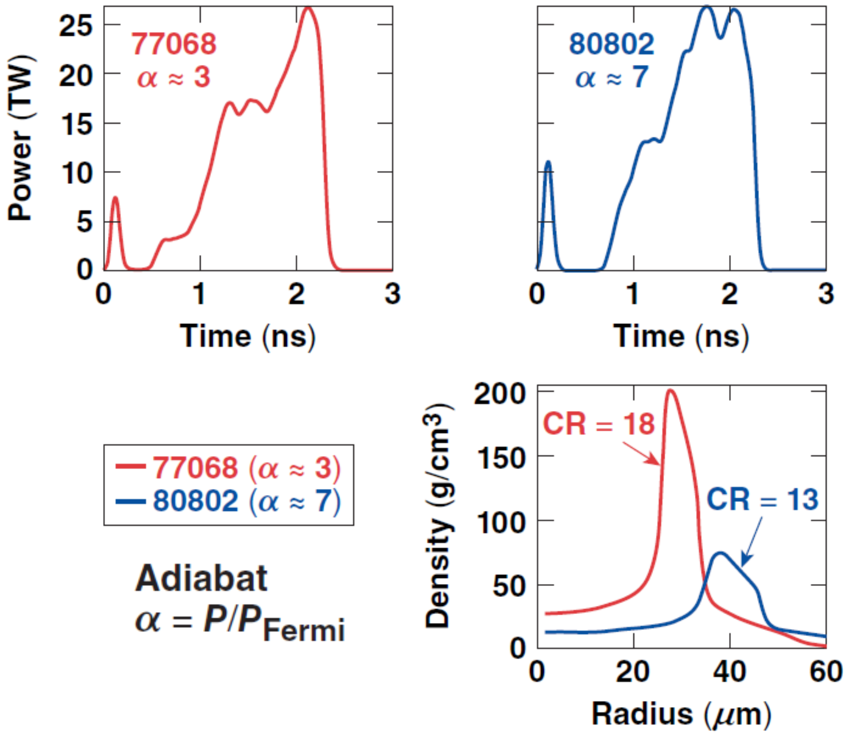
Lasers are used to set up the conditions for a hotspot and propagating burn



Design parameters (adiabat and implosion velocity) are varied by varying targets and pulse shapes



Ice thickness is varied for different implosion velocities



Adiabat
$\alpha = P/P_{Fermi}$

TC13096b

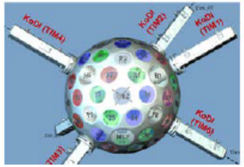
A range of diagnostics are used to study the hot spot

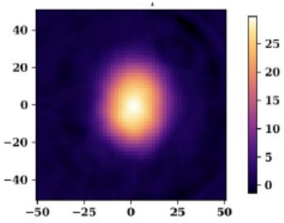
Inference of the core pressure

NTOF
+
Activation

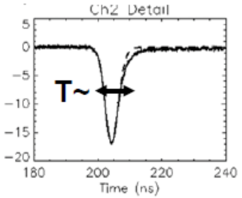
$$Yield \sim n^2 \langle \sigma v \rangle V\tau \sim P^2 \frac{\langle \sigma v \rangle}{T^2} V\tau$$

x ray + neutron images

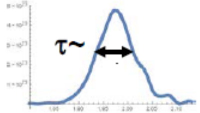




NTOF
Brisk

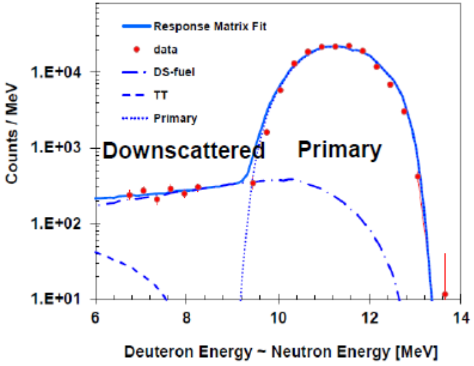


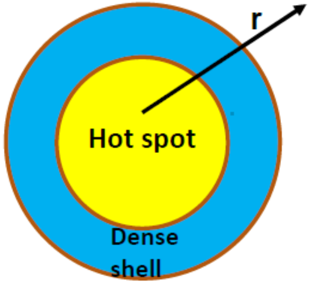
Neutron+γ-ray+x-ray temporal diagnostic



$$< \sigma V > \sim T^4 \sim V_{imp}^{5.9}$$

Inference of the areal density



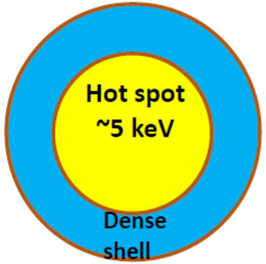


$$\rho R = \int_0^\infty \rho dr \sim DSR = \frac{\text{Downscattered}}{\text{Primary}}$$

$\rho R \sim \alpha^{-0.5}$

Several measures of target performance indicating how close an implosion is to ignition have been identified

$$\rho R = \int_0^\infty \rho dr$$



- Rewrite Lawson for ICF using an imploding shell compressing a plasma rather than a static plasma:

$$\chi = \frac{P\tau}{[P\tau]_{ign}} \approx \left\langle \rho R_{g/cm^2} \right\rangle^{0.61} \left(\frac{0.12 Yield_{16}}{M^{mg}_{DTstag}} \right)^{0.34}$$

Other forms of ignition criterion using hot spot areal density and temperature**

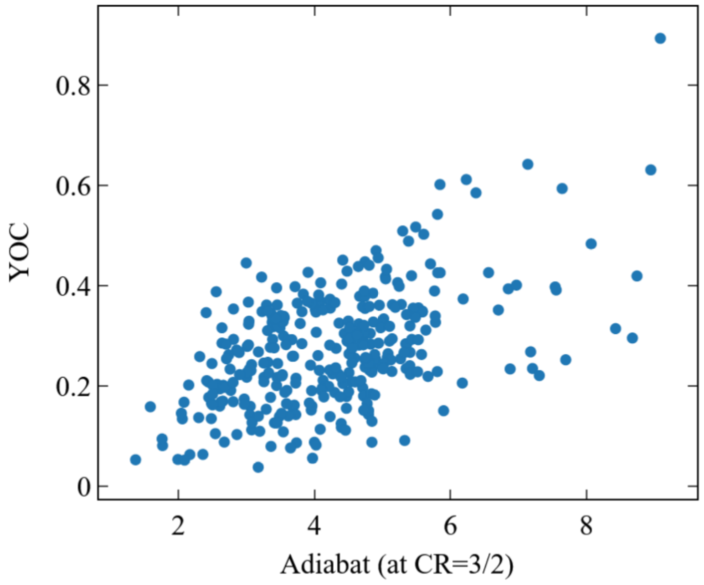
$$(\rho R)_{HotSpot}\, T_{ion} > 0.3\times 5 \text{ g/cm}^2 \text{ keV}$$

