An Introduction to Inertial Confinement Fusion (ICF)

2019 SULI Introductory Course on Plasma Physics

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June 14, 2019

LLNL-PRES-752840
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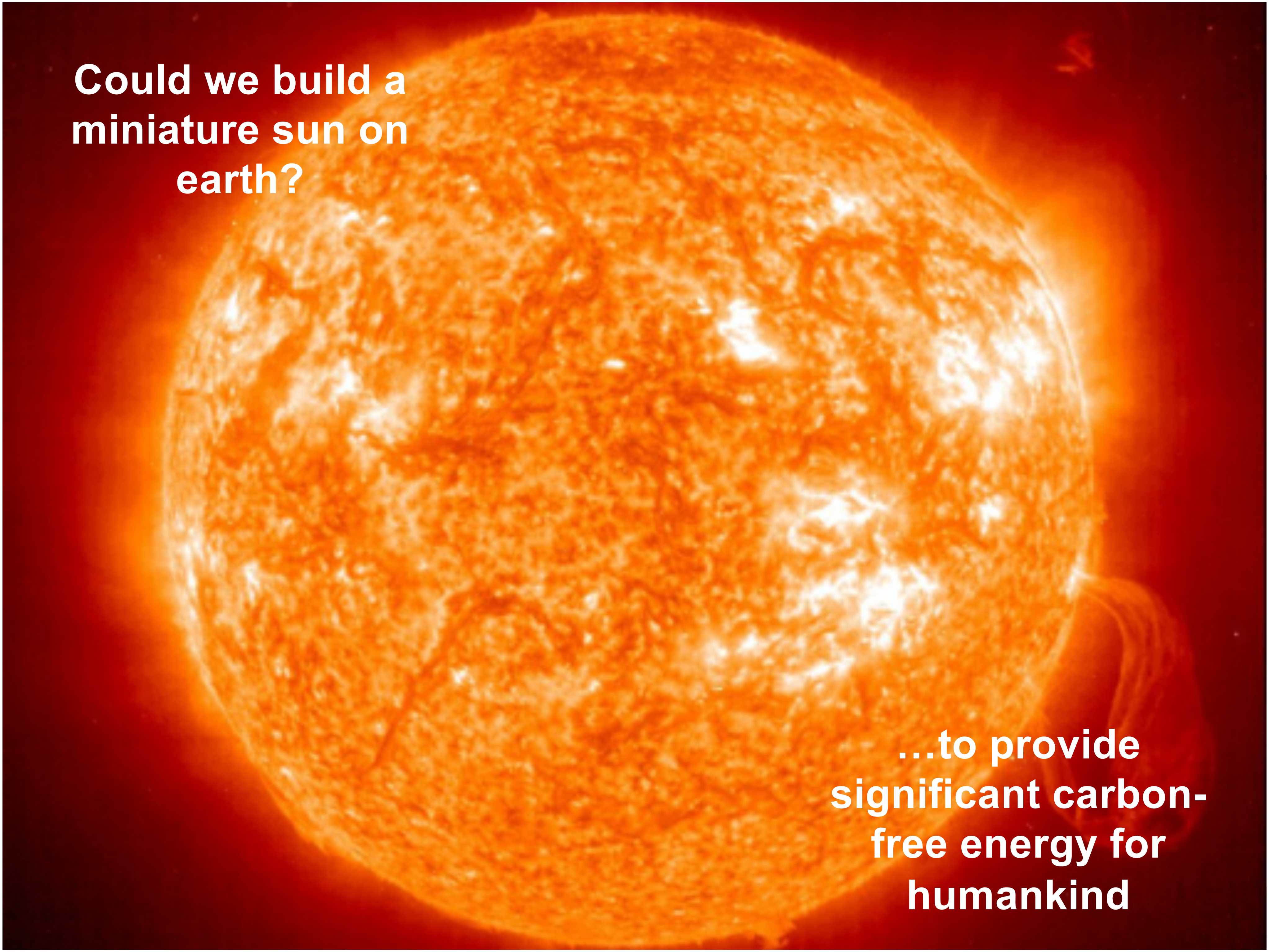
Could we build a miniature sun on earth?
…to provide significant carbon-free energy for humankind

Outline

Fusion Basics

Inertial Confinement Fusion (ICF) Principles

ICF Facilities

- **The OMEGA Laser Facility**
- **The Z Pulsed Power Machine**
- **The National Ignition Facility (NIF)**

Status of NIF Indirect-Drive ICF Experiments

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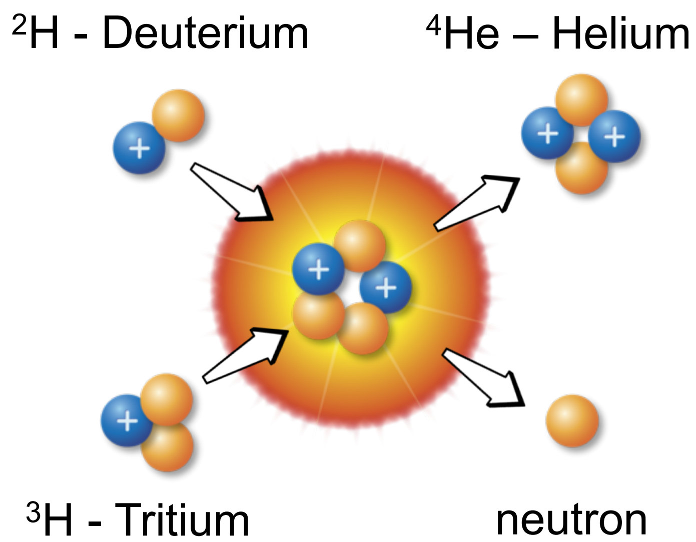
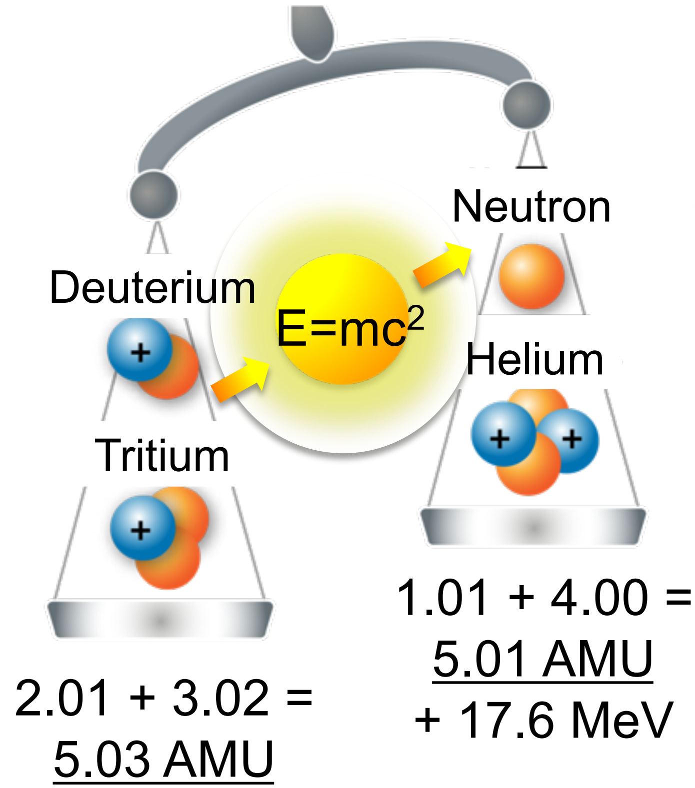
Fusion combines light nuclei into a heavier nucleus and releases huge amounts of energy

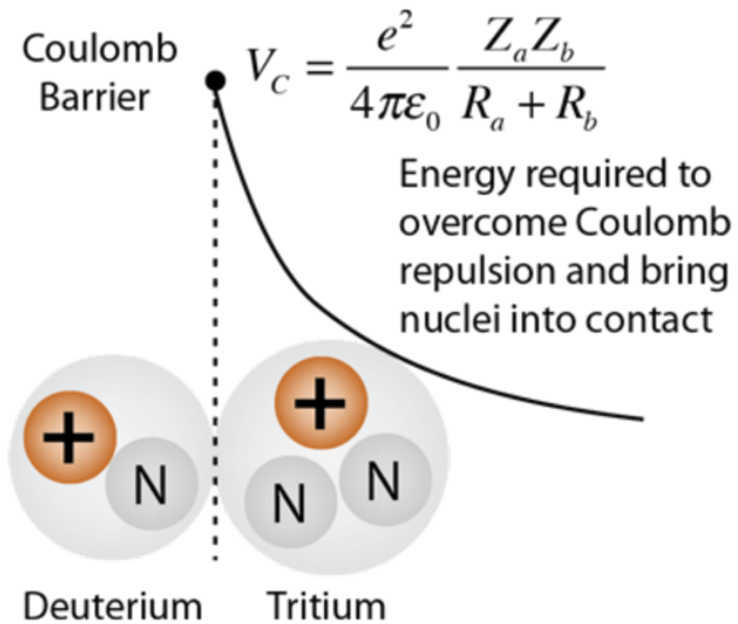




$$D + T \rightarrow \alpha(3.5\text{MeV}) + n(14.1\text{MeV})$$

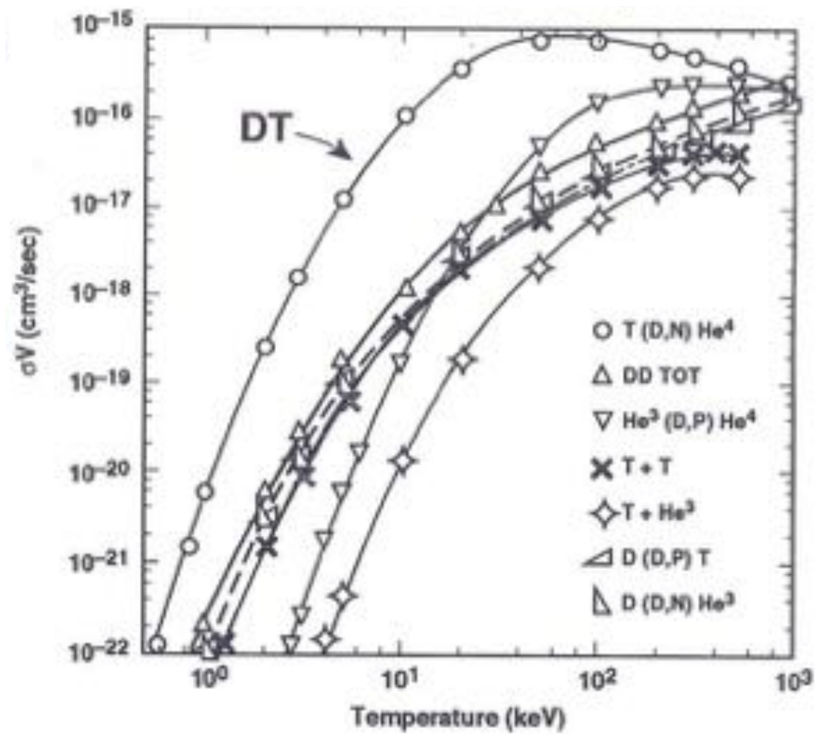
$$Q_{fusion} = 3.3 \times 10^{11}\ \text{J/g}$$

The Coulomb barrier makes high temperatures necessary for DT thermonuclear fusion



Hyperphysics

Fusion Rate vs. Temperature



Atzeni and Meyer-Ter-Vehn
The Physics of Inertial Fusion

$$Yield = n_i \times n_j \times \langle \sigma v \rangle \times Volume \times time$$

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

The Lawson criterion defines the conditions required to achieve ignition

Assuming the plasma consists of deuterons and tritons of density *n/2* each, the rate of fusion processes (*W)* in such a hot dense plasma state is:

$$W = \frac{n^2}{4} \langle \sigma v \rangle$$

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The particles in the plasma have Maxwell-Boltzmann distributed velocities with an average kinetic energy of

$$E_k = \frac{3k_B T}{2}$$

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The energy produced per unit time (*t)* depends on the kinetic energy (*Q)* of the reaction products and the rate of the fusion processes (*W)* and is given by

$$E = W\tau Q = \frac{n^2}{4}\langle \sigma v \rangle \tau Q$$

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Rate of fusion processes

$$W = \frac{n^2}{4}\overbrace{\langle \sigma v \rangle}^{\text{reactivity}}$$

Fusion cross-section

Relative velocity of the two nuclei

The particles in the plasma have Maxwell-Boltzmann distributed velocities with an average kinetic energy of

Kinetic energy

$$E_k = \frac{3k_B T}{2}$$

Boltzmann constant

Temperature

The energy produced per unit time (*t)* depends on the kinetic energy (*Q)* of the reaction products and the rate of the fusion processes (*W)* and is given by

Energy produced

$$E = W\tau Q = \frac{n^2}{4}\langle \sigma v \rangle \tau Q$$

Confinement time

Kinetic energy of the reaction products; for DT = 17.6 MeV

The Lawson criterion defines the conditions required to achieve ignition

The ultimate aim in ICF is to produce energy, so the energy obtained from the fusion process has to be greater than the energy to heat the plasma to such temperatures

$$3nk_BT < \frac{n^2}{4}\langle\sigma v\rangle\tau Q$$

$$n\tau > \frac{12k_BT}{\langle\sigma v\rangle Q}$$

Lawson criterion

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Lawson criterion

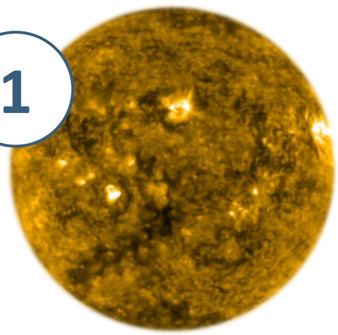
In addition to the problem of confinement, the fusion particles have to have enough kinetic energy for a sufficient number of fusion reactions to take place. For DT fuel this implies a temperature of approximately 5 keV.

So in the case of a DT reaction with Q=17.6 MeV and an operating temperature of a reactor of ~5-10 keV, the Lawson criterion becomes

$$n\tau \simeq 10^{14} - 10^{15} \text{ s/cm}^3$$

There are at least three ways to achieve nuclear fusion

1



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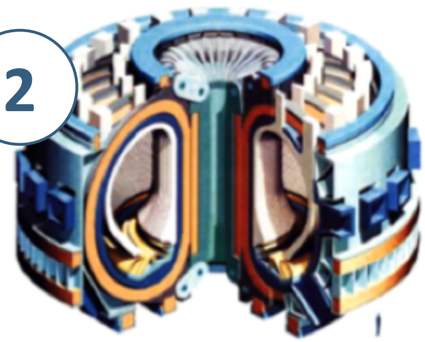

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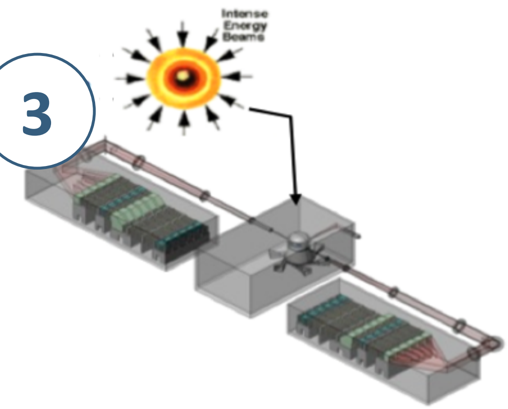

	Gravitational Confinement	Magnetic Confinement	Inertial Confinement
Density	10^4 x solid	solid / 10^8	10^3 x solid
Temperature	1 keV	10 keV	10 keV
Confinement time	10^5 years	seconds	10^{-10} seconds

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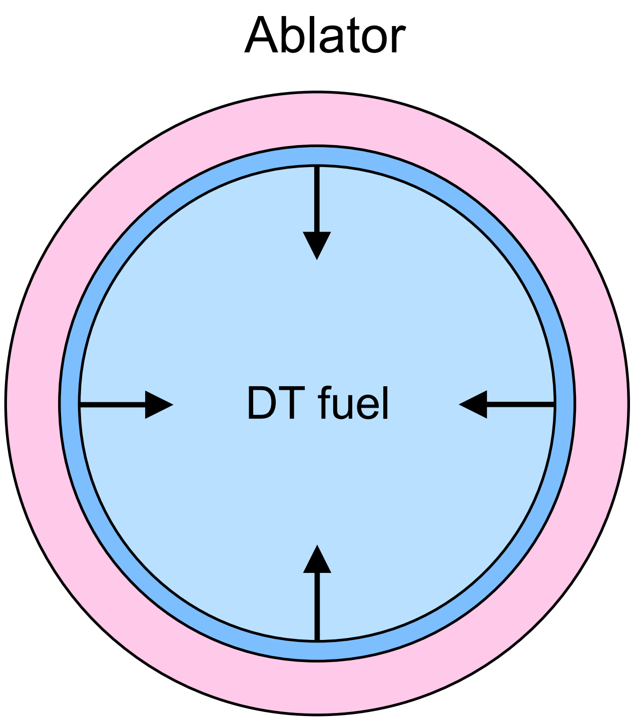
ICF uses the inertia of the dense fuel itself to confine the plasma before it blows apart under its own pressure



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

$$\langle \tau \rangle \simeq \frac{1}{M} \int_0^R \rho \frac{R - r}{c_s} \, 4\pi r^2 \, dr$$

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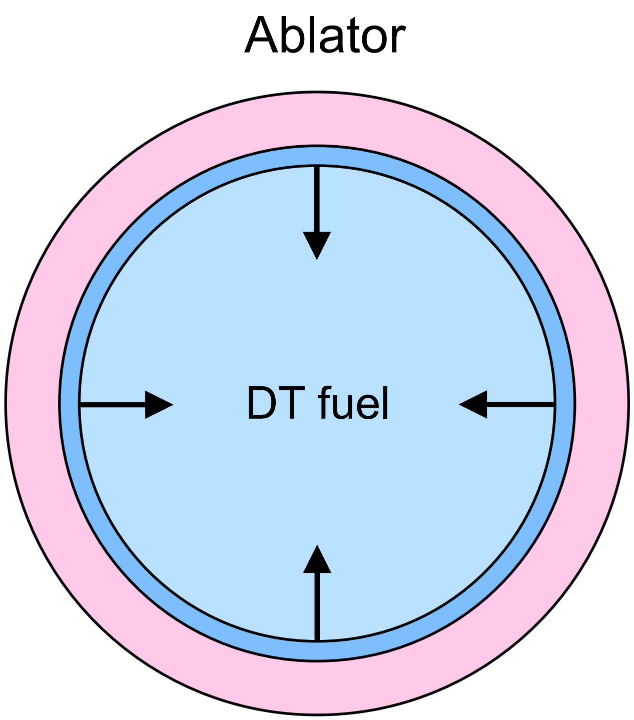

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initial radius

final radius

density

mass of fuel

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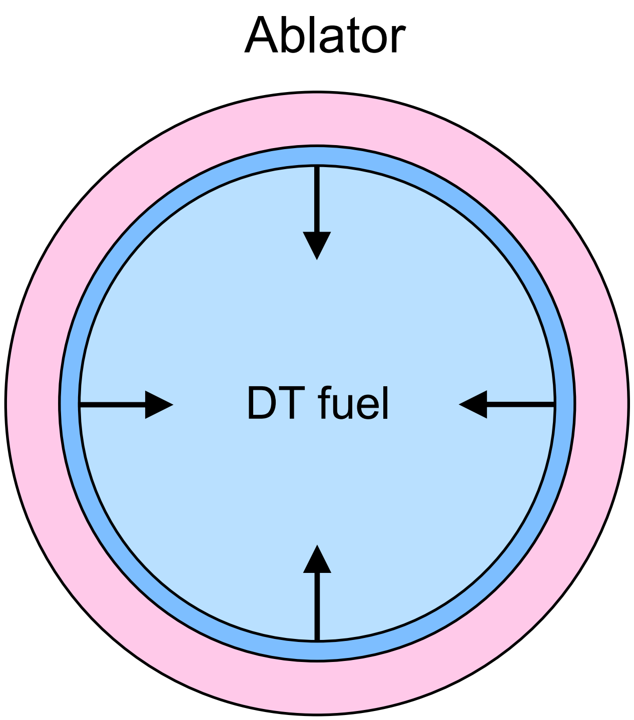


The confinement time (τ) can be expressed in terms of the sound speed c_s:

$$\langle\tau\rangle \simeq \underbrace{\frac{1}{M}}_{\text{mass of fuel}} \int_0^R \underbrace{\rho}_{\text{density}} \frac{\overbrace{R}^{\text{initial radius}} - \overbrace{r}^{\text{final radius}}}{c_s} 4\pi r^2\, dr$$

$$= \frac{4\pi \dfrac{\rho}{c_s} \left(\dfrac{Rr^3}{3} - \dfrac{r^4}{4}\right)\Big|_0^R}{\dfrac{4\pi}{3}\rho R^3}$$

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

$$c_s = 2.7 \times 10^7 \sqrt{\underbrace{T}_{\text{temperature}}\ (\text{keV})}\ \text{cm/s}$$

Areal density, or ρR, is a key performance parameter in ICF

The number density *n* is related to the fuel density by $n = \rho/m$, so the confinement parameter $n\tau$ can now be expressed as:

$$n\tau \simeq \frac{nR}{4c_s} = \frac{\rho R}{4Mc_s}$$

Areal density (ρR) is defined as the line-averaged density:

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

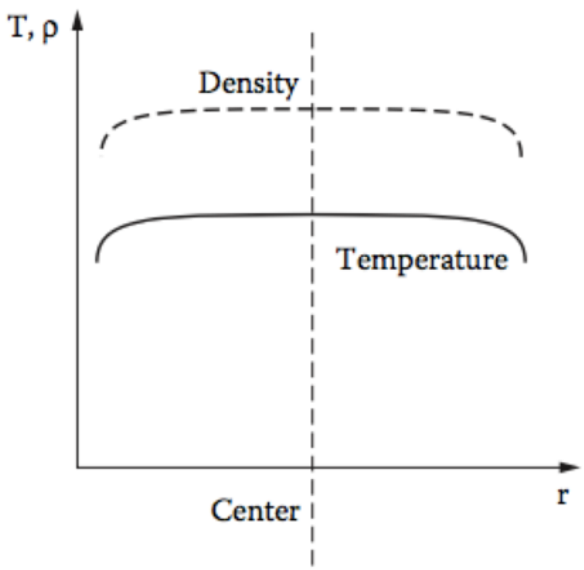
Efficient burn requires $n\tau$ to be well above the Lawson criterion. Using $n\tau \sim 2\text{x}10^{15}$ s/cm^3 leads to a first rough estimate of

$$\rho R \simeq 3 \text{ g/cm}^2$$

The idea of ICF is to compress fuel to thermonuclear conditions

In the early days of fusion research, we thought the whole fuel should be compressed to fusion conditions at the end of the compression phase

Volume ignition



This would take an unrealistically high driver energy!

