UCRL-PRES-207384

ICF basics, NIF and IFE

Mark C. Herrmann

Lawrence Livermore National Laboratory

Special Thanks to Mordy Rosen, whose lecture notes helped form the basis of this presentation

Thanks to Bruce Hammel, John Lindl, and Ed Moses for viewgraphs

This work was performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

UCRL-PRES-207384

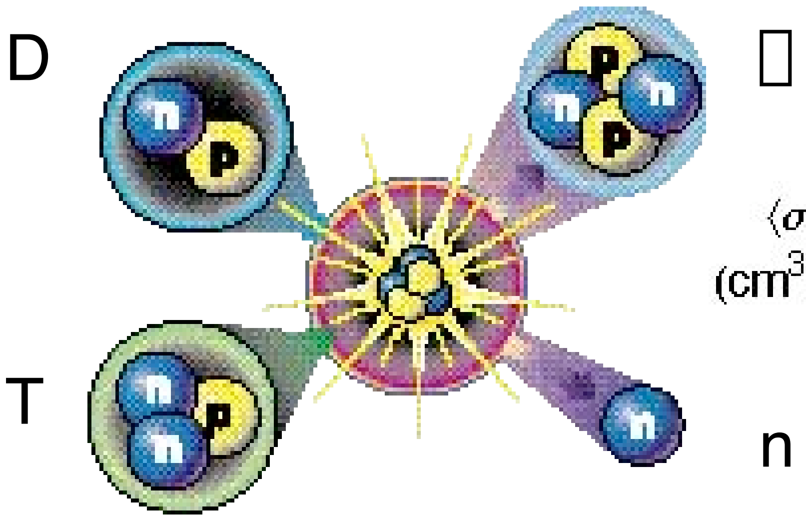
Definitions

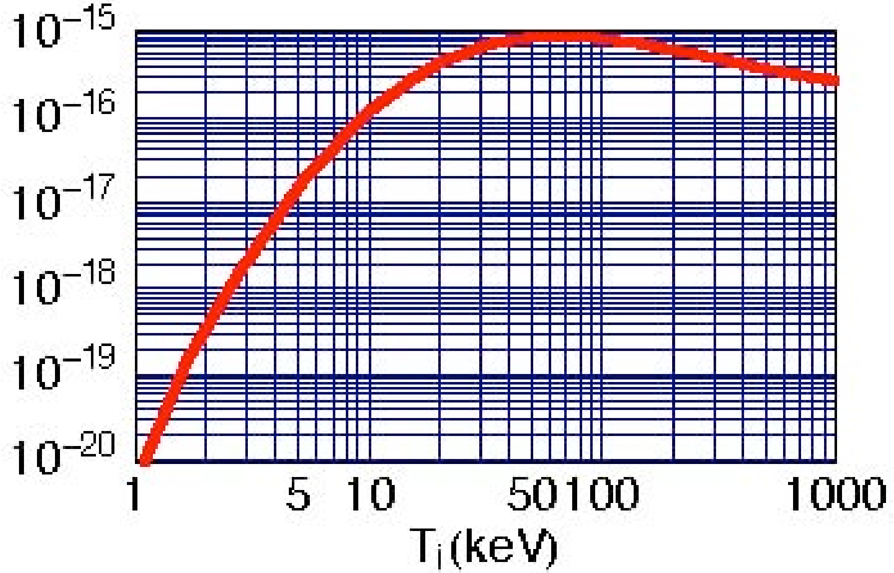
- **IFE=Inertial Fusion Energy**
- **ICF=Inertial Confinement Fusion**
- **Inertial "Confinement" is hardly confinement at all! Having "inertial" mass, means, that for a given achievable force, that there will be a finite time that it takes to move away a certain distance, and disassemble:**
  - F=ma

$$d = \frac{1}{2} a t^2 = \frac{1}{2}\frac{F}{m} t^2 \square \quad t_c = \sqrt{\frac{2dm}{F}} \sim \sqrt{\frac{R\left(\square R^3\right)}{(\square T)R^2}} \sim \frac{R}{\sqrt{T}}$$

- **Other confinement:**
- **gravity/stars (pressure force balanced by g)**
- **Magnetic (pressure force balanced by B^2)**
- **NIF= National Ignition Facility**

Coulomb barrier makes high temperatures necessary for DT thermonuclear fusion





$$D + T \,\square\, \square + n$$

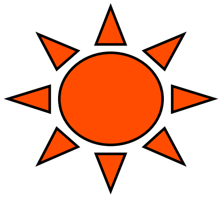
3.5 MeV 14.1 MeV

Neutral, escapes without depositing energy

Charged particle deposits energy locally

$$\boxed{Q_{Fusion} = 3.3 \cdot 10^{11} J / g}$$

What conditions are necessary for significant burn up of the DT?



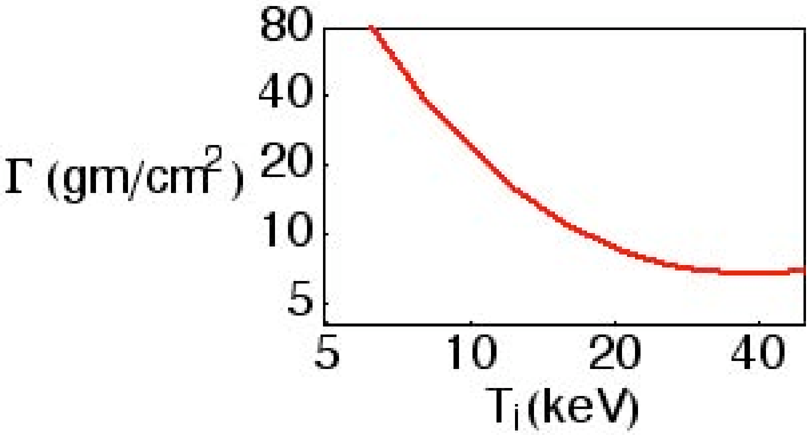
For inertial confinement: $\tau_{conf} \sim \frac{R}{c_s}$

The time scale for burn is: $\tau_{burn} \sim \frac{1}{n_i\langle\sigma v\rangle} \sim \frac{1}{\rho\langle\sigma v\rangle}$

$$f_{burn} \sim \frac{\tau_{conf}}{\tau_{burn}} \sim \rho R \frac{\langle\sigma v\rangle}{\mathrm{c_s}}(T_i)$$

This breaks when $\tau_{conf} > \tau_{burn}$ including effects of burn depletion:

$$f_{burn} = \frac{\rho R}{\rho R + \Gamma(T_i)(\mathrm{gm/cm^2})}$$



Thus ICF conditions ~ $\rho R \approx 1 g/cm^2$

$T \approx 10\ keV$

Tremendous pressures are needed to access this regime at reasonable energy

$$P(\mathrm{Bar}) = 8 * 10^{8}\, \rho(\mathrm{gm/cm}^{3})\, T_i(\mathrm{keV})$$

For ICF conditions: $\rho R \approx 1 g/cm^{2}$ $\quad PR \sim 10^{10}\mathrm{B} \cdot \mathrm{cm}$

$T \approx 10\ keV$

$$\mathrm{E} \sim PV \sim 10^{9} R(cm)^{2} (\mathrm{J})!$$

$$\mathrm{E} < 100\,\mathrm{kJ} \Rightarrow R \sim 100\,\mu\mathrm{m} \quad P \sim 1\,\mathrm{TB} \quad \rho \sim 100\ \mathrm{gm/cm}^{3}$$

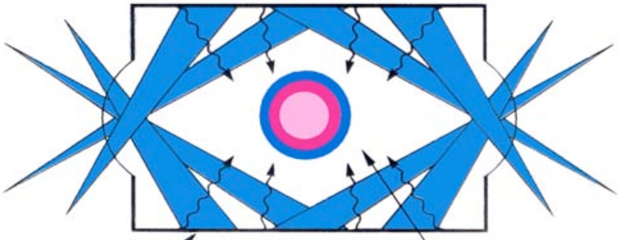
$$\tau_{conf} \sim \frac{R}{c_s} \sim 100\, ps \qquad \mathrm{Power} \sim \frac{E}{\tau} \sim 1 PW$$

How are such high pressures and high densities achieved?

Carefully tuned spherical implosions

There are two principal approaches to compression in Inertial Confinement Fusion

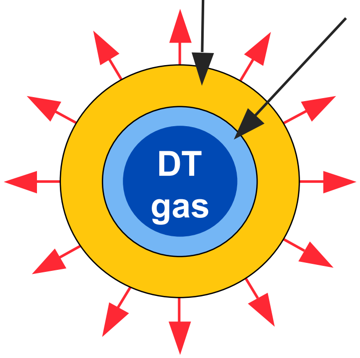
Indirect Drive



Lasers, Ion beams or Z pinches used to heat up a miniature oven called a hohlraum and bathes capsule in x-rays.

Direct Drive

Lasers directly shined on capsule

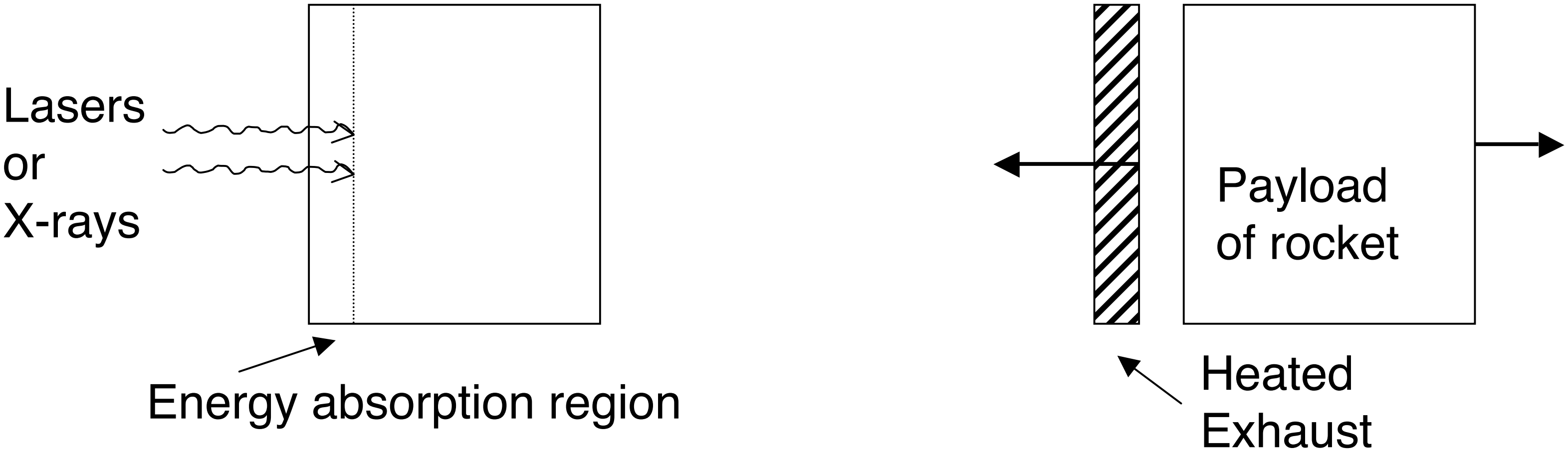


Low-z Ablator for Efficient absorption

Cryogenic Fuel for Efficient compression

Both schemes rely on spherical ablation with pulse shaping results in a rocket-like implosion of near Fermi-degenerate fuel

We generate pressure by ablation



- **Acceleration comes from particle momentum (classic rocket).**
- **Irradiance (W/cm² = J/cm³ * cm/sec) is balanced by outflow of heated material**

$$I_{x-ray} \approx \sigma T_r^4 \sim nT\,c_s$$

$$\Rightarrow \; P_{ablation} \sim \frac{\sigma T_r^4}{c_s} \sim T_r^{3.5}$$

$$\mathrm{T_r} \sim 300\mathrm{eV}\left(\mathrm{I_{x\text{-}ray}} \sim 8*10^{14}\mathrm{W/cm^2}\right)$$

$$P_{ablation} \sim 100\mathrm{MB}$$

$$P_{ablation} V_0 \sim P_{stag} V_{stag}$$

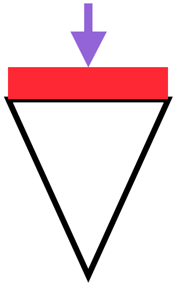
$$\frac{P_{stag}}{P_{ablation}} \sim 10^4 \Rightarrow \frac{V_0}{V_{stag}} \sim 10^4 \Rightarrow \frac{R_0}{R_{stag}} \sim 20$$

This is like taking a basketball and compressing it to the size of a pea

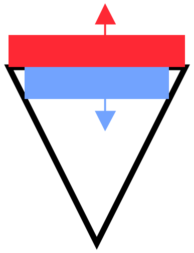
Summary of energy flow in ICF implosions

- **Driver energy E_D**

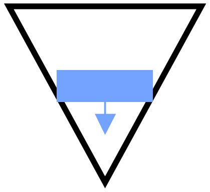
- **E_{cpl} = coupled energy.**
- **$E_{CPL} = \eta_C E_D$**



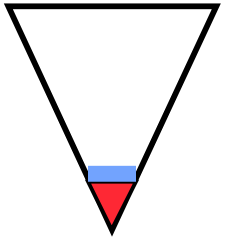
- **Thermal and**
- **kinetic energy**



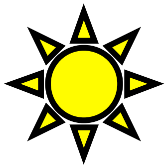
- **K.E. = $\eta_H E_{CPL}$. $E_{KE} = \eta_H \ \eta_C \ E_D$**



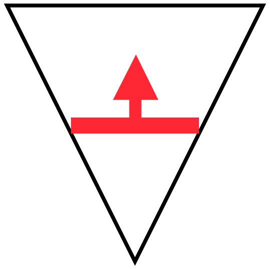
- **Assembled Thermal Energy**
- **$E_{AF} = \eta_H \ \eta_C \ E_D$**



- **Thermonuclear burn**



- **Dis - assembly**



So what if we heated all of the DT to 10 keV?

