Inertial Fusion Energy

2024 PPPL Introductory Course on Plasma Physics

Dr. Raspberry Simpson

On behalf of the global team making ignition possible

June 14, 2024

LLNL-PRES-860619

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

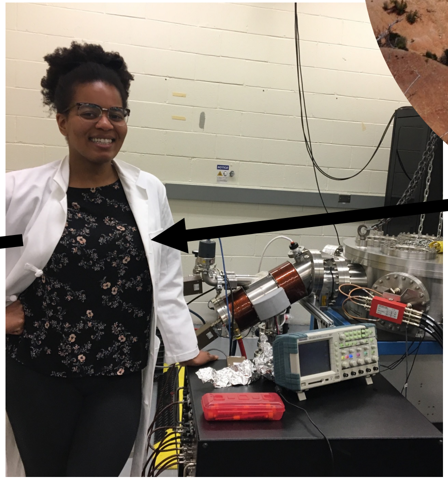
Lawrence Livermore National Laboratory

About me ☺

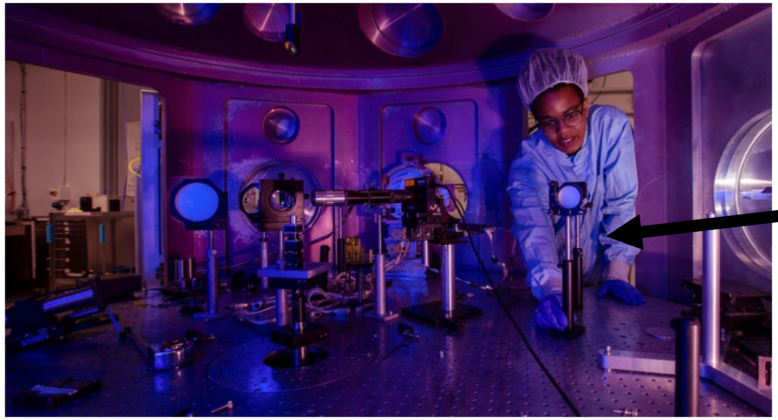
B.Sc. Physics @ Columbia

A.A. Physics

Took 2 years off of school



PhD Nuclear Engineering @ MIT



Post Doc @ Lawrence Livermore National Laboratory

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/cm^3
- 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

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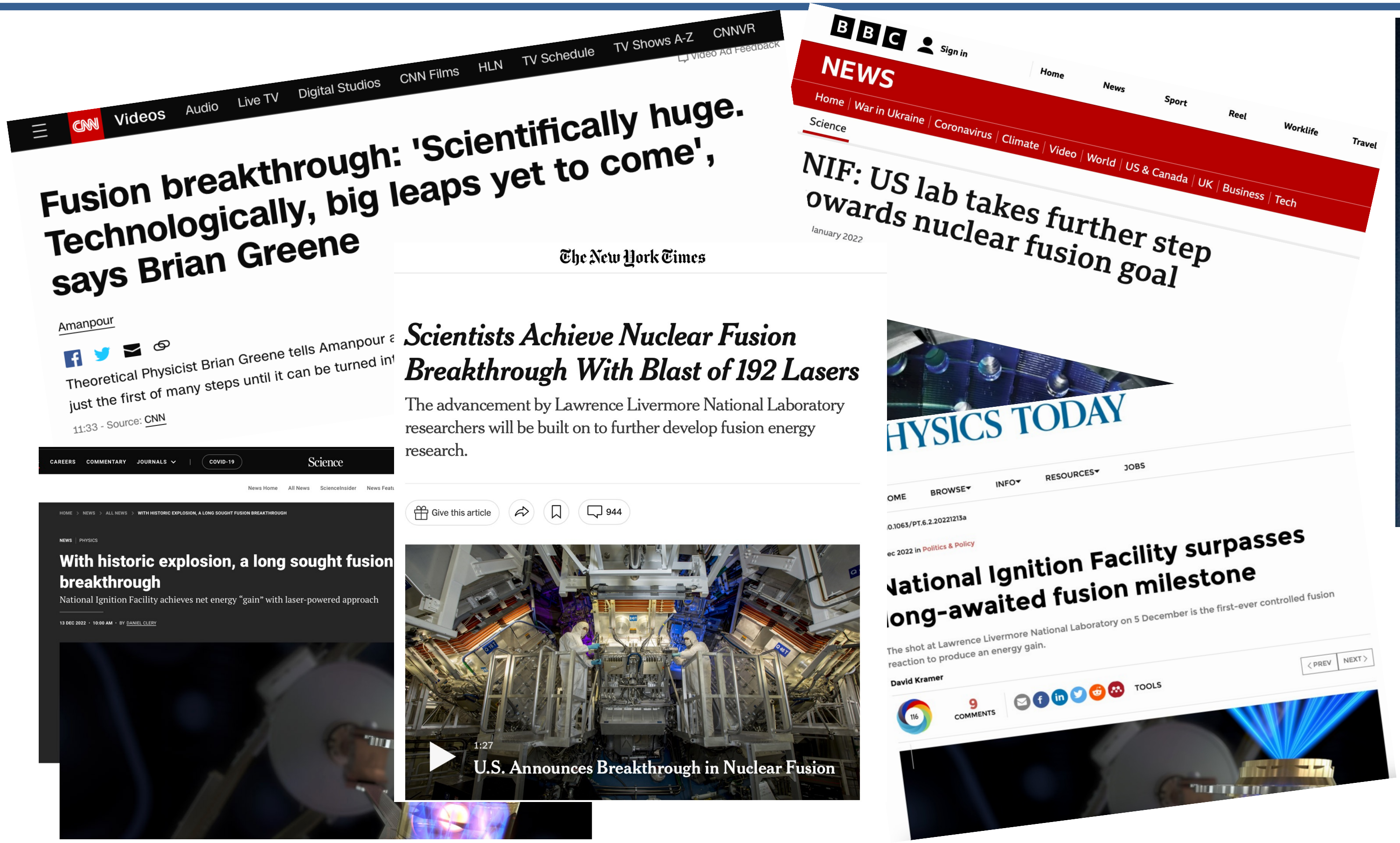

Left to Right:
LLNL Director, Kim Budil,
NNSA Administrator, Jill Hruby
U.S. Secretary, Jennifer Granholm

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

cea

Los Alamos NATIONAL LABORATORY

AWE

Diamond Materials Advanced Diamond Technologies

UR LLE

PPPL

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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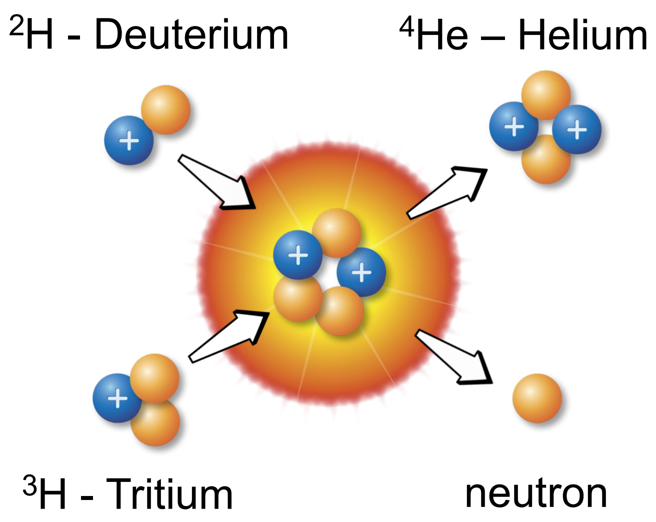
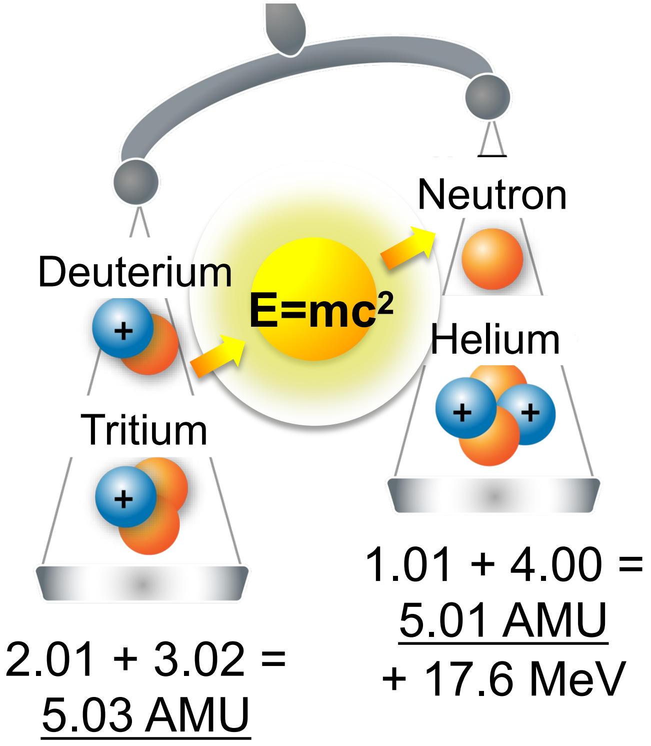
Lawrence Livermore National Laboratory

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



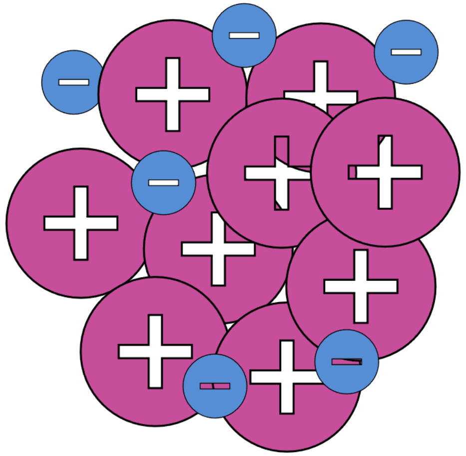


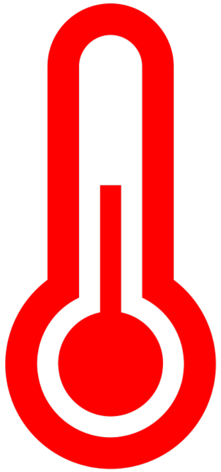
$$D + T \rightarrow \alpha(3.5\mathrm{MeV}) + n(14.1\mathrm{MeV})$$

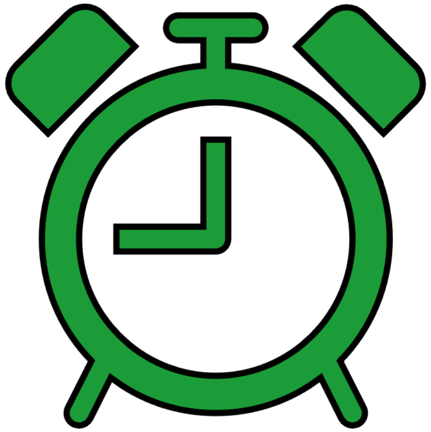
$$Q_{fusion} = 3.3 \times 10^{11}\ \mathrm{J/g}$$

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

Density (n) | **Temperature (T)** | **Time (τ)**



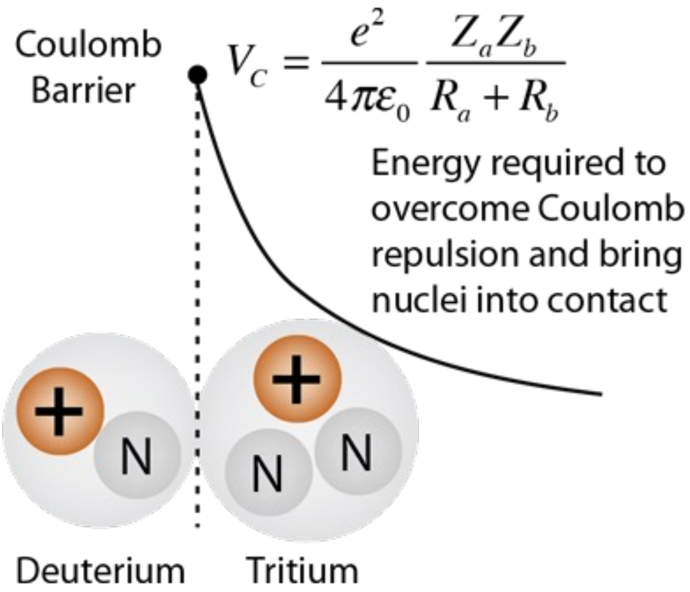




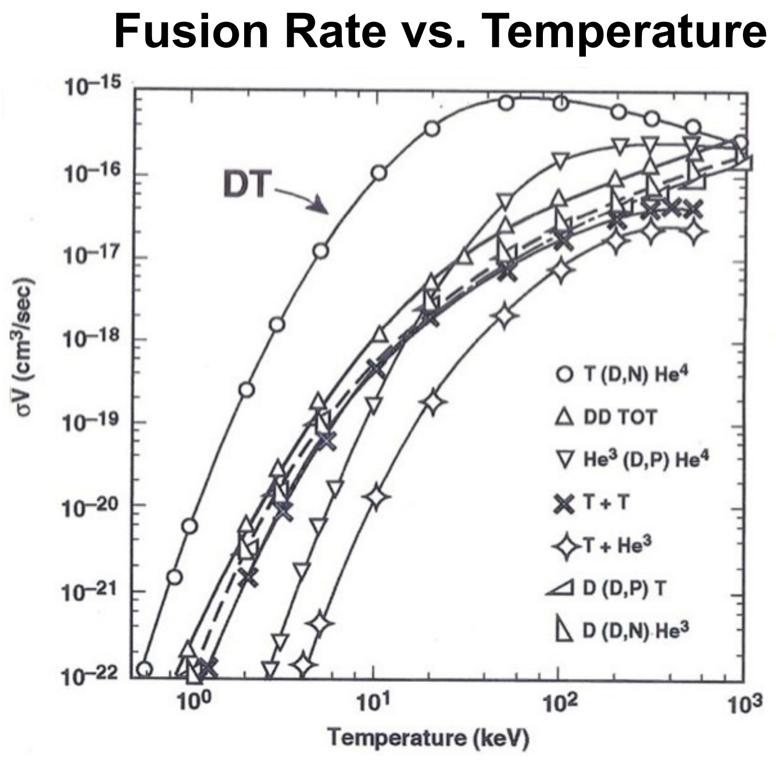
Fusion Triple Product

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

The Coulomb barrier makes high temperatures necessary for DT thermonuclear fusion



Hyperphysics

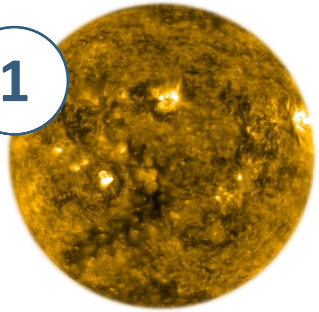
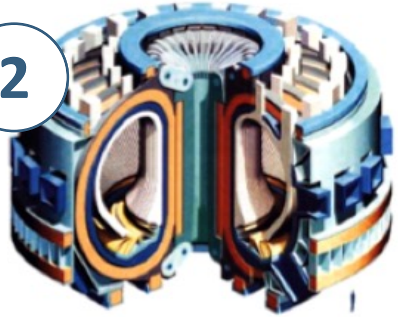
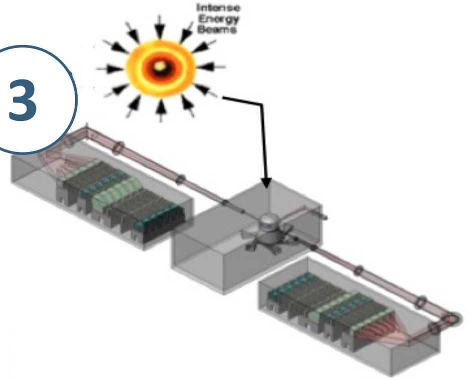


Atzeni and Meyer-Ter-Vehn
The Physics of Inertial Fusion

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

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

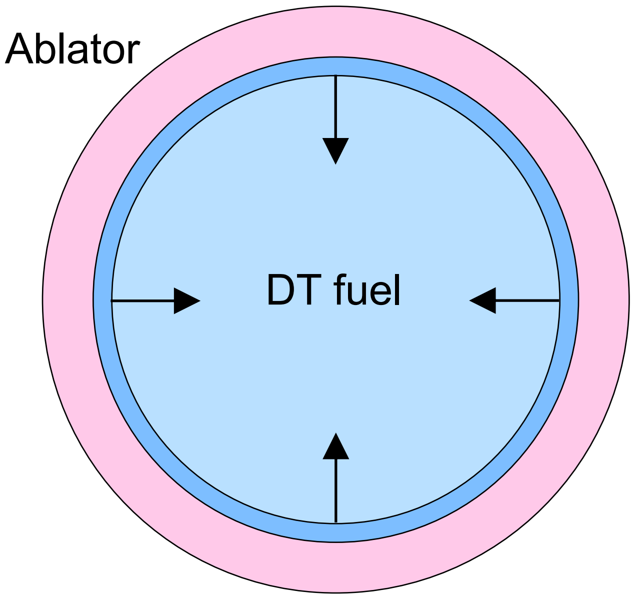
There are at least three ways to achieve nuclear fusion

