Inertial Confinement Fusion

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In the beginning…

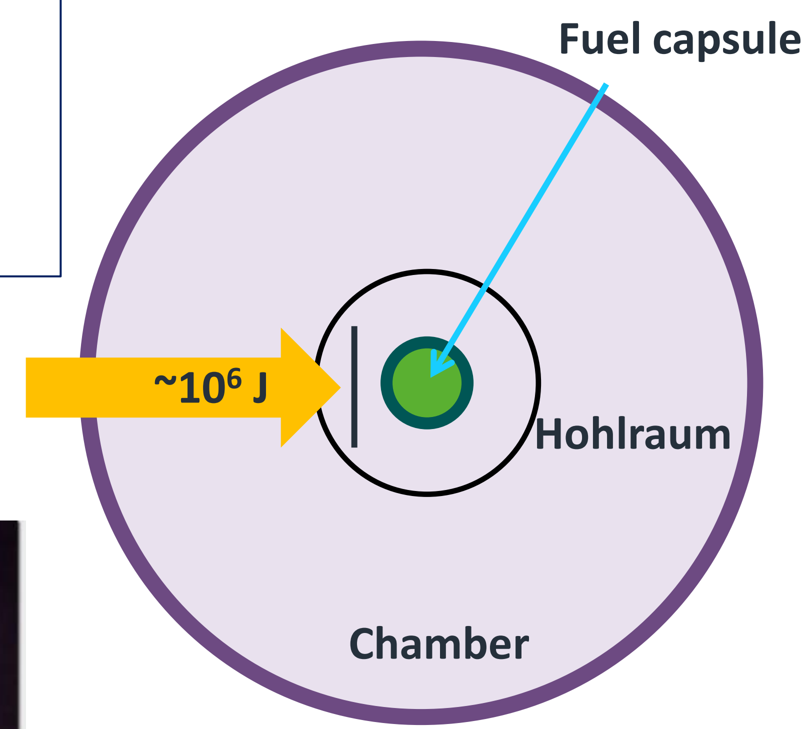
In the late fifties, alternative applications of nuclear explosions were being considered – the number one suggestion was fusion energy generation.

Thoughts turned towards how to miniaturise fusion explosions, and what primary driver would replace fission.

Driver:

Charged particle accelerator
Pulsed power
Plasma gun
Pellet gun

Pre-laser concept of ICF



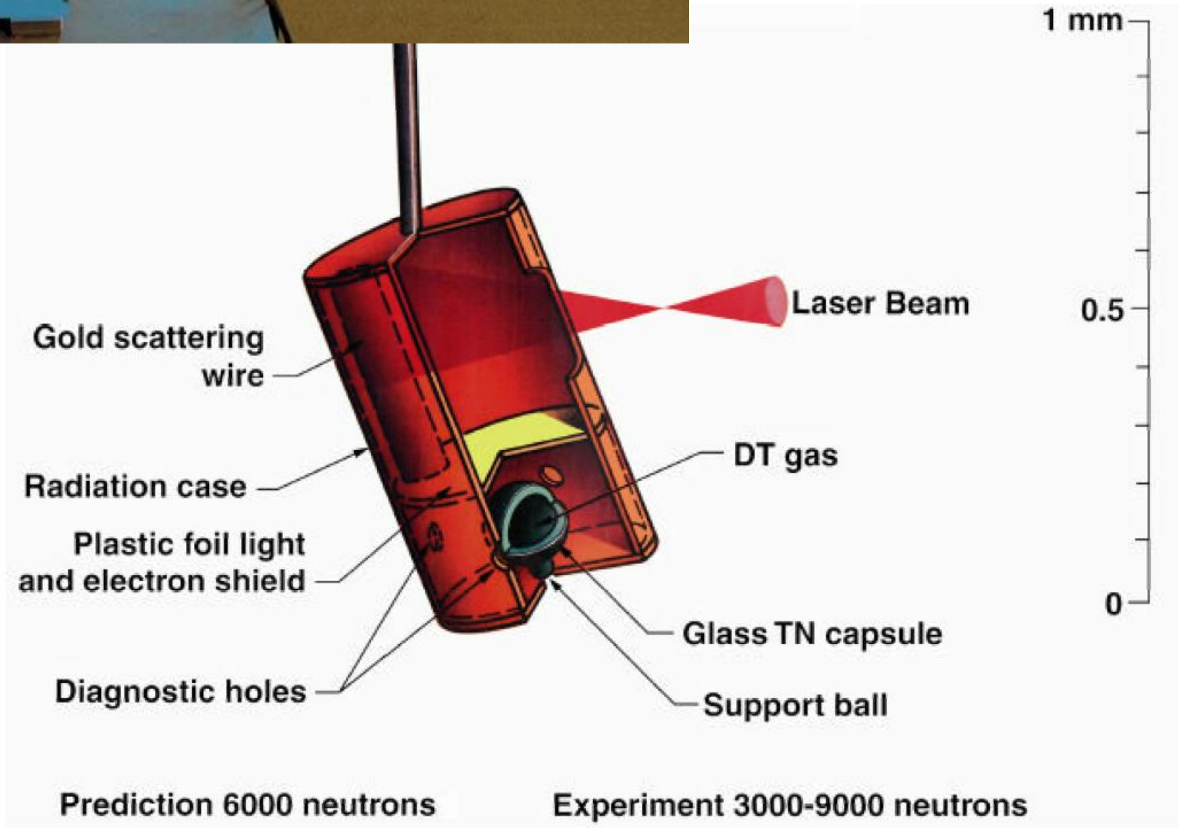
John Nuckolls, LLNL

In the beginning…

Once lasers had been realised, it was blindingly obvious that they were the perfect driver for ICF

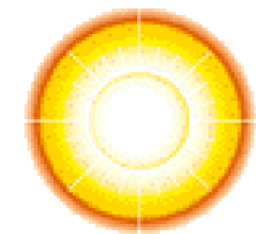
ICF for fusion energy wasn't taken seriously at LLNL, but since indirectly driven implosions had overlap with the weapons program, a laser program could be pursued in earnest in the 70's

1976 - first indirect drive laser implosion experiments on single beam 100J 1.06μm Cyclops (Nd-glass) laser at Livermore

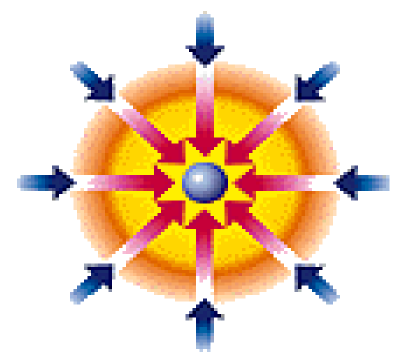


How it works

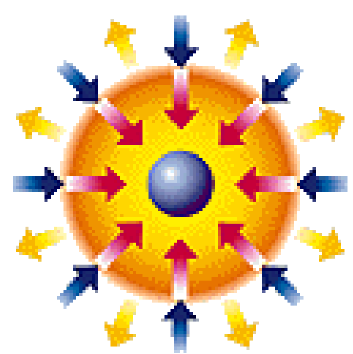
A capsule made of deuterium and tritium is imploded by laser or x-ray drive



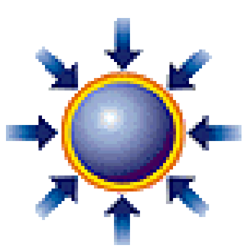
Hot ignition region formed at the centre of the fuel by piston-like action of imploding shell



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



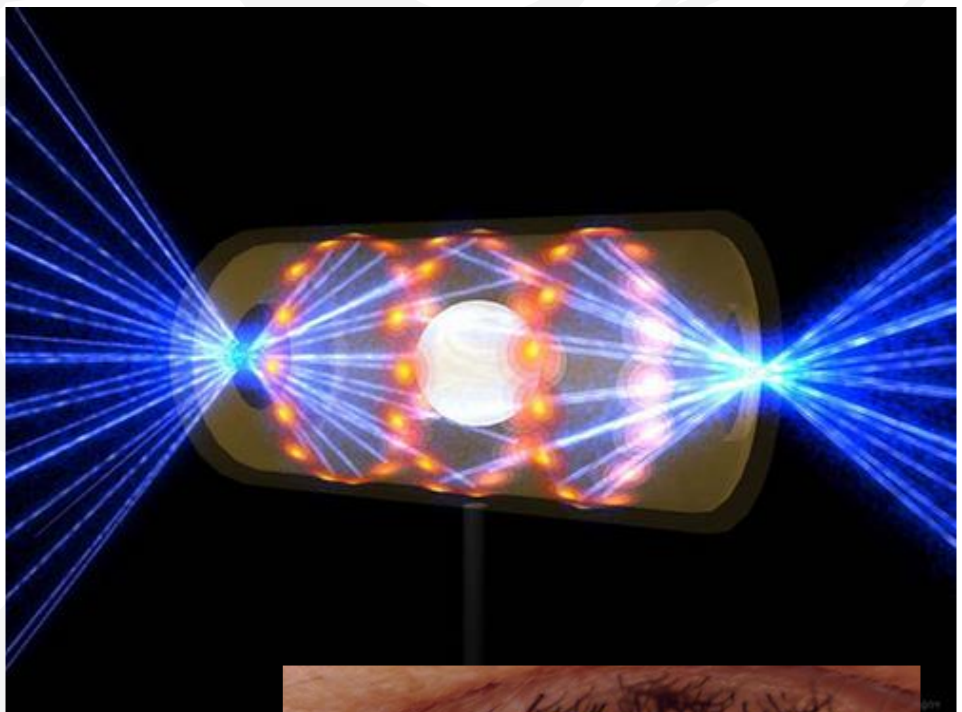
Hot plasma expands into vacuum causing shell to implode with high velocity