Pfalzner, An Introduction to Inertial Confinement Fusion

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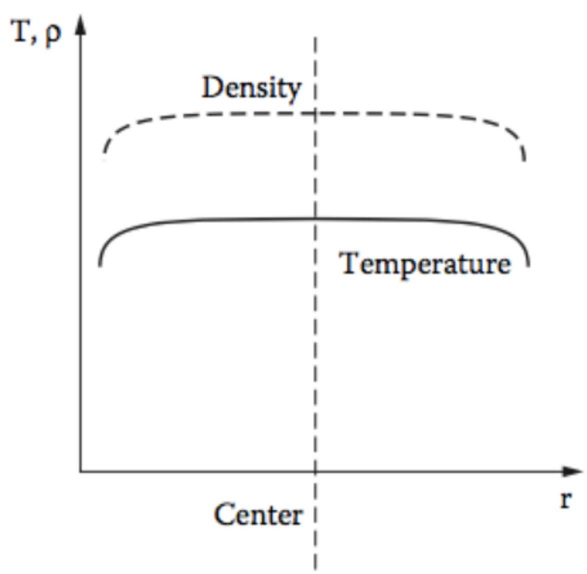

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It turns out, that

(1) It takes more energy to heat fuel than to compress it, and
(2) The compression of hot material is more energy-consuming than for cold material

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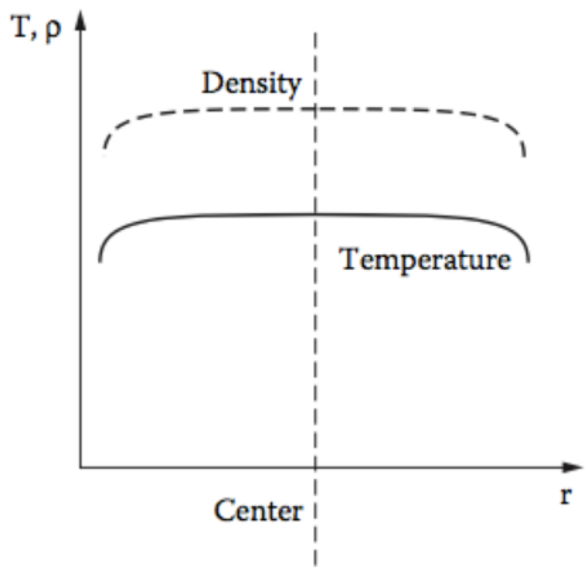

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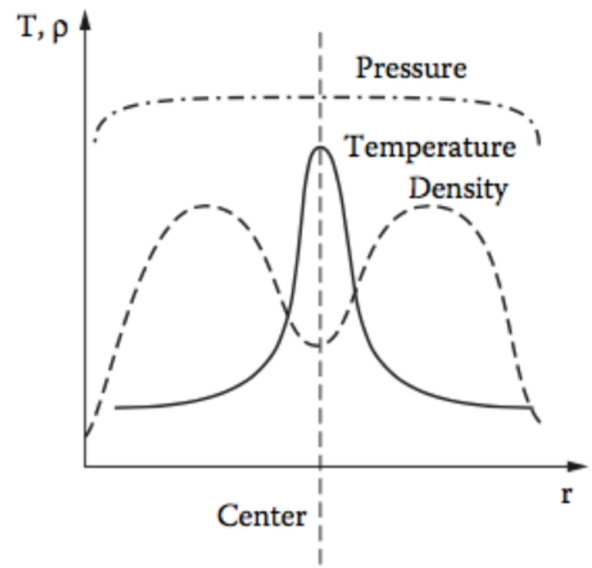
Hot-spot ignition



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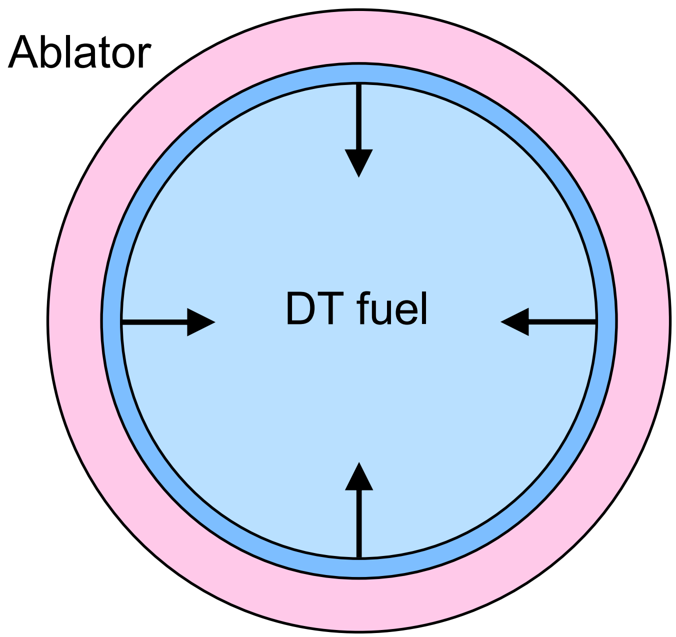
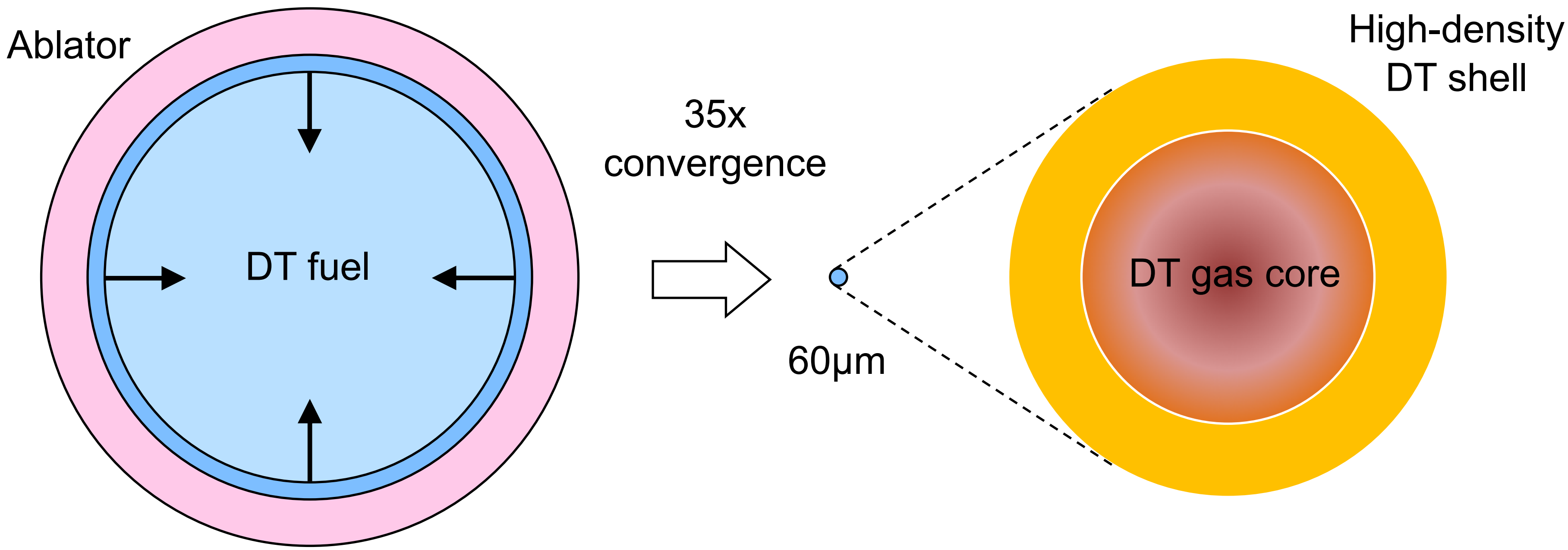


$R \sim 1000\ \mu m$
$\rho_{DT} = 0.25\ g/cm^3$

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

The idea of ICF is to compress fuel to thermonuclear conditions



R ~ 1000 µm
ρ_{DT} = 0.25 g/cm^3

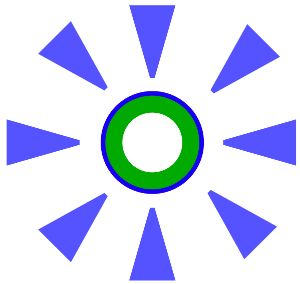
ρR_{DT} ~ 0.03 g/cm^2

R ~ 30 µm
ρ_{DT} = 700 g/cm^3

ρR_{DT} ~ 3 g/cm^2

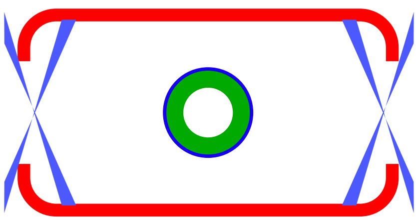
There are two different laser-drive schemes

Direct Drive



Laser directly irradiates fuel capsule

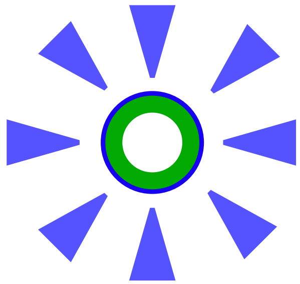
Indirect Drive



Laser produces x-rays inside a hohlraum, or cavity, which irradiate the fuel capsule

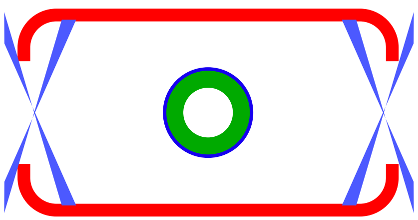
There are two different laser-drive schemes

Direct Drive



- ~8% efficiency
- Reduced laser-plasma interaction effects

Indirect Drive



- ~4% efficiency
- Relaxed beam uniformity
- Reduced hydrodynamic instability

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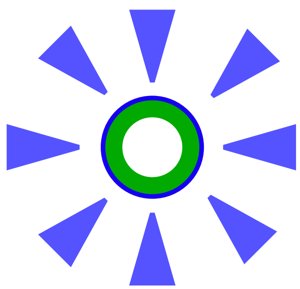
Direct Drive



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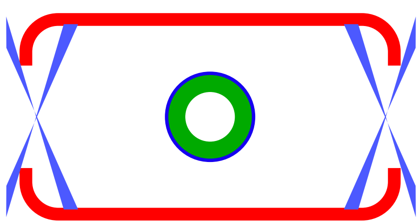
Indirect Drive



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- Relaxed beam uniformity
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Fuel is compressed by blowoff in rocket-like reaction

Fuel core reaches 20x density of lead, ignites at 100,000,000˚ C

Thermonuclear burn spreads, yielding many times the input energy

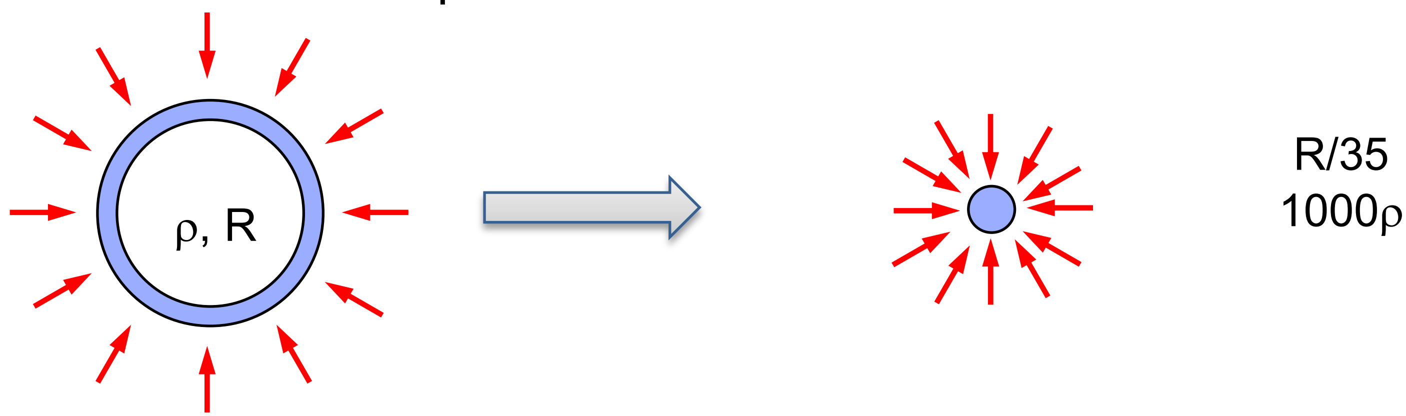
Image taken from "Matter at High-Energy Densities," Univ of Rochester, Laboratory for Laser Energetics

The most efficient compression is spherical

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

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

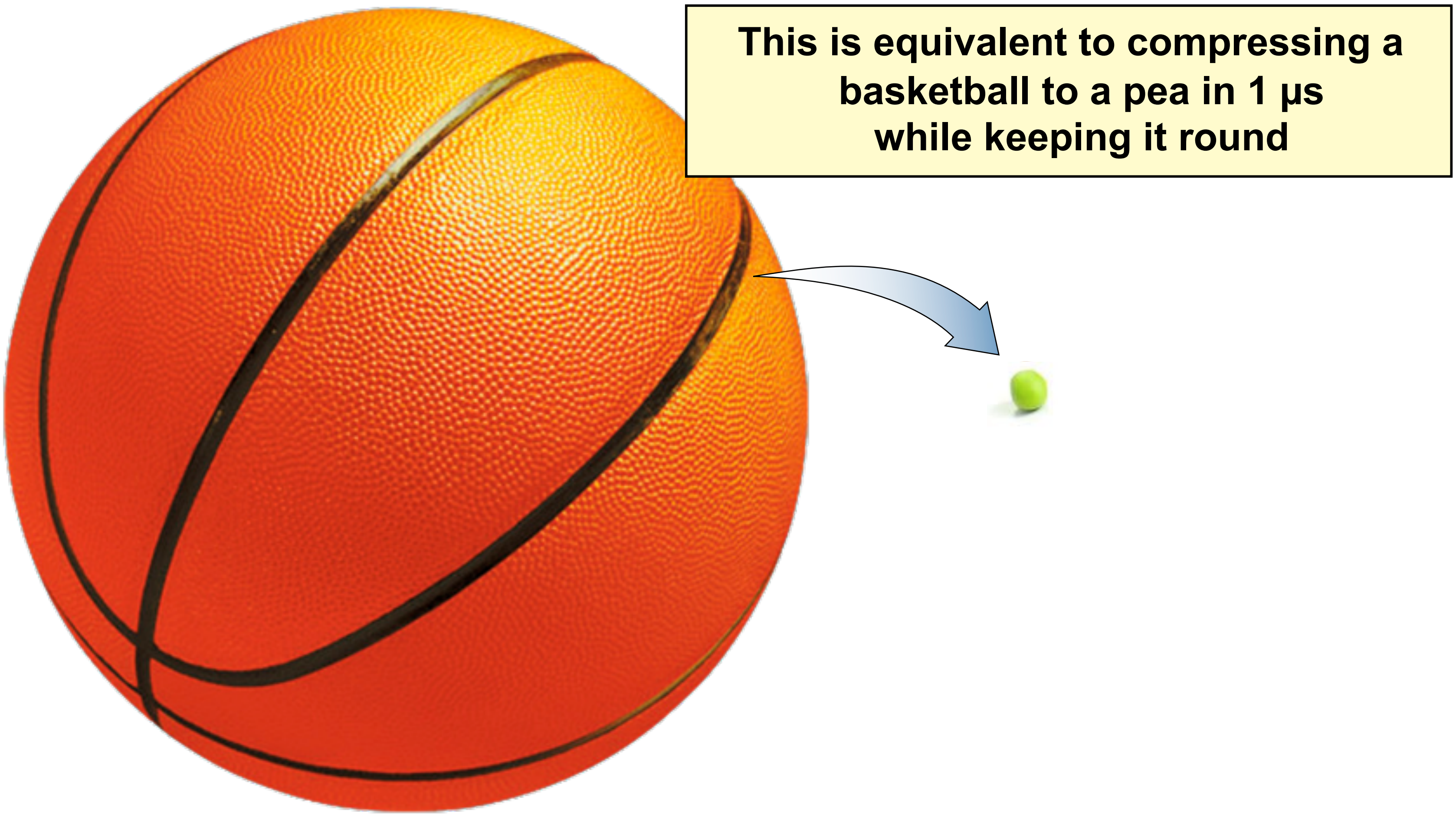
In practice, a hollow shell has more surface area and is easier to push with a given pressure than a solid sphere of the same mass



Goal: Convert shell kinetic energy to compression energy to thermal energy

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

The capsule must be compressed 35x in radius, or 40,000x in volume



Keeping the implosion round requires a highly spherical drive and extremely smooth capsules