	Gravitational Confinement	Magnetic Confinement	Inertial Confinement
	1	2	3
			
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

<u>Fusion Triple Product</u>

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

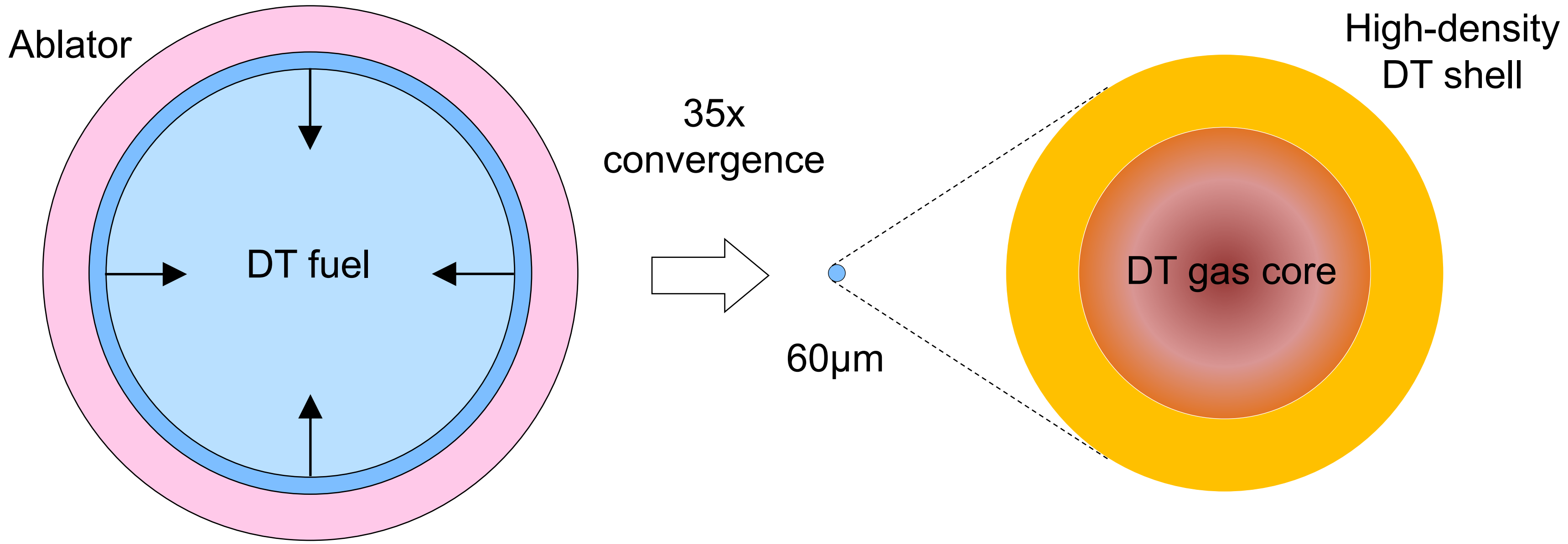
Inertial Confinement Fusion (ICF) relies on the inertia of the target itself to provide confinement



R ~ 1000 µm
ρ_{DT} = 0.25 g/cm^3

ρR_{DT} ~ 0.03 g/cm^2

The idea of ICF is to compress fuel to thermonuclear conditions



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

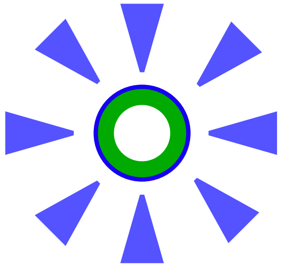
$\rho R_{DT} \sim 0.03\ g/cm^2$

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

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

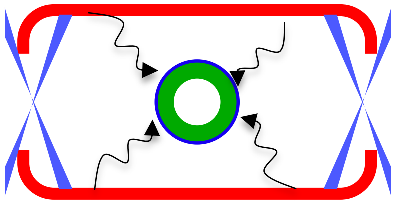
There are two different laser-drive schemes and the aim of both is to drive a spherical implosion

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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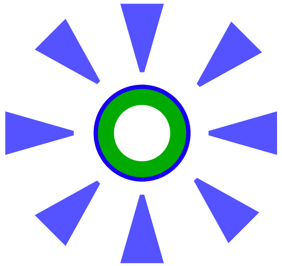
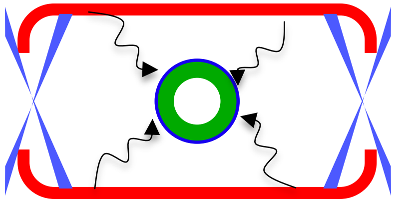
Direct Drive



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

Indirect Drive



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

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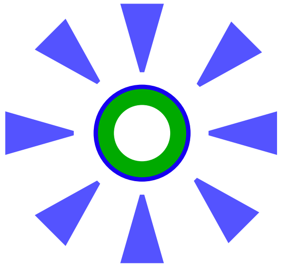
Direct Drive



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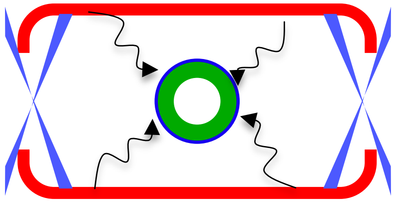
Indirect Drive



- ~4% efficiency
- Relaxed beam uniformity
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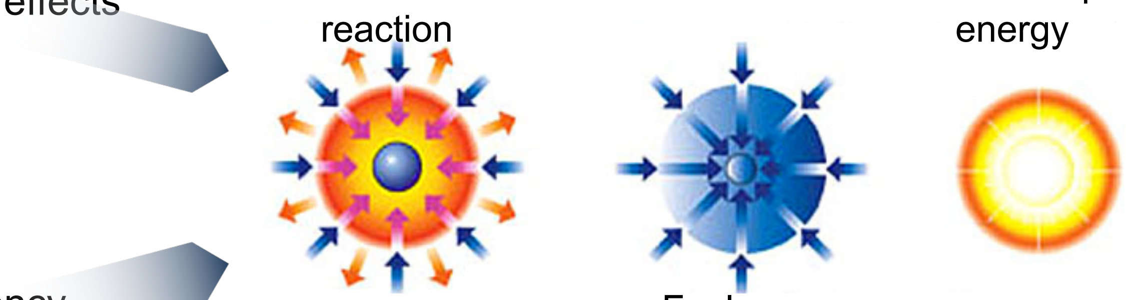
Fuel is compressed by blowoff in rocket-like reaction

Thermonuclear burn spreads, yielding many times the input energy



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

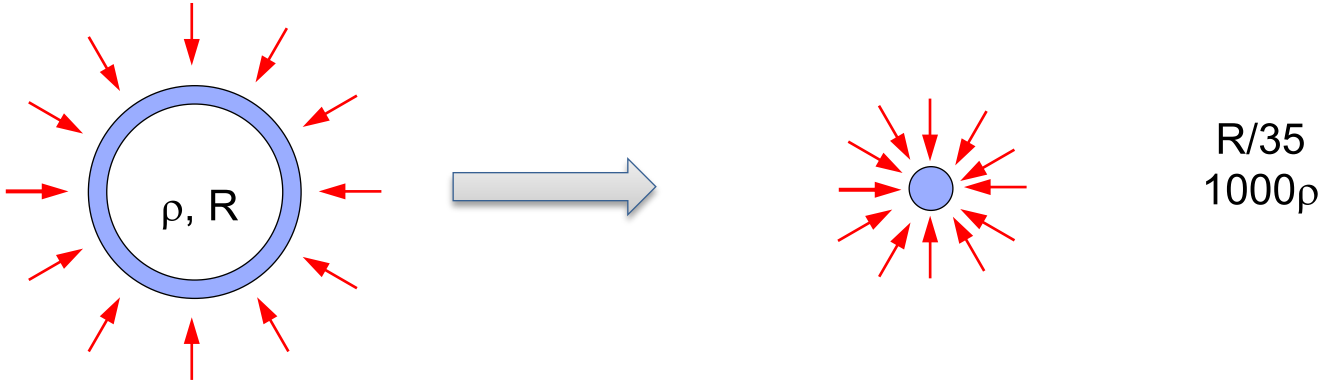
Image taken from "Matter at High-Energy Densities," Univ of Rochester, Laboratory for Laser Energetics

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

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

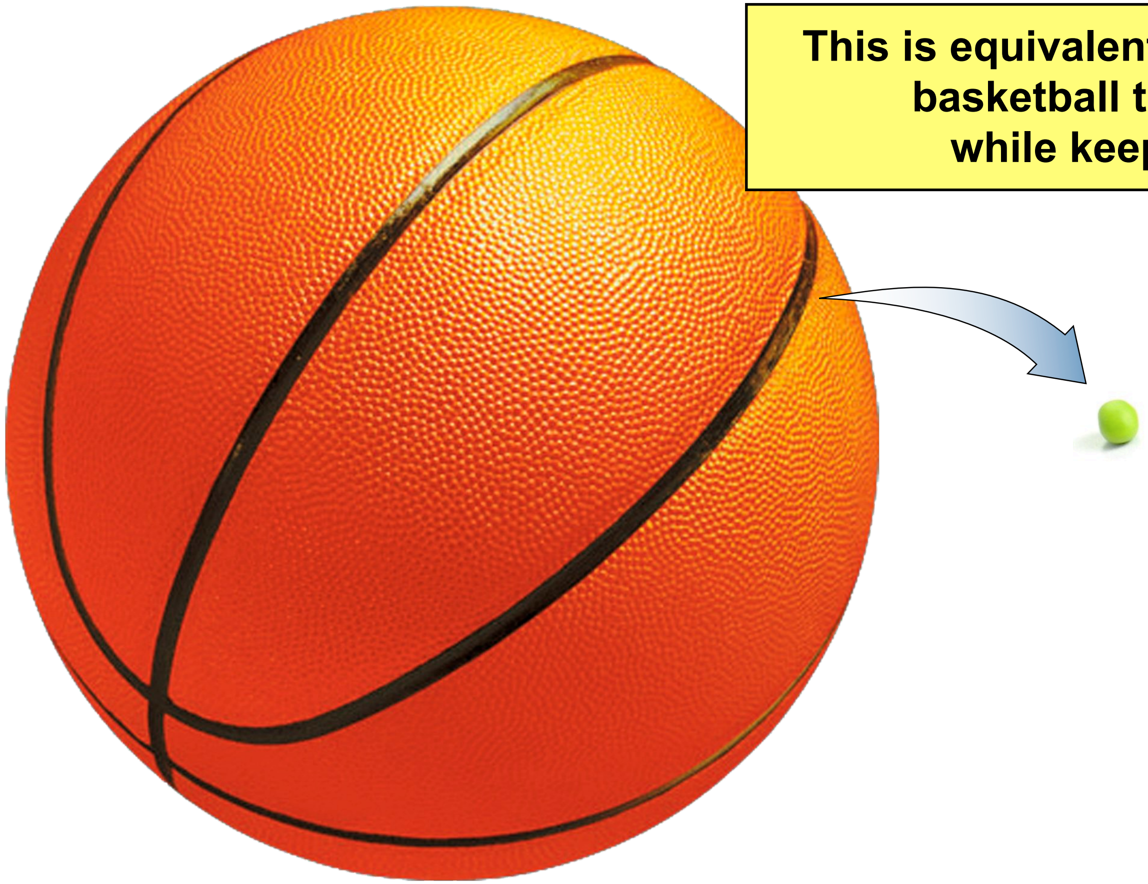
In practice, a hollow shell has more surface area and is easier to push with a given pressure than a solid sphere of the same mass



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

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

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 µs 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

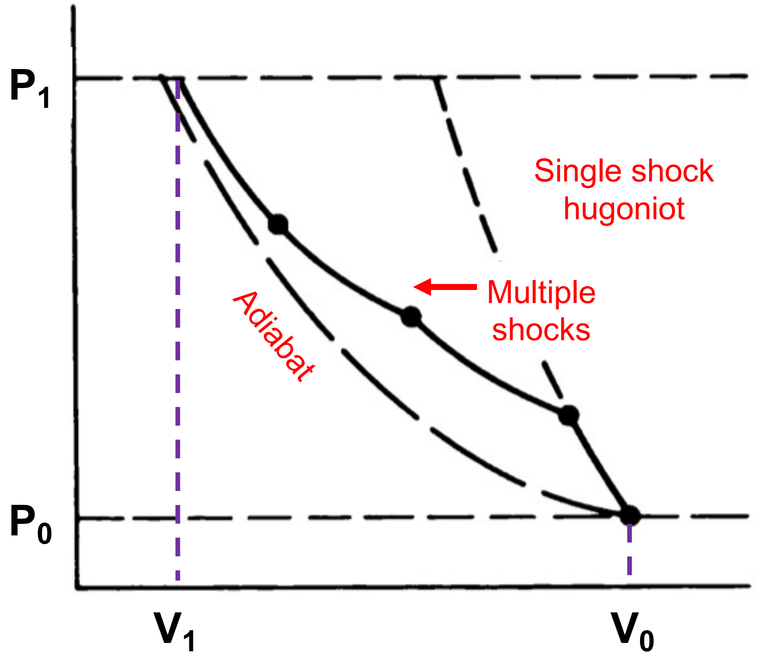
From thermodynamics:

$$dU = Tds - PdV$$

$$PdV = Tds - dU$$

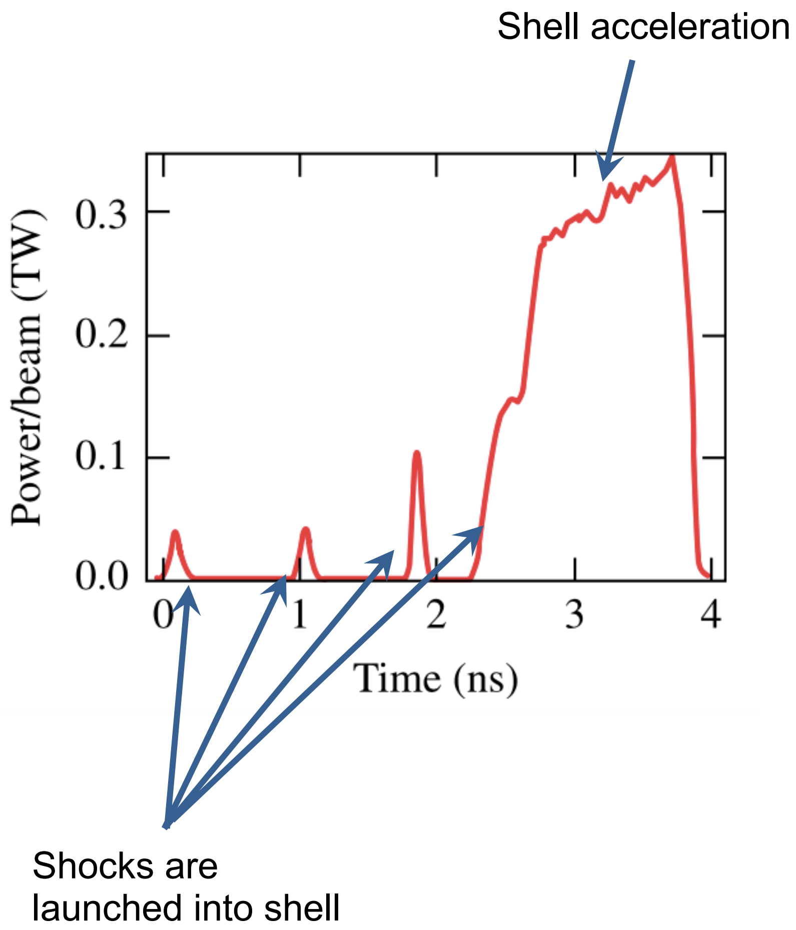
Minimize work needed to compress ⟺ Minimize entropy generation

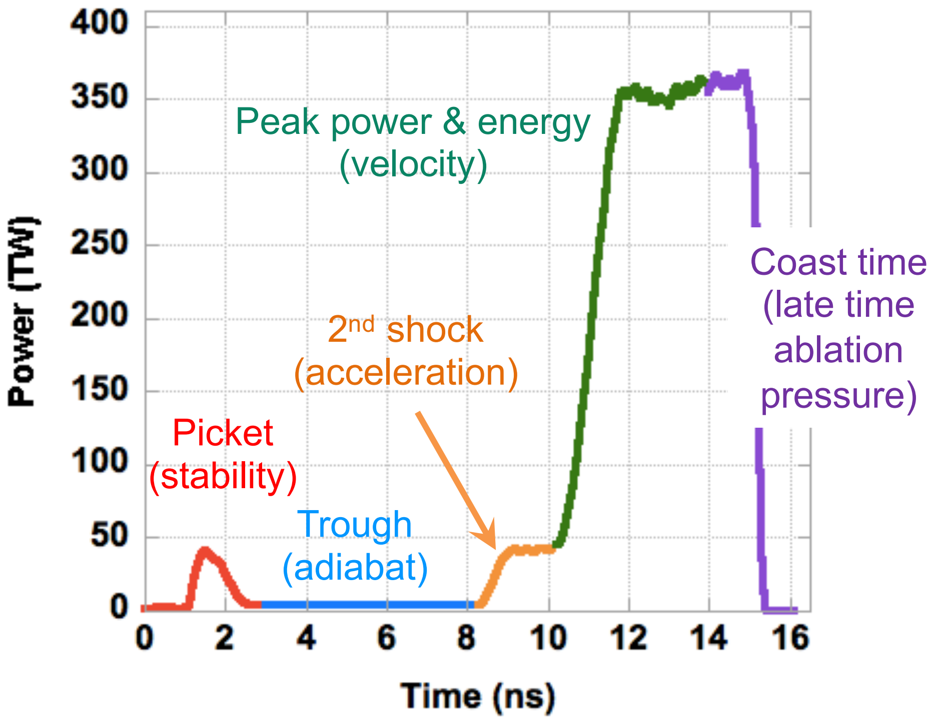
P-V Diagram



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

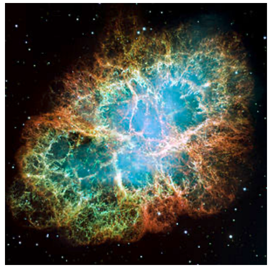




Mixing of the ablator into the hot dense fuel can cause a significant amount of energy loss, degrading performance