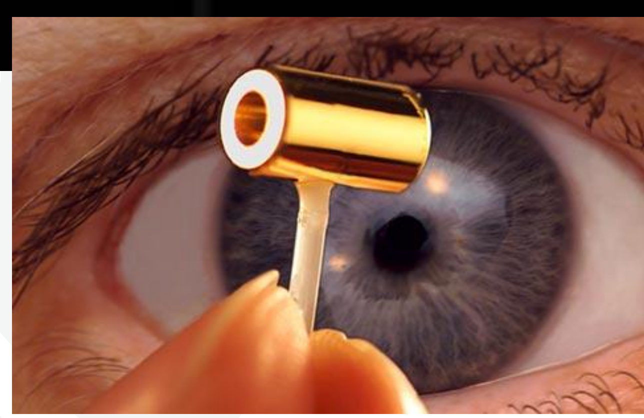


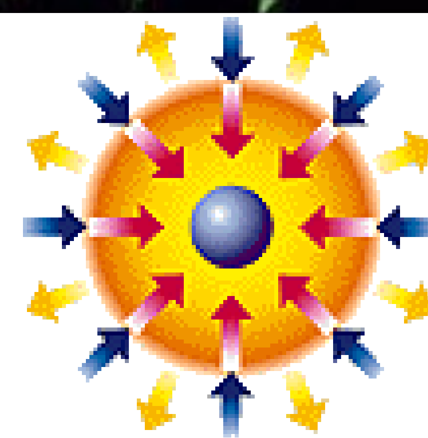
Lasers or X-rays symmetrically irradiate pellet

Implosion results in compression, heating and finally thermonuclear ignition + burn

Direct vs indirect drive







Ignition and gain

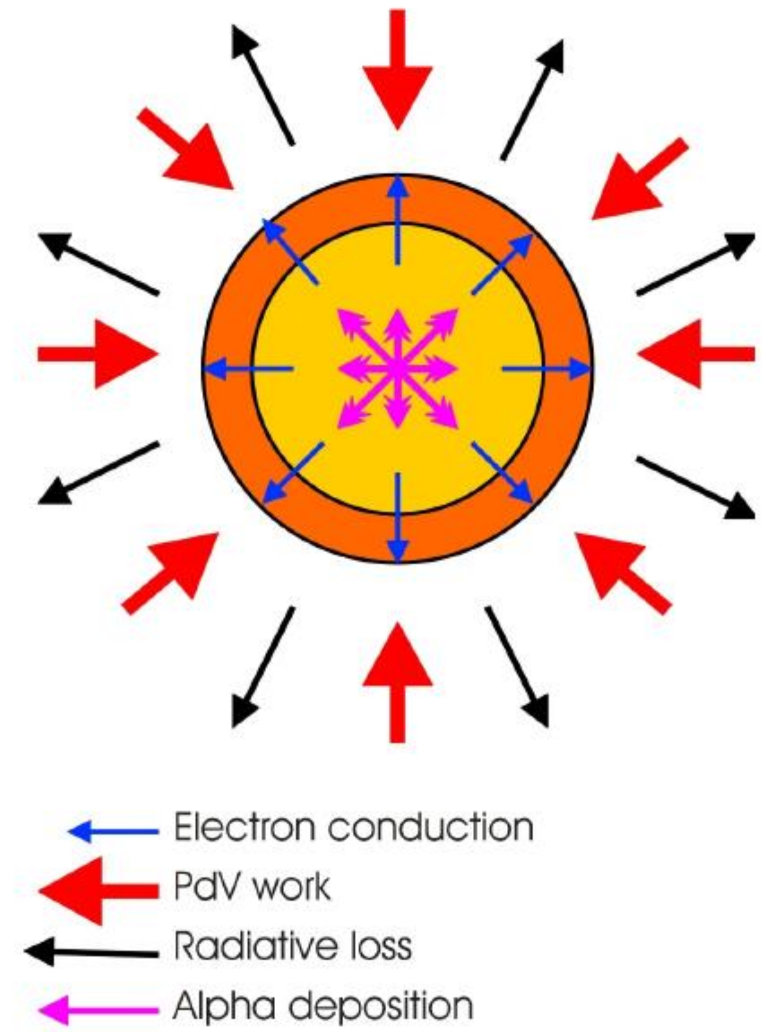
Goal of fusion is to produce energy!

These systems, whether ICF or MCF, are lossy
We must produce enough energy through fusion to overcome these losses

Ignition: point at which fusion is self-sustaining
In ICF: this is the self-sustaining fusion burn wave

To get ignition and gain (net energy out) we must over come losses in ICF:

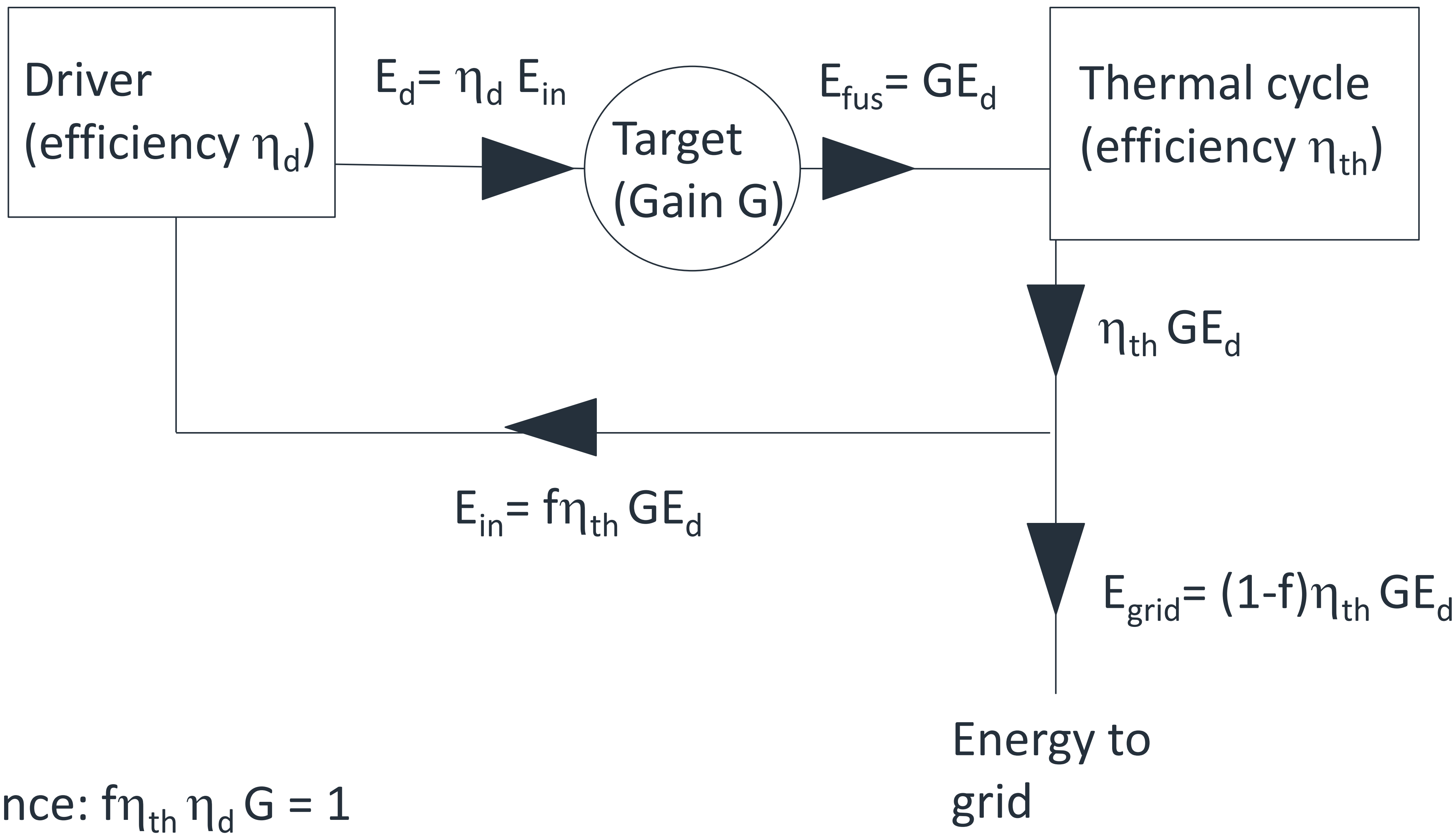
$$P_w + P_\alpha - P_e - P_b > 0$$



The Lawson criterion for magnetic confinement is $n\tau > 10^{20}\ m^{-3}\ s$

The equivalent condition for ICF is $\rho R > 3 gcm^{-2}$

Gain requirements for a reactor



For balance: $f\eta_{th} \eta_d G = 1$
Assuming $\eta_{th} = 40\%$, and $f < ¼$
$G \eta_d > 10$
So G = 30-100 (for driver efficiencies of 10-33%)

Why compress the fuel?

