Inertial Confinement Fusion

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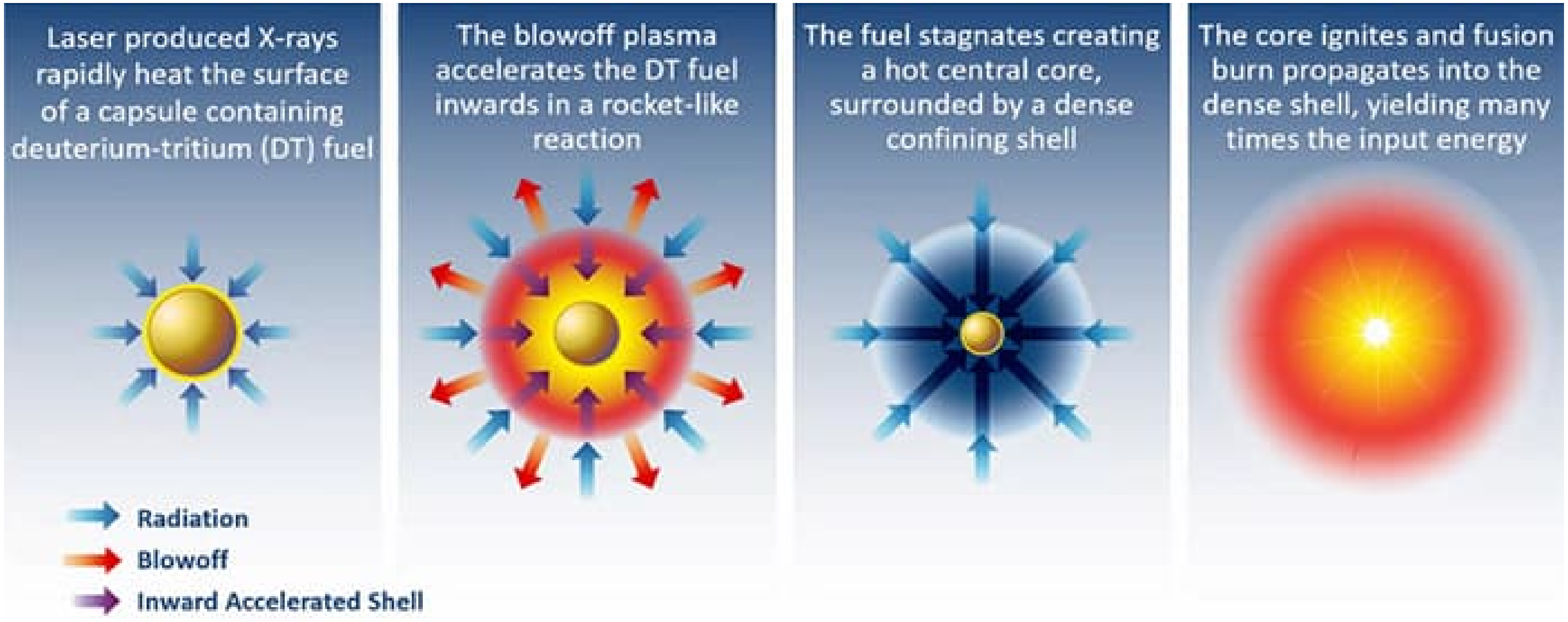
Outline

- **Principles of Inertial confinement fusion**
  - Implosion/compressions physics
  - Direct and indirect drive
  - Hydrodynamic instabilities
- **Results and status of National Ignition Facility (NIF) → recent experiments including ignition**
- **Plans for future inertial power plants**

Principles of inertial confinement fusion

Process of ignition



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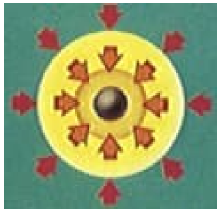
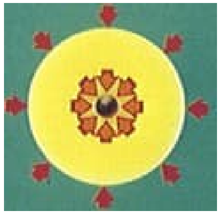
In inertial confinement fusion, the confinement parameter is given by the product of ρR

- **Surface heated plasma expands in time:**

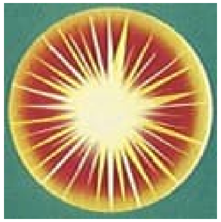
$$\mathrm{R(t)} = R_f - c_s t$$



with $c_s = \sqrt{2k_B T / m_f}$



- **Confinement time:** $\tau_{conf} = R_f / c_s$
- **Reaction time:** $\tau_{fus} = 1/n_0\langle\sigma v\rangle$



- **Ignition conditions:** $\dfrac{R_f}{c_s} \geq \dfrac{1}{n_0\langle\sigma v\rangle}$

Ignition in inertial confinement fusion

- **A shell of cryogenic D-T fuel accelerated inward by direct laser irradiation or by the x-rays produced by heating a high-Z enclosure**
- **At stagnation, the compressed fuel is ignited by a central hot spot surrounded by a cold, dense shell.**
- **Central ignition when the alpha-particle heating of the hot spot exceeds all the energy losses. (in exercises: "ideal ignition where alpha-particle heating overcomes Bremsstrahlung losses")**
- **A metric is needed to assess how an implosion experiment performs with respect to the ignition condition.**
- **In a stationary plasma, the ignition condition is given by the Lawson criterion → what is ignition condition in ICF in terms of measurable parameters?**

  P.Y.Chang PRL 2010

Implode: *Explode inward. The NIF fuel capsule implodes at speeds up to 400 kilometers a second.*

Comparing ignition in inertial vs. magnetic confinement fusion (present research)

Magnetic confinement fusion:

- Experiments typically D-D: relevant physics without complication of operation with tritium→ no neutrons (for energy production D-T needed)
- In MCF, τ measured from decay time of plasma energy

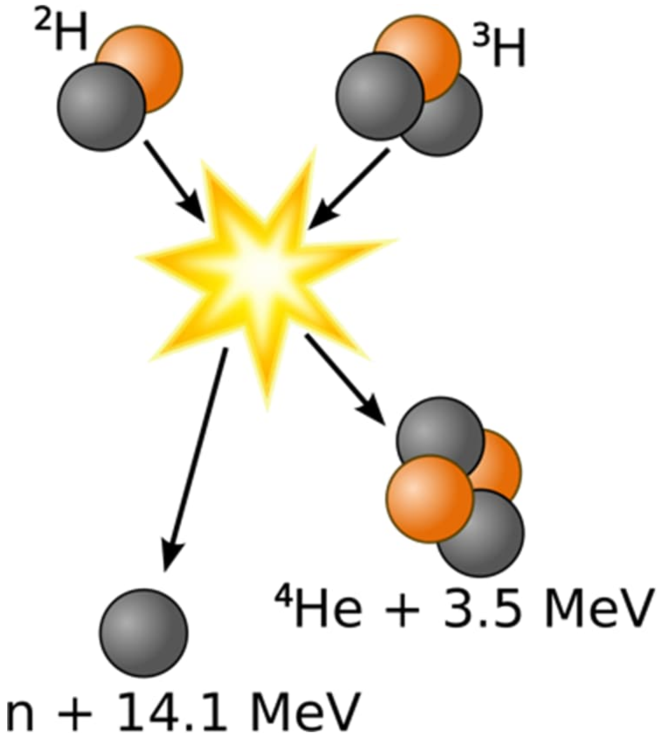
Inertial confinement fusion:

- D-T: Tritium inventory small → tritium commonly used in cryogenic target experiments
- Neutron yield important measure
- τ cannot be directly measured (related to width of neutron-rate history)
- In addition to neutron yield, measurable parameters of the ICF fuel assembly are the **total areal density, and the ion temperature**.

Areal Density: *The combined thickness and density of the imploding frozen fusion fuel shell. The areal density of the fuel and the temperature and shape of the implosion at peak compression are two critical experimental factors for achieving ignition. See more definitions: https://lasers.llnl.gov/education/glossary*

Inertial confinement time scales significantly lower than those in magnetic confinement

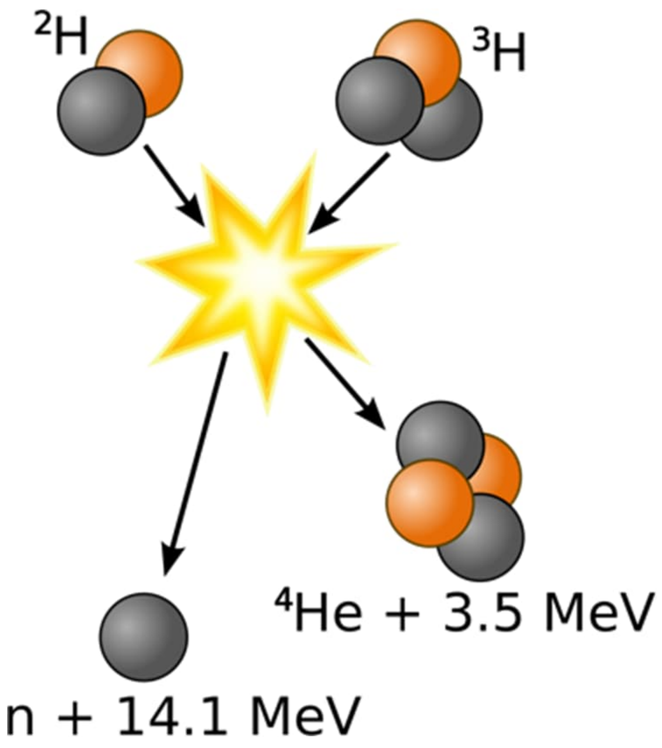
Lawson criterion: $n\tau \approx 10^{20} m^{-3} s$



- **Magnetic confinement fusion**
  - Density $\approx 10^{20} m^{-3}$
  - Confinement time $\approx$ 1 (to 10) s $\Rightarrow$ quasi steady state
- **Inertial confinement fusion**
  - Density $\approx 10^{31} m^{-3}$
  - Confinement time $\approx$ 10 ps (10^{-11}s) $\Rightarrow$ pulsed

Substituting ρ and R for n and τ yields the modified Lawson criterion for inertial fusion

Lawson criterion: nτ ≈ $10^{20} m^{-3} s$



- $\mathbf{n\tau \geq 10^{20} m^{-3} s \rightarrow \rho R \geq 1\ g/cm^2}$
- **Fuel fraction burned:**

$$\phi = \rho R/(H_B + \rho R)$$

- **Burn parameter** $\mathbf{H_B \approx 7 g/cm^2}$

⇒ 30% burn-up, one needs $\mathbf{\rho R \geq 3 g/cm^2}$

⇒ 1 mg fuel ⇔ fuel density 300 g/cm³, or 1500 x compression

Compressing 1 mg of DT isentropically to 1500x solid density requires about 10 kJ

$$pV^{\gamma} = constant$$

$$W_{1\to 2}\int_1^2 pdV = constant\int_1^2 V^{-\gamma}\, dV$$

$$W_{1\to 2} = \frac{nk_B}{1-\gamma}T_1\left[\left(\frac{V_1}{V_2}\right)^{\gamma-1} - 1\right]$$

- **Early estimates by Nuckolls et al. (*Nature* 1972) estimated only 1 kJ for laser ignition**

Nuckolls' initial calculations over-optimistically dismissed laser-plasma and hydrodynamic instabilities

- **Laser-plasma instabilities:**
  - Long-scale length plasma are susceptible to electromagnetic instabilities
  - Laser light may be reflected or channeled into a very few, very high-energy electrons ⇒ fuel preheat
- **Implosion process is inherently unstable:**
  - Raleigh-Taylor, Richtmyer-Meshkov, and Kelvin-Helmholtz instabilities
  - Initial perturbations must be extremely small
  - Turbulence and material mix (DT with high-Z ablator)

Nuckolls' initial calculations over-optimistically dismissed laser-plasma and hydrodynamic instabilities

- **Hydrodynamic instability growth was overly optimistic:**
  - Assumed ablative "polishing" would remove high-mode perturbations

  ⇒ In reality, capsule suffers high Rayleigh-Taylor growth rates from these modes

- **Laser intensities of 10^{17} W/cm^2 were assumed ⇒ laser-plasma instabilities limit intensities to 10^{15} W/cm^2**
  - Produces high ablation velocities, thus high efficiency and beneficial aspect ratio implosions
  - Some improvements at shorter laser wavelength ($\sim \lambda^2$)

- **Beam imprint and capsule manufacture limitations**

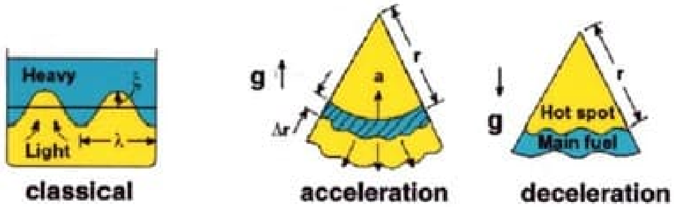
Fluid instabilities lead to non-spherical implosion of the capsule and unwanted material mixed into fuel

- **Rayleigh–Taylor instability** is an instability of an interface between two fluids of different densities which occurs when the lighter fluid is pushing the heavier fluid. In ICF uneven compression on the target surface can cause RT-instability

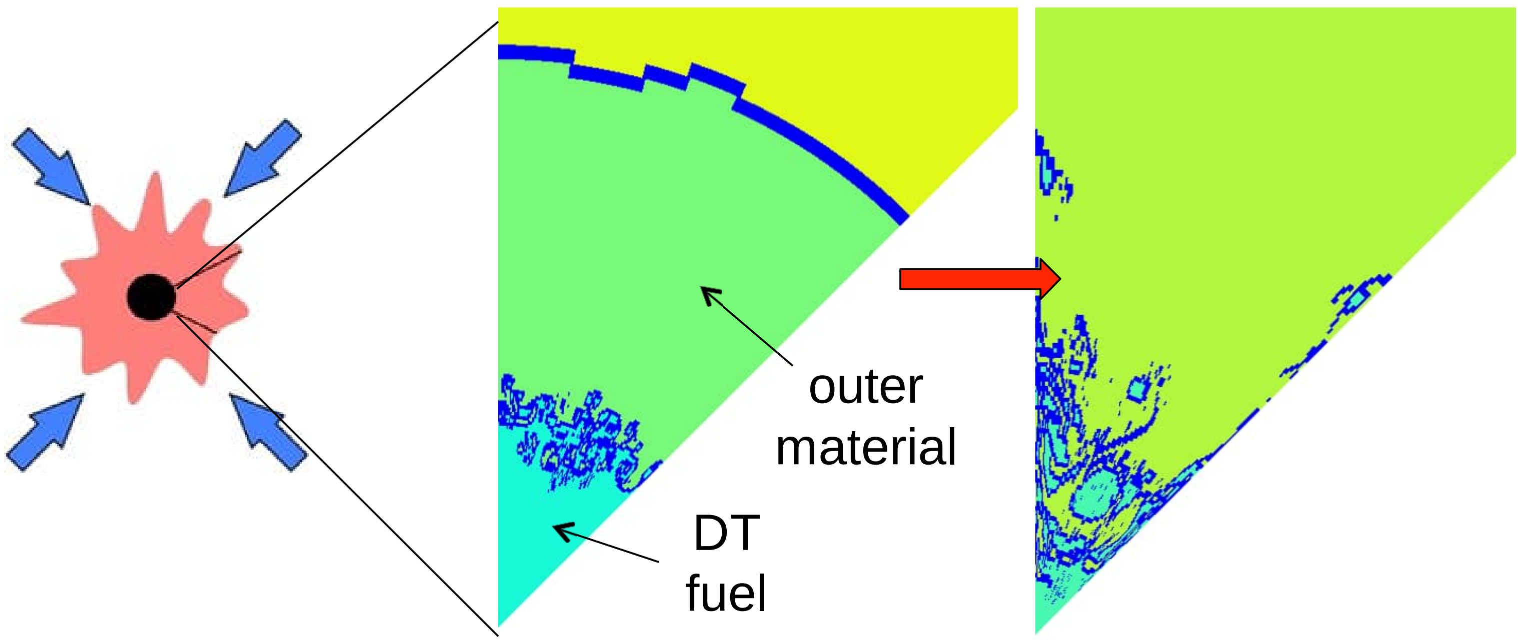
- **Richtmyer–Meshkov instability** → impulsive-acceleration limit of the Rayleigh–Taylor instability.

- → RT and RM instabilities can cause capsule surface and interface **imperfections to grow** and if severe enough, the **instabilities can cause ablator material to mix into the core and radiatively cool the hot spot,** decreasing the hot spot temperature and nuclear yield.

