Inertial Confinement Fusion

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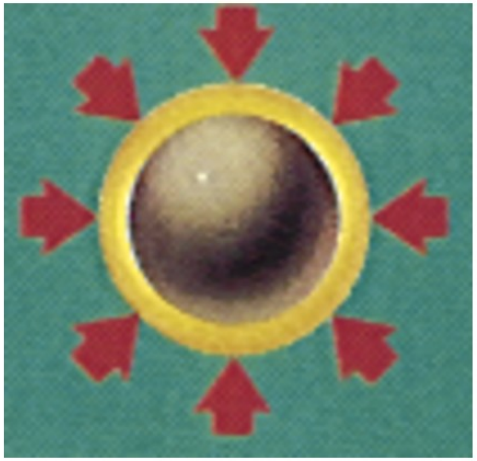
Outline

- **Principles of inertial confinement fusion**
  - **Implosion/compression physics**
  - **Direct and in-direct drive**
  - **Hydrodynamic instabilities**
- **Results and status of the National Ignition Facility (NIF)**
  ⇒ Has ignition been achieved?
- **Plans for future inertial confinement fusion power plants**

Principles of inertial confinement fusion

The basic principle of inertial confinement fusion is the rocket principle

- **Surface heating by intense radiation (e.g., γ, x-ray, laser)**



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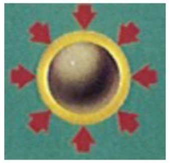
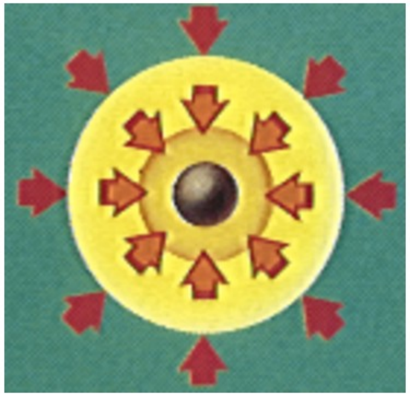


- **Fuel compression by surface ablation and rocket principle**



Ablation: *Laser ablation is a process in which the molecular bonds of a material are dissolved by a laser. During an ignition experiment, laser beams strike the inside walls of the hohlraum and generate x rays that ablate the outer plastic shell and cause the capsule to implode like a spherical rocket at velocities greater than 350 kilometers per second.*

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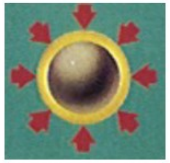
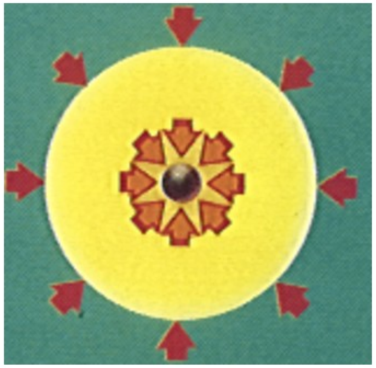
- **Surface heating by intense radiation (e.g., γ, x-ray, laser)**



- **Fuel compression by surface ablation and rocket principle**

- **Central ignition**



The basic principle of inertial confinement fusion is the rocket principle

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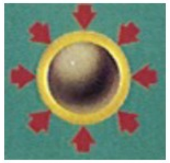
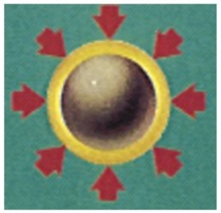


- **Fuel compression by surface ablation and rocket principle**

- **Central ignition**

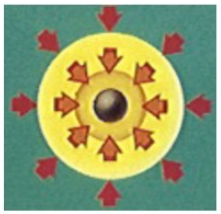
- **Burn**

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

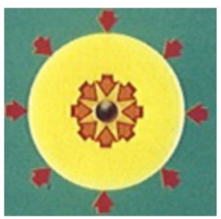


- **Surface heated plasma expands in time:**

$$R(t) = R_f - c_s t$$



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:** $$\frac{R_f}{c_s} \geq \frac{1}{n_0 \langle \sigma v \rangle}$$

Ignition in inertial confinement fusion

- A shell of cryogenic D-T thermonuclear fuel is 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”)
- To measure progress toward ignition, 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:

- Present experiments typically D-D: relevant physics without complication of operation with tritium → no neutrons (for energy production D-T is needed)
- In magnetic confinement fusion τ measured from decay time of plasma energy

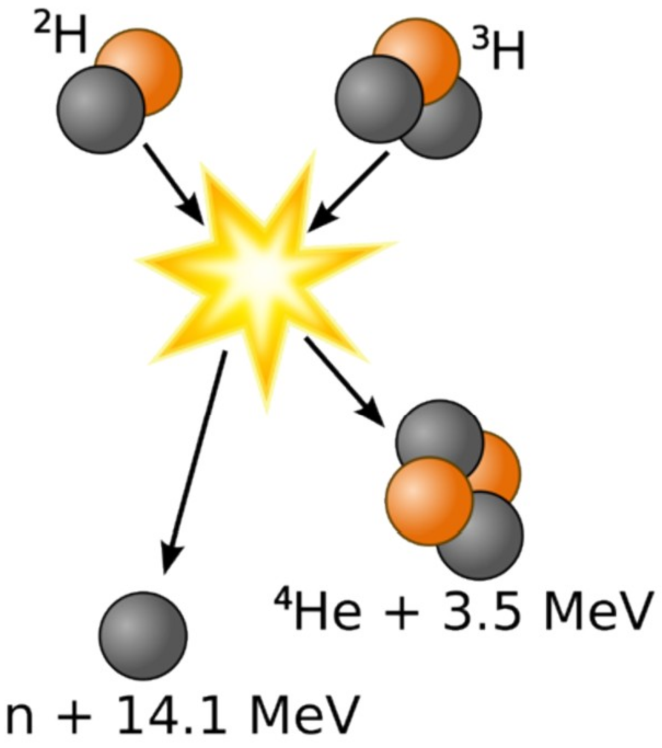
Inertial confinement fusion:

- D-T: Tritium inventory small → tritium commonly used in cryogenic target experiments
- Neutron yield important measure
- In ICF, 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 are significantly lower than those in magnetic confinement

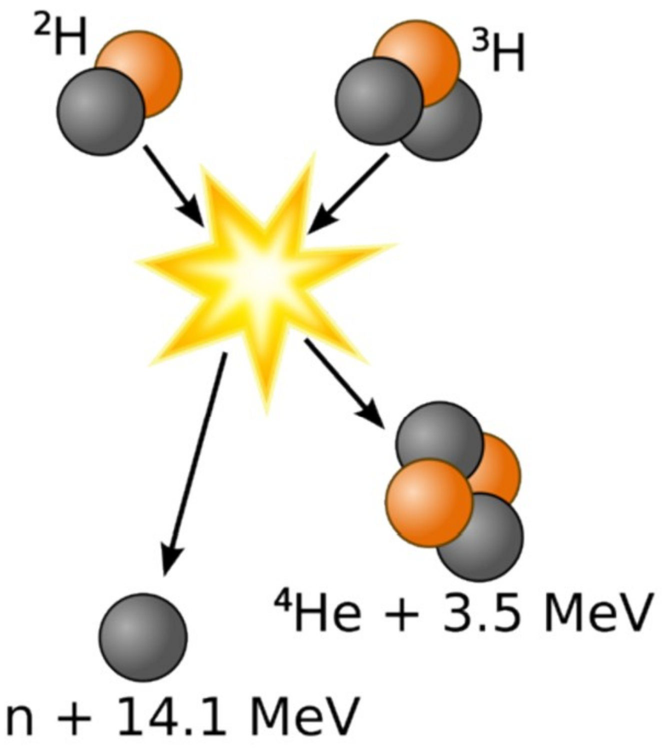
Lawson criterion: $n\tau \approx 10^{20}$ m^{-3} s



- **Magnetic confinement fusion**
  - Density ≈ 10^{20} m^{-3}
  - Confinement time ≈ 1 (to 10) s ⇒ quasi steady state (Stellarators inherently steady state)
- **Inertial confinement fusion**
  - Density ≈ 10^{31} m^{-3}
  - Confinement time ≈ 10 ps (10^{-11} s) ⇒ pulsed

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

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



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

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

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

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

⇒ **1 mg fuel ⇔ fuel density 300 g/cm^3, or 1500 x compression**

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

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

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

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

$\gamma = C_p/C_V = -(dp/p)/(dV/V)$
Is heat capacity ratio

- **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**

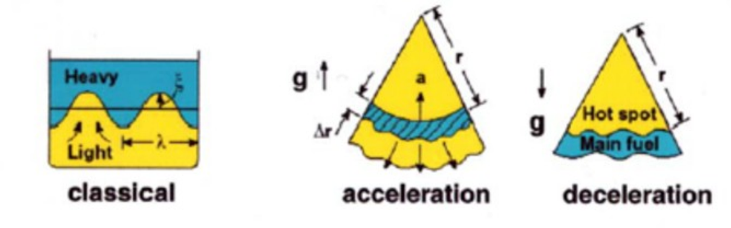
Fluid instabilities lead to non-spherical implosion of the capsule and unwanted material mixed into fuel

- **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

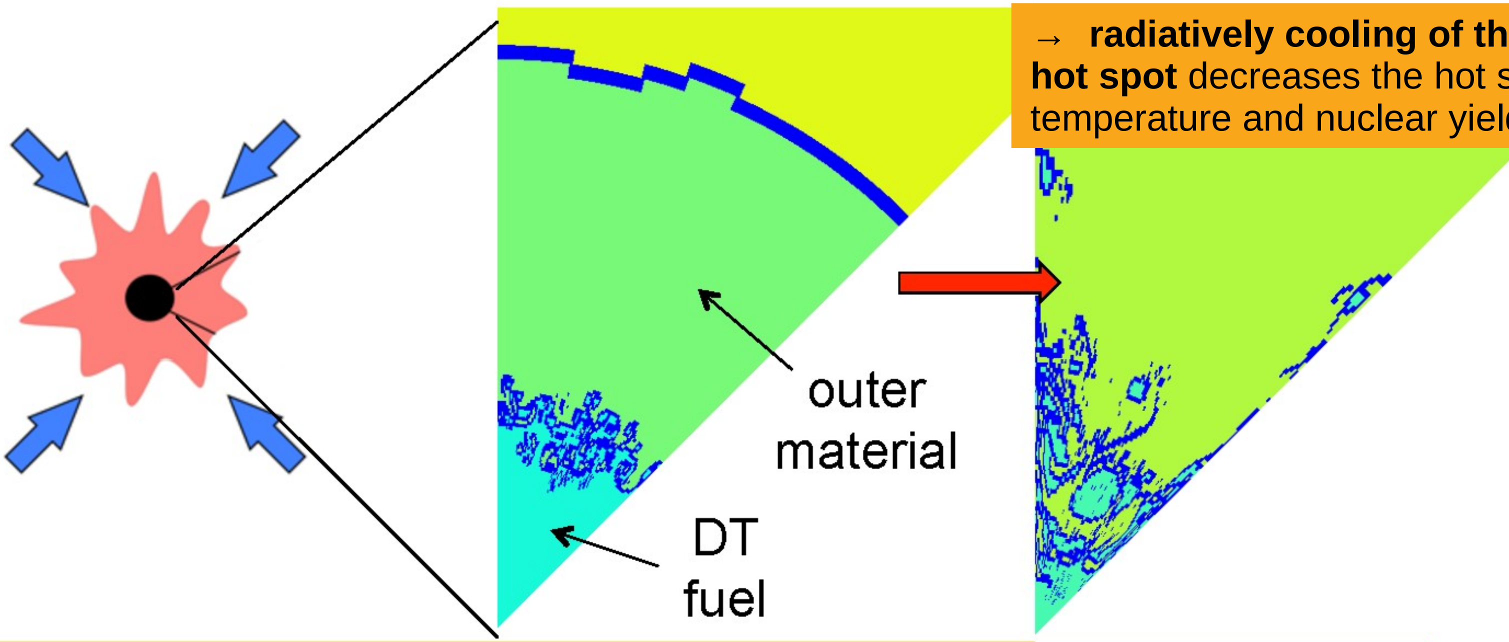
- **Richtmyer–Meshkov instability** → impulsive-acceleration limit of the Rayleigh–Taylor instability.

  → 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



→ **radiatively cooling of the hot spot** decreases the hot spot temperature and nuclear yield.

A more realistic estimate requires a driver energy of 100 MJ

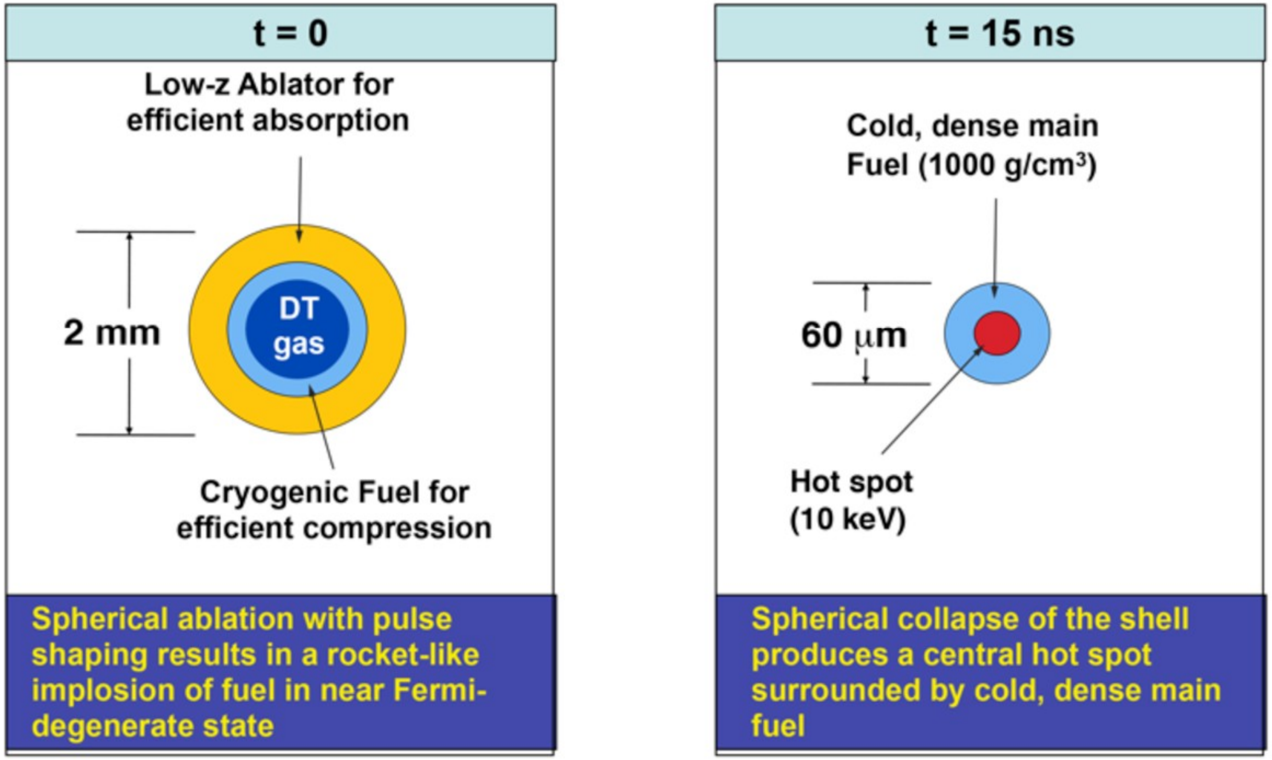
- **1mg of DT of a velocity of 3×10^{17} cm/s has a kinetic energy of 50 kJ**

⇒ 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

Ablator: *Plastic outer layer of the fuel capsule.*



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

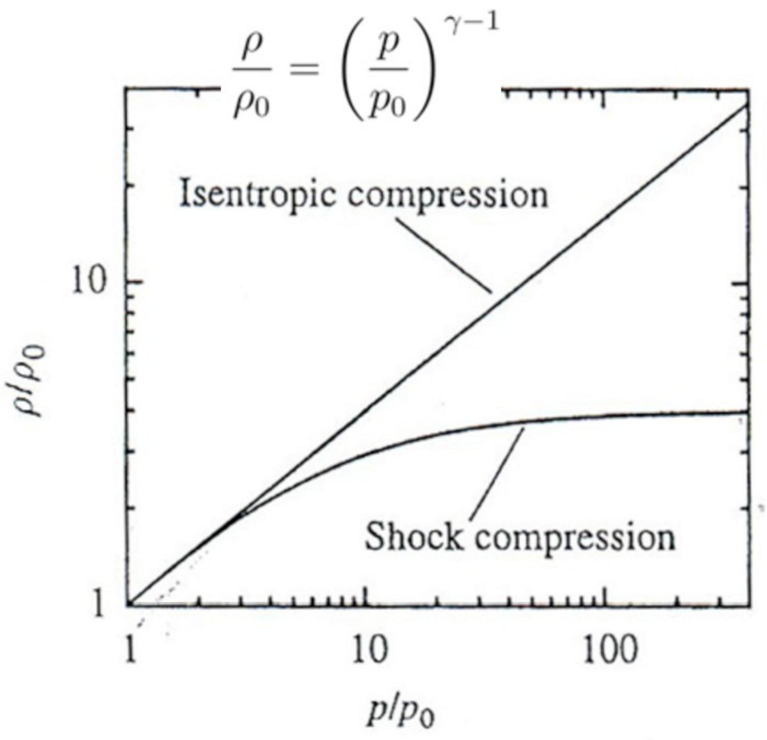
Shock wave compression saturates at certain pressure ratios

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

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

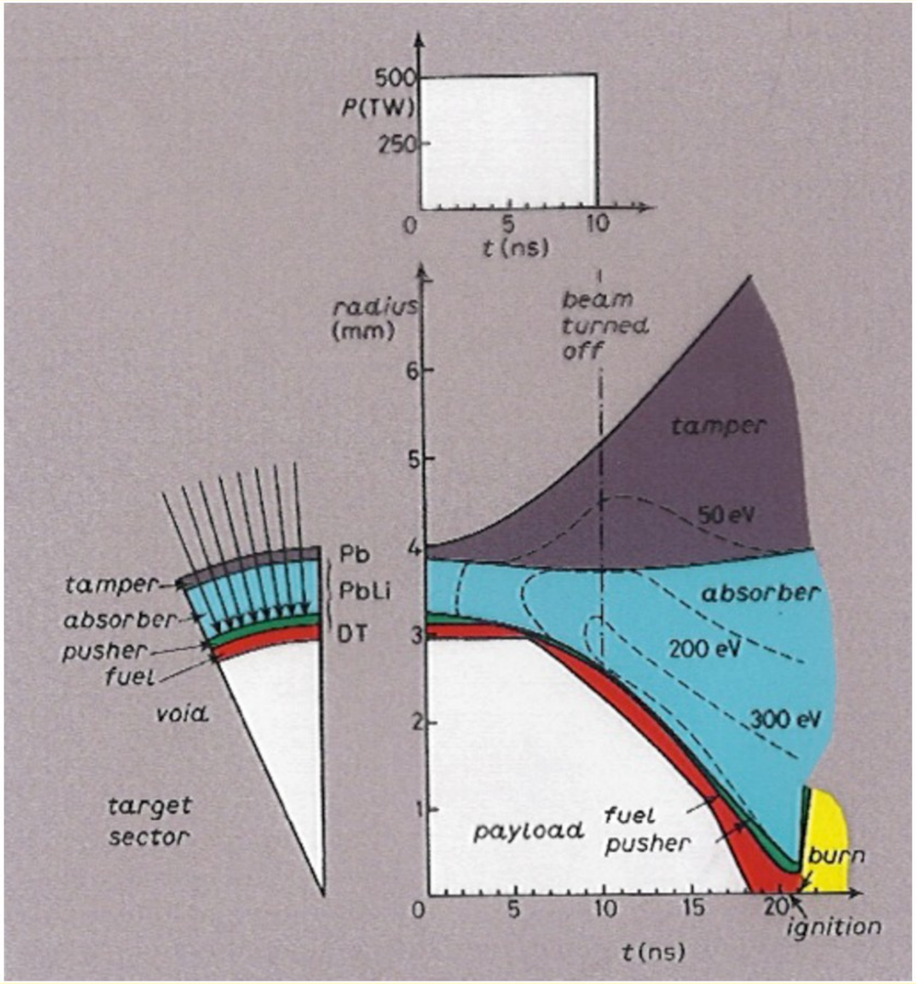
$$\gamma = \frac{7}{5} \Longrightarrow \left(\frac{\rho_2}{\rho_1}\right)_{max} = 6$$

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



a shock wave = a type of propagating disturbance that moves faster than the local speed of sound in the medium.

