

Inertial Fusion Energy

2026 PPPL Introductory Course on Plasma Physics

Dr. Elizabeth Grace

On behalf of the global team making ignition possible

June 5, 2026

About me



Washington, DC



B.A. Physics



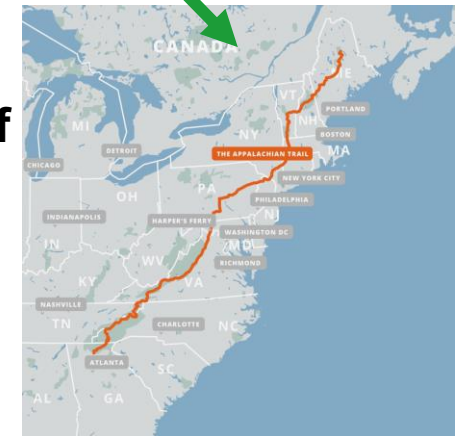
PhD Physics



Postdoctoral
Fellowship to Staff
Scientist



Took 1 year off
to hike entire
Appalachian
Trail



The National Ignition Facility (NIF) is the world's most energetic laser enabling the study of matter in extreme conditions



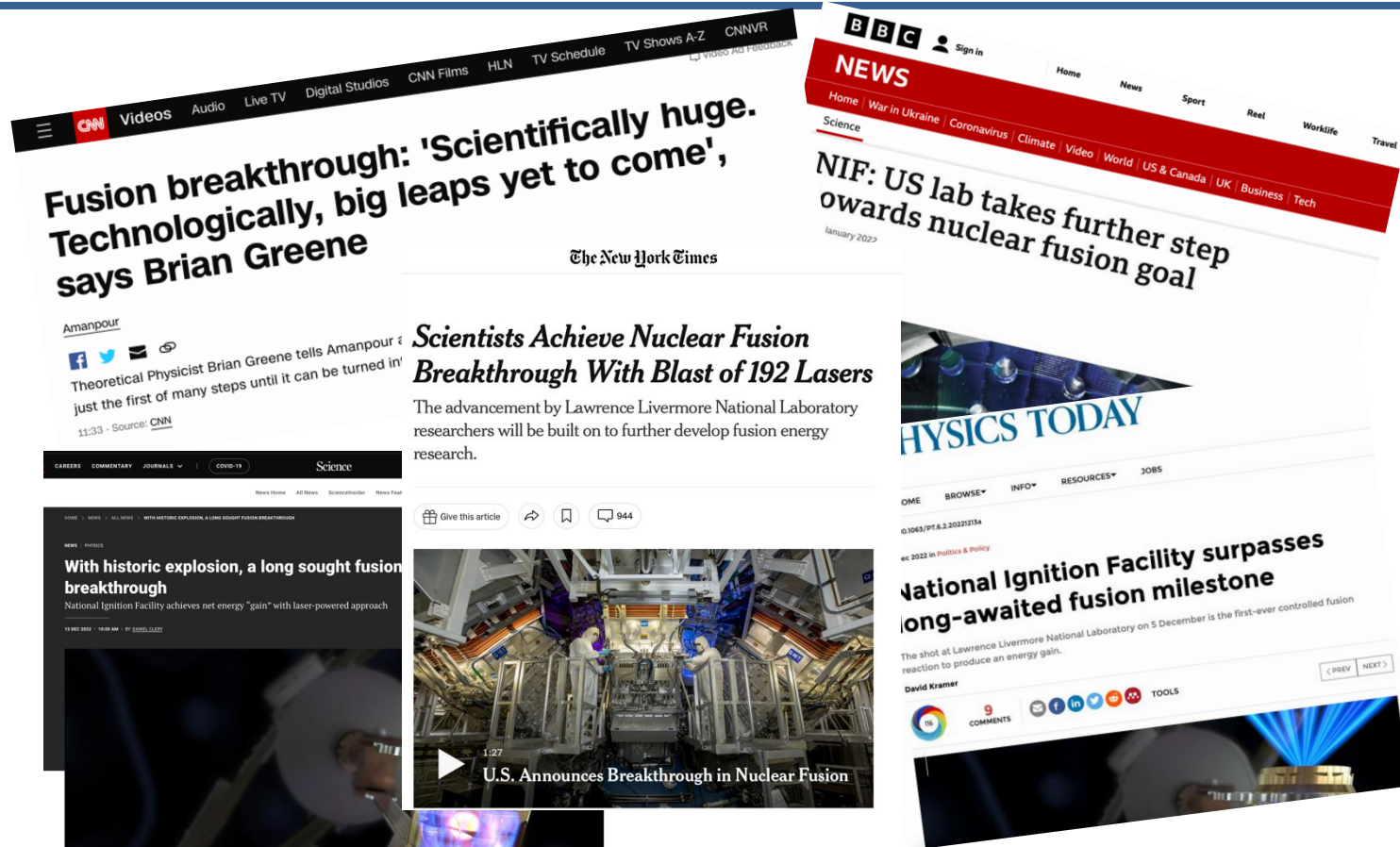
- 192 Beams, 2.2 MJ Energy, 500 TW Power
- Matter temperature >10 keV (10^8 K)
- Radiation temperature >300 eV (3.5×10^6 K)
- Densities $>10^2$ g/cm³
- Pressures $>10^{11}$ atm
- Number of Diagnostics >120



On Dec. 5, 2022, the National Ignition Facility demonstrated fusion ignition in the laboratory for the first time

- NIF delivered 2.05 MJ of laser energy to a target, creating a plasma with a temperature of 130 million °C and producing 3.15 MJ of fusion energy
- This met the National Academy of Sciences' 1997 definition of fusion ignition

On Dec. 5, 2022, the National Ignition Facility demonstrated fusion ignition in the laboratory for the first time



Left to Right:
LLNL Director, Kim Budil,
NNSA Administrator, Jill Hruby
U.S. Secretary of Energy, Jennifer Granholm

This achievement was the result of many generations of scientists and engineers working collaboratively around the world towards fusion ignition!



 **Lawrence Livermore
National Laboratory**

 **Sandia
National
Laboratories**



 **Los Alamos
NATIONAL LABORATORY**



**Diamond
Materials**
Advanced Diamond Technologies



MIT | PSFC Plasma Science and Fusion Center

 **GENERAL ATOMICS**

NNSA
National Nuclear Security Administration

...and many more

After this seminar, we hope to answer...

What is fusion energy and inertial confinement fusion ?

What are the major types of inertial confinement fusion schemes ?

What is the status of ICF experiments at the NIF?

What are the pathways to inertial fusion energy (IFE) ?

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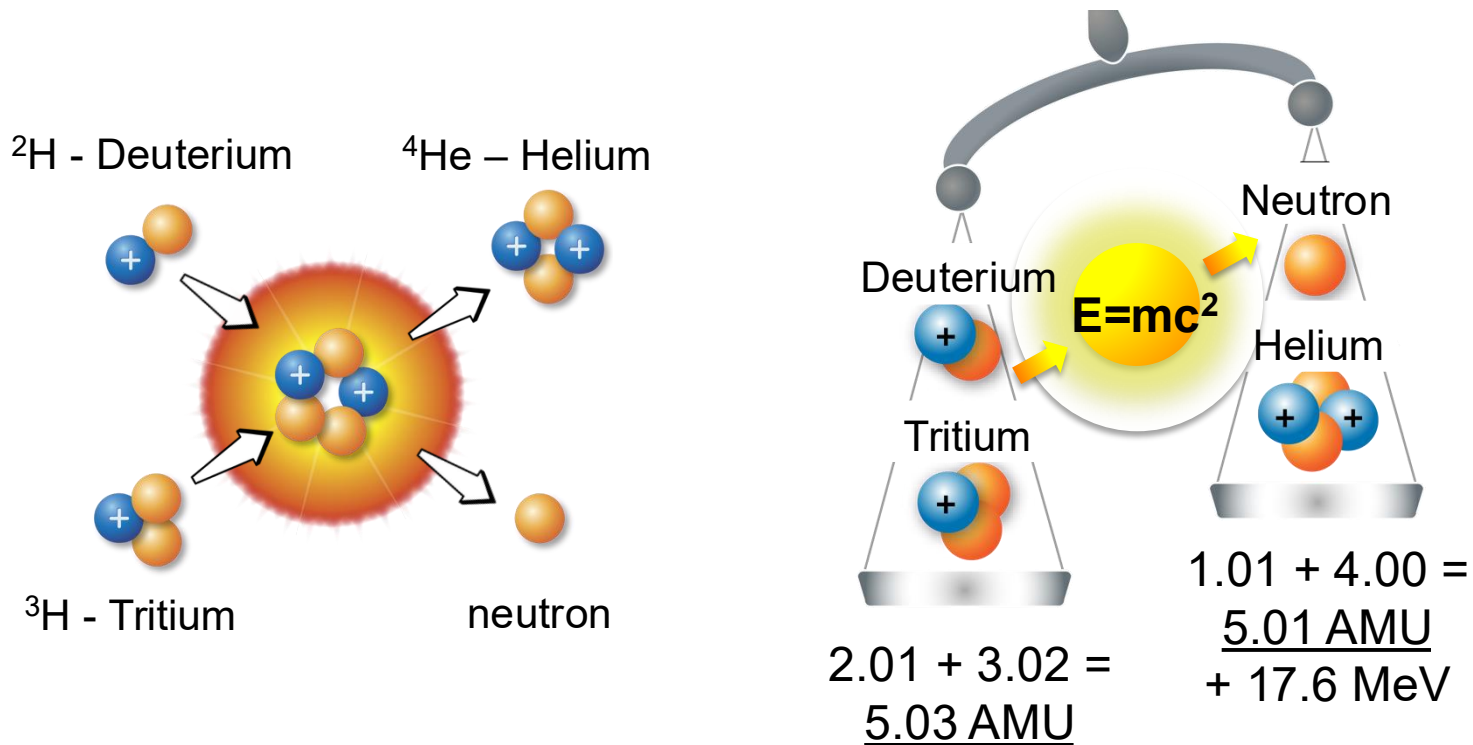
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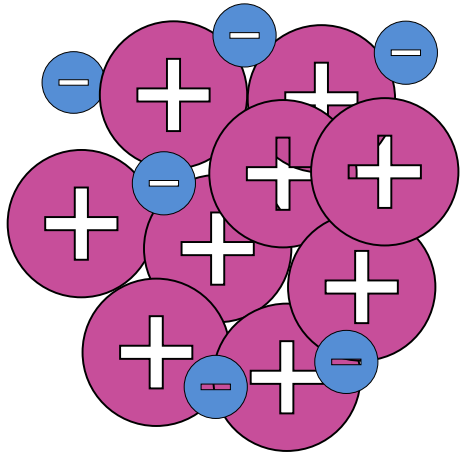
Fusion combines light nuclei into a heavier nucleus and releases huge amounts of energy



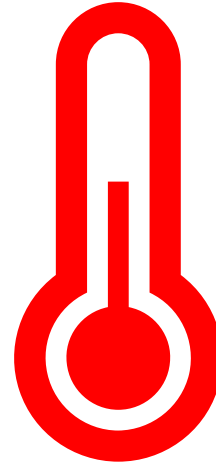
$$Q_{\text{fusion}} = 3.3 \times 10^{11} \text{ J/g}$$

The ingredients for the recipe of net fusion energy are: Density, Temperature and Time

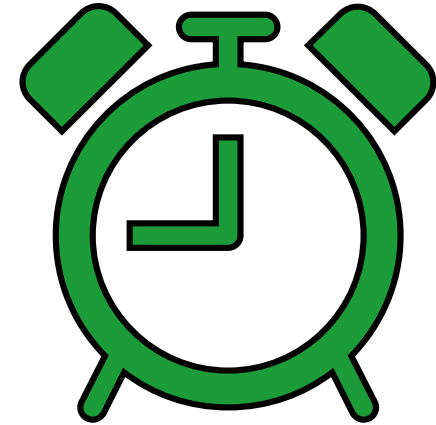
Density (n)



Temperature (T)

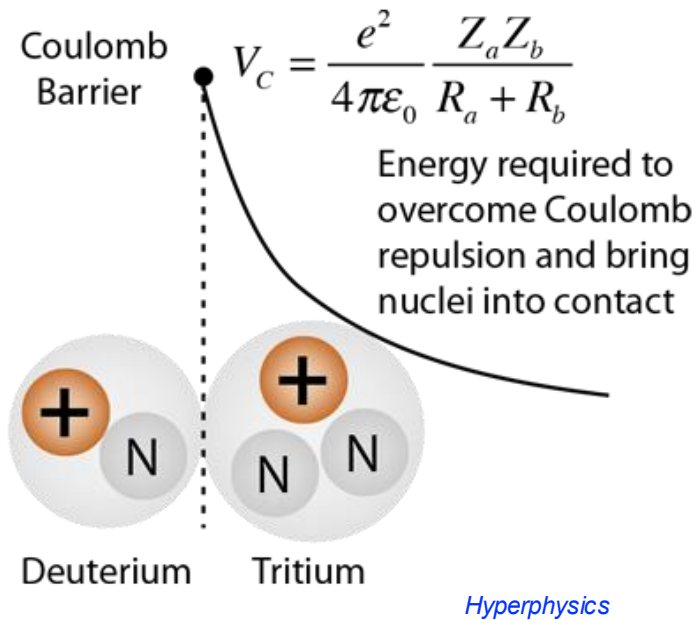


Time (τ)

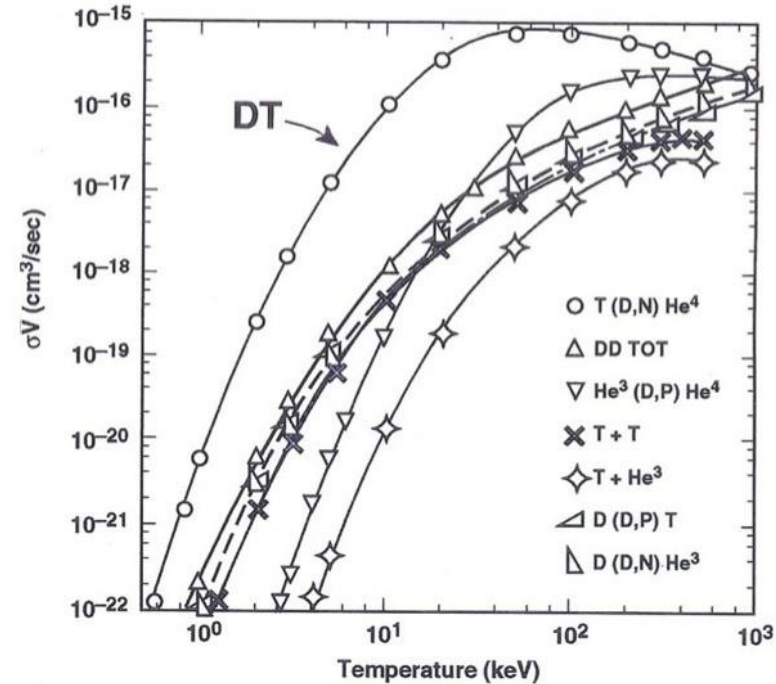


Fusion Triple Product
 $nT\tau > 5 \times 10^{21} \text{ m}^{-3} \text{ keV s (for DT fusion)}$

The Coulomb barrier makes high temperatures necessary for DT thermonuclear fusion



Fusion Rate vs. Temperature



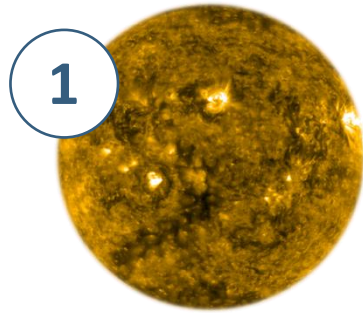
*Atzeni and Meyer-Ter-Vehn
The Physics of Inertial Fusion*

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

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

There are at least three ways to achieve nuclear fusion

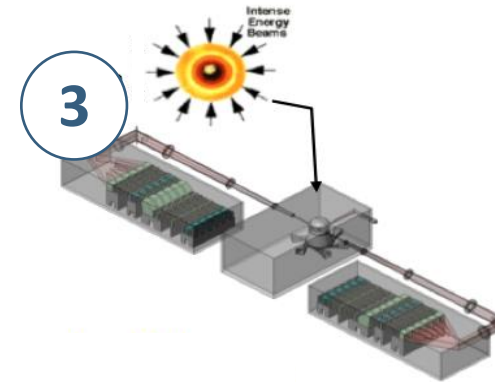
Gravitational Confinement



Magnetic Confinement



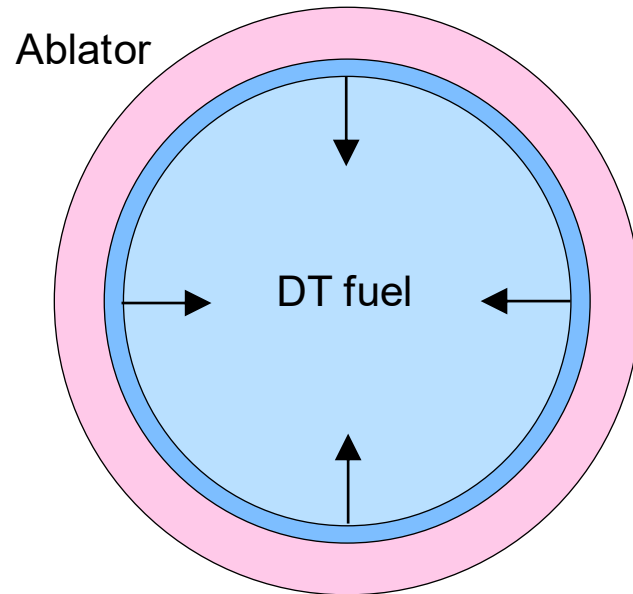
Inertial Confinement



Density	$10^4 \times \text{solid}$	$\text{solid} / 10^8$	$10^3 \times \text{solid}$
Temperature	1 keV	10 keV	10 keV
Confinement time	10^5 years	seconds	10^{-10} seconds