Fluid instabilities lead to non-spherical implosion of the capsule and unwanted material mixed into fuel



Cut-away sections of imploded capsule



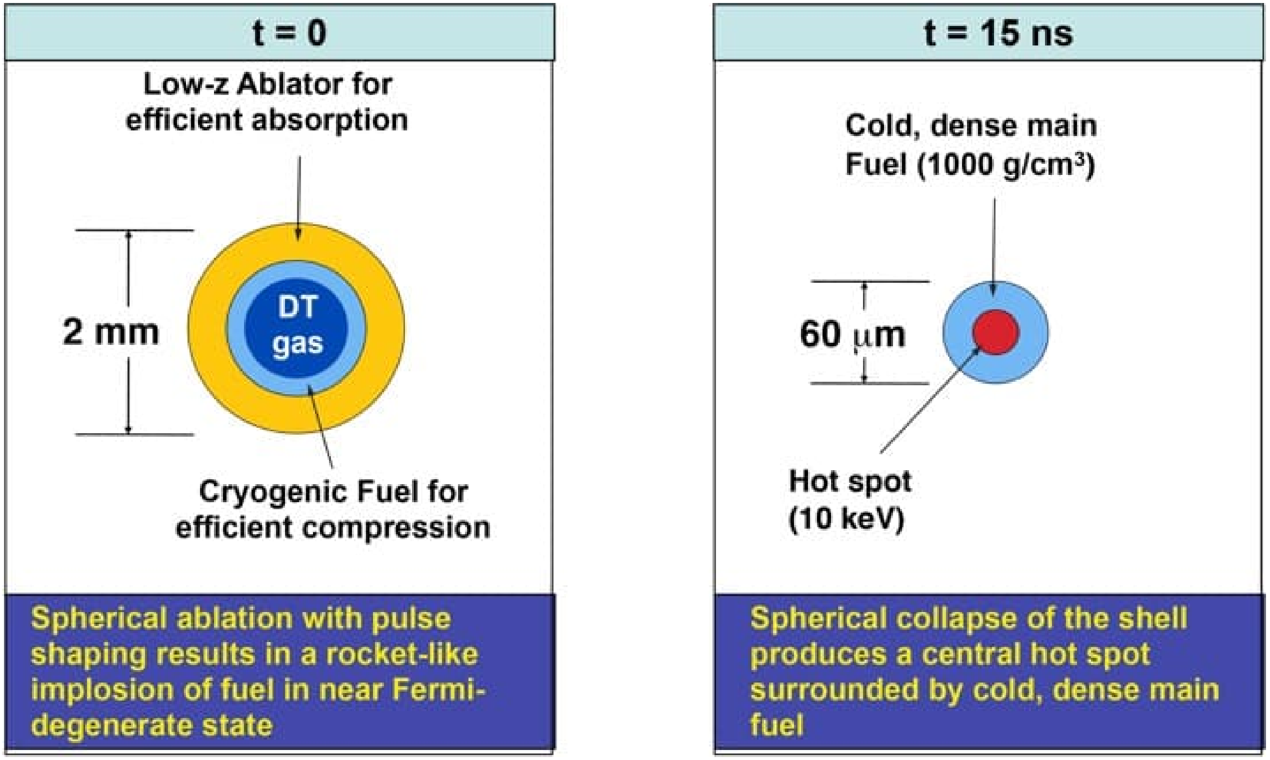
A more realistic estimate requires a driver energy of 100 MJ

- **1mg of DT of a velocity of 3×10^{17} cm/s has a kinetic energy of 50 kJ**

⇒ At 10% implosion efficiency, required driver energy of 500 kJ

- **Estimate is still too low! ⇒ for compression ratios of 100, the driver energy is more likely to be 1 MJ, or above**

Inertial confinement fusion ignition is driven by the ablation-driven rocket force



- **C.f., convergence ratio (R_i/R_f) ~ 30 (basketball to pea), implosion velocity ~ 300 km/s (1/2 of galactic escape)**

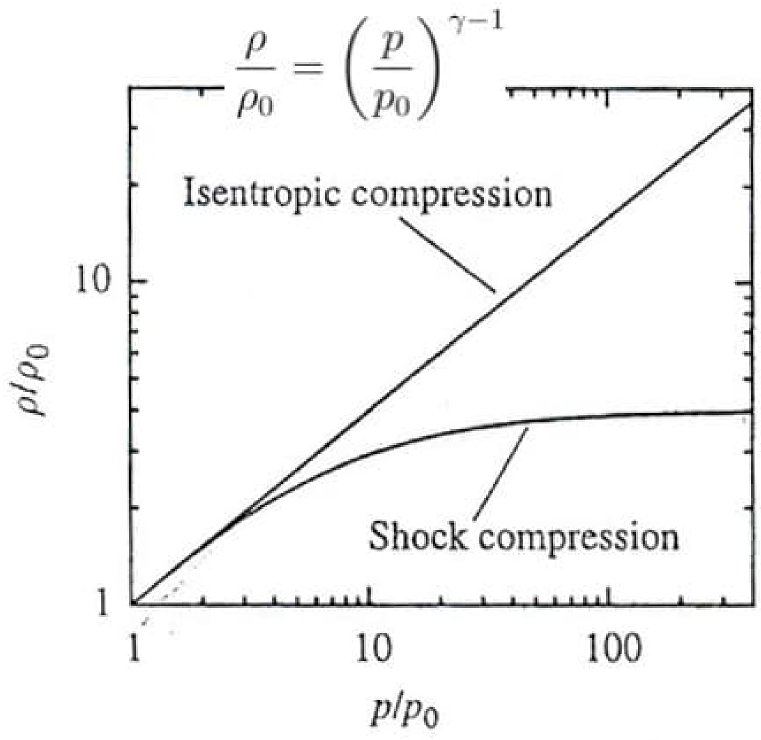
Shock wave compression saturates at certain pressure ratios

- **Strong (planar) shock give an upper limit for compression:**

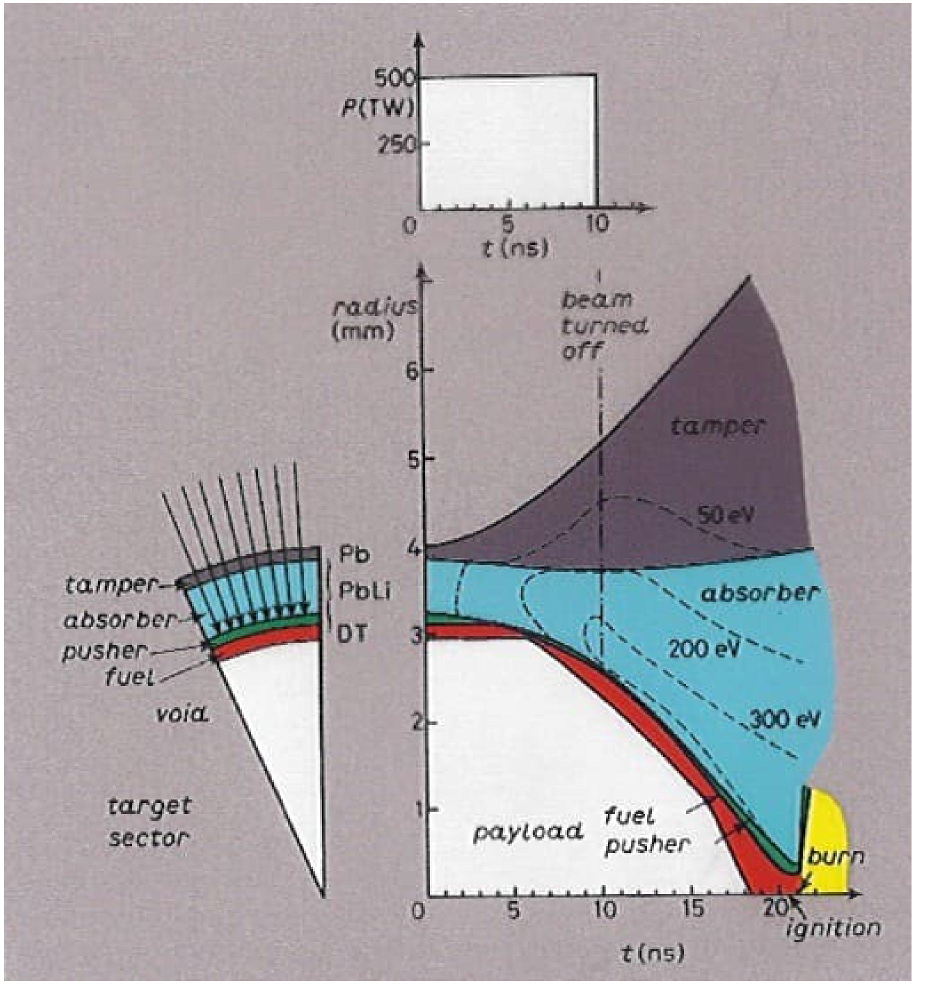
$$\gamma = \frac{5}{3} \Rightarrow \left(\frac{\rho_2}{\rho_1}\right)_{max} = 4$$

$$\gamma = \frac{7}{5} \Rightarrow \left(\frac{\rho_2}{\rho_1}\right)_{max} = 6$$

- **Shock waves lead to strong heating instead compression ⇒ not suitable for ICF**

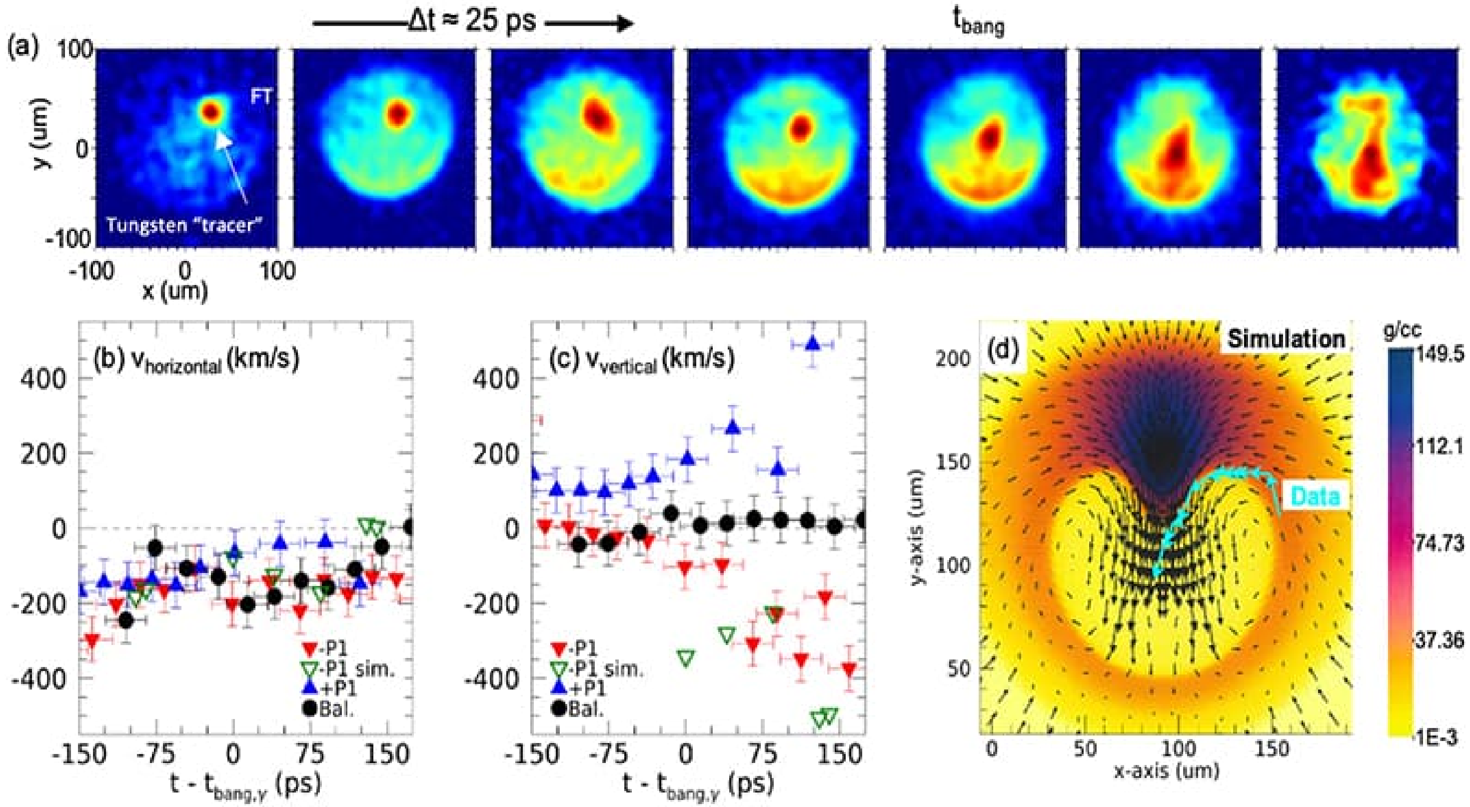


The ablation pressure results in a shock wave within 5 ns



- **While the outer capsule layer expands, the absorber implodes into the fuel**
- **Simple model estimate burn after just 20 ns**
- **Compression factors in excess of 1000 are necessary**

Measured and simulated flows in ICF hot spot



(a) Time-resolved x-ray emission is used to track the bright "tracer" particle during an implosion. (b) Horizontal and (c) vertical flow velocity for three asymmetry drives: Upward (▲) and downward (▼) driven implosions show strong large vertical flows. (d) Streamline data of internal flows from downward (▼) drive, overlaid on flow field from 2D HYDRA simulation at tbang + 65 ps.

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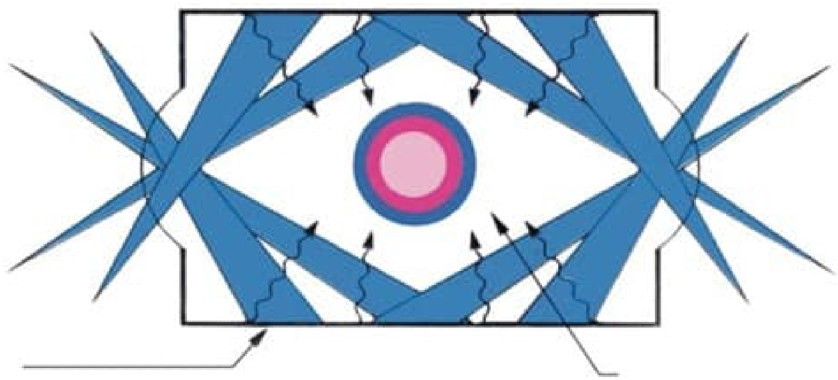
The two primary methods to compress fuel are direct and indirect drive