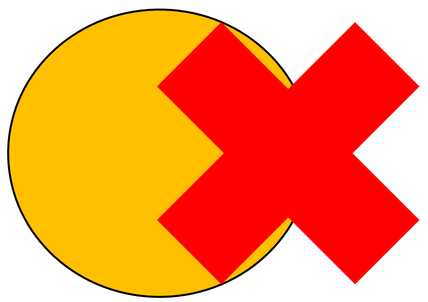
If you release more than a few GJ of energy the “mirco-explosion” will damage the reactor vessel. 1GJ is equivalent to energy release of 250 kg of high explosives!

Fuel restricted to 10’s mg in order to obey this limit

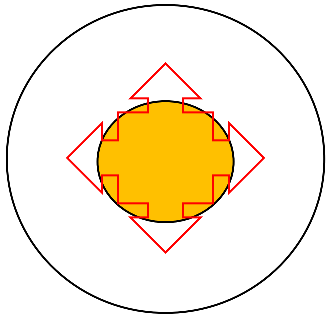
To burn these small masses, fuel must be compressed to more than 1000 x solid density to satisfy ρR condition of 3 g/cm^2

Hot spot ignition

Uniformly heating compressed DT fuel to 5 KeV does not give enough gain – only 20.
As we have seen before we need gain of 30-100 for ICF to work



Instead we must heat a small volume of the fuel which we call the hot spot. This fuel self heats via fusion reactions and then a burn wave propagates out into the cold fuel. The hot spot ρR must be sufficient that a large fraction of the a-particles deposit their energy within the hotspot



Hot spot $\rho R > 0.2 – 0.5\ \mathrm{g/cm^2}$

Numbers

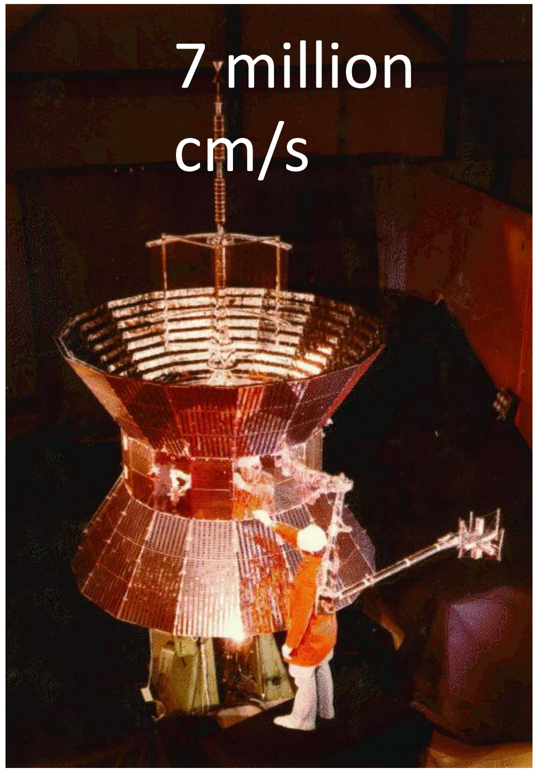
Ablation velocity: ~10^7 cm/s

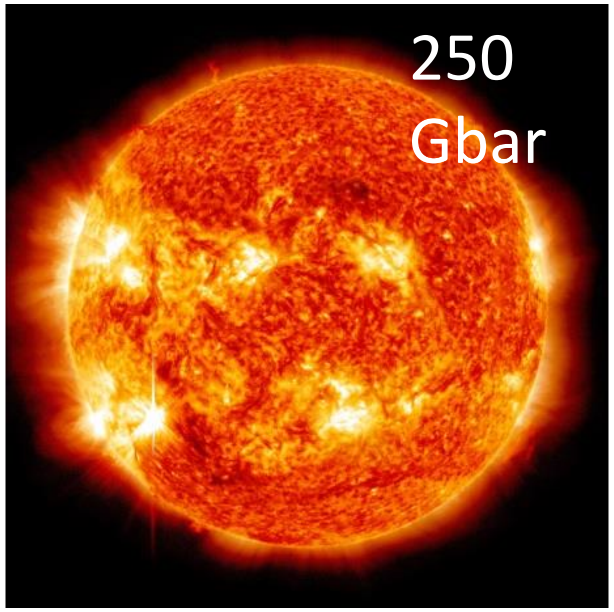
Implosion velocity: ~10^7 cm/s

Ablation pressure: 100s Mbar

Peak pressure: 100s Gbar (pressure amplification due to spherical convergence)

