Laser Inertial Fusion Energy

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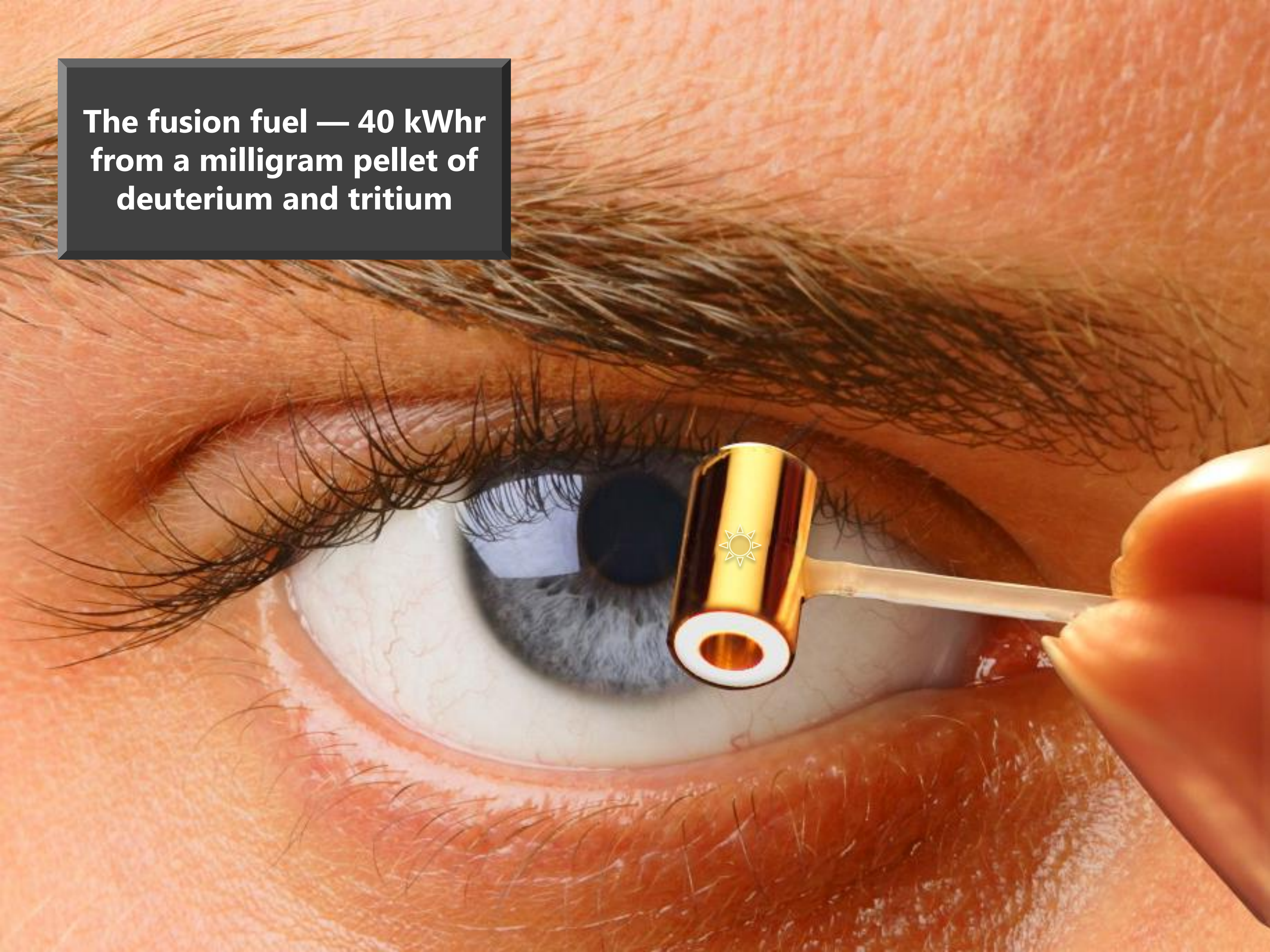
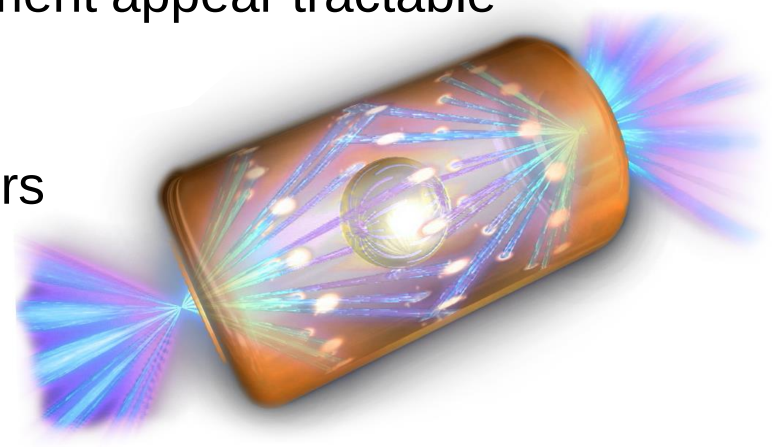
Could we build a miniature sun on earth?
. . . to provide significant carbon-free energy for humankind.

The fusion fuel — 40 kWhr from a milligram pellet of deuterium and tritium

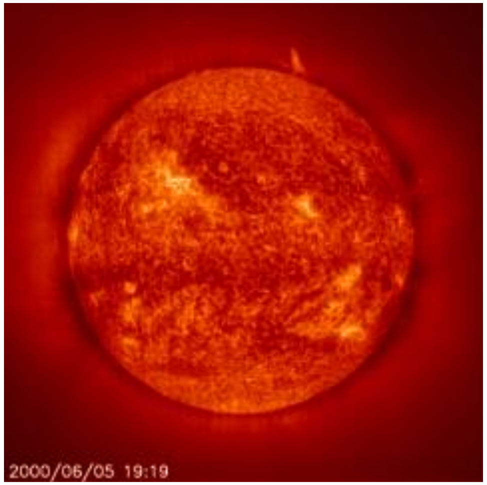


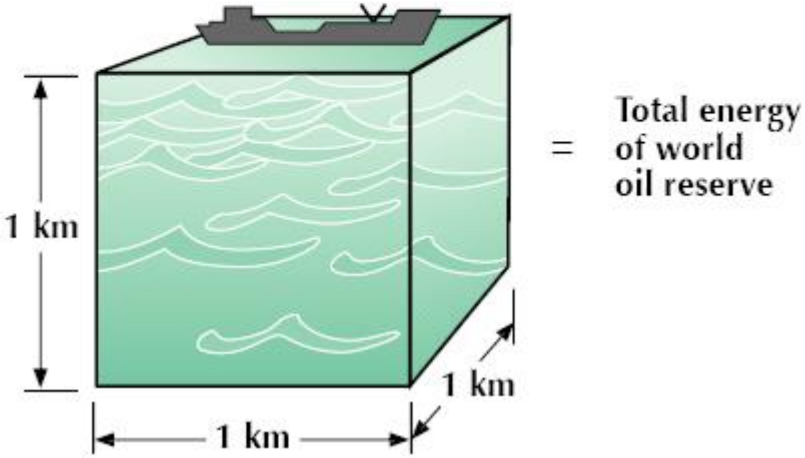
Fusion's characteristics have attracted sustained investment – but await full-scale proof

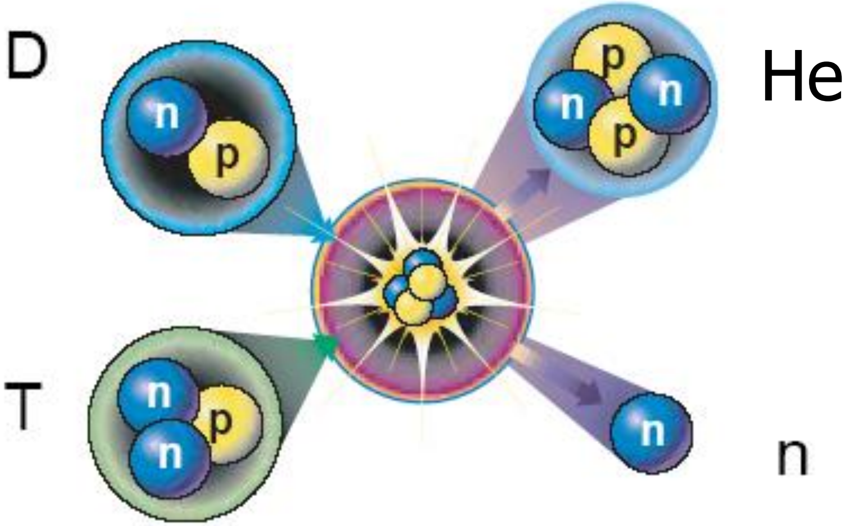
- **Able to provide baseload power at a global scale**
- **Power excursions self-limited by inherent processes**
  - "run-away" reactions are physically impossible, unlike chemical or nuclear fuels
- **No long-lived radioactivity, or use of nuclear materials**
- **Reduced environmental footprint**
  - Very low lifecycle emissions
  - Potential for economic dry cooling
  - Waste disposition and tritium management appear tractable
  - Fuel cycle not extractive
  - Efficient land use, and near load-centers
  - Good local air quality



We know fusion works …







$$D + T \rightarrow \alpha + n$$

3.5 MeV   14.1 MeV

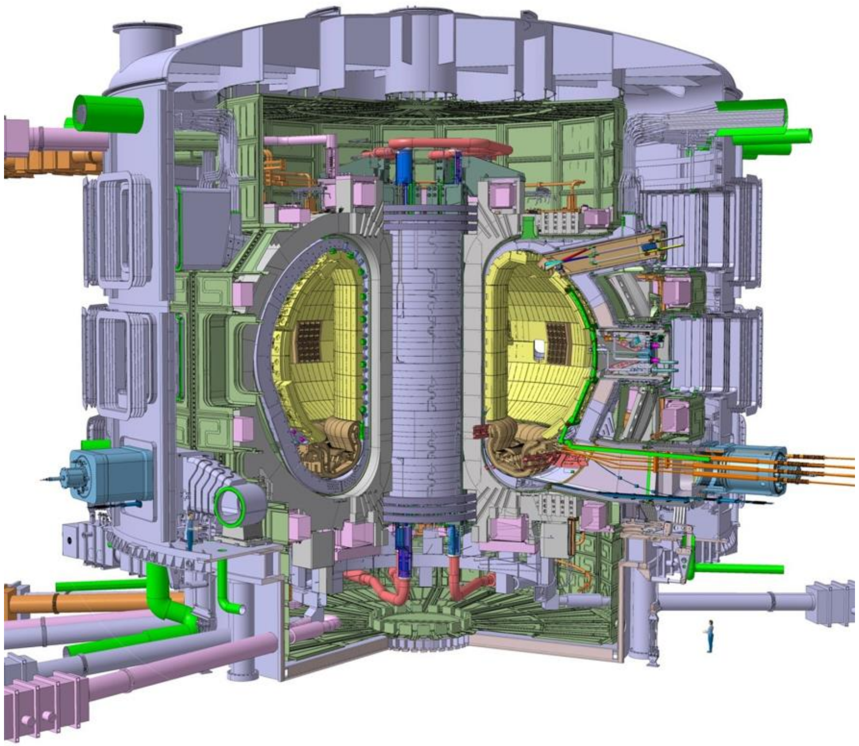
$$E = m c^2$$

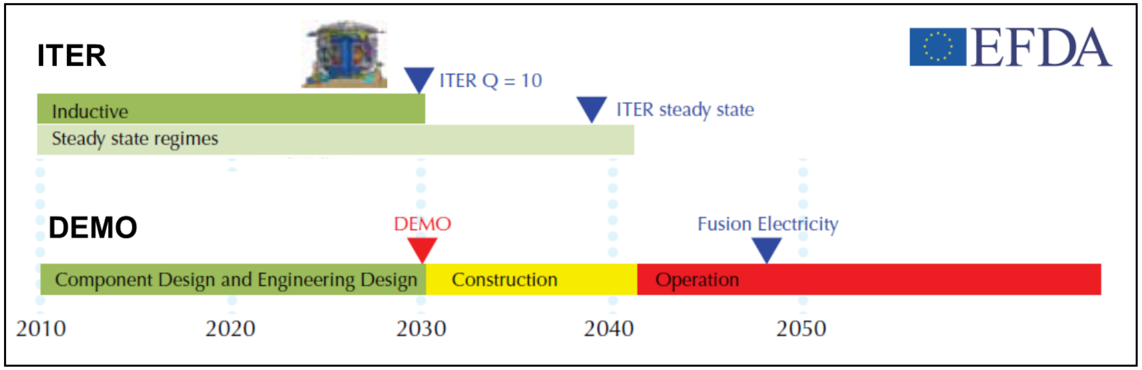
Mass difference between initial & final particles = [ZMp + (A-Z)Mn – M] / A

This energy is a few million times greater than in chemical reactions

Approach #1: Magnetic Fusion Energy (MFE)

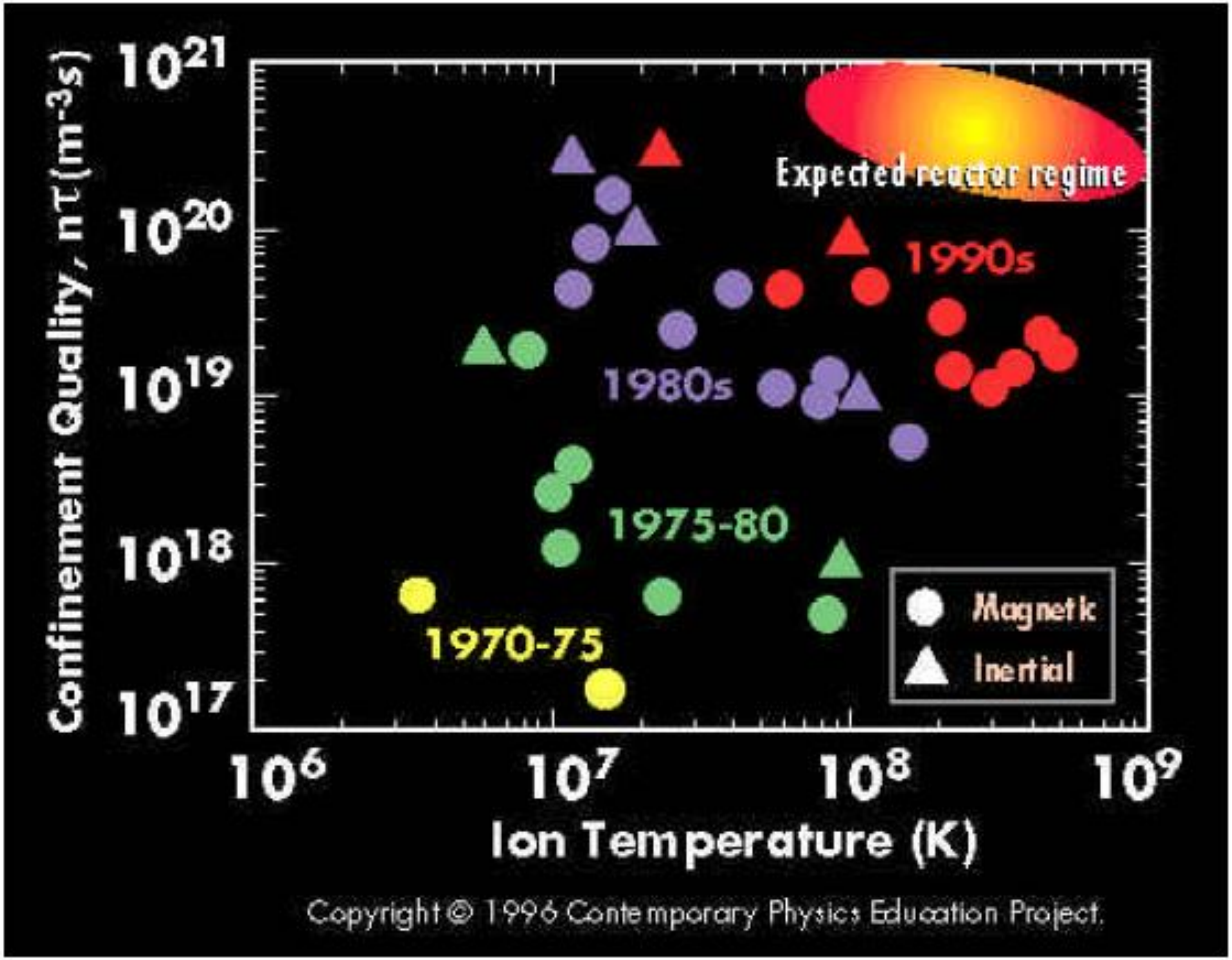
ITER project





Approach #2: Inertial Fusion Energy (IFE)

