# An Introduction to Inertial Confinement Fusion

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**SULI Introductory Course on Plasma Physics**
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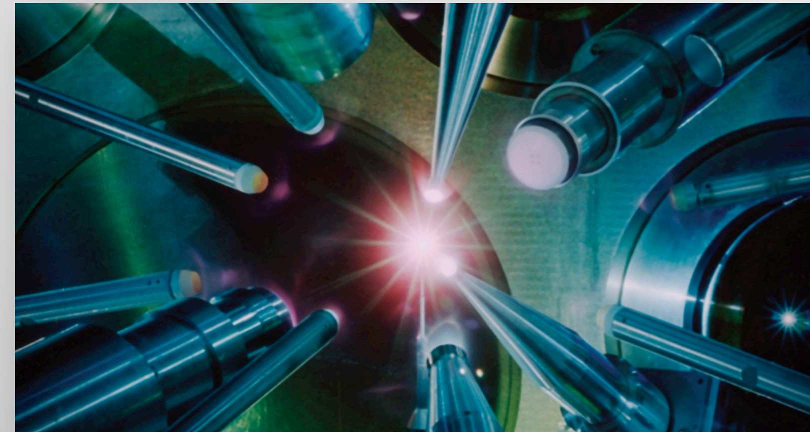
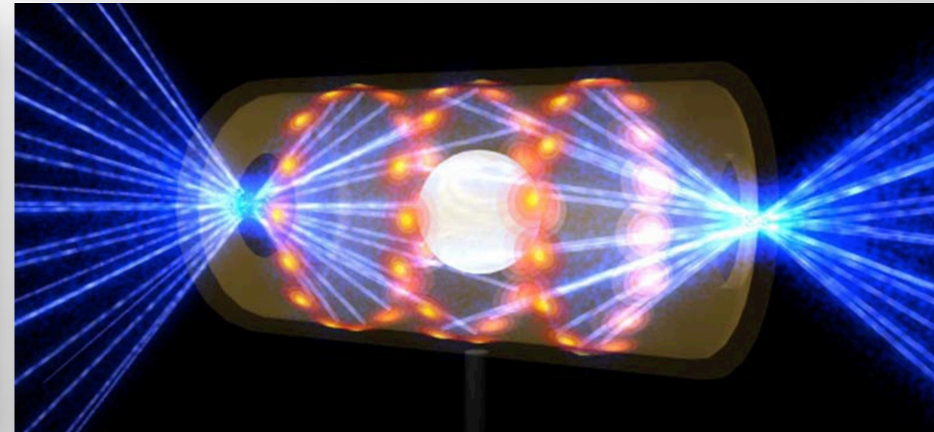
# Outline.

## I. Inertia

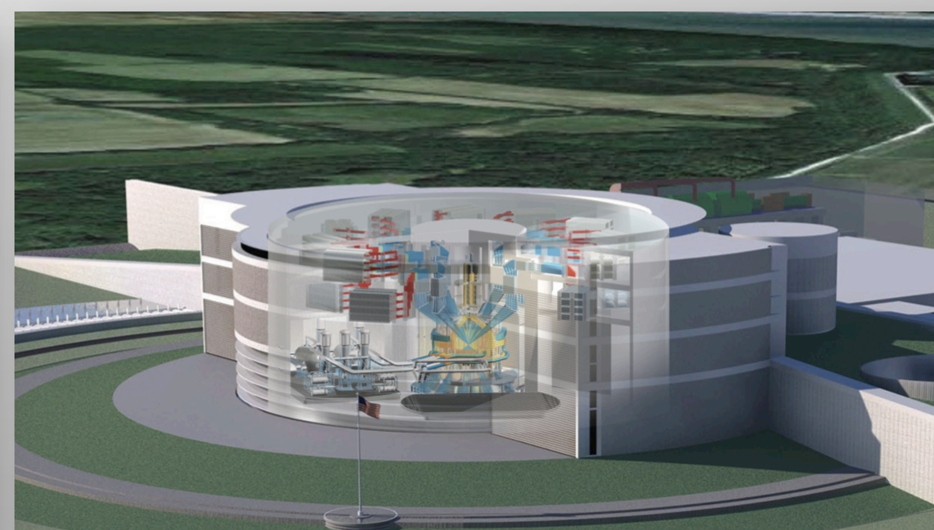


## II. Compression



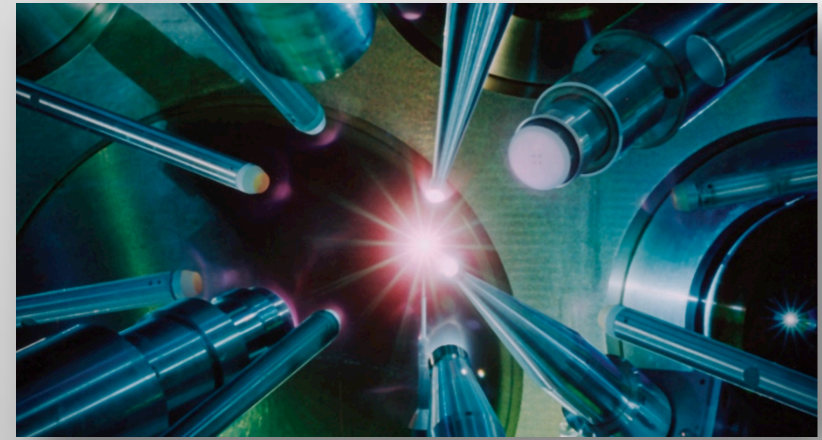
## III. Ignition


## IV. Power



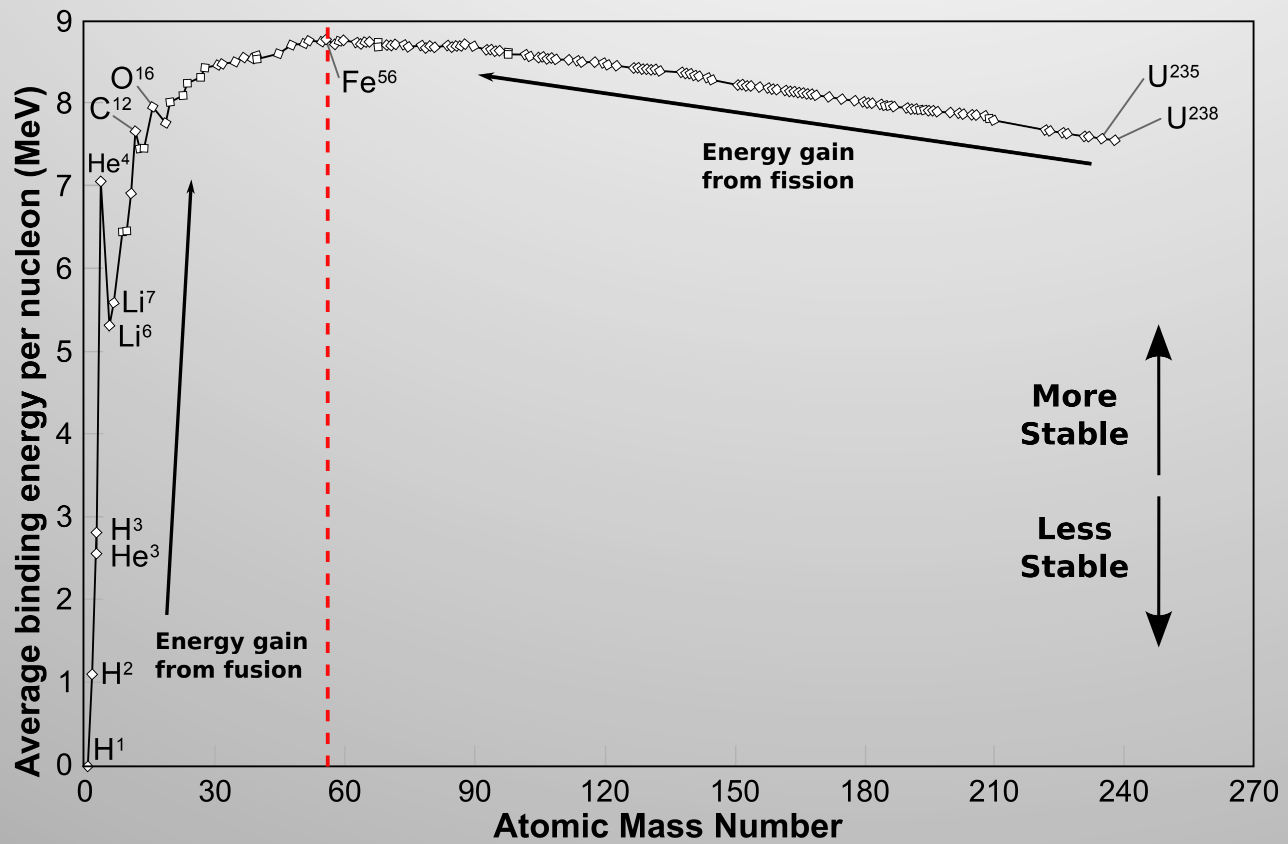
# Outline.

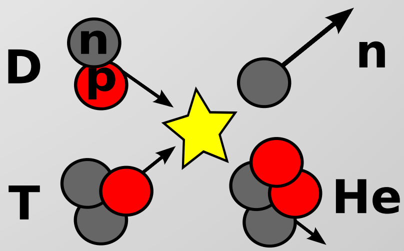
**I. Inertia**



- When does fusion occur?
- How does inertial fusion compare to magnetic fusion?
- What is the basic idea behind inertial confinement fusion?

# When light atoms fuse, they can release a lot of energy




**Energy Density**

**DT Reaction**
17.6 MeV/5 amu
$3.4 \times 10^8$ MJ/kg

**Burning Coal**
24 MJ/kg

# But fusion requires a hot, dense plasma

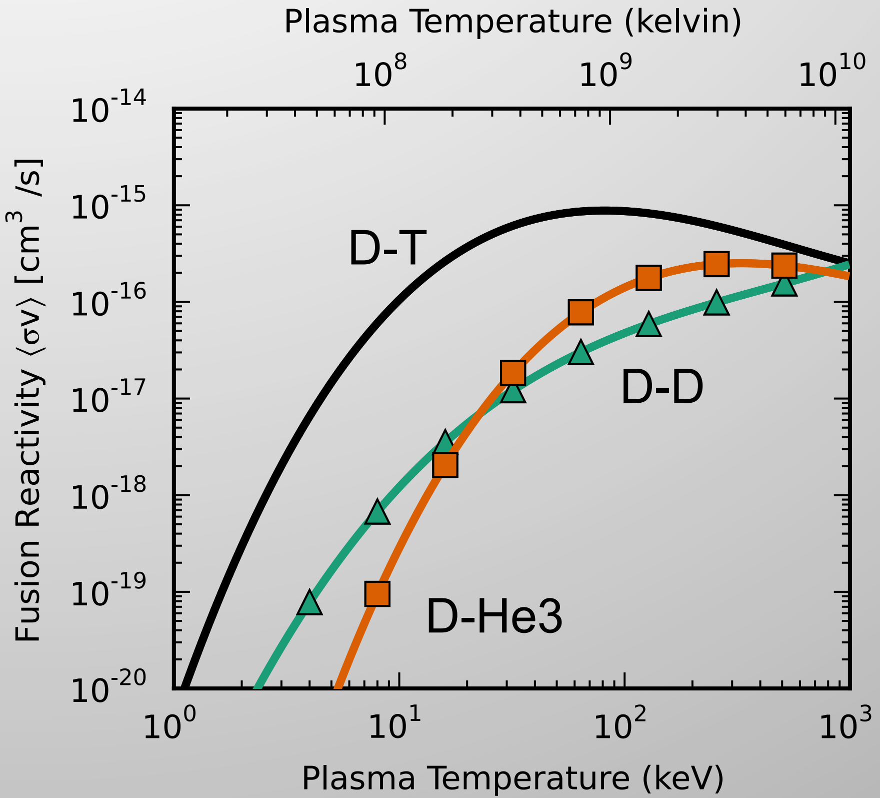
- Energy to overcome Coulomb barrier

$$T_i \sim 10\ \mathrm{keV} \sim 10^8\ \mathrm{K}$$

- Confinement (Lawson Condition)

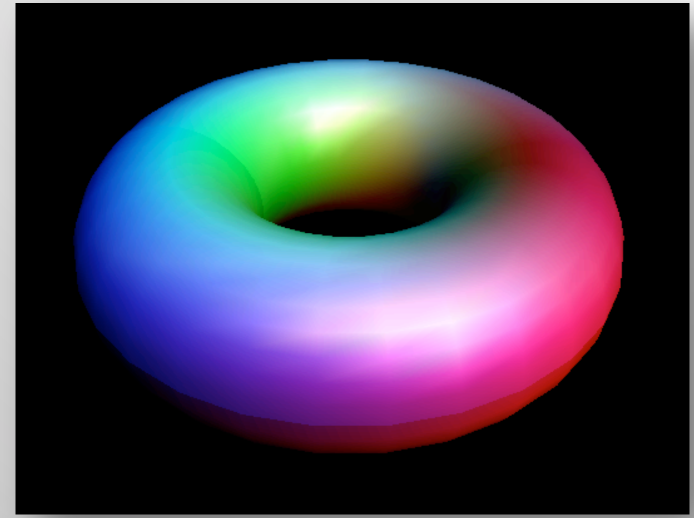
$$n\tau \geq 10^{14}\ \mathrm{s/cm}^3$$

**Fusion Reactivities**




**At fixed temperature, can trade-off between density and confinement time.**

**Magnetic Confinement Fusion**

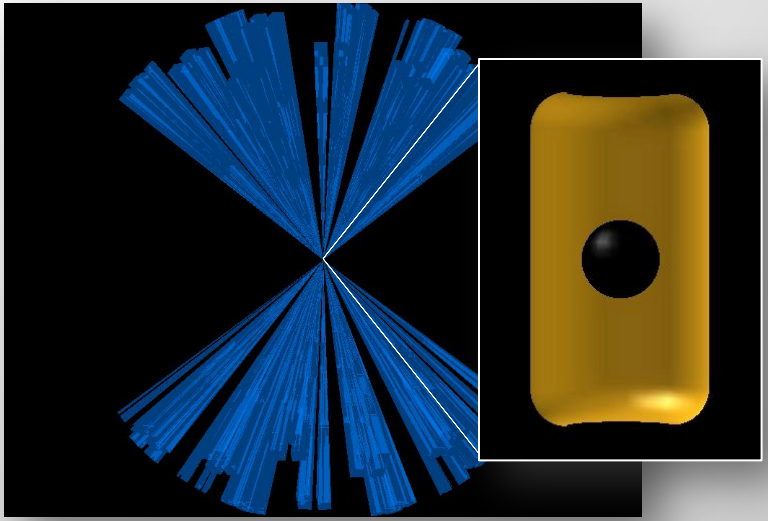


$$\tau \sim 10 \quad \mathrm{s}$$

$$n \sim 10^{14}\ \mathrm{cm}^{-3}$$

Atmospheric Pressure

**Inertial Confinement Fusion**

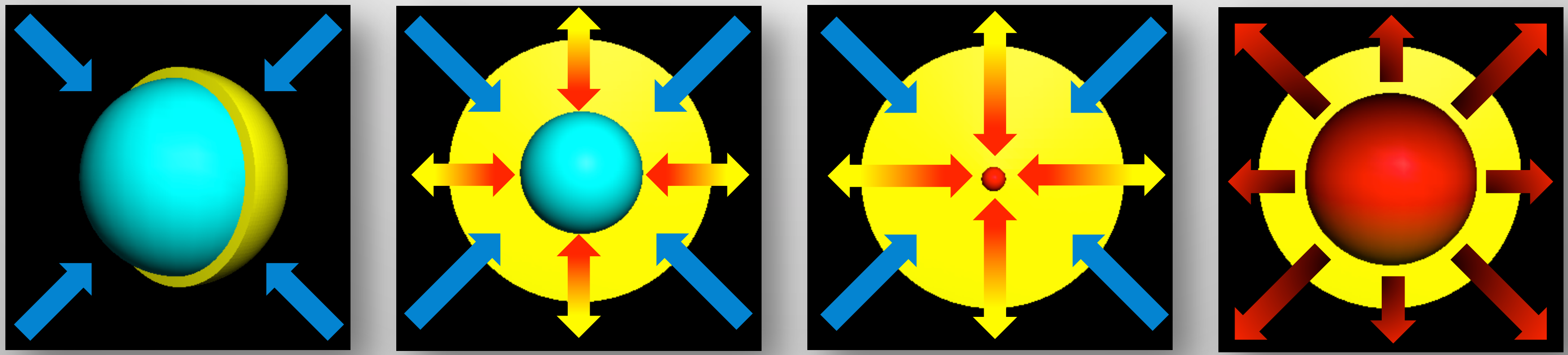


$$\tau \sim 10^{-11}\ \mathrm{s}$$

$$n \sim 10^{26}\ \mathrm{cm}^{-3}$$

100 Billion × Atmospheric Pressure

# The basic idea of ICF is to compress fuel to thermonuclear conditions



Laser or other driving beam impinges on a millimeter scale capsule of cryogenic fuel.

Capsule surface blows off (ablates), driving fuel inward.

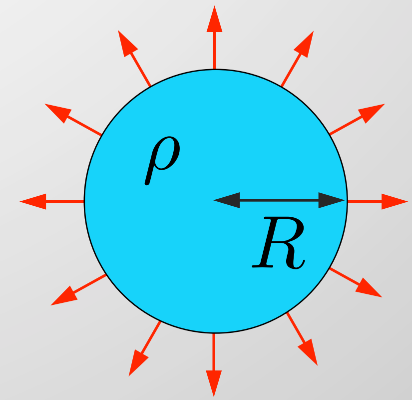
Fuel compresses and heats to thermonuclear conditions.

Fusion ignition occurs at capsule center.

Burn wave propagates out, consuming fuel.