The most efficient compression is isentropic

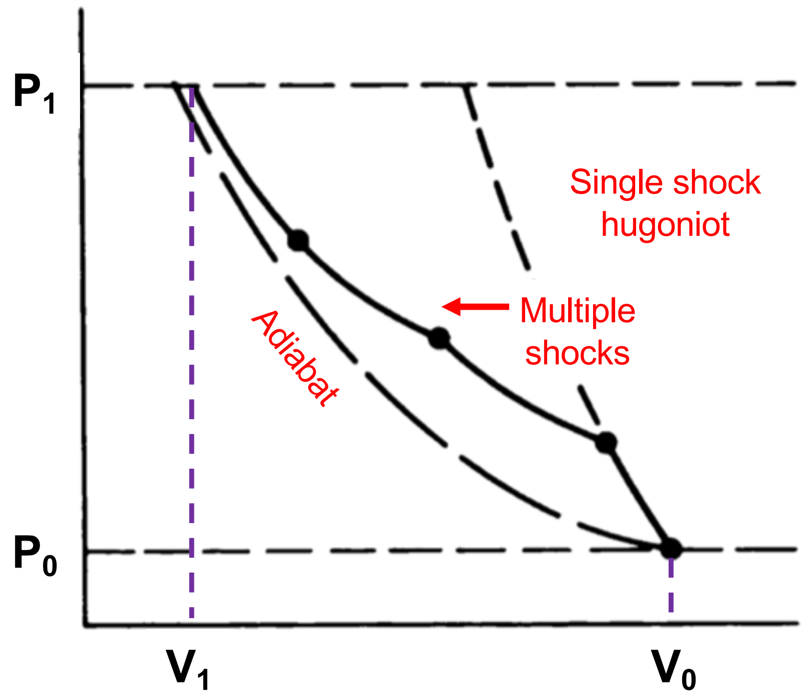
From thermodynamics:

$$dU = Tds - PdV$$

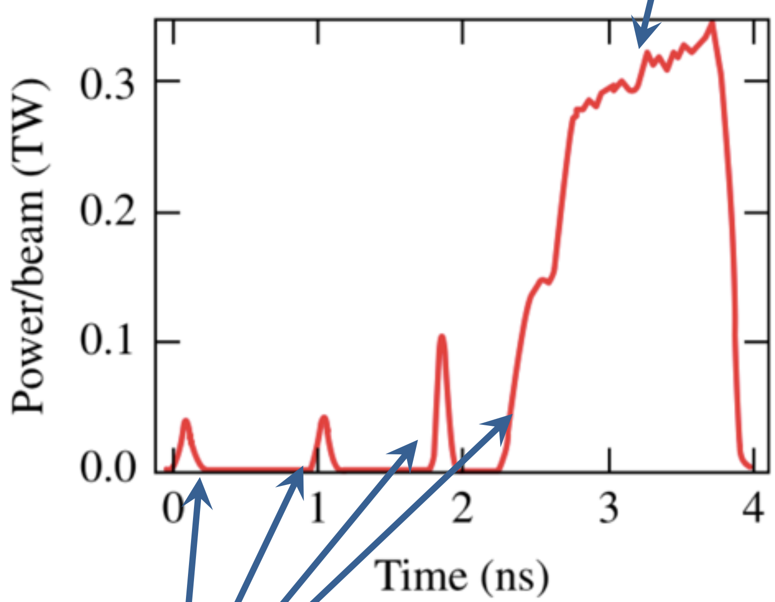
$$PdV = Tds - dU$$

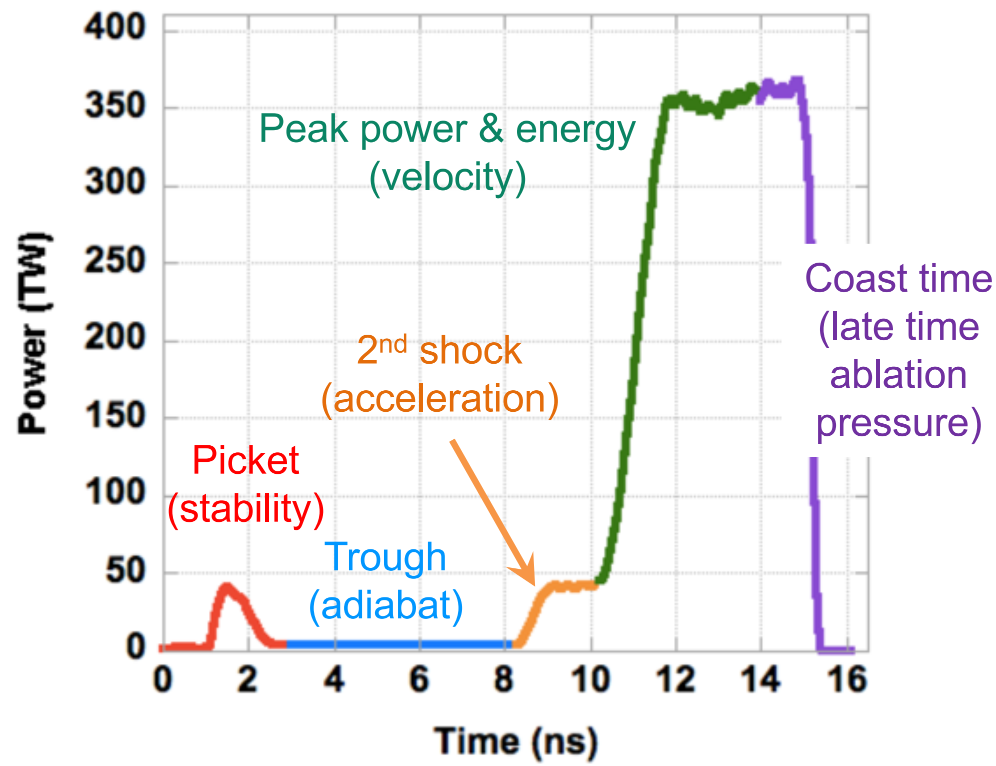
Minimize work needed to compress ⟺ Minimize entropy generation

P-V Diagram

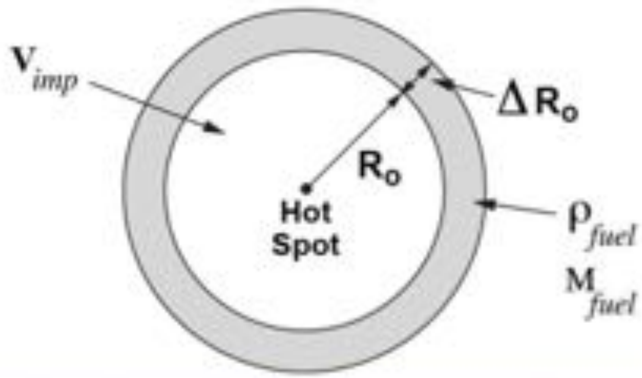


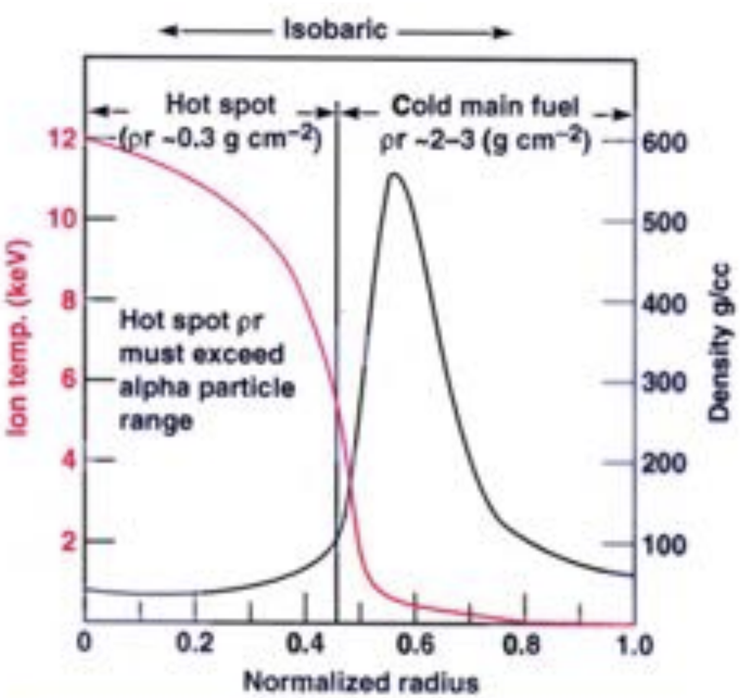
Shaped laser pulses are therefore used





The most efficient implosion is fast





Implosion velocity for Fermi degenerate case

$$KE = \frac{1}{2} M_{fuel} v_{imp}^2 \approx (ignition\ margin) \times E_{fuel} \approx 2E_{fuel}$$

$$\Rightarrow\ v_{imp} = \sqrt{\frac{4E_{fuel}}{M_{fuel}}} \approx 3.6\times10^7 \text{ cm/s}$$

E_{fuel} determined by pressure equilibrium with hot spot

Ablation pressure to generate implosion velocity

$$KE = \frac{1}{2} M_{fuel} v_{imp}^2 = P_{abl} \Delta V$$

$$\Rightarrow\ P_{abl} \sim 100 \text{ Mbar}$$

ΔV corresponds to $R_0 \rightarrow R_0/2$ (useful area for compression)

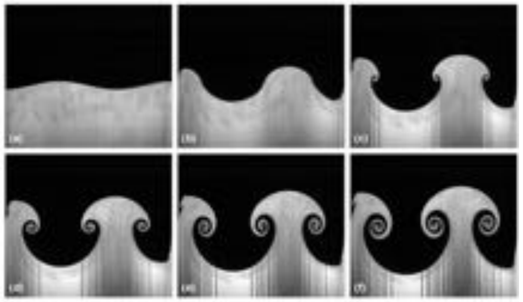
The most efficient implosion does not mix

Rayleigh-Taylor
- **Low density attempts to push high density**

Evolution of RTI in two immiscible fluids

Rayleigh-Taylor "fingers" in Crab Nebula

Richtmyer-Meshkov
- **Shock-driven vorticity**



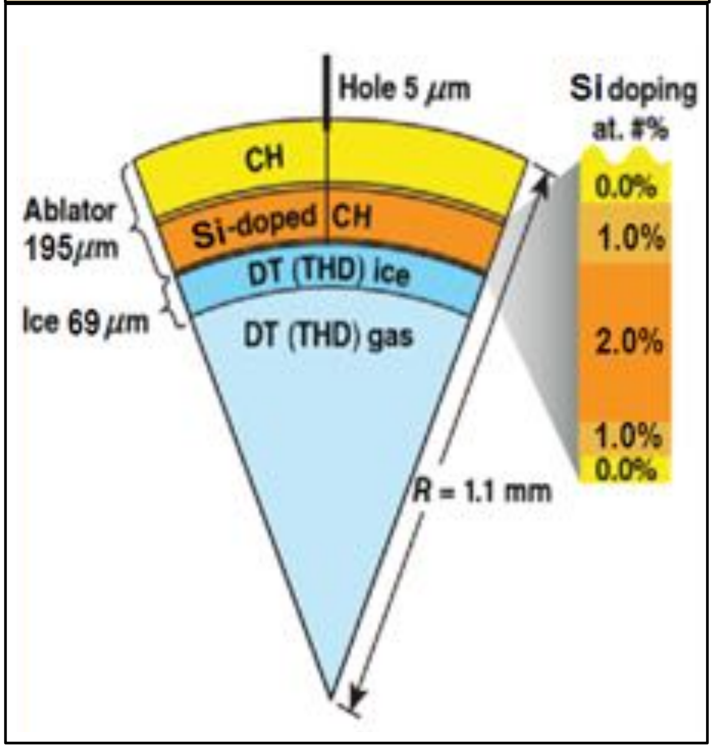
Evolution of Richtmyer-Meshkov at the interface of two fluids

Kelvin-Helmholtz
- **Shear**

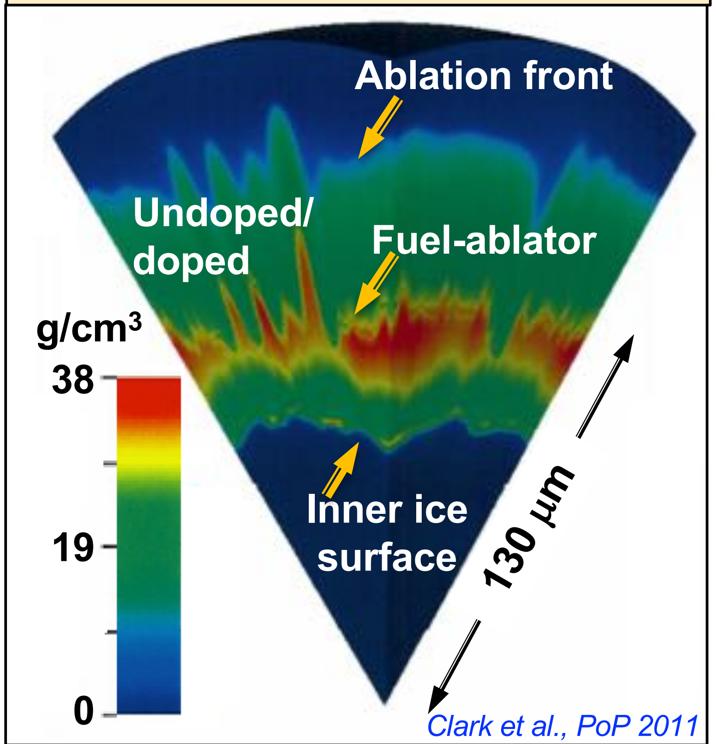
Kelvin-Helmholtz roll-up in clouds

Mix is caused by hydrodynamic instabilities that grow at various capsule interfaces

Rev. 5 capsule design



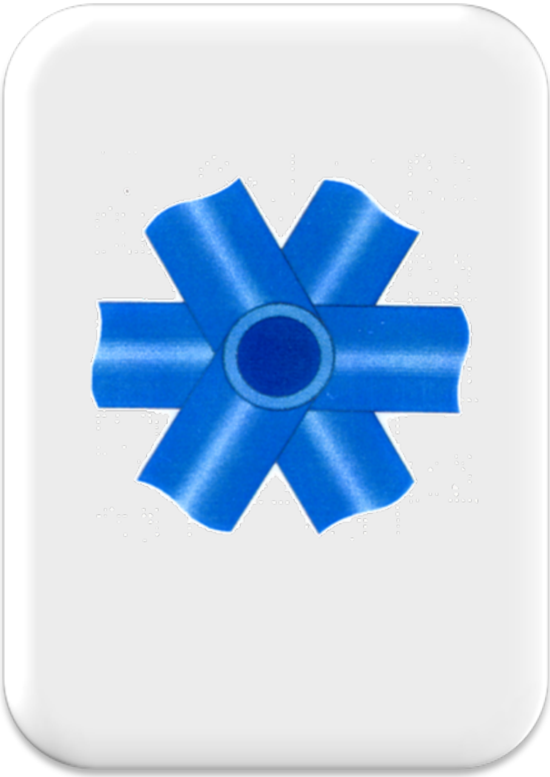
3D simulation at peak velocity



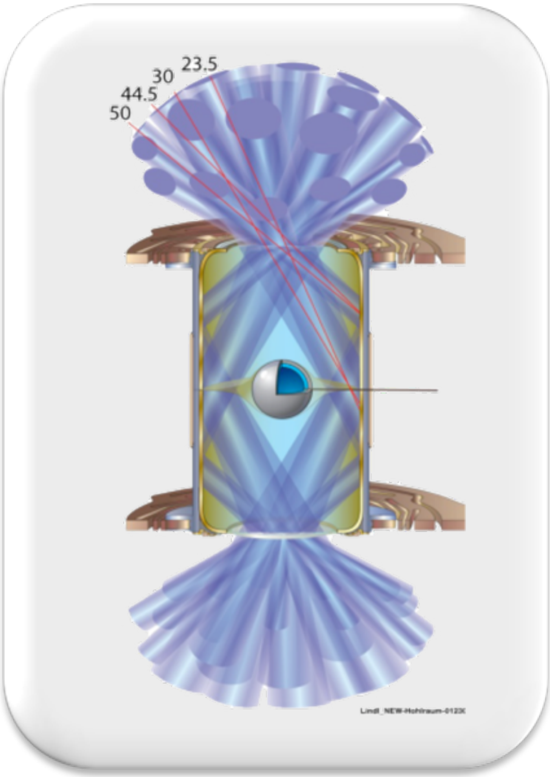
Mixing of ablator material into the hot spot due to the hydrodynamic instabilities can increase the radiative cooling and degrade capsule performance in ICF implosions

In addition to the two laser drives, there is a magnetic drive scheme, for a total of three primary approaches to ICF

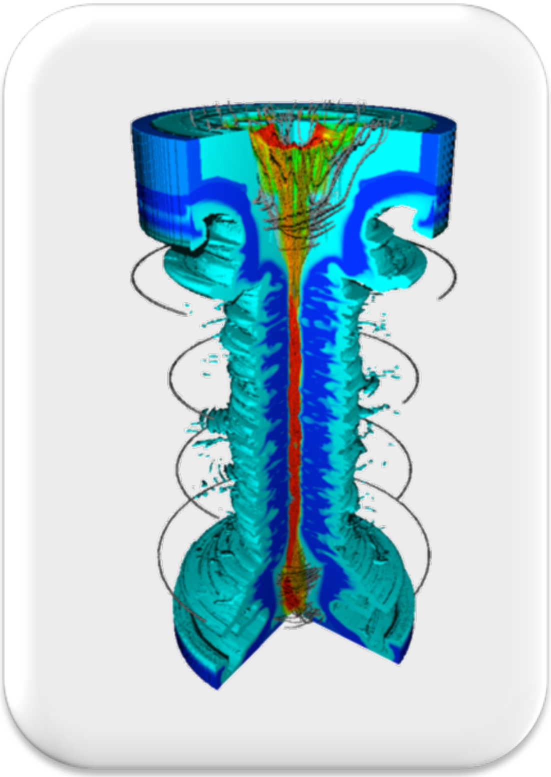
Laser Direct Drive



Laser Indirect Drive



Magnetic Direct Drive



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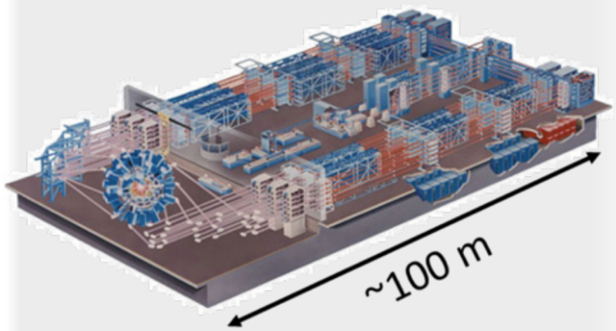
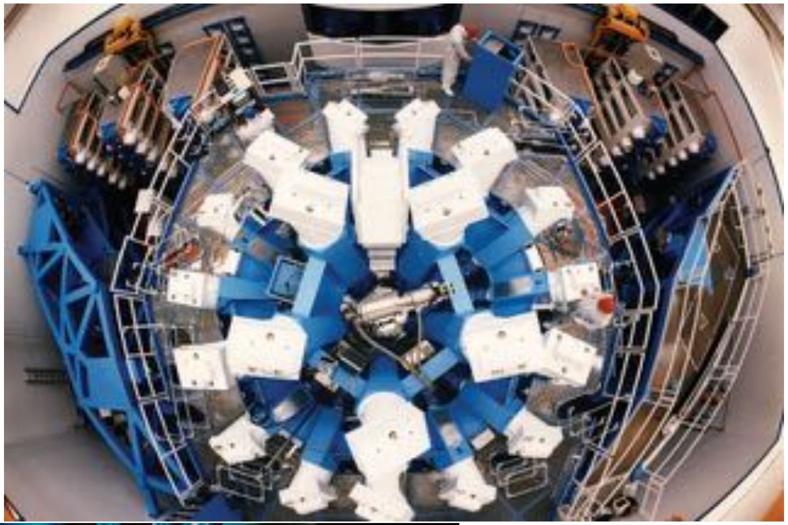
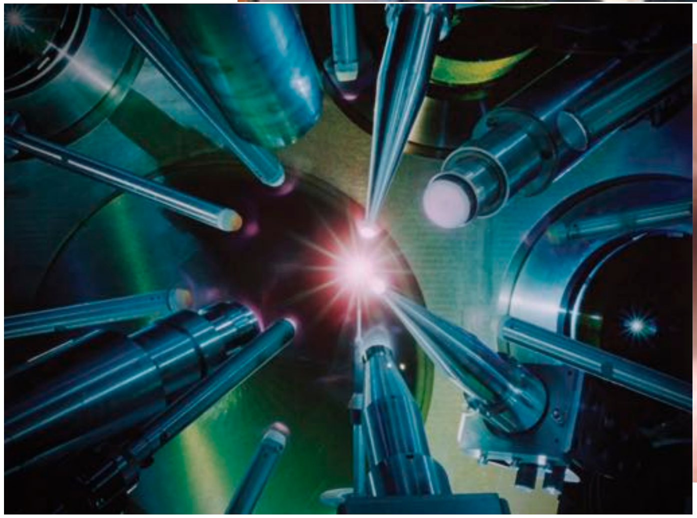
The OMEGA laser facility at the University of Rochester, NY, uses the direct-drive approach