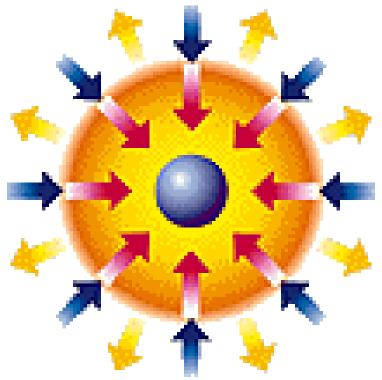
Historical progress with MFE and IFE



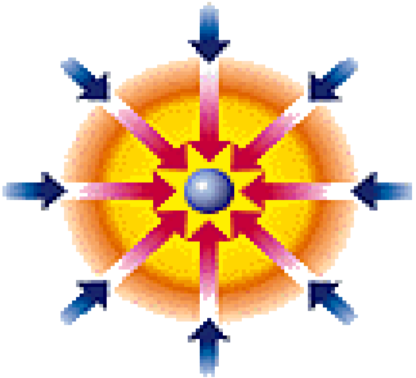
Laser (Inertial) Fusion Energy

A spherical, pulsed rocket

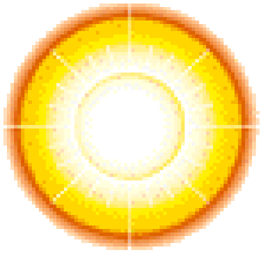
Lasers or X-rays symmetrically irradiate pellet



Hot plasma expands into vacuum causing shell to implode with high velocity



Material is compressed to ~1000 gcm^{-3}



Hot spark formed at the centre of the fuel by convergence of accurately timed shock waves

The NIF facility is the culmination of many decades of US leadership and investment in this field

NIF can demonstrate full-scale performance for a 1000 MWe plant

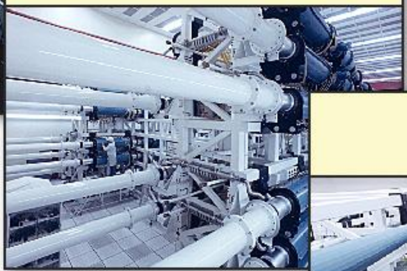
Janus, 1974

100J IR

Argus, 1976

1kJ IR

Shiva, 1977

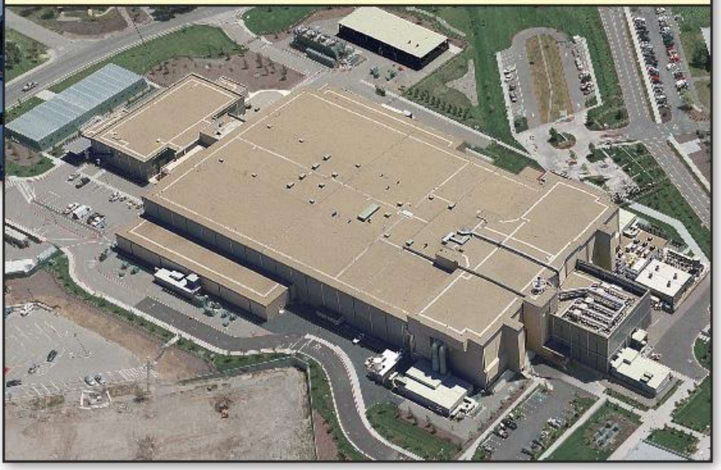


10kJ IR

Nova, 1984

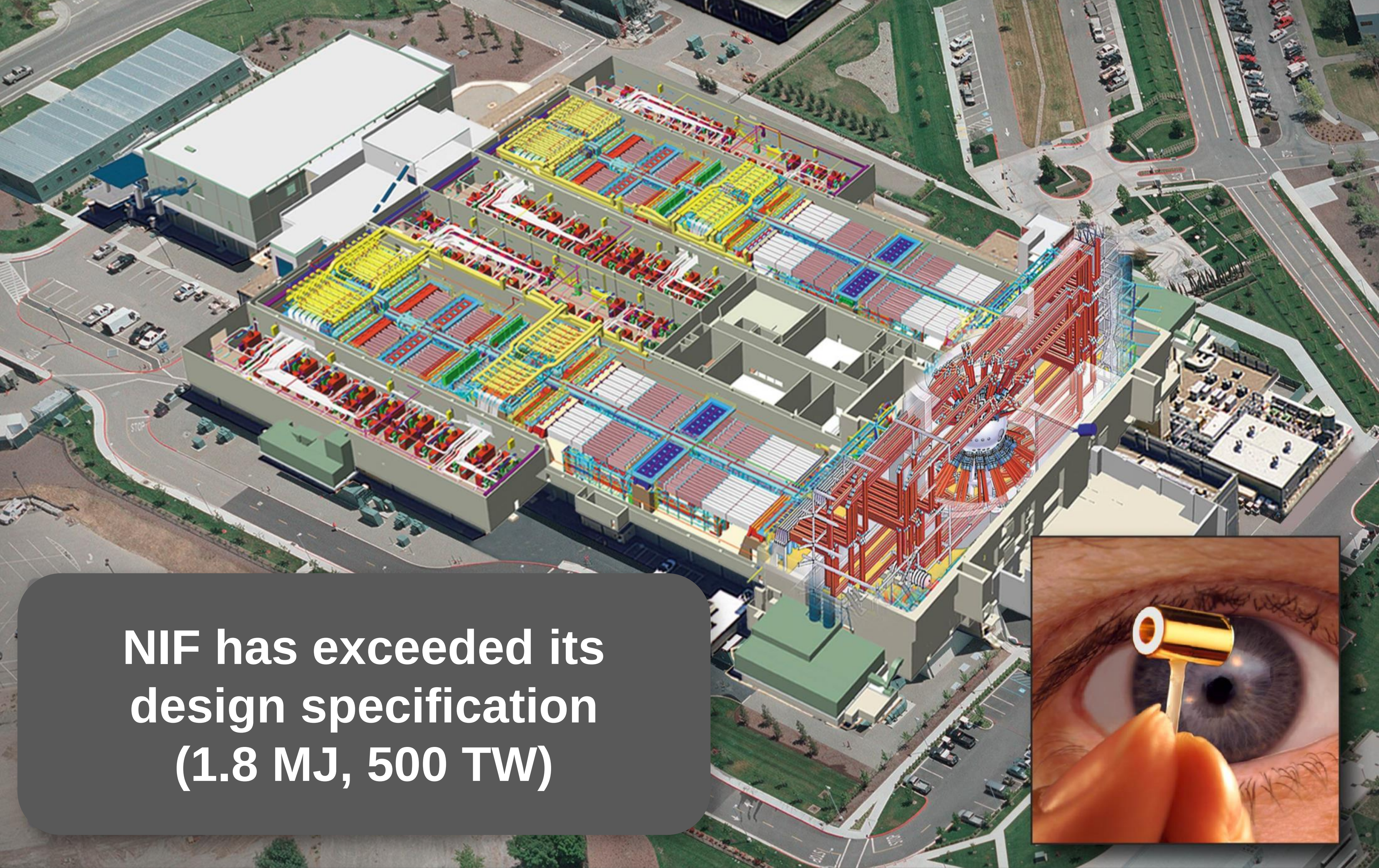
30kJ UV

NIF, 2009



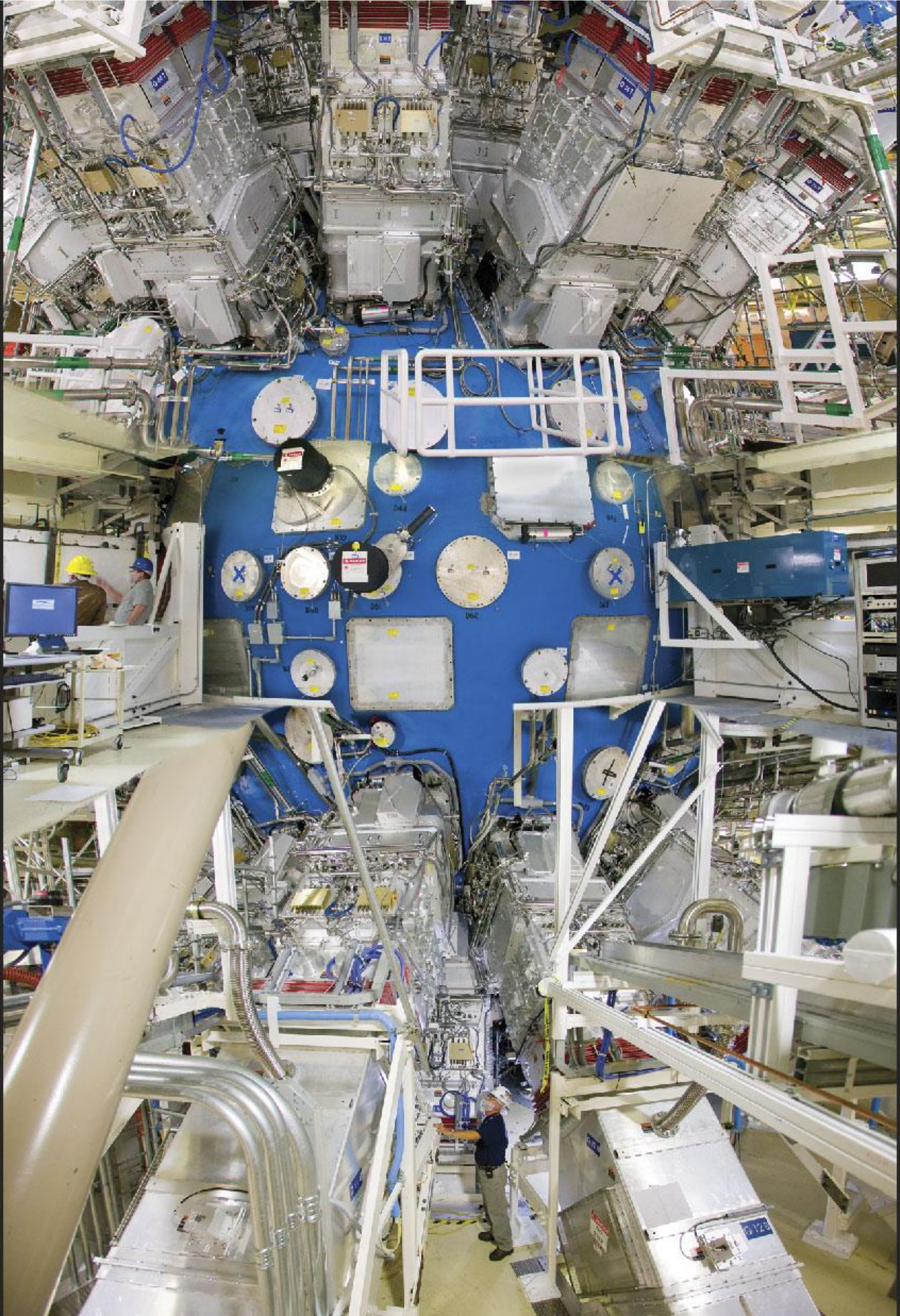
1.8 MJ UV

NIF concentrates all 192 laser beam energy in a football stadium-sized facility into a mm³



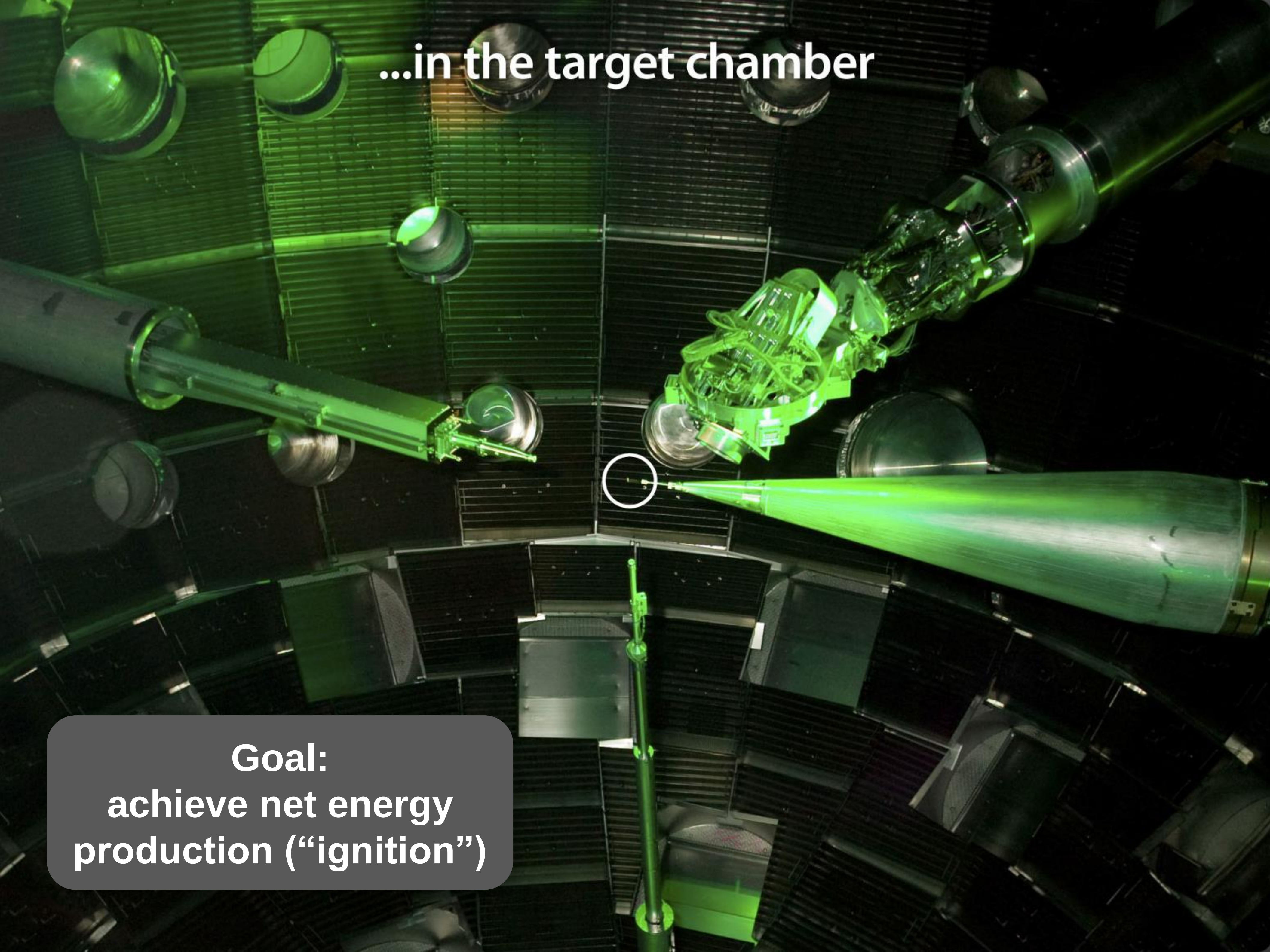
NIF has exceeded its design specification (1.8 MJ, 500 TW)