- **In order for fusion to occur we need to heat the plasma ~ 10 keV**

$$\boxed{Q_{Fusion} = 3.3 \cdot 10^{11}\, J/g} \qquad \boxed{Q_{10\,keV} = 1.1 \cdot 10^{9}\, J/g}$$

$$\text{GAIN} = \frac{\text{Fusion Output}}{\text{Heating Input}} \sim 300\, f_{burn}$$

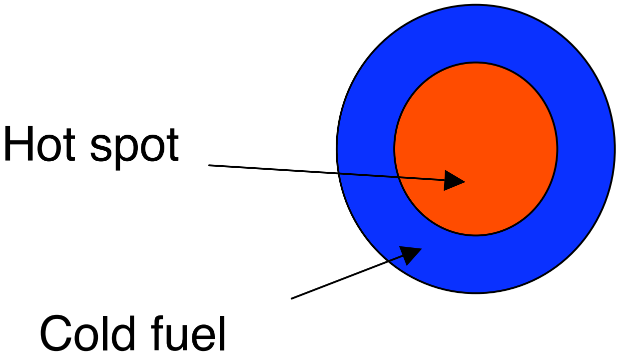
- **Seems like enough!**
- **But in ICF we need to include the fuel assembly efficiencies η_c and η_H**
- **Typically**

Typically	**Direct Drive**	**Indirect Drive**
η_c	**0.8**	**0.2**
η_H	**0.1**	**0.2**

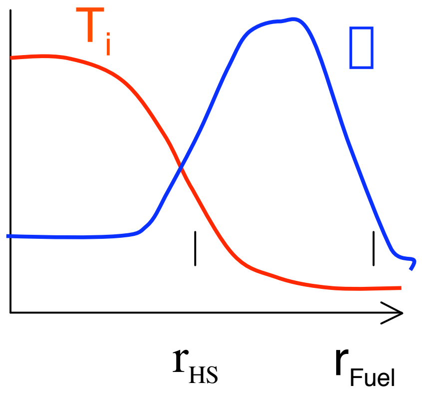
- **So, ICF must overcome inefficiencies of equation of order**
  0.08 (DD) or 0.04 (ID).
- **So a volume heated DT *assembly*, which has a gain of 100, has an actual target gain of 8 or 4. Considering the efficiency of turning heat into electricity and electricity into driver energy this is way too low!**

Burn must propagate to get high gain for ICF

Gain too low. Solution: heat a small amount of the fuel to high T and use fusion α's to heat cold fuel to fusion temperatures.



Pressure equilibrium



$$\boxed{Q_{FD} = 3.3 \cdot 10^{7}\, \alpha \left(\frac{\rho}{1000\,\mathrm{gm/cm^{3}}} \right)^{2/3} \mathrm{J/g}}$$

Note hot next to cold what happens if they mix?

What gains should we expect?

η_C = coupling efficiency

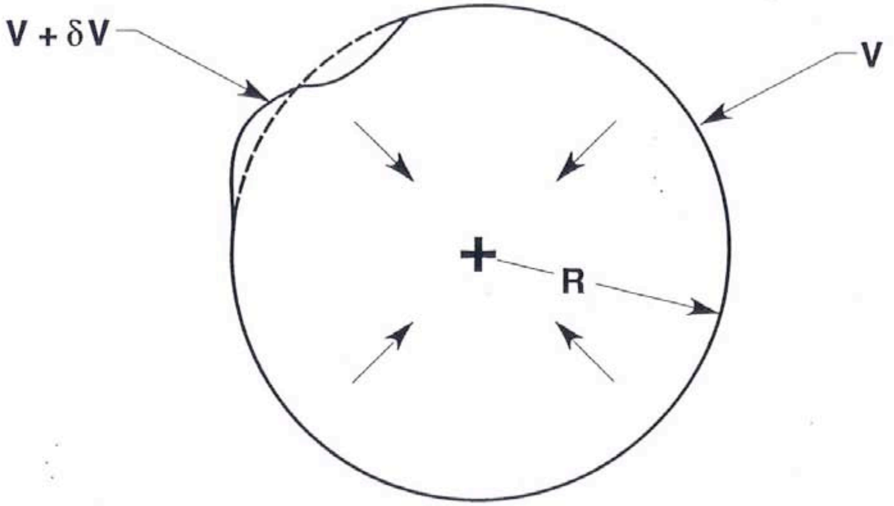
η_H = hydro efficiency

$f_b \approx \dfrac{\rho R}{6 + \rho R}$

<u>Driver scale</u>		$G \approx \dfrac{(\varepsilon_{DT}/\varepsilon_{fuel})}{\alpha_{FD} \text{x } I_{gn} \text{ Margin}}$	• η_c	• η_H	• f_b	$= \underline{G}$
1–2 MJ	NIF_{ID}:	$\dfrac{10^4}{1.5 \times 2}$	• (0.1)	• (0.2)	• (0.2)	≈ 13
	NIF_{DD}:	$\dfrac{10^4}{3 \times 2}$	• (0.8)	• (0.1)	• (0.2)	≈ 26
5–10 MJ	HiY_{ID}:	$\dfrac{2 \bullet 10^4}{1.5 \times 2}$	• (0.2)	• (0.2)	• (0.3)	≈ 80
	HiY_{DD}:	$\dfrac{2 \bullet 10^4}{2 \times 2}$	• (0.8)	• (0.1)	• (0.3)	≈ 120

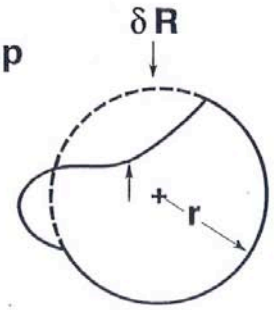
Implosion symmetry is an important issue for high convergence ratio targets

Small nonuniformity when outershell is at large radius



Becomes magnified when shell is imploded to a very small radius

Lower peak compression, temp
Lower ρR

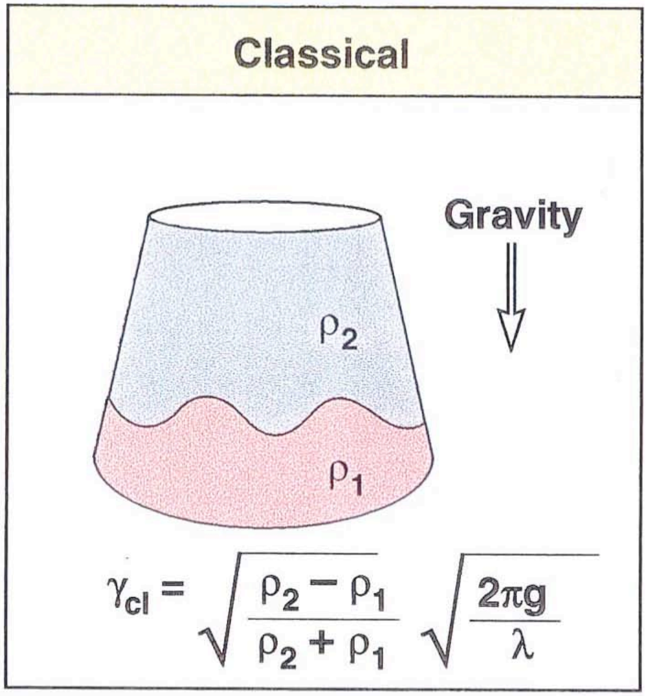


$$\delta R = (\delta V)t \sim \delta V \frac{R}{V} < 1/2\ r$$

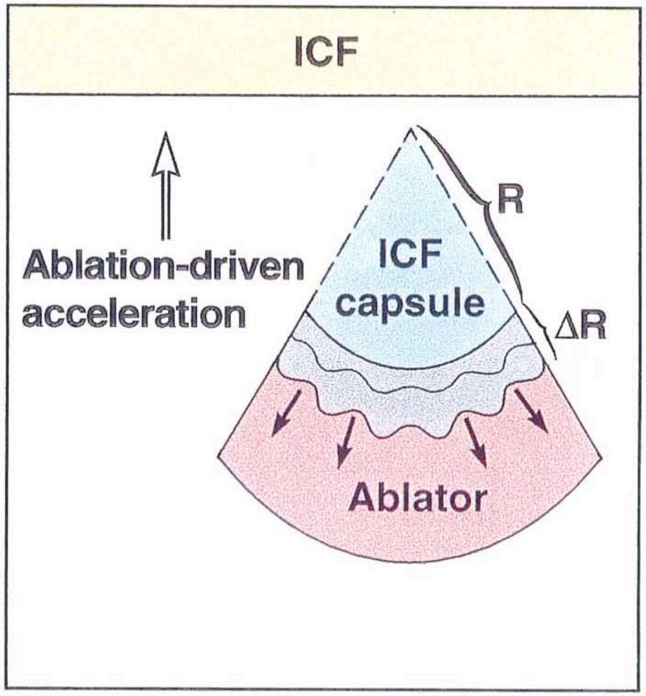
$$\therefore\ \frac{\delta R}{r} = \left(\frac{\delta V}{V}\right)\frac{R}{r} < 1/2$$

$$\therefore\ \frac{\delta V}{V} < 1/2\,\frac{r}{R} < 1/2\ (\text{conv. ratio})^{-1}$$

Rayleigh-Taylor instabilities are a major concern



$$\gamma_{cl} = \sqrt{\frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}}\sqrt{\frac{2\pi g}{\lambda}}$$



RT growth ~$e^{\gamma t}$

Worst $\lambda \approx \Delta R$

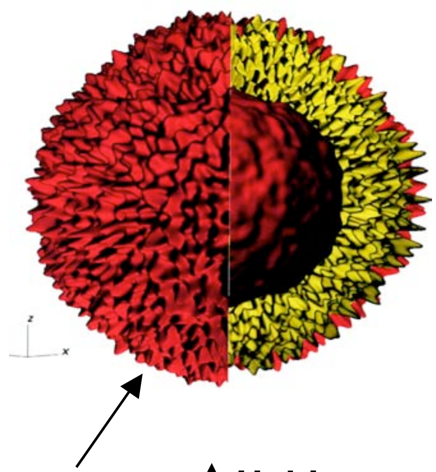
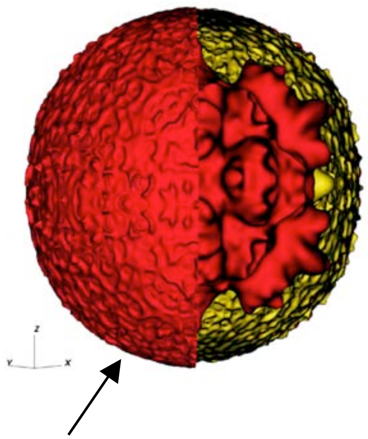
$$d = \frac{R}{2} = \frac{1}{2} at^2$$

$$\gamma^2 t^2 = \frac{2\pi}{\lambda} at^2 = \frac{2\pi}{\lambda} R = 2\pi\left(\frac{R}{\Delta R}\right)$$