**Atzeni and Caruso, Nuovo Cimento 1984
Kemp, Meyer-ter-vehn and Atzeni, PRL 2001

*R. Betti et al, PRL 2015
A. Christopherson et al, PoP (2018 and 2019)
Lindl, PoP, 2018
Spears, PoP 2012 (ITFx)

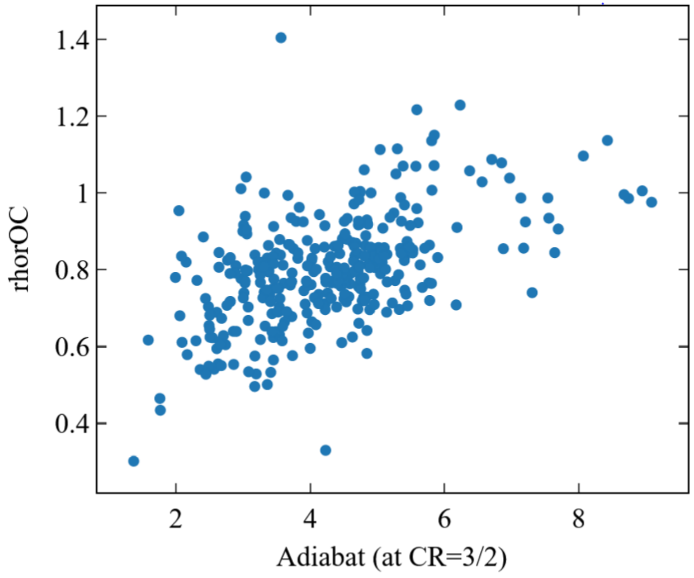
Observations deviate from simulations with increasing convergence or decreasing adiabat

Yield degradation (Measured yield/Simulated yield)



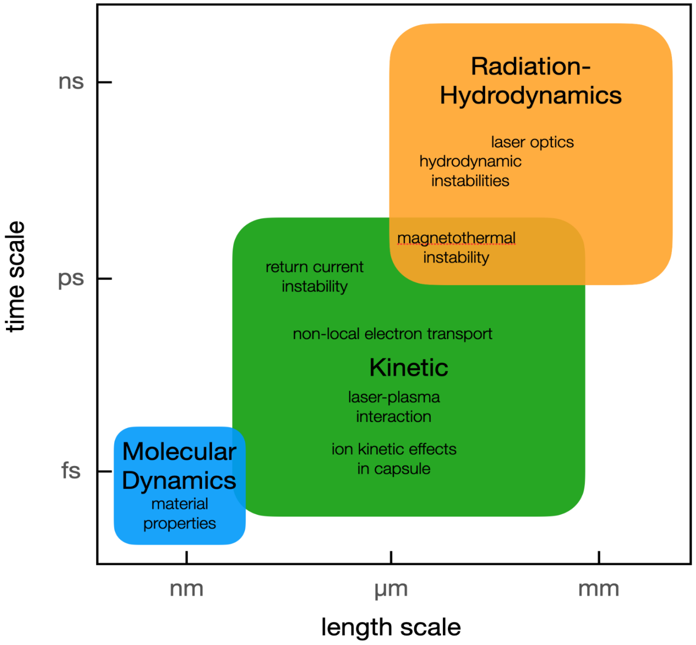
Increasing convergence

Areal density degradation (Measured ρR/Simulated ρR)

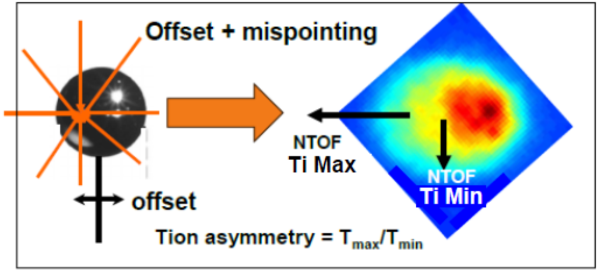


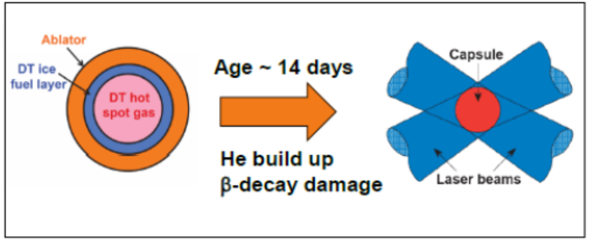
Increasing convergence

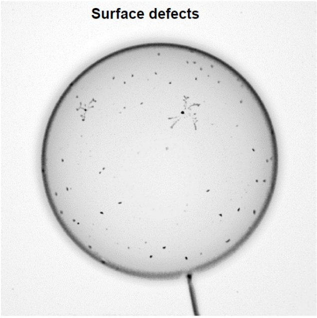
Implosion predictions are challenging because of the multi-scale and multi-physics involved



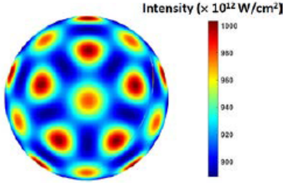
Limited simulation predictability can be due to modeling errors, uncertainties in input to codes or engineering aspects not captured by codes



