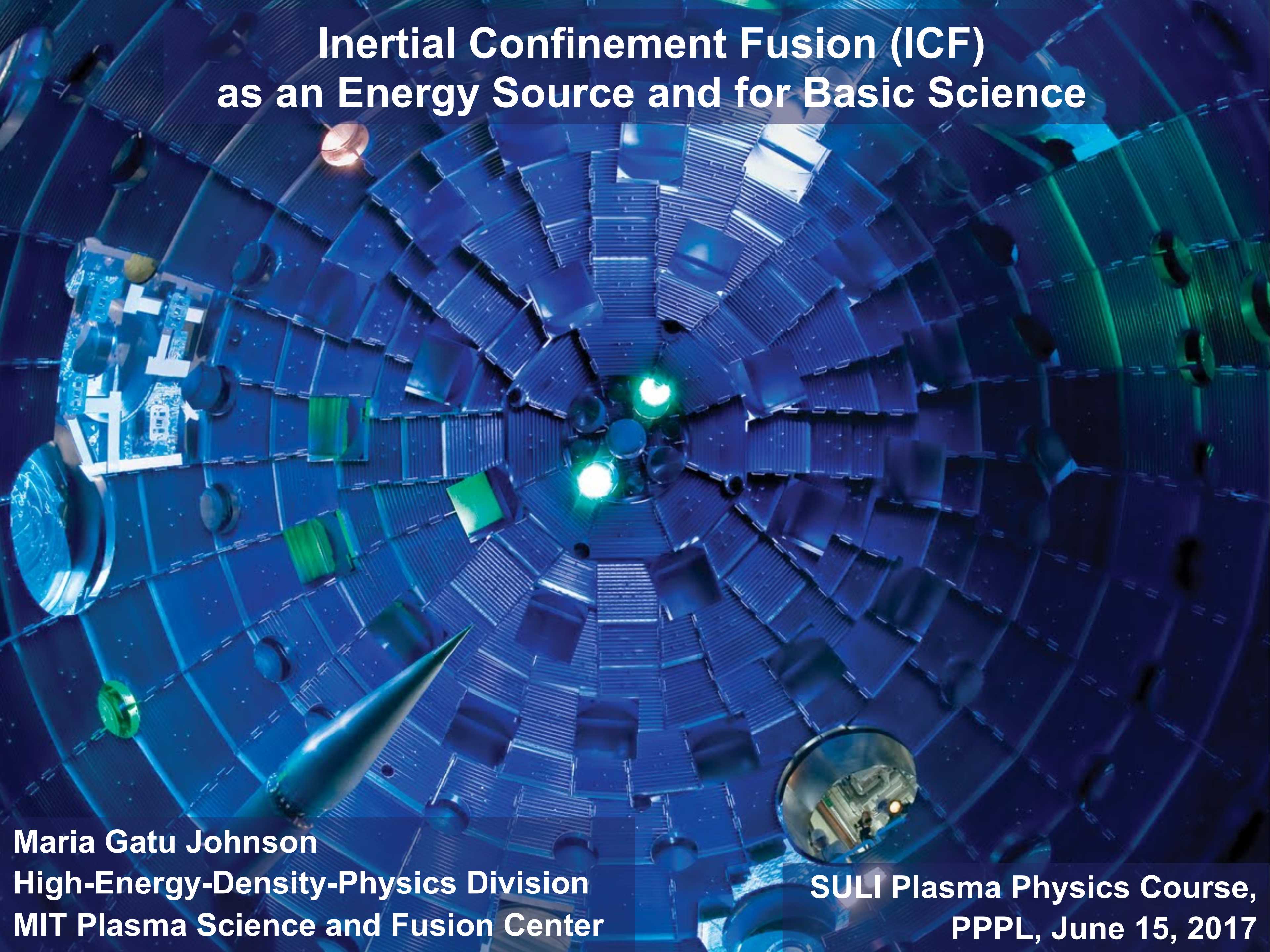
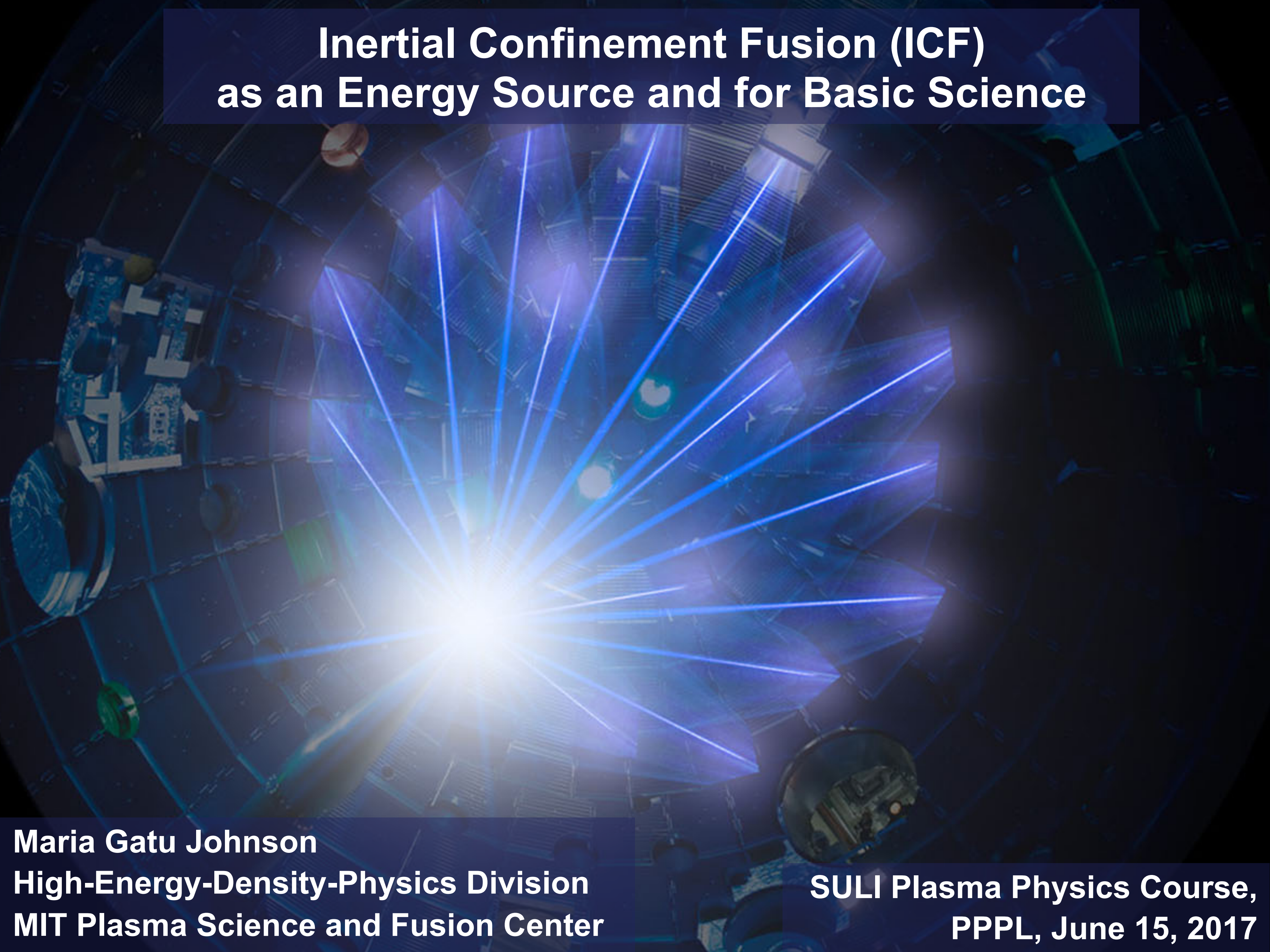


Inertial Confinement Fusion (ICF) as an Energy Source and for Basic Science

Maria Gatu Johnson
High-Energy-Density-Physics Division
MIT Plasma Science and Fusion Center

SULI Plasma Physics Course,
PPPL, June 15, 2017



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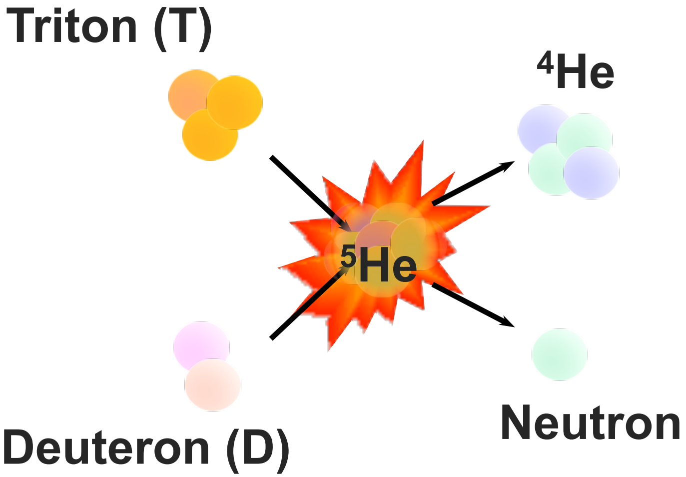
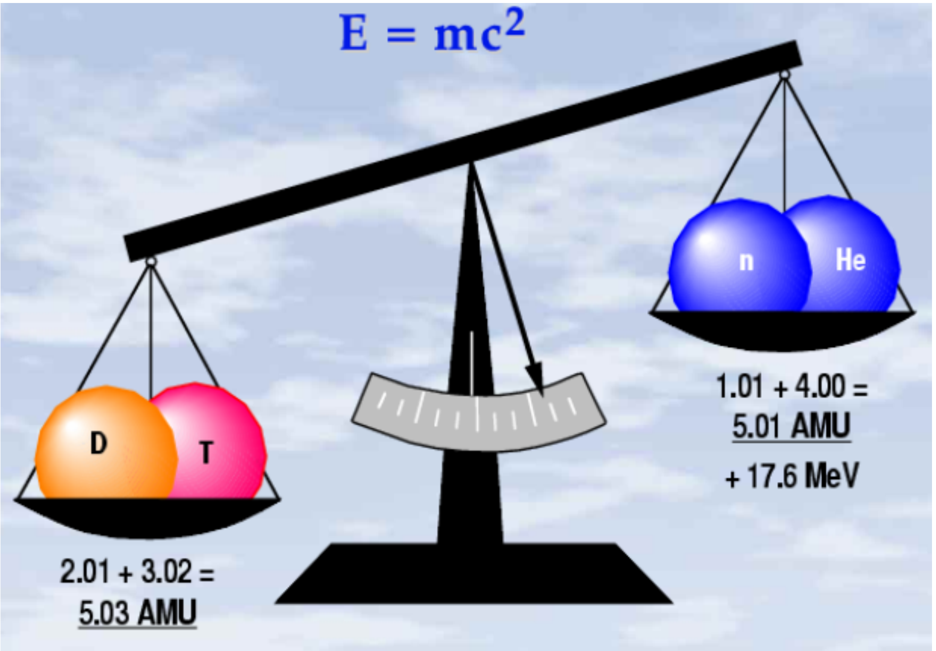
Outline

- **Fusion Basics**
- **The principle of Inertial Confinement Fusion (ICF)**
- **ICF facilities**
  - The OMEGA laser facility
  - The Z pulsed power machine
  - The National Ignition Facility (NIF)
- **NIF experiments**
  - Status
  - Engineering and scientific challenges
- **Basic-science experiments on OMEGA and the NIF**

Fusion combines light nuclei to a heavy nucleus and releases huge amount of energy (~10^6× more than fossil fuel / AMU)

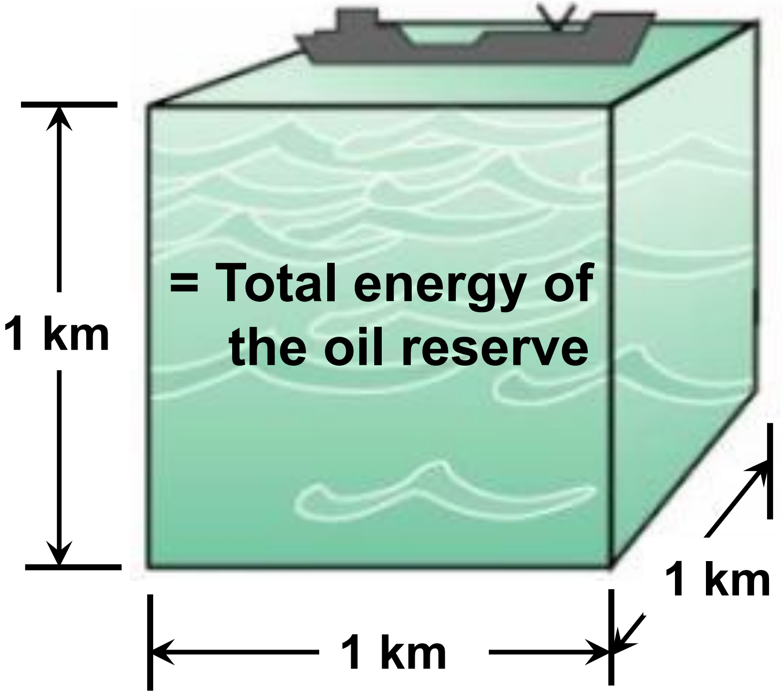
D + T → ^{4}He + Neutron + Kinetic energy





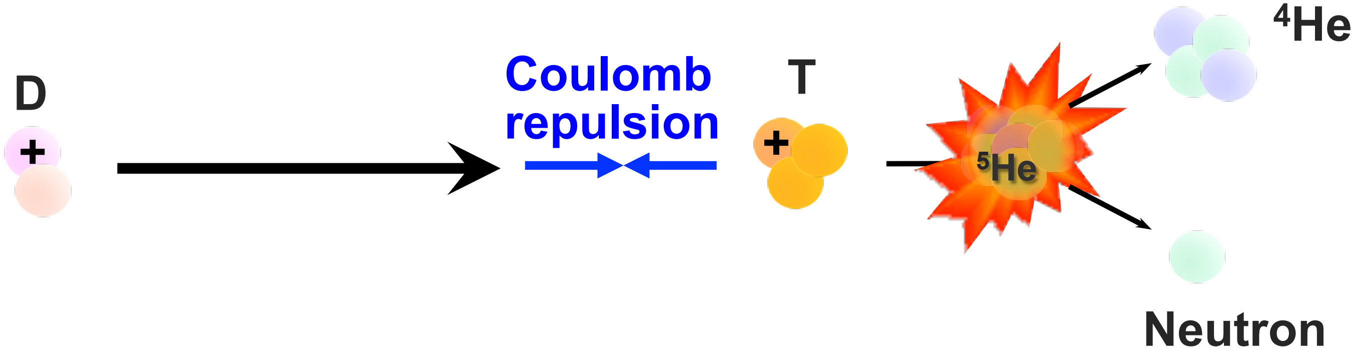
In DT fusion, ~0.4 % mass is converted to kinetic energy

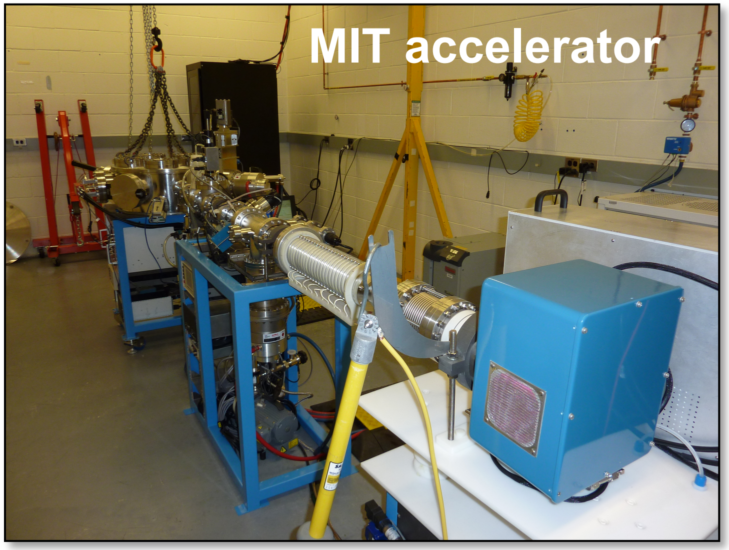
Deuterium is extracted from sea water (~1 part in 5000 of the hydrogen in seawater is deuterium)



Tritium is unstable and does not exist naturally. It must be produced in a reactor via the n+^{6}Li and n+^{7}Li reactions

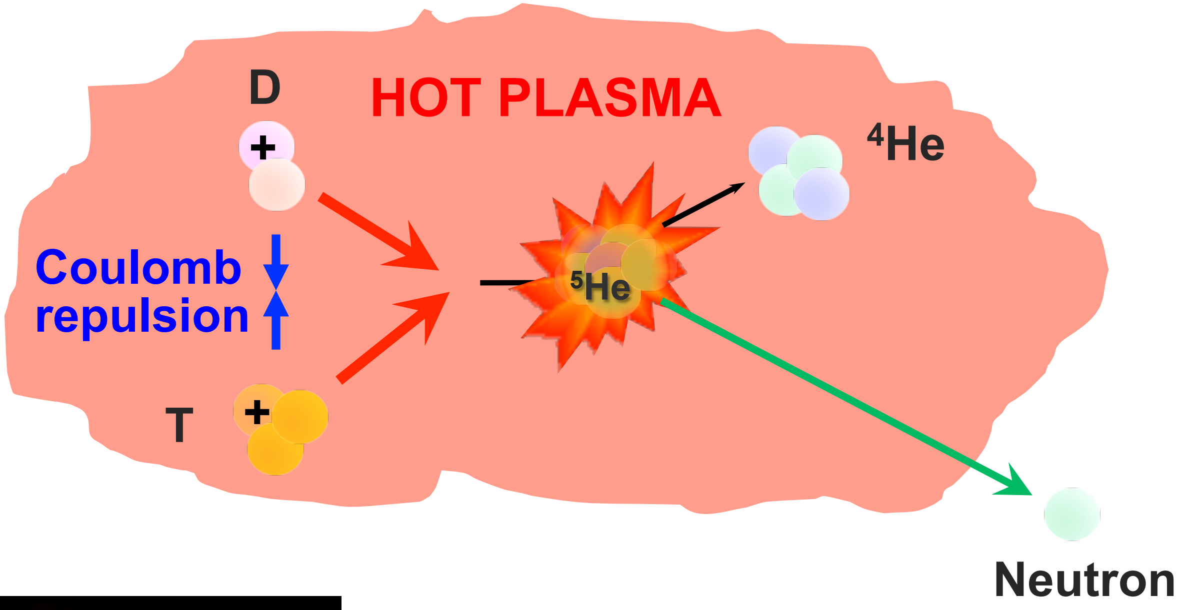
It takes energy to overcome the Coulomb barrier. Particles can be accelerated (Beam Fusion)

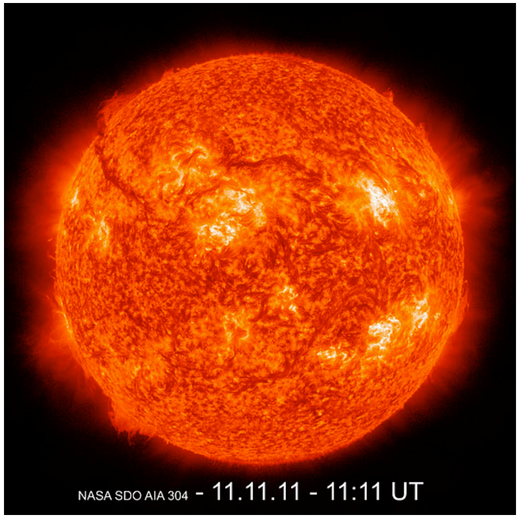




Very ineffective approach as most energy is lost to heating the cold target electrons

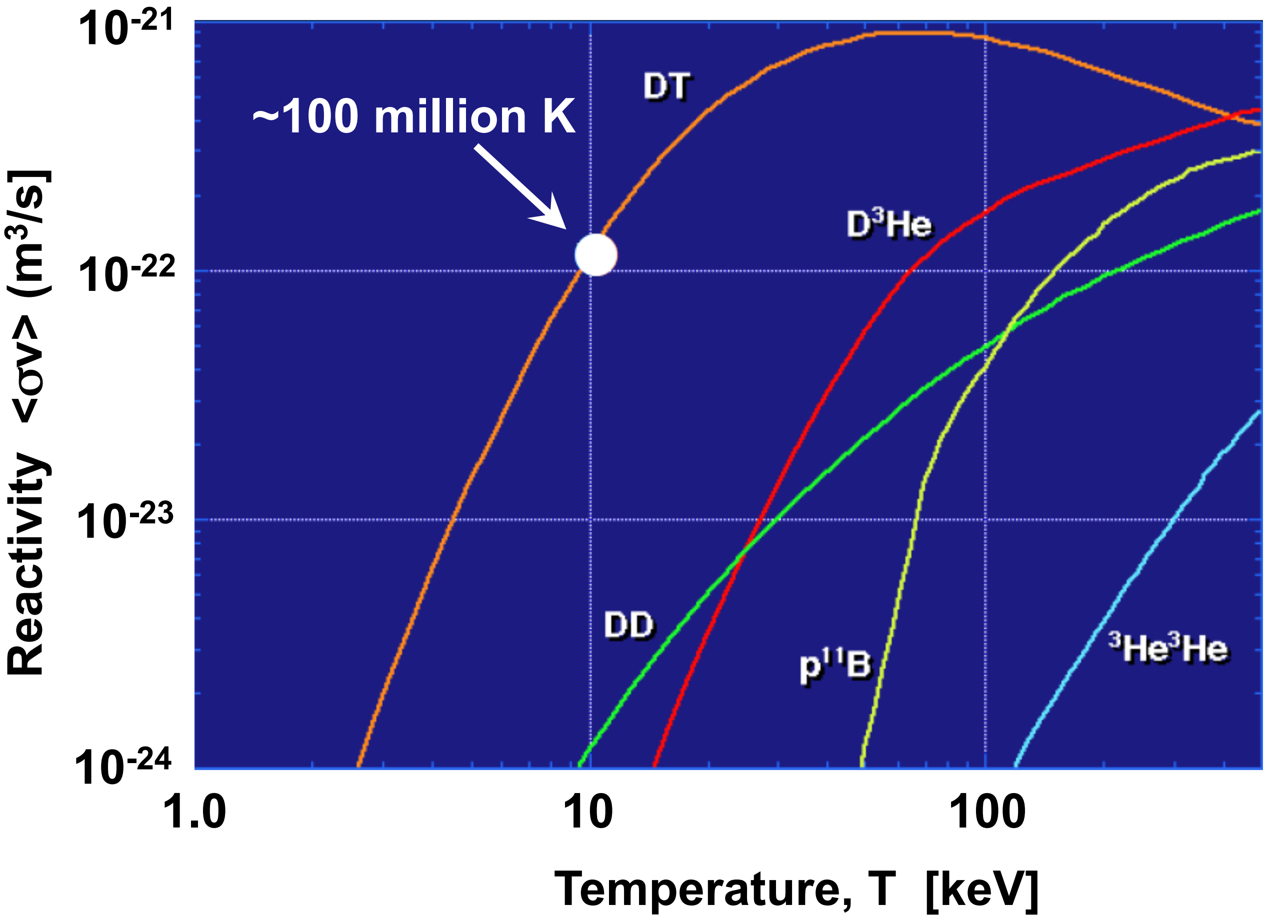
It takes energy to overcome the Coulomb barrier. Particles can be heated (Thermonuclear Fusion)





If the ions are sufficiently hot (i.e. large random velocity), they can overcome the coulomb repulsion and fuse

Fusion does not come easy! We need ~100 million Kelvin for a significant number of fusion reactions to occur

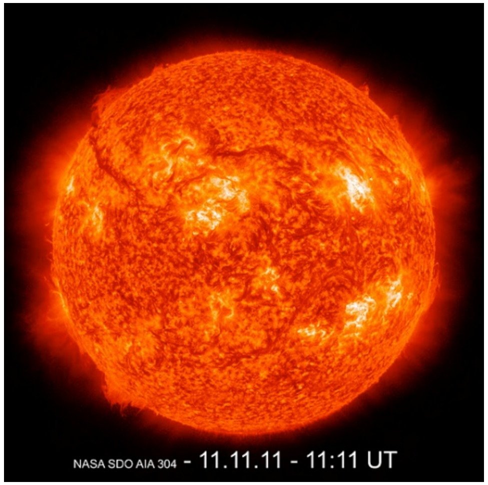


$\text{Yield} = n_i \times n_j \times <\sigma v>_{ij} \times \text{Volume} \times \text{time}$

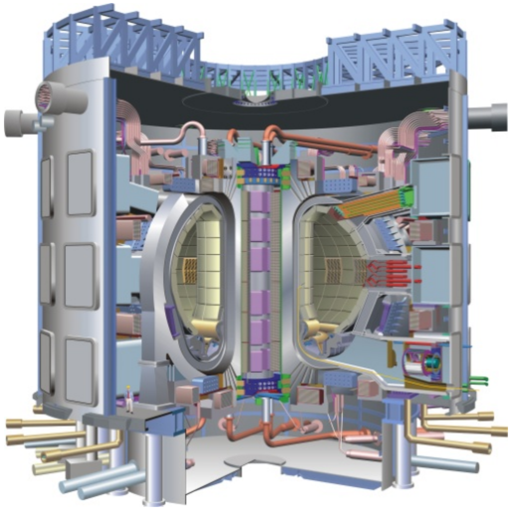
The plasma also needs to be at high enough density and confined for a long enough time…

There are three main approaches to confining a fusion plasma

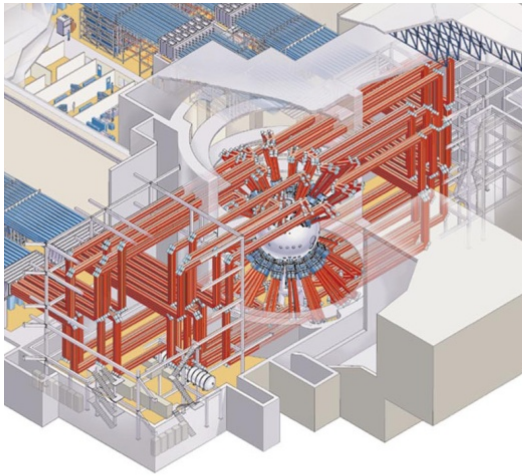
Gravitational confinement

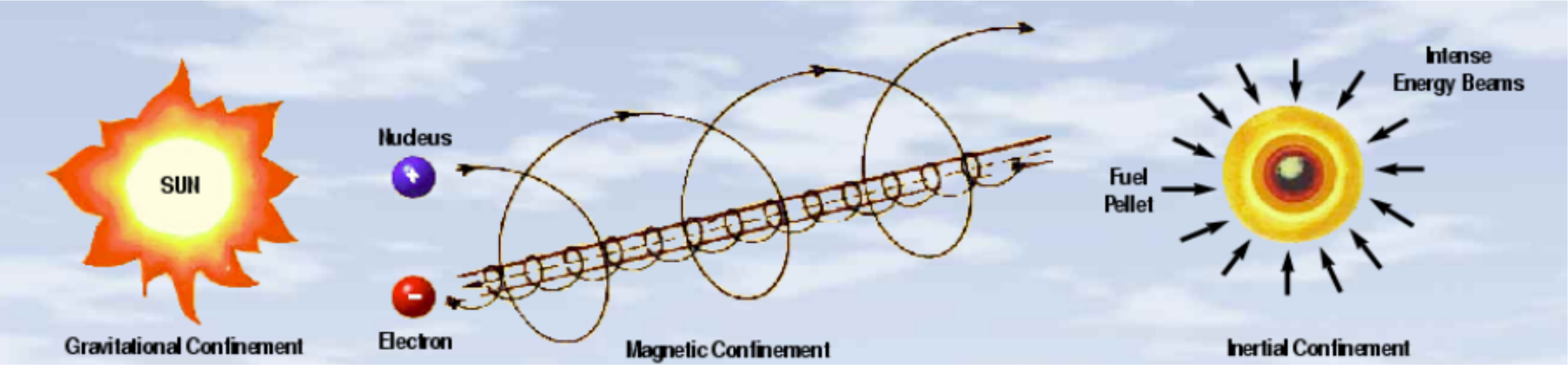


Magnetic confinement



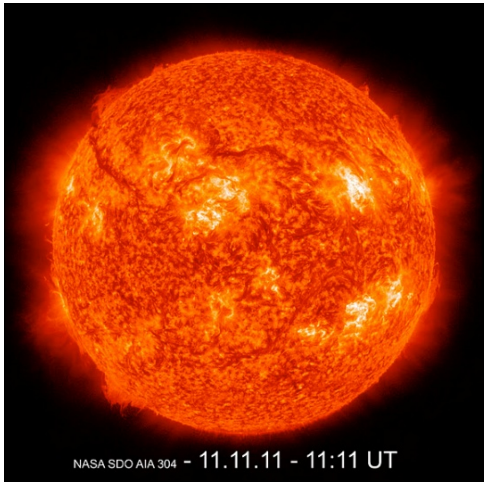
Inertial confinement



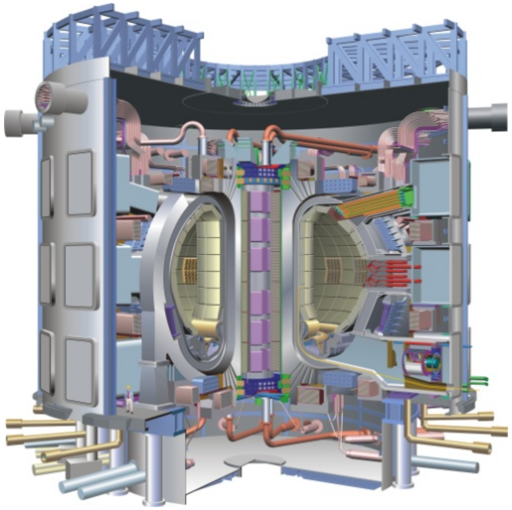


The fusion plasma conditions and confinement times are very different for the three approaches