Fusion "target" chamber

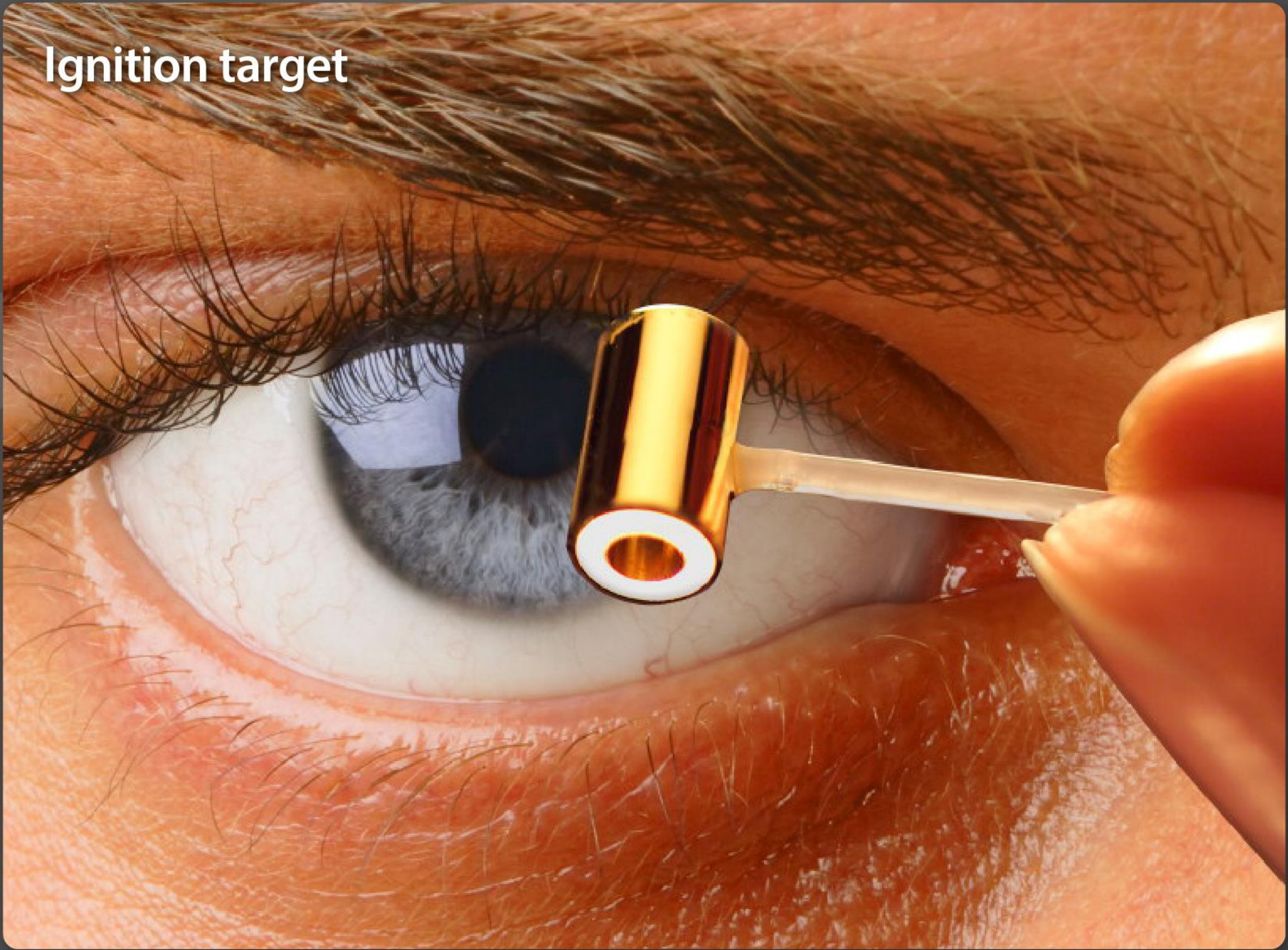


22EIM/lh • NIF-0609-16541s2r1L2

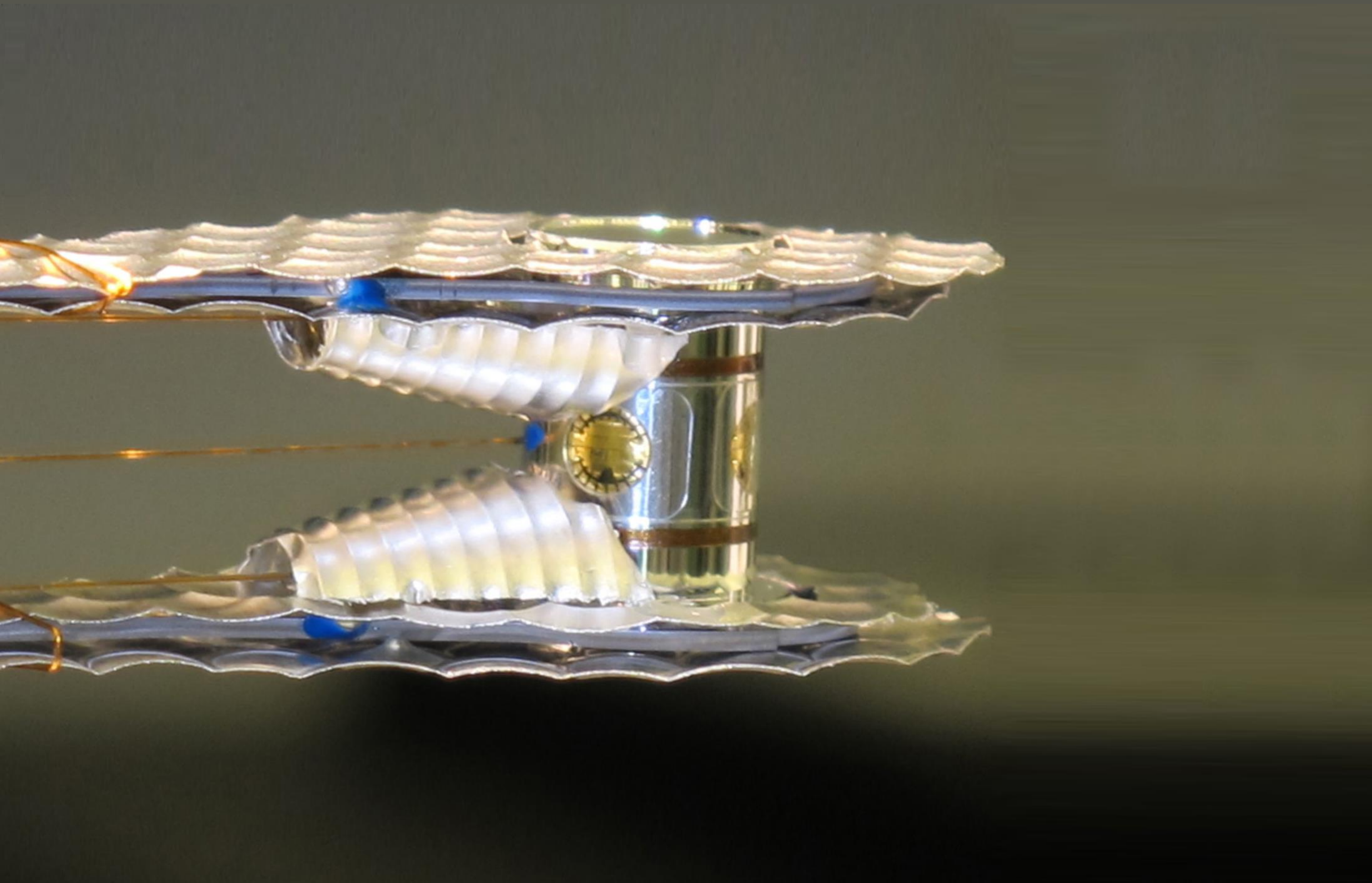
Inside the target chamber


...in the target chamber
Goal:
achieve net energy
production ("ignition")

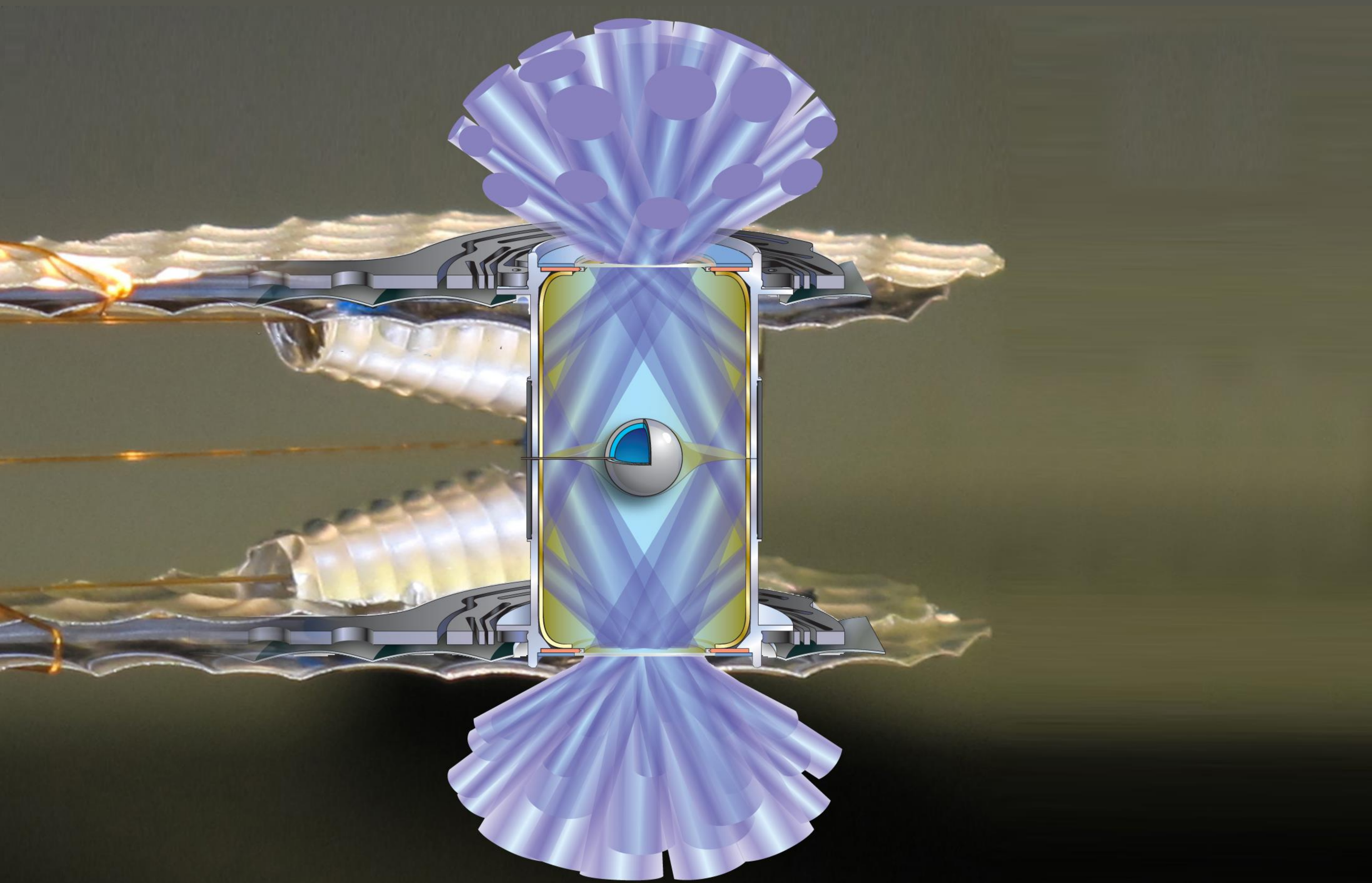
Ignition target



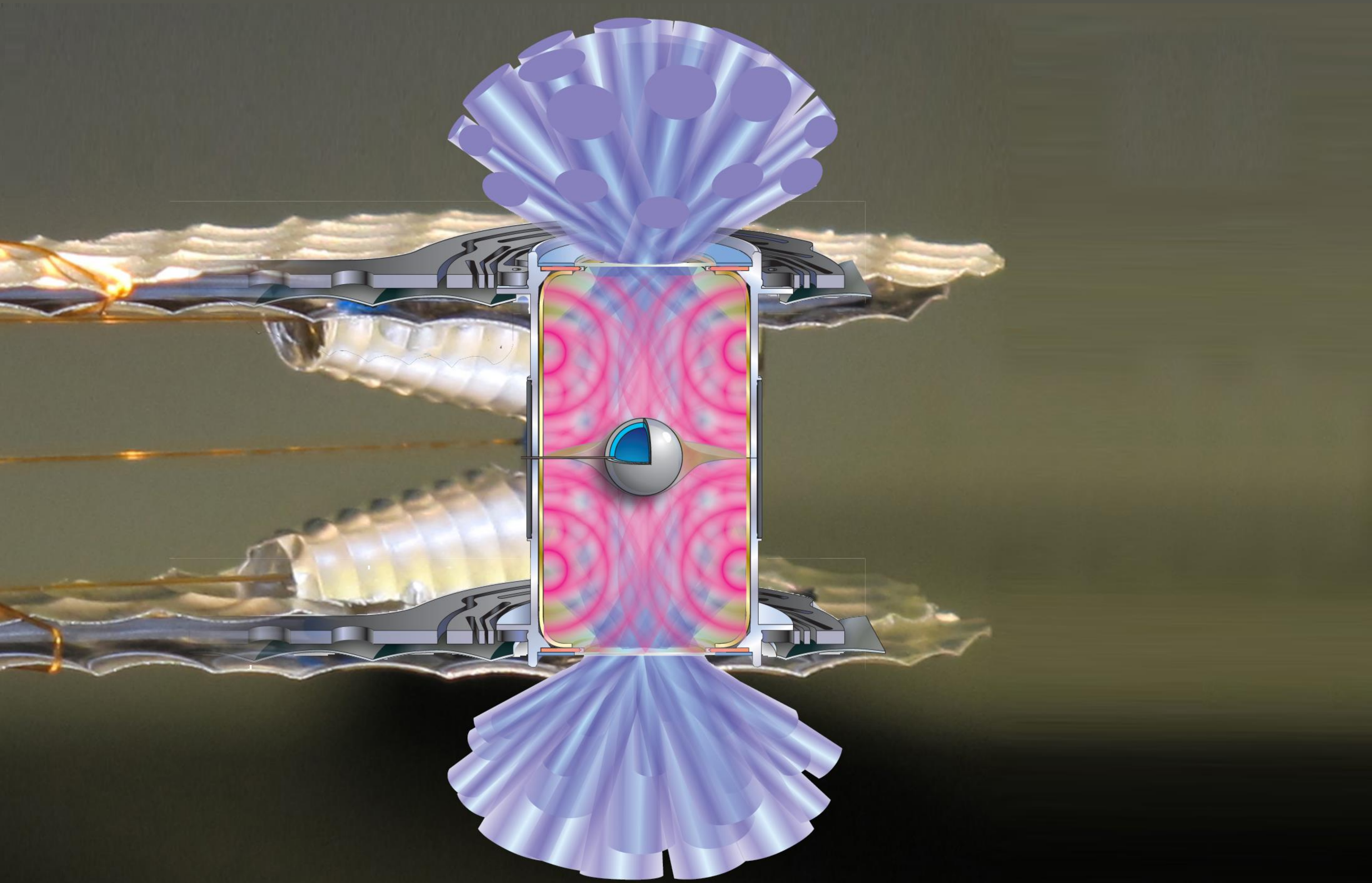
A hohlraum sits at the center of the target chamber



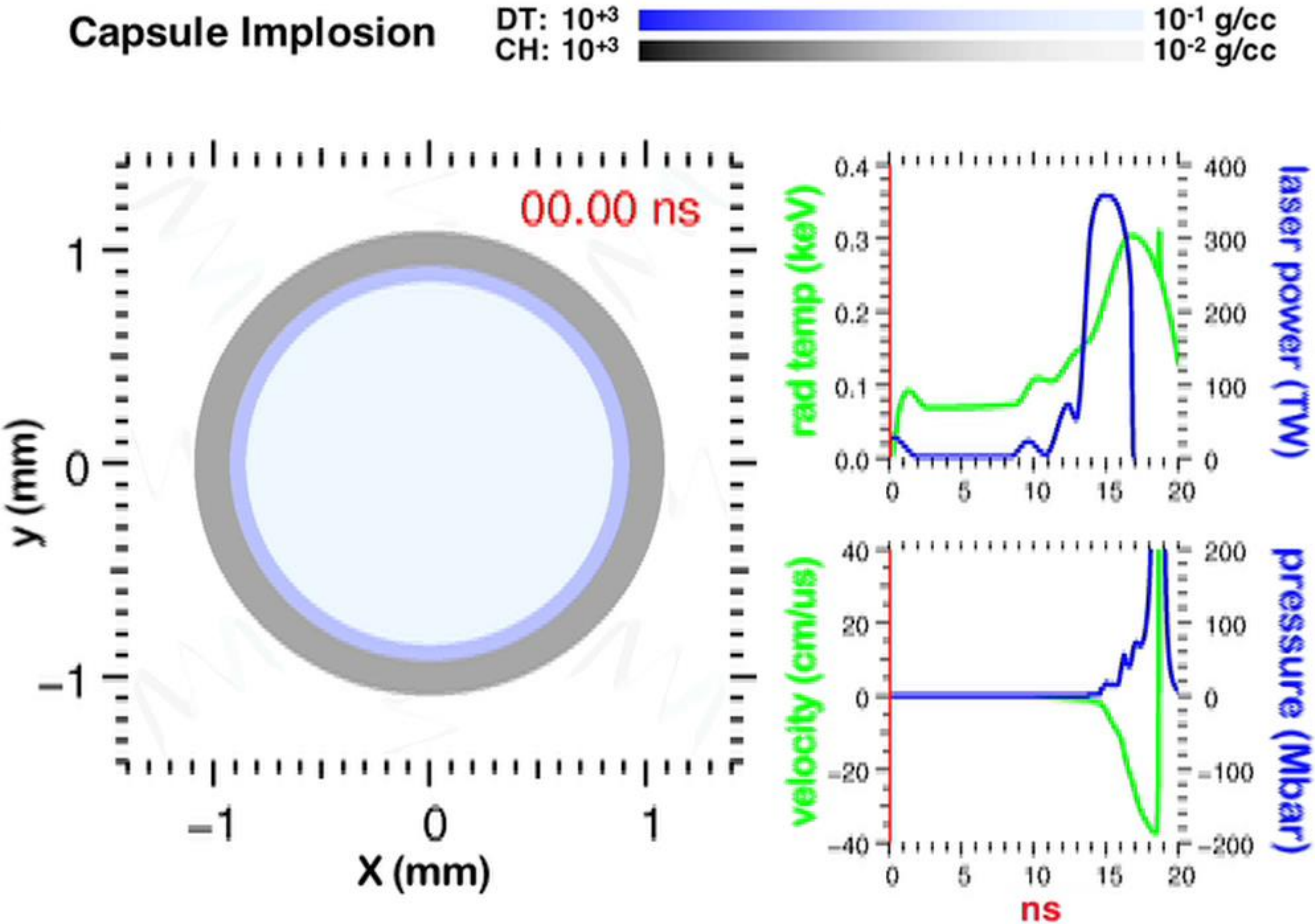
192 beams are focused through the Laser Entrance Hole in the hohlraum



