



Fusion Technologies Overview

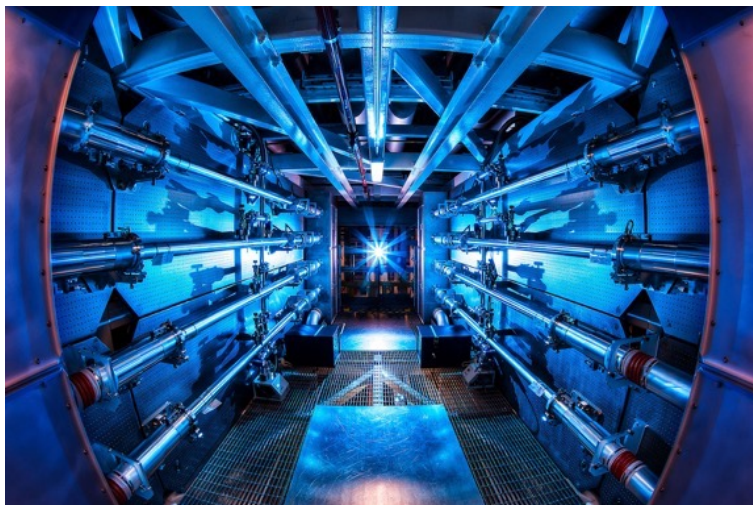
Daniel Sinars, Director, Chief Research Office
NM Science, Tech, & Telecommunications Committee
9/9/2026



Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

SAND2026-26086PE

By the end of this talk I hope you will understand how these things are related...



The world's largest laser and largest pulsed power machine

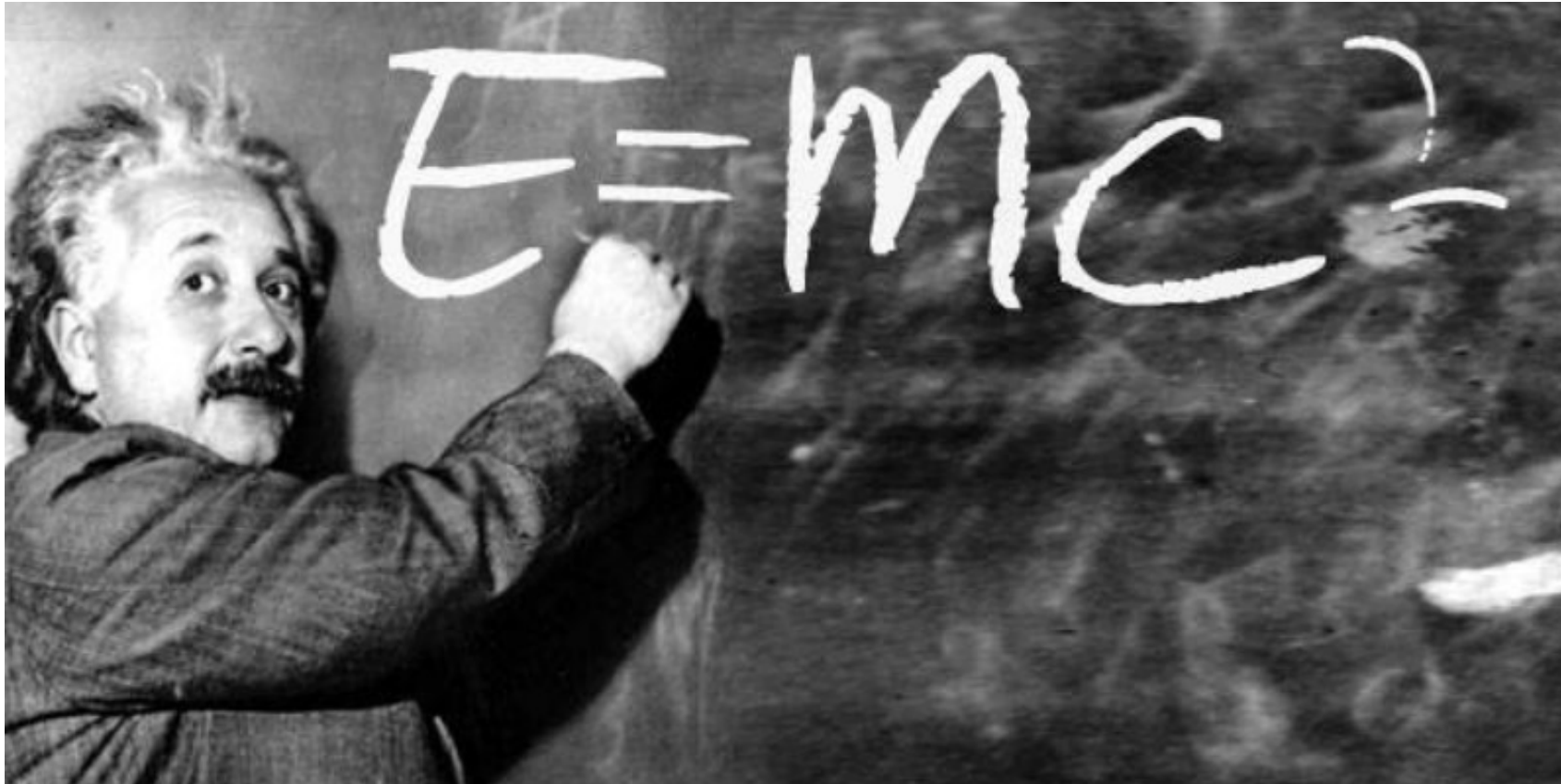


Nuclear weapons



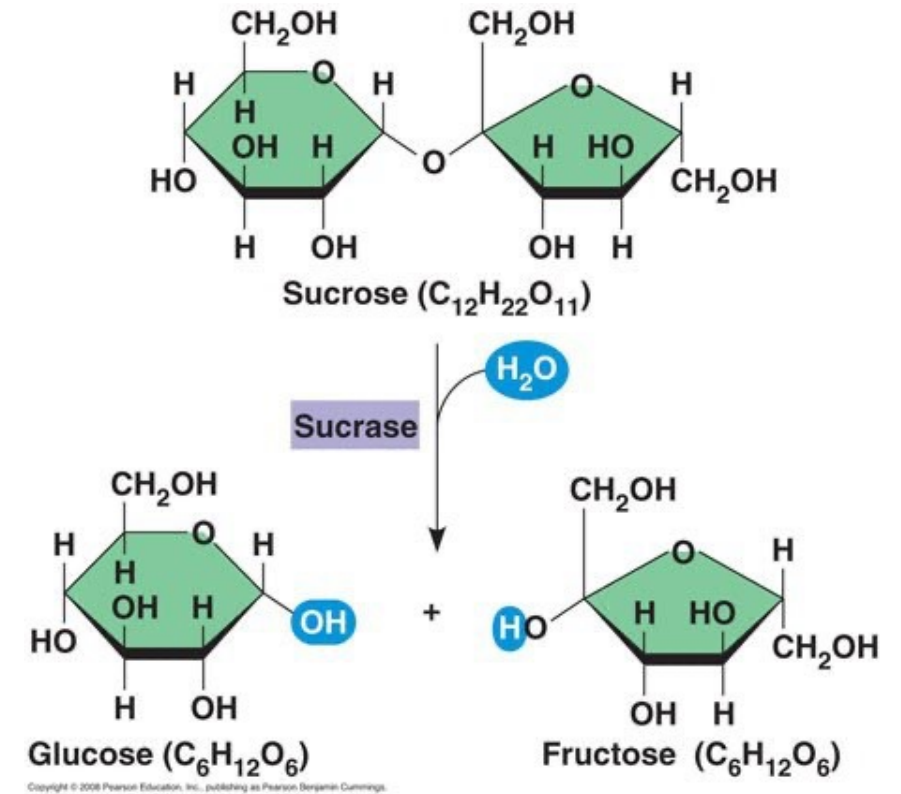
Jelly doughnuts

Our journey begins with a famous person and one of his most famous equations...



Published in 1905, this equation makes a powerful statement:
Mass and energy can be converted into one another

You mean it took physicists until 1905 to realize that eating jelly doughnuts releases energy???



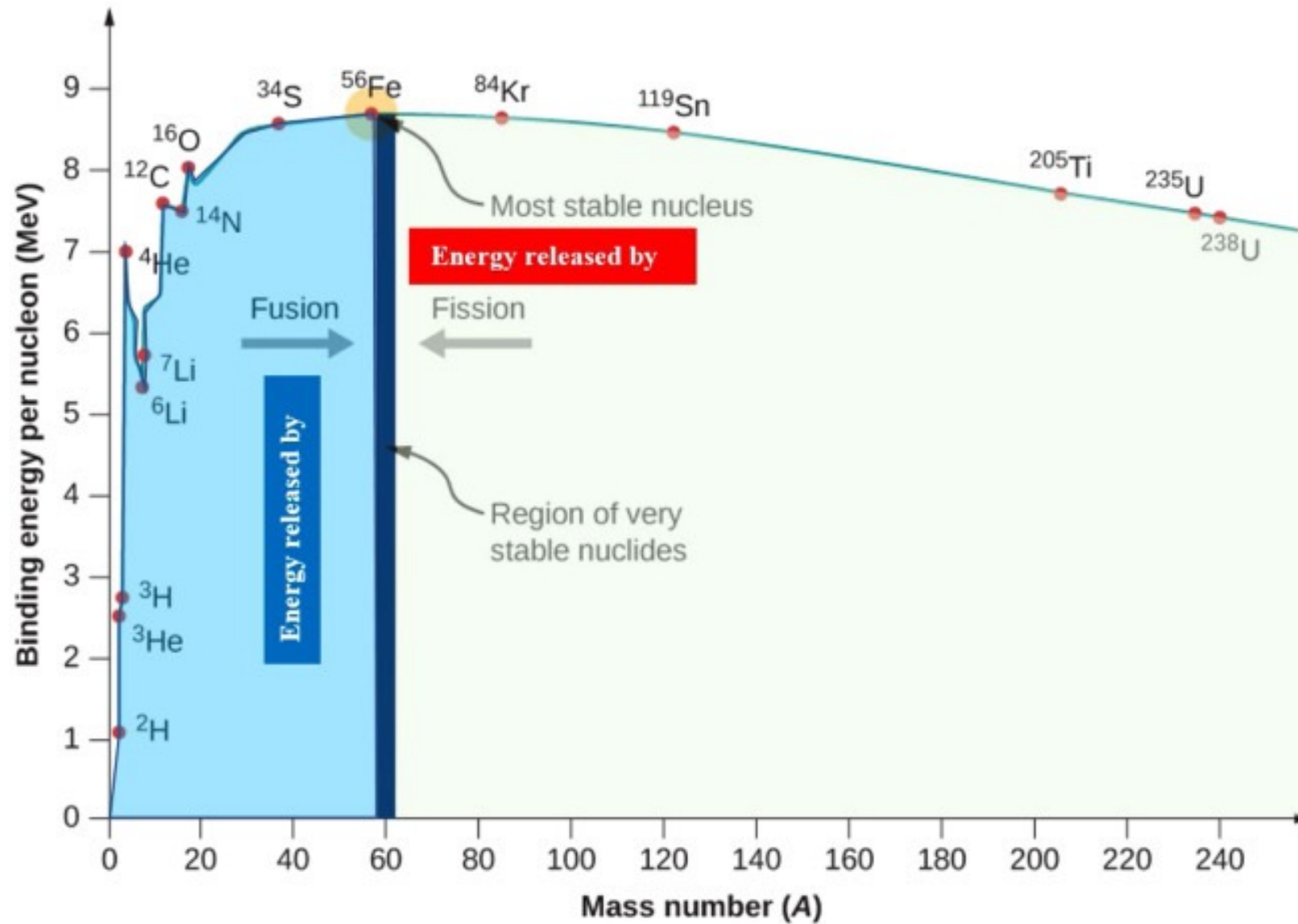
Hold on! Eating food breaks down chemical bonds that join molecules together in your food, but it doesn't change the atoms. Einstein was talking about creating and destroying matter/atoms!

All matter is made up of atoms with different properties, masses, etc. Einstein's famous equation speaks about what happens when you create/destroy this matter.