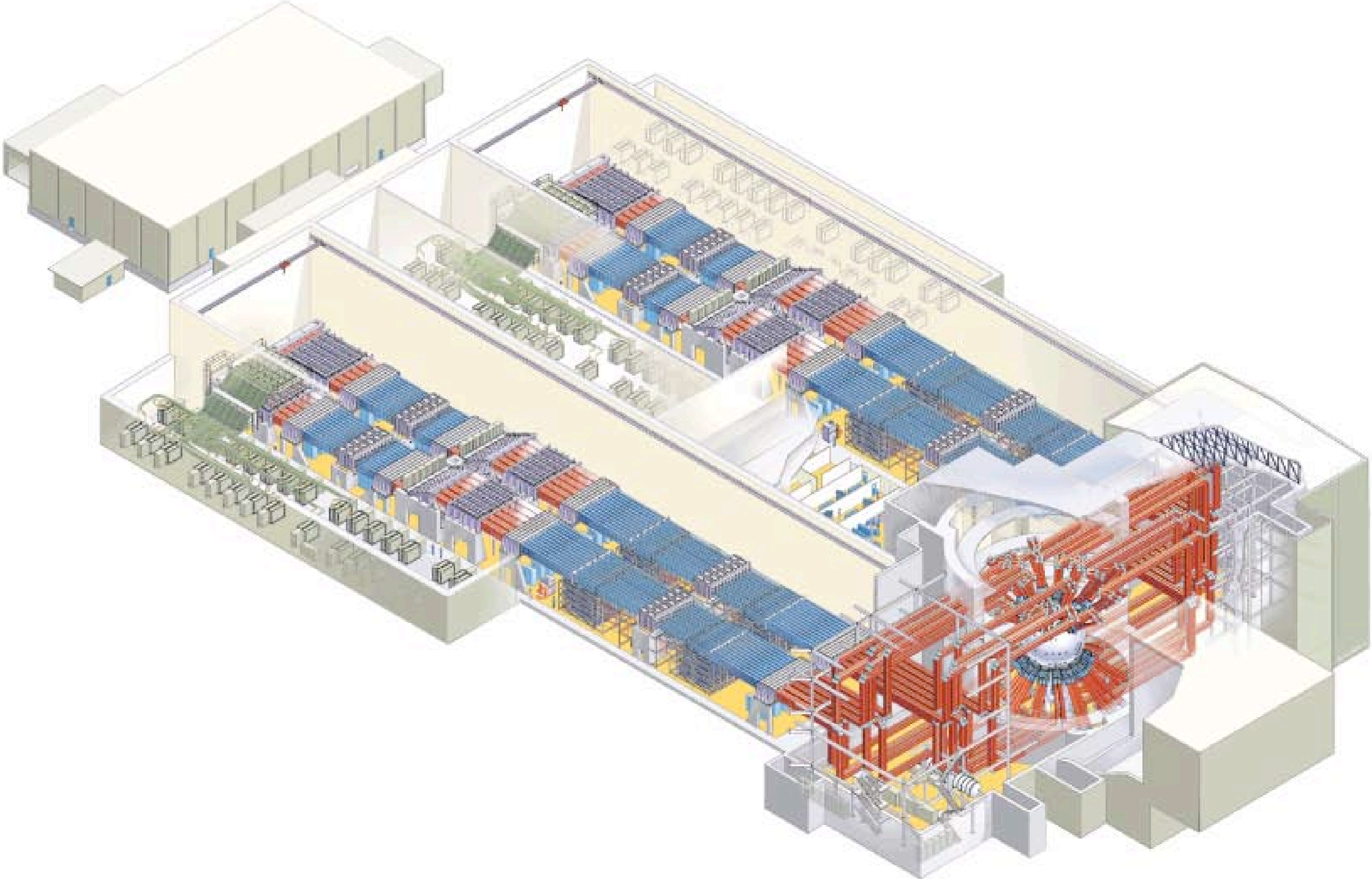
At stagnation time these perturbations lead to mix of cold fuel with hot spot which can quench the burn and prevent the capsule from igniting

3D calculations are used to assess capsule performance in the presence of perturbations

- Capsule simulations have asymmetry and fabrication perturbations
- 3D asymmetry inferred from integrated hohlraum simulation
- Nominal "at spec" perturbations on ice and ablator in low, intermediate, and high modes

140 ps before ignition time	Ignition time
 Plastic/DT interface ↕ Hohlraum axis	 Stagnation shock
60 g/cc density isosurface	400 g/cc density isosurface (different scale)

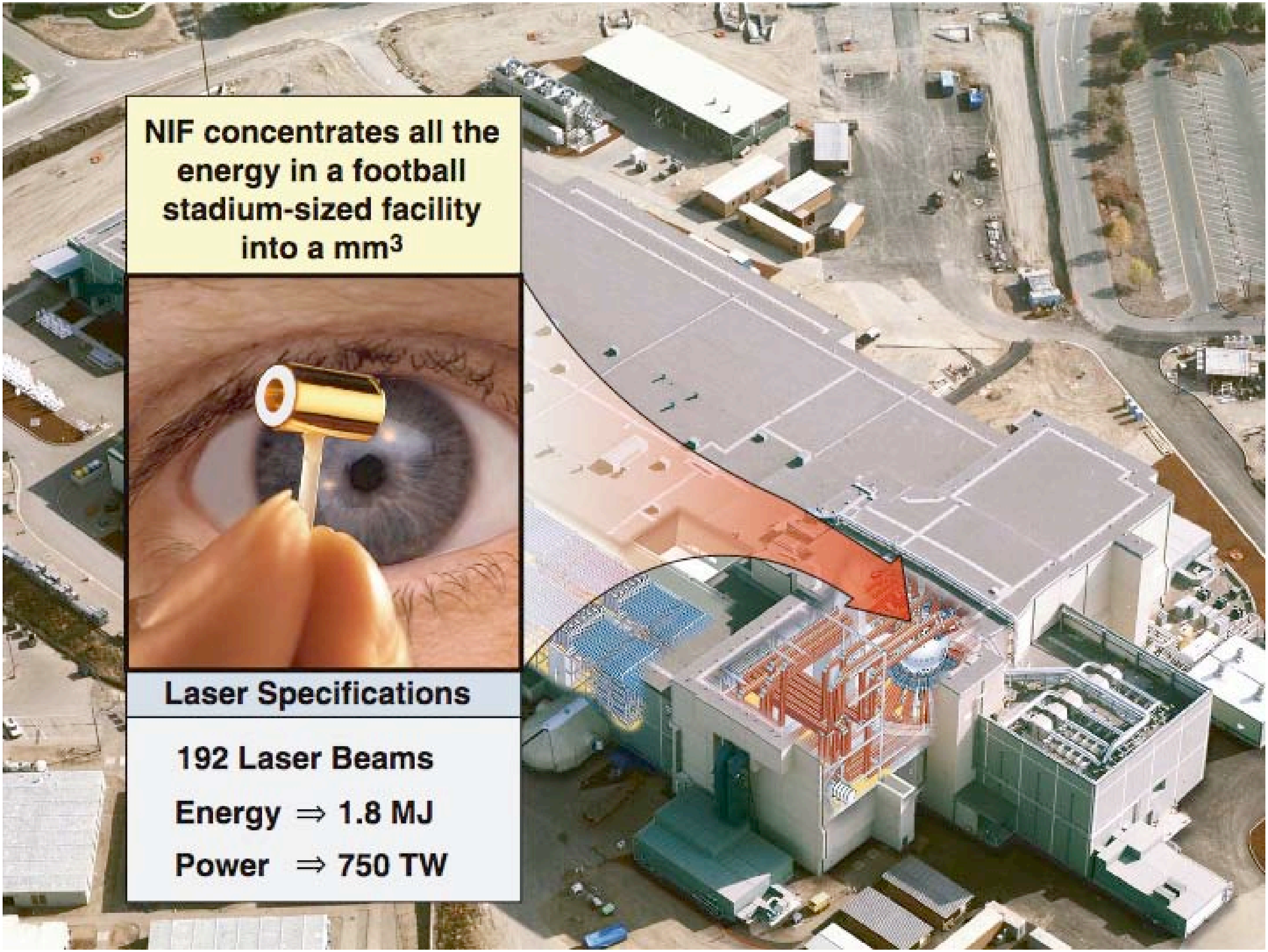
The National Ignition Facility is a 192 beam laser currently under construction at LLNL