Fusion Triple Product
 $nT\tau > 5 \times 10^{21} \text{ m}^{-3} \text{ keV s}$ (for DT fusion)

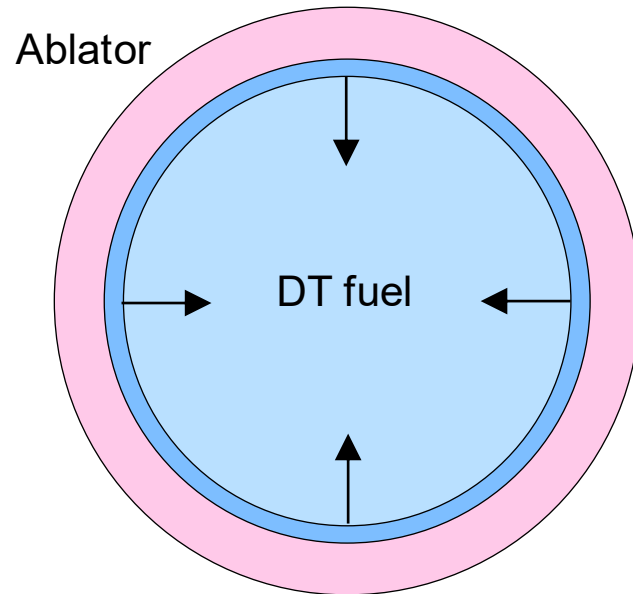
Inertial Confinement Fusion (ICF) relies on the inertia of the target itself to provide confinement



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

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

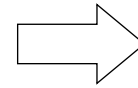
The idea of ICF is to compress fuel to thermonuclear conditions



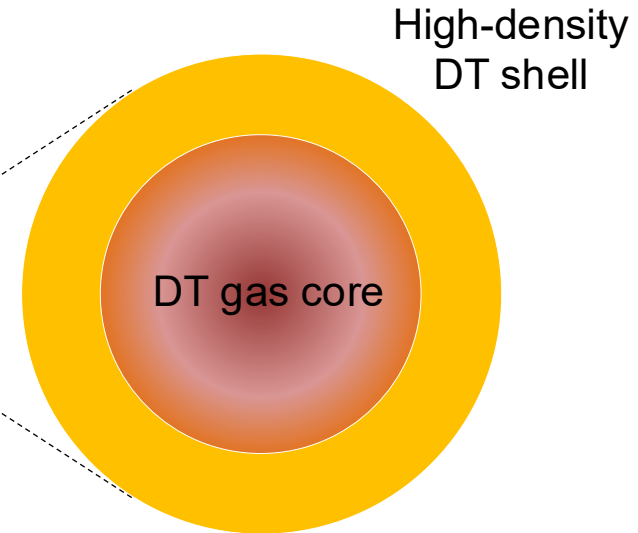
$$R \sim 1000 \mu\text{m}$$
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$$\rho R_{\text{DT}} \sim 0.03 \text{ g/cm}^2$$

35x
convergence



60 μm

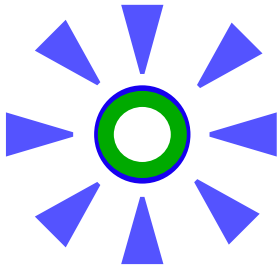


$$R \sim 30 \mu\text{m}$$
$$\rho_{\text{DT}} = 700 \text{ g/cm}^3$$

$$\rho R_{\text{DT}} \sim 3 \text{ g/cm}^2$$

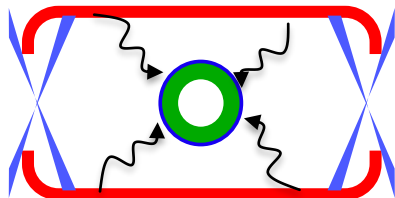
There are two different laser-drive schemes and the aim of both is to drive a spherical implosion

Direct Drive



Laser directly irradiates fuel capsule

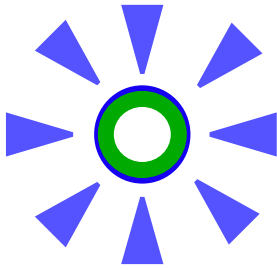
Indirect Drive



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

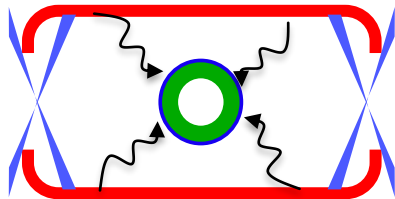
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Direct Drive



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

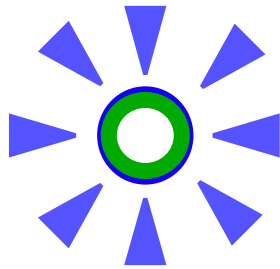
Indirect Drive



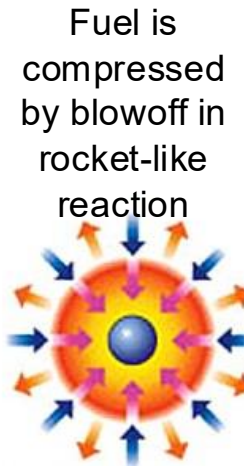
- ~4% efficiency
- Relaxed beam uniformity
- Reduced hydrodynamic instability

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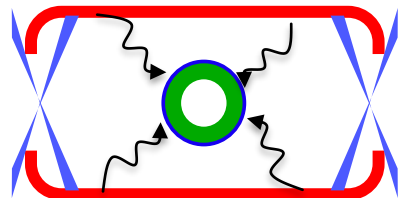
Thermonuclear burn spreads, yielding many times the input energy



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



Indirect Drive



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

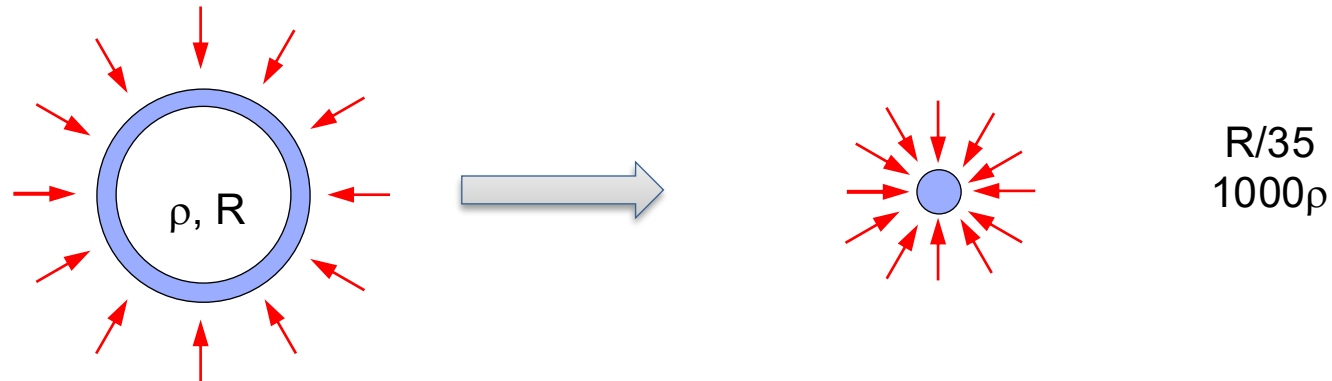
Image taken from "Matter at High-Energy Densities," Univ of Rochester, Laboratory for Laser Energetics

The most efficient compression is spherical because the scaling with a spherical geometry is the most favorable

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

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

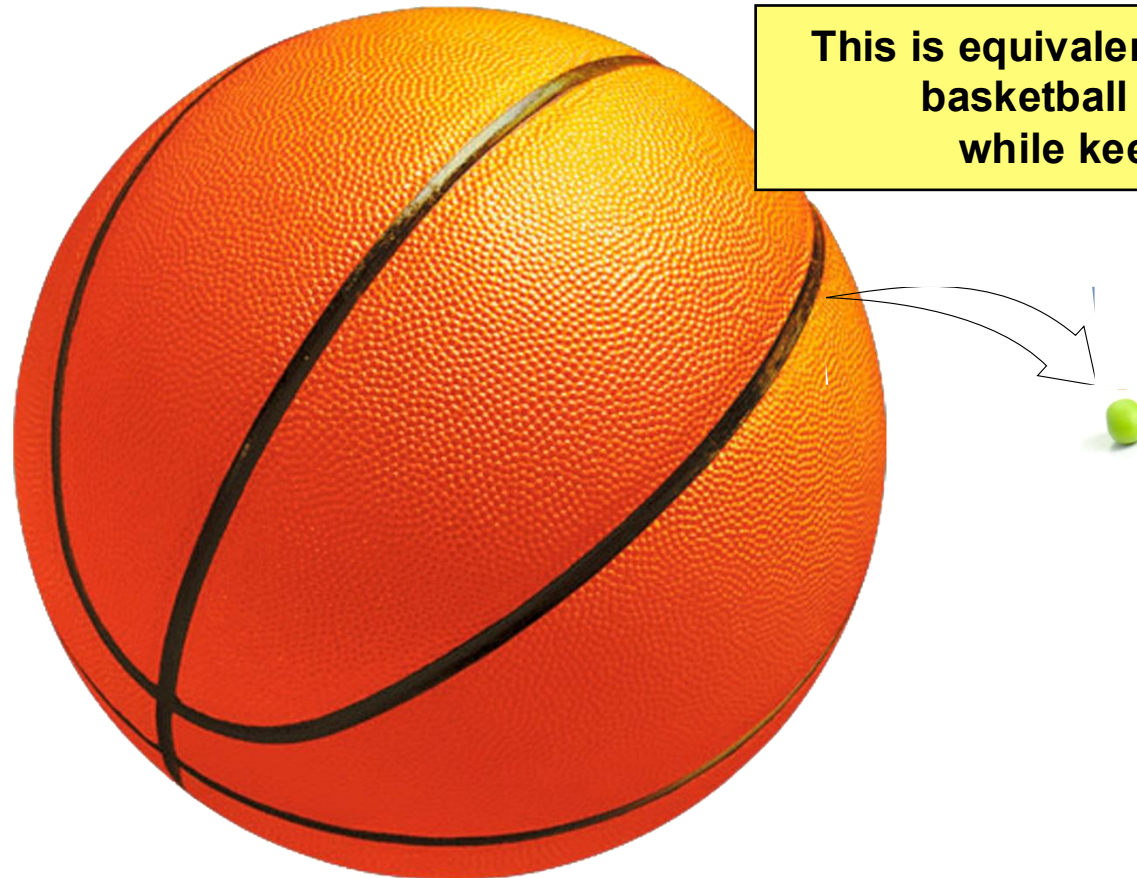
In practice, a hollow shell has more surface area and is easier to push with a given pressure than a solid sphere of the same mass



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

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

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



This is equivalent to compressing a basketball to a pea in 1 μ s while keeping it round

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

The most efficient compression is isentropic, that is, minimizes entropy generation

From thermodynamics:

$$dU = Tds - PdV$$

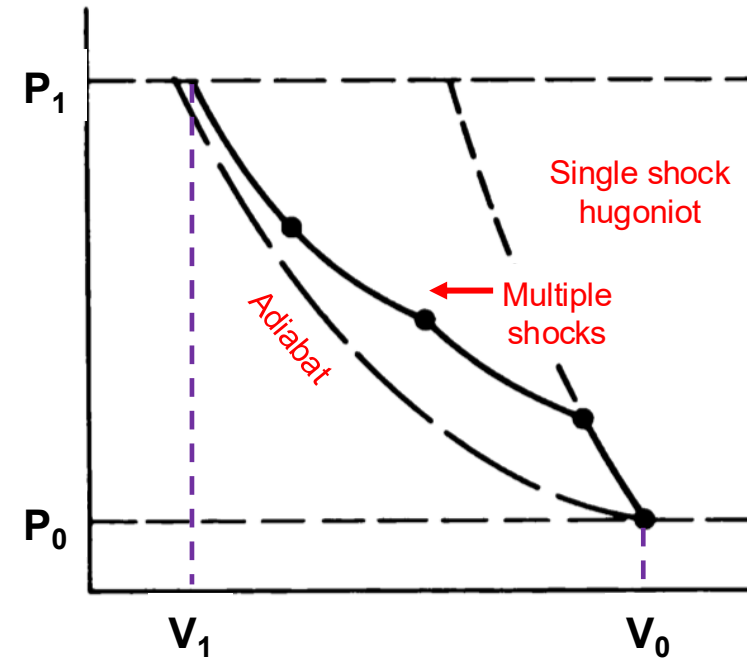
$$PdV = Tds - dU$$

Minimize
work needed
to compress



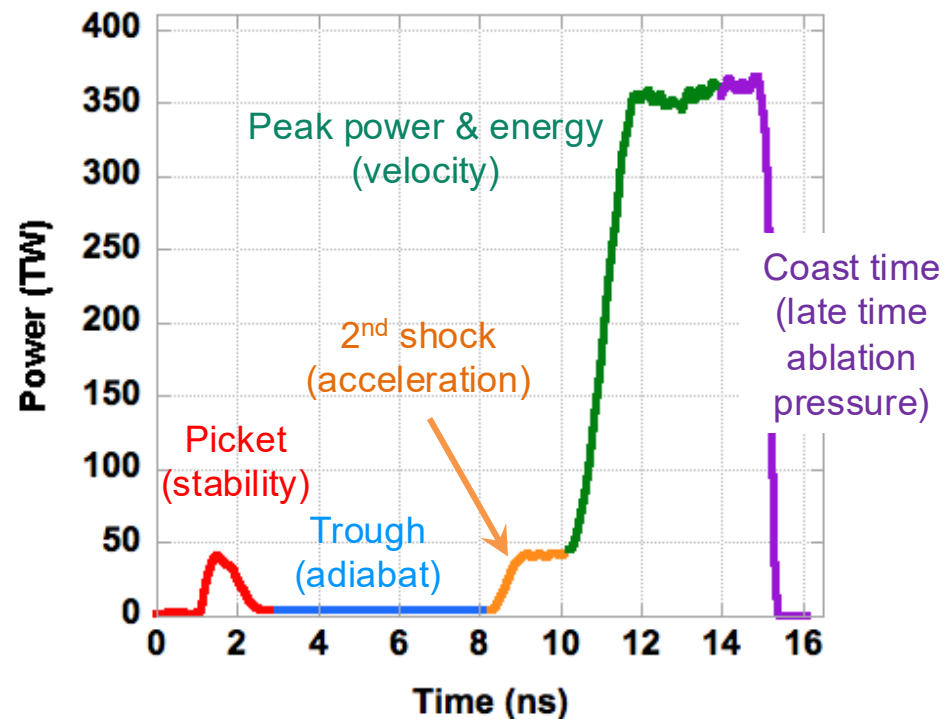
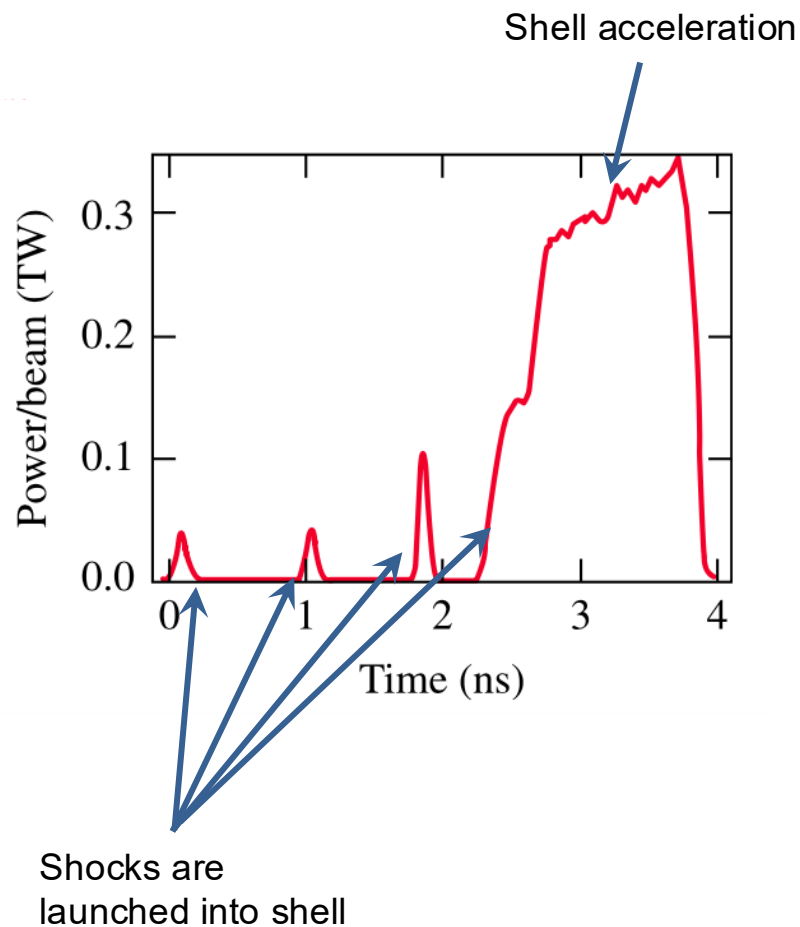
Minimize
entropy
generation

P-V Diagram



Fast implosions (~3e7 cm/s) are also important to impart more kinetic energy into the shell, which ultimately increases the pressure

Precision shaped pulses enable us to compress while minimizing the introduction of entropy



Mixing of the ablator into the hot dense fuel can cause a significant amount of energy loss, degrading performance