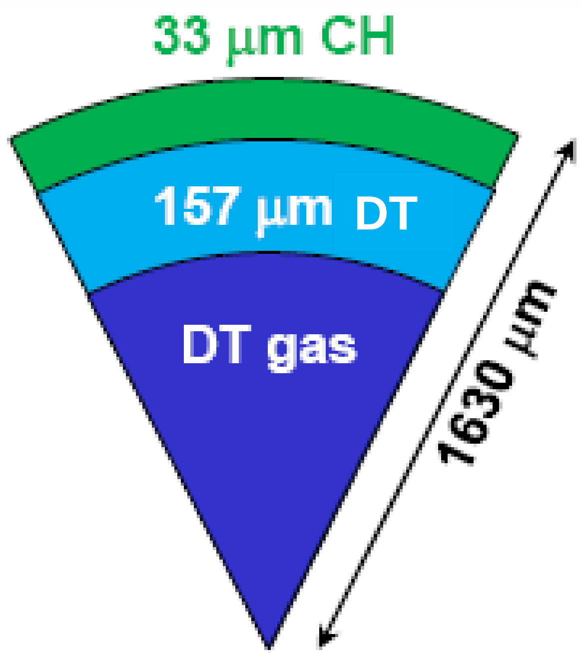
Energy for ignition: ~MJs



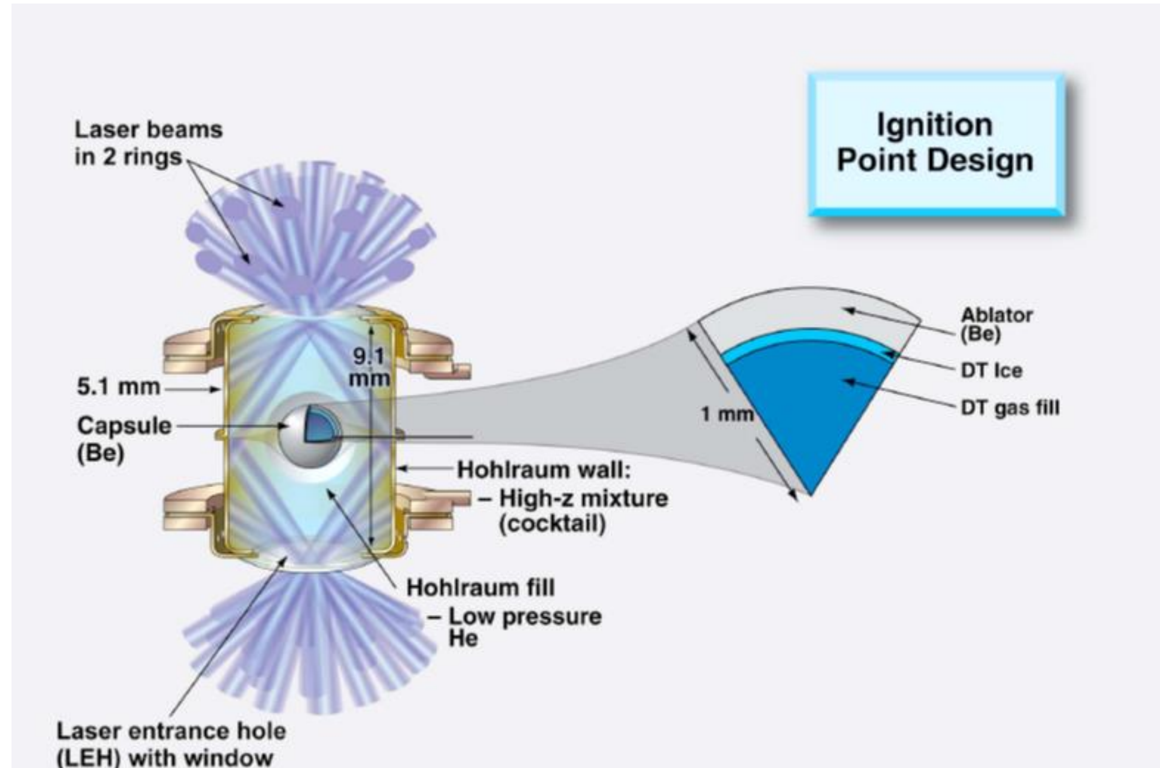


973,000 J

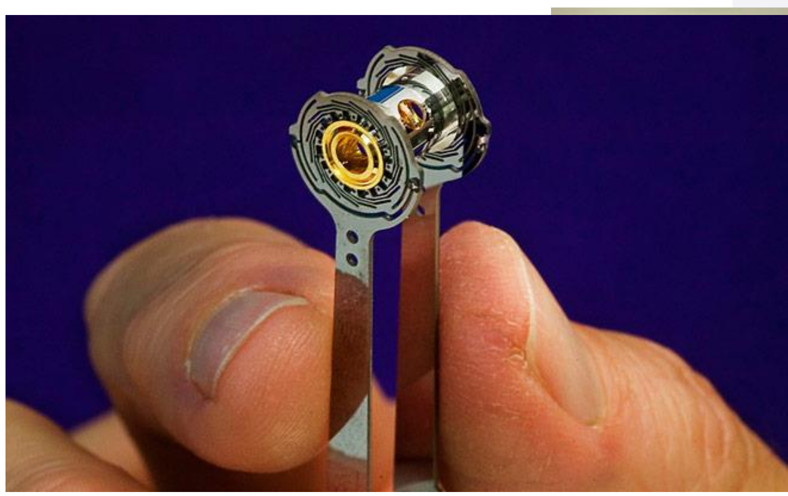
Targets

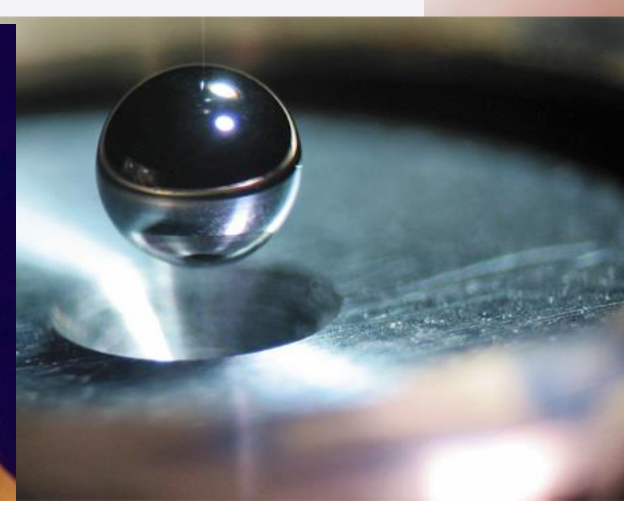


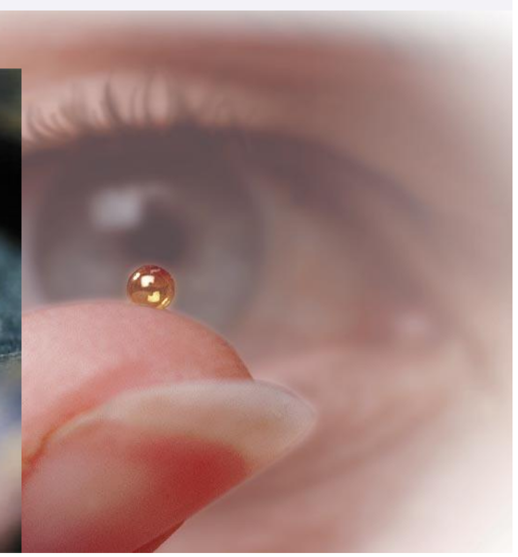
33 μm CH
157 μm DT
DT gas
1630 μm



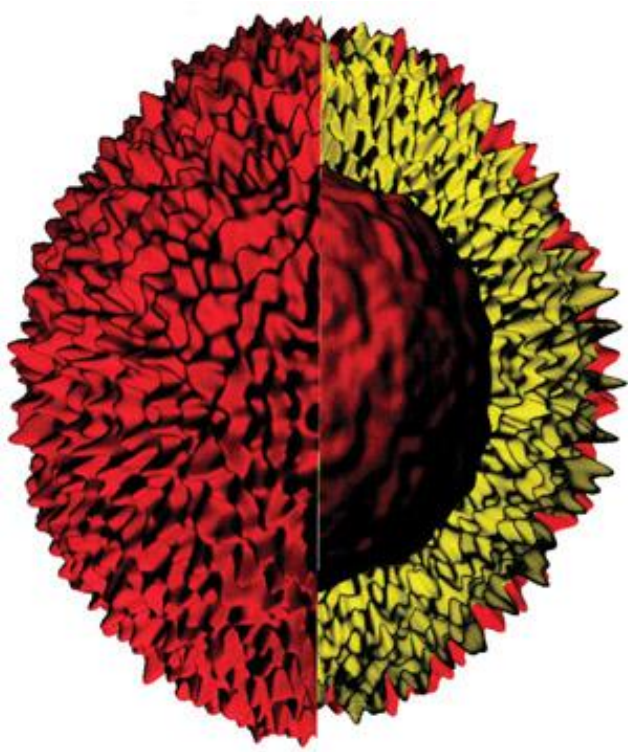
Ignition Point Design
Laser beams in 2 rings
5.1 mm
9.1 mm
Capsule (Be)
Hohlraum wall: – High-z mixture (cocktail)
Hohlraum fill – Low pressure He
Laser entrance hole (LEH) with window
1 mm
Ablator (Be)
DT Ice
DT gas fill

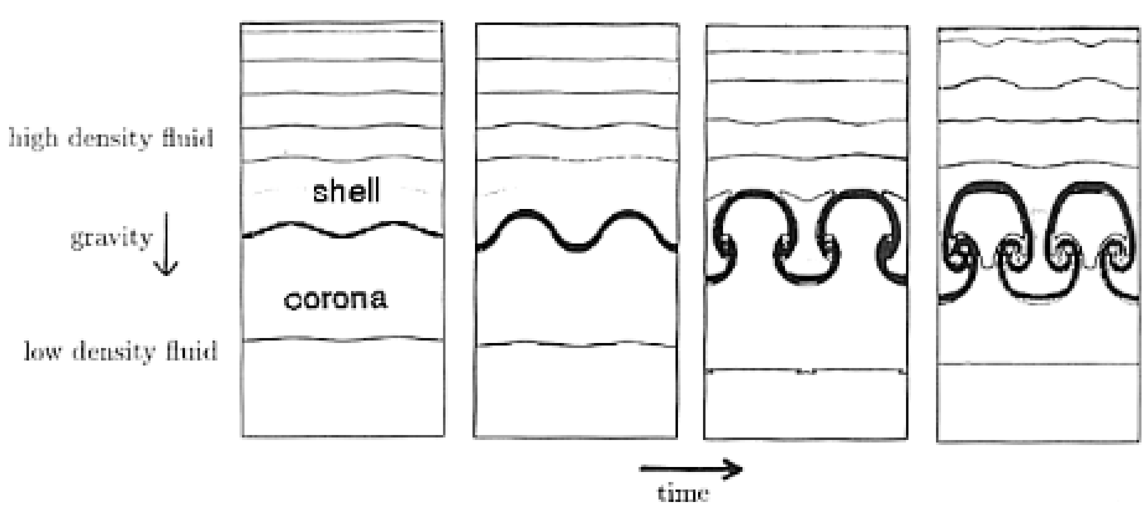






Problems for ICF: Rayleigh-Taylor Instability





RT instability can have a number of unfortunate effects including mixing of hot and cold fuel, non-spherical hot spots, contamination of fuel with non-DT

Reduce problem of RT by:

Ensuring extremely uniform capsule illumination and very smooth capsule surface

Growth can be stabilised somewhat by increasing ablation velocity -> unstable fluid ejected into exhaust before it can get too unstable