# What is "Inertial Confinement"?

- Minimum form of confinement
- Fuel held together only by its own inertia




**Mass-Averaged Confinement Time**

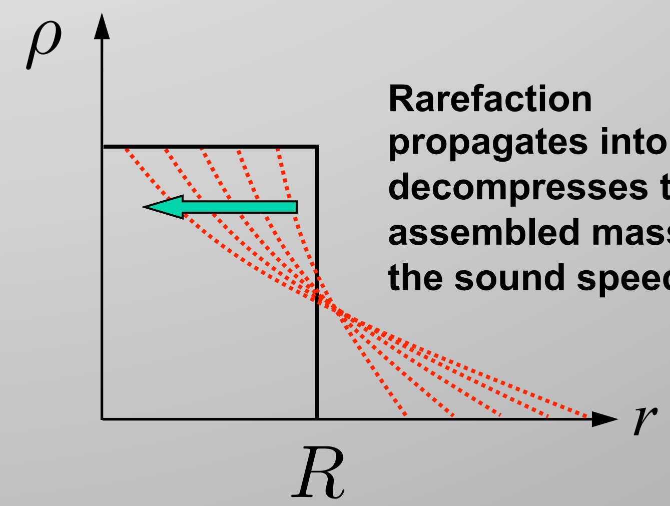
$$\langle \tau \rangle \simeq \frac{1}{M} \int_0^R \rho \frac{R-r}{c_s} 4\pi r^2 dr$$

Local confinement time

$$= \frac{\left. 4\pi \frac{\rho}{c_s} \left( \frac{Rr^3}{3} - \frac{r^4}{4} \right) \right|_0^R}{\frac{4\pi}{3} \rho R^3}$$

$$= \frac{1}{4} \frac{R}{c_s}$$

Most mass is at large radius




**Rarefaction propagates into and decompresses the assembled mass at the sound speed $c_s$**

# The fraction of fuel burned up depends on the "areal density" $\rho R$

**Fusion burn rate**

$$\frac{dn_T}{dt} = n_T n_D \langle \sigma v \rangle$$

$$\Rightarrow \frac{dn}{dt} = \frac{n^2}{2}\langle \sigma v \rangle; \quad n_T = n_D = \frac{n}{2}$$

**Integrate over confinement time**

$$\frac{1}{n_{\text{final}}} - \frac{1}{n_{\text{init}}} = \frac{1}{2}\langle \sigma v \rangle \tau$$

$$\tau \simeq \frac{R}{4c_s}$$

**Burn fraction**

$$f = 1 - \frac{n_{\text{final}}}{n_{\text{init}}} = \frac{\rho R}{\rho R + 8 m_i c_s / \langle \sigma v \rangle} \simeq \frac{\rho R}{\rho R + 6 \ \text{g/cm}^2}; \ T_i = 30 \ \text{keV}$$

**For** $f \geq 1/3$ **need** $\rho R \geq 3.0 \ \text{g/cm}^2 \Leftrightarrow n\tau \geq 2.0 \times 10^{15} \ \text{s/cm}^2$

# A reasonable fuel mass requires high fuel compression

**Areal density requirement** → **Spherical imploded mass**

$$\rho R \geq 3.0 \text{ g/cm}^2$$

$$M = \frac{4\pi}{3}\rho R^3 = \frac{4\pi}{3}\frac{(\rho R)^3}{\rho^2}$$

| | $\rho$ [g/cm$^3$] | $\rho R$ [g/cm$^2$] | $R$ [cm] | $M$ [g] | $Y$ [MJ] |
|---|---|---|---|---|---|
| **DT @ 18 K** | **0.25** | **3.0** | **12.0** | **$2.6 \times 10^3$** | **$2.9 \times 10^8$ ~ 70 kilotons TNT!** |
| **1000 × compression** | **250** | **3.0** | **0.012** | **$1.8 \times 10^{-3}$** | **612 ~ 1/7 ton ⇒ 1GW with 5 pulses/sec** |

# How can even 600 MJ be contained?

- 1/7 ton TNT = several hundred pounds of high explosives!

# Won’t that destroy a target chamber?

# No, because momentum/impulse leads to damage.

$$p = mv = \sqrt{2Em} = \sqrt{2 \cdot 600\ \mathrm{MJ} \cdot 1.8 \times 10^{-3}\ \mathrm{g}} \simeq 50\ \mathrm{kg\ m/s}$$

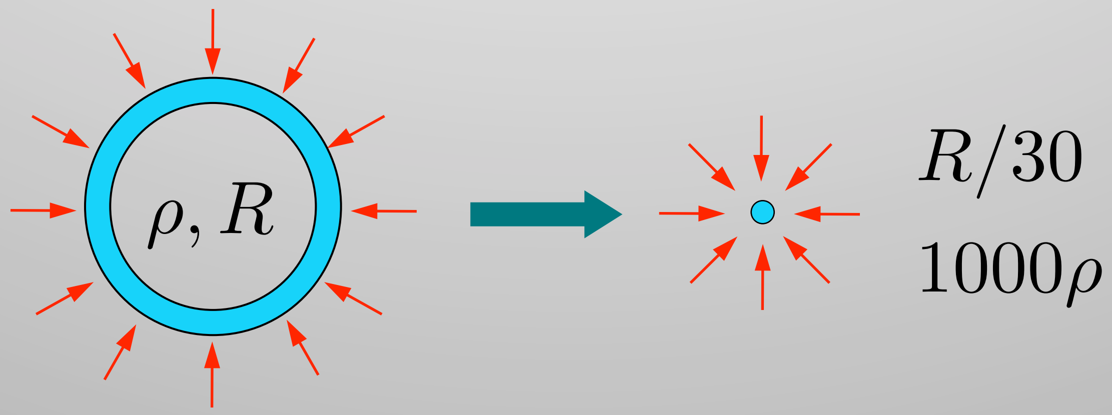
- A person walking into a wall. Not fun, but not catastrophic
- The momentum equivalent mass of TNT is ~ 1 firecracker
- Protecting the wall from neutron damage is another story…

# Achieving such high densities requires spherical compression

**Must exploit $R^3$ compression with spheres – $R^2$ or $R^1$ scaling with cylindrical or planar compression is not adequate**

$$M = \frac{4\pi}{3}\rho_{\rm init}R_{\rm init}^3 = \frac{4\pi}{3}\rho_{\rm final}R_{\rm final}^3 \Rightarrow \frac{\rho_{\rm final}}{\rho_{\rm init}} = \left(\frac{R_{\rm init}}{R_{\rm final}}\right)^3$$

**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**

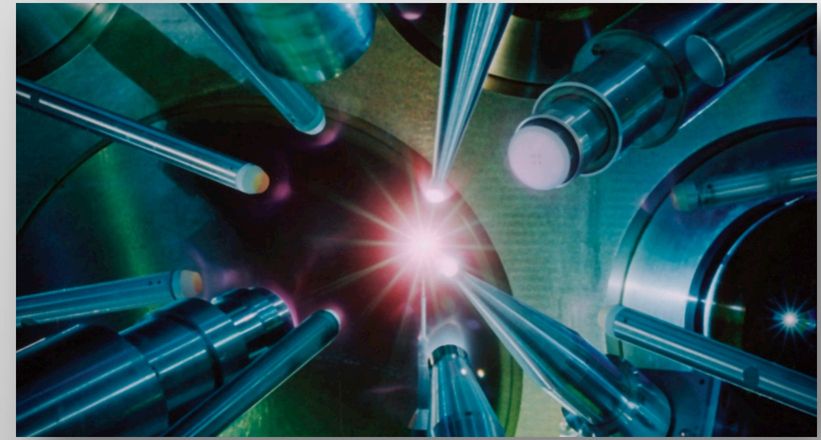



**Goal: Convert shell kinetic energy to compression energy**

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

# Outline.

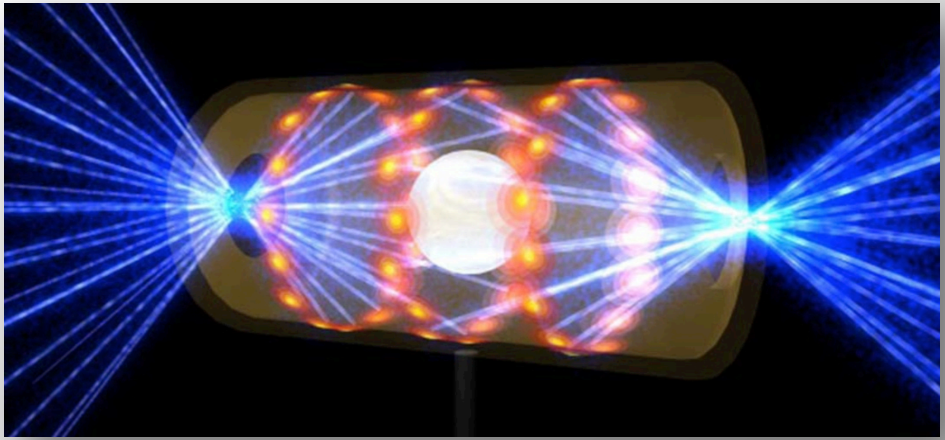
**I. Inertia**



- Fusion requires a confined, hot, and dense plasma
- ICF uses the capsule's own inertia for plasma confinement
- Such confinement doesn't last very long
- With short confinement we need to reach very high densities
- Spherical compression is required

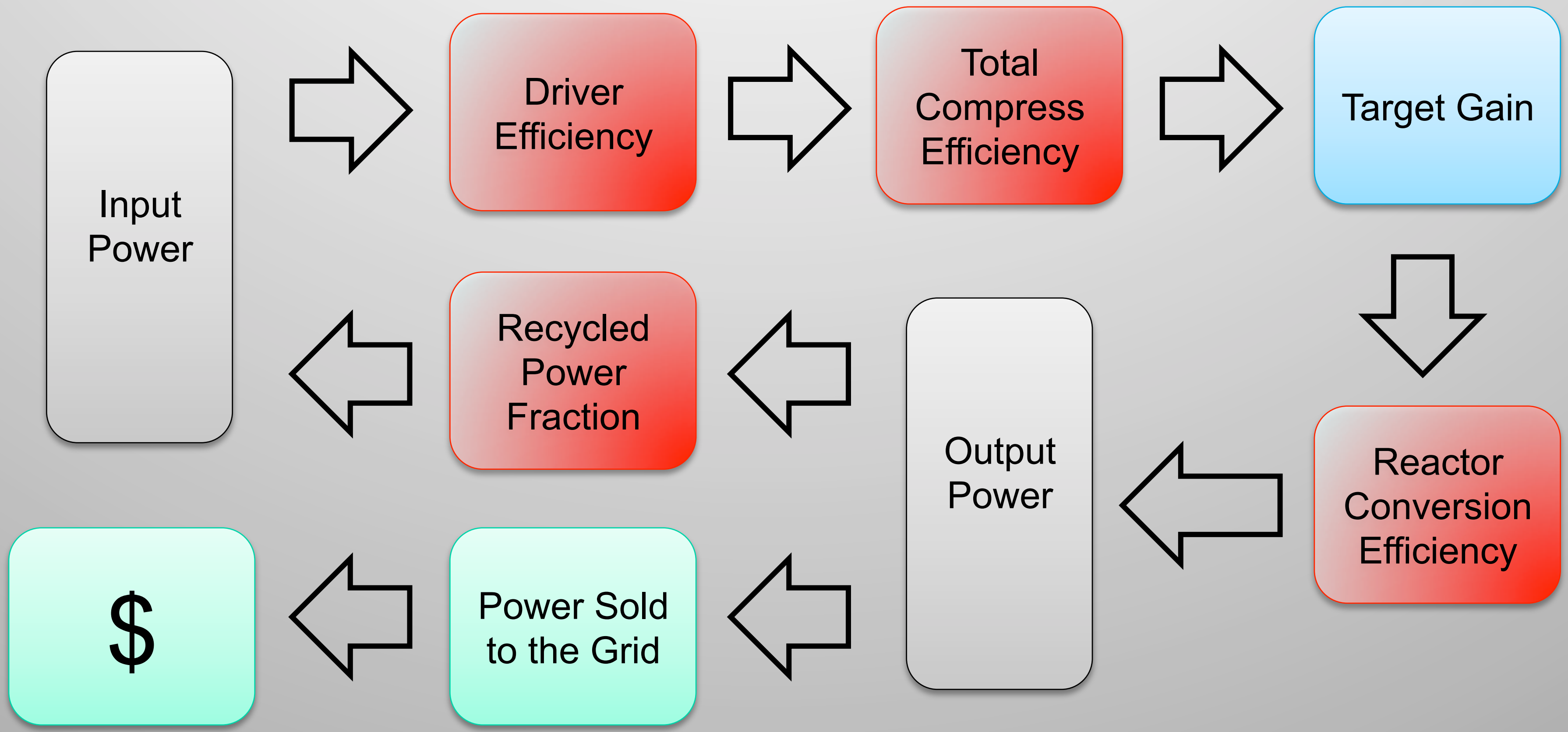
# Outline.

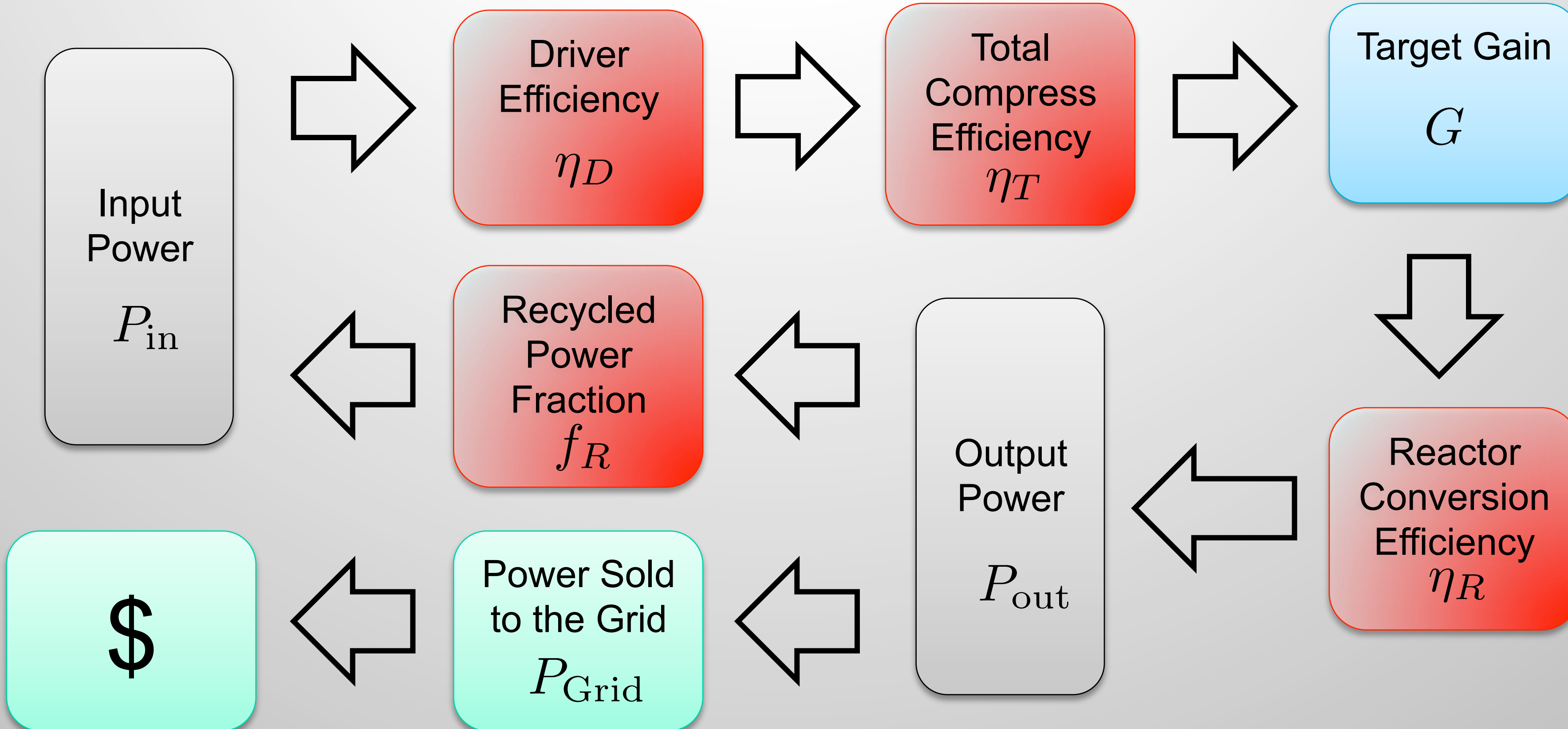
II. Compression



- What is the most efficient way to compress?
- How does the shell compress?
- What are “indirect” and “direct” drive?
- How much energy is necessary?

