Inertial Confinement Fusion: progress through close coupling of theory and experiment

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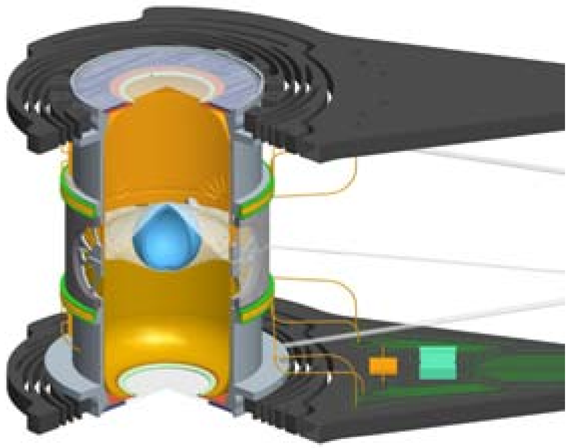
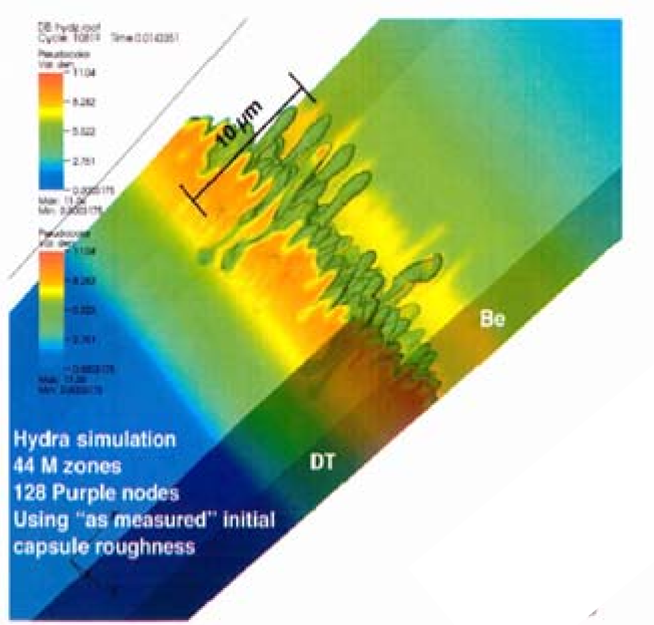
- John Soures (LLE)

Summary: Inertial Confinement Fusion (ICF) and HEDP is entering a decade of major discovery



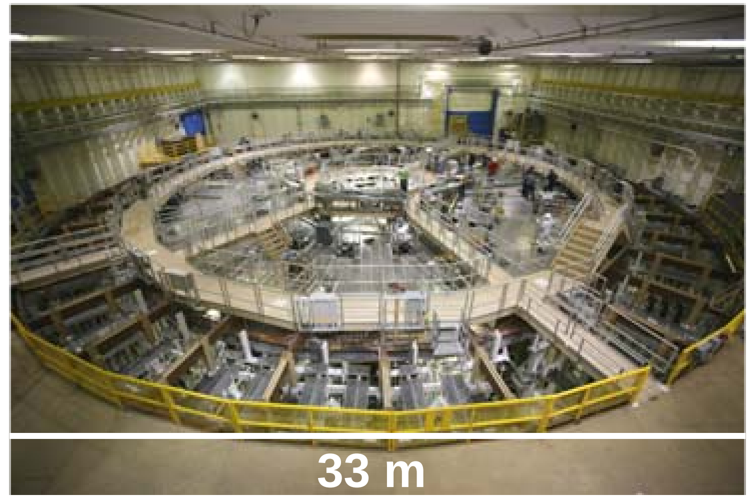


- **The National Ignition Facility (NIF) laser system is poised to achieve ignition in the next few years**
- **Several nations have made major investments in facilities and capabilities**
  - **e.g NIF, Z, OMEGA EP, LMJ, FIREX I, Orion**
- **Advances in computing (Petaflop), diagnostics (psec, μm, keV) and targets (precision nanofabrication) enable unprecedented learning and progress**
- **Separation of driver from the target enables great flexibility in innovation and discovery in ICF**
- **Innovative new concepts will lead to revolutionary advances in fusion gain and yield**
- **These advances will enable development of a pilot fusion power plant**

The US ICF Program has three major facilities for ICF and high energy density science experiments

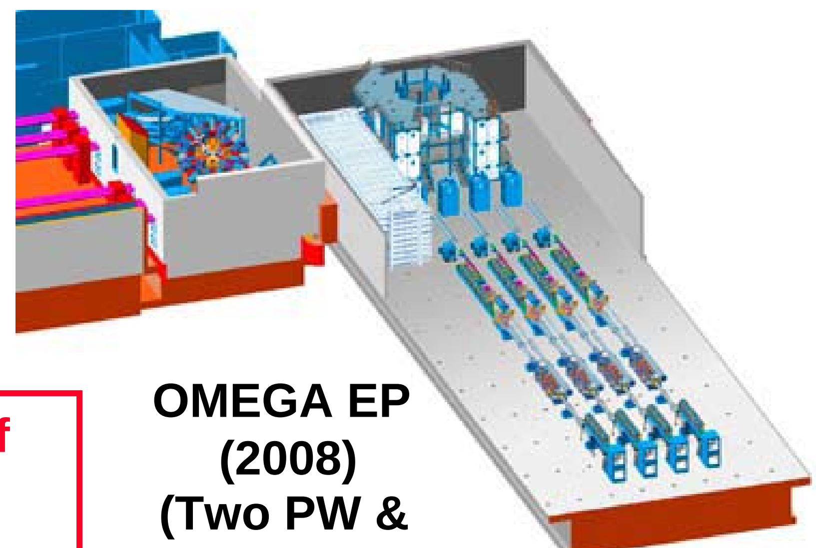
NIF (2009)
(1.8 MJ @ 0.35 μm)

Refurbished Z (2007)
(3 MJ)



OMEGA

(30 kJ @ 0.35 μm)



OMEGA EP (2008)
(Two PW & two ns beams)

After 40 years of research, the components of simulations, drivers, diagnostics, and targets are in place to test ignition concepts

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Inertial Fusion is a grand challenge that has attracted the interest of scientists throughout the world for 50 years

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ICF has come a long way from its roots in the nuclear weapons program

1960-72	**Early x-ray and direct drive ICF target concepts**
	Lasers become available
	Sophisticated computer models and programs developed
1972-97	**Evolution of high energy, high power laser and pulsed power facilities**
	Declassification of ICF begins (1972)
	Laboratory production of fusion neutrons (1974)
	X-ray-driven targets demonstrate 100-times liquid density (1979)
	Halite (LLNL) and Centurion (LANL) underground nuclear experiments (1977-87)
	Thirty kJ short λ Nova laser/experiments/Nova Technical Contract (1985-99)
1997 -	**Investment in major facilities**
present	**DOE declassification of x-ray driven ICF capsule concepts (1994)**
	Construction of NIF; LMJ; Z Refurbishment; OMEGA EP
	Advances with alternate fusion targets (Z-pinch, fast ignition, direct drive)
2010	**National Ignition Campaign begins on NIF**

Adapted from John Nuckolls, "Contributions to the Genesis and Progress of ICF"

John Nuckolls and colleagues recognized the key elements of ICF 50 years ago

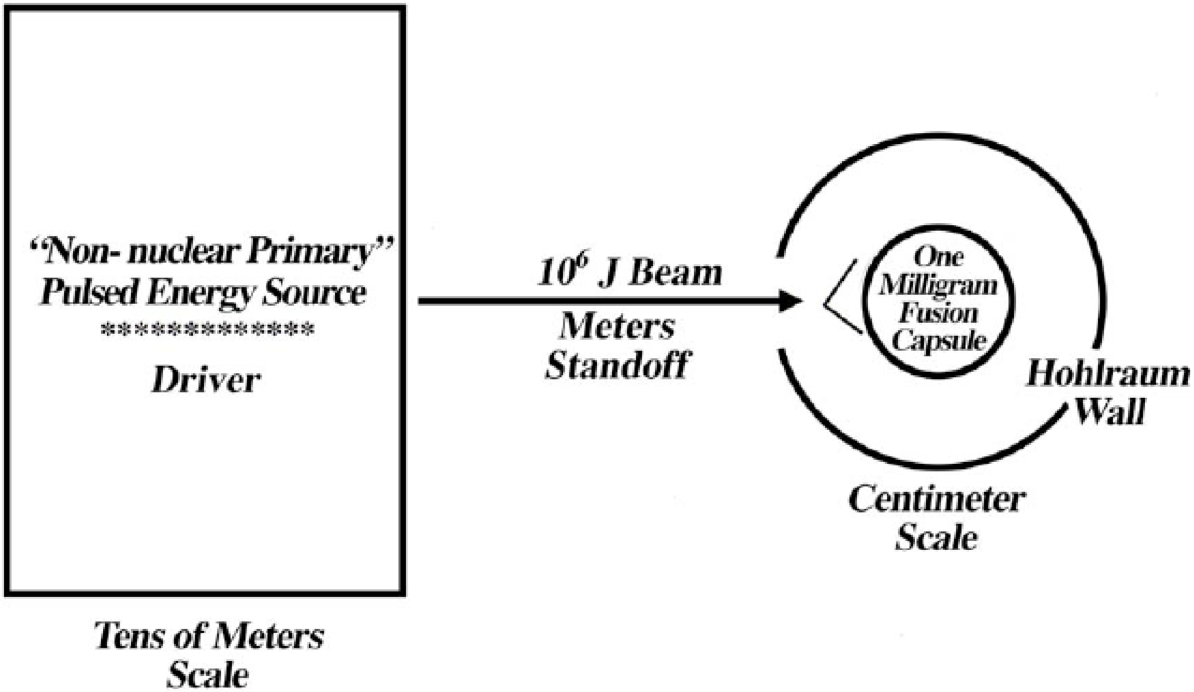
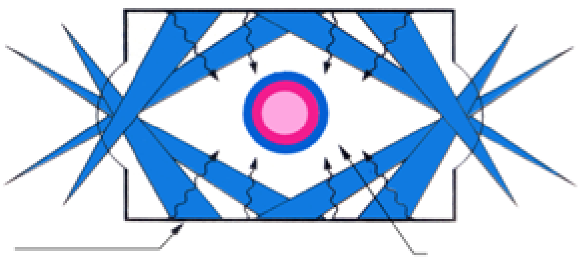
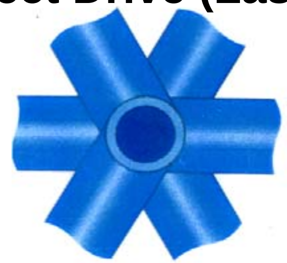


Figure 4. Non-nuclear primary/indirect drive scheme (1960)
Nuckolls, "Contributions to the Genesis and Progress of ICF"

Indirect Drive (X-ray)

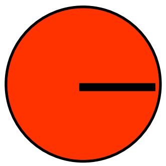


Direct Drive (Laser)