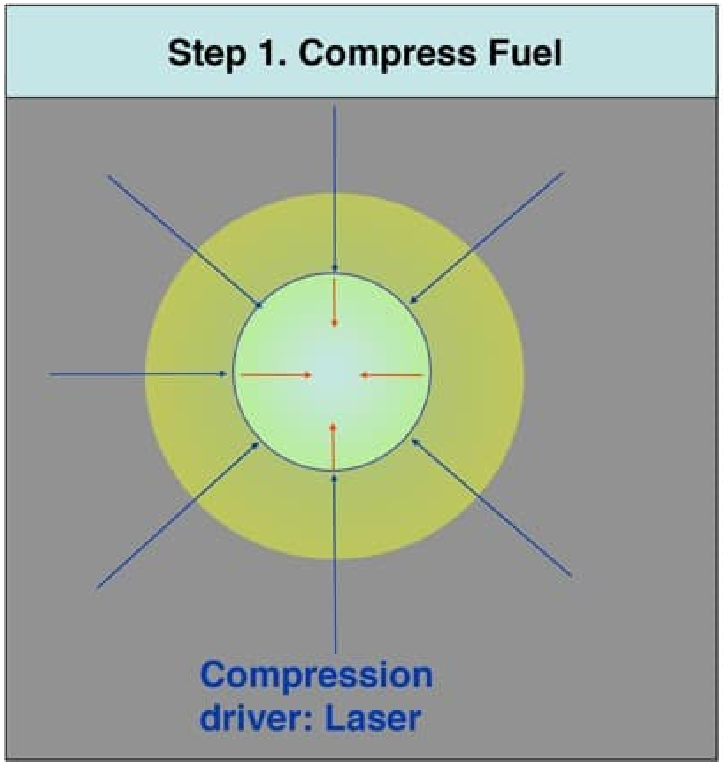
direct drive

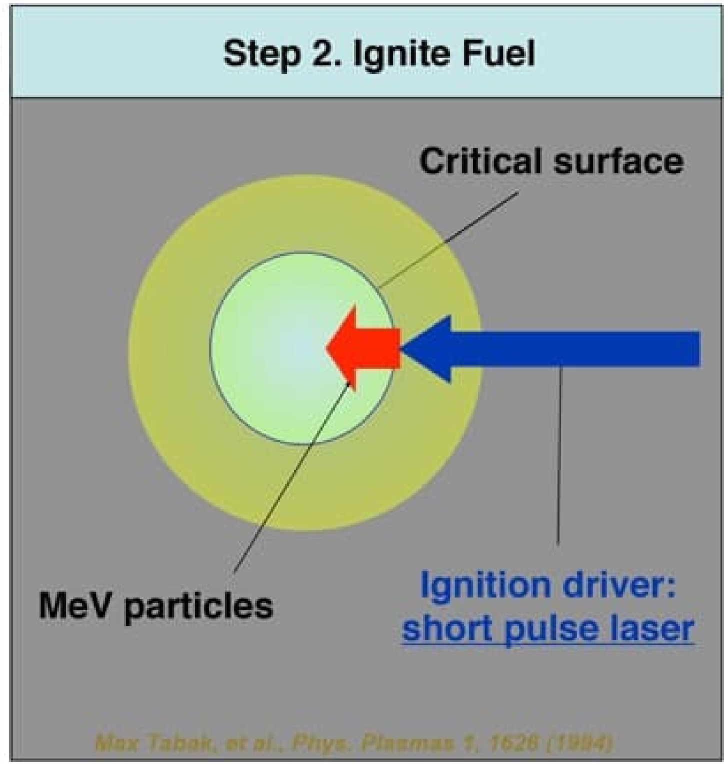
indirect drive



- **Driver = laser, converted into x-ray source**
- **Direct drive is more efficient, but symmetric implosion is harder to achieve**

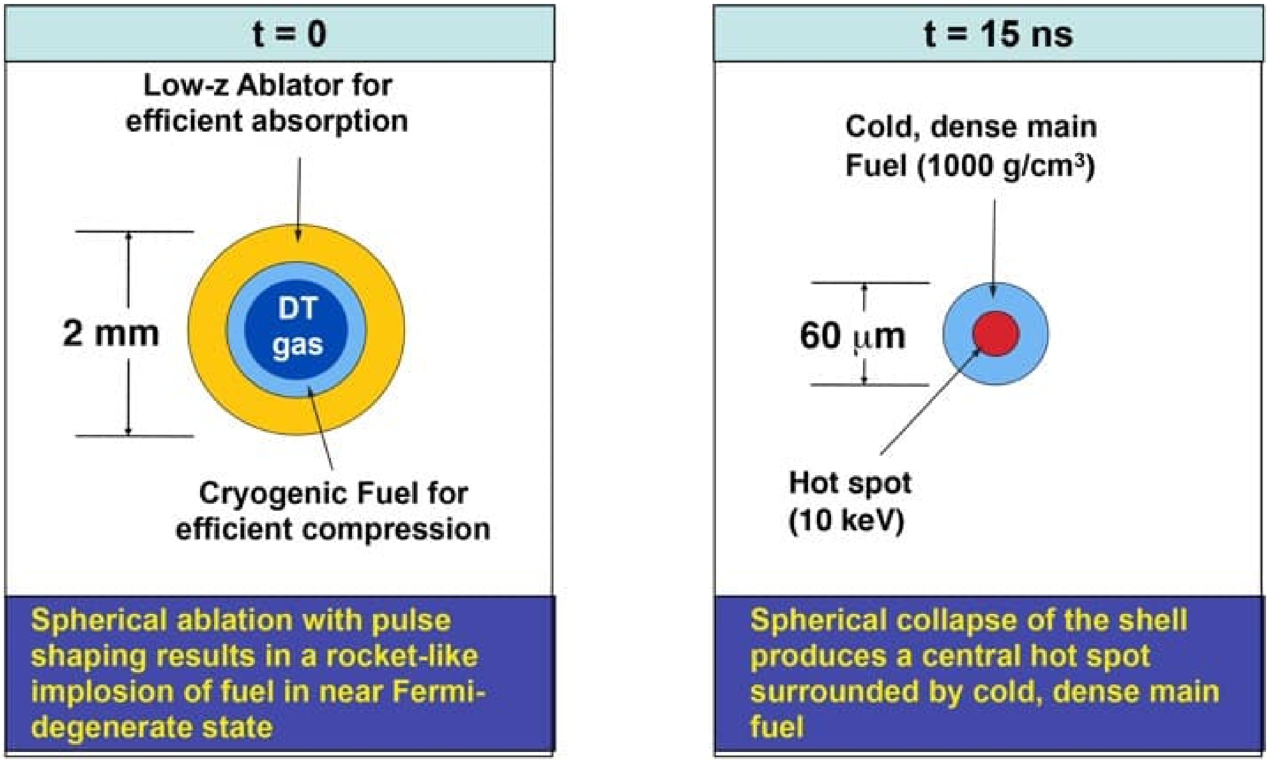
Fast ignition separates compression and ignition of the fuel (spark plug in gas engine)





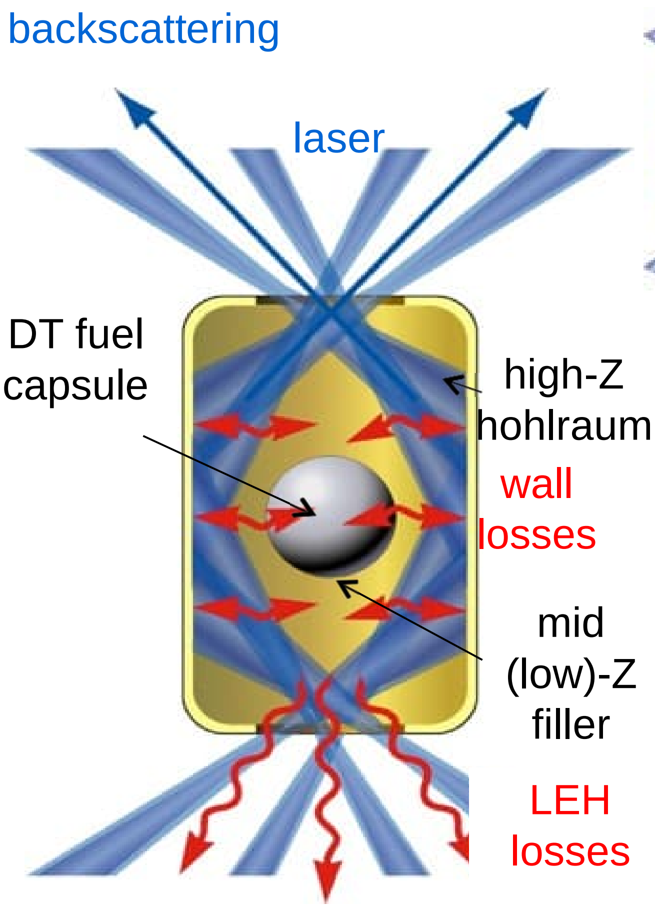
- **Main advantages: less compression required (= more fuel) and symmetry relaxed**

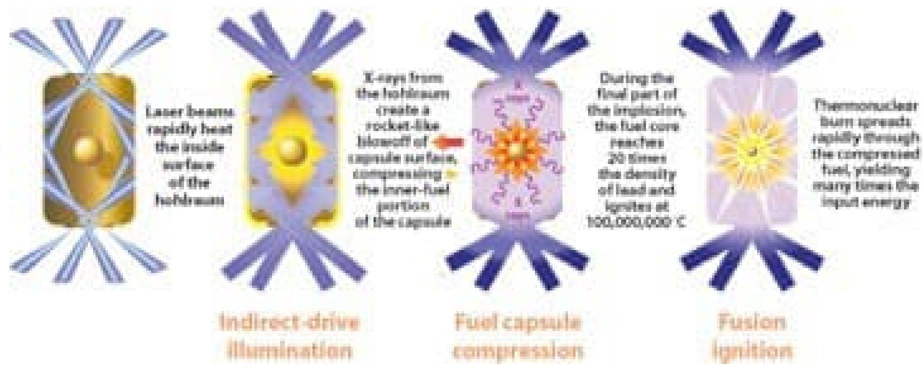
Inertial confinement fusion ignition is driven by the ablation-driven rocket force



- **C.f., convergence ratio (R_i/R_f) ~ 30 (basketball to pea), implosion velocity ~ 300 km/s (1/2 of galactic escape)**

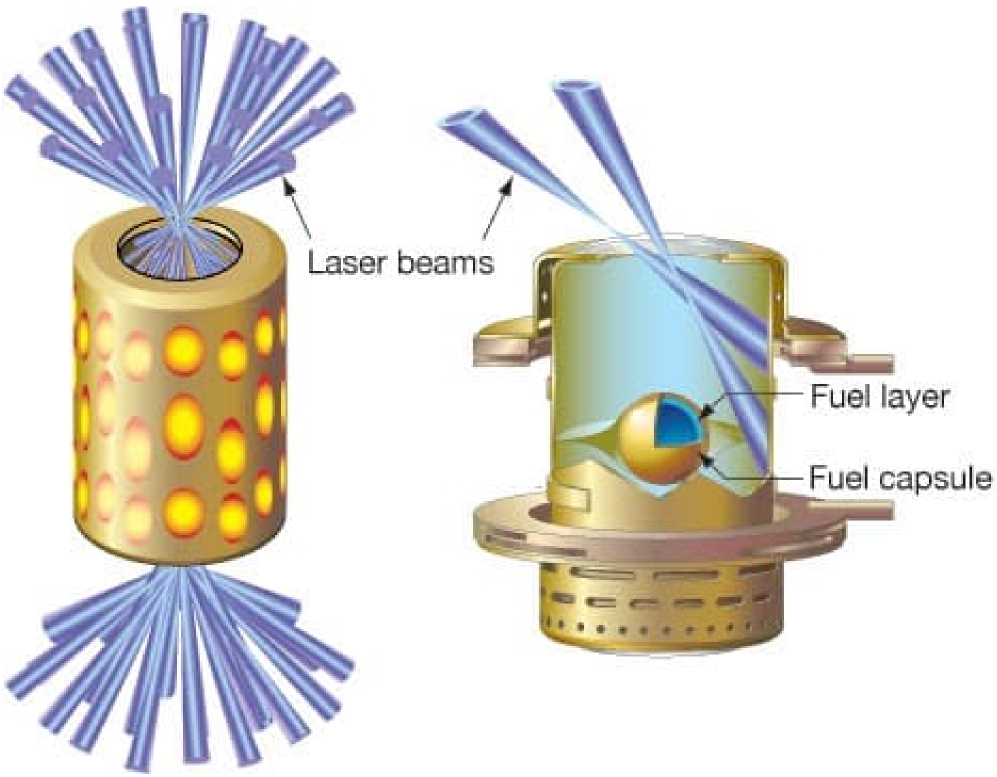
In indirect drive, DT fuel is compressed by x-rays produced by laser heating of a high-Z hohlraum

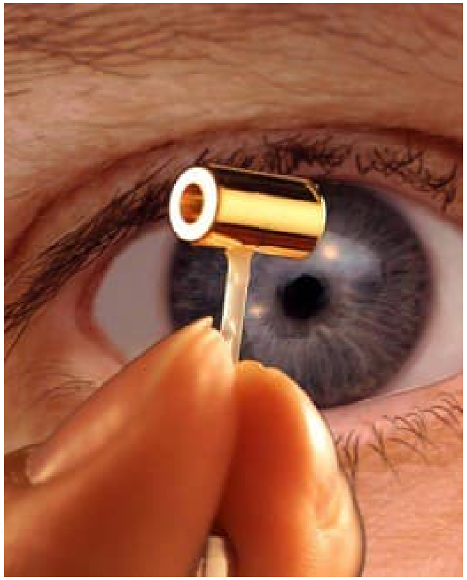




- **Optimization of hohlraum energetics**
  - Laser absorption, backscattering, re-emission efficiency
- **Compression symmetry, laser timing**

Indirect drive (e.g., laser irradiation of an gold hohlraum) is the most promising concept





http://lasers.llnl.gov

Advanced ignition schemes

- **Separate fuel compression from ignition. First step with slow implosion which is less prone to instabilities. Second step: Ignition with**
- **High-intensity pulse of electrons or ions (Fast Ignition)**
- **Short and intense laser pulse (Shock Ignition)**
- **Magneto-inertial fusion: use targets embedded in magnetic fields to reduce heat losses**

Presemo quiz #1

https://presemo.aalto.fi/fet/

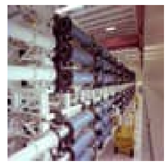
The National Ignition Facility (NIF)

Inertial fusion is tightly coupled to development of high-power lasers

1970 - 1980 | 1980-2008 | 2009-2012 | 2020?

JANUS
100 J IR

ARGUS
1 kJ IR



SHIVA
10 kJ IR

NOVA
30 kJ UV

NIF: 1.8 MJ UV,
500 TW

LIFE

US line of laser development ⇒ fission/fusion hybrids

- **Laser / inertial fusion development also in the EU (France) and Japan**

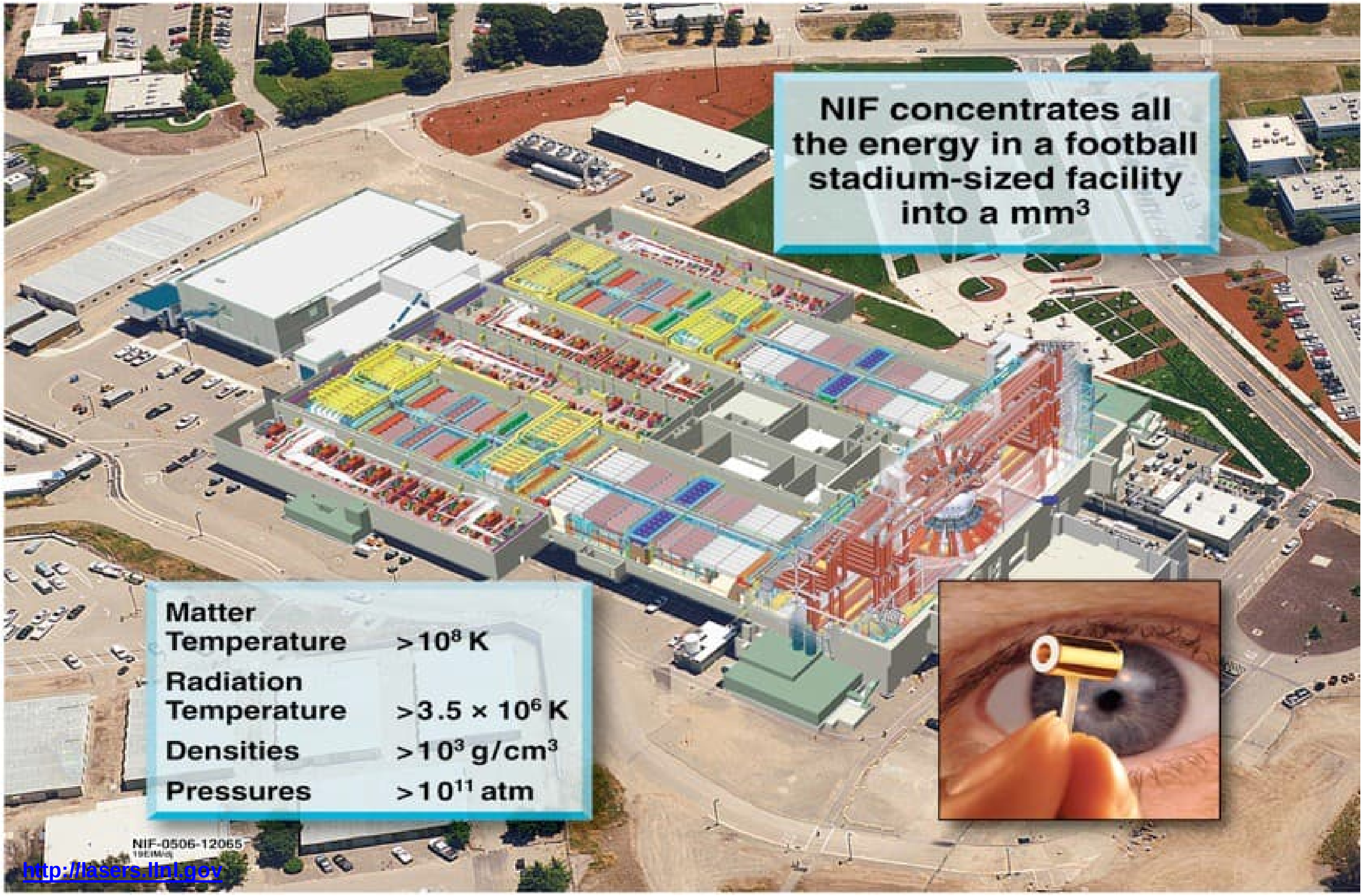
The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory, California