# The goal is convert driver energy into compression energy as efficiently as possible






$$P_{\text{Grid}} = (1 - f_R)P_{\text{out}}$$

$$P_{\text{in}} = f_R P_{\text{out}} = f_R \eta_R G \eta_T \eta_D P_{\text{in}}$$

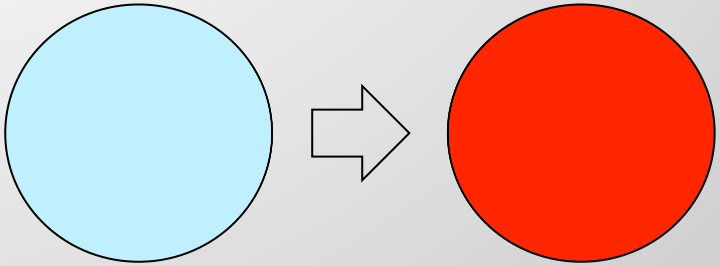
$$\Rightarrow f_R \eta_R G \eta_T \eta_D = 1$$

**If we want:** $f_R < 1/4;\ \eta_R = 0.4$

**We need:** $G \eta_T \eta_D > 10$

# Volumetrically heating DT is not efficient enough

Heating the ball of DT (one D, one T, two electrons) to 10 keV costs about



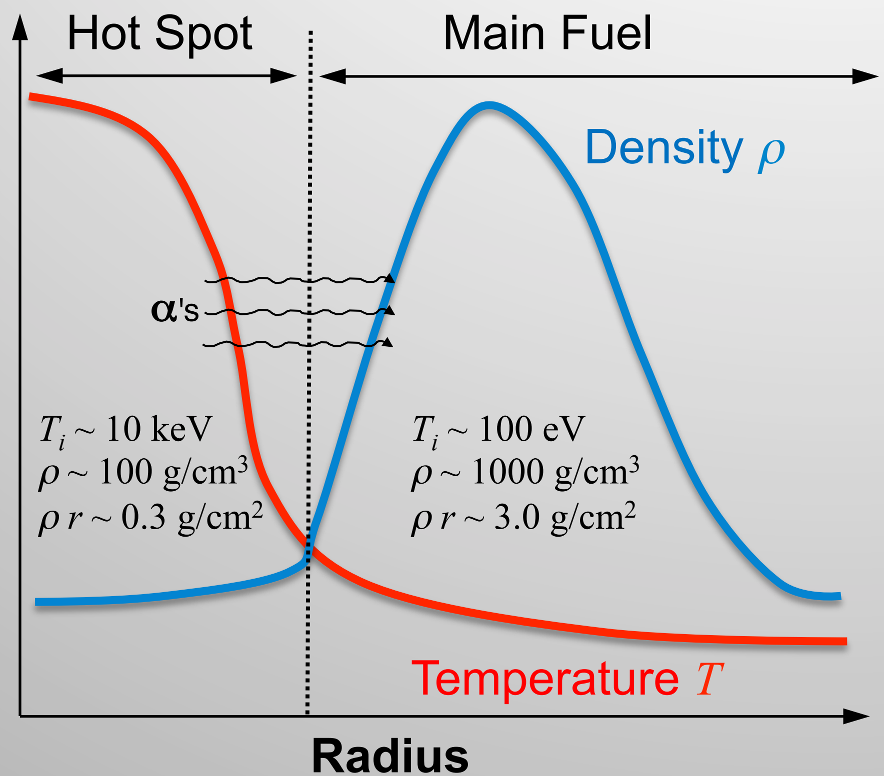
$$n\frac{3}{2}kT/M = 4\frac{3}{2}\left[10\ \mathrm{keV}\right]/\left[5\ \mathrm{amu}\right] = 10^9\ \mathrm{J/g}$$

The fusion energy output from burning 1/3 of the DT is

$$\frac{1}{3}\left[3.4\times 10^{11}\ \mathrm{J/g}\right] \simeq 10^{11}\ \mathrm{J/g}$$

Or a total gain of about 100 times the total efficiency of the driver/capsule compression, which is ~<10 %. Total gain: <10. How can we do better?

# Compression can get higher gain: "Hot Spot Ignition"




**Don't heat all of fuel; compress center.**

$PdV$ **work on low-density central region ("hot spot") naturally heats it to** $T_i \sim 10$ keV

**If hot spot** $\rho r > 0.3$ g/cm$^2$, **α particles bootstrap temperature to** $T_i \sim 100$ keV

**Thermonuclear burn wave propagates into cold main fuel and gives high yield**

**Total energy is now dominated by compression energy instead of heating energy and the gain can be much higher**

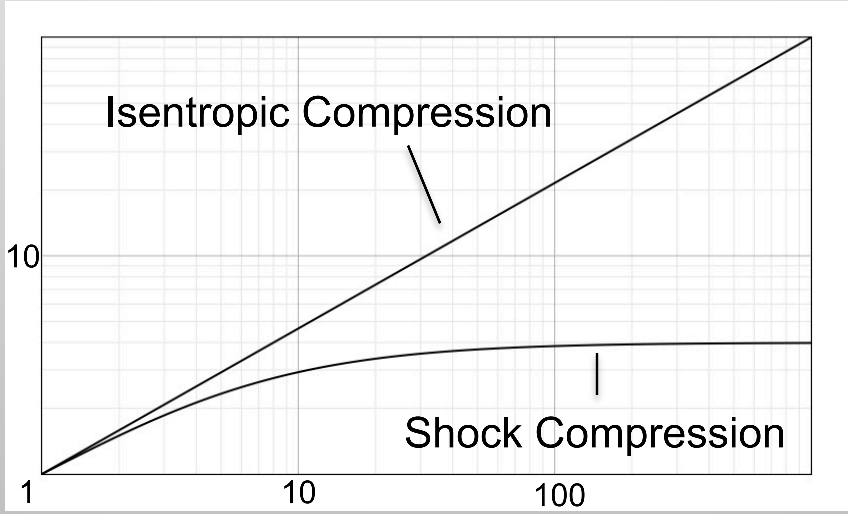
# The most efficient compression is isentropic

$$dU = TdS - PdV$$

$$-PdV = dU - TdS$$

**Minimize Work Needed to Compress** ⇔ **Minimize Entropy Generation**

**Change in Density** $\rho/\rho_0$




**Change in Pressure** $P/P_0$

Classical isentropic compression can reach arbitrarily high densities

# But ICF doesn't have ideal compression

- Fast time-scales lead to shocks, which have compression limits
  - Solution: Multiple timed shocks to keep implosion as efficient as possible. A "shaped" pulse.
- High fuel compression means quantum back-pressure becomes important

Particle occupies a minimum phase space volume

$$\Delta x^3$$

$$\Delta p^3$$

Uncertainty Principle

$$\Delta p \geq h/\Delta x$$

Minimum Kinetic "Fermi" Energy

$$\epsilon_F \simeq \frac{\Delta p^2}{2m}$$

# The Fermi energy sets the minimum energy needed to compress

$$\epsilon_F \simeq \frac{\Delta p^2}{2m} = \frac{h^2}{2m}\frac{1}{\Delta x^2} = \frac{h^2}{2m}\frac{1}{(V/N)^{2/3}}$$

$$P_F \sim \frac{N\epsilon_F}{V}$$

$$\sim \frac{h^2}{2m}\left(\frac{N}{V}\right)^{5/3}$$

$$\epsilon_F \propto \rho^{2/3}$$

$$P_F \propto \rho^{5/3}$$

For DT: $P_F\ [\mathrm{Mbar}] = 2.2\rho^{5/3}\ [\mathrm{g/cm^3}]$

# During compression, we want to minimize deviations from isentropic compression

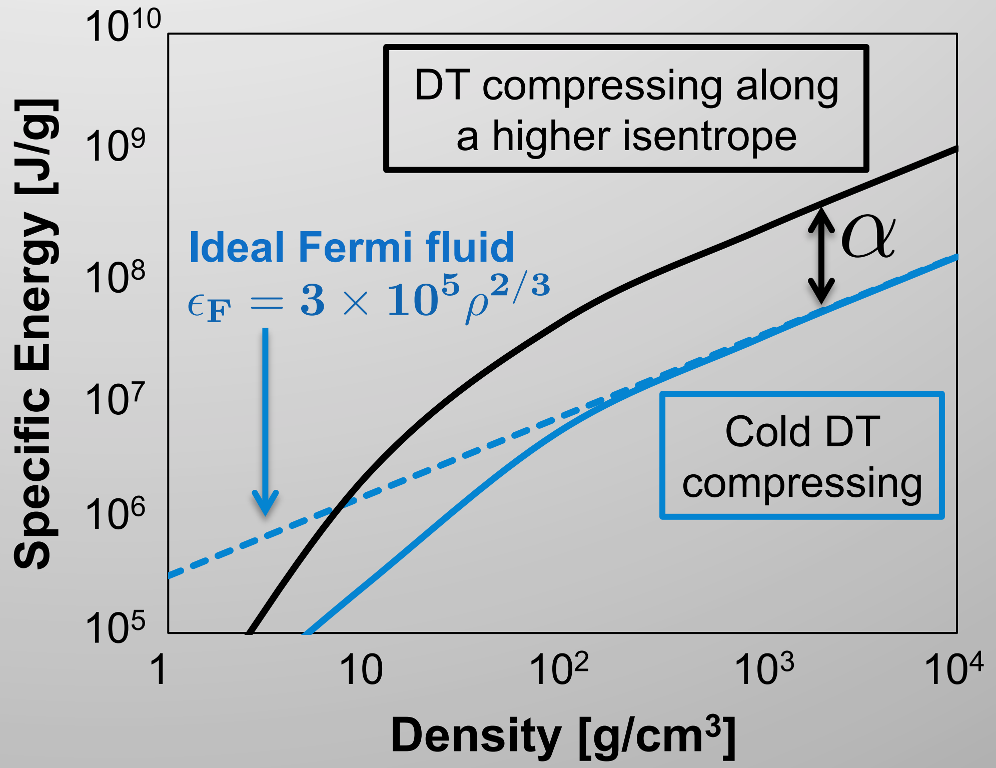
Deviations are measured with the *isentrope parameter*

$$\alpha = P(\rho, T)/P_F(\rho)$$

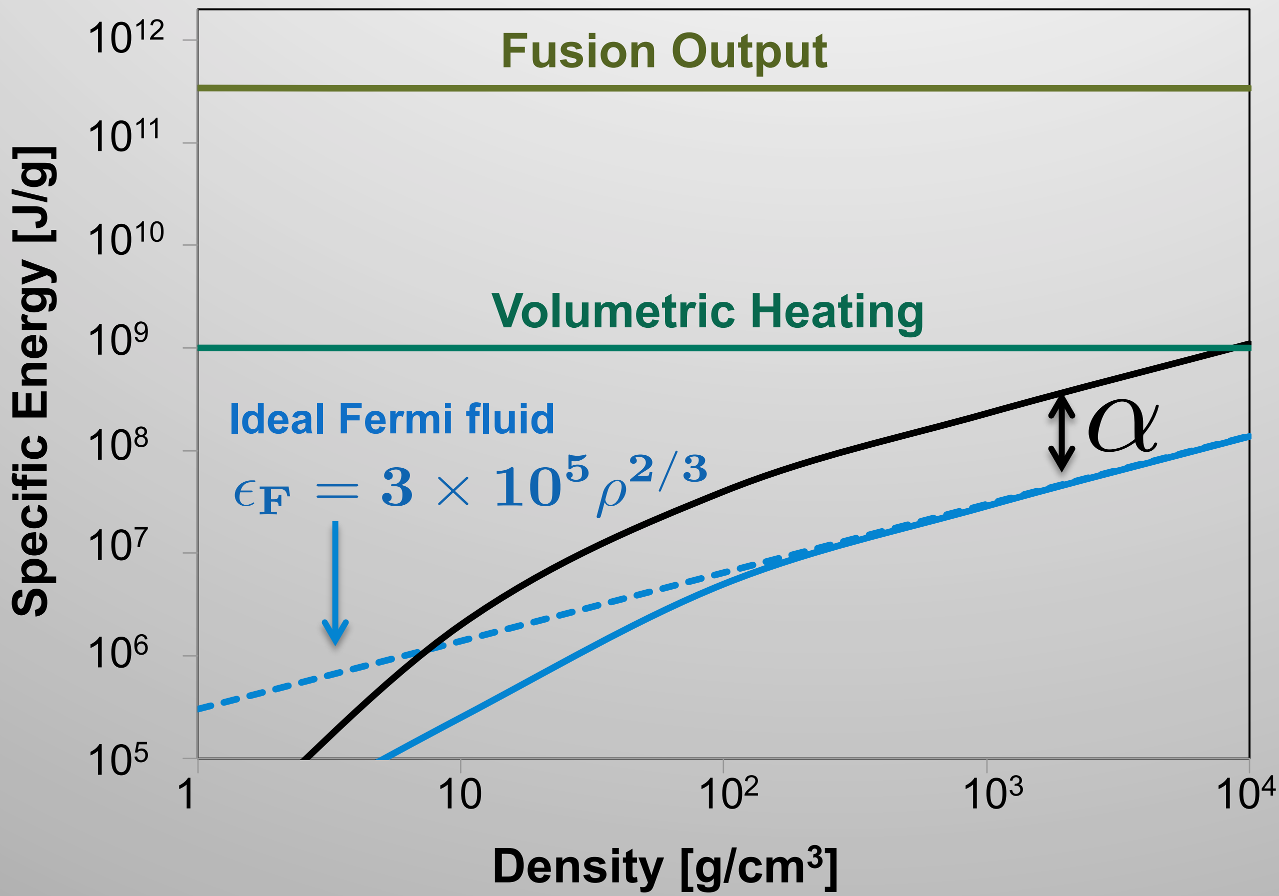
Compressions with lower values of $\alpha$ are more efficient.

$$\epsilon = \alpha\ \epsilon_F$$

$$= \alpha \left[3 \times 10^5 \rho^{2/3}\right]$$



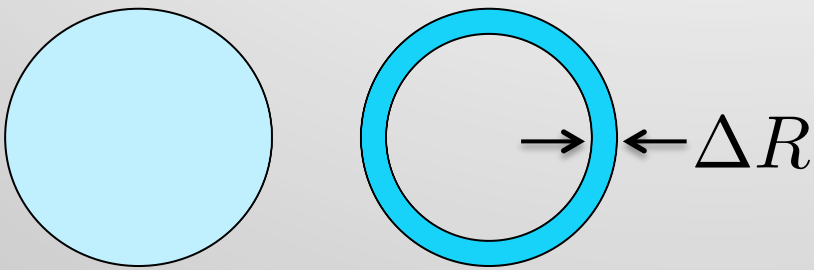
# Compression costs less energy than volumetric heating, if α stays low




Energy cost is 100x less at $10^3$ g/cm$^3$

# Hollow shells of DT ice have advantages for compression

- Require less pressure to accelerate than spheres

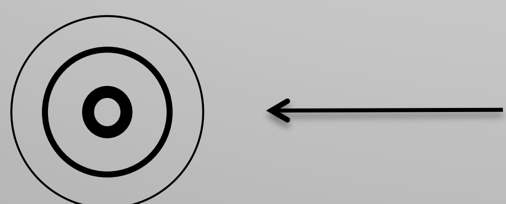



A shell has greater surface area / mass ratio

$$P \propto v_{\mathrm{imp}}^2 \Delta R / R$$

- Easier to compress isentropically

$$\alpha \propto P_0 / \rho_0^{5/3}$$ ← Maximize initial density: solid ice



Converging shocks strengthen, create more entropy: shock fuel at large radius

# What velocity is required to compress 1000x?

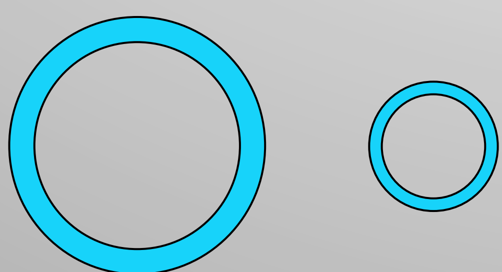
$$\frac{1}{2} M v_{\rm imp}^2 = E_{\rm comp} = M\epsilon$$

$$\Rightarrow v_{\rm imp} \simeq 3.5 \times 10^6 \rho^{1/3} \alpha^{1/2} \text{ cm/s}$$

$$\simeq 3.5 \times 10^7 \text{ cm/s}$$

**350 km/s > 780,000 mph**
**Earth orbital speed: 30 km/s**

$$\rho = 10^3 \text{ g/cm}^3; \; \alpha = 1$$



**Implosions reach peak velocity at ~ half initial radius**

**At 1/2 radius, 1/8 volume**
**Smaller radius, smaller volume, less potential for PdV work**

# What pressure is required to compress 1000x?

$$\frac{1}{2}Mv_{\mathrm{imp}}^2 = P\Delta V$$

$$\frac{1}{2}\left[\rho_{\mathrm{init}}4\pi R^2\Delta R\right]v_{\mathrm{imp}}^2 = P\frac{4\pi}{3}\left[R^3 - \left(\frac{R}{2}\right)^3\right]$$

$$\Rightarrow P \simeq 300\Delta R/R \text{ Mbar}$$

$$= 60 \text{ Mbar}; \;\; \Delta R/R = 1/5$$

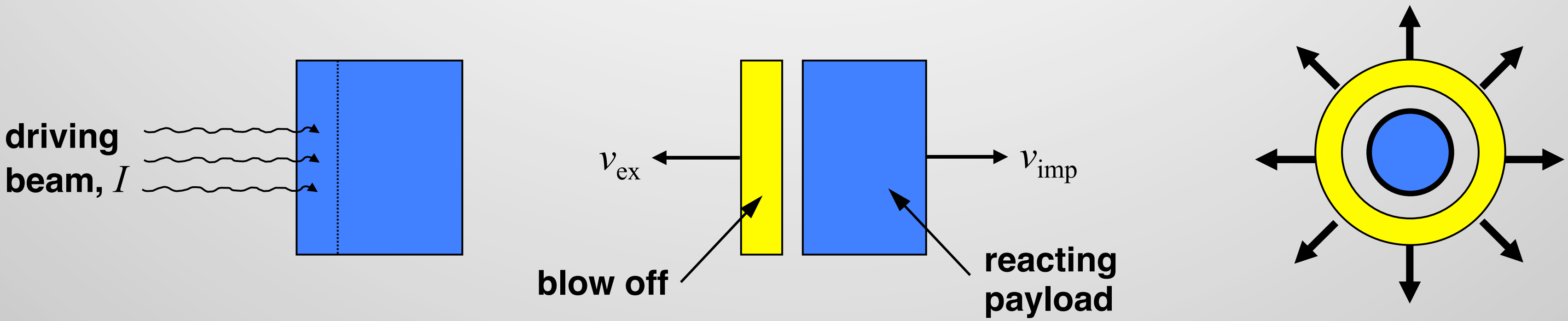
**The stagnation pressure is much higher than the driving pressure: Convergence is Crucial**

$$P_{\mathrm{final}} \;[\mathrm{Mbar}] \simeq 2.2\rho^{5/3} \;[\mathrm{g/cm}^3] \simeq 10^5 \text{ Mbar} \gg 60 \text{ Mbar}$$