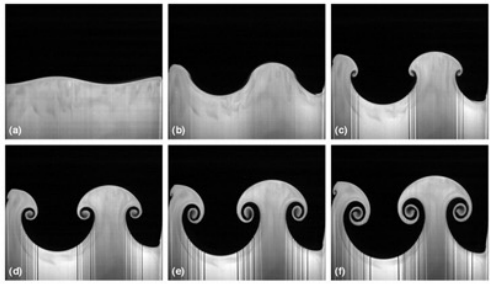
Rayleigh-Taylor
- **Low density attempts to push high density**

Evolution of RTI in two immiscible fluids



Rayleigh-Taylor "fingers" in Crab Nebula

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



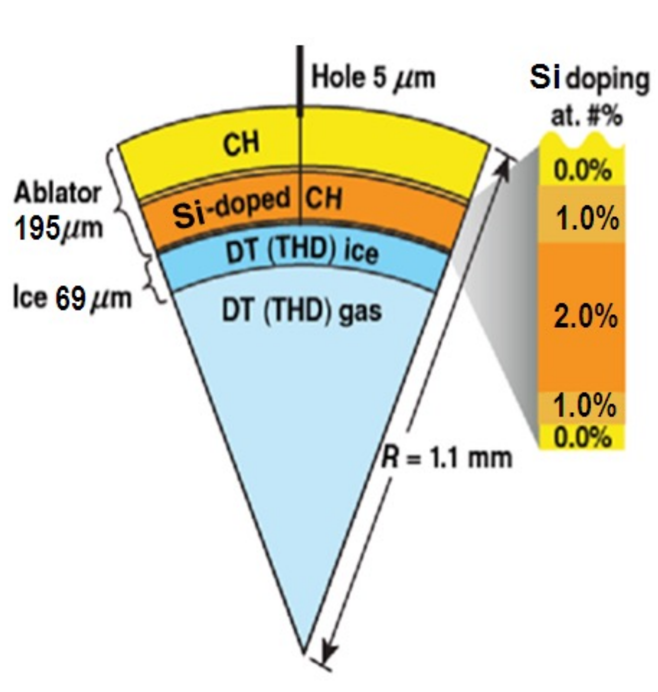
Evolution of Richtmyer-Meshkov at the interface of two fluids

Kelvin-Helmholtz
- **Shear**

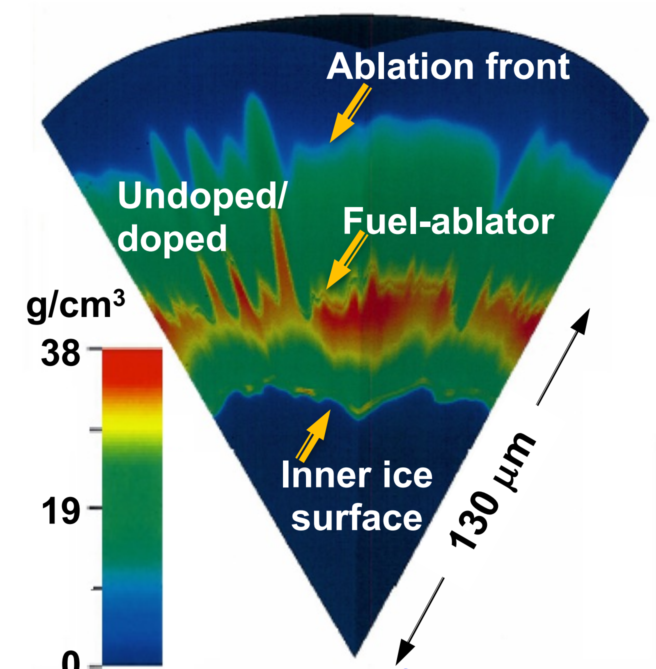
Kelvin-Helmholtz roll-up in clouds

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

Rev. 5 capsule design



3D simulation at peak velocity

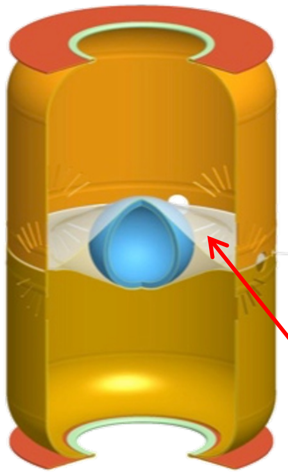


Clark et al., PoP 2011

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

Asymmetric
x-ray drive



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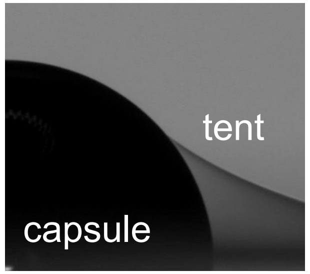
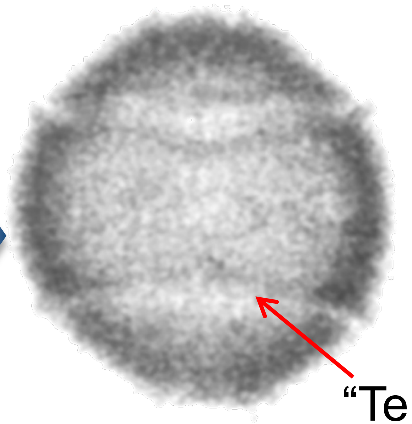


Engineering features such as capsule support "Tent"

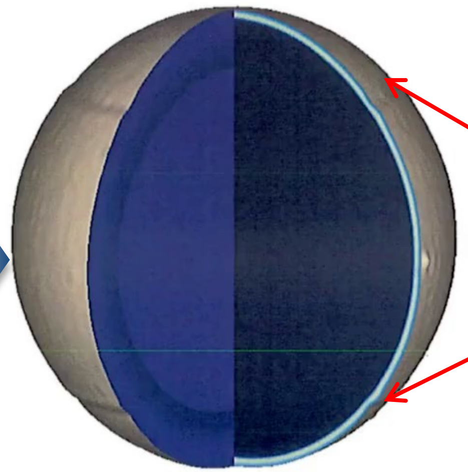
Distorted
implosion



"Tent"

Processed in-flight radiograph

Inefficient fuel assembly

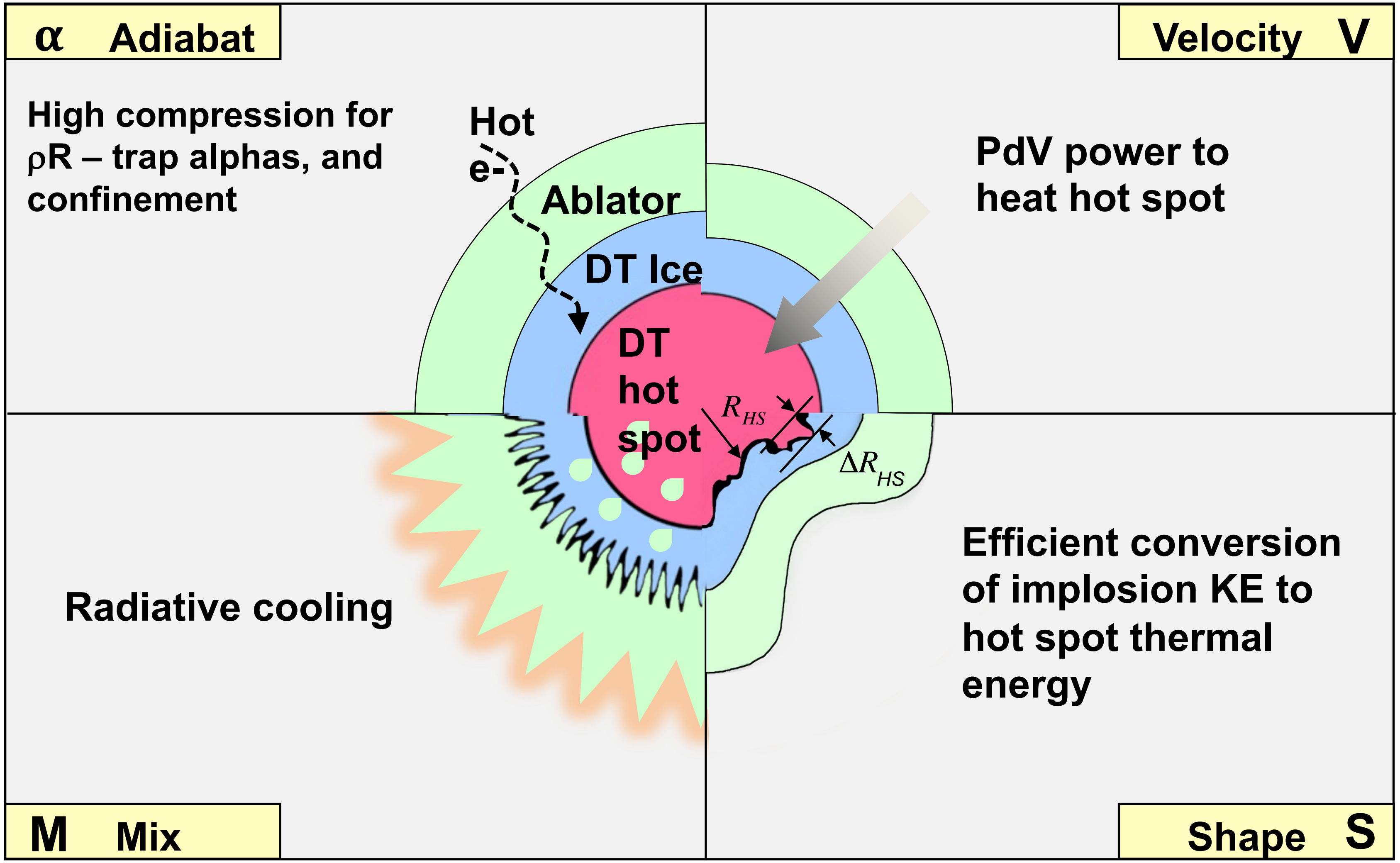


"Tent"

3D full-res.
400,000,000 zones
6144 CPUs
1 month runtime

Simulated DT fuel at stagnation

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



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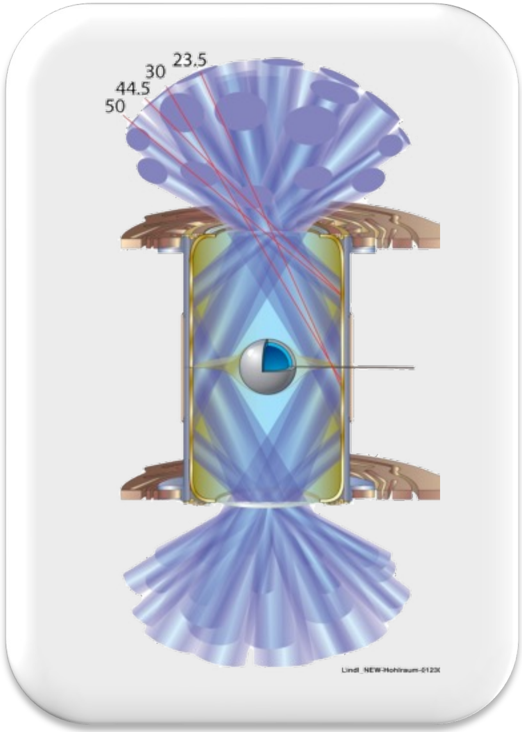
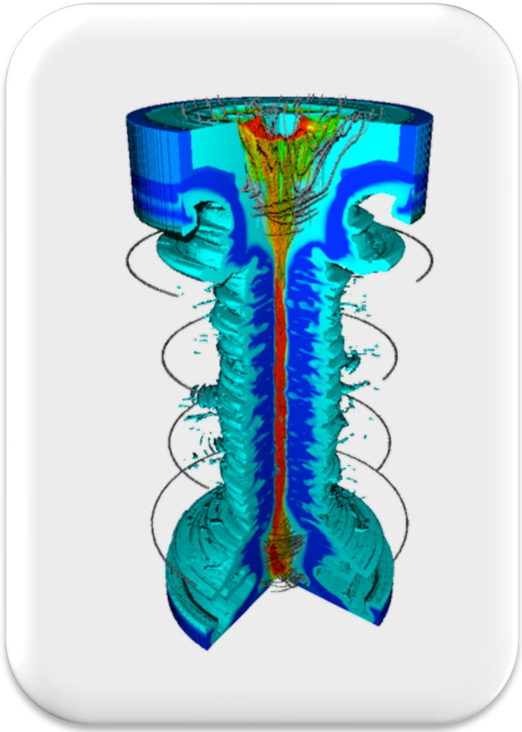
In addition to the two laser drives, there is a magnetic drive scheme, for a total of three primary approaches to ICF

Laser Direct Drive

Laser Indirect Drive

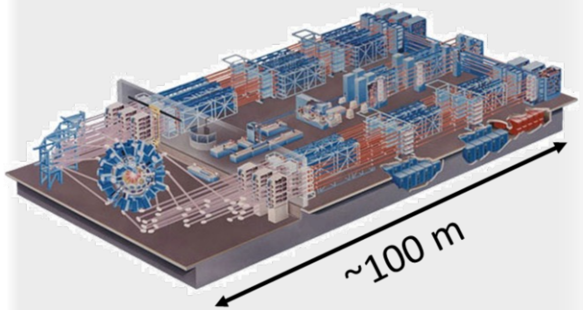


Magnetic Direct Drive

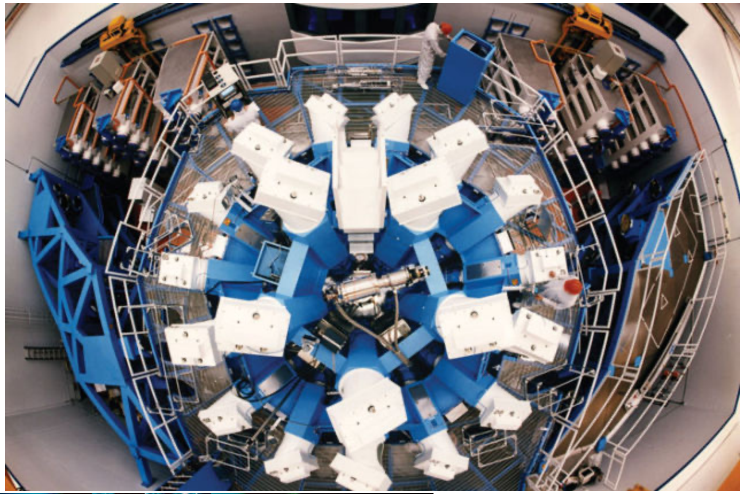


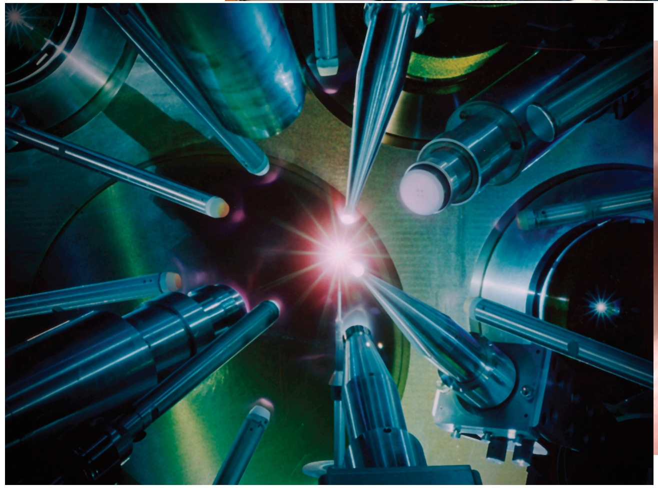
The OMEGA laser facility at the University of Rochester, NY, uses the direct-drive approach

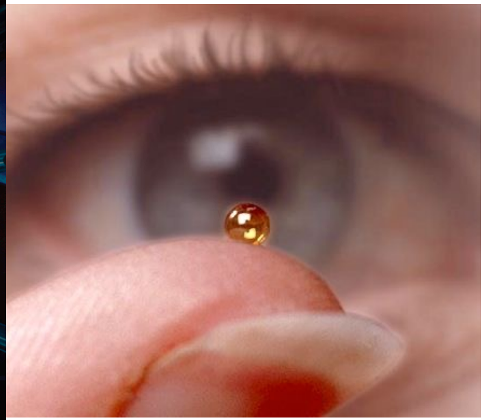
OMEGA Facility



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







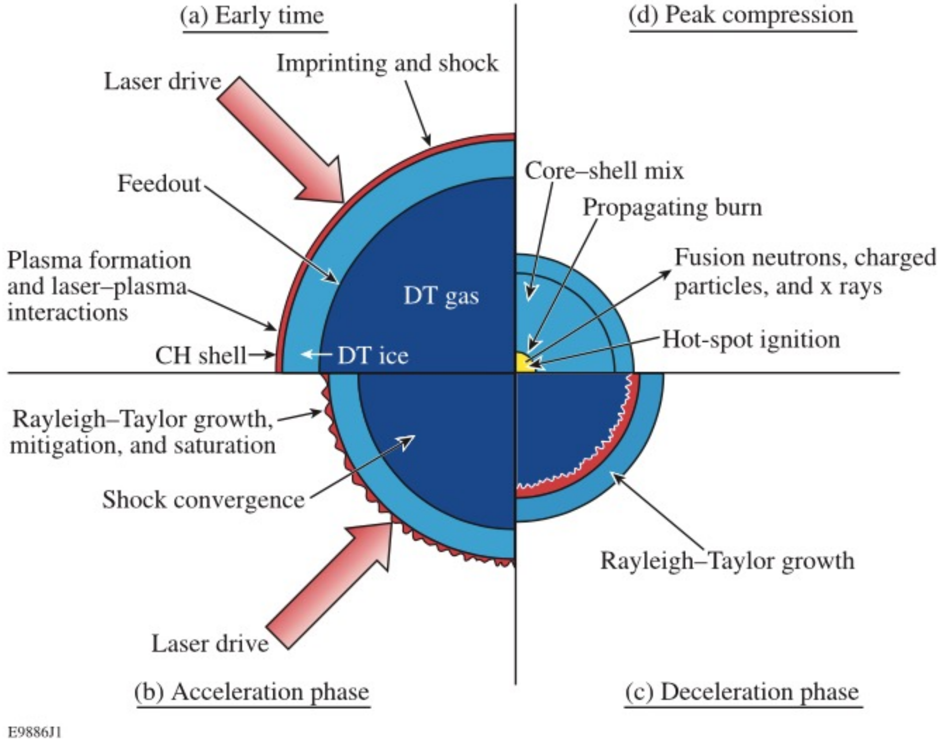
The goal of experiments at OMEGA is to demonstrate and understand the physics of laser direct drive

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.