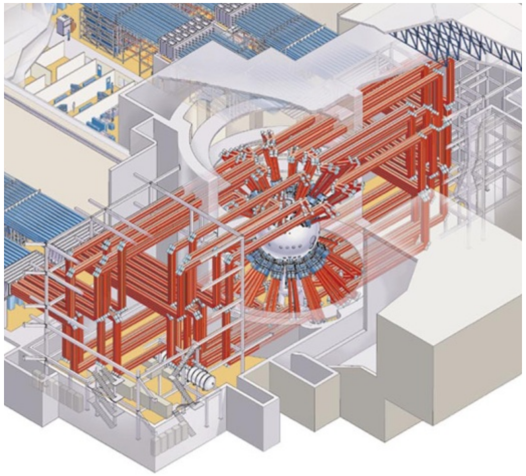
Gravitational confinement


NASA SDO AIA 304 - 11.11.11 - 11:11 UT

Magnetic confinement



Inertial confinement



Gravitational confinement	Magnetic confinement	Inertial confinement
$n \sim 10^{26}$ cm^{-3}	$n \sim 10^{14}$ cm^{-3}	$n \sim 10^{26}$ cm^{-3}
$T \sim$ 15 million K	$T \sim$ 100 million K	$T \sim$ 100 million K
$\tau_c \sim 10^4$ years	$\tau_c \sim 1$ s	$\tau_c \sim 3\times10^{-11}$ s

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ICF uses the inertia of a dense shell to confine the plasma before it blows apart under its own pressure

The confinement time (τ_c) can be expressed in terms of the sound speed c_s:

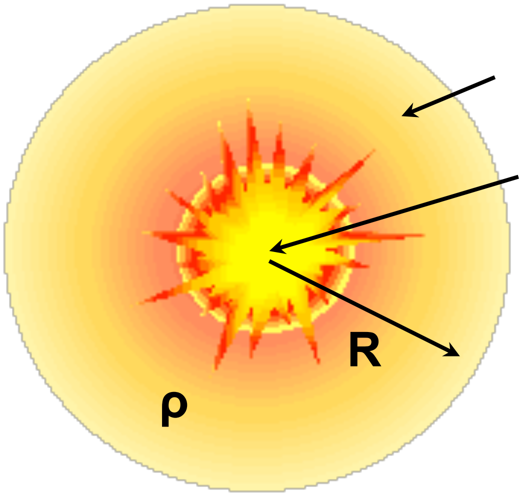
Local confinement time:

$$\tau_{local} = \frac{R-r}{c_S}$$

Mass average:

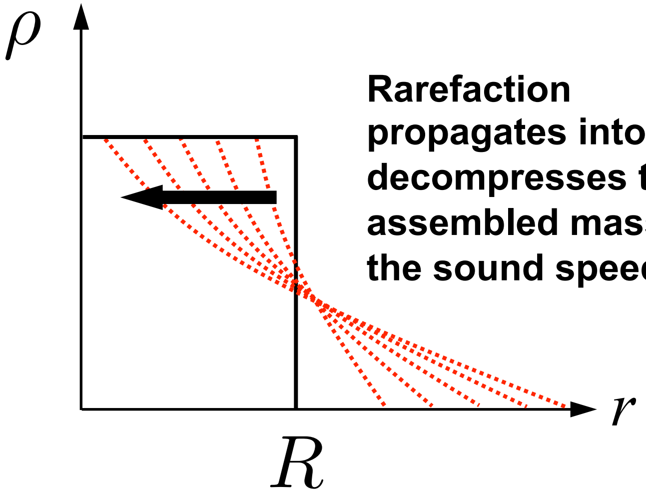
$$\tau_c = \int \tau_{local} \frac{\rho dV}{\rho V} = \int_0^R \frac{R-r}{c_S} \frac{4\pi r^2}{4/3\,\pi r^2} dr =$$

$$= \frac{R}{4c_S}$$



High-density DT shell

DT gas core



Rarefaction propagates into and decompresses the assembled mass at the sound speed c_s

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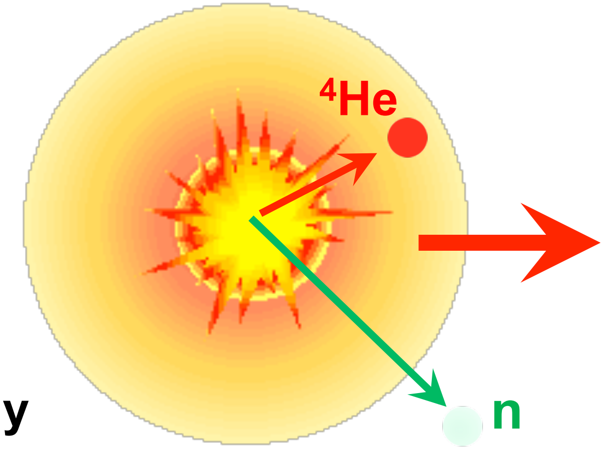
M. Rosen, Phys. Plasmas **6**, 1690 (1999)

"Areal density" ρR is a key performance parameter in ICF

The confinement parameter *($n\tau_c$)* can now be expressed as:

$$n\tau_c = \frac{\rho_{DT}}{m_{DT}}\frac{R}{4C_s} = \frac{1}{4m_{DT}C_s}\rho R$$

Ignition occurs when fusion energy carried/deposited by the ^{4}He ions balances the energy losses



Energy losses:

- ~~Radiation~~
- ~~Thermal conduction~~
- PdV expansion

^{4}He ion energy = 3.6 MeV

Ideal gas law

$$V\frac{\varepsilon_\alpha}{4}\left\langle n_i^2\langle\sigma v\rangle\right\rangle > \frac{3pV}{2\tau_c} = \frac{3n_iT}{\tau_c}V \Rightarrow n\tau_c > \frac{12T}{E_\alpha\langle\sigma v\rangle_{DT}} > 2\times10^{15}\,cm^{-3}s$$

at ~5 keV

Fusion reactivity **Energy confinement**

The ignition criterion for ICF is ~20 times higher than that of MCF due to inefficiencies in assembling the fuel

The fuel burn fraction (f) depends on ρR

Fusion burn rate

$$\frac{dn_T}{dt} = -n_T n_D \langle \sigma v \rangle$$

$$\frac{dn}{dt} = -\frac{n^2}{2}\langle \sigma v \rangle \quad ; \quad n_T = n_D = \frac{n}{2}$$

Integrate over confinement time

$$\frac{1}{n_{\text{final}}} - \frac{1}{n_{\text{init}}} = \frac{1}{2}\langle \sigma v \rangle \tau$$

$$\tau \simeq \frac{R}{4c_s}$$

$$n_{init} = \rho / m_{DT}$$

Burn fraction

$$f = 1 - \frac{n_{\text{final}}}{n_{\text{init}}} = \frac{\rho R}{\rho R + 8 m_i c_s / \langle \sigma v \rangle} \simeq \frac{\rho R}{\rho R + 6 \text{ g/cm}^2}; \; T_i = 30 \text{ keV}$$

M. Rosen, Phys. Plasmas **6**, 1690 (1999)

A high ρR is required for high $n\tau_c$ values and for a significant fraction of the fuel to burn before it disassembles

$$\left.\begin{array}{l} \text{If } f_b = 25\% \text{ (required for ignition)} \longrightarrow \rho R_{DT} \sim 2\ \text{g/cm}^2 \\ \rho_{DT,\ \text{solid}} = 0.25\ \text{g/cm}^3 \end{array}\right\} \longrightarrow$$

For ignition, we need a DT-fuel mass (m_{DT}) of about

$$m_{DT} = \rho_{DT} V = \frac{4\pi}{3} \frac{(\rho_{DT} R)^3}{\rho_{DT}^2} = \frac{4\pi}{3} \frac{(2g/cm^2)^3}{(0.25g/cm^3)^2} \sim 0.5\ kg$$

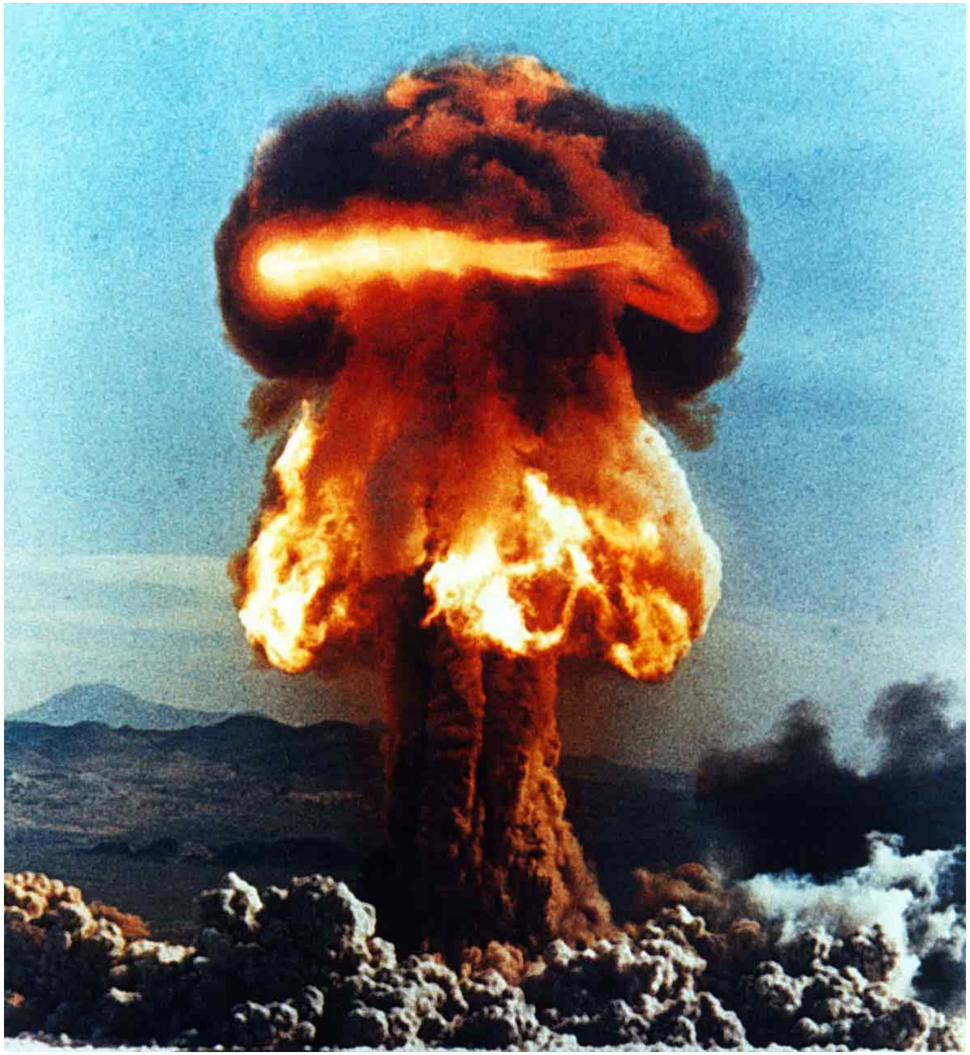
So what's the problem? Why can we not work with 0.5 kg of DT fuel in a fusion reactor?

Burn fraction

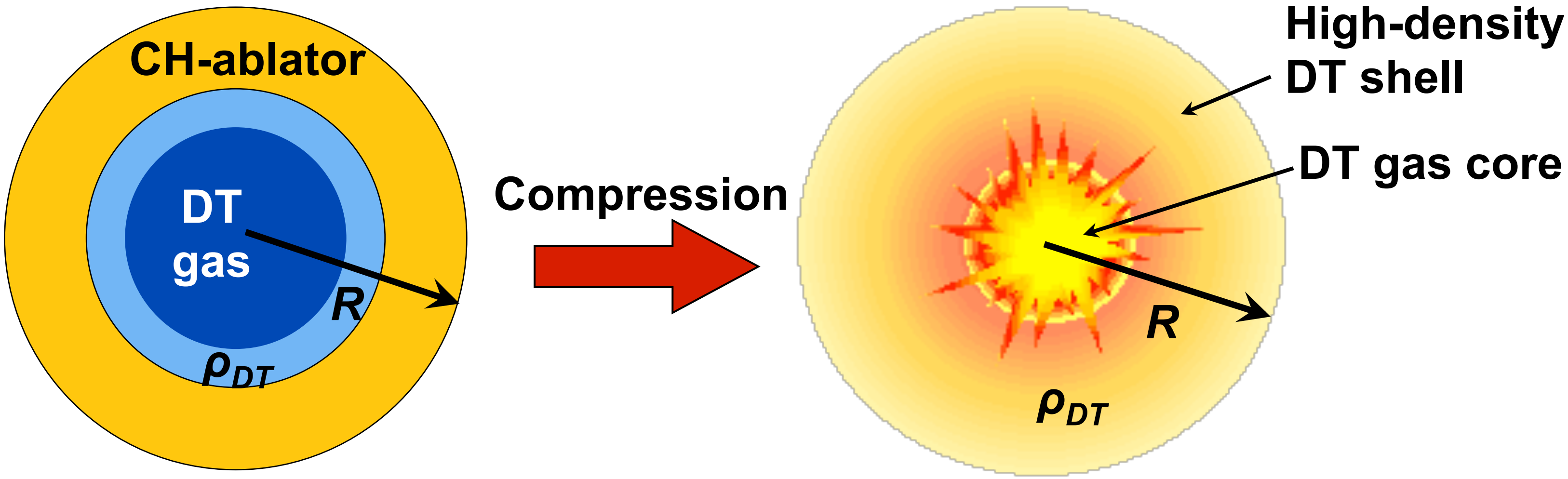
DT mass

$$Yield = 0.25 * (0.5\,kg)\left(\frac{80\,kT}{kg}\right)$$

$$Yield \sim 10\,kT$$



Solution: compress the ICF capsule to increase ρ_{DT}



$R \sim 1100\ \mu\text{m}$

$\rho_{DT} = 0.25\ \text{g/cm}^3$

$\rho R_{DT} \sim 0.03\ \text{g/cm}^2$

$R \sim 30\ \mu\text{m}$

$\rho_{DT} \sim 700\ \text{g/cm}^3$

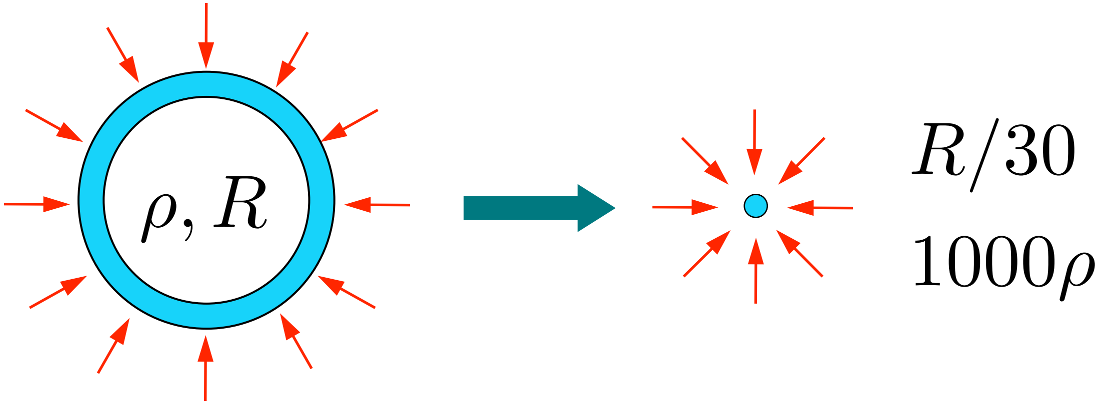
$\rho R_{DT} \sim 2\ \text{g/cm}^2$

Spherical compression is most efficient

Must exploit R^3 compression with spheres – R^2 or R^1 scaling with cylindrical or planar compression is not adequate

$$M = \frac{4\pi}{3}\rho_{\mathrm{init}}R_{\mathrm{init}}^3 = \frac{4\pi}{3}\rho_{\mathrm{final}}R_{\mathrm{final}}^3 \Rightarrow \frac{\rho_{\mathrm{final}}}{\rho_{\mathrm{init}}} = \left(\frac{R_{\mathrm{init}}}{R_{\mathrm{final}}}\right)^3$$

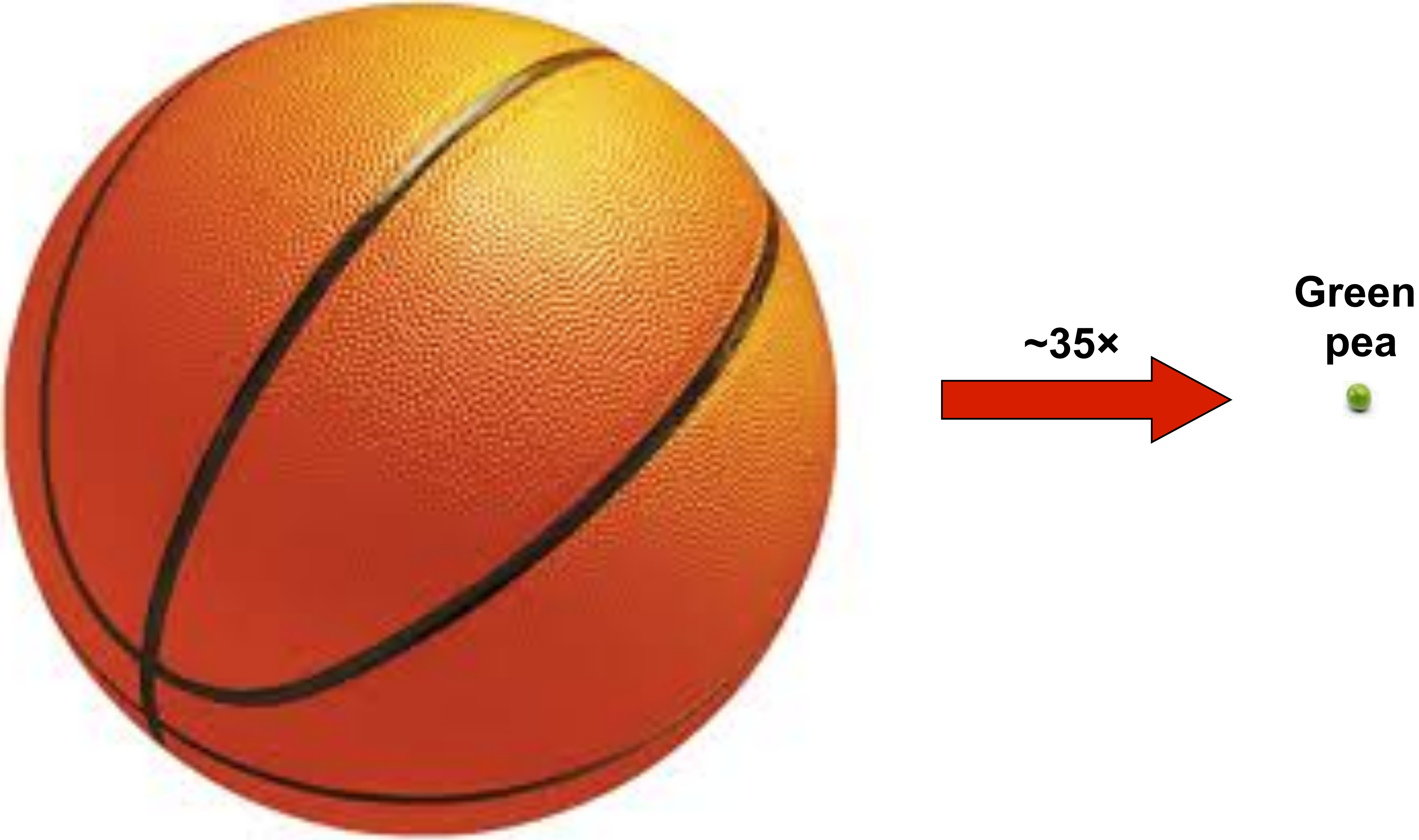
In practice, a hollow shell has more surface area and is easier to push with a given pressure than a solid sphere of the same mass



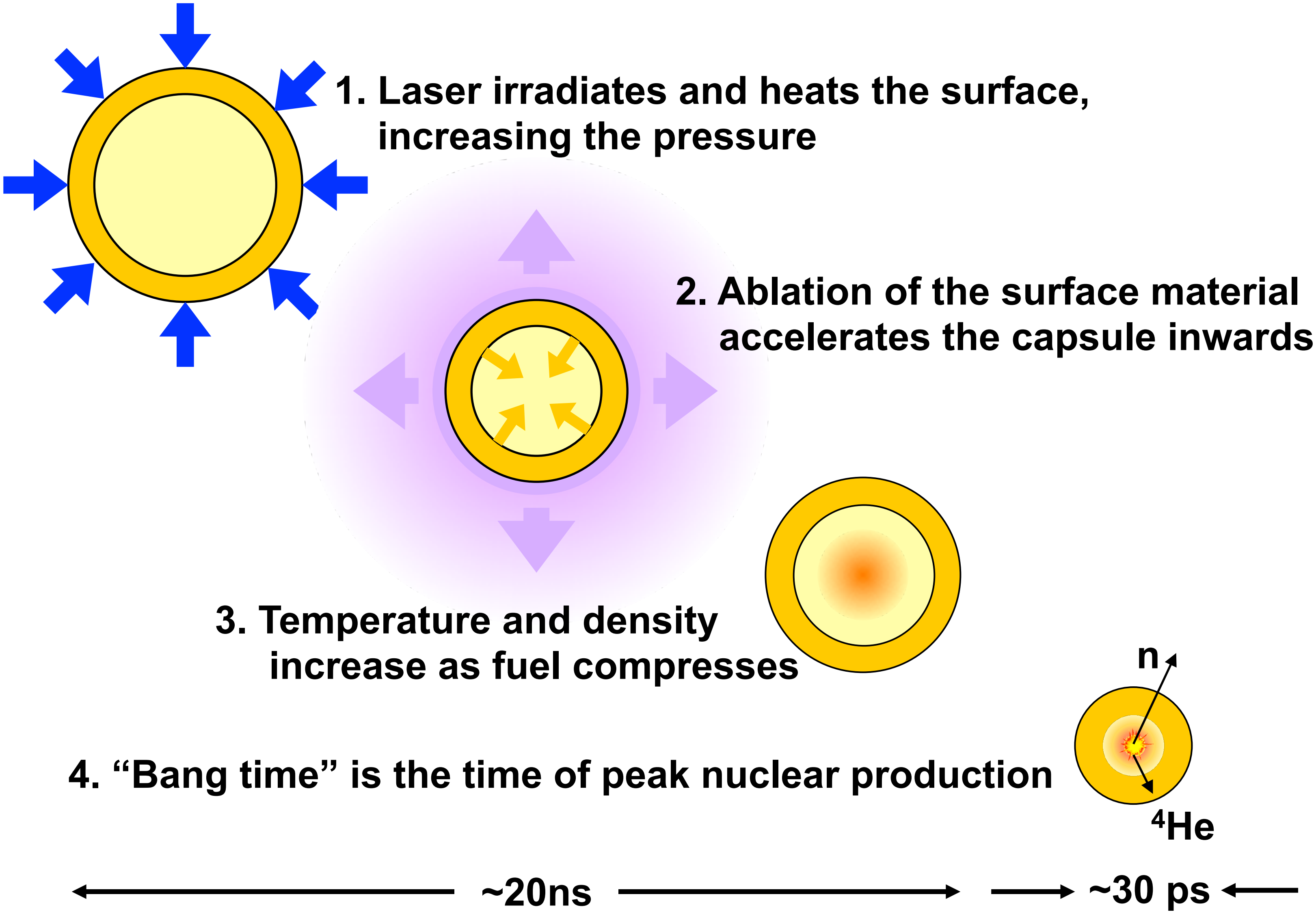
Goal: Convert shell kinetic energy to compression energy

$$\frac{1}{2}Mv_{\mathrm{imp}}^2 \rightarrow E_{\mathrm{comp}}$$

The capsule must be compressed ~35× ($\delta R/R < 1\%$) to achieve the right conditions (Basketball → green pea)



ICF implosion timeline



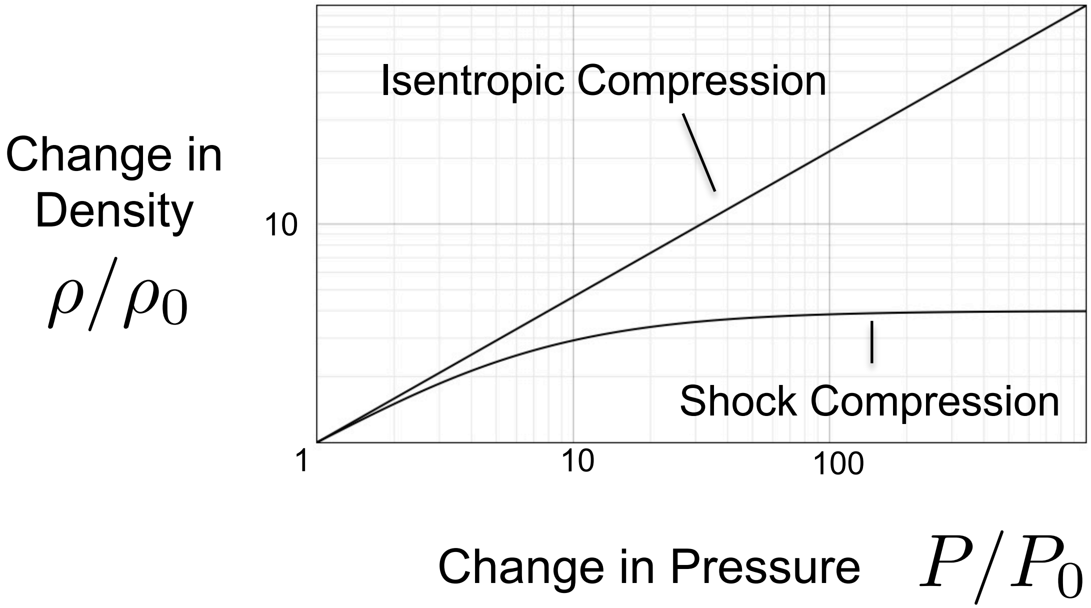
1. Laser irradiates and heats the surface, increasing the pressure
2. Ablation of the surface material accelerates the capsule inwards
3. Temperature and density increase as fuel compresses
4. “Bang time” is the time of peak nuclear production

The most efficient compression is isentropic

From thermodynamics: $dU = TdS - PdV$

$$-PdV = dU - TdS$$

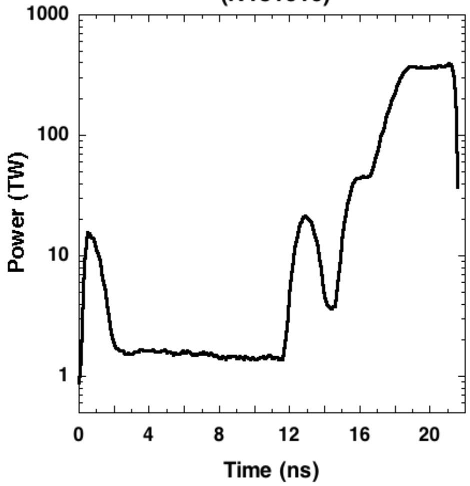
Minimize Work Needed to Compress ⟺ **Minimize Entropy Generation**

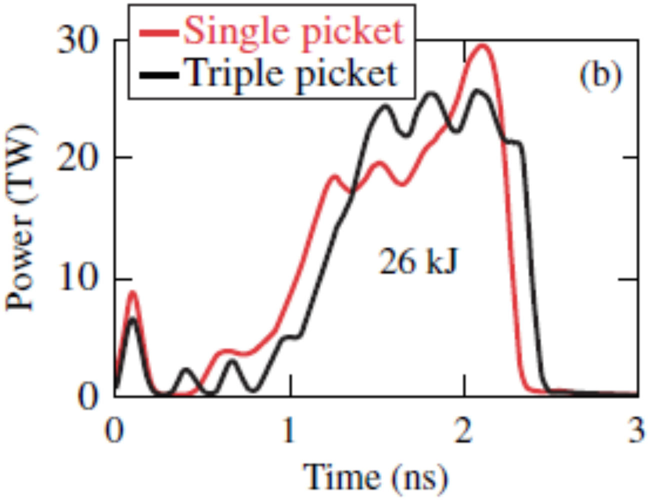


But ICF doesn’t have ideal compression

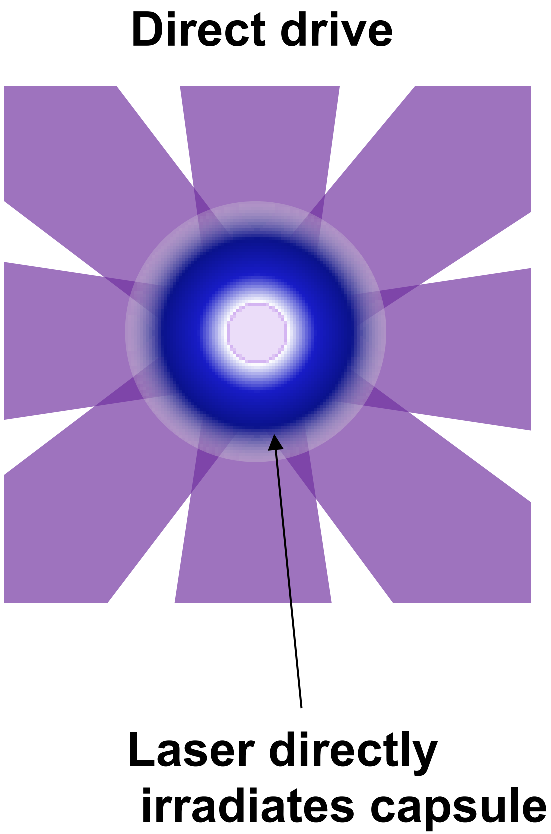
- Fast time-scales lead to shocks, which have compression limits
  - Solution: Multiple timed shocks to keep implosion as efficient as possible. A “shaped” pulse.