$$\rho = 10^3 \text{ g/cm}^3$$

# ICF is actually rocket science!

**Ablation-driven compression works like a rocket — conservation of momentum — but in spherical geometry**




## Exhaust Velocity

$$v_{\text{ex}} \sim c_s \propto \sqrt{T}$$

$$\Rightarrow I \sim nTv_{\text{ex}} \propto nT^{3/2}$$

$$\Rightarrow T \sim (I/n)^{2/3}$$

$$\Rightarrow v_{\text{ex}} \sim c_s \propto (I/n)^{1/3}$$

## Payload Velocity

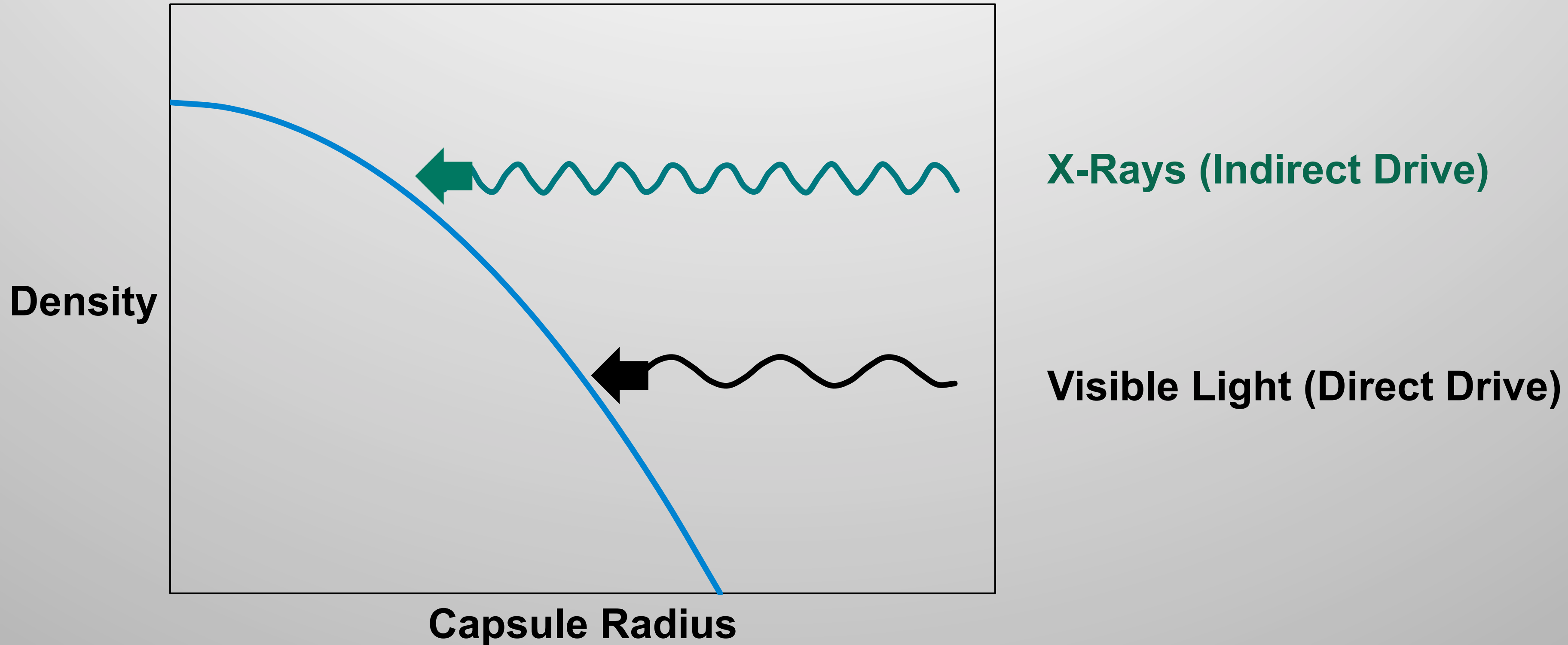
$$m\frac{dv}{dt} = v_{\text{ex}}\frac{dm}{dt}$$

$$\Rightarrow v_{\text{imp}} = v_{\text{ex}} \ln X$$

$$\sim (I/n)^{1/3} \ln X;$$

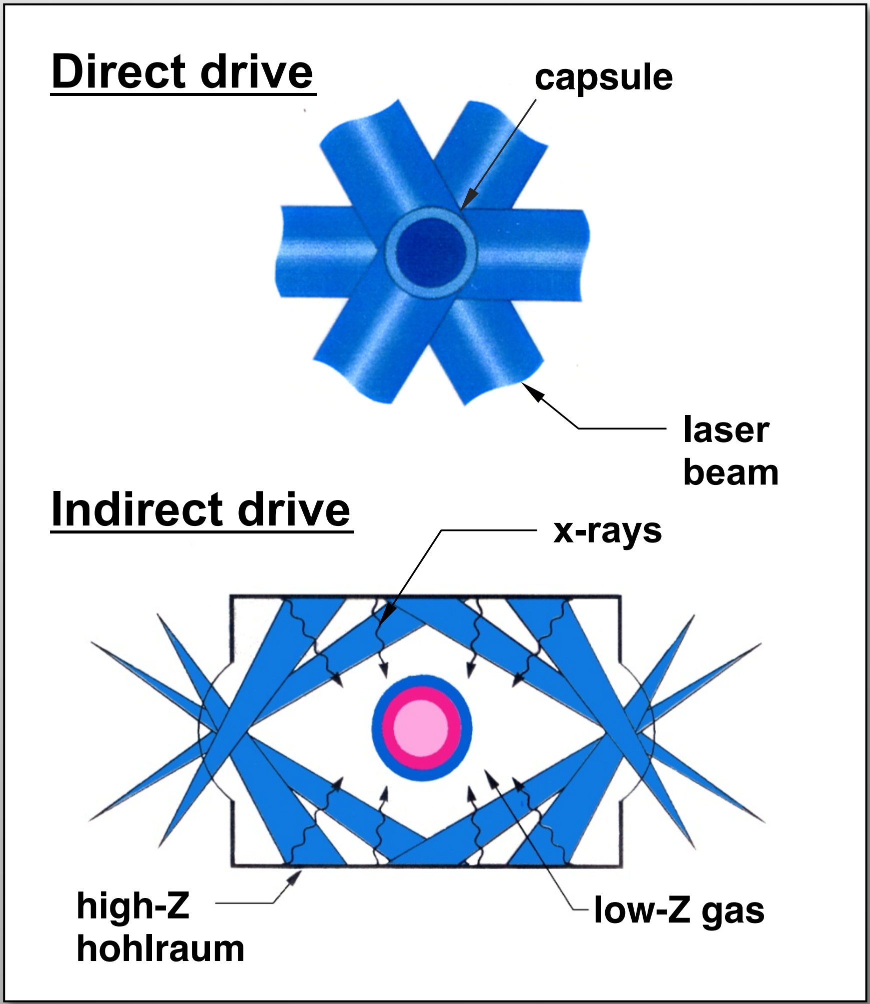
$$X = m_{\text{final}}/m_{\text{initial}}$$

# The absorption density depends on the radiation (plasma physics)




**Higher frequency waves** can penetrate into higher density plasma

# Two approaches to ICF trade efficiency for drive uniformity




Laser beams impinge directly on capsule

High coupling efficiency $\eta_C \sim 80\ \%$

Requires very uniform illumination

Lasers illuminate walls of high-Z enclosure (*hohlraum*), produces soft x-rays that irradiate capsule

Hohlraum smooths some nonuniformity

But significantly reduces coupling efficiency $\eta_C \sim 20\ \%$

# Indirect drive ablates more mass and reaches higher drive pressures

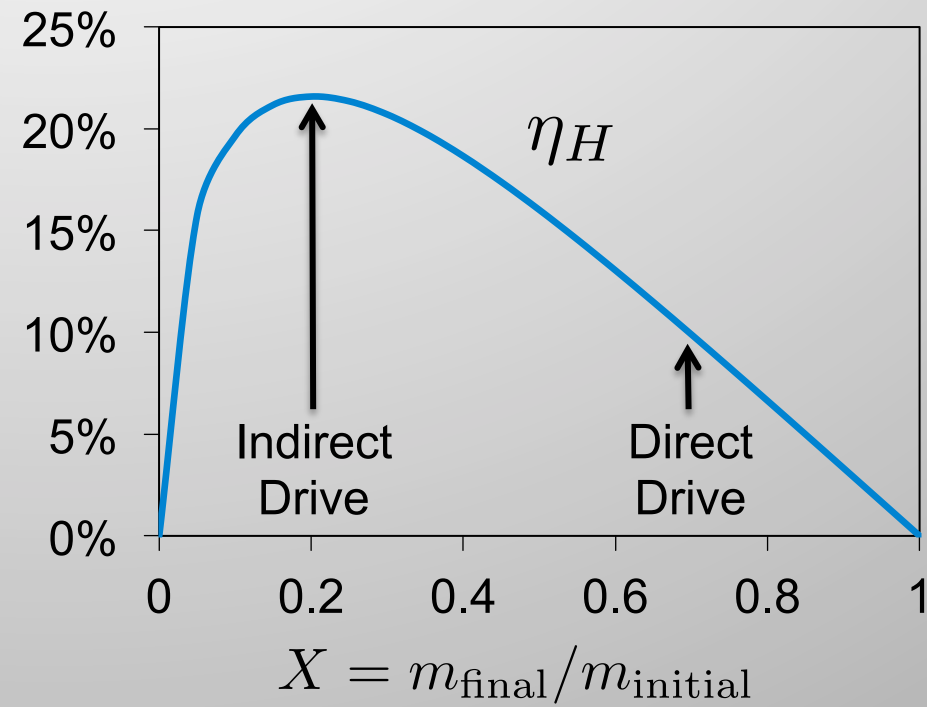
| | Direct drive | Indirect drive |
|---|---|---|
| $v_{imp}$ | $\sim 3\times10^7$ cm/sec | $\sim 3\times10^7$ cm/sec |
| $I$ | $\sim 10^{15}$ W/cm$^2$ | $\sim 10^{15}$ W/cm$^2$ |
| $n_{absorb}$ | $\sim 10^{21}$ cm$^{-3}$ | $\sim 10^{24}$ cm$^{-3}$ |
| $v_{ex} \sim c_s \sim T^{1/2} \sim (I/n)^{1/3}$ | $\sim 10^8$ cm/sec | $\sim 2\times10^7$ cm/sec |
| $P \sim nT \sim n^{1/3} I^{2/3}$ | 90 Mbar | 400 Mbar |
| $v_{imp} \sim v_{ex} \ln X \Rightarrow X$ | 0.7 | 0.2 |

# Indirect drive has a higher hydrodynamic ("rocket") efficiency

## Hydrodynamic Efficiency

$$\eta_H = \frac{\frac{1}{2} m_{\text{final}} v_{\text{imp}}^2}{\frac{1}{2}\left(m_{\text{initial}} - m_{\text{final}}\right) v_{\text{ex}}^2}$$

$$\simeq \frac{1}{3} \frac{X\left(\ln X\right)^2}{1 - X}$$




But this advantage is offset by the lower coupling efficiency

$$\eta_T = \eta_C \cdot \eta_H$$

$$\eta_{\text{direct}} = 0.8 \cdot 0.1 = 8\%$$

$$\eta_{\text{indirect}} = 0.2 \cdot 0.2 = 4\%$$

# Compression and hot spot ignition gives more gain than volume heating

$\epsilon_{DT} = 3.4 \times 10^{11}\ \mathrm{J/g}$ $\epsilon_F = 3.0 \times 10^5 \left(\rho\ \ [\mathrm{g/cm^3}]\right)^{2/3}\ \mathrm{J/g}$ $\epsilon_{\mathrm{Vol.\ Heat}} = 10^9\ \mathrm{J/g}$

$$\overbrace{\eta_C \cdot \eta_H}^{\eta_T} \cdot \overbrace{f \cdot \varepsilon}^{G} = E_{\mathrm{out}}/E_{\mathrm{in}}$$

| | | $\eta_C$ | $\eta_H$ | $f$ | $\varepsilon$ | $E_{\mathrm{out}}/E_{\mathrm{in}}$ |
|---|---|---|---|---|---|---|
| | | | | | $\epsilon_{DT}/\epsilon_{\mathrm{Vol.\ Heat}}$ | |
| Volumetric Heating | direct drive | 0.8 | 0.1 | 1/3 | 340 | 10 |
| | indirect drive | 0.2 | 0.2 | 1/3 | 340 | 5 |
| | | | | | $\epsilon_{DT}/\alpha_F\epsilon_F$ | |
| Hot Spot Ignition | direct drive | 0.8 | 0.1 | 1/3 | $(2\times10^4)/2.0$ | 120 |
| | indirect drive | 0.2 | 0.2 | 1/3 | $(2\times10^4)/1.5$ | 80 |

# About how much energy would you need to do indirect drive hot spot ignition / high gain?

**A simple estimate:**

$$E_{\text{driver}} \cdot \eta_C \cdot \eta_H > E_{\text{comp}} = \frac{1}{2} M v_{\text{imp}}^2$$

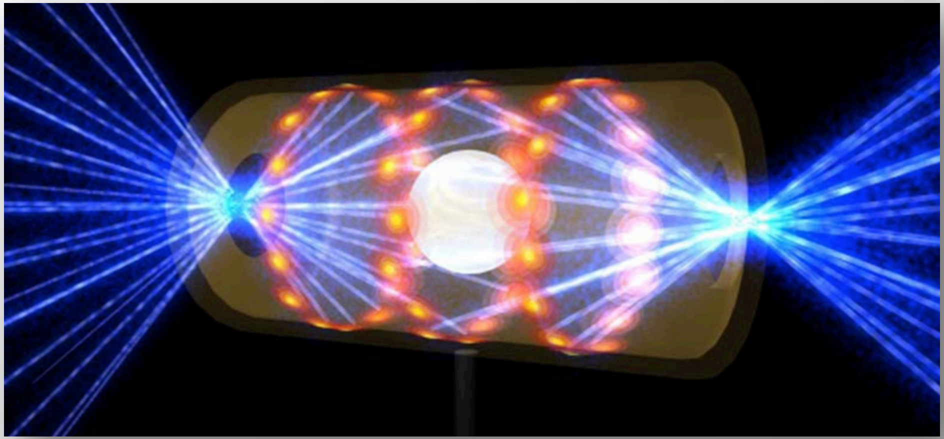
$$\Rightarrow E_{\text{driver}} > \frac{M v_{\text{imp}}^2}{2\eta_C \eta_H} = \frac{\left[1.8 \times 10^{-3}\ \text{g}\right]\left[3 \times 10^{7}\ \text{cm/s}\right]^2}{2 \cdot 0.2 \cdot 0.2}$$

$$\Rightarrow E_{\text{driver}} > 2.0\ \text{MJ}$$

**Numerical simulations show that ignition and high gain are possible with a driver with energy of ~ 1 MJ**

# Outline.

## II. Compression



- Compressing and igniting a central hot spot is more efficient than volumetrically heating the DT
- Low entropy compression is easier
- The capsule is a spherical rocket, uses ablation
- Indirect drive ablates with x-rays, has higher rocket efficiency
- Direct drive ablates directly with lasers, has higher coupling efficiency
- About 1 MJ is necessary for indirect drive hot spot ignition

# Outline.

- What is the National Ignition Facility?
- What are its goals? specifications?
- What does the facility look like?

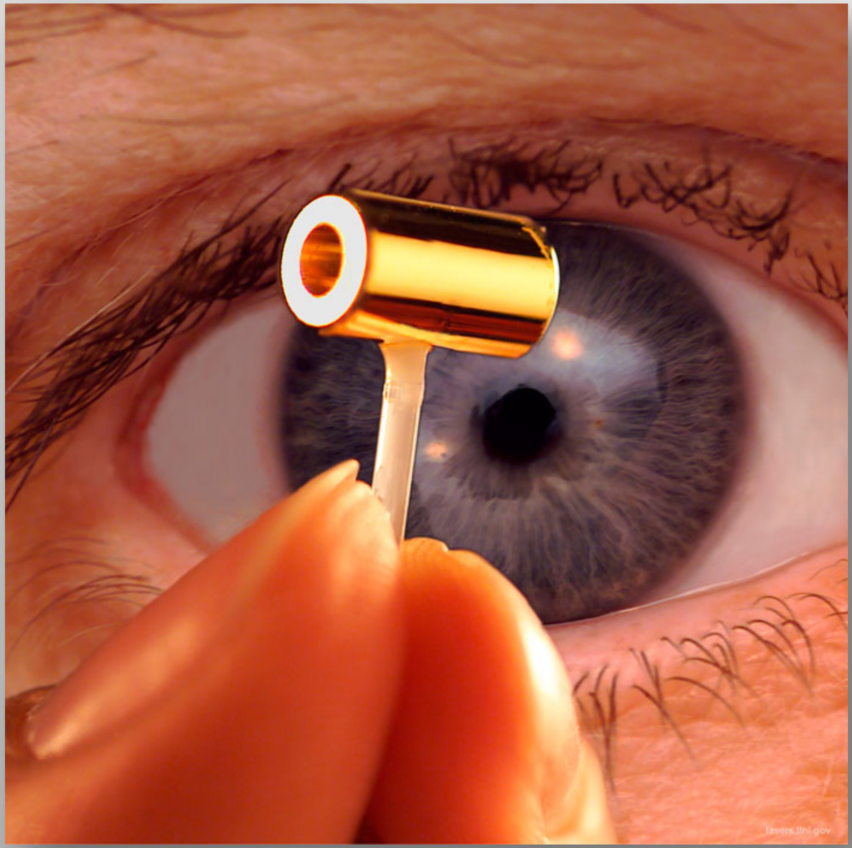
**III. Ignition**

# The National Ignition Facility (NIF) is a 192 beam laser system at Lawrence Livermore National Laboratory

**2009: Dedicated**
**2010: Began Ignition Experiments**
**2013: Transitioned to User Facility**


San Francisco
LLNL
National Ignition Facility
NIF-0605-10997-L50
27EIM/cld

# NIF aims to ignite an indirectly driven ICF capsule



**Direct 192 laser beams into a hohlraum the size of a pencil eraser**

**NIF has delivered over 500 TW of power and 1.8 MJ of energy**

**Typical pulse length is about 20 ns long**

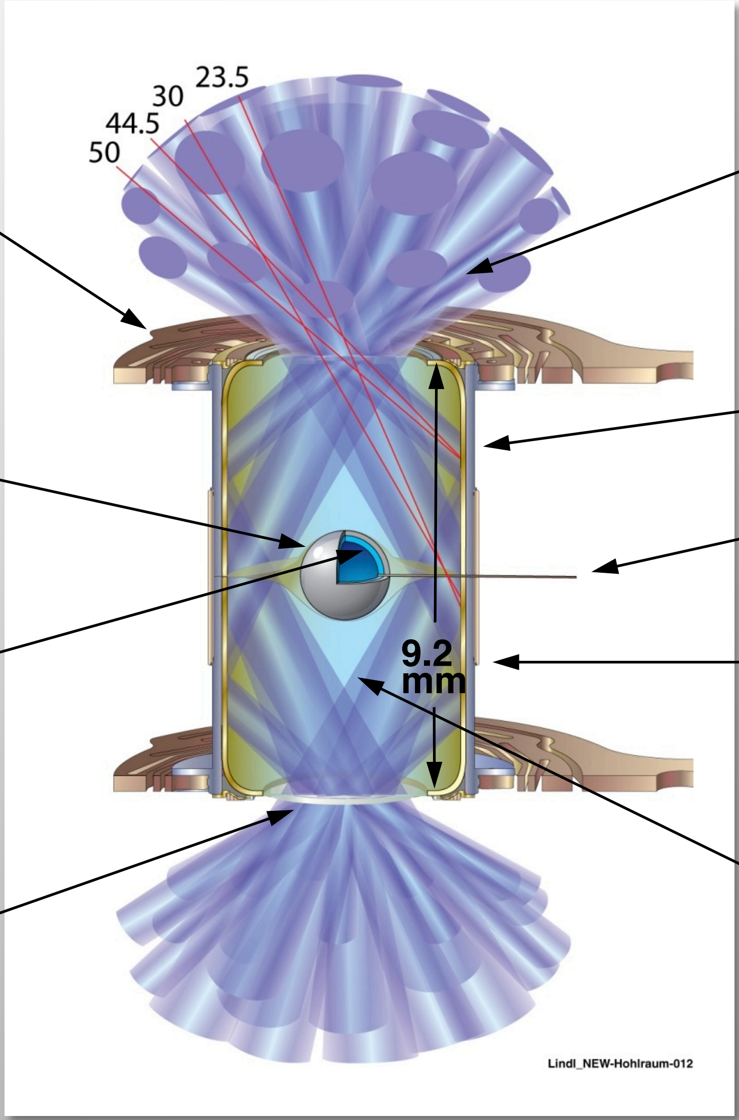
# A NIF Target

Cryo-cooling ring

Capsule (plastic or other)