- Radiation-driven implosions partially control physical processes that limit performance, including asymmetries and fluid instabilities
  - Driver: Input power = few hundred TW; energy = few MJ
  - Fusion yield = ~50 MJ
  - 240 eV drive leads to 100s Mbar driving pressure and isentropic compression
- Near-Fermi-degenerate hot spot is required to achieve high efficiency and gain

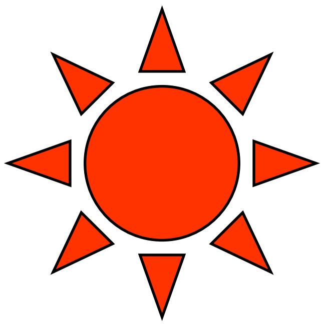
Under extreme conditions a mass of DT can undergo significant thermonuclear fusion before falling apart



ρ, R, T

- Consider a mass of DT with radius R, density ρ, and temperature T
- How does the disassembly time compare with the time for thermonuclear burn?

$$\tau_{disassembly} \sim \frac{R}{c_s} \sim \frac{R}{\sqrt{T}} \qquad \tau_{burn} \sim \frac{1}{n_i\langle\sigma v\rangle} \sim \frac{1}{\rho\langle\sigma v\rangle}$$



- The fractional burn up of the DT (for small burn up) is:

$$f_{burn} \approx \frac{\tau_{disassembly}}{\tau_{burn}} \sim \rho R \frac{\langle\sigma v\rangle}{\sqrt{T}}$$

- At sufficiently high ρR and T the fractional burn up becomes significant and the energy deposited by alpha particles greatly exceeds the initial energy in the fusion fuel ("ignition")

- Typical conditions are:

$$\rho R \approx 0.6\,\mathrm{g/cm^2}$$
$$T \approx 5\,\mathrm{keV}$$

The fusion fuel must be brought to a pressure of several hundred billion atmospheres to achieve the goal of ignition

For ignition conditions:

$$\left\{ \begin{array}{l} \rho R \approx 0.6\,\mathrm{g/cm^2} \\ T \approx 5\,\mathrm{keV} \end{array} \right\} \quad \rho R T \approx 3.0 \left(\frac{\mathrm{g\,keV}}{\mathrm{cm^2}} \right)$$

$$P(\mathrm{Bar}) = 8 \bullet 10^8 \rho\left(\mathrm{g/cm^3}\right) T_i\,(\mathrm{keV}) \qquad PR \sim 2.4 \bullet 10^9\,\mathrm{Bar-cm}$$

$$\mathrm{E} \sim \frac{3}{2} PV \sim \frac{3}{2} P\left(\frac{4\pi}{3} R^3\right) \sim 1.5 \bullet 10^9 R^2 (cm)(\mathrm{J})$$

$$\mathrm{E_{NIF}} \sim 15\mathrm{kJ} \Rightarrow R \sim 30\mu\mathrm{m} \Rightarrow \quad P \sim 800\mathrm{GBar} \quad \text{and} \quad \rho \sim 200\, g/cm^3$$

$$\tau_{conf} \sim \frac{R}{c_s} \sim 30\,ps \qquad \mathrm{Power} \sim \frac{E}{\tau_{conf}} \sim 0.5 \bullet 10^{15} W$$

Note for magnetic confinement fusion ignition

$$\tau_{conf} \sim \text{few seconds} \qquad P \sim \text{few Bars} \quad \rho \sim \text{few } 10^{-10}\, g/cm^3$$

High velocity, low adiabat thin shells are needed to reach these pressures

In either direct or indirect drive, peak drive pressures are of order ~ 50-150 MBars

We need to get pressures to >1000X that for ignition

Spherical implosions enable us to store energy in the fusion fuel in the form of kinetic energy, which is converted to pressure at stagnation

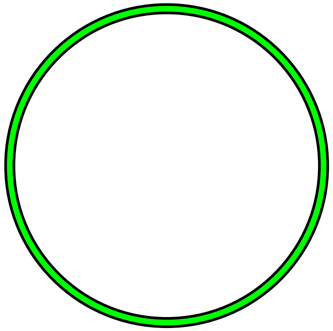
$$P_{stag} \sim \alpha\,\rho_{stag}^{5/3} \qquad \alpha\,\rho_{stag}^{2/3} \sim \mathrm{v}^2 \Rightarrow P_{stag} \sim \mathrm{v}^5 / \alpha^{3/2}$$

$$\alpha \equiv P / P_{Fermi}$$

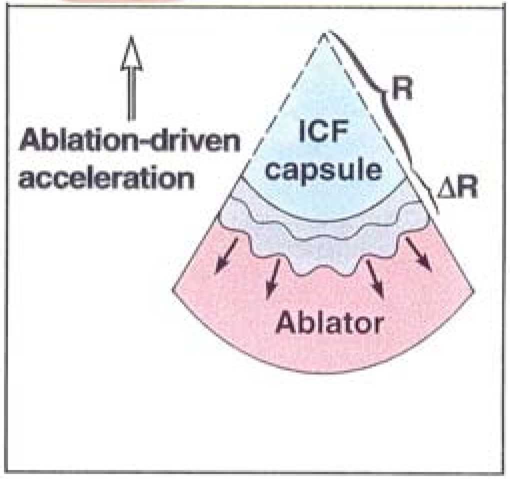
Thin shell implosions can reach the 200-400 km/sec needed for ICF

$$\int P_{drive}\,\mathrm{dV} = \frac{1}{2} m \mathrm{v}^2 \qquad m \sim 4\pi R^2 \rho\,\delta R$$

$$P_{drive} R^3 \sim R^2 \rho\,\delta R\,\mathrm{v}^2 \Rightarrow \mathrm{v}^2 \sim \frac{P_{drive}}{\rho}\frac{R}{\delta R}$$



Providing symmetric pressure drive and mitigating instabilities are a major challenge

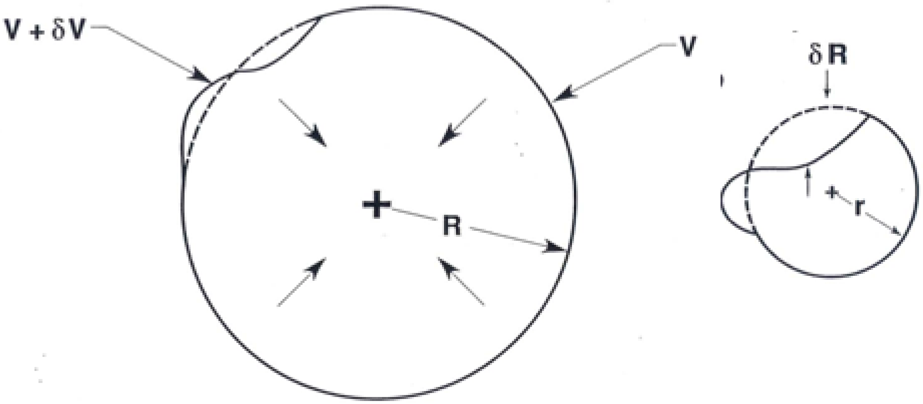


If shell is too thin, or instability growth too large, the thin shell could be ripped up by Rayleigh-Taylor instabilities

Smooth surfaces and designs optimized for stability help mitigate this risk

Large densities at stagnation are needed to obtain sufficient confinement for burn

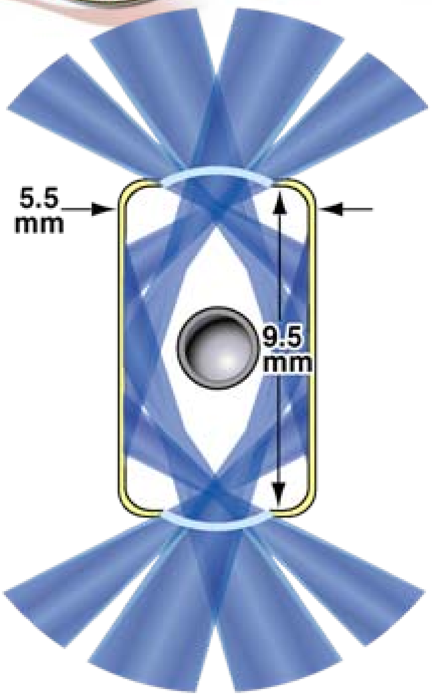
$$\rho \sim 100-1500\,\frac{g}{cm^3} \Rightarrow \frac{R_0}{R_{stagnation}} \sim 20-40!$$



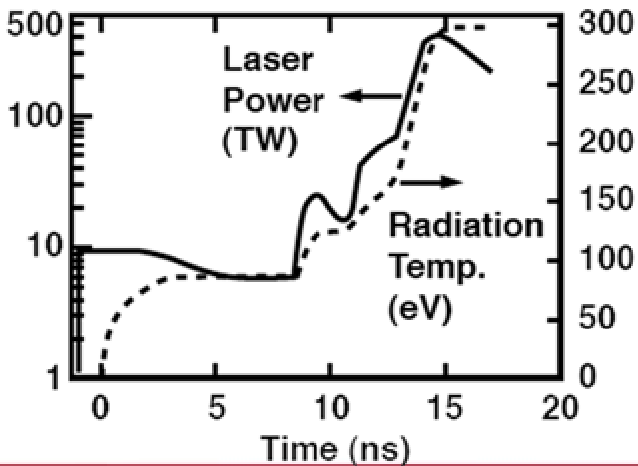
This compression is like squeezing a basketball into the size of a pea

Since non uniformities grow as capsule implodes very stringent requirements on illumination uniformity are needed

The approach to ignition will be guided by simulations, and the precision data gathered will enable an increased understanding of multiple physics issues