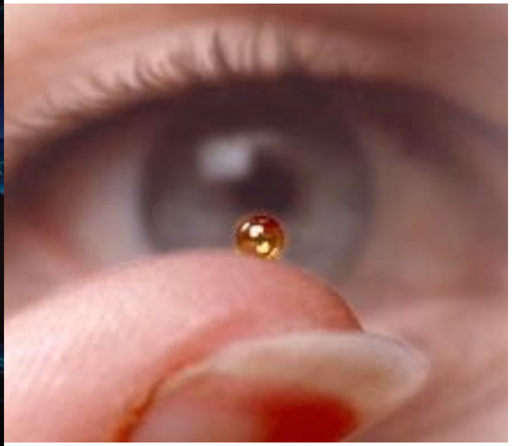
OMEGA Facility



- 60 laser beams (351 nm)
- Up to ~30 kJ of laser energy
- Optimized for direct drive illumination







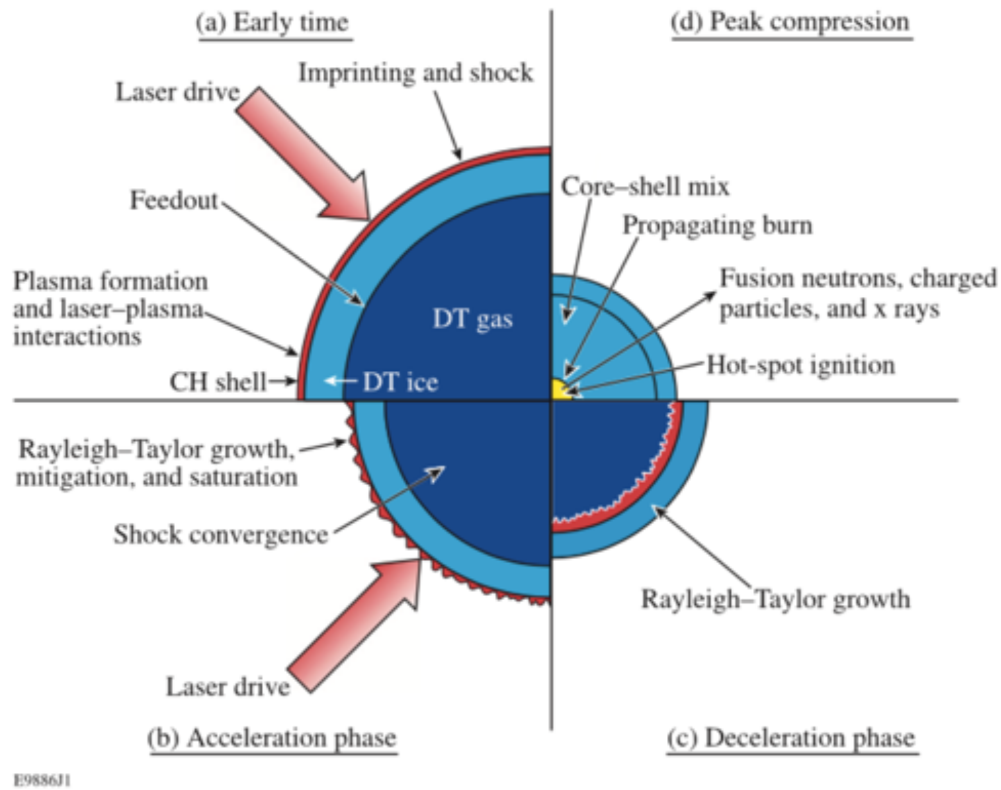
The goal of experiments at OMEGA is to demonstrate and understand the physics of laser direct drive

30 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.

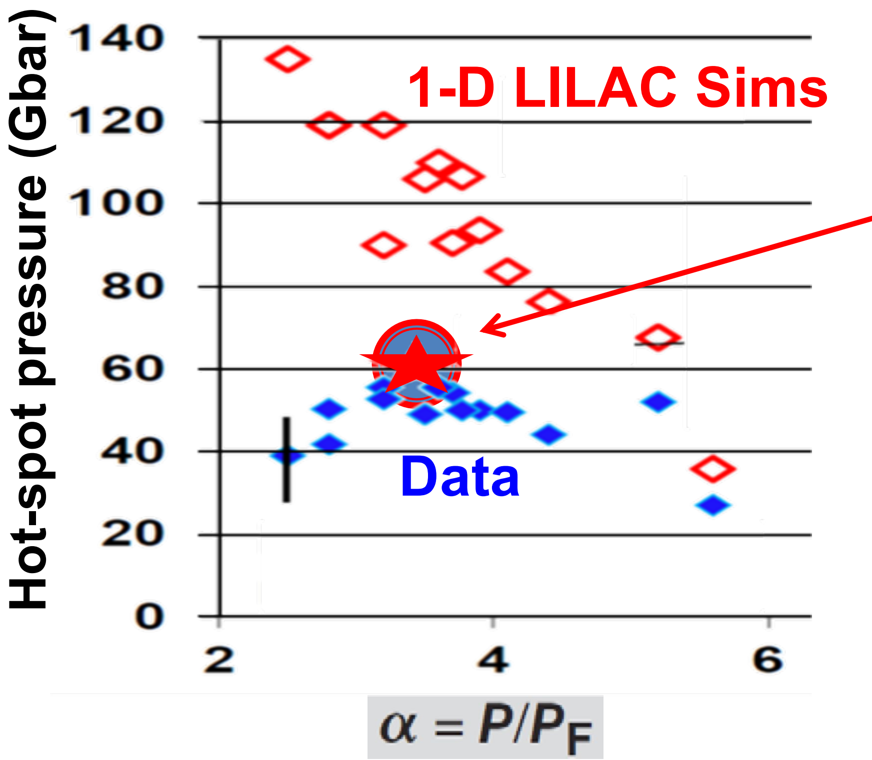
56 Gbar demonstrated so far.



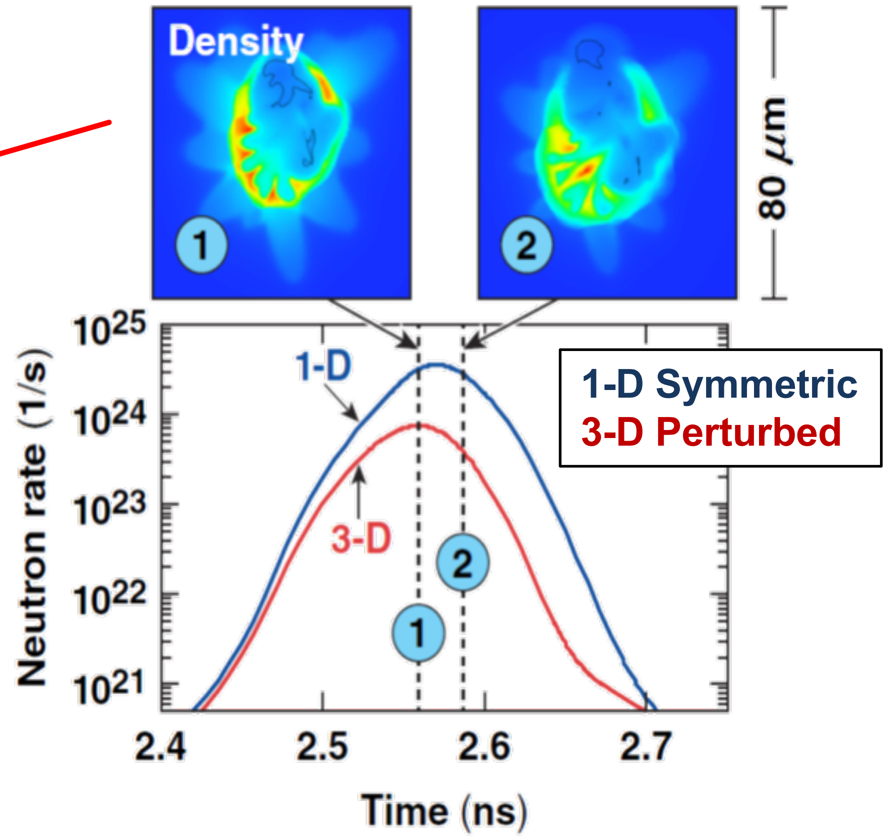
Craxton et al., PoP 2015

The 3D morphology of the direct drive implosion is one of the main challenges

Stagnation Pressure vs. Fuel Adiabat

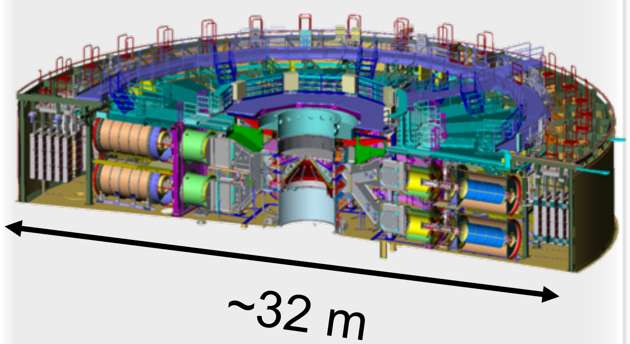


3-D ASTER simulations show effect of errors in beam pointing, power balance, and capsule placement

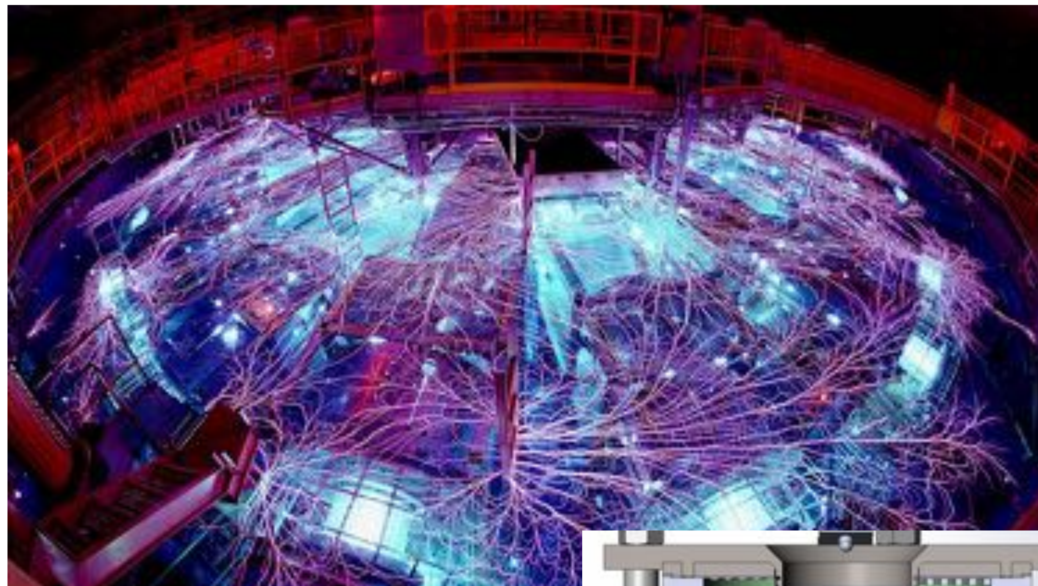


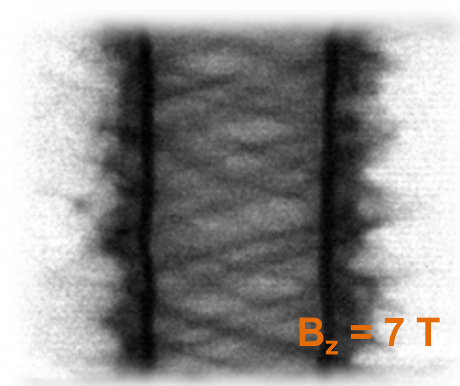
Magnetic drive ICF is being pursued at the Z pulsed power facility at Sandia National Labs, NM

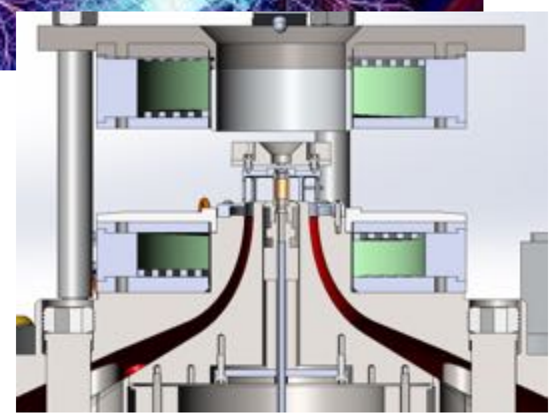
Z Facility



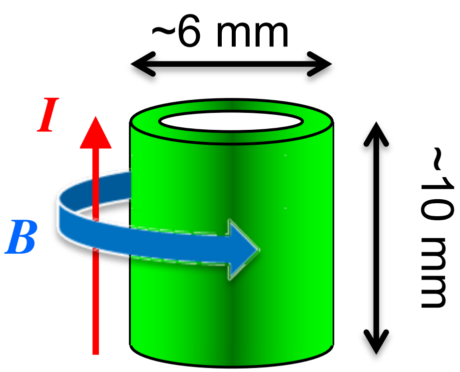
- 80 TW peak electrical power
- Up to ~1 MJ of electrical energy
- Optimized for magnetic drive







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

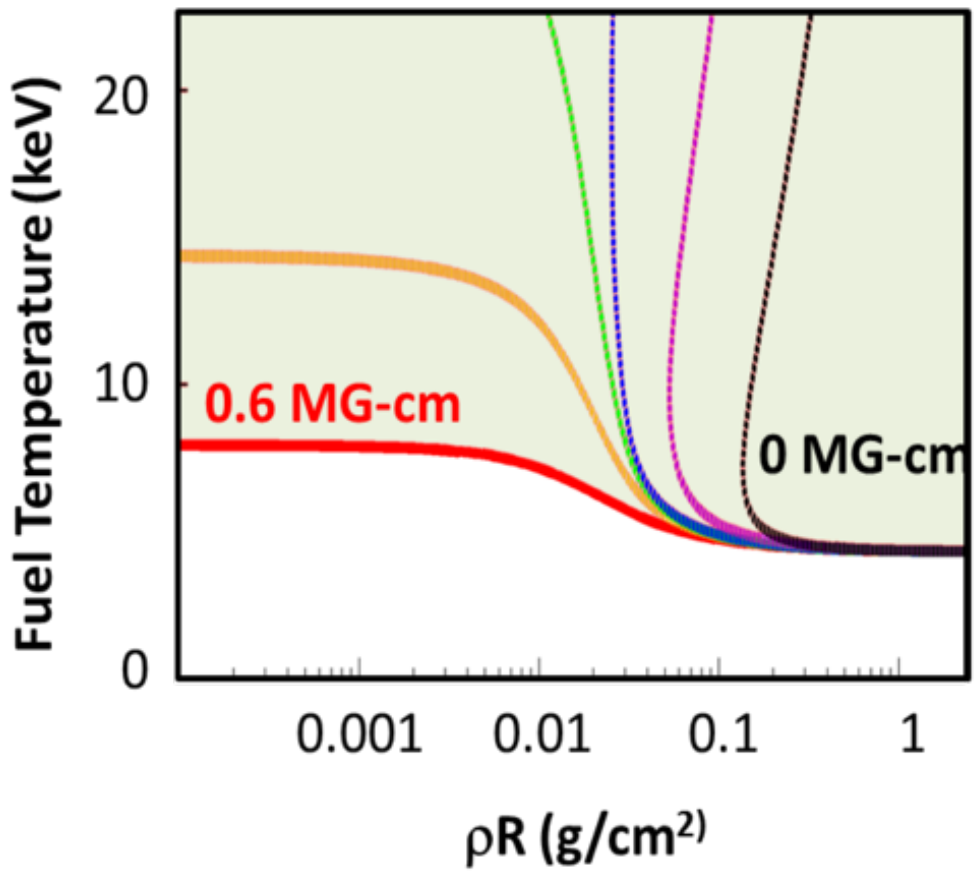


Drive Pressure

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

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

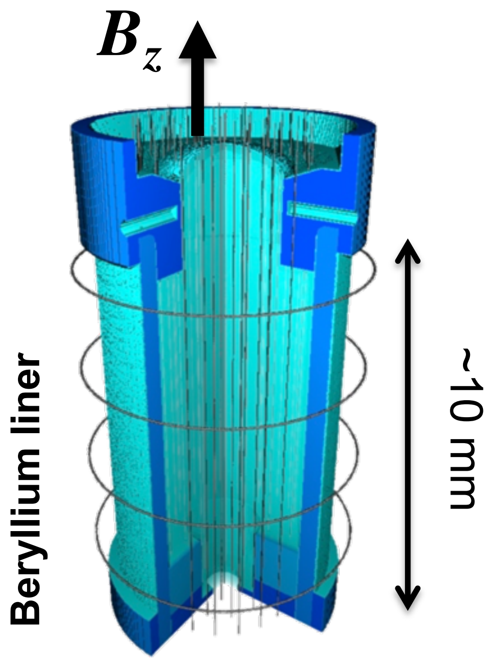
Imposing an axial B-field relaxes ρr requirements



Rochau, IFSA 2017

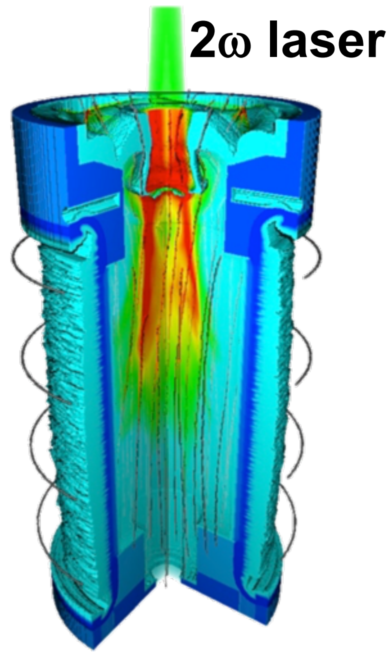
The US is studying a form of magnetic direct drive called Magnetized Liner Inertial Fusion (MagLIF)

Pre-Magnetize



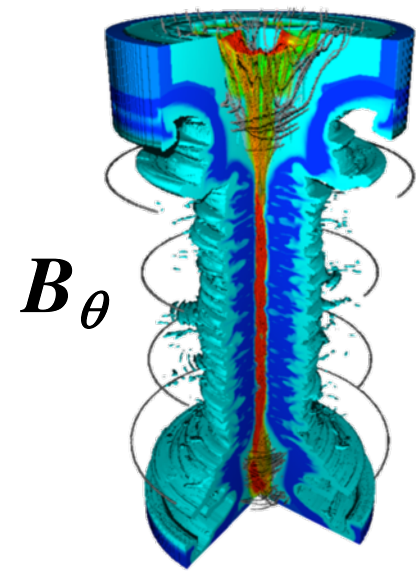
- B_z = 10-30 T
- Inhibit e^- conduction
- Confine α's

