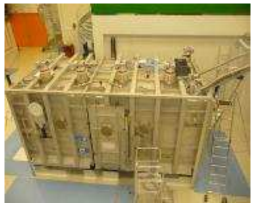
Overview of the Inertial Confinement Fusion program

Sébastien Le Pape

hall laser LULI2000

enceinte d'expérience MILKA

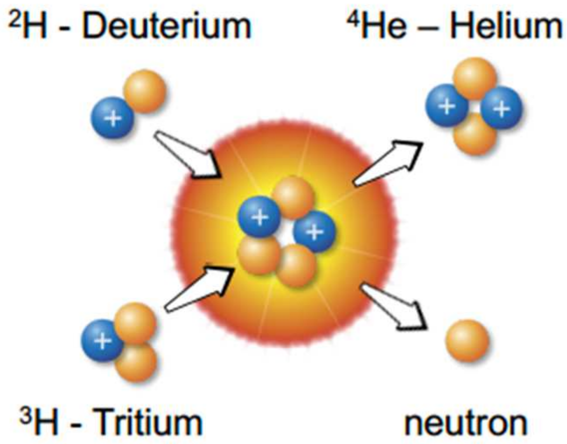


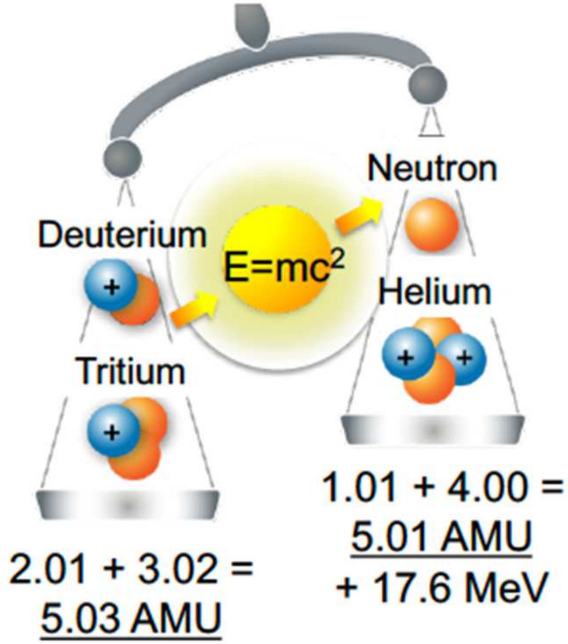
compresseur APOLLON

outline

- A brief introduction to Inertial Confinement Fusion
- Improvement neutron yield by the use of diamond ablator
- into the burning plasma regime

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

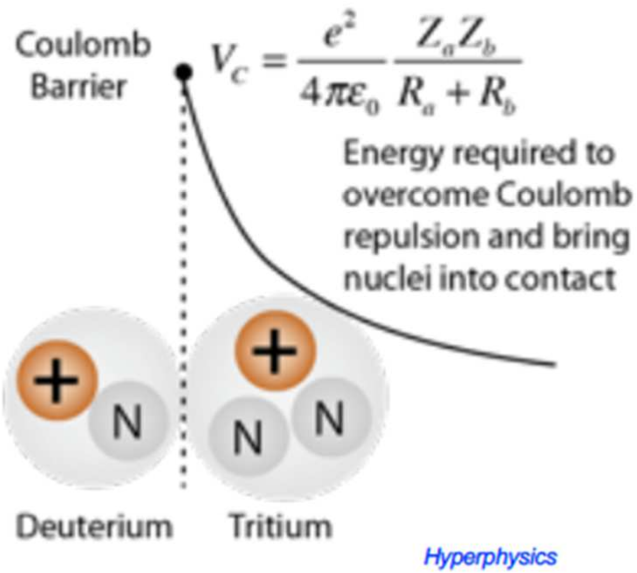


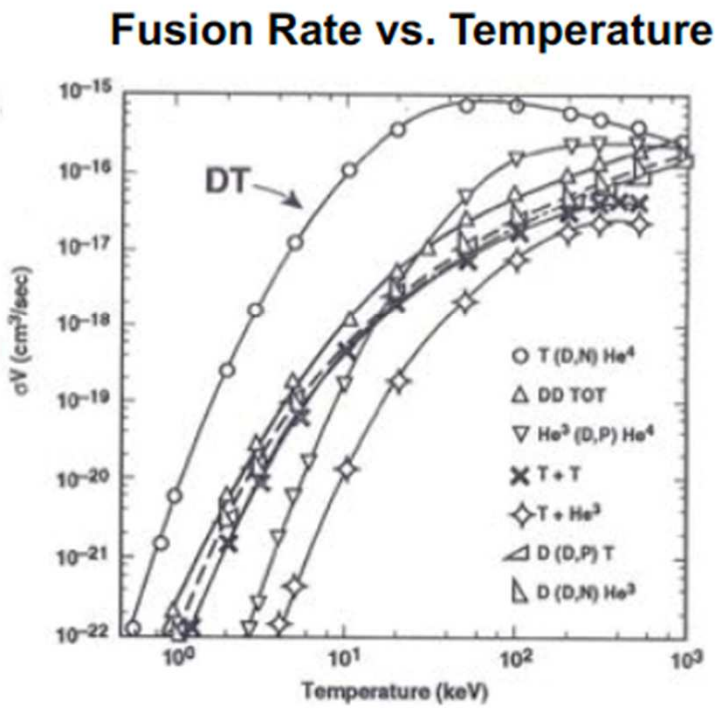


$$D + T \rightarrow \alpha(3.5\text{MeV}) + n(14.1\text{MeV})$$

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

The Coulomb barrier makes high temperatures necessary for DT thermonuclear fusion



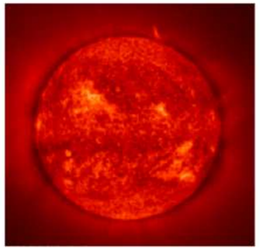


Atzeni and Meyer-Ter-Vehn
The Physics of Inertial Fusion

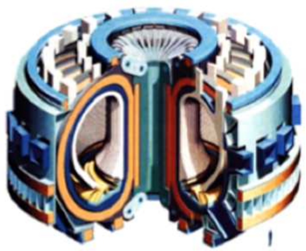
$$Yield = n_i \times n_j \times \langle \sigma v \rangle \times Volume \times time$$

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

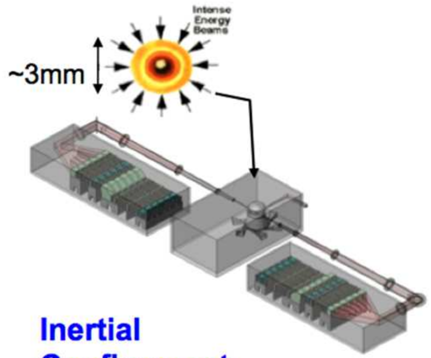
There are at least three ways to achieve nuclear fusion