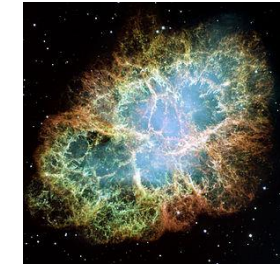


Rayleigh-Taylor

- Low density attempts to push high density



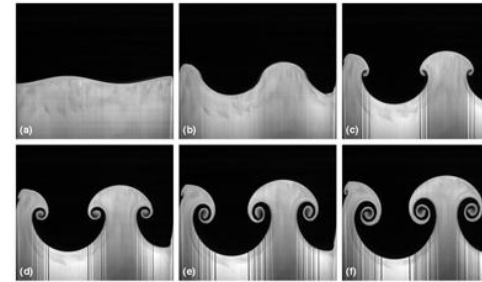
Evolution of RTI in two immiscible fluids



Rayleigh-Taylor "fingers" in Crab Nebula

Richtmyer-Meshkov

- Shock-driven vorticity



Evolution of Richtmyer-Meshkov at the interface of two fluids

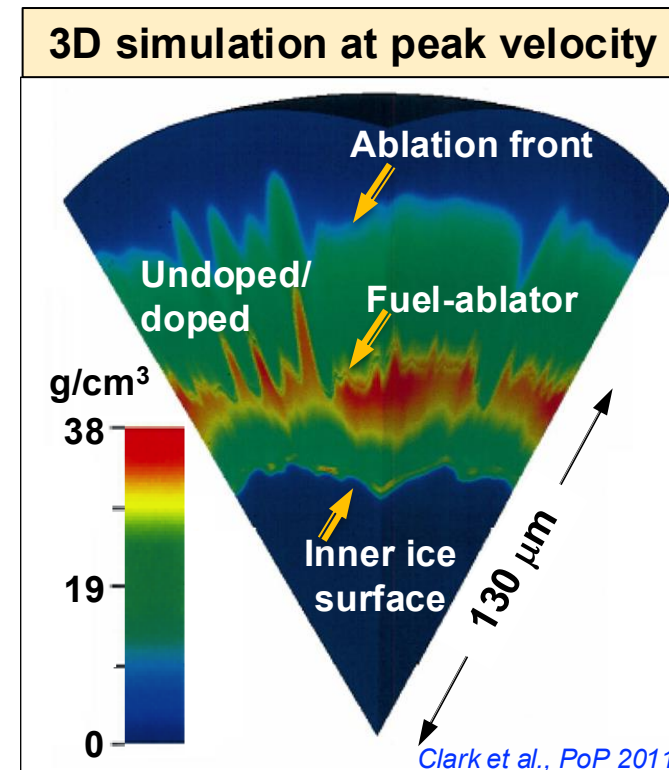
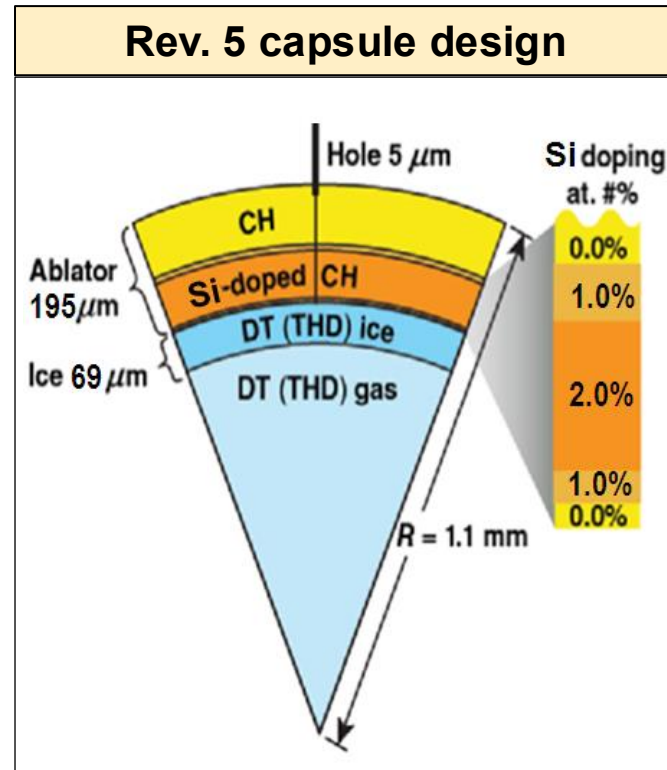
Kelvin-Helmholtz

- Shear



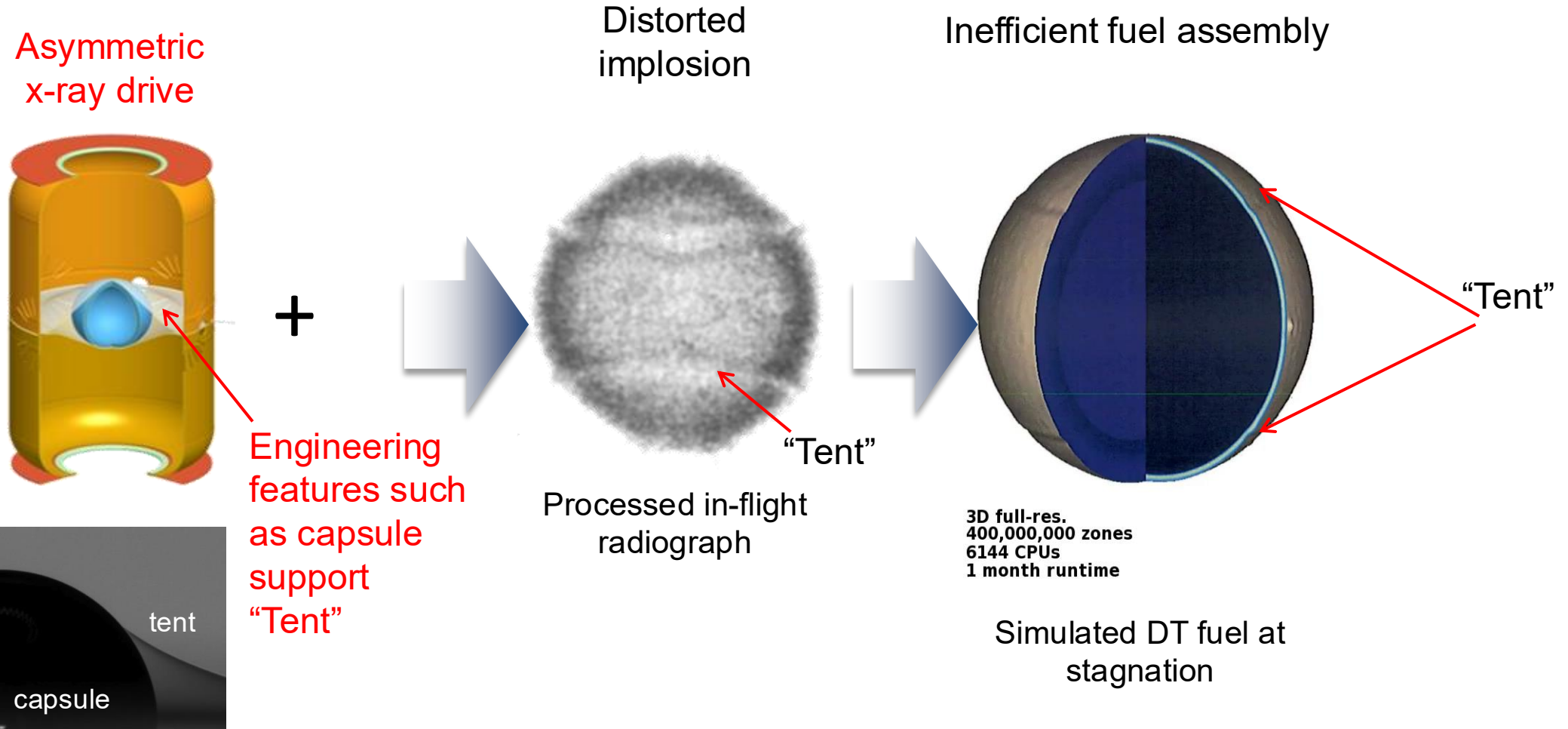
Kelvin-Helmholtz roll-up in clouds

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

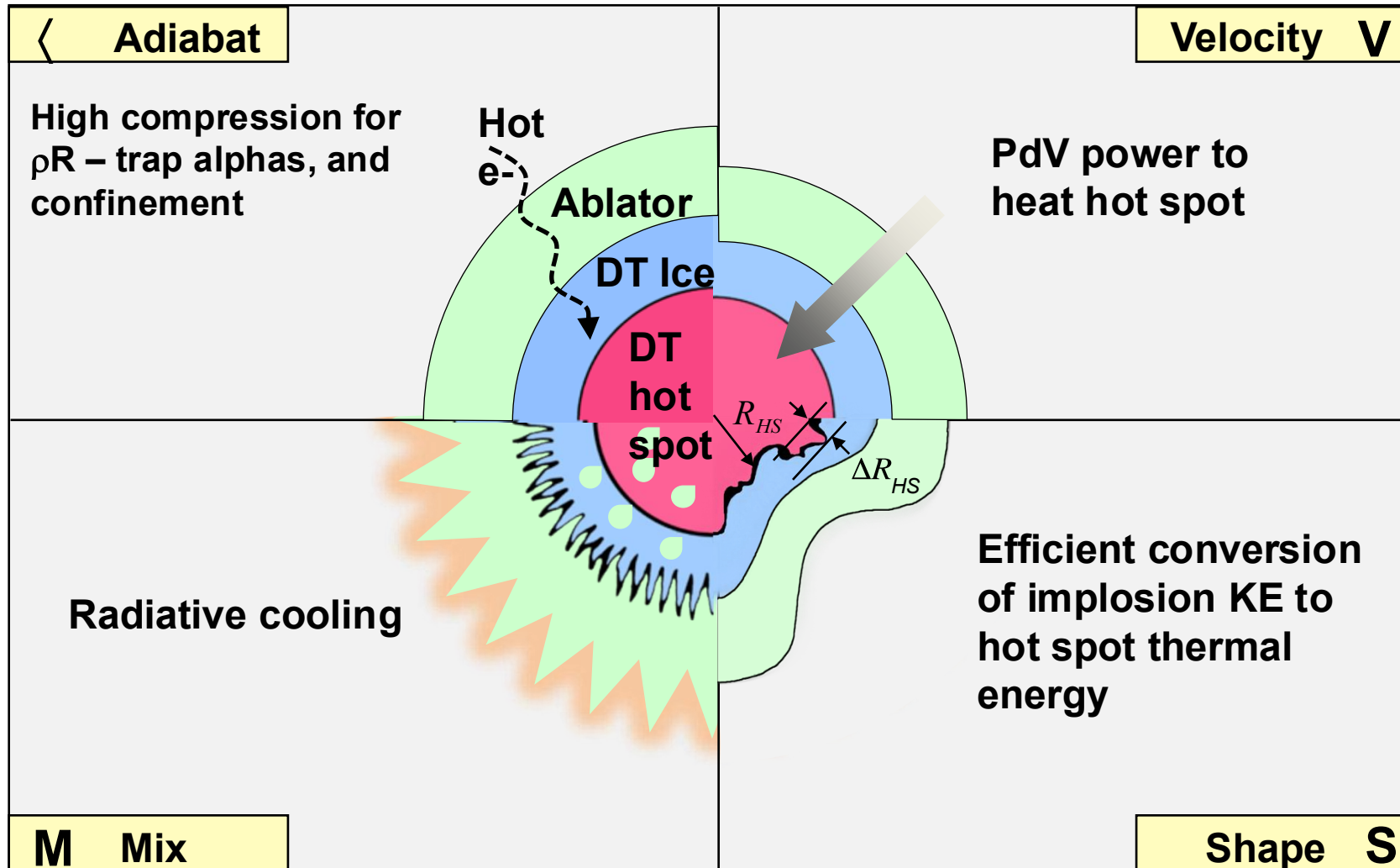


Mixing of ablator material into the hot spot due to the hydrodynamic instabilities can increase the radiative cooling and degrade capsule performance in ICF implosions

Other asymmetries in the implosion shape can be caused by engineering features in the target design



Ignition performance is optimized around four key variables, which we must carefully balance to create a burning plasma



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What is the status of ICF experiments at the NIF?

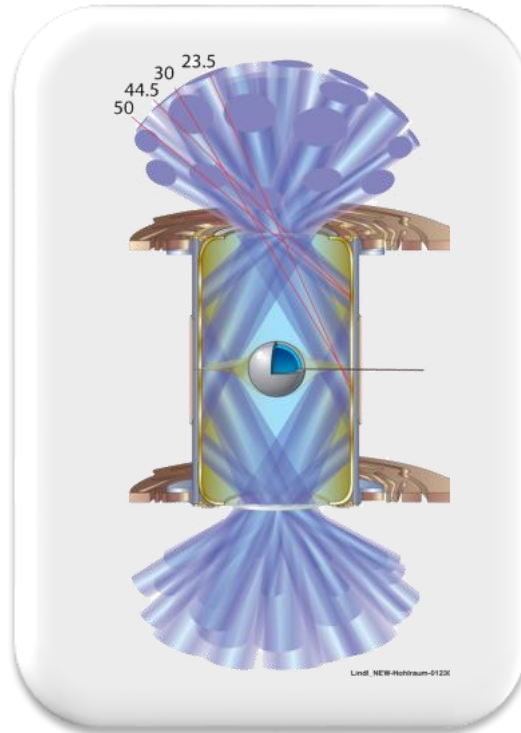
What are the pathways to inertial fusion energy (IFE) ?

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

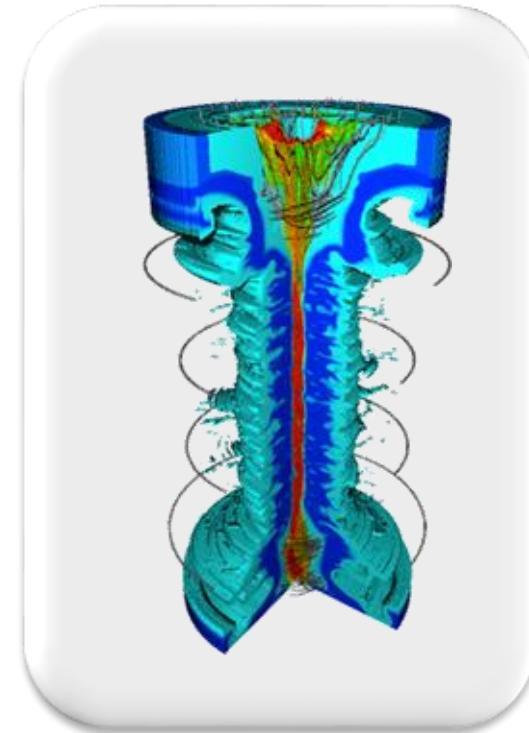
Laser Direct Drive



Laser Indirect Drive



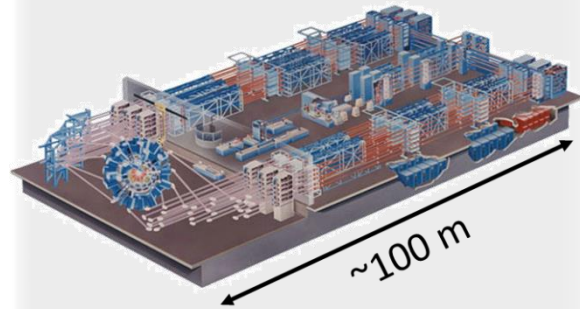
Magnetic Direct Drive



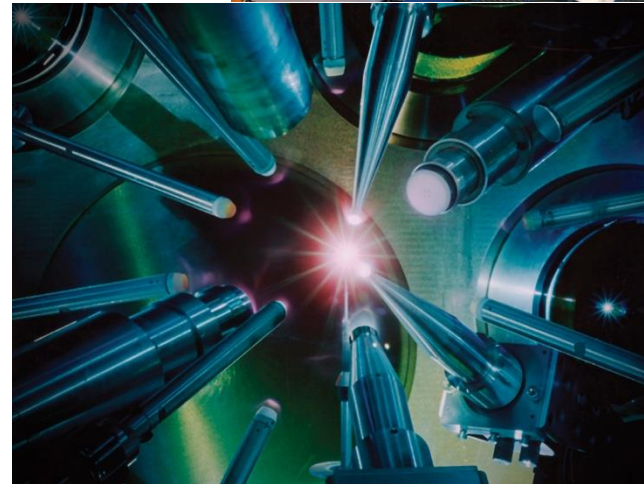
The OMEGA laser facility at the University of Rochester, NY, uses the direct-drive approach



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

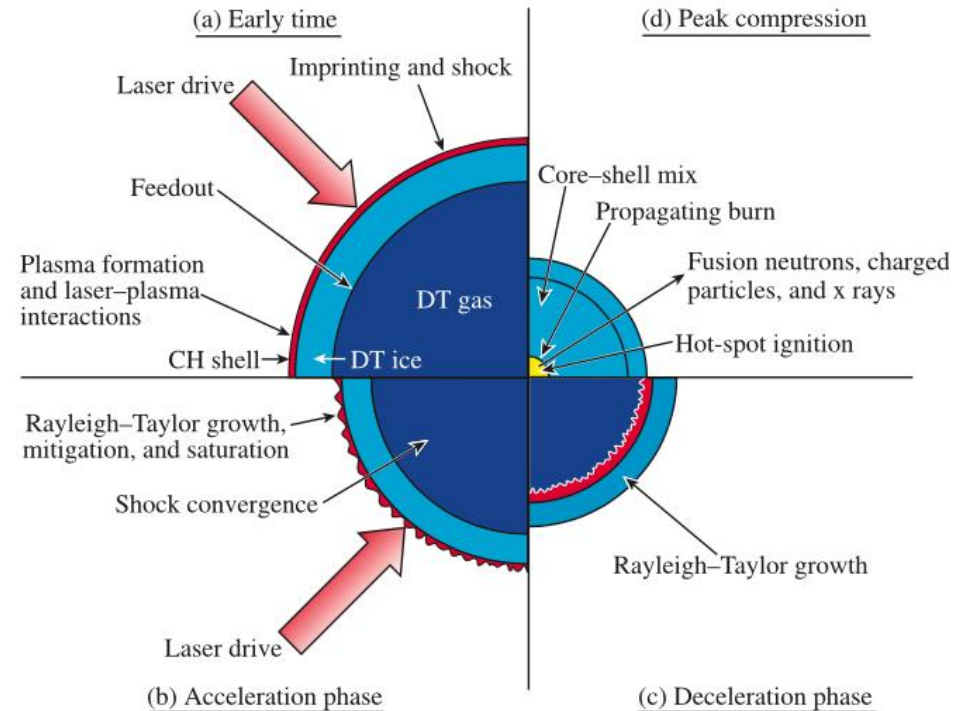


30 kJ energy available on OMEGA.