The ablation pressure results in a shock wave within 5 ns

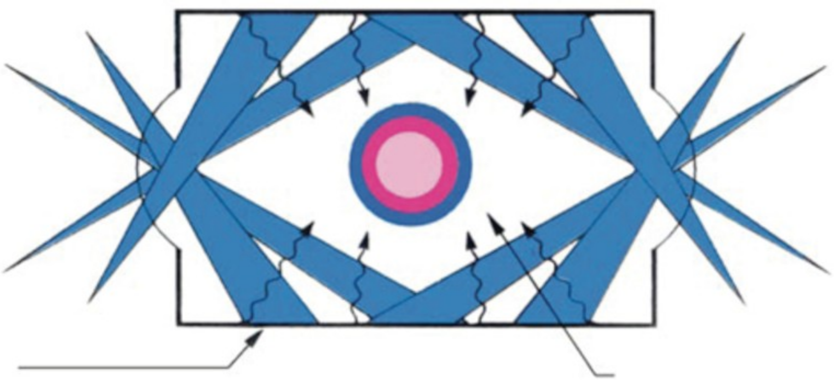


- **While the outer capsule layer expands, the absorber implodes into the fuel**
- **Simple model estimate burn after just 20 ns**
- **Compression factors in excess of 1000 are necessary**

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

direct drive

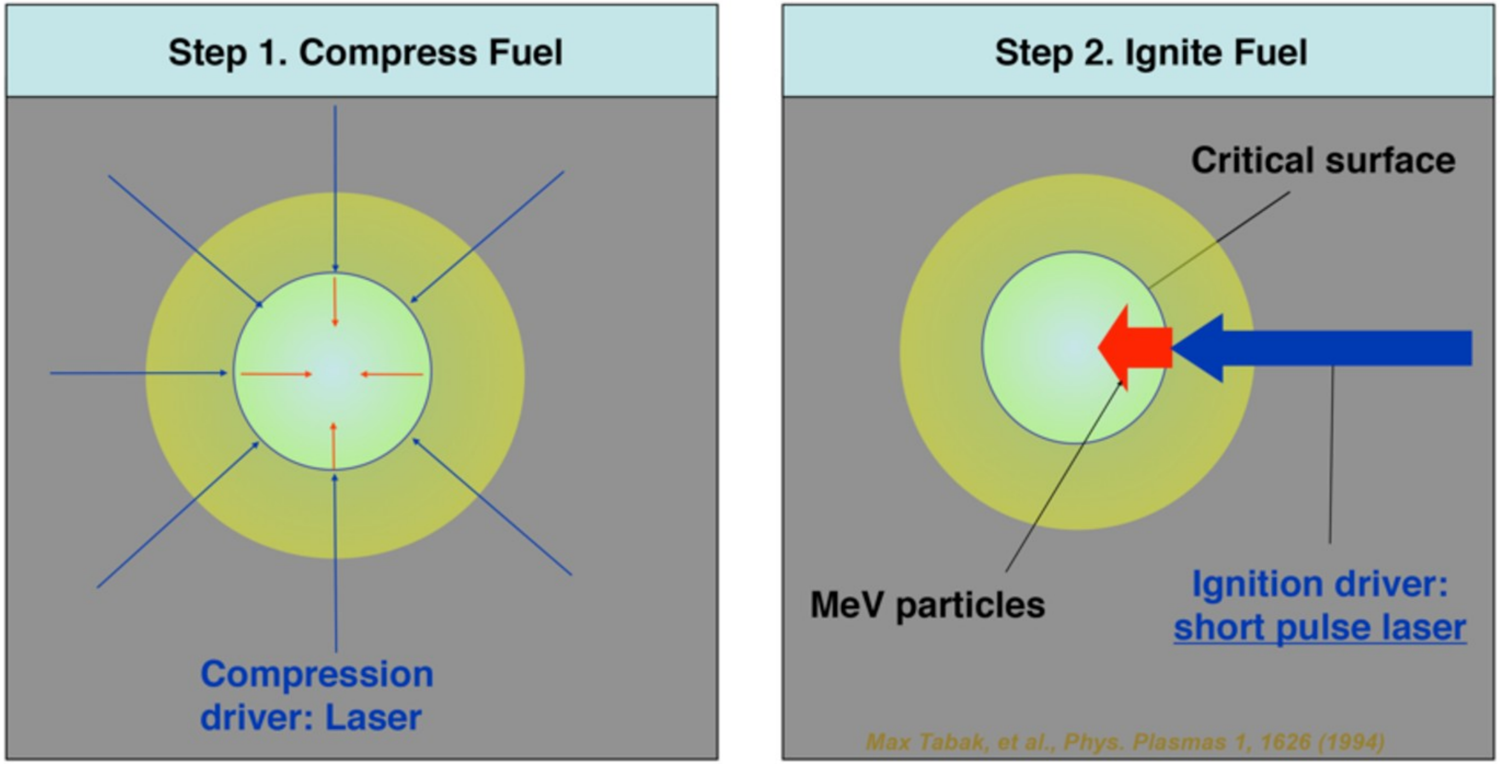
indirect drive



Hohlraum: *German for "hollow space," a hohlraum is a hollow metal cylinder the size of a pencil eraser surrounding a fusion fuel capsule. The hohlraum converts energy from laser light into x-ray radiation that symmetrically compresses a fuel capsule.*

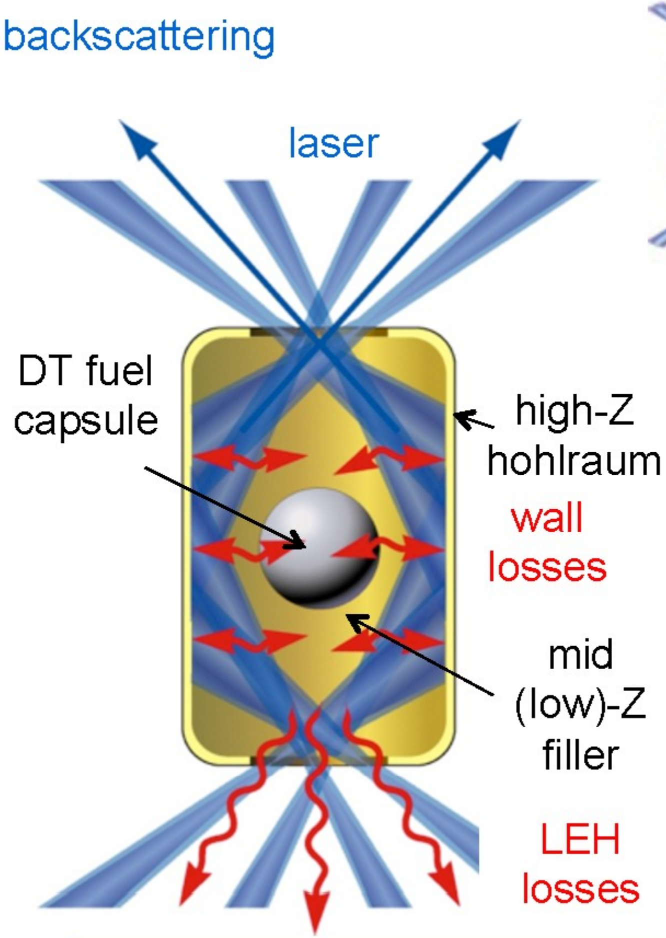
- **Driver = laser, converted into x-ray source**
- **Direct drive is more efficient, but symmetric implosion is harder to achieve**

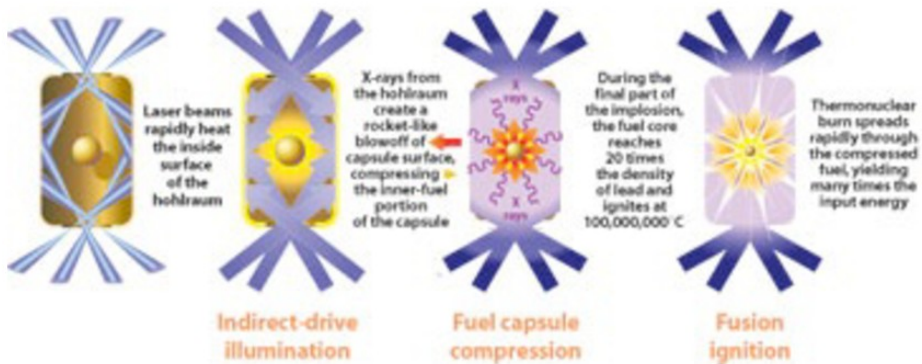
Fast ignition separates compression and ignition of the fuel (spark plug in gas engine)



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

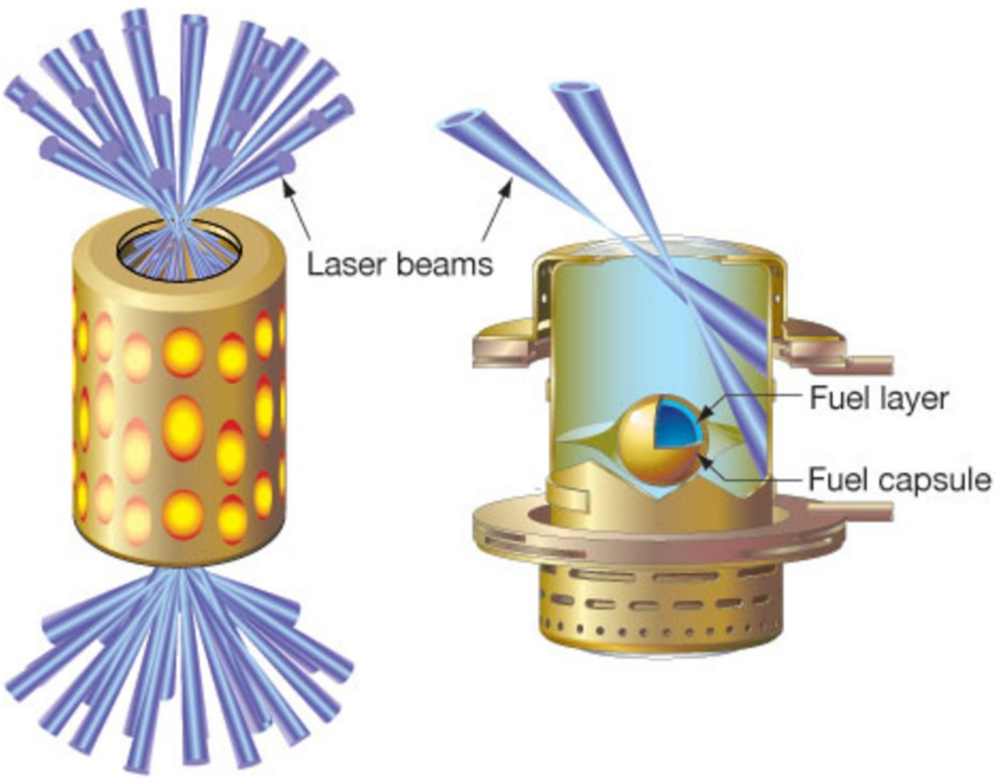
In indirect drive, DT fuel is compressed by x-rays produced by laser heating of a high-Z hohlraum

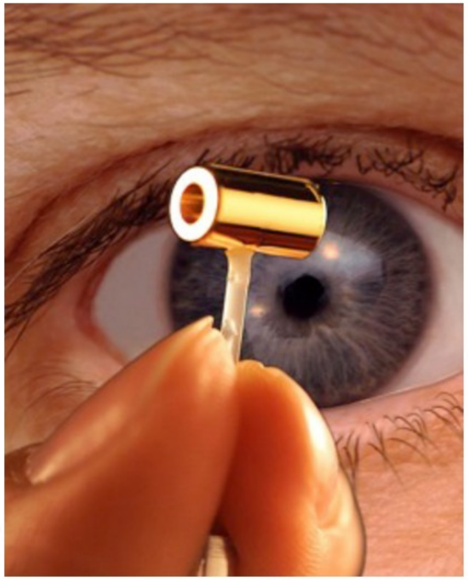




- **Optimization of hohlraum energetics**
  - Laser absorption, backscattering, re-emission efficiency
- **Compression symmetry, laser timing**

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

What about breakeven?

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

"Engineering" breakeven: takes into account that

1) only a fraction $(1-f_{ch})$ of fusion energy goes to blanket

2) cooling fluid of blanket drives steam turbines with efficiency η_{elec} = 35-40 %

3) fraction f_{recirc} of P_{elec} recirculated back into the heaters

4) 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...

<u>“Engineering” breakeven:</u>

- $Q_E = P_{fus}/P_{heat} = 1 / [(1-f_{ch})\, \eta_{elec} f_{recirc}\, \eta_{heat}]$
- **Typical values: f_{ch} = 0.2 (D-T), η_{heat} = 0.7 and η_{elec} = 0.4 → Q = 5 for engineering breakeven (f_{recirc} = 1) but at least Q > 20 (f_{recirc} = 0.2) for significant energy production (“economic breakeven”)**
- **Note on ICF: lasers have order of η_{heat} = 0.015 (1.5%) → Real energy gain in ICF very low although it is close to “scientific breakeven”. Trick is to redefine Q with energy**

put into the driver → delivered by the driver

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

The National Ignition Facility (NIF)

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

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

US line of laser development ⇒ fission/fusion hybrids

JANUS
100 J IR

ARGUS
1 kJ IR

SHIVA
10 kJ IR

NOVA
30 kJ UV

NIF: 1.8 MJ UV,
500 TW

LIFE

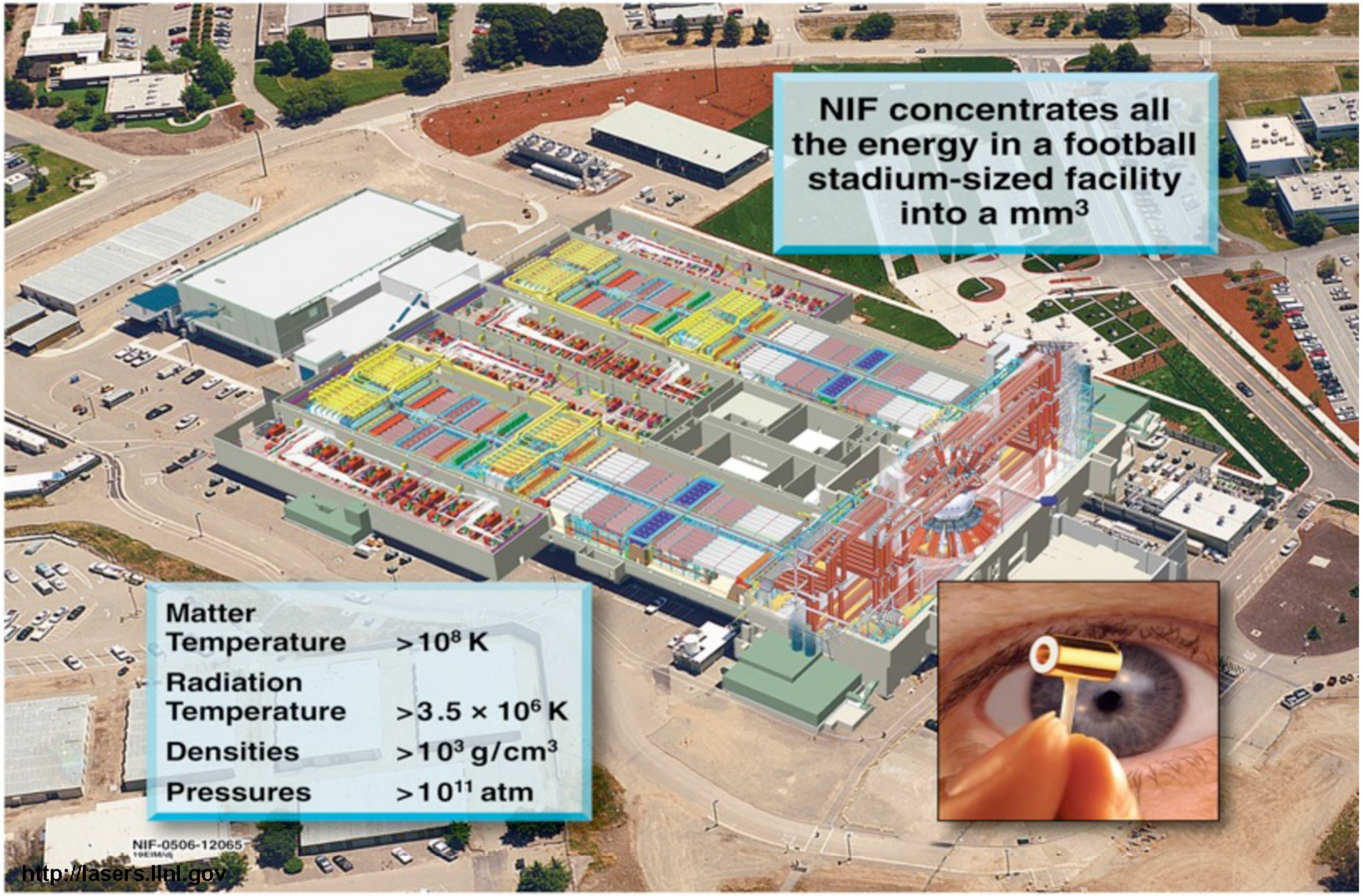
- **Laser / inertial fusion development also in the EU (France) and Japan**