Typical Pulse Shape

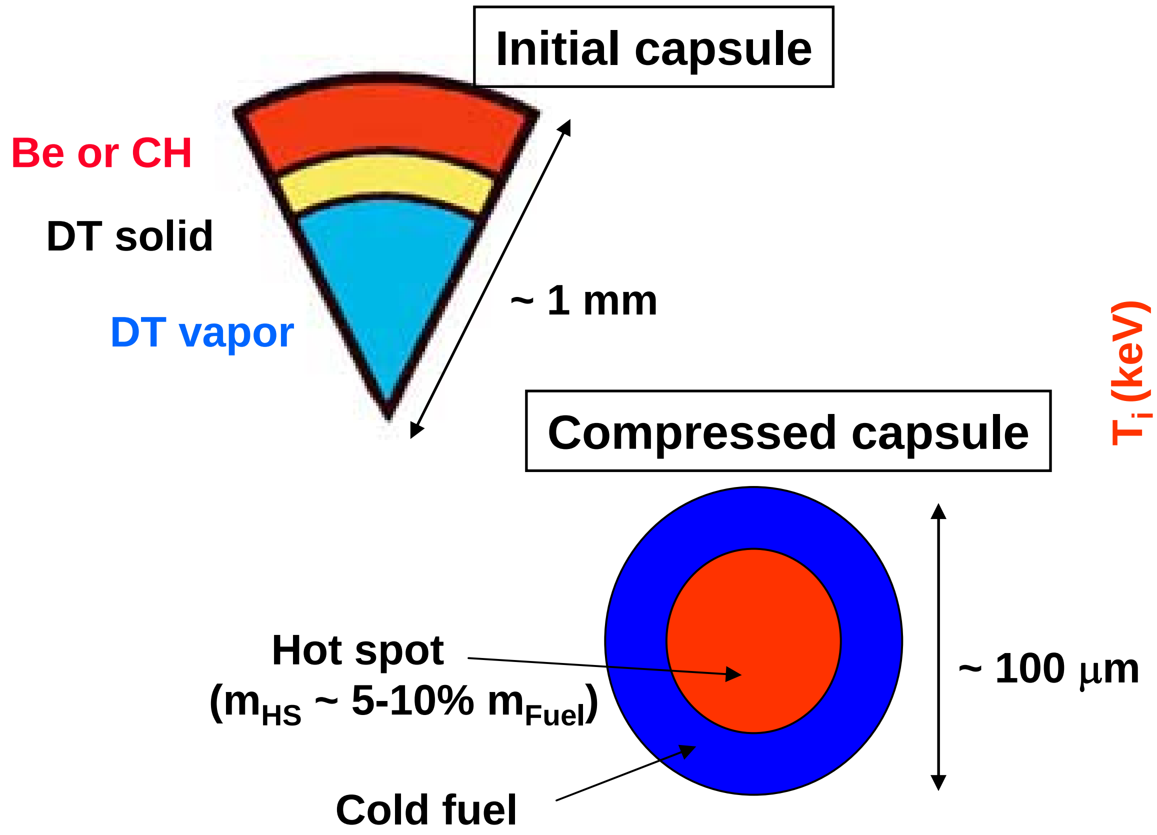


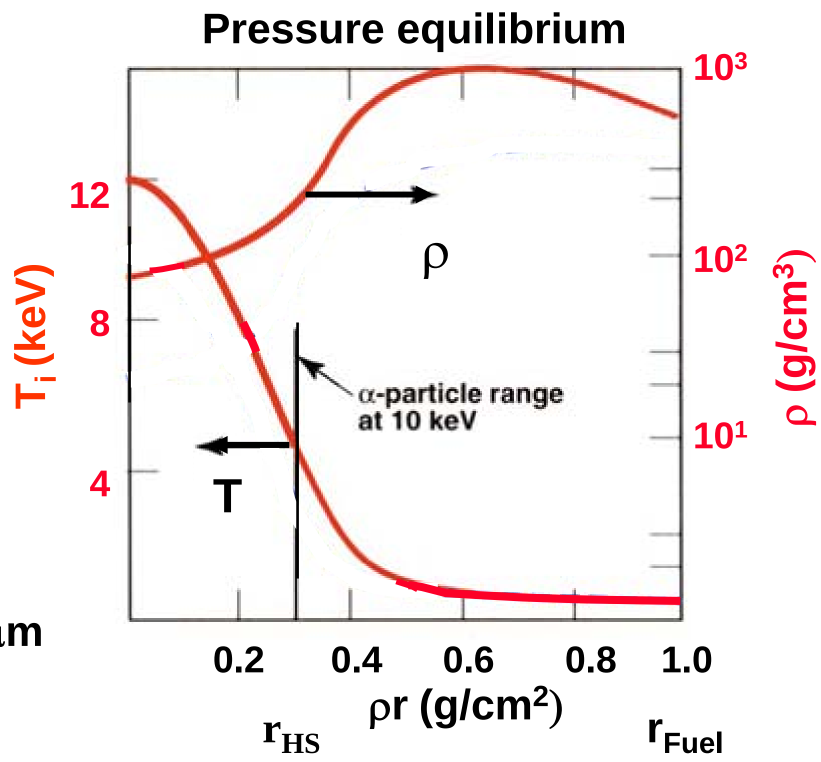
- **Measurements during the ignition campaign**
  - **Laser Plasma Interaction - A few % in photon scattering**
  - **Hohlraum energetics- A few % in radiation flux**
  - **Capsule absorption - ~1 % in ablator mass remaining**
  - **Implosion Symmetry- ~ <1% uniformity of radiation flux**
  - **Pulse Shaping - ~50 ps shock timing**

- **Integrated nature of experiments may make isolation of critical phenomena a challenge**

The hot spot ignition concept is the baseline for the National Ignition Campaign plan

Challenge for hot spot ignition: use a single hydrodynamic system to assemble DT into two distinct regions





$Q_{\text{Cold fuel}}$ ~ 33 MJ/g << $Q_{\text{Hot spot}}$ ~ 1200 MJ/g

A strength of Inertial Fusion is the driver modularity and flexibility in coupling energy to the fusion target

Driver Technology

- Lasers
- Pulsed Power
- Ion accelerators

→

Coupling Mechanism

- Laser photons
- X-rays
- Particles
- Magnetic fields

→

Fusion fuel ignition mechanism

- Hot spot ignition
- Fast ignition
- Shock ignition
- Volume ignition
- Magnetized fuel

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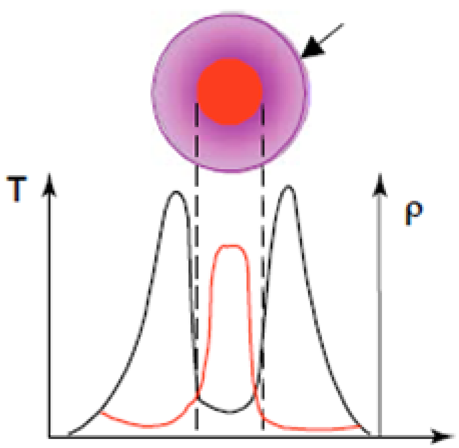
Fast Ignition is an approach to ICF which decouples compression from ignition

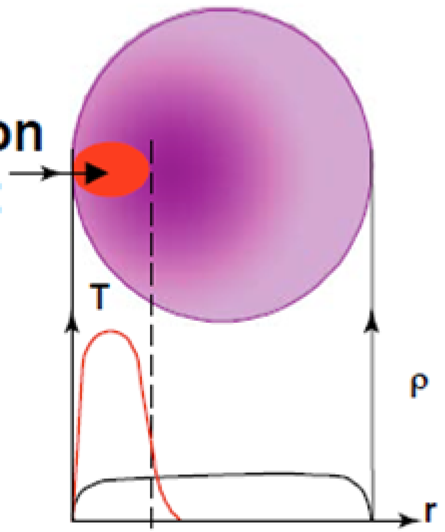
Hot Spot ICF

($I \sim 10^{15}$ w/cm^2)
(1-10 ns pulse)



Fast Ignition

Fast injection of heat ($I \sim 10^{20}$ w/cm^2) (~10ps pulse)

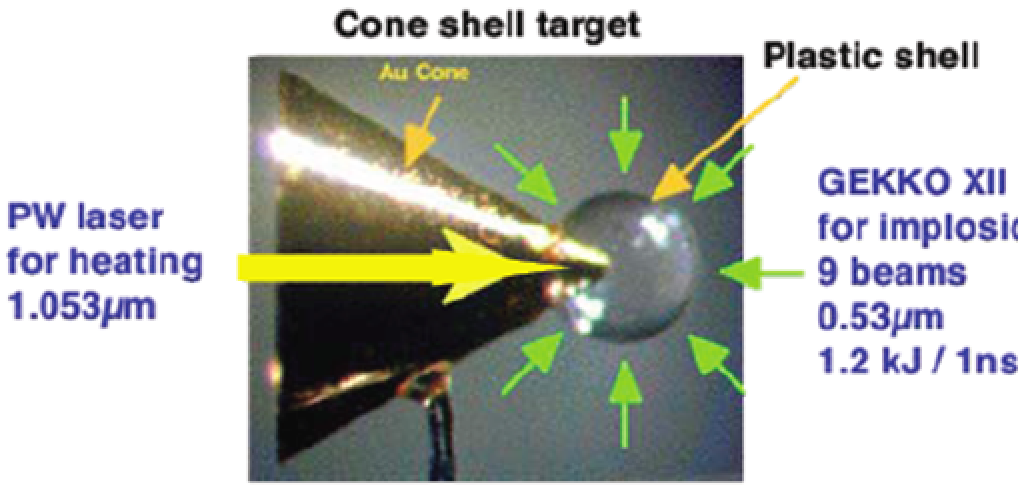


- Central hot spot ignition relies on precise control of implosion symmetry and hydrodynamic instability
- Fast ignition will require significant advances in the understanding of charged particle production and transport at ultra-high intensity

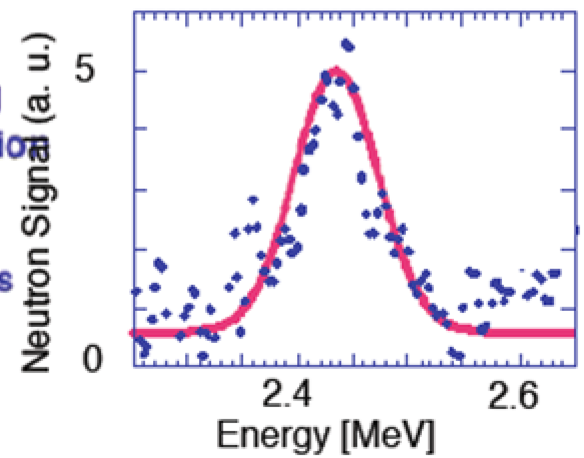
A New Invention in Laser Fusion

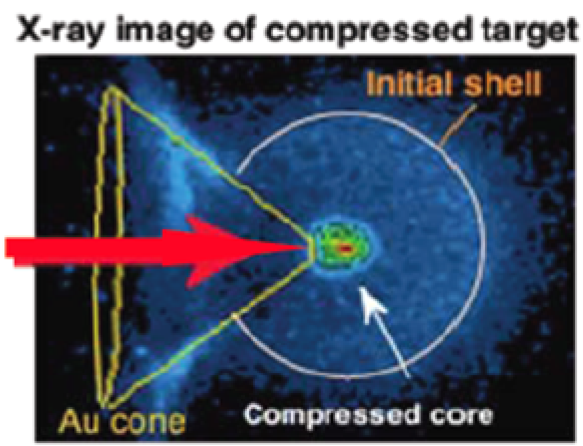
Fast ignition with Cone Target (ILE-RAL Collaboration)

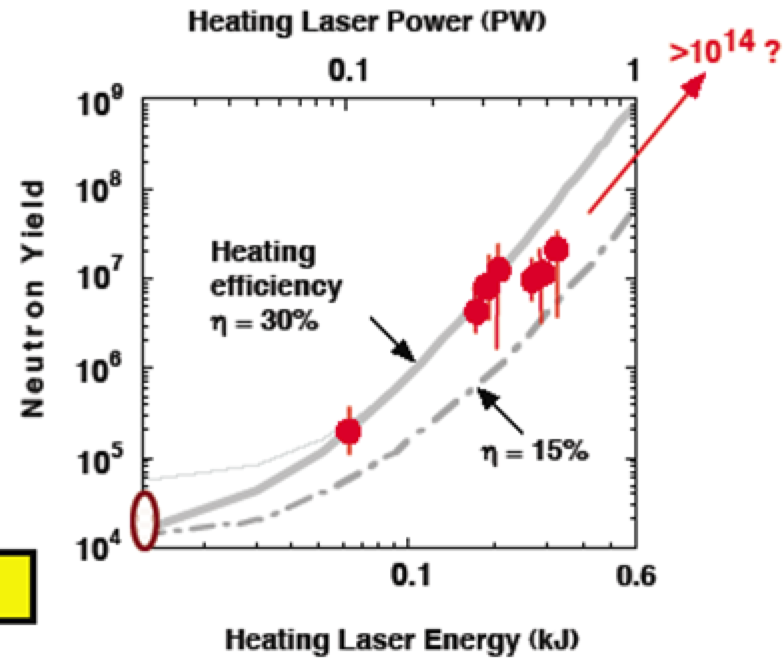
ILE OSAKA



Neutron spectrum
Ti ≈ 0.8-1 keV







R. Kodama, et al., Nature 2001, 2002

Efficient heating with $\eta \sim 0.2$ demonstrated.