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.

~80 Gbar demonstrated so far.



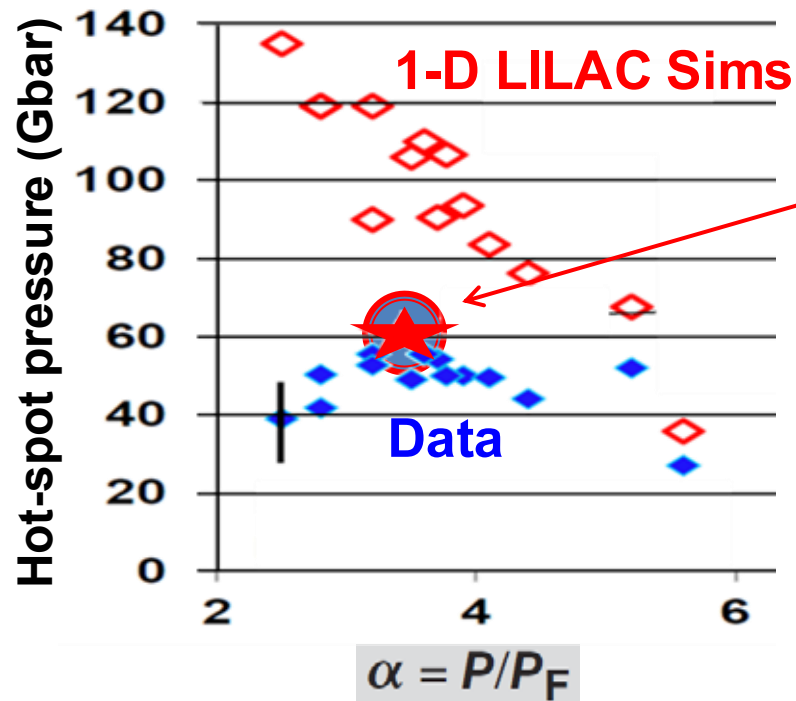
E988611

Craxton et al., PoP 2015

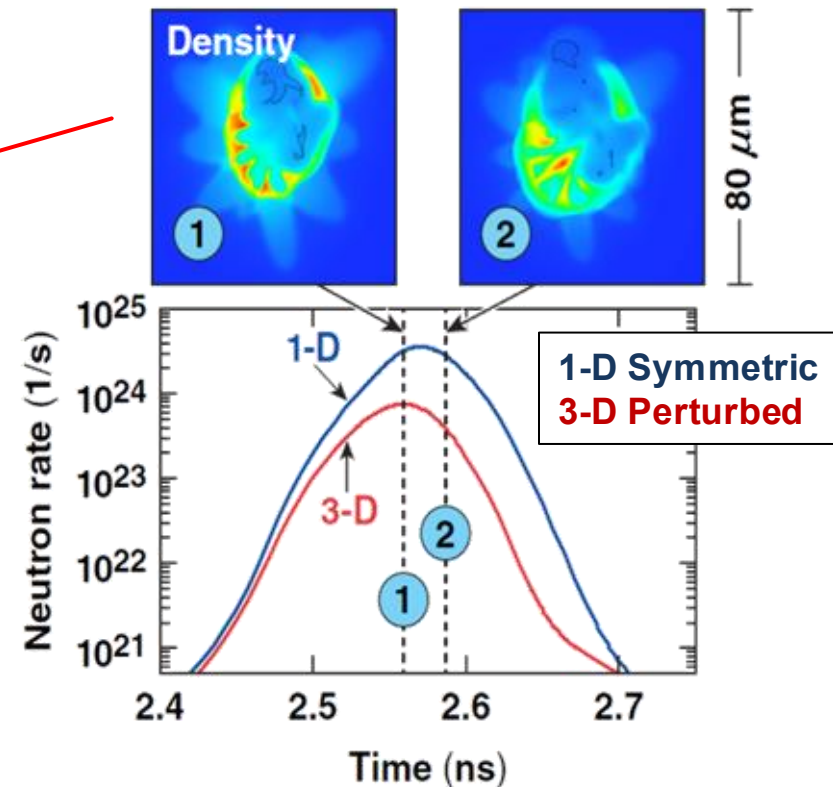
The 3D morphology of the direct drive implosion is one of the main challenges



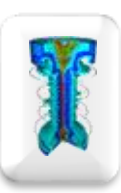
Stagnation Pressure vs. Fuel Adiabatic



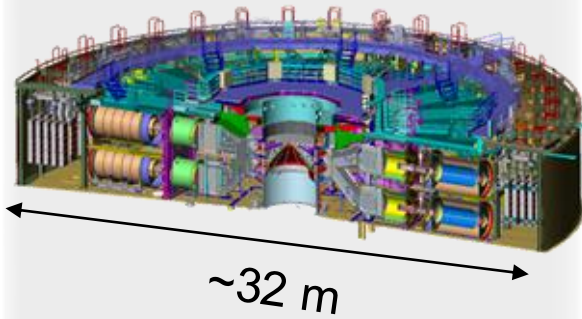
3-D ASTER simulations show effect of errors in beam pointing, power balance, and capsule placement



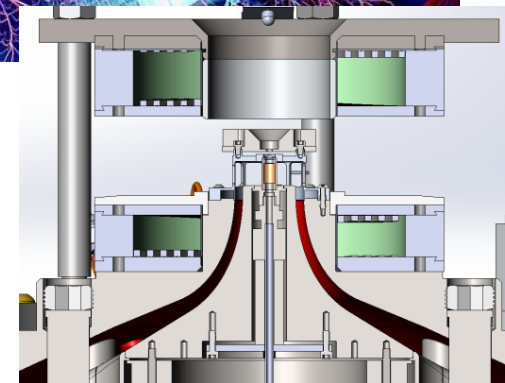
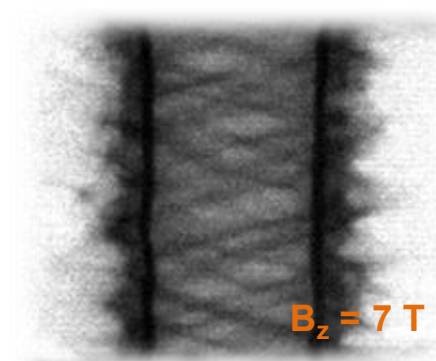
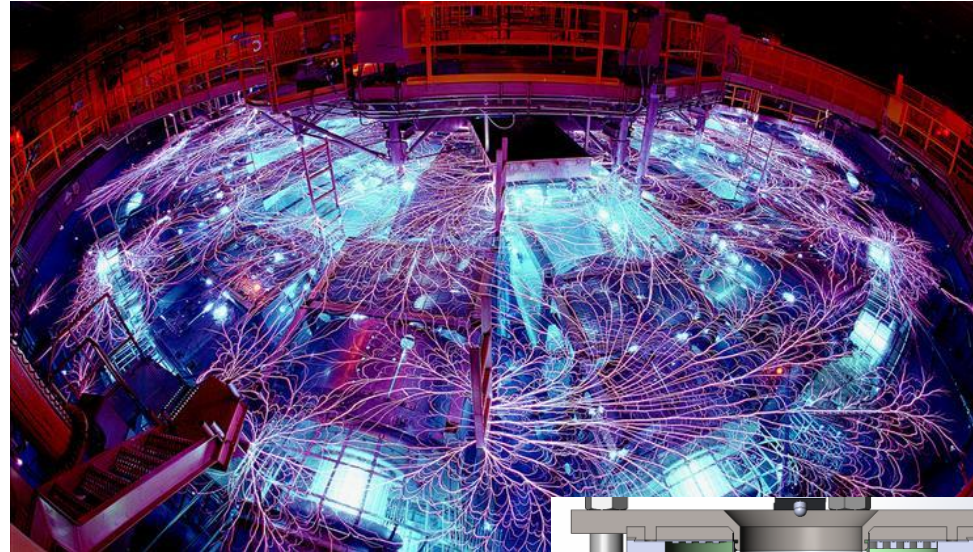
Magnetic drive ICF is being pursued at the Z pulsed power facility at Sandia National Labs, NM



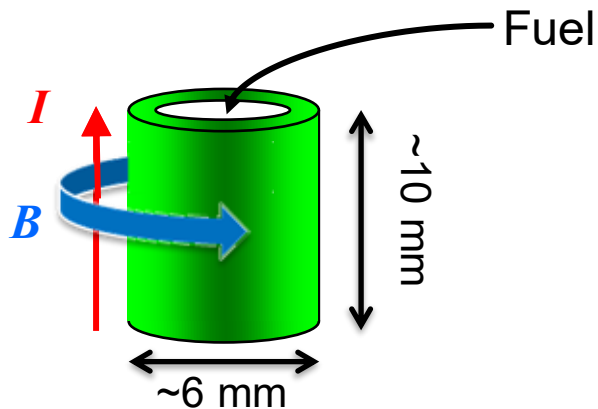
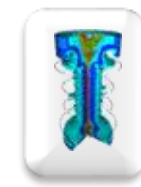
Z Facility



- 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

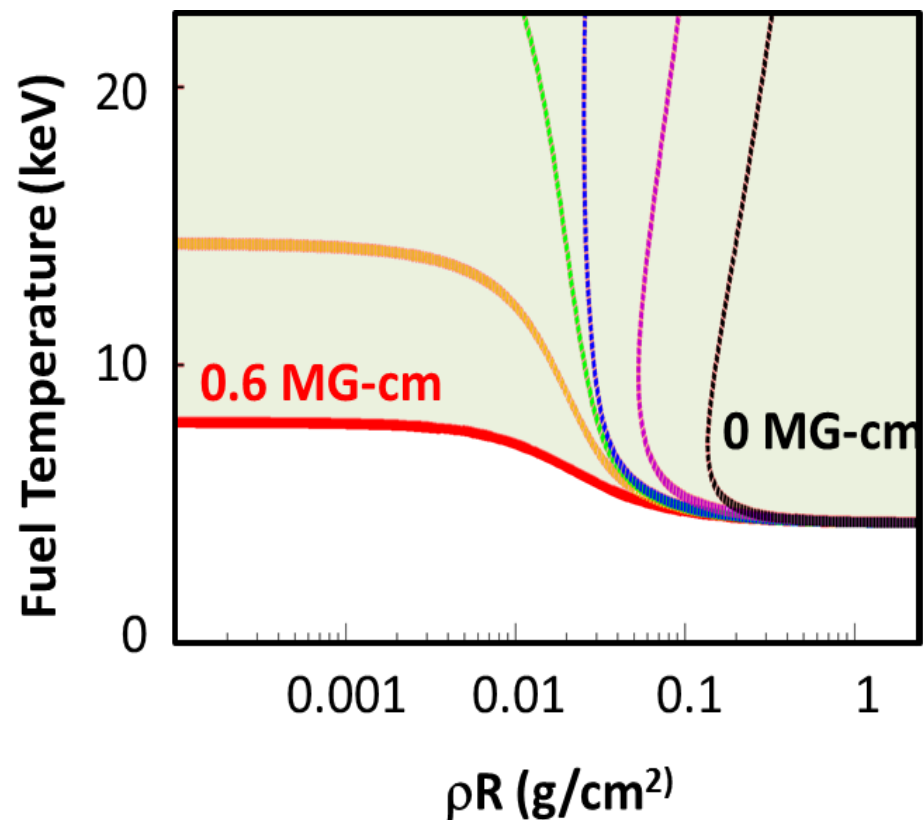


Drive Pressure

$$P = \frac{B^2}{8\pi} = 105 \frac{I_{MA}^2}{R_{mm}^2} \text{ Mbar}$$

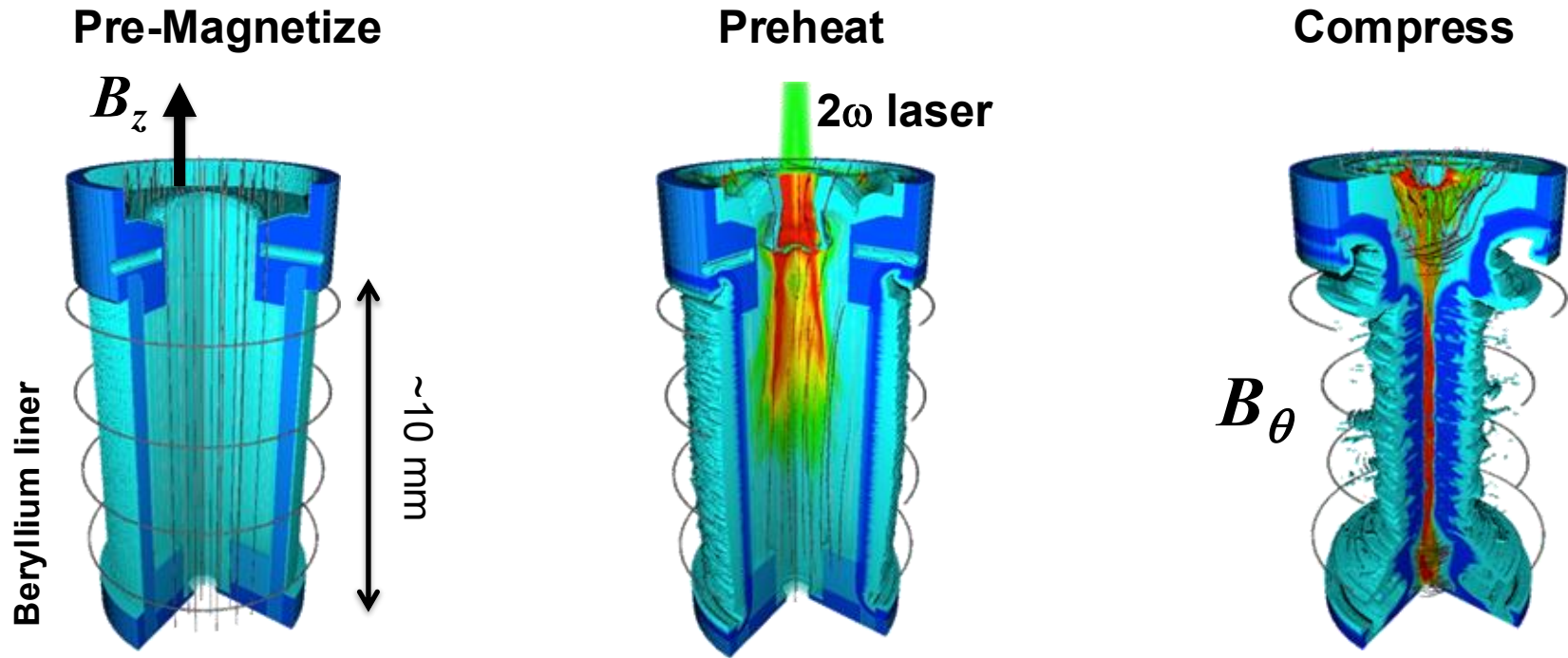
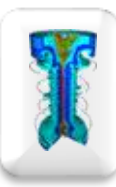
- Cylindrical convergence
 - Harder to achieve high ρr
- Thick liners ($\sim 500 \mu\text{m}$)
 - Harder to achieve high velocity

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)

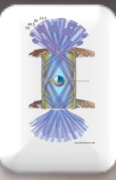


- $B_z = 10\text{-}30$ T
- Inhibit e^- conduction
- Confine α 's

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

- CR ~ 35
- $\rho R \sim 0.003$ g/cm²
- P ~ 5 Gbar
- BR ~ 0.5 MG-cm

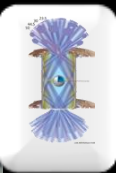
Goal: demonstrate ~100 kJ DT-equivalent fusion yield