Preheat



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

Compress



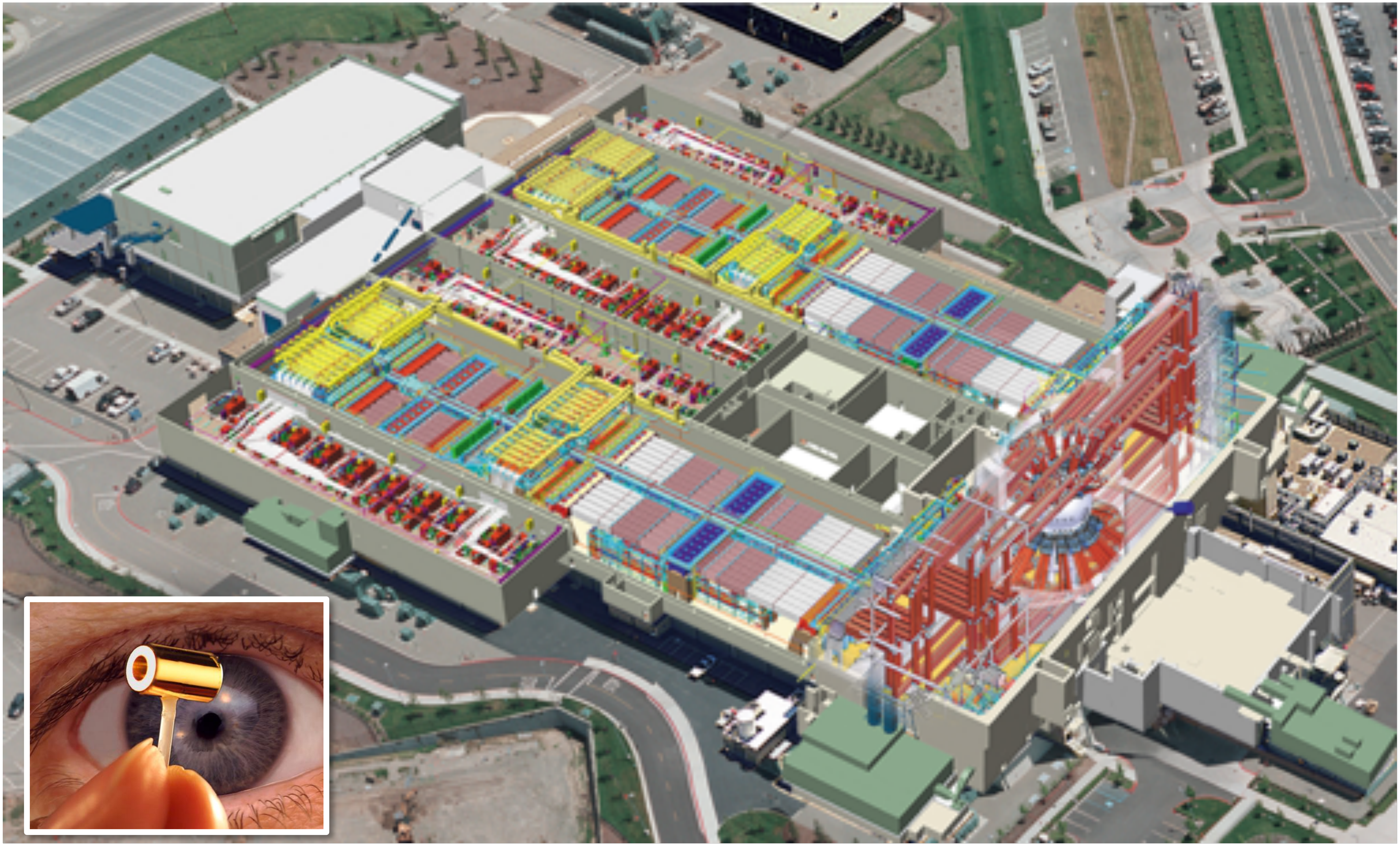
- CR ~ 35
- ρR ~ 0.003 g/cm^2
- P ~ 5 Gbar
- BR ~ 0.5 MG-cm

Goal: demonstrate ~100 kJ DT-equivalent fusion yield

The National Ignition Facility at Lawrence Livermore National Lab, CA is the world's largest, most energetic laser, which uses the indirect-drive approach

- 192 Beams
- Energy: 1.8 MJ
- Power: 500 TW
  (1,000x power of US electrical grid)
- Frequency tripled Nd glass
- Wavelength: 351 nm
- Pulse length: ~25 ns

NIF concentrates the energy of 192 laser beams into a mm^2



NIF in Star Trek: Into Darkness

Courtesy of Scott Chambliss, Paramount Pictures and Bad Robot Productions

Outline

Fusion Basics

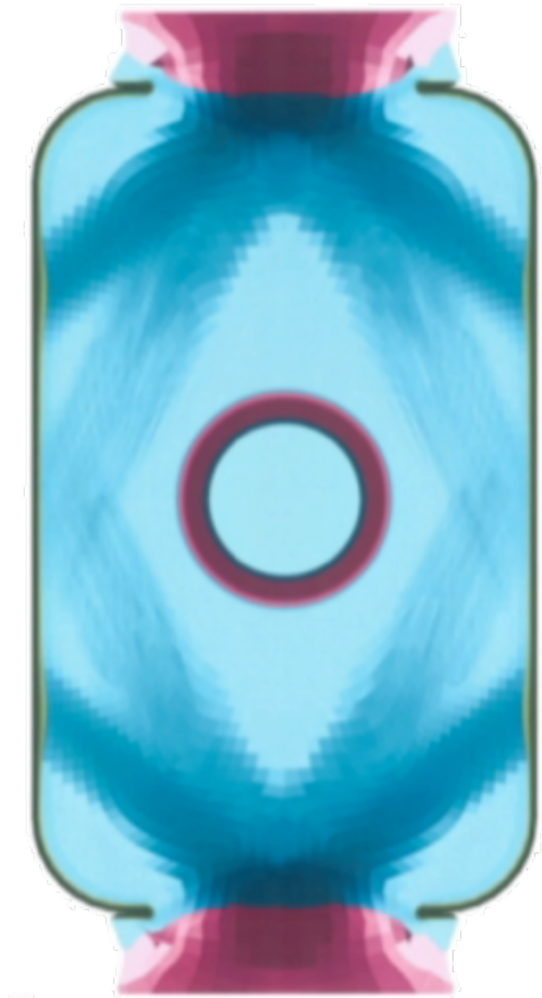
Inertial Confinement Fusion (ICF) Principles

ICF Facilities

- **The OMEGA Laser Facility**
- **The Z Pulsed Power Machine**
- **The National Ignition Facility (NIF)**

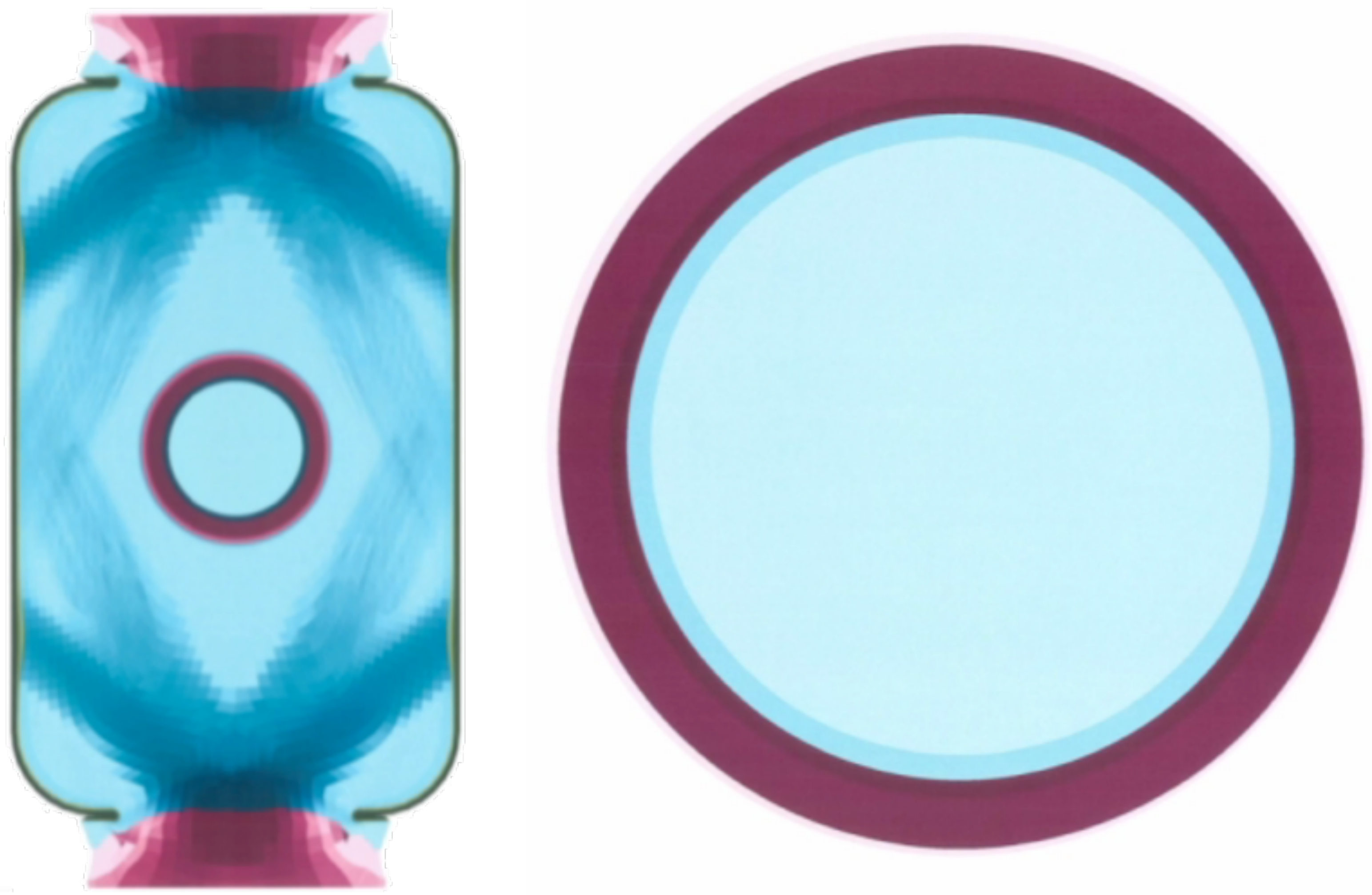
Status of NIF Indirect-Drive ICF Experiments

The interaction of the laser with the hohlraum plasma is complex and highly dynamic

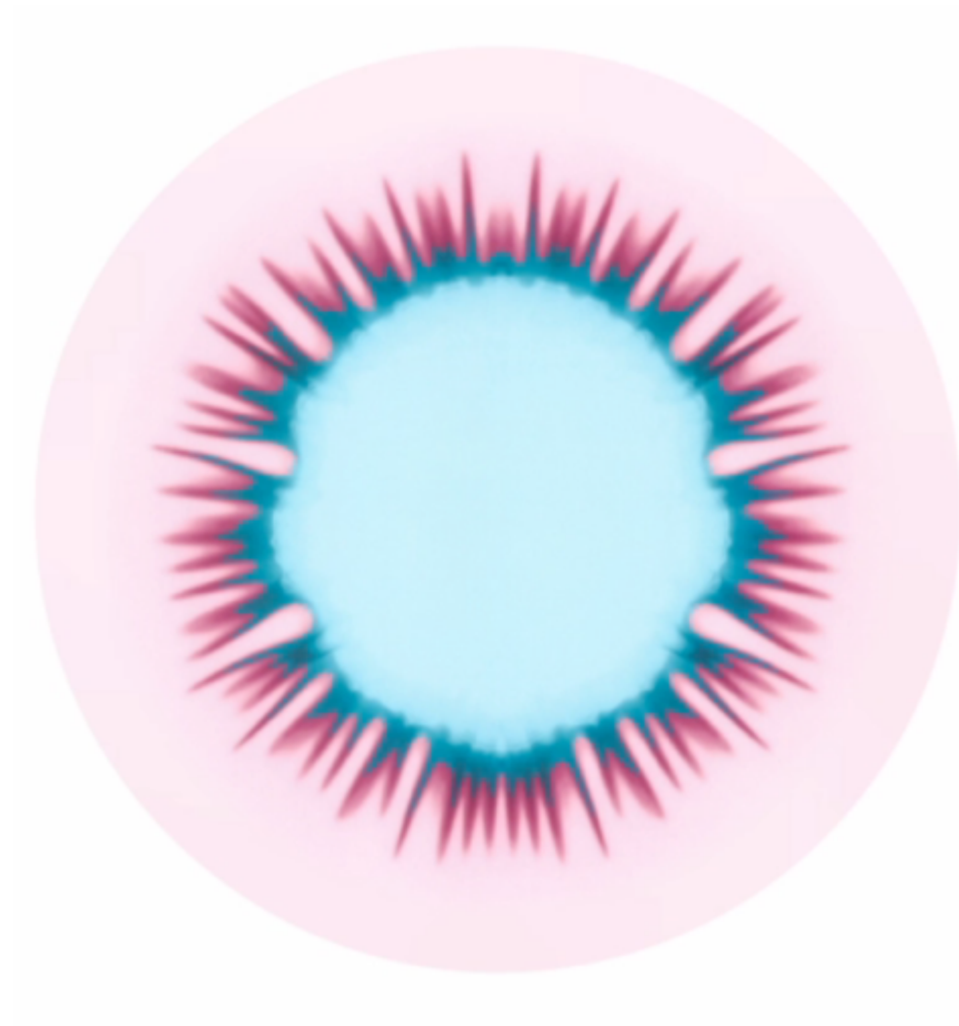


The interaction of the laser with the hohlraum plasma is complex and highly dynamic

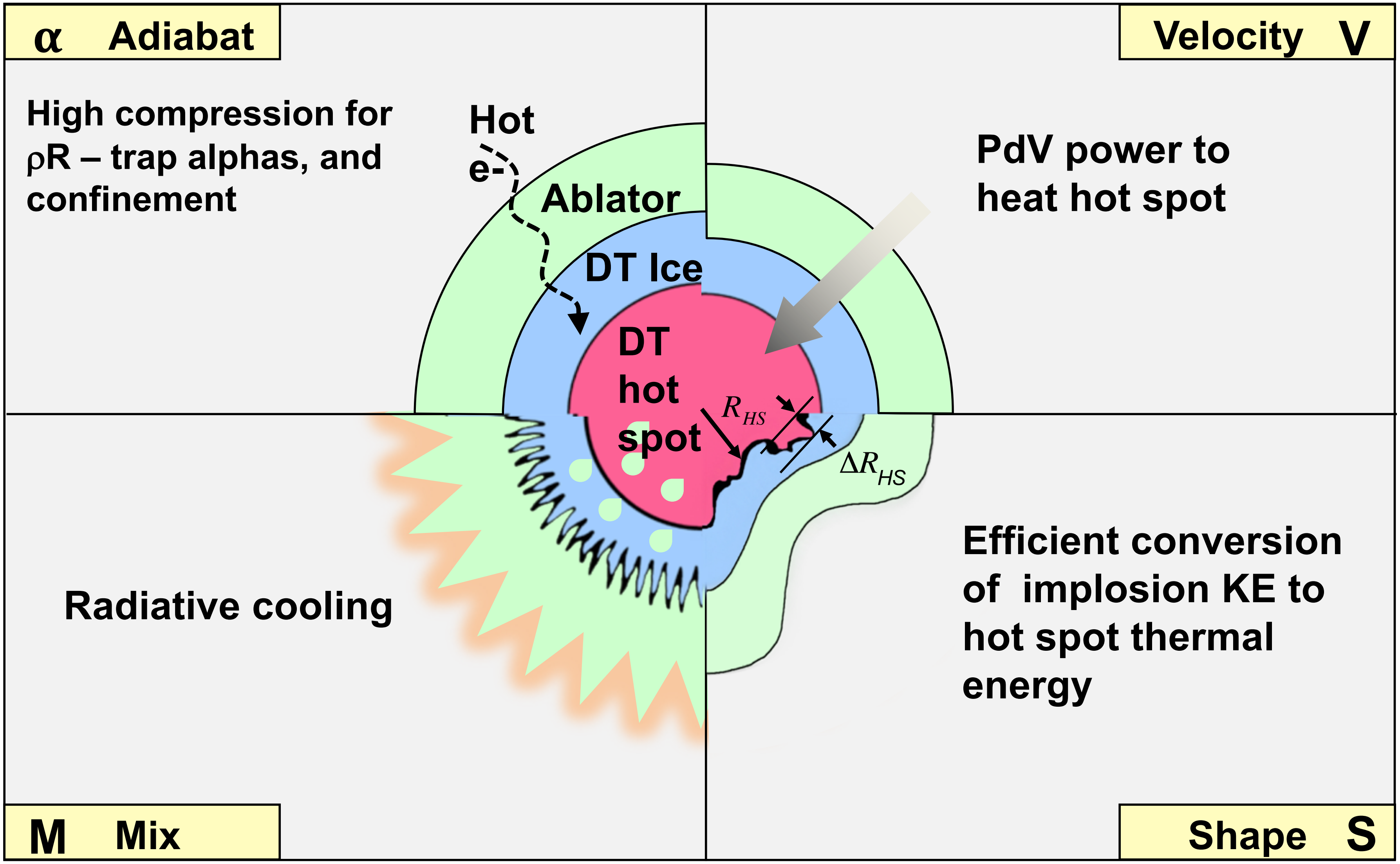
The principal challenge with compressing a capsule by >30x convergence is controlling hydro-instabilities



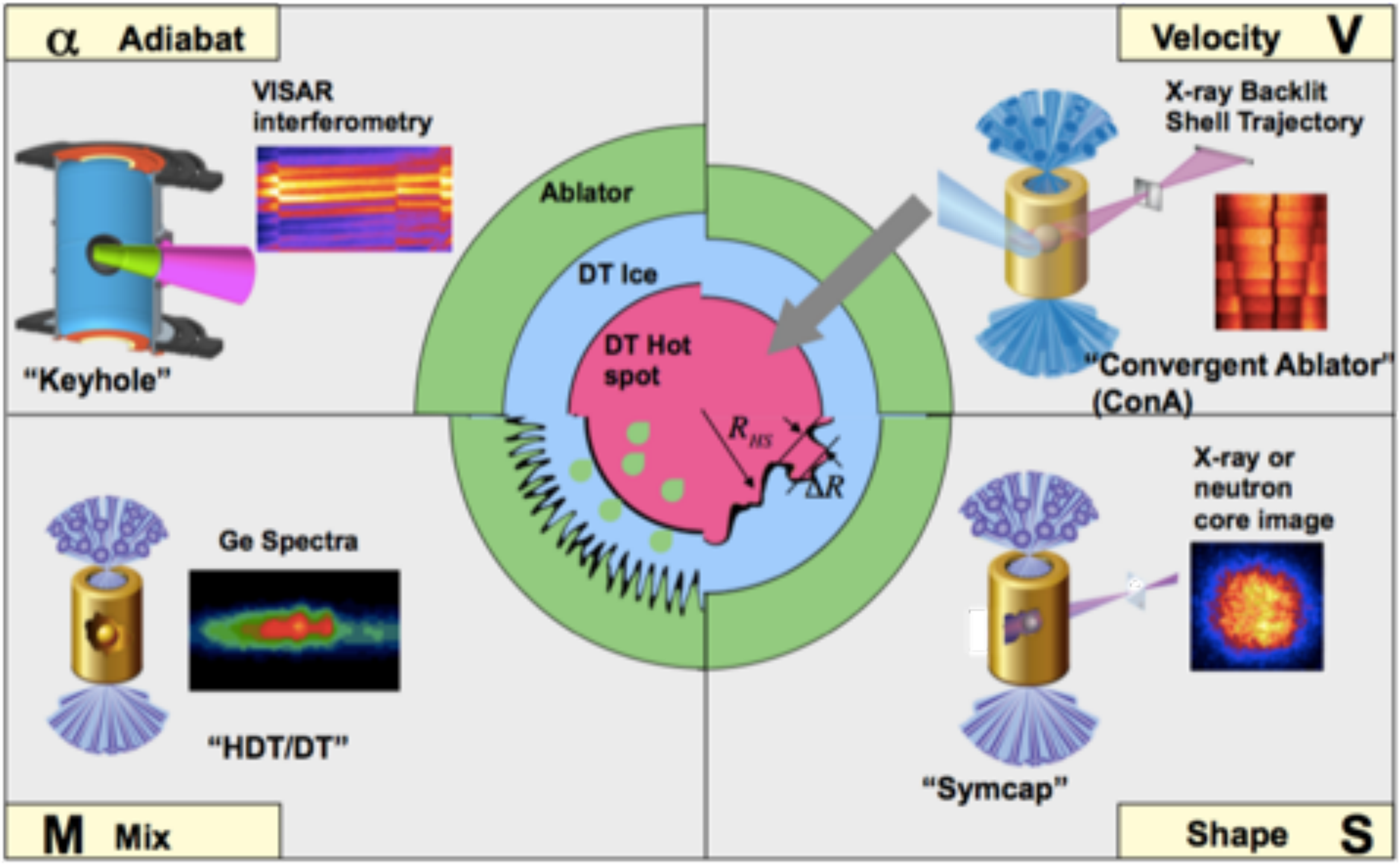
The principal challenge with compressing a capsule by >30x convergence is controlling hydro-instabilities