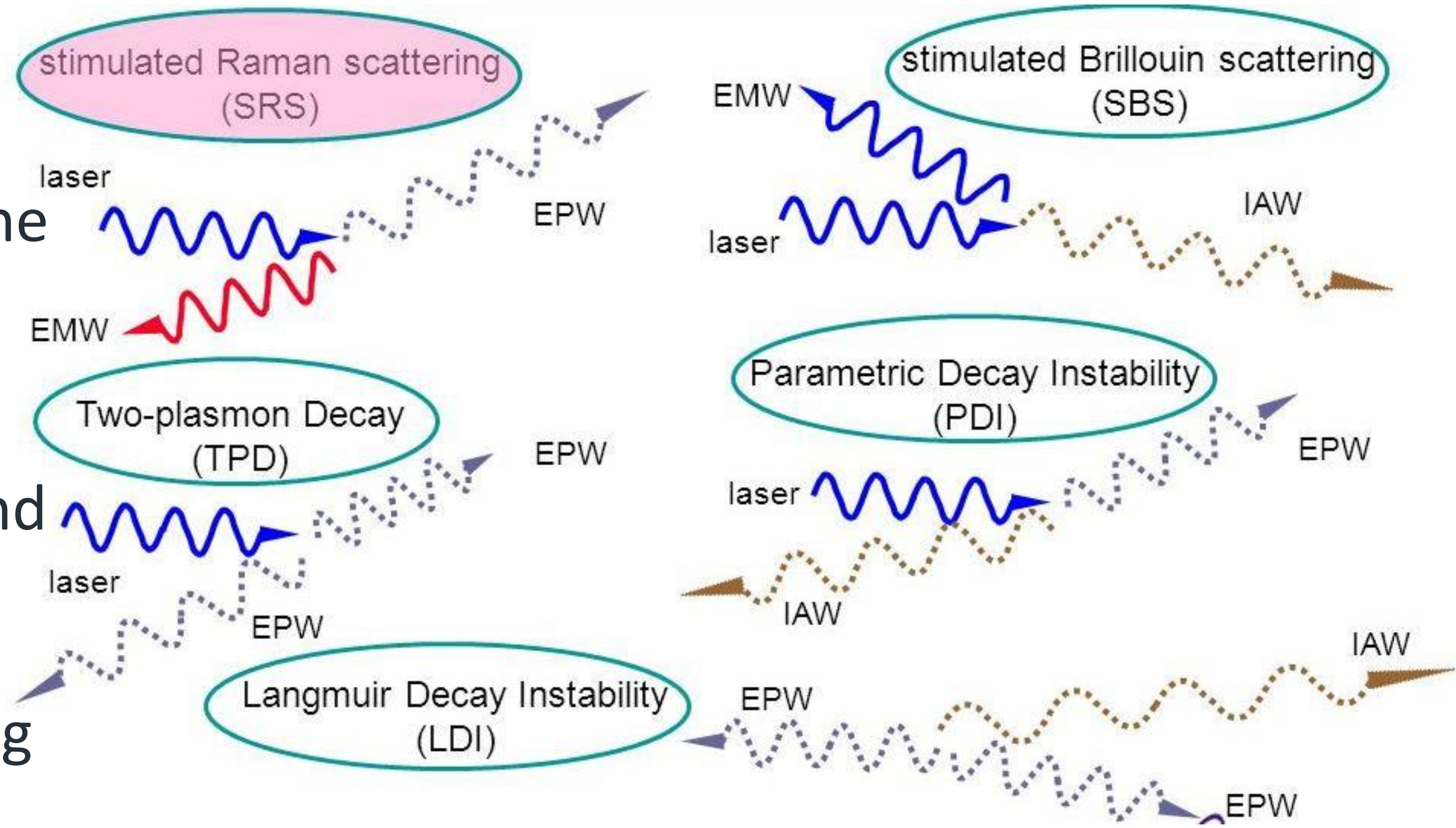
Parametric Instabilities

When intense lasers are absorbed in materials, energetic electrons tend to be created via a variety of mechanisms

These electrons tend to penetrate through the ablator and preheat the fuel, making it more difficult to compress

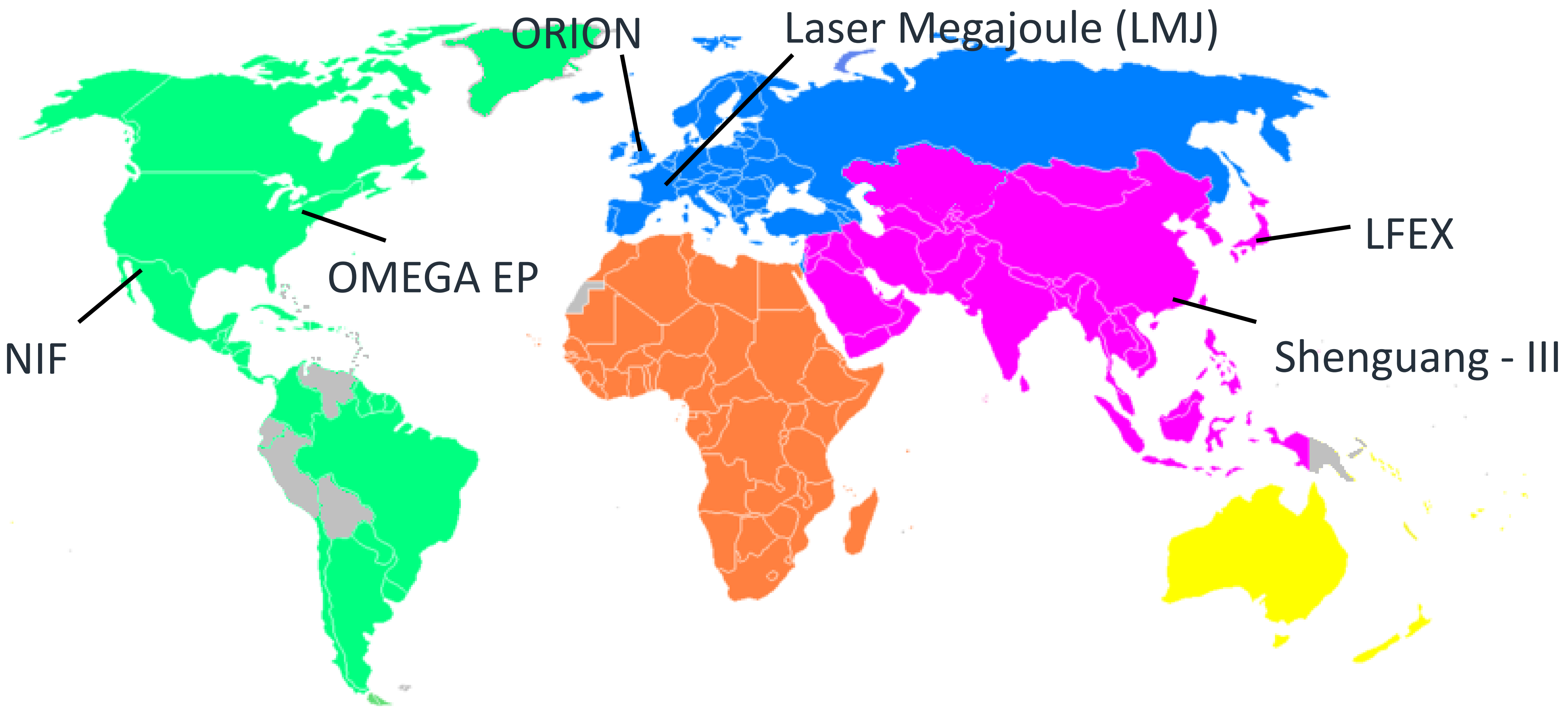
This problem affects both direct and indirect drive ICF

These problems are solved by going to shorter laser wavelengths (ultra violet) where energetic electron production occurs less