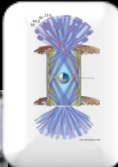


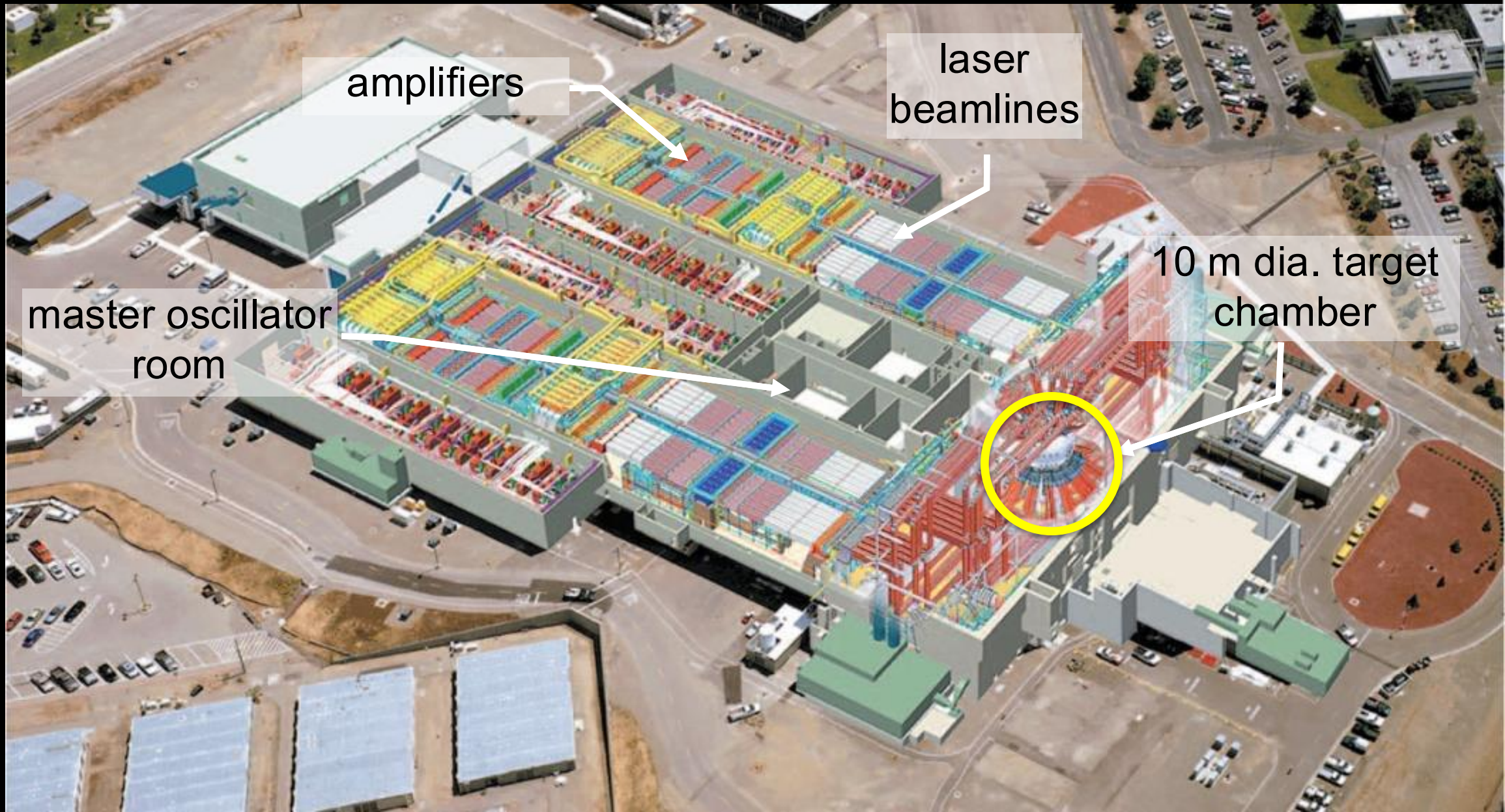
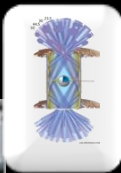
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- Matter temperature >10 keV (10^8 K)
- Radiation temperature >300 eV (3.5×10^6 K)
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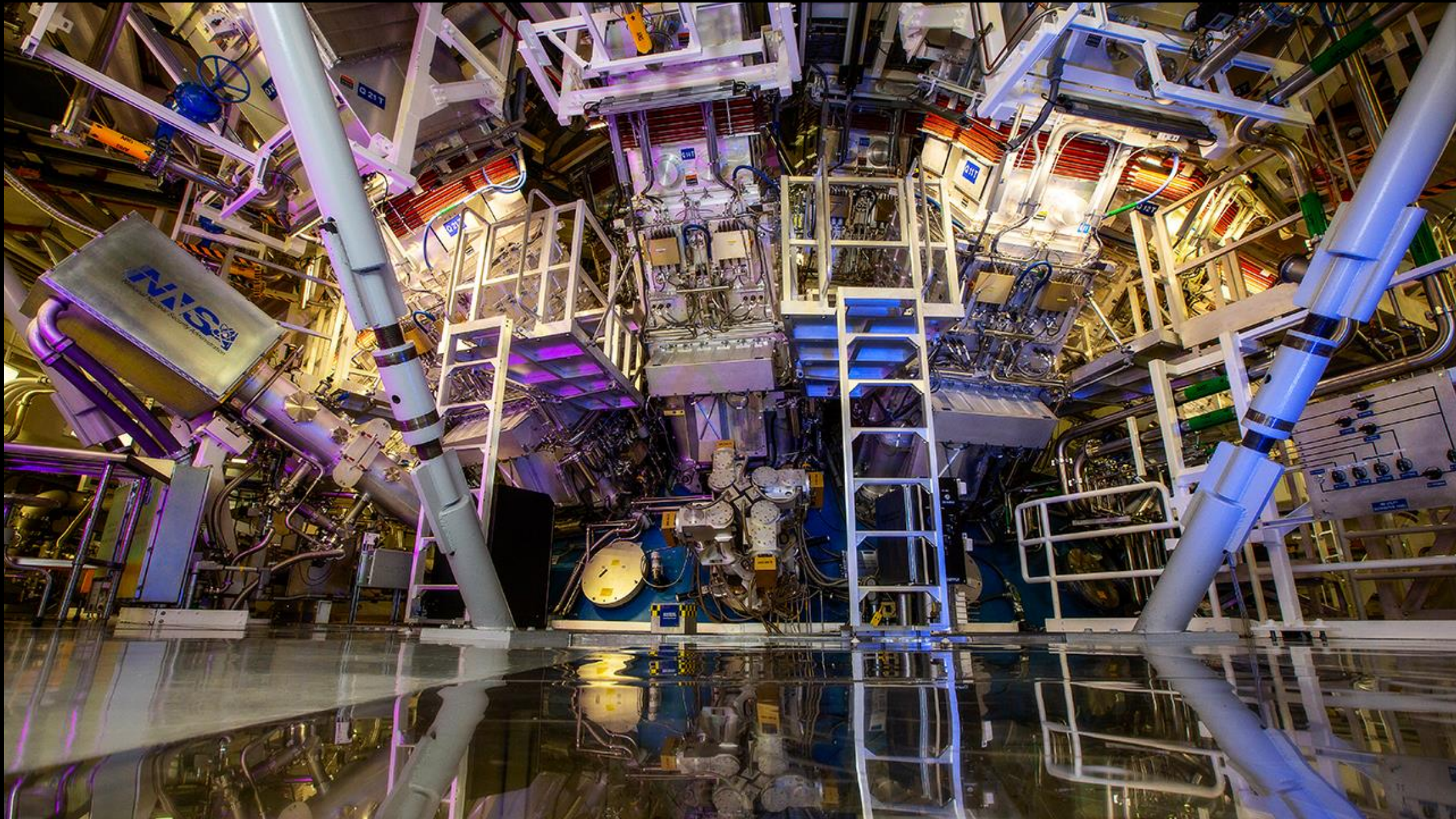
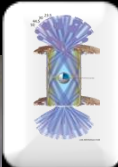


amplifiers

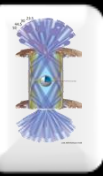
laser beamlines

master oscillator room

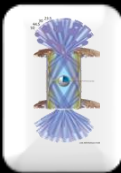
10 m dia. target chamber



NIF in Star Trek: Into Darkness



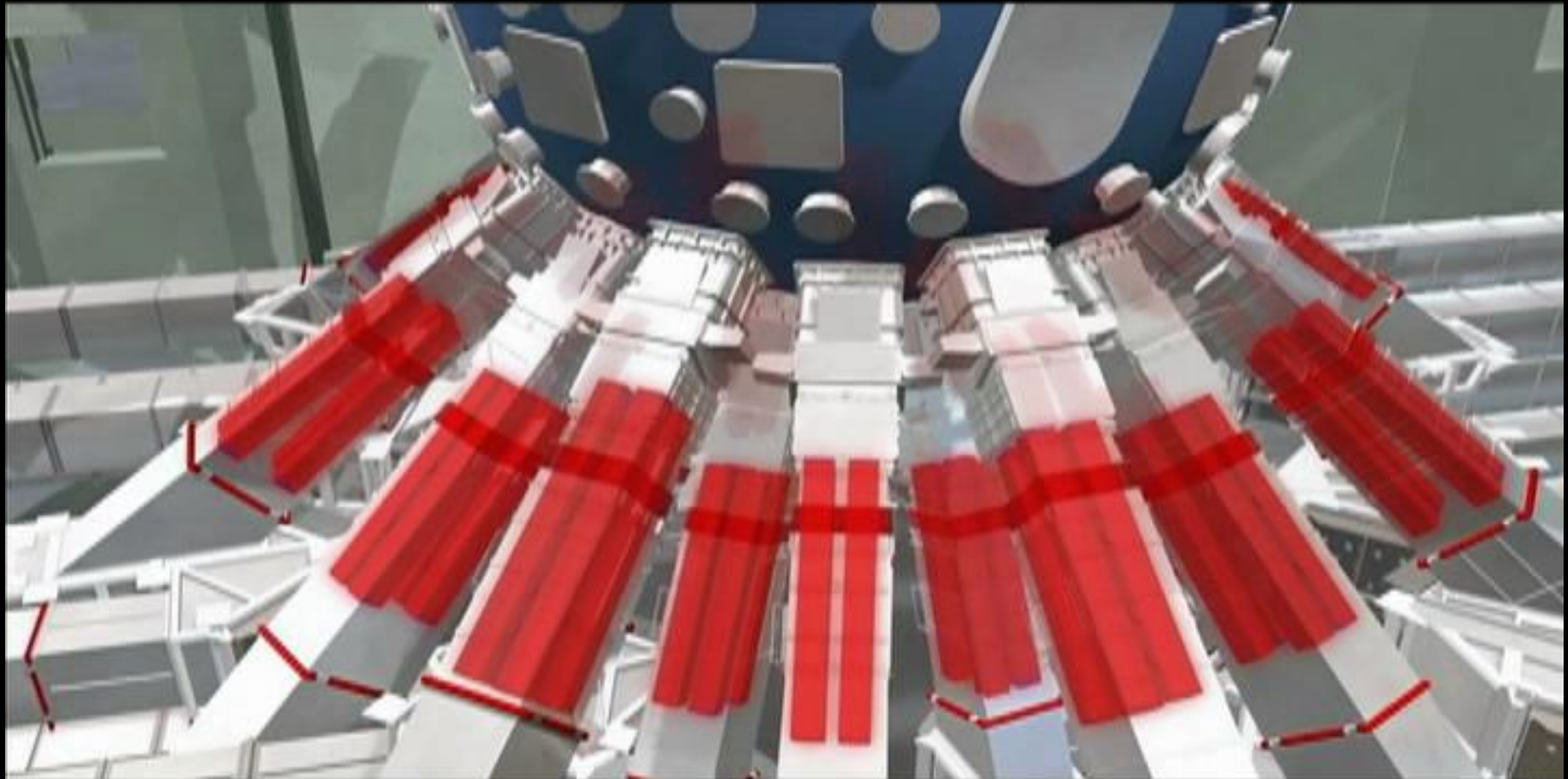
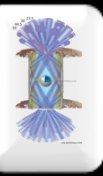
Courtesy of Scott Chambliss, Paramount Pictures and Bad Robot Productions



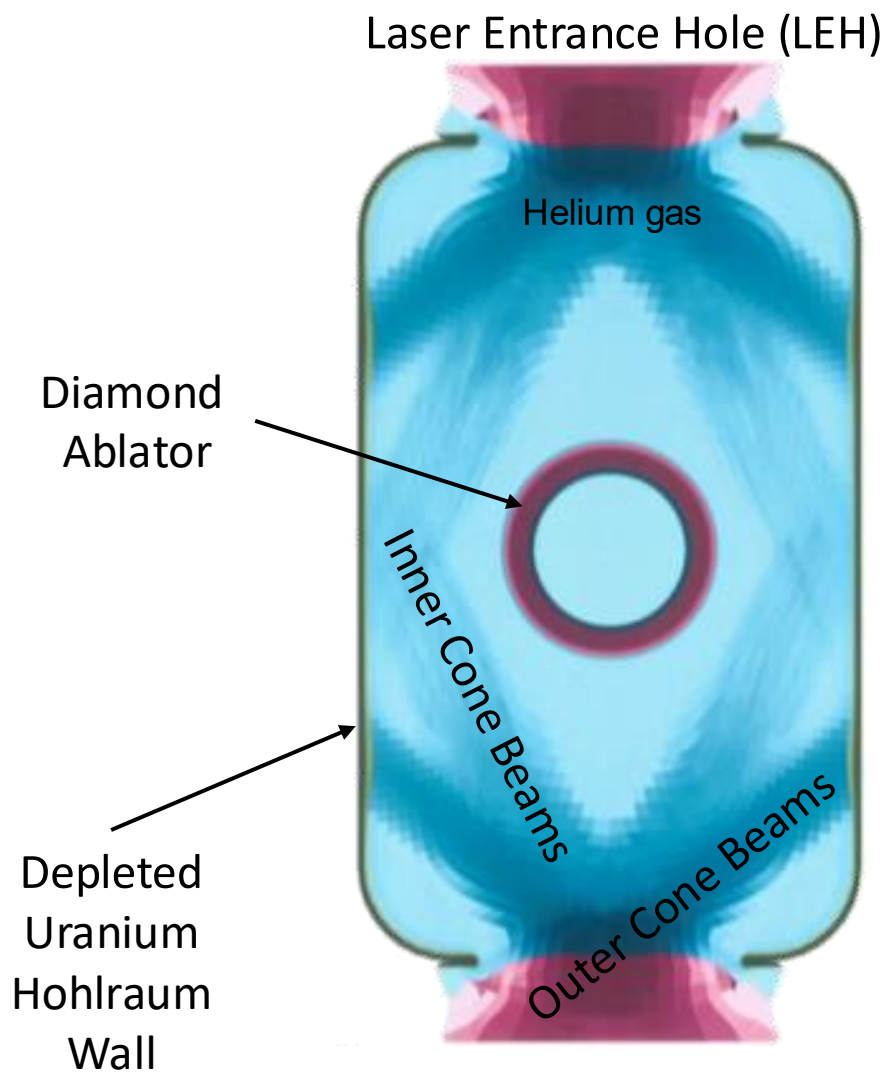
In the Target Chamber



Indirect drive inertial confinement fusion (ICF) uses x-rays to ablate and accelerate a capsule of fusion fuel to extreme velocity



On Dec. 5th, NIF delivered 2.05 MJ of laser energy to a target producing 3.15 MJ of fusion energy



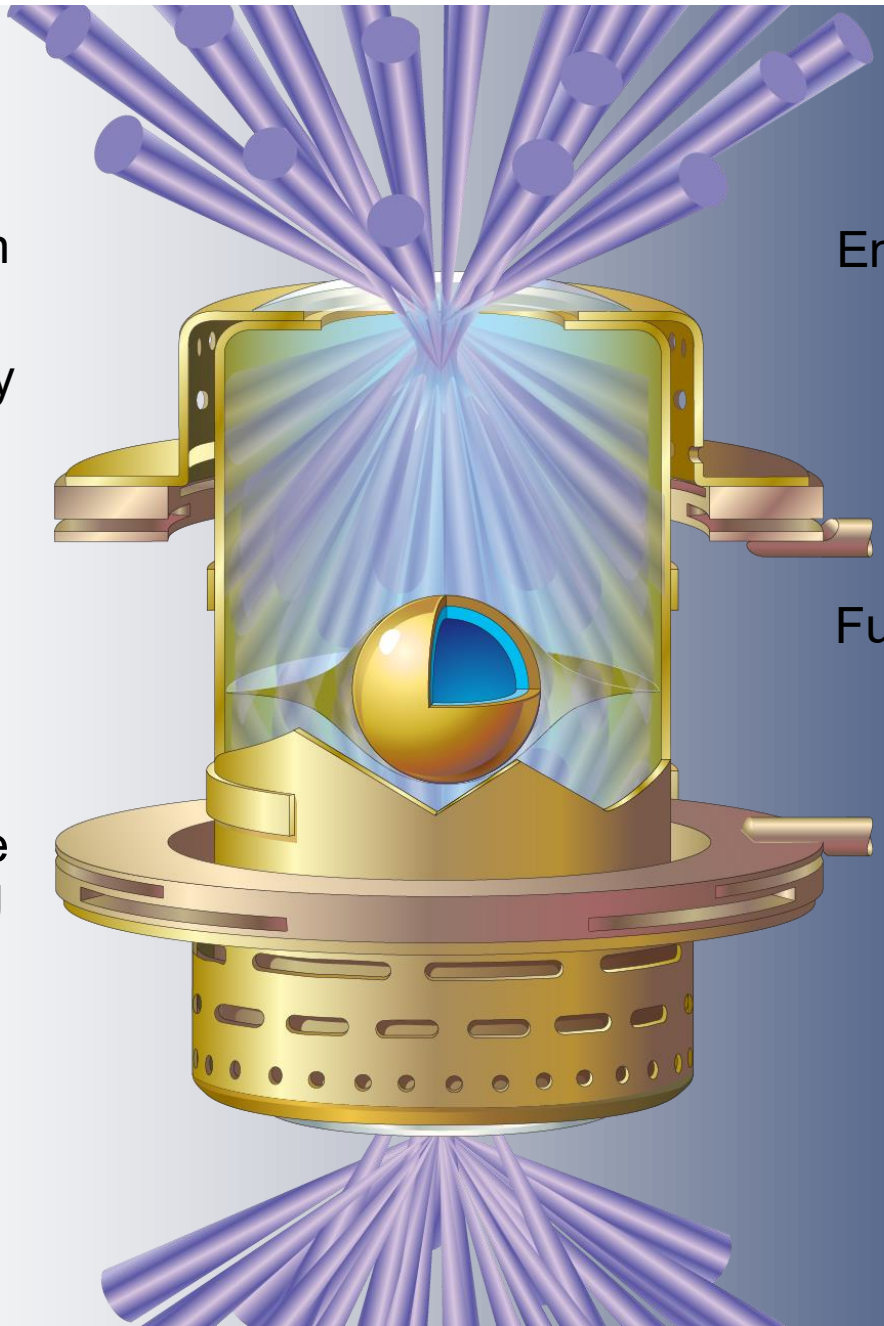
Energy In

Electricity 322 MJ

Laser 2.05 MJ

Capsule ~250 kJ

Fusion Fuel ~20 kJ



After this seminar, we hope to answer...