NIF is currently the worlds's largest laser facility (total cost approx. 4bn USD)

The roof top of the facility would fit three American football and 2 soccer stadiums

http://lasers.llnl.gov

NIF concentrates all the energy in a football stadium-size facility into a mm^3 of DT fuel



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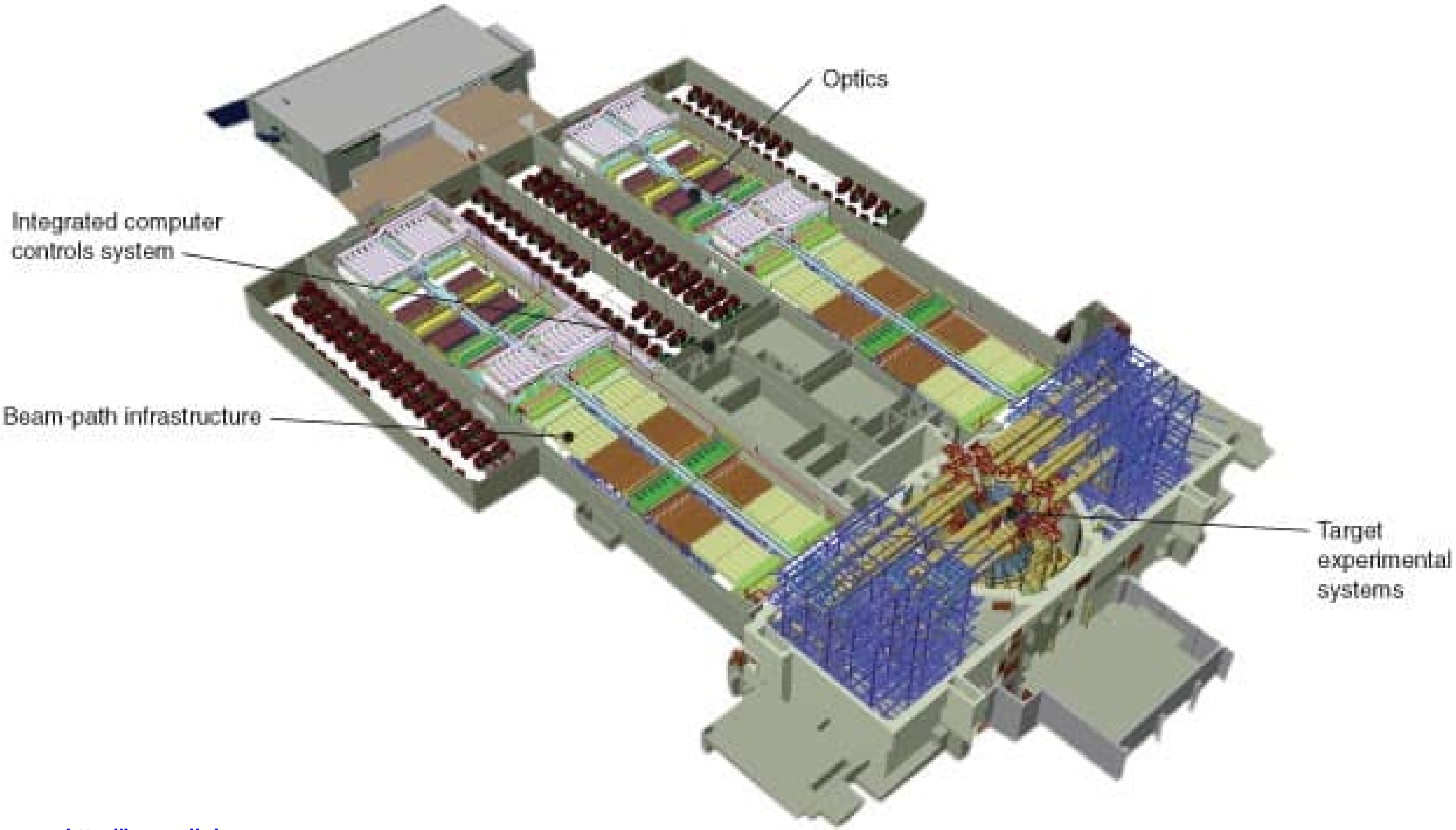
The main pieces of NIF are the laser beam production, the beam-path infrastructure and the target hall



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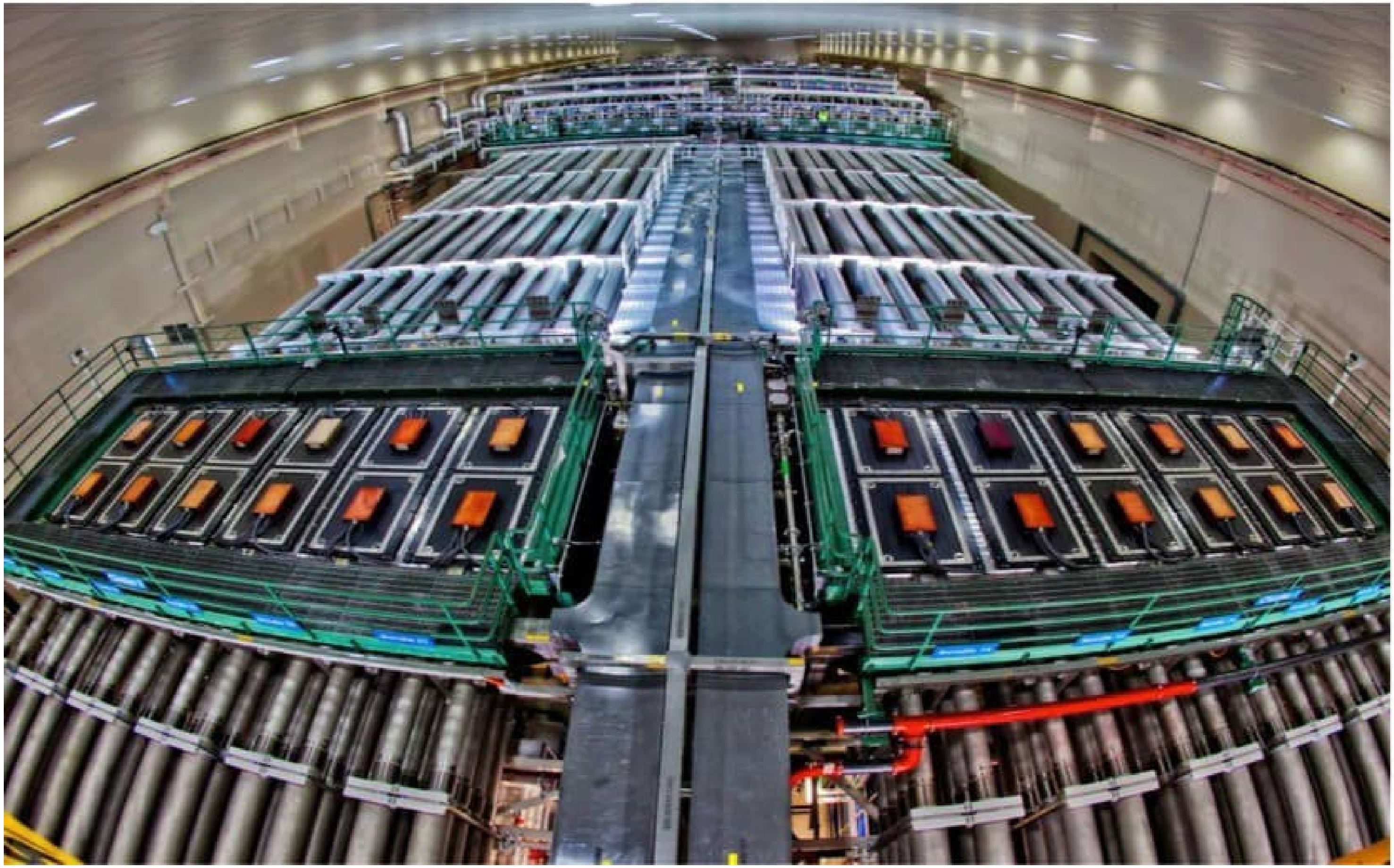
View of the laser banks filling a high-bay area the size of a football stadium (192 beams)



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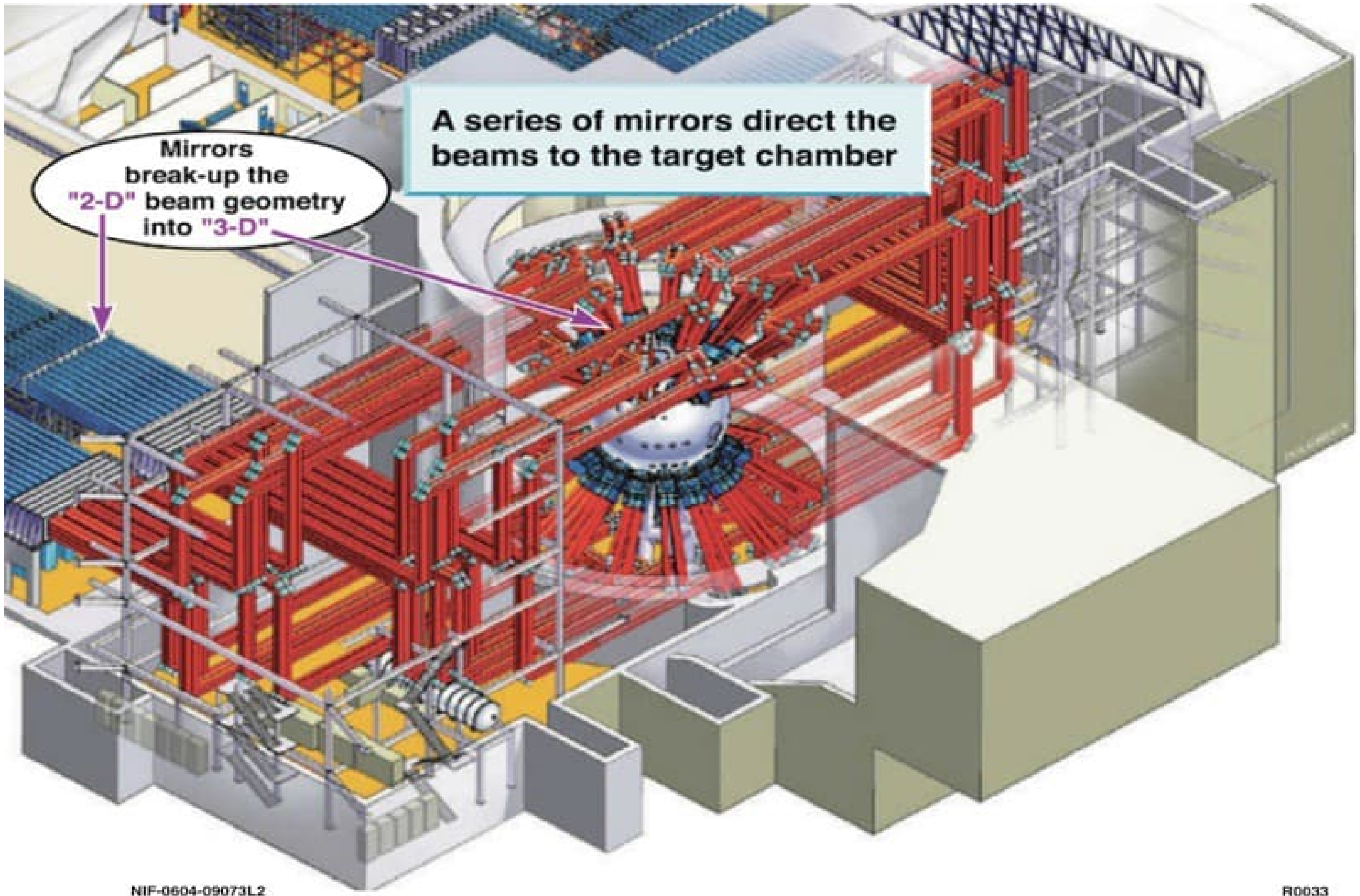
A series of mirrors direct the beams to the target chamber



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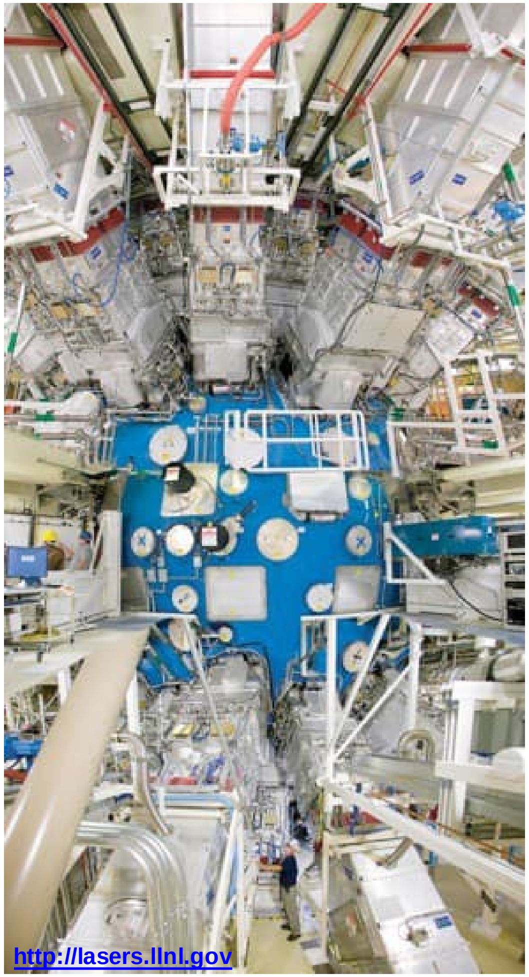
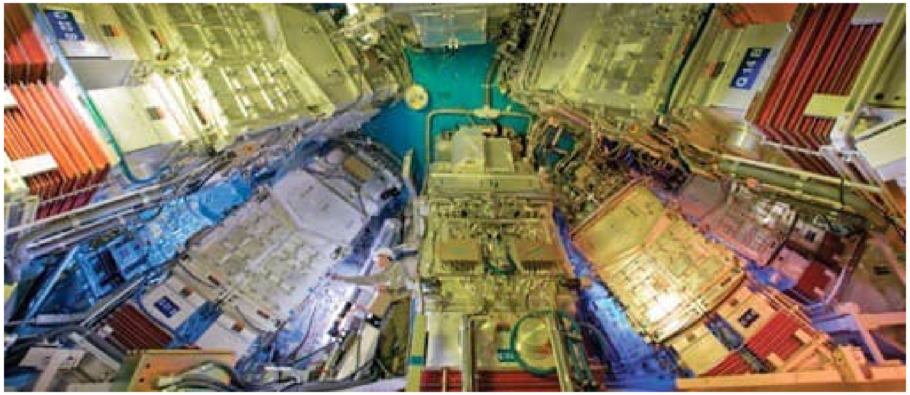
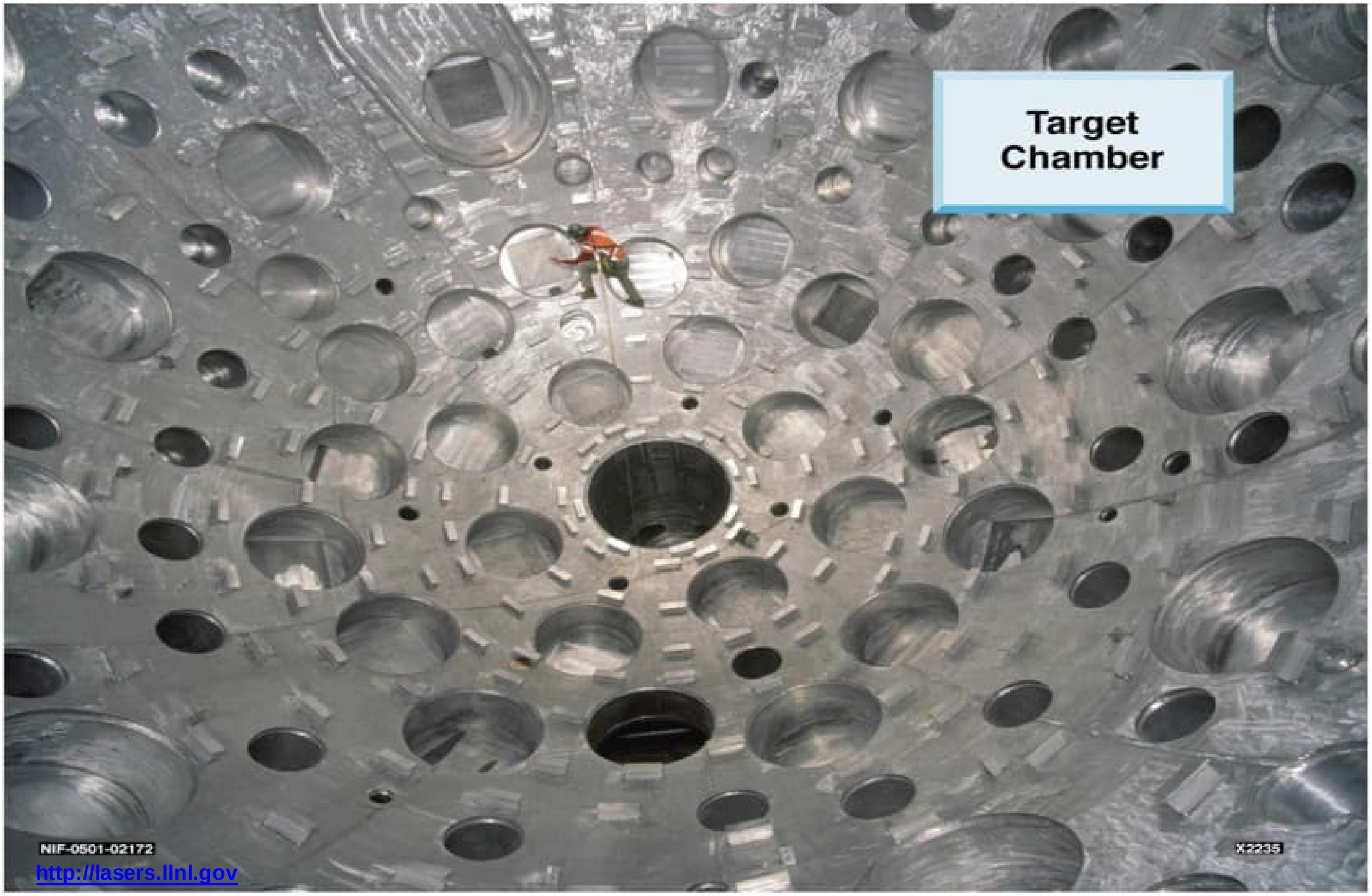