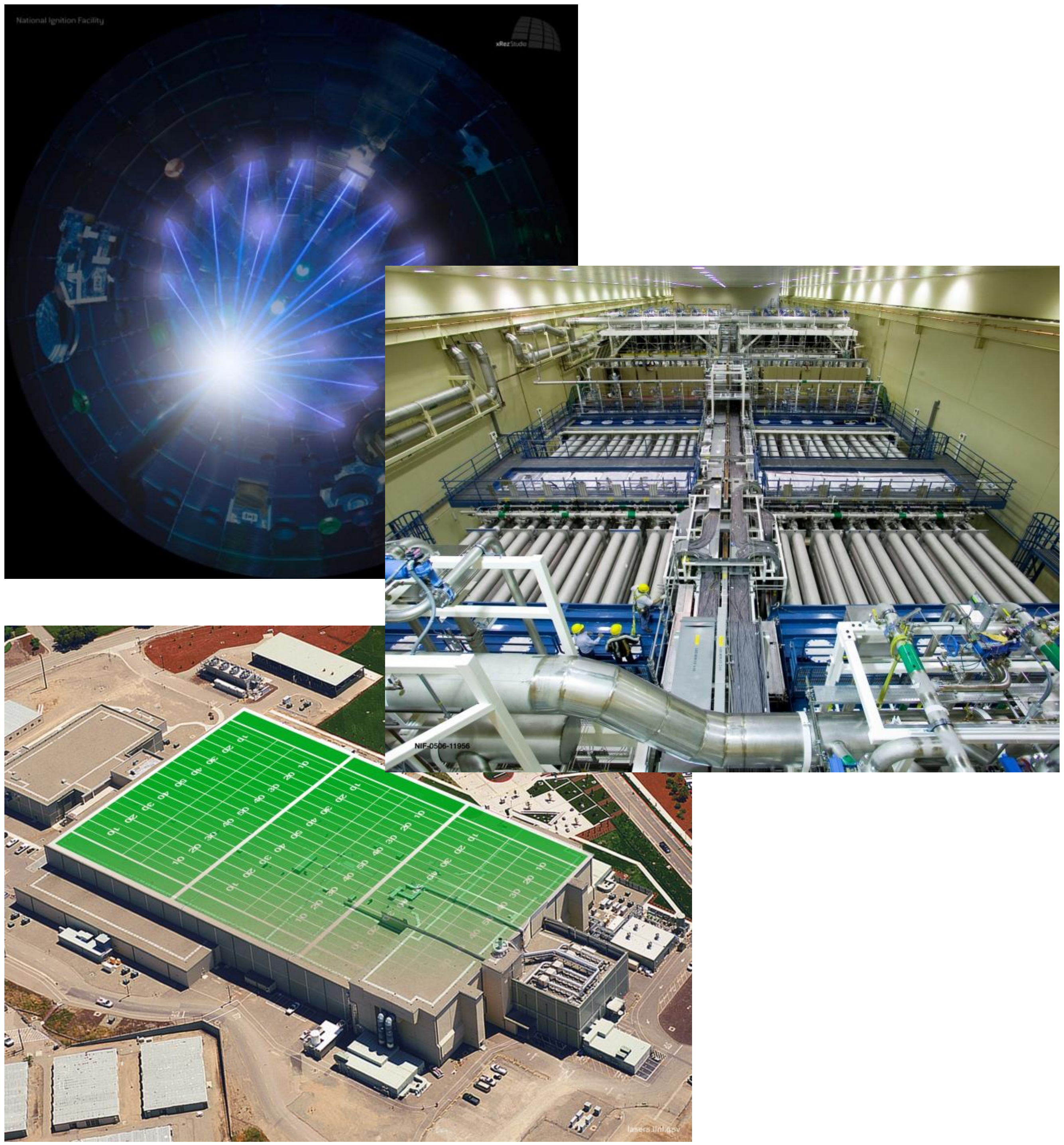


Global ICF facilites

University of York



The National Ignition Facility



Spec:
λ= 0.35mm
Total energy (to target) = 2 MJ
Pulse length = 20 ns
Number of beams = 192
Beam configuration = polar
Scheme = Indirect drive

Biggest laser system ever built

Has been operating since 2008 – ignition campaign began 2010

Produced record breaking numbers of neutrons and alpha particle heating

National ignition campaign

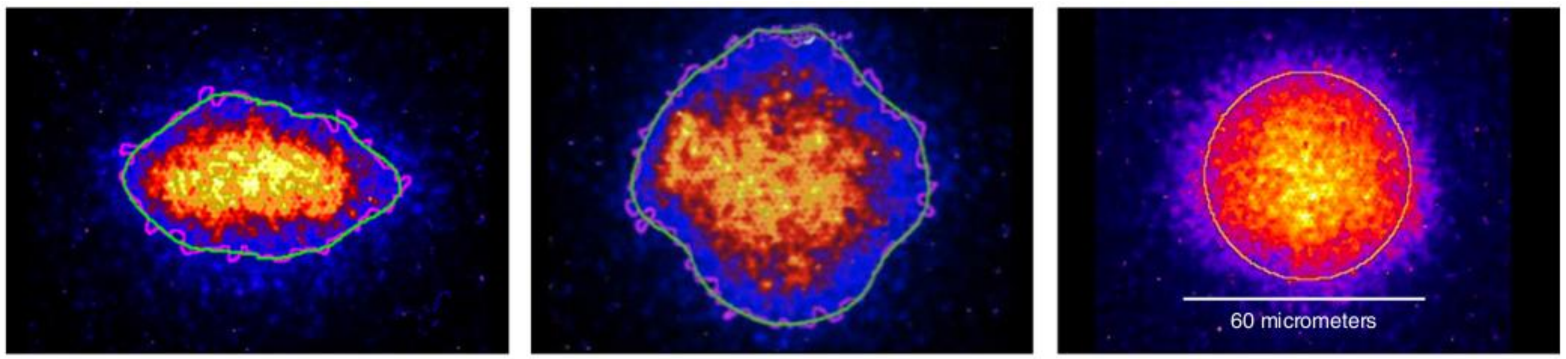
What was NIC for?

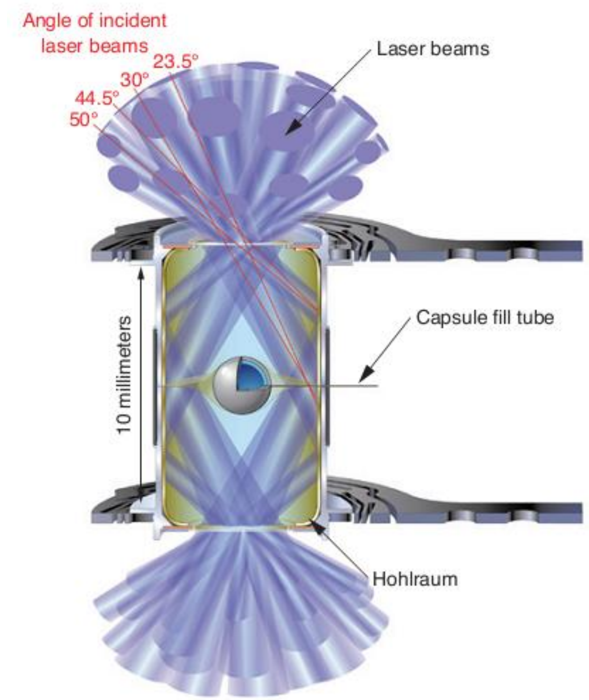
Obviously the desired outcome was ignition!
NIC, which ran from 2006 (prior to laser completion in 2009) through to Sep 2012 also had other objectives:

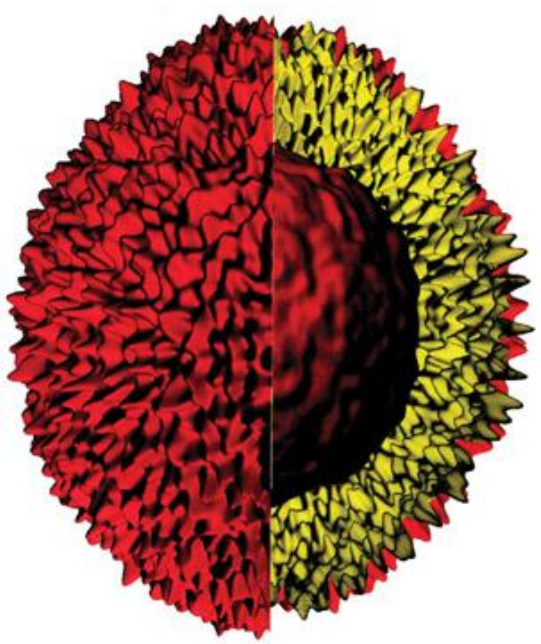
- Operation and optimisation of NIF
- Fielding of over 50 optical, x-ray, and nuclear diagnostics
- Target fabrication

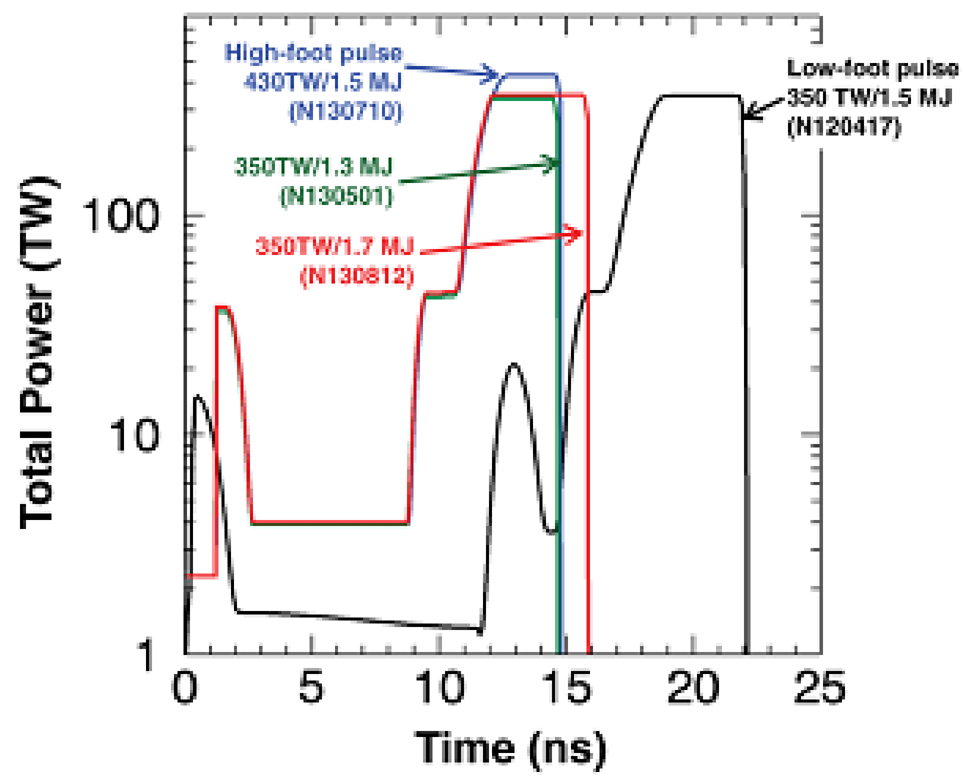
The campaign achieved 37 cryogenic shots and whilst ignition has not yet been achieved, they have massed a huge body of scientific knowledge about large scale indirect drive implosion experiments