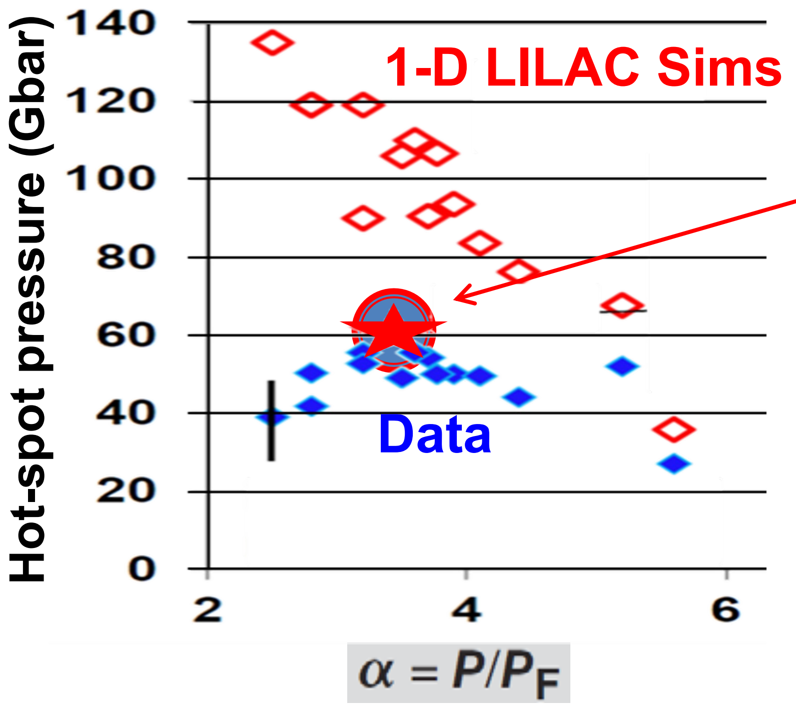
~80 Gbar demonstrated so far.



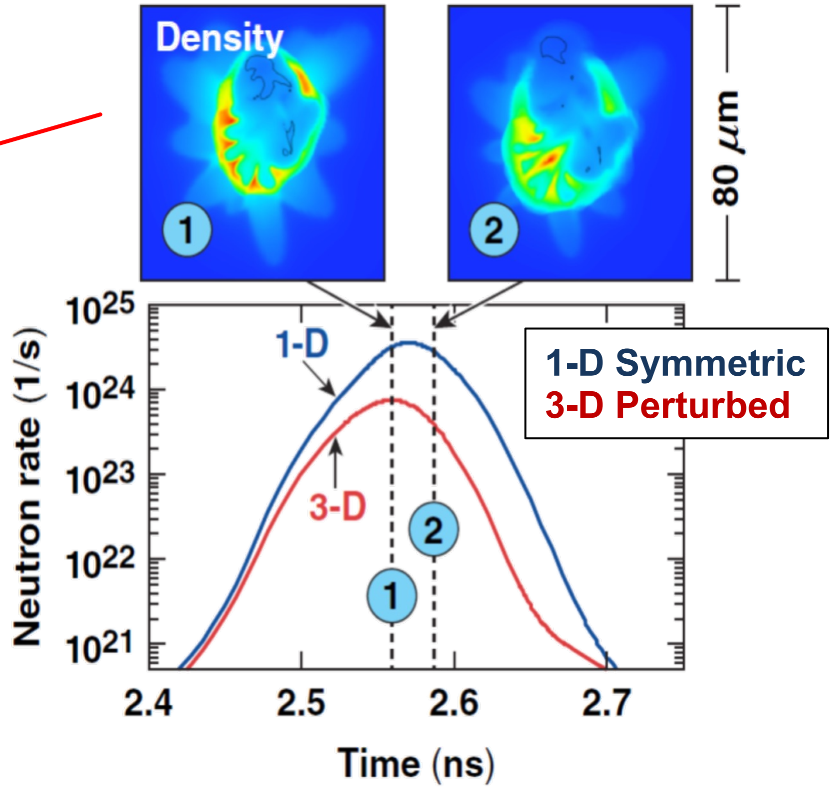
Craxton et al., PoP 2015

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

Stagnation Pressure vs. Fuel Adiabat

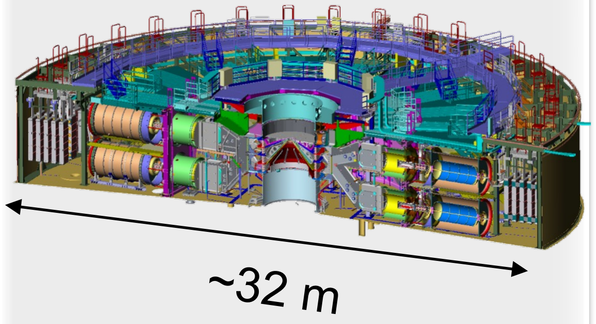


3-D ASTER simulations show effect of errors in beam pointing, power balance, and capsule placement

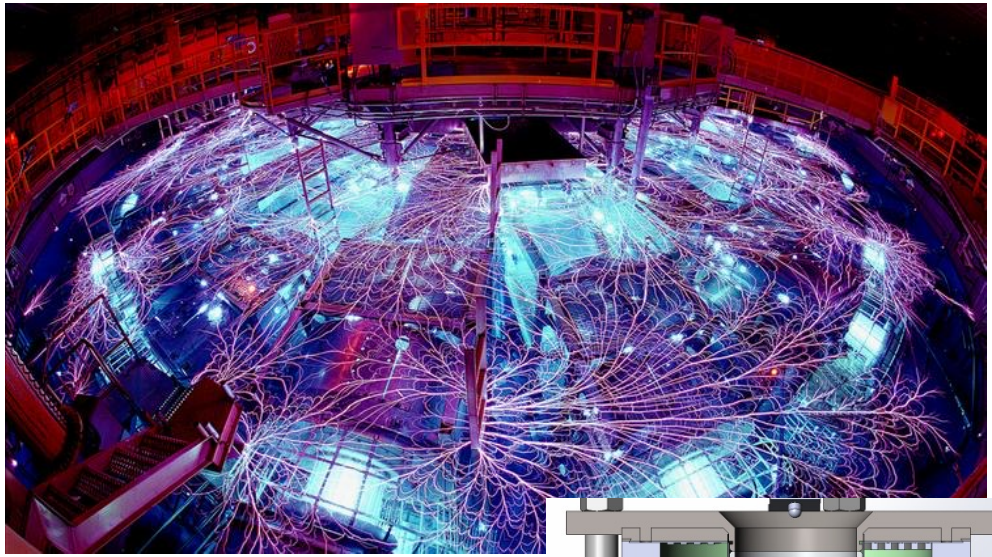


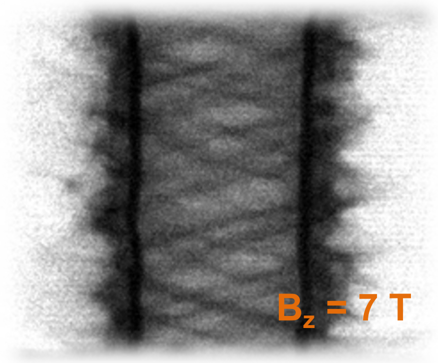
Magnetic drive ICF is being pursued at the Z pulsed power facility at Sandia National Labs, NM

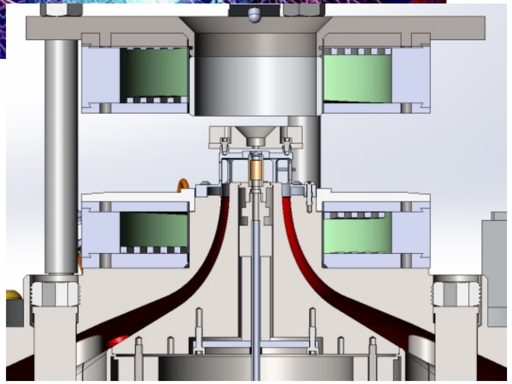
Z Facility



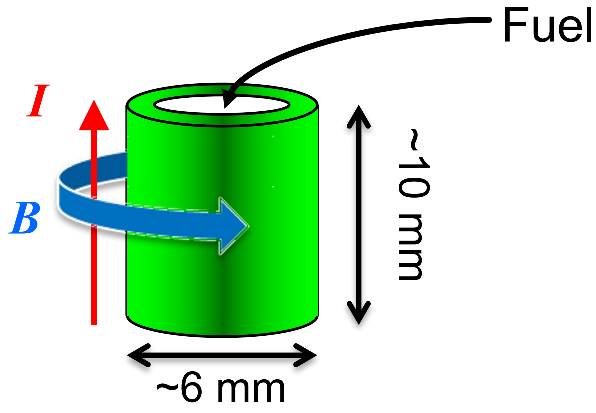
- 80 TW peak electrical power
- Up to ~1 MJ of electrical energy
- Optimized for magnetic drive







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

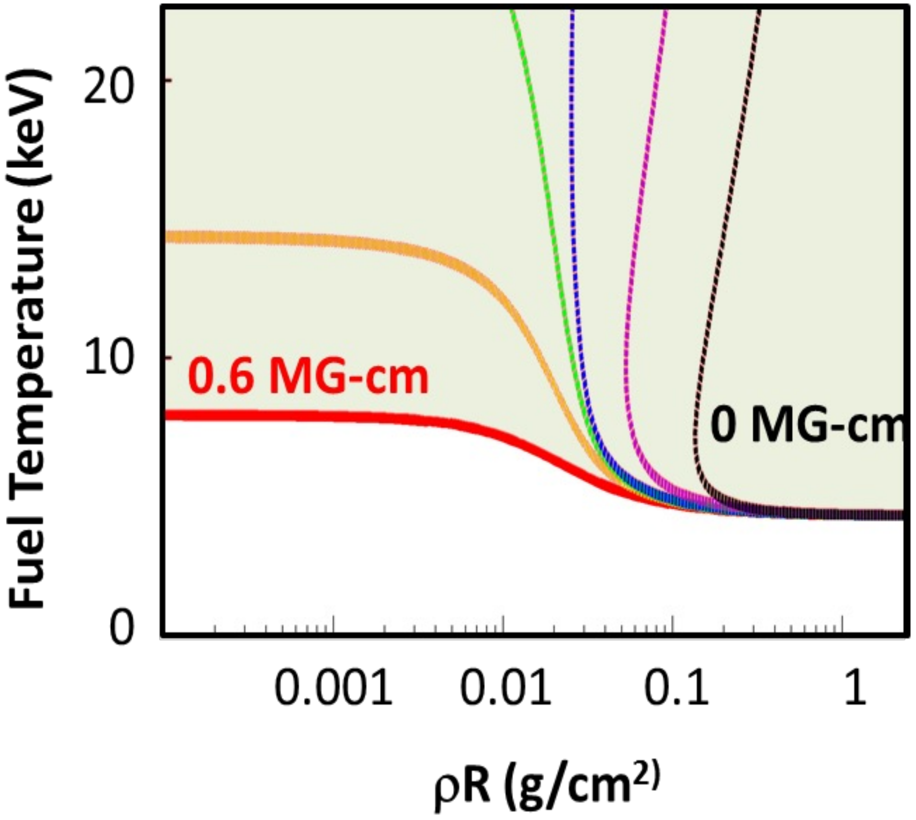


Drive Pressure

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

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

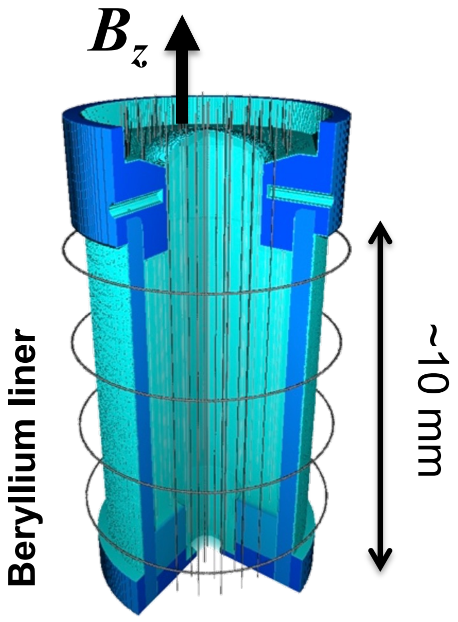
Imposing an axial B-field relaxes ρr requirements



Rochau, IFSA 2017

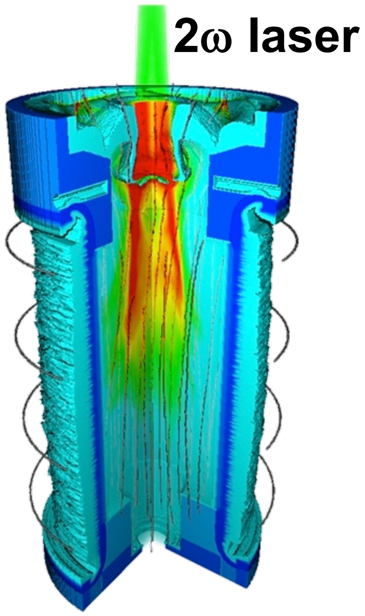
The US is studying a form of magnetic direct drive called Magnetized Liner Inertial Fusion (MagLIF)

Pre-Magnetize



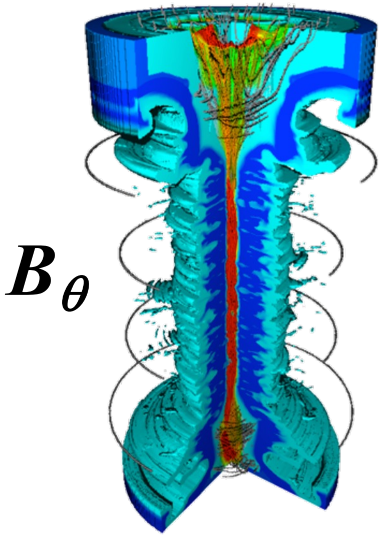
- B_z = 10-30 T
- Inhibit e^- conduction
- Confine α's