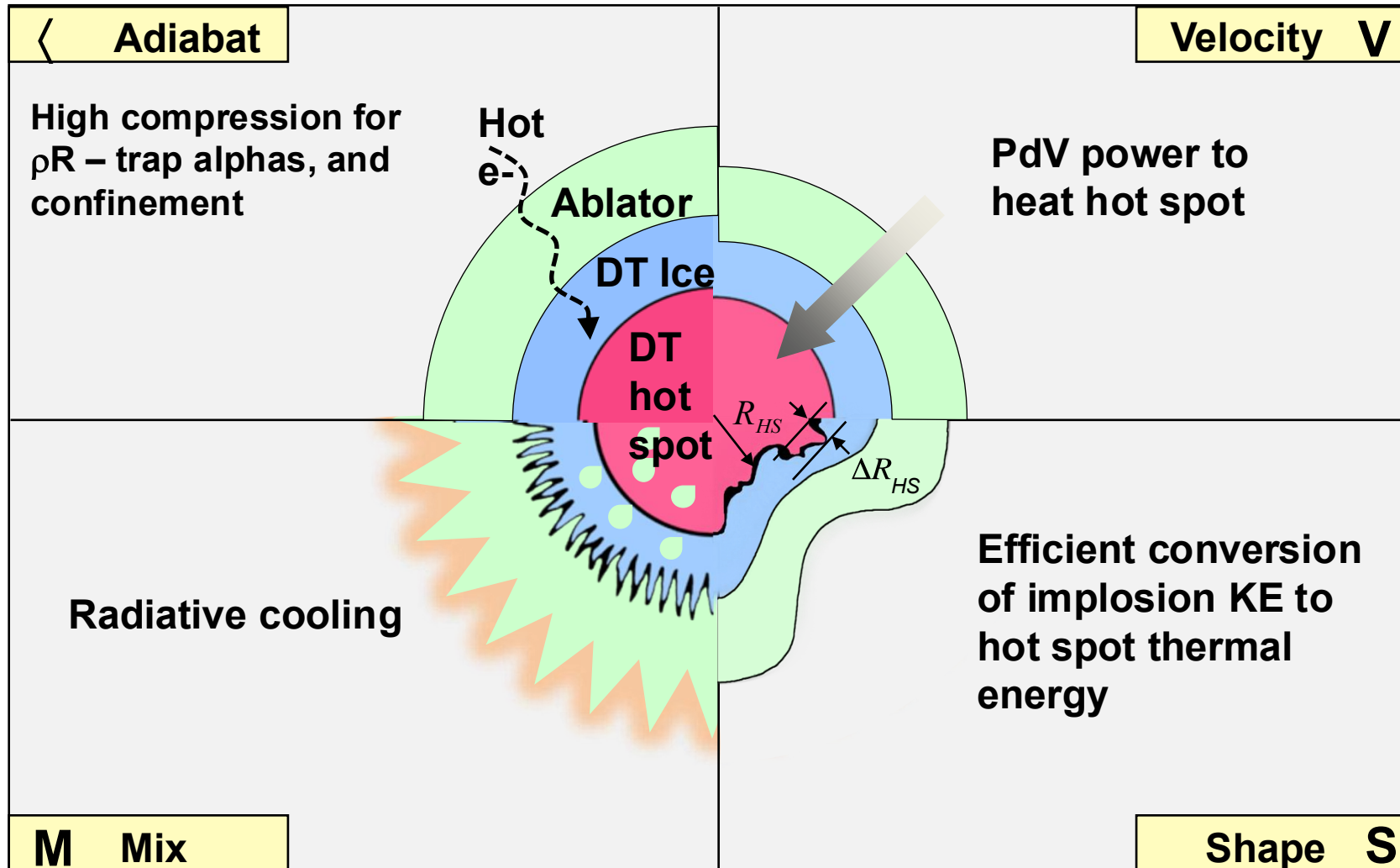
What is fusion energy and inertial confinement fusion ?

What are the major types of inertial confinement fusion schemes ?

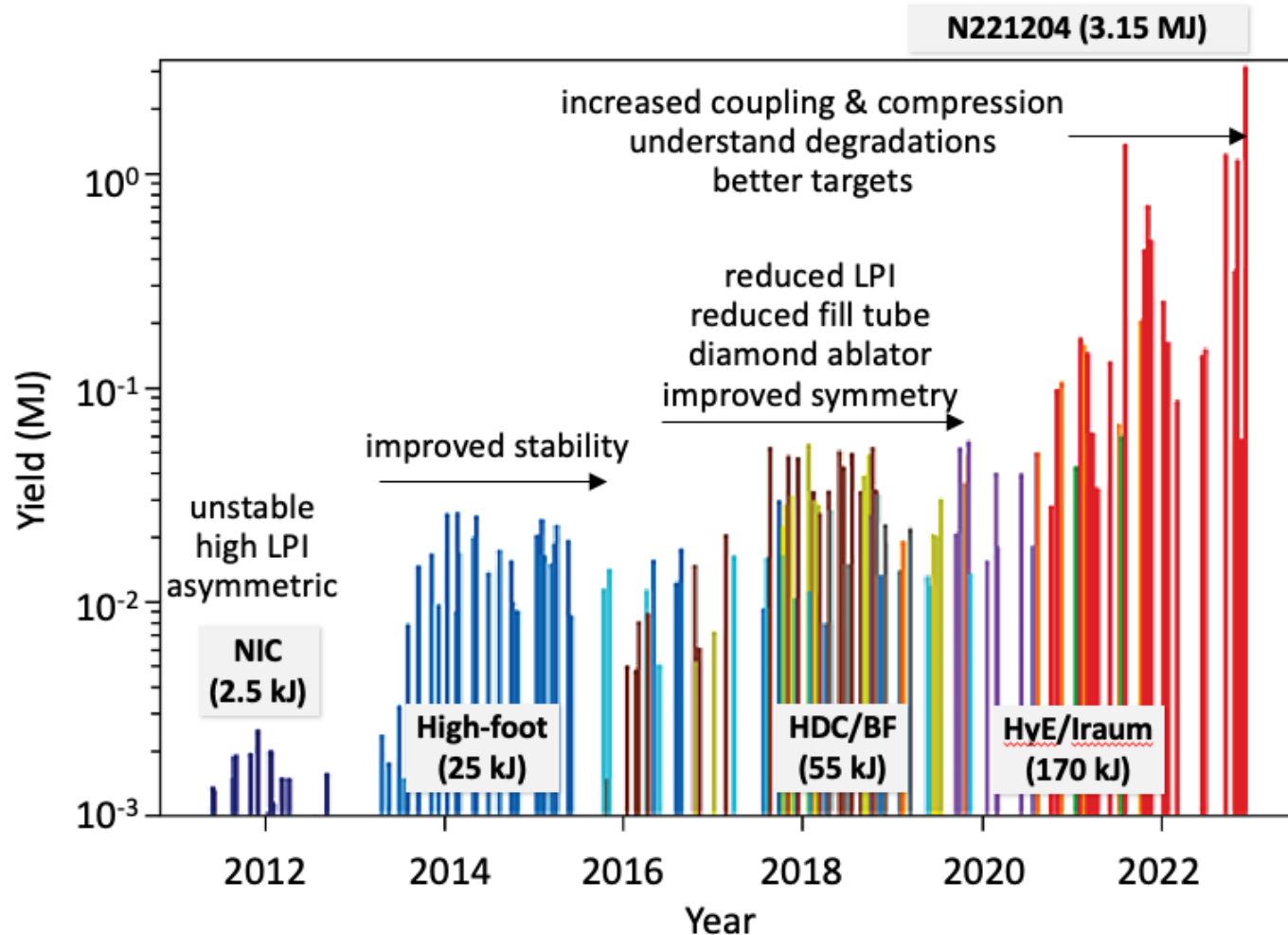
What is the status of ICF experiments at the NIF?

What are the pathways to inertial fusion energy (IFE) ?

Ignition performance is optimized around four key variables



The program steadily advanced physics understanding and technology over the last decade to improve performance, culminating in ignition (target gain >1) on Dec. 5th, 2022



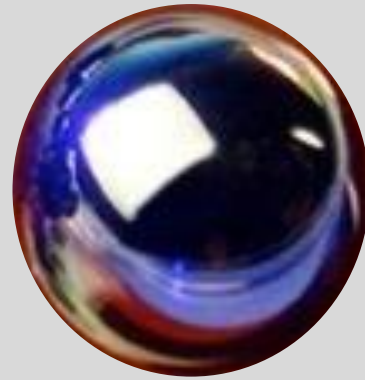
Targets require state-of-the-art microfabrication precision

Gold lined Uranium Hohraum



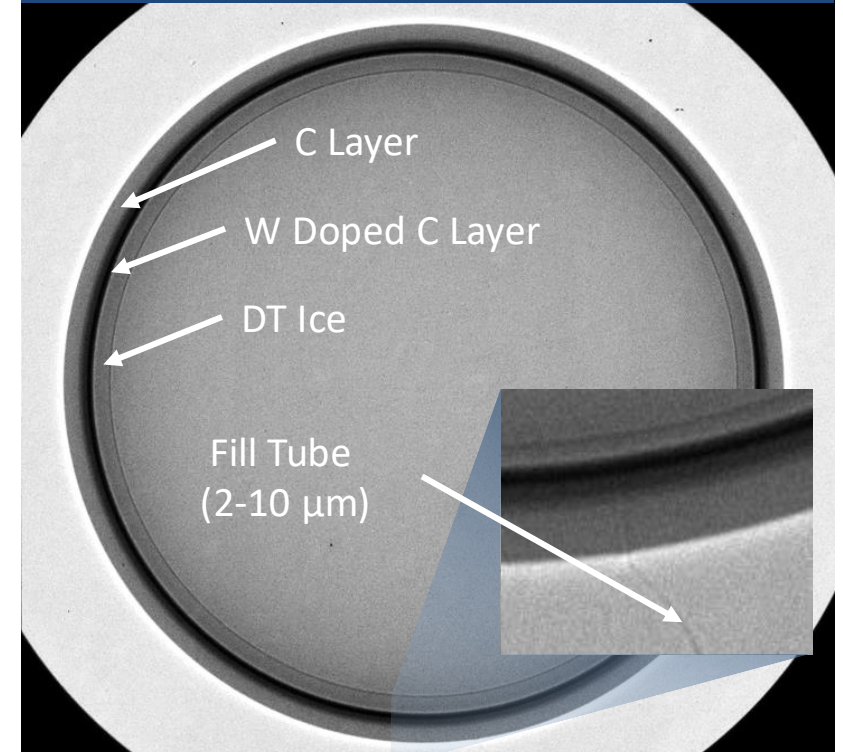
~ 1 cm long
Cryogenic
0.3 mg/cc He fill

Diamond Nanocrystalline Capsule
(High Density Carbon – HDC)



≈ 2 mm diameter, smooth to 10 nm
→ Earth with no hill > 64 m

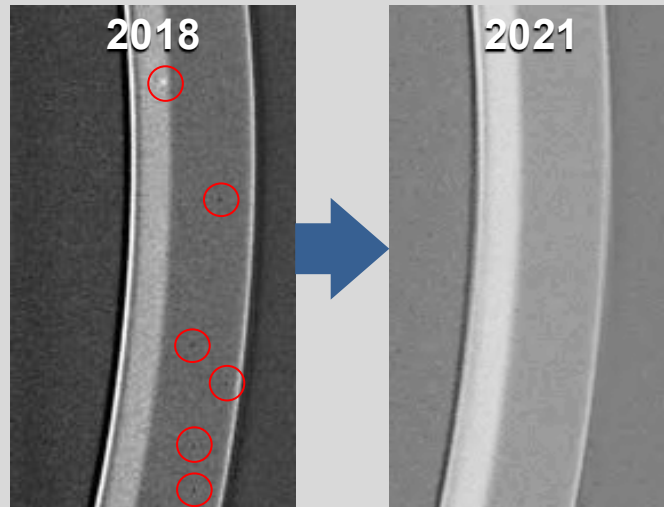
Capsule with DT Layer @ 19 K



Ignition could not have been achieved without developing better targets and improving our ability to characterize them

Target improvements have focused on reducing material and engineering defects

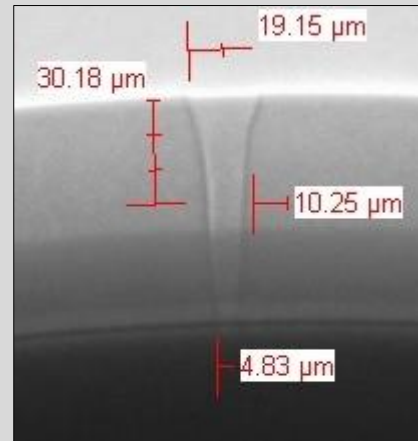
Capsule Quality



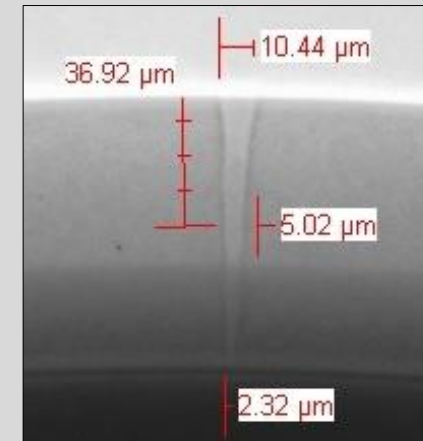
We have reduced pits and voids by two orders of magnitude

Fill-Tube Hole Diameter

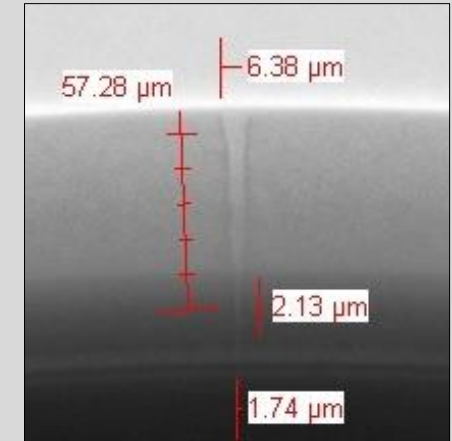
10 μm Fill-Tube



5 μm Fill-Tube



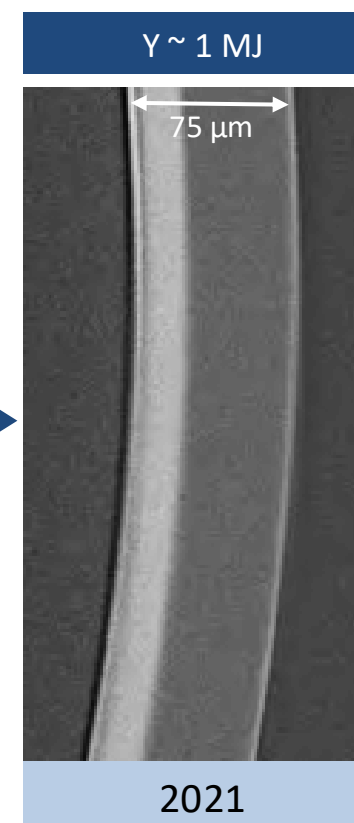
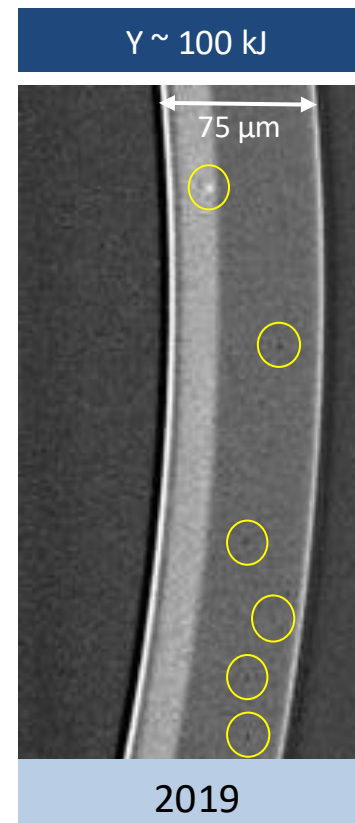
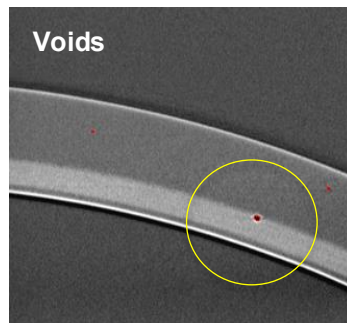
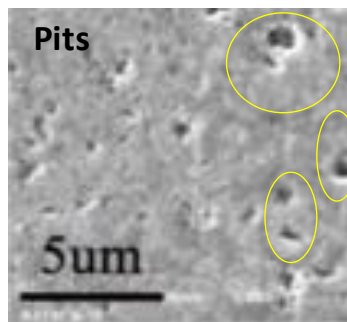
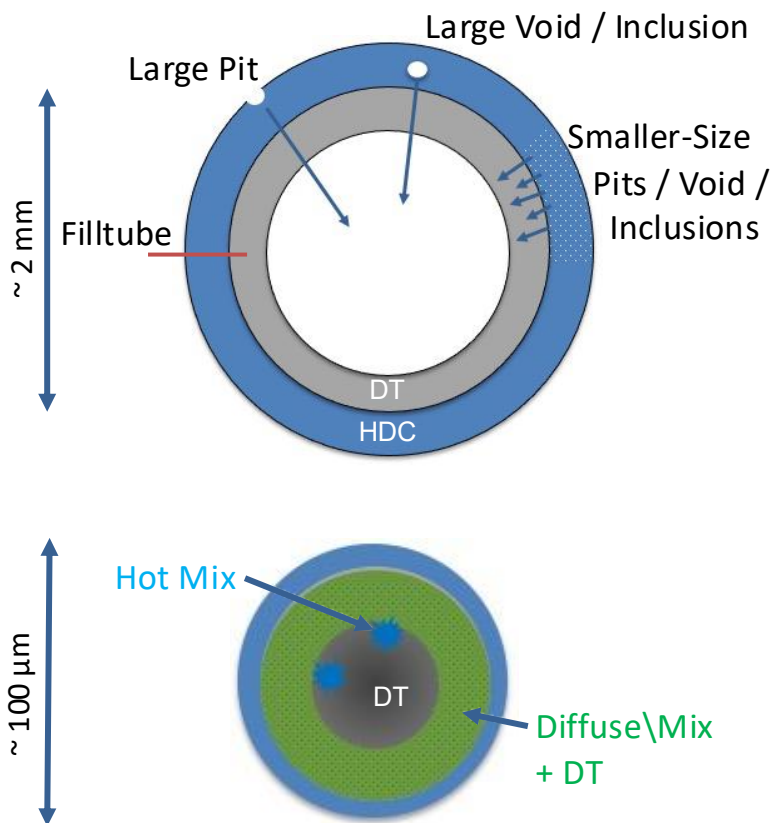
2 μm Fill-Tube