Gravitational Confinement



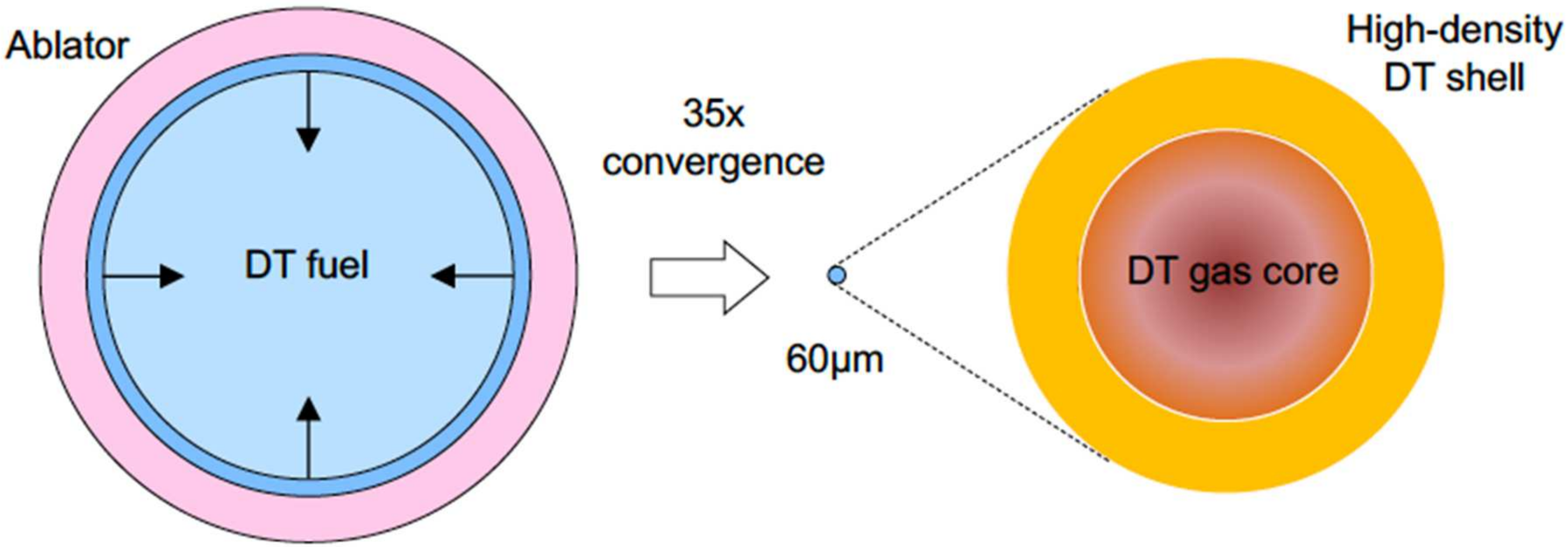
Magnetic Confinement



Inertial Confinement
by Laser Implosion

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's ps

The idea of ICF is to compress fuel to thermonuclear conditions



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

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

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

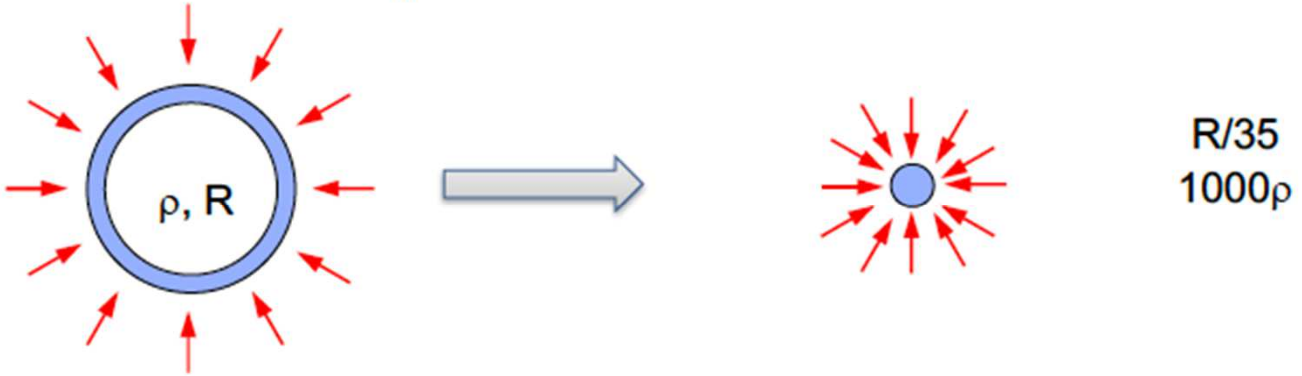
$\rho R_{DT} \sim 3\ g/cm^2$

The most efficient compression is spherical

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

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

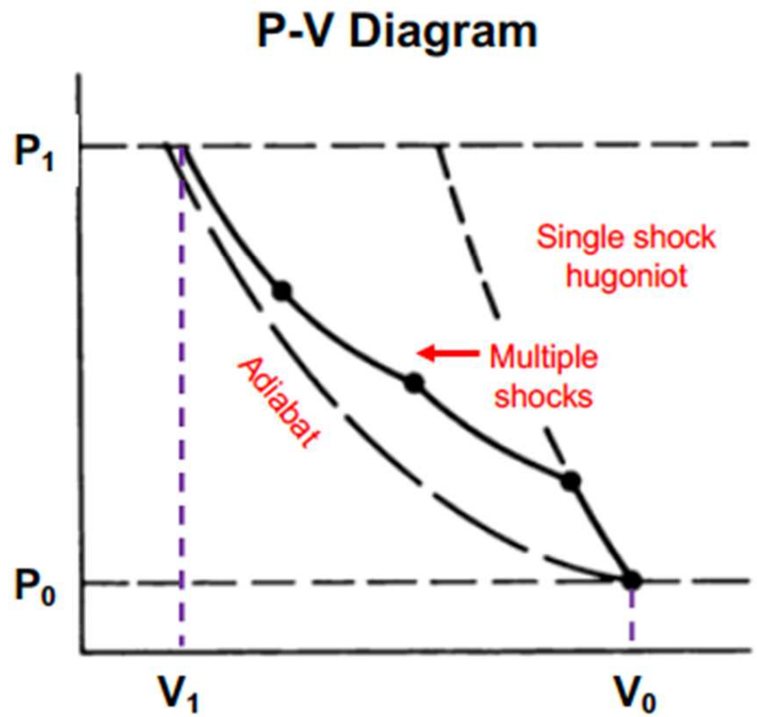
The most efficient compression is isentropic

From thermodynamics:

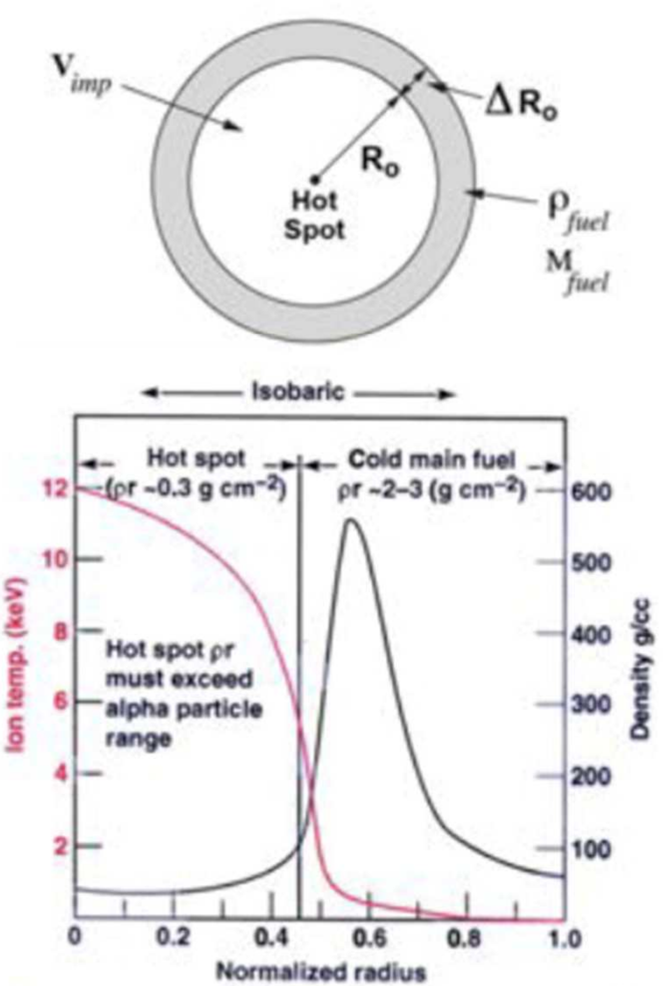
$$dU = Tds - PdV$$

$$PdV = Tds - dU$$

Minimize work needed to compress ⇔ Minimize entropy generation



The most efficient implosion is fast



Implosion velocity for Fermi degenerate case

$$KE = \frac{1}{2} M_{fuel} v_{imp}^2 \approx (ignition\ margin) \times E_{fuel} \approx 2E_{fuel}$$

$$\Rightarrow v_{imp} = \sqrt{\frac{4E_{fuel}}{M_{fuel}}} \approx 3.6 \times 10^7 \text{ cm/s}$$