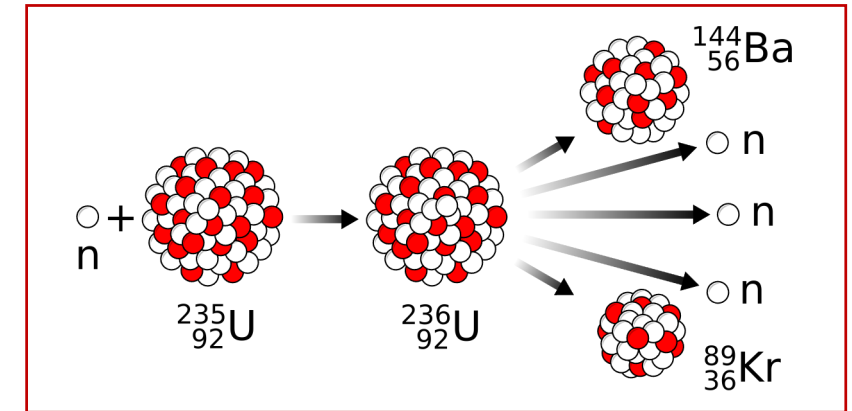


Periodic Table of the Elements																		18 VIII A 8A
1 1IA 1A	2 IIA 2A											13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	2	
H Hydrogen 1.0079																		He Helium 4.00260
3 Li Lithium 6.941	4 Be Beryllium 9.01218																	
11 Na Sodium 22.989768	12 Mg Magnesium 24.305	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 Al Aluminum 26.981539	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948	
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.95591	22 Ti Titanium 47.88	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938	26 Fe Iron 55.847	27 Co Cobalt 58.9332	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.64	33 As Arsenic 74.92159	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80	
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium 98.9072	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.9055	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.90447	54 Xe Xenon 131.29	
55 Cs Cesium 132.90543	56 Ba Barium 137.327	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.9665	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98037	84 Po Polonium [208.9824]	85 At Astatine 209.9871	86 Rn Radon 222.0176	
87 Fr Francium 223.0197	88 Ra Radium 226.0254	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown	
Lanthanide Series		57 La Lanthanum 138.9055	58 Ce Cerium 140.115	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.24	61 Pm Promethium 144.9127	62 Sm Samarium 150.36	63 Eu Europium 151.9655	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92534	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967		
Actinide Series		89 Ac Actinium 227.0278	90 Th Thorium 232.0381	91 Pa Protactinium 231.03588	92 U Uranium 238.0289	93 Np Neptunium 237.0482	94 Pu Plutonium 244.0642	95 Am Americium 243.0614	96 Cm Curium 247.0703	97 Bk Berkelium 247.0703	98 Cf Californium 251.0796	99 Es Einsteinium [254]	100 Fm Fermium 257.0951	101 Md Mendelevium 258.1	102 No Nobelium 259.1009	103 Lr Lawrencium [262]		
		Alkali Metals	Alkaline Earths	Transition Metals	Basic Metals	Semi-Metals	Nonmetals	Halogens	Noble Gases	Lanthanides	Actinides							

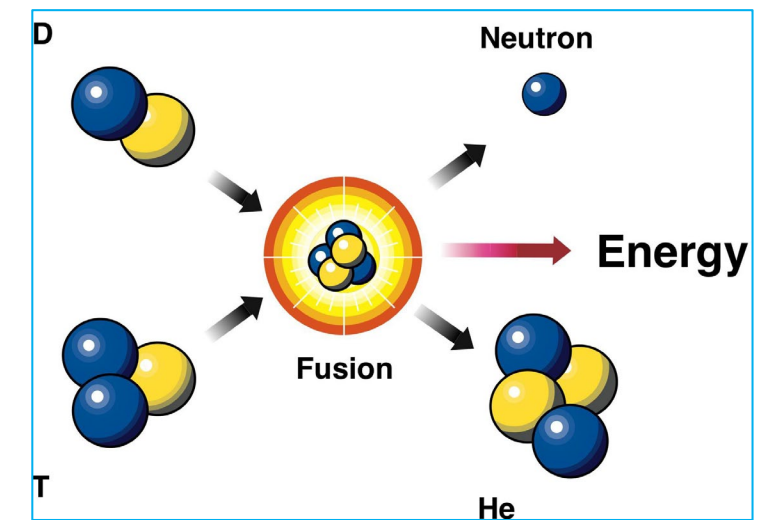
We can release and harness energy from matter through one of two processes



Fission



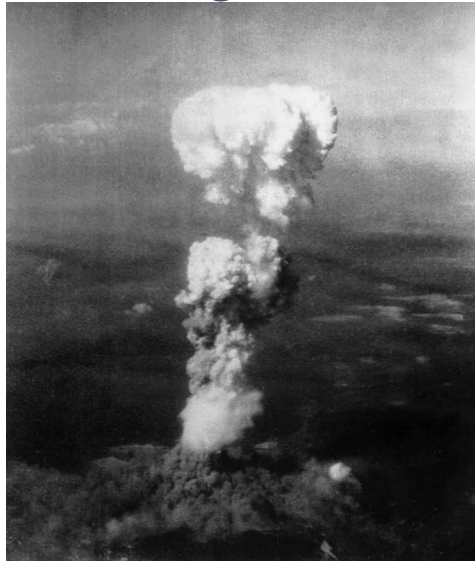
Fusion



Nuclear fission played a key role in the development of the world's first nuclear weapons by the United States

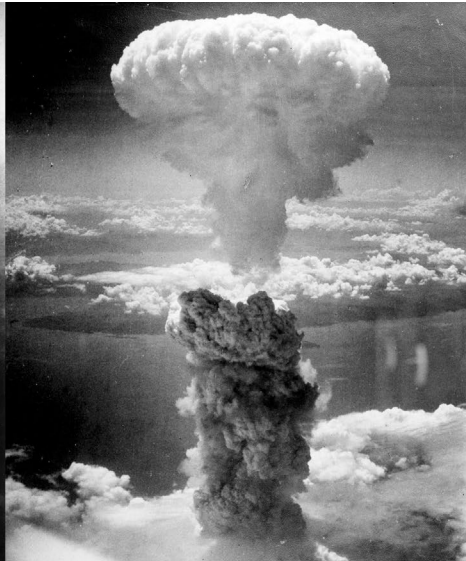


Nagasaki

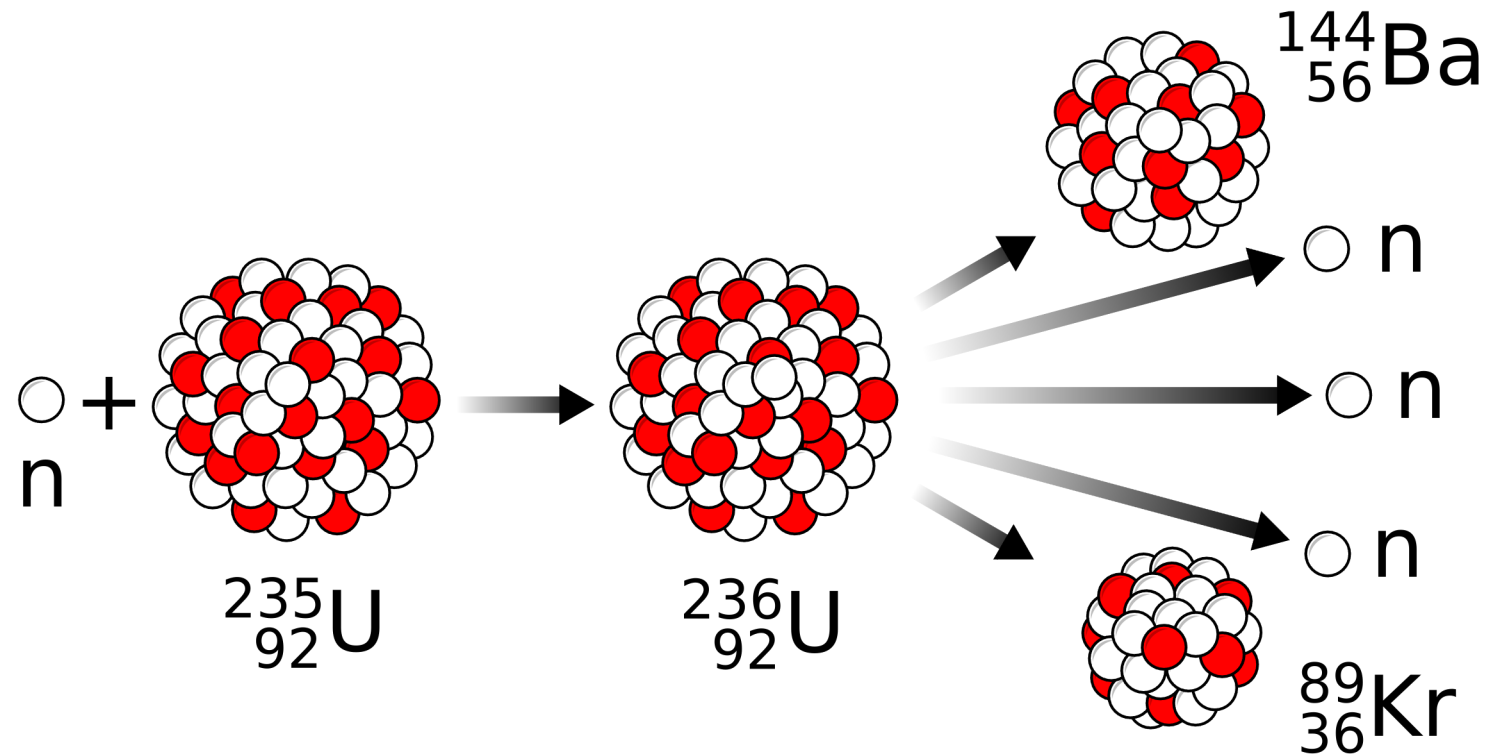


^{239}Pu weapon

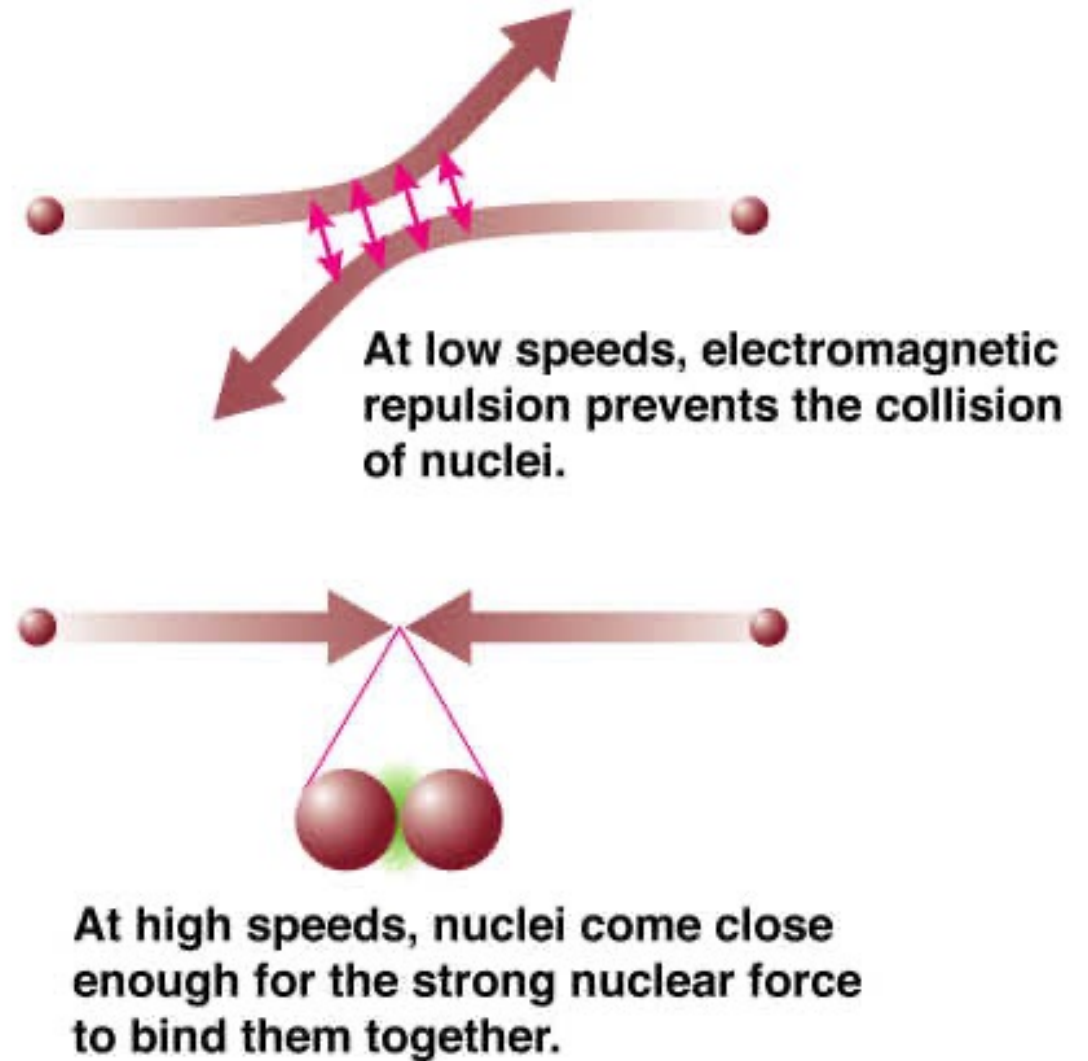
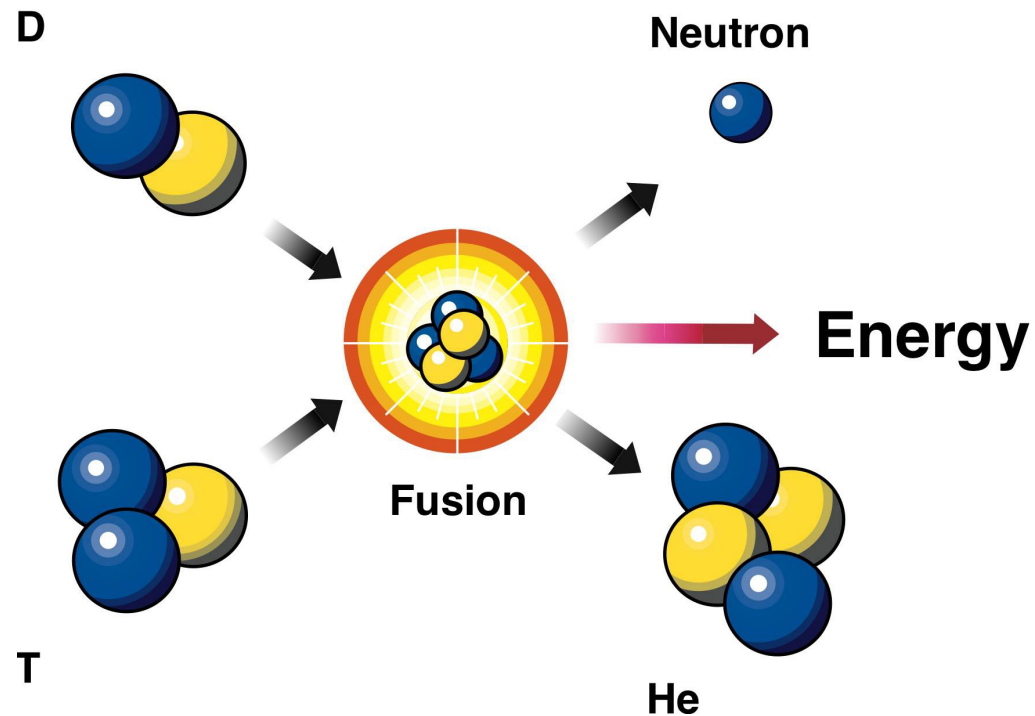
Hiroshima