10x reduction in the surface area perturbation

The advances in both target quality and our ability to characterize them have been pivotal in achieving our current implosion performance

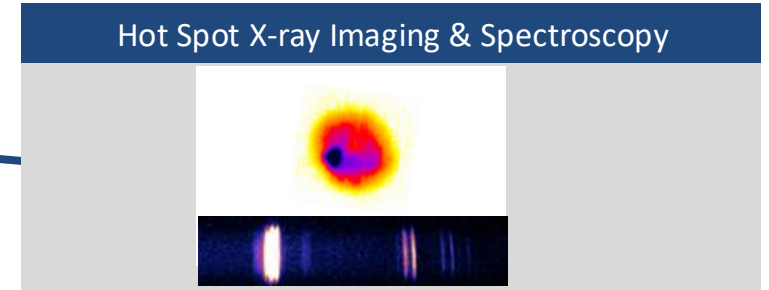
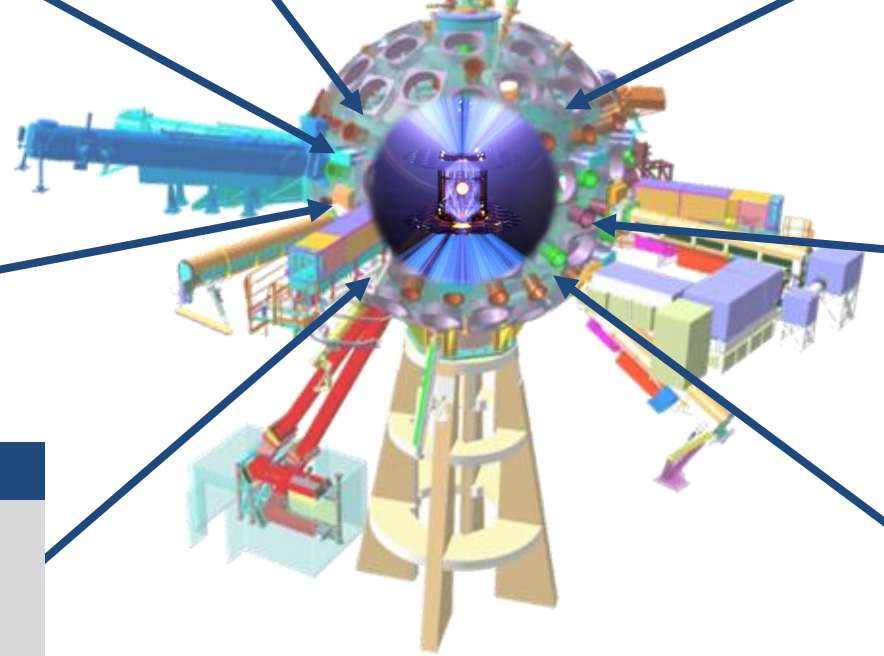
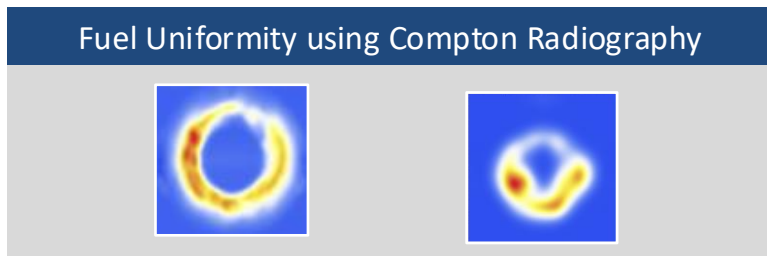
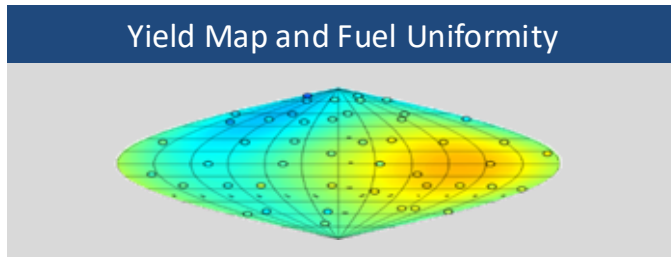
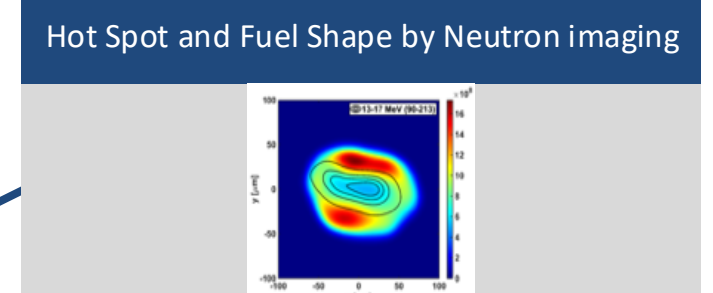
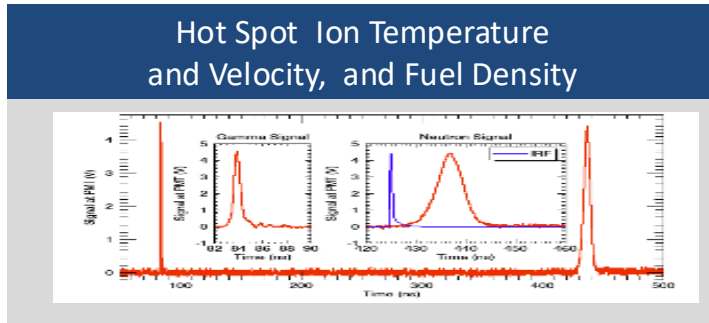
Microscopic capsule imperfections amplified by hydrodynamics instabilities are the dominant degradation mechanism



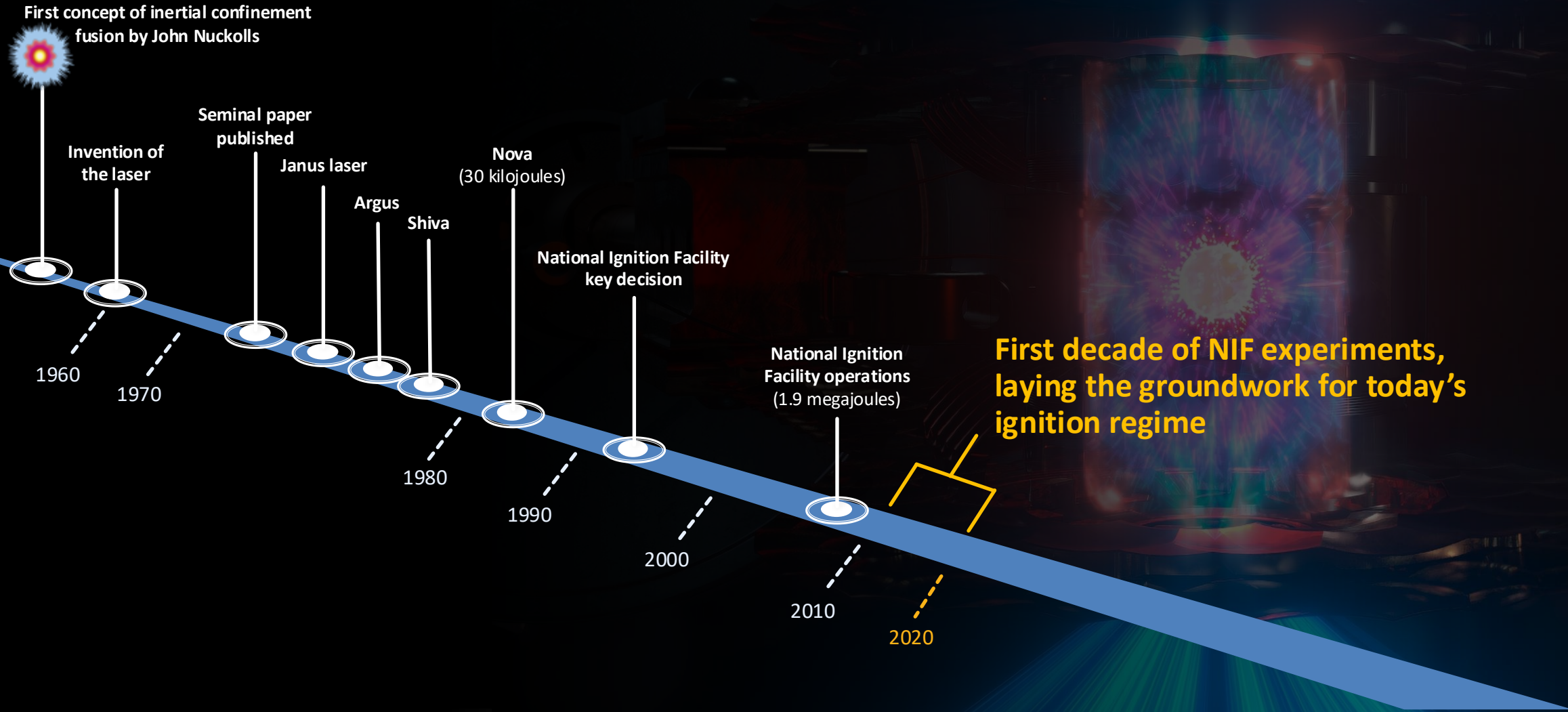
(images:)

This motivated capsule design changes to use the new 2.05MJ laser capability to drive heavier, more stable capsules

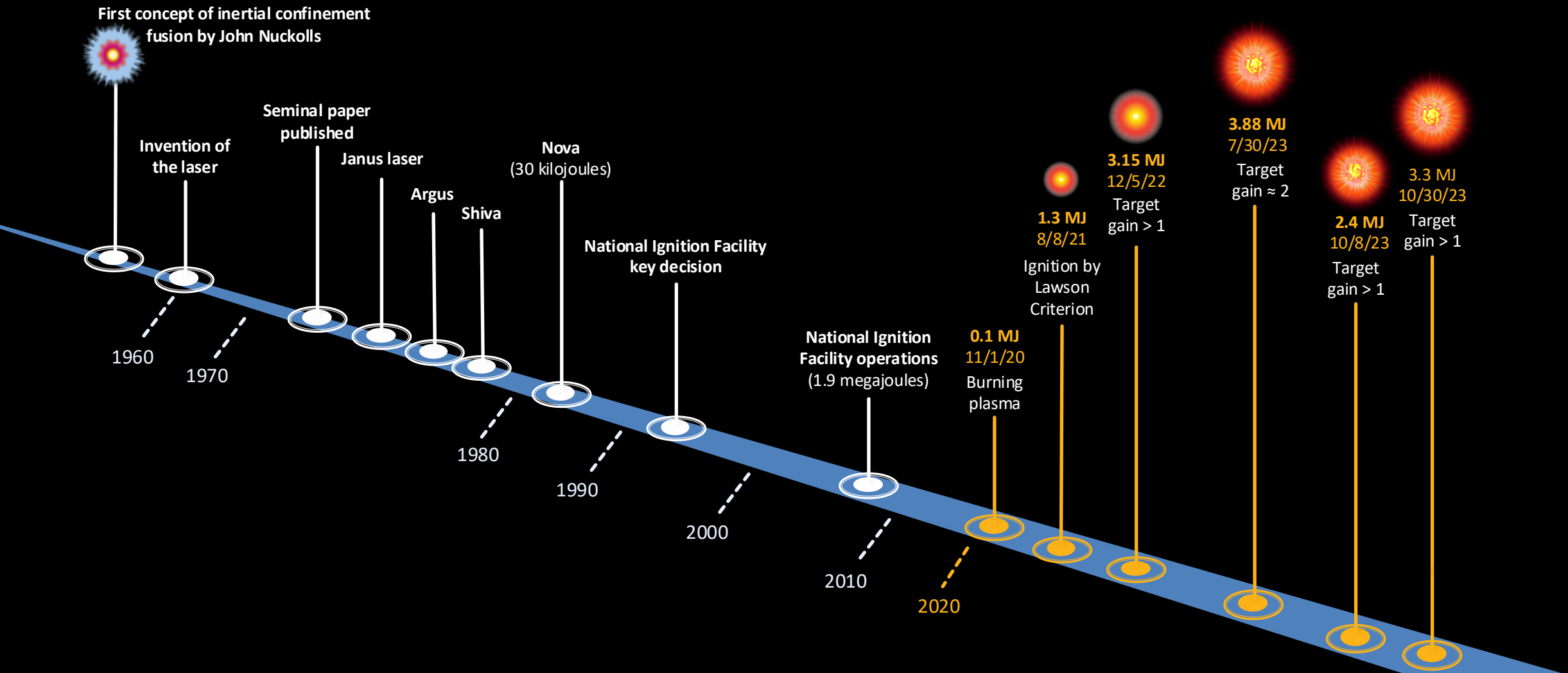
A unique set of best-in-class diagnostics is applied to each experiment, improving our understanding of the implosions



Ignition is the result of six decades of passion, hard work, and learning



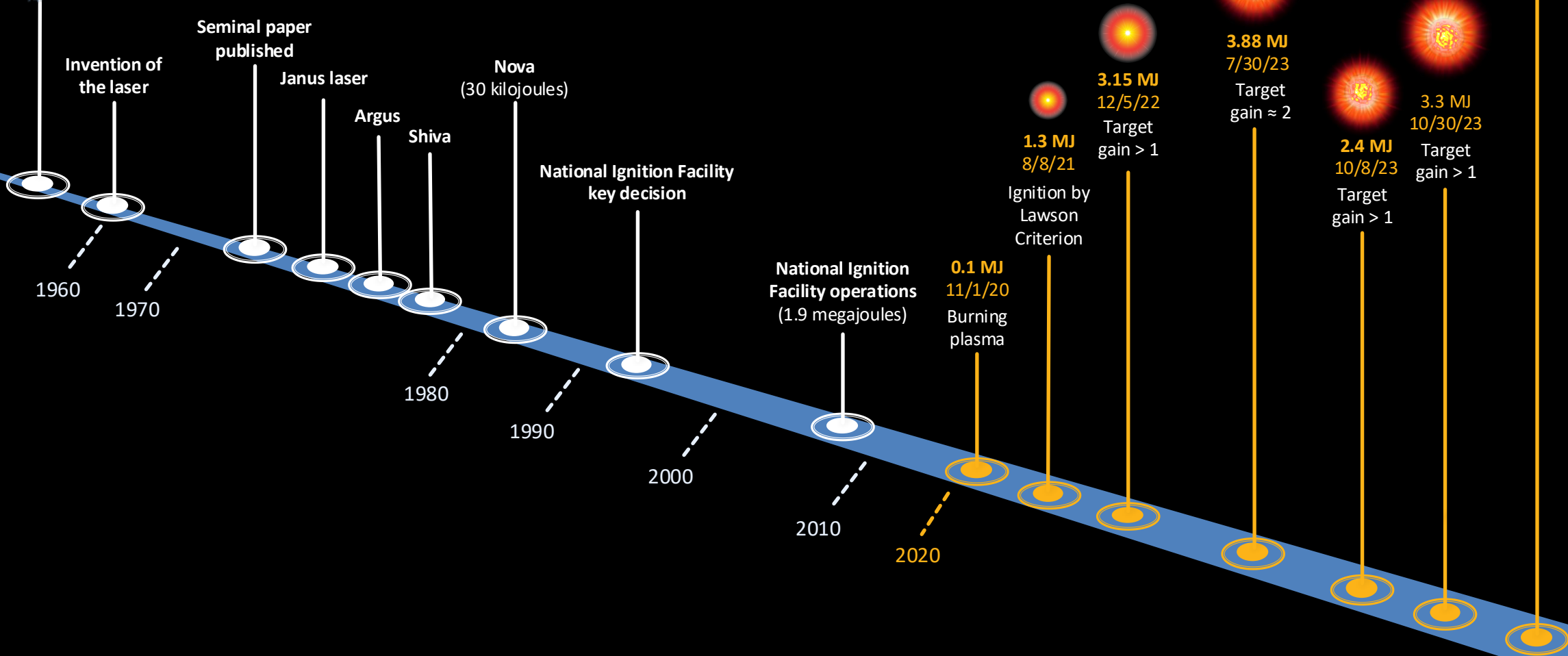
Three repeats achieved in the first year of ignition



Three repeats achieved in the first year of ignition

...and gain > 2 in February 2024

First concept of inertial confinement fusion by John Nuckolls



After this seminar, we hope to answer...

What is fusion energy and inertial confinement fusion ?

What are the major types of inertial confinement fusion schemes ?

What is the status of ICF experiments at the NIF?

What are the pathways to inertial fusion energy (IFE) ?