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

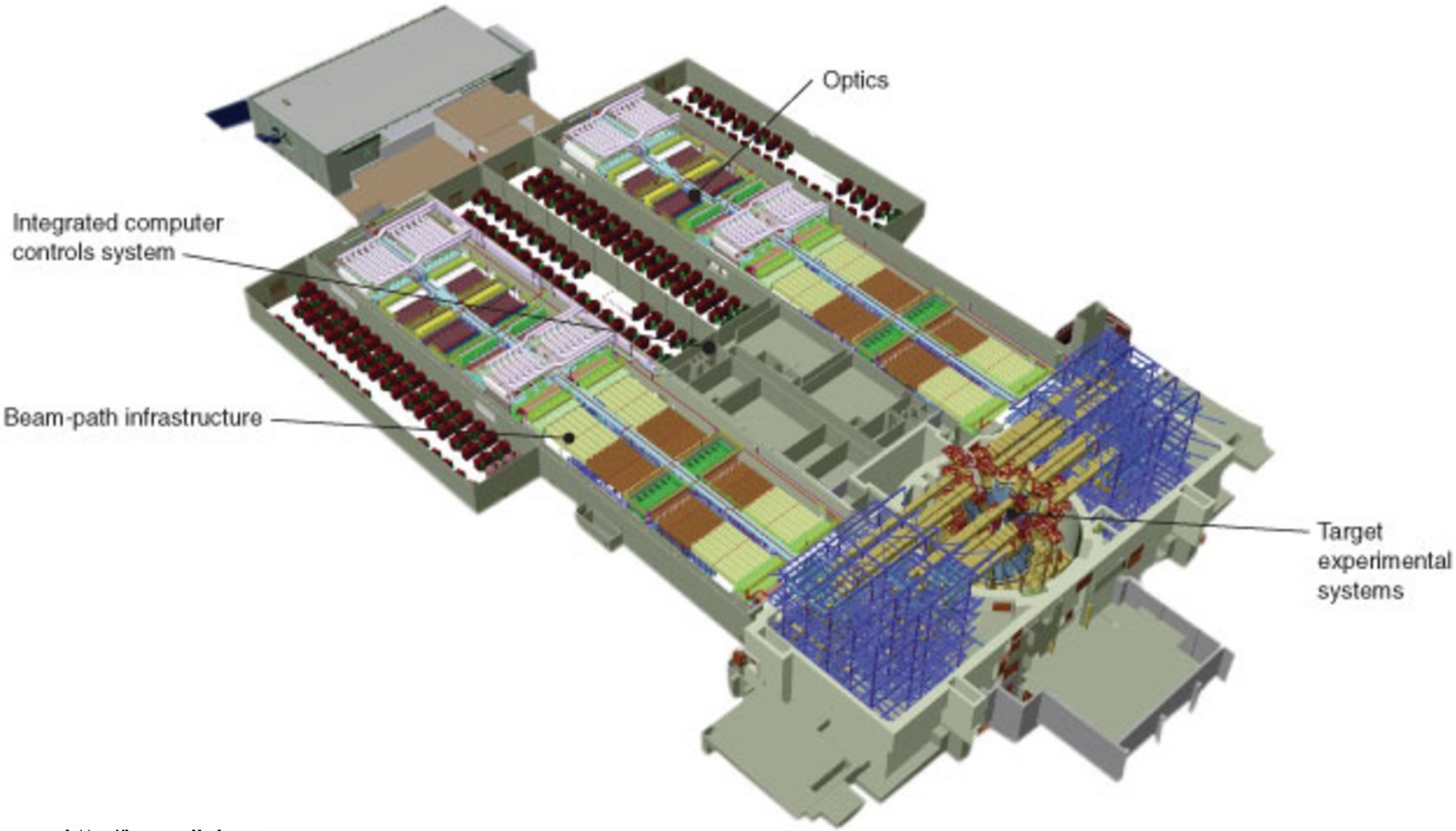
NIF is currently the world's largest laser facility (total cost approx. 4 bn USD)

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

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



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



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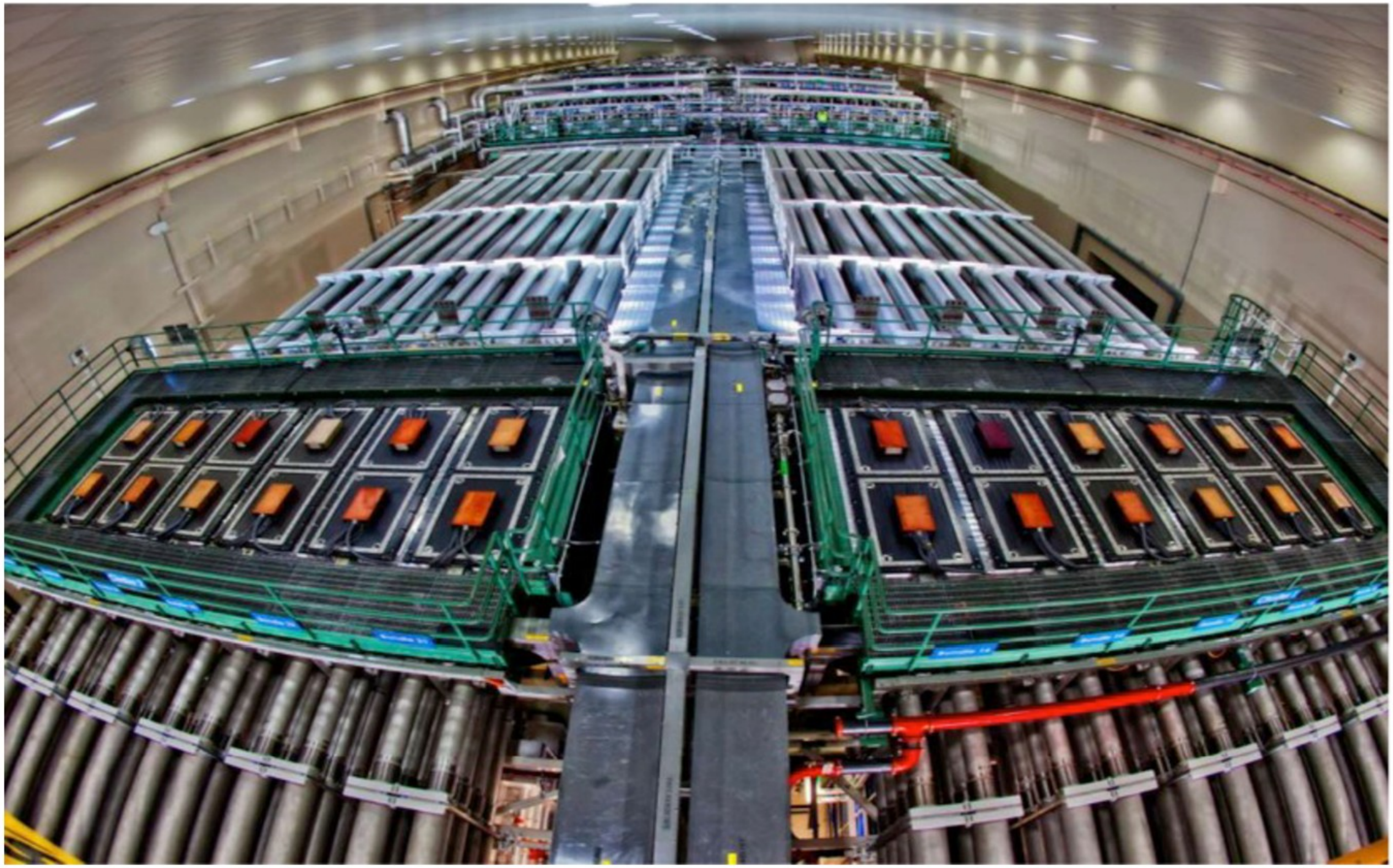
View of the laser banks filling a high-bay area the size of a football stadium (192 beams)



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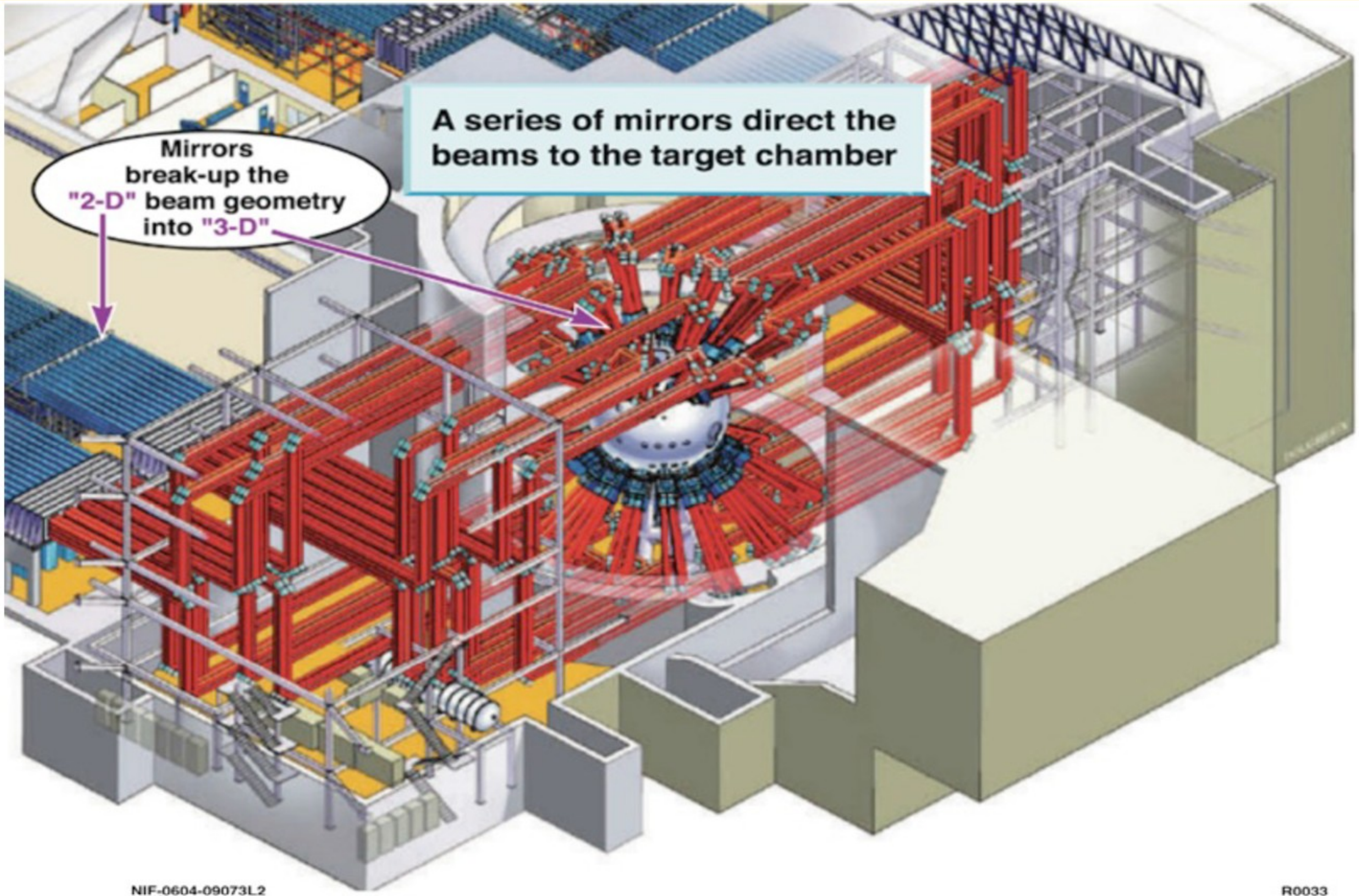
A series of mirrors direct the beams to the target chamber



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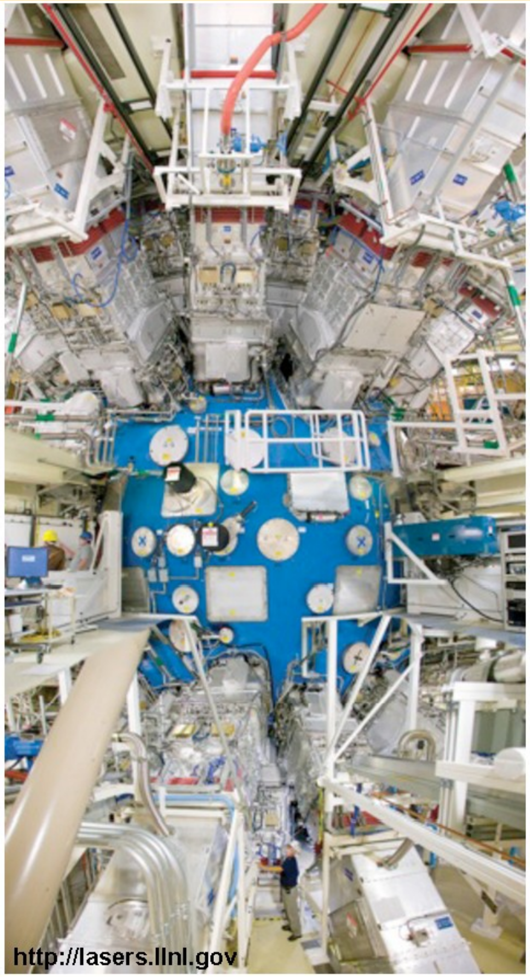
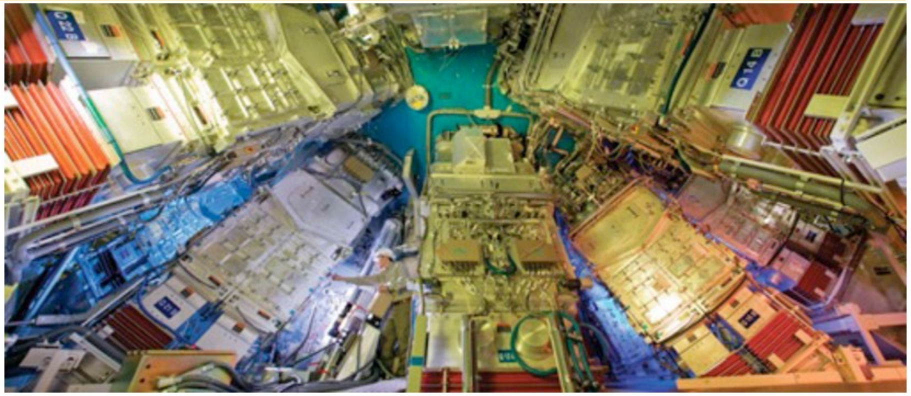
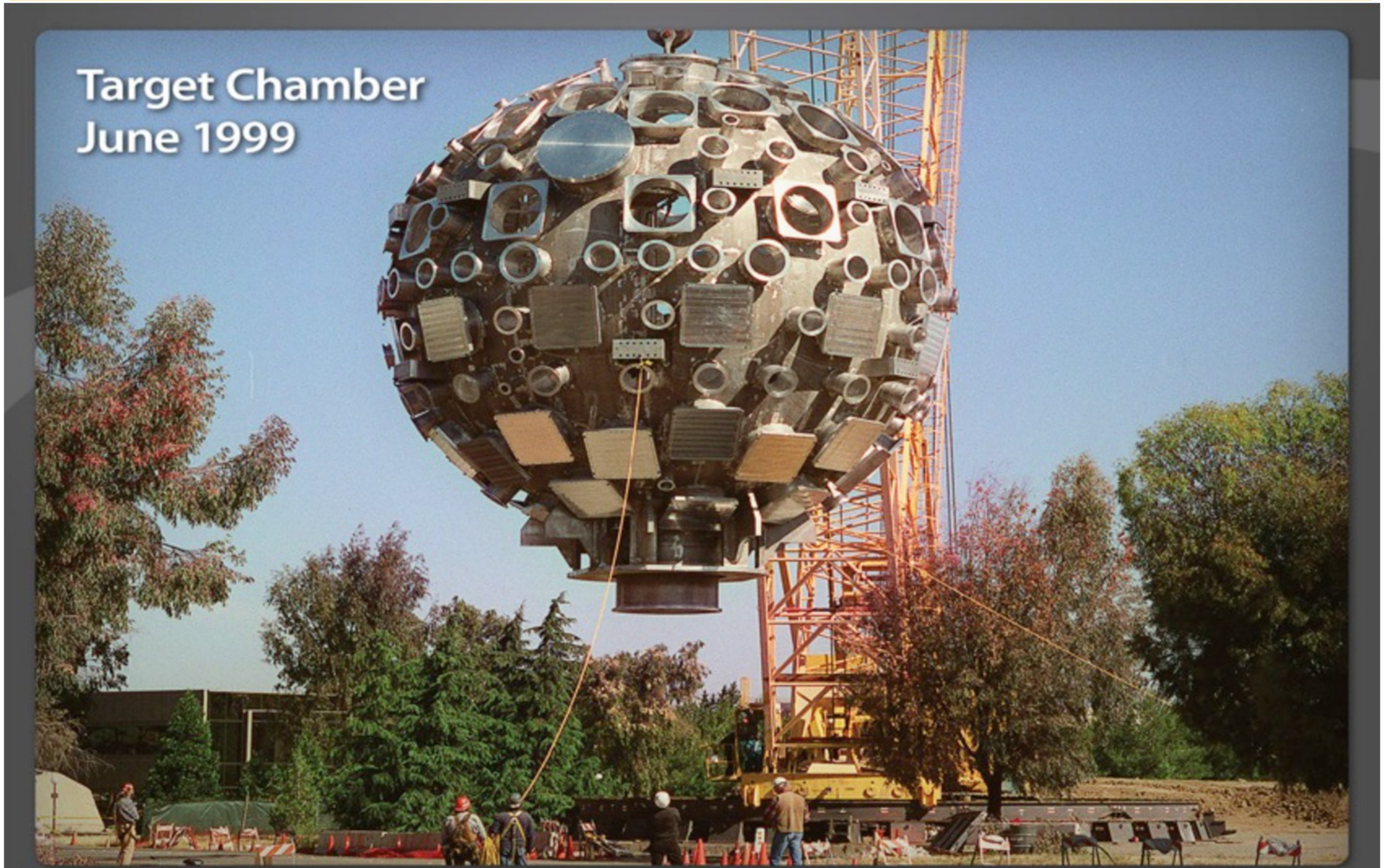