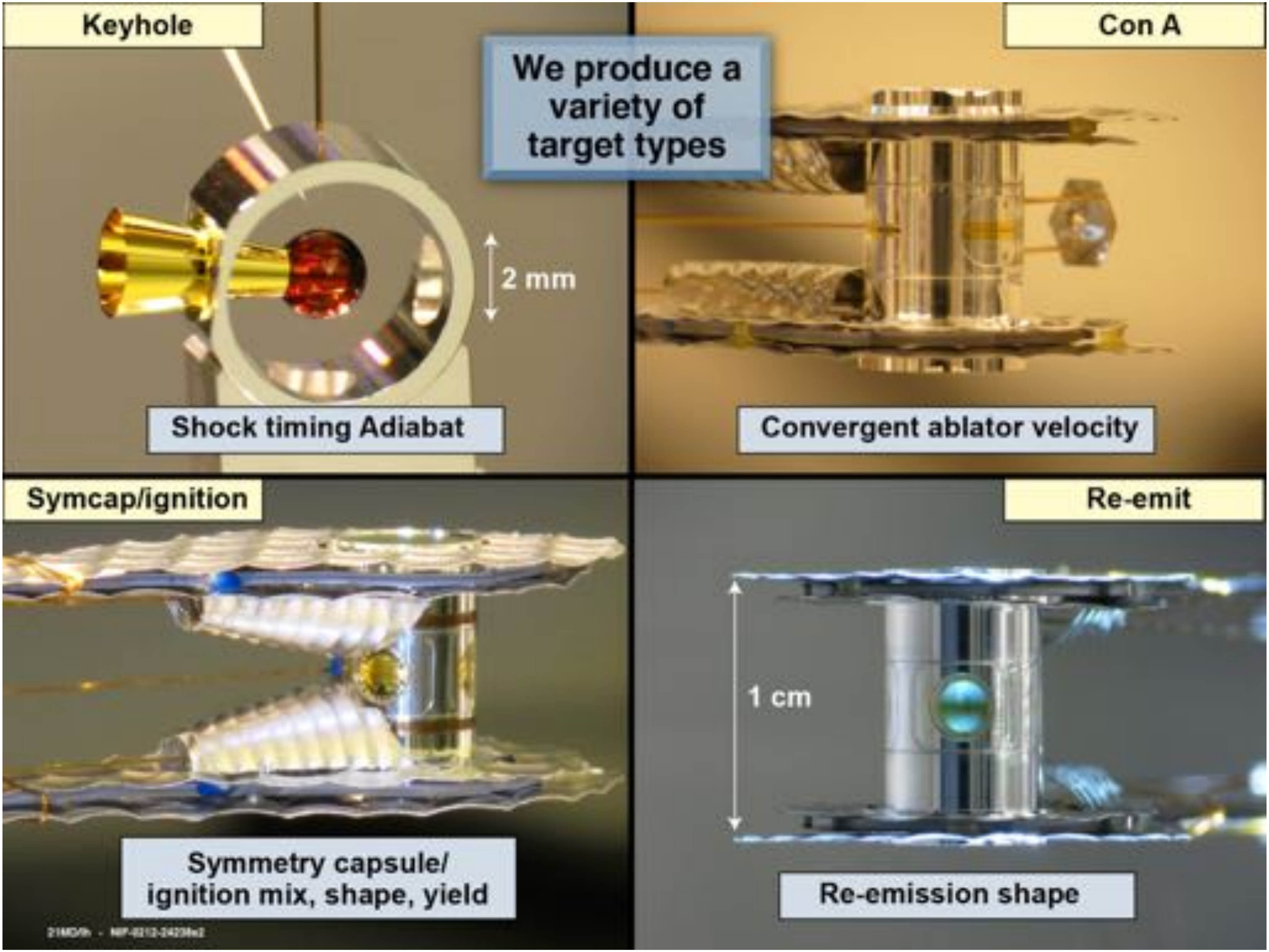


Ignition performance is optimized around four key variables



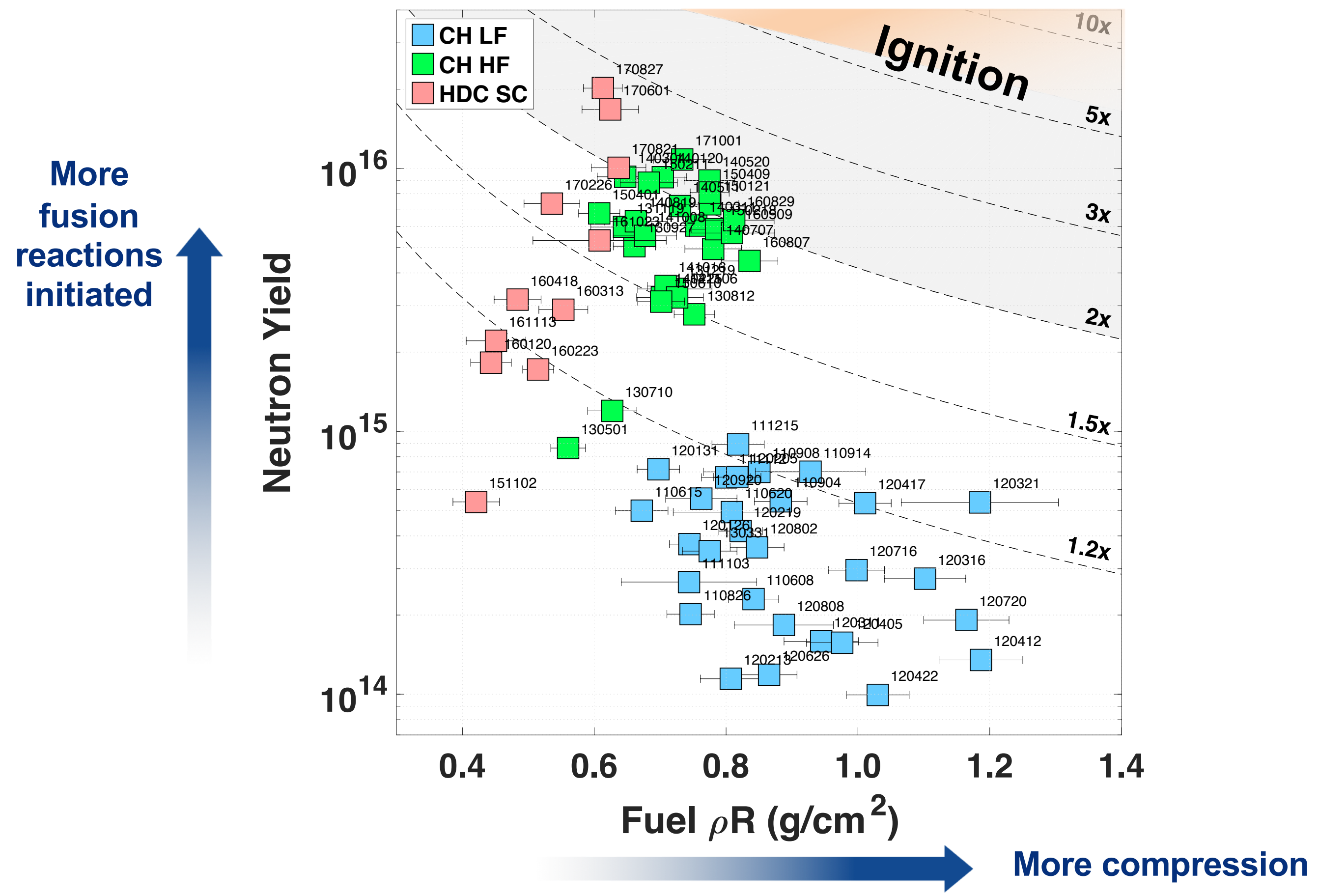
We use a variety of platforms to tune the capsule shape, adiabat, velocity, and mix





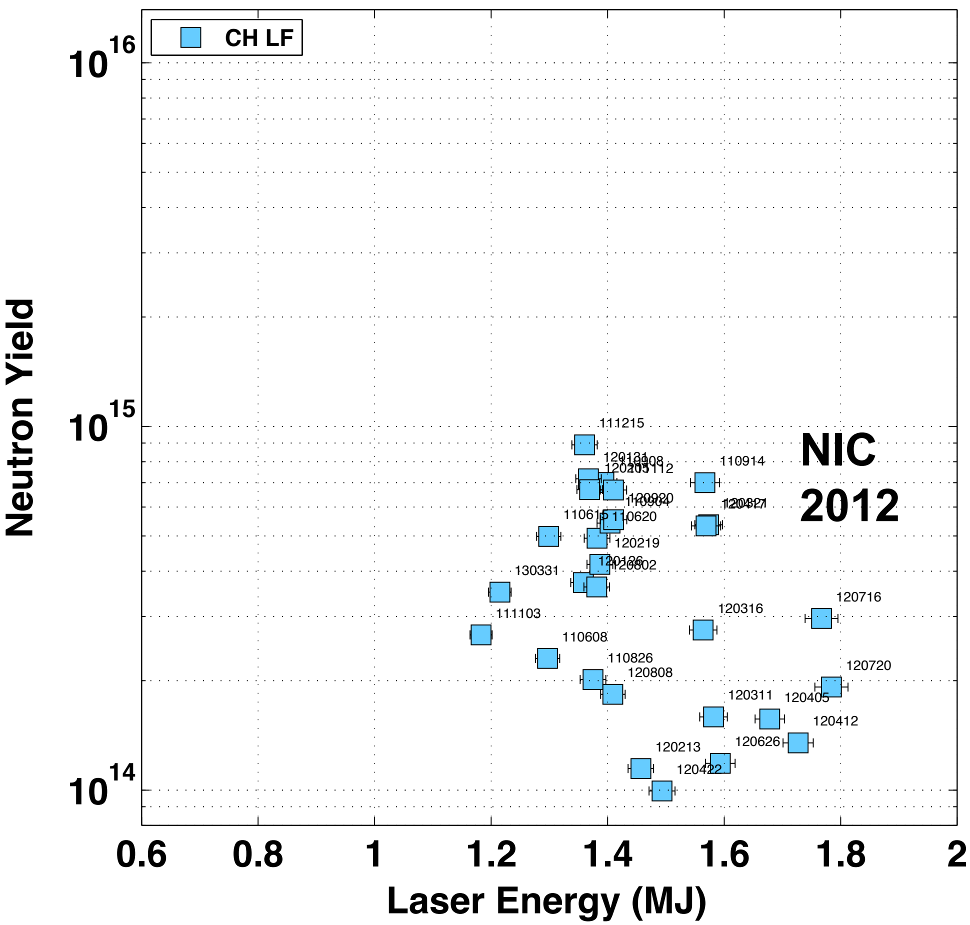
Keyhole
We produce a variety of target types
Con A
2 mm
Shock timing Adiabat
Convergent ablator velocity
Symcap/ignition
Re-emit
1 cm
Symmetry capsule/ ignition mix, shape, yield
Re-emission shape

Current status: We recently demonstrated fusion yields > 1e16, and fuel gains > 2

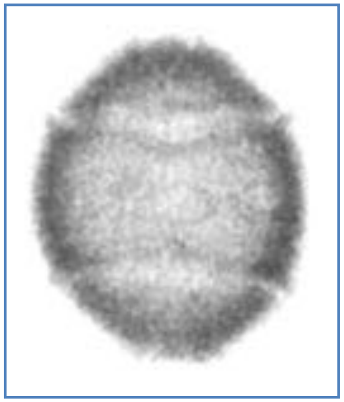


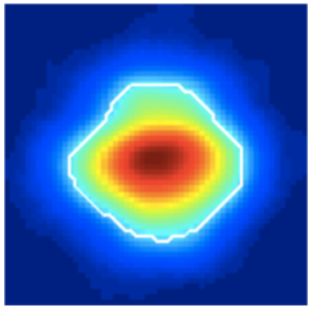
If no further improvement were possible, would need ~ 2x energy in the fuel to ignite: now we need to close the gap

The NIF implosions in 2012 performed well below expectations



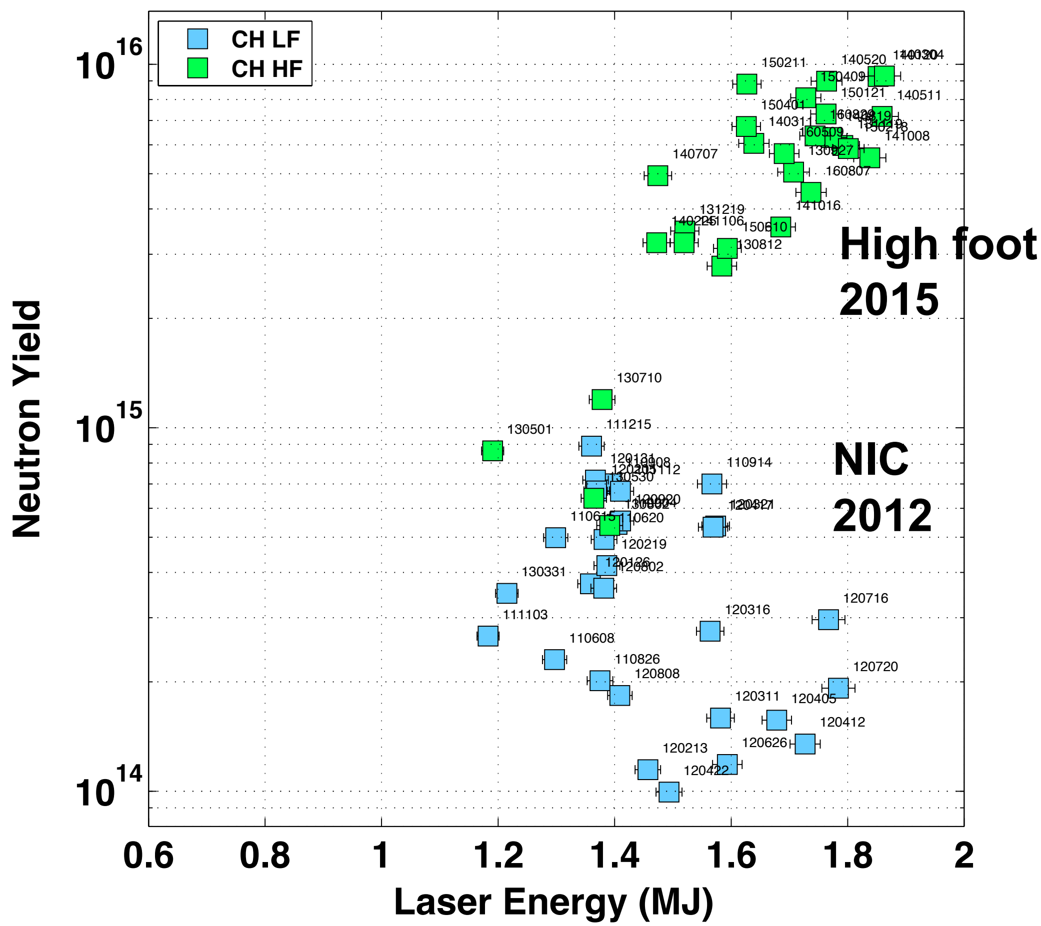
- Drive asymmetry and hydrodynamic instability were suspected, but the exact causes were unknown



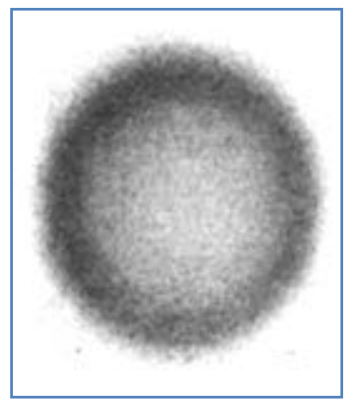


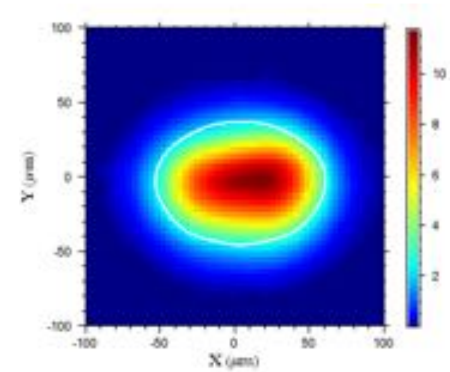
Low-foot
α ~1.5

The lower convergence, more hydro stable high-foot implosions resulted in higher performance limit



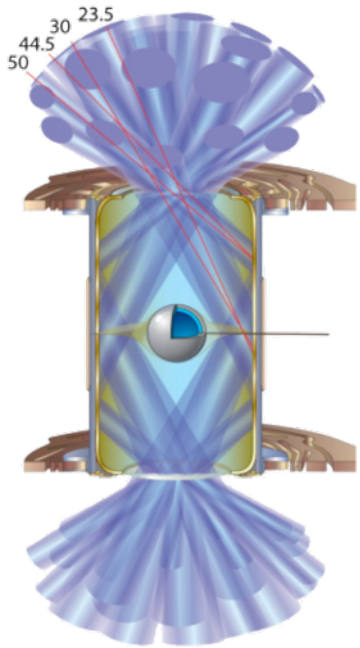
- The HF implosions showed reduced susceptibility to tent imprint
- However, symmetry swings remained



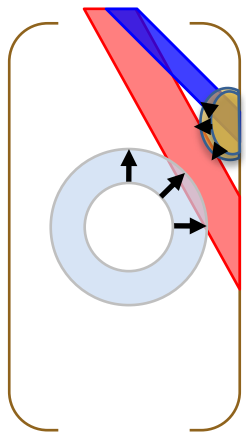


High-foot
α ~2.5

We are also exploring ways of improving the coupling of laser energy into the hohlraum

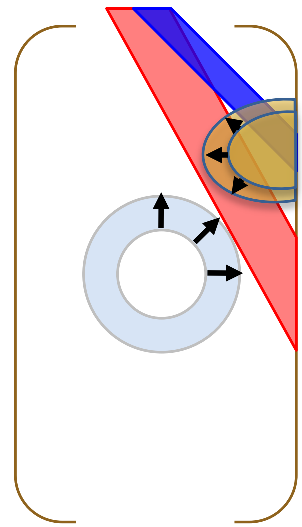


Smaller hohlraum with high density fill



- Increased drive
- Symmetry difficult to control
- LPI dominated
- Complicated physics, complicated symmetry

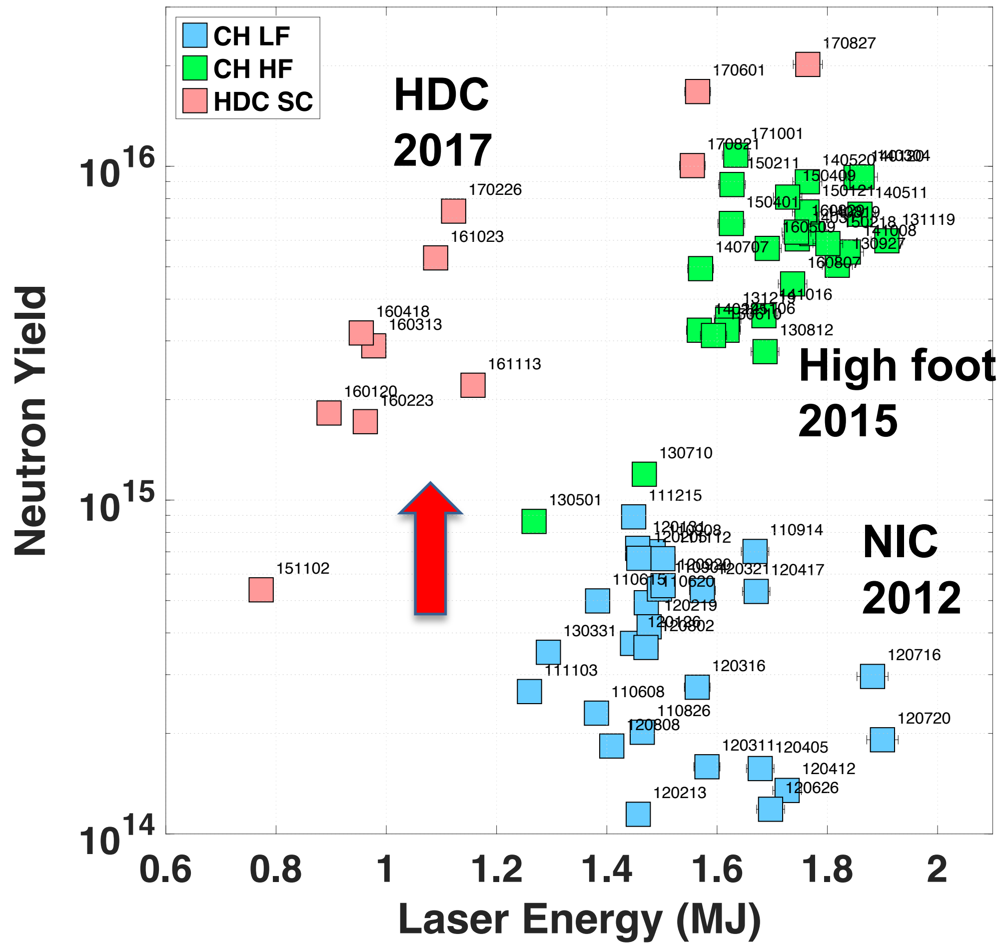
Larger hohlraum with low density fill



- Increased beam clearance
- More x-ray drive smoothing
- Low LPI, more efficient
- Much simpler physics and symmetry