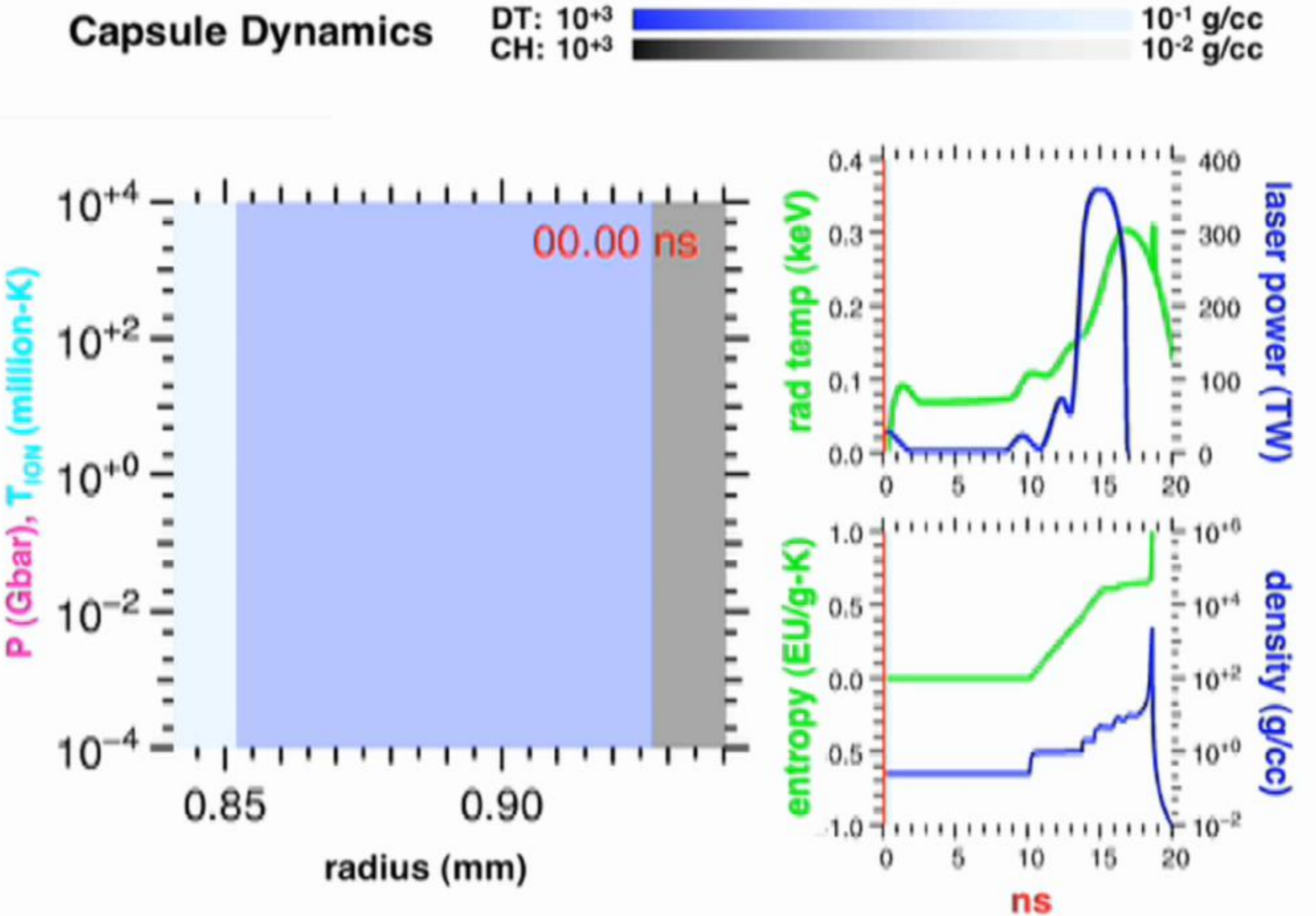
The hohlraum transforms light into x-rays that drive implosion of the capsule



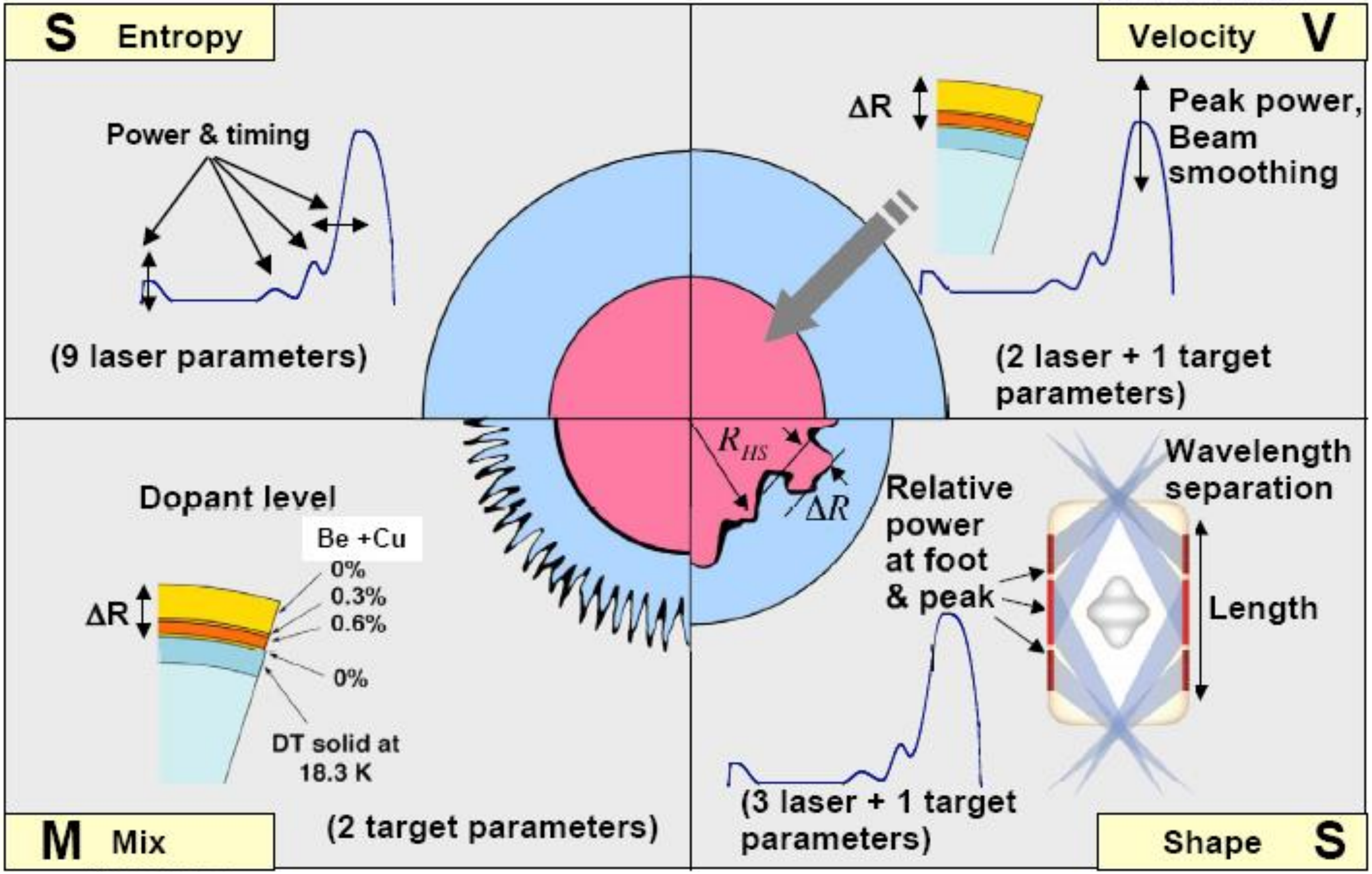
Capsule Implosion



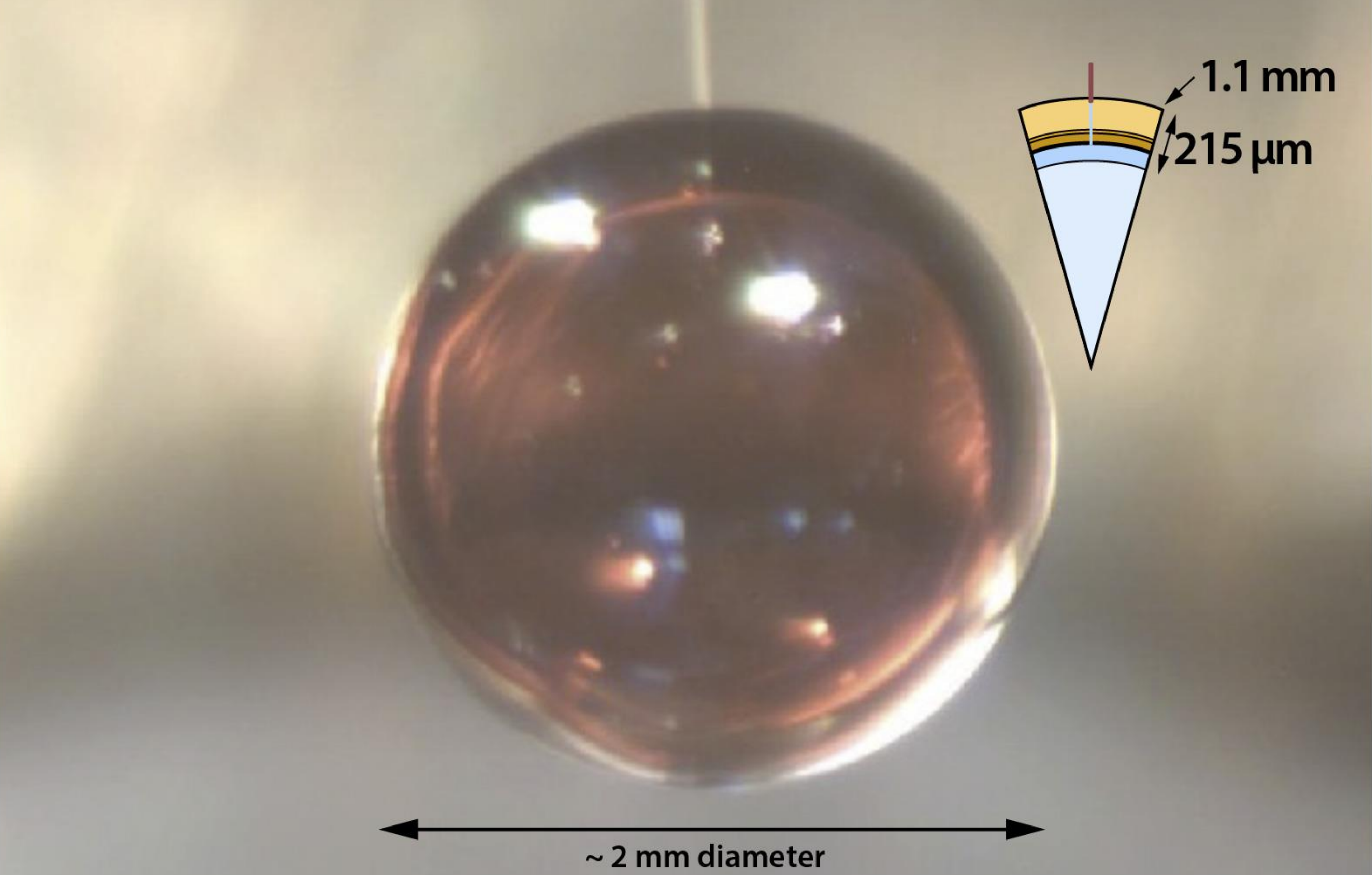
Capsule Dynamics



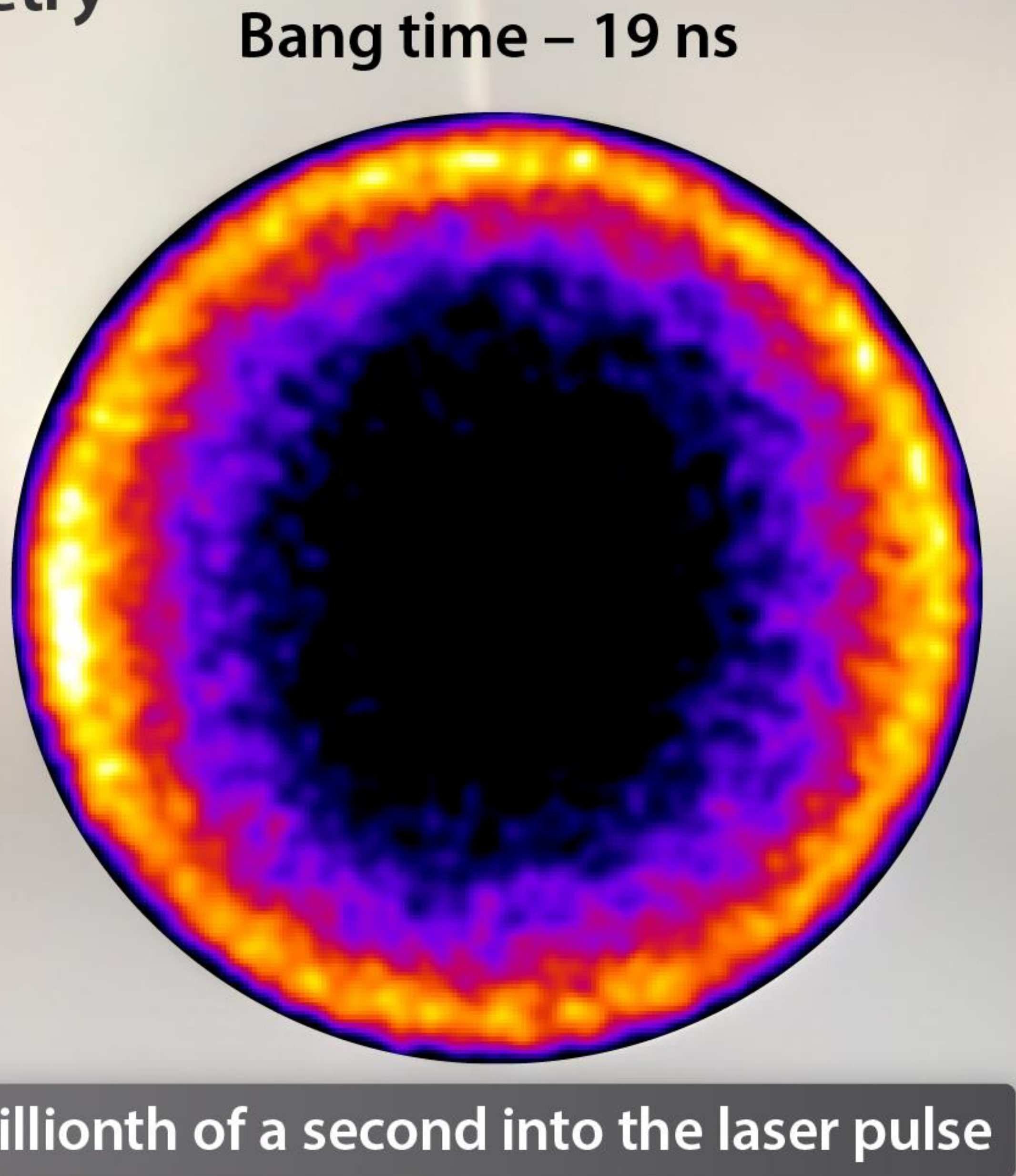
The implosion performance can be optimized by considering 4 weakly-coupled physical characteristics