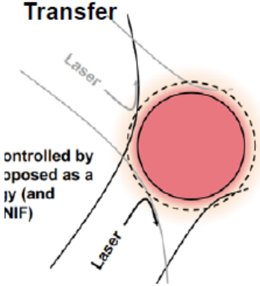




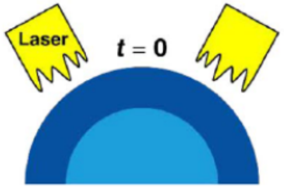
Illumination asymmetry



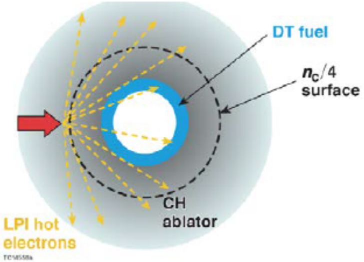
Cross-beam Energy Transfer



Laser imprinting



Two-plasmon Decay



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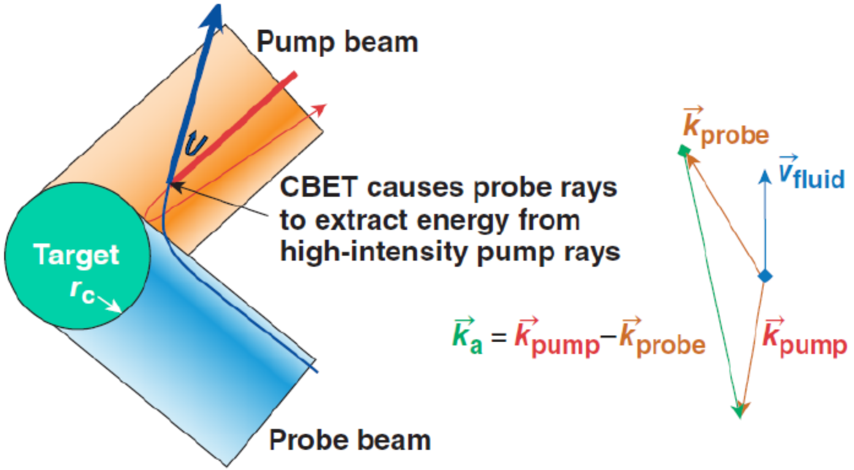
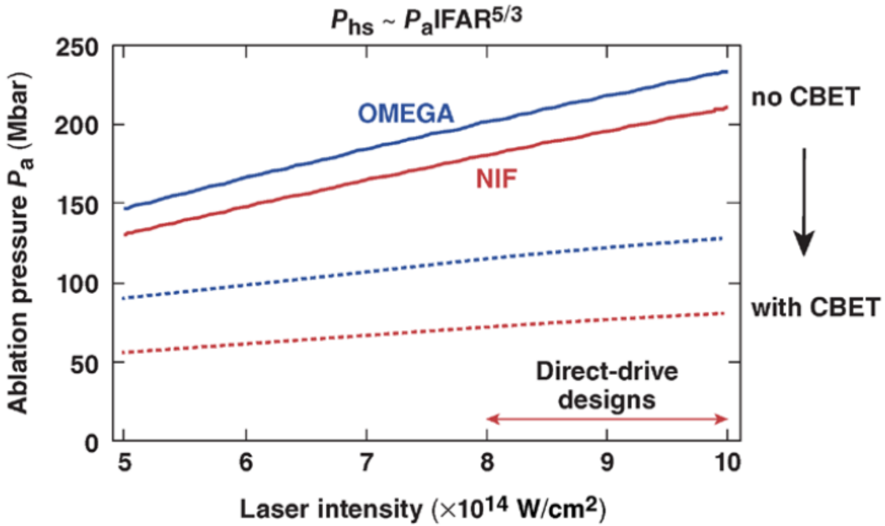
Cross beam energy transfer can significantly reduce the ablation pressure





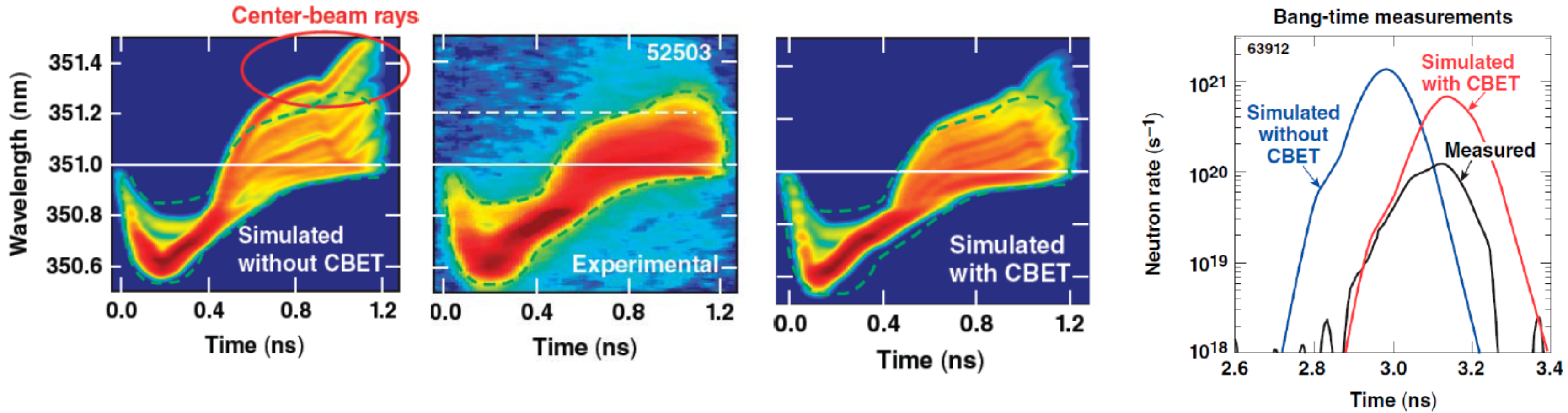
P_{hs} = Hot spot pressure

IFAR = shell radius/ shell thickness

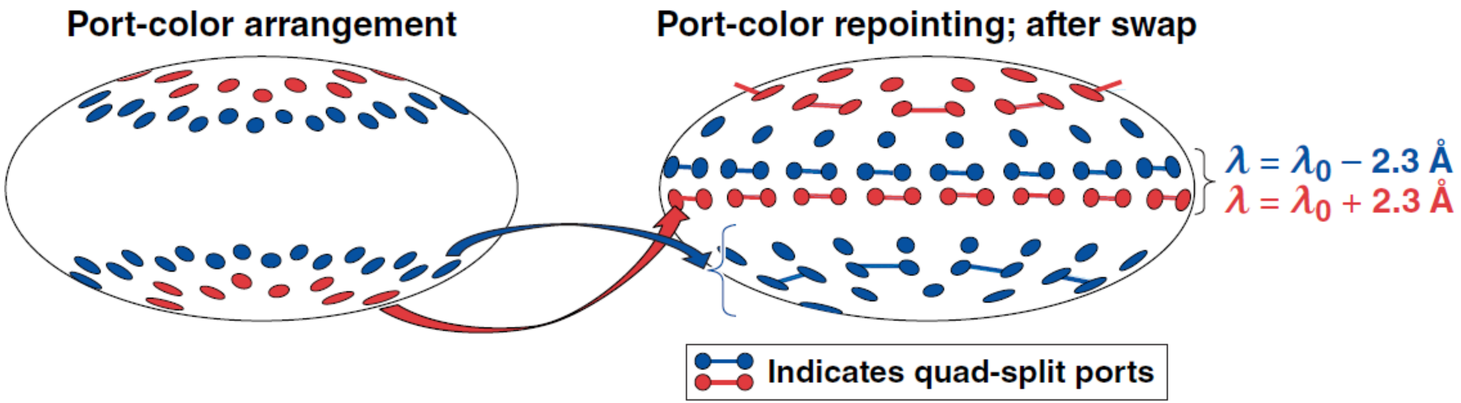
P_a = Ablation pressure

Laser deposition models in rad-hydro codes have been improved to include the effect of CBET

As an example: introducing cross beam energy transfer models in hydrocodes



Detuning the wavelengths of the crossing beams can improve ablation pressure as demonstrated on the NIF