The laser beams (currently 192) were commissioned in 2008

The target chamber was completed in 1999 and shipped to LLNL



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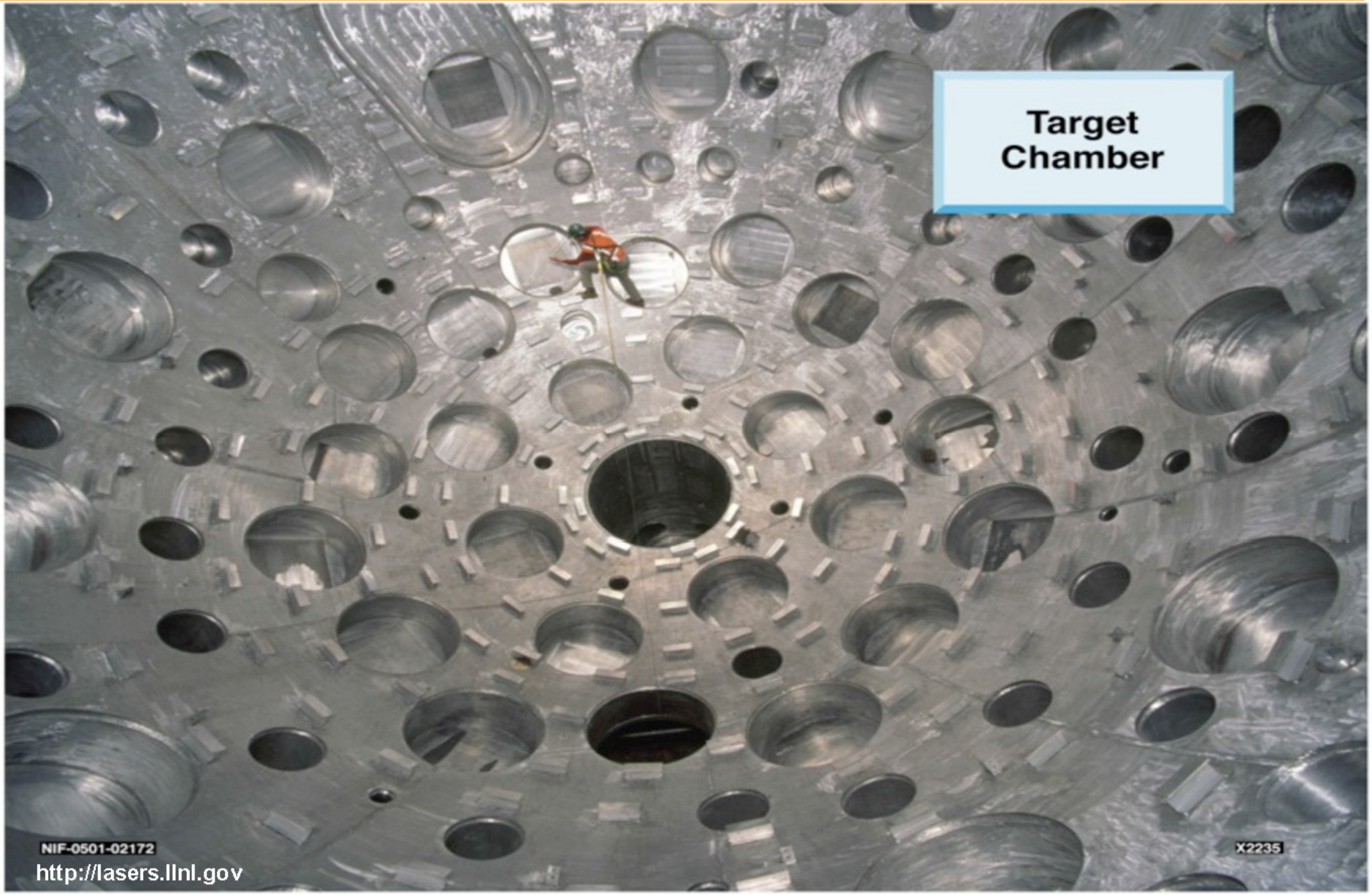
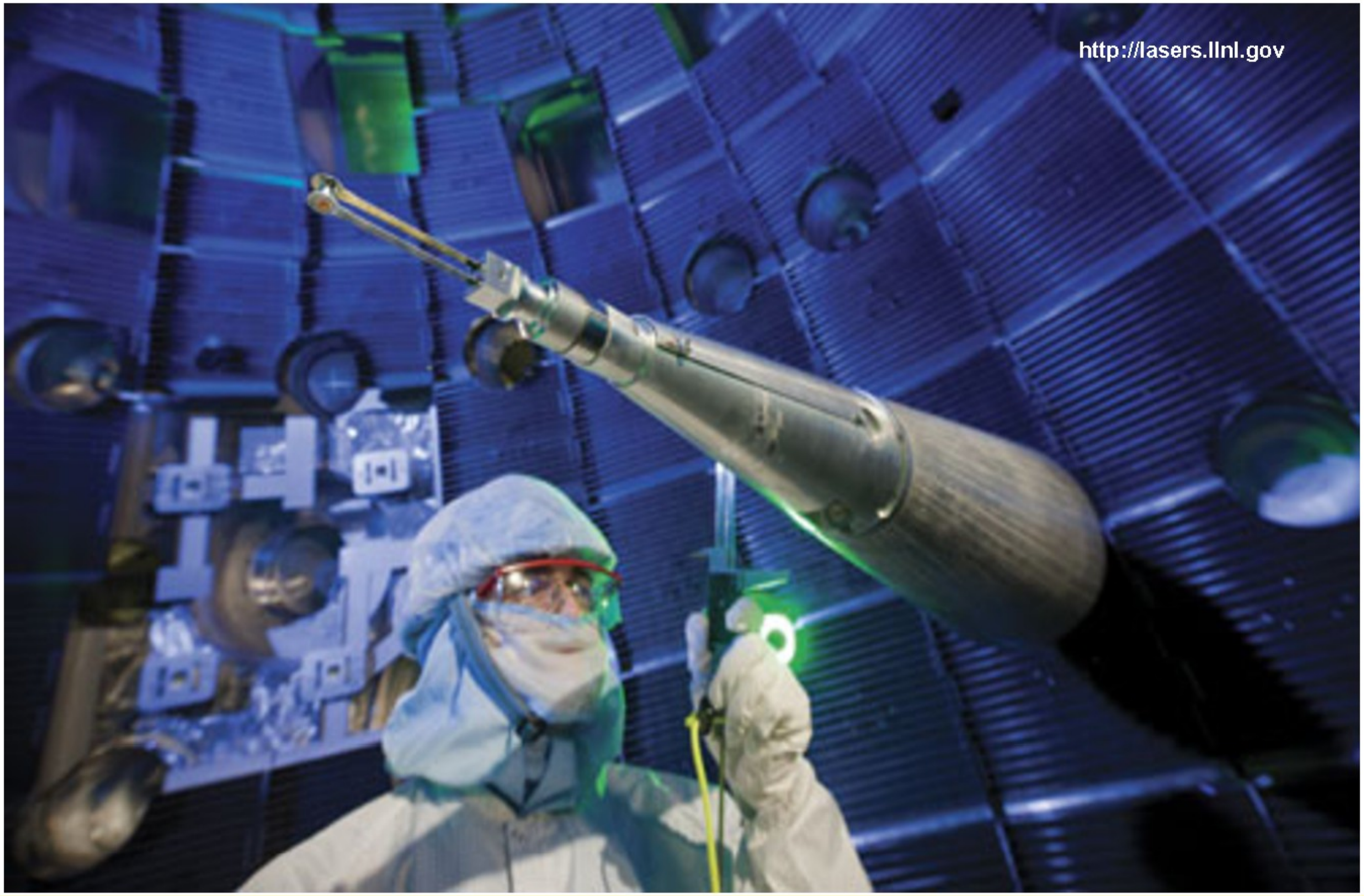
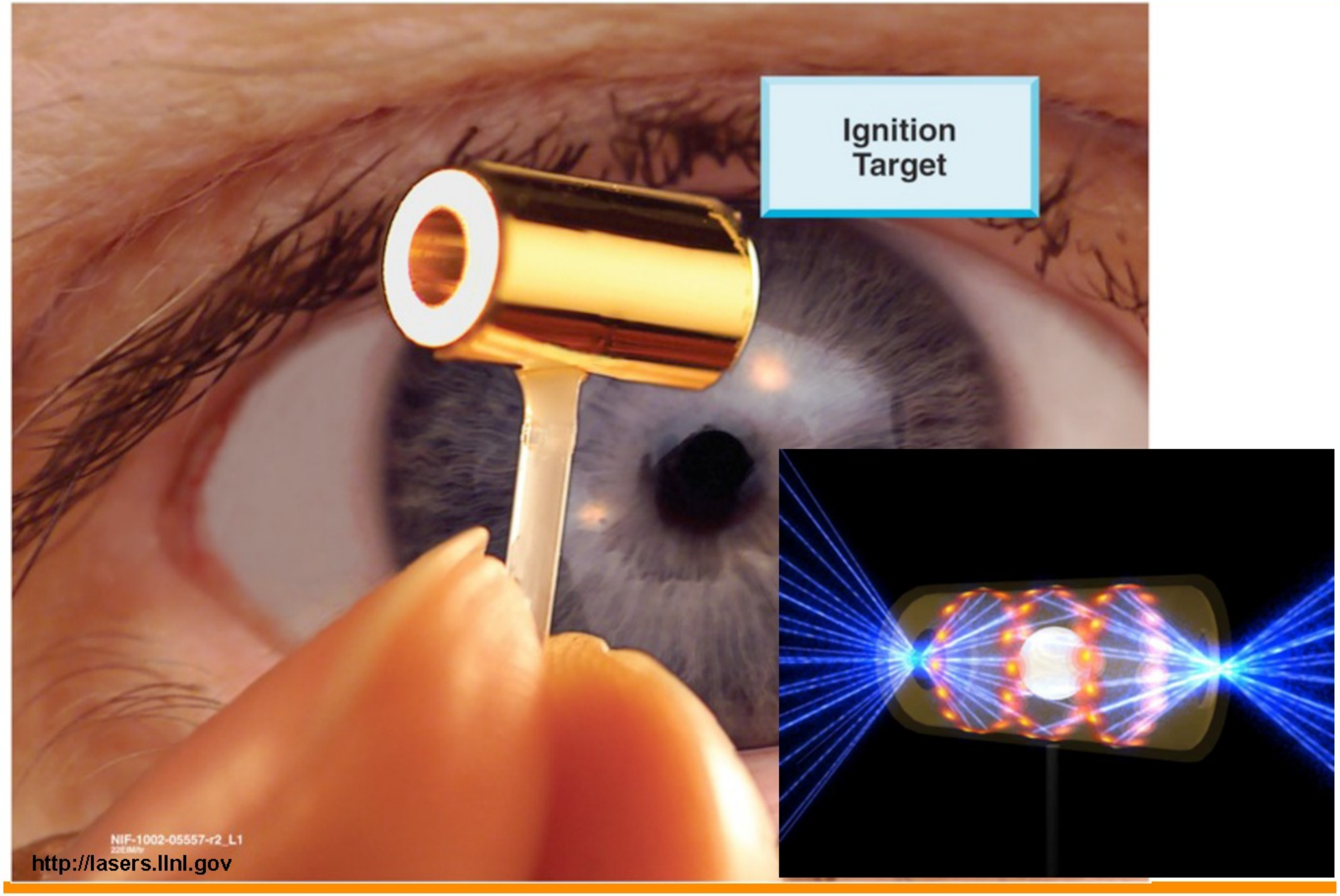
The NIF (spherical) target chamber is 10 m in diameter and 130 tons heavy



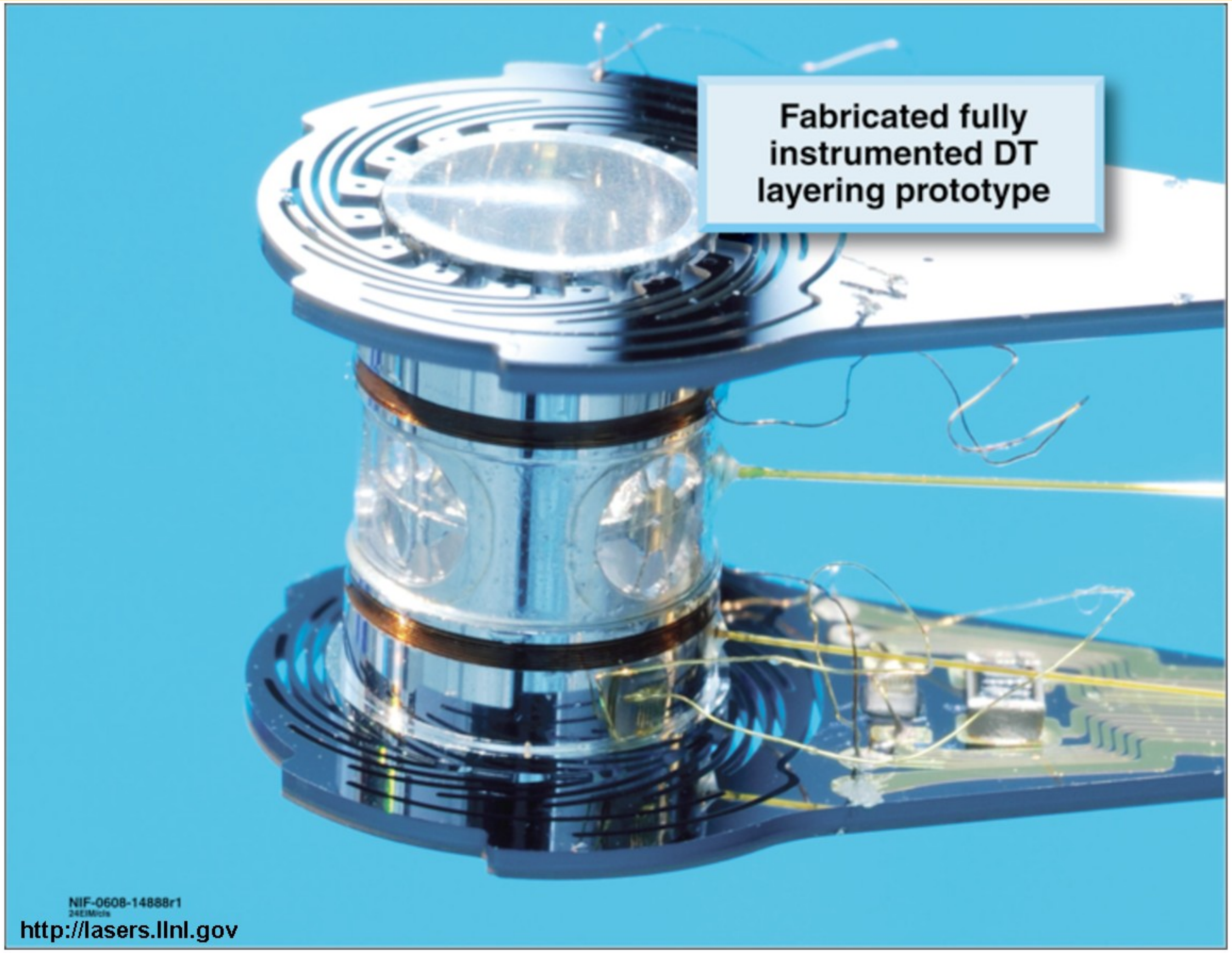
In NIF, laser energy from a 192-beam system is bundled onto a sub-centimeter capsule