The capsule starts at 2mm diameter

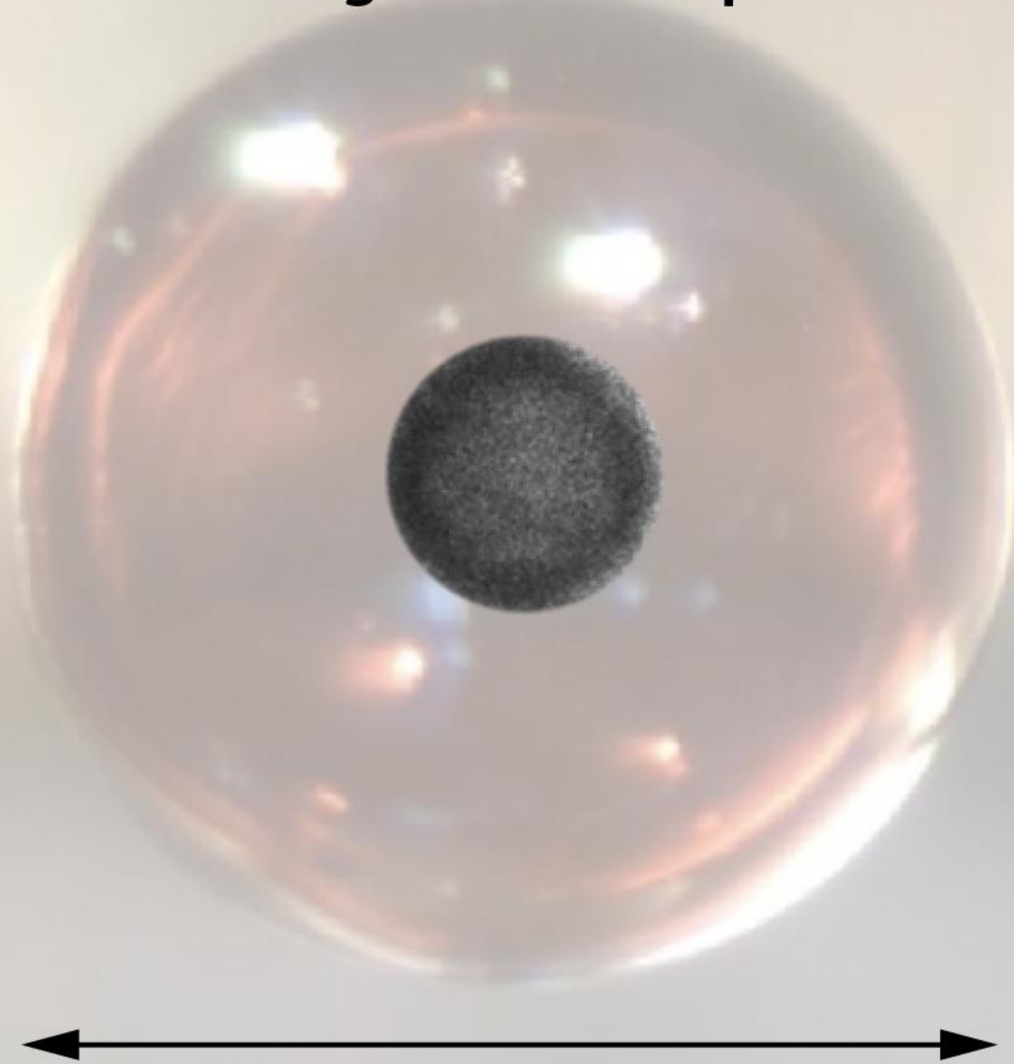


Re-emmission sphere measures early time x-drive symmetry



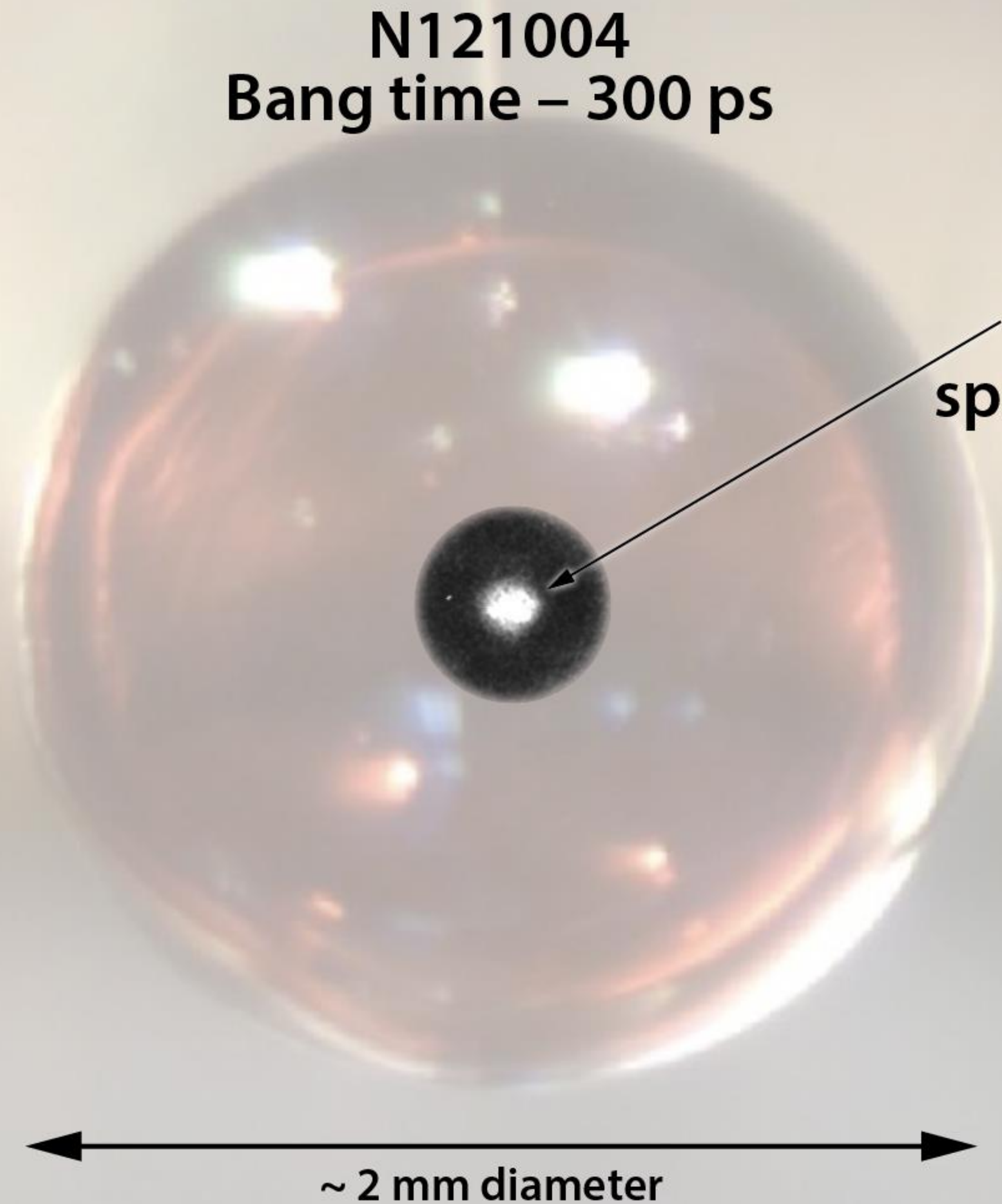
Radiography measures the shape of the capsule in-flight

N121004
Bang time – 600 ps

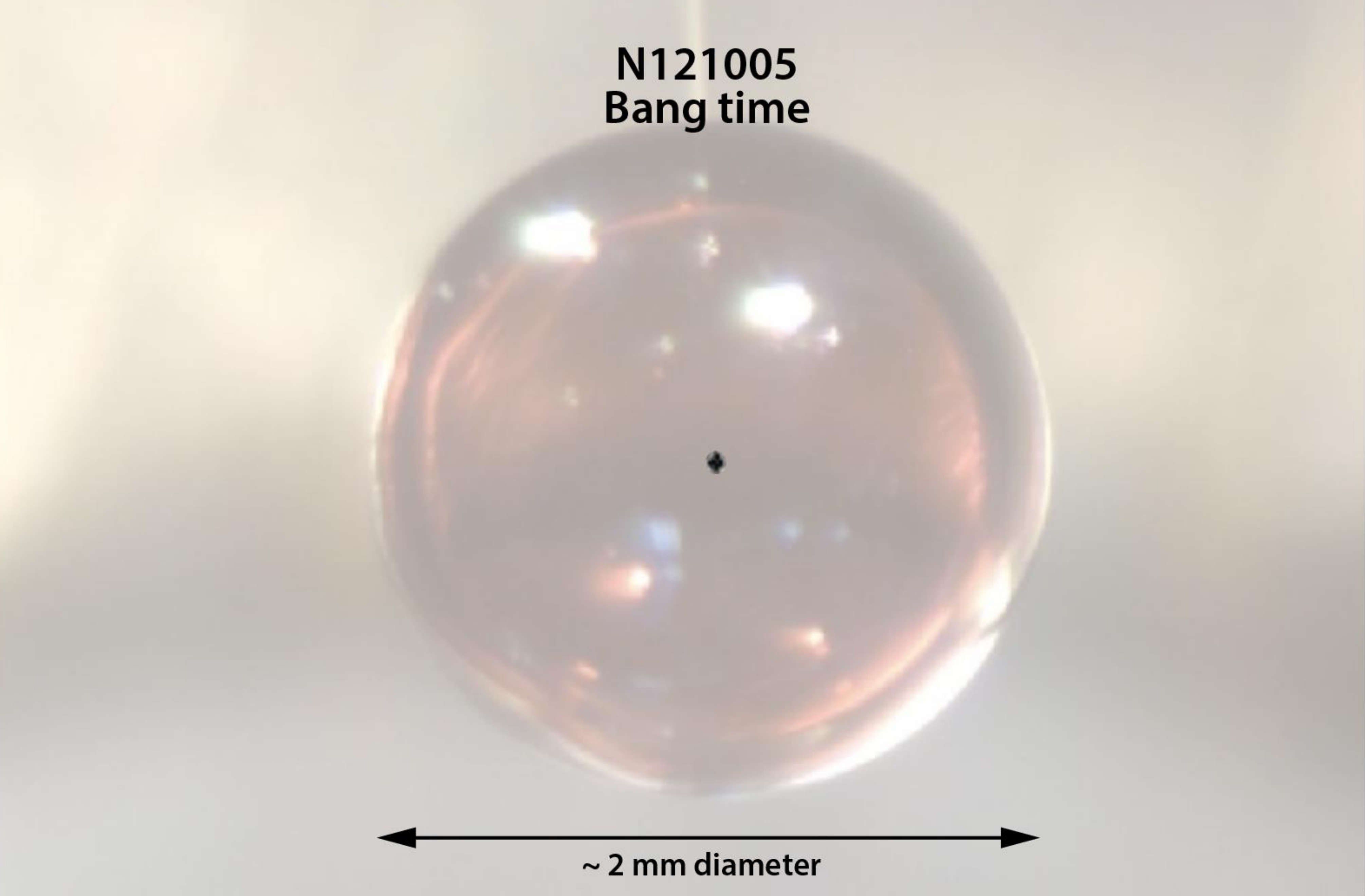


~ 2 mm diameter

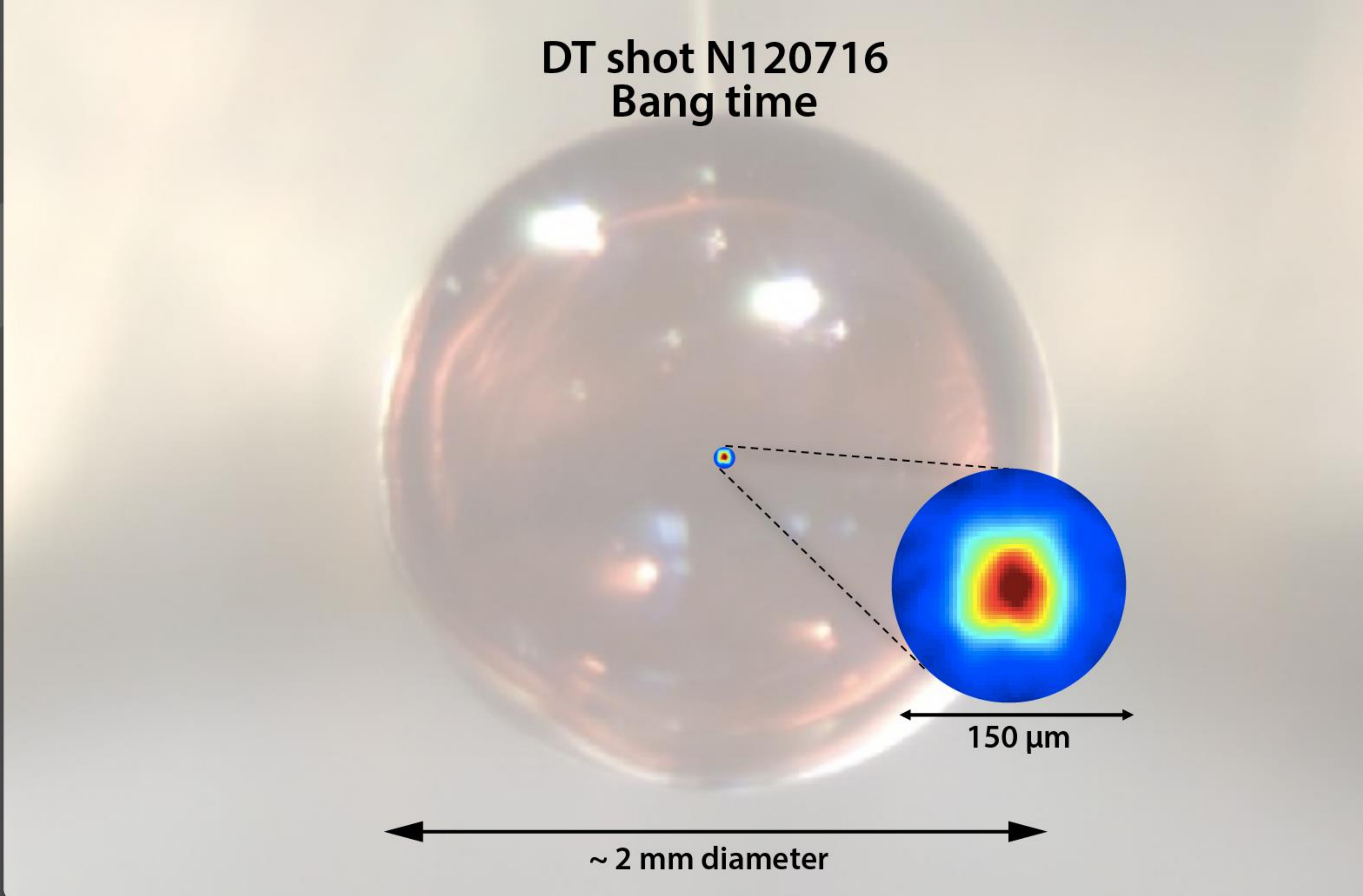
Radiography measures the shape of the capsule in-flight



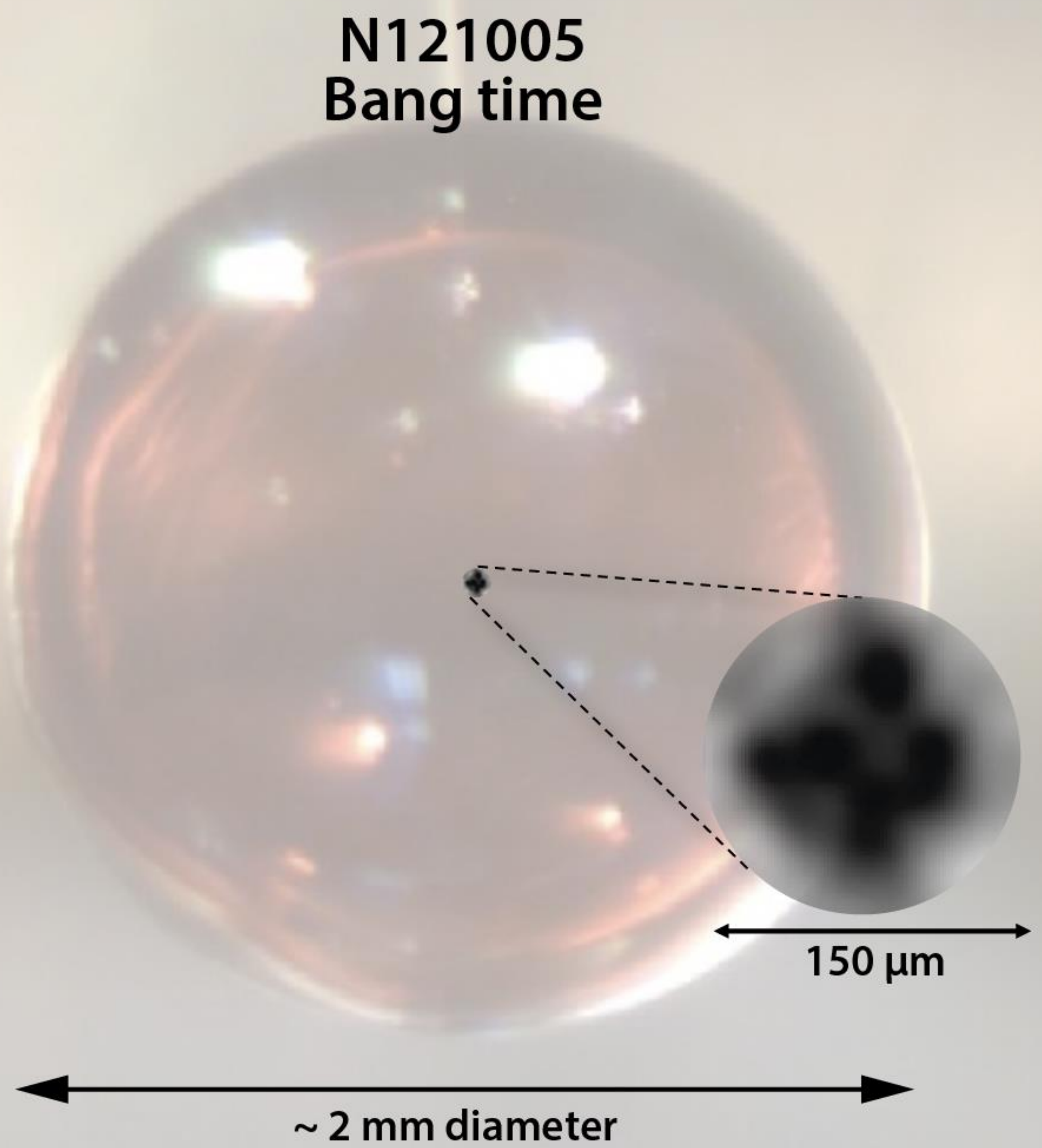
Compton radiography probes fuel shape at stagnation