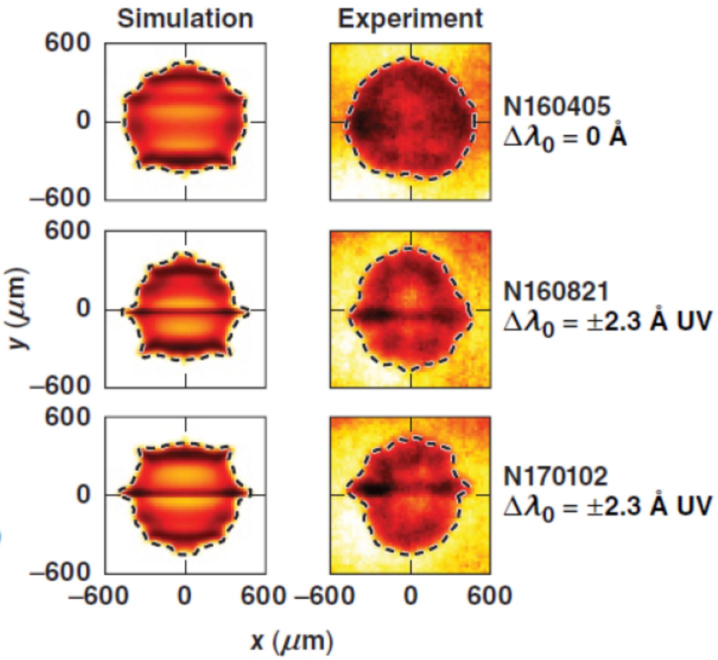


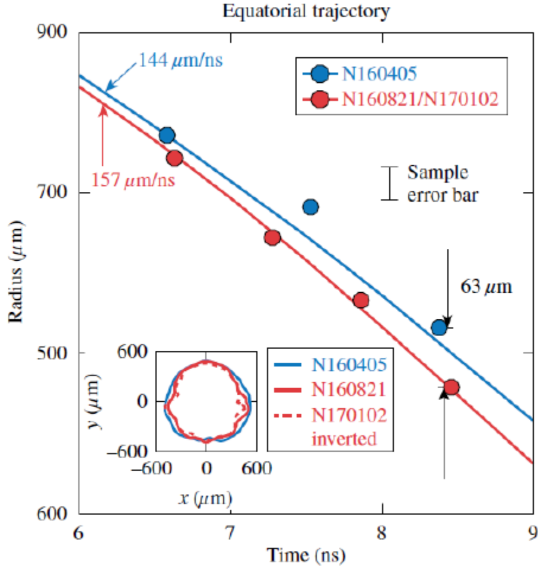
J. Marozas et al, Phys. Rev. Lett (2018).

NIF’s wavelength detuning capability has been used to demonstrate mitigation of CBET in proof-of-principle experiments

Cone-swap south

Cone-swap north (view of antipodal pole)





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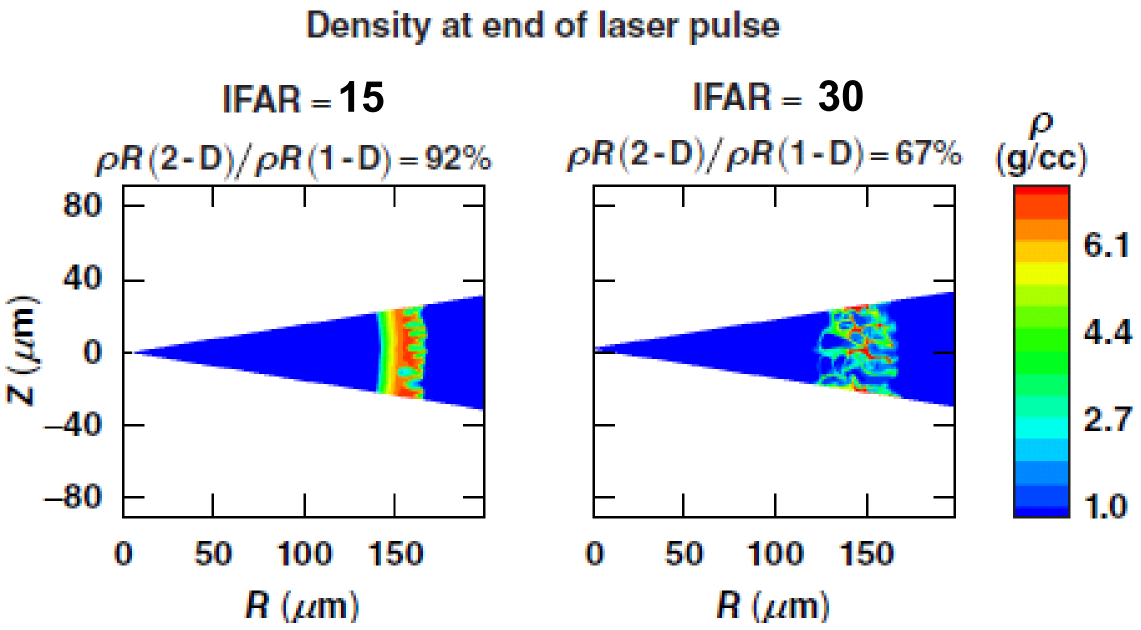
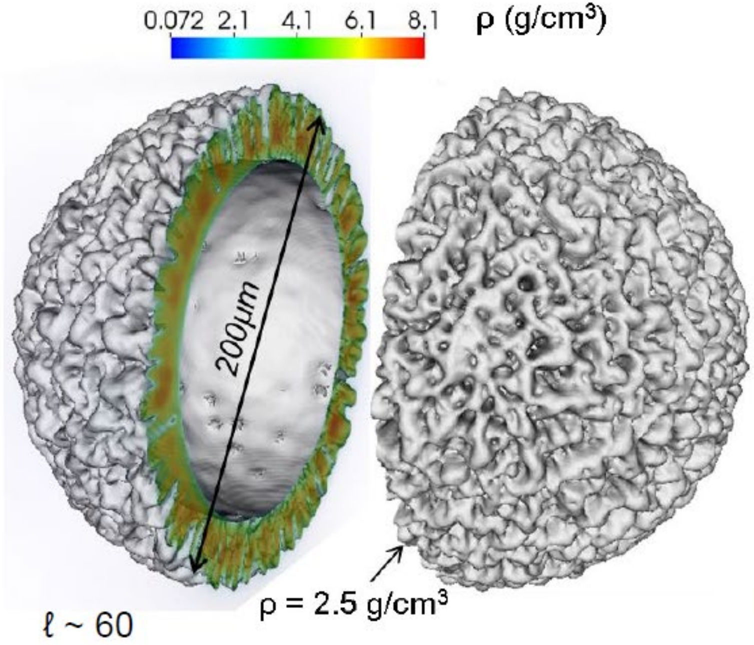
Laser speckle can reduce the areal density for high IFAR implosions