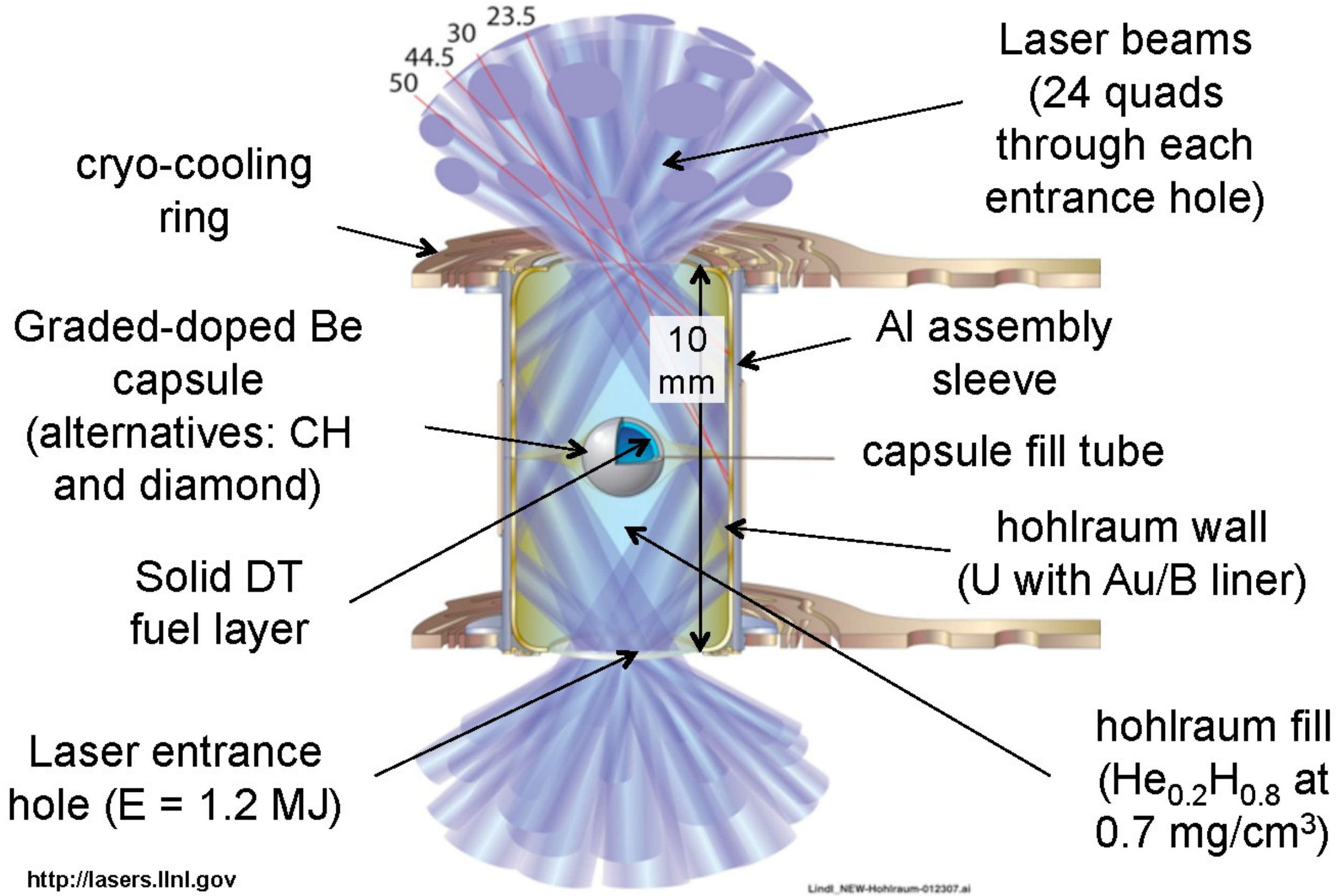
The ignition target is an about 10 mm long cylinder for indirect drive



Fabricated and fully instrumented prototype



Currently, NIF uses a graded-doped, beryllium capsule in a Au or B lined hohlraum



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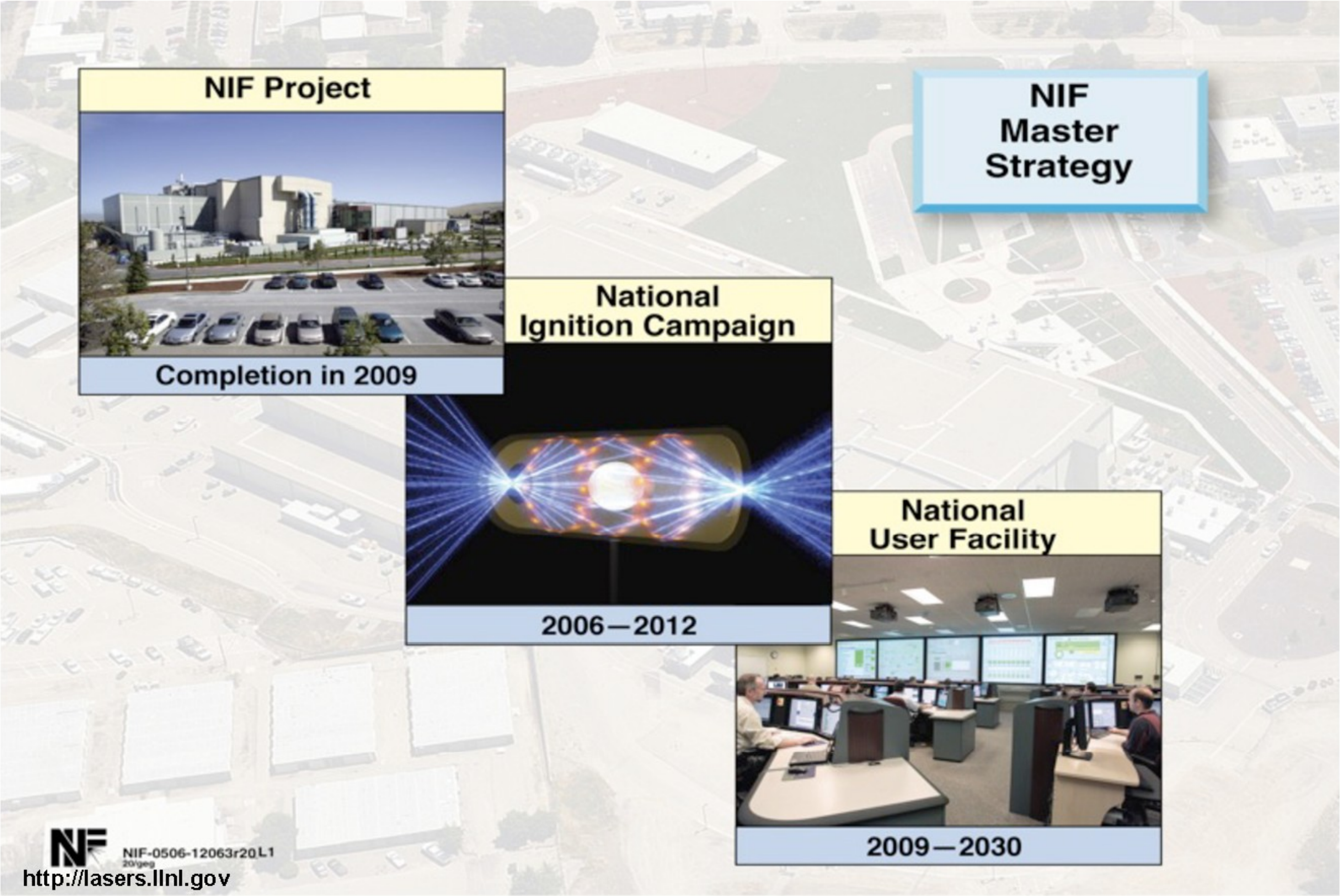
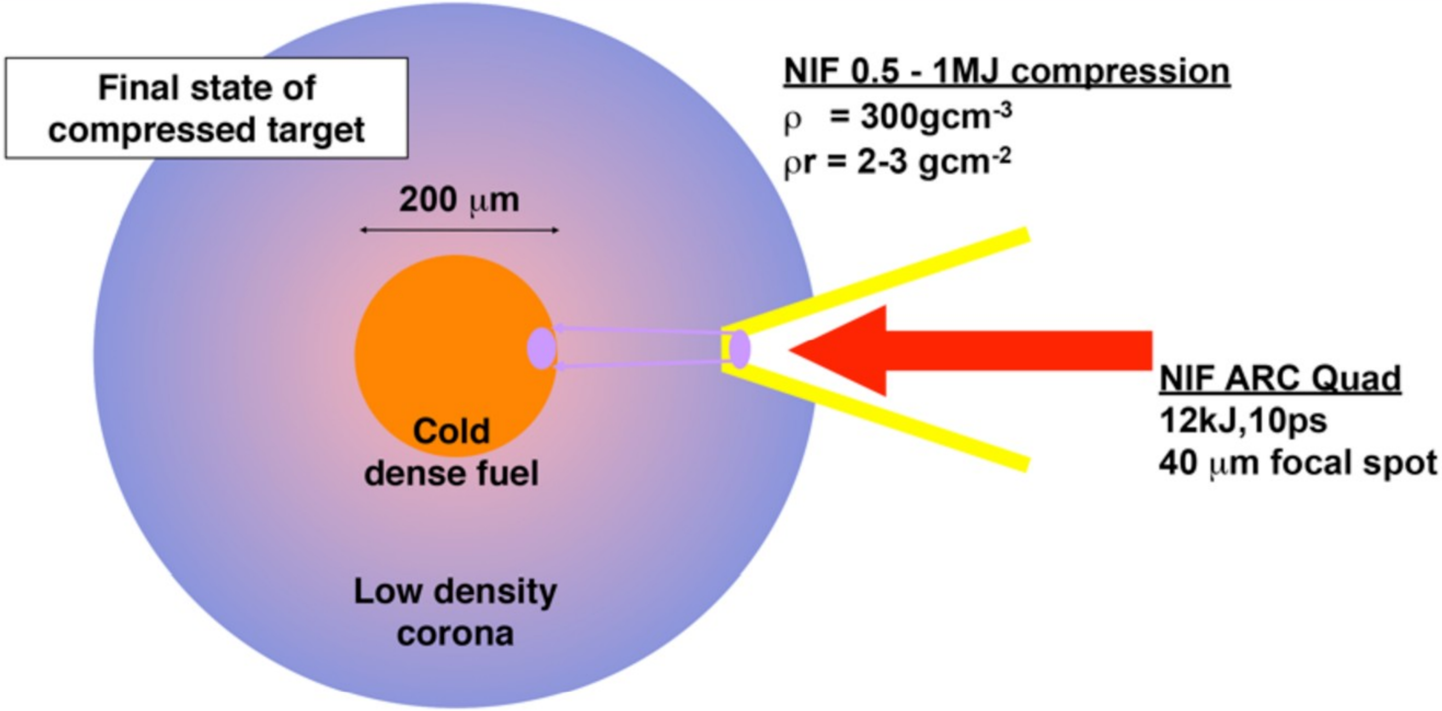
Upon completion of the project in 2009, NIF ran a national ignition campaign

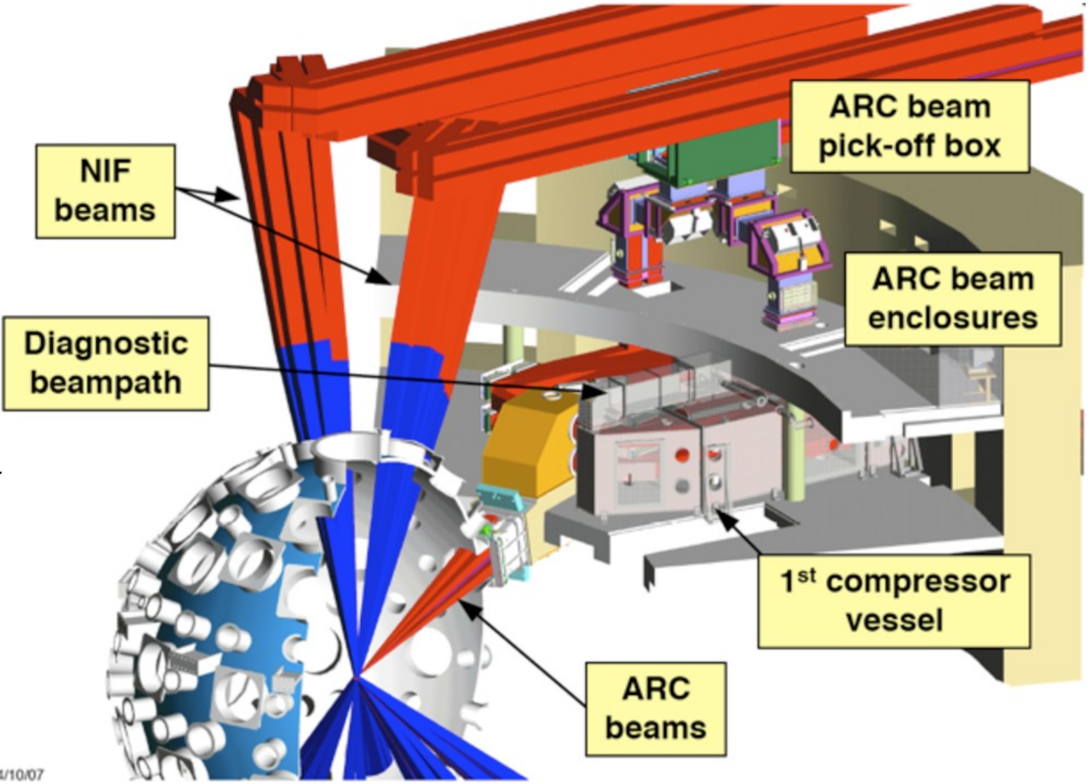


A proof-of-principle fast-ignition experiment is planned at NIF



- **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**

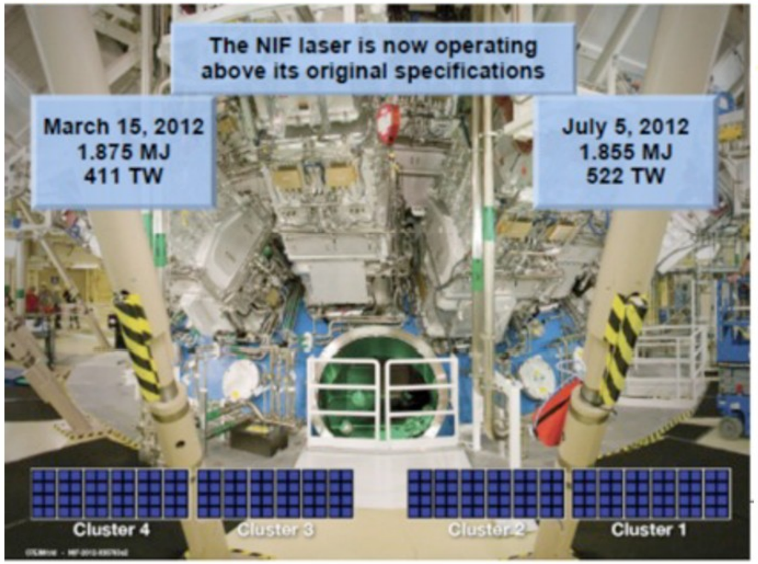
How NIFs works?

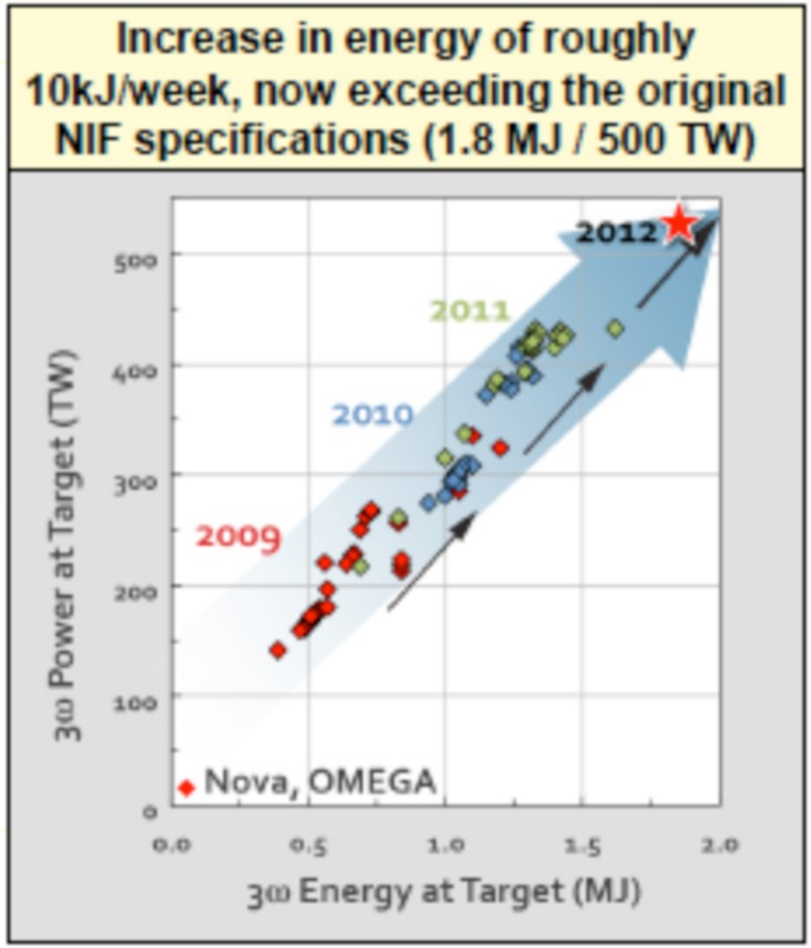
Video: How NIF works (5.21)

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

Has NIF achieved ignition?