Solid DT fuel layer

Laser Entrance Hole (LEH) with window




Laser beams (24 quads through each LEH arranged to illuminate two rings on the hohlraum wall)

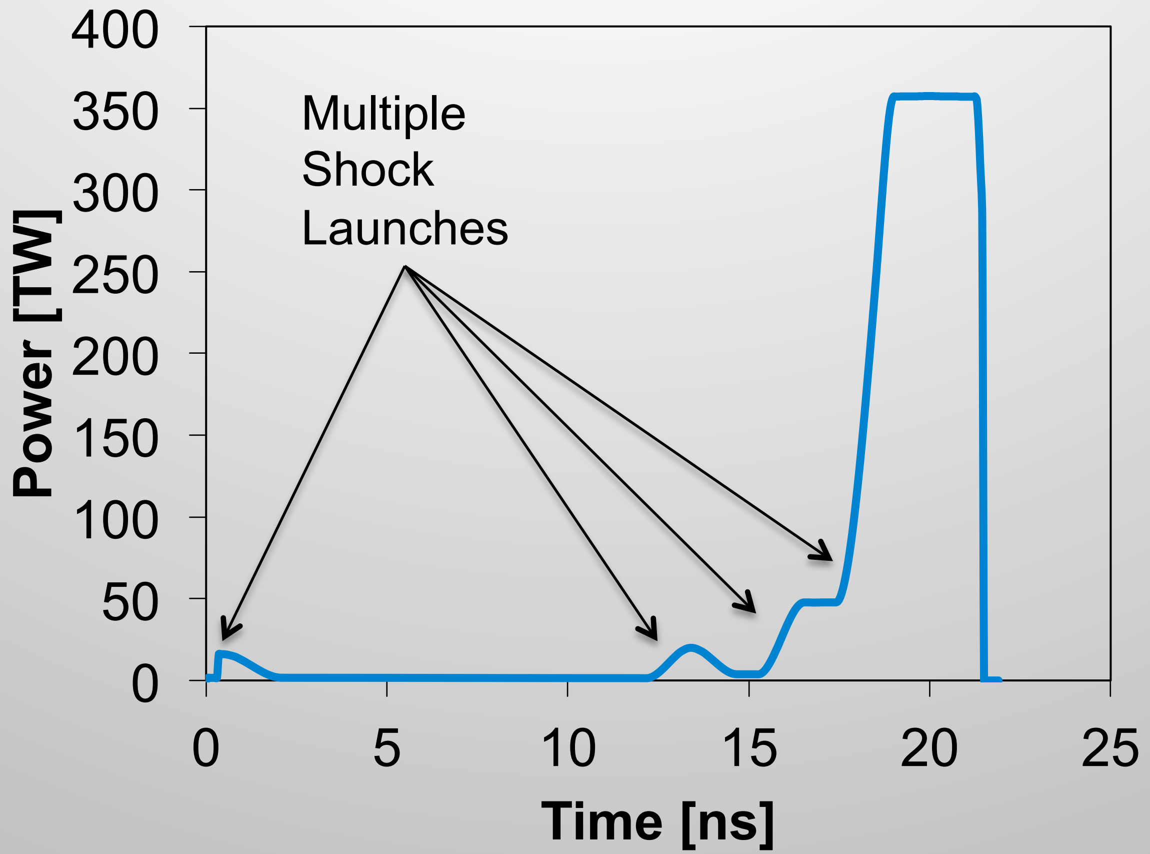
Aluminum assembly sleeve

Capsule fill tube

Hohlraum wall
– High-Z for opacity

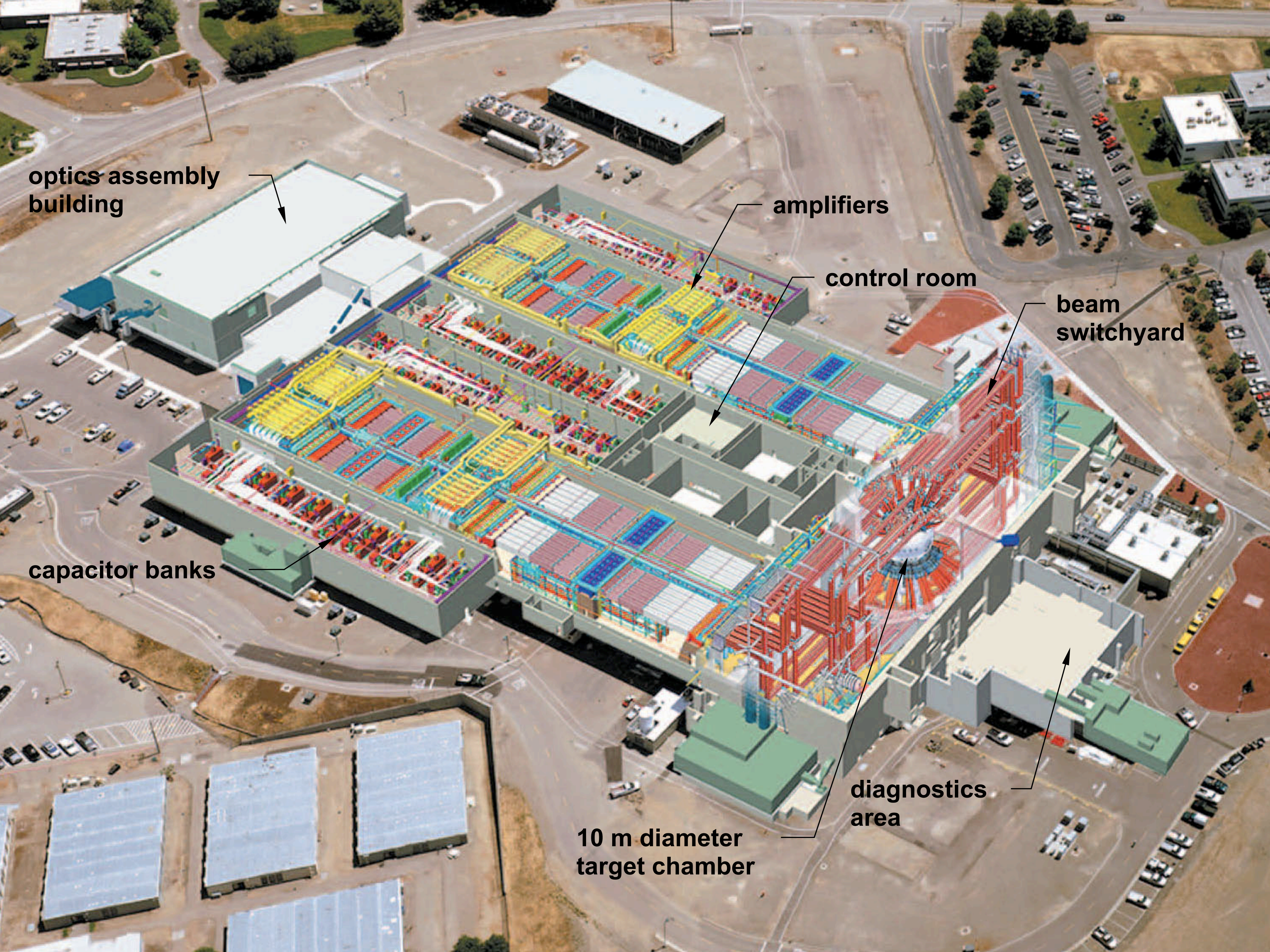
Hohlraum fill
– He gas (1.3 mg/cm$^3$) (or He/H)

# A NIF Laser Pulse

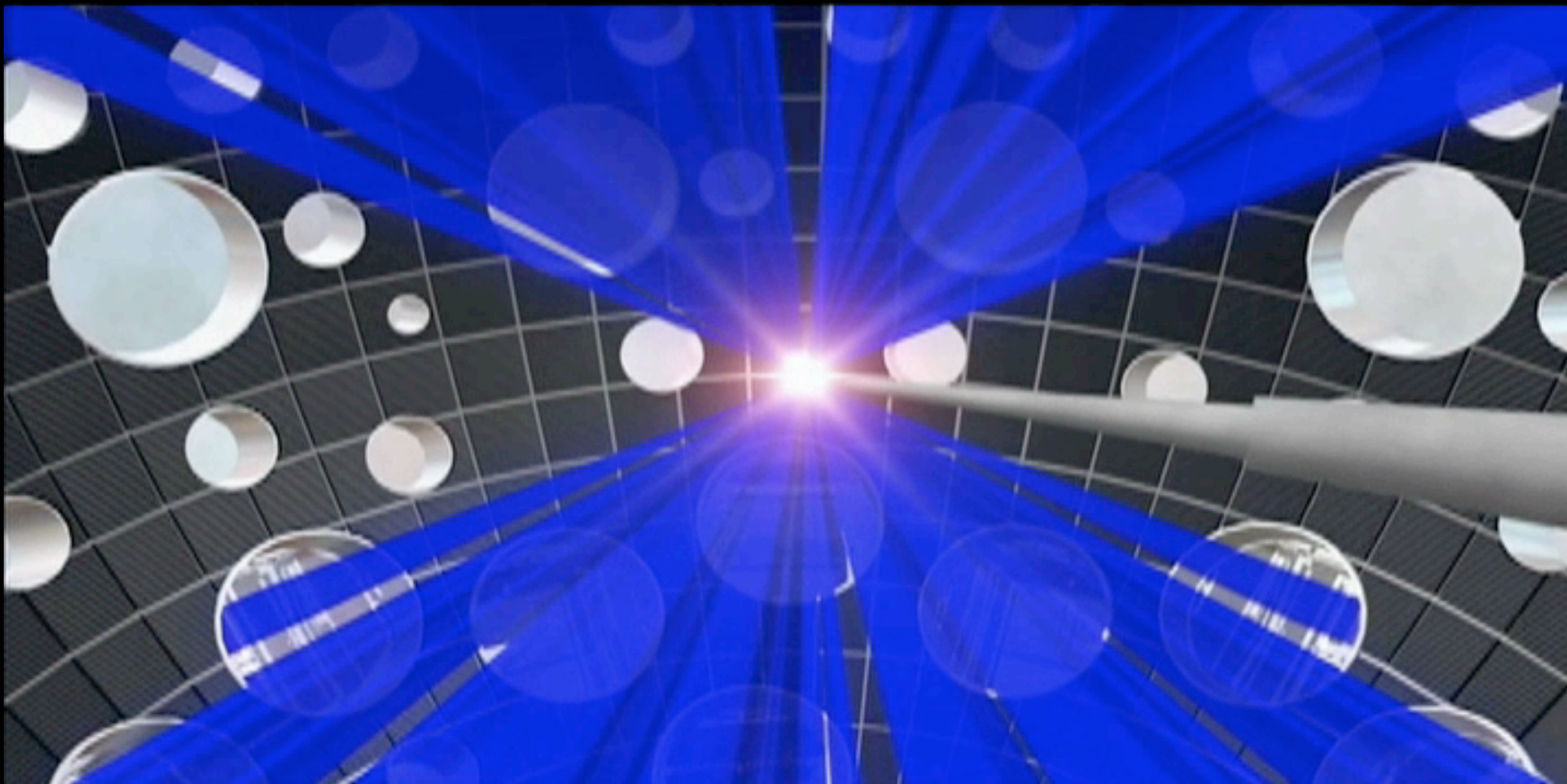



- Multiple, carefully timed shocks
- The whole laser beam is about 20 ns long (or 20 feet in length!)


Cardinal
Stanford
GOLDEN BEARS
CALIFORNIA
Bruins
UCLA

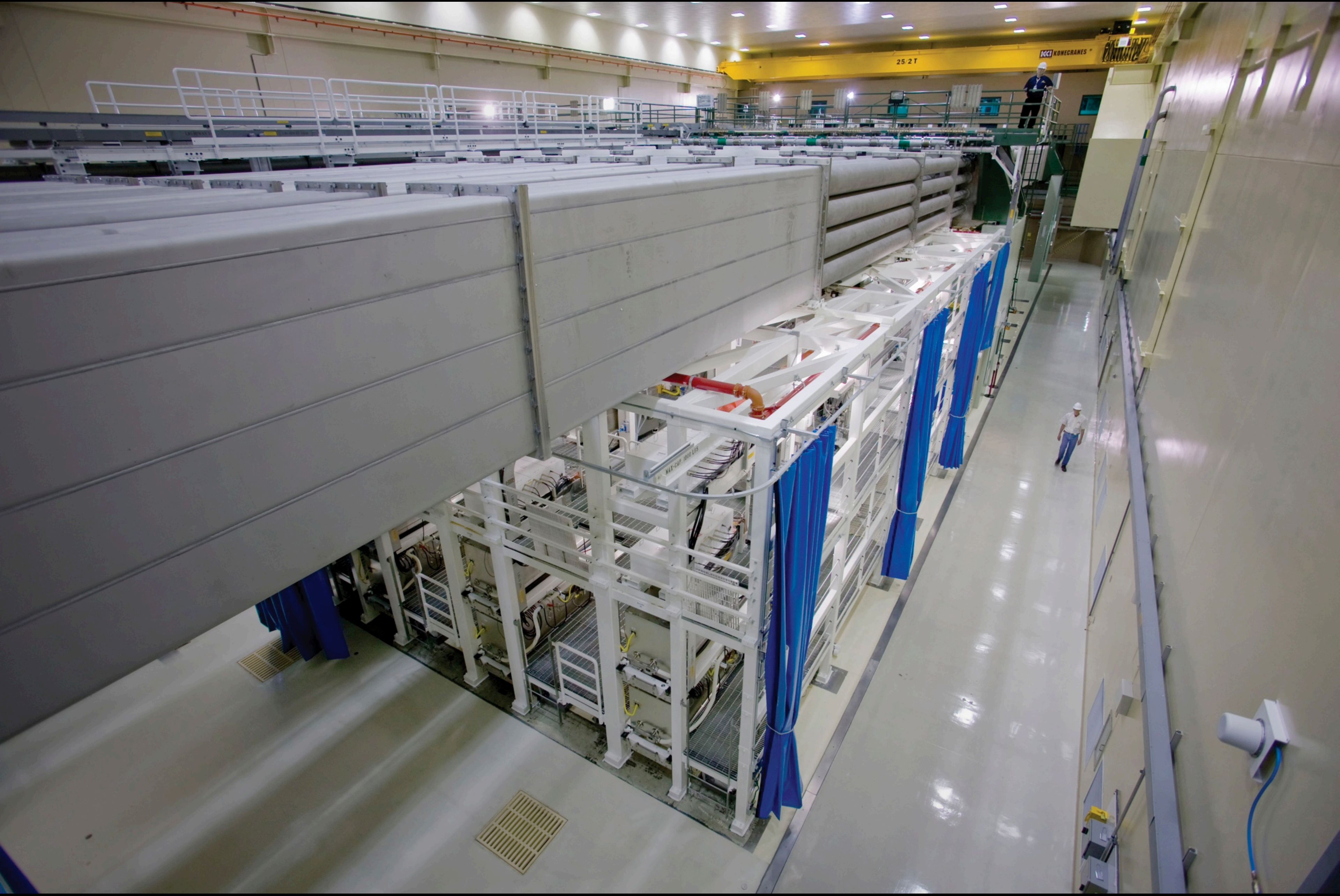

optics assembly building
amplifiers
control room
beam switchyard
capacitor banks
diagnostics area
10 m diameter target chamber