The NIF (spherical) target chamber is 10 m in diameter and 130 tons heavy



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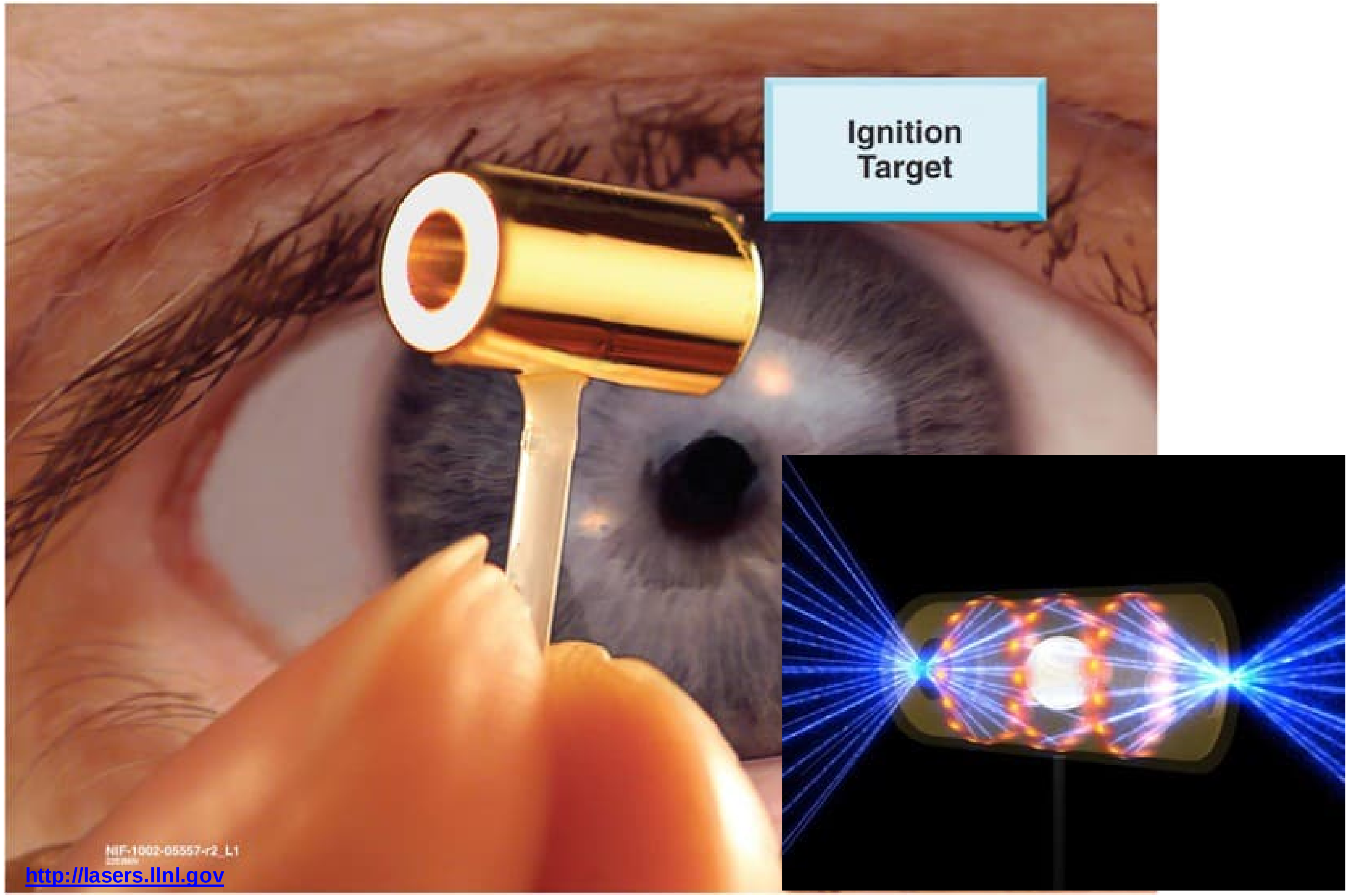
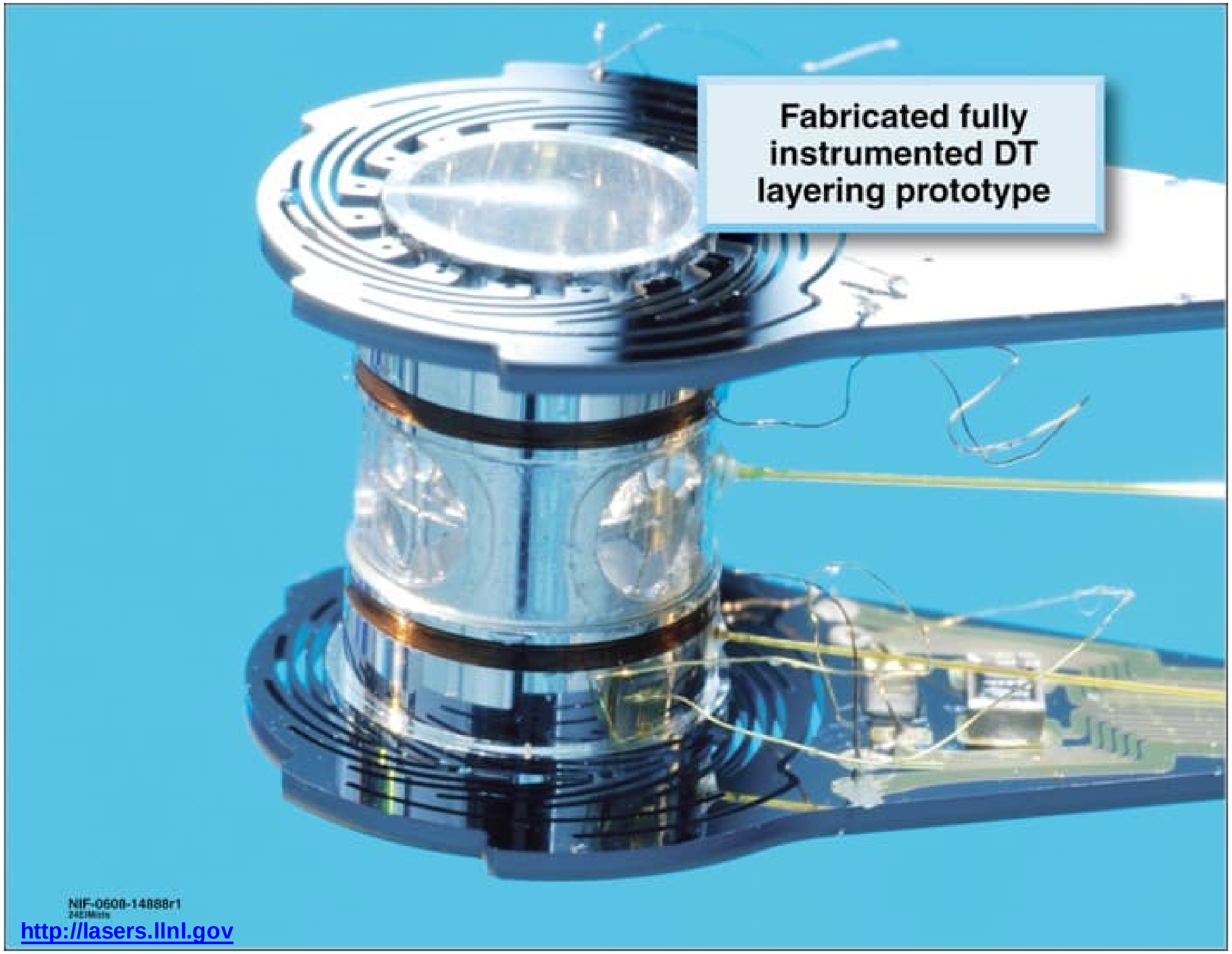
In NIF, laser energy from a 192-beam system is bundled onto a sub-centimeter capsule

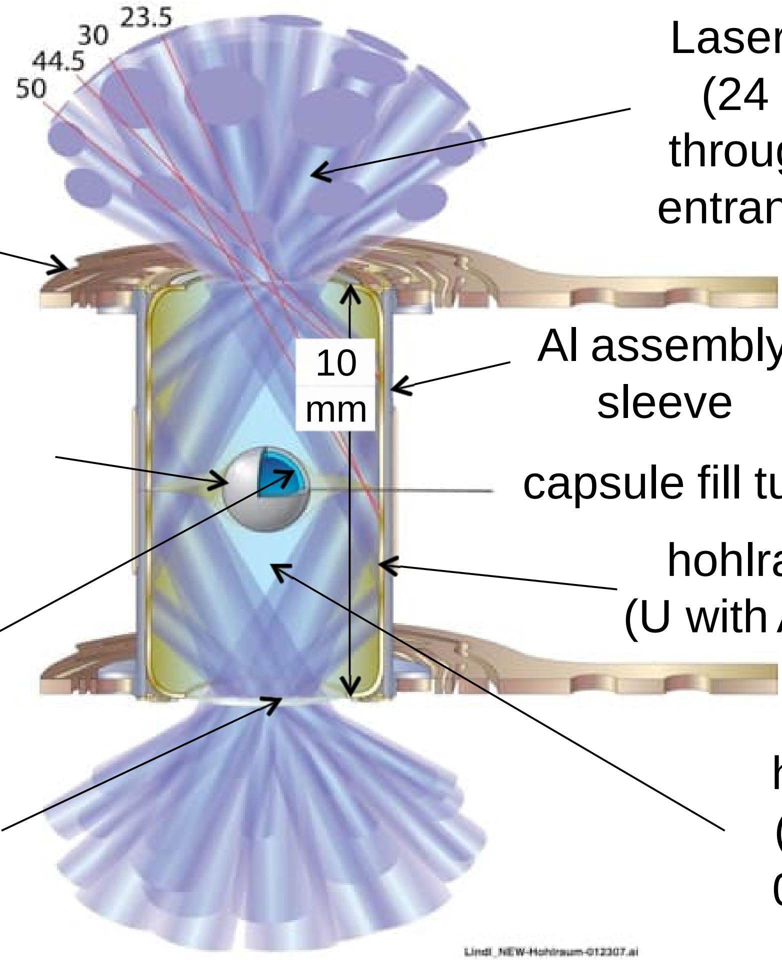
The ignition target is an about 10 mm long cylinder for indirect drive



Fabricated and fully instrumented prototype



Example of capsule design: graded-doped, beryllium capsule in a Au or B lined hohlraum



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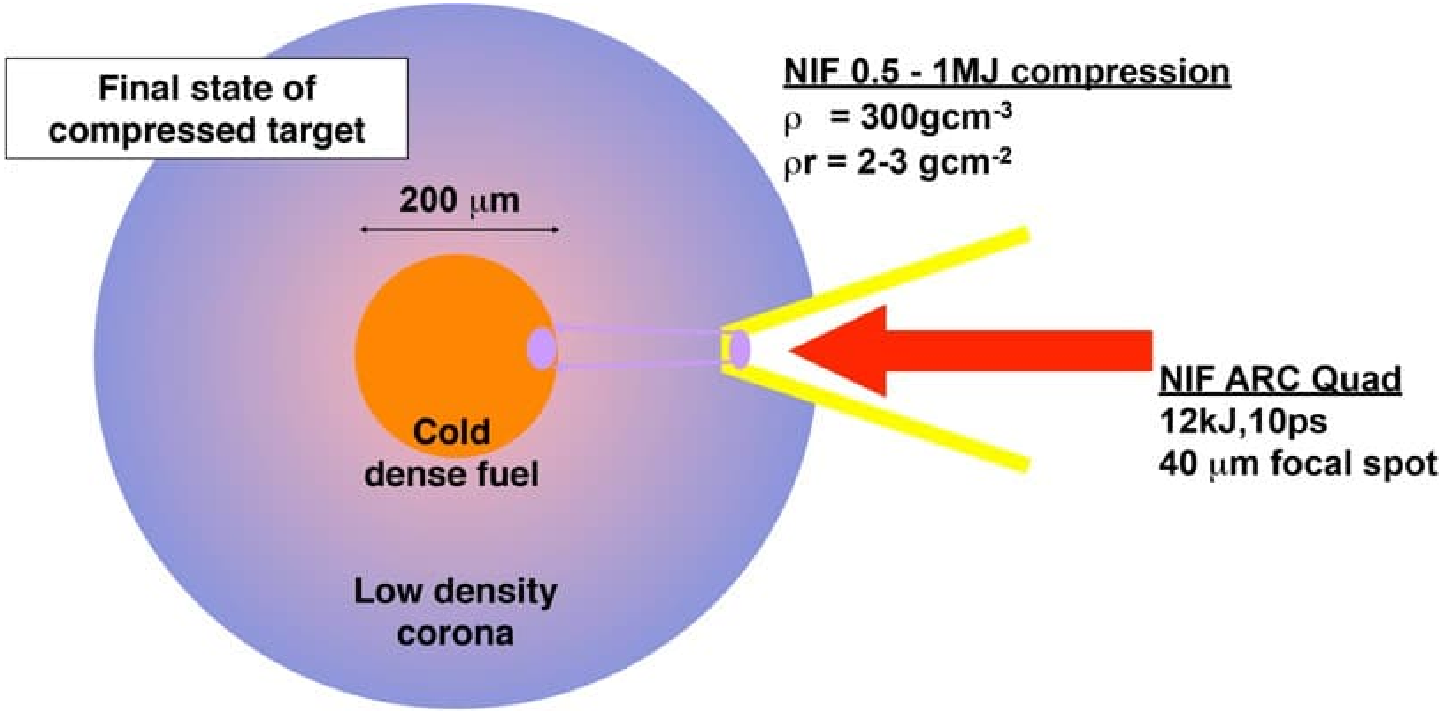
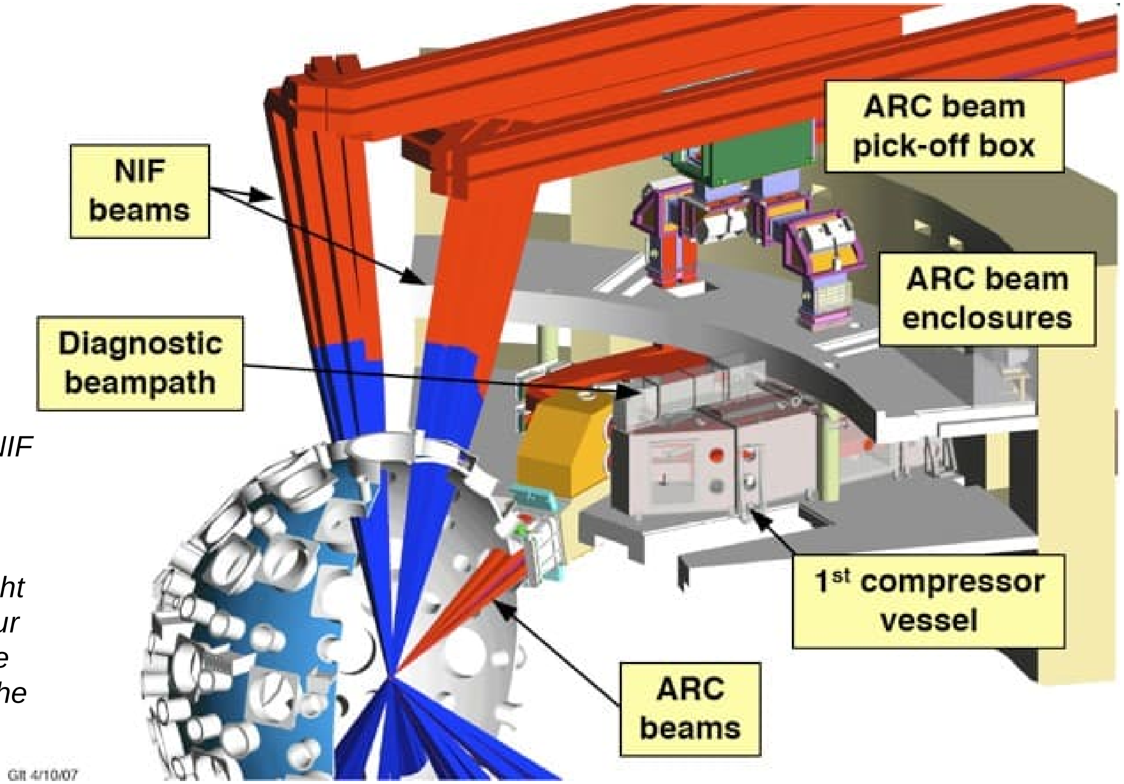
A proof-of-principle fast-ignition experiment is planned at NIF