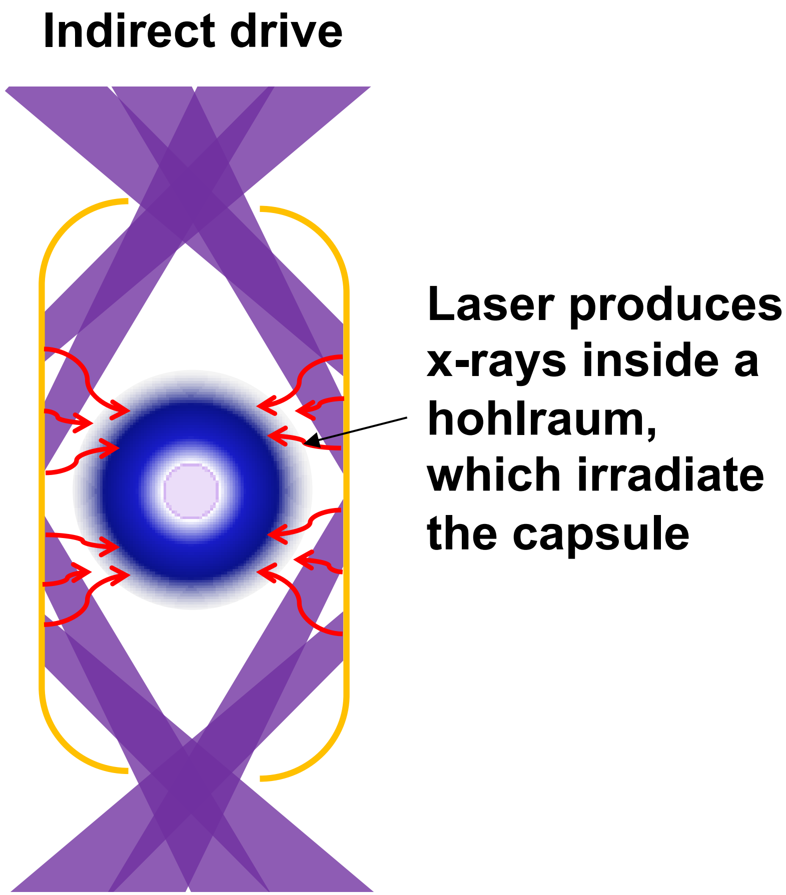
For this reason, shaped laser pulse are used


Laser pulse for standard low-foot (N131010)



There are two different laser-drive schemes





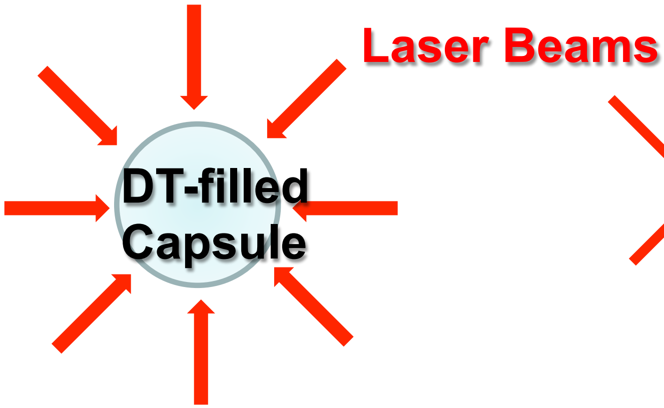
~8% efficiency

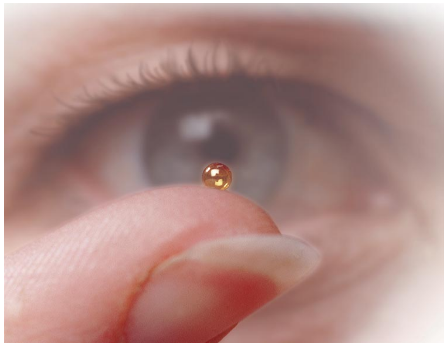
~4% efficiency

The two approaches trade efficiency for uniformity

In addition, there is also a magnetic drive scheme, for a total of three primary approaches to ICF

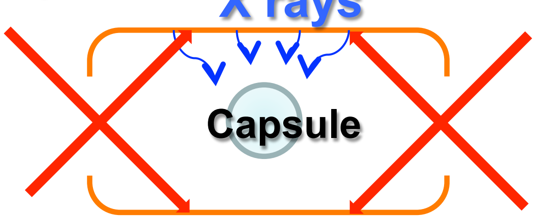
Direct Drive

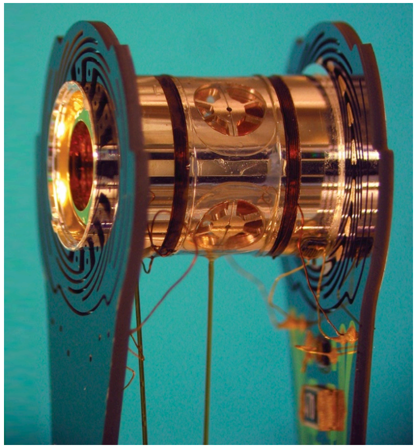




A NIF Capsule
(2 mm diam.)

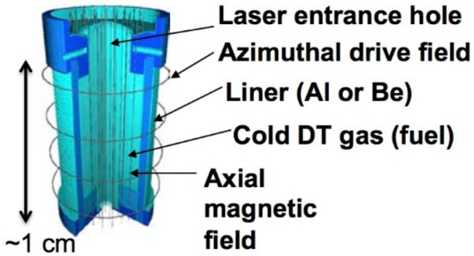
Indirect Drive

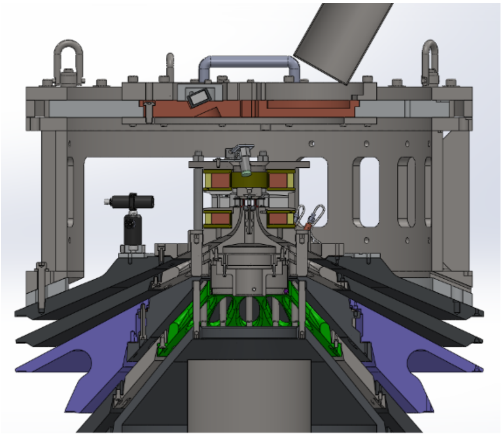




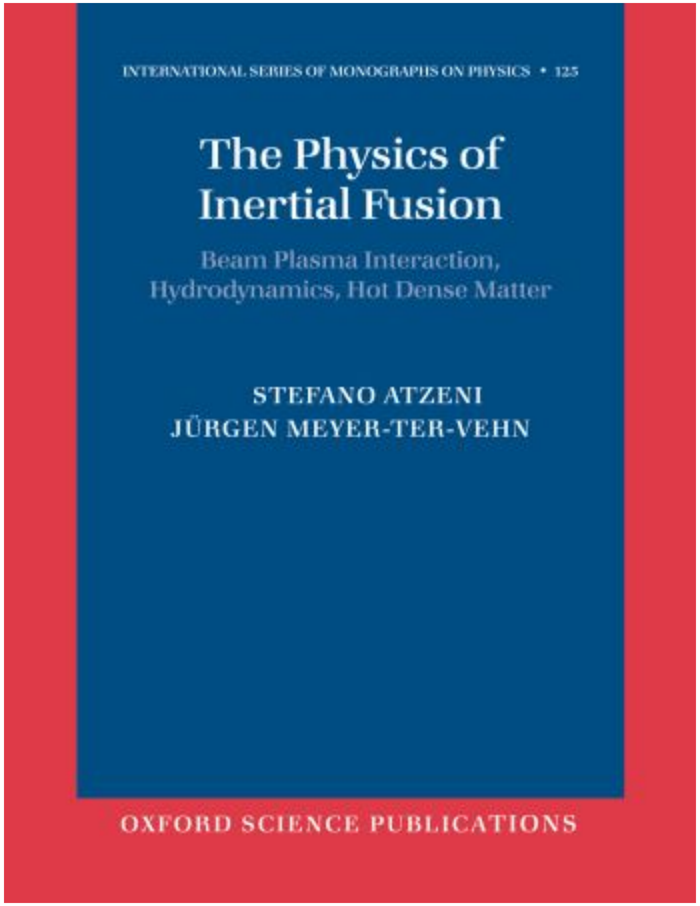
High-Z Hohlraum

Magnetic Drive





Want to know more? A good book on the basics of ICF is "The Physics of Inertial Fusion" by Atzeni and Meyer-Ter-Vehn



INTERNATIONAL SERIES OF MONOGRAPHS ON PHYSICS • 125

The Physics of
Inertial Fusion

Beam Plasma Interaction,
Hydrodynamics, Hot Dense Matter

STEFANO ATZENI
JÜRGEN MEYER-TER-VEHN

OXFORD SCIENCE PUBLICATIONS

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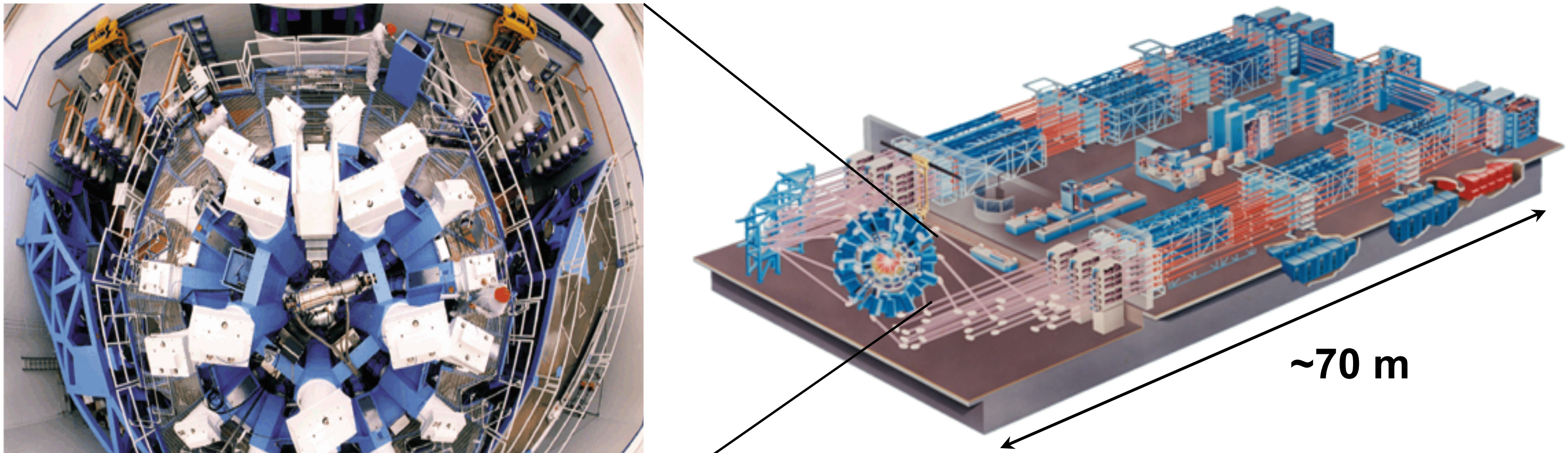
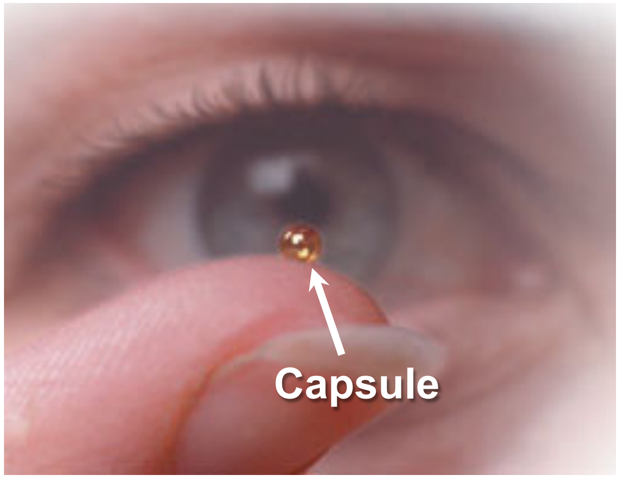
The OMEGA laser facility at University of Rochester uses the direct-drive approach




Direct-drive implosion



60 laser beams delivering 30 kJ

The goal of direct-drive experiments at OMEGA is to demonstrate ignition feasibility for indirect drive

60 kJ energy available on OMEGA.

If laser energy was scaled up to 2 MJ, would the direct drive implosions ignite?

Currently trying to demonstrate this by reaching 100 Gbar pressure. 50 Gbar demonstrated

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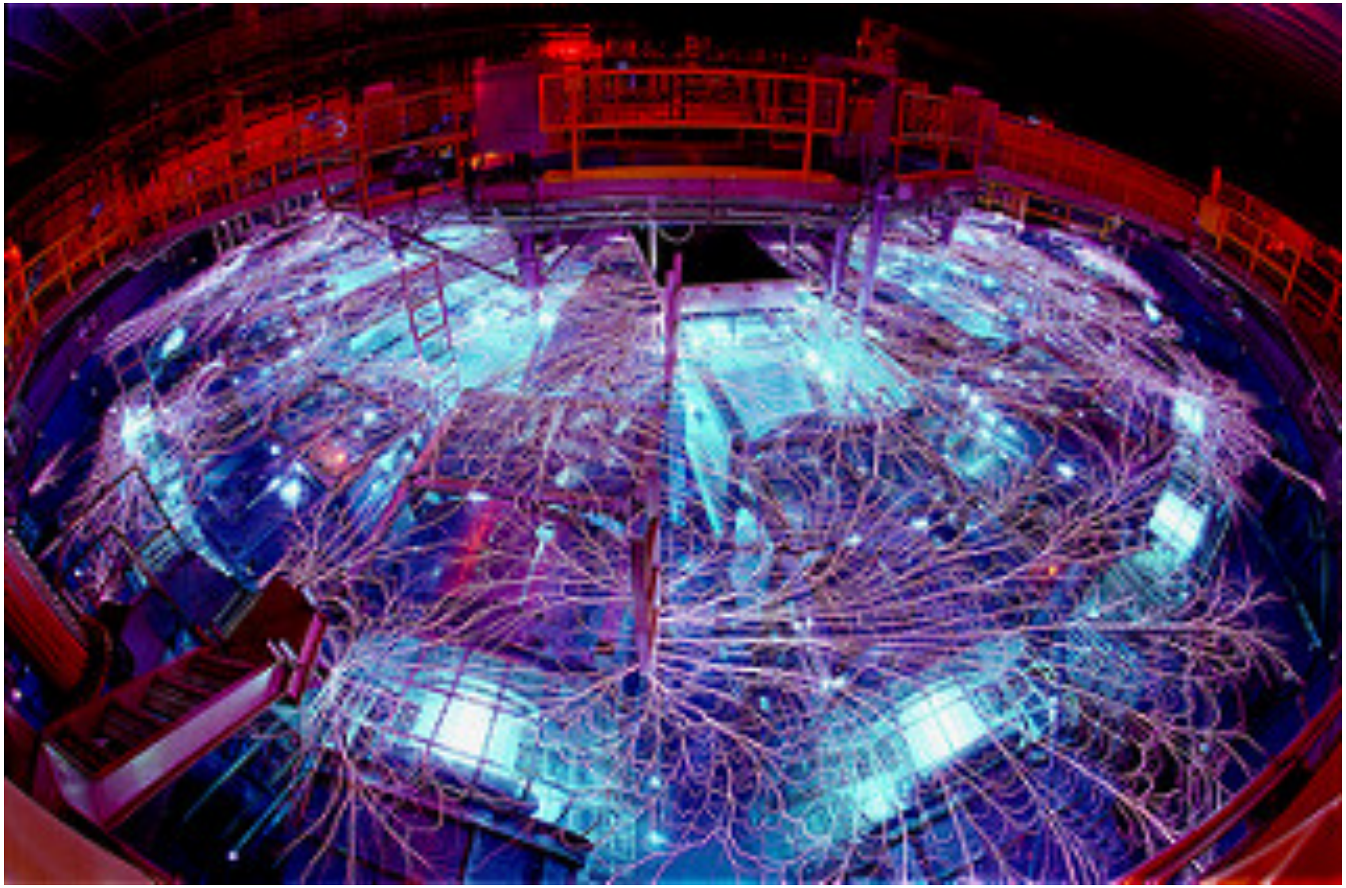
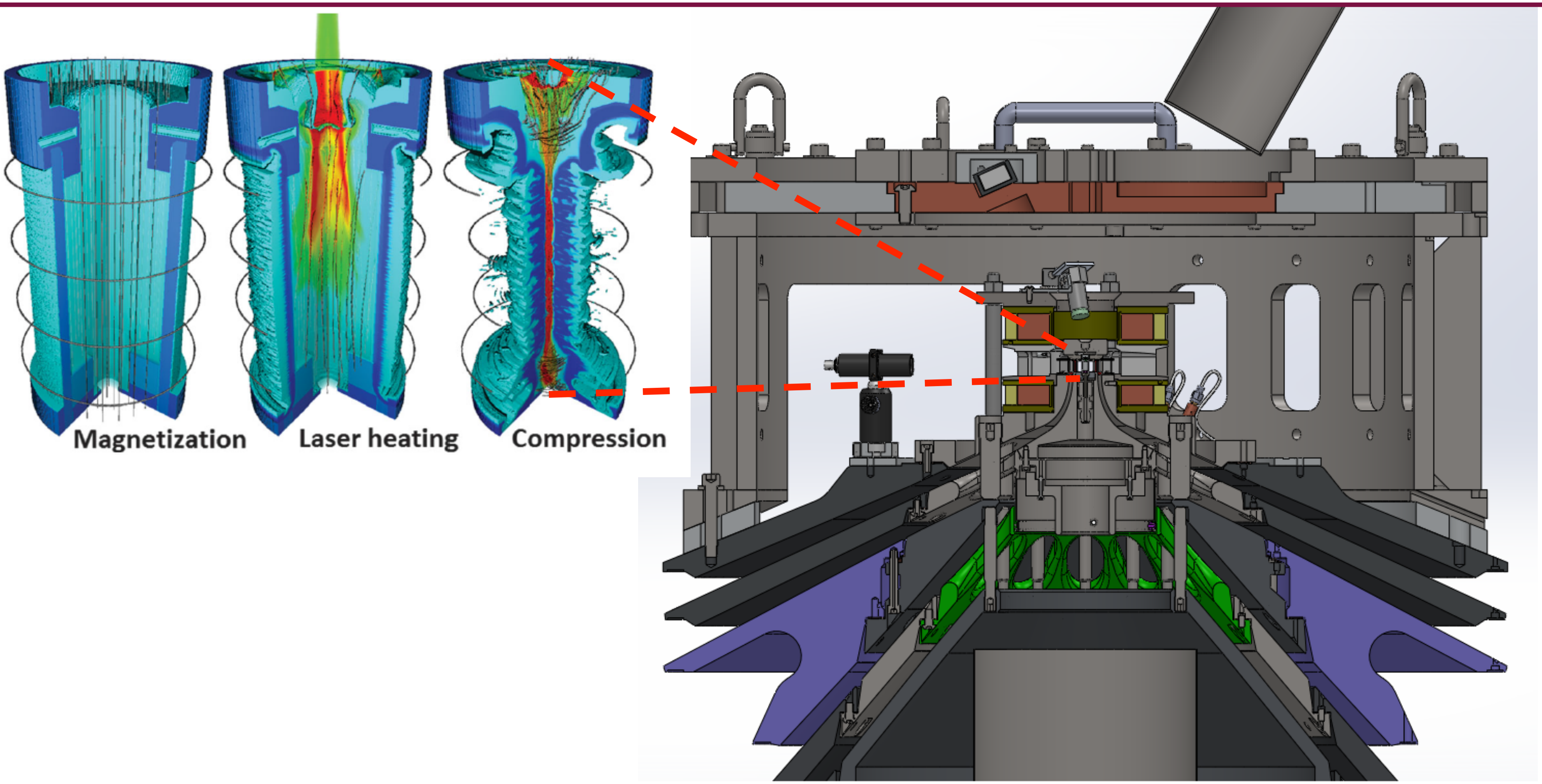
S. Regan, Phys. Rev. Lett. **117**, 025001 (2016)

Magnetic drive ICF is being pursued at the Z pulsed power facility at Sandia National Labs, NM



- 80 TW
- 33 Meter diameter
- 26 MA
- 22 MJ Stored Energy

In magnetic drive ICF, an axial current creates a JxB force that is used to implode a gas-filled, pre-magnetized target

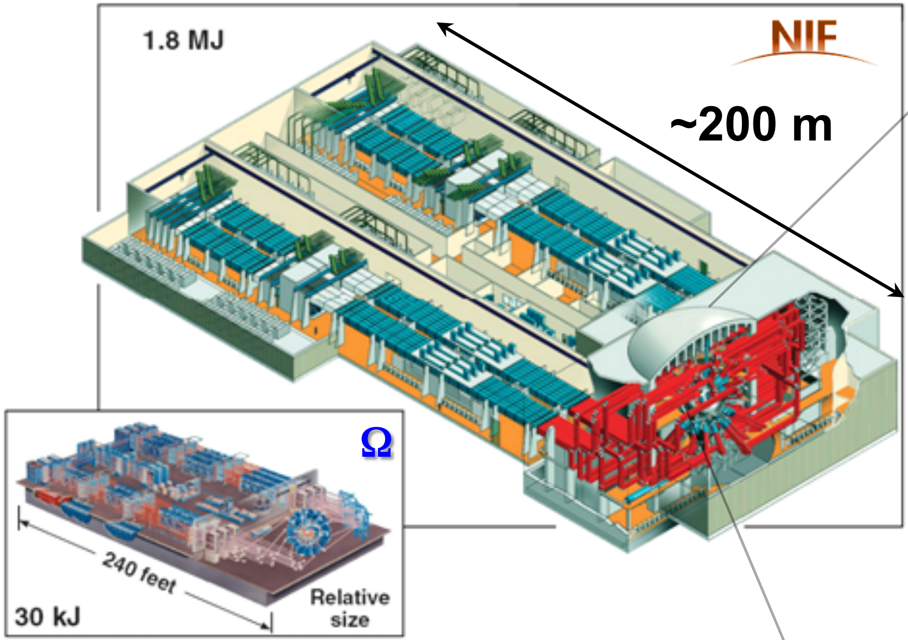


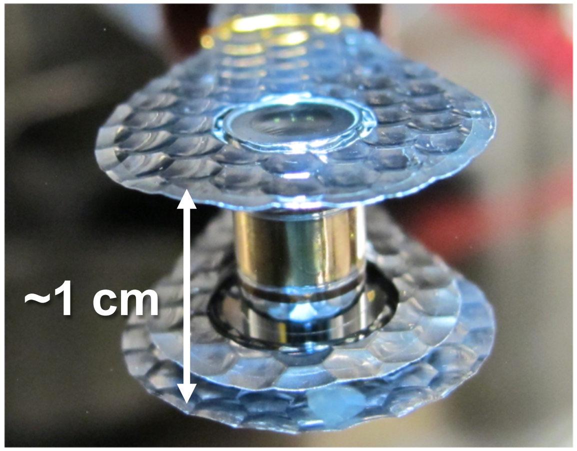
Goal: Demonstrate ~100kJ DT eq fusion yield

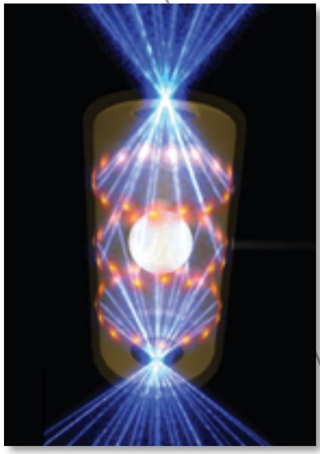
The National Ignition Facility (NIF) is a three football stadium-sized laser, which uses the indirect-drive approach

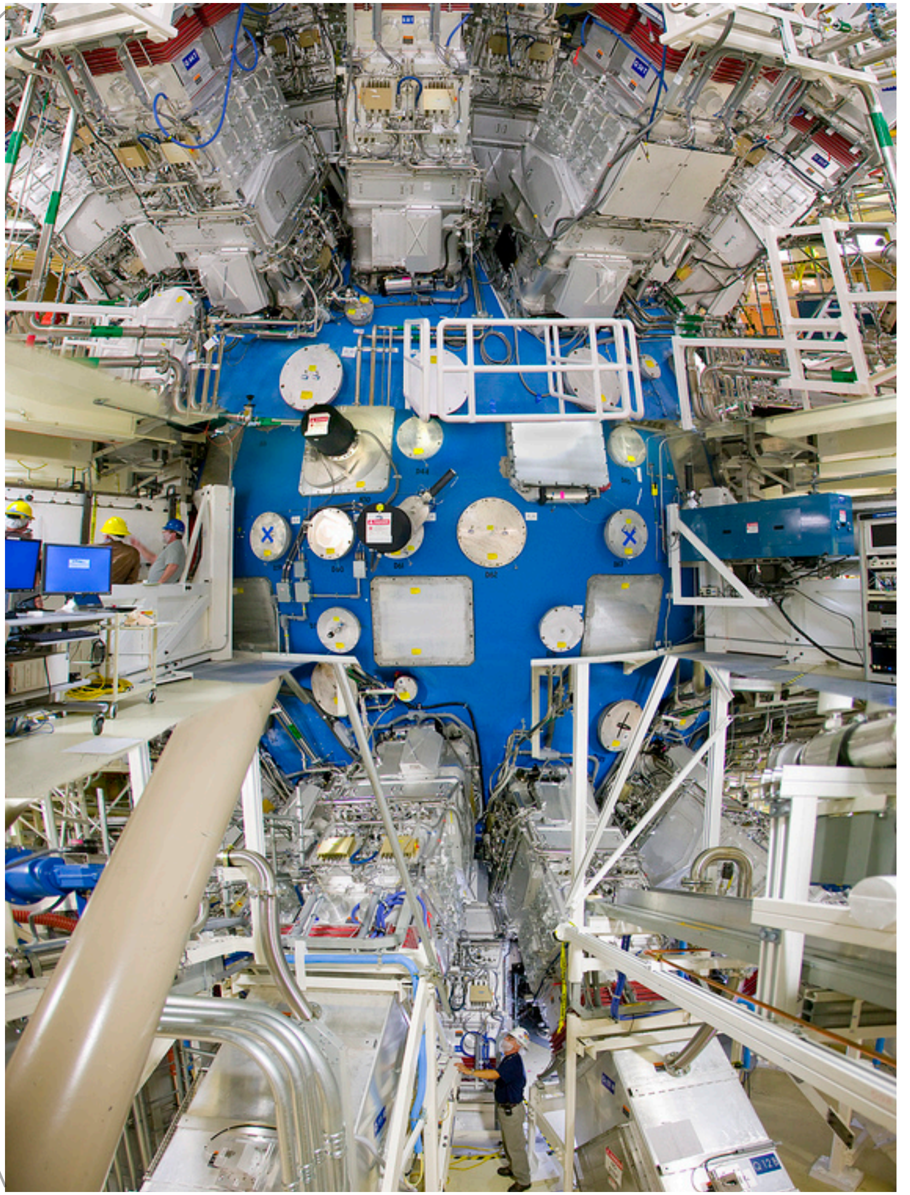
10 m diameter chamber
192 beams
Temperature > 100 MK
Density > 1000× solid
Pressure > 10^{11} atm

NIF delivers about 1.8 MJ of laser energy to a cm-scaled hohlraum

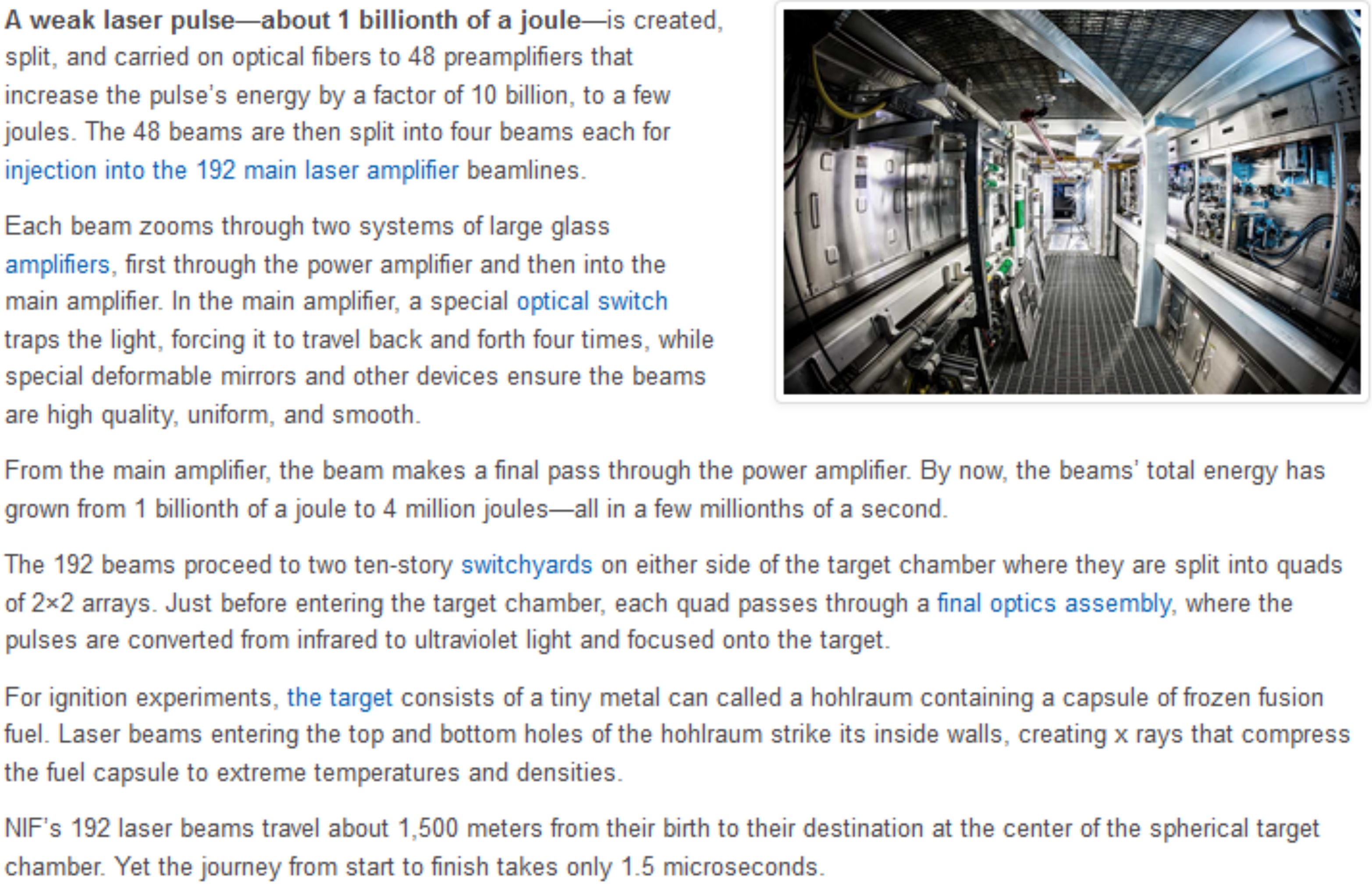








Movie time!