E_{fuel} determined by pressure equilibrium with hot spot

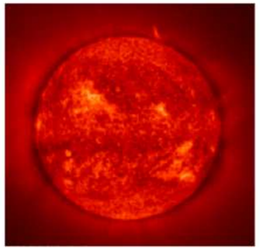
Ablation pressure to generate implosion velocity

$$KE = \frac{1}{2} M_{fuel} v_{imp}^2 = P_{abl} \Delta V$$

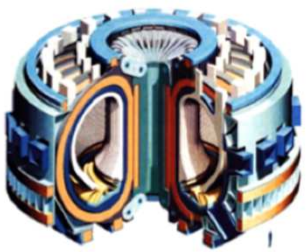
$$\Rightarrow P_{abl} \sim 100 \text{ Mbar}$$

ΔV corresponds to $R_0 \rightarrow R_0/2$ (useful area for compression)

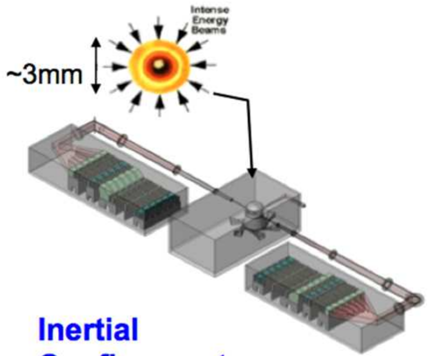
There are at least three ways to achieve nuclear fusion



Gravitational Confinement



Magnetic Confinement



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by Laser Implosion

Density	10^4 x solid	solid / 10^8	10^3 x solid
Temperature	1 keV	10 keV	10 keV
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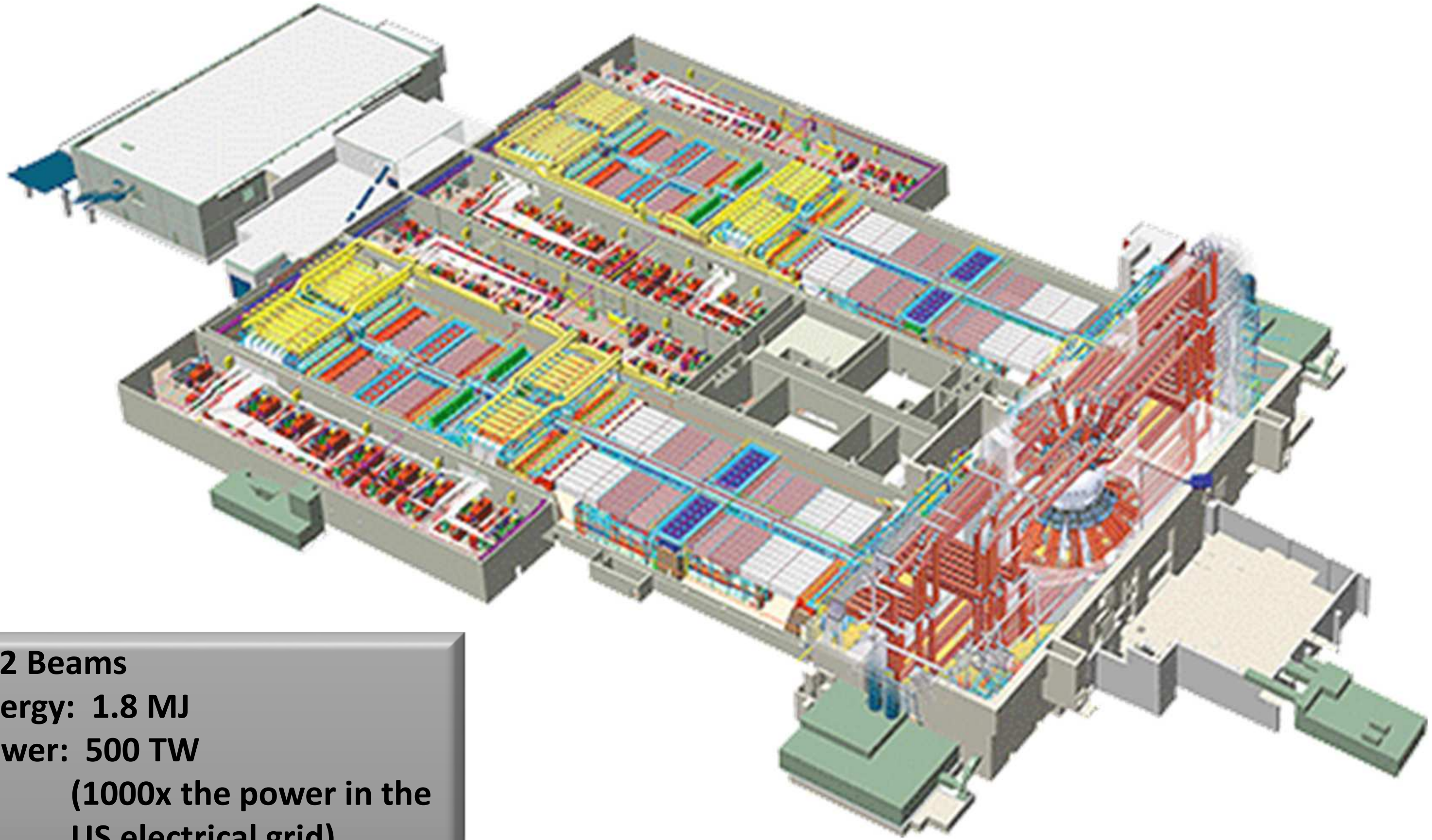
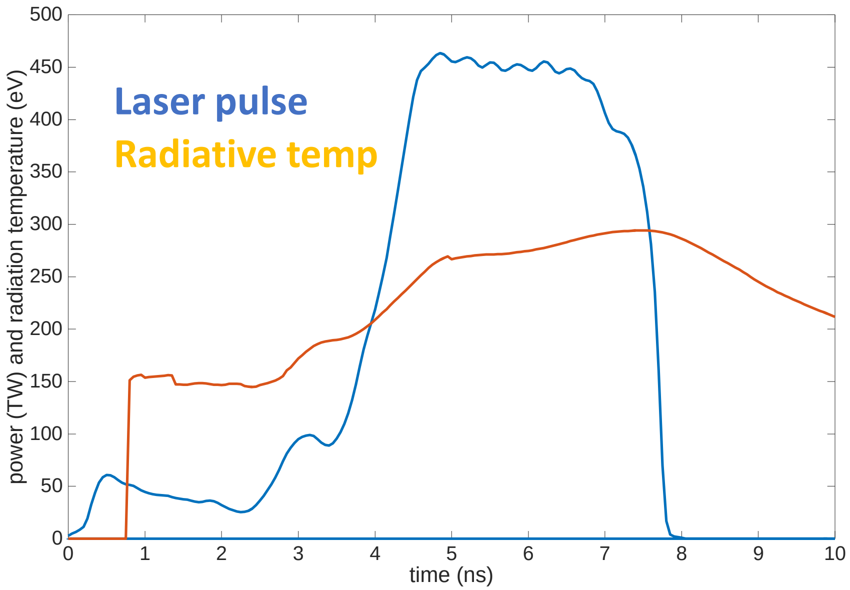
~600 MJ of electricity is used to generate 1.8MJ/480TW