Larger hohlraums with lower gas fill give us better symmetry control and lower laser-plasma interaction effects

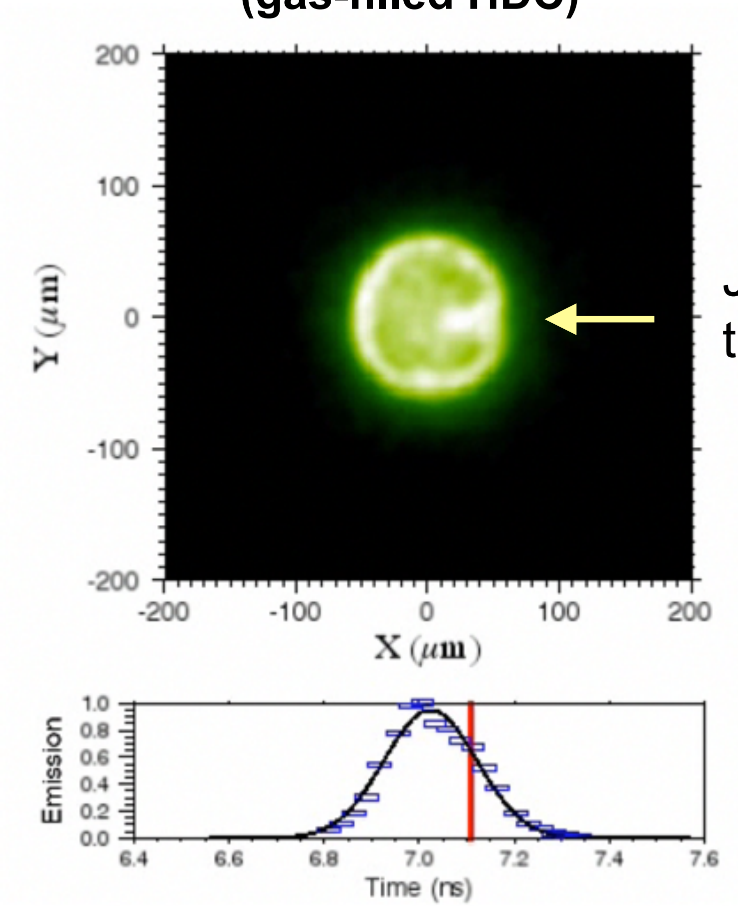
HDC implosions with low LPI have yields similar to high-foot, but using ~half the laser energy



- Lower density helium gas fill in the hohlraum largely eliminated laser plasma instabilities
- The highest performing HDC implosions are driven fairly symmetrically
- Additional benefit - hohlraum also now more predictable
- Simulations in 2D including a model for the fill tube reproduce observed yield

With improved symmetry, large-scale hydro features are becoming more evident

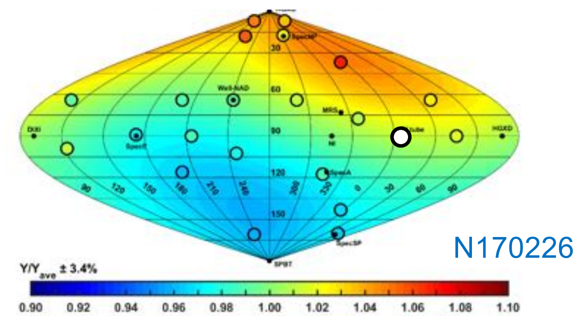
X-ray image of hot spot (gas-filled HDC)



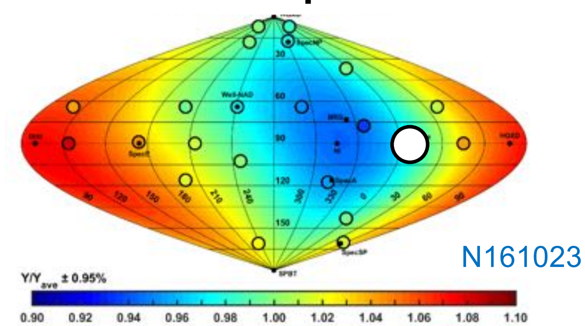
Jet due to fill tube

Nuclear Activation maps

HDC DT w/ 5 μm fill tube

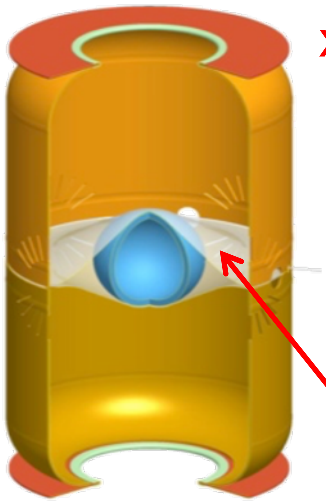


HDC DT w/ 10 μm fill tube



Simulations do not yet predict this a priori for HDC

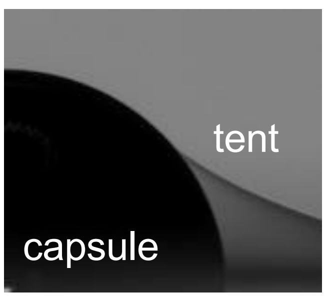
We currently know of two major factors preventing ignition – others may be found



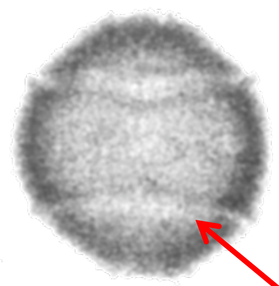
Asymmetric x-ray drive

+

Engineering features such as capsule support "Tent"



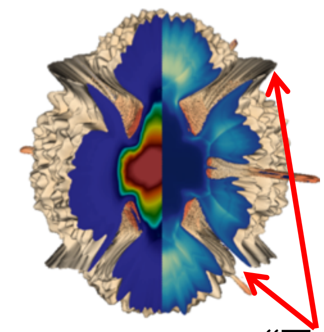
Distorted implosion



"Tent"

Processed in-flight radiograph

Inefficient fuel assembly



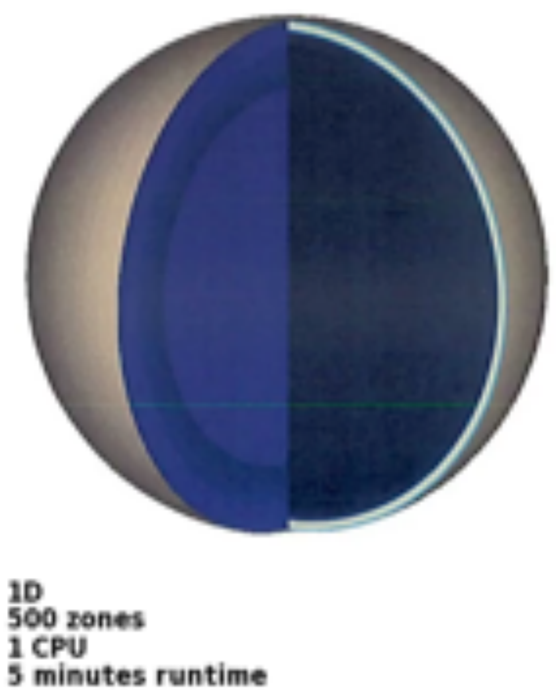
"Tent"

Simulated DT fuel at stagnation

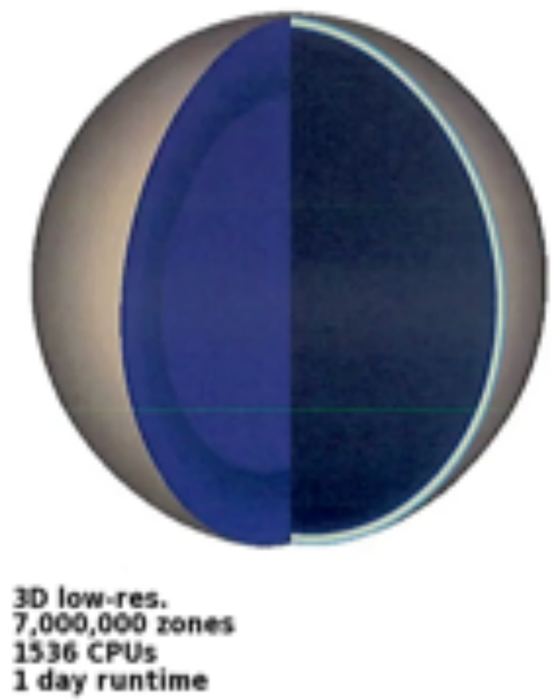
But there are important knowledge gaps (e.g. cannot see the shell or cold fuel at stagnation) and the model is not perfect

Tent and asymmetry are predicted to conspire to limit capsule performance – relative contribution depends on design

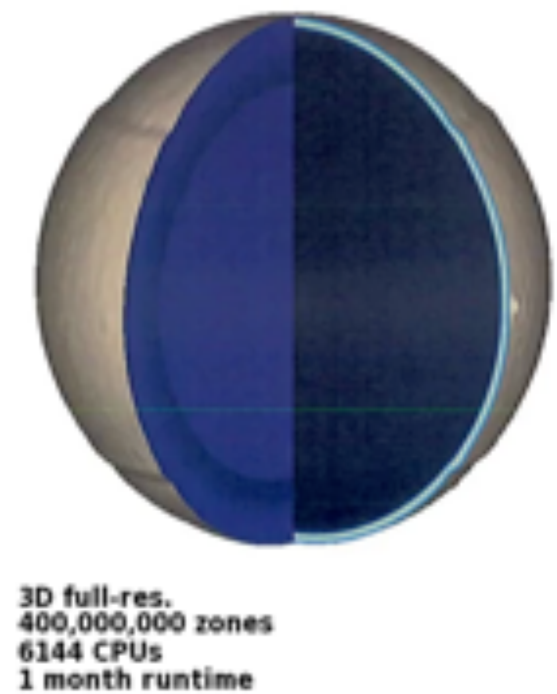
1D



3D, including low modes



3D, including all perturbations

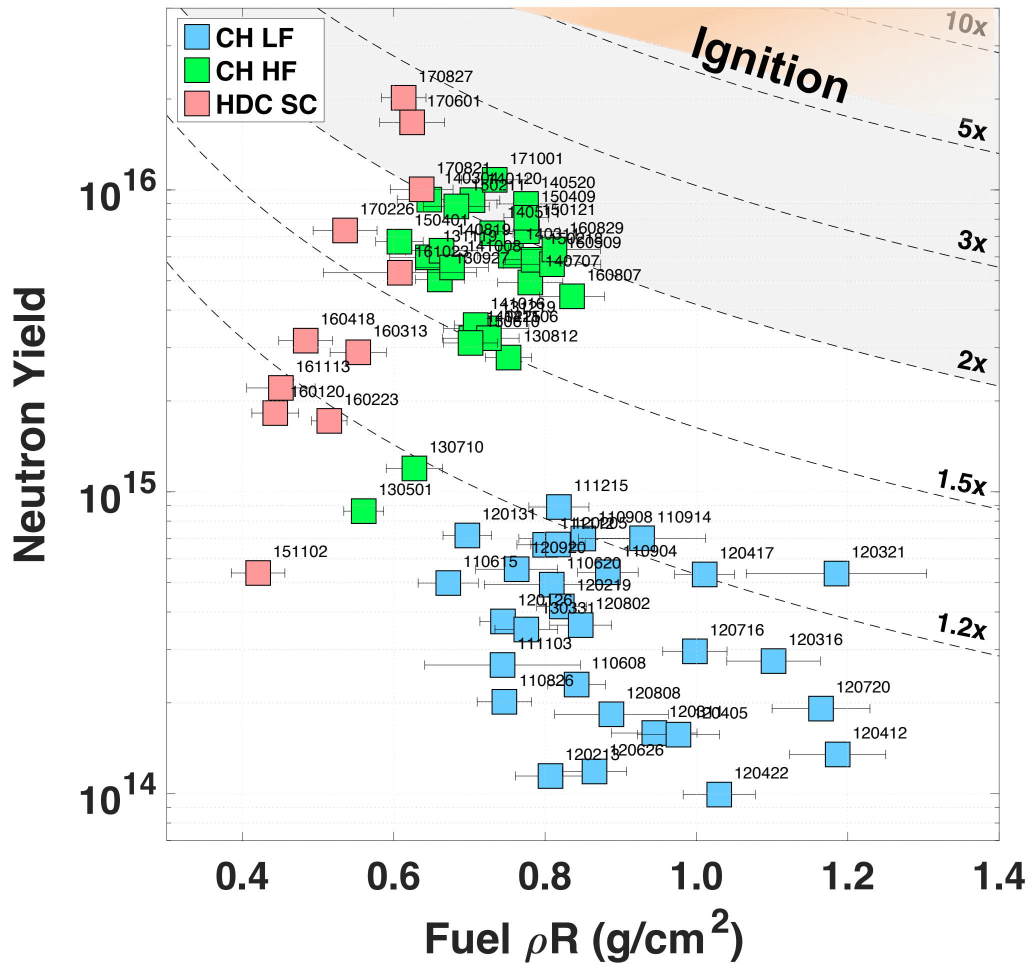


Post-shot simulation of N120405
D. Clark *et al*., Phys. Plasmas **23**, 056302 (2016).

We must rely on simulations to unravel the complex physics of our experiments

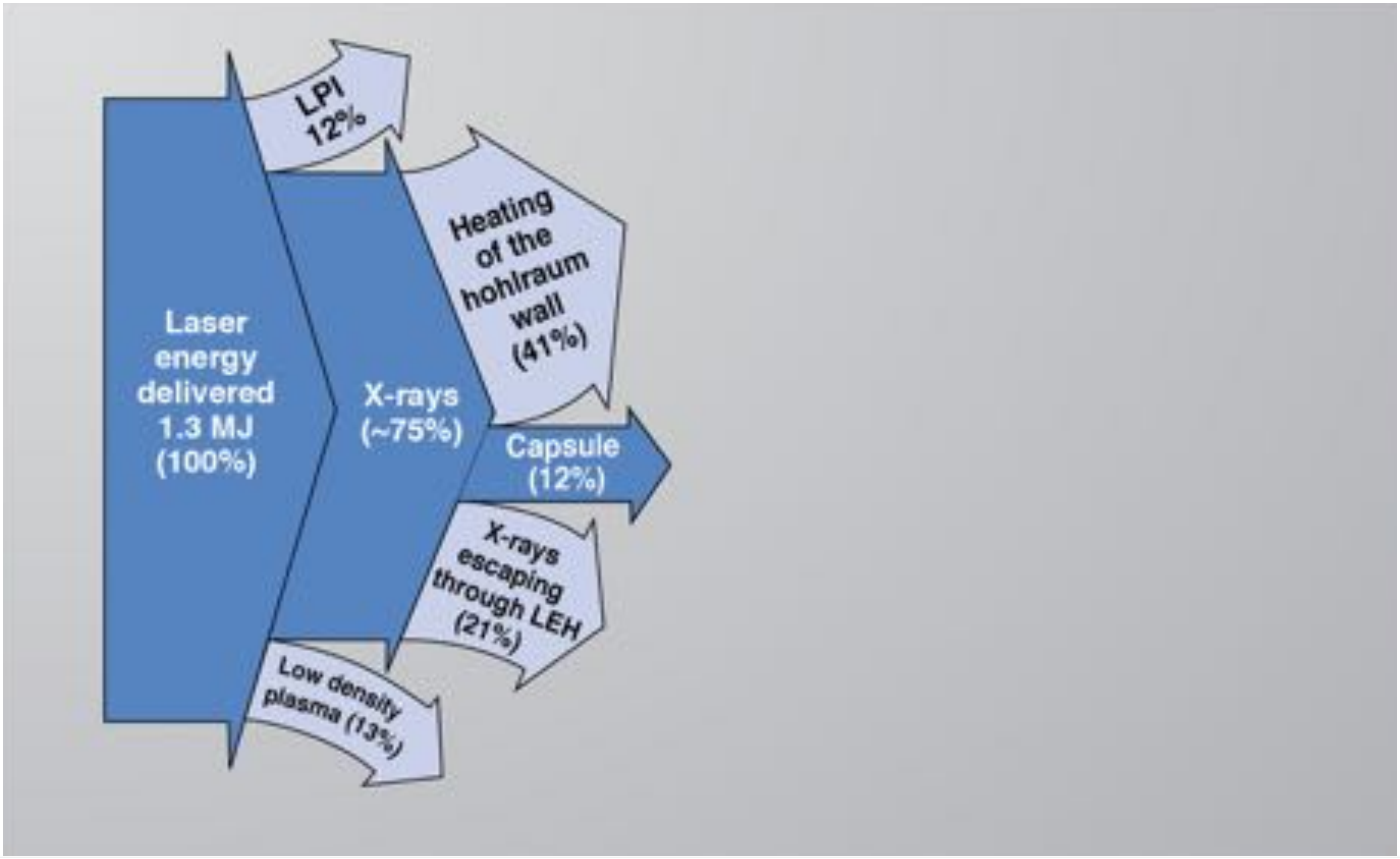
Simultaneously achieving high compression and high neutron yield is very challenging

More fusion reactions initiated



More compression

What is the typical energy flow for an ignition experiment?