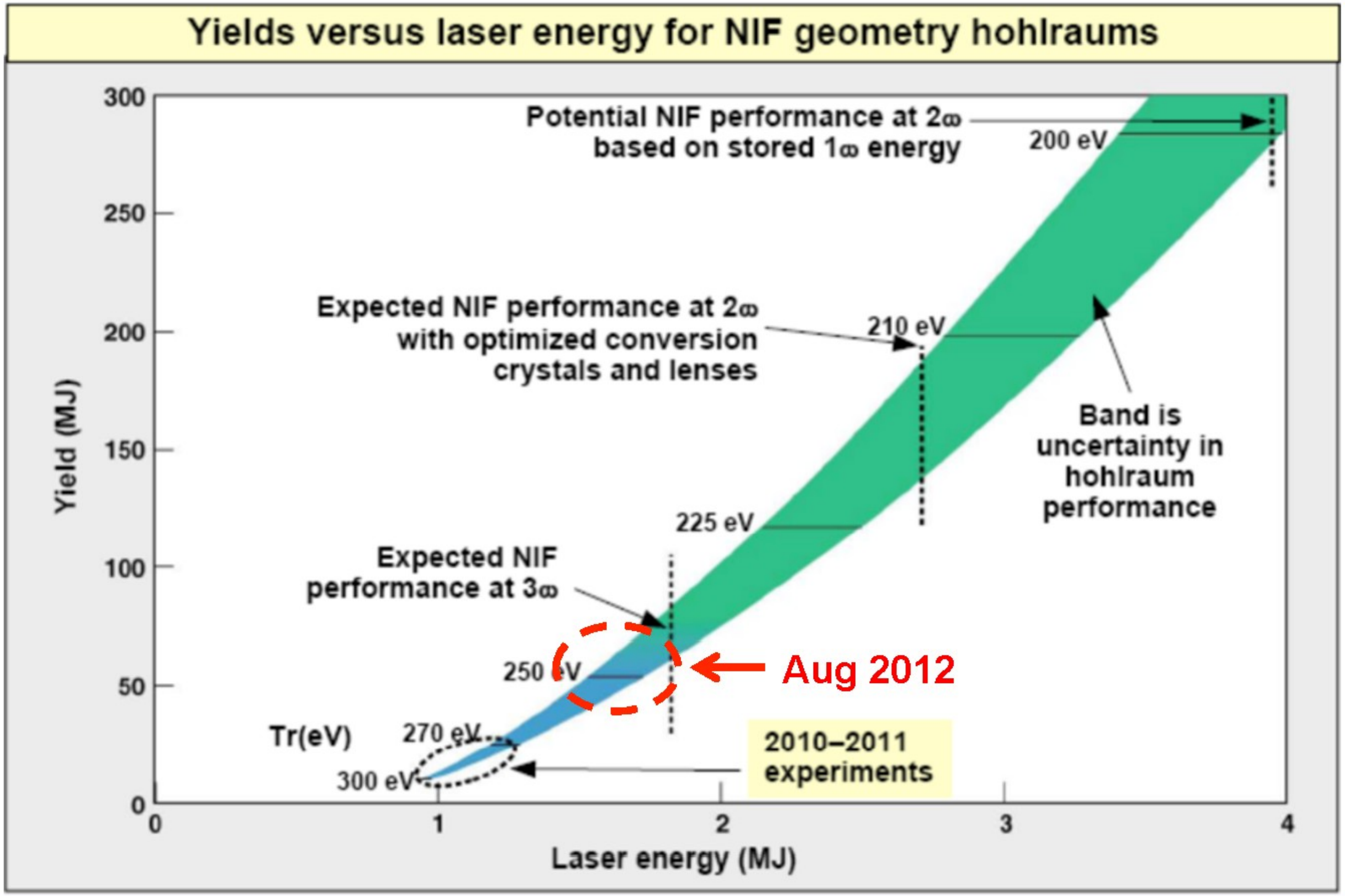
NIF has exceeded its original design specs for energy and power



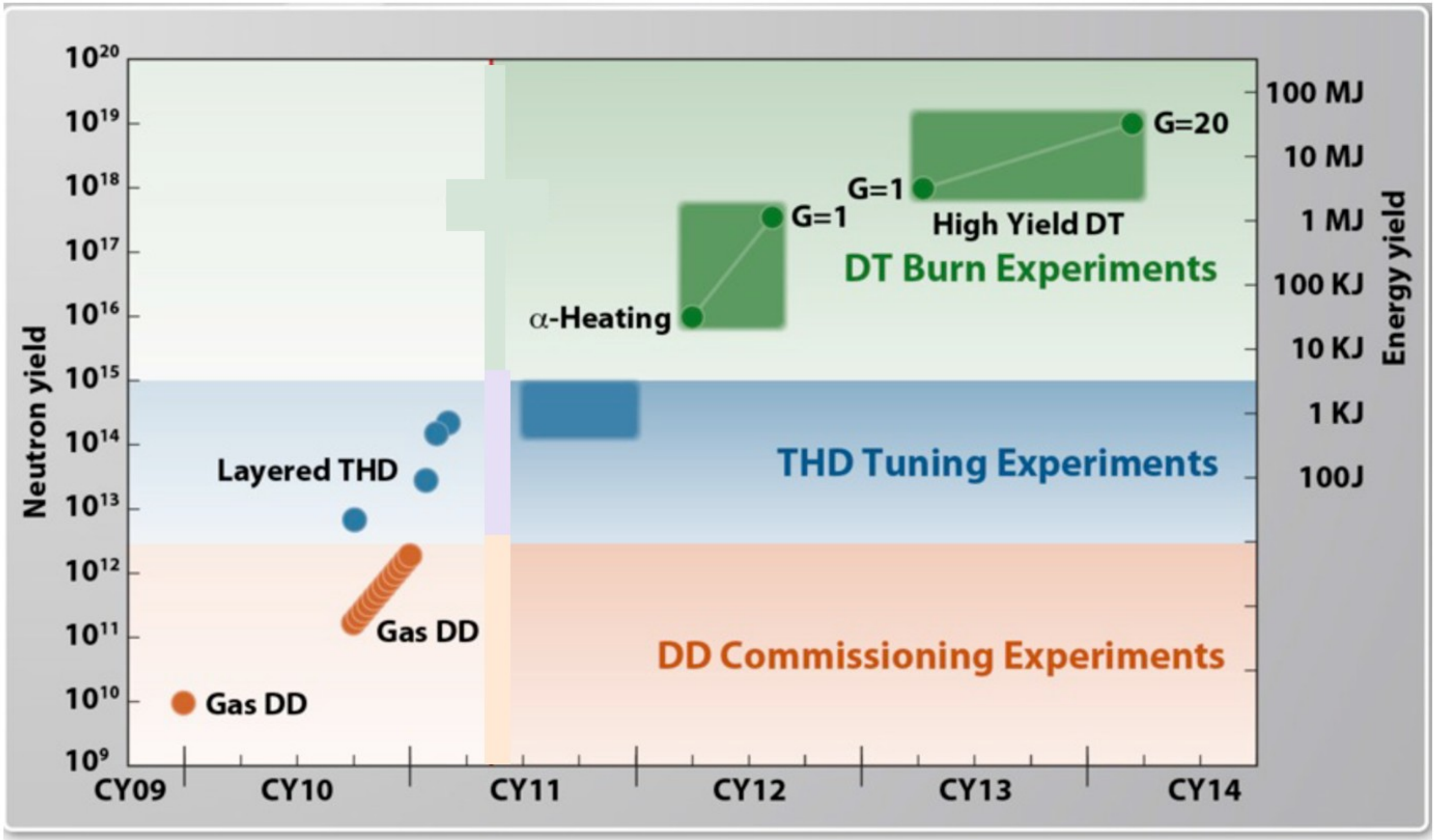


- **Design specs in the 90s were 1.8 MJ and 500 TW, power density 9 J/cm^3**

Initial (2011) experiment gave yields of ~20 MJ, in 2012 three times more, about 60 MJ



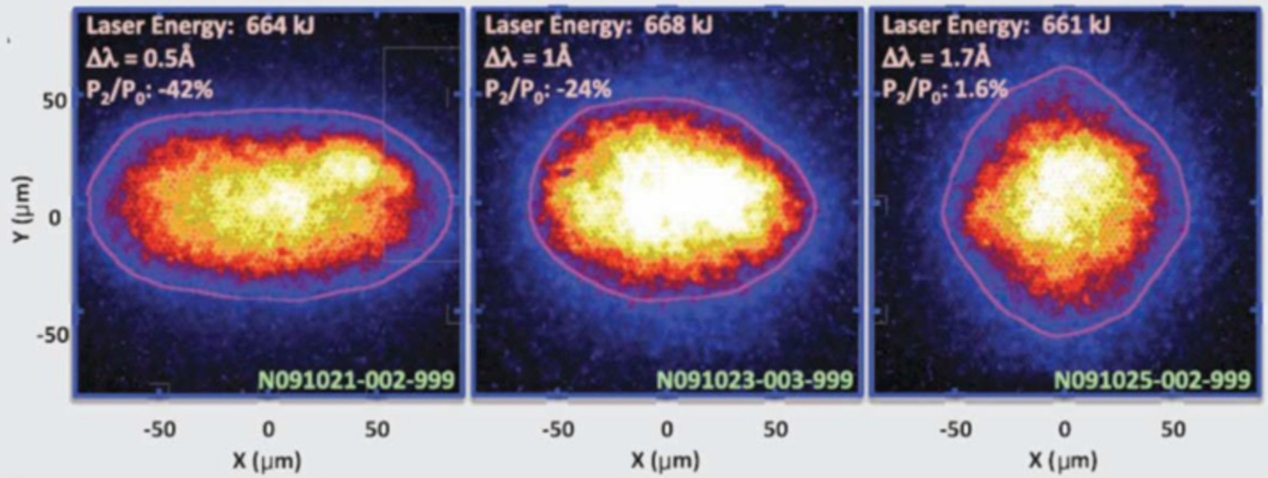
On August 13, 2013, NIF reached neutron yields of 3×10^{15}, pushing toward burn experiments



SCIENCE March 5, 2010: symmetrical implosions of cryogenic target capsules were achieved in NIF

Symmetric Inertial Confinement Fusion Implosions at Ultra-High Laser Energies

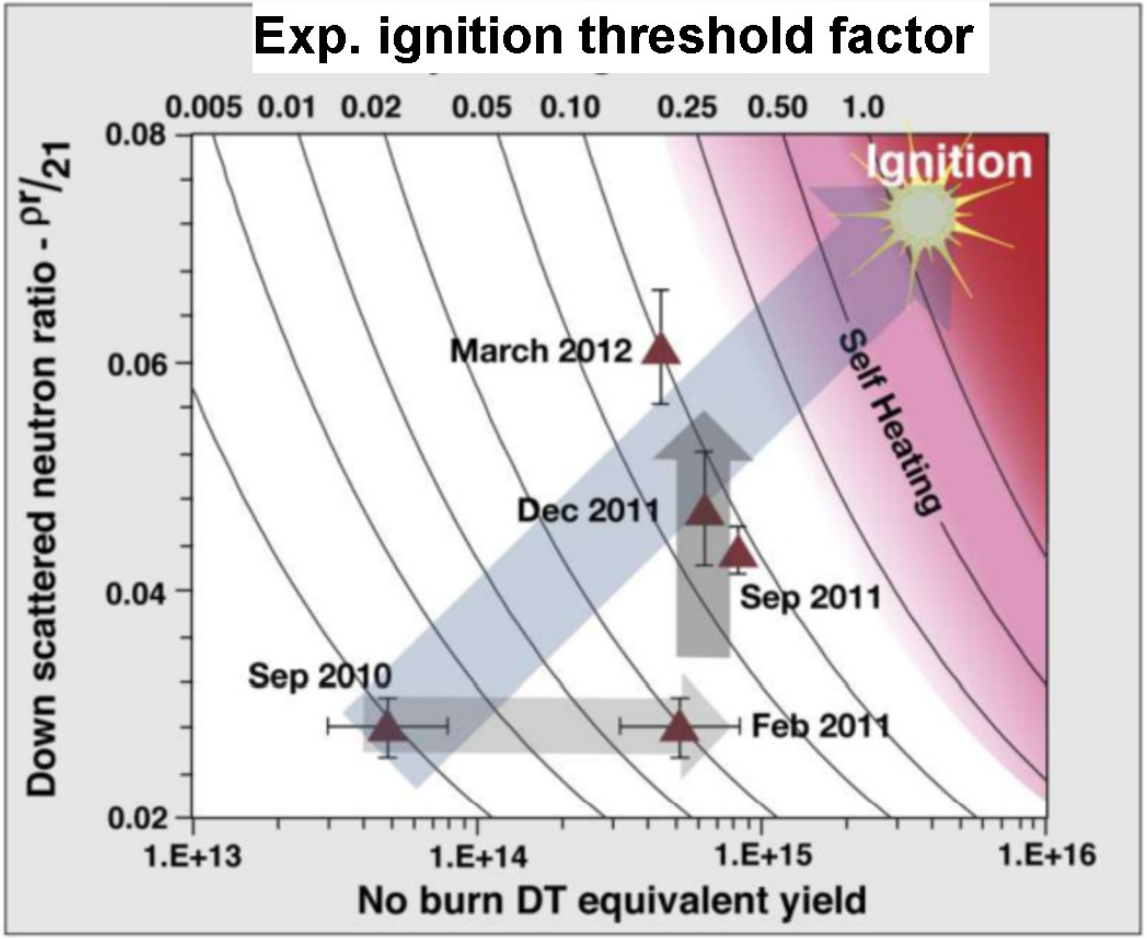
S. H. Glenzer,[1*] B. J. MacGowan,[1] P. Michel,[1] N. B. Meezan,[1] L. J. Suter,[1] S. N. Dixit,[1] J. L. Kline,[2] G. A. Kyrala,[2] D. K. Bradley,[1] D. A. Callahan,[1] E. L. Dewald,[1] L. Divol,[1] E. Dzenitis,[1] M. J. Edwards,[1] A. V. Hamza,[1] C. A. Haynam,[1] D. E. Hinkel,[1] D. H. Kalantar,[1] J. D. Kilkenny,[3] O. L. Landen,[1] J. D. Lindl,[1] S. LePape,[1] J. D. Moody,[1] A. Nikroo,[3] T. Parham,[1] M. B. Schneider,[1] R. P. J. Town,[1] P. Wegner,[1] K. Widmann,[1] P. Whitman,[1] B. K. F. Young,[1] B. Van Wonterghem,[1] L. J. Atherton,[1] E. I. Moses[1]



Since 2010, NIF has slowly approached self-heating and ignition (within ~5x of significant α-heating)

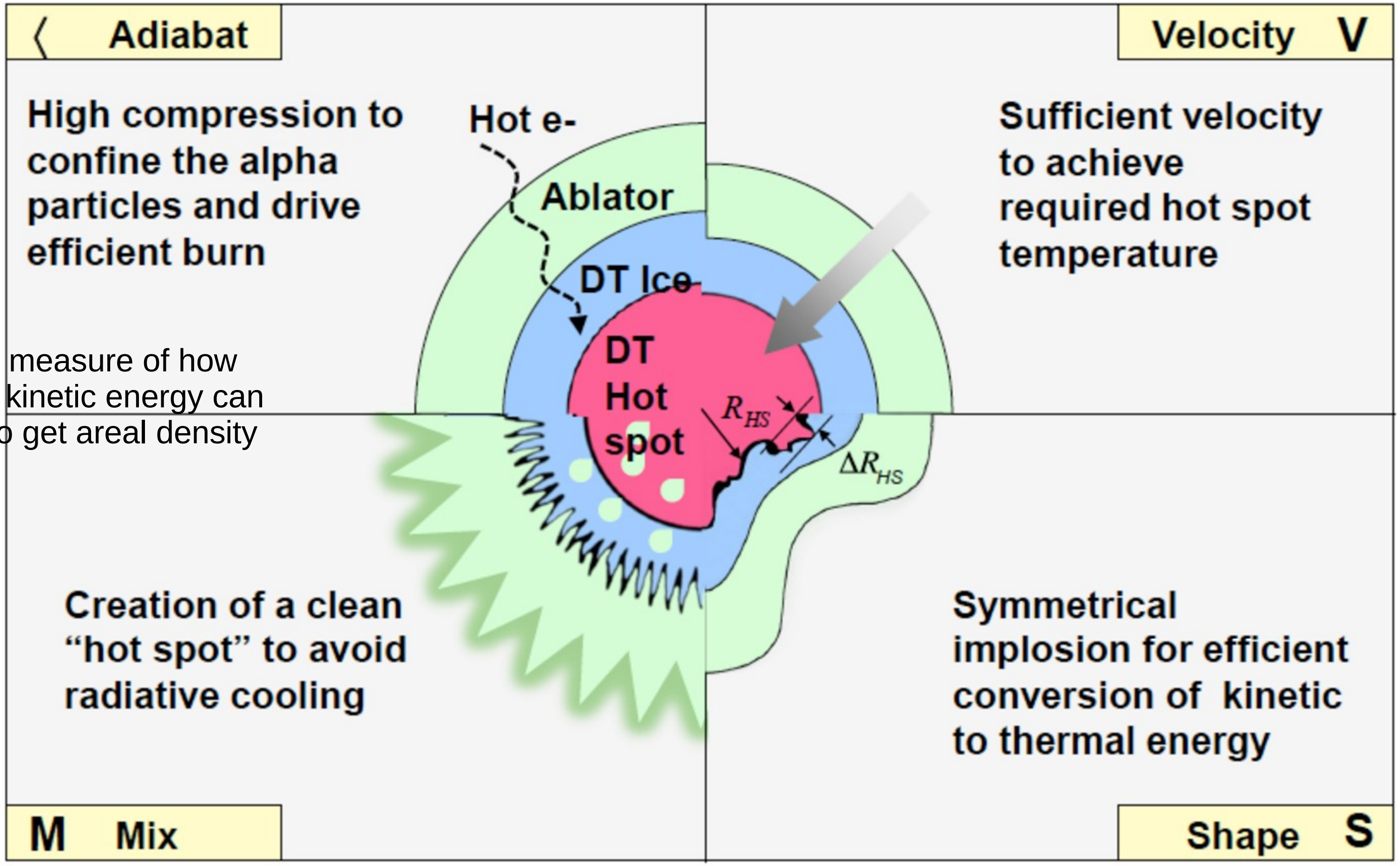
Lawson criterion for IFE:

ρR > 1 g/cm^2



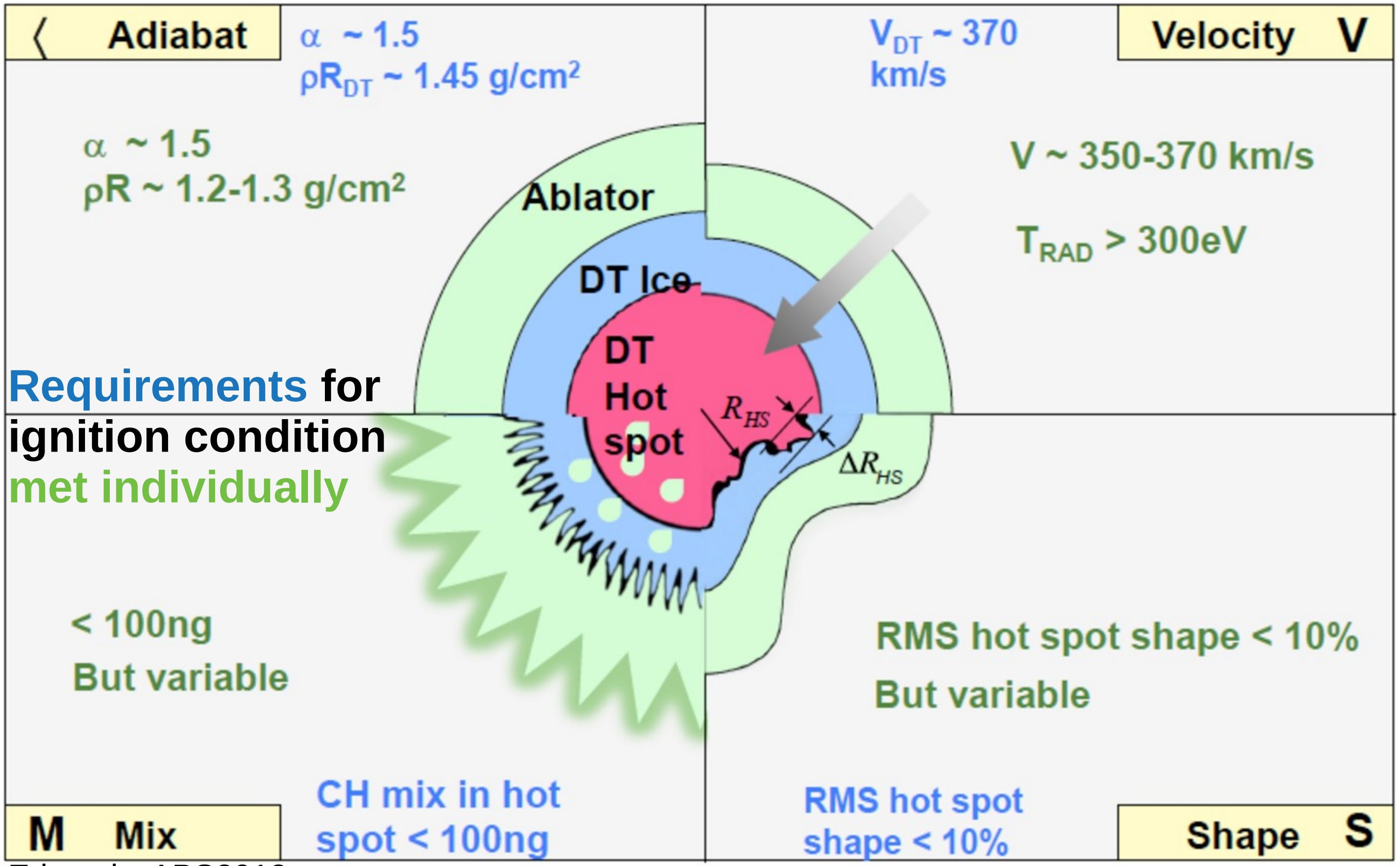
Dunne et al. TOFE 2012

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

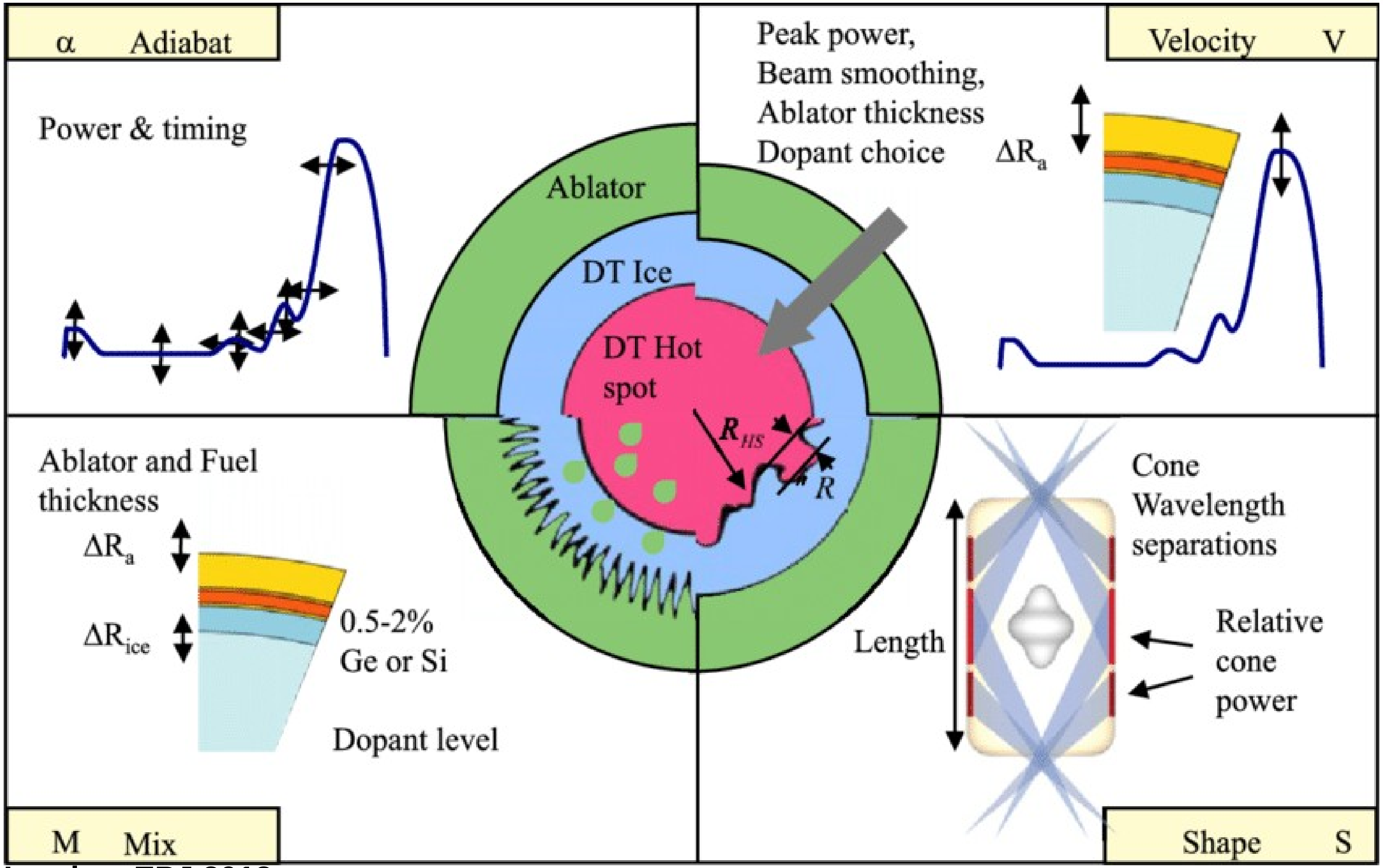
The focus of present research is on improving the fuel capsule



Requirements for ignition condition met individually

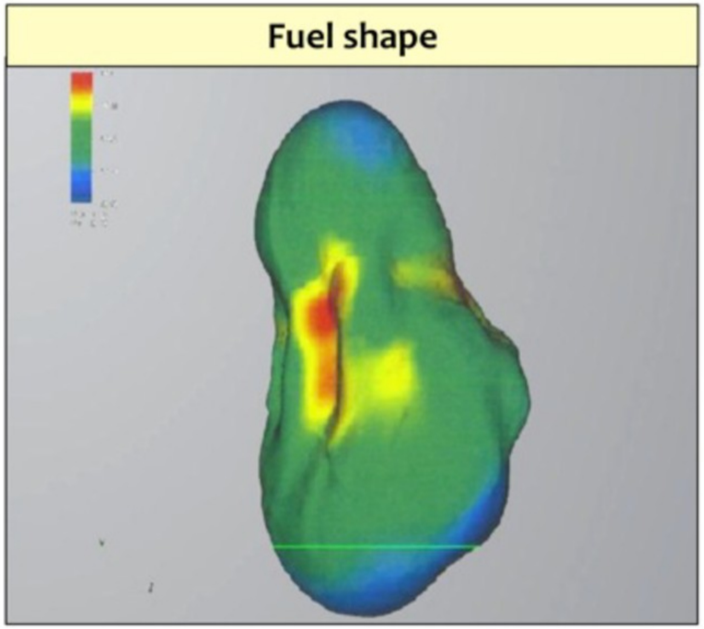
Edwards, APS2012

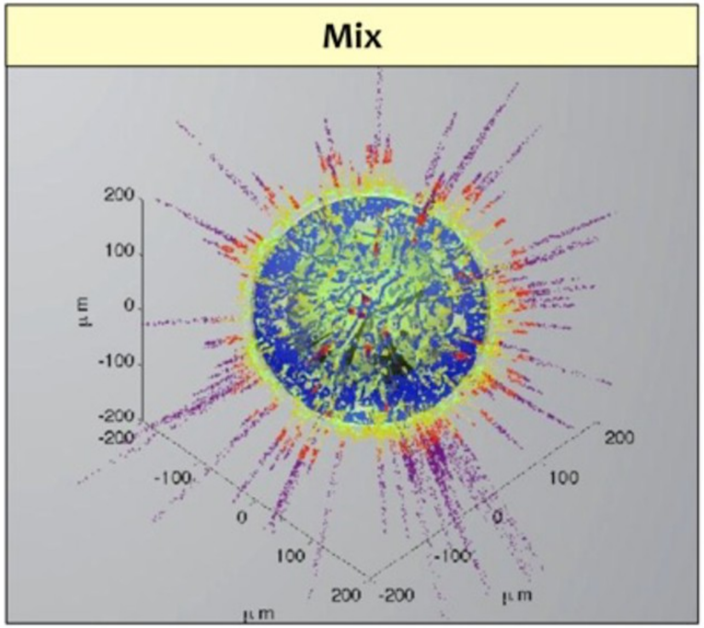
To achieve better performance, the dopant levels and ablator thicknesses need to be improved



Landen, EPJ 2013

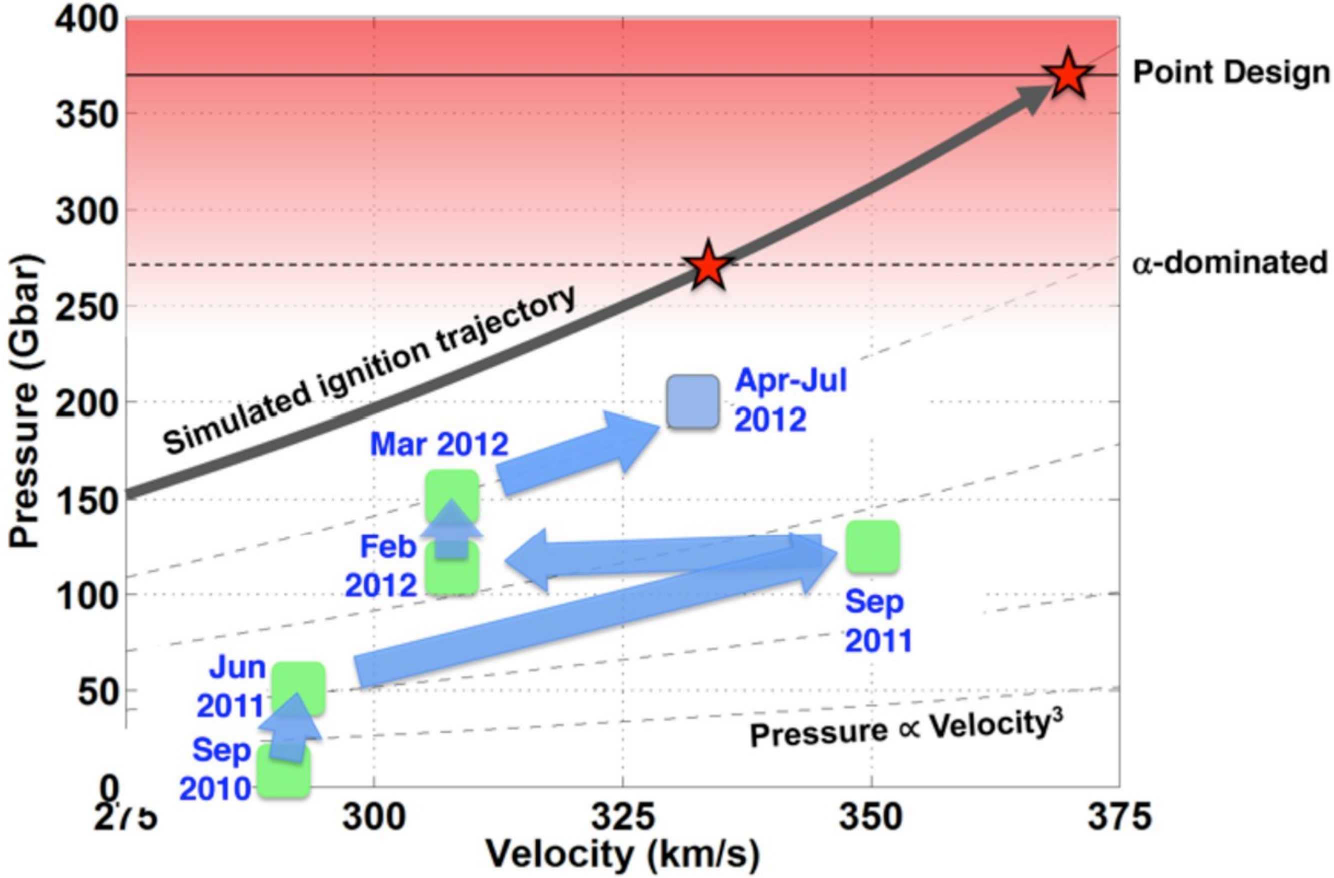
Performance likely limited by combination of low-mode x-ray drive asymmetry and cold fuel shape



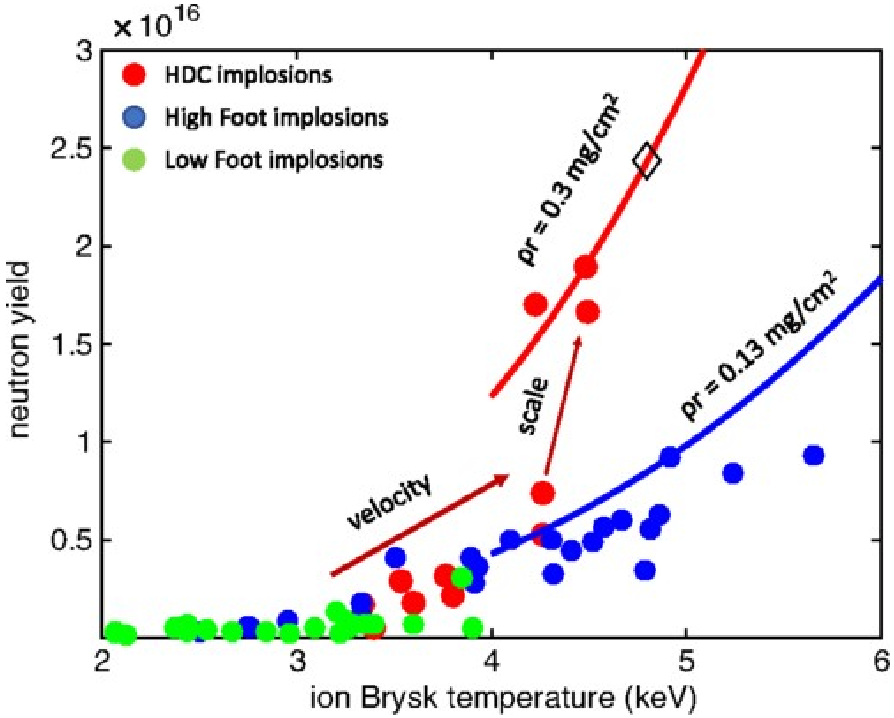


- **Experimental asymmetries due to hydrodynamic instabilities significantly higher than simulated (LASNEX) ⇒ drive/radiation control**

Increasing the implosion velocity also increases pressure, but simultaneously the mix variability



Recent progress: new record in neutron yield (2018)

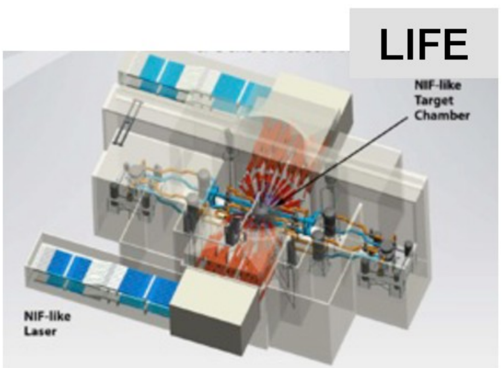


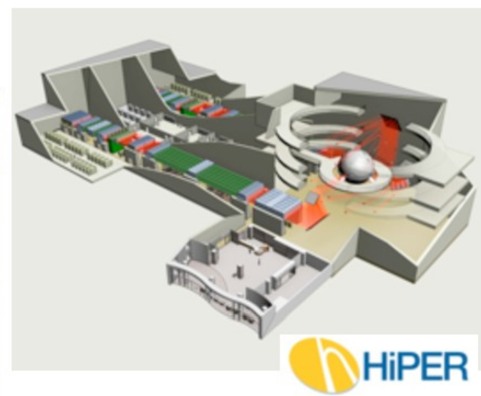
- **Total fusion neutron yield of $1.9\text{x}10^{16}$ and 54 KJ of fusion energy output achieved**
- **The record-breaking experiments utilized a diamond capsule seated inside a depleted uranium hohlraum → improved control over the symmetry of the X-rays → more symmetric implosions.**
- **Spot pressure ~360 Gbar → exceeds the pressure at the center of the sun.**

Total DT neutron yield as a function of ion temperature, The neutron yield is plotted against the lowest burn averaged DT ion temperature measured by NTOF detectors (Brysk temperature). Black diamond is the point where α deposited energy equals bremsstrahlung and conduction losses. Solid curves are a yield extrapolation with temperature using a constant ρr and adiabat. (S. Le Pape et al. Phys. Rev. Lett. 2018)