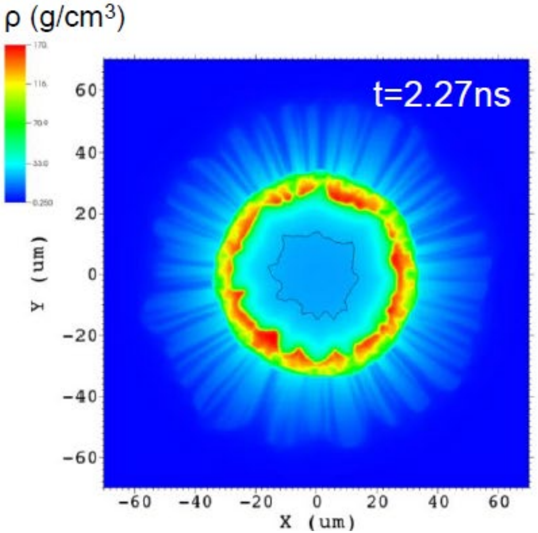


Highly resolved 3D simulations are now possible to model the effect of laser imprint

Target at end of acceleration, t=2.1 ns



Target at peak neutron production



Relative neutron yield (3-D over 1-D) = 0.812

I. Igumenschev, PRL (2019)

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UR LLE

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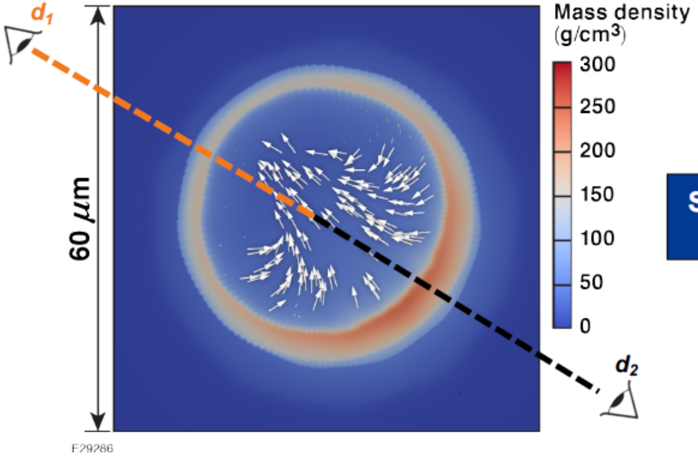
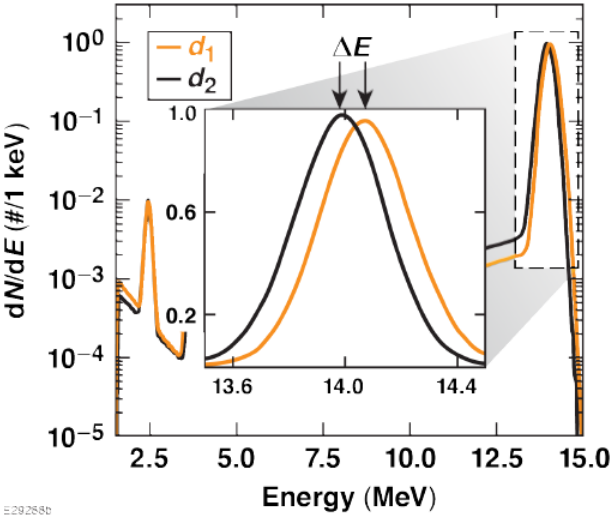
Hot spot flow, diagnosed by the Doppler shift in the DT neutron peak, can result in an inefficient conversion of the shell kinetic energy into hot spot energy

_ASTER_* radiation-hydrodynamic simulation at peak neutron production



Synthetic neutron diagnostics

Synthetic neutron energy spectrum emitted from target**

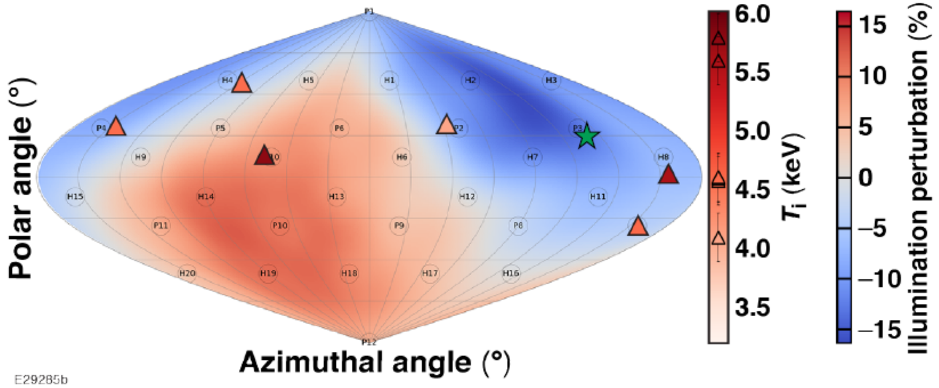


Three-dimensional neutron diagnostics provide information on the hot-spot velocity (first moment), apparent ion temperature (second moment), and the shell areal density (down-scatter ratio).

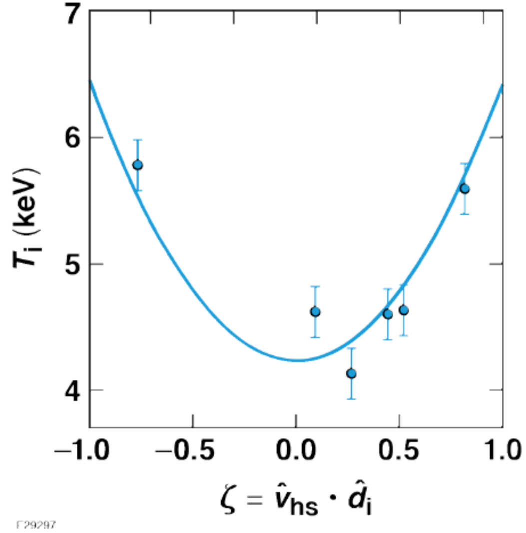
* I. V. Igumenshchev *et al.*, Phys. Plasmas 23, 052702 (2016).
** F. Weilacher, P.B. Radha, and C. Forrest, Phys. Plasmas 25, 042704 (2018).