Preheat



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

Compress



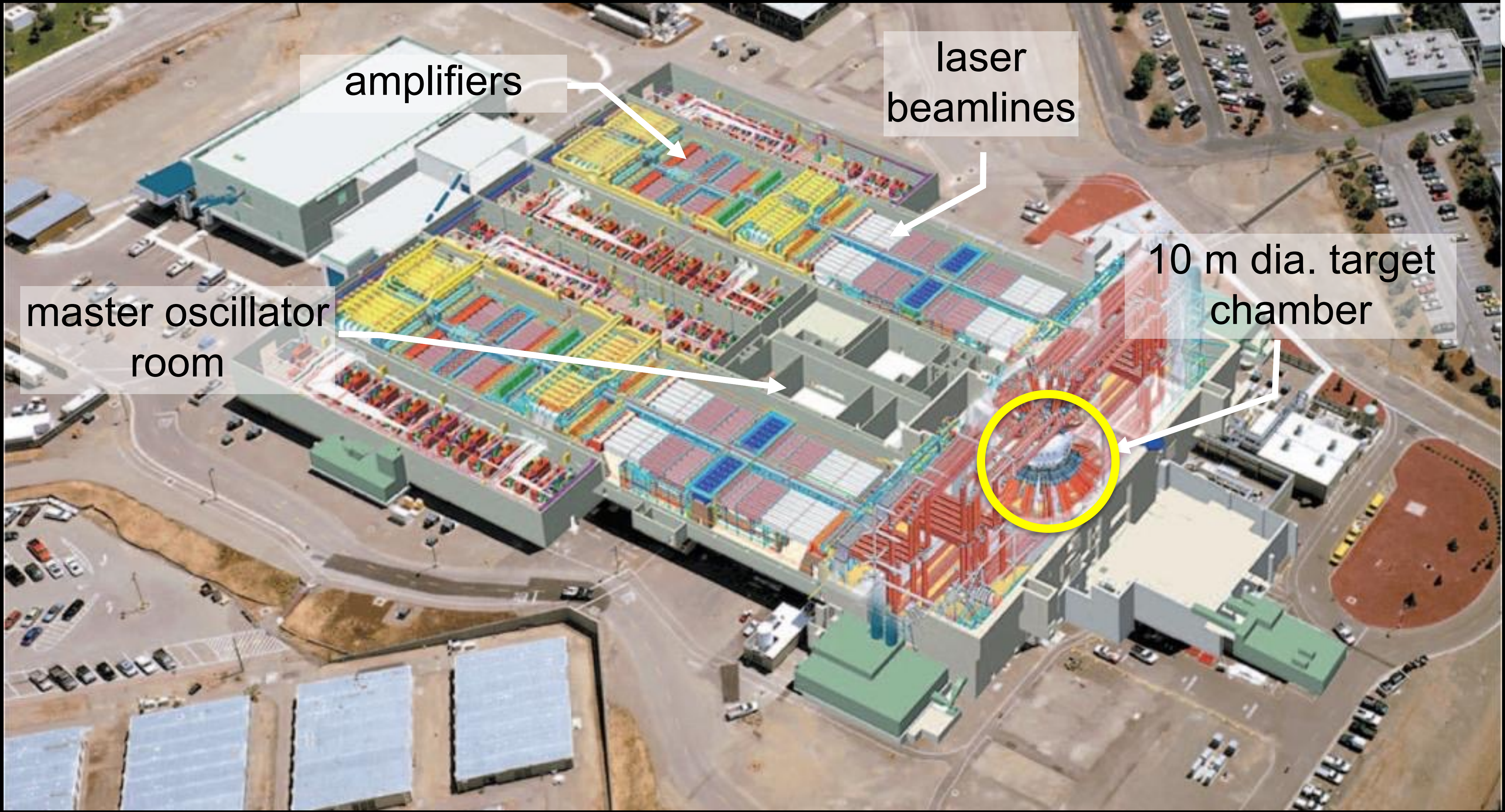
- CR ~ 35
- ρR ~ 0.003 g/cm^2
- P ~ 5 Gbar
- BR ~ 0.5 MG-cm

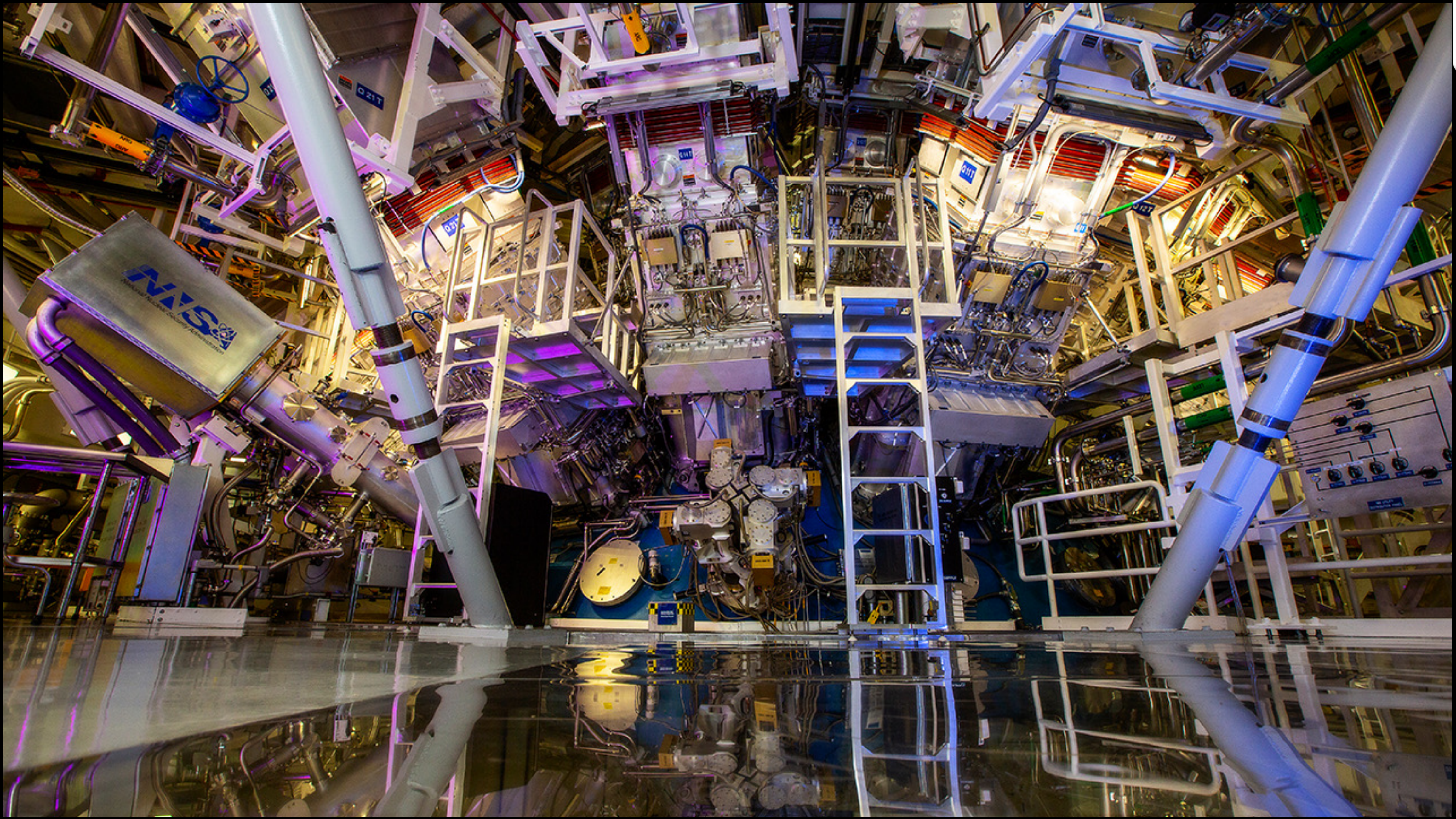
Goal: demonstrate ~100 kJ DT-equivalent fusion yield

The National Ignition Facility (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/cm^3
- Pressures $>10^{11}$ atm
- Number of Diagnostics >120


Cardinal
Stanford
GOLDEN BEARS
CALIFORNIA
Cal
Bruins
UCLA
Ucla Bruins


amplifiers
laser beamlines
master oscillator room
10 m dia. target chamber

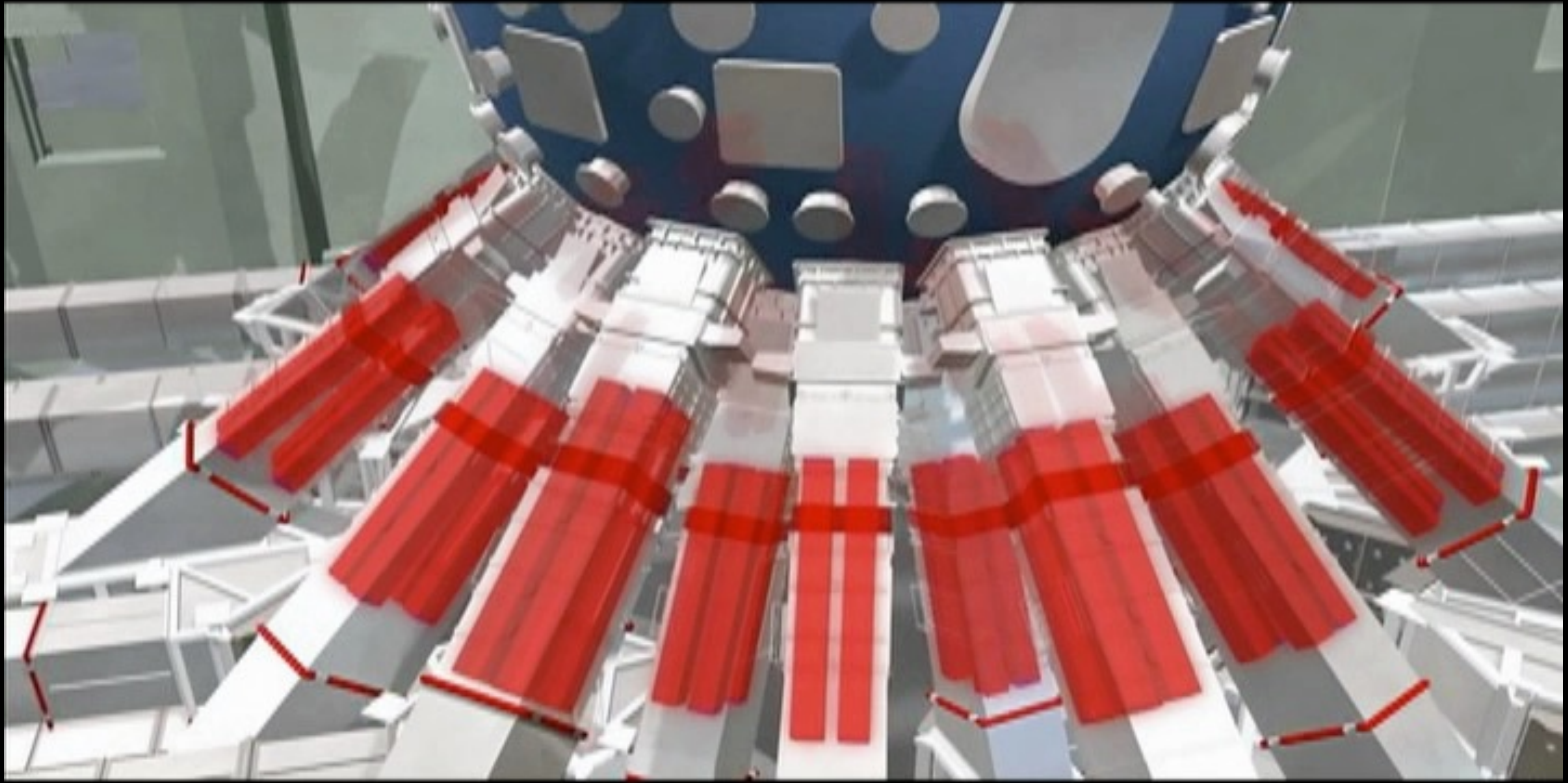

NNSA

NIF in Star Trek: Into Darkness

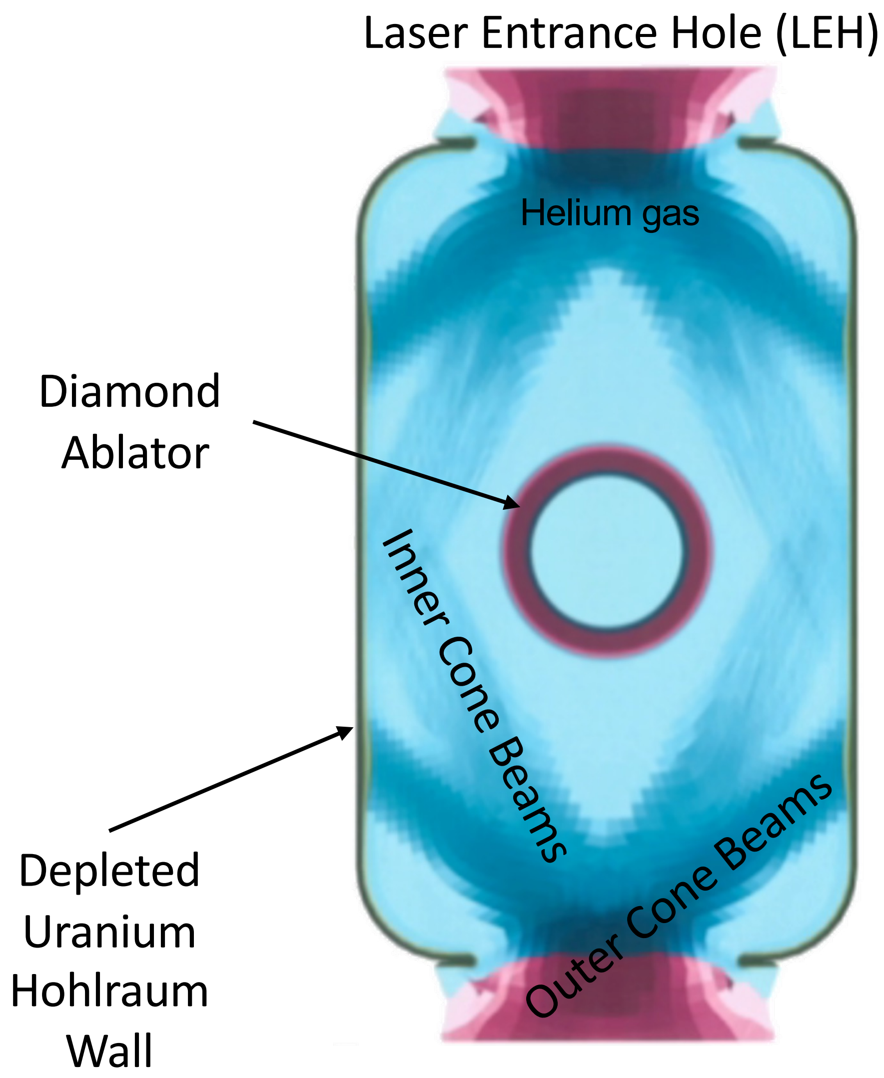
Courtesy of Scott Chambliss, Paramount Pictures and Bad Robot Productions


In the Target Chamber
21EIM/cld · NIF-0110-18213s2r1L5

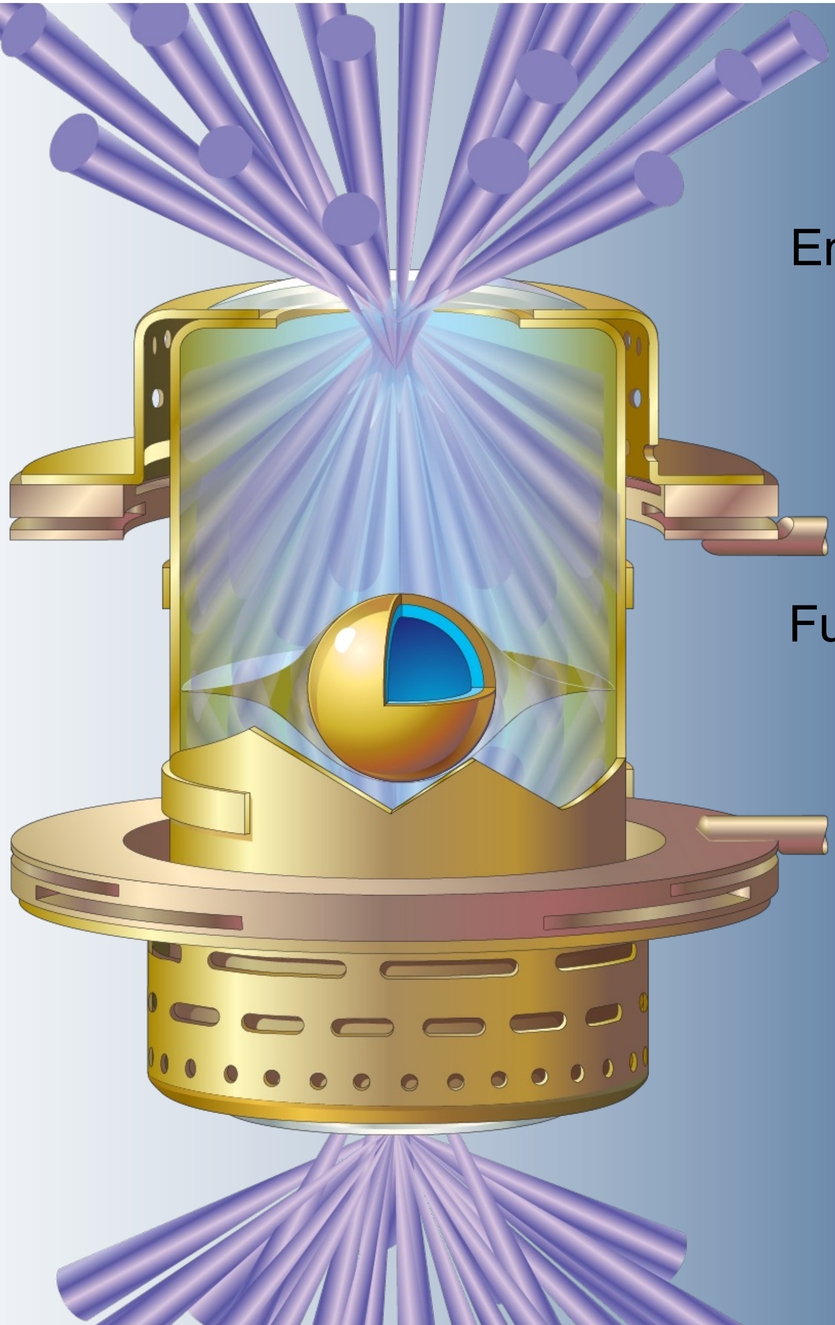
Indirect drive inertial confinement fusion (ICF) uses x-rays to ablate and accelerate a capsule of fusion fuel to extreme velocity



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



Energy In	Energy Out
Electricity 322 MJ	
Laser 2.05 MJ	Fusion Yield 3.15 MJ
Capsule ~250 kJ	
Fusion Fuel ~20 kJ	



After this seminar, we hope to answer…

What is fusion energy and inertial confinement fusion ?