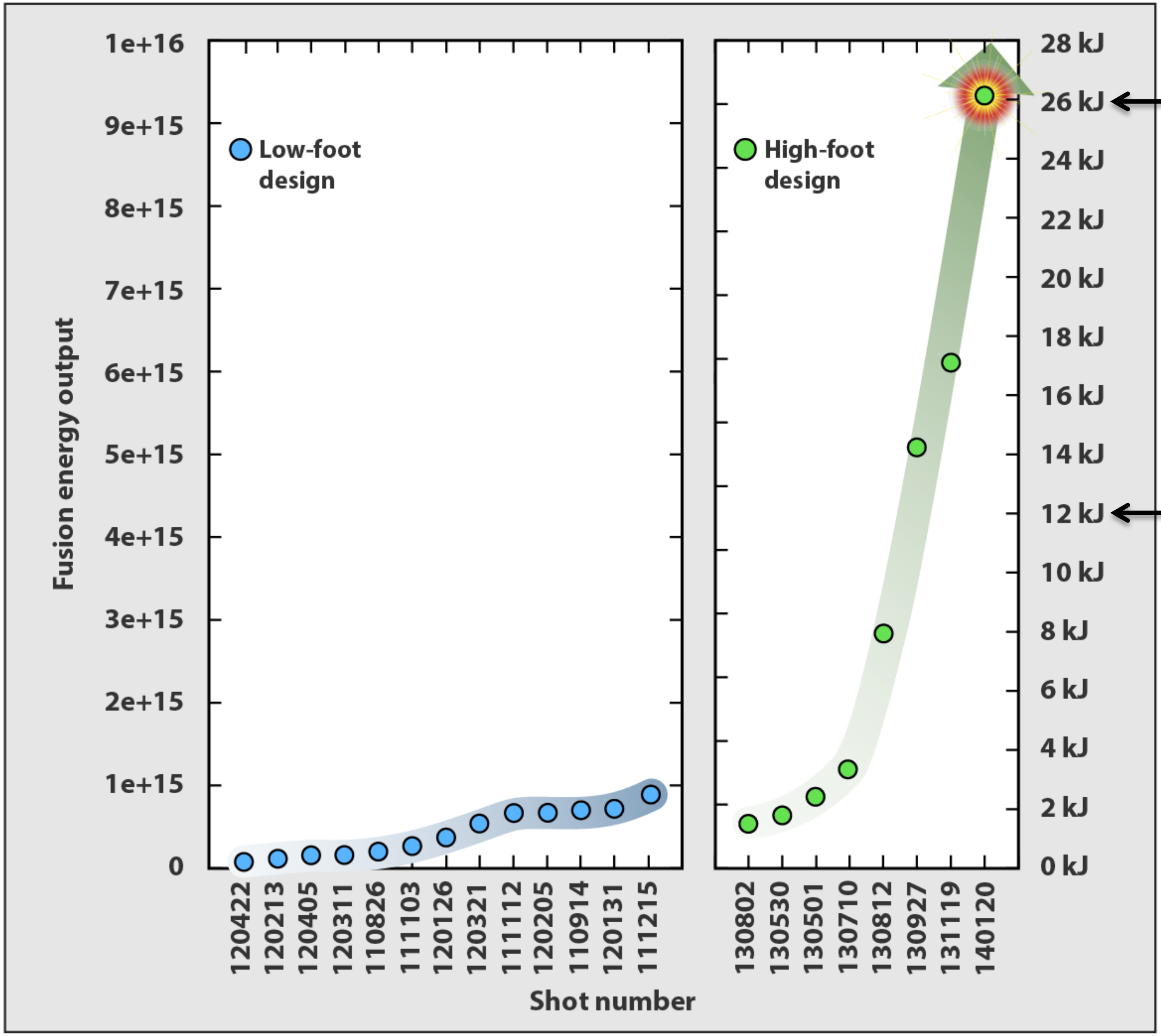
The hot spot looks quite round!



Compton radiography probes fuel shape at stagnation



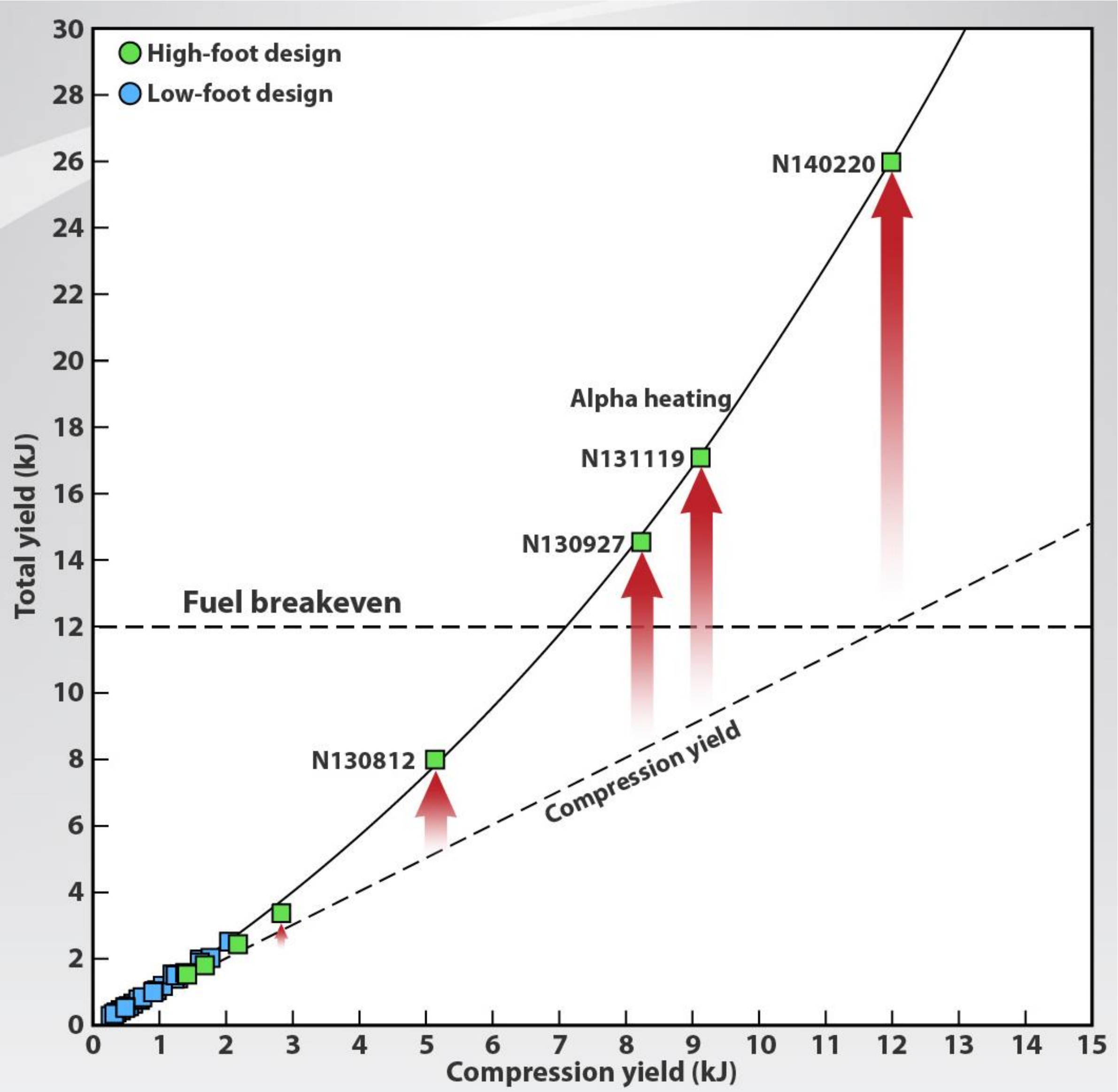
Recent performance on NIF has shown significant progress towards ignition



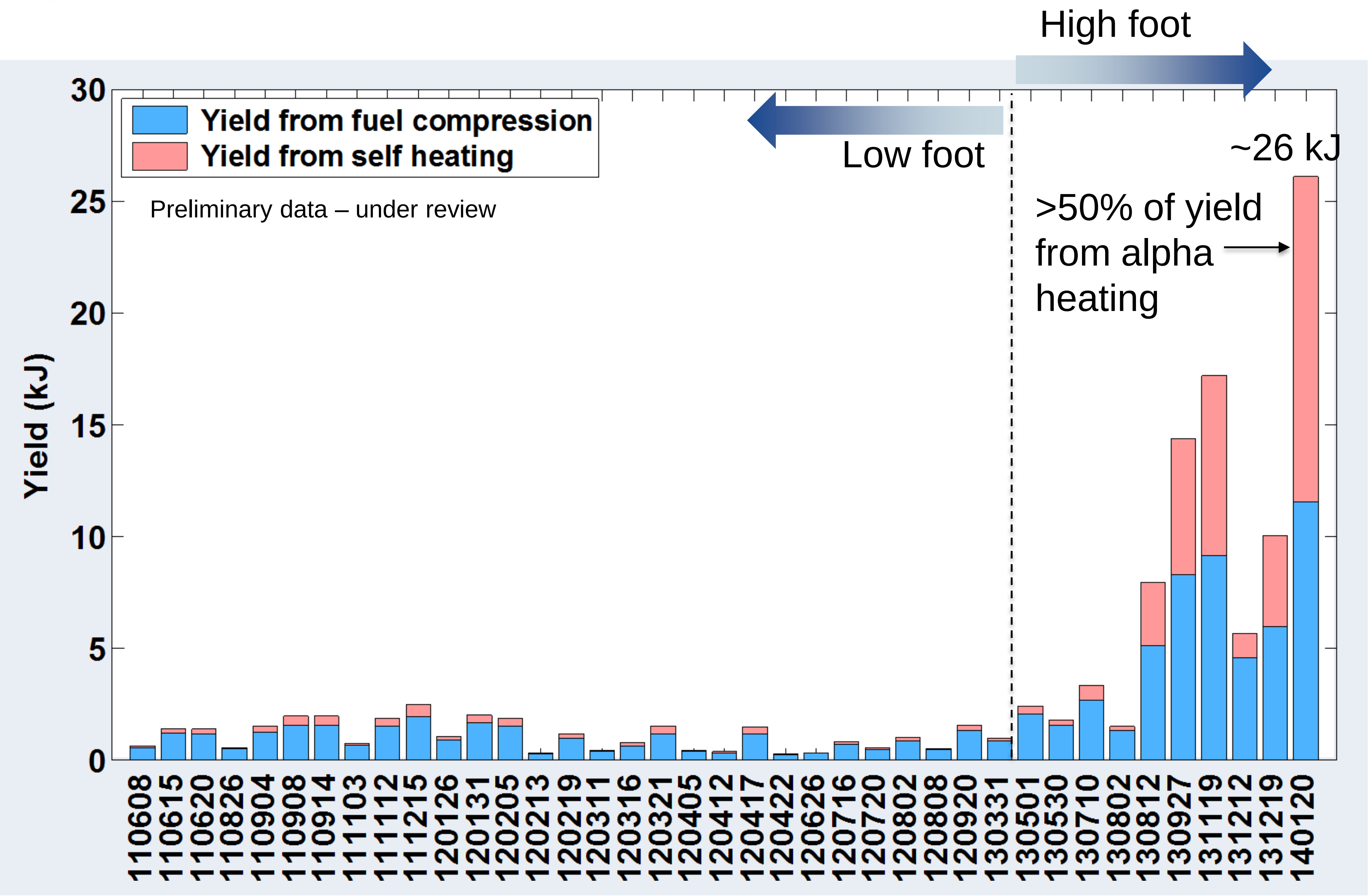
Energy out

Energy in to the fuel

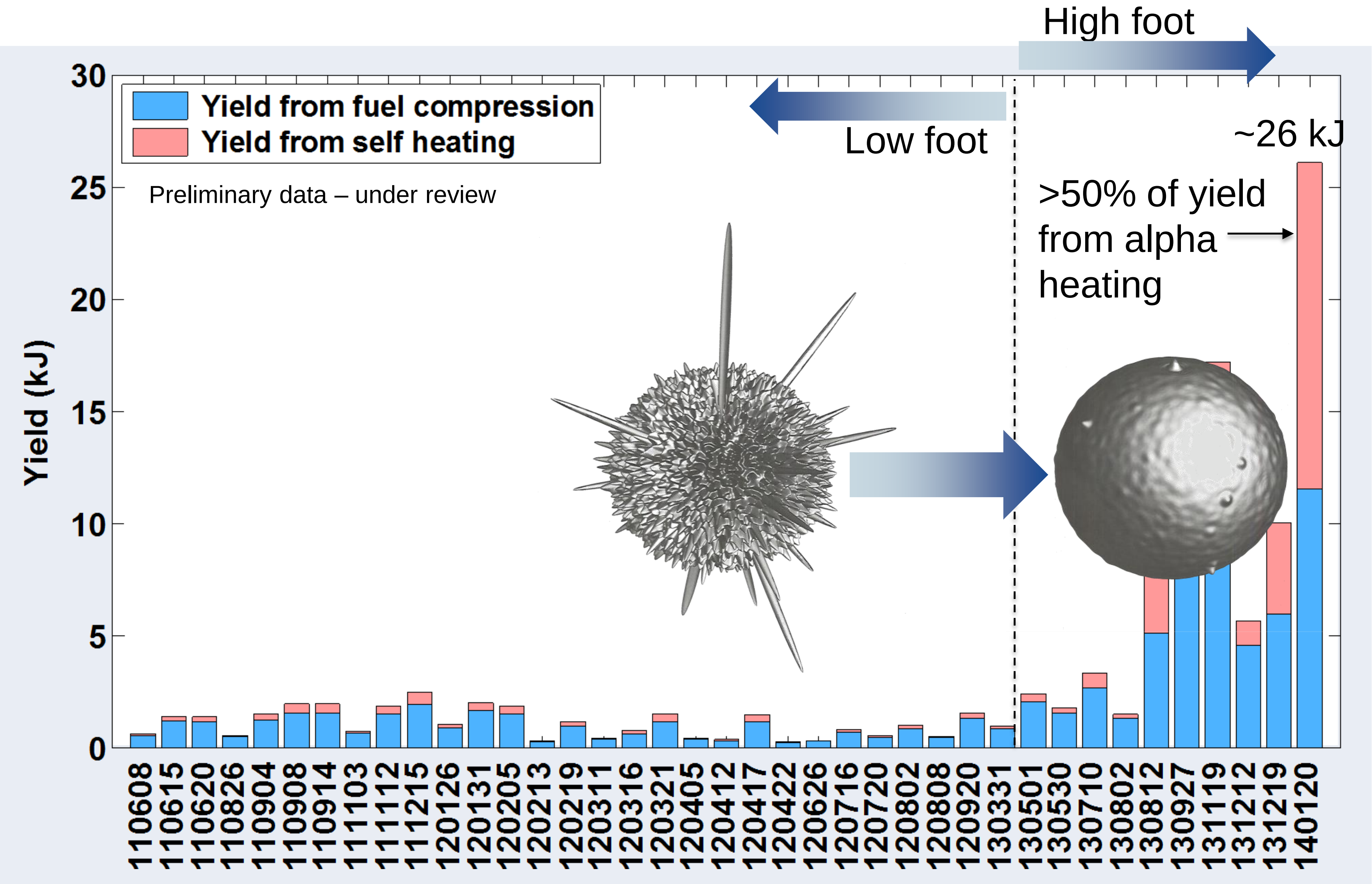
Latest series of experiments have exceeded yield-doubling (for the first time for any fusion system)



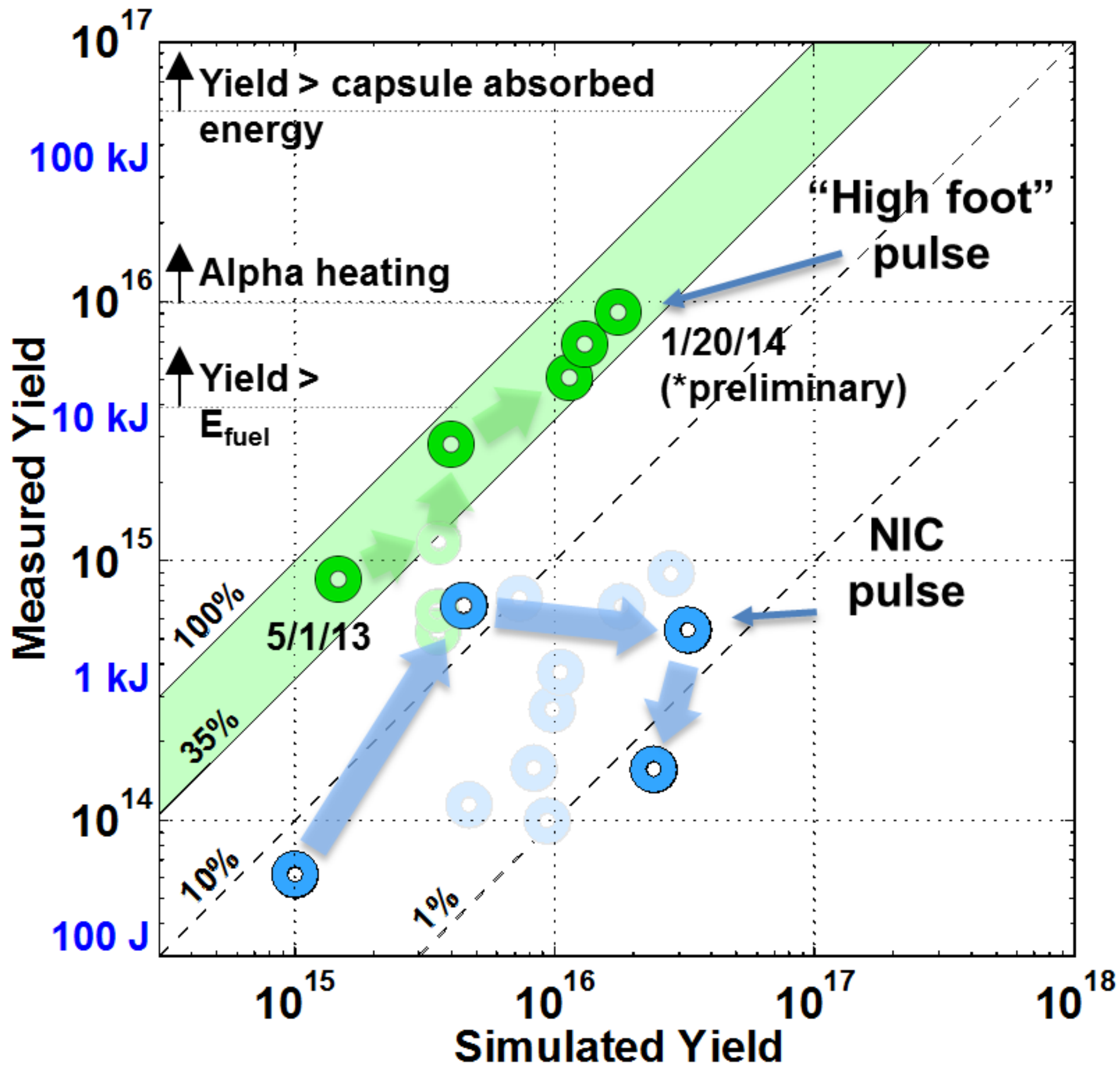
Recent experiments
- entering a different regime