40-00-0996-2100
14GHM/ncz


LLNL
National Ignition Facility


Cardinal
Stanford
GOLDEN BEARS
CALIFORNIA
Cal
Bruins
UCLA
Ucla BRUINS



NIF concentrates all the energy in a football stadium-sized facility into a mm^3

Laser Specifications

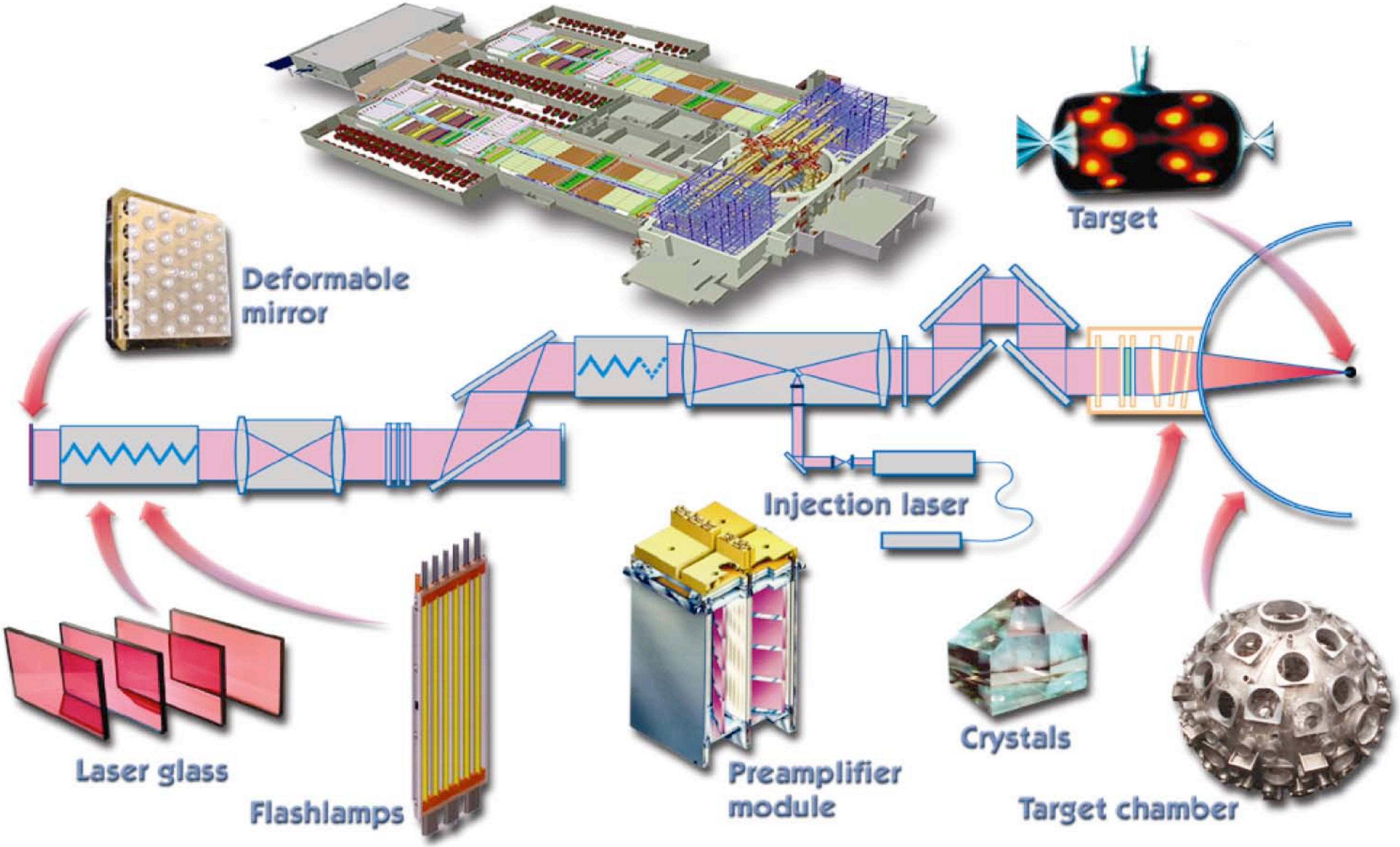
192 Laser Beams

Energy ⇒ 1.8 MJ

Power ⇒ 750 TW

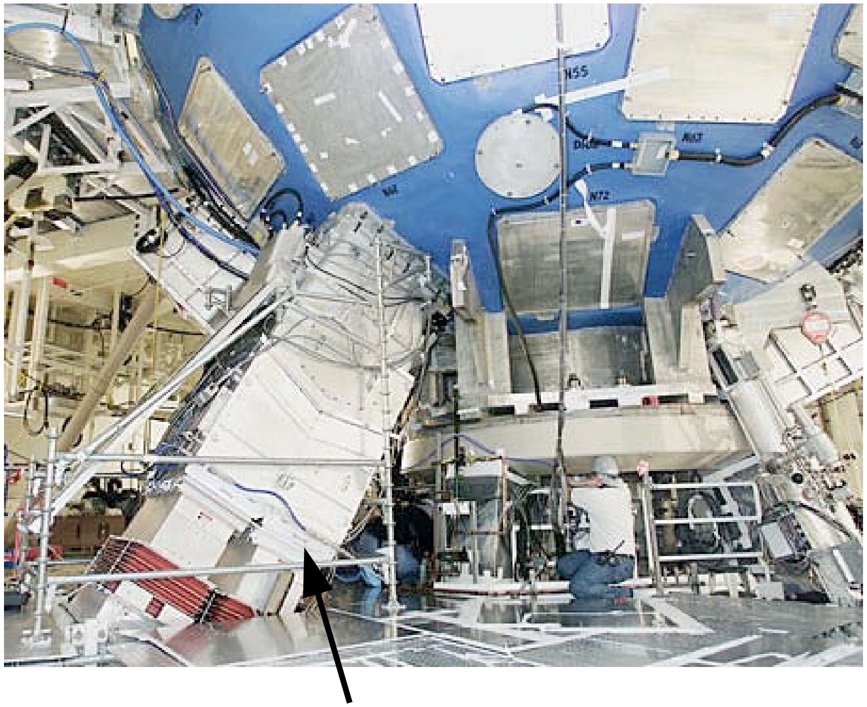
How NIF Works

The National Ignition Facility

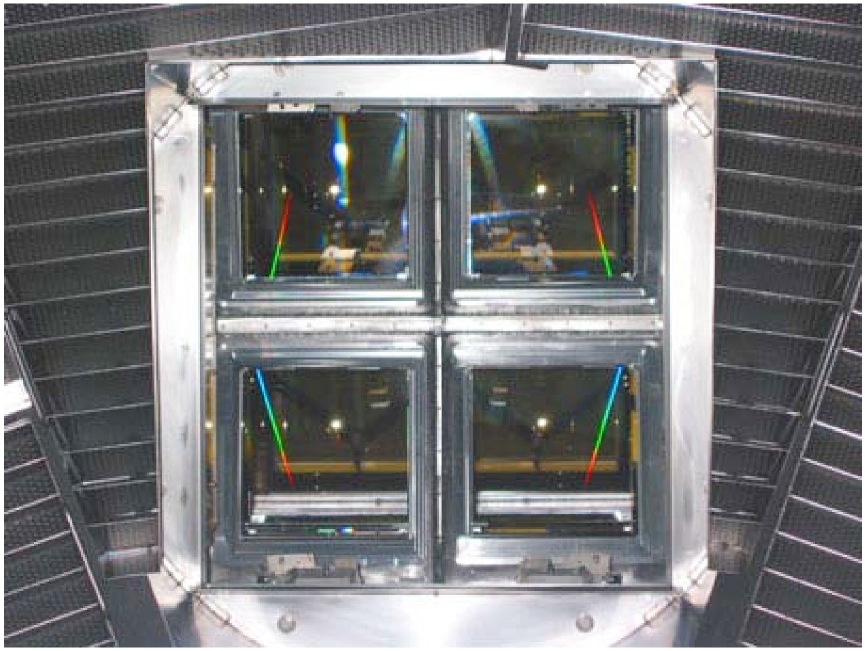


NIF-0201-00289

The first four NIF beams are operational and have been used for a number of experiments