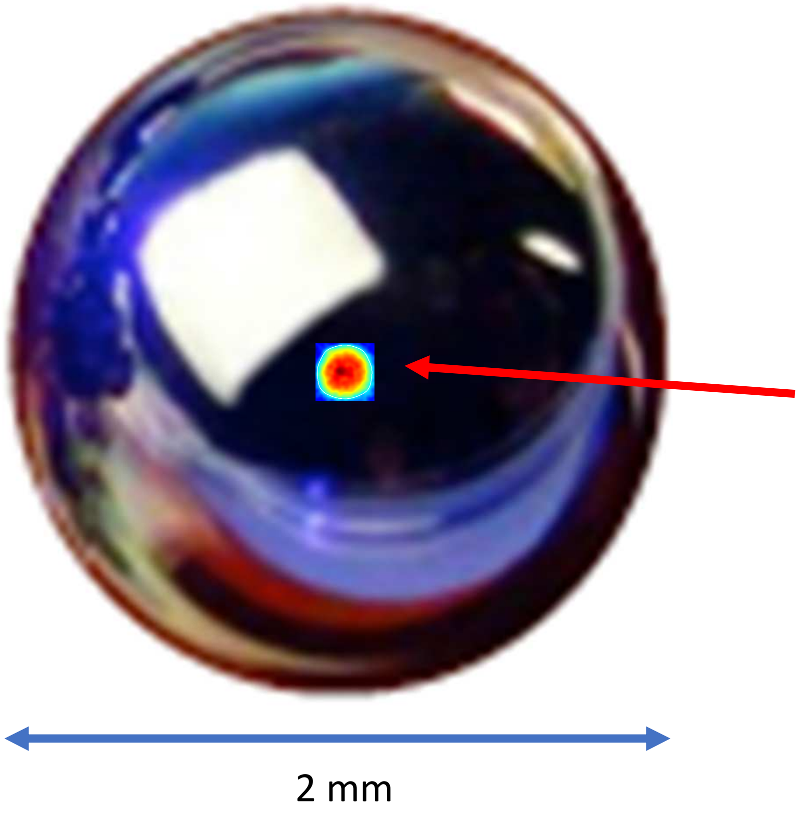
- 192 Beams
- Energy: 1.8 MJ
- Power: 500 TW
  (1000x the power in the US electrical grid)
- Frequency Tripled Nd Glass
- Wavelength: 351 nm
- Pulselength: ~25 ns

~1.3MJ of X-rays is generated by the interaction of the laser with a high Z cavity



Major challenge: laser beam pointing and energy repartition in the hohlraum must be designed to symmetrically drive the capsule

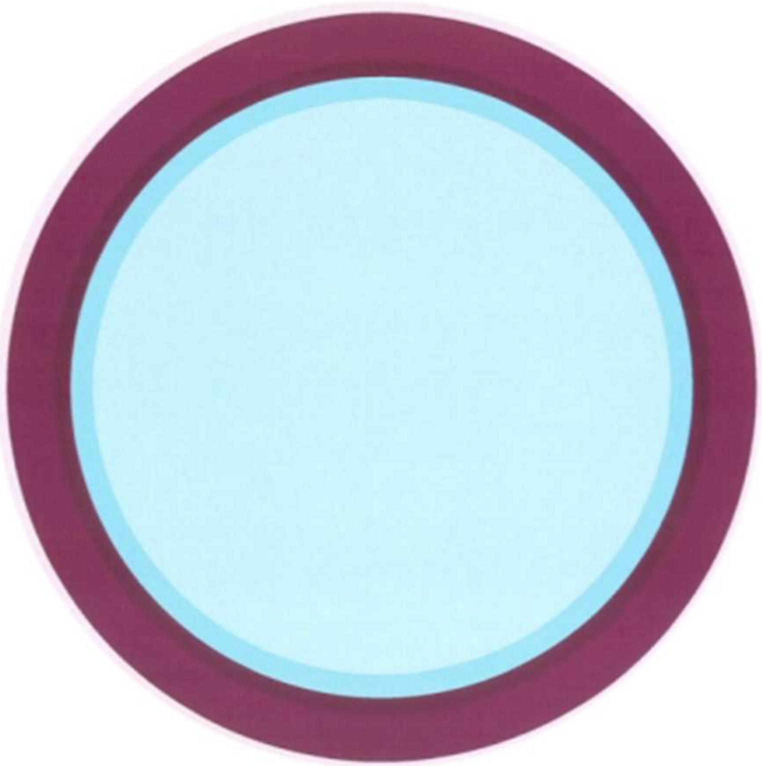
~150 KJ of energy is absorbed by the 2 mm diameter low Z capsule