My friends are clever

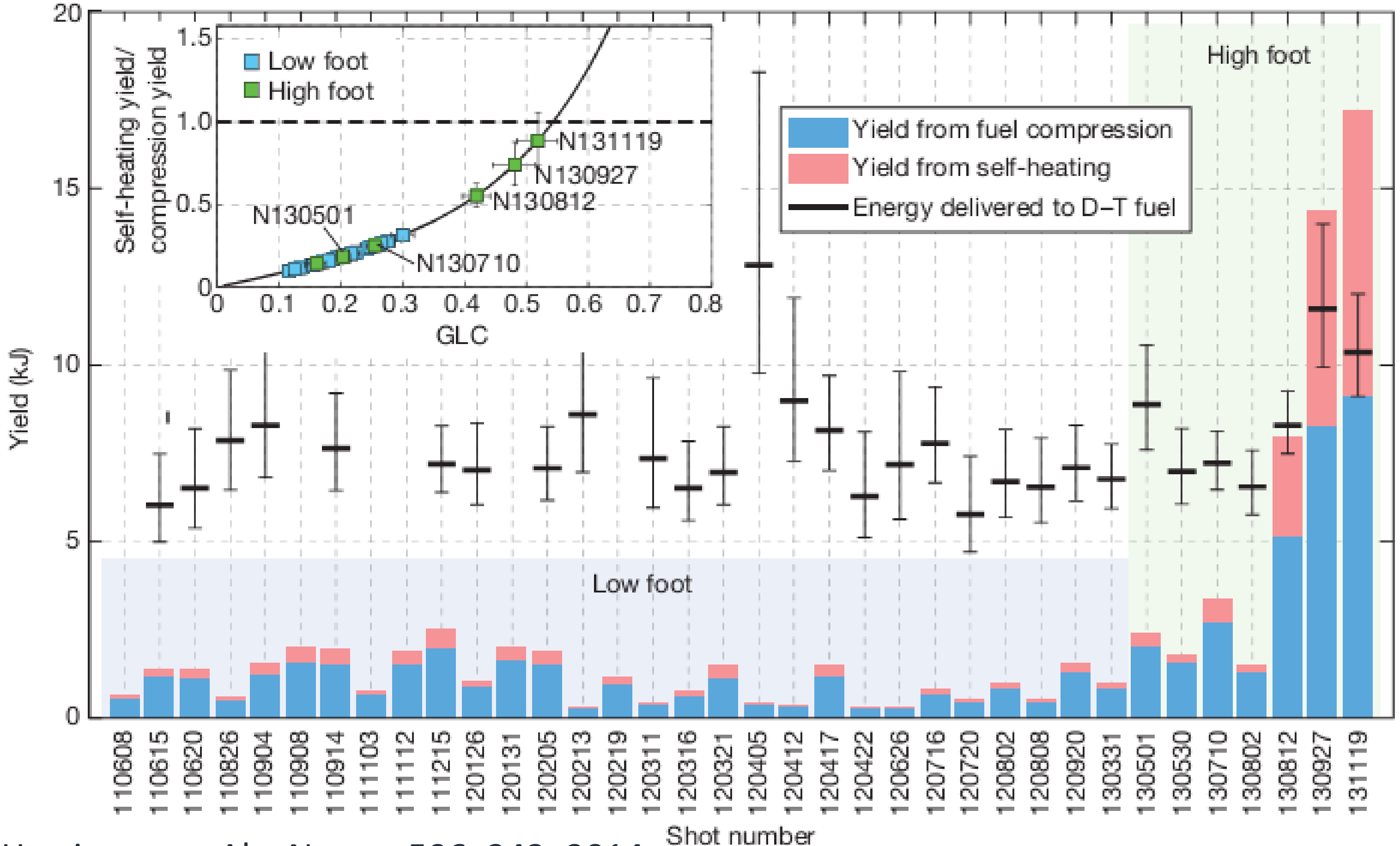




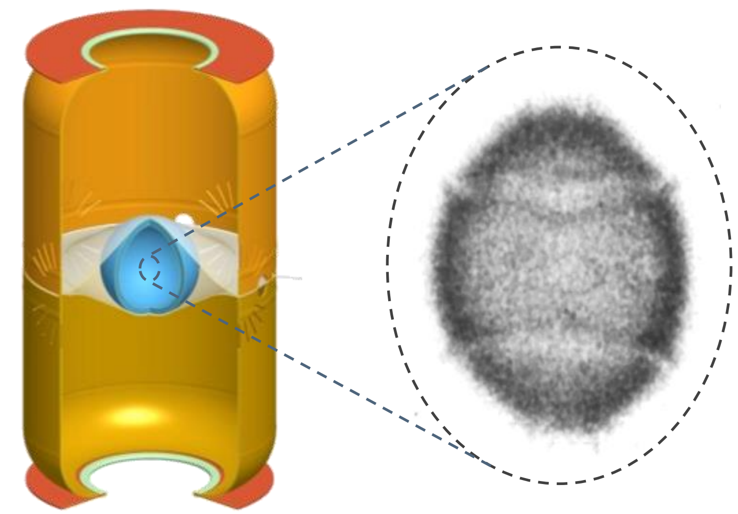




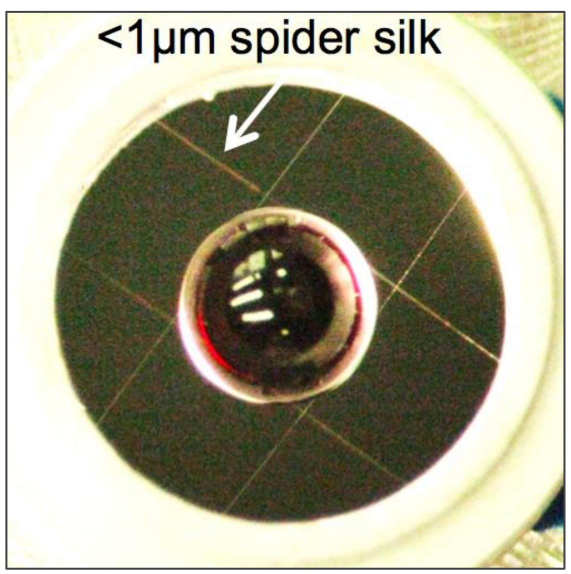
Where are we at?