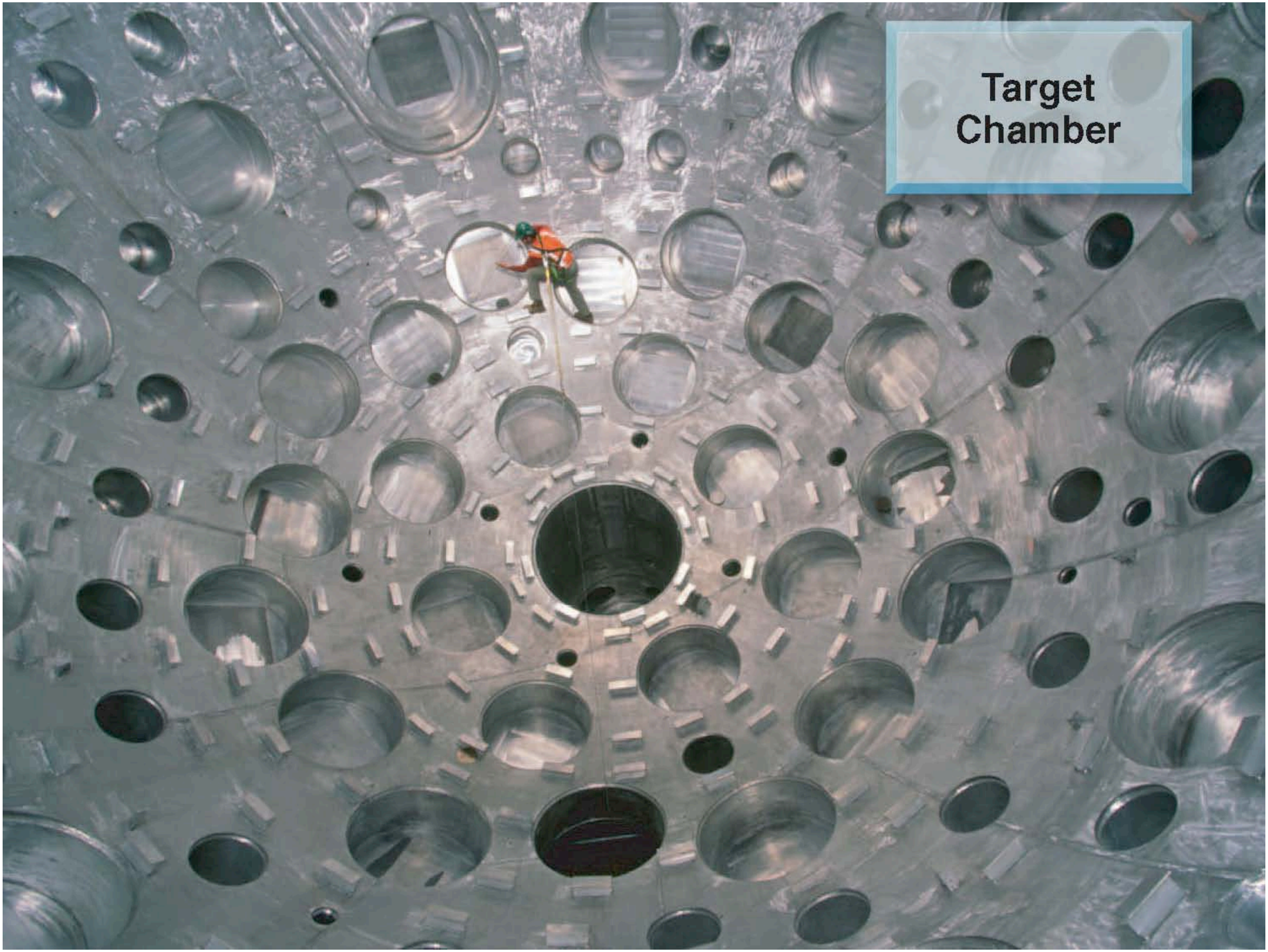


Quad 31b beamtubes

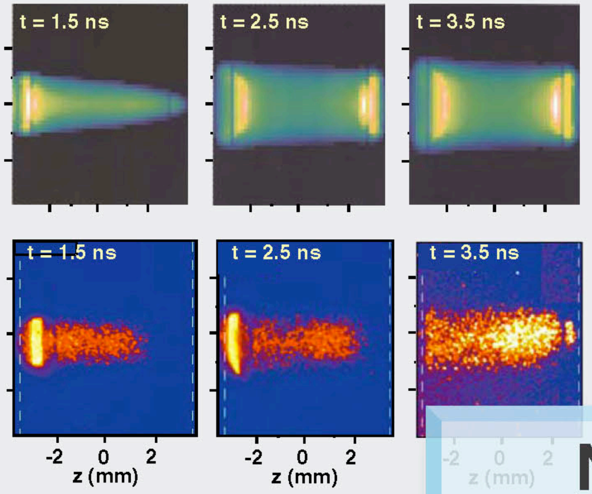


View from inside the target chamber

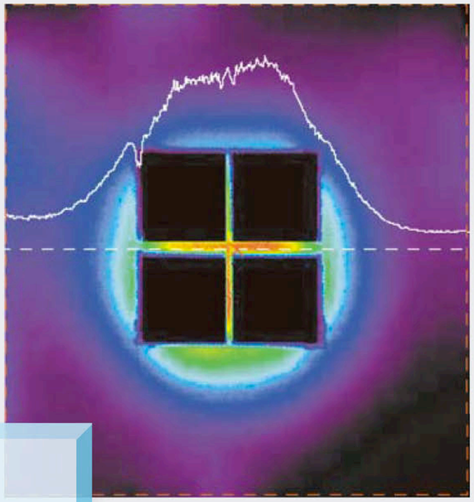
Target Chamber



LPI

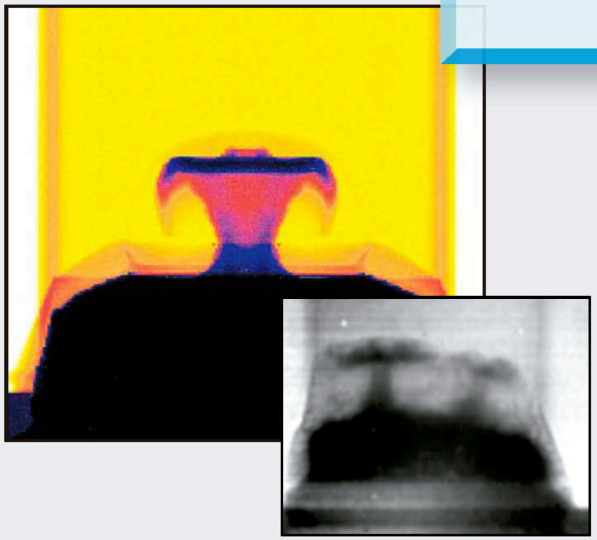


Hohlraums

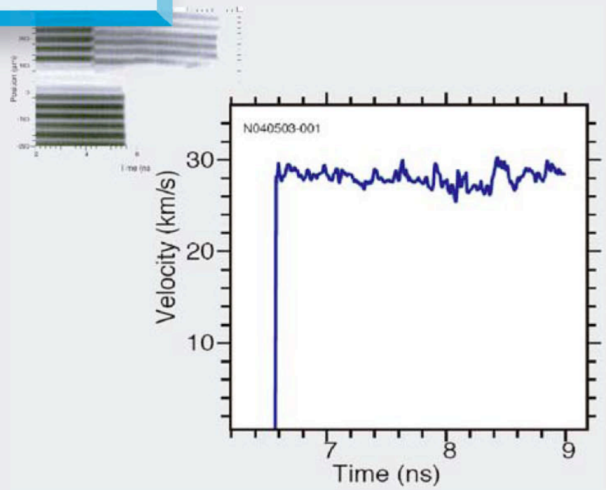


NIF is steadily developing a large range of experimental capabilities

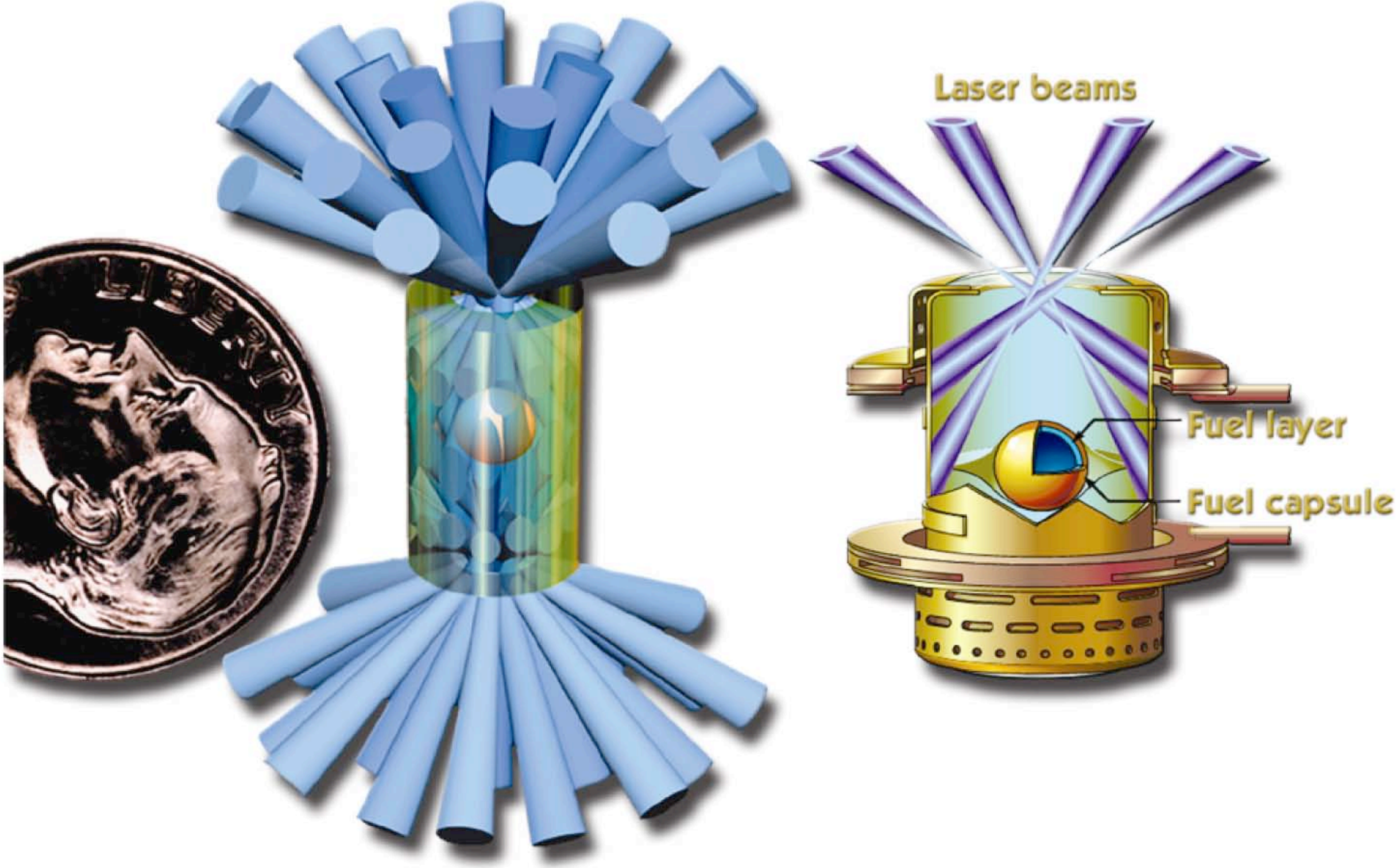
Hydro



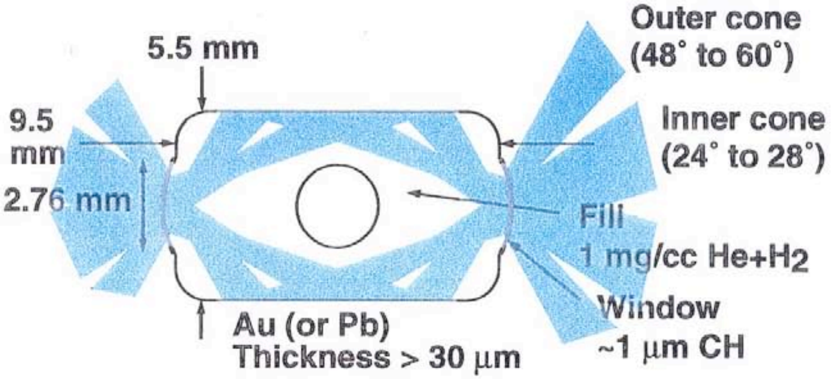
EOS

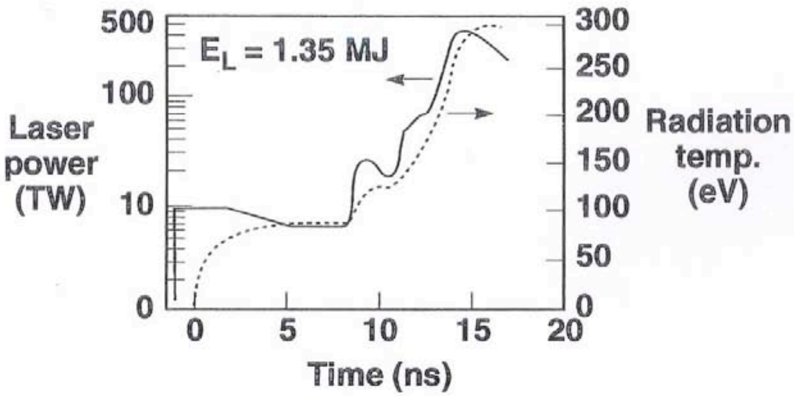


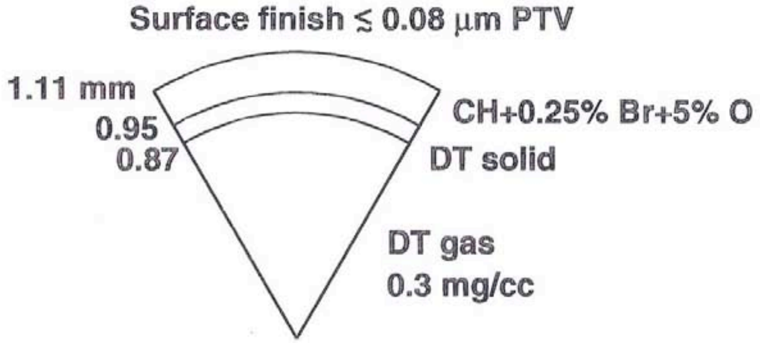
NIF Fusion Target



An old NIF ignition design







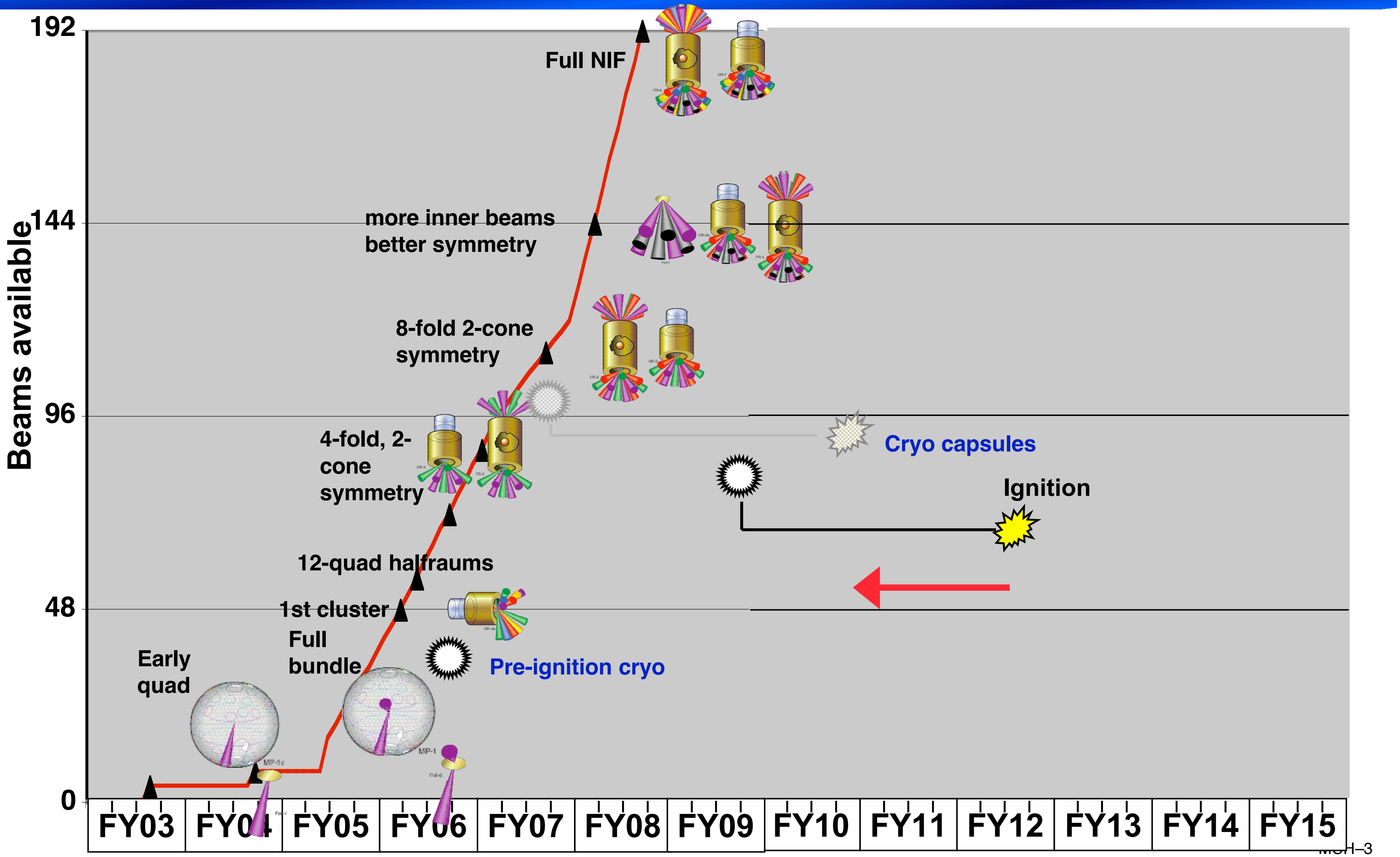
Absorbed energy 0.15 MJ

Yield 15 MJ

Critical issues tested on Nova

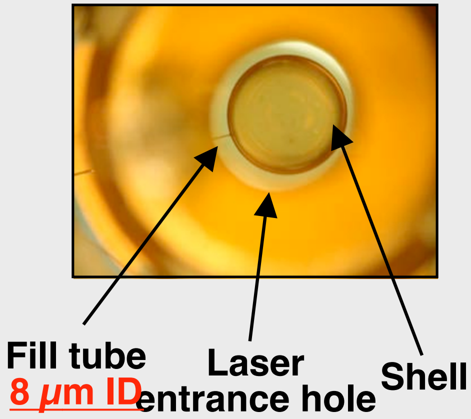
- Low SBS and SRS from the hohlraum plasma
- 300 eV in a shaped pulse
- X-ray drive symmetry 1%
- Controllable hydrodynamic implosion instability

This old viewgraph showed the plan as of 2 years ago. Several things have changed.