X-ray self-emission image from a DT implosion at peak compression

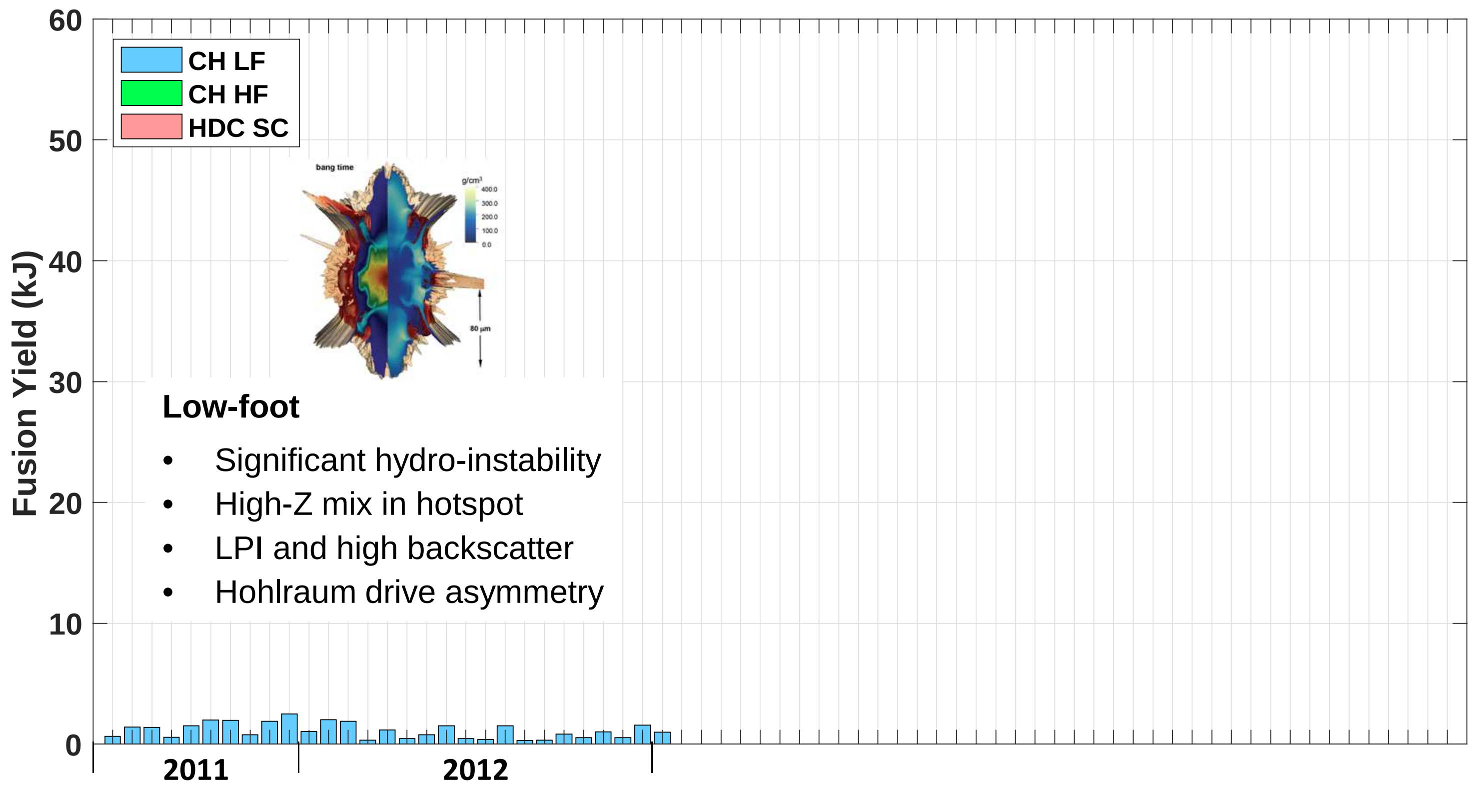
Diameter ≈ 50 µm

~20 KJ of kinetic energy is reached at peak velocity of the capsule

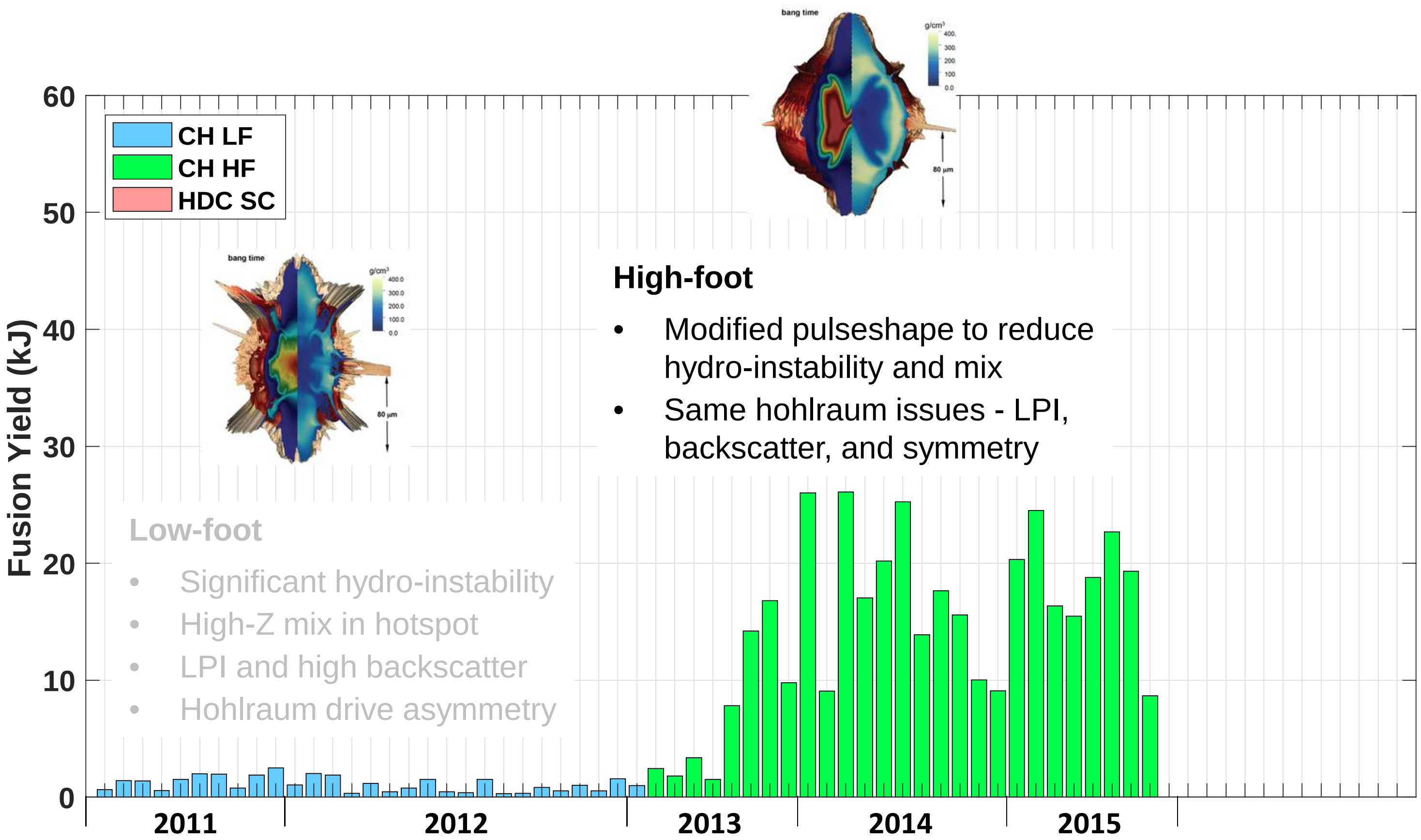


Major challenge: The capsule must be designed and driven to withstand hydro instabilities

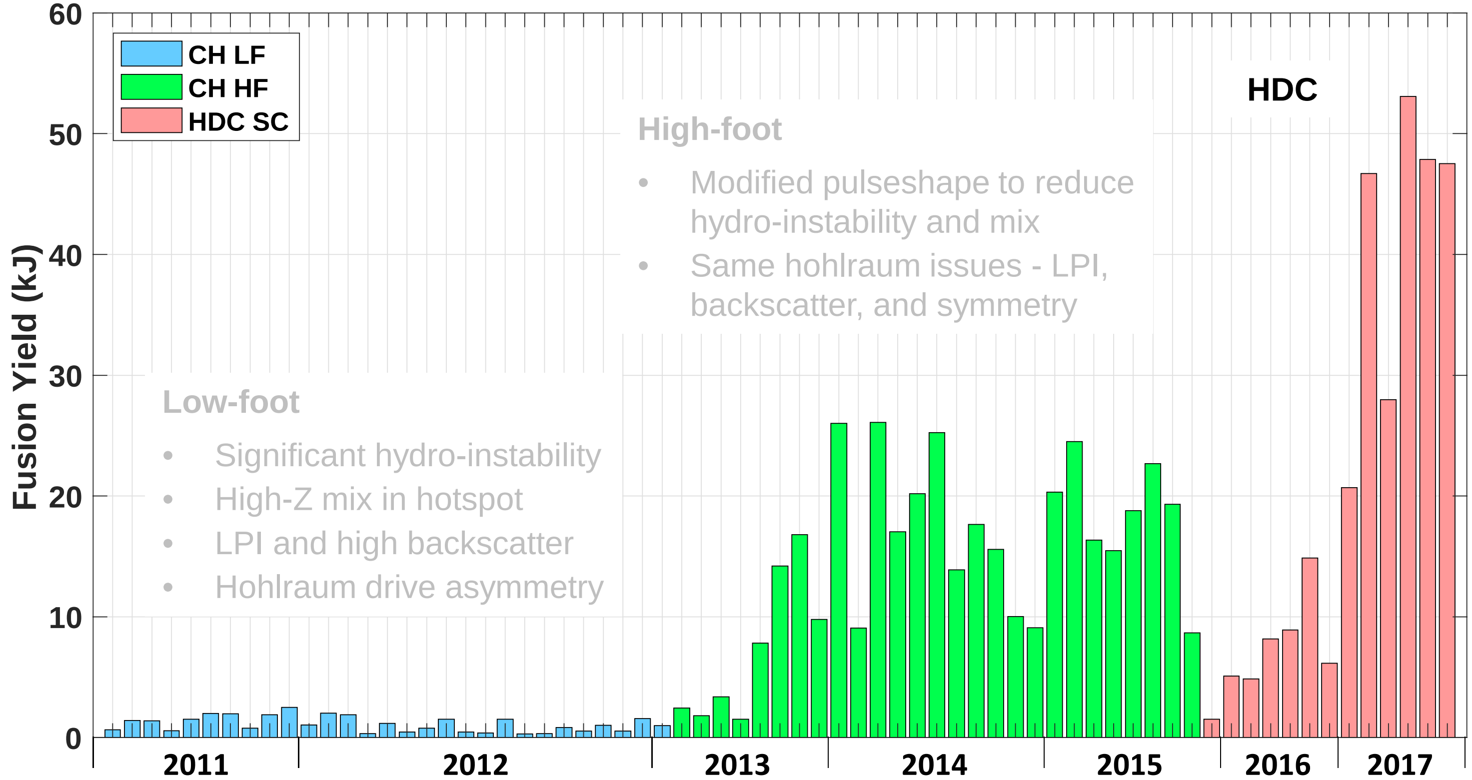
In the first experiments we encountered a number of problems