Implosions with large flows also indicate asymmetries in the measured width of the neutron spectrum (apparent ion temperature variations)

On-target laser illumination uniformity*



T_i versus projection along mode-1 direction



▲ **NtoF detectors**

★ **Flow**

* Includes energy balance, beam pointing, timing, target offset

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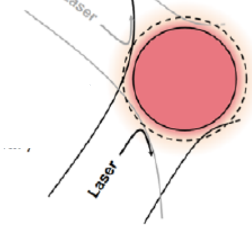
Yield degradation mechanisms have been quantified through a multi-variate regression model with observed and simulated dependencies

Yield degradation → $$YOC = \text{Yield-Over-Clean} = \frac{\text{Yield (measured)}}{\text{Yield (1D codes)}}$$

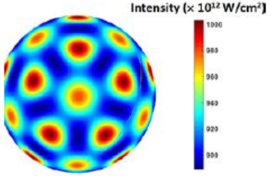
CBET/1D physics? | Beam mode | Short wavelengths | ℓ=1 | T-decay

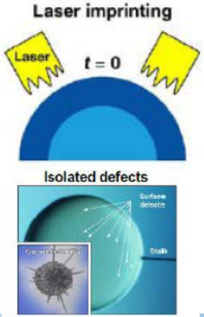
$$YOC \sim \left(\frac{Rb}{Rt}\right)^{b_1} e^{-(b_2+b_3\alpha+b_4 CR)\sigma_{rms}^{b_5}} \left(\frac{\alpha_F^{b_6}}{IFAR}\right)^{b_7,b_8} Max\left[\left(\frac{T_{max}}{b_9 T_{min}}\right),1\right]^{b_{10}} YOC_{He3}^{b_{11}} YOC_{res}$$

1D coupling (corrections)

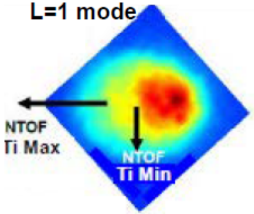


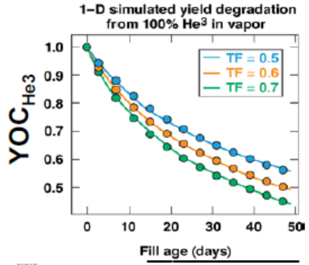
Beam mode





L=1 mode

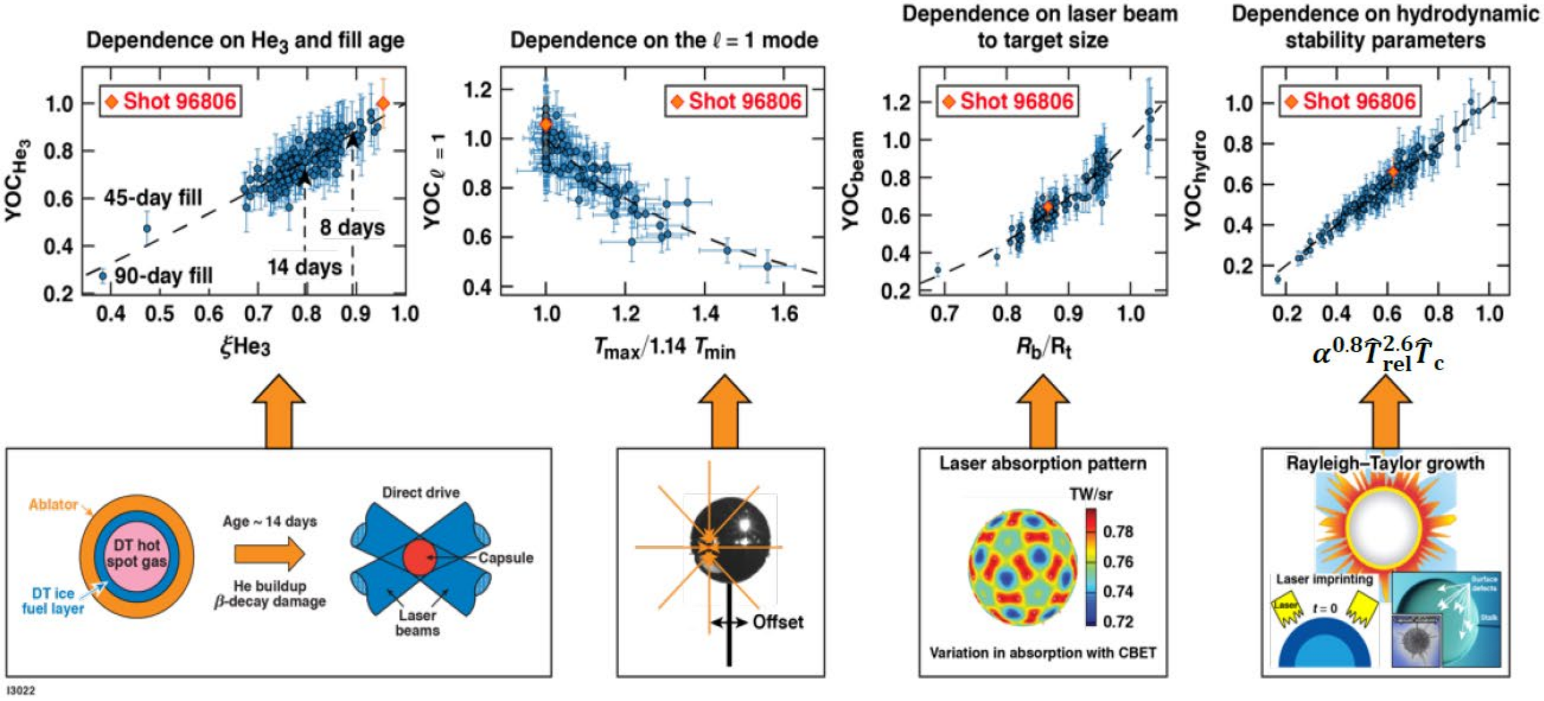




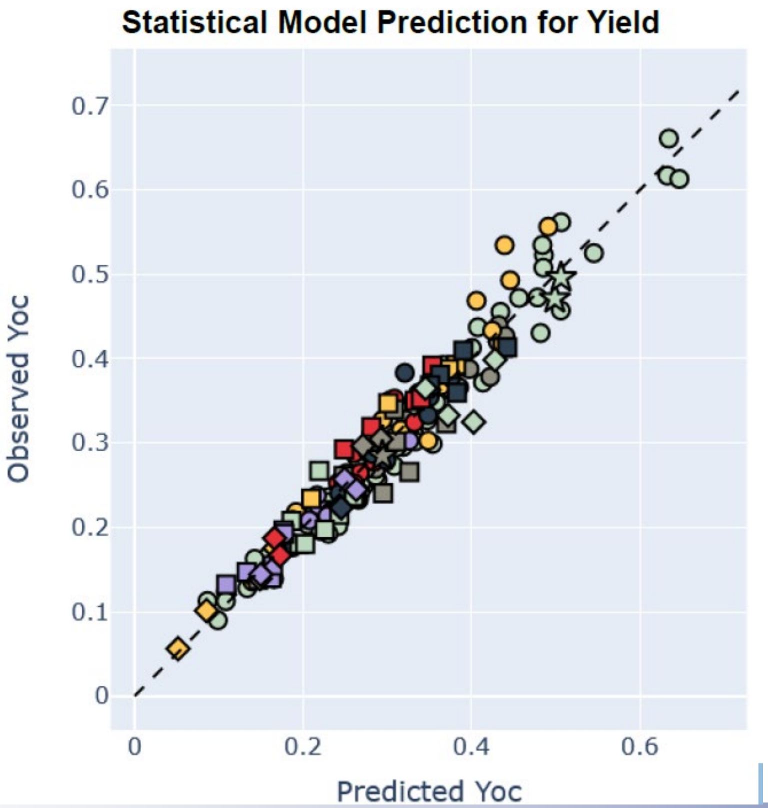
* V. Gopalaswamy, Nature 565, 581–586 (2019)