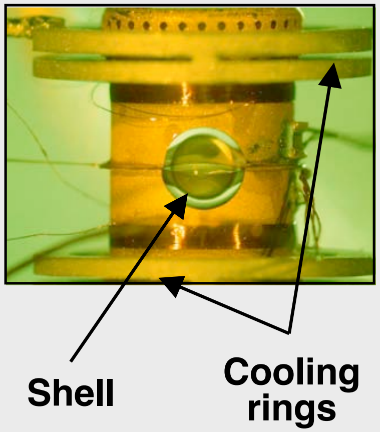


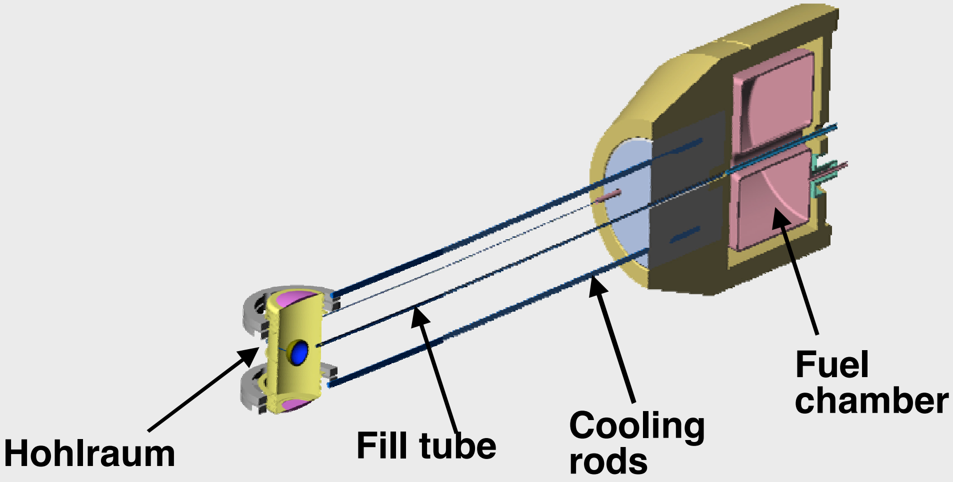
The target is filled through a small fill-tube using a self-contained fuel reservoir

View of 2mm shell through laser entrance hole

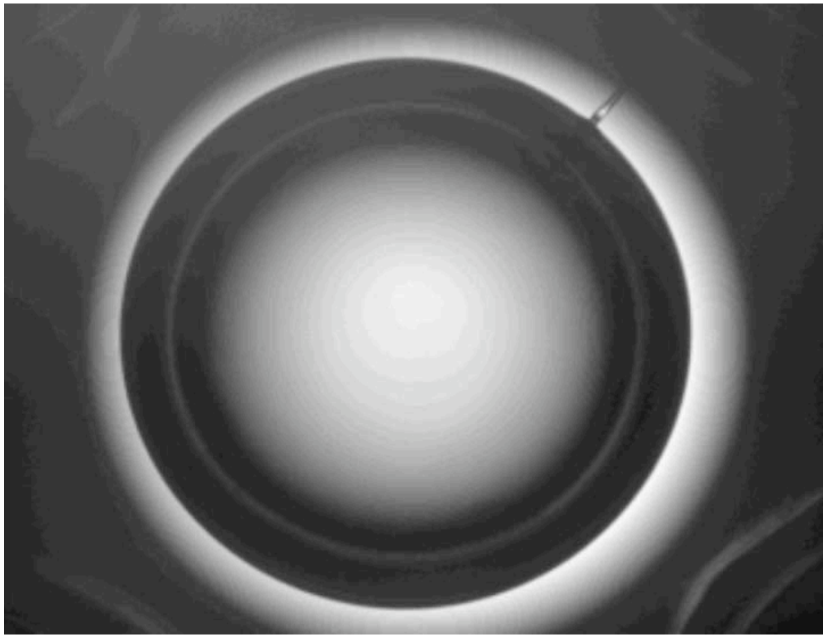


View of 2mm shell through side hole





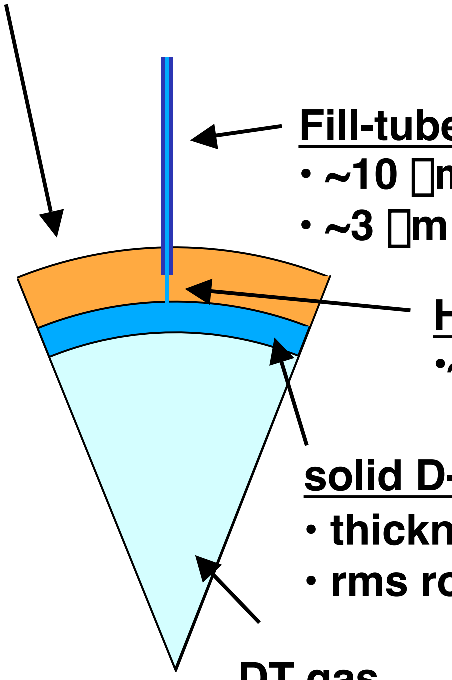
- Fuel pressure 2-3 atm
  - ~ 5 Ci DT
- Capsule filled *in target inserter* by temperature control on fuel reservoir and hohlraum



Ignition designs require cryogenic targets: A hohlraum containing a capsule "layered" with DT ice

Ablators (priority order):
1. Be w graded Cu
2. Be w constant Cu
2. CH w graded Ge

Surface roughness:
≈ 10 - 100's nm



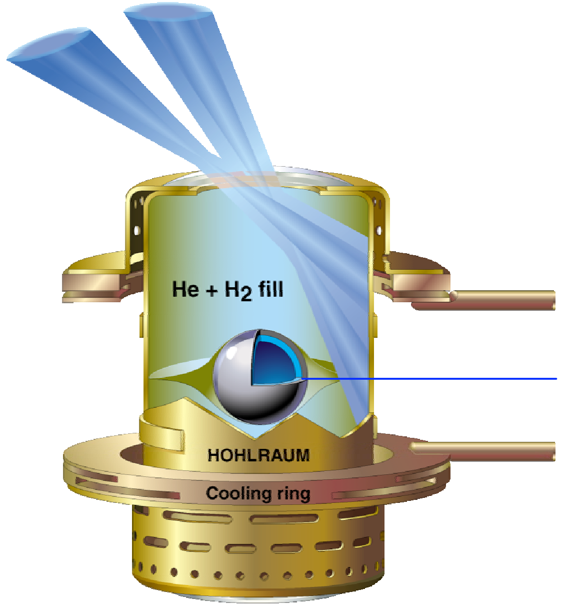
Fill-tube
- ~10 μm OD
- ~3 μm ID

Hole
- ~3 μm diam

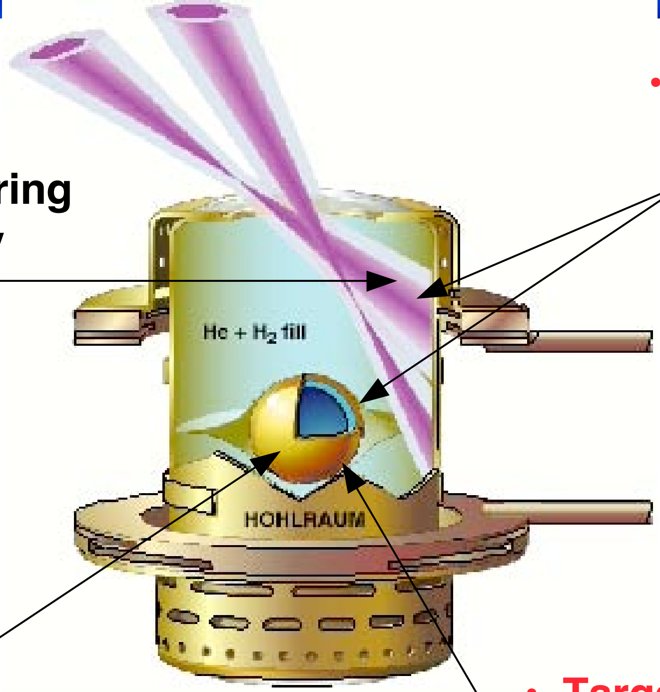
solid D-T (β-layered)
- thickness ≈ 100 μm
- rms roughness ≈ 1-5 μm

DT gas
0.3-0.5 mg/cc

Cryogenic hohlraums to shape and maintain the fuel layer



Ignition requires optimization of the energetics, symmetry, implosion dynamics, target design and fabrication



- Hohlraum Energetics
  - — Laser absorption
    - — Stimulated scattering
  - — Conversion efficiency to x-rays
  - — Albedo/X-ray wall loss

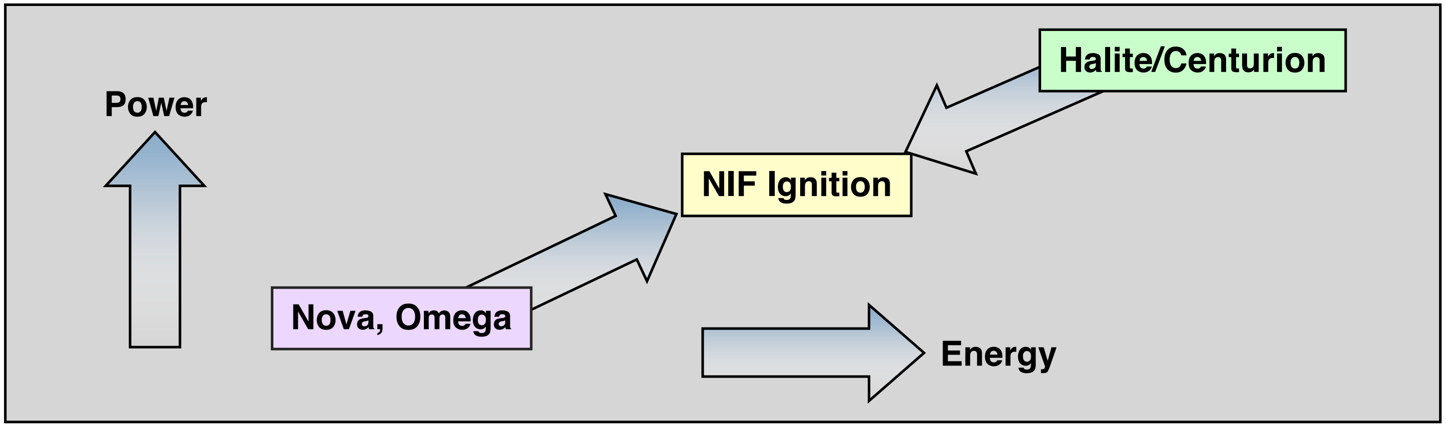
- Drive Symmetry
  - — Measurement
  - — Control (uniformity to 1% or 1 degree pointing)

- Implosion Dynamics
  - — Accurate measurement techniques for shock timing
  - — Material studies (EOS, ablation rate, etc. (Shock timing to 100 ps)

- Target Design and Fabrication
  - — Ablator choice (Be, CH, PI)
  - — Capsules (smooth to 10’s of nanometers)
  - — Cryogenic fuel layer (smooth to ~1µm)

Why do we believe that ignition will work on NIF?