The pulseshape was modified to reduce the capsule ablation-front growth factors



In the last six years we've focused on addressing these hohlraum issues

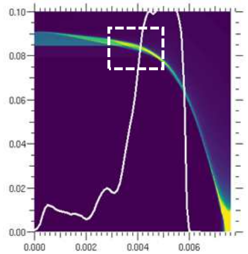


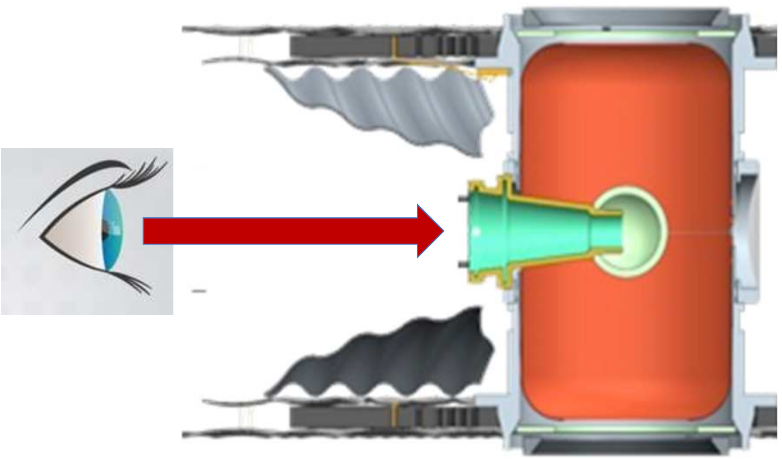
outline

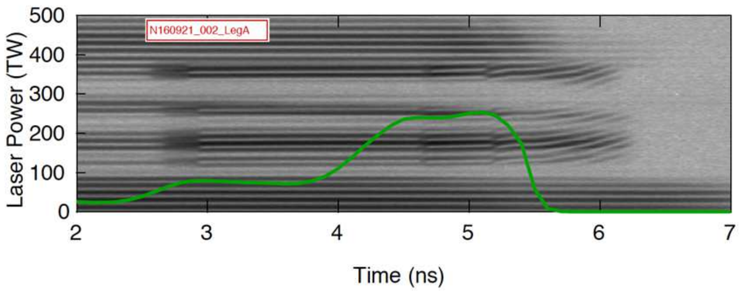
- A brief introduction to the Inertial Confinement Fusion program at LLNL
- Improvement neutron yield by the use of diamond ablator
- Into the burning plasma regime

Having found an optimum in term ablator and hohlraum, we can now tune the implosion symmetry

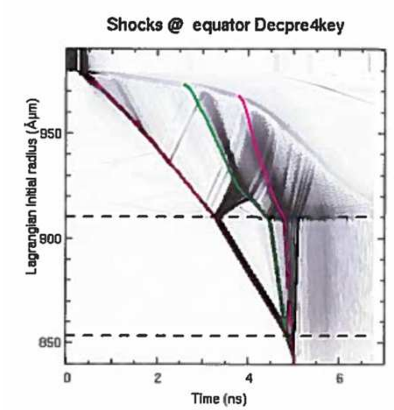
VISAR through a “keyhole” target

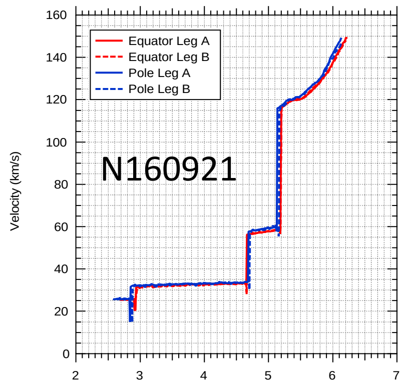






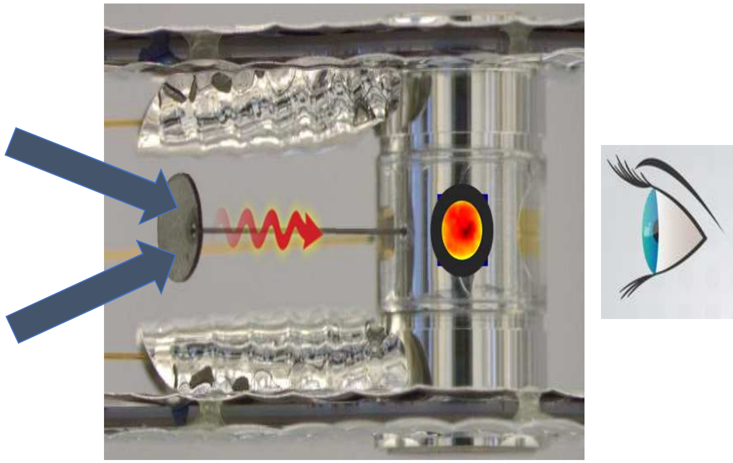
Measured shocks Velocity

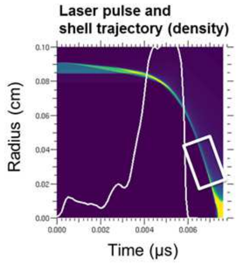




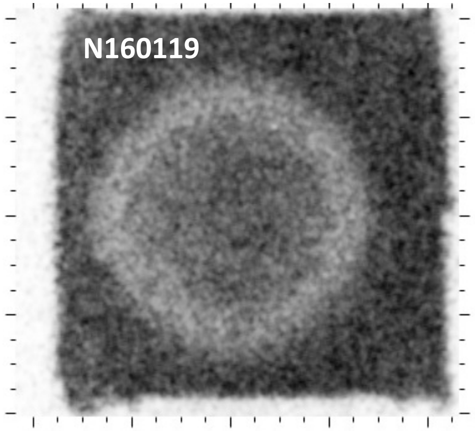
Radiographs of imploding shell diagnose symmetry through convergence ~5x

2D X ray radiography of the convergent ablator





Measured shell shape



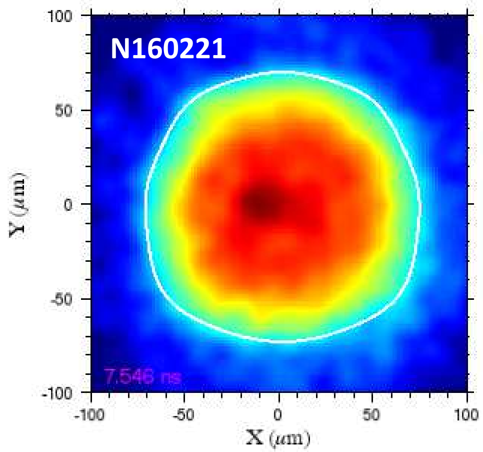
P2: -5 µm
P4: +7 µm

- **Lasers heat external material to form backlit radiographed image**
- **Measures symmetry of shell as implosion progresses**
- **First view of shell symmetry**

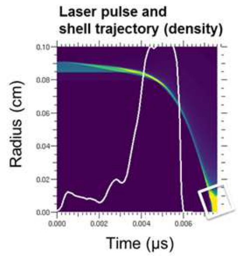
- **Symmetry requirement (±5 µm P2) maintained in multiple experiments**

X-ray emission from final hotspot in gas-filled capsule demonstrates symmetry control at convergence ~12x