- **Coupling efficiency at full hydro scale**
- **Determine short-pulse laser energy for high gain and high yield**

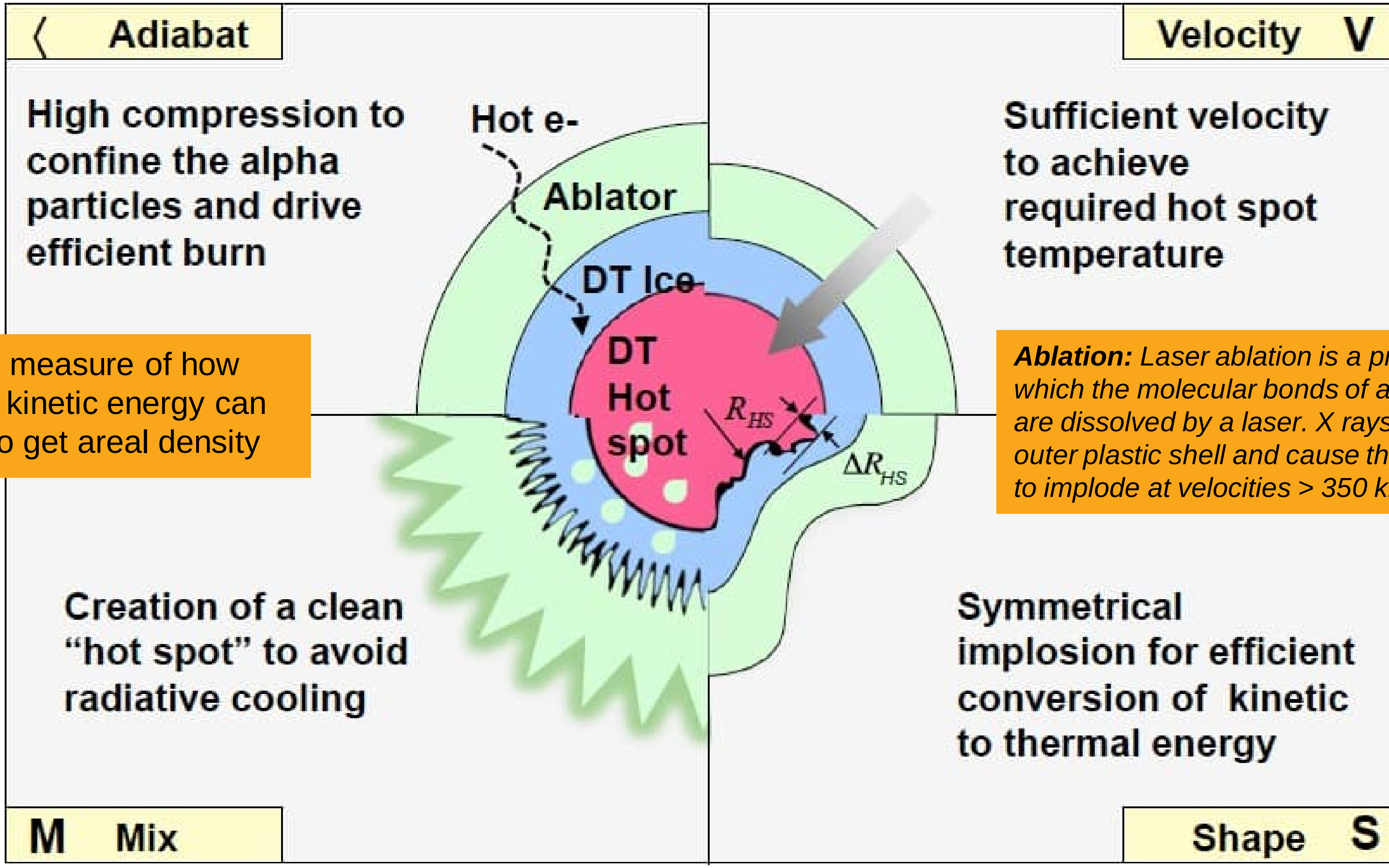
One quad of NIF beams is being converged for high-energy, short-pulse operation at 7.7 kJ and 5 ps

Quad: *A group of four NIF main laser beamlines. Two quads = bundle, six bundles = cluster.*
Bundle: *An array of eight laser beams stacked four high and two across, the basic building block of the NIF main laser system.*



- **Advanced Radiographic Capability (ARC) compressors are installed and operational in 2011**

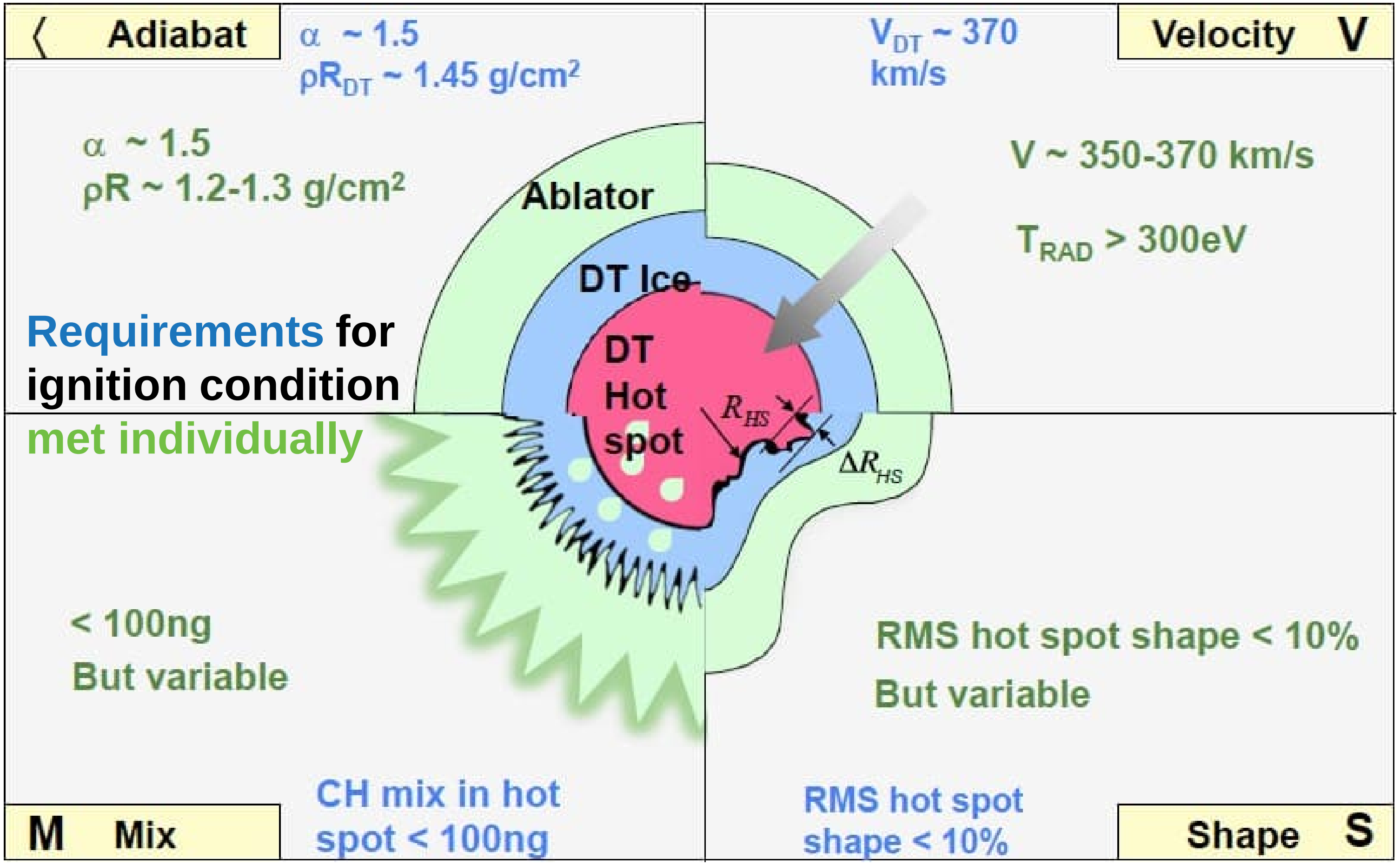
The focus of present research is on improving the fuel capsule



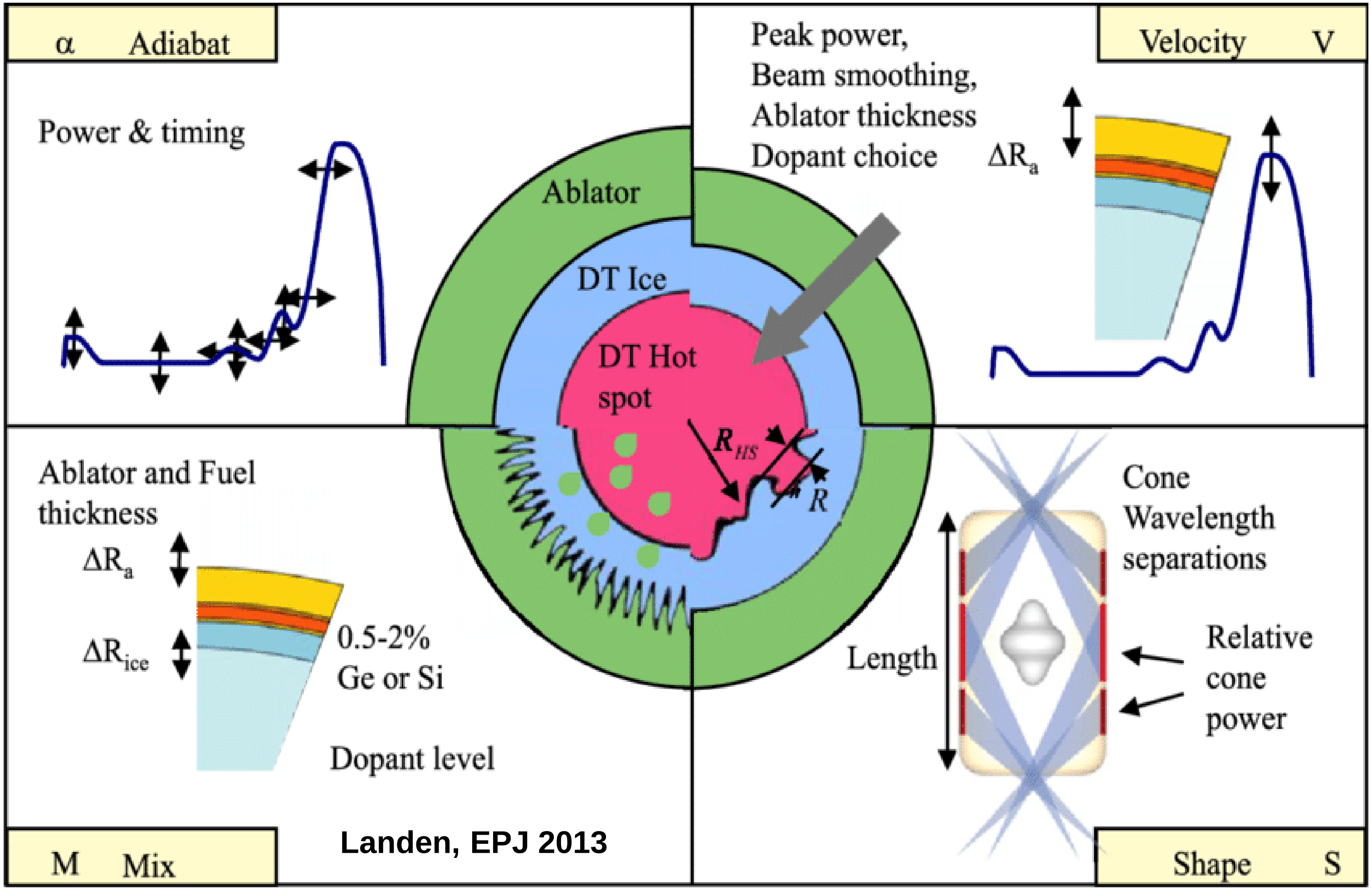
Adiabat ~ measure of how efficiently kinetic energy can be used to get areal density

Ablation: *Laser ablation is a process in which the molecular bonds of a material are dissolved by a laser. X rays ablate the outer plastic shell and cause the capsule to implode at velocities > 350 km/s.*

The focus of present research is on improving the fuel capsule



To achieve better performance, the dopant levels and ablator thicknesses need to be improved



Landen, EPJ 2013

How NIF works?