** A. Lees, Phys. Rev. Lett.127, 105001 (2021)

Multi-variate regression techniques are being used in parallel to identify quantities that determine implosion performance

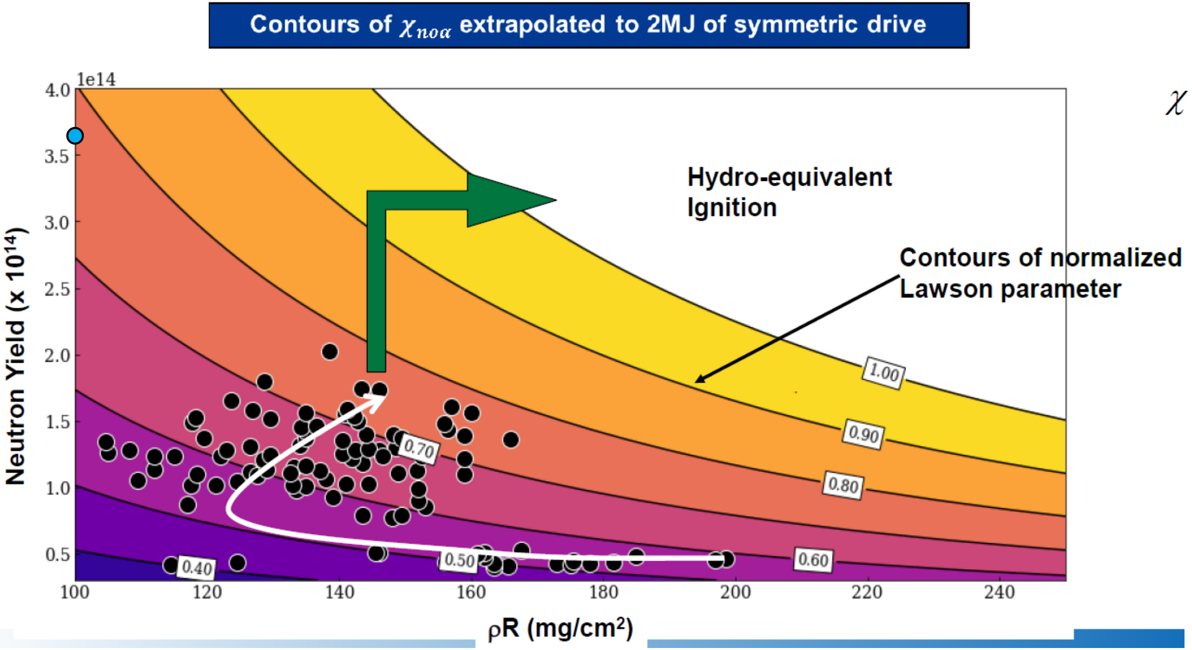


The statistical model predicts yield accurately and is used to design higher performing implosions



The remaining scatter is due to shot-to-shot variations in laser delivery, target quality, and any other design-dependent physics that is not accounted for.

Hydrodynamic scaling requires a modest increase in yield and areal density



$$\chi = \frac{P\tau}{[P\tau]_{ign}} \approx \left\langle \rho R_{g/cm^2} \right\rangle^{0.61} \left(\frac{0.12 Yield_{16}}{M^{mg}_{DTstag}} \right)^{0.34}$$

C. Williams, Phys. Plasmas (2022).

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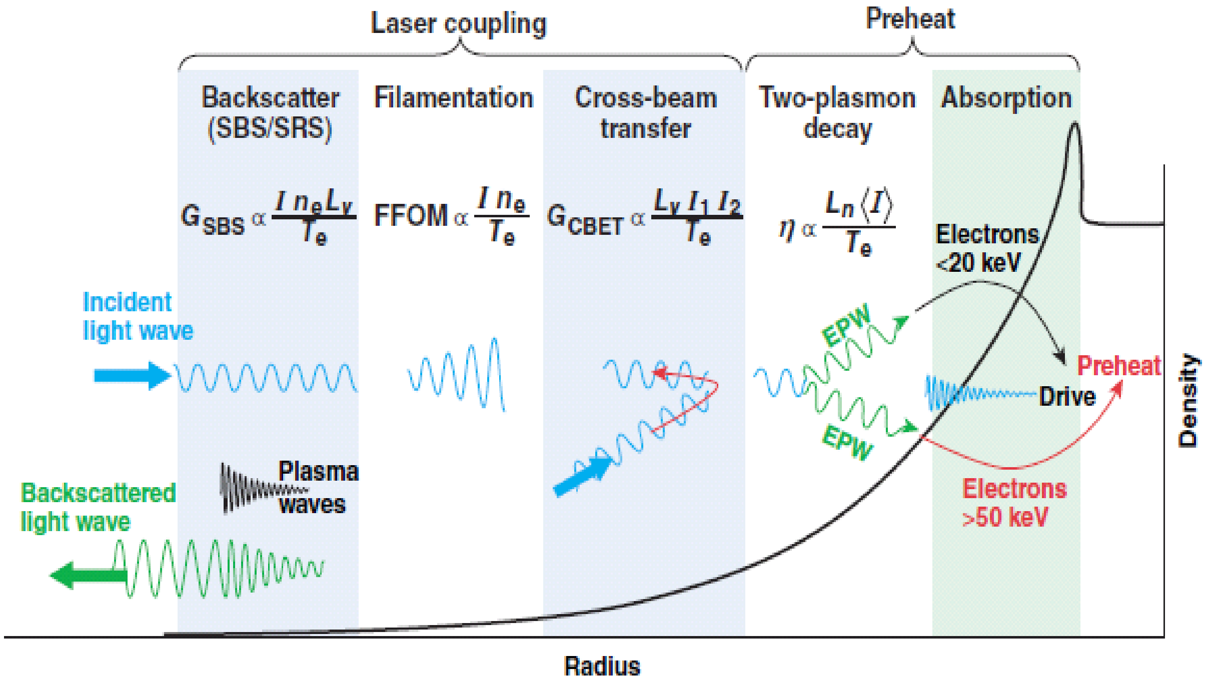
- Scaling to Mega-Joule facilities

Many coronal processes influence laser energy deposition and electron transport to the ablation surface