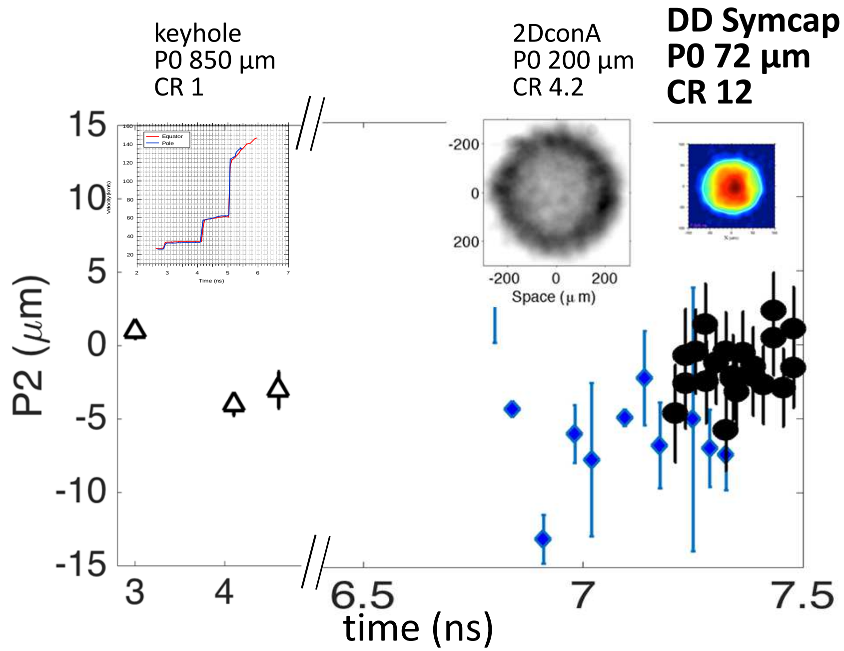
Time integrated Equatorial X ray image



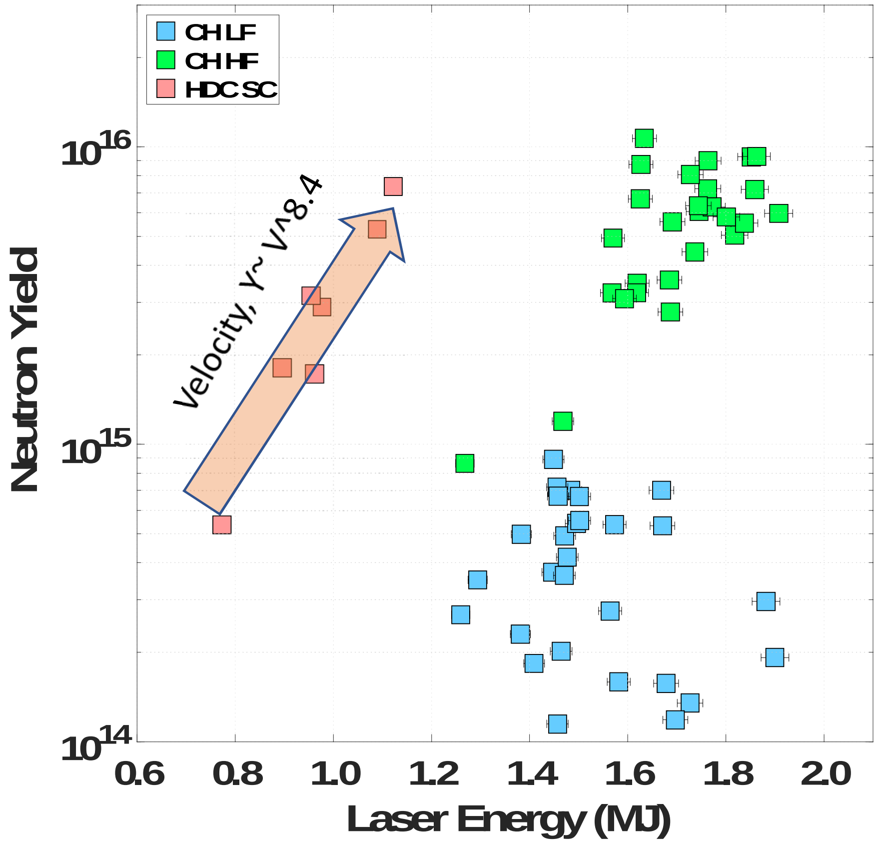
P2: -1%
P4: 0.4%



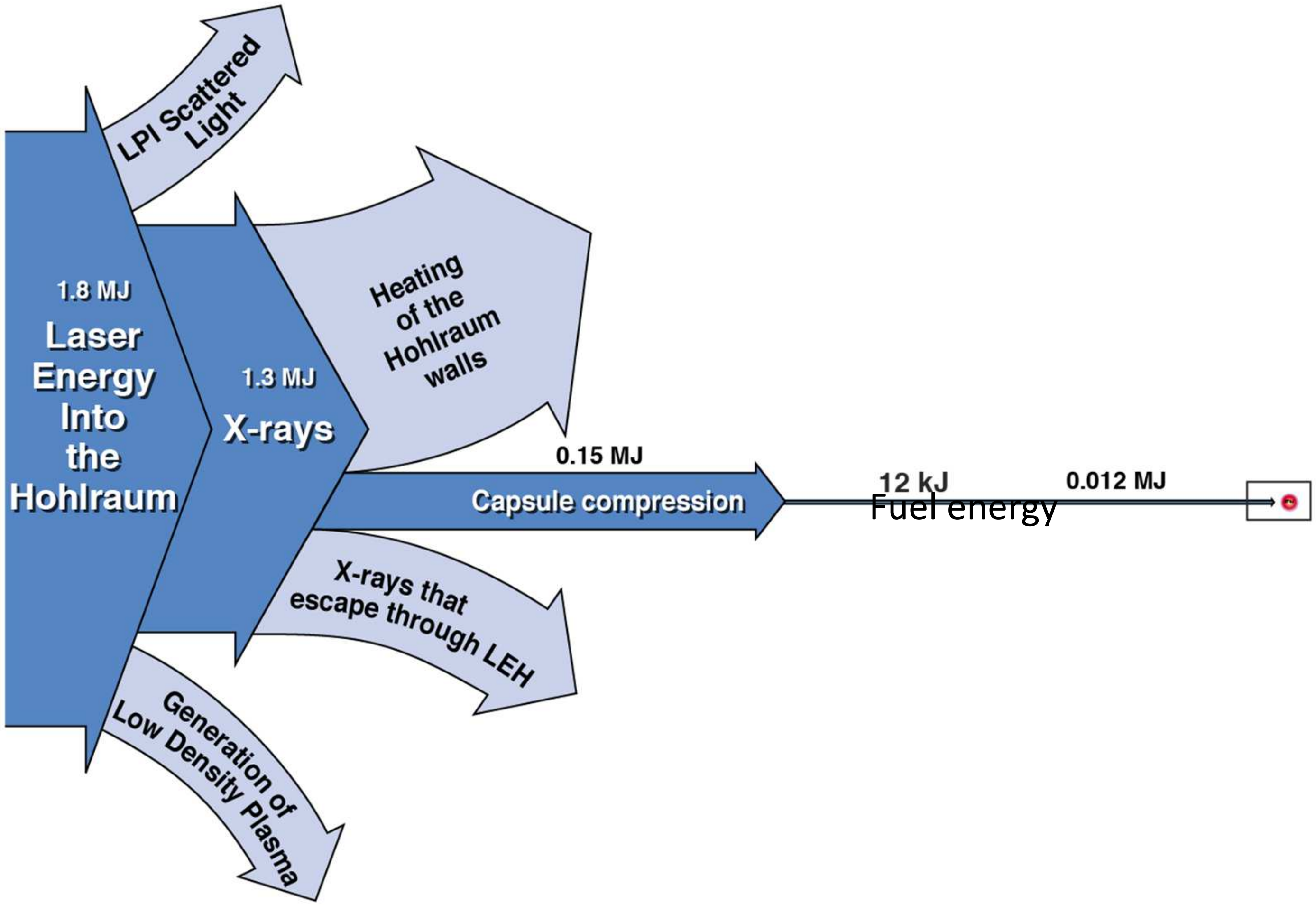
Capsule symmetry through the laser history



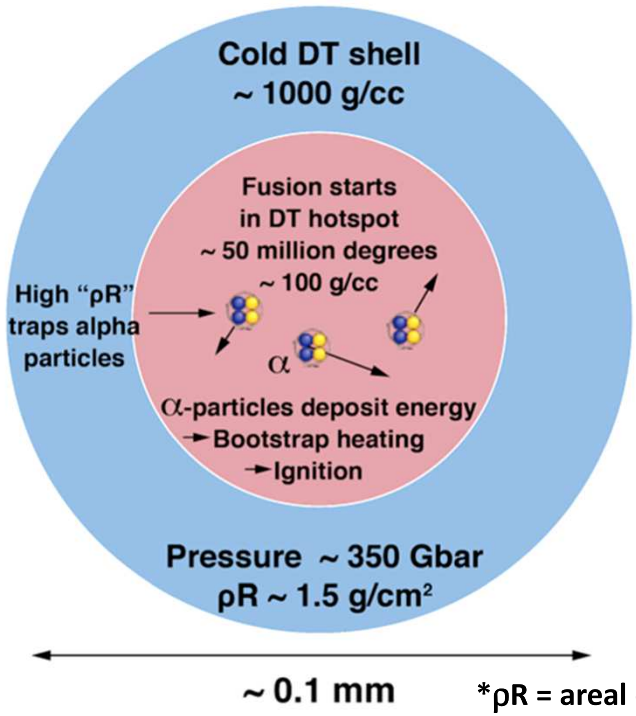
Symmetry control resulted in high neutron yield at ~ half of the laser energy of previous platforms



Where does the energy go?