A weak laser pulse—about 1 billionth of a joule—is created, split, and carried on optical fibers to 48 preamplifiers that increase the pulse's energy by a factor of 10 billion, to a few joules. The 48 beams are then split into four beams each for injection into the 192 main laser amplifier beamlines.

Each beam zooms through two systems of large glass amplifiers, first through the power amplifier and then into the main amplifier. In the main amplifier, a special optical switch traps the light, forcing it to travel back and forth four times, while special deformable mirrors and other devices ensure the beams are high quality, uniform, and smooth.

From the main amplifier, the beam makes a final pass through the power amplifier. By now, the beams' total energy has grown from 1 billionth of a joule to 4 million joules—all in a few millionths of a second.

The 192 beams proceed to two ten-story switchyards on either side of the target chamber where they are split into quads of 2×2 arrays. Just before entering the target chamber, each quad passes through a final optics assembly, where the pulses are converted from infrared to ultraviolet light and focused onto the target.

For ignition experiments, the target consists of a tiny metal can called a hohlraum containing a capsule of frozen fusion fuel. Laser beams entering the top and bottom holes of the hohlraum strike its inside walls, creating x rays that compress the fuel capsule to extreme temperatures and densities.

NIF's 192 laser beams travel about 1,500 meters from their birth to their destination at the center of the spherical target chamber. Yet the journey from start to finish takes only 1.5 microseconds.

https://lasers.llnl.gov/about/how-nif-works

NIF was inaugurated in 2009 and is now being used for ignition and basic-science experiments

NIF also played an important role in the movie Star Trek – Into Darkness

Courtesy of Scott Chambliss, Paramount Pictures and Bad Robot Productions.

The ICF targets are really small!

Outline

- **Fusion Basics**

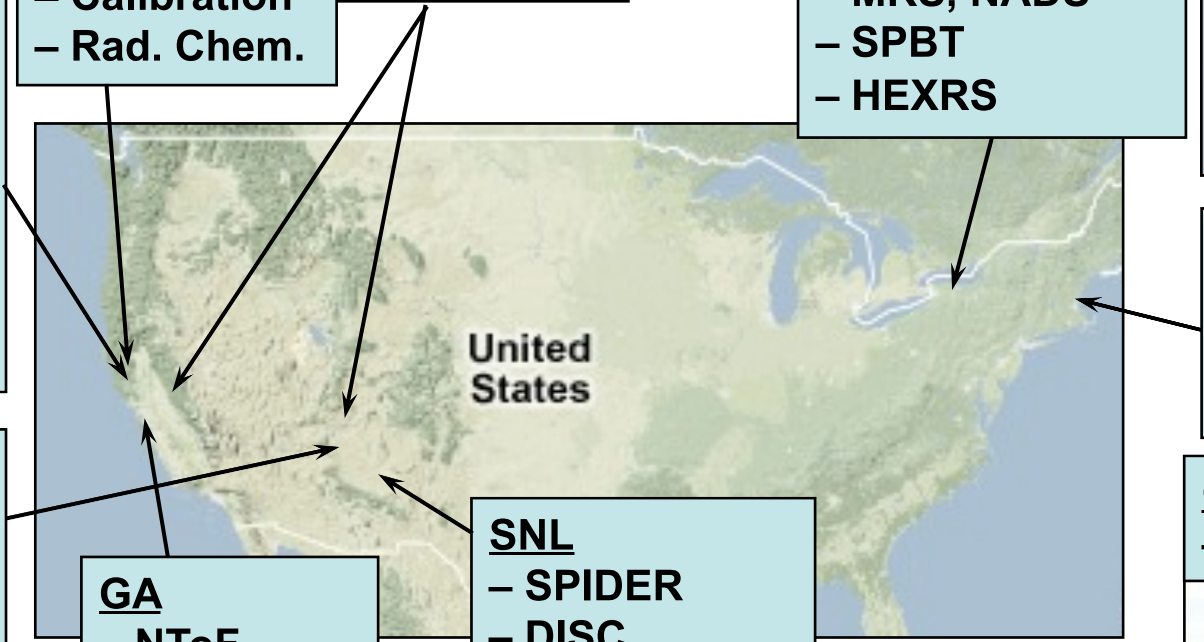
- **The principle of Inertial Confinement Fusion (ICF)**

- **ICF facilities**
  - The OMEGA laser facility
  - The Z pulsed power machine
  - The National Ignition Facility (NIF)

- **NIF experiments**
  - Status
  - Engineering and scientific challenges

- **Basic-science experiments on OMEGA and the NIF**

Many institutions are involved in the experiments on the NIF



LLNL
- FABS, NBI
- Dante I & II
- VISAR
- DISC
- RAGS
- hGXI
- ARIANE
- DIXI
- NAD

LBNL
- Calibration
- Rad. Chem.

NSTec
- Calibration
- NToF

LLE
- NToF
- 4ω fidu system
- MRS, NADS
- SPBT
- HEXRS

AWE
- FFLEX

MIT
- MRS
- WRF
- pTOF

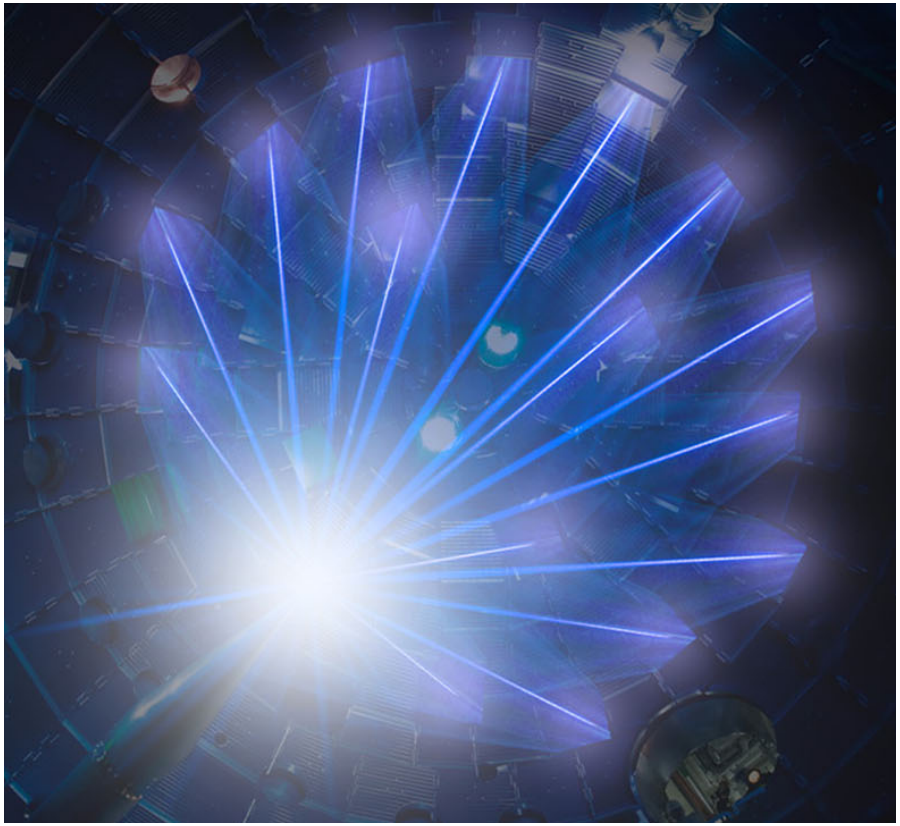
LANL
- GXD
- γ burn
- Rad. Chem. II
- N imaging

GA
- NToF
- Capsules

SNL
- SPIDER
- DISC
- NAD (Cu)
- NToF
- RAGS

CEA
- N imaging

A DT implosion is diagnosed with optical, x-ray and nuclear techniques on the NIF



Fusion yield:
- From DT neutrons

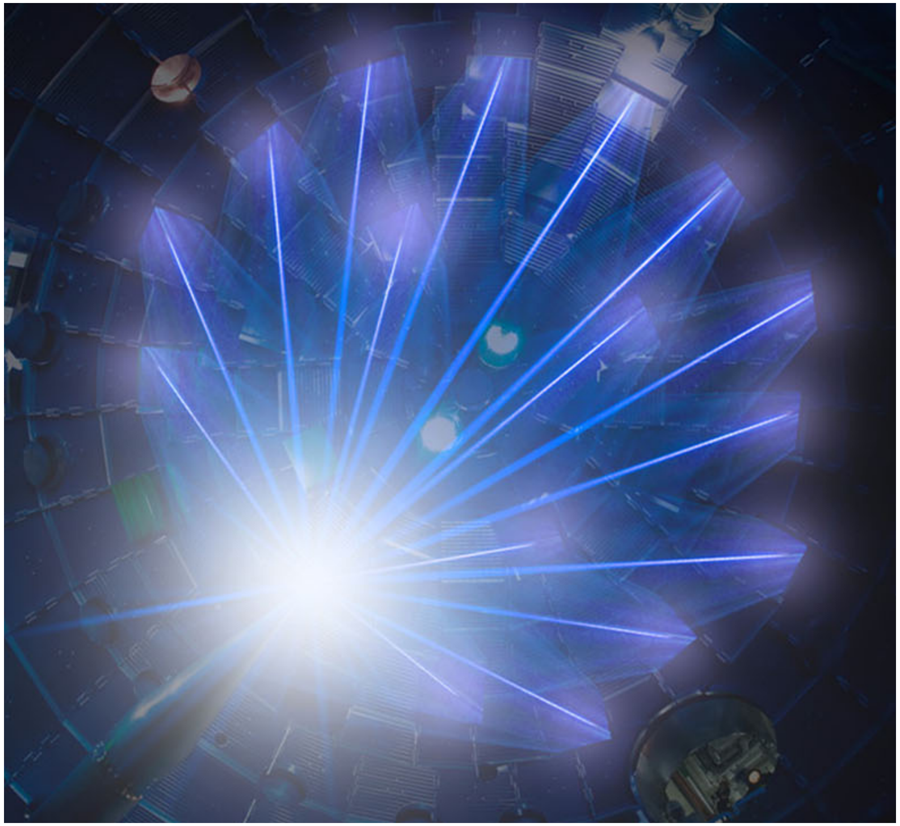
Fuel Ion temperature
- From DT-neutron spectrum

Areal density (ρR)
- From scattered DT neutrons

Implosion and burn history
- X-ray and neutron production

Implosion shape
- From x-ray and neutron images

A DT implosion is diagnosed with optical, x-ray and nuclear techniques on the NIF



Fusion yield:
- From DT neutrons

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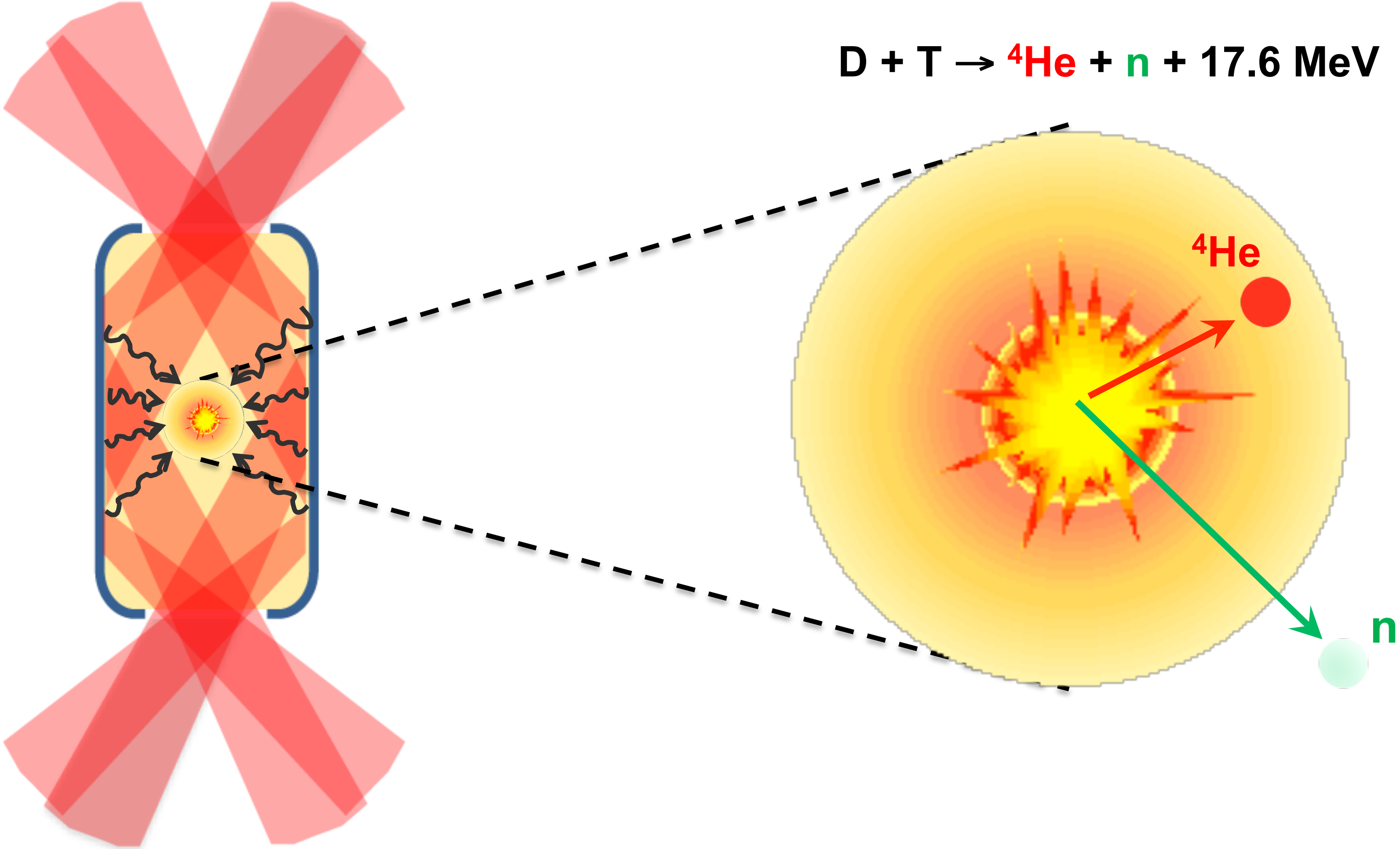
- From scattered DT neutrons

Implosion and burn history
- X-ray and neutron production

Implosion shape
- From x-ray and neutron images

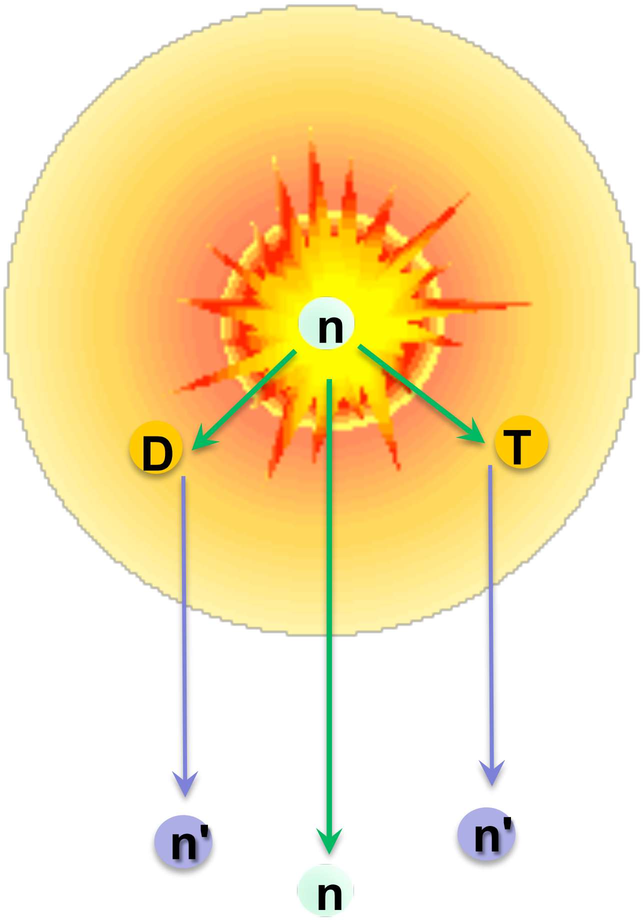
The ^{4}He ions (or alphas) are confined and heat the DT fuel, while the neutrons escape

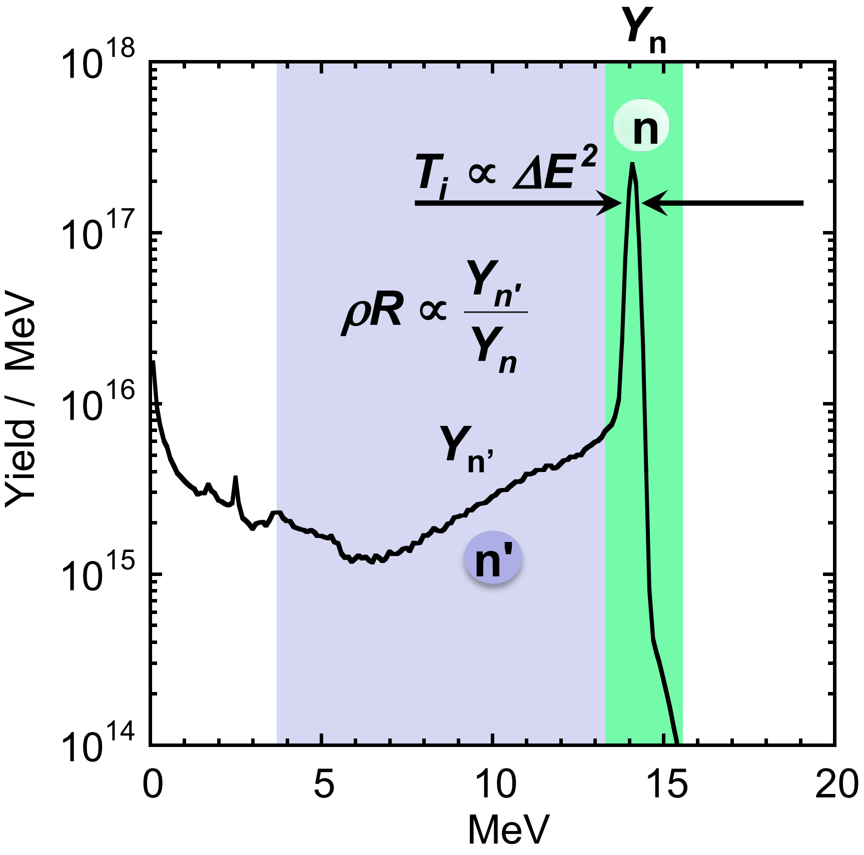
$D + T \rightarrow {}^4He + n + 17.6\ MeV$



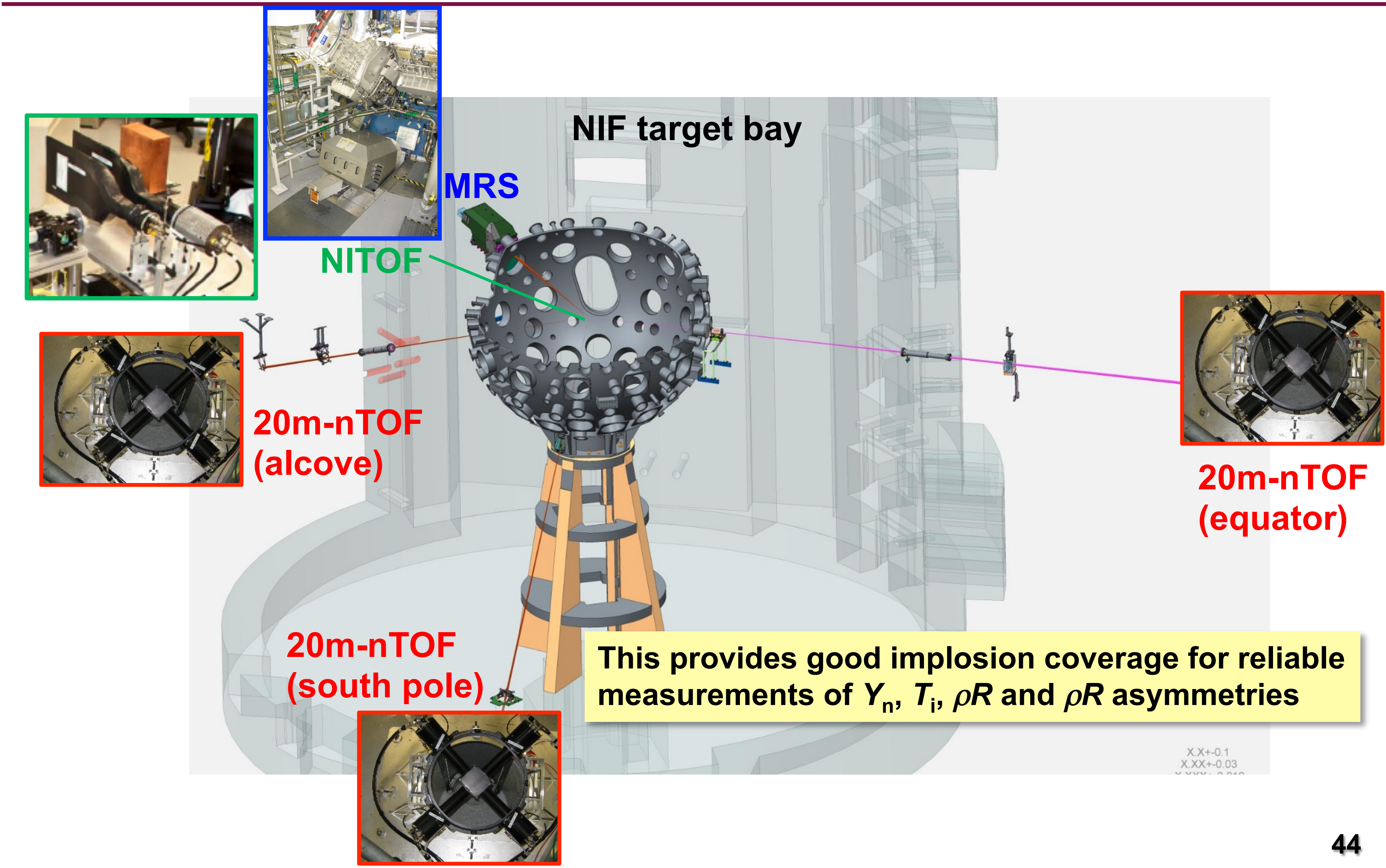
The conditions in the implosion can be diagnosed by measuring the spectrum of the emitted neutrons

The neutron spectrum provides info on ρR, T_i and Y_n – Essential info for assessing the implosion performance



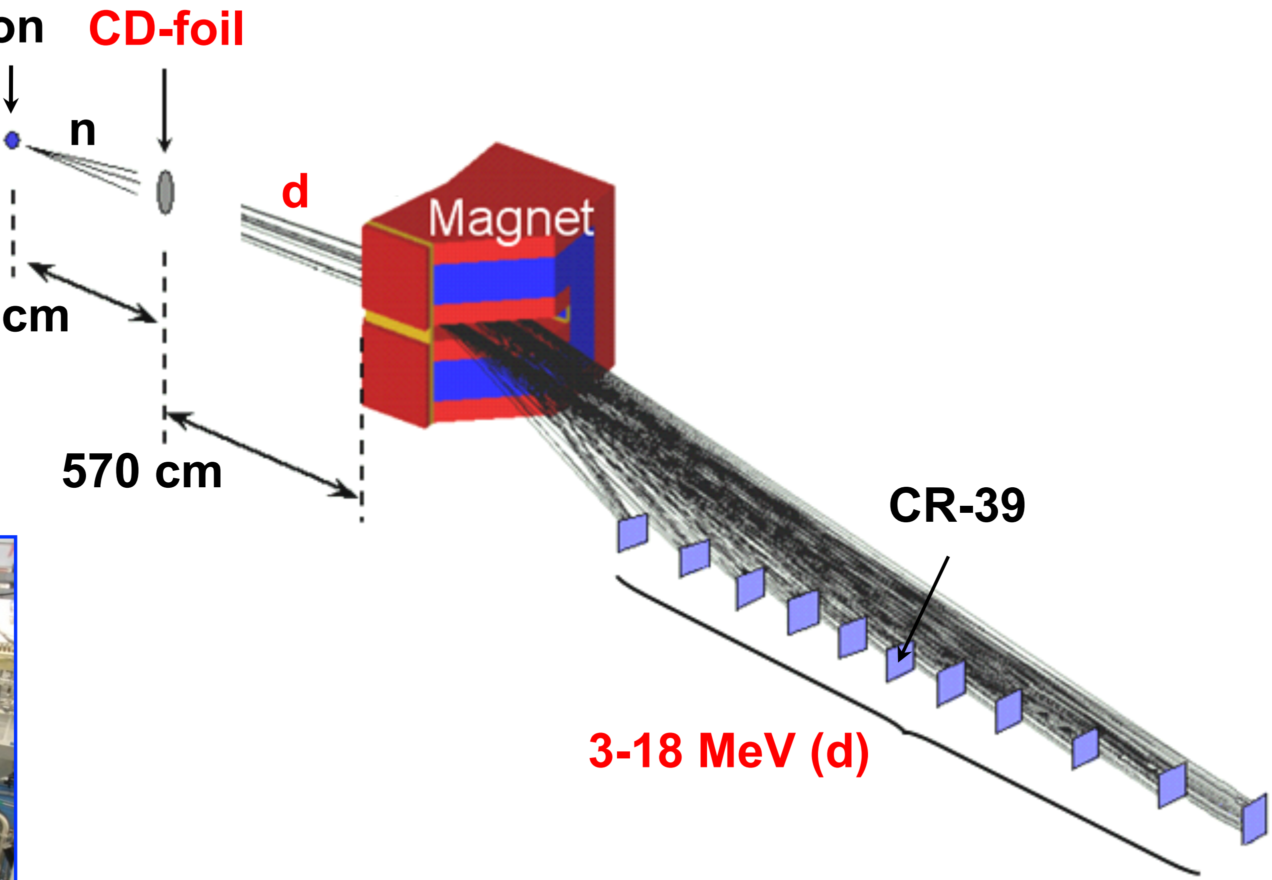


Several neutron spectrometers are fielded at various locations on the NIF

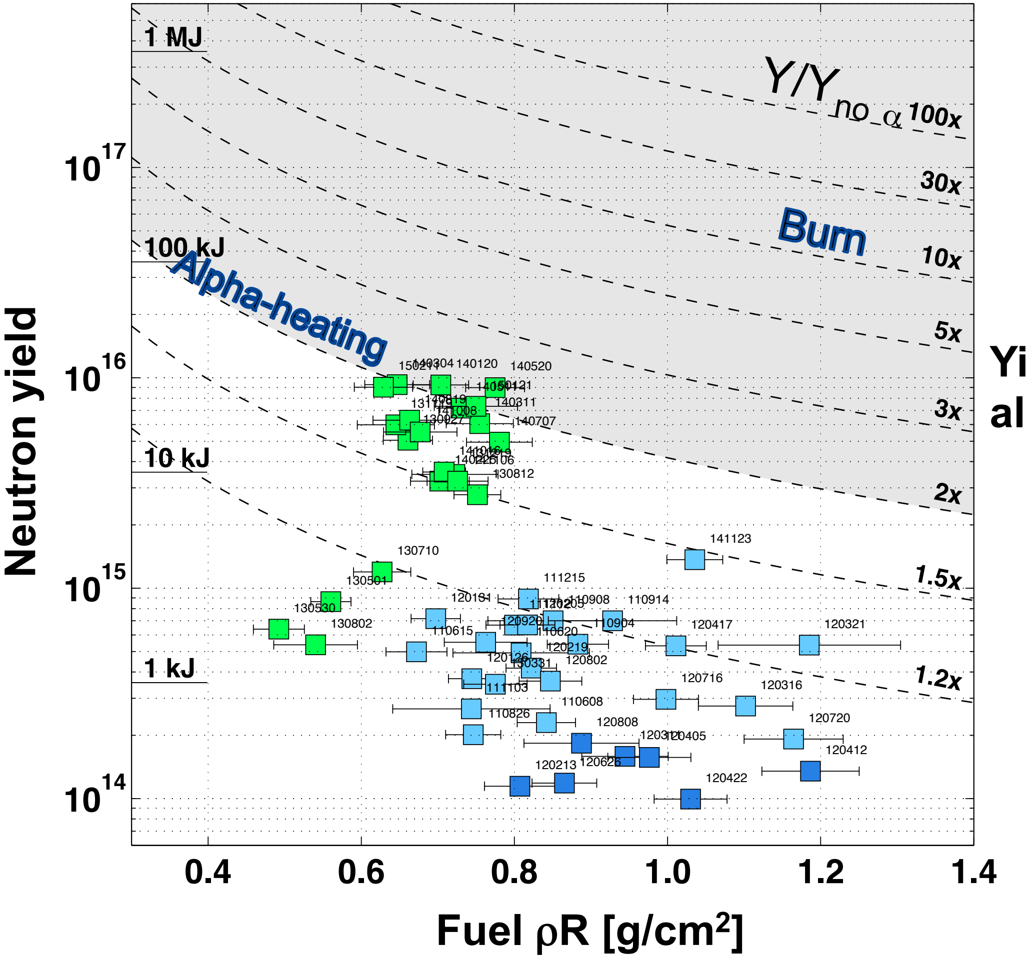


This provides good implosion coverage for reliable measurements of Y_n, T_i, ρR and ρR asymmetries