Success in laboratory fusion requires simulations, drivers, diagnostics, and targets

Simulations ⟷ Experiments

Simulations

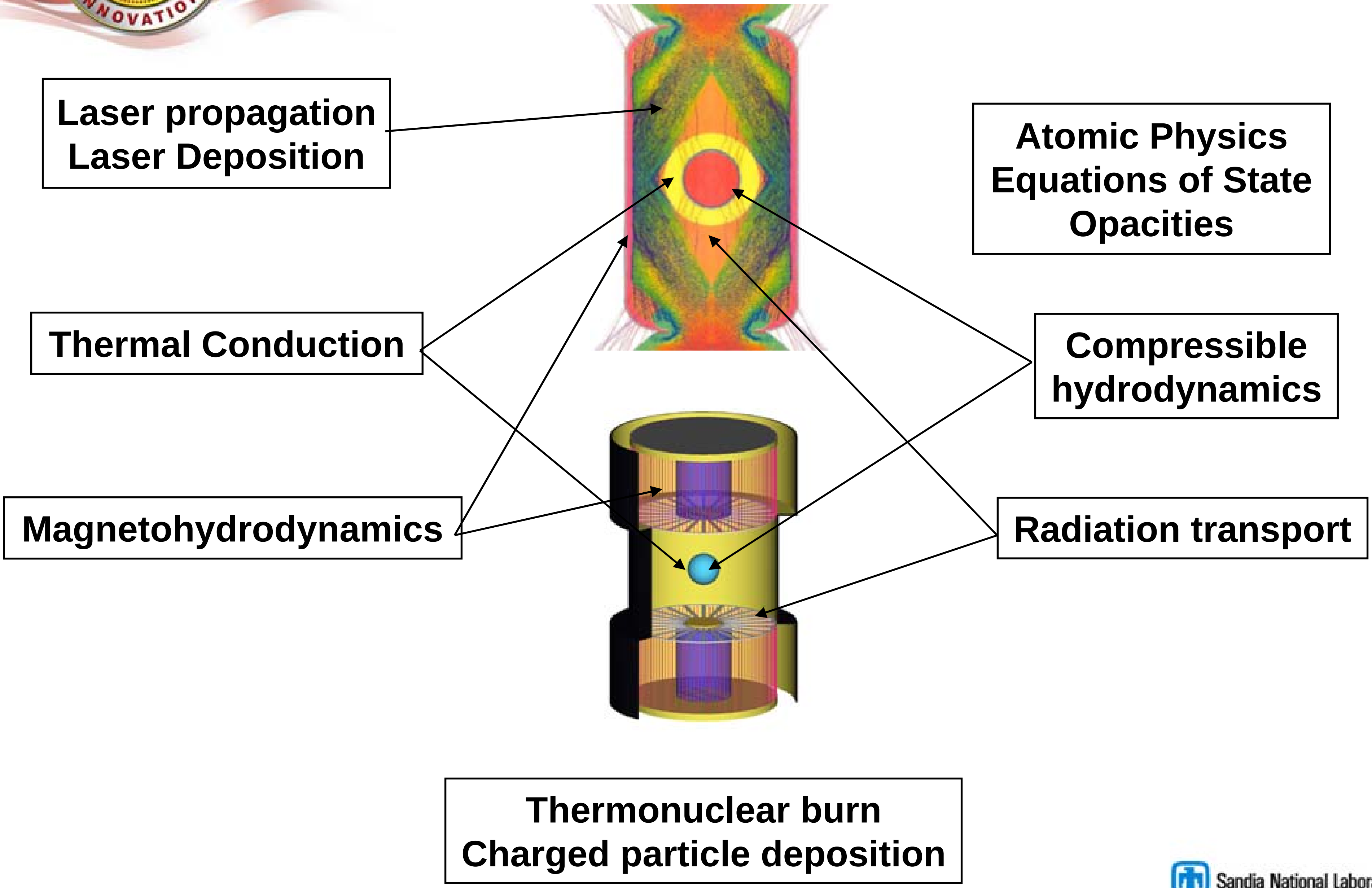
- Multi-physics
- 3-D
- Use best available computing capability

Experiments

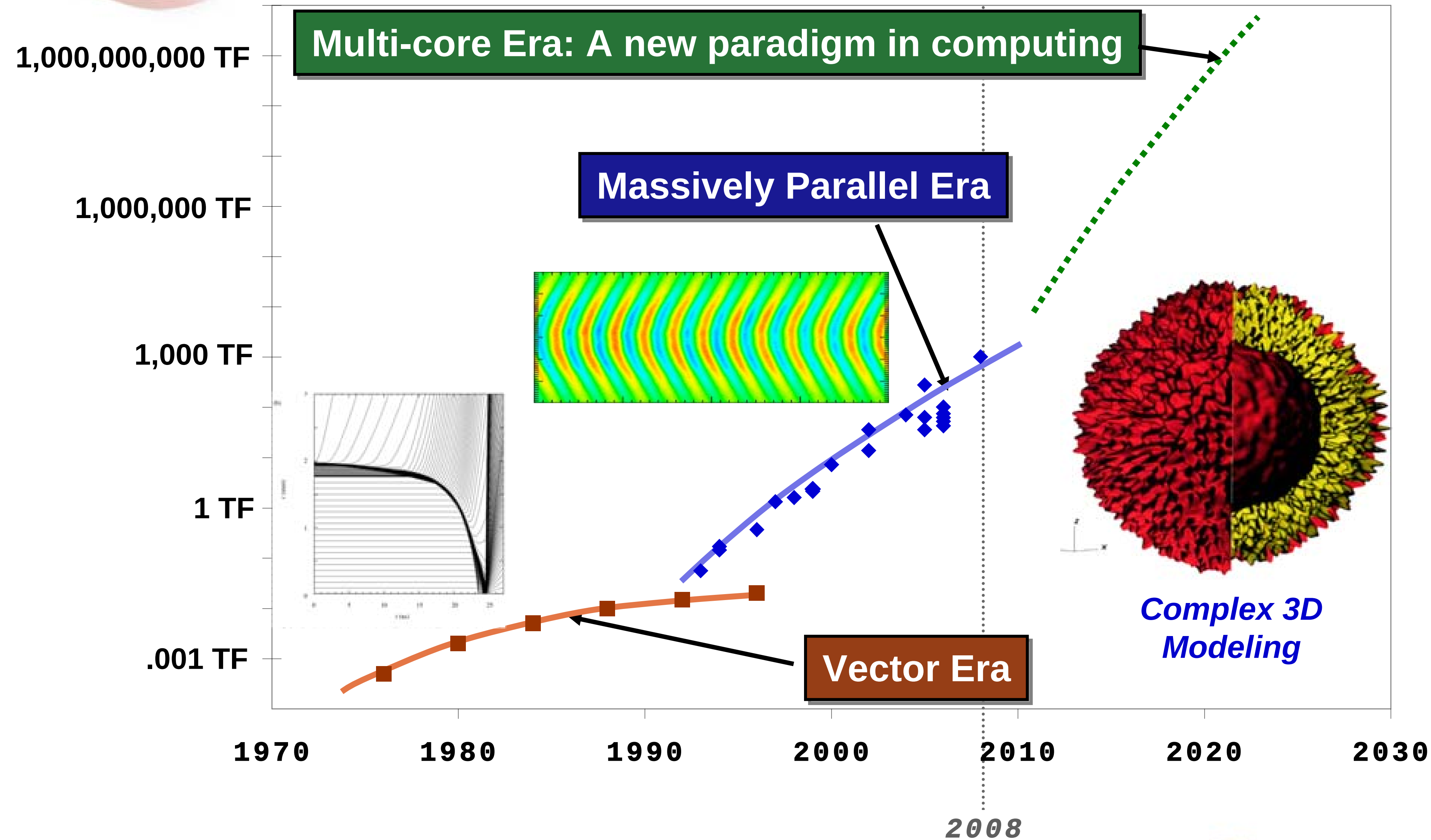
- Targets (precise to ~10 nm)
- Drivers
  - Energy to target is >MJ
  - Precise timing
- Diagnostics (psec, μm, 10s of keV)

Advances in each area have increased the rate of progress; we expect this rate of progress to increase in the future

Multiphysics computational tools are indispensable aids in studying the science of ICF

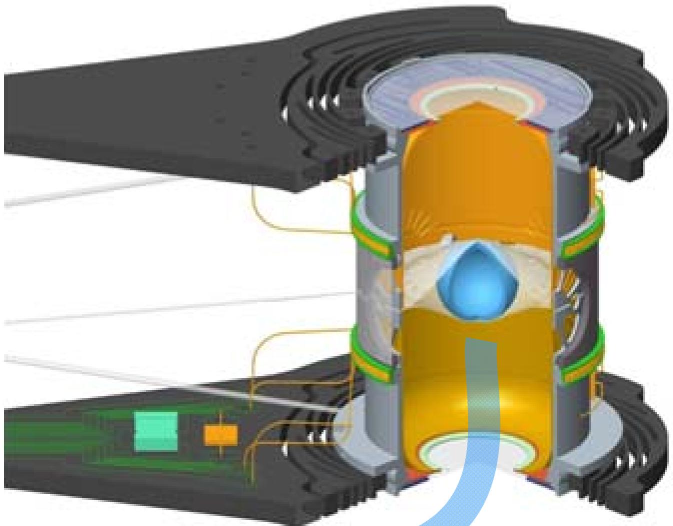


Computing capability has increased by 10^{15} since its inception

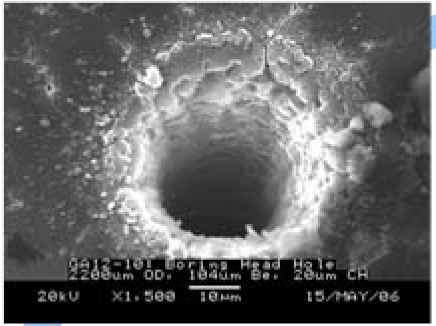


ICF targets: 3D mesoscale objects with nanofabrication tolerances comprised of exotic materials made at cryogenic temperatures