^{235}U weapon



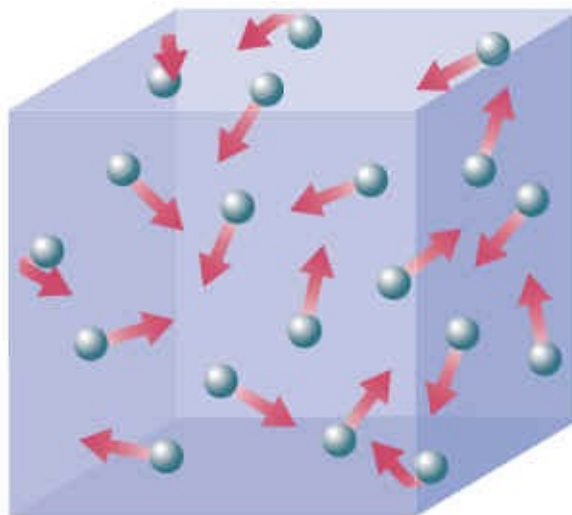
A key challenge for fusion is that the reacting particles are both positively charged, which will cause them to repel each other unless their velocities are high enough



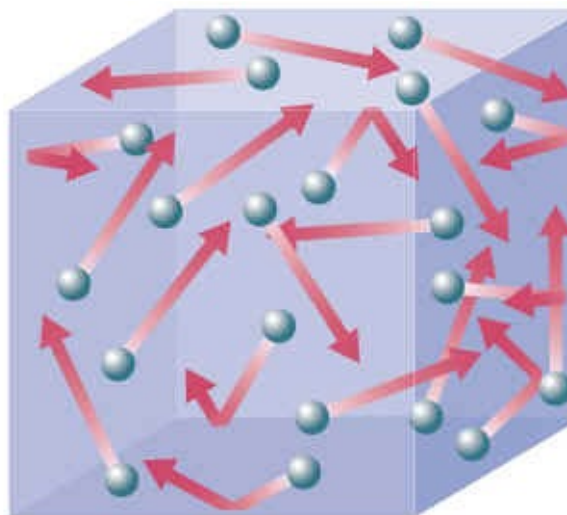
To enable the fusion reaction to occur, the particles must be moving at very high velocities, which corresponds to needing a very high temperature



Lower temperature
(slower particles)

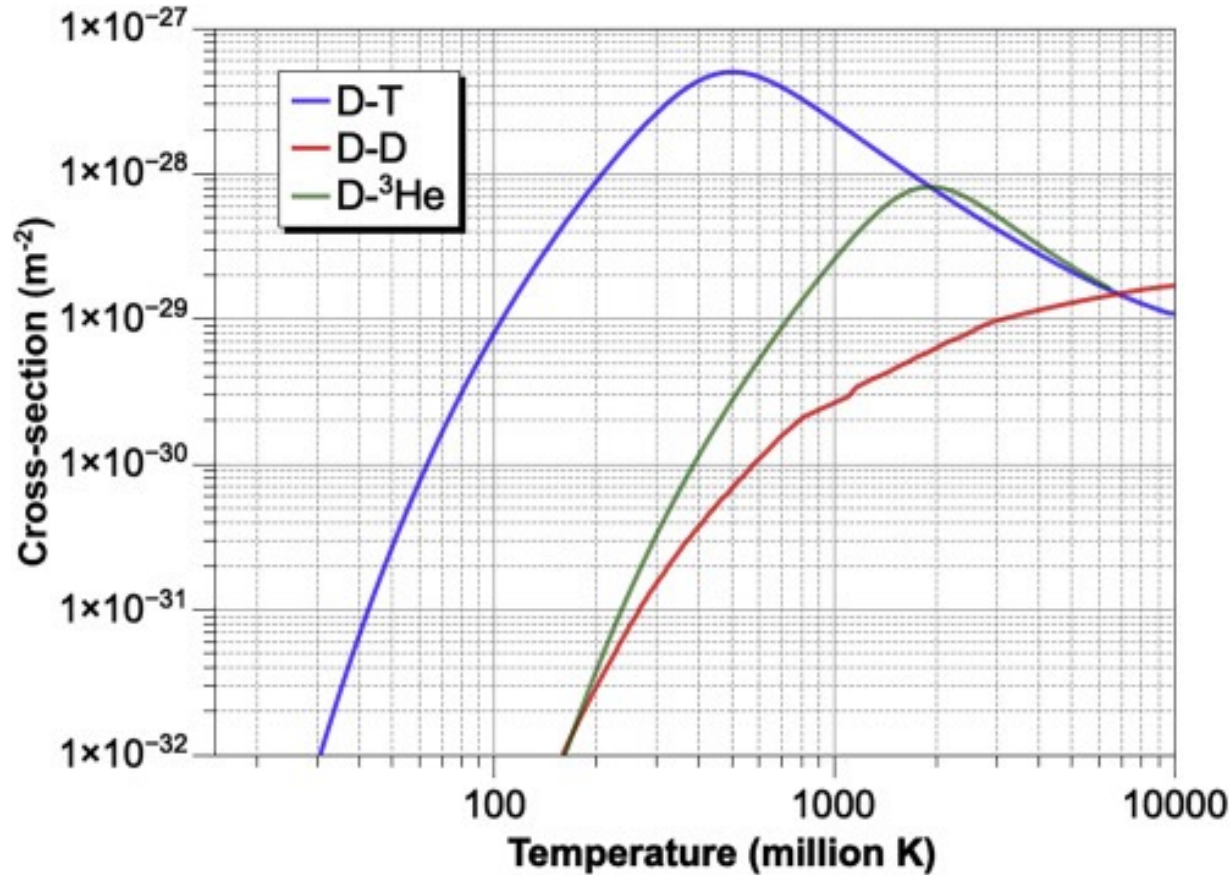


Higher temperature
(faster particles)

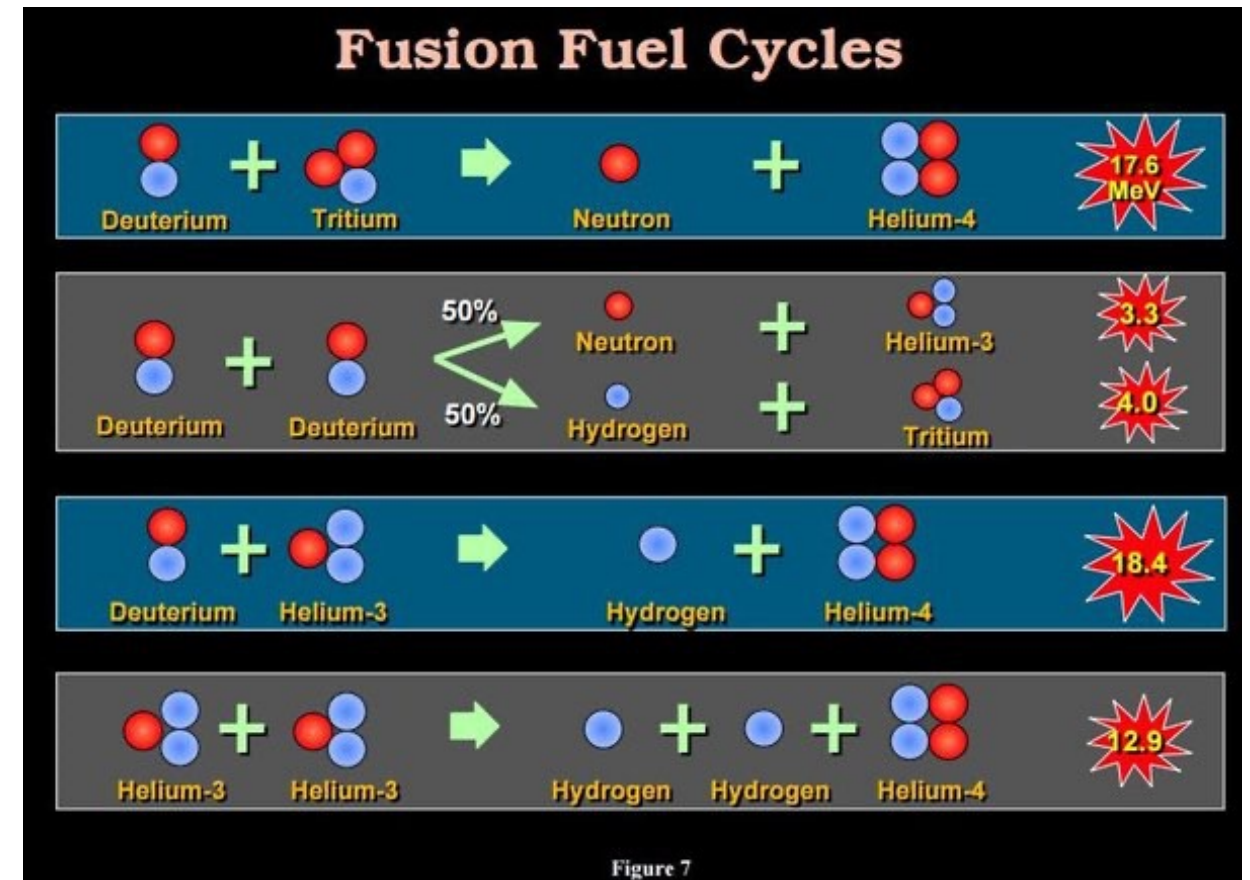


Longer arrows mean higher average speed.

How hot must our fuel be? Hundreds of millions of degrees! At these temperatures the atoms are ionized (meaning their electrons have been stripped off).