MIT built the Magnetic Recoil Spectrometer (MRS), which measures the neutron spectrum

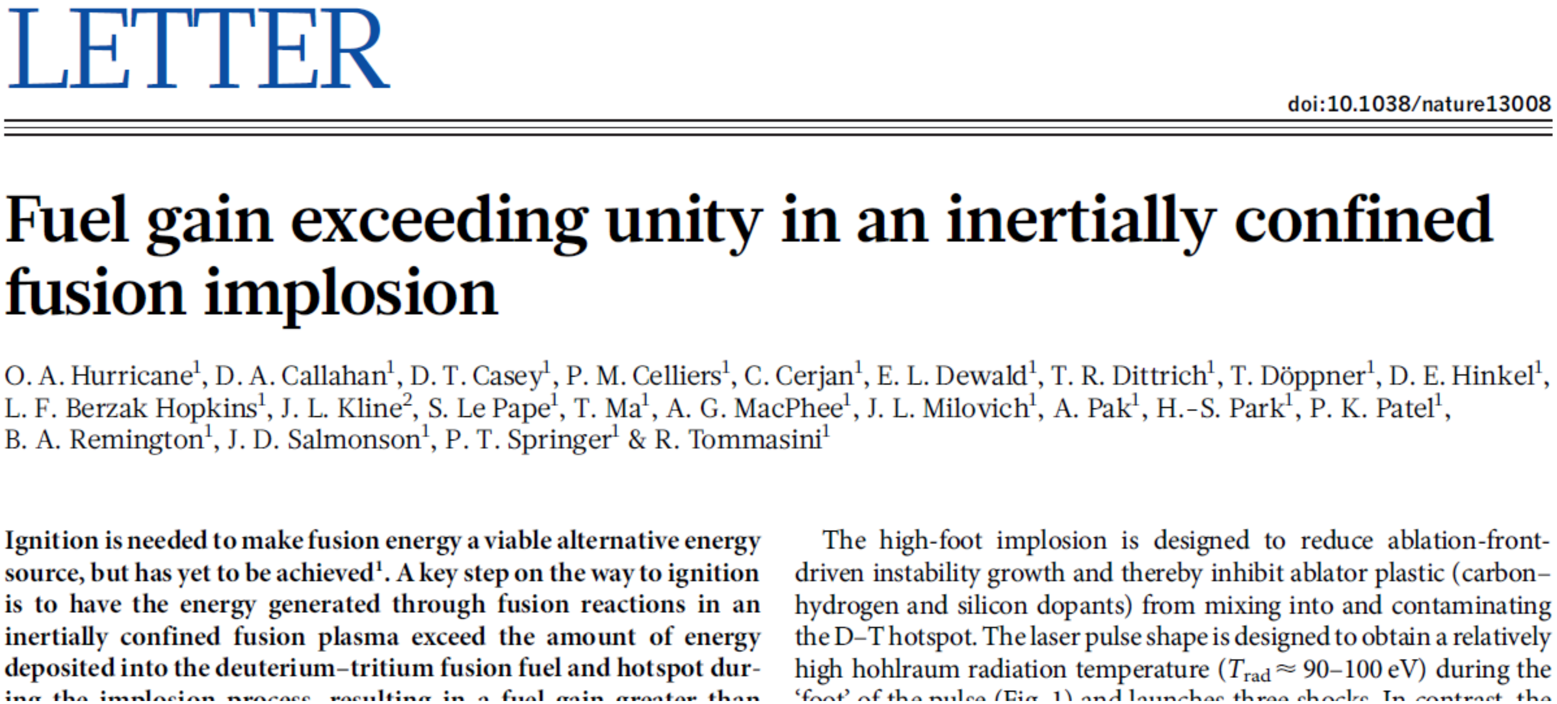


Yield and ρR derived from neutron data determine implosion performance; significant progress has been made



Yield magnification from alpha heating

Big news (Nature, Feb 2014):
NIF reached "scientific breakeven"!!



LETTER

doi:10.1038/nature13008

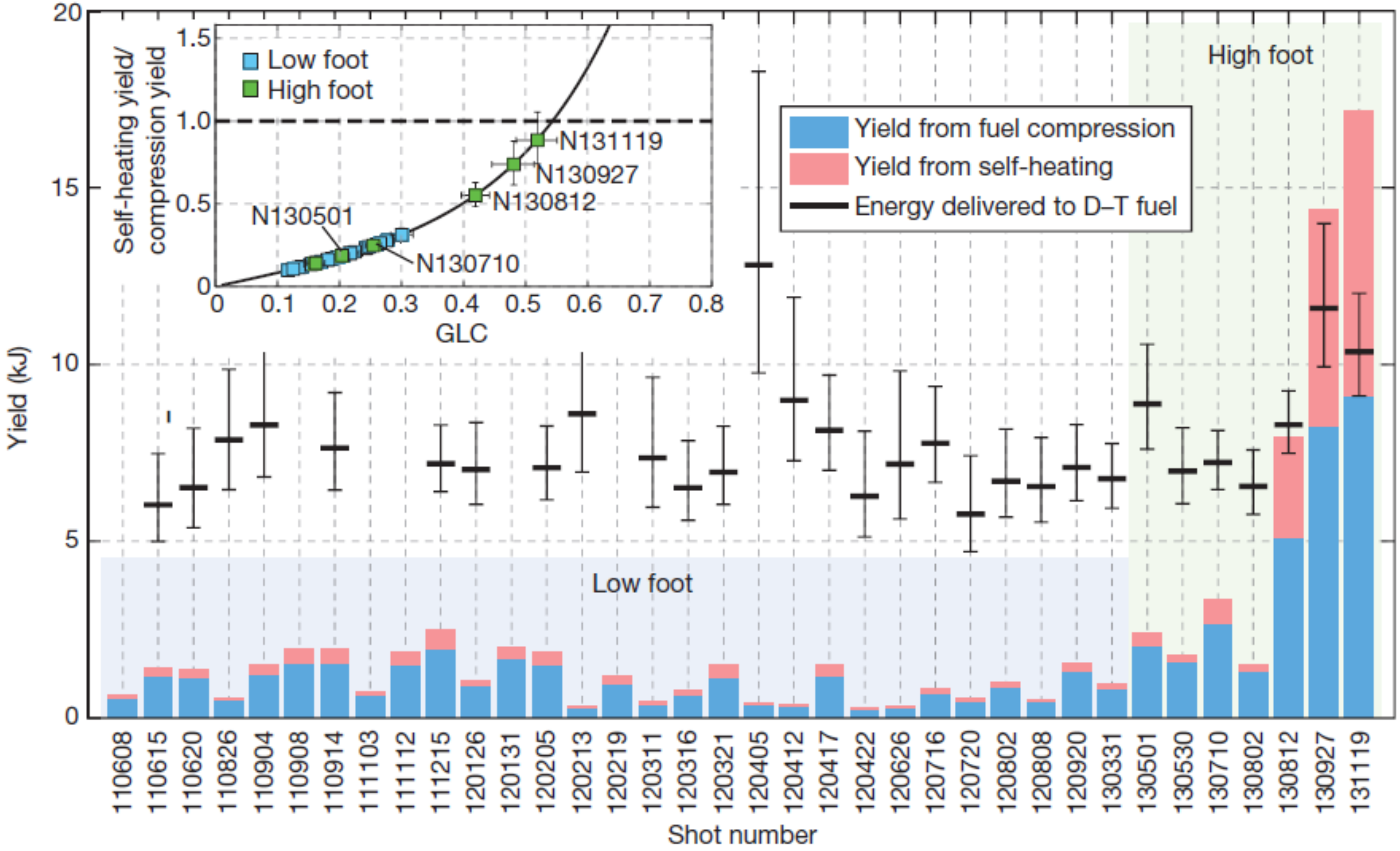
Fuel gain exceeding unity in an inertially confined fusion implosion

O. A. Hurricane[1], D. A. Callahan[1], D. T. Casey[1], P. M. Celliers[1], C. Cerjan[1], E. L. Dewald[1], T. R. Dittrich[1], T. Döppner[1], D. E. Hinkel[1], L. F. Berzak Hopkins[1], J. L. Kline[2], S. Le Pape[1], T. Ma[1], A. G. MacPhee[1], J. L. Milovich[1], A. Pak[1], H.-S. Park[1], P. K. Patel[1], B. A. Remington[1], J. D. Salmonson[1], P. T. Springer[1] & R. Tommasini[1]

Ignition is needed to make fusion energy a viable alternative energy source, but has yet to be achieved[1]. A key step on the way to ignition is to have the energy generated through fusion reactions in an inertially confined fusion plasma exceed the amount of energy deposited into the deuterium–tritium fusion fuel and hotspot dur-

The high-foot implosion is designed to reduce ablation-front-driven instability growth and thereby inhibit ablator plastic (carbon–hydrogen and silicon dopants) from mixing into and contaminating the D–T hotspot. The laser pulse shape is designed to obtain a relatively high hohlraum radiation temperature ($T_{\mathrm{rad}} \approx 90$–$100$ eV) during the

"Scientific breakeven" means that more energy was generated than was coupled into the DT FUEL



NIF was built to achieve ignition – working definition of ignition is yield higher than input laser energy (>1MJ)

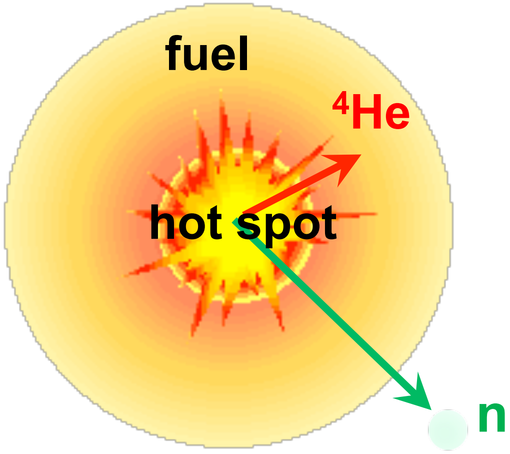
"Energy generated" is simply calculated from the measured neutron yield

$$E_{\text{fusion}} = Y_{DT} \times \underbrace{17.6\ \text{MeV}}_{\text{Total energy release in each D+T reaction}}$$

Measured by neutron diagnostics!

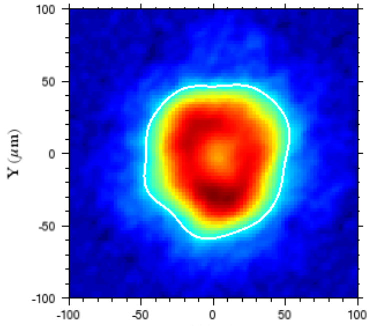
“Energy coupled to the fuel” is calculated based on measured parameters

$$\overset{\text{Total energy coupled}}{\boxed{E_{DT,total}}} = \underbrace{E_{hs} + E_{fuel}}_{\text{Energy in hot spot and fuel at time of implosion}} + \overset{\text{Energy lost at time of implosion}}{\boxed{\frac{1}{2} e^{-\tau_{fuel}} E_{brems}}} - \underbrace{\frac{1}{2} E_{\alpha}}_{\text{Energy deposited through fusion burn at time of implosion}}$$

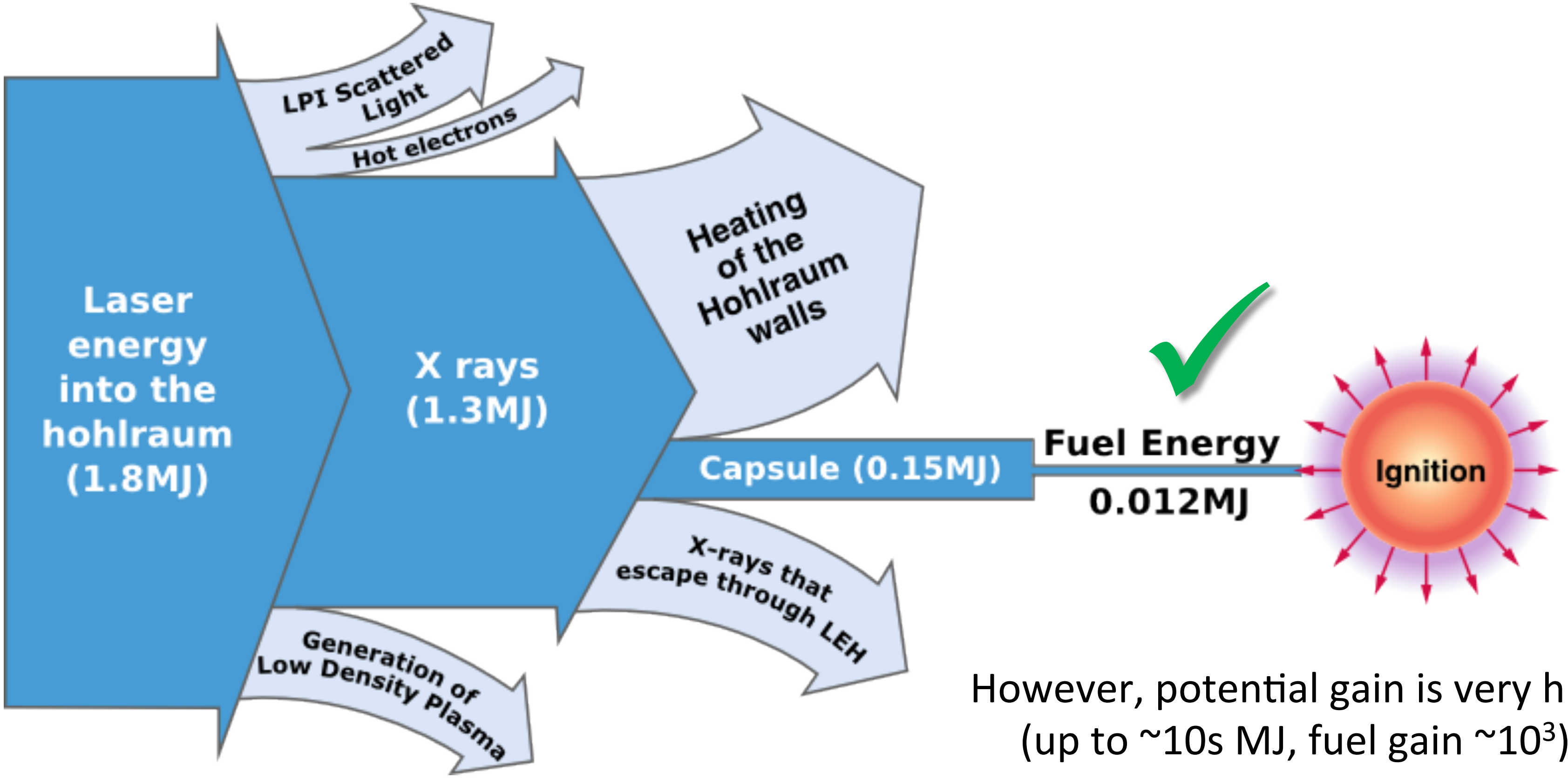


All quantities are calculated from:

- hot spot radius/shape, burn duration (x-rays)
- yield, downscattered neutrons, ion temperature (neutrons)



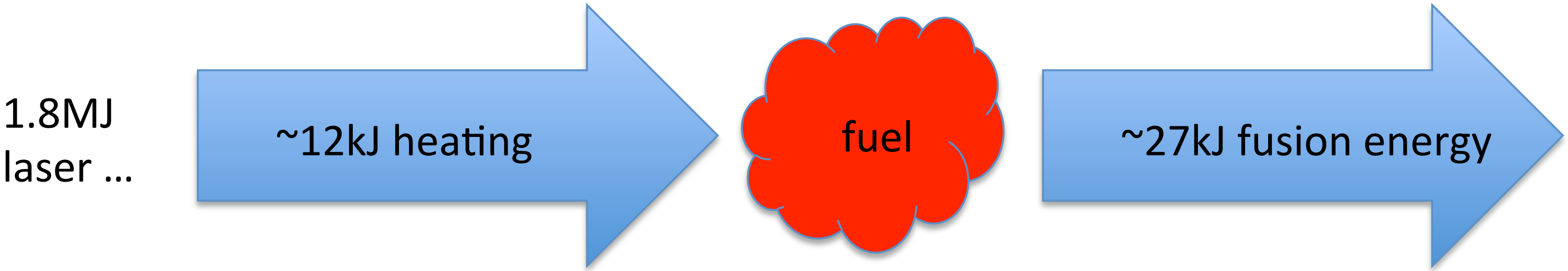
Energy coupling in inertial fusion is very inefficient - there are still many steps remaining before net energy gain is achieved



However, potential gain is very high (up to ~10s MJ, fuel gain ~10^3)

Capacitors ~ 400MJ

More progress has been made since Nature publication – the fuel now has gain ~2

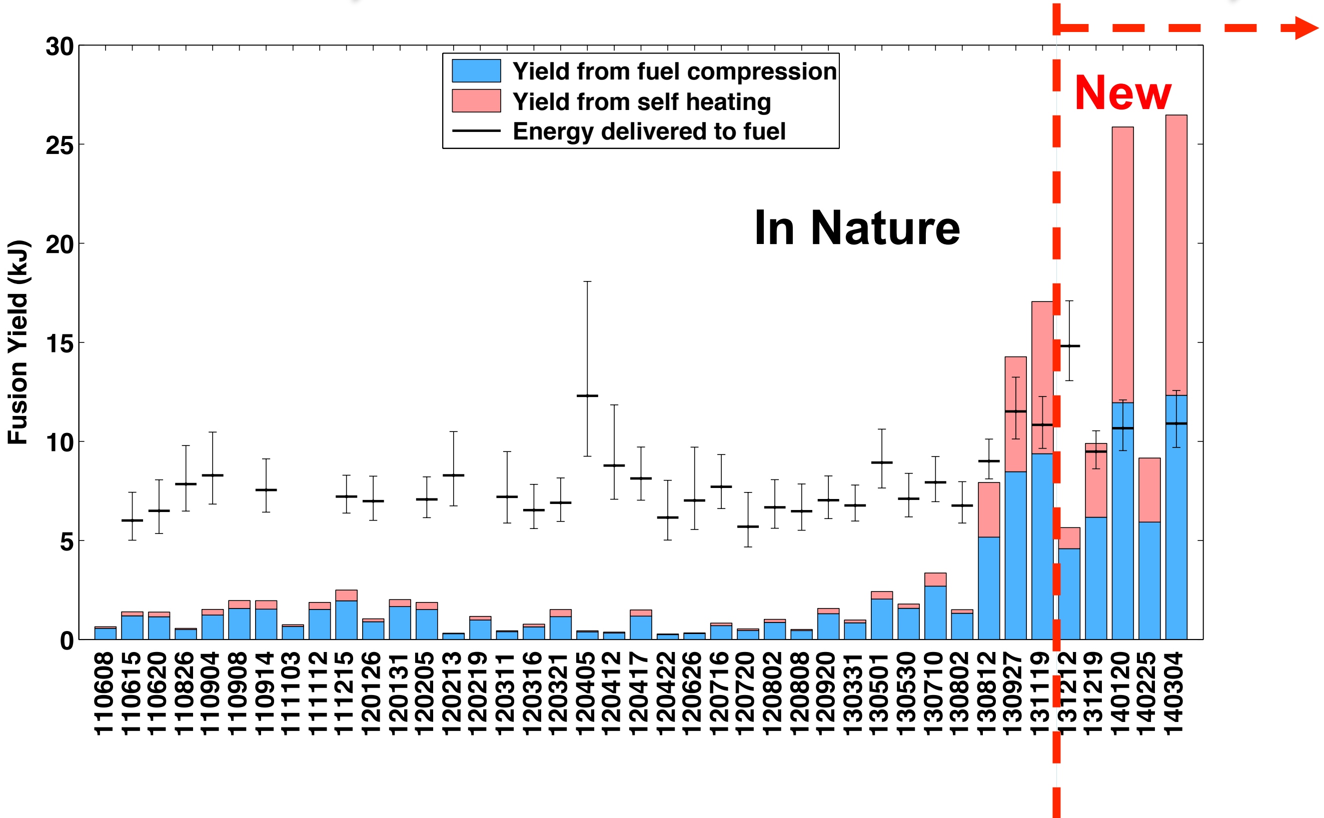


1.8MJ laser …

~12kJ heating

fuel

~27kJ fusion energy



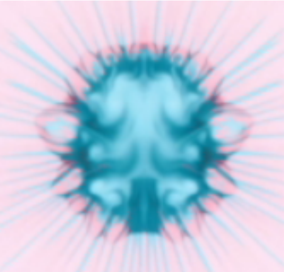
What are the challenges?

Ignition designs must simultaneously manage instability growth, symmetry, fuel entropy, and laser-plasma interactions

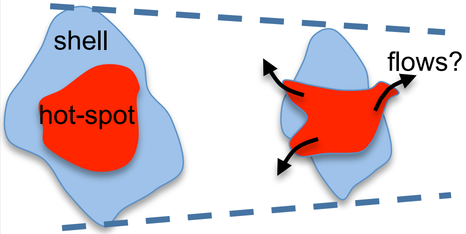
Ignition requires:
Good hotspot coupling
High compression
High implosion velocity

Needed for high hotspot coupling

Manage RT growth



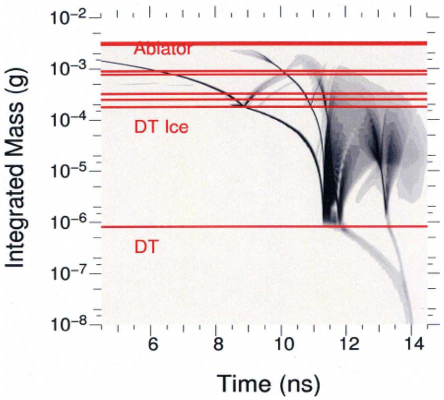
Manage hotspot and shell shape



Compression →

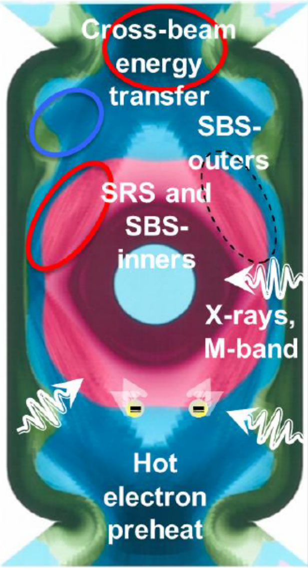
Needed for high ρR

Manage fuel entropy



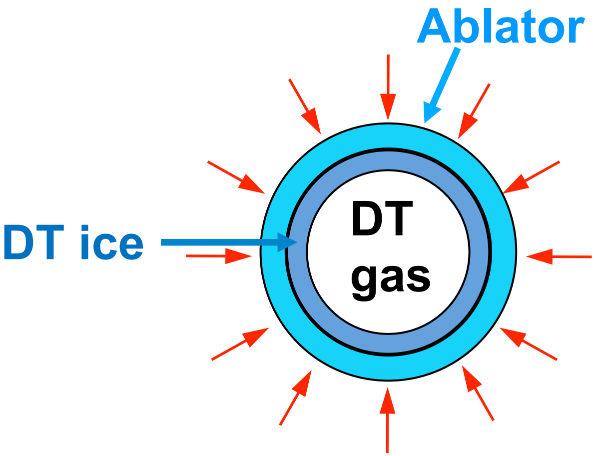
Needed for high V and ρR

Manage LPI

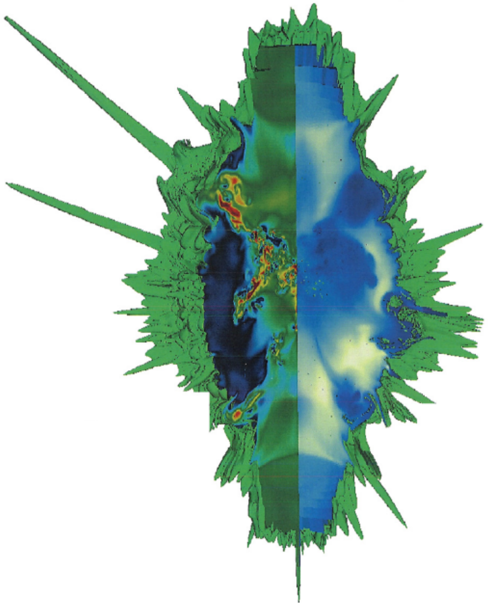


There is growing evidence that NIF implosions are highly 3D in nature at burn

Cartoon concept:

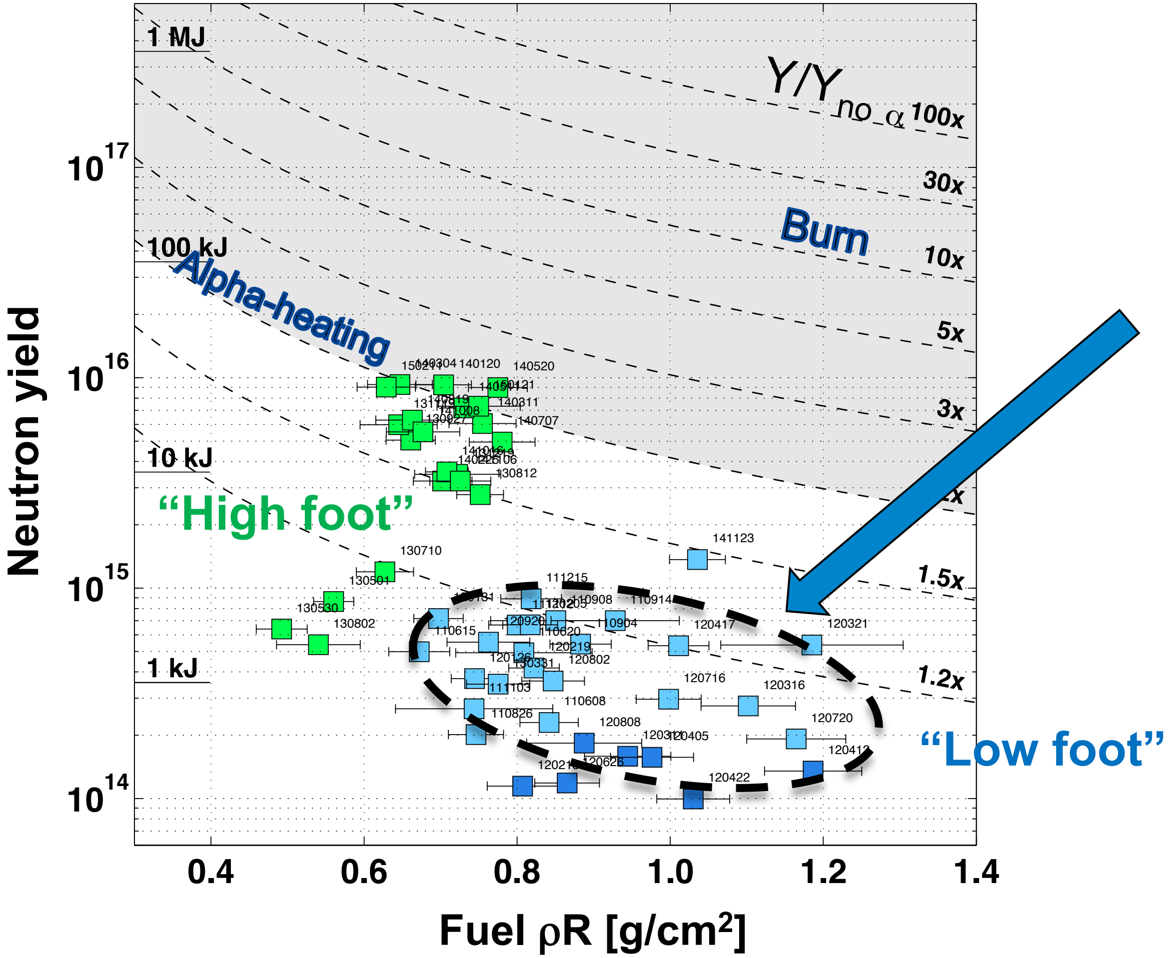


Reality?