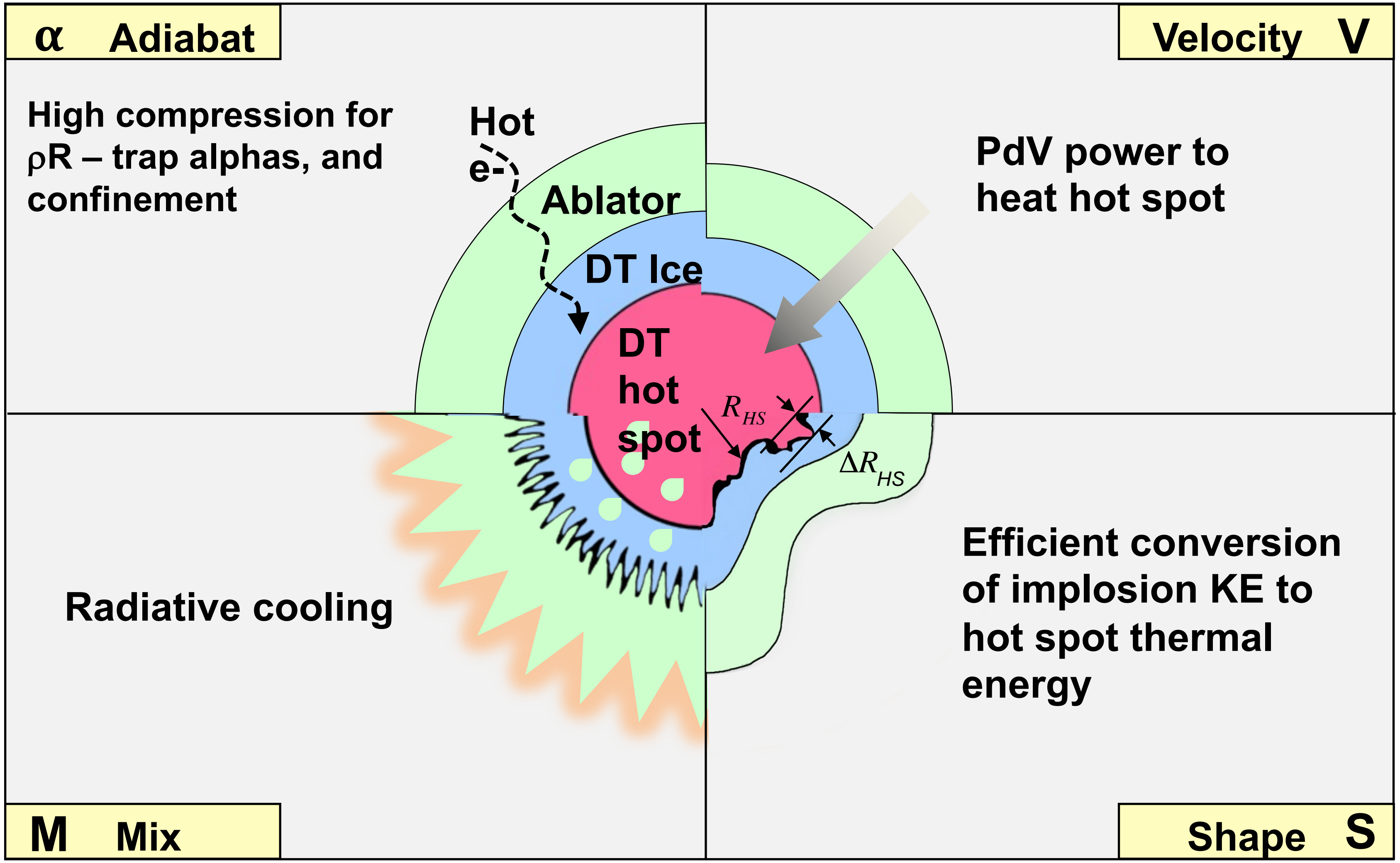
What are the major types of inertial confinement fusion schemes ?

What is the status of ICF experiments at the NIF?

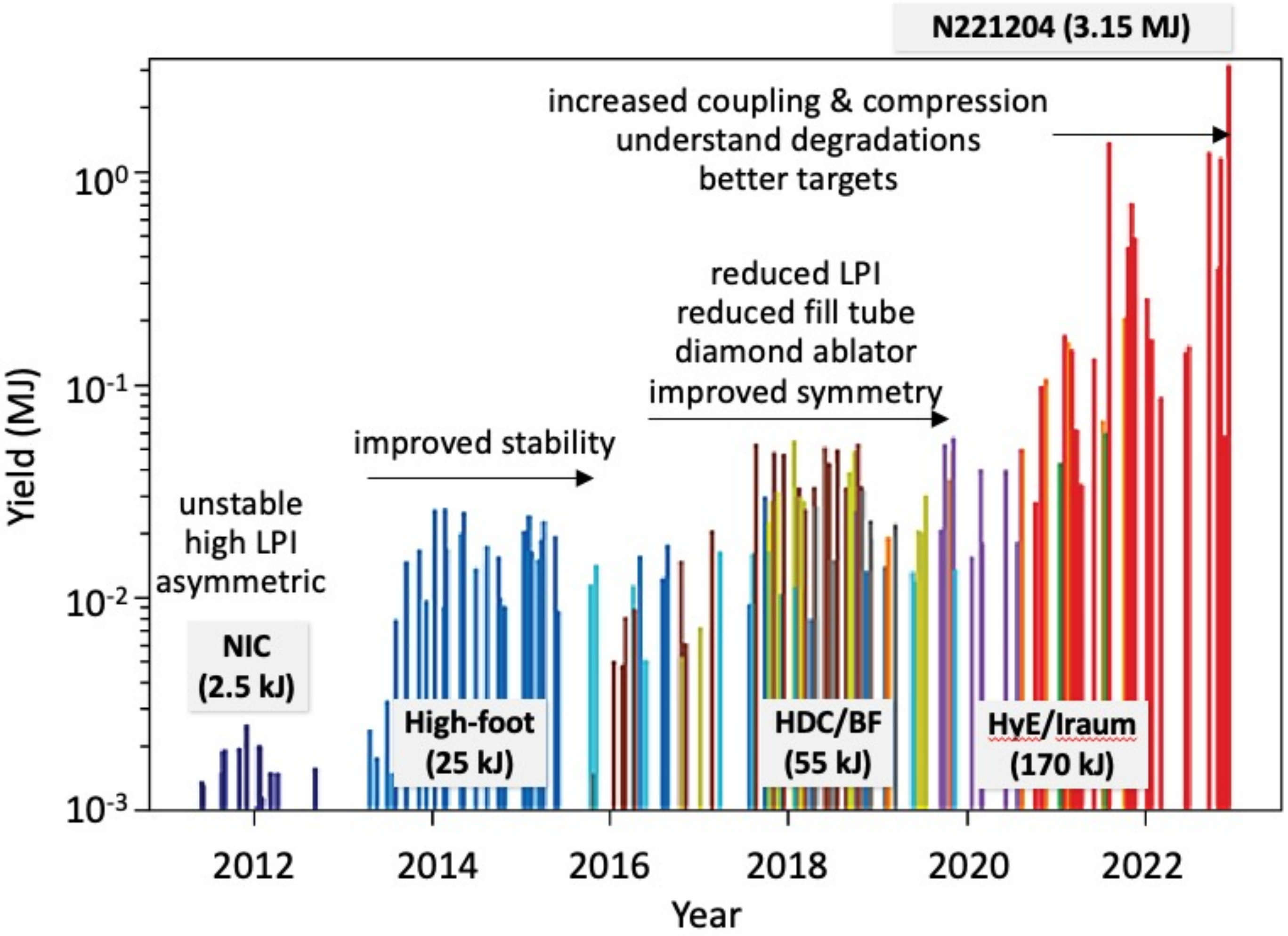
What are the pathways to inertial fusion energy (IFE) ?

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Ignition performance is optimized around four key variables

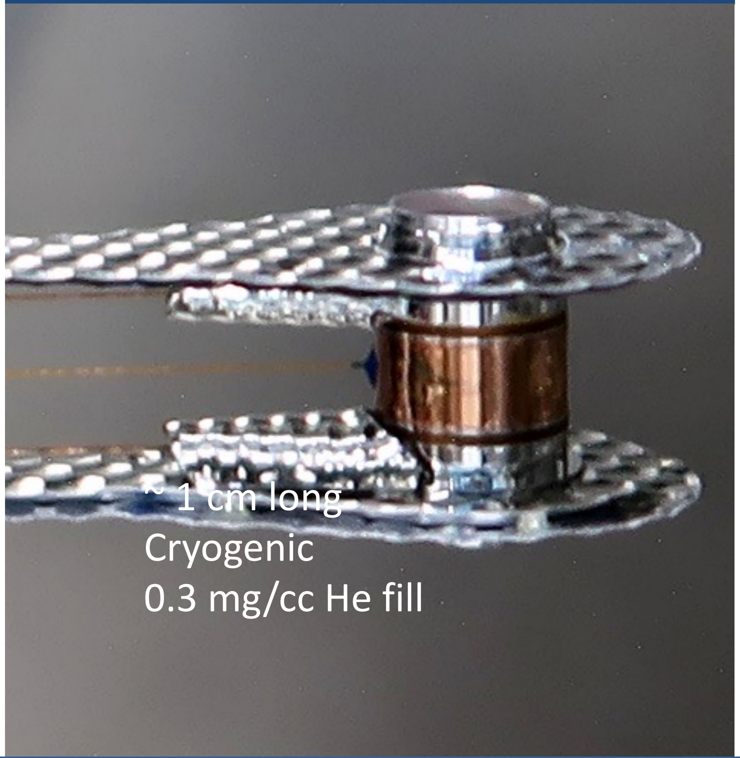


The program steadily advanced physics understanding and technology over the last decade to improve performance, culminating in ignition (target gain >1) on Dec. 5th, 2022

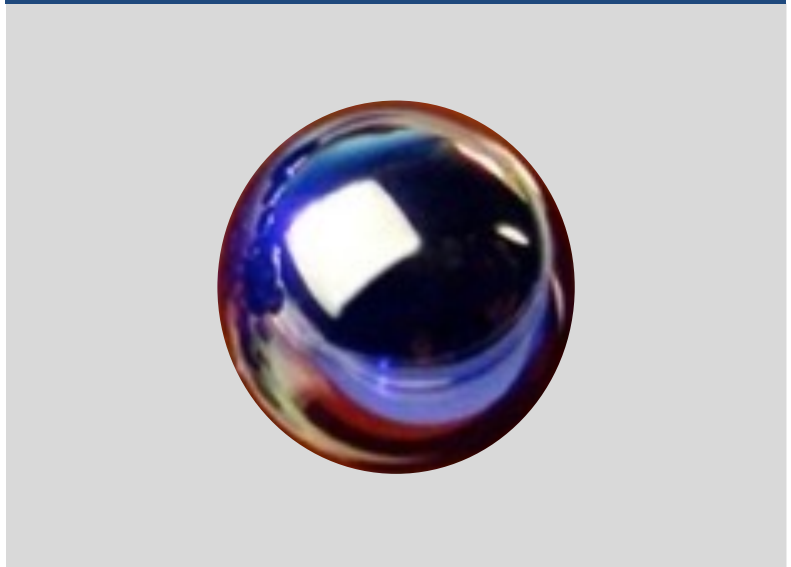


Targets require state-of-the-art microfabrication precision

Gold lined Uranium Hohlraum



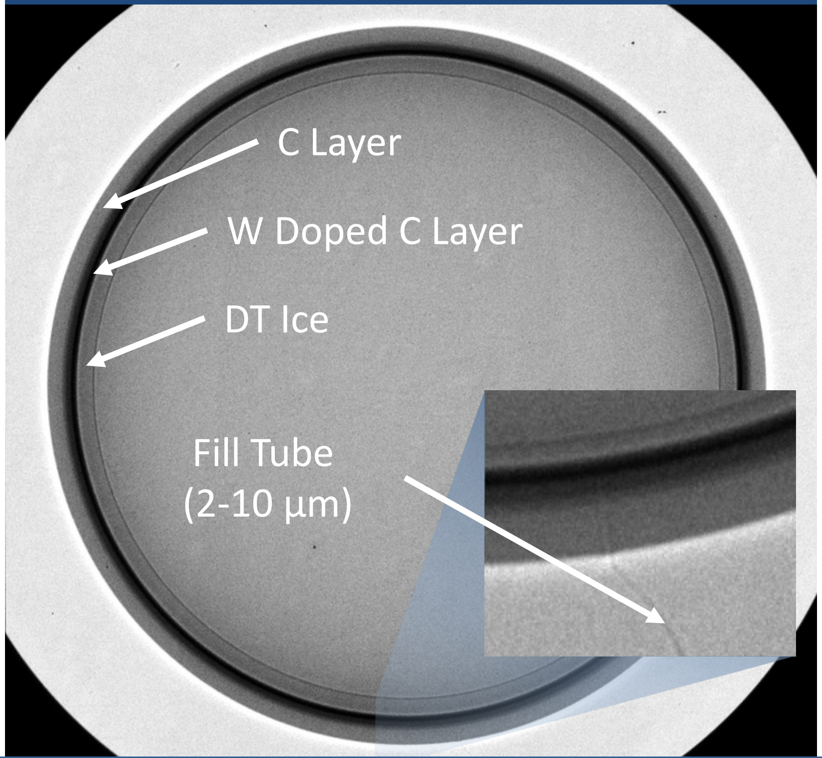
Diamond Nanocrystalline Capsule (High Density Carbon – HDC)



≈ 2 mm diameter, smooth to 10 nm

→ Earth with no hill > 64 m

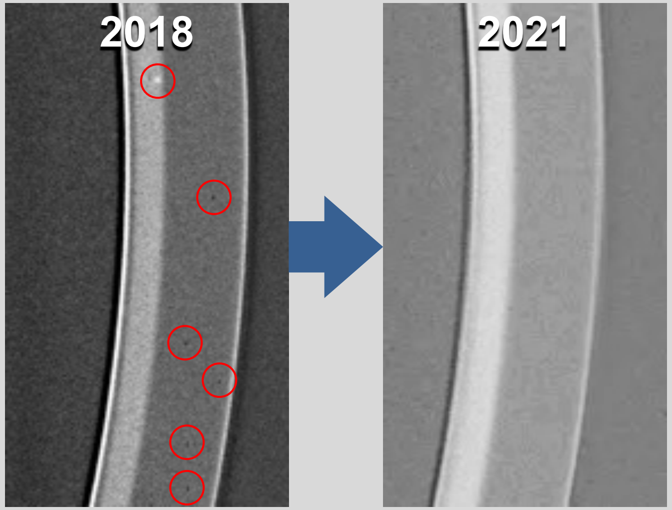
Capsule with DT Layer @ 19 K



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

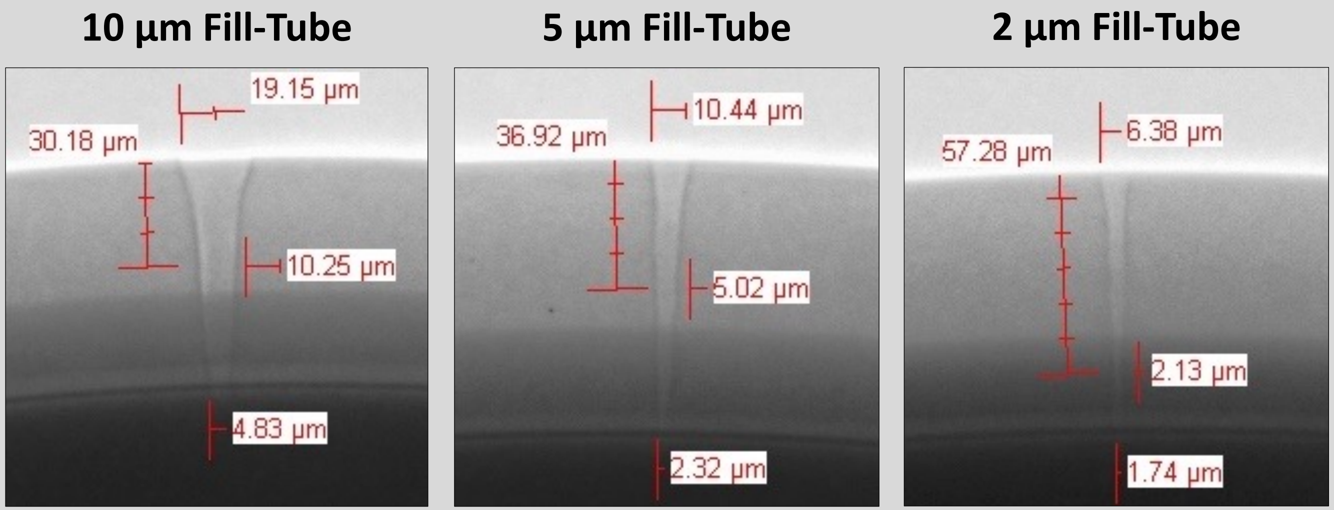
Target improvements have focused on reducing material and engineering defects