Concept



Drilling



10 µm

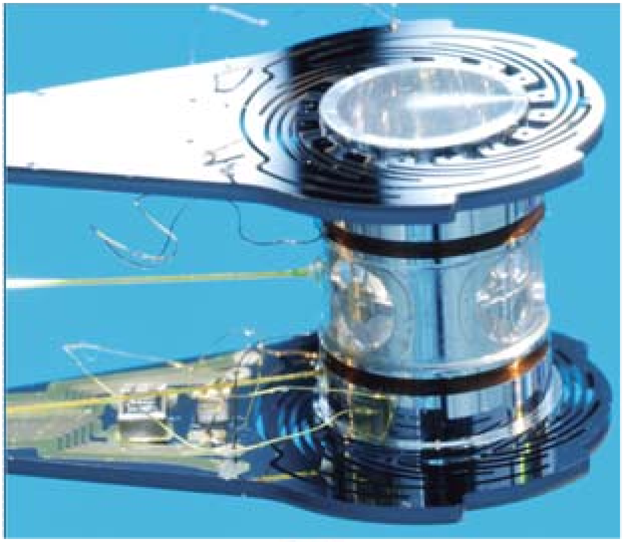
Fill tube

Coating

Polishing

<10 nm finish

Target



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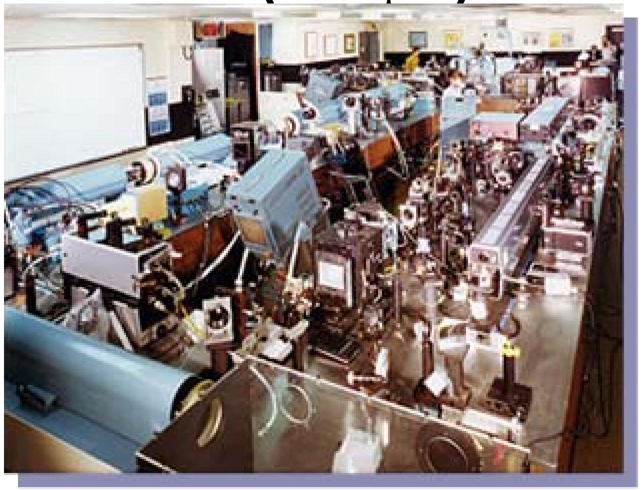
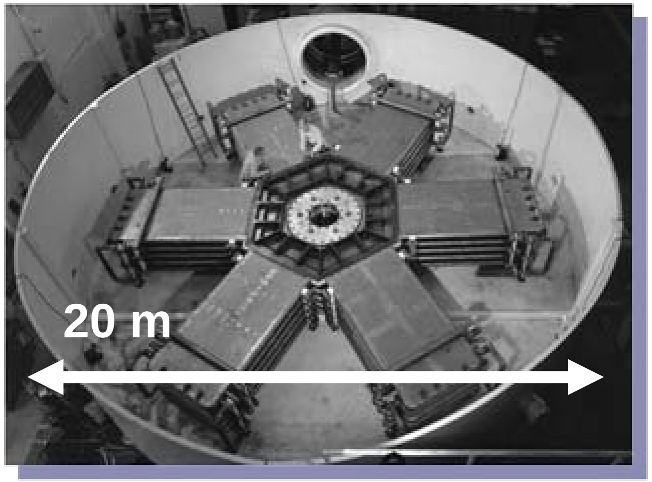
Over the past 40 years, driver energy has increased from Joules to MegaJoules

Janus 1974
20 J (1.06 μm)

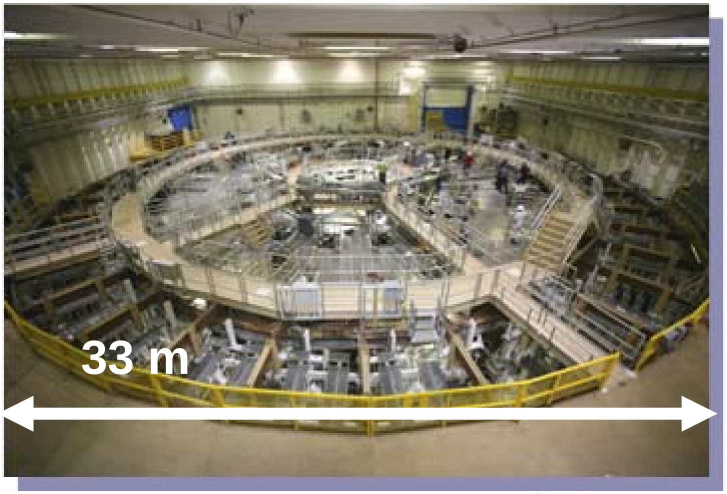


NIF 2009
1.8 MJ (.35 μm)

Proto I 1974
12 kJ



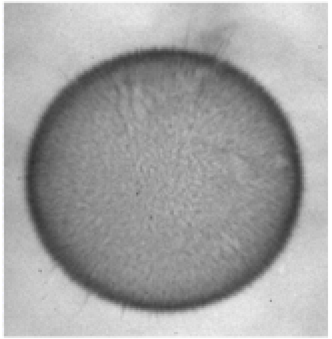
Refurbished Z 2007
3 MJ



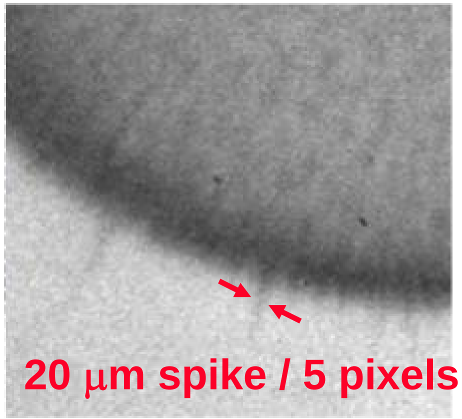
Diagnostics capabilities have evolved to meet the space, time, and frequency resolution requirements

Recall: psec, μm, keV

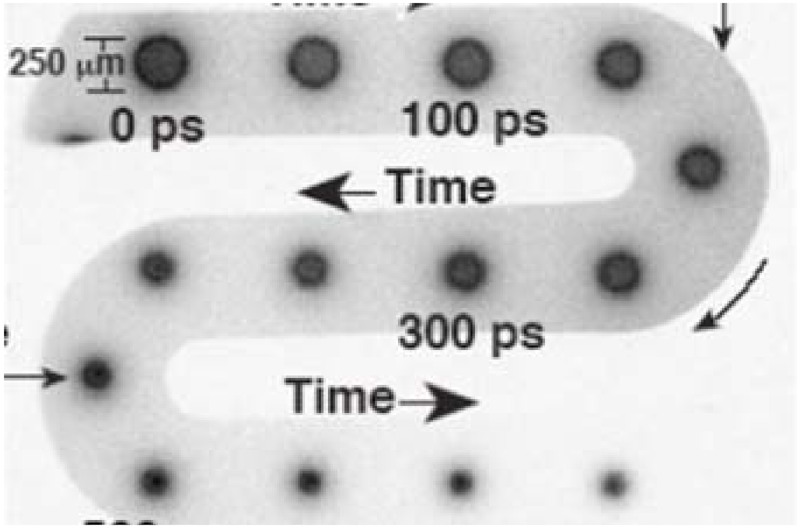
X-ray radiograph of a capsule implosion on the Z facility with 1 nsec, 10 μm resolution



~ 1 mm



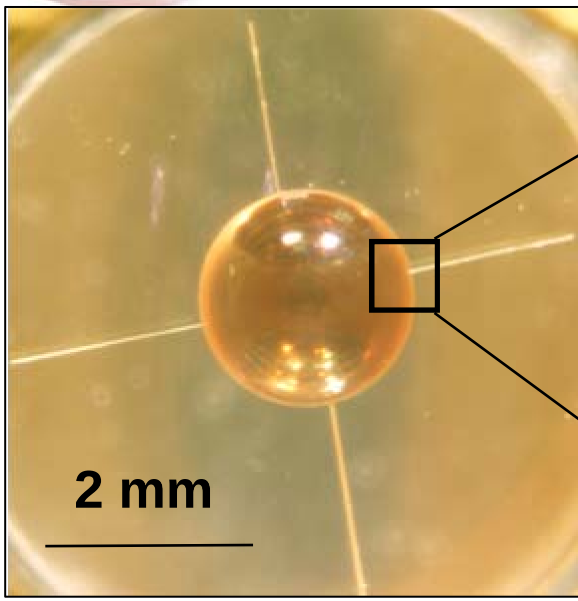
Fourteen frame sequence of images of an imploding capsule recorded in 700 psec on the Omega facility

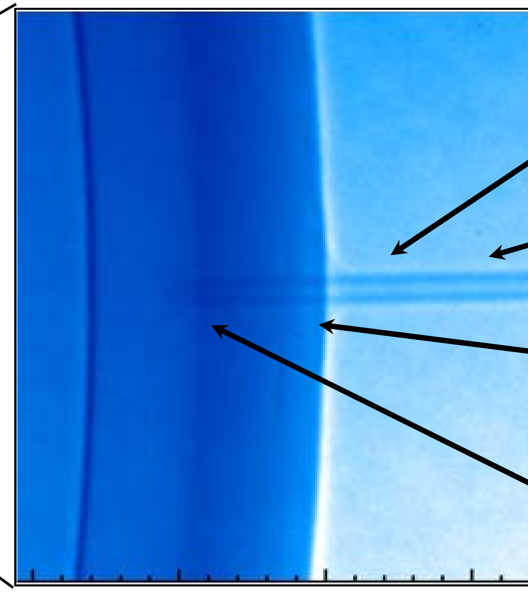


OMEGA scale ~ .25 mm

Diagnostic images are on the same spatial scale

Recent Z experiments tested our ability to predict the perturbations arising from fill tubes





Optical image of CH capsule with 4 fill tubes (12- 45 micron OD) attached around an equator

High resolution Xradia image of as built configuration gives important details for simulation

Simulations using ASC Purple led to specification for targets.
High quality, well characterized targets were rapidly developed and fielded.