D.S. Clark et al., Phys. Plasmas 22, 022703 (2015)

Progress comes from "taking a step back" to improve understanding – more systematic approach

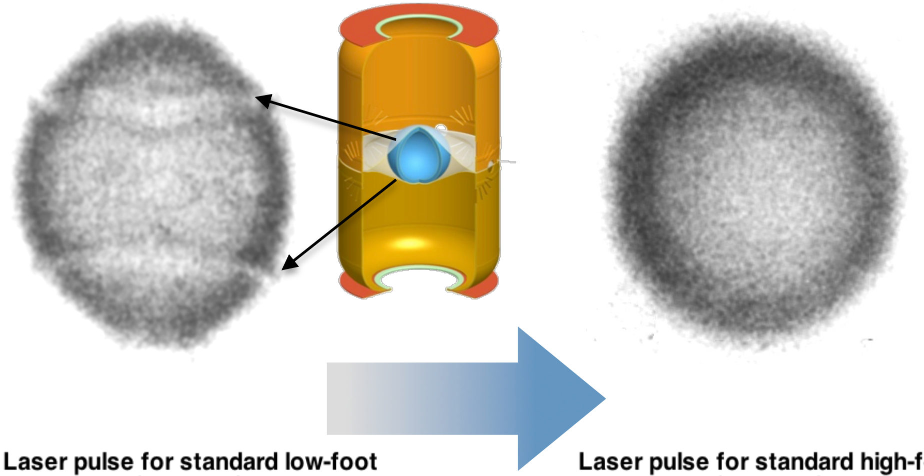


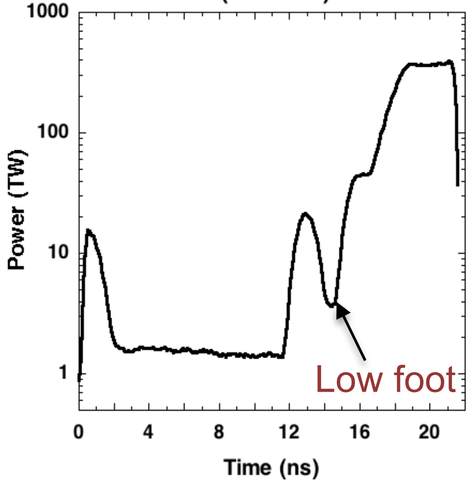
We now understand that hydrodynamic instability growth limited the performance of these implosions

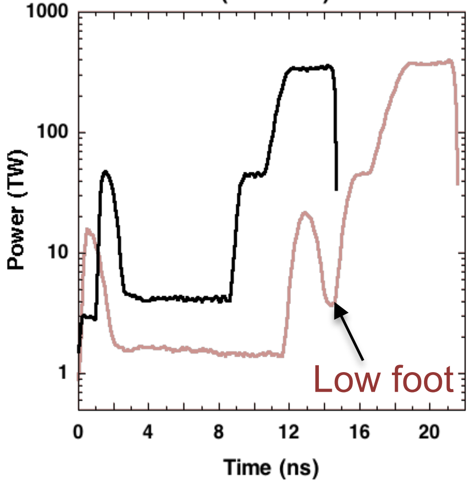
The difference between the high and low foot experiments are in how isentropically they are compressed

Low foot
$\alpha \sim 1.5$

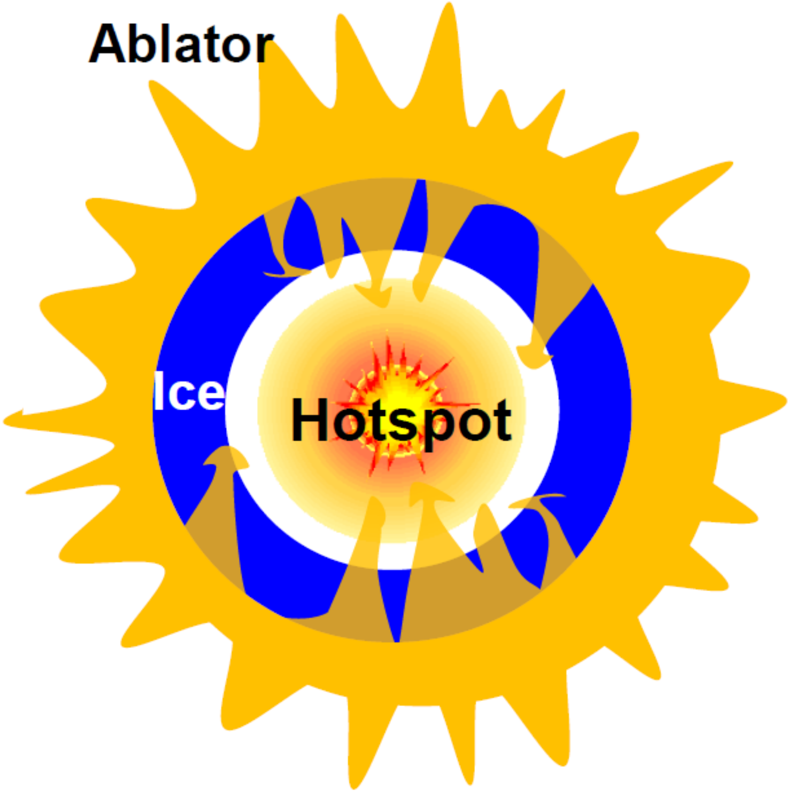
High foot
$\alpha \sim 2.5$



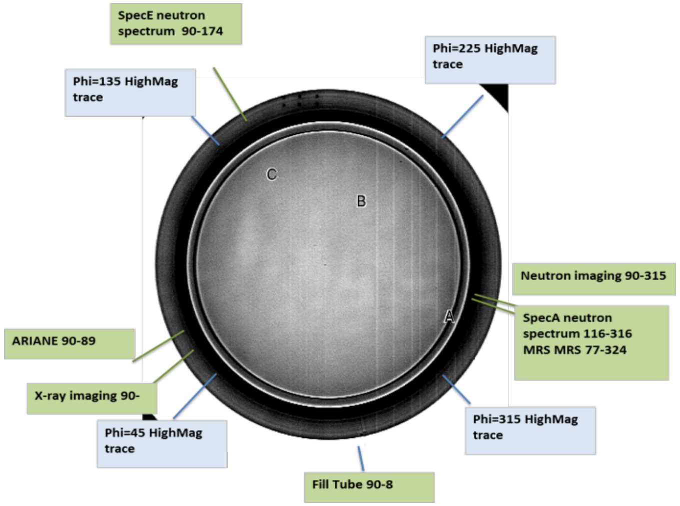

Laser pulse for standard low-foot (N131010)


Laser pulse for standard high-foot (N130508)

Hydrodynamic instability leads to mix of highly radiating material into the hotspot, which quenches the burn

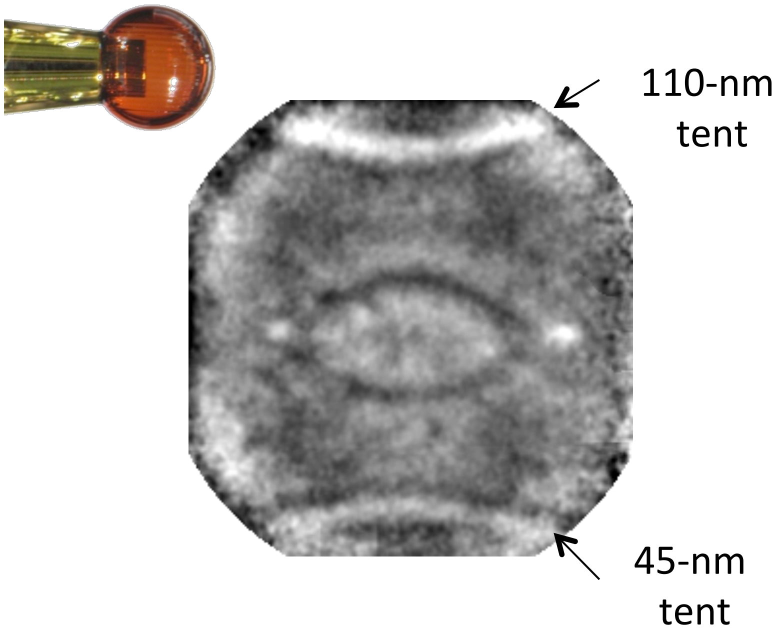


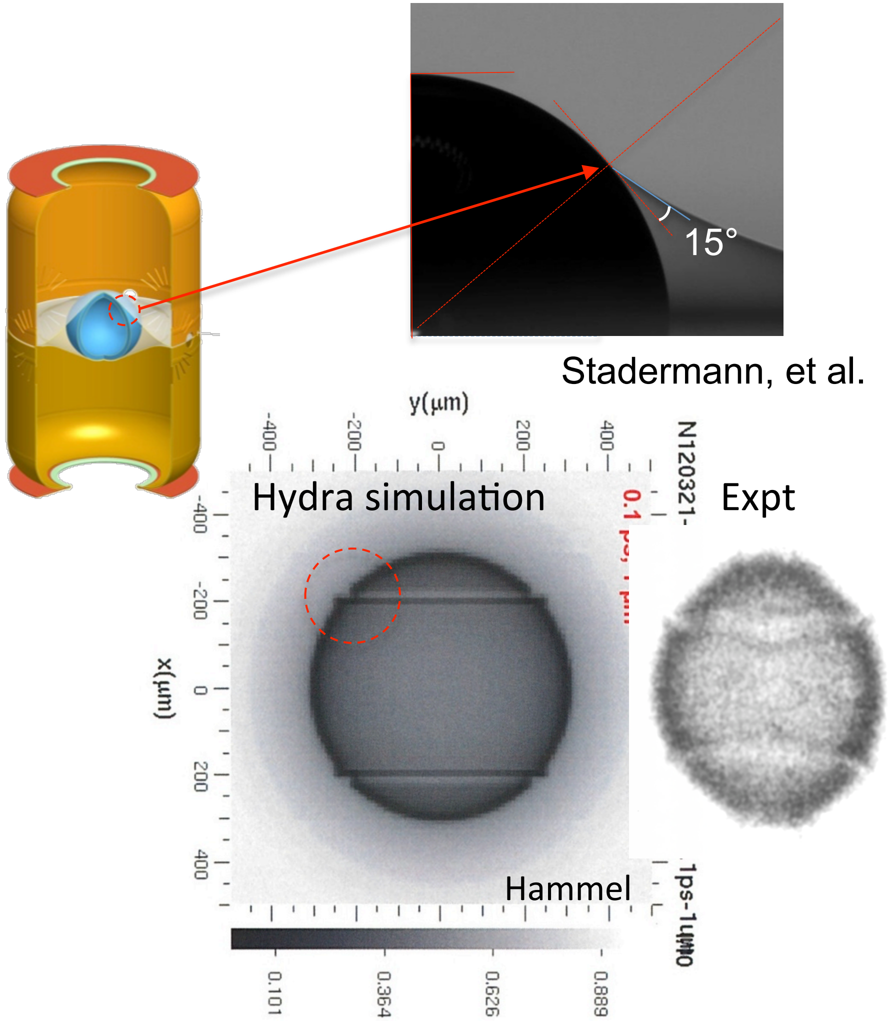
Impurities in target act as seeds for instability growth:



The "tent" used to hold the capsule in the hohlraum is believed to seed instability and break the symmetry

Optical Depth Image showing tent "scar"

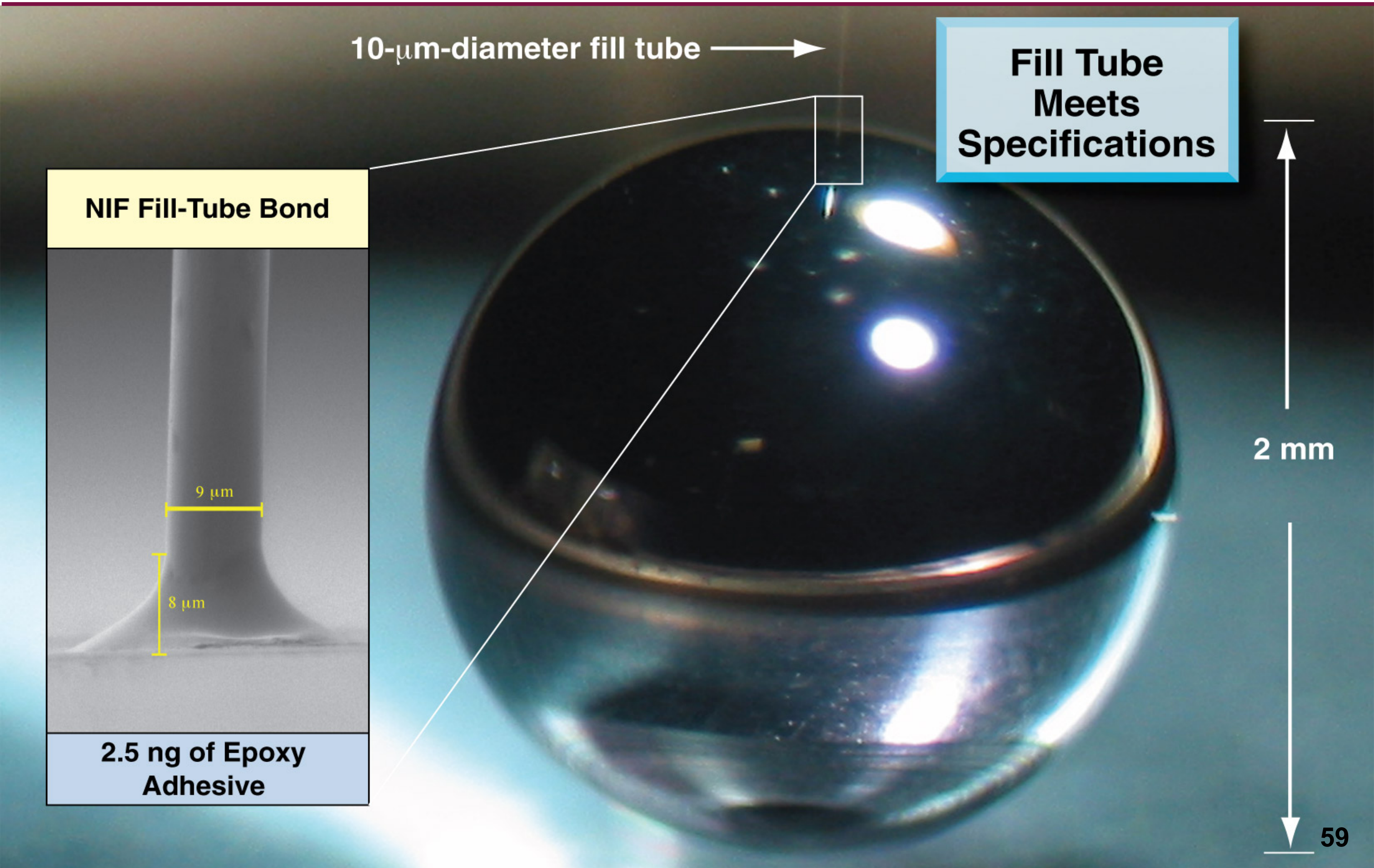




Stadermann, et al.

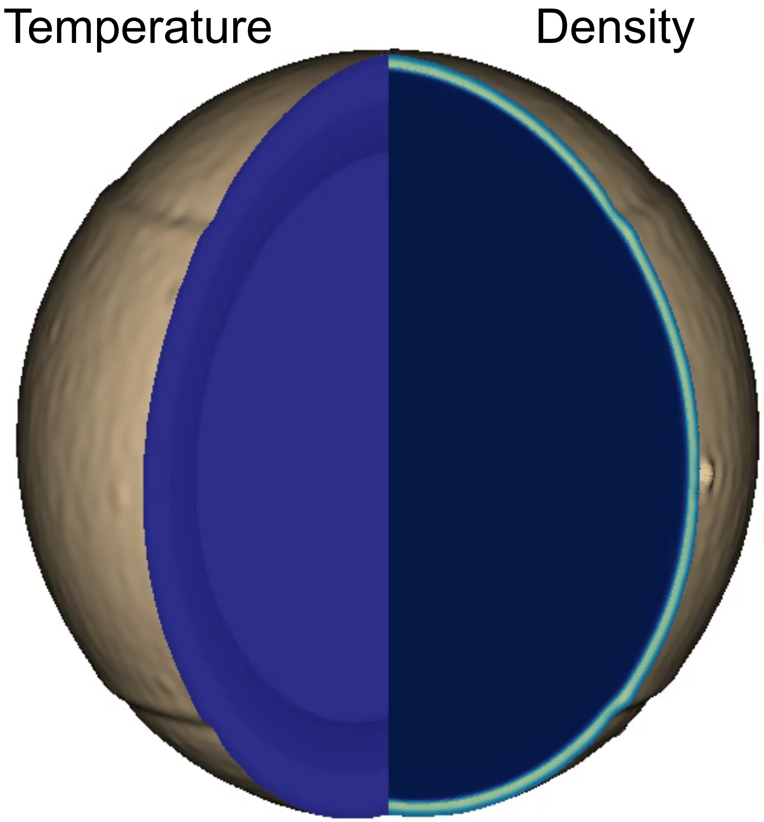
Hammel

The fill tube used to add DT gas to the capsule is also a possible source of instability growth



Simulations predict perturbations will grow and severely damage the implosion at stagnation

3D HYDRA
simulation of final
stagnation phase

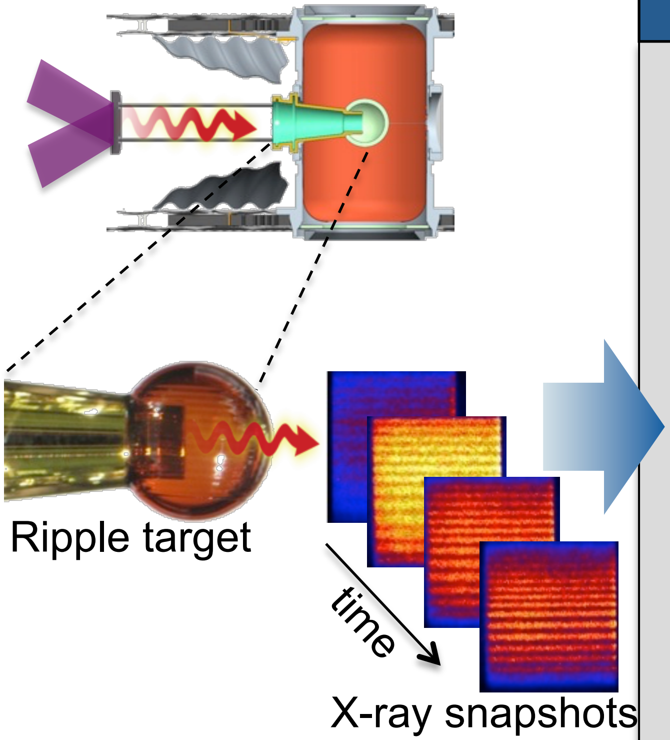


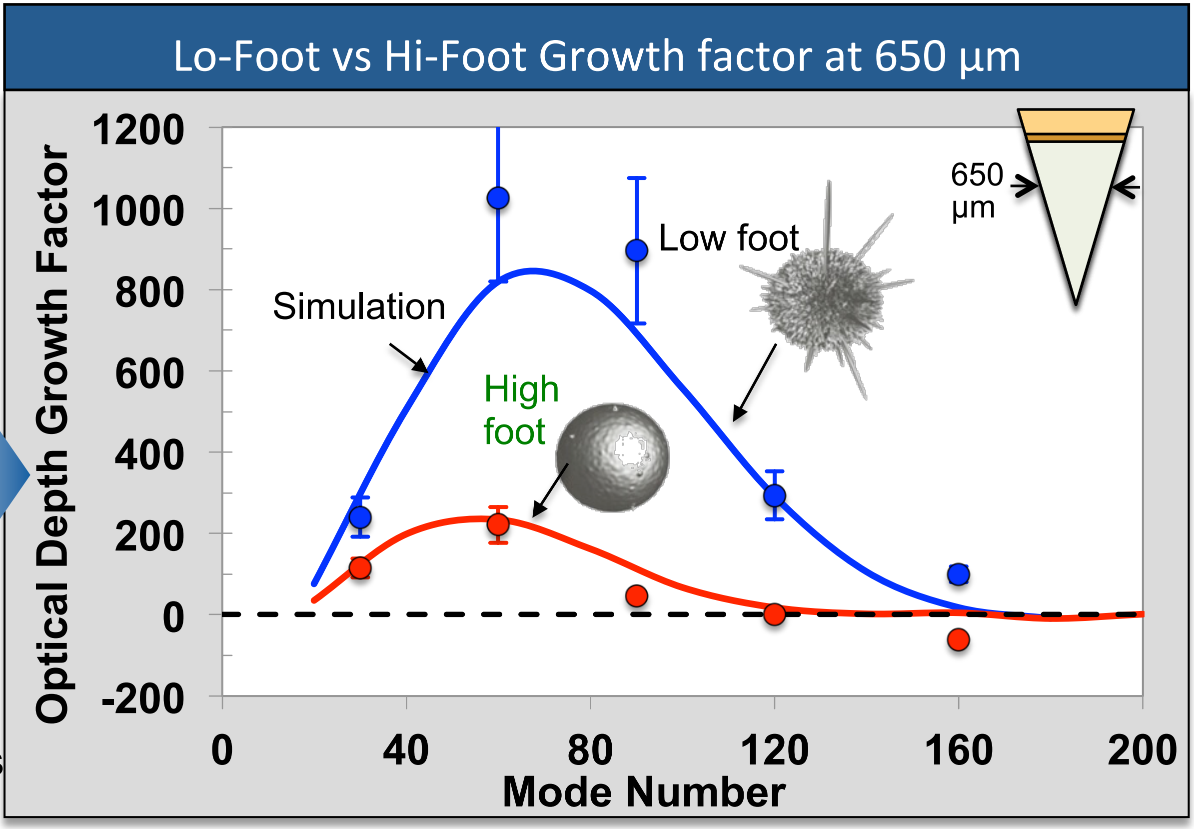
D. Clark –
3D Simulation of low
foot N120405

C. Weber –
Postprocessed
movie

Simulations are useful to help peer into details of the experiment otherwise inaccessible

The recent, lower convergence implosions are more resilient to small target imperfections due to lower growth rates

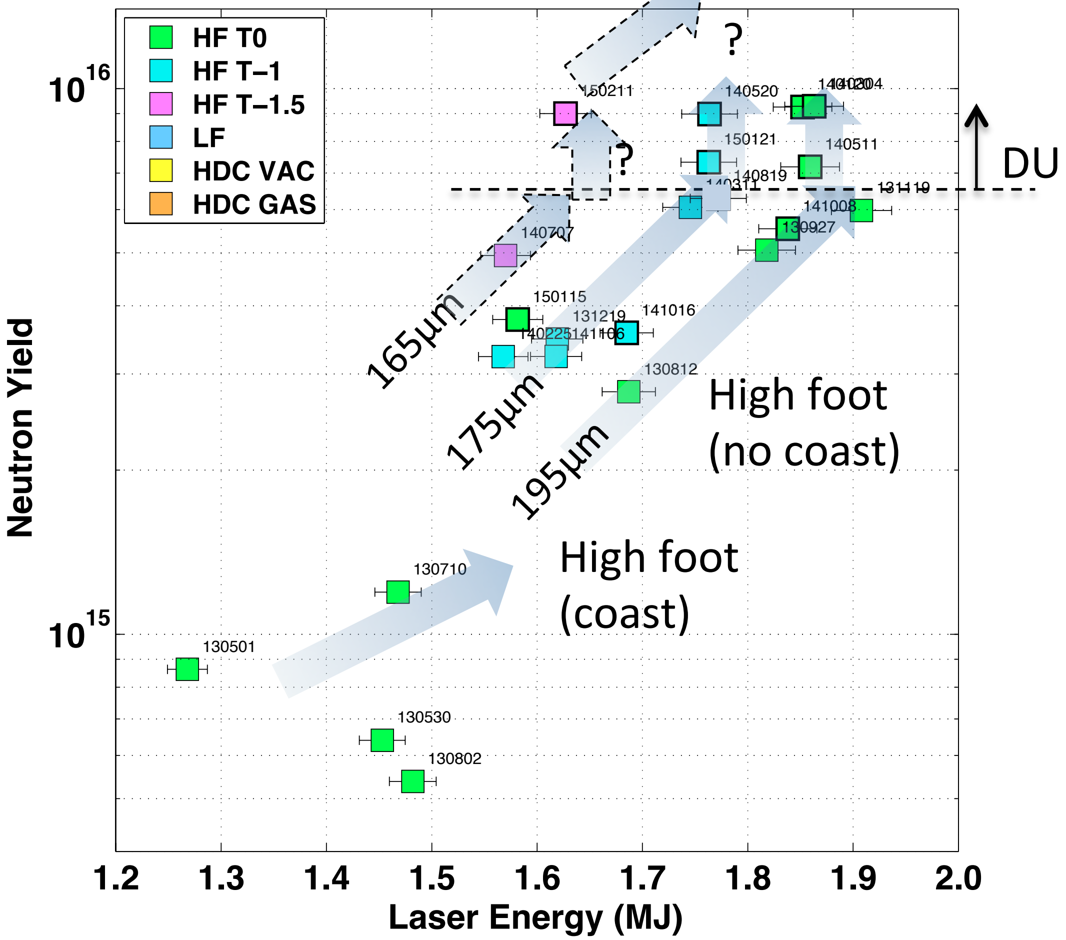




Recent implosions have had low mix because they converged less
Now we want to go back to higher convergence without introducing mix

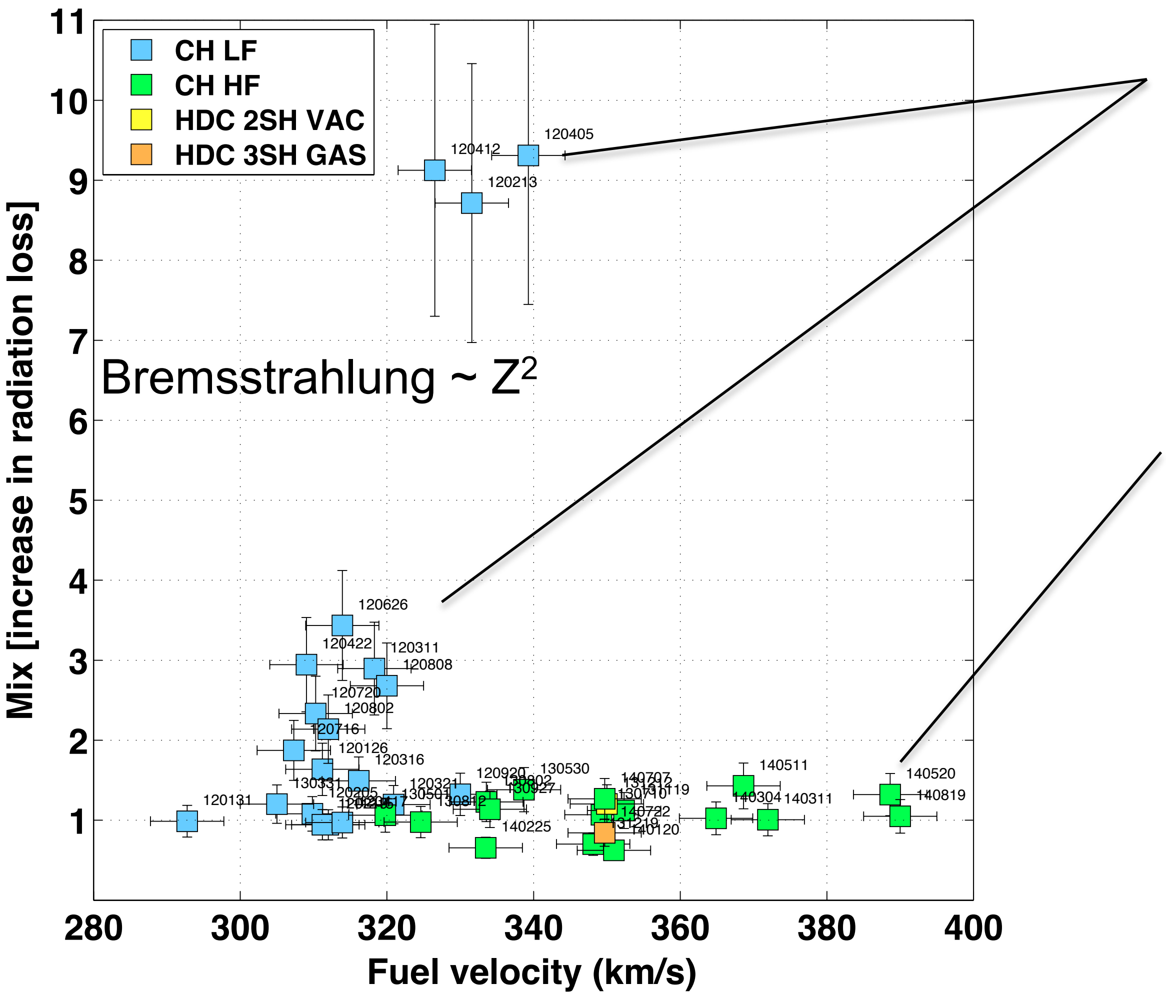
First test: Push these low-convergence implosions to higher velocity using thinner ablator layers

DT Yield vs. Laser Energy



This was demonstrated to work well – implosions did not mix even at very high velocity

Mix vs. implosion Velocity



Bremsstrahlung ~ Z^2

Low-foot:
High mix at intermediate velocity

High-foot:
mix free at high velocity

Another outstanding question concerns inefficiencies in assembling the fuel

Non-uniformities in hotspot

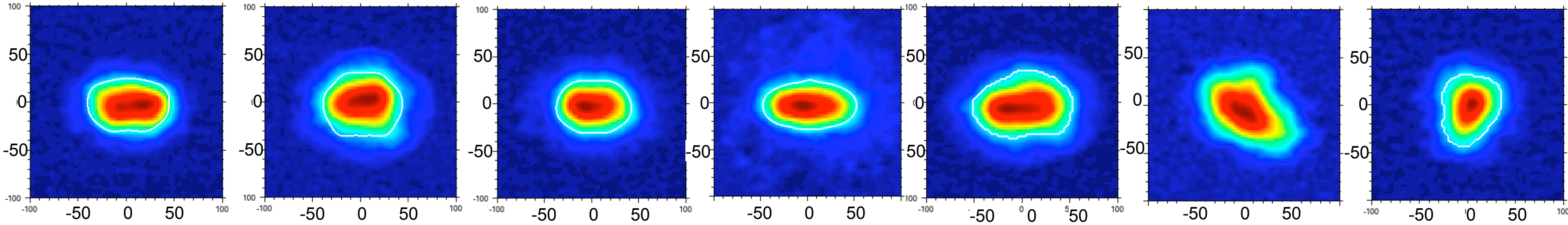
→ pdV work lost to setting fuel in motion