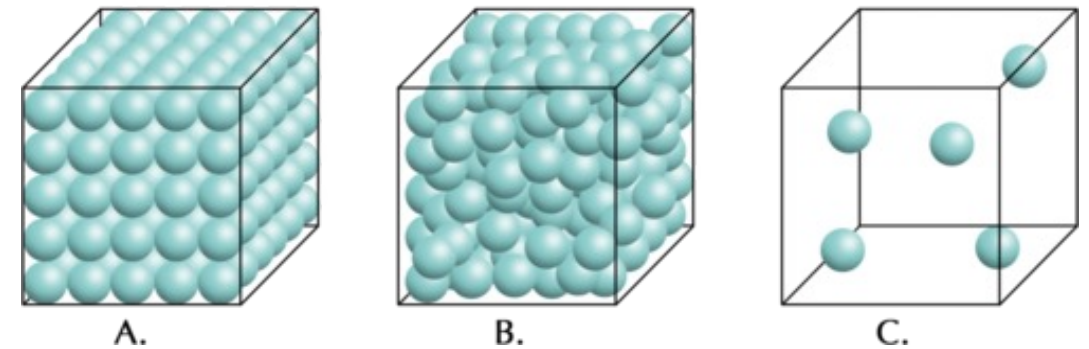
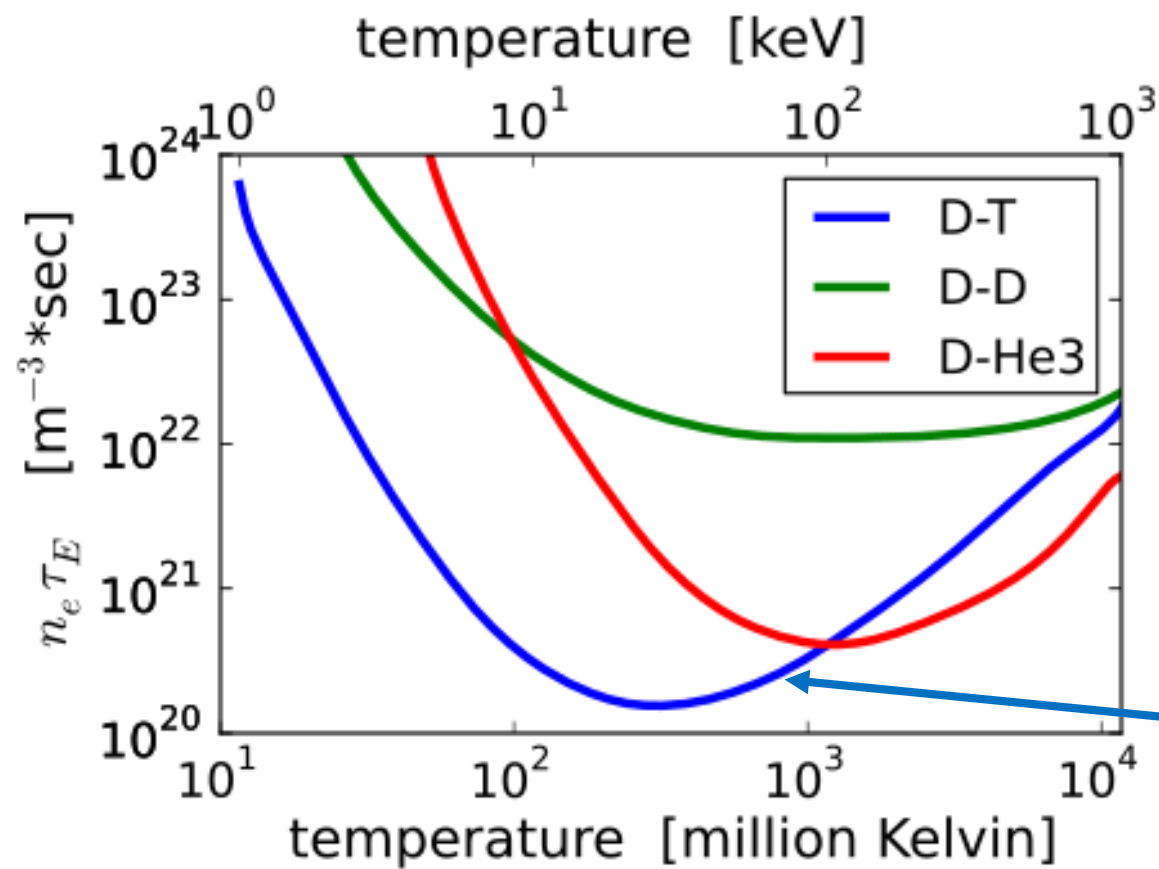


100 million Kelvin = 180 million degrees Fahrenheit
 1 keV = 11.6 million K



There are many possible fusion reactions, but D-T reactions appear to be the easiest to make.

Making some simplifying approximations, a scientist named John Lawson showed that to get a sustained nuclear fusion reaction to occur, one needs to satisfy a minimum density-confinement-time product



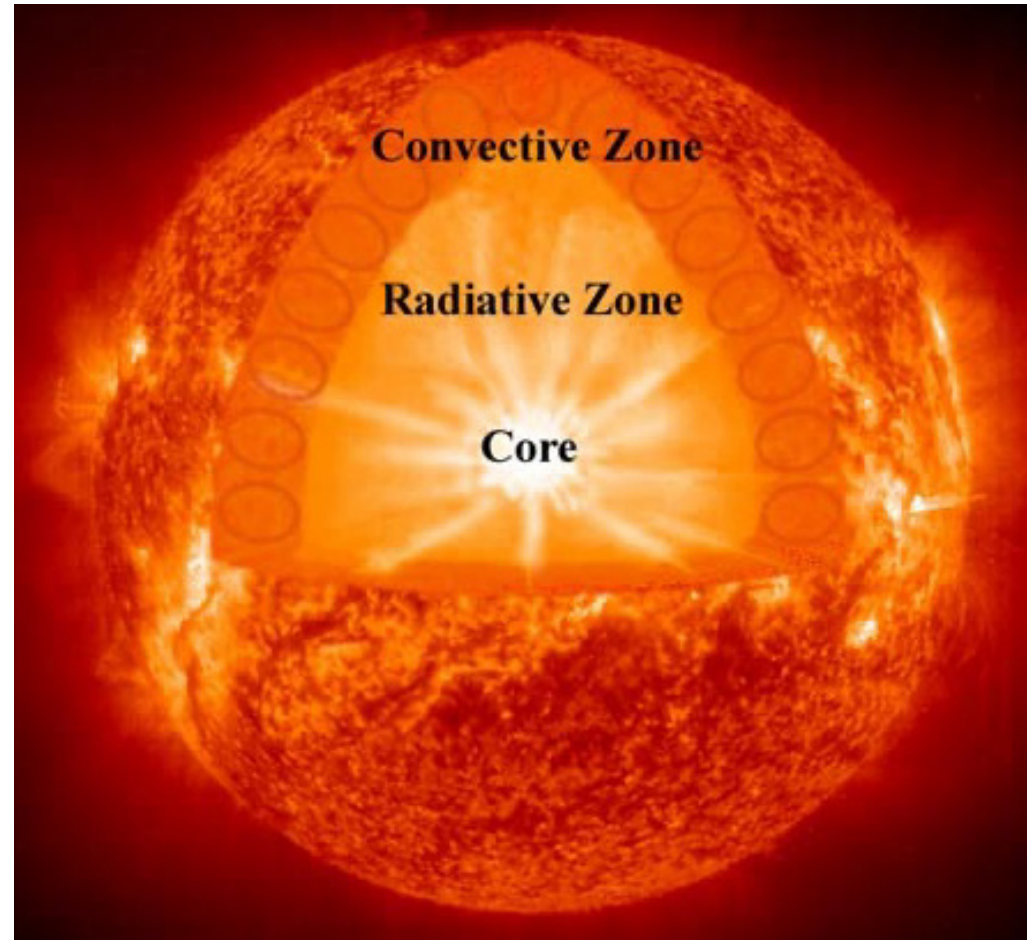
Higher $\longleftrightarrow$ Lower
Number of particles/unit volume

Lawson criterion (DT)

$$n\tau_E \geq 1.5 \cdot 10^{20} \frac{\text{s}}{\text{m}^3}$$

Intuitively, higher particle densities mean more collisions, so less time is required to reach the requisite number of collisions (fusions)

Fusion reactions occur naturally in stars, where immense gravitational forces and large sizes can confine plasmas at the high temperatures needed for fusion

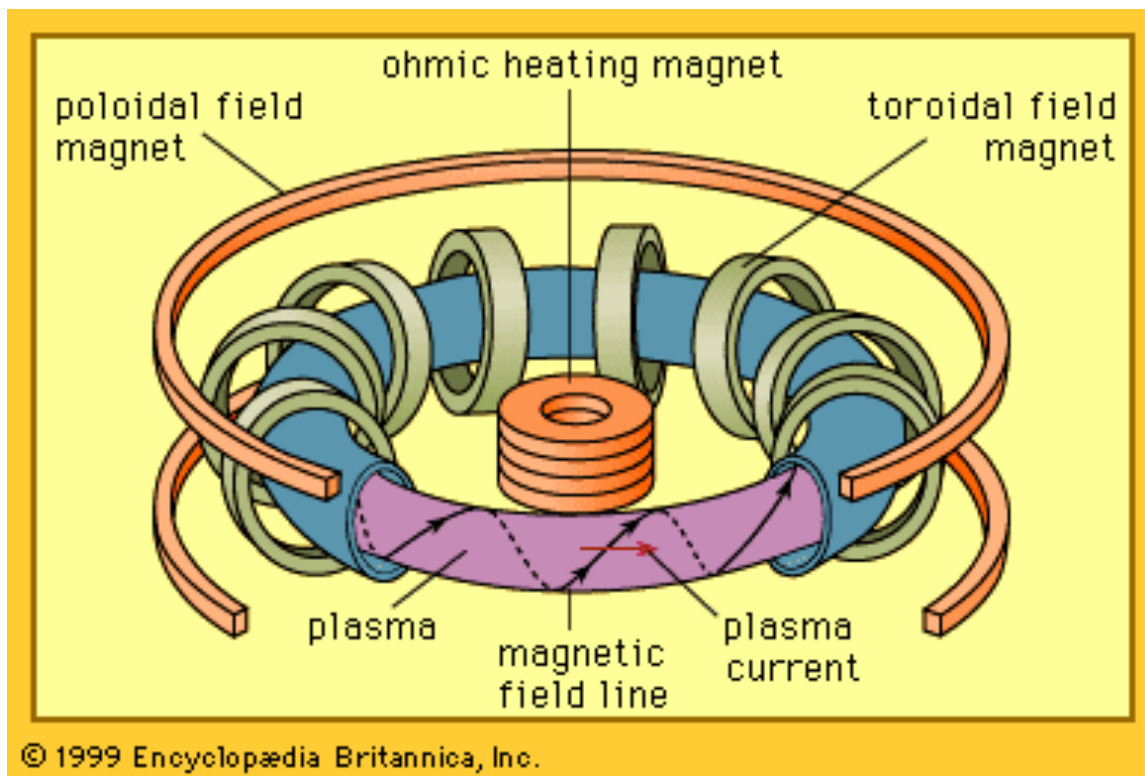


How can you hold and confine fuel (plasma)
that is hundreds of millions of degrees on earth?
Stainless steel melts at <3000 degrees!

For many decades now, scientists have investigated two general approaches to creating high-temperature fusion plasmas in the laboratory

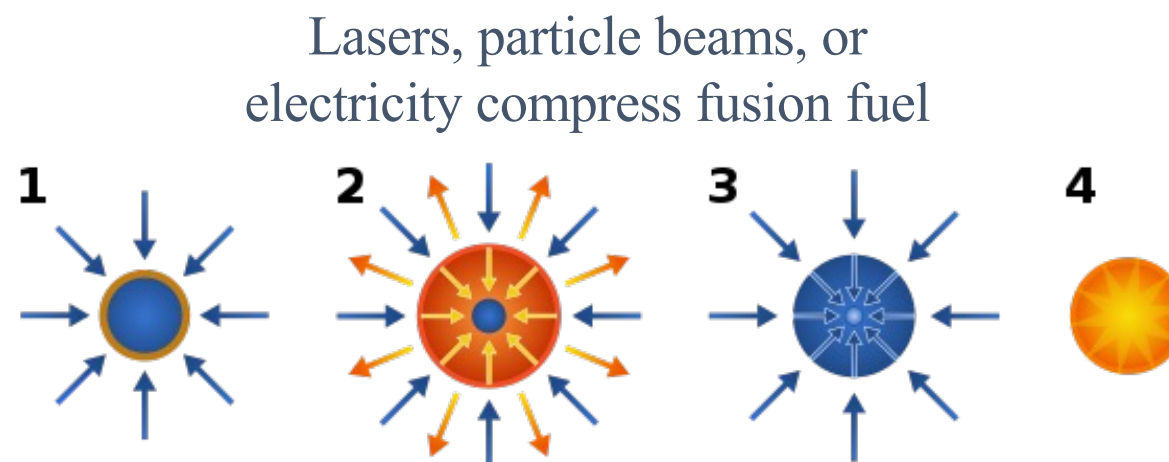


Magnetic Confinement Fusion



Use very strong magnetic fields to confine low density fuel for a long time—nothing touches the hot plasma