GENERAL ATOMICS
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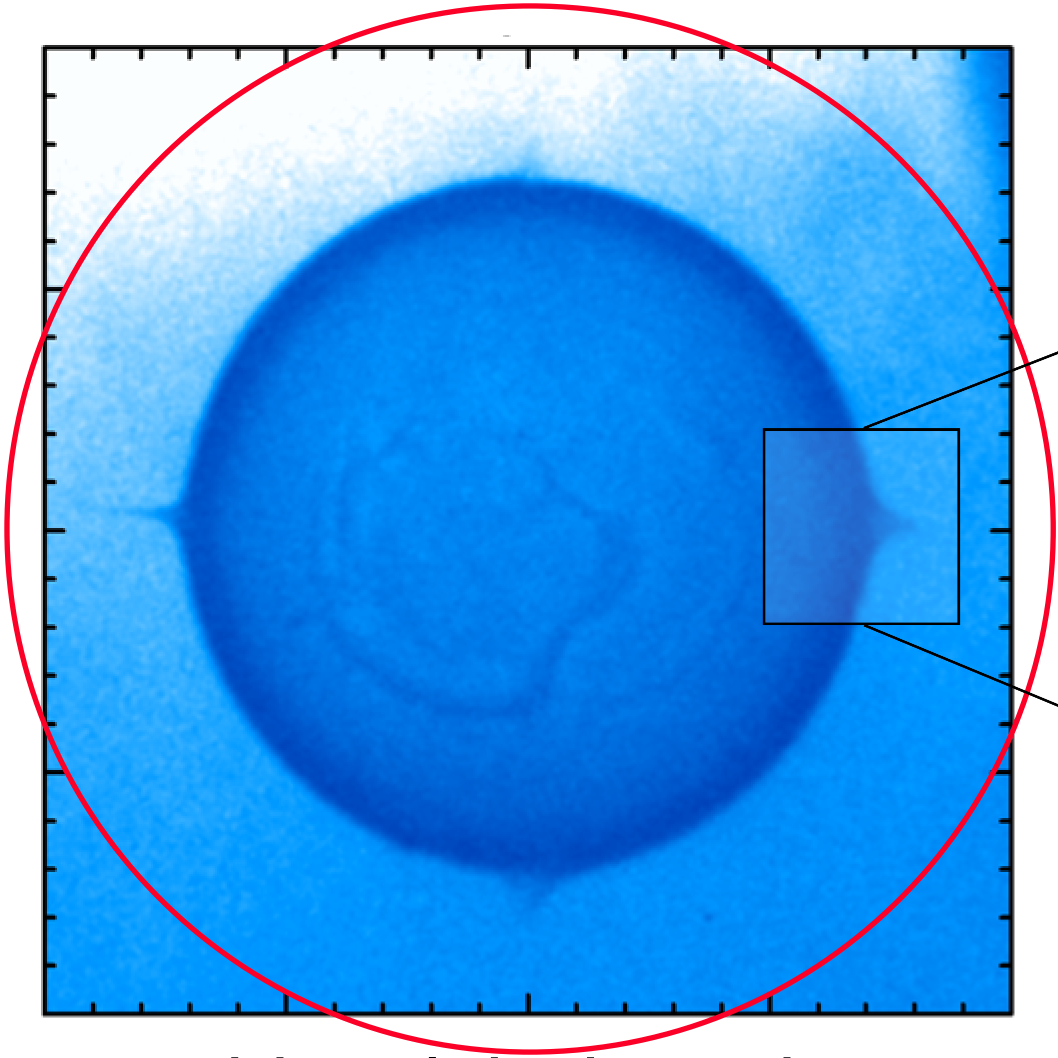
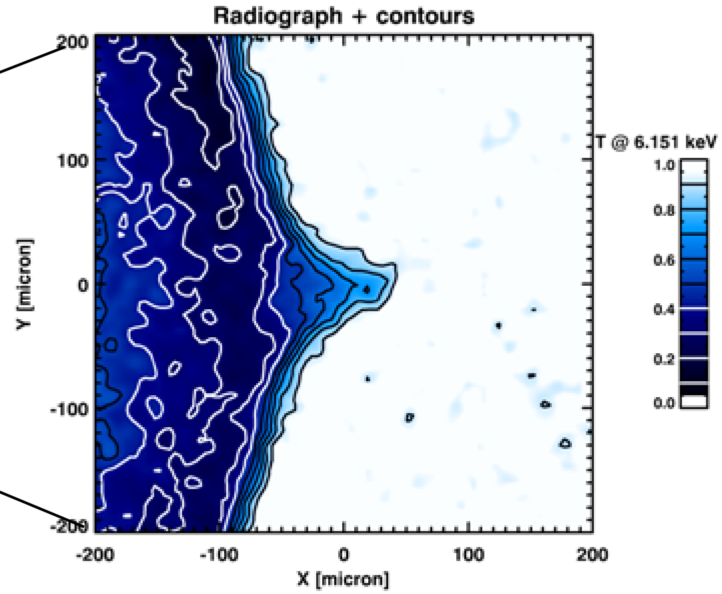
High resolution images of the imploding capsule enables detailed, quantitative comparison with simulation

Initial Capsule Position





High resolution (~ 20 μm) monochromatic x-ray images

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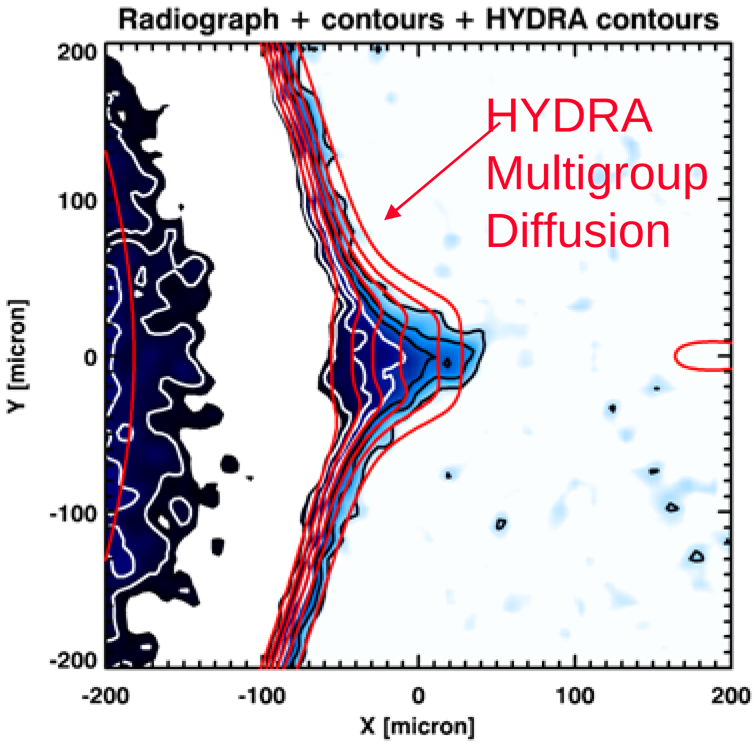
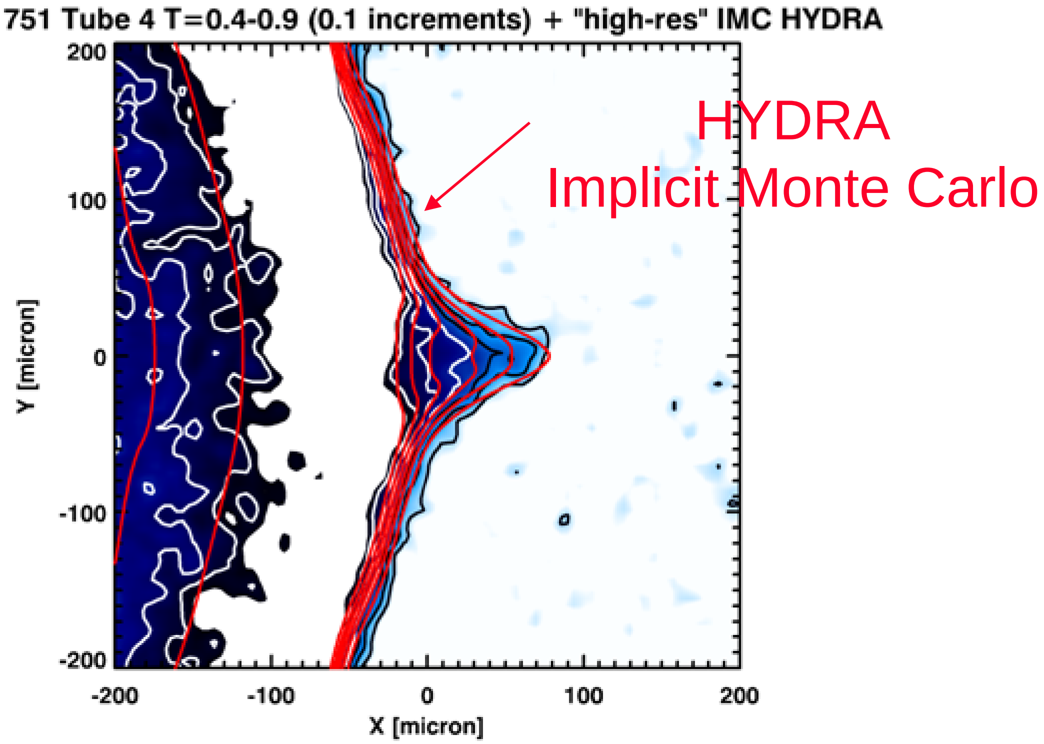
Excellent comparisons with simulations increase confidence in our simulation capability

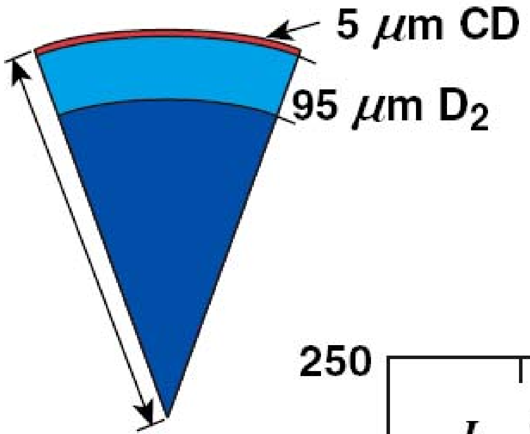


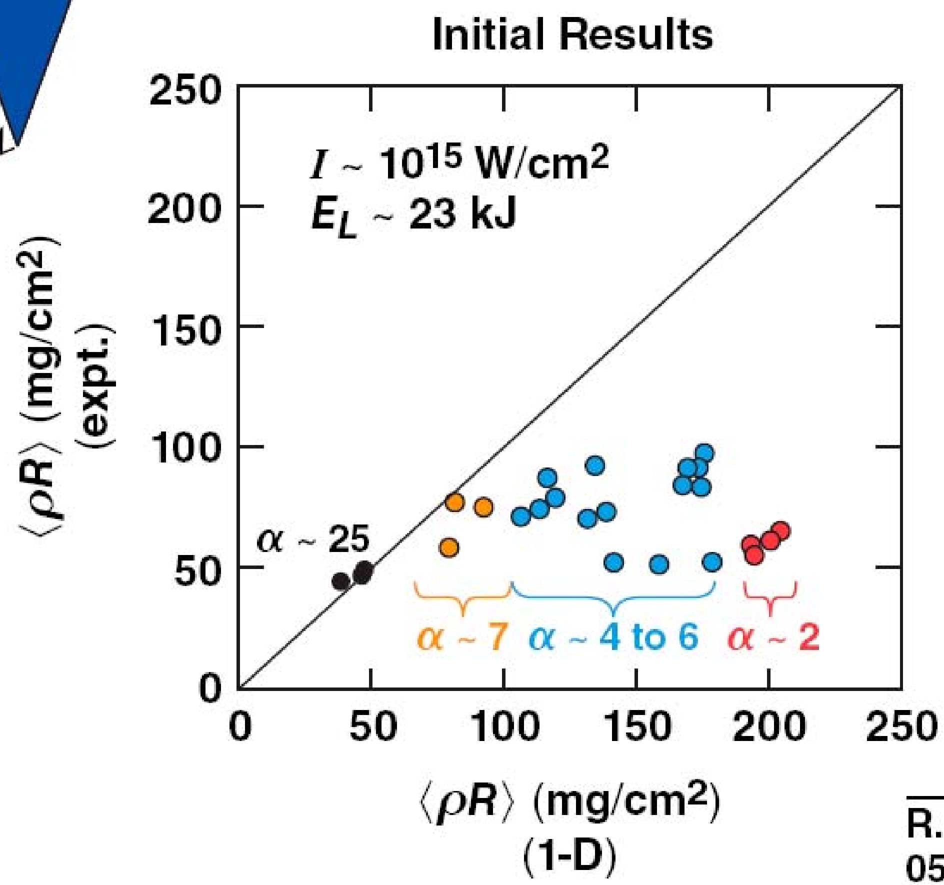


G.R. Bennett, et al., PRL, (2007)