Video: How NIF works (5.21)

Motivation: to get idea how NIF works from technological point of view

Record experiment in NIF (Aug 2021, preceding the ignition experiments)

Previous record in fusion yield achieved Aug 2021

- **Aug. 8 2021, NIF made a significant step toward ignition, achieving a yield of more than 1.3 megajoules (MJ)**
- **This is a 25X increase over NIF's 2018 record yield**
- **The experiment built on several advances including:**
  - **new diagnostics**
  - **target fabrication improvements in the hohlraum, capsule shell, and fill tube**
  - **improved laser precision**
  - **design changes to increase the energy coupled to the implosion and the compression of the implosion.**

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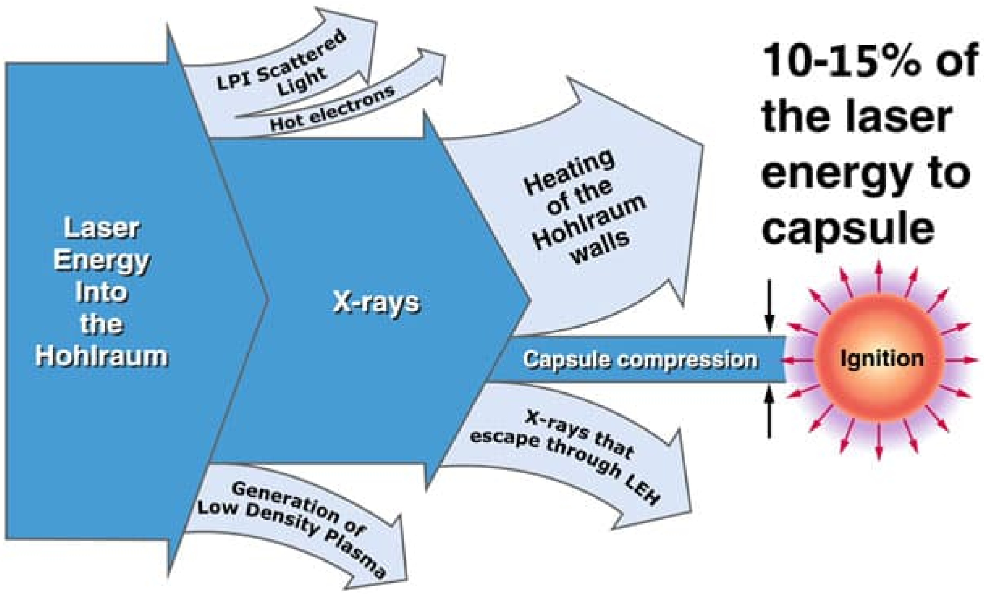
New record required improved energy coupling efficiency

- Of the ~1.9 MJ of laser energy delivered to the hohlraum, only ~10%–15% is absorbed by the capsule (Zylstra PRL 2021)



- The majority of the energy absorbed by the capsule is invested in ablation, with only a few percent coupled into the imploded fuel's kinetic energy (~10kJ in the record experiment)

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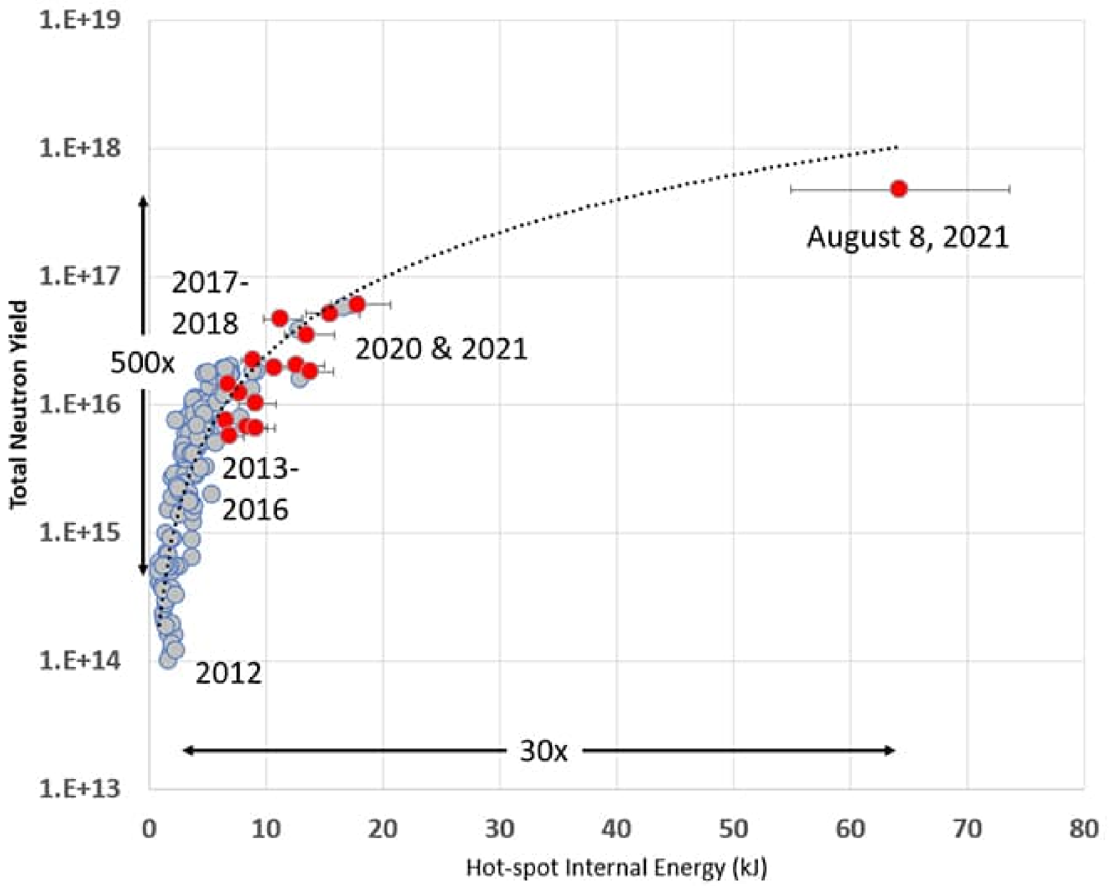
New record in neutron yield is 8x higher than in spring 2021



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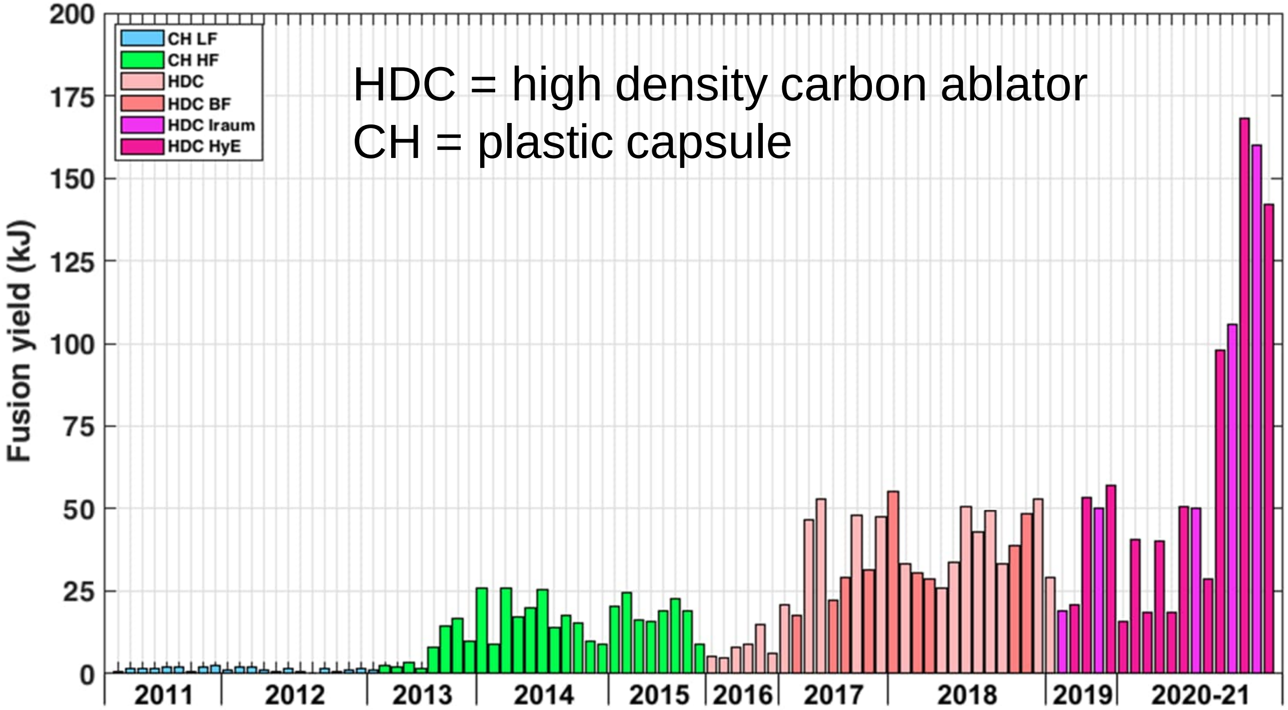
HDC capsule contributed to the new record

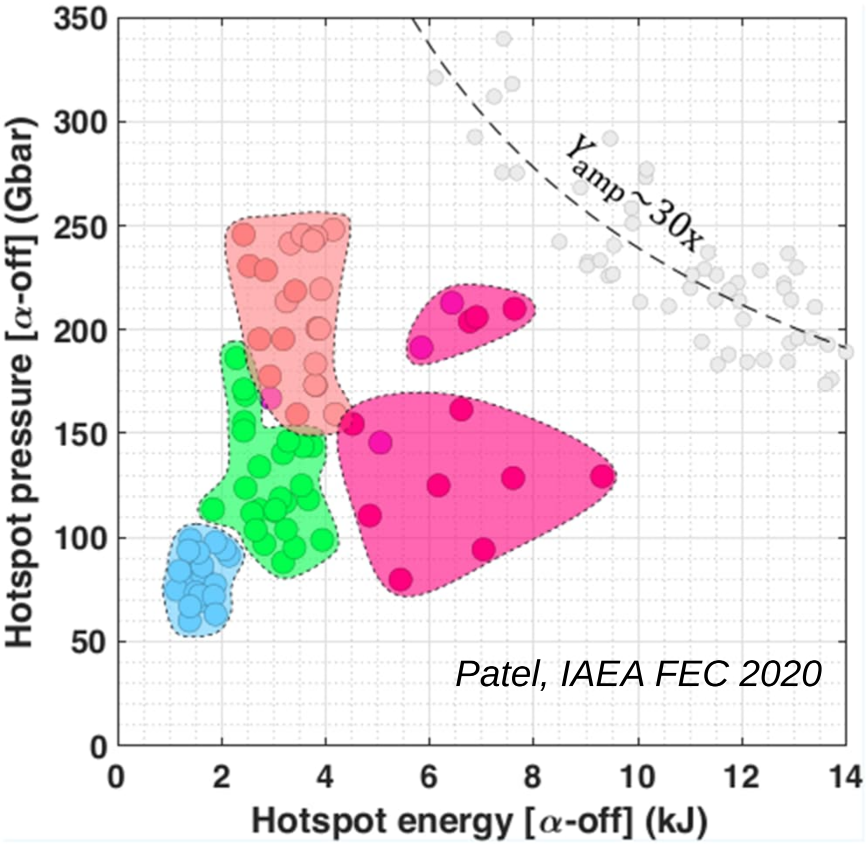


Patel, IAEA FEC 2020

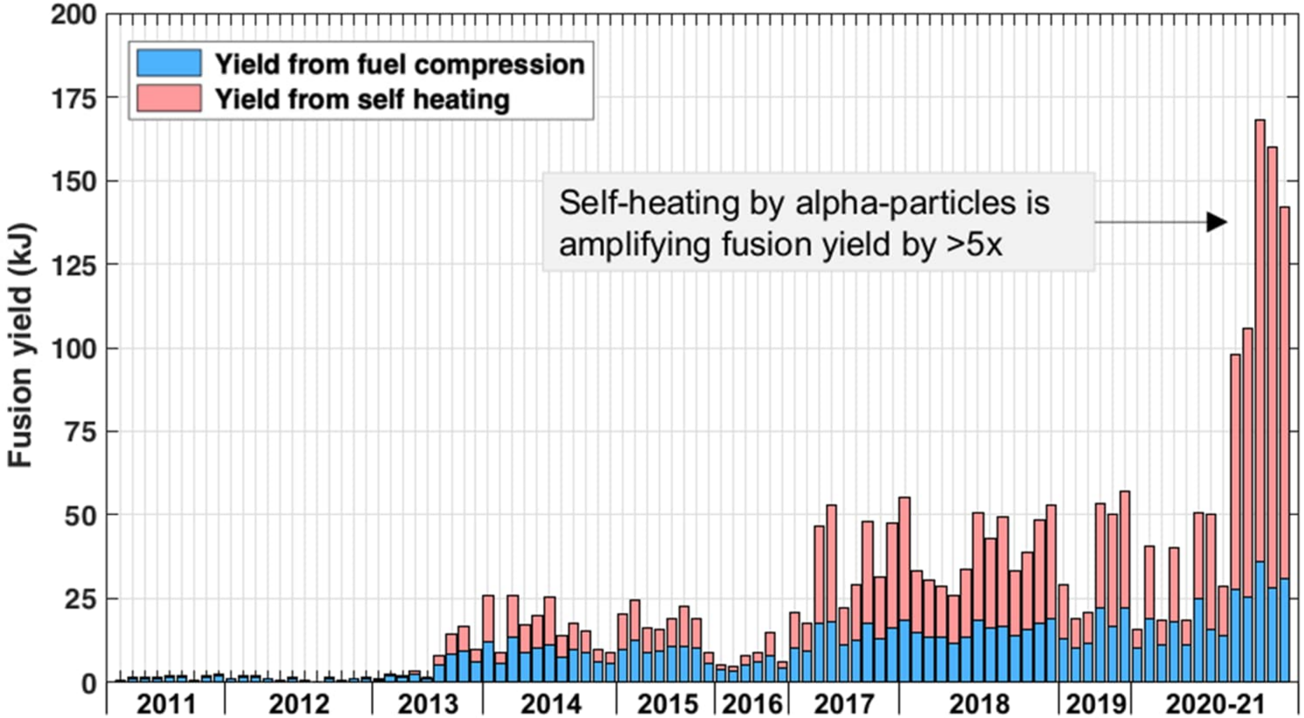
- **Quality of the high-density carbon, or diamond, target capsule used contributed to the record**

Recent experiments are close to ignition

- **Ignition boundary ($Y_{amp} \sim 30x$) is quite well defined in hotspot pressure-energy space**
- **1.35MJ record is 70% of the energy of the laser pulse that triggered it**



Self-heating amplifies fusion-yield by factor 5

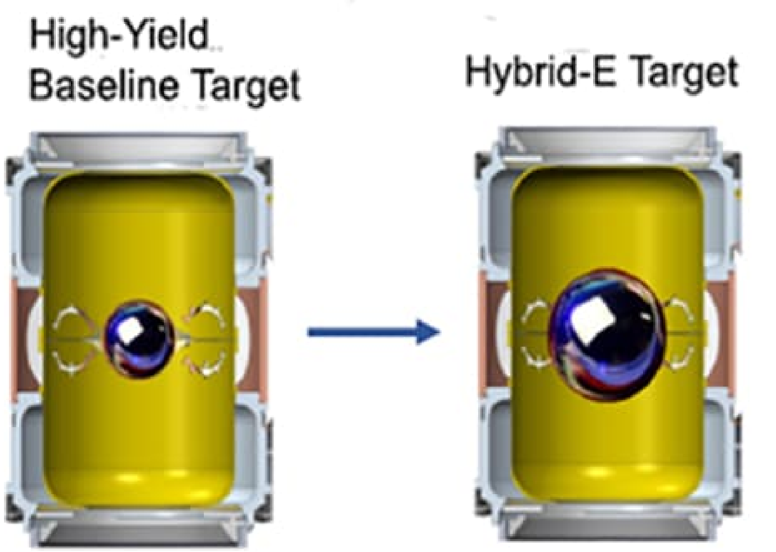


Patel, IAEA FEC 2020/2021

- **In Aug. 8 2021, a yield of more than 1.3 megajoules (MJ) which 8x more than in spring 2021 (in figure)**

Larger capsules were used in the record for increases energy efficiency

- **Capsules about 15 % bigger than in previous high-yield experiments were used**
- **Decreasing ratio of the hohlraum size to capsule size enhances energy efficiency but...**