Capsule Quality



We have reduced pits and voids by two orders of magnitude

Fill-Tube Hole Diameter

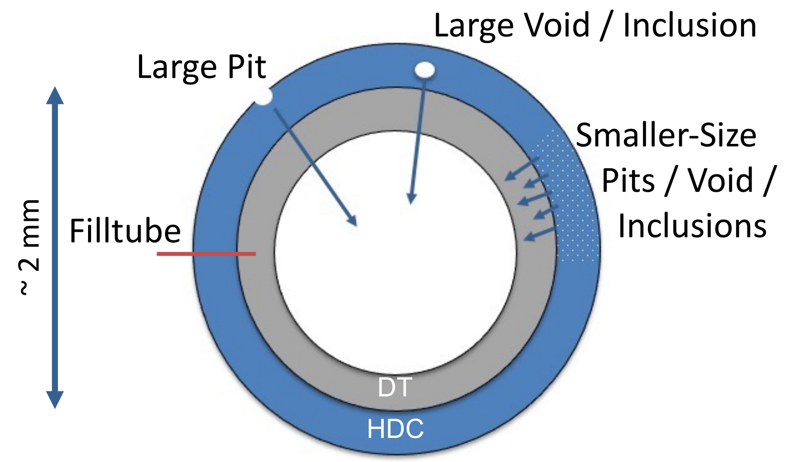


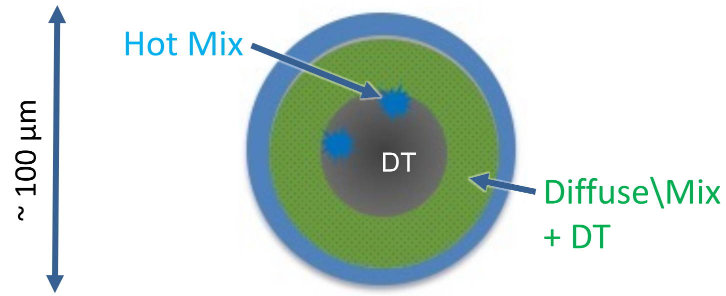
10x reduction in the surface area perturbation

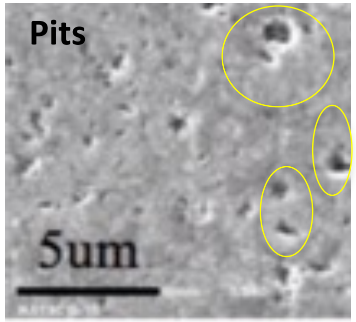
The advances in both target quality and our ability to characterize them have been pivotal in achieving our current implosion performance

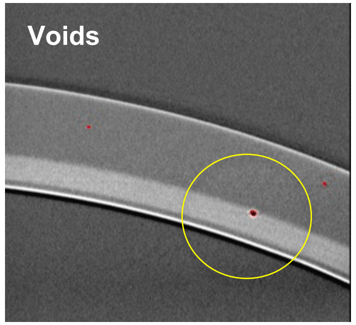
Braun, et al, Nuc. Fusion (2022)

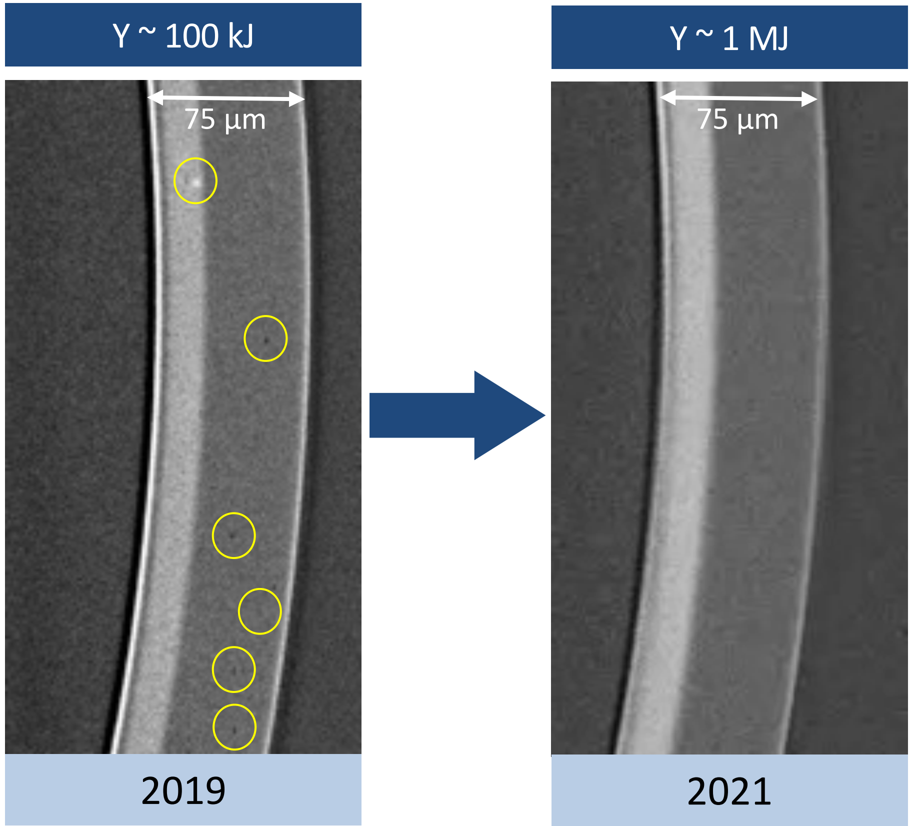
Microscopic capsule imperfections amplified by hydrodynamics instabilities are the dominant degradation mechanism











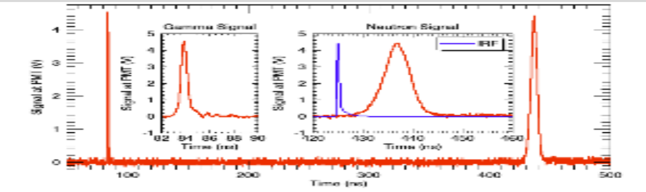
(images:)

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

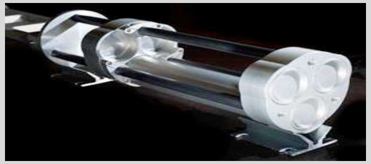
Braun, et al, Nuc. Fusion (2022)

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

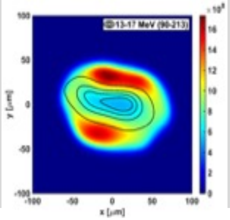
Hot Spot Ion Temperature and Velocity, and Fuel Density



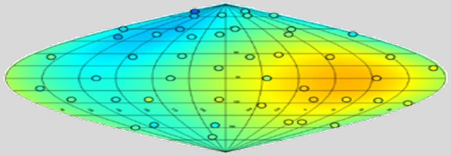
Neutron Yield

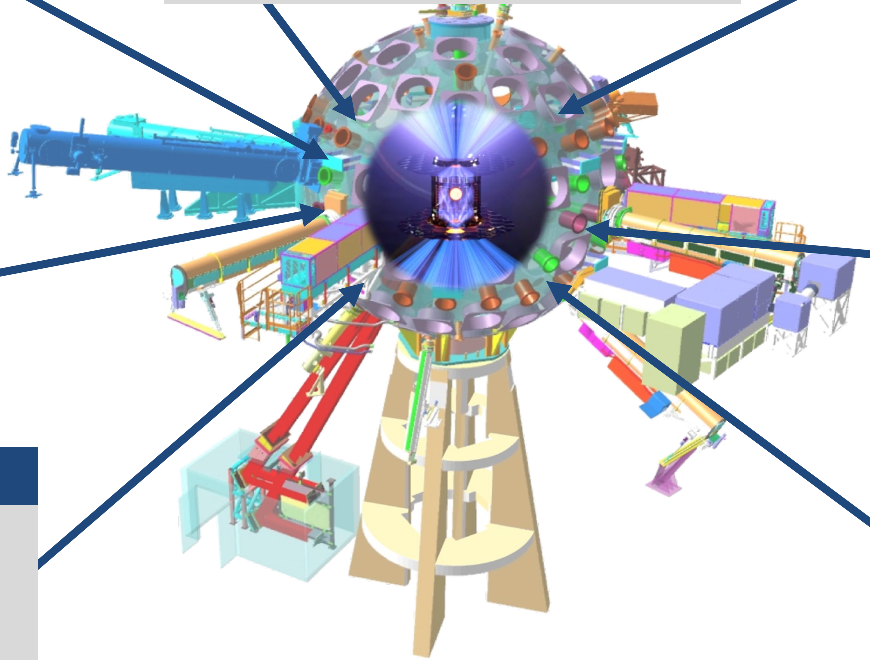


Hot Spot and Fuel Shape by Neutron imaging

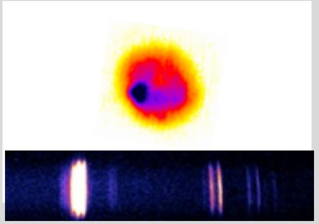


Yield Map and Fuel Uniformity

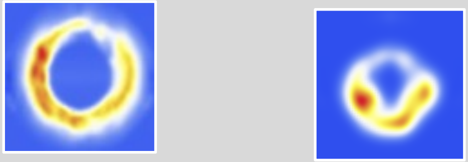




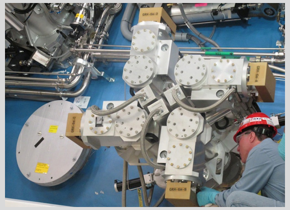
Hot Spot X-ray Imaging & Spectroscopy



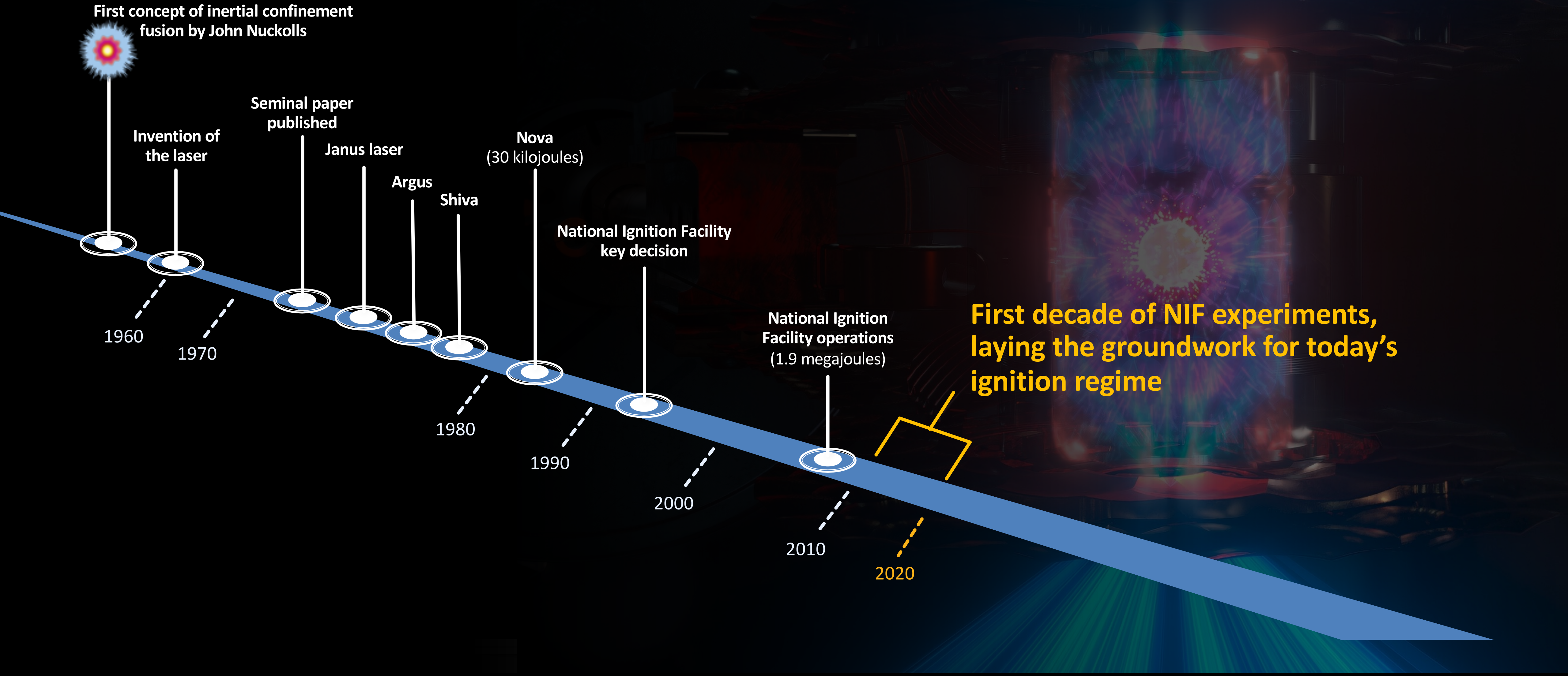
Fuel Uniformity using Compton Radiography