Tuning of high-performance cryogenic target implosions requires detailed analysis of key physics processes

UR LLE





Physics issues:

- laser coupling and drive
- thermal transport
- shock timing
- shell condition (adiabat)
- sampling timing (burn history)

Well-characterized diagnostics are necessary to validate the models used to design targets for ignition.

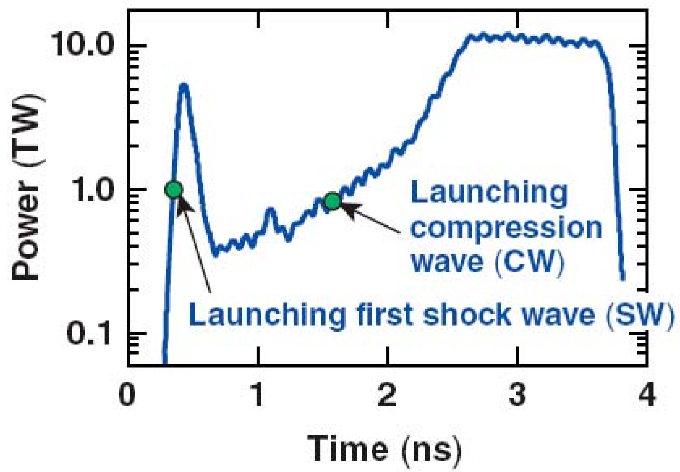
R. L. McCrory *et al*., Phys. Plasmas 15, 055503 (2008).

TC7833d

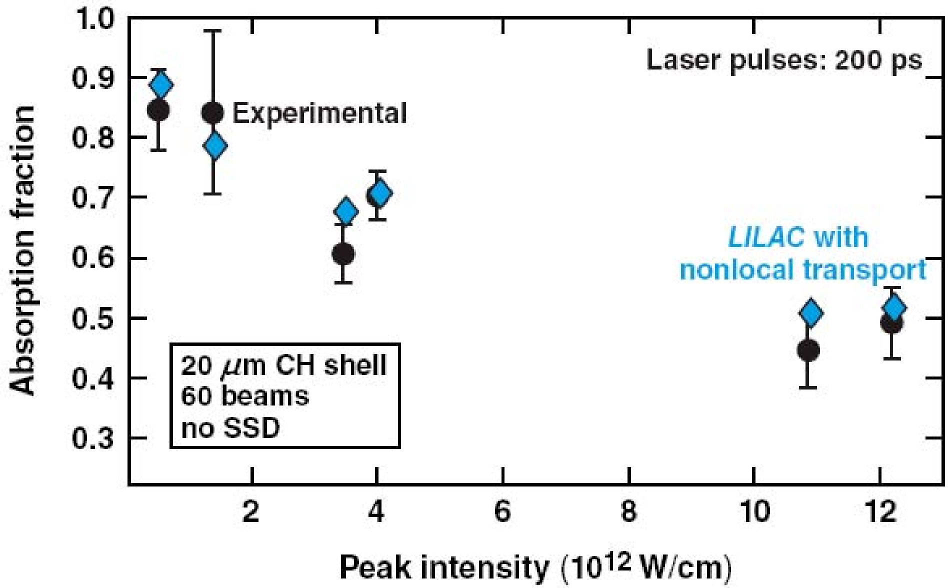
Accurate modeling of laser coupling is required to set the initial shell conditions

UR LLE

Timing of hydrodynamic waves



Scattered light measurements



$$\frac{\Delta t_{shock}}{t_{shock}} < 5\%, \; t_{shock} \sim E_p^{-1/2} \Rightarrow \boxed{\frac{\Delta E_p}{E_p} < 10\%}$$

Precise modeling of initial absorption is essential for setting up low-adiabat-implosion experiments.

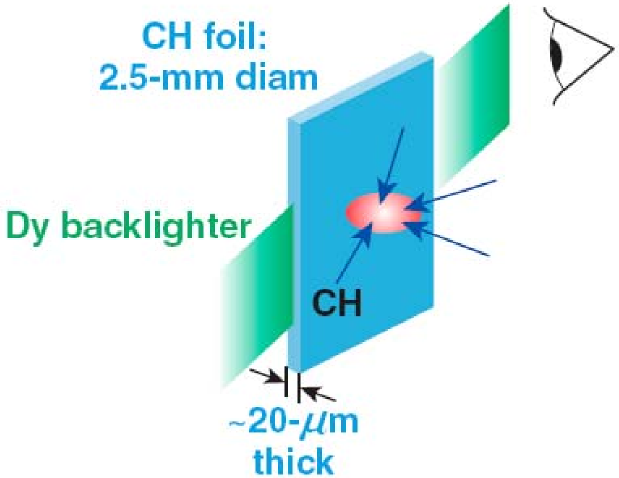
V. N. Goncharov *et al.*, Phys. Plasmas 15, 056310 (2008).

W. Seka *et al.*, Phys. Plasmas 15, 056312 (2008).

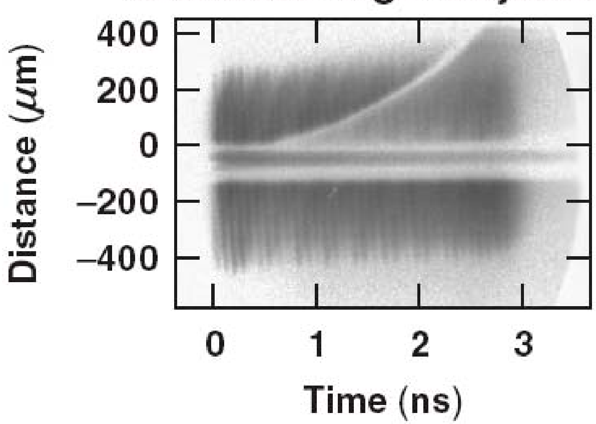
TC8390

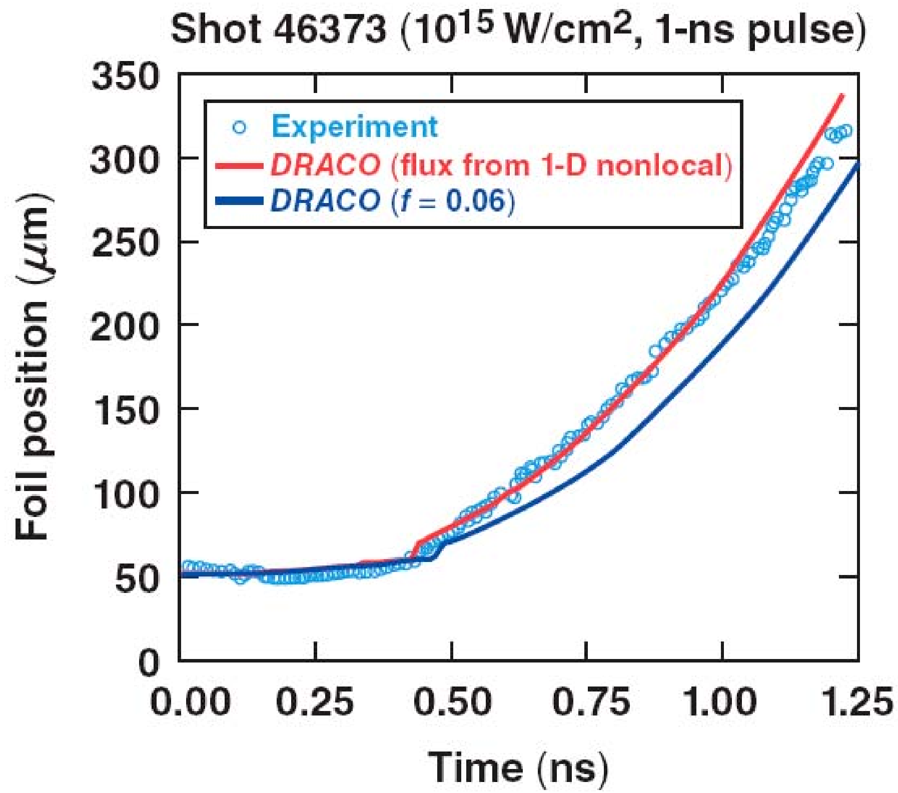
Foil trajectory measurements determine the accuracy of thermal transport modeling[1]

Experimental setup



Measured target trajectory[2]