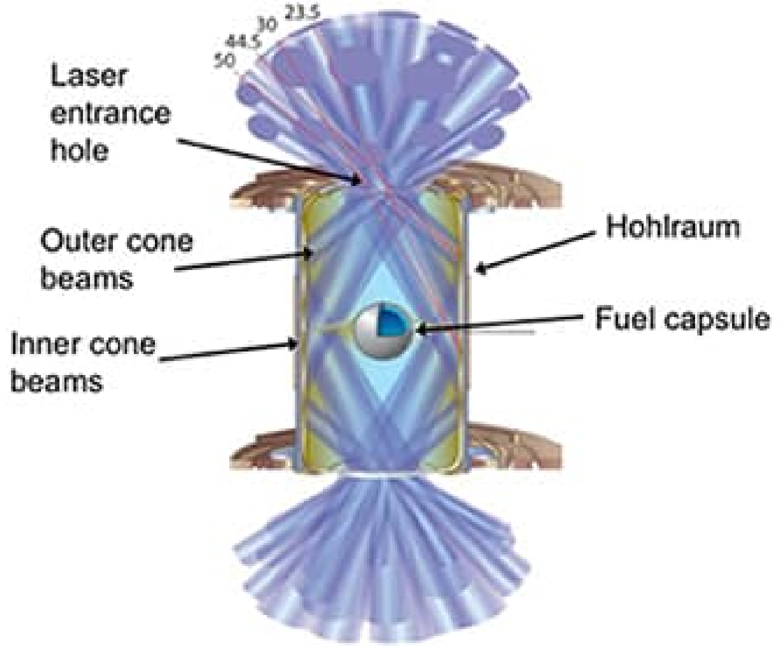


- **...control of other aspects such as symmetry of the x-ray drive on the capsule then more difficult**

lasers.llnl.gov

HybridE (HyE) -design was used in record

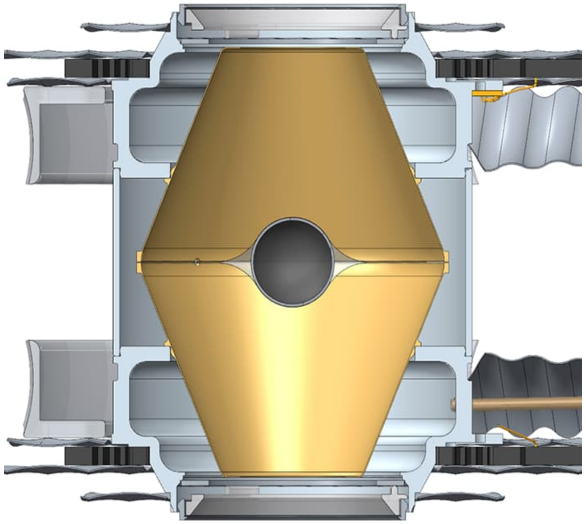
- **Cylindrical 11.24mm x 6.4mm hohlraum**
- **Made of Au-lined depleted uranium and filled with helium gas.**
- **Four laser entrance holes for beams (as shown in figure)**

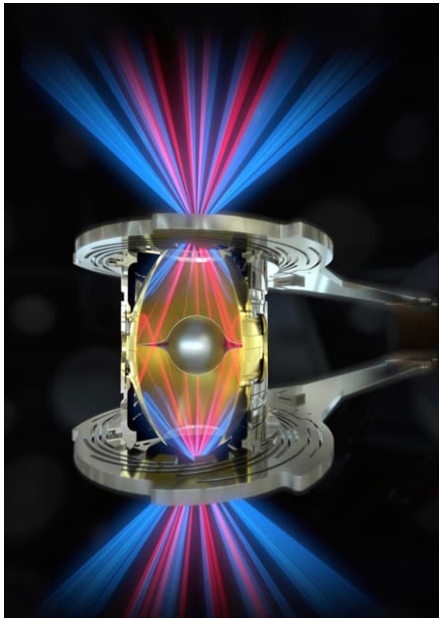


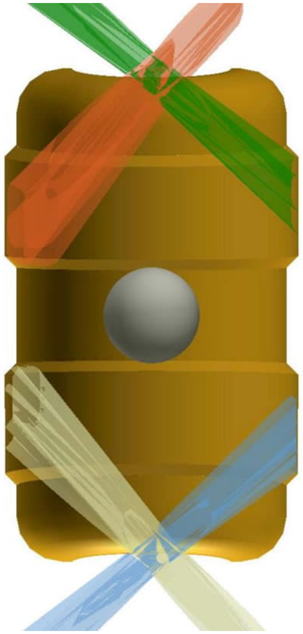
- **Three-shock laser pulse shape with adiabat α ~ 2.5.**
- **Ratio of the inner power to total power 33%**

(A.B.Zylstra, Phys. Rev. Lett. 126, 025001 (2021))

Progress in Hohlraum design







- **Different hohlraum designs are still tested for improving efficiency**

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Ignition experiment in NIF (Dec 2022)

Breakeven in NIF (press release 13.12.2022)

- For the first time more energy from a fusion reaction than was delivered to the capsule.
- The input of 2.05 megajoules (MJ) to the target heated the diamond-shelled, spherical capsule to over 3 million degrees Celsius and yielded 3.15 MJ of fusion energy output.
- This is scientific break-even which has never been achieved before in fusion devices (not even in tokamaks)

Breakeven in NIF

- **Ignition shot was part of a new NIF campaign that began in September 2022**
- **a new laser capability and a thicker capsule for the fusion fuel were introduced and changes made to improve implosion symmetry**
- **the net energy yield confirmed using multiple independent diagnostics to measure the number of neutrons that escaped the reaction, including radioactive decay and a magnetic spectrometer**

Energy gain Q>1 gives scientific breakeven but...

<u>"Engineering" breakeven:</u> takes into account that

- **Only a fraction ($1-f_{ch}$) of fusion energy goes to blanket**
- **Cooling fluid of blanket drives steam turbines with efficiency $\eta_{elec} = 35 - 40$ %.**
- **Fraction f_{recirc} of P_{elec} recirculated back into the heaters**
- **η_{heat} is the efficiency that power supplied to the heating systems is turned into heat in the fuel**

$$P_{heat} = (1 - f_{ch})\eta_{elec} f_{recirc}\, \eta_{heat} P_{fus}$$

Fusion energy gain Q>1 gives scientific breakeven but...

"Engineering" breakeven:

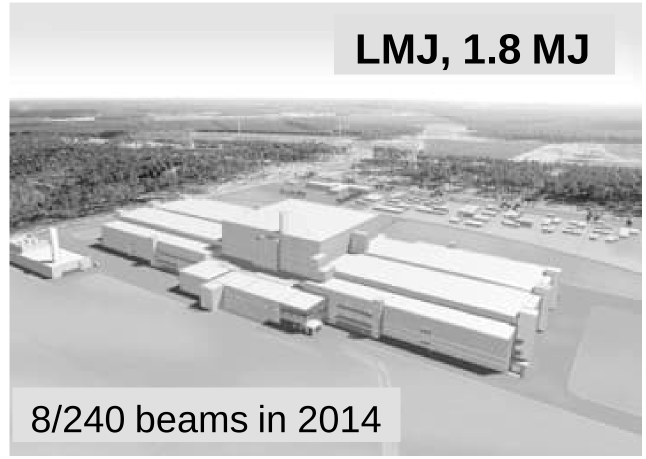
- $\mathbf{Q_E = P_{fus}/P_{heat} = 1/[(1 - f_{ch})\eta_{elec} f_{recirc}\, \eta_{heat}}$
- **For** $f_{ch} = 0.2$ **(D-T),** $\eta_{heat} = 0.7$ **and** $\eta_{elec} = 0.4$ $\longrightarrow$ $\mathbf{Q = 5}$ **for engineering breakeven (**$\mathbf{f_{recirc} = 1}$**) but at least Q > 20 (**$\mathbf{f_{recirc} = 0.2}$**) for significant energy production ("economic breakeven")**
- **Note on ICF: for lasers** $\eta_{heat} \approx 0.015$ **(1.5%)** $\Rightarrow$ **Real gain very low even close to "scientific breakeven". Trick: redefine Q with energy**

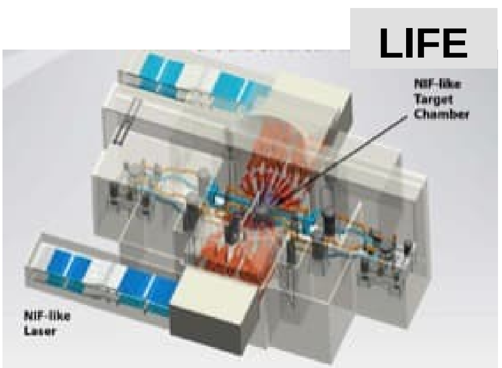
put into the driver $\longrightarrow$ **delivered by the driver**

- In exercises: efficiency of laser absorption and hydrodynamic processes: 10 %, driver efficiency: 10 % (and η_{elec} = 0.4)

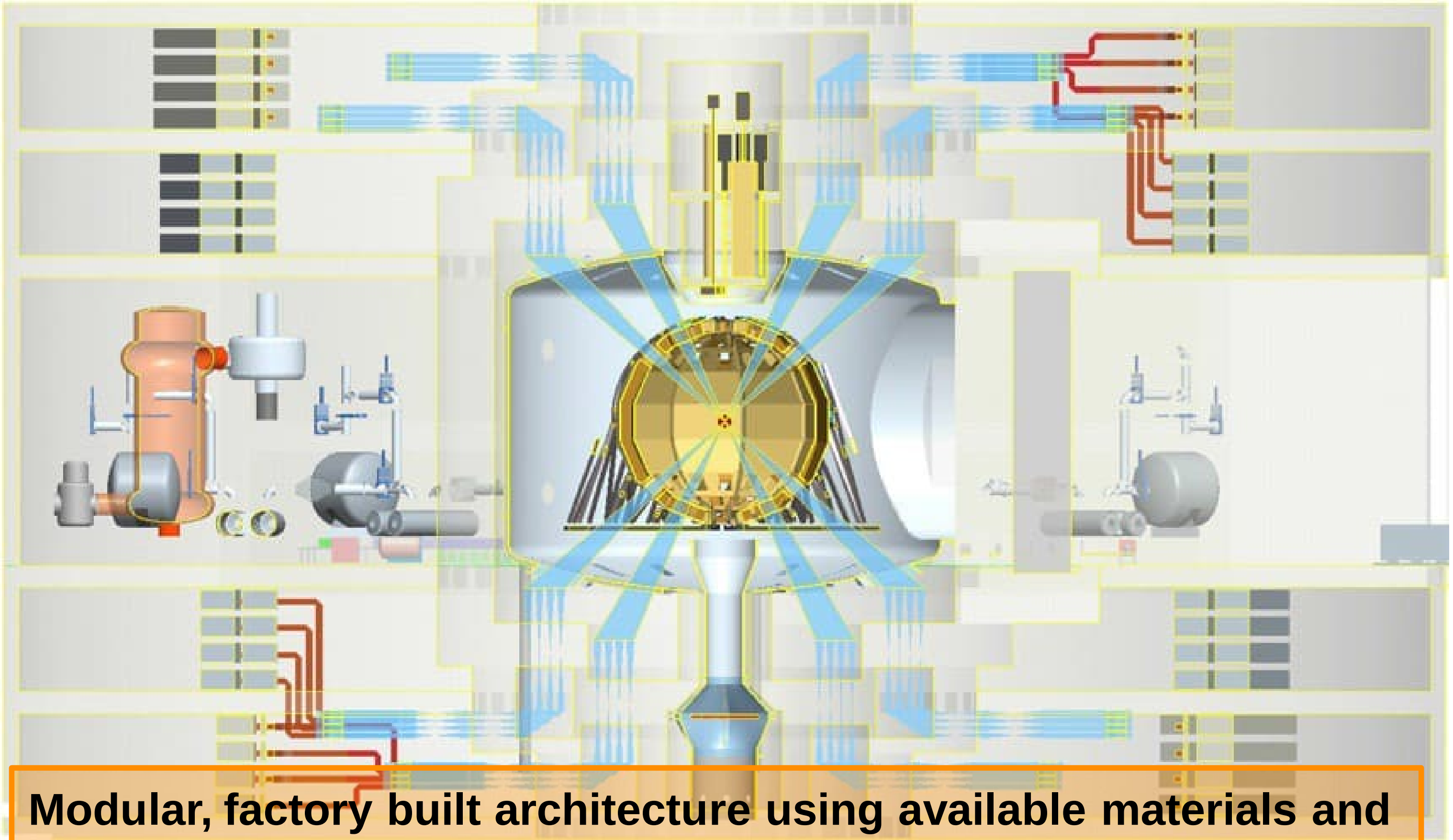
Future plants

Several national and European projects are planned to succeed NIF and LMJ



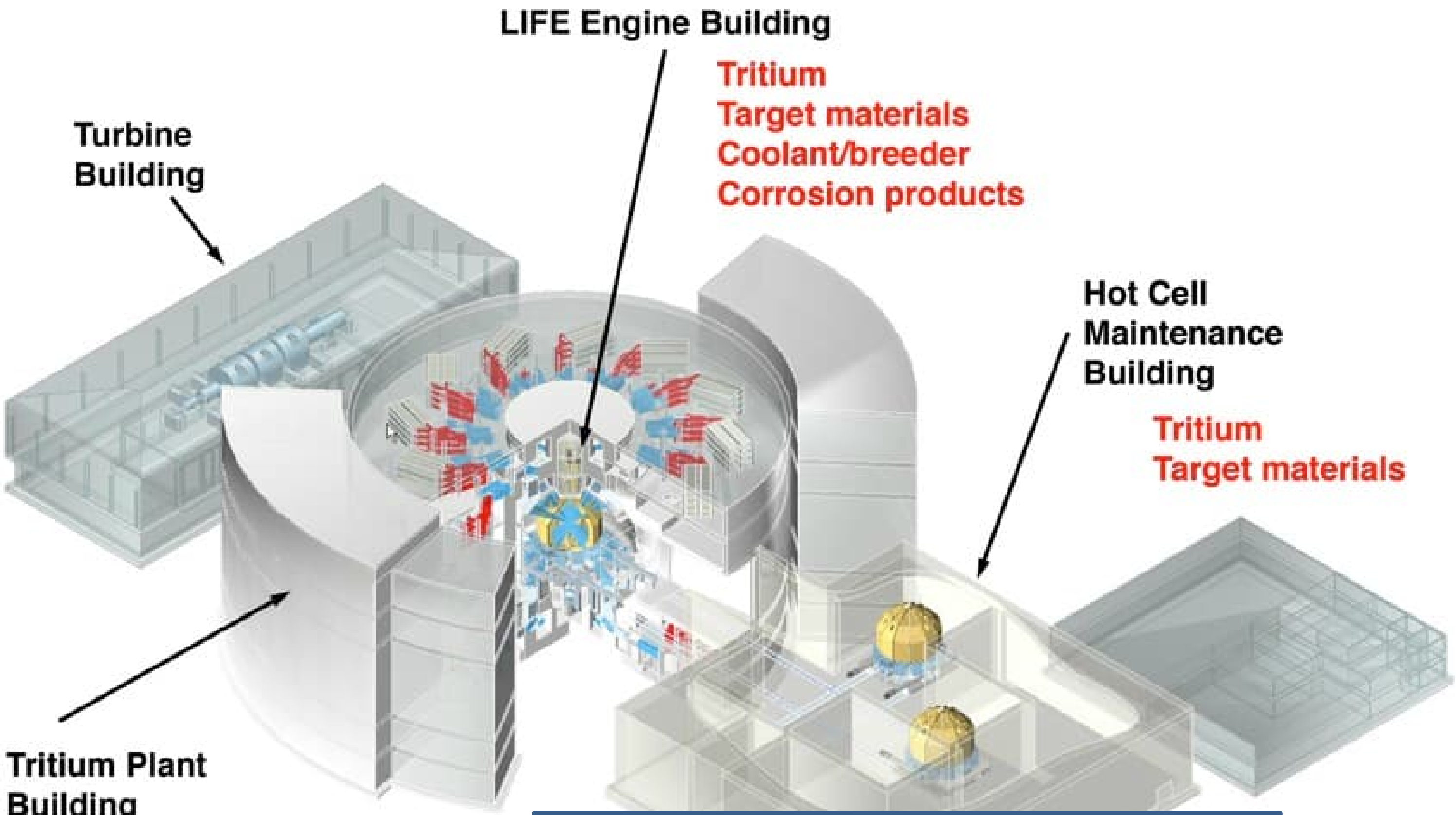


LIFE builds on NIF, configure into an integrated power plate for 400 – 1500 MWe



Modular, factory built architecture using available materials and technology. Optimized for high plant availability

A hazards assessment has been completed to identify potential release pathways



The LIFE effort was quietly cancelled 2013 as ignition was too far away

Presemo quiz #2

https://presemo.aalto.fi/fet/

Summary

- **Fusion of D-T fuel has been achieved in inertial confinement system ⇒ concept was first to achieve scientific break-even (NIF, Dec 2022)**
- **Powerful lasers with energy (MJ) and power (TW) were developed as drivers to reach required power densities**
- **Direct (including fast ignition) and indirect drive (via x-rays, irradiating an Au hohlraum) are used**
- **Performance is limited by hydrodynamic instabilities ⇒ current focus on capsule design and laser pulse timing**
- **NIF is currently the largest inertial confinement fusion facility: 1.8 MJ and 500 TW**
- **Future plants are being considered/designed along NIF**