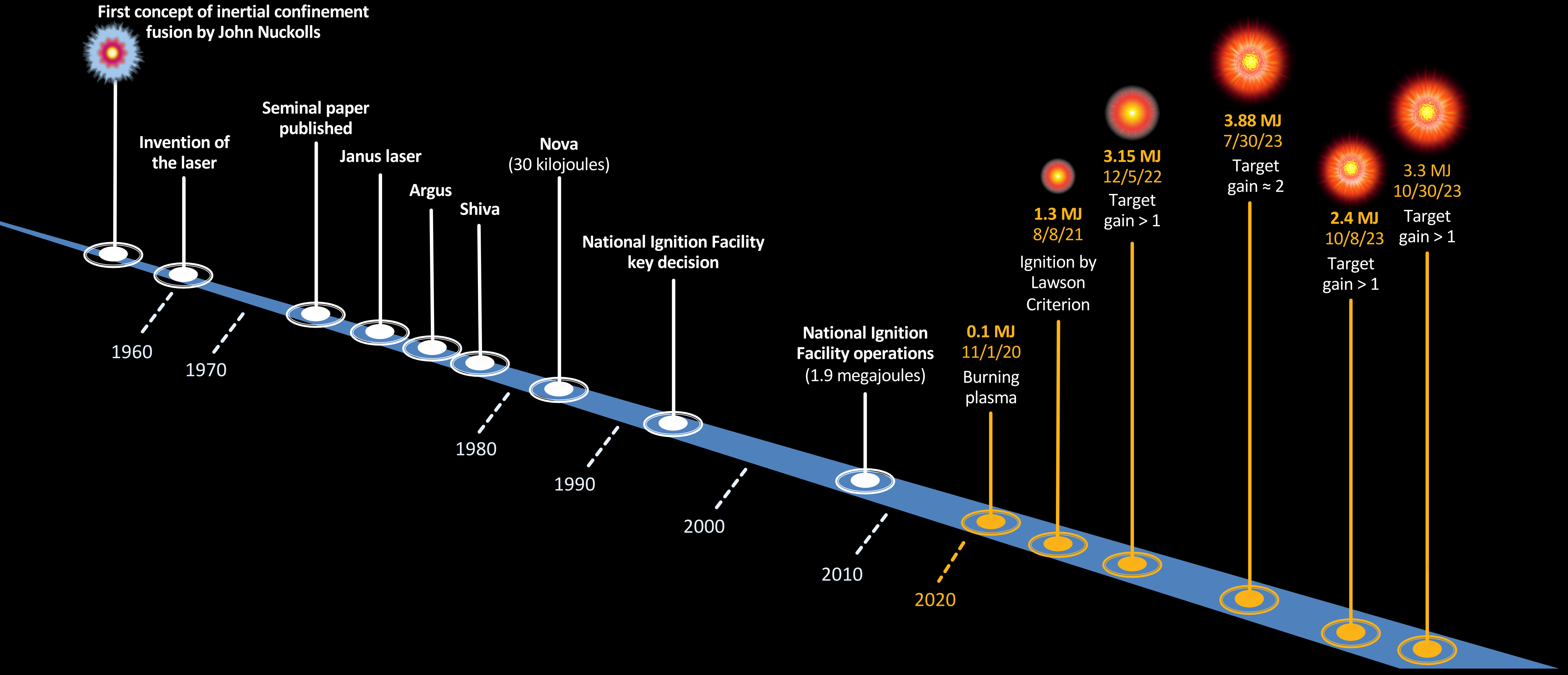
Hot Spot Gamma Spectroscopy



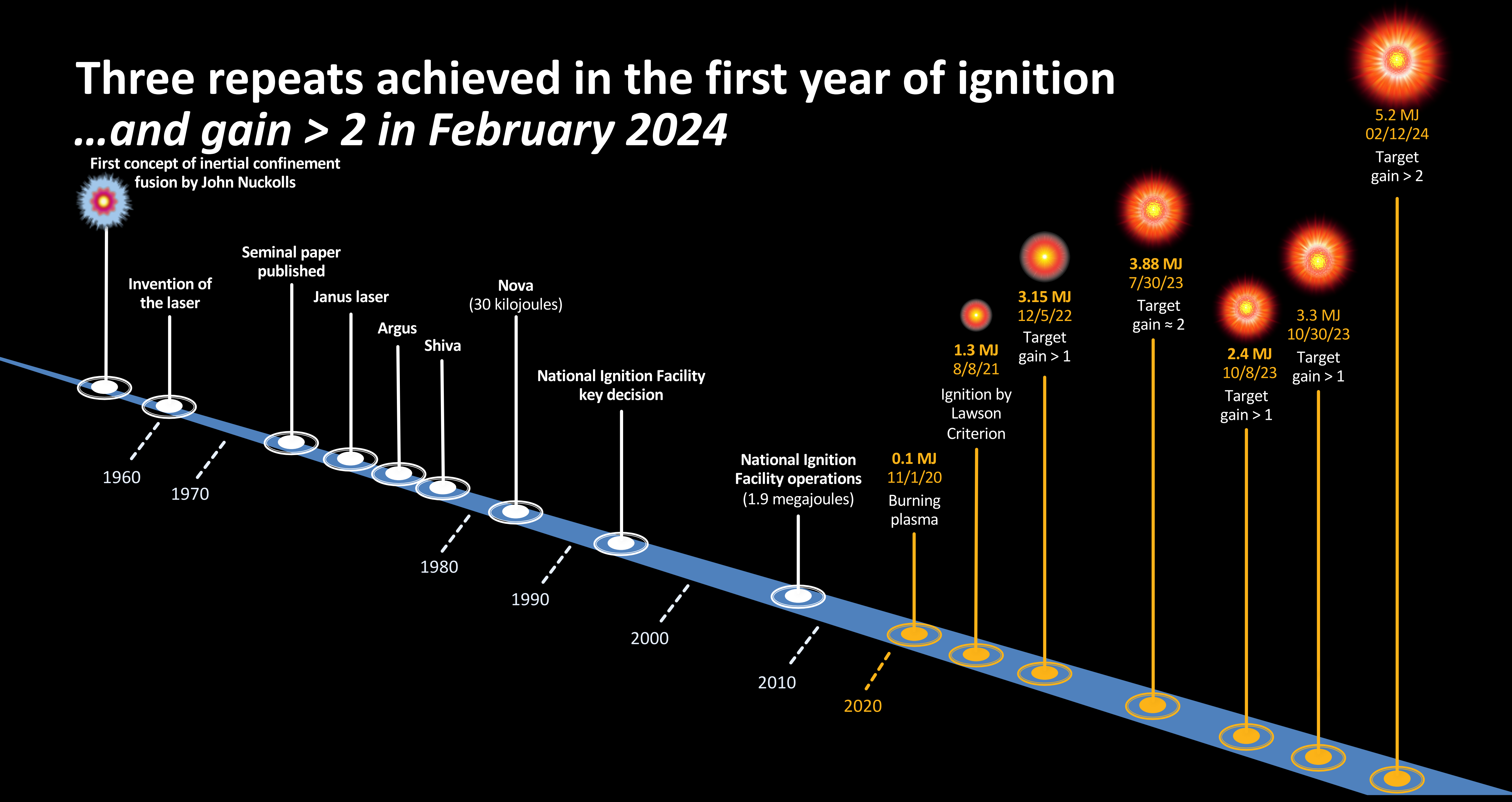
Ignition is the result of six decades of passion, hard work, and learning



Three repeats achieved in the first year of ignition



Three repeats achieved in the first year of ignition
…and gain > 2 in February 2024



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LLNL-PRES-860619
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Lawrence Livermore National Laboratory

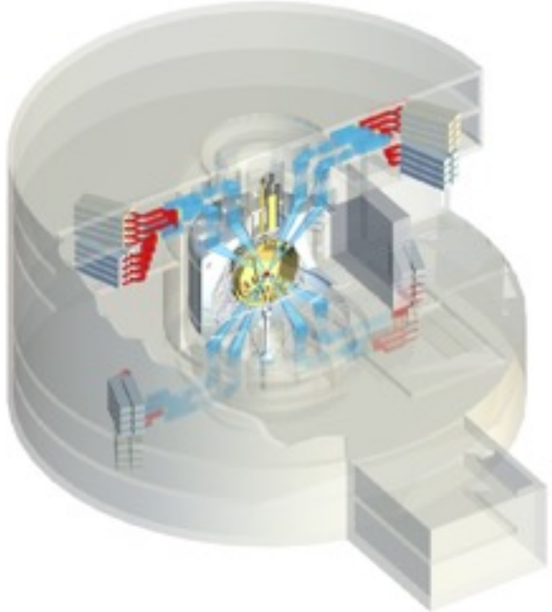
Ignition provides fresh impetus and the scientific foundation for Inertial Fusion Energy (IFE)

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, H_2 and biofuels, H_2O production)
- Energy security, sovereignty, and diversification

Fusion has the potential to meet all of these!

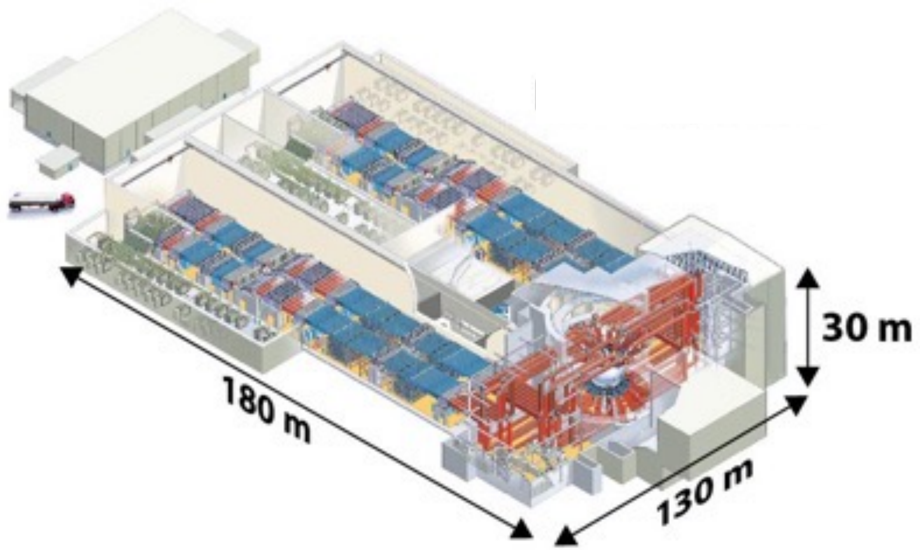


Advantages of fusion energy:

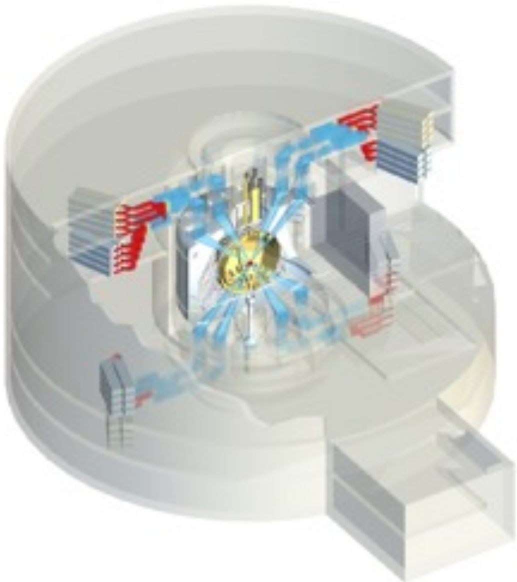
- Inherently safe
- Baseload and load following
- Carbon free
- Near-unlimited, domestic fuel source
- No long-lived nuclear waste

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



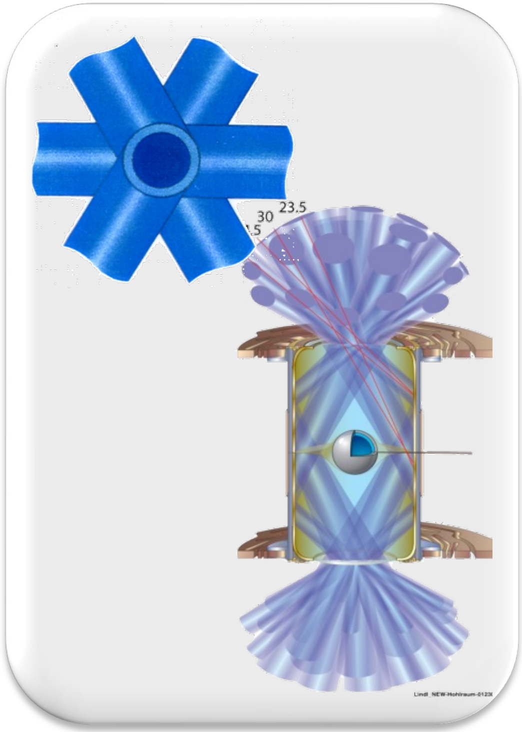
An electricity-producing IFE power plant would require:

- 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

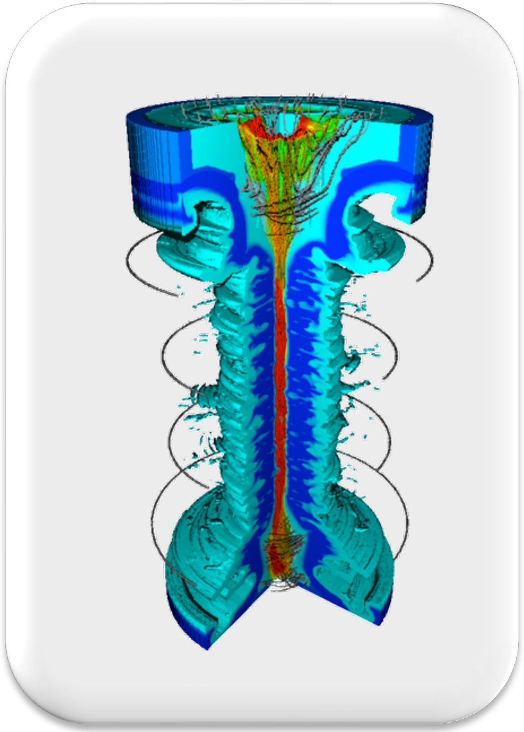
NIF provides a unique opportunity to experiment at "fusion scale" now, but there are yet many outstanding technical questions that must be solved to make IFE a reality

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

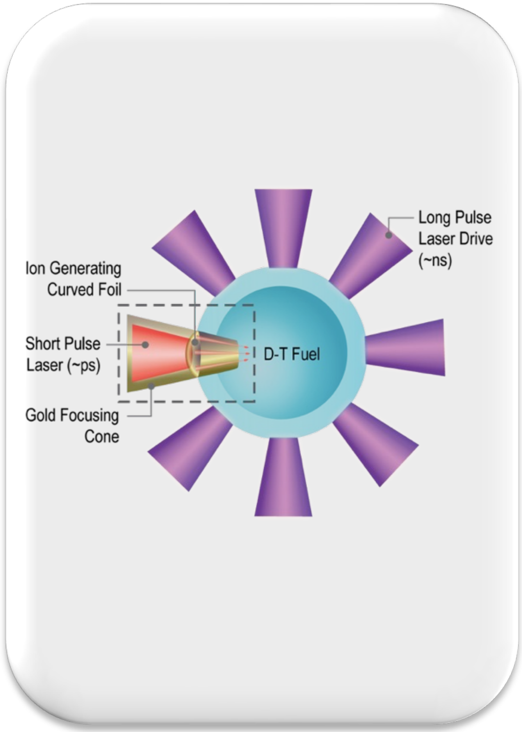
Direct Drive or Indirect Drive ICF



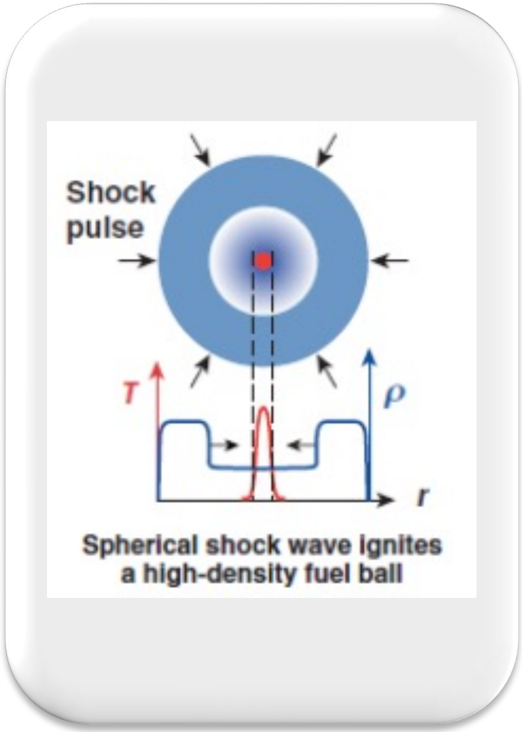
Magnetic Direct Drive



Fast Ignition

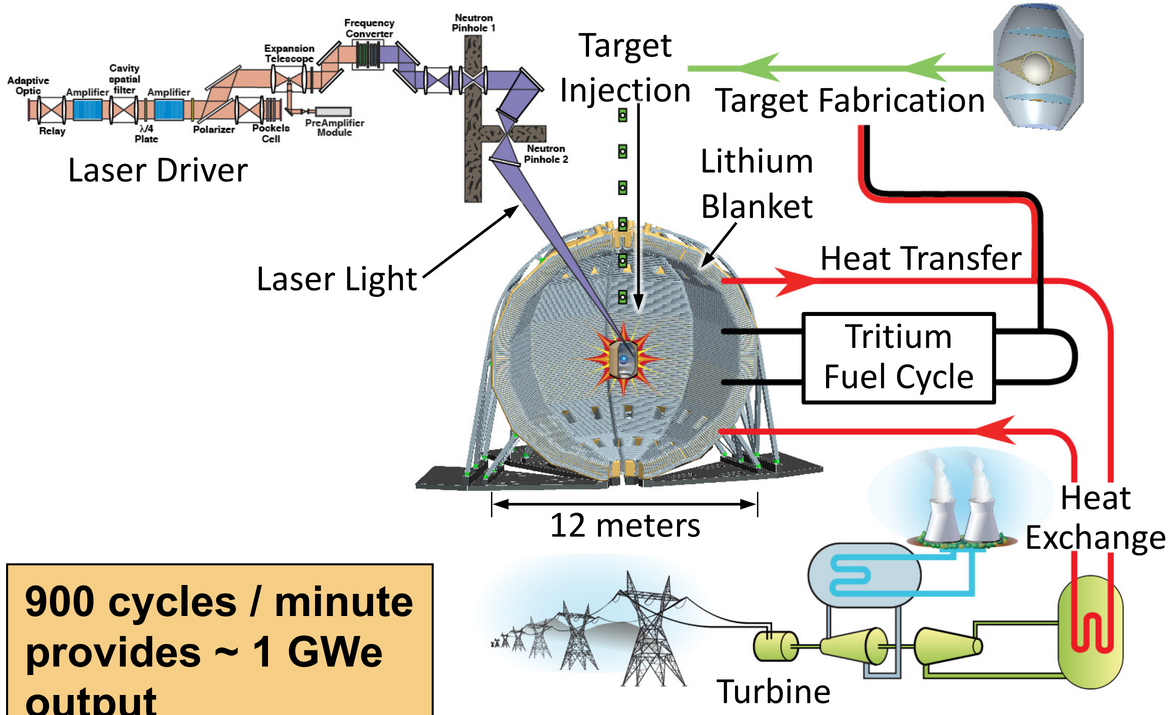


Shock Ignition



…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

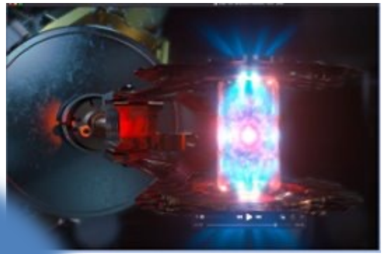
- Separation between driver and fusion source
- Attractive economic development path (spin-out technologies)
- Energy security

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

Novel Laser Architectures

Efficient MJ Driver

High Gain Design

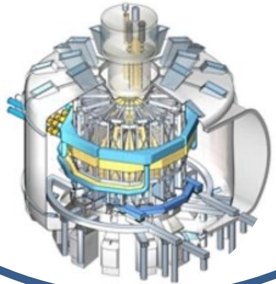


Alternative ICF Schemes

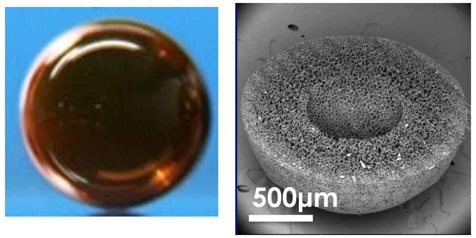
Inertial Fusion Energy

Machine Learning for Optimization and Scientific Discovery

Autonomous Monitoring and Control



Reproducible Target



Additive Manufacturing of IFE relevant targets

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@llnl.gov

NATIONAL IGNITION FACILITY

Lawrence Livermore
National Laboratory