- Over 15,000 experiments on Nova, Omega and other facilities have provided an extensive data base to develop confidence in the numerical codes
- Benchmarked numerical simulations provide a first principles description of x-ray target performance (except for laser-plasma interactions)
- The Halite/Centurion experiments using nuclear explosives have demonstrated excellent performance, putting to rest fundamental questions about basic feasibility to achieve high gain



Power

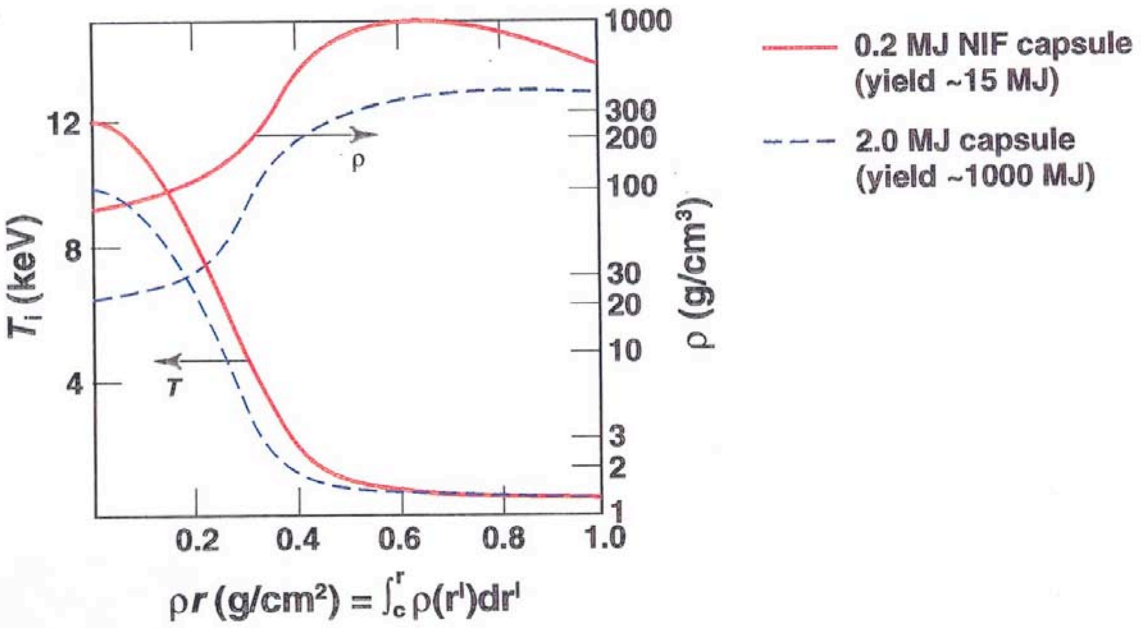
Halite/Centurion

NIF Ignition

Nova, Omega

Energy

NIF vs high-yield targets show similar ignition conditions but ρ scaling



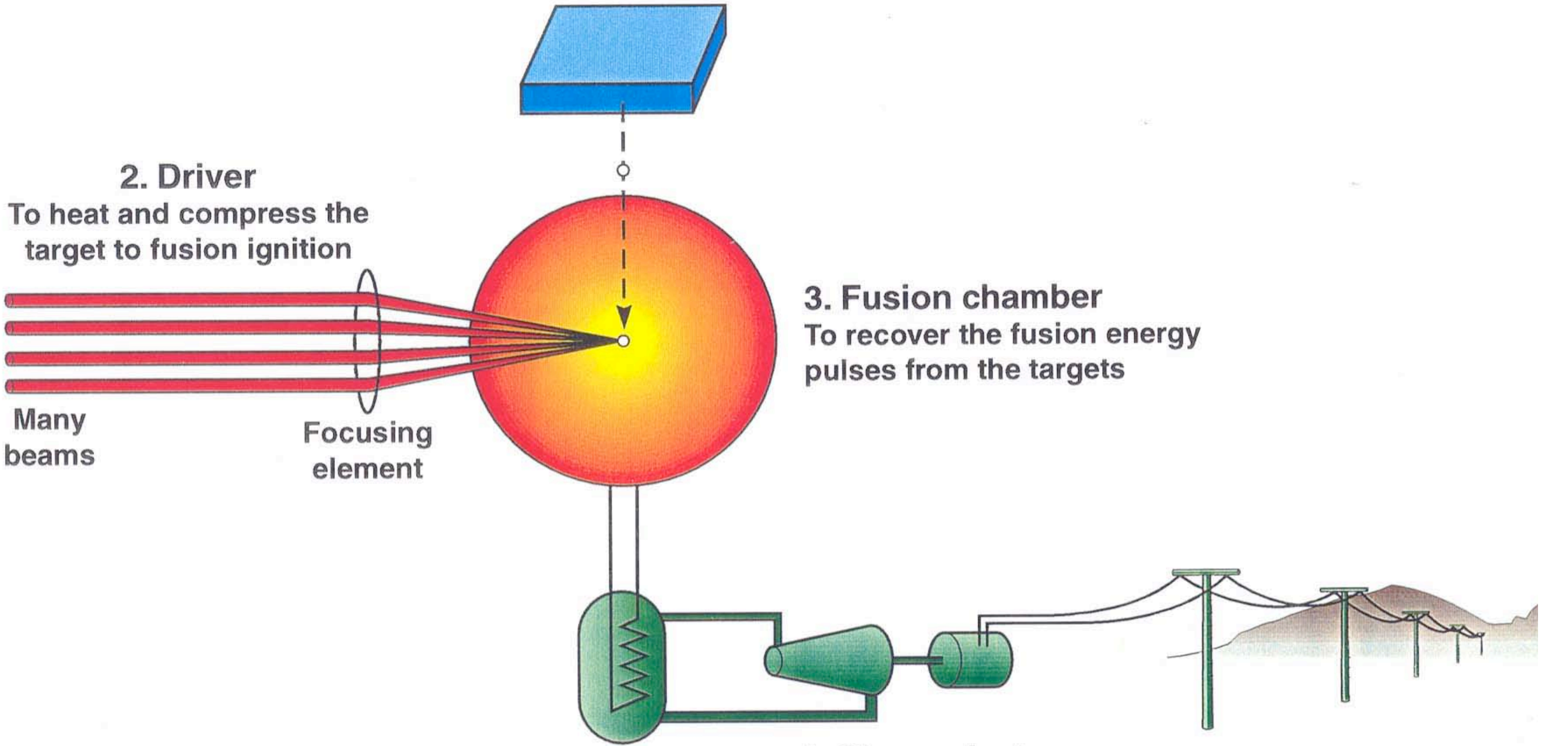
- Hot-spot temperature profiles and ρr are nearly independent of size at ignition
- Smaller capsules must have higher density to achieve the required hot spot $\rho r \approx 0.3\mathrm{g/cm^2}$

50-00-0590-0107C

9

If we can achieve ignition on NIF we are confident we will be able to get high gain with more energy.

IFE: The big picture



1. Target factory
To produce many low-cost targets

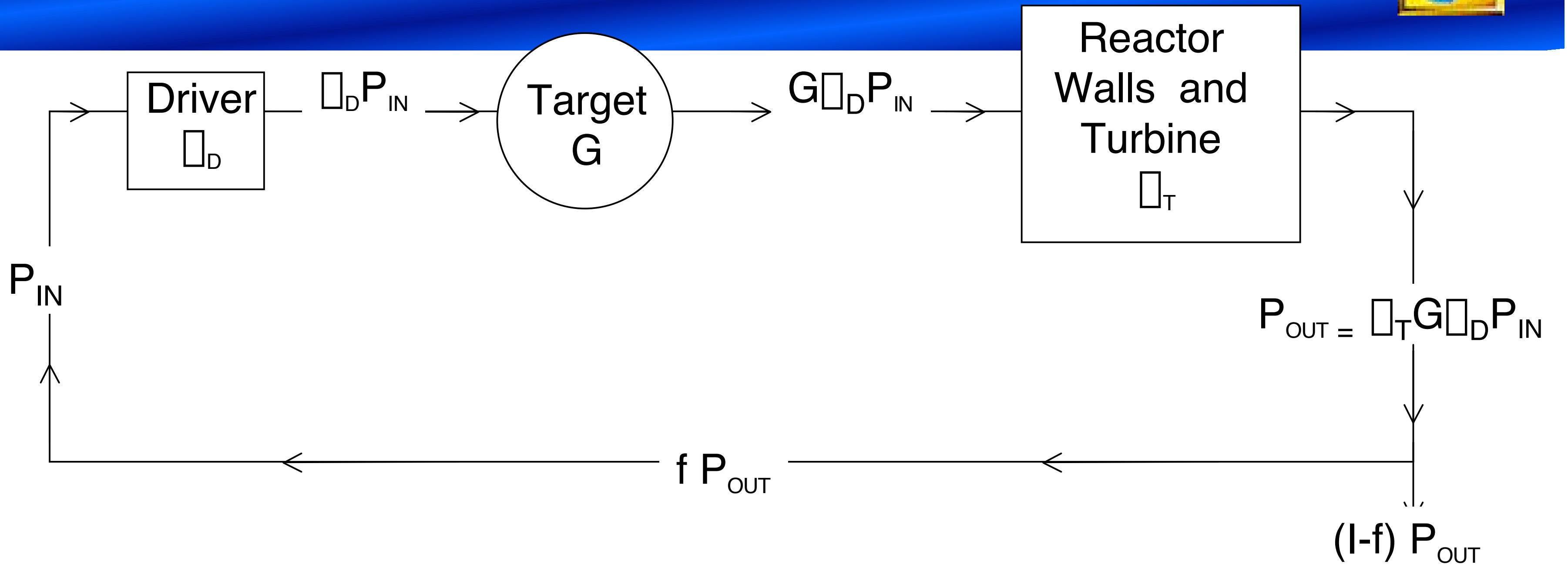
2. Driver
To heat and compress the target to fusion ignition

3. Fusion chamber
To recover the fusion energy pulses from the targets

4. Steam plant
To convert fusion heat into electricity

A power-plant driver would fire about five targets per second to produce as much electricity as today's 1000-megawatt power plant

IFE reactor: general requirements



Driver η_D

$\eta_D P_{IN}$

Target G

$G\eta_D P_{IN}$

Reactor Walls and Turbine η_T

$P_{OUT} = \eta_T G \eta_D P_{IN}$

f P_{OUT}

(I-f) P_{OUT}

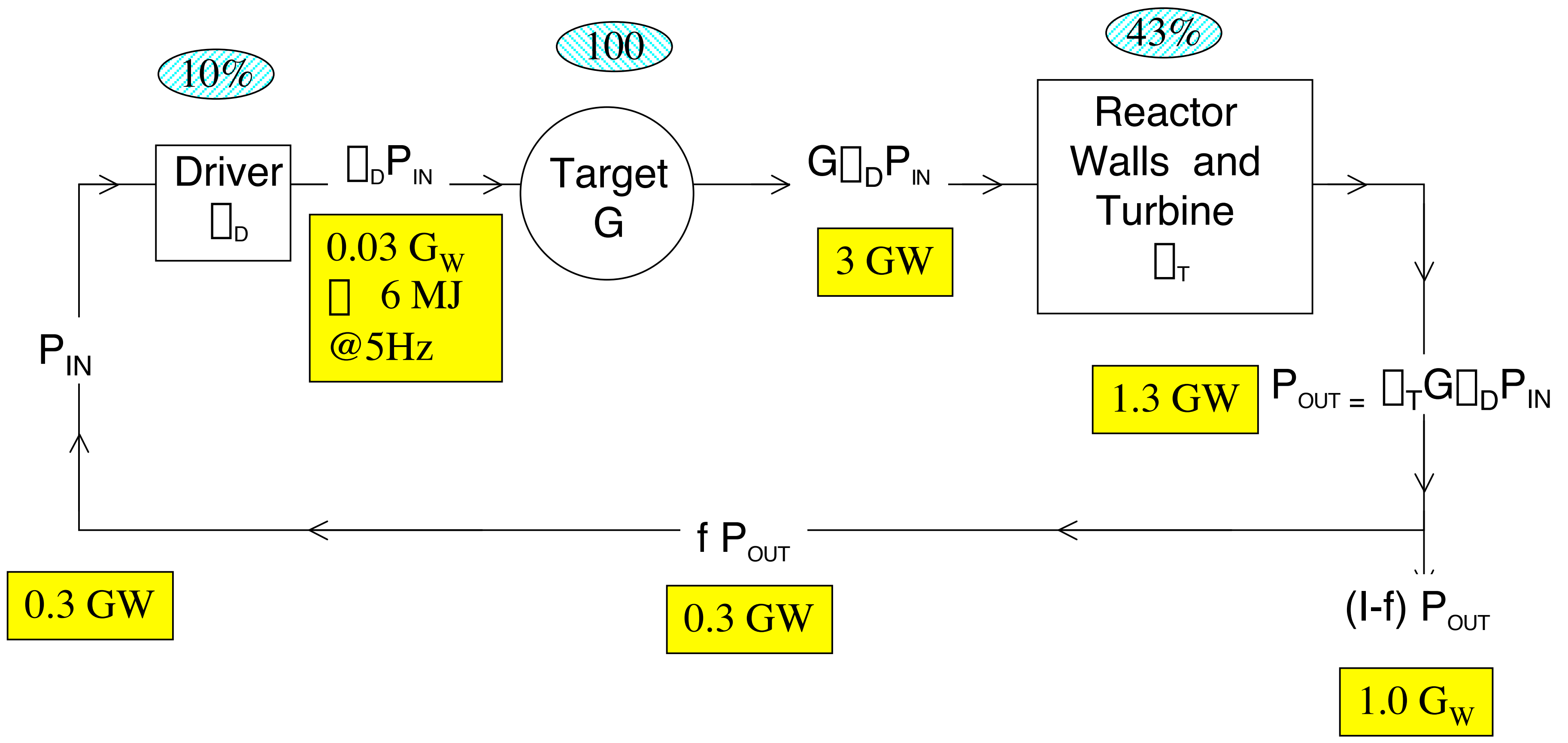
P_{IN}

$$P_{IN} = f\,P_{out} = f\,\eta_T G \eta_D P_{IN}$$

$$\Rightarrow \quad f\,\eta_T G \eta_D = 1$$

We want $f < \frac{1}{4}$. With $\eta_T \approx 0.4 \Rightarrow$ $\boxed{\eta_D G \geq 10}$