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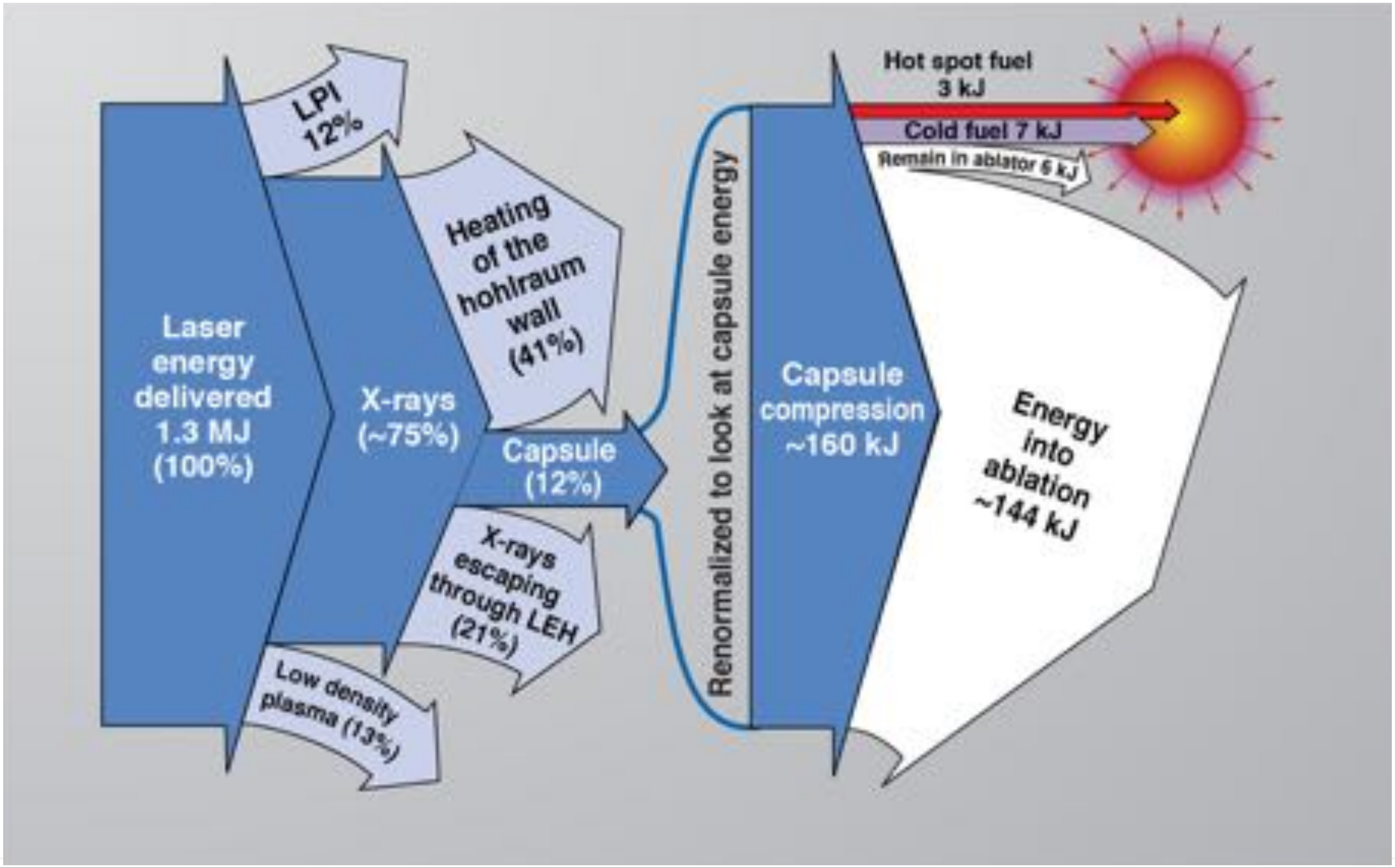

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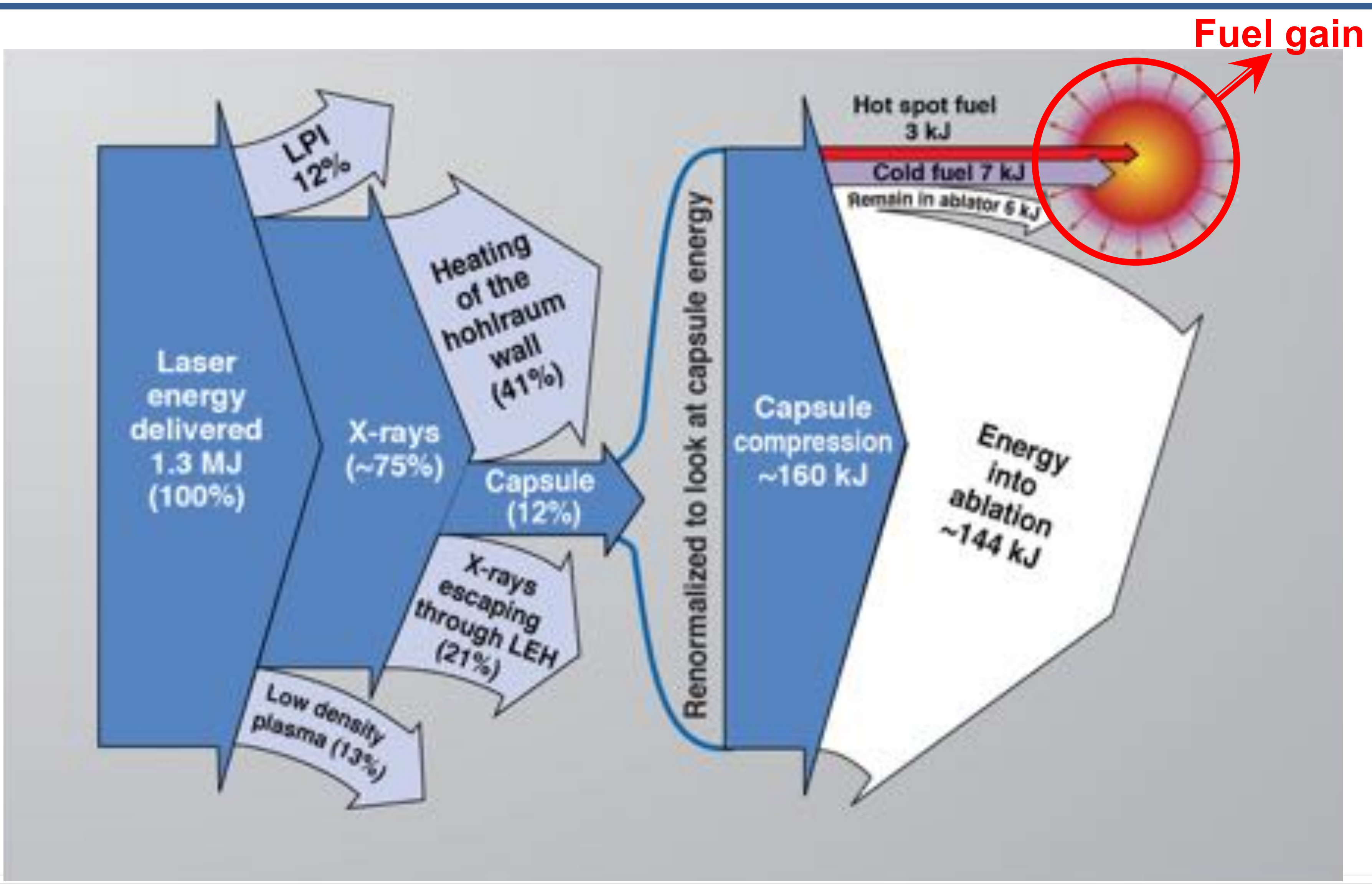

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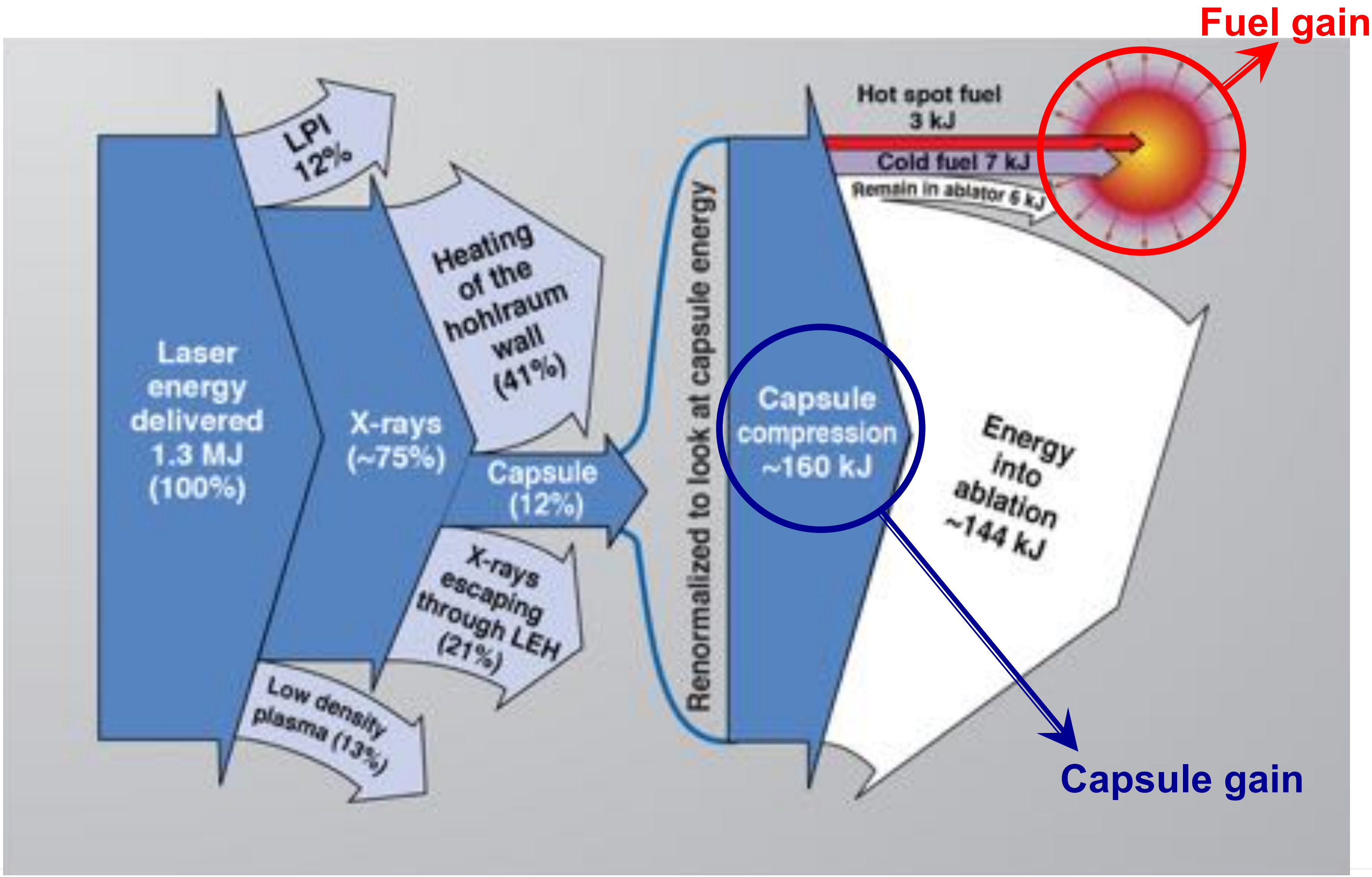

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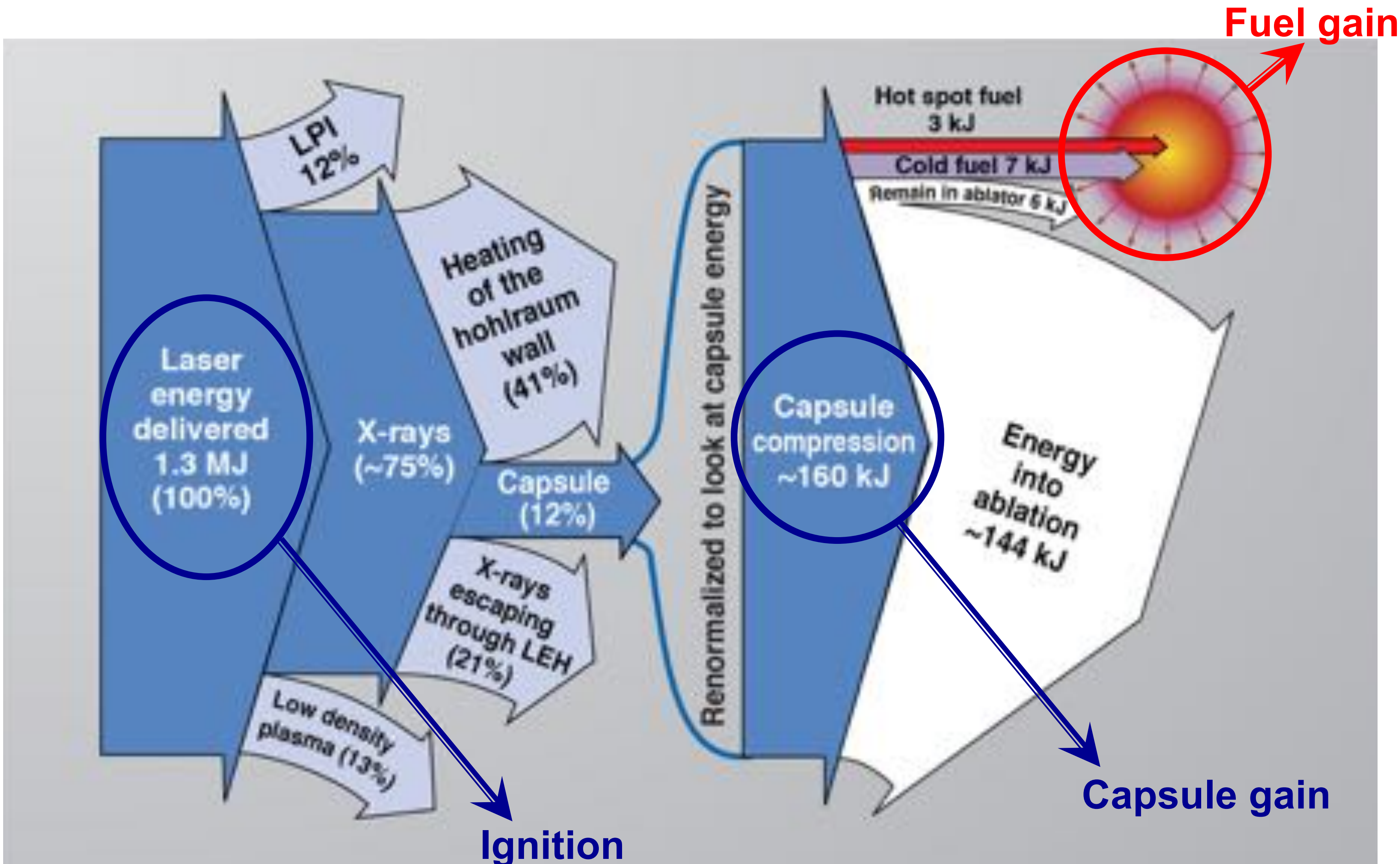
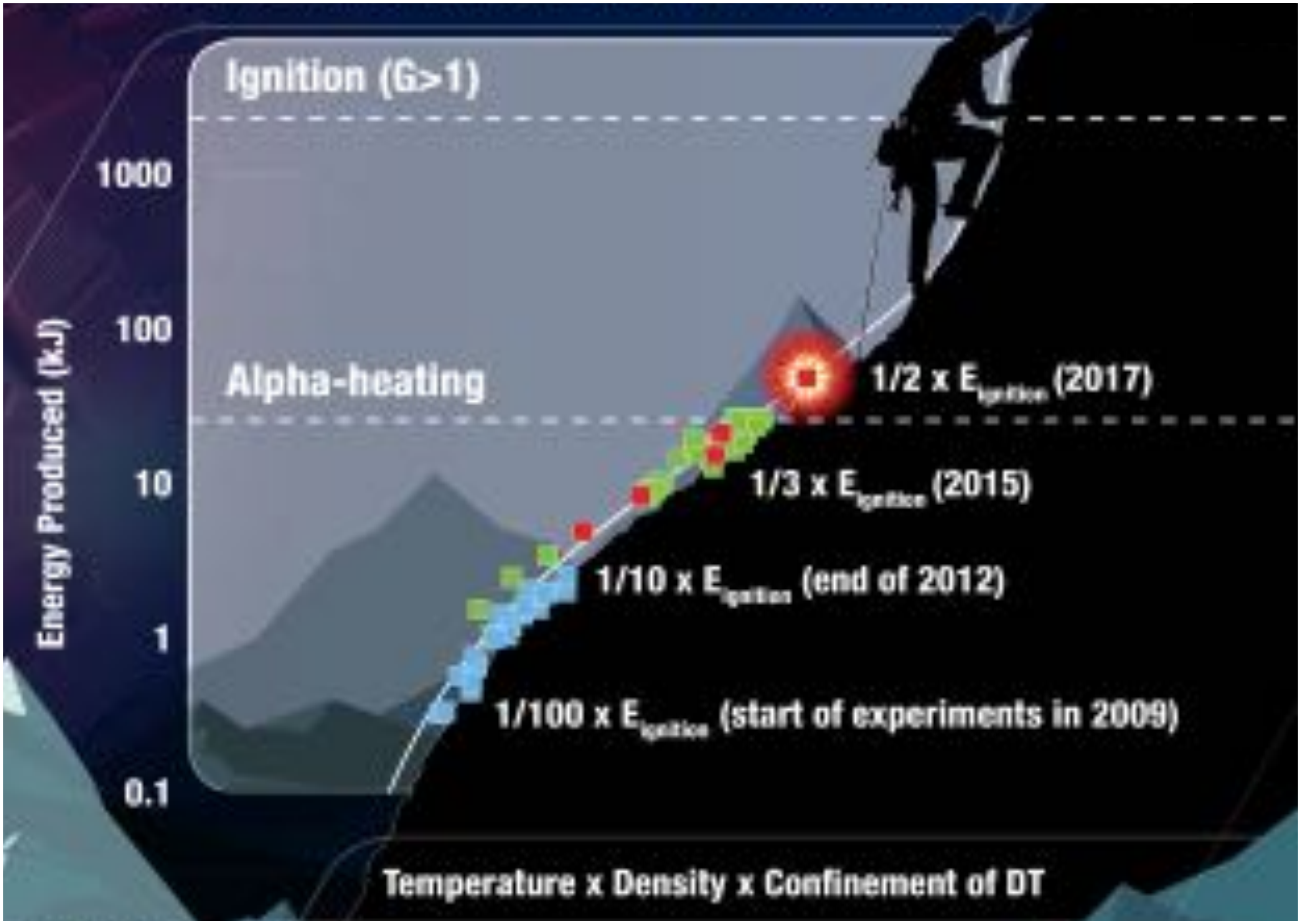


We are making considerable progress toward ignition



Inertial Confinement Fusion is a very challenging, but promising approach to fusion ignition

- Experiments are ongoing in the three main schemes of ICF: Laser Indirect-Drive, Laser Direct-Drive ICF, and Magnetized Liner ICF

- Performance on the NIF so far:
  - ~3X yield from alpha-heating
  - Fuel gain > 2
  - Still need better control of the symmetry of the x-ray drive and engineering features

- If no further improvement were possible, would need roughly ~ 2X energy in the fuel to ignite.

- In ~2012 that number was about ~10X more energy while early experiments were ~100X, so we are making progress.

- Our job is to figure out how to close the rest of the gap!

Opportunities at NIF

- **The NIF Discovery Science Program supports a wide variety of fundamental science experiments**

  https://lasers.llnl.gov/for-users/nif-user-group

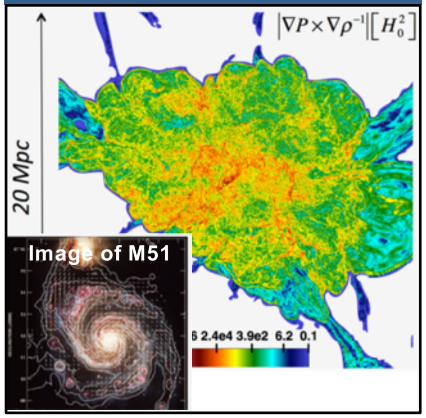
- **Summer Scholar Program**

  http://students.llnl.gov

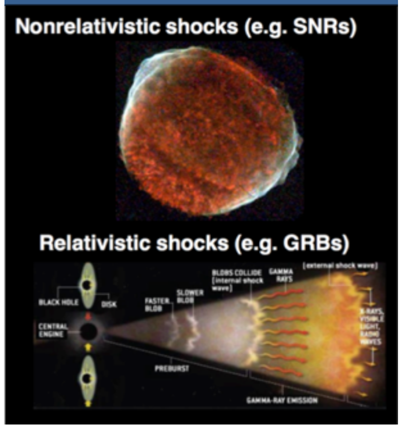
- **Jobs**

  http://jobs.llnl.gov

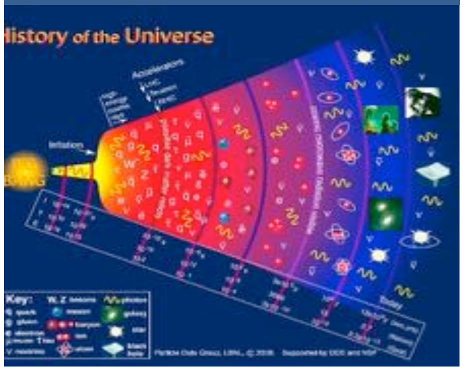
Turbulent dynamo B field amplification



Collisionless astrophysical shocks



Stellar and Big Bang nucleosynthesis



http://lasers.llnl.gov

Lawrence Livermore National Laboratory

Dr. Tammy Ma
ma8@llnl.gov | 1 · 925 · 423 · 8902

LDRD Laboratory Directed Research and Development

NIF&PS

NNSA National Nuclear Security Administration

Concept for an ICF power plant