Fusion Technologies Overview

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NM Science, Tech, & Telecommunications Committee
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U.S. DEPARTMENT OF ENERGY NNSA

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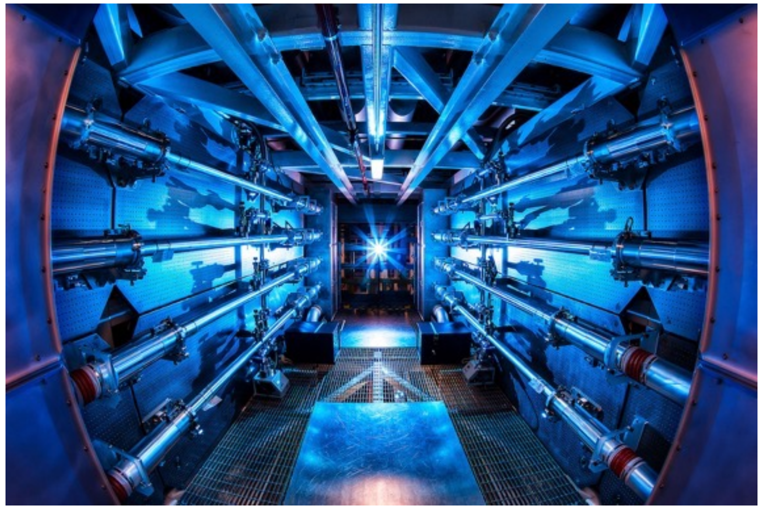
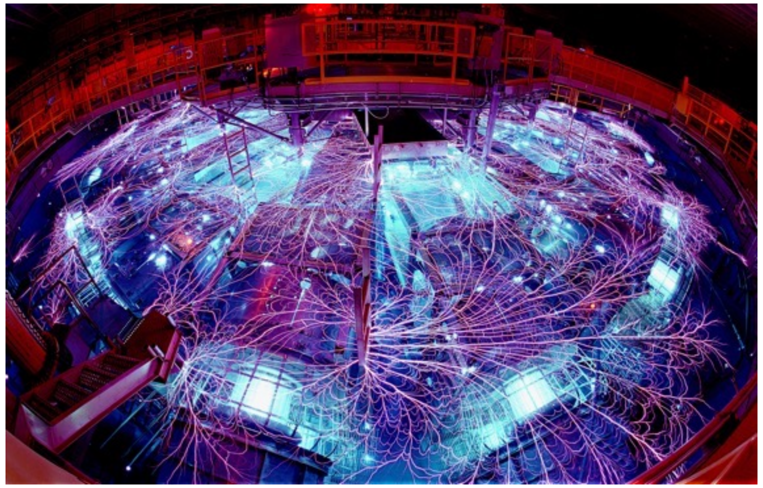
By the end of this talk I hope you will understand how these things are related…