Ignition provides fresh impetus and the scientific foundation for Inertial Fusion Energy (IFE)



Fusion energy may be the ultimate clean and limitless energy source



Desirable features for future energy sources

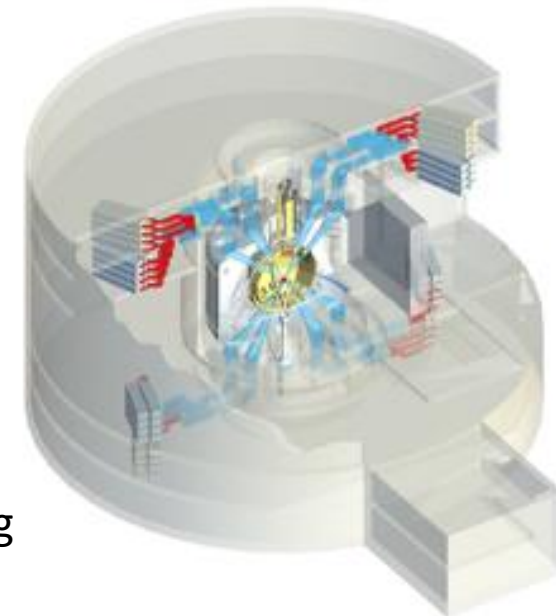
- Carbon-free
- Abundant and geographically diverse fuel
- Environmentally sustainable
- Passively safe
- Ability to meet baseload, while “load following” to meet variable demand
- Can be generated near population centers
- Flexible energy products (electricity, process heat, H₂ and biofuels, H₂O production)
- Energy security, sovereignty, and diversification



Fusion has the potential to meet all of these!

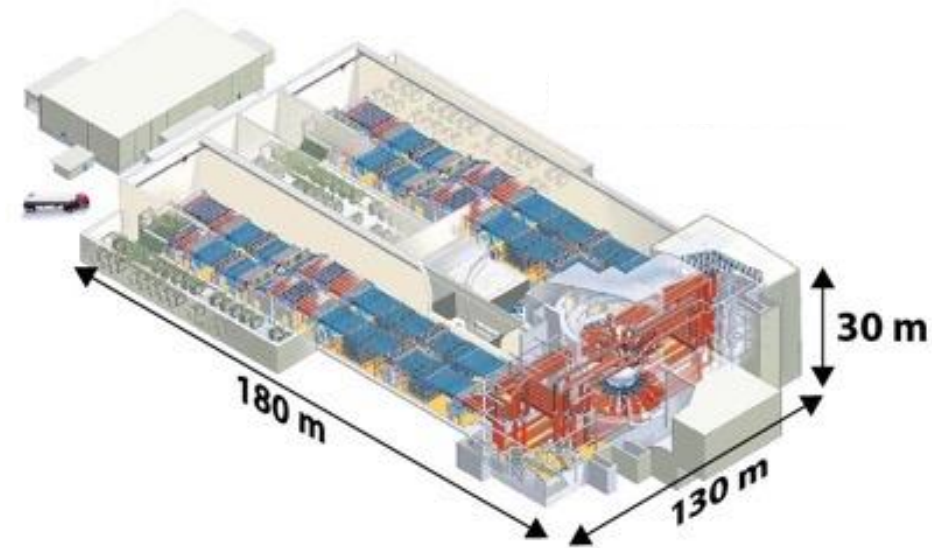
Advantages of fusion energy:

- Inherently safe
- Baseload and load following
- Carbon free
- Near-unlimited, domestic fuel source
- No long-lived nuclear waste

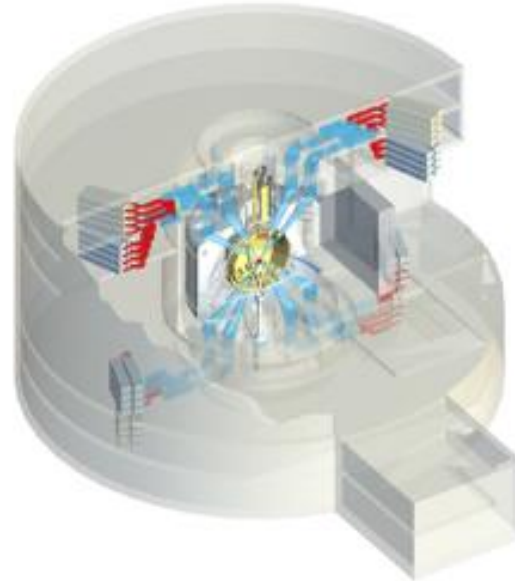


NIF is a scientific exploration facility and demonstrated laboratory ignition is possible. An IFE power plant would be very different.

NIF: Single Shot



IFE plant: >10 Hz



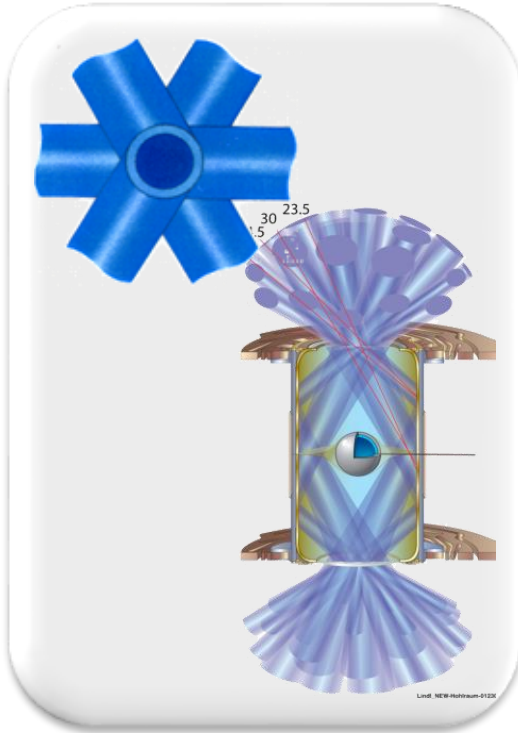
An electricity-producing IFE power plant would require:

- A more robust, high-margin ignition scheme
- A high-efficiency, high rep-rate driver
- High rep-rate target injection and tracking
- Energy conversion system
- Robust first walls and blankets for wall protection
- Tritium processing and recovery
- Remote maintenance systems
- Viable economics

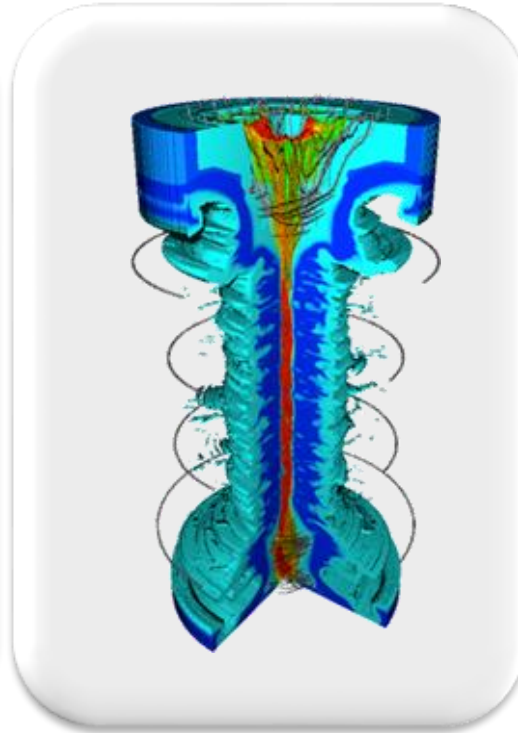
NIF provides a unique opportunity to experiment at “fusion scale” now, but there are yet many outstanding technical questions that must be solved to make IFE a reality

There are several ICF target concepts that could be explored in an IFE program

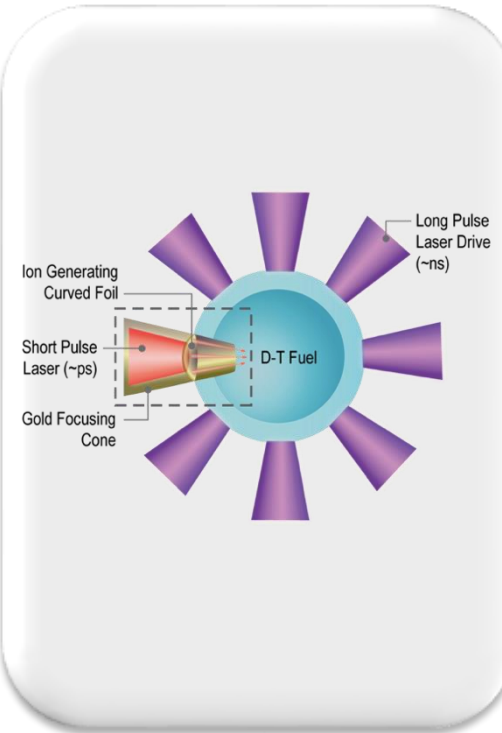
Direct Drive or Indirect Drive ICF



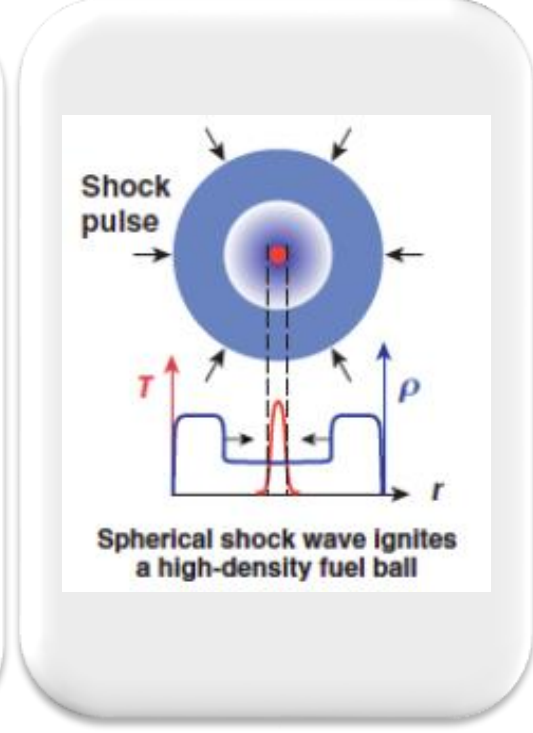
Magnetic Direct Drive



Fast Ignition

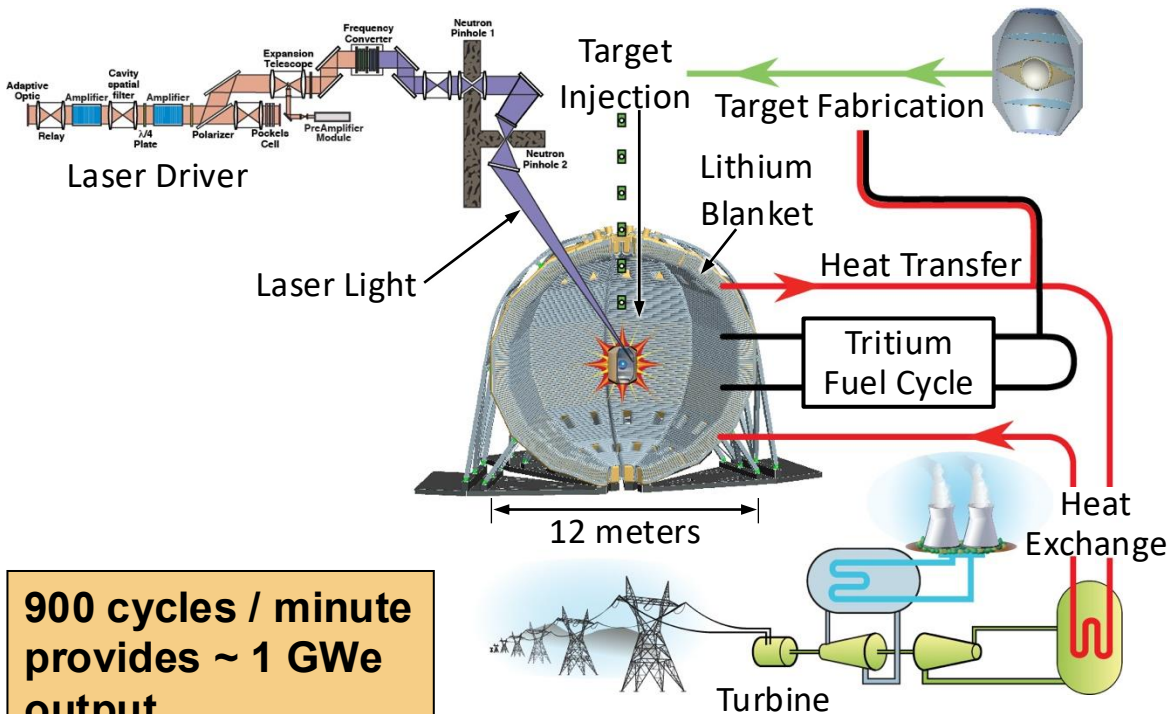


Shock Ignition



...and many more including heavy ion fusion, dense plasma focus, projectile concepts etc.

Ignition provides fresh impetus and the scientific foundation for inertial fusion energy



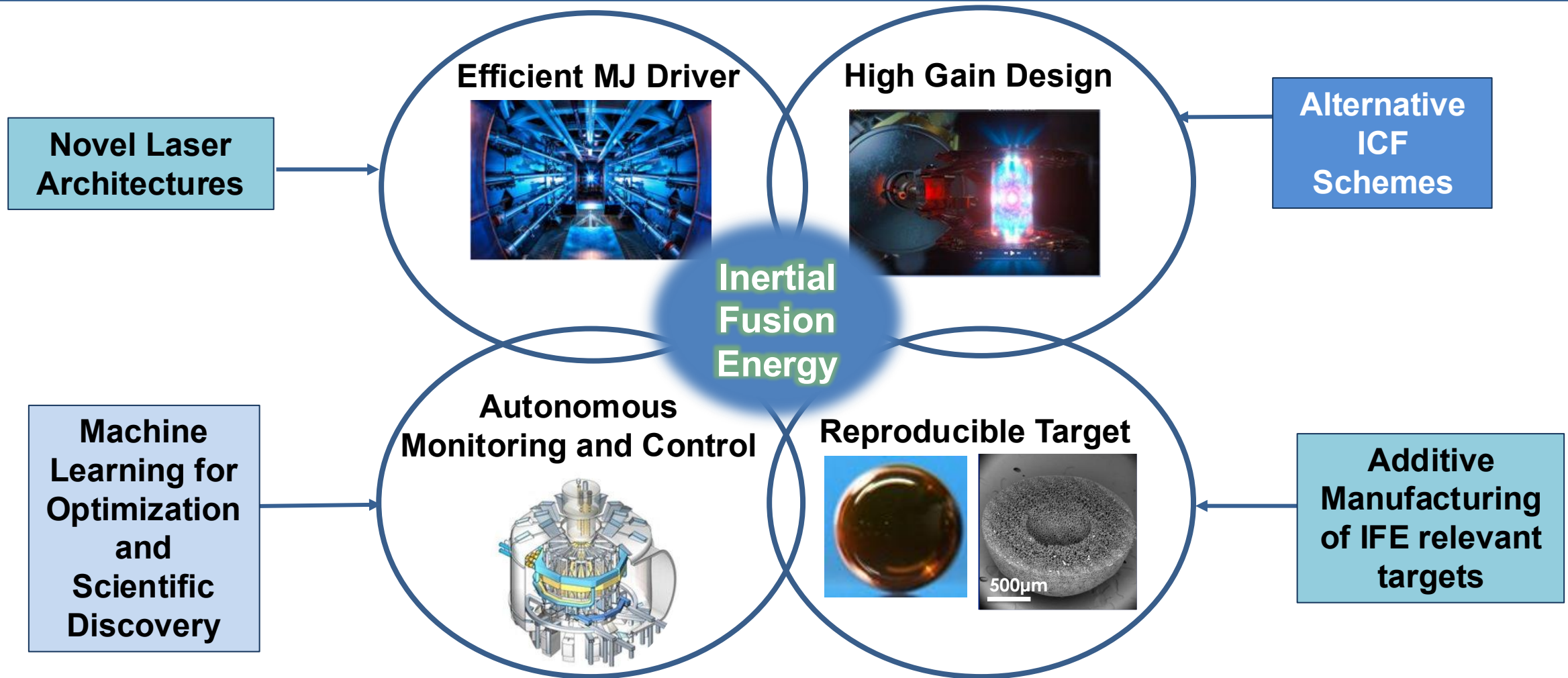
900 cycles / minute provides ~ 1 GWe output

- ### The Challenges are Many...
- Ignition and then high gain
 - High efficiency, high rep-rate laser
 - Target production and cost
 - Lifetime of the fusion chamber and optics
 - Safety and licensing
 - Plant operations



- ### ...But the Benefits Outweigh the Challenges
- Separation between driver and fusion source
 - Attractive economic development path (spin-out technologies)
 - Energy security

The roadmap to inertial fusion energy requires focused studies in areas ranging from laser science to additive manufacturing



The roadmap to inertial fusion energy requires large teams to continue this interdisciplinary work

- Inertial Fusion Energy is a game-changing technology
- The time is now!
 - Ignition has been demonstrated on NIF!
 - Unprecedented fusion energy momentum in the public and private spheres
- IFE is a multi-decadal endeavor, and will require innovation to enable economical energy source

Fusion energy is a multi-decade effort and we need help solving problems

- Inertial Fusion Energy – Postdoctoral Researcher
- Postdoctoral Fellowships – Lawrence & High Energy Density Science (HEDS) Center Fellowship
- HED Physics - Postdoctoral Experimental Physicists
- Design Physics Division Postdoctoral Researcher
- Laser Postdoctoral Researcher, APT
- Machine Learning Postdoctoral Research Staff
- www.llnl.gov/join-our-team/careers/postdocs
- www.llnl.gov/join-our-team/careers/students

With ignition, we can accelerate progress toward the long-sought dream of fusion energy!

careers@lnl.gov

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