# A NIF Shot

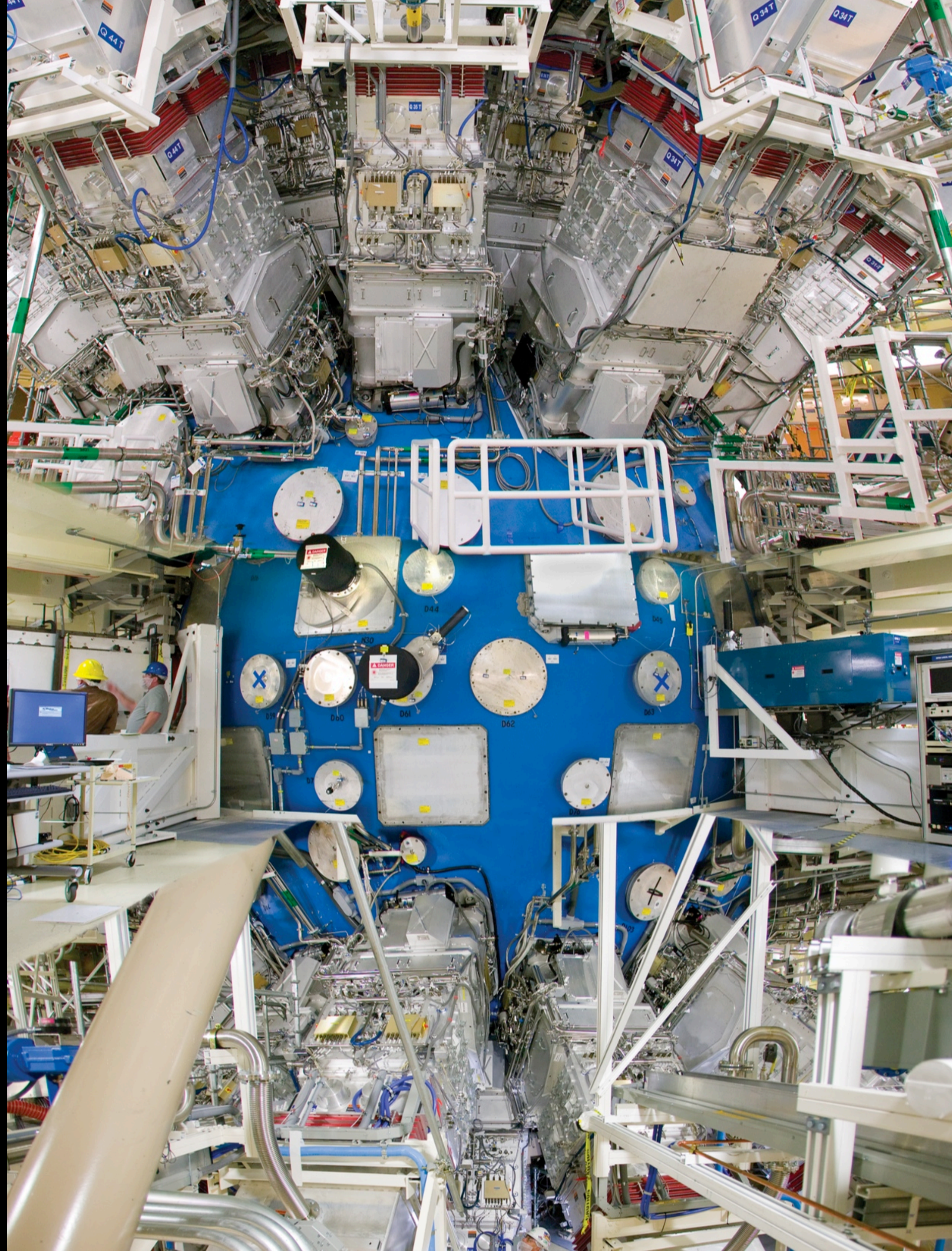


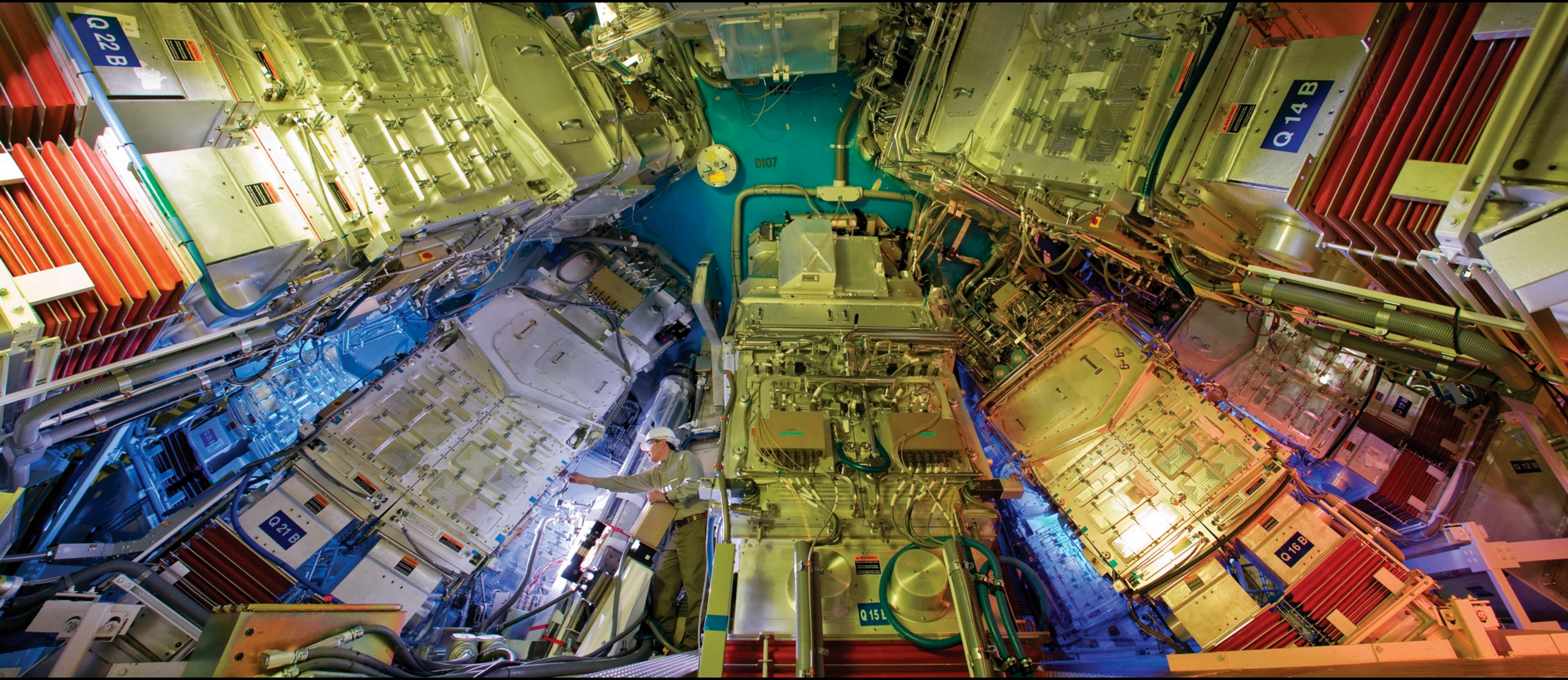
Movie: https://lasers.llnl.gov/media/video-gallery/ride-the-beamline