O. Hurricane et. Al. , Nature 506, 343, 2014



S. Nagel, Phys. Plasmas 22, 022704 (2015)



Images courtesy P. Patel, LLNL

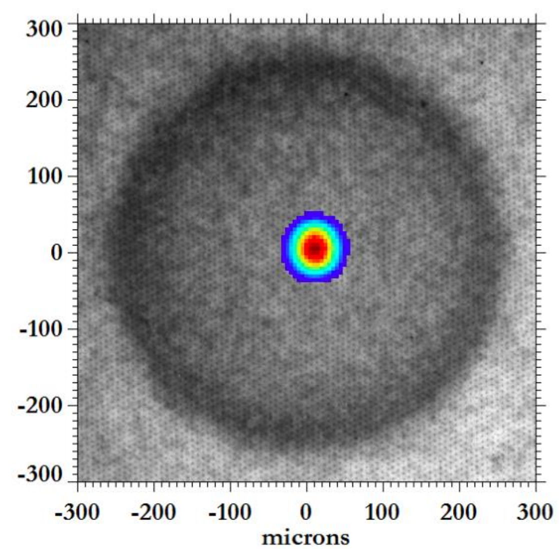
1.0-1.6 mg/cm^3 gas fill

Low LPI

Higher coupling, and less time-dependent CBET

More predictable

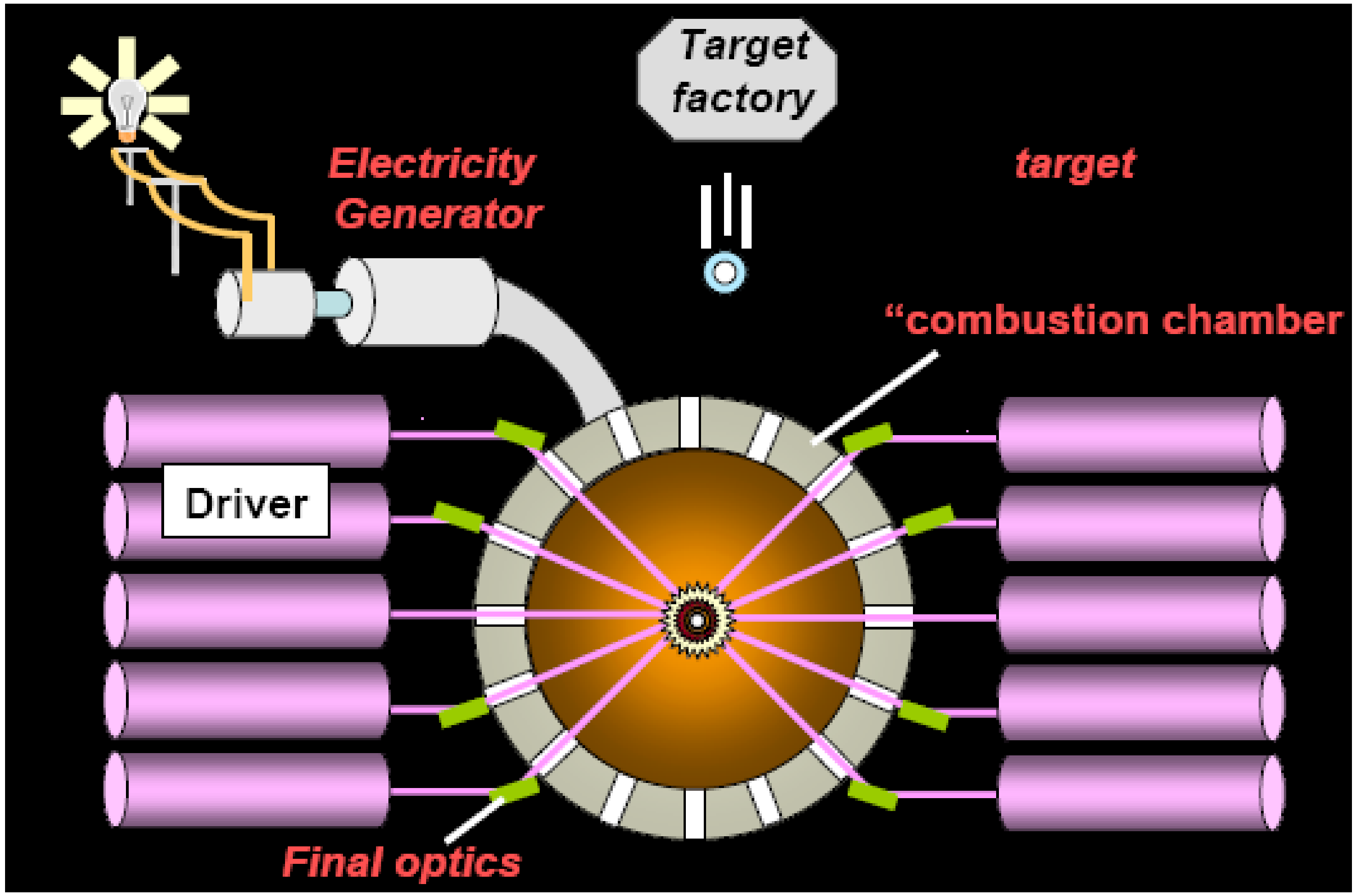
0-0.6 mg/cm^3 gas-fill



S. MacLaren, J. Salmonson, T. Ma, S. Khan et al.


STAR TREK
INTO DARKNESS
Spigot

IFE power plant

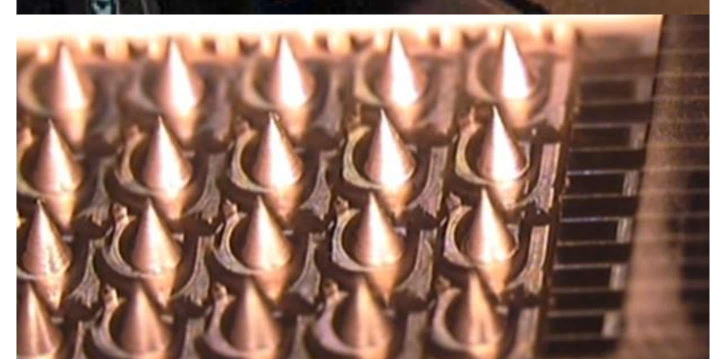


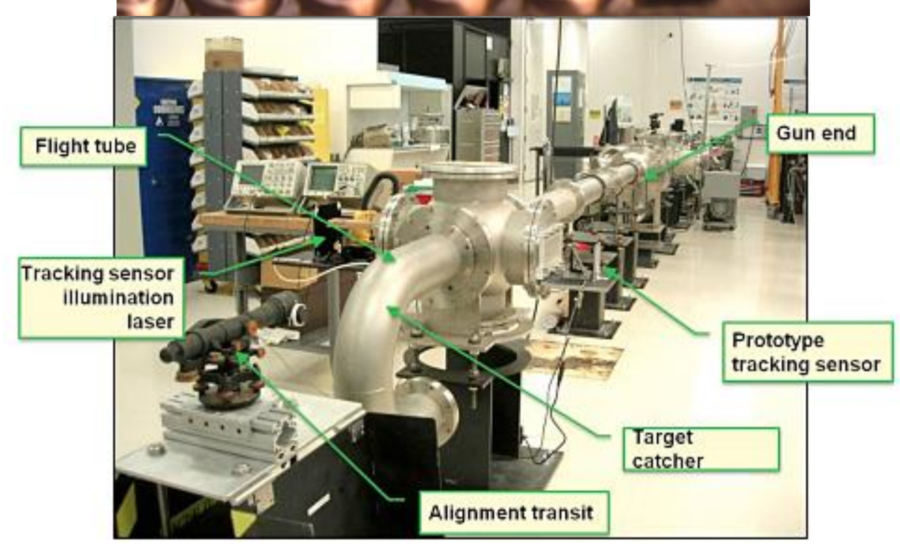
Technological challenges

Challenges that need addressing for IFE:

- High-repetition rate, high-energy lasers
- High repetition rate diagnostics
- Reactor wall technology
- Cryogenic target micro-fabrication – mass production
- Target injection systems
- Materials appropriate for extreme conditions
- Lasers in “dirty” environment

Plus common challenges with MCF – tritium breeding and inventory, energy extraction, neutronics…





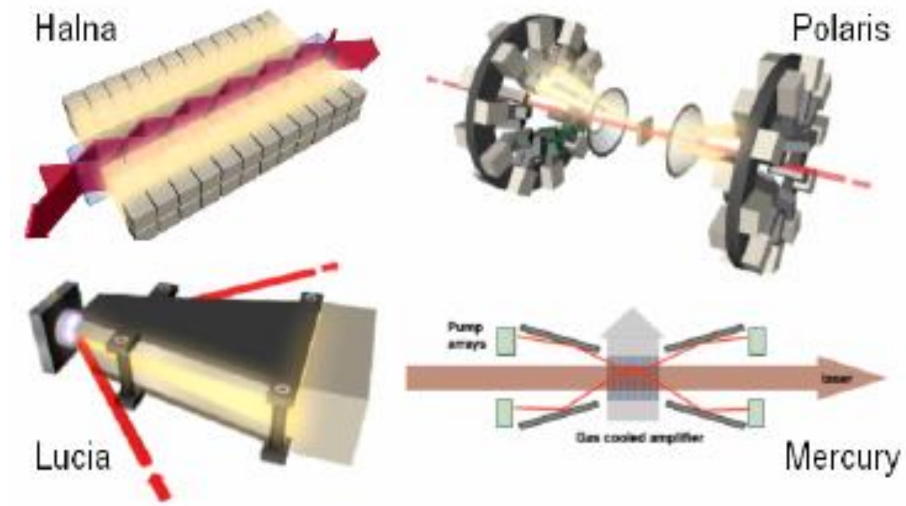
New lasers for IFE

Current lasers (NIF, LMJ) based on Nd:Glass laser technology.

Nd:glass rods pumped by flash lamps low repetition rate (~once per hour). Only ~1% efficient.

Ideally need driver efficiencies of 10-20% for high gain and 10Hz rep rate

Options:
Diode Pumped Solid State lasers (DPSSLs)
Krypton Fluoride lasers (KrF)



DiPOLE -UK

Thank you!