Principal change: high foot implosions are more stable



The new "high foot" design achieved the goal of an implosion that performs closer to simulations



* uses pre-shot simulation

Preliminary data – under review

Translating the performance on NIF into a practical energy source

- Starts with the presumption that NIF will demonstrate ignition
- Future energy applications can leverage the current investments for national security applications
- Integrated plant design work is determining what is possible in the way of energy production, and what would it take to get there
- Integrated product delivery approach to concept development and commercial delivery planning
- The conclusions challenge the common perception that fusion is too distant to be relevant

Primary Criteria for a laser fusion power plant were informed by diverse set of stakeholders

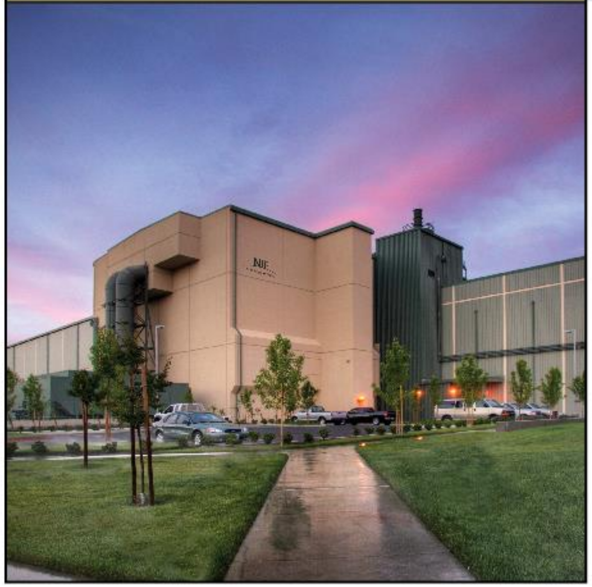
Plant Primary Criteria (partial list)
Cost of electricity
Rate and cost of build
Licensing simplicity
Reliability, Availability, Maintainability, Inspectability (RAMI)
High capacity credit & load factor
Predictable shutdown & quick restart
Meet urban environmental and safety standards (minimize grid impact)
Public acceptability near load centers
Acceptable waste stream
Learn from commercial operating experience
O&M personnel qualifications
Timely delivery

Design informed by:

- Electric utilities
- Process heat and water industry
- Plant and technology vendors
- Environmental groups
- Sustainability experts
- Non-proliferation policy groups
- Investment advisors
- Public policy advisors
- Regulatory and licensing experts
- NIF & PS team
- Academia and US National Labs

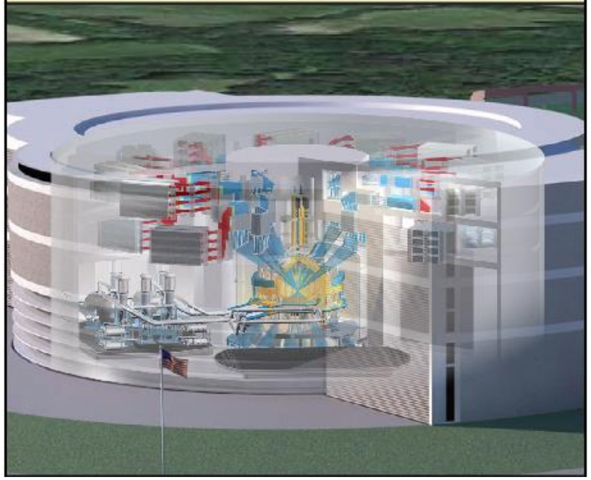
Top level market requirement is the timely demonstration of utility-scale power production

National Ignition Facility



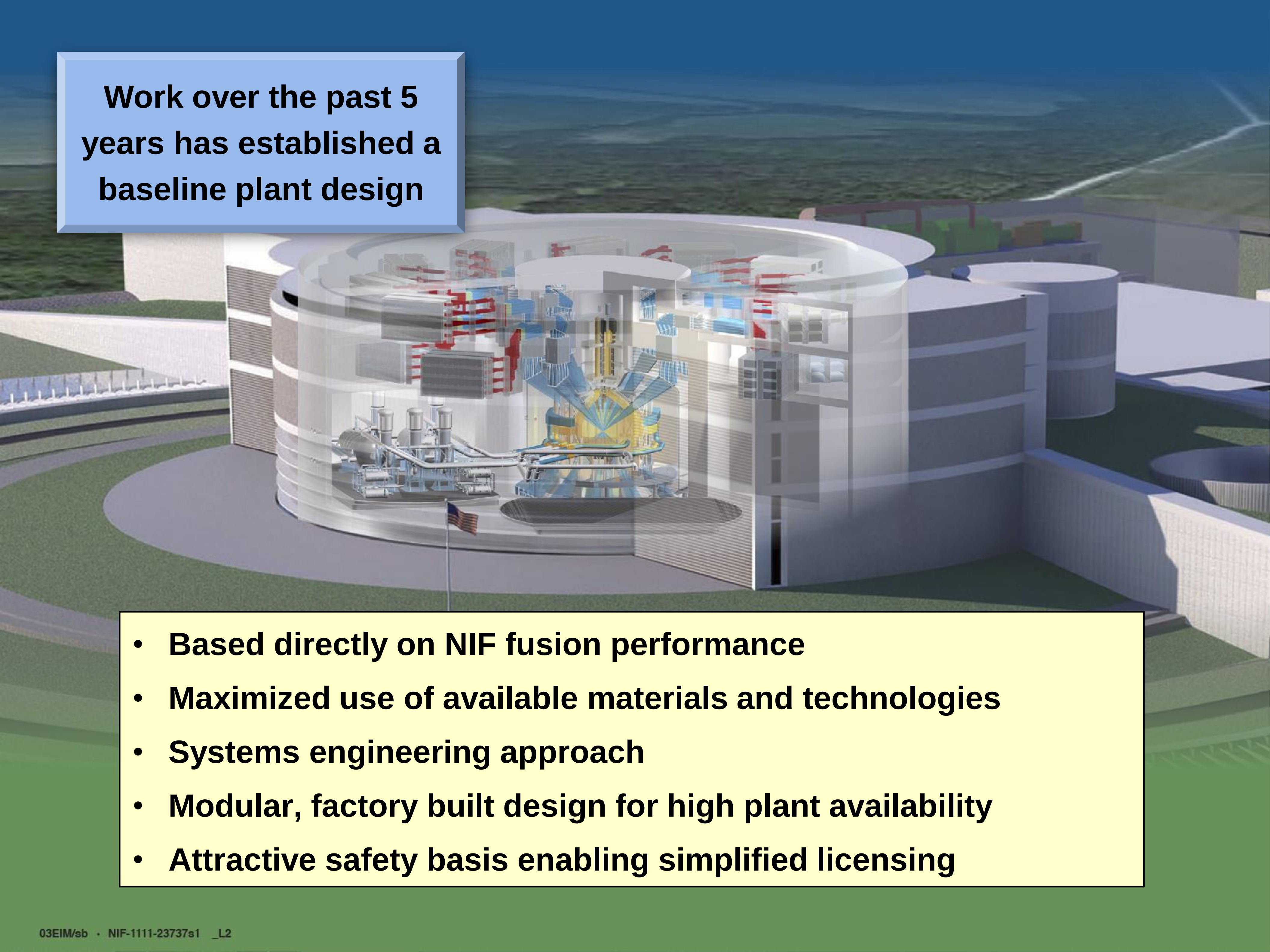
Performance

Market Entry Plants



Integration

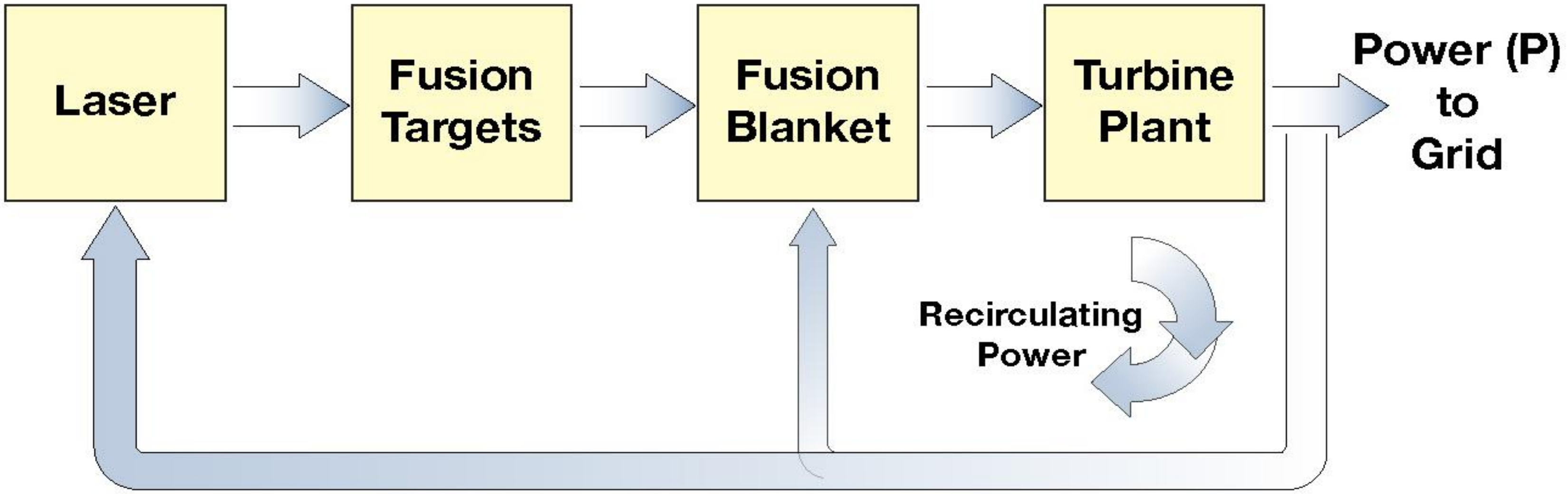
Mature LIFE Technology

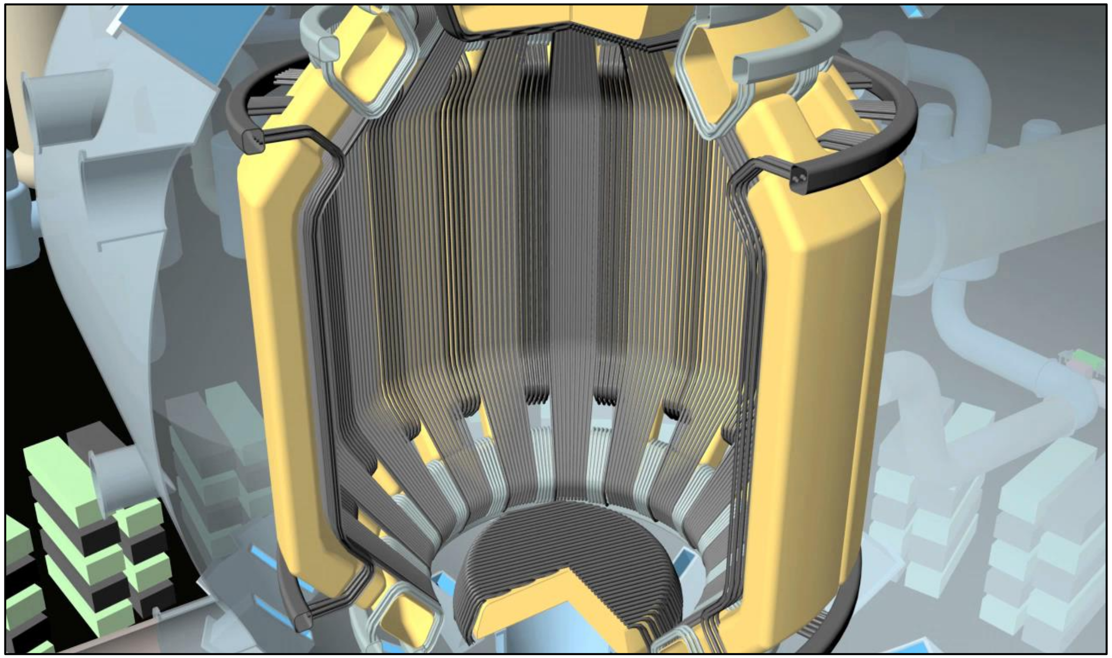


Work over the past 5 years has established a baseline plant design

- **Based directly on NIF fusion performance**
- **Maximized use of available materials and technologies**
- **Systems engineering approach**
- **Modular, factory built design for high plant availability**
- **Attractive safety basis enabling simplified licensing**

Fusion power production

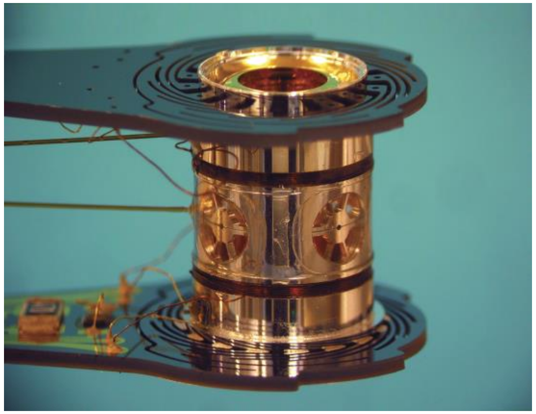




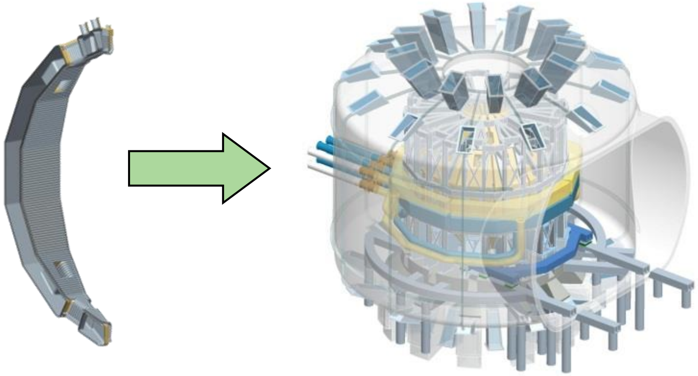
Engine operation of 900 cycles / minute delivers ~ 1 GWe

Current R&D work is addressing the long-standing science and technology challenges for fusion

Fuel performance to be validated at full scale on the NIF (for 1GWe plant)



Ability to use conventional structural materials



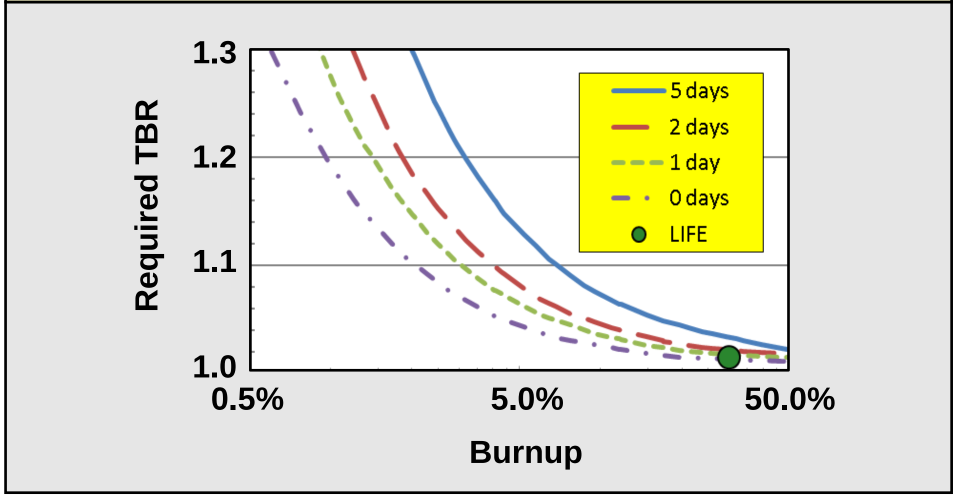
Low tritium inventory, transforming the safety basis

Modular technology allowing very high plant availability

Keys to IFE fuel cycle

- Targets with **~30% burn-up** greatly relax requirements for fuel self-sufficiency
- Li blanket with **TBR up to 1.27** enough to cover T losses and TBR uncertainties (nuclear data and system definition)
- **High T solubility in Li** reduces permeation and T retention in structures
- **High availability** of target production allows for minimum stored tritium
- **Molten salt extraction** method allows for blanket inventory < 100 g-T