Inertial Confinement Fusion



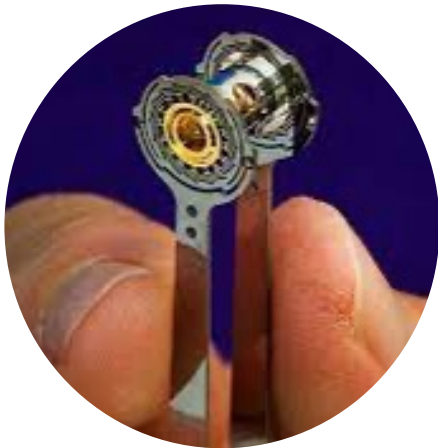
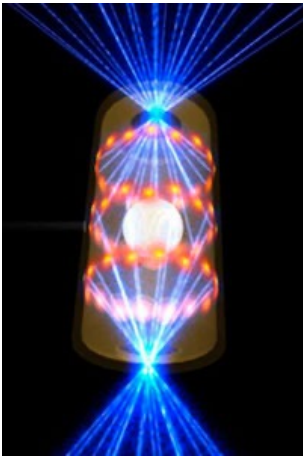
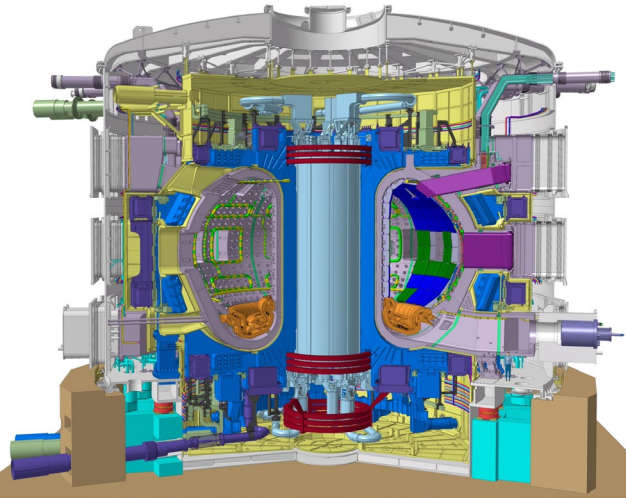
Compress fuel to very high densities for short periods of time—nothing touches the hot plasma

The largest laboratory fusion projects today are focused on magnetic or inertial confinement fusion, though there is growing interest in intermediate regimes



Magnetic Confinement Fusion (e.g., ITER)
Large volumes, low density, long confinement

Inertial Confinement Fusion (e.g., NIF)
Small volume, high density, short confinement



	MCF	Lawson criterion (DT)	ICF
Density	$1 \times 10^{20} \text{ m}^{-3}$	$n\tau_E \geq 1.5 \cdot 10^{20} \frac{\text{s}}{\text{m}^3}$	$2\text{--}20 \times 10^{31} \text{ m}^{-3}$
Duration	$300\text{--}500 \text{ s}$		$5\text{--}10 \times 10^{-11} \text{ s}$
Volume	$8 \times 10^2 \text{ m}^3$		$6 \times 10^{-14} \text{ m}^3$
Magnetic field	100,000 G		0 G

Note: A refrigerator magnet is ~50 G

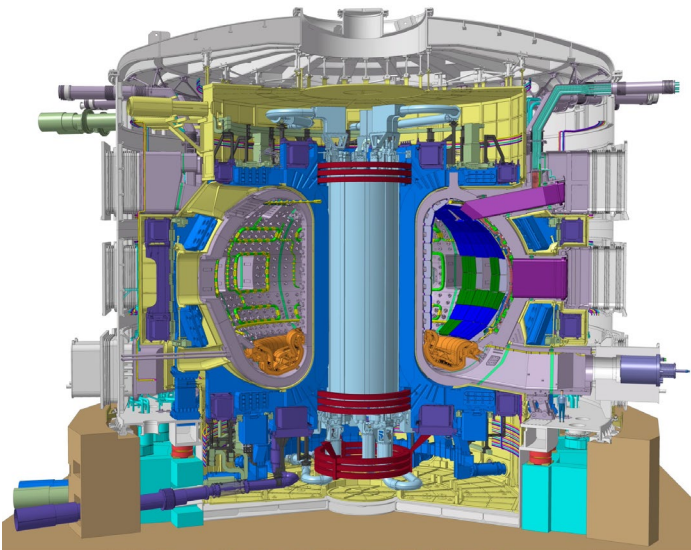
Note: Solid density DT ~ 10^{29} m^{-3} !!!

Fusion concepts at intermediate densities and confinement times are also possible. Many fusion startups operate in between these extremes.

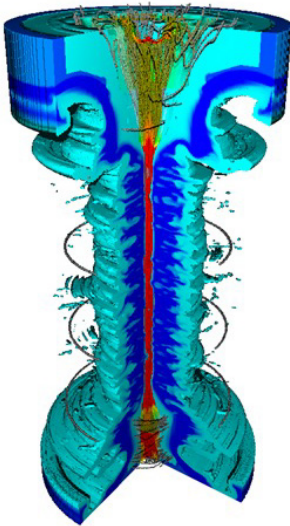
Magnetic inertial fusion (MIF) uses magnetic fields to help bridge the gap between magnetic confinement fusion (MCF) and inertial confinement fusion (ICF)



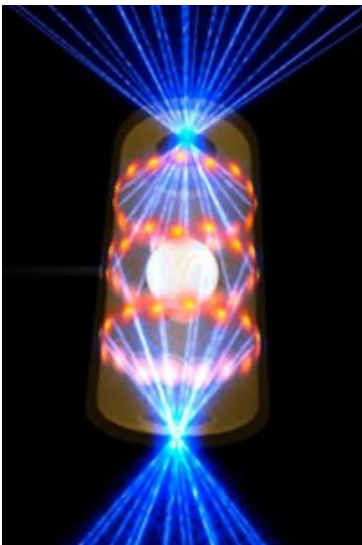
MCF (e.g. ITER)



MIF (e.g. MagLIF)



ICF (e.g. NIF)



MCF

- B field confines plasma
- B field traps α 's

MIF

- B field reduces conduction losses during implosion
- B field increases path length of α 's, reducing density reqts.

ICF

- Plasma inertially confined
- α 's stopped by high density

	MCF	MagLIF	ICF
Density	$1 \times 10^{20} \text{ m}^{-3}$	$1 \times 10^{29} \text{ m}^{-3}$	$2\text{-}20 \times 10^{31} \text{ m}^{-3}$
Duration	300-500 s	$1\text{-}2 \times 10^{-9} \text{ s}$	$5\text{-}10 \times 10^{-11} \text{ s}$
Volume	$8 \times 10^2 \text{ m}^3$	$8 \times 10^{-11} \text{ m}^3$	$6 \times 10^{-14} \text{ m}^3$
Magnetic field	100,000 G	$\sim 100,000,000 \text{ G}^*$	0 kG

*Achieved by flux compression

Sandia first demonstrated that magneto-inertial fusion worked using the Z-machine, leading to ARPA-E program and new startups using similar principles

Fusion companies with ties to New Mexico are primarily on the pulsed, inertial fusion end of the spectrum (including magneto-inertial fusion)



• **Pacific Fusion**



• **Liberty Fusion**



• **Fuse (Fuse Energy Technologies)**

Fusion startups adapt their approaches routinely, but at this time all these companies are working with plasma densities $\sim 10^{27}$ - 10^{31} m^{-3} , i.e., far closer to inertial fusion than magnetic fusion

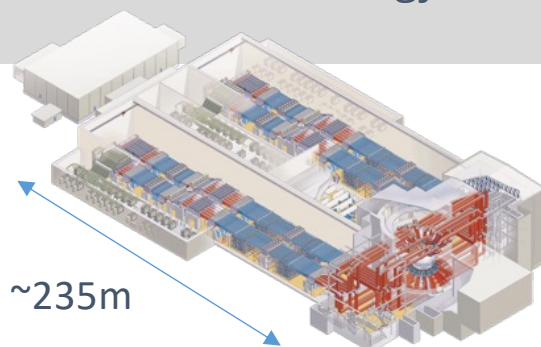
The NNSA funds Inertial Confinement Fusion research on three major facilities, including the Z machine here in Albuquerque at Sandia



Lawrence Livermore National Laboratory

National Ignition Facility (NIF)

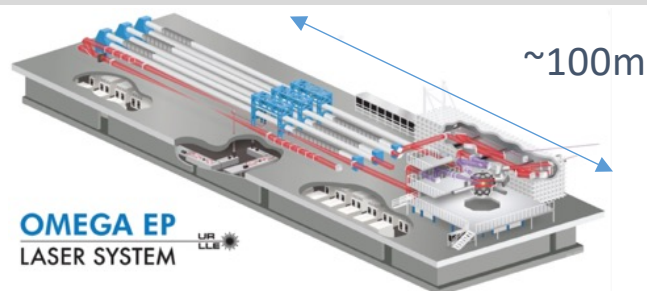
- Largest Laser on Earth
- Primary facility for Laser Indirect Drive fusion
- 400 TW / 1.8 MJ (Max Power & Energy)



University of Rochester

OMEGA Laser Facility

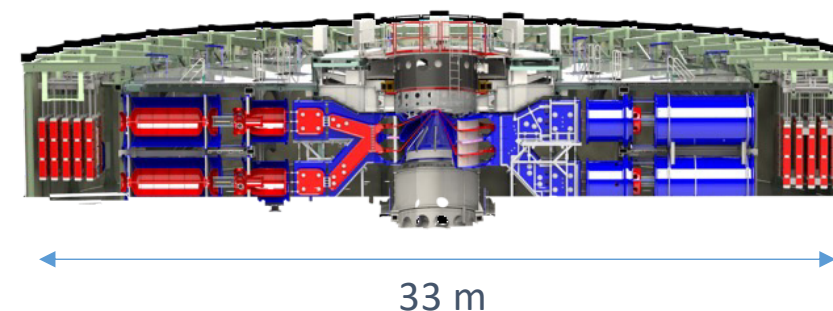
- High shot-rate academic laser facility
- Primary facility for Laser Direct Drive fusion
- 20 TW/0.03 MJ (Max Power & Energy)



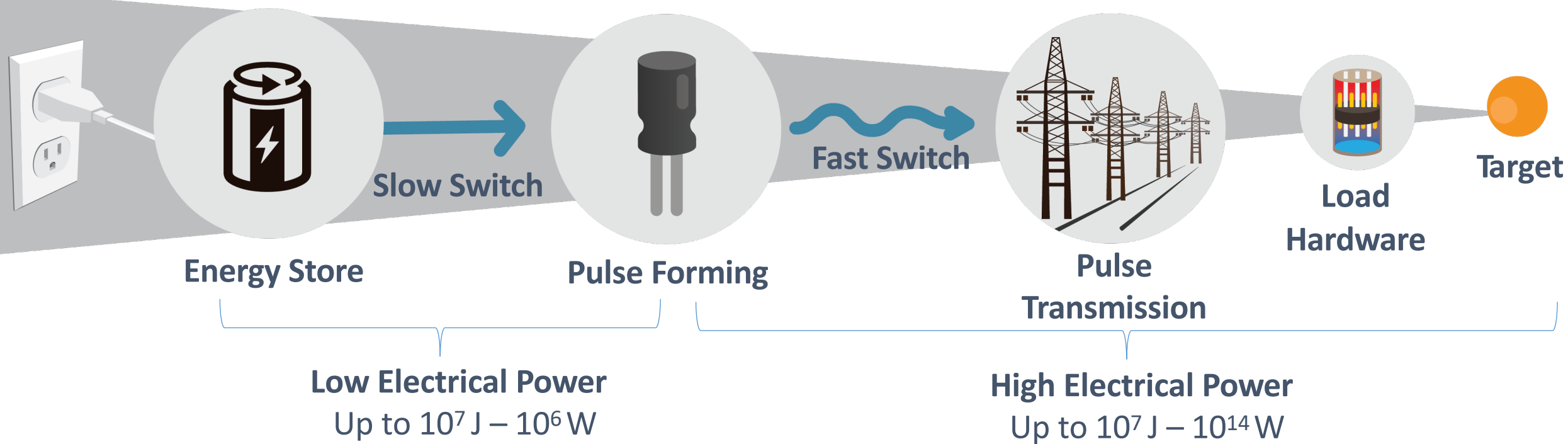
Sandia National Laboratories

Z Facility

- Largest Pulsed Power Facility on Earth
- Primary facility for Magnetic Direct Drive fusion
- 80 TW / 3 MJ (Max Power & Energy)