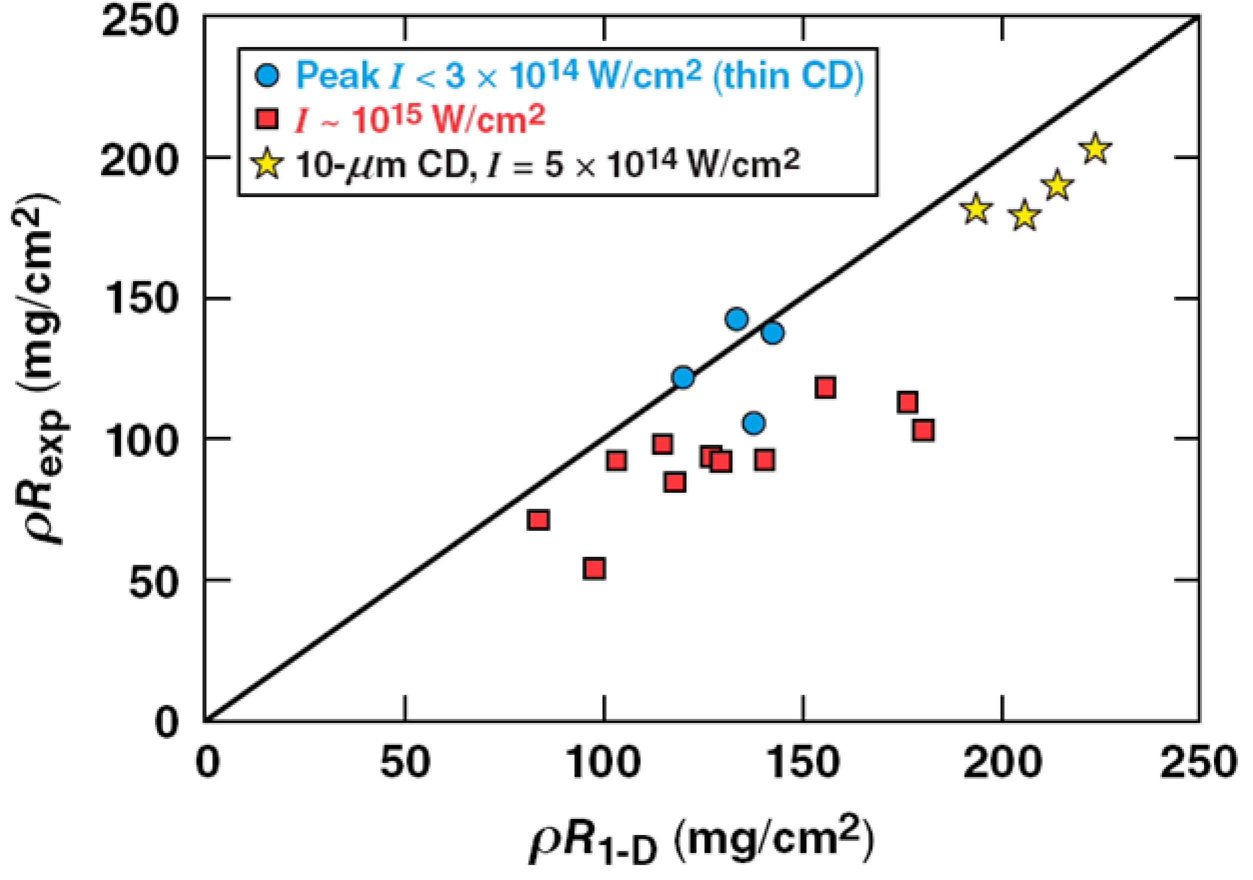


[1]S. Hu *et al*., Phys. Rev. Lett. 101, 055002 (2008).
[2]V. Smalyuk *et al*., presented at the 37th Anamolous Absorption Conference, Maui, HI, 27–31 August 2007

TC7940a

High fuel areal densities were achieved after tuning the design models with experimental data

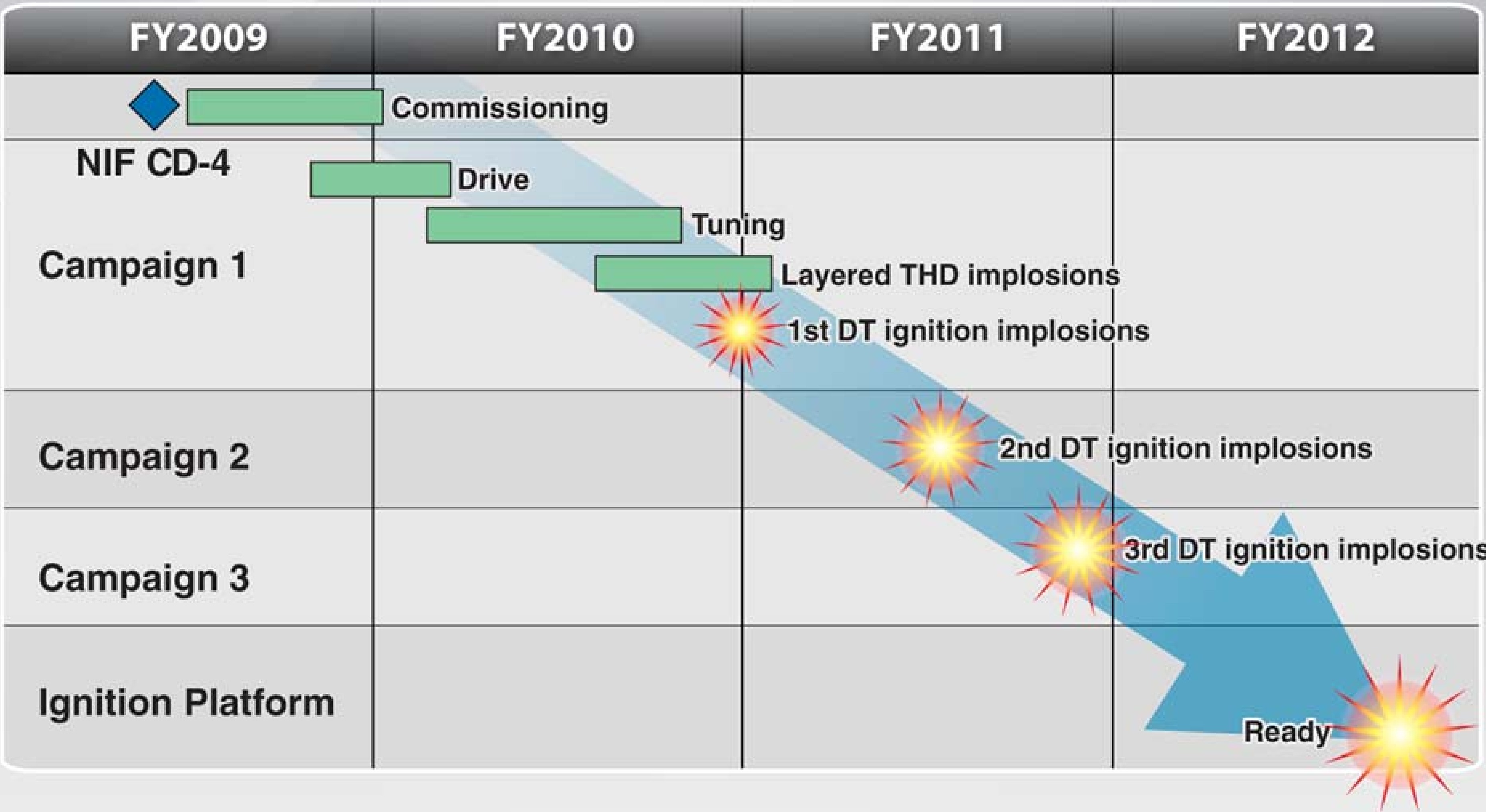
All simulations use nonlocal thermal-transport model



R. L. McCrory *et al*., Phys. Plasmas 15, 055503 (2008).

TC8037k

NIF will execute four major ignition campaigns in the next four years

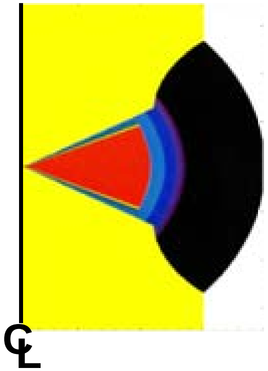


Fusion ignition will be the beginning of a new era of innovation and progress

National Ignition Facility

- **1950-2010**
  - The Physics of Plasmas
- **2010 and beyond**
  - The Physics of Fusion
  - Fusion ignition and propagating burn
  - Innovative target concepts that improve efficiency, gain, and yield
  - Advanced drivers for efficient, repetitive pulsing
  - Fusion-Fission hybrids on the path to pure fusion energy
  - The Engineering and Materials Science of Fusion (“Demo 1”)
  - Fusion Reactor Development (“Demo 2”) and fielding

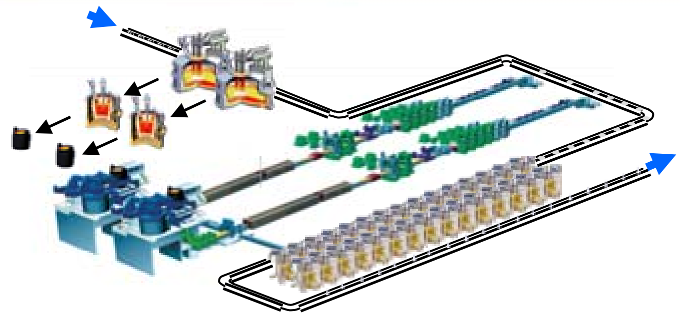
LTD cavity
(70% efficient)



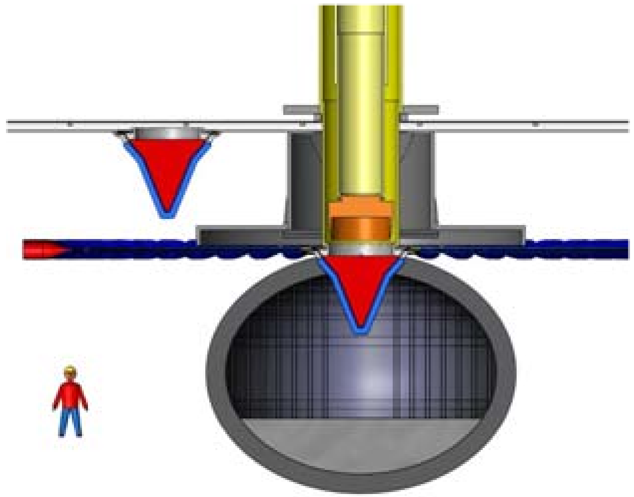
Magnetically driven fusion target
(>x10 increase in coupling energy to fuel)

Sandia National Laboratories

A conceptual IFE power plant design has five major elements



- **Consumables factory**
  - **Reduce cost**
- **Driver**
  - **Increase driver efficiency, η_D**
  - **Reliable, repetitive pulsing**
  - **Coupling driver energy to the target**
- **Target**
  - **Increase gain, G**
  - **Increase efficiency of coupling energy to the fuel, η_T**
- **Fusion Chamber/Blanket**
  - **Target wall materials**
  - **Fusion-Fission hybrid**
    - » **Multiplies yield, M**
    - » **Reduces fusion power requirements**
- **Power Conversion System**



$$\eta_D MG >> 10$$

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Summary

- The National Ignition Facility (NIF) laser system is poised to achieve ignition in the next few years
- Inertial Confinement Fusion (ICF) has several positive features
  - Strong computational background; collisional plasmas greatly simplify modeling
  - Modularity of the driver technology
  - Flexibility to couple energy in many different forms to fusion targets
- After ignition is experimentally achieved:
  - Innovative new concepts will lead to revolutionary advances in fusion gain and yield
    - » Fusion target concepts and configurations
    - » Advanced drivers and reductions in efficiency/size/cost
- These advances will enable development of a pilot fusion power plant
  - Grand Challenge: practical power plants that generate low-cost, clean, inexhaustible fusion energy
- Drivers for inertial fusion enable new regimes of high-energy-density physics
  - XR0.00002 Perspectives on High-Energy-Density Physics , R. Paul Drake