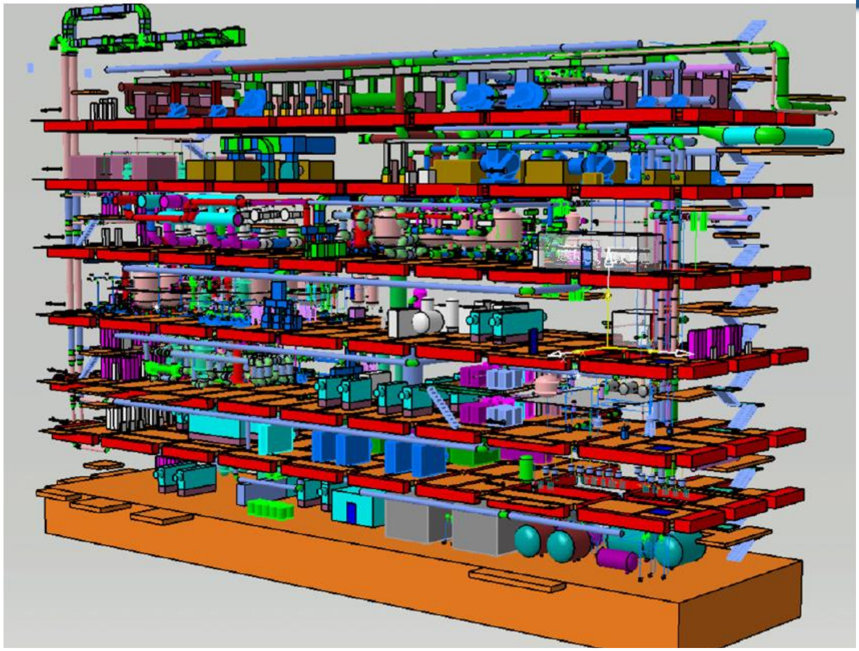
High burnup results in low TBR requirement for reasonable storage times (Abdou 1986)



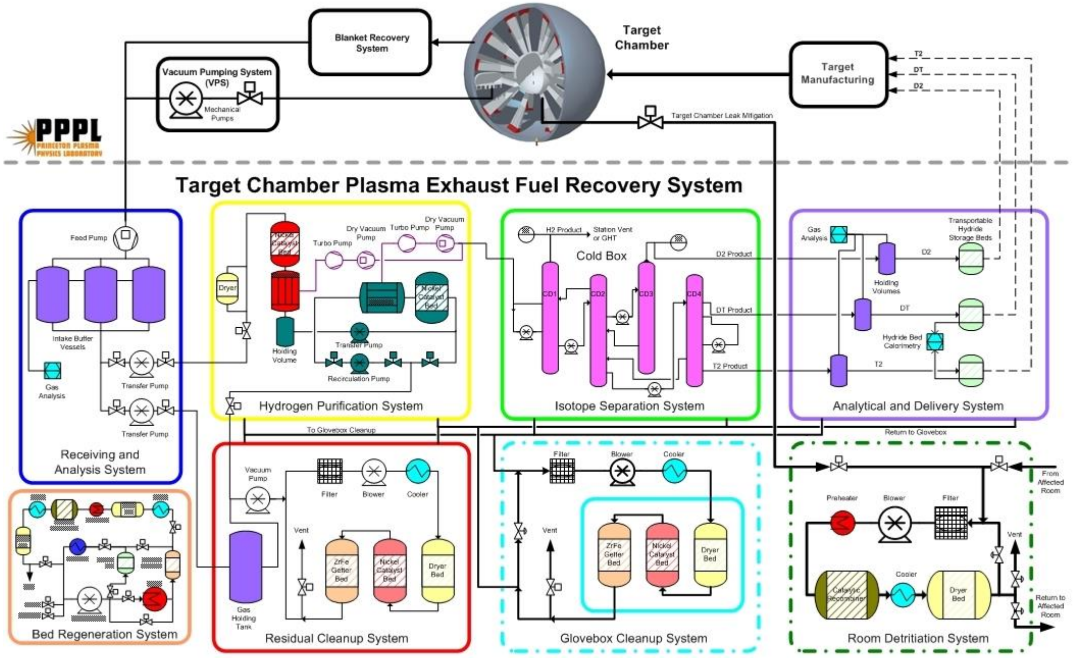
- **Chamber gas handling system** processing leads to steady state T inventory in chamber ~10 g-T

Relative scale of IFE tritium processing systems

- IFE tritium plant is more compact than proposed previously:
  - ITER systems sized for 200 Pam^3/s of DT~ 100 SLPM
  - IFE systems ~ 8 SLPM
- Reduced flow rates and protium allow for isotope separation via TCAP
- Simpler requirements for storage and delivery towards target manufacturing



ITER tritium plant (Glugla et al., ITER Organization)

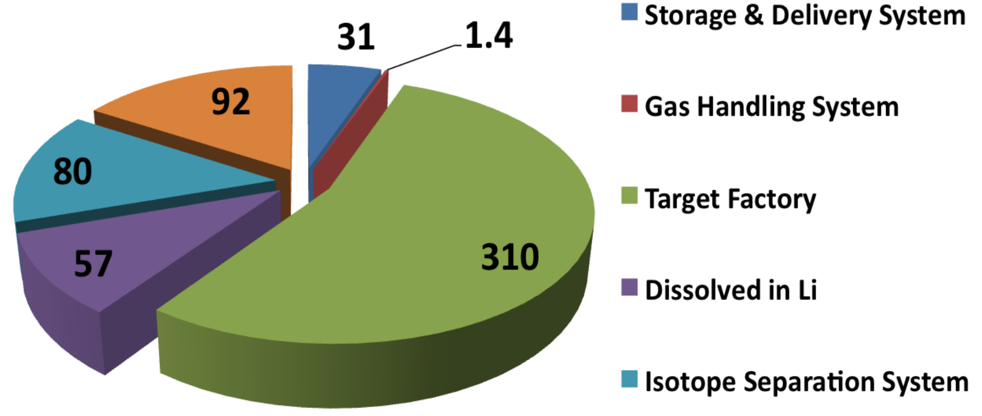


HAPL tritium plant (Langish et al., PPPL)

System studies accounting for operational and off-normal safety response led to a new tritium paradigm

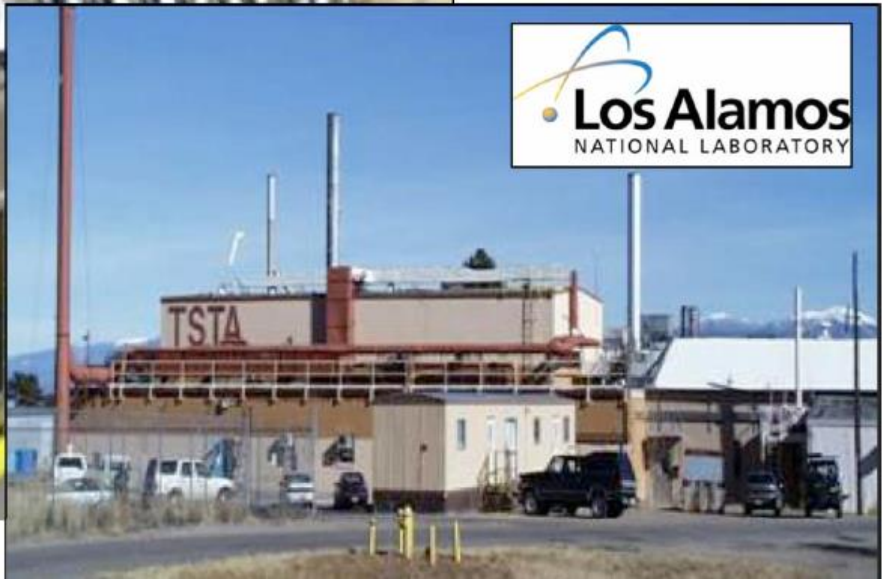
- IFE provides for:
  - — High fuel burn-up efficiency (~30%)
  - — Use of Li coolant (high T solubility, binding the tritium). This minimizes any T permeation, and allows localized removal using known techniques.

Limited on-site tritium inventory, a factor 10-100 lower than most prior designs

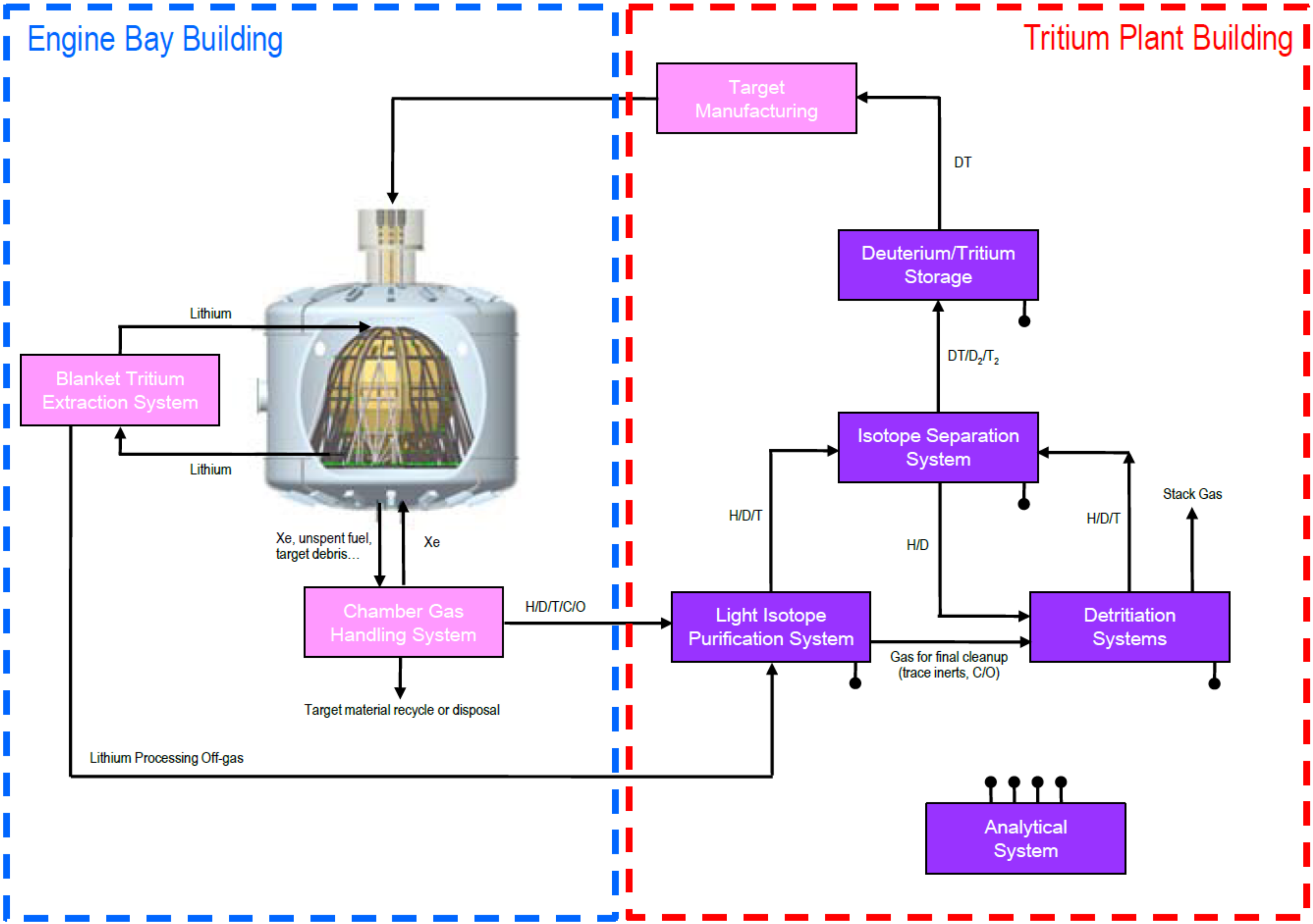


Major impact on the safety case and licensing pathway
Plant rollout will no longer be limited by tritium availability

IFE fuel cycle design uses design experience at Savannah River and Los Alamos

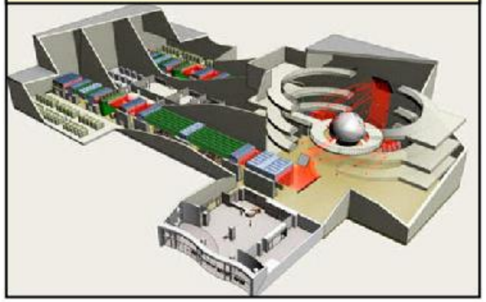


Simplified block diagram of the IFE fuel cycle

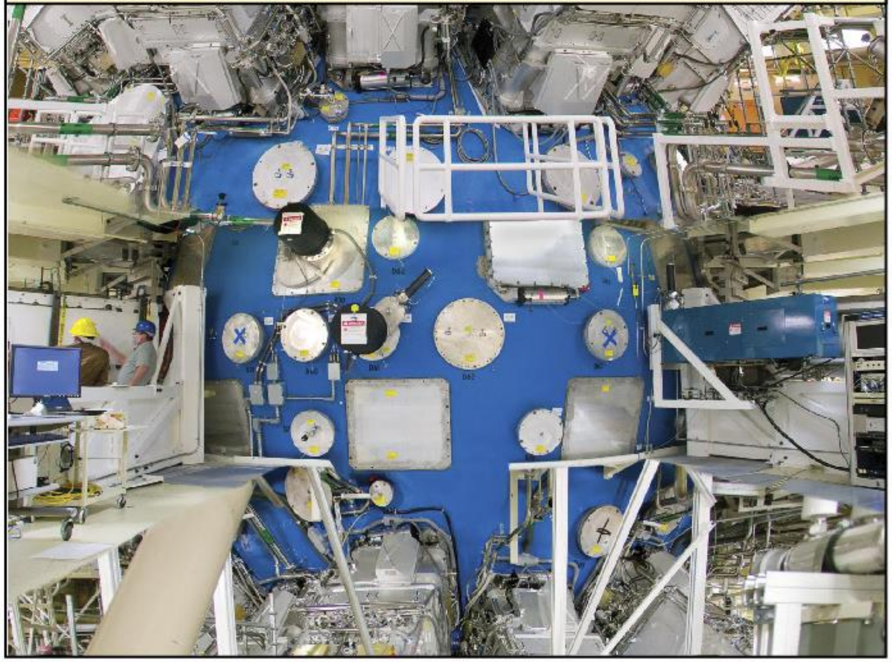


Laser fusion is being pursued around the world, with a consistent technical basis

EU - HiPER

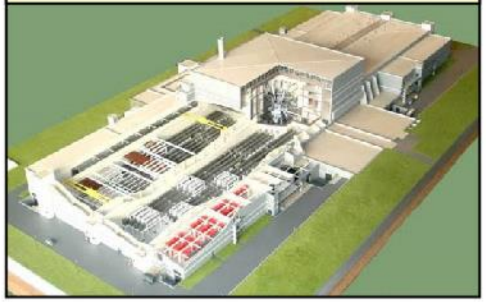


USA - NIF Laser

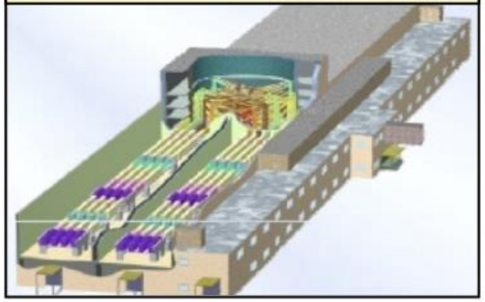


UK - ORION

France - LMJ

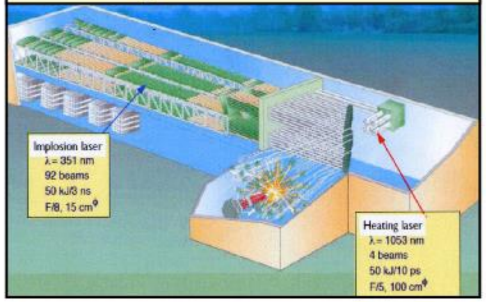


Russia - ISKRA

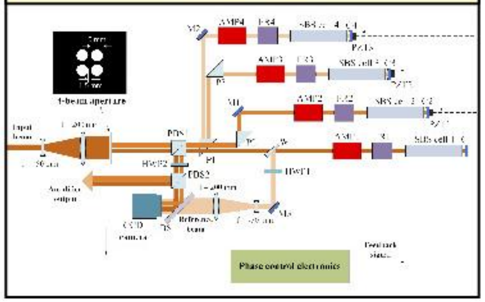


China- SG-III

Japan - FIREX



Korea



National Academies' study into Inertial Fusion Energy (2012)

- "Compelling rationale for establishing inertial fusion energy R&D as a part of the long-term U.S. energy R&D portfolio
- External reviews were unanimous in concluding that ignition was achievable on the NIF
- "Planning should begin for making effective use of the NIF as one of the major program elements in an assessment of the feasibility of IFE"

Full report: http://www.nap.edu/catalog.php?record_id=18289

Achieving ignition on NIF can be a defining moment for the world's energy future


NIF