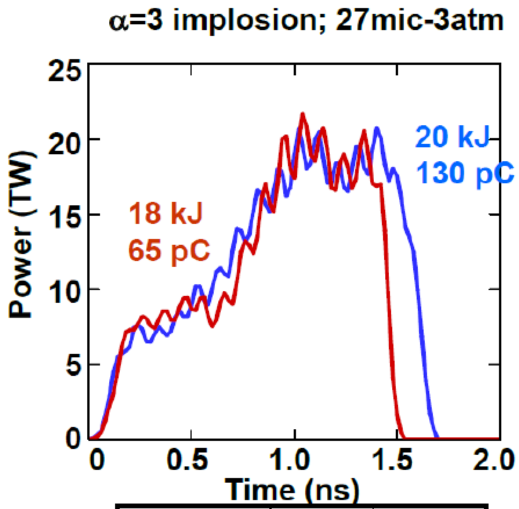


Progress in direct drive implosions is being made through feedback between experiments and codes, and physics-informed data science techniques

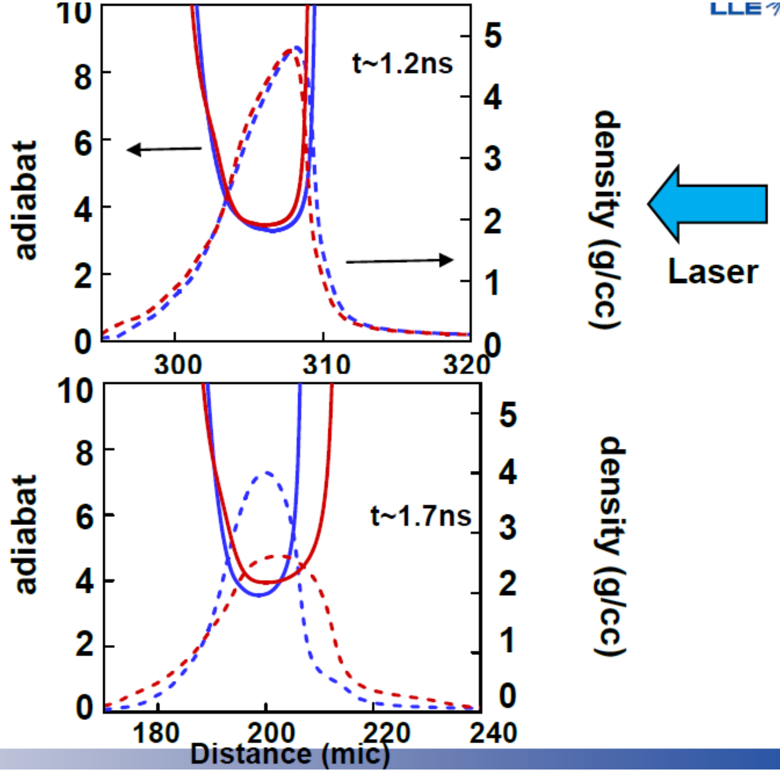
- **Direct drive applications include yield, studies related to stockpile stewardship, nuclear astrophysics, studies of matter under extreme conditions etc.**
- **Several approaches in parallel are being pursued in parallel to improve performance in proof-of-principle DT-layered OMEGA implosions (kJ scale)**
  - **Surrogate implosions, targeted science experiments to guide design of cryogenic implosions and improve simulation predictability**
  - **Improved tools for postprocessing simulations to identify signatures and potential failure metrics**
  - **Data driven models incorporating failure metrics to improve performance**
- **Modern computing is permitting large scale simulations with improved models.**

Coasting Phase

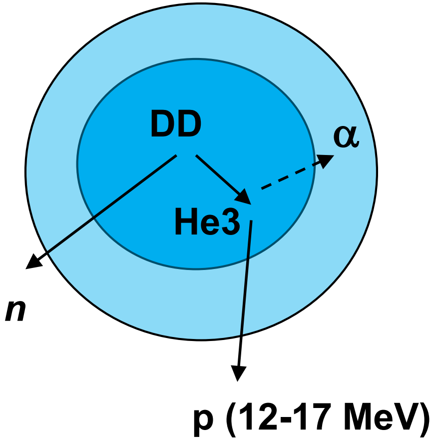
Maintaining ablation pressure till the implosion bang time is key to improving compression



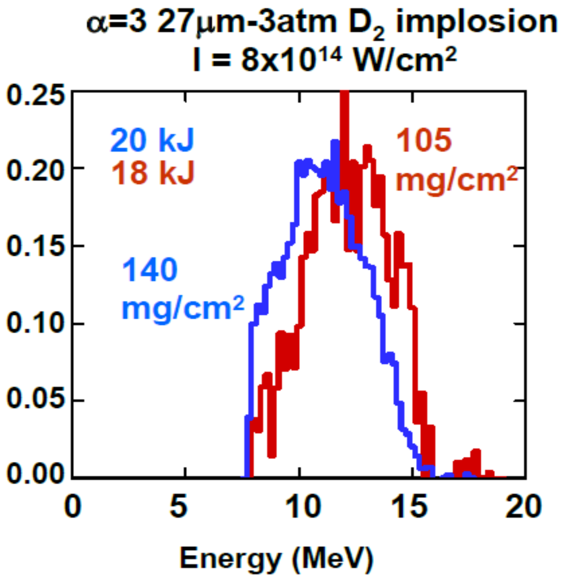
	20 kJ	18 kJ
Max ρR (mg/cm²)	292	206

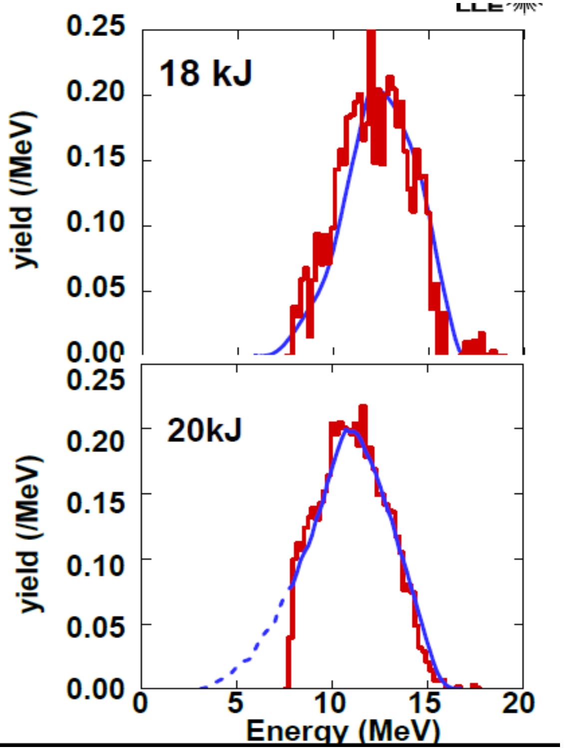


The improved compression by maintaining ablation pressure has been demonstrated in OMEGA implosions



Measured proton spectrum





Lines – Synthetic spectrum (IRIS)