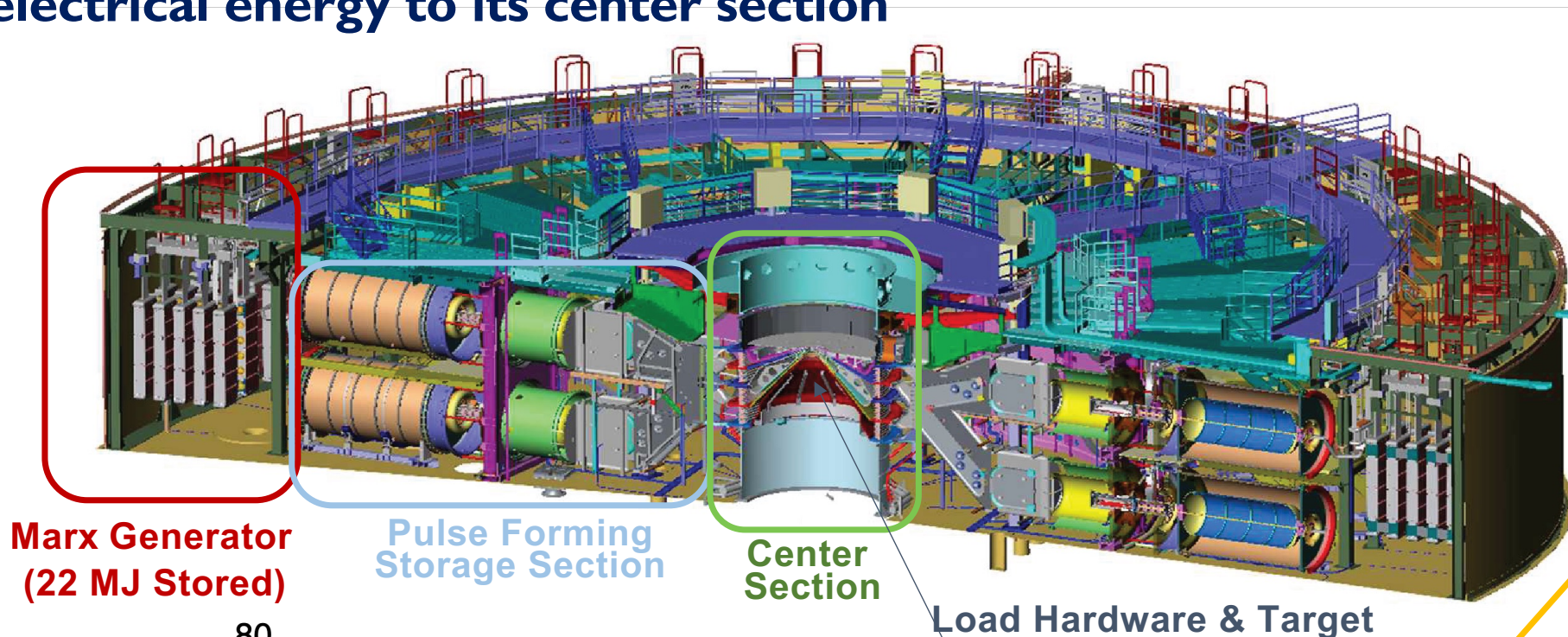


How does pulsed power work?



Pulsed power compresses electrical energy in both space and time to produce short bursts of high power.

Z, the world's largest pulsed power machine, delivers 80 TW and 6 MJ of electrical energy to its center section

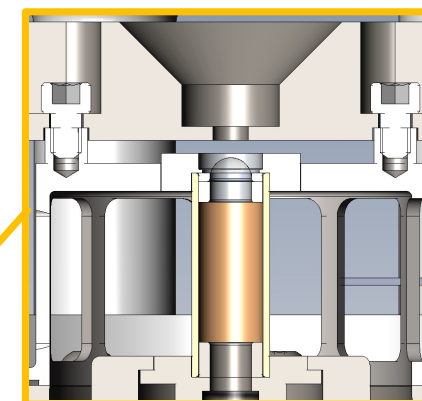


**Marx Generator
(22 MJ Stored)**

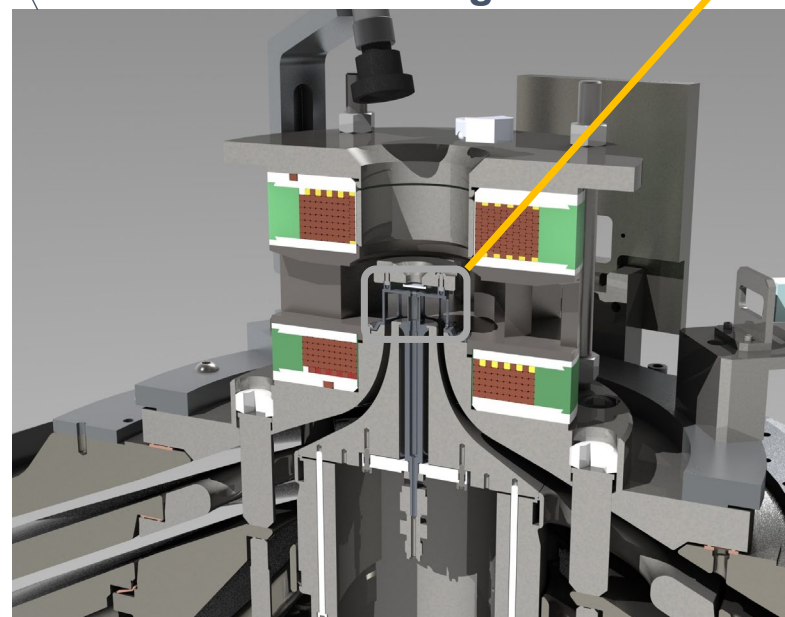
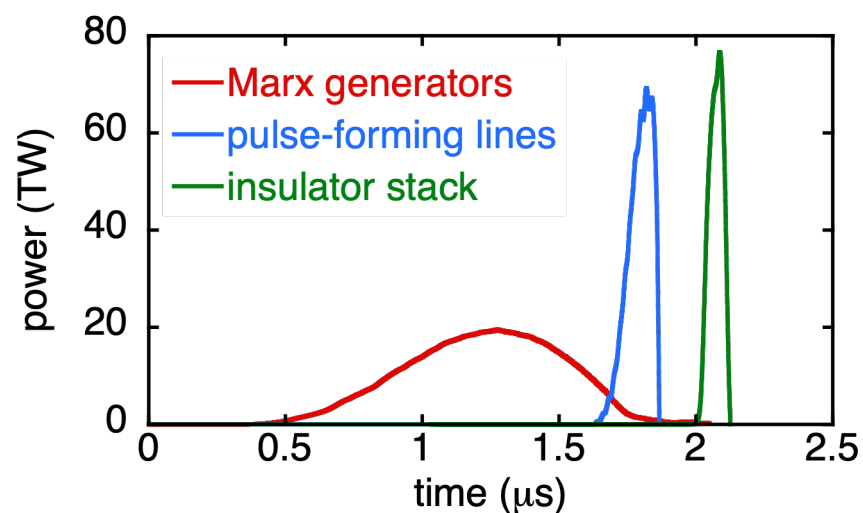
**Pulse Forming
Storage Section**

**Center
Section**

Load Hardware & Target



**Z-pinch
target**



Z today couples several MJ out of 22 MJ stored to the load hardware region at the machine center.

To understand the extreme nature of inertial confinement fusion, let's make sure we all understand the key concepts of energy, power, and energy density



Which of these releases the most energy?

Calories in a Krispy Kreme
raspberry jelly doughnut



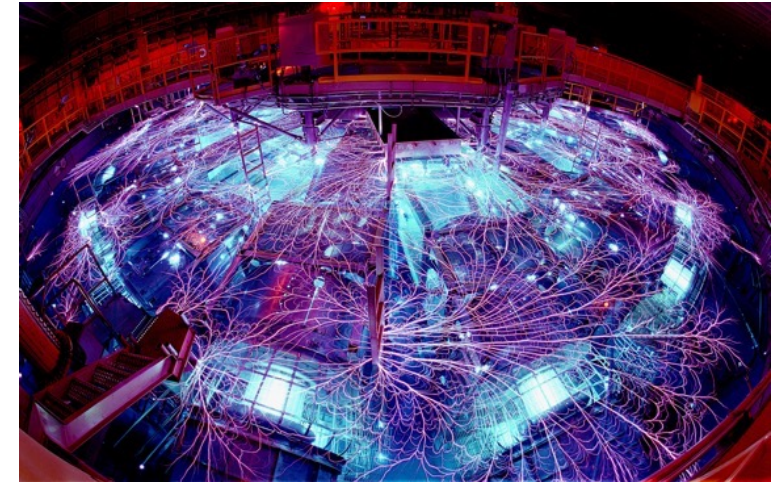
290 Calories = 1.2 MJ

A stick of dynamite



About 1 MJ

Energy delivered by
Z to a fusion target



About 1 MJ

To understand the extreme nature of inertial confinement fusion, let's make sure we all understand the key concepts of energy, power, and energy density



Which of these releases the most power (energy/time)?

Eating a Krispy Kreme
raspberry jelly doughnut



290 Calories = 1.2 MJ

It takes your body roughly
60 minutes to digest

$1,200,000 \text{ J} / 3,600 \text{ sec} = 330 \text{ Watts}$

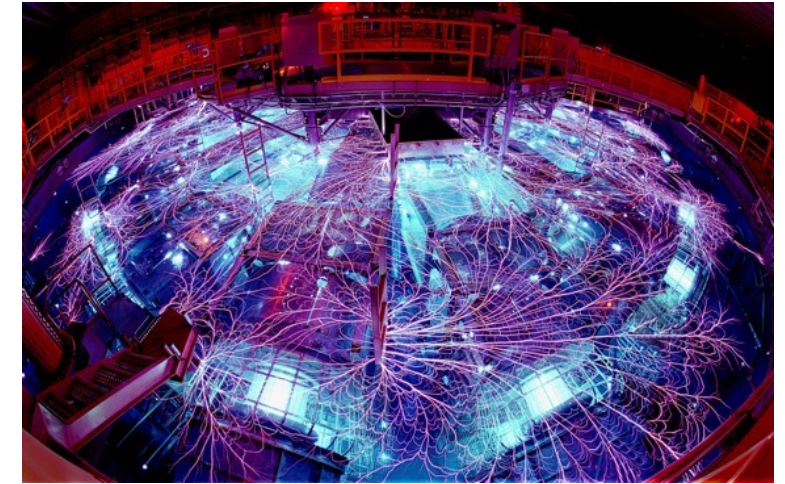
An electric power plant



Vary from 1 MW to 2 GW,
i.e., up to

2,000,000,000 Watts

Power delivered by
Z to a fusion target



Power entering the insulator
stack is 80 TW, i.e.,
80,000,000,000,000 Watts

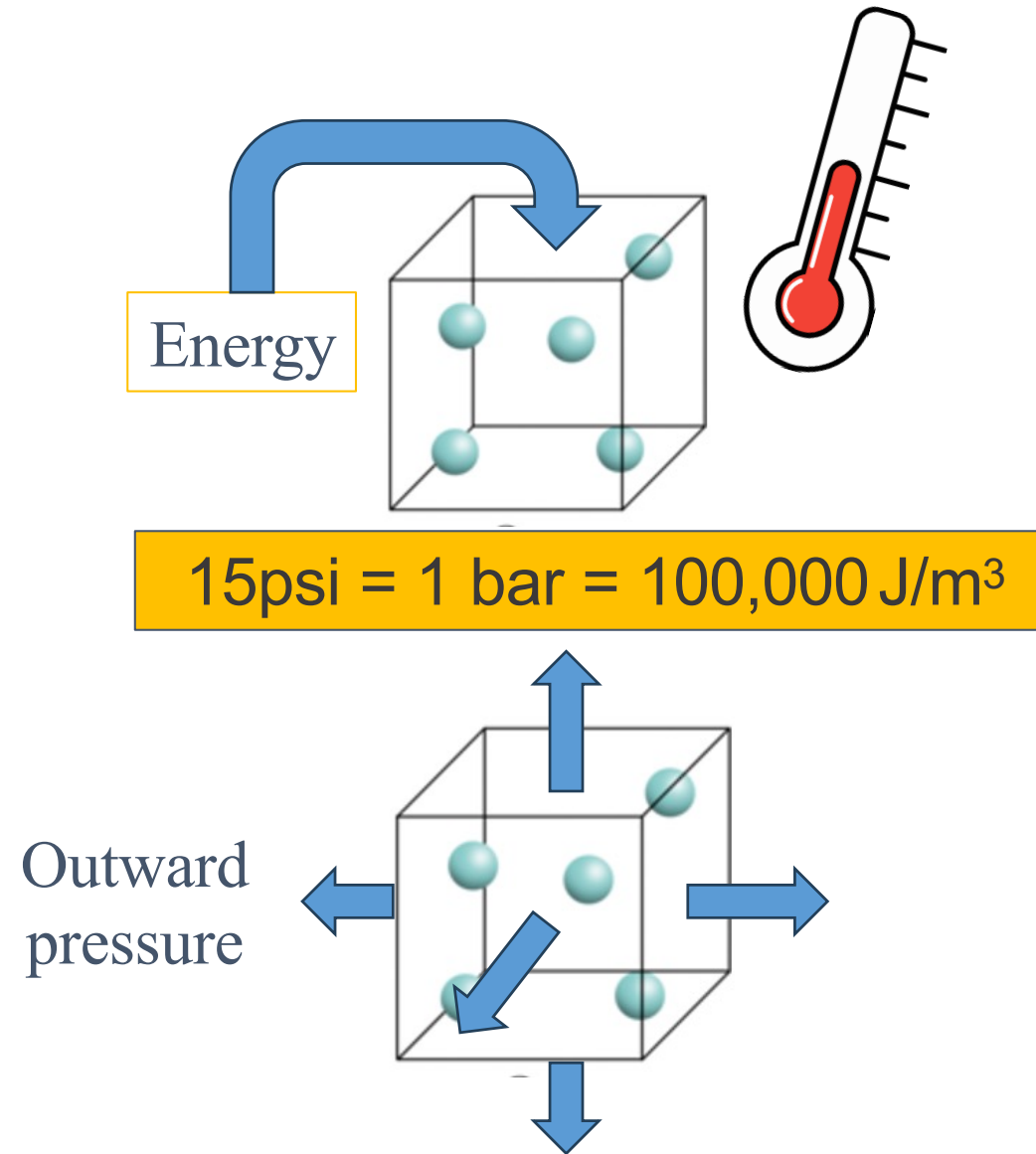
To understand the extreme nature of inertial confinement fusion, let's make sure we all understand the key concepts of energy, power, and energy density