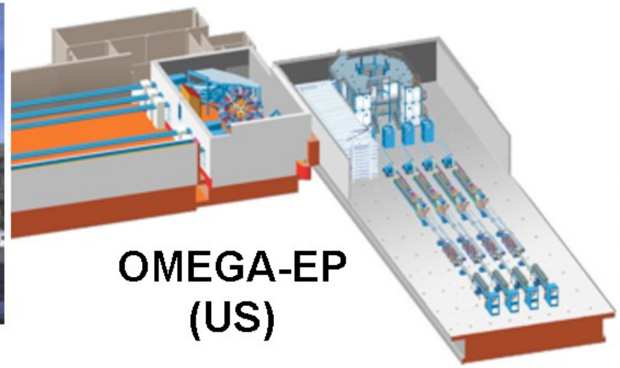
Future plants

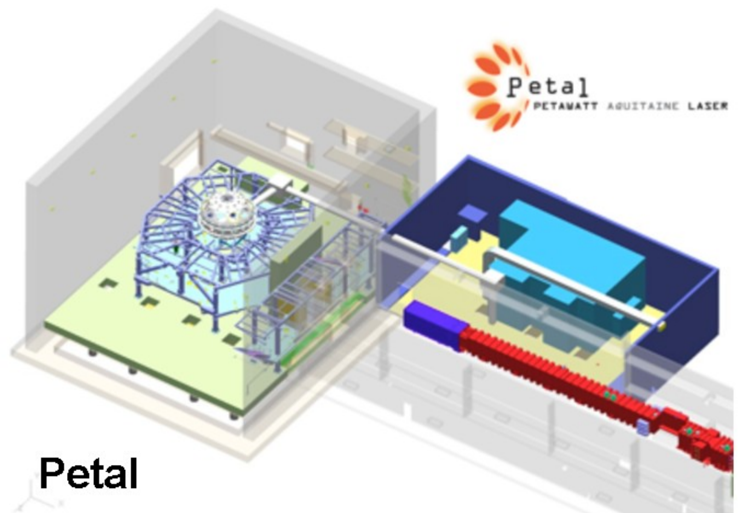
Several national and European projects are planned to succeed NIF and LMJ





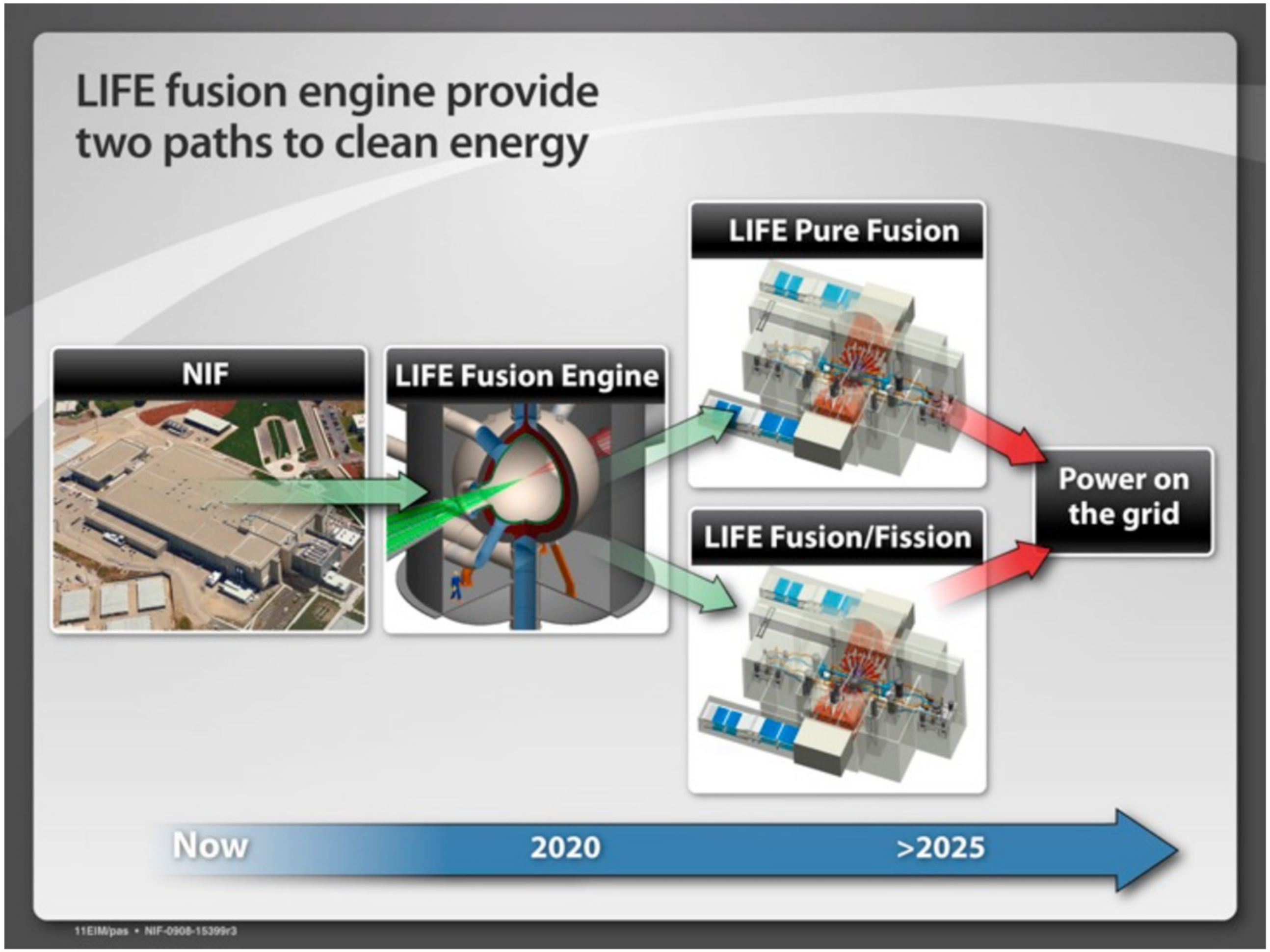
Several national and European projects are planned to succeed NIF and LMJ



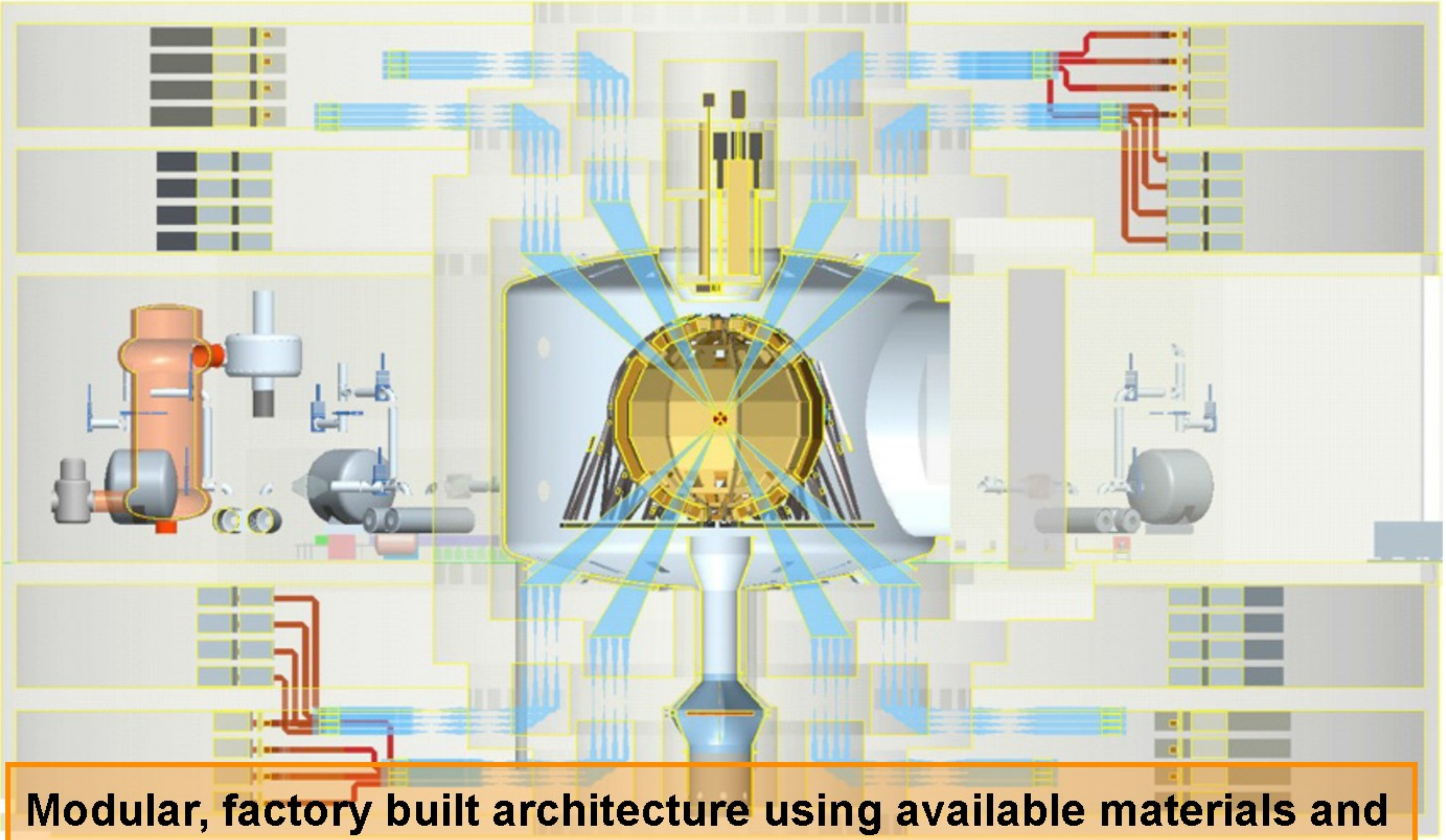


Based on NIF, LIFE is an integrated approach for a plant design

LIFE was planned to be either pure-fusion or fission-fusion hybrid

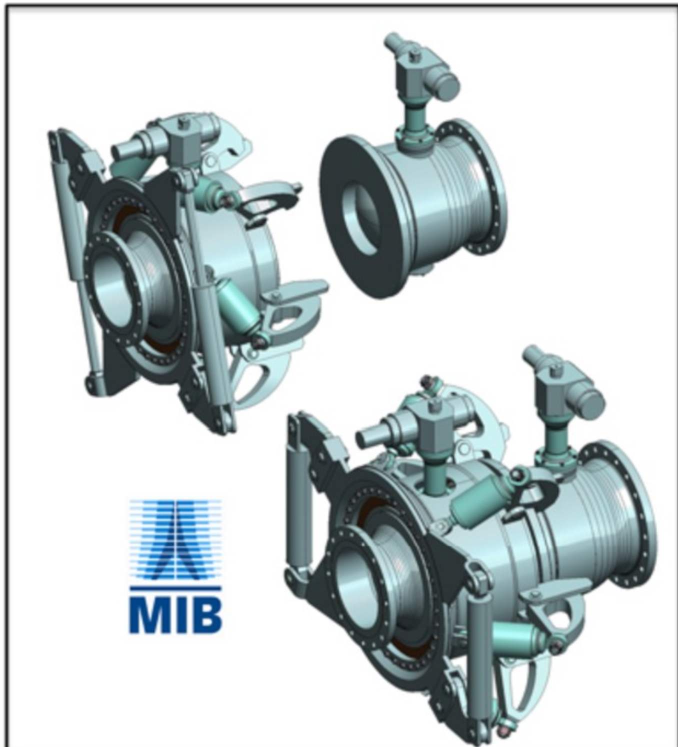


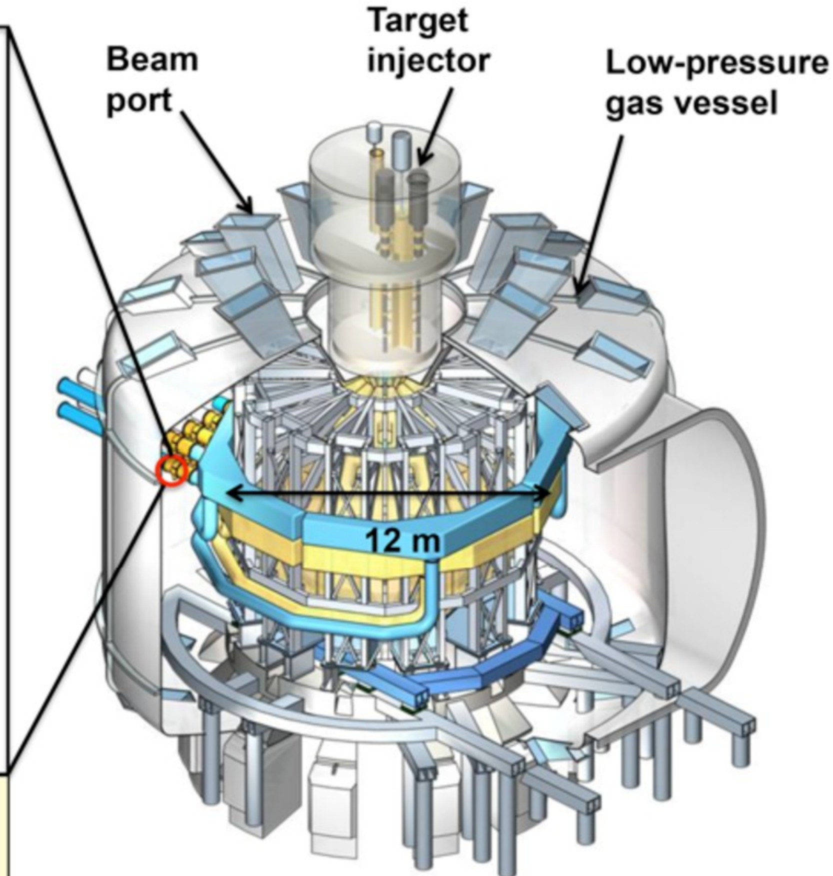
LIFE builded on NIF, configure into an integrated power plate for 400-1500 MWe



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

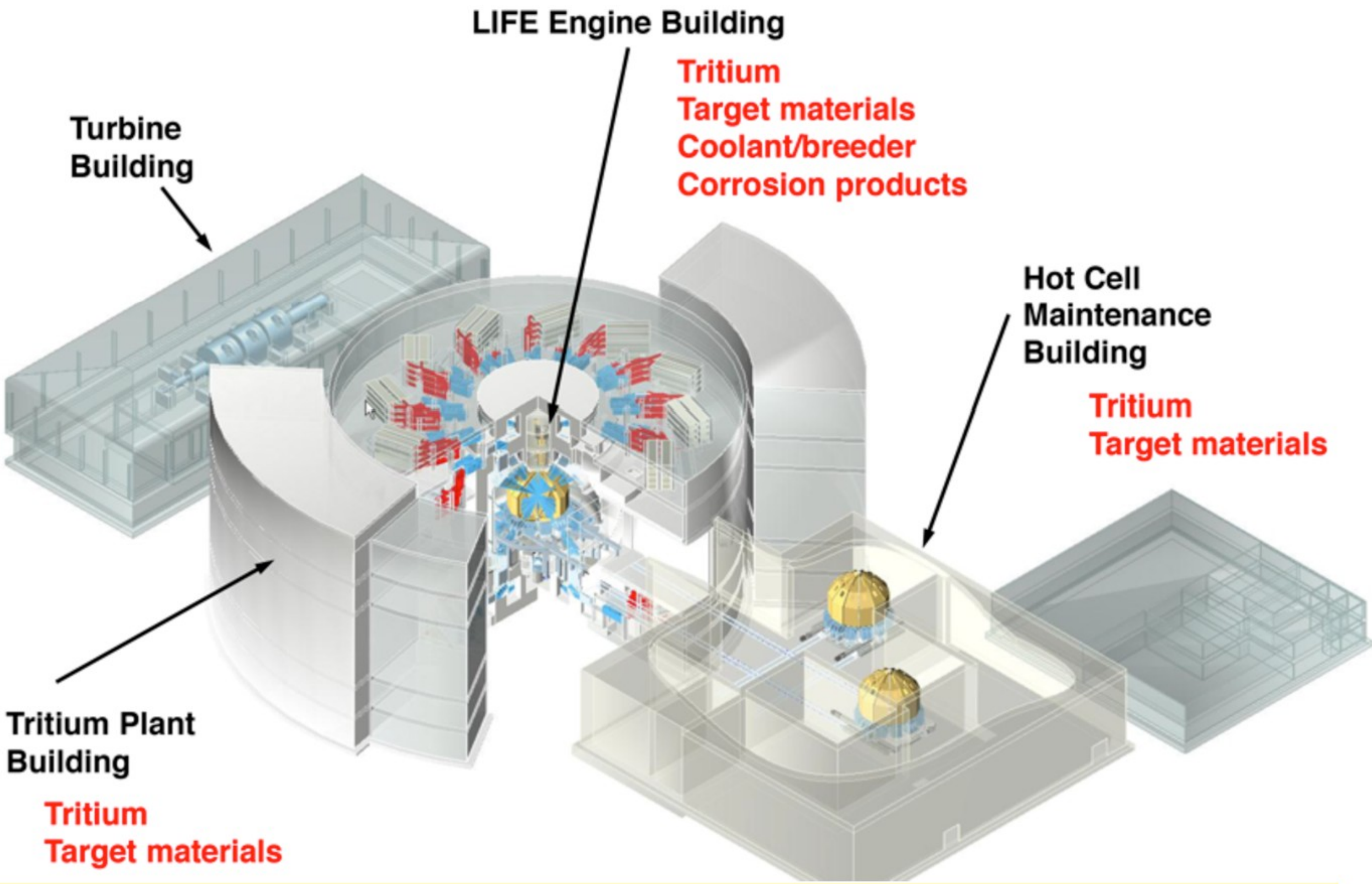
The LIFE chamber is an unsealed, segmented array sitting within a vacuum vessel environment





Once in the engine bay, cooling connections are made with industrial hydraulic couplers

A hazards assessment has been completed to identify potential release pathways



End of LIFE: focus on scientific challenges of ignition

- NIF construction was completed in 2009
- National Ignition Campaign was aiming to reach ignition by 09/2012 → By the end of 2012 still only 1⁄10 of the pressures needed to achieve ignition
- 2015 the best result is still 1⁄3 away from the required densities, and the method used may not be suitable for closing that gap
- National Academy of Sciences review board: time for new IFE program is when ignition is achieved and ignition using laser indirect drive is not likely in the next several years.
- The LIFE effort was quietly cancelled in early 2013
- LLNL's acting director, Bret Knapp:

"The focus of our inertial confinement fusion efforts is on understanding ignition on NIF rather than on the LIFE concept. Until more progress is made on ignition, we will direct our efforts on resolving the remaining fundamental <u>scientific challenges</u> to achieving fusion ignition."

Summary

- **Fusion of D-T fuel has been achieved in inertial confinement system ⇒ concept is close to achieving break-even**
- **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**