Non-uniformities in fuel layer

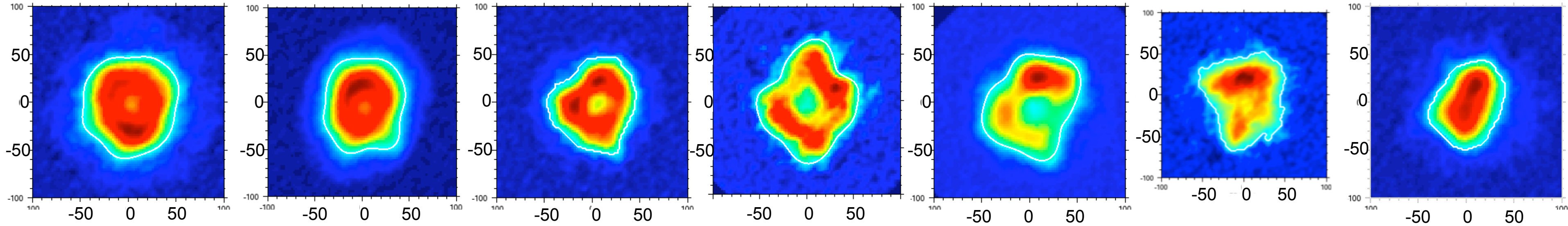
→ less efficient inertial confinement

X-ray and neutron measurements of hot-spot shape indicate significant hot-spot asymmetry

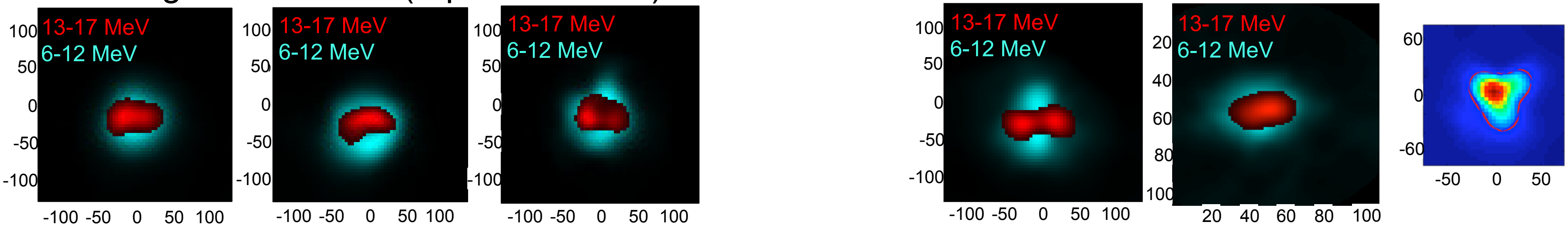
Time-integrated x-ray emission (equatorial view)



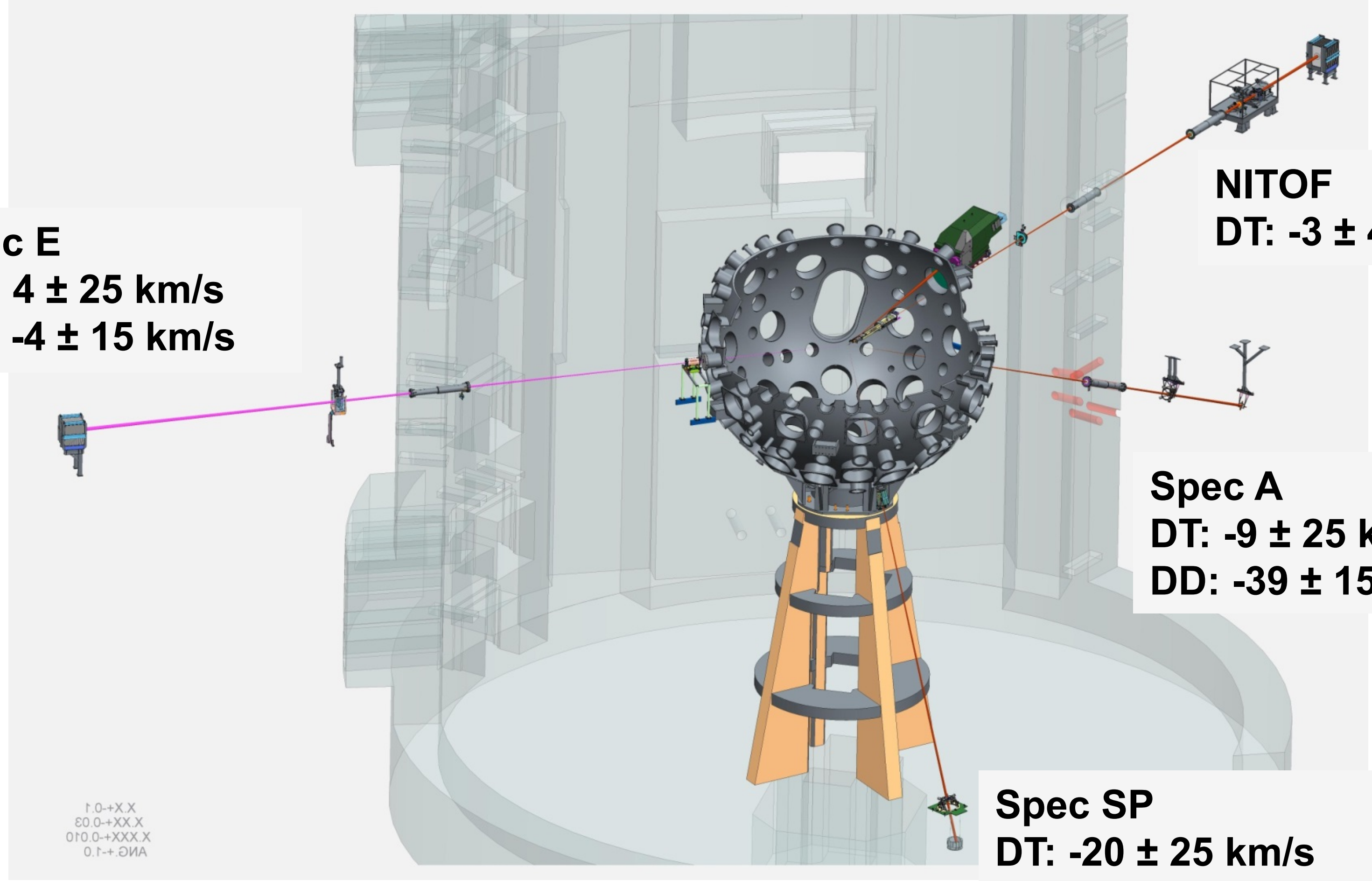
Time-integrated x-ray emission (polar view)



Time integrated neutron (equatorial view)



Neutron spectrometry measurements indicate directional motion of the hotspot during burn



Spec E
DT: 4 ± 25 km/s
DD: -4 ± 15 km/s

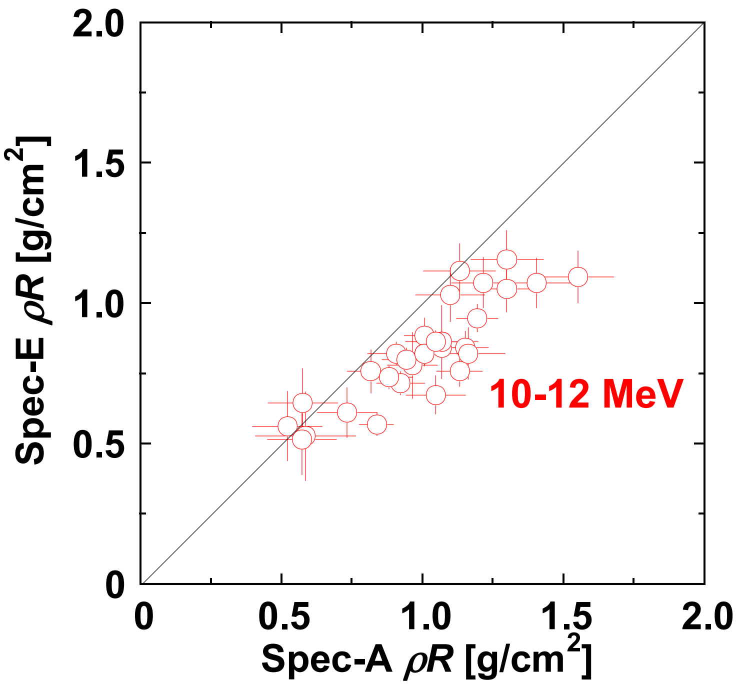
NITOF
DT: -3 ± 4 km/s

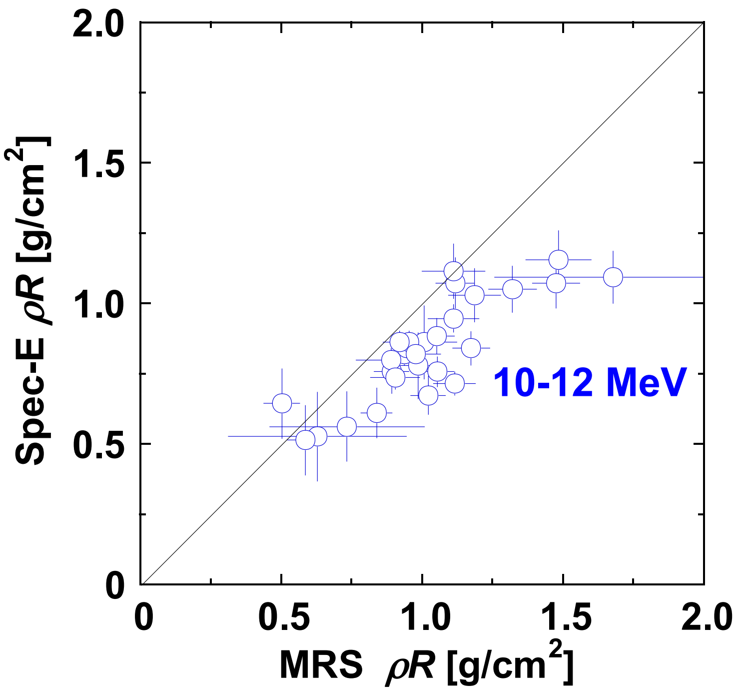
Spec A
DT: -9 ± 25 km/s
DD: -39 ± 15 km/s

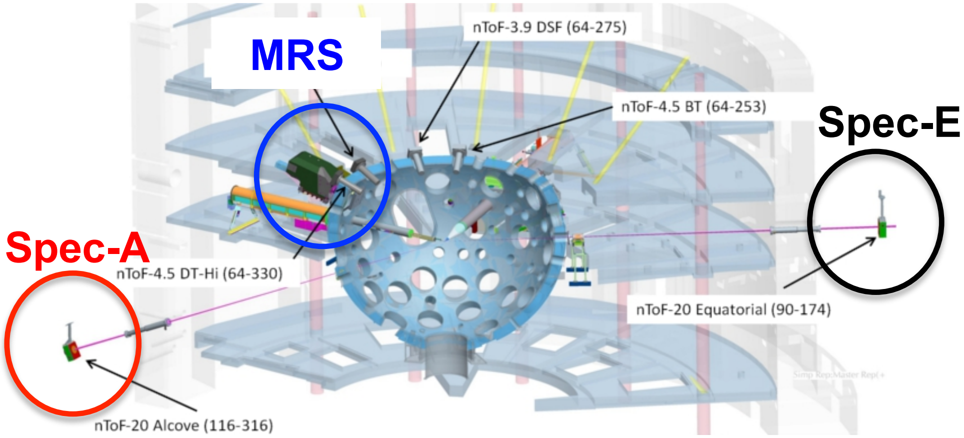
Spec SP
DT: -20 ± 25 km/s
DD:-37 ± 15 km/s

Directional or turbulent motion “steals” kinetic energy from the pdV work on the hotspot and must be minimized

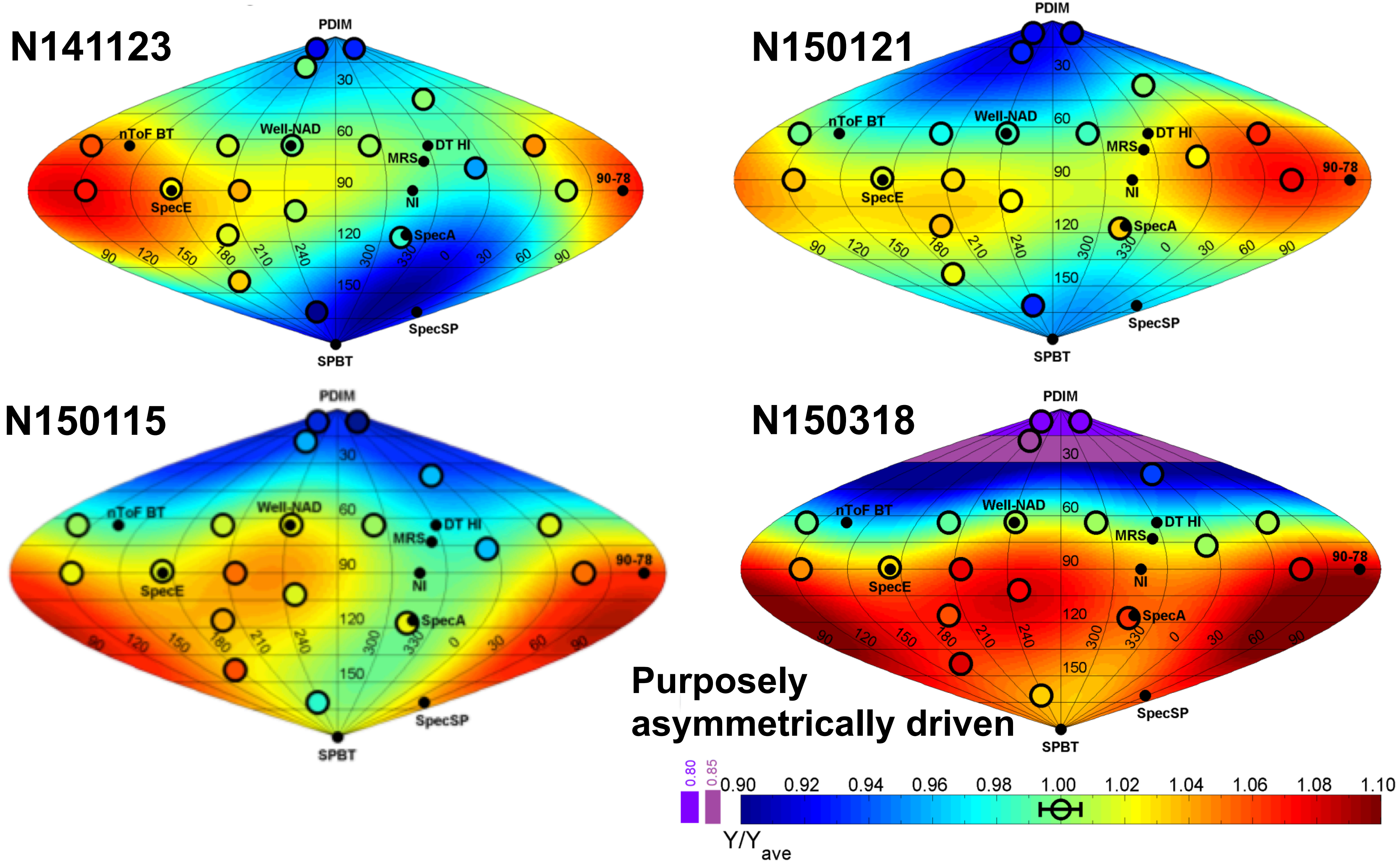
Neutron spectrometry measurements indicate substantial, systematic low-mode dense fuel *ρR* asymmetry







Directional neutron yield measurements also indicate substantial dense fuel ρR asymmetry



N141123

N150121

N150115

N150318

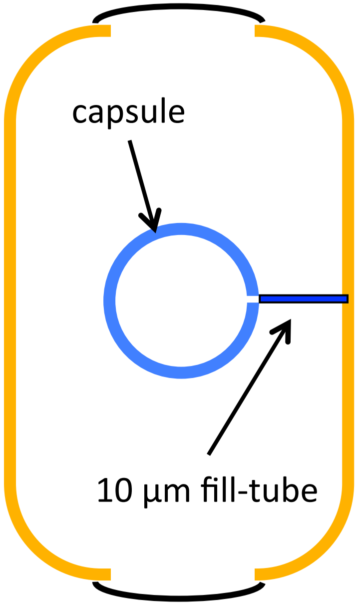
Purposely asymmetrically driven

Fuel maps from neutron activation

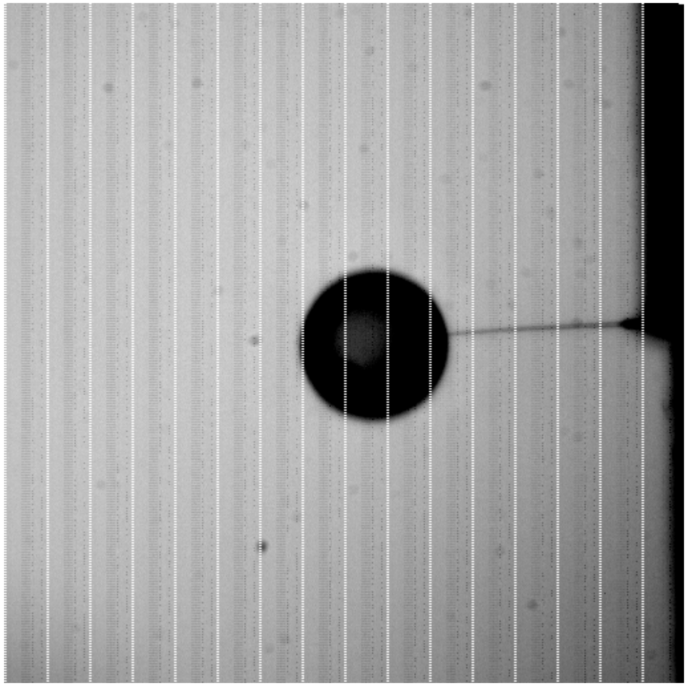
So, we are still struggling with symmetry. Current path forward:

- Control asymmetry seeding due to engineering features
- Improve understanding of hohlraum physics to control asymmetry seeding due to non-uniform drive

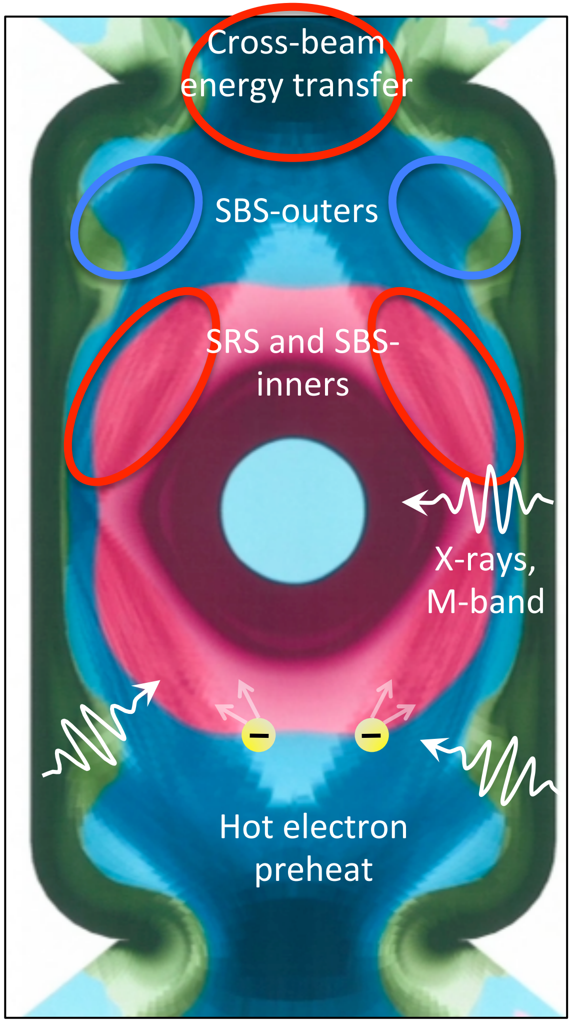
Engineering features: The best solution would be to eliminate the tent altogether but there are challenges



30 µm free-standing fill-tube vibration test



A better understanding of and ability to control laser-plasma interactions in the hohlraum is essential

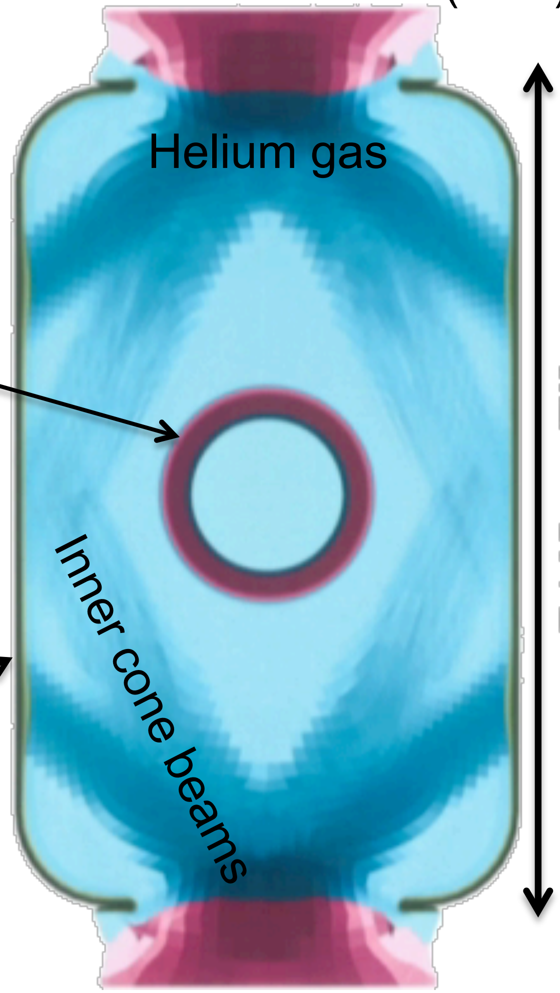


The hohlraum drive is not yet predictable

- **Hohlraum physics may impact implosion symmetry**
- **A ~15% loss of drive energy cannot be accounted for in simulations**

The hohlraum must provide a symmetric x-ray drive to enable efficient transfer of the drive to the hotspot

HYDRA Simulation Jose Milovich



Laser entrance hole (LEH)

Helium gas

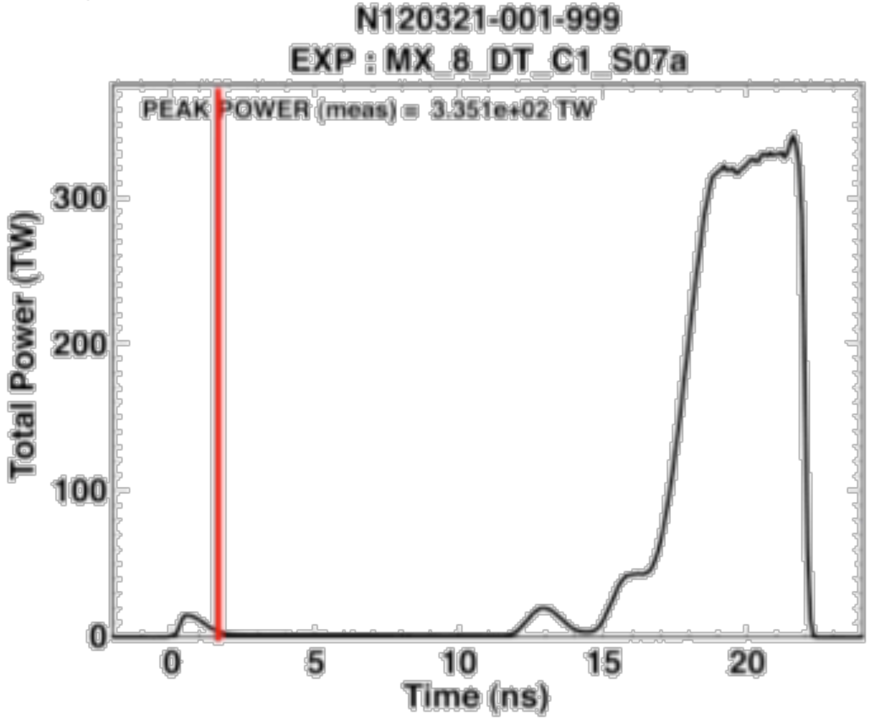
Plastic Ablator

Inner cone beams

Gold hohlraum wall

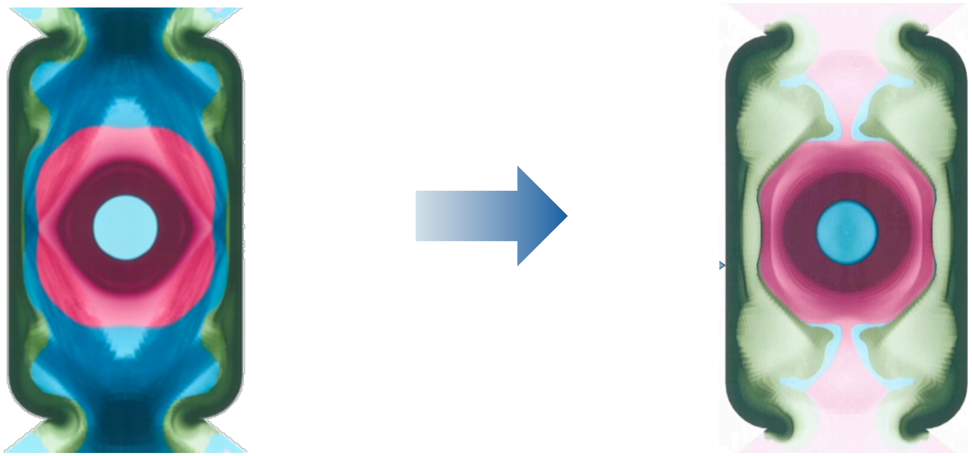
~ 1cm

Laser "Pulse-shape"



A better understanding of and ability to control laser-plasma interactions in the hohlraum is essential

One research direction: low-gas fill hohlraums → better predictability

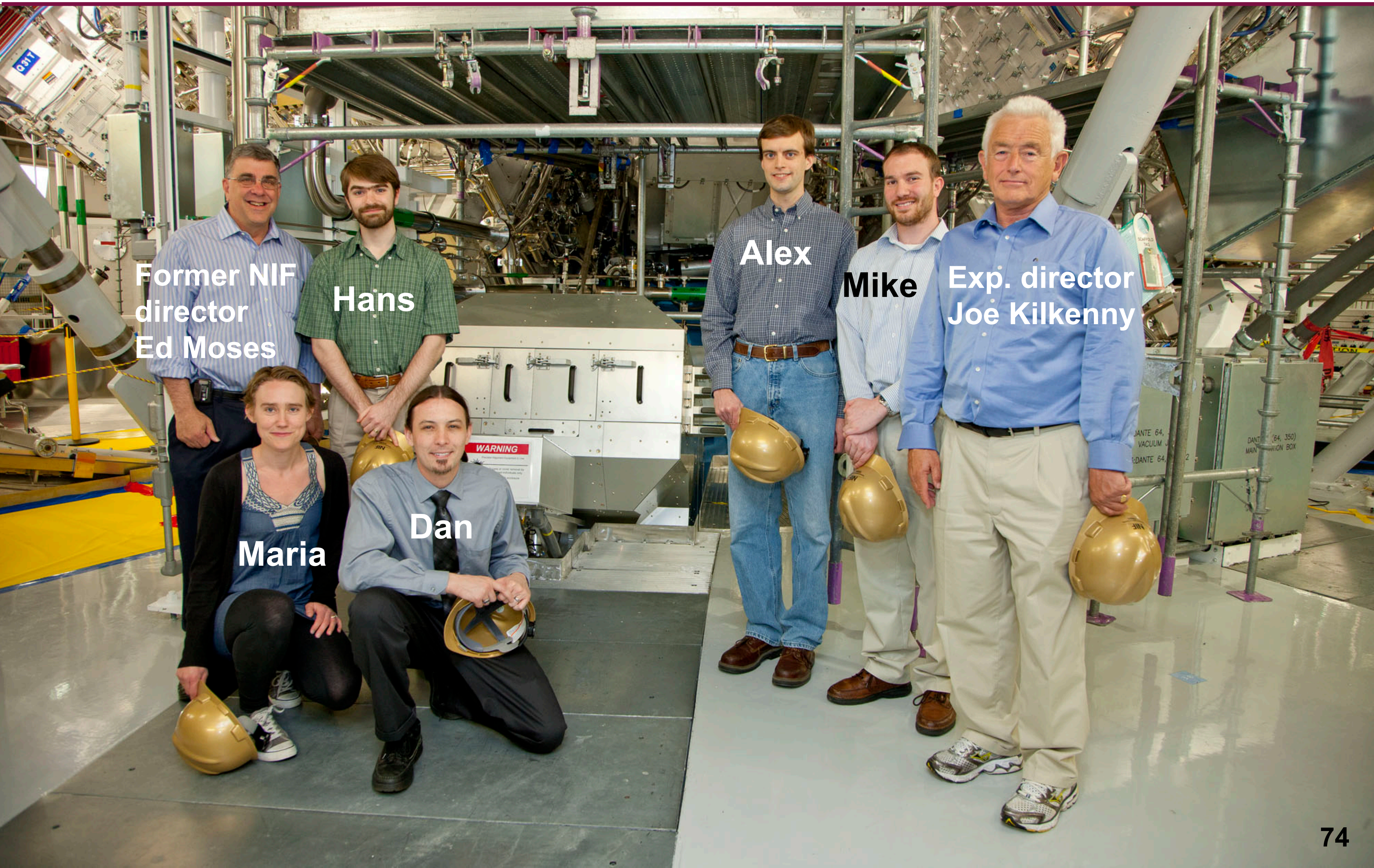


Gas-filled

Near vac

Other potential options: Different hohlraum shape, e.g., different case-to-capsule ratio, rugby