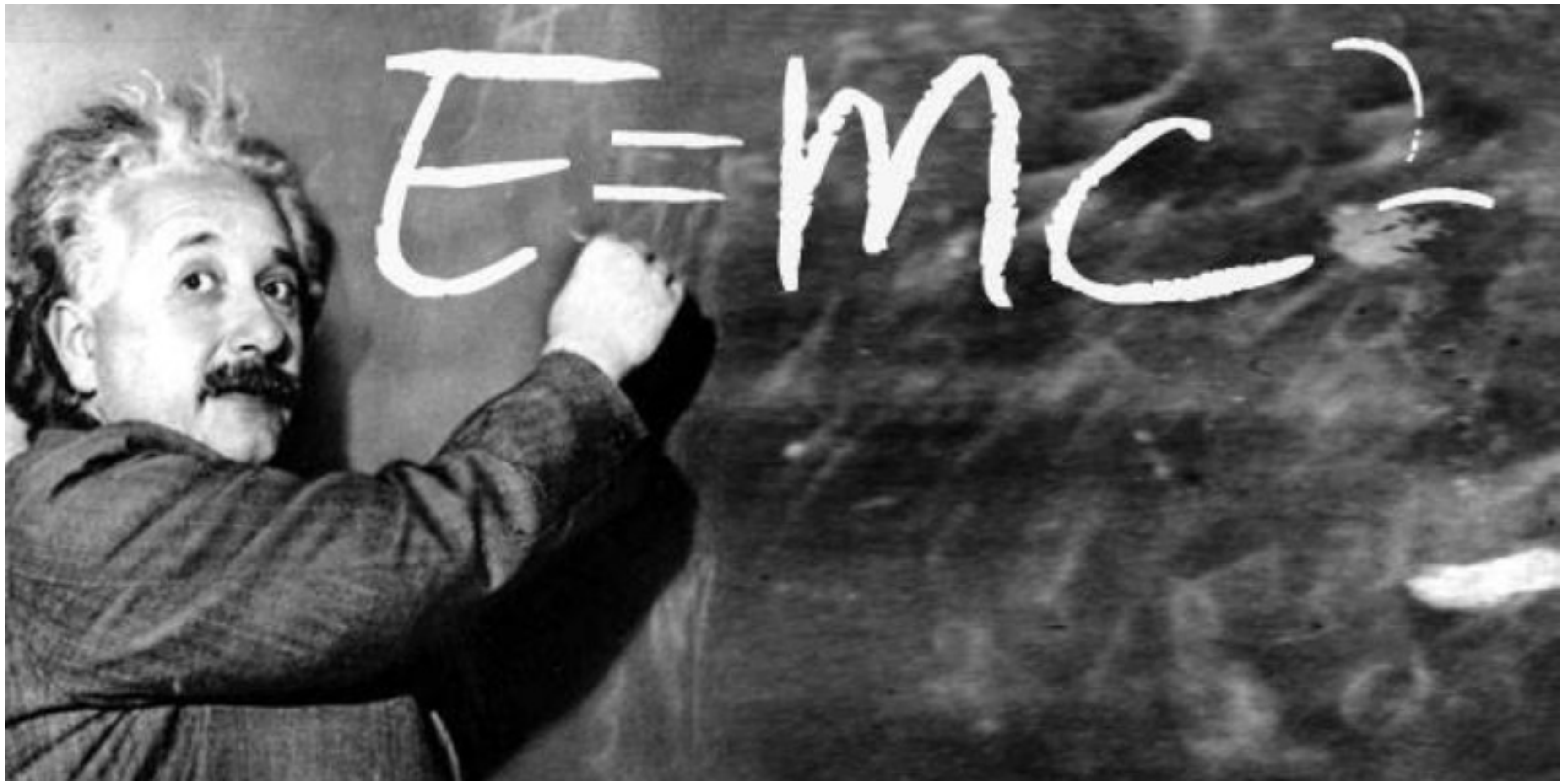


The world's largest laser and largest pulsed power machine

Nuclear weapons

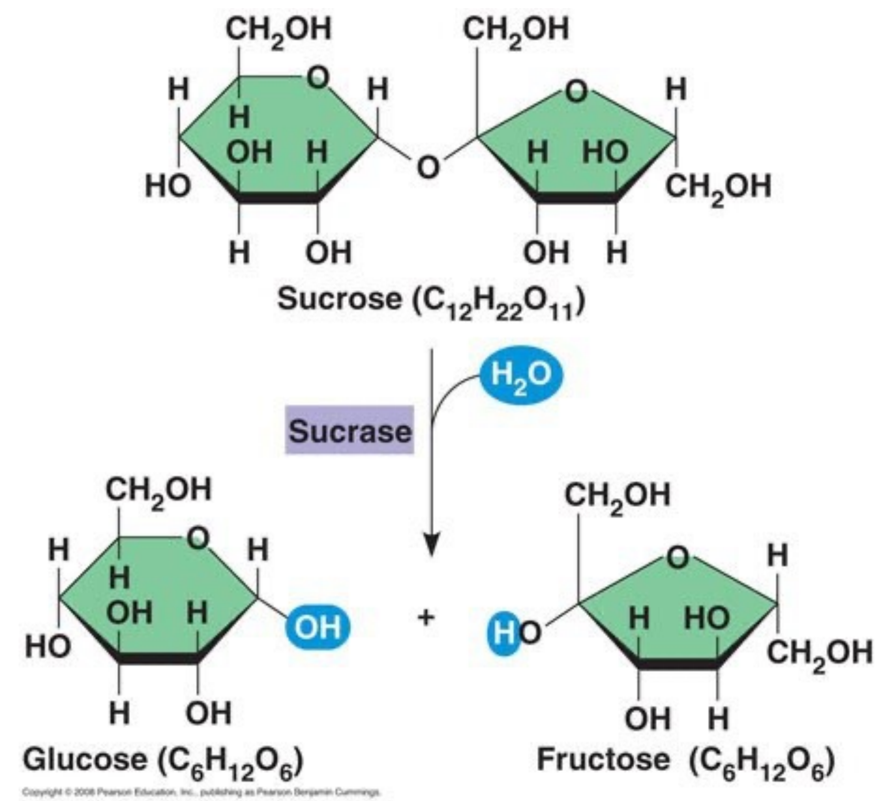
Jelly doughnuts

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