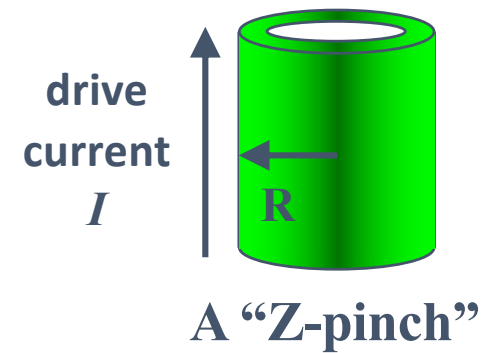
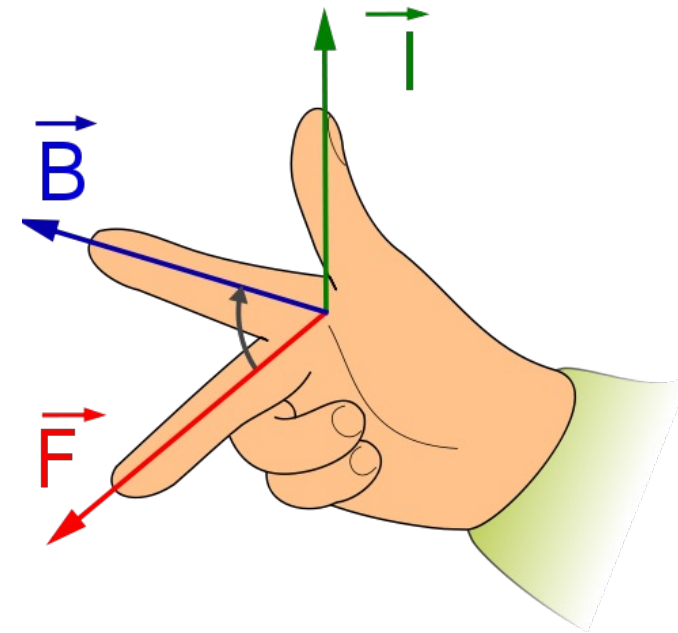
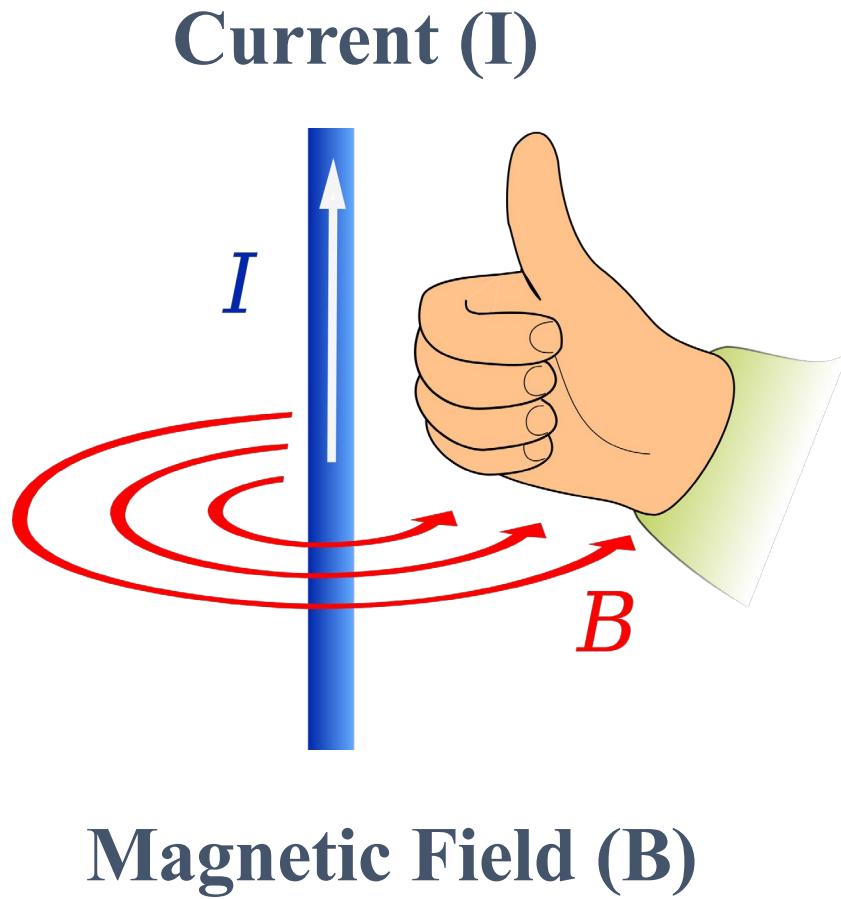
Energy corresponds to how much work you can do.

Power is energy per unit time, which corresponds to how quickly you can do work.

Energy density is the energy per unit volume, which is equivalent to a pressure (force per unit area).



The Z machine can create large currents, which create a strong azimuthal magnetic fields, which results in a radially inward force

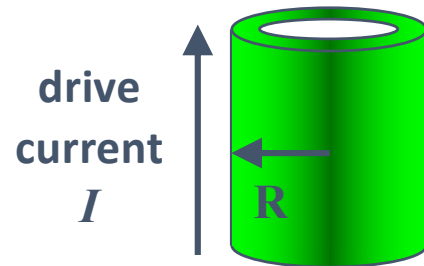


Pulsed power can generate ~100 Mbar drive pressures, which can be used to obtain even higher pressures such as those in fusion



Magnetically Driven Implosion

$$P = \frac{B^2}{8\pi} = 105 \left(\frac{I_{MA}/26}{R_{mm}} \right)^2 \text{ MBar}$$



100 MBar at 26 MA and 1 mm

100 GPa = 1 Mbar $\approx 10^6$ atmospheres

Pressure equivalent to Energy Density (J/m^3)