MIT has been heavily involved in the NIF program



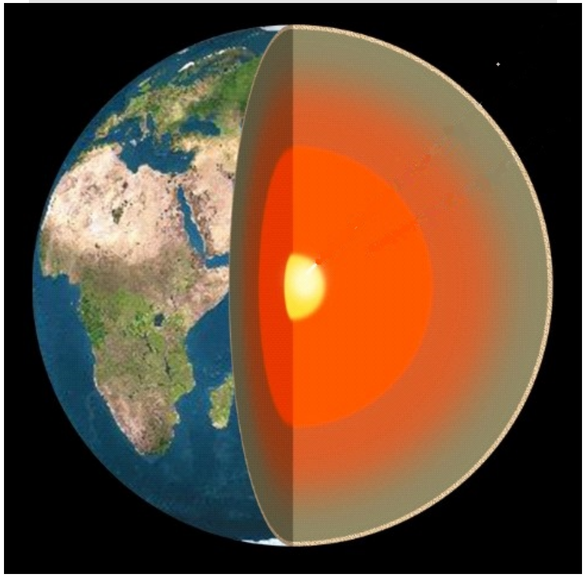
1st PhD thesis based on NIF data was presented by former MIT graduate student Dan Casey

Outline

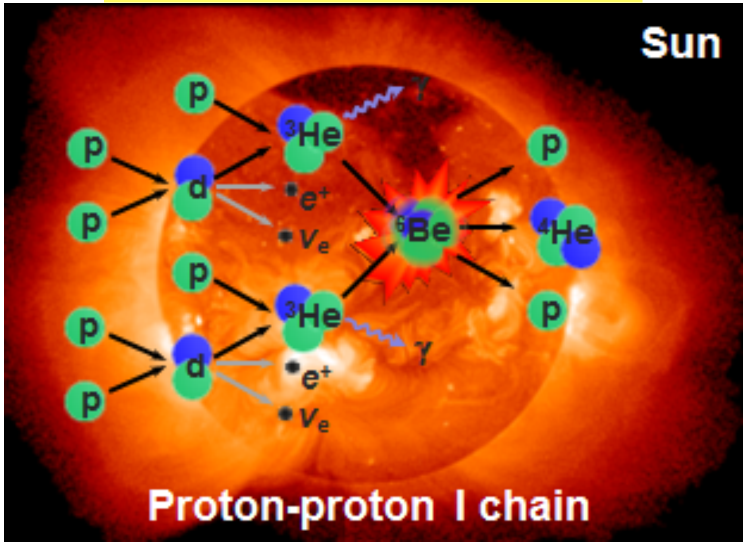
- **Fusion Basics**
- **The principle of Inertial Confinement Fusion (ICF)**
- **ICF facilities**
  - The OMEGA laser facility
  - The Z pulsed power machine
  - The National Ignition Facility (NIF)
- **NIF experiments**
  - Status
  - Engineering and scientific challenges
- **Basic-science experiments on OMEGA and the NIF**

High-Energy-Density Physics (HEDP) involves studies of matter under extreme states of pressure (~ 1 Mbar to ~ 1000 Gbar)

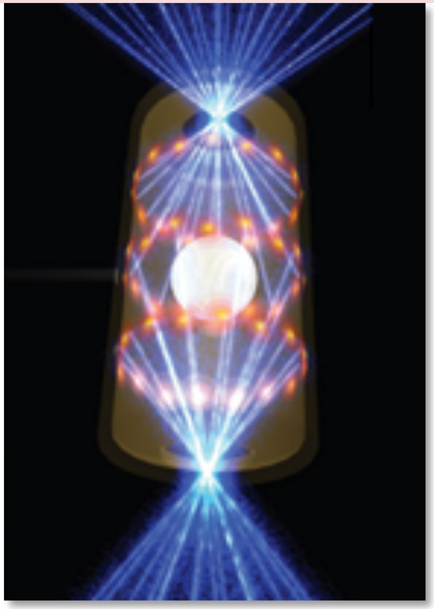
Earth's core ~ 3 Mbar



Solar core ~ 250 Gbar



Igniting ICF implosion ~ 300 Gbar

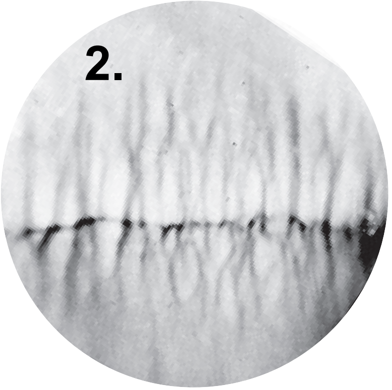


We exploit the extreme conditions at the OMEGA and NIF laser facilities and the Z pulsed power machine for astrophysical, nuclear, ICF and other HEDP experiments

The ICF platform lends itself to a wide range of basic science experiments

1. Plasma/WDM stopping power
2. Collisionless shocks
3. Astrophysical jets
4. Magnetic reconnection
5. Nuclear astrophysics

2.



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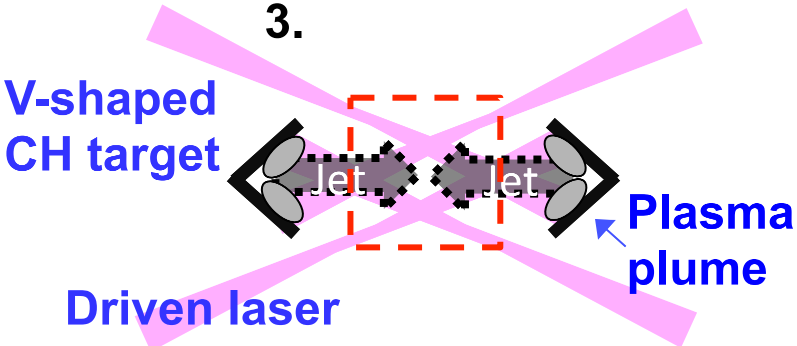
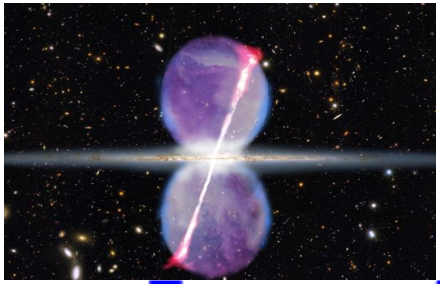


V-shaped CH target

Plasma plume

Driven laser beams



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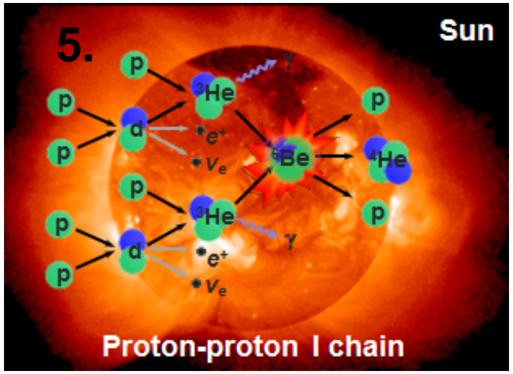
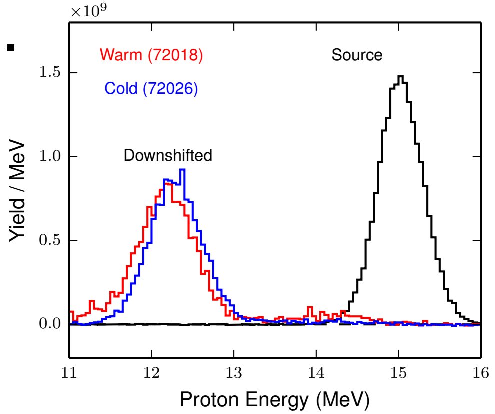
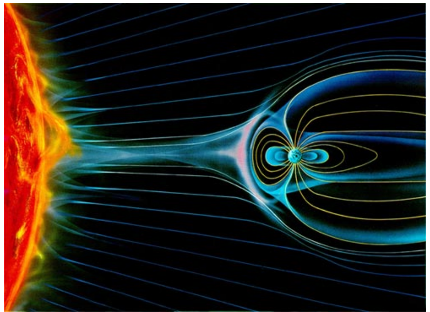


1.





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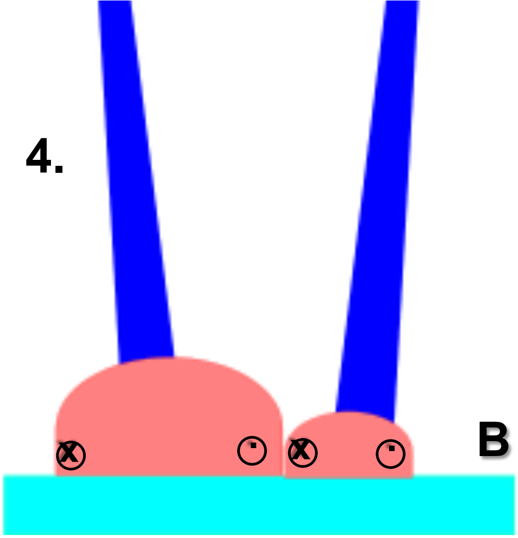
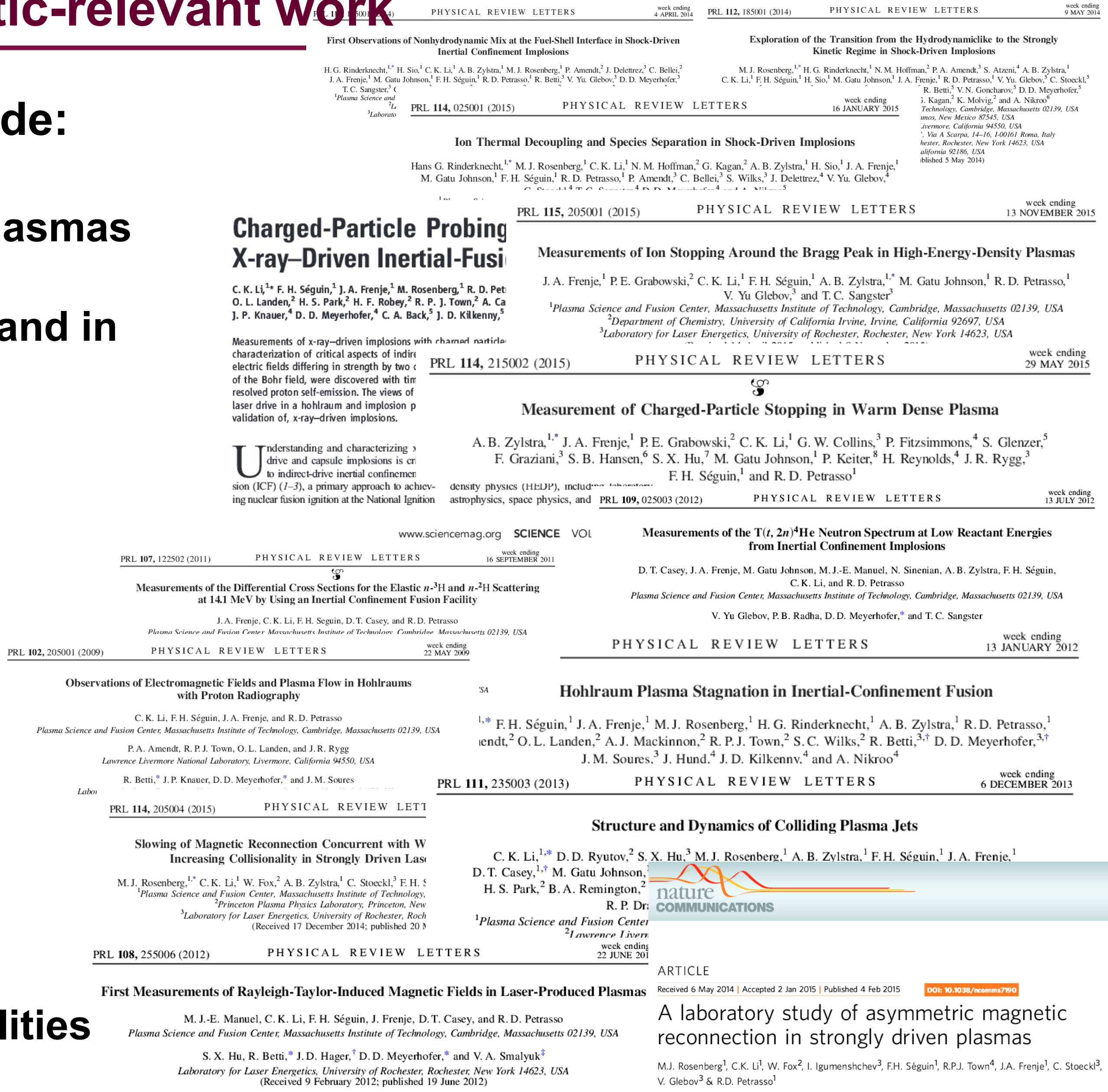


MIT's own OMEGA experiments include basic science as well as ICF programmatic-relevant work

Recent examples include:

- Kinetic effects in ICF plasmas
- Stopping power in ICF and in Warm Dense Matter
- Stellar and Big-Bang Nucleosynthesis
- Basic nuclear physics
- Astrophysical Jets
- Fields in hohlraums
- Magnetic reconnection
- Rayleigh-Taylor instabilities



P PHYSICAL REVIEW LETTERS week ending 4 APRIL 2014

First Observations of Nonhydrodynamic Mix at the Fuel-Shell Interface in Shock-Driven Inertial Confinement Implosions

H. G. Rinderknecht,[1,*] H. Sio,[1] C. K. Li,[1] A. B. Zylstra,[1] M. J. Rosenberg,[1] P. Amendt,[2] J. Delettrez,[3] C. Bellei,[2] J. A. Frenje,[1] M. Gatu Johnson,[1] F. H. Séguin,[1] R. D. Petrasso,[1] R. Betti,[3] V. Yu. Glebov,[3] D. D. Meyerhofer,[3] T. C. Sangster,[3]

PRL 112, 185001 (2014) PHYSICAL REVIEW LETTERS week ending 9 MAY 2014

Exploration of the Transition from the Hydrodynamiclike to the Strongly Kinetic Regime in Shock-Driven Implosions

M. J. Rosenberg,[1,*] H. G. Rinderknecht,[1] N. M. Hoffman,[2] P. A. Amendt,[3] S. Atzeni,[4] A. B. Zylstra,[1] C. K. Li,[1] F. H. Séguin,[1] H. Sio,[1] M. Gatu Johnson,[1] J. A. Frenje,[1] R. D. Petrasso,[1] V. Yu. Glebov,[5] C. Stoeckl,[5] R. Betti,[5] V. N. Goncharov,[5] D. D. Meyerhofer,[5] K. Molvig,[2] and A. Nikroo[6]

PRL 114, 025001 (2015) PHYSICAL REVIEW LETTERS week ending 16 JANUARY 2015

Ion Thermal Decoupling and Species Separation in Shock-Driven Implosions

Hans G. Rinderknecht,[1,*] M. J. Rosenberg,[1] C. K. Li,[1] N. M. Hoffman,[2] G. Kagan,[2] A. B. Zylstra,[1] H. Sio,[1] J. A. Frenje,[1] M. Gatu Johnson,[1] F. H. Séguin,[1] R. D. Petrasso,[1] P. Amendt,[3] C. Bellei,[3] S. Wilks,[3] J. Delettrez,[4] V. Yu. Glebov,[4]

Charged-Particle Probing X-ray–Driven Inertial-Fusi

C. K. Li,[1*] F. H. Séguin,[1] J. A. Frenje,[1] M. Rosenberg,[1] R. D. Pet O. L. Landen,[2] H. S. Park,[2] H. F. Robey,[2] R. P. J. Town,[2] A. Ca J. P. Knauer,[4] D. D. Meyerhofer,[4] C. A. Back,[5] J. D. Kilkenny,[5]

Measurements of x-ray–driven implosions with charged particle characterization of critical aspects of indire electric fields differing in strength by two of the Bohr field, were discovered with tim resolved proton self-emission. The views of laser drive in a hohlraum and implosion p validation of, x-ray–driven implosions.

Understanding and characterizing x drive and capsule implosions is cri to indirect-drive inertial confinemen sion (ICF) (1–3), a primary approach to achiev- ing nuclear fusion ignition at the National Ignition

www.sciencemag.org SCIENCE VOL

PRL 115, 205001 (2015) PHYSICAL REVIEW LETTERS week ending 13 NOVEMBER 2015

Measurements of Ion Stopping Around the Bragg Peak in High-Energy-Density Plasmas

J. A. Frenje,[1] P. E. Grabowski,[2] C. K. Li,[1] F. H. Séguin,[1] A. B. Zylstra,[1,*] M. Gatu Johnson,[1] R. D. Petrasso,[1] V. Yu Glebov,[3] and T. C. Sangster[3]

[1]Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
[2]Department of Chemistry, University of California Irvine, Irvine, California 92697, USA
[3]Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA

PRL 114, 215002 (2015) PHYSICAL REVIEW LETTERS week ending 29 MAY 2015

Measurement of Charged-Particle Stopping in Warm Dense Plasma

A. B. Zylstra,[1,*] J. A. Frenje,[1] P. E. Grabowski,[2] C. K. Li,[1] G. W. Collins,[3] P. Fitzsimmons,[4] S. Glenzer,[5] F. Graziani,[3] S. B. Hansen,[6] S. X. Hu,[7] M. Gatu Johnson,[1] P. Keiter,[8] H. Reynolds,[4] J. R. Rygg,[3] F. H. Séguin,[1] and R. D. Petrasso[1]

density physics (HEDP), includ astrophysics, space physics, and

PRL 109, 025003 (2012) PHYSICAL REVIEW LETTERS week ending 13 JULY 2012

Measurements of the $T(t,2n)^4He$ Neutron Spectrum at Low Reactant Energies from Inertial Confinement Implosions

D. T. Casey, J. A. Frenje, M. Gatu Johnson, M. J.-E. Manuel, N. Sinenian, A. B. Zylstra, F. H. Séguin, C. K. Li, and R. D. Petrasso
Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

V. Yu Glebov, P. B. Radha, D. D. Meyerhofer,* and T. C. Sangster

PRL 107, 122502 (2011) PHYSICAL REVIEW LETTERS week ending 16 SEPTEMBER 2011

Measurements of the Differential Cross Sections for the Elastic n-^{3}H and n-^{2}H Scattering at 14.1 MeV by Using an Inertial Confinement Fusion Facility

J. A. Frenje, C. K. Li, F. H. Seguin, D. T. Casey, and R. D. Petrasso
Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

PRL 102, 205001 (2009) PHYSICAL REVIEW LETTERS week ending 22 MAY 2009

Observations of Electromagnetic Fields and Plasma Flow in Hohlraums with Proton Radiography

C. K. Li, F. H. Séguin, J. A. Frenje, and R. D. Petrasso
Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

P. A. Amendt, R. P. J. Town, O. L. Landen, and J. R. Rygg
Lawrence Livermore National Laboratory, Livermore, California 94550, USA

R. Betti,* J. P. Knauer, D. D. Meyerhofer,* and J. M. Soures

PHYSICAL REVIEW LETTERS week ending 13 JANUARY 2012

Hohlraum Plasma Stagnation in Inertial-Confinement Fusion

F. H. Séguin,[1] J. A. Frenje,[1] M. J. Rosenberg,[1] H. G. Rinderknecht,[1] A. B. Zylstra,[1] R. D. Petrasso,[1] O. L. Landen,[2] A. J. Mackinnon,[2] R. P. J. Town,[2] S. C. Wilks,[2] R. Betti,[3,†] D. D. Meyerhofer,[3,†] J. M. Soures,[3] J. Hund,[4] J. D. Kilkenny,[4] and A. Nikroo[4]

PRL 114, 205004 (2015) PHYSICAL REVIEW LETT

Slowing of Magnetic Reconnection Concurrent with W Increasing Collisionality in Strongly Driven Las

M. J. Rosenberg,[1,*] C. K. Li,[1] W. Fox,[2] A. B. Zylstra,[1] C. Stoeckl,[3] F. H. S
[1]Plasma Science and Fusion Center, Massachusetts Institute of Technology,
[2]Princeton Plasma Physics Laboratory, Princeton, New
[3]Laboratory for Laser Energetics, University of Rochester, Roch
(Received 17 December 2014; published 20 M

PRL 111, 235003 (2013) PHYSICAL REVIEW LETTERS week ending 6 DECEMBER 2013

Structure and Dynamics of Colliding Plasma Jets

C. K. Li,[1,*] D. D. Ryutov,[2] S. X. Hu,[3] M. J. Rosenberg,[1] A. B. Zylstra,[1] F. H. Séguin,[1] J. A. Frenje,[1] D. T. Casey,[1,†] M. Gatu Johnson, H. S. Park,[2] B. A. Remington,[2] R. P. Dr
[1]Plasma Science and Fusion Center

PRL 108, 255006 (2012) PHYSICAL REVIEW LETTERS week ending 22 JUNE 201

First Measurements of Rayleigh-Taylor-Induced Magnetic Fields in Laser-Produced Plasmas

M. J.-E. Manuel, C. K. Li, F. H. Séguin, J. Frenje, D. T. Casey, and R. D. Petrasso
Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

S. X. Hu, R. Betti,* J. D. Hager,† D. D. Meyerhofer,* and V. A. Smalyuk‡
Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA
(Received 9 February 2012; published 19 June 2012)

nature COMMUNICATIONS

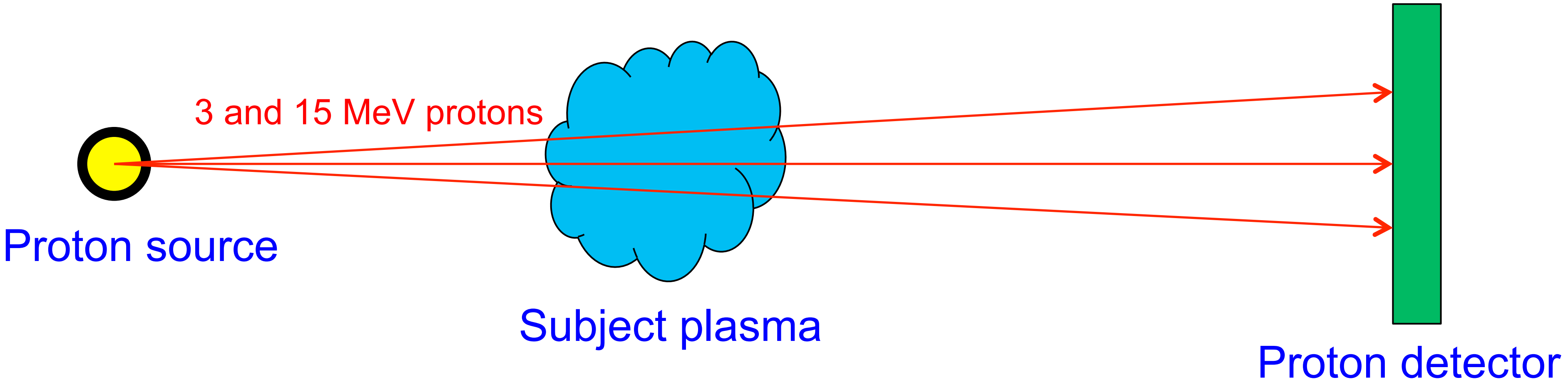
ARTICLE

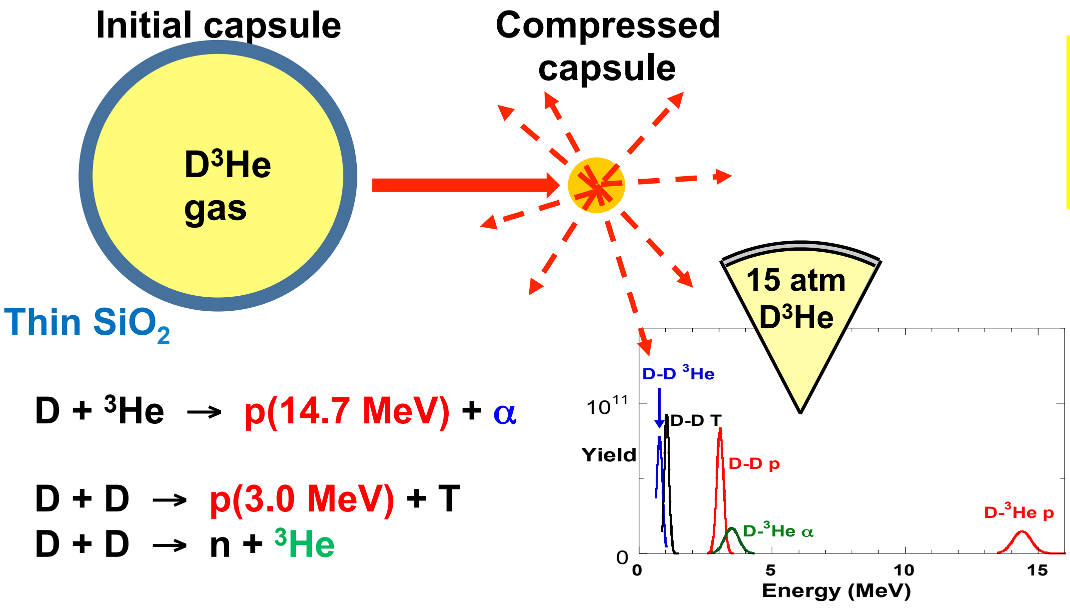
Received 6 May 2014 | Accepted 2 Jan 2015 | Published 4 Feb 2015 DOI: 10.1038/ncomms7190

A laboratory study of asymmetric magnetic reconnection in strongly driven plasmas

M.J. Rosenberg[1], C.K. Li[1], W. Fox[2], I. Igumenshchev[3], F.H. Séguin[1], R.P.J. Town[4], J.A. Frenje[1], C. Stoeckl[3], V. Glebov[3] & R.D. Petrasso[1]

MIT has developed a D3He monoenergetic particle platform for radiography of HEDP experiments





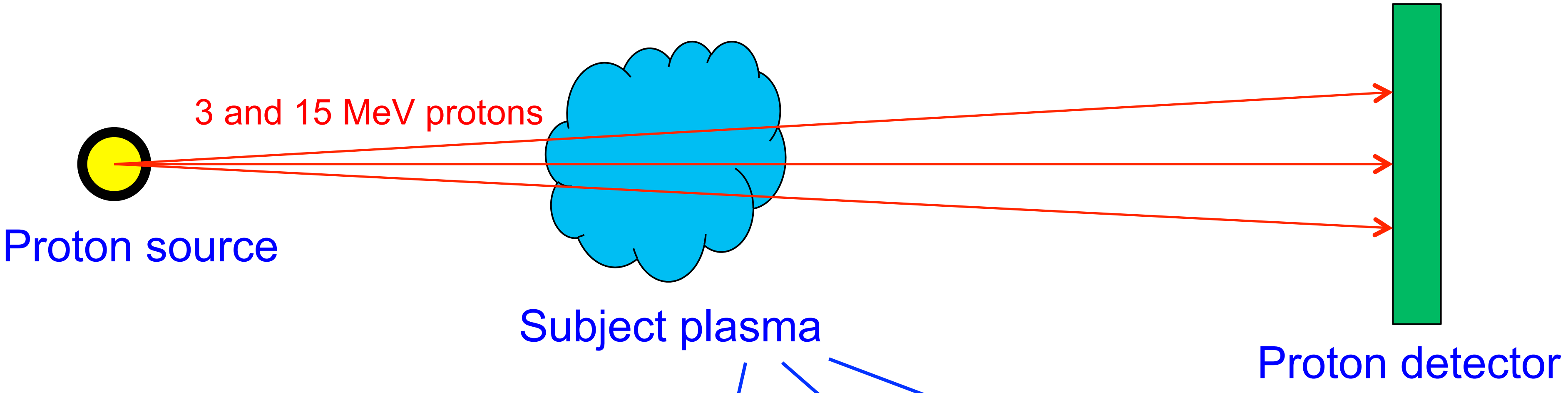
Spatial resolution: ~ 40 μm (FWHM)
Energy resolution: ~ 3%
Temporal resolution: ~ 80 ps

$D + {}^3He \rightarrow p(14.7\ MeV) + \alpha$

$D + D \rightarrow p(3.0\ MeV) + T$
$D + D \rightarrow n + {}^3He$

C. K. Li *et al.*, Phy .Rev. Lett. (2006)
C. K. Li *et al.*, Rev.Sci.Instrum (2006)
F. Seguin *et al.*, Rev.Sci.Instrum (2003

MIT has developed a D3He monoenergetic particle platform for radiography of HEDP experiments



3 and 15 MeV protons

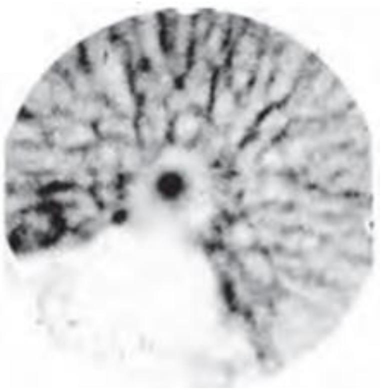
Proton source

Subject plasma

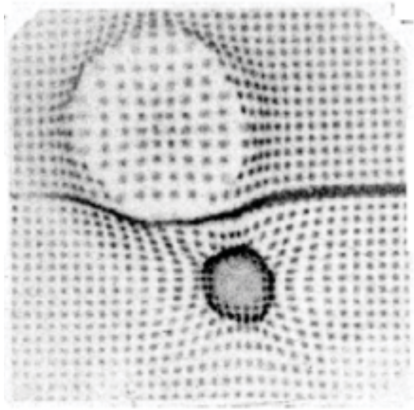
Proton detector

Phenomena investigated with monoenergetic proton radiography at OMEGA include:

- Laser-foil interactions
- Magnetic reconnection
- Magnetic flux compression
- RT instability
- Weibel instability
- ICF capsule implosions
- ICF hohlraums
- Charged-particle stopping



Fast-ignition capsule



Laser-foil plasma bubble

ICF hohlraum

Thank you for your attention!

Concept for an ICF power plant