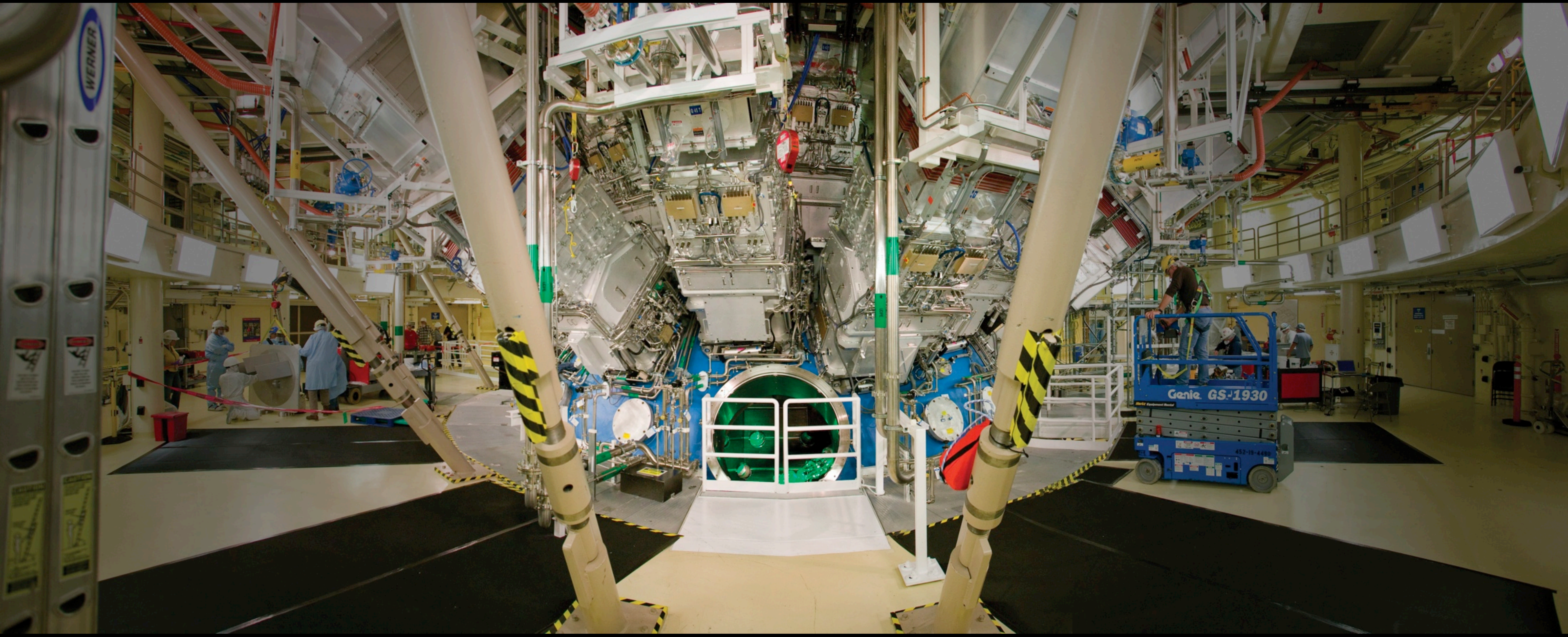

lasers.llnl.gov

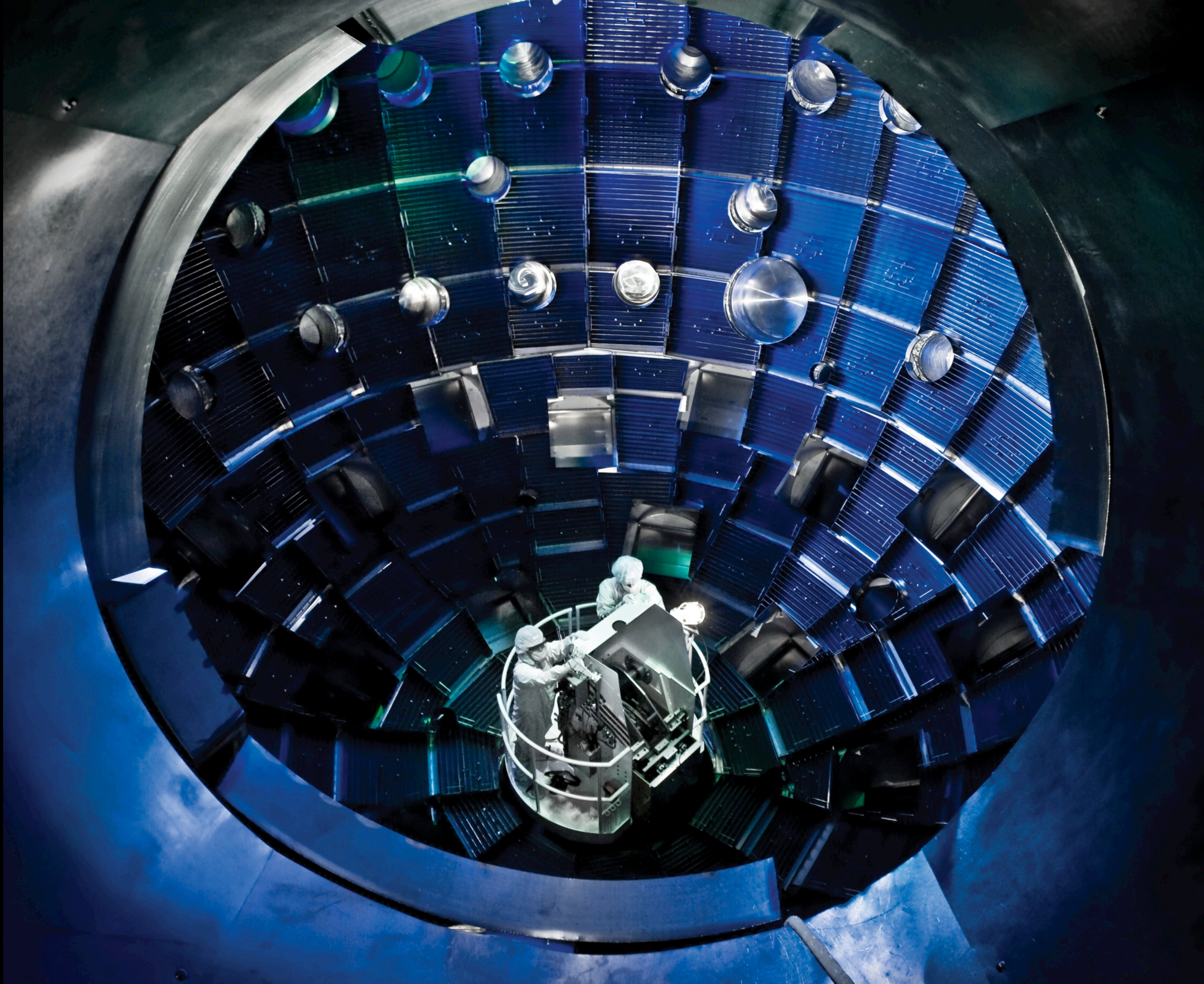

25/2 T
KONECRANES

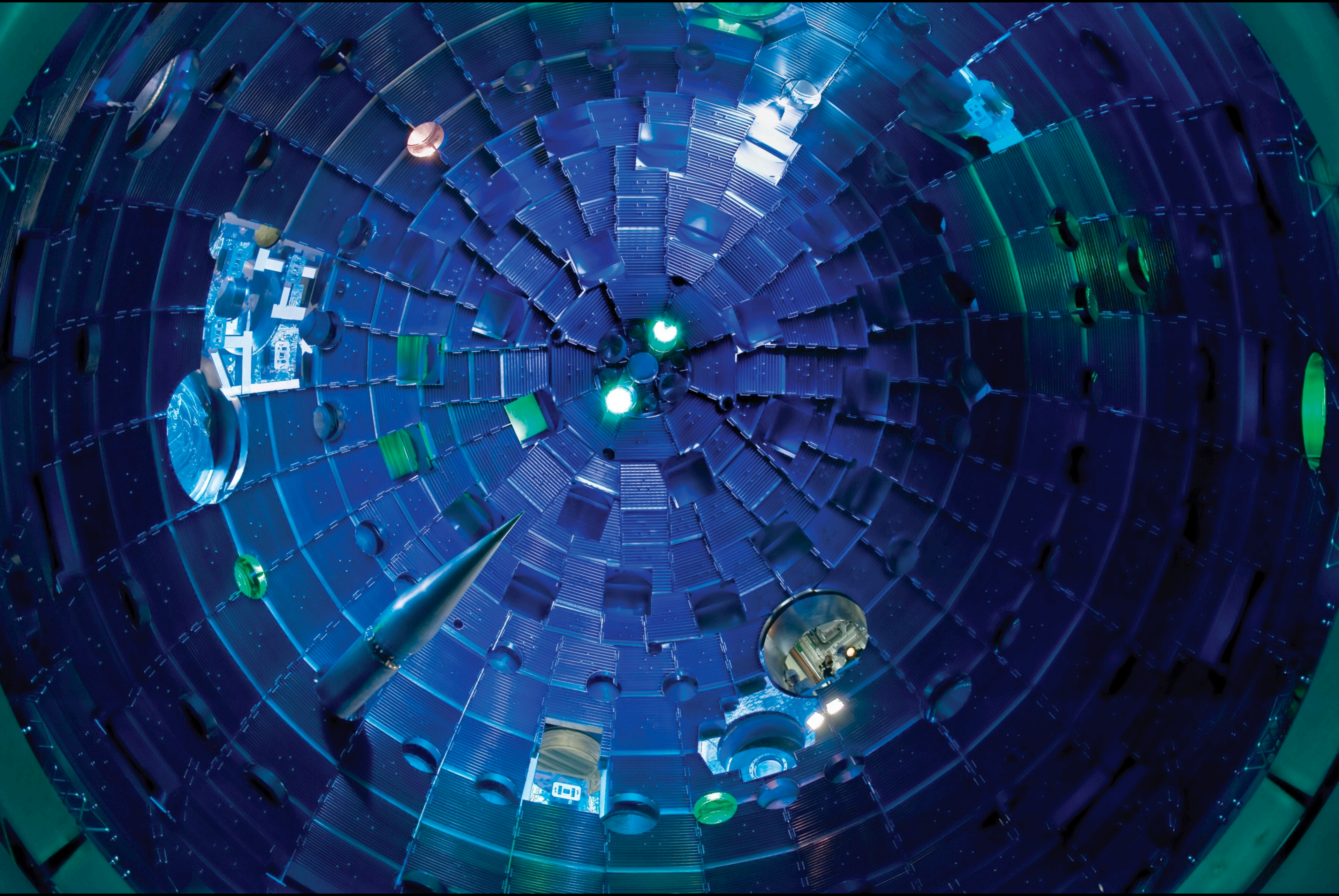

Star Trek into Darkness
Paramount Pictures

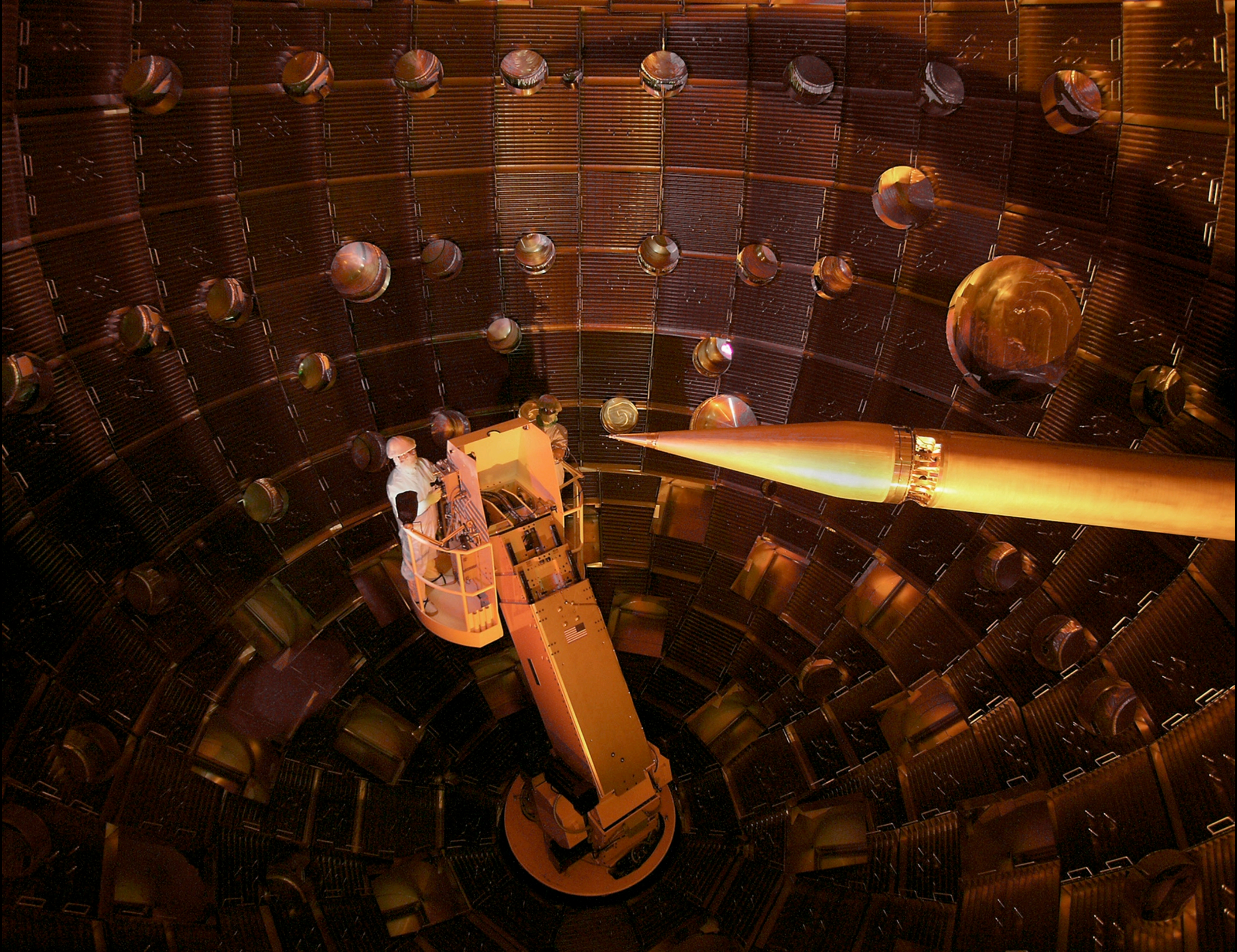

Q 44 T
Q 34 T
D44
D62

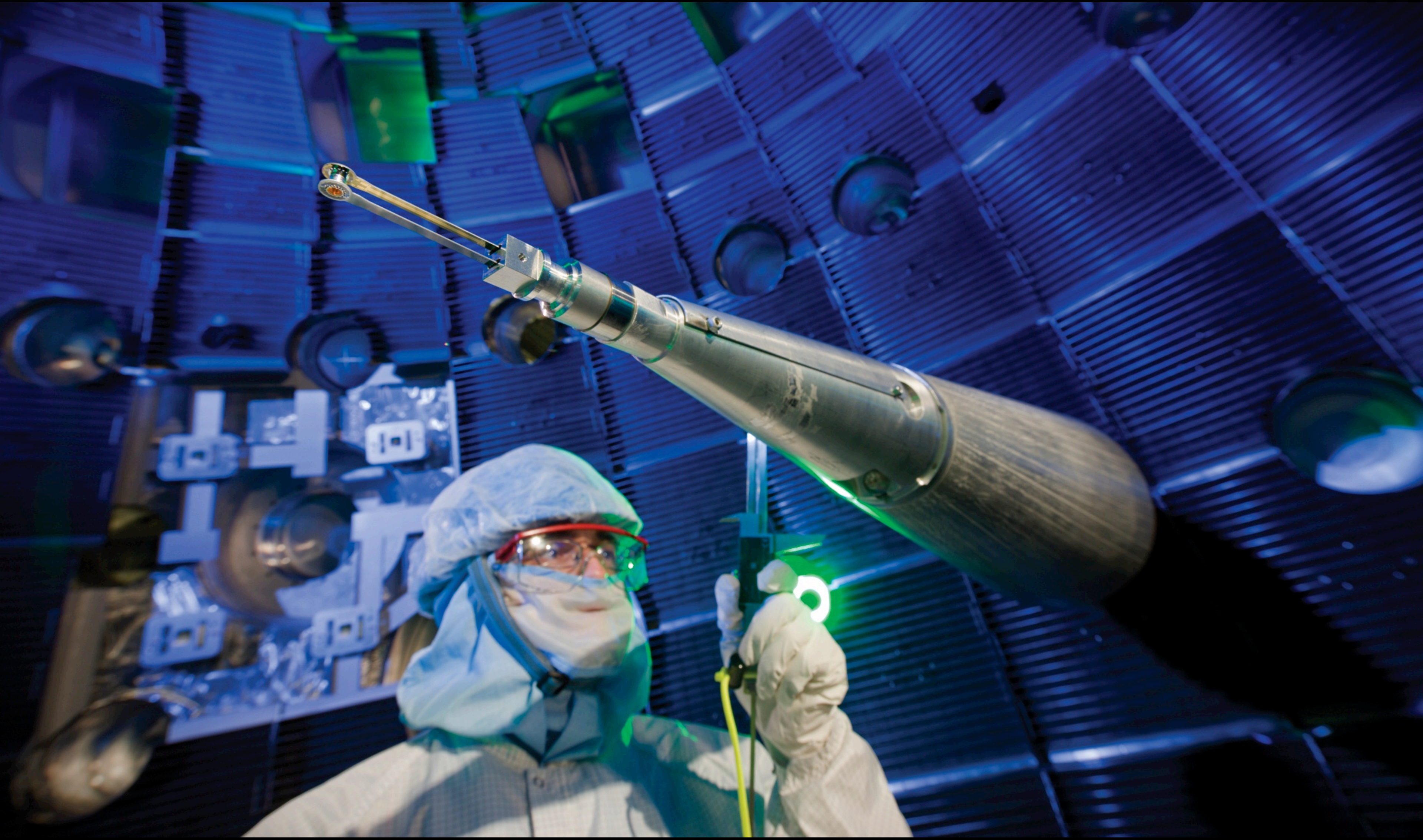

Q 22 B
Q 14 B
D107
Q 21 B
Q 16 B
Q 15 L

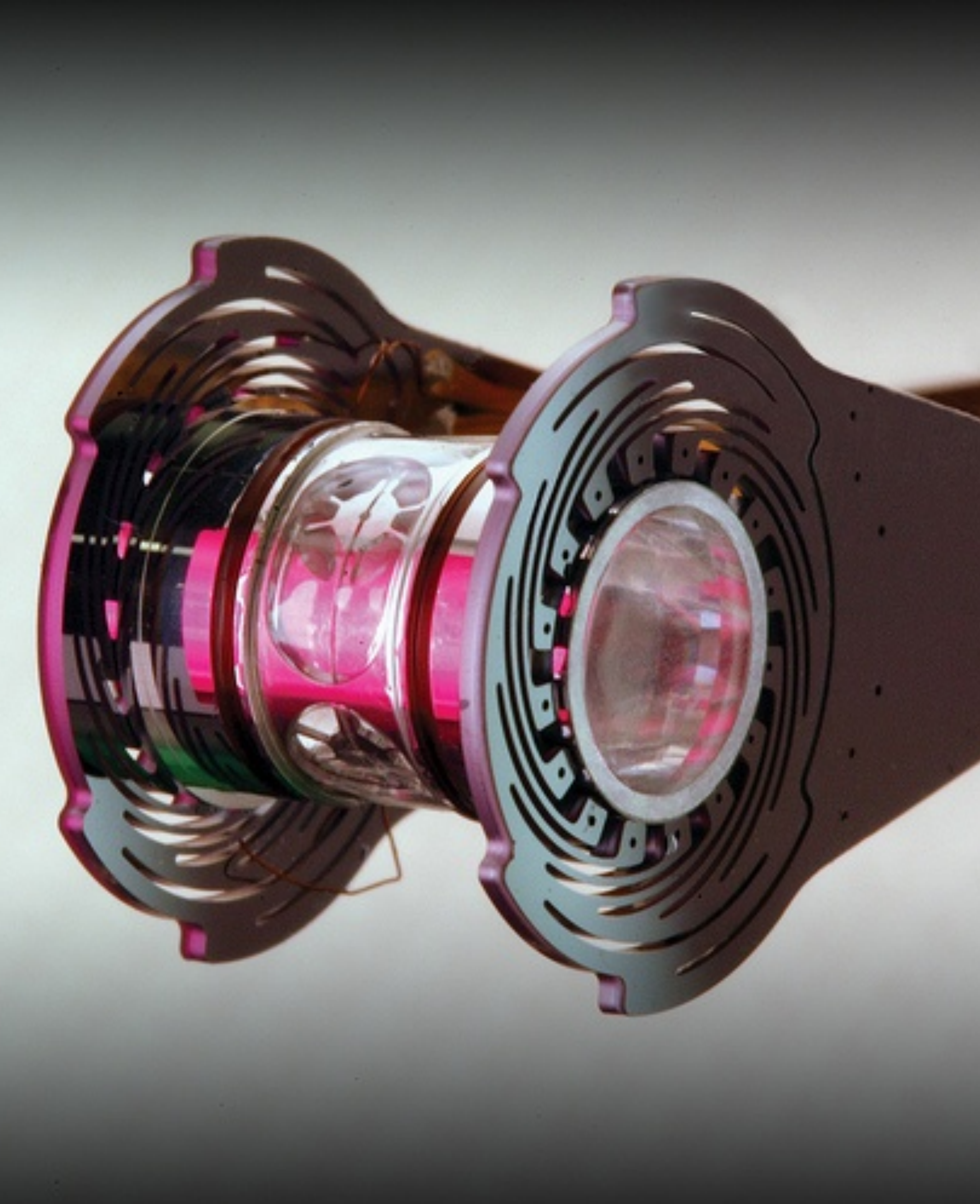
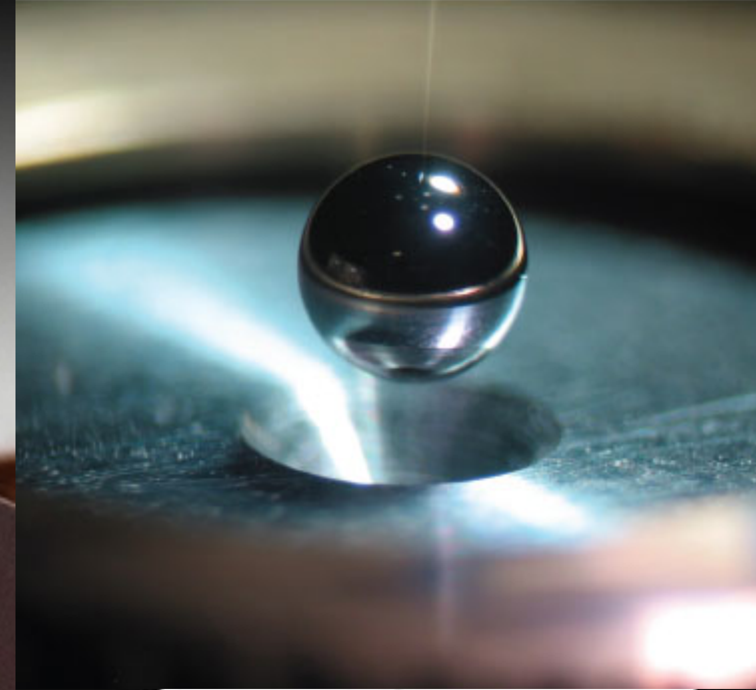

WERNER
Genie GS-1930



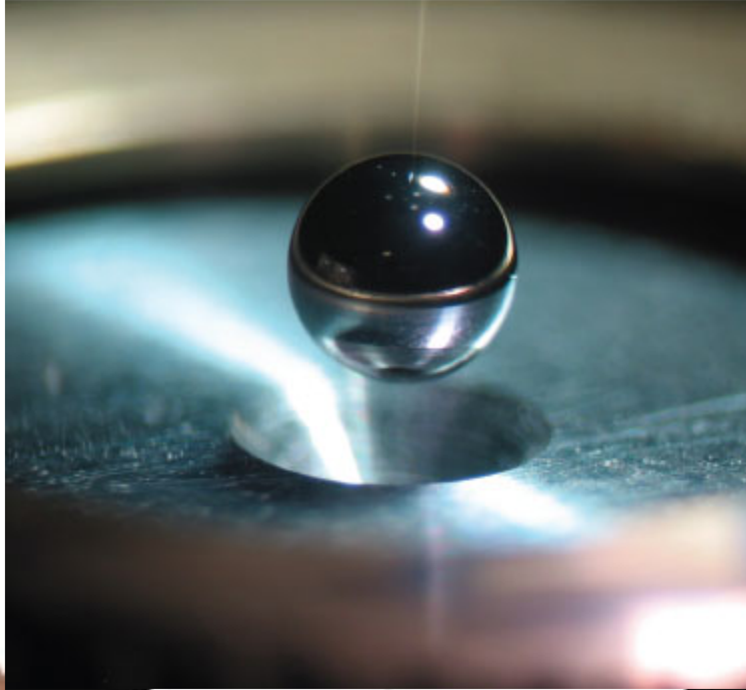
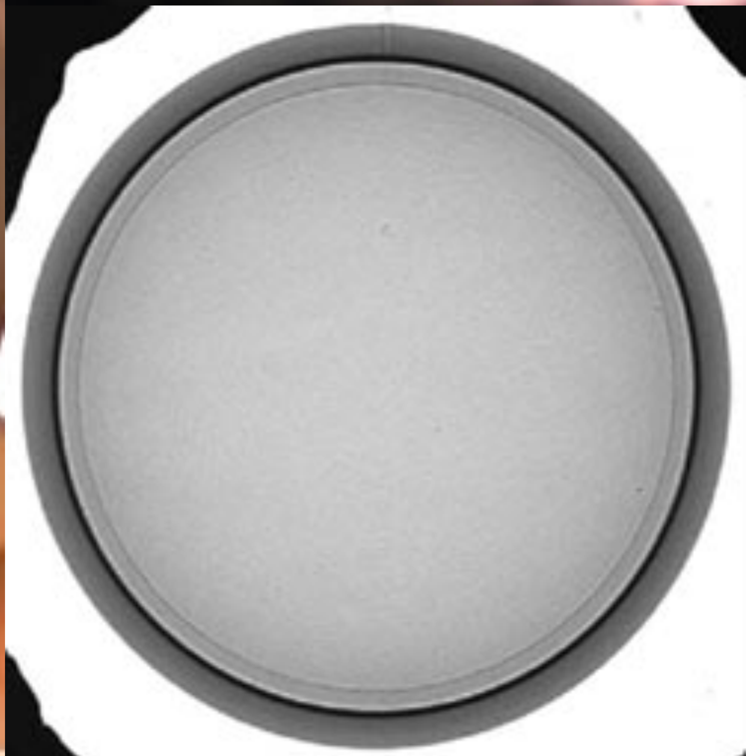


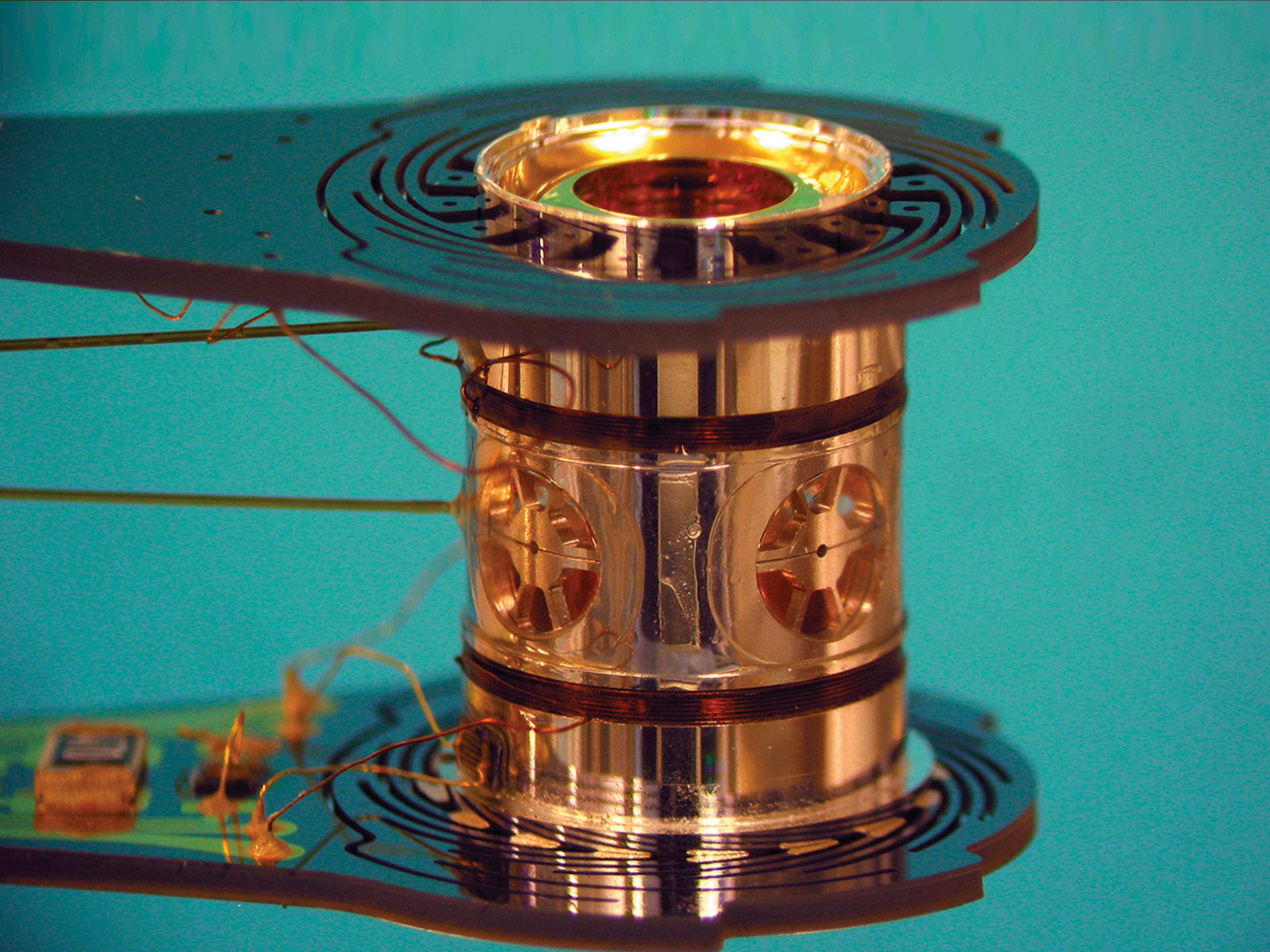








# Outline.

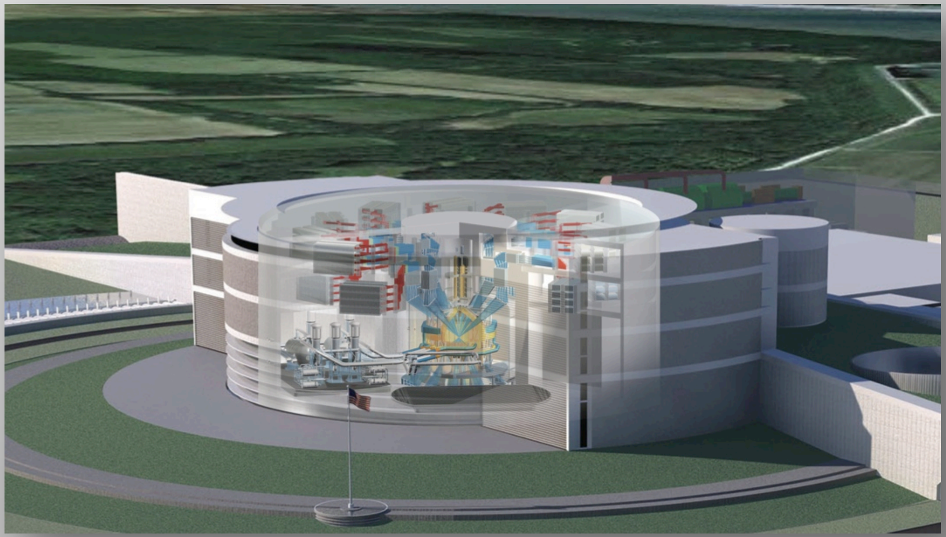
- The National Ignition Facility (NIF) is an inertial confinement fusion facility at Lawrence Livermore National Laboratory
- NIF aims to ignite an indirectly driven capsule