Energy balance in the hot spot



*ρR = areal density

$$C_{DT}\frac{DT}{\delta t} = f_\alpha Q_\alpha - Q_e - Q_B$$

Assuming isochoric

$$Q_B = 3.1 \times 10^7 \rho\sqrt{T}\ GJ/(g.s)$$

Is the Bremsstrahlung loss term

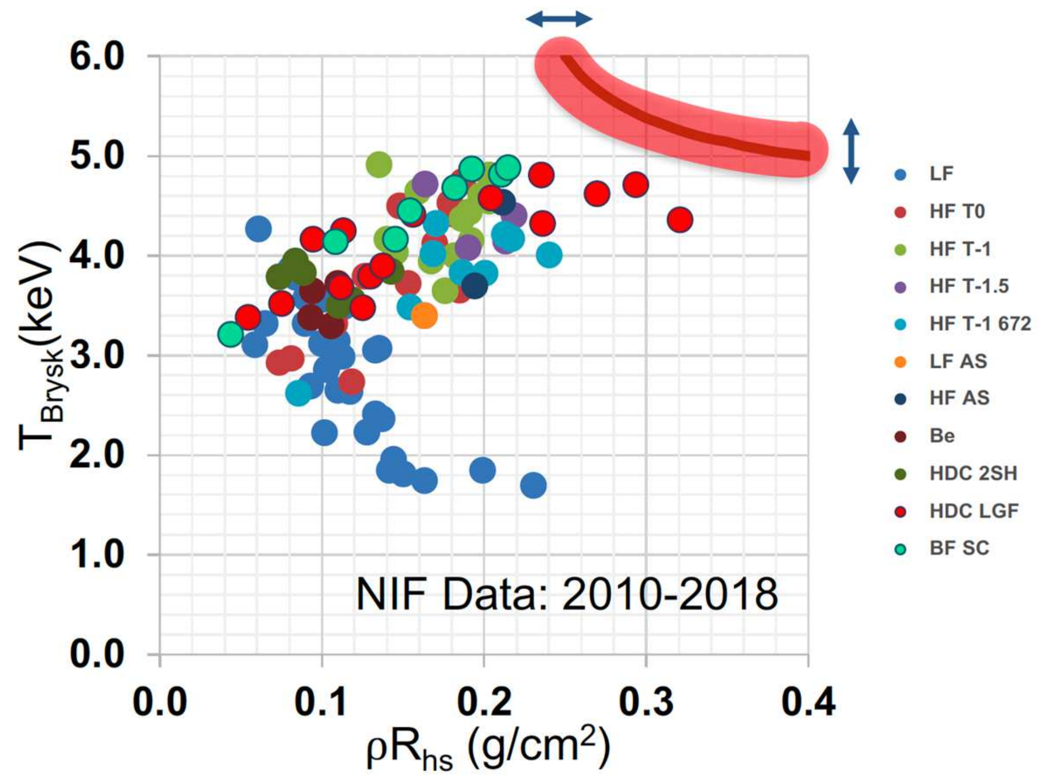
$$Q_e = 5.9 \times 10^3 \frac{T^{3.5}}{\rho R^2}\ GJ/(g.s)$$

Is the electron conduction term

Energy balance in the hot spot

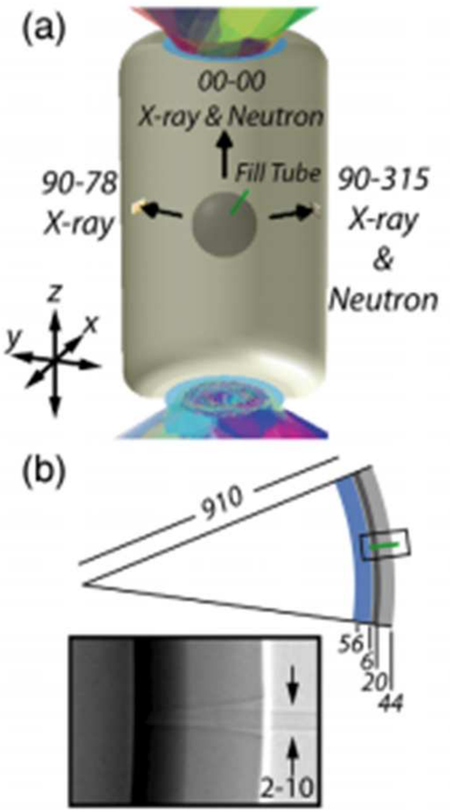
- **Kinetic energy of the shell : 21 KJ**
- **Hot spot energy :** $\frac{3}{2} P_{stag} Volume$ **= 4.7 ± 1.17 kJ**
- **Alpha deposited energy : 8.7 ± 1.36 kJ**
- **Bremsstrahlung loss: 7 ± 2 kJ**
- **Electron conduction loss: 3.4 ± 1 kJ**
- **Fusion energy : 57 KJ**

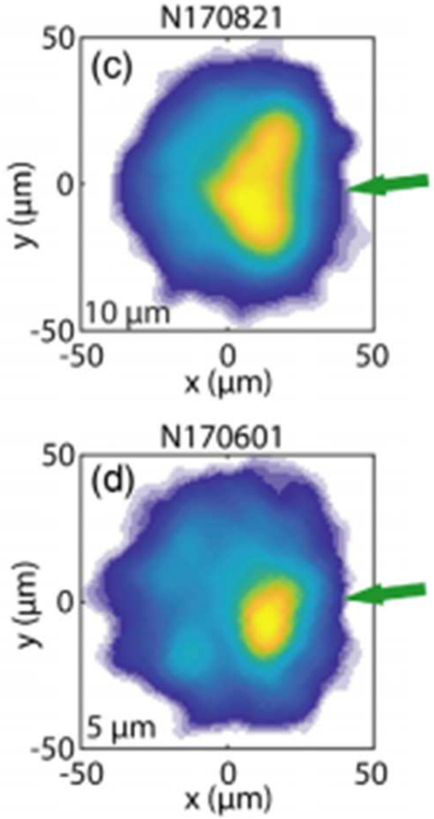
Symmetry control with low gas-fill hohlraums has extended implosion efficiency and performance in all hot-spot metrics

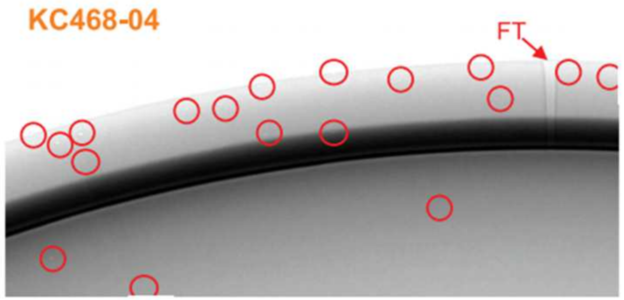


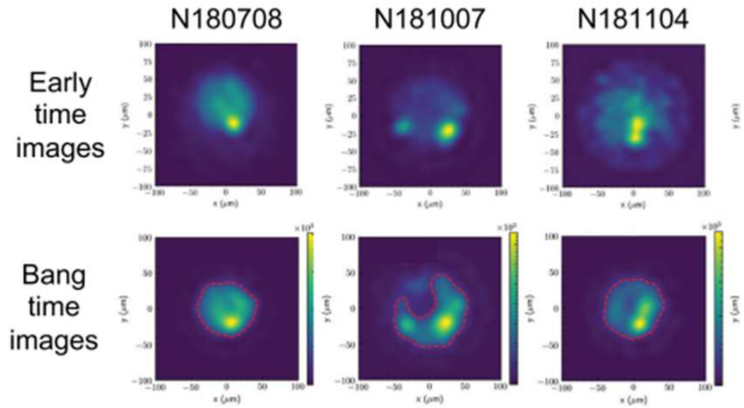
Experiments are making progresses, what about the simulations?

Further improvement of the yield was achieved By reducing mix in the hot spot









The latest experiment in August has reached the burning plasma regime close to ignition