IFE Reactor: Representative numbers for a 10% efficient driver



10%

Driver

η_D

$\eta_D P_{IN}$

0.03 G_W

≈ 6 MJ

@5Hz

100

Target

G

$G \eta_D P_{IN}$

3 GW

43%

Reactor Walls and Turbine

η_T

1.3 GW

$P_{OUT} = \eta_T G \eta_D P_{IN}$

P_{IN}

0.3 GW

f P_{OUT}

0.3 GW

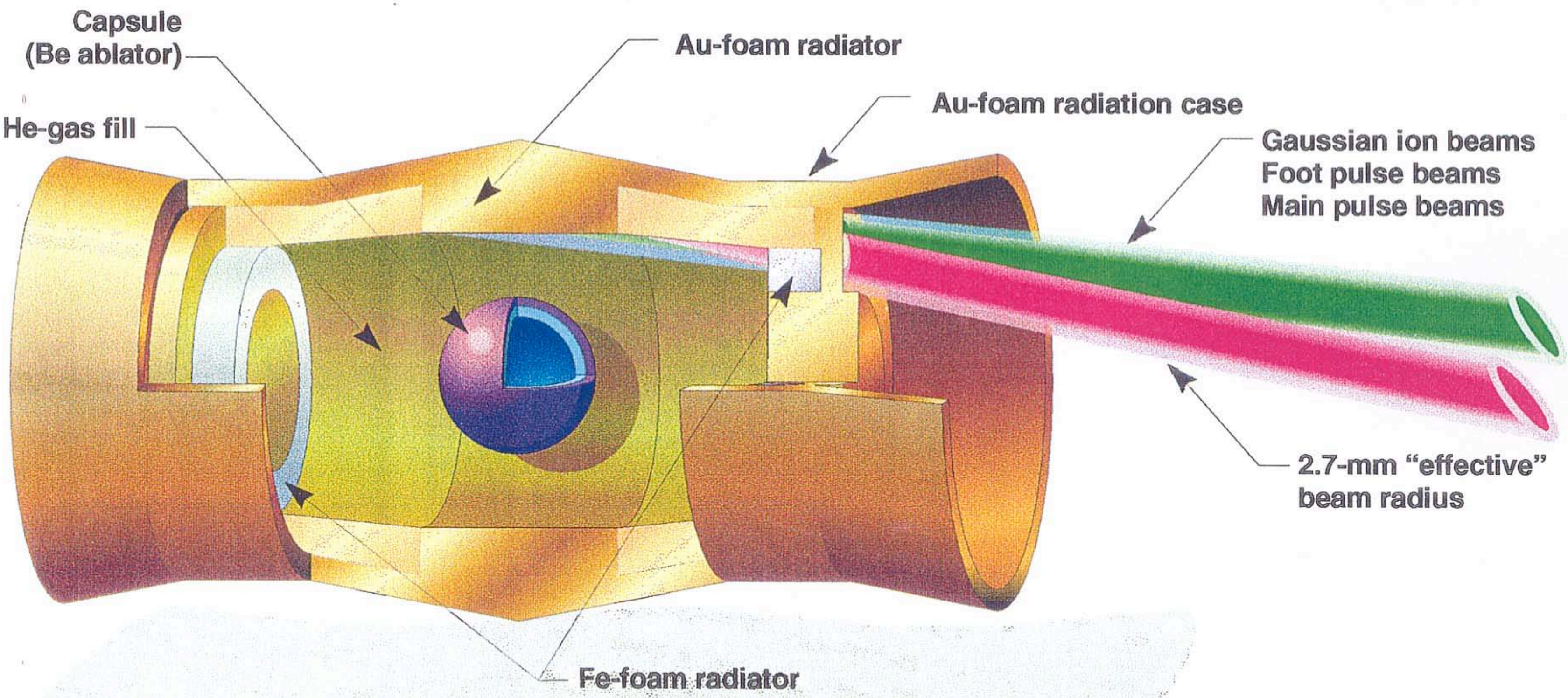
(I-f) P_{OUT}

1.0 G_W

How can 600 MJ be contained?

- 600 MJ has the <u>energy equivalent mass</u> of 1 / 7 of a ton of TNT !
- Q: Shouldn’t that easily destroy the target chamber?
- A: No, because it is momentum / impulse that leads to damage:
  - For our reactor scenario:
    - $p_{DT} = mv = (2\,E\,m)^{1/2} = (2 \times 6\;10^{8} \times 5.4\;10^{-6})^{1/2} = 80$ kg m /s
  - For TNT, $Q_{TNT} = E_{TNT} / m_{TNT} = 4.2\;10^{12}$ J / KT $= 4.2\;10^{6}$ J / kg
  - $p_{TNT} = (2\,E_{TNT}\,m_{TNT})^{1/2} = (2\,Q_{TNT})^{1/2}\,m_{TNT} = 2.9\;10^{3}\,m_{TNT}$
  - So the <u>momentum equivalent mass</u> of TNT can be found by setting $p_{TNT} = p_{DT} = 80$ kg m /s. This gives m_{TNT} □ 29 gm = 1 firecracker !
- Protecting the first wall from neutron damage introduces more mass. This leads to many fascinating engineering issues.

Detailed designs with more than adequate gain have been designed for Heavy Ion Fusion

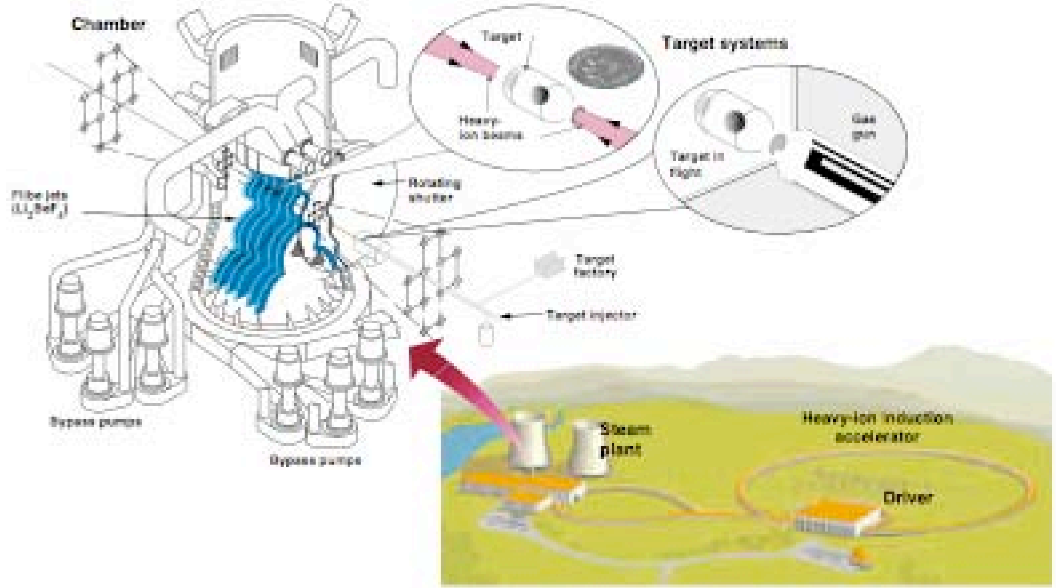


2-D LASNEX calculation produces $G \approx 130$ at 3.3 MJ

IFE Power Plant Concepts

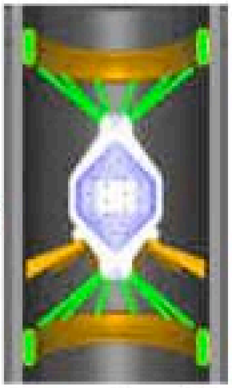
HYLIFE-II

HYLIFE-II is an IFE power plant that uses a heavy-ion driver. The chamber uses liquid jets of Flibe (a fluorine, lithium, beryllium molten salt) to protect the fusion chamber from neutrons. This results in long lifetime components, reduced maintenance costs and low environmental impact.



Sombrero

Sombrero is a fusion chamber concept for direct-drive laser targets. The chamber (far right) is made of low-activation carbon-composites. The flowing ceramic coolant is shown in green. The power plant shown uses a diode-pumped solid-state laser driver. A KrF gas laser could also be used with the Sombrero chamber.



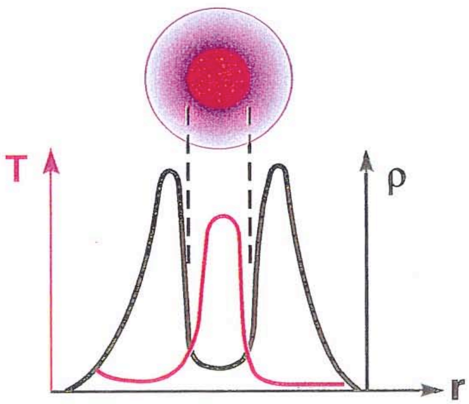
Cross-section of the SOMBRERO Chamber

Some References

- References: (first 4: ICF; next 4: HEDP)
  - The Physics of Inertial Fusion by S. Atzeni and J. Meyer-ter-Vehn
  - "Inertial Confinement Fusion" by J.D. Lindl, Springer Verlag, NY (1998) ; Phys. Plasmas 2, 3933 (1995)
  - M. D. Rosen, Phys. Plasmas 6, 1690 (1999)
  - J.D. Lindl, R. McRory, & E.M. Campbell, Physics Today 45, 32 (1992)
  - M. D. Rosen, Phys. Plasmas 3, 1803 (1996)
  - R. Jeanloz, Physics Today 53, 44 (2000)
  - K. O'Nions et. al., Nature 415, 853 (2002)
  - "Physics of Shock Waves & High Temperature Hydrodynamic Phenomena" by Ya. B. Zeldovich & Yu. P. Raizer, (edited by W. D. Hayes & R. F. Probstein) Academic Press, NY (1966)

The fast ignitor approach can lead to higher gain

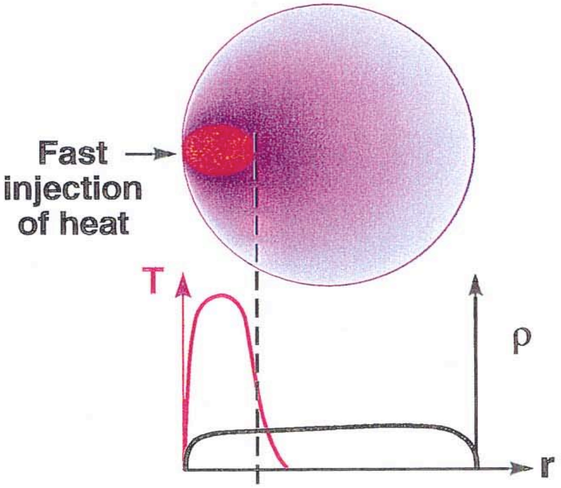
Conventional ICF



Shock heated central spot ignites a high density cold shell

$P_{HS} \approx P_c = \alpha\rho_c^{5/3}$

Fast Ignitor



Fast-e^- heated side spot ignites a lower density, larger uniform fuel ball $P_{HS} >> P_c$

Advantages of Fast Ignitor

- Fast Ignitor implosions are less stressing: (mix, convergence, ...)
- Lower $\rho \Rightarrow$ more mass to burn ($E_c \approx \alpha M_c\rho_c^{2/3}$) $\Rightarrow$ Higher Gain