**III. Ignition**

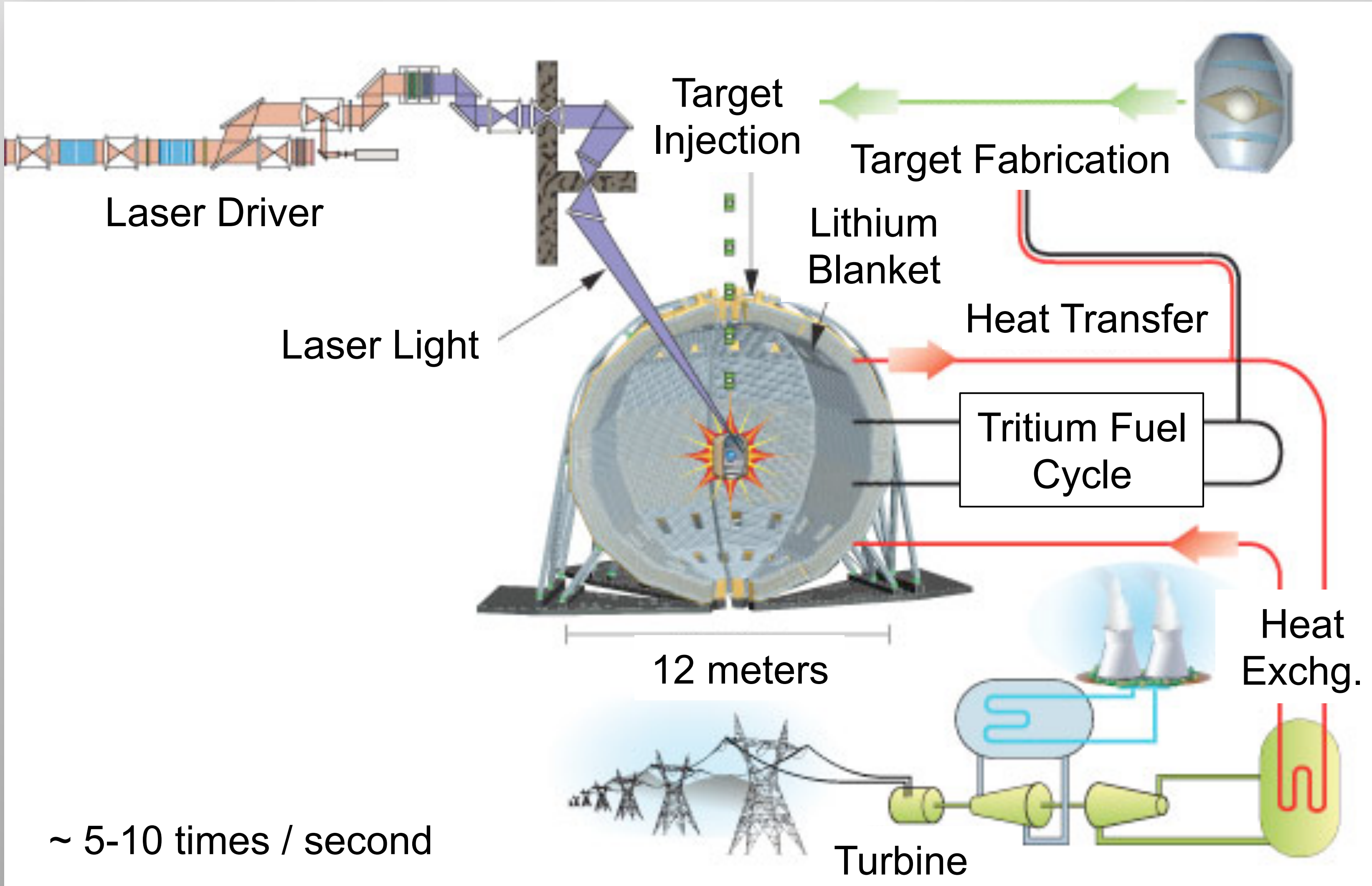
# Outline.

- What would an Inertial Fusion Energy power plant look like?
- How could it work?
- What are some technologies/concepts being considered?

**IV. Power**

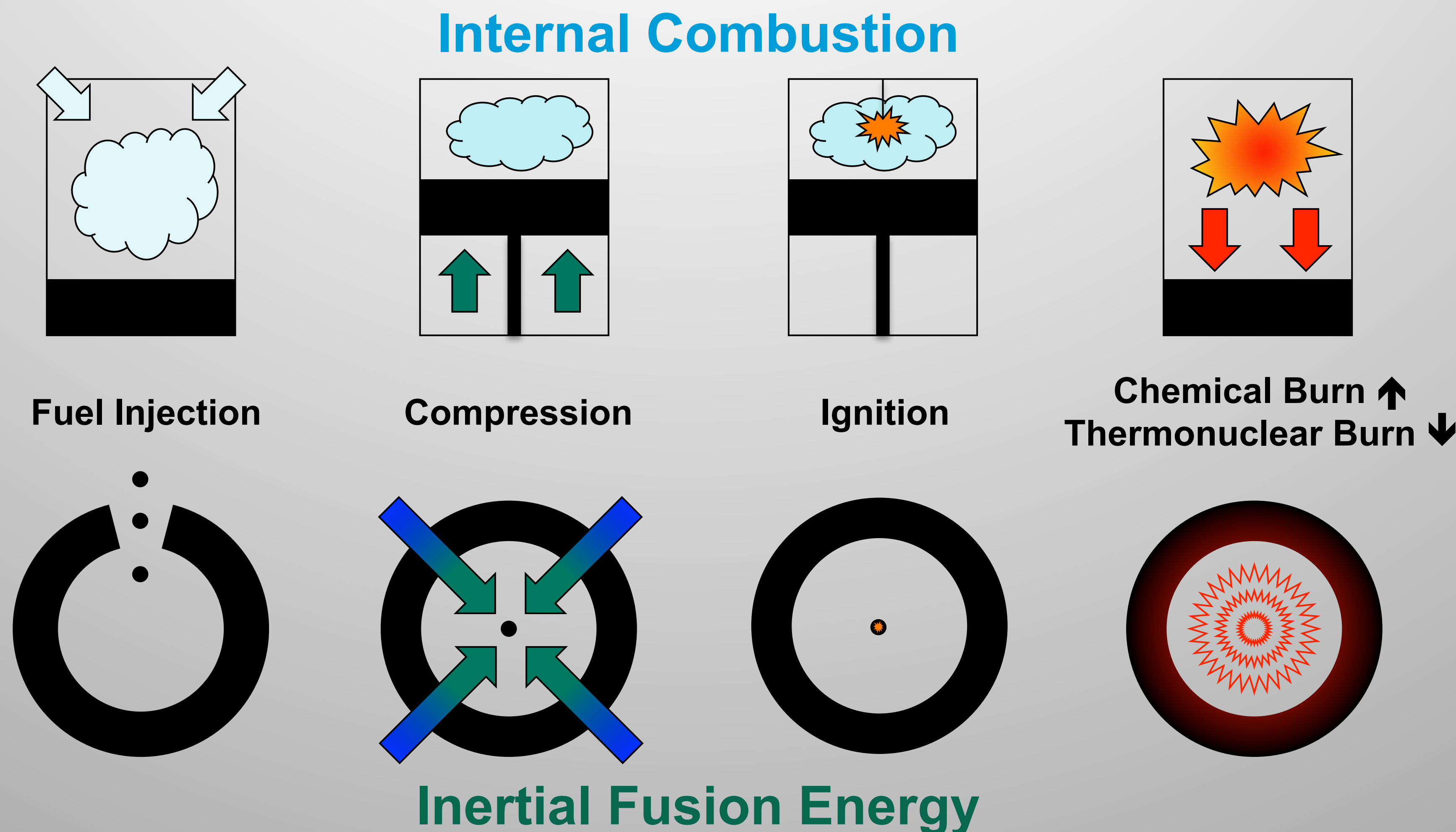


# A conceptual Laser IFE power plant

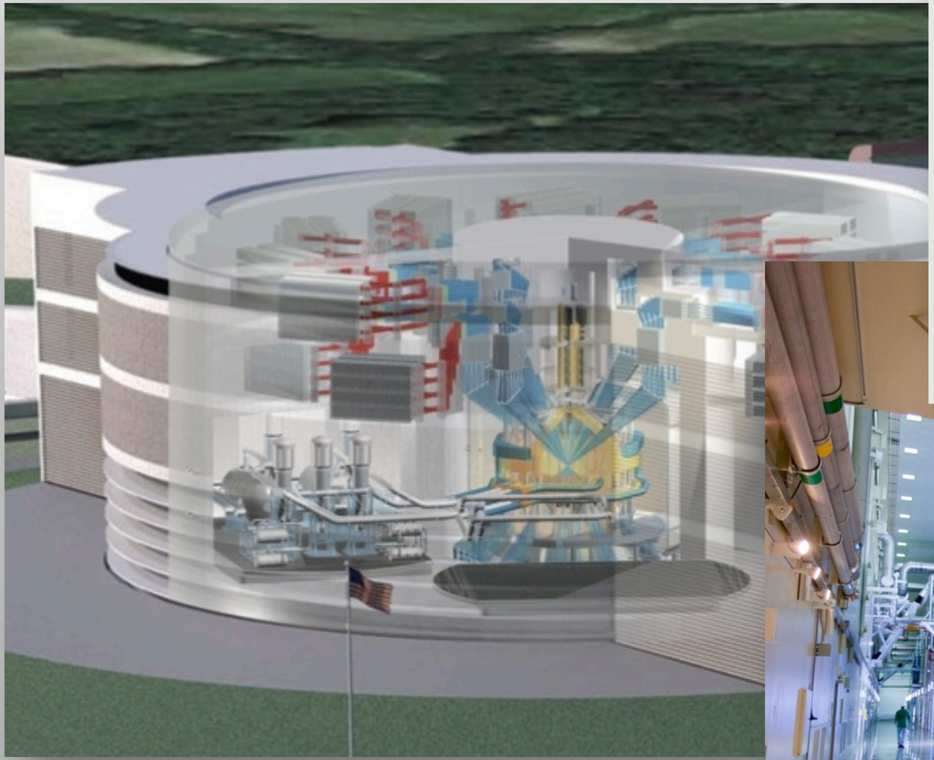


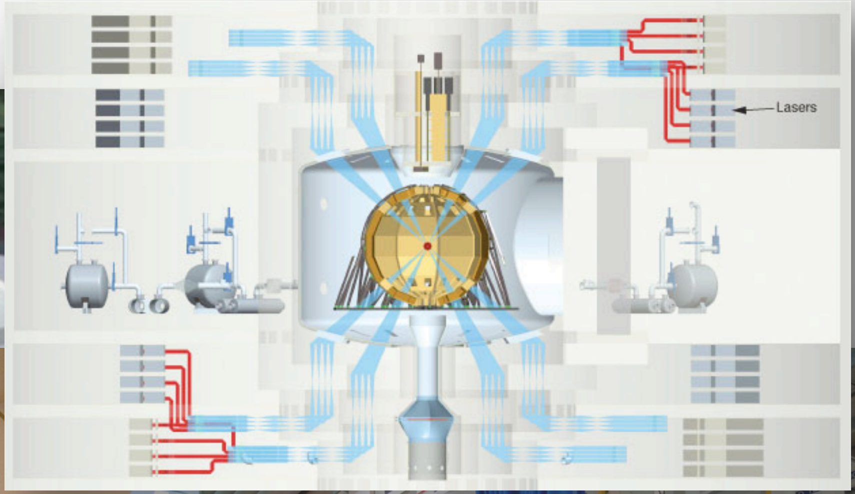

ST&R, 7/11

# IFE would be like a fusion internal combustion engine



# Technology development on IFE is a parallel effort

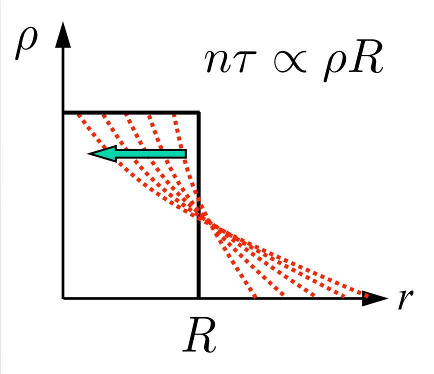


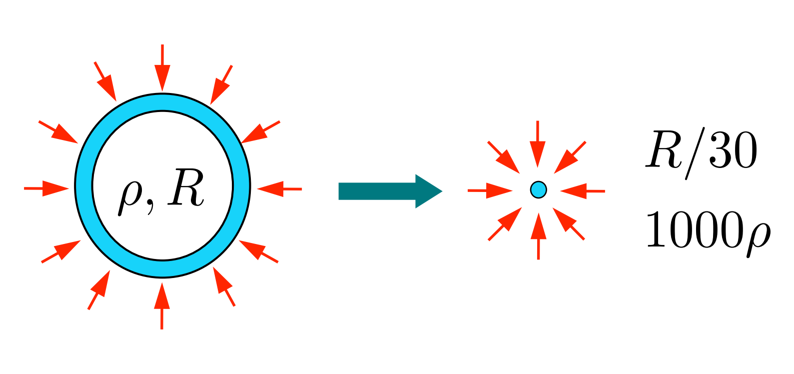


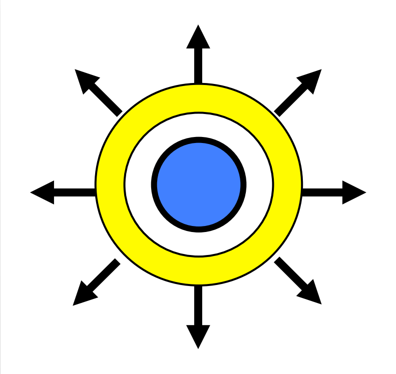

**LIFE Project**

**life.llnl.gov**

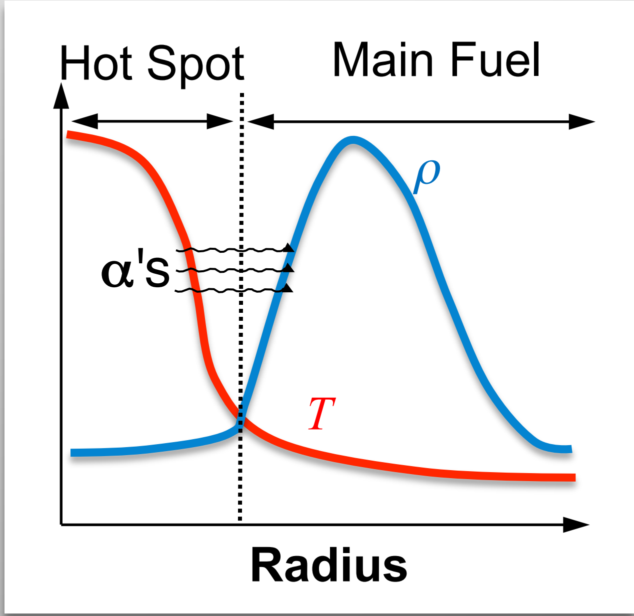
# A summary



- Confinement depends on ρR > 3 g/cm²
- Need to compress density ×1000 at high velocity ~ 300 km/s
- Works w/ ablation like a spherical rocket
- Low entropy compression and hot spot ignition can reach high gain
- NIF is designed to demonstrate ignition



# Experiments at NIF are shedding light on material under the extreme conditions necessary for ICF

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*NATURE* | LETTER

日本語要約

## Fuel gain exceeding unity in an inertially confined fusion implosion

O. A. Hurricane, D. A. Callahan, D. T. Casey, P. M. Celliers, C. Cerjan, E. L. Dewald, T. R. Dittrich, T. Döppner, D. E. Hinkel, L. F. Berzak Hopkins, J. L. Kline, S. Le Pape, T. Ma, A. G. MacPhee, J. L. Milovich, A. Pak, H.-S. Park, P. K. Patel, B. A. Remington, J. D. Salmonson, P. T. Springer & R. Tommasini

Affiliations | Contributions | Corresponding author

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# It's an exciting time for science!

# Thanks!

Lawrence Livermore
National Laboratory