1 Mbar = 10^{11} J/m^3 , threshold of High Energy Density regime

Z Storage capacitor



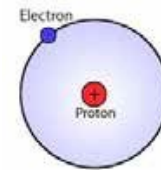
2e-6 Mbar

TNT



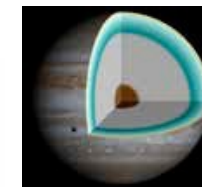
0.07 Mbar

Internal Energy of H atom



1 Mbar

Metallic H in Jupiter's core



30 Mbar

Z Magnetic Drive Pressure



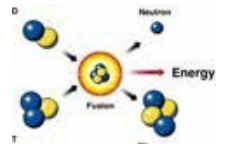
~100 Mbar

Center of Sun



250,000 Mbar

Burning ICF plasma



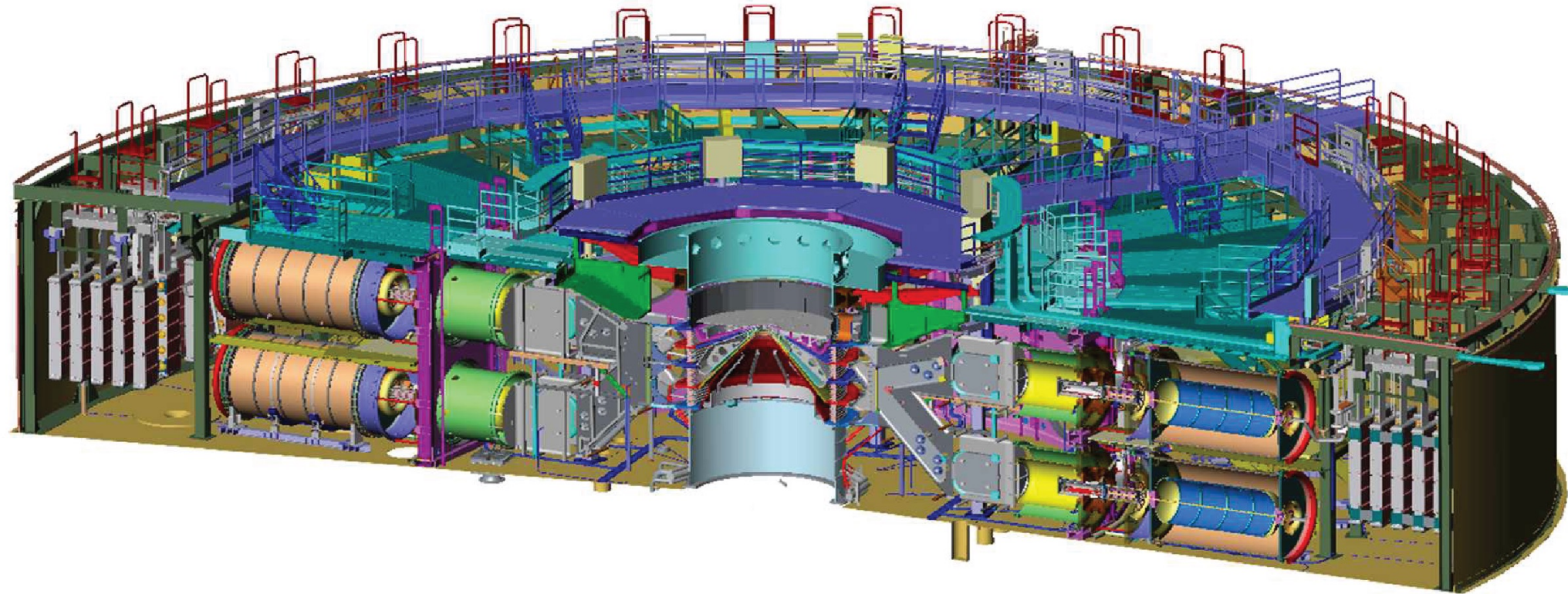
800,000 Mbar

Push on samples

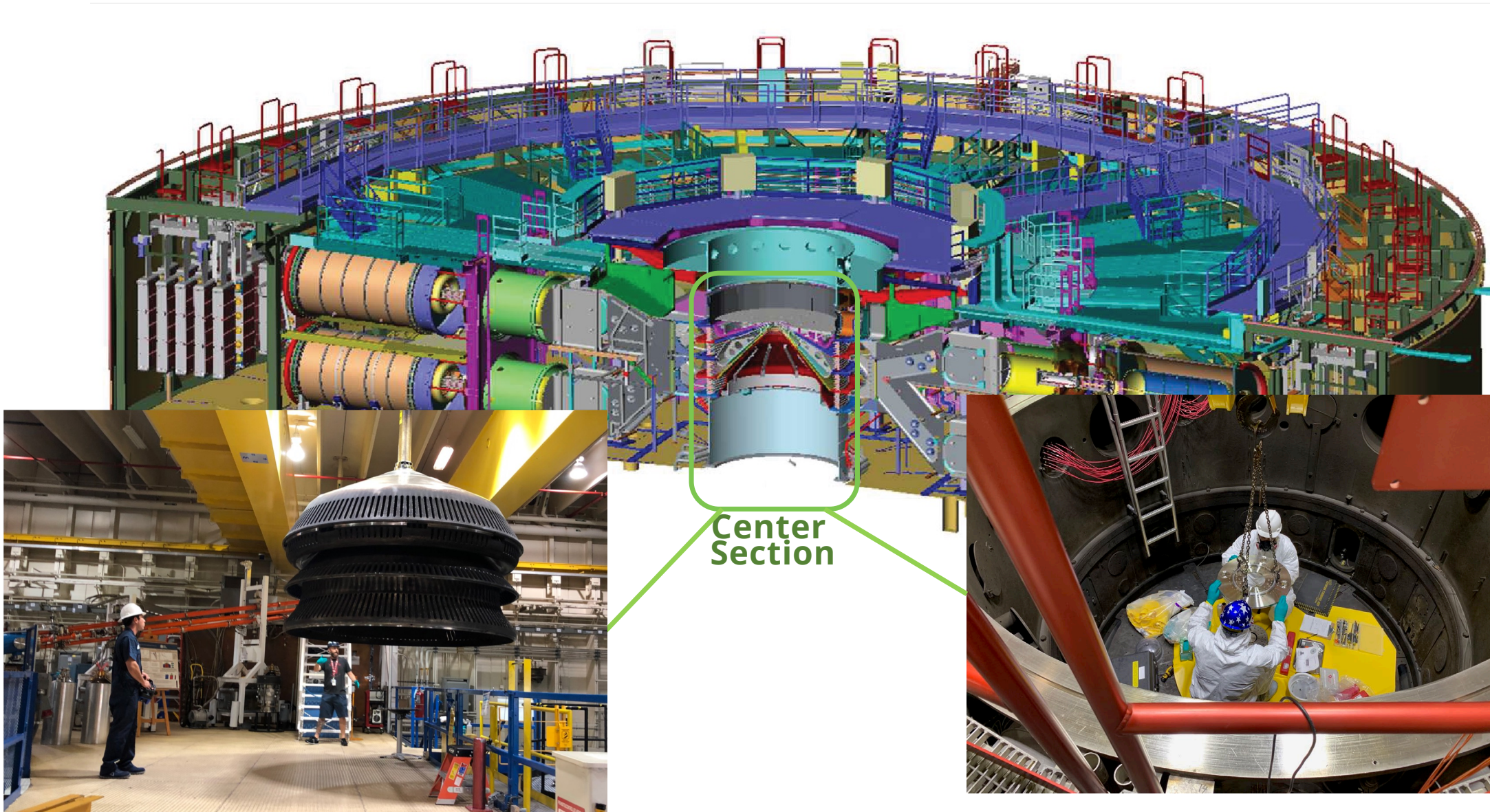


Compress fuel at high velocity

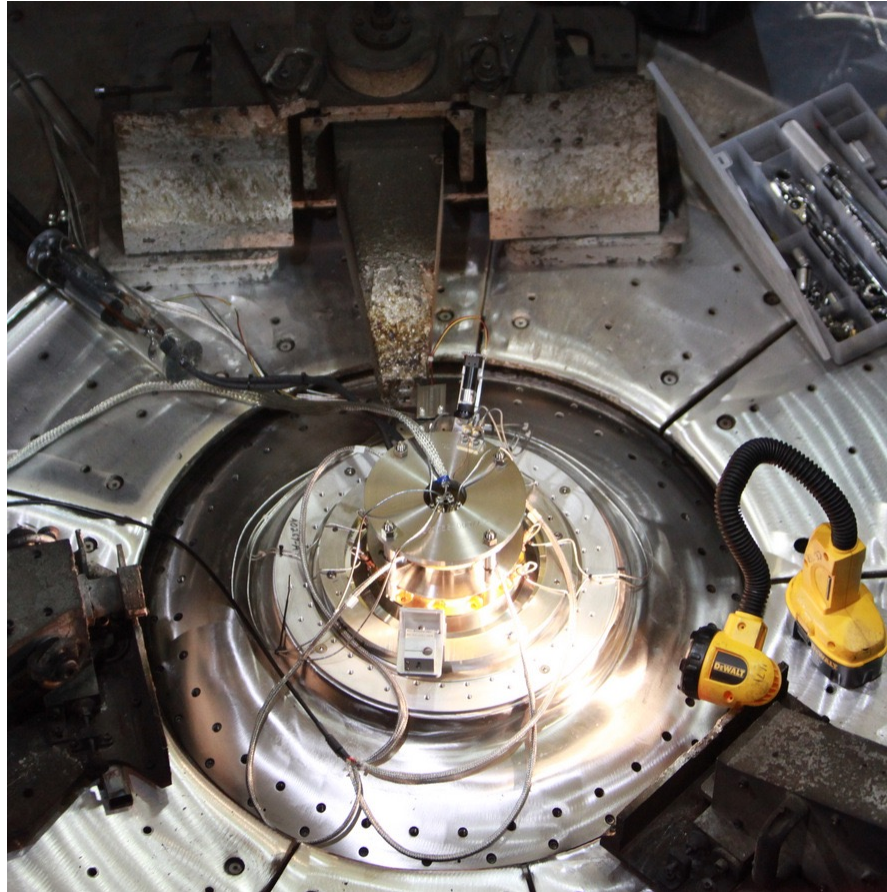
The purpose of the Z machine is to compress energy in both space and time to create extremely high energy density conditions at its focal point, creating conditions similar to those within or produced by a nuclear weapon



Workers on Z fire ~150 shots per year on a wide range of experiments that support our NNSA mission or university collaborators (only ~40% of these shots are fusion-related). Our facility is not designed for high repetition rates.



Each experiment on Z destroys the center of the machine!
(~2-3 MJ energy release equivalent to 2-3 sticks of dynamite!)



Pre-shot photo of coils
and target hardware



Post-shot photo

Both the NNSA and pulsed inertial fusion energy companies seek to produce ~100-1000 MJ per pulse, so there is significant overlap in the target physics and some overlap in driver technologies



The key difference is that fusion energy requires repetition rates of ~1-10 Hz!

NNSA fusion research facilities fire about one to four times per day.

NIF typically waits a couple of days after each MJ-class shot before the next shot, to allow short-lived radiation activation to decrease.

1000 MJ is equivalent to a quarter-ton of TNT—future high-yield facilities must contain any debris and energy release

Fusion energy will require a lot of engineering to achieve high repetition rates that has never been demonstrated at scale. The target physics is the “easy” part!

These are exciting times for fusion energy research! Creating cost-effective energy on the grid will require significant engineering and supply chain development.



- A nominal ~1 GW power plant based on DT reactions would consume the world's supply of civilian tritium in just a few days
 - It is possible to “breed” tritium in a fusion plant once it gets started, but this remains to be demonstrated at scale
 - Alternative fuels are possible, but each option has its own unique challenges
- All pulsed driver technologies (pulsed power, lasers, plasma jets) require capacitors to store and discharge energy. The supply chain to make these at scale and with long lifetimes is still under development.
- 100-1000 MJ yields will create debris. At 1-10 Hz repetition rates, injecting the next target and properly coupling energy to it has yet to be demonstrated at scale.
- Magnetic fusion plasmas (e.g., ITER) will contain >300 MJ of energy. If the plasma containment was lost, this energy would be rapidly dumped into the walls and extreme currents could be induced in the surrounding magnetic field coils.
- Neutrons created by fusion reactions will damage the chamber walls and the facility. The study of ideal first-wall materials remains an active area of research.

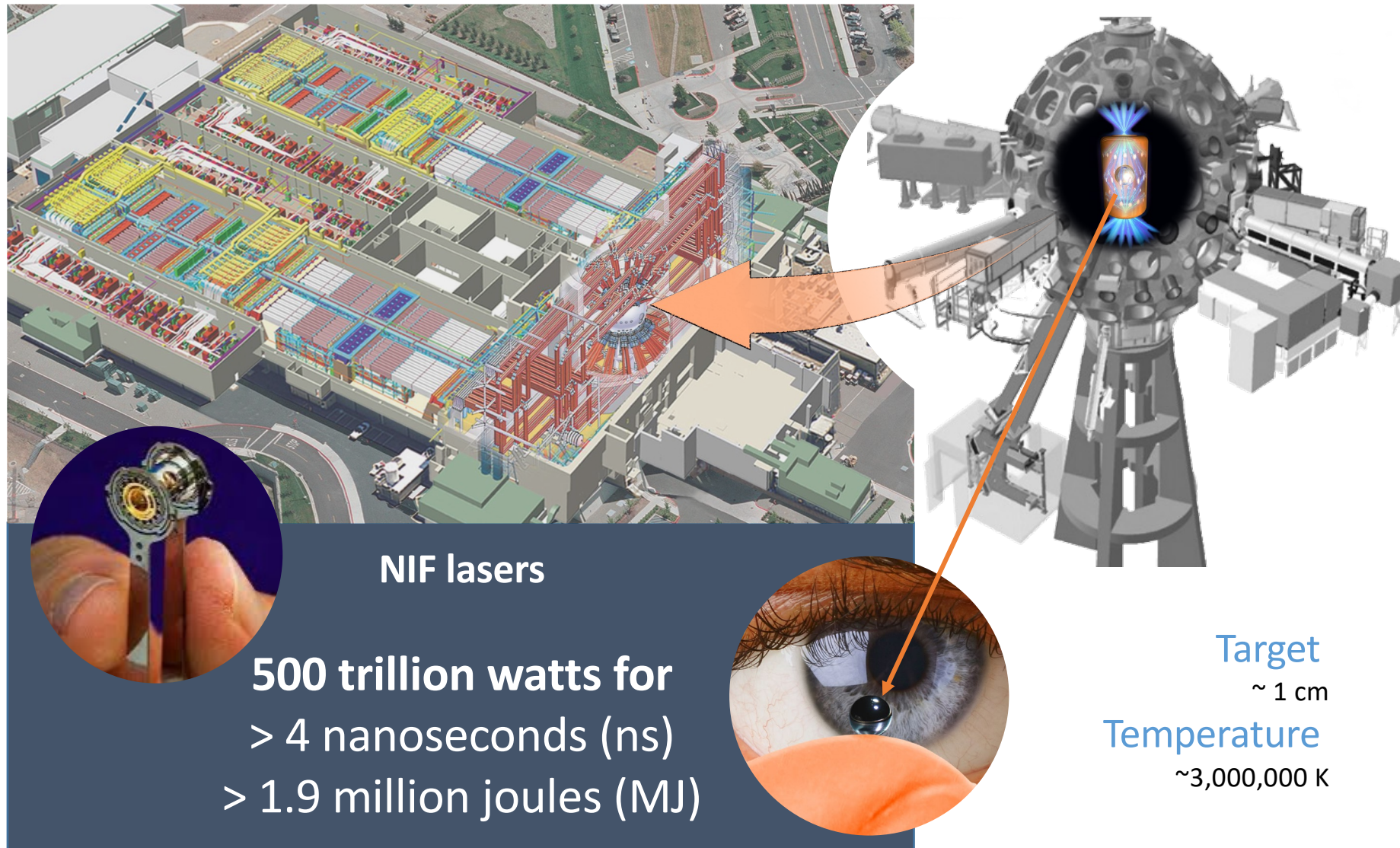
Fusion energy is not impossible to achieve. The key question is which approach will achieve it in a cost-effective manner. It is good to have many options today!

Have you had your fill of Fusion yet?

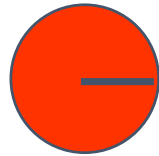


Questions?

Like the Z machine, the National Ignition Facility compresses energy in both space and time to create the extreme conditions for fusion



For hot-spot ignition, the fusion fuel must be brought to a pressure of a few hundred billion atmospheres, quickly & symmetrically

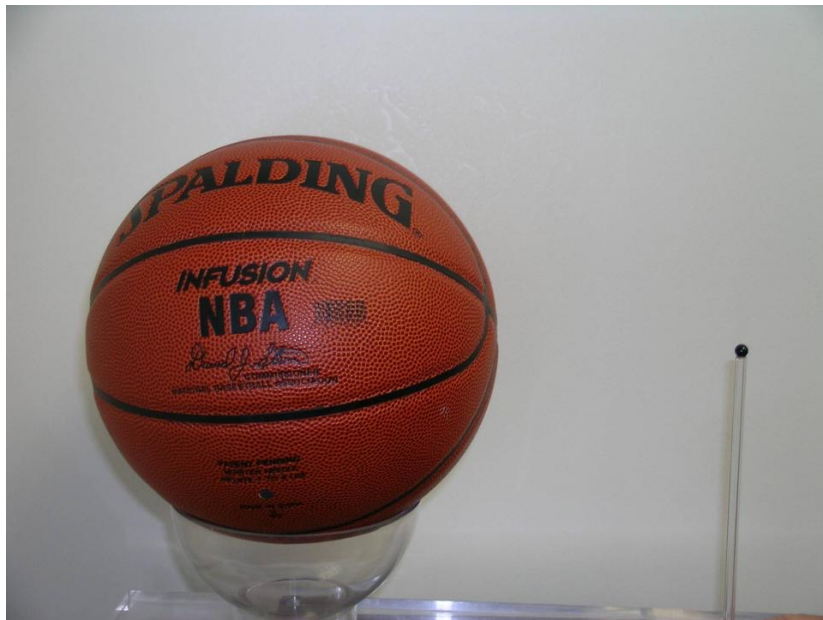


ρ, R, T

For ignition conditions:

$$\left\{ \begin{array}{l} \rho R \approx 0.4 \text{ g/cm}^2 \\ T \approx 5 \text{ keV} \end{array} \right\}$$

$$E_{\text{NIF}} \sim 15 \text{ kJ} \Rightarrow P \sim 400 \text{ GBar} \quad R \sim 30 \mu\text{m} \Rightarrow \text{ and } \rho \sim 130 \text{ g/cm}^3$$



- 35:1 convergence ratio
- Basketball to pea
- Need <1—2% deviation from a perfect sphere
- If capsule scaled to size of earth, it would have to be smoother than earth
- Volume compression >40,000x



- 380 km/s implosion
- Faster than a speeding bullet! (~3000 km/h)
- Going from NY to LA (about 4000 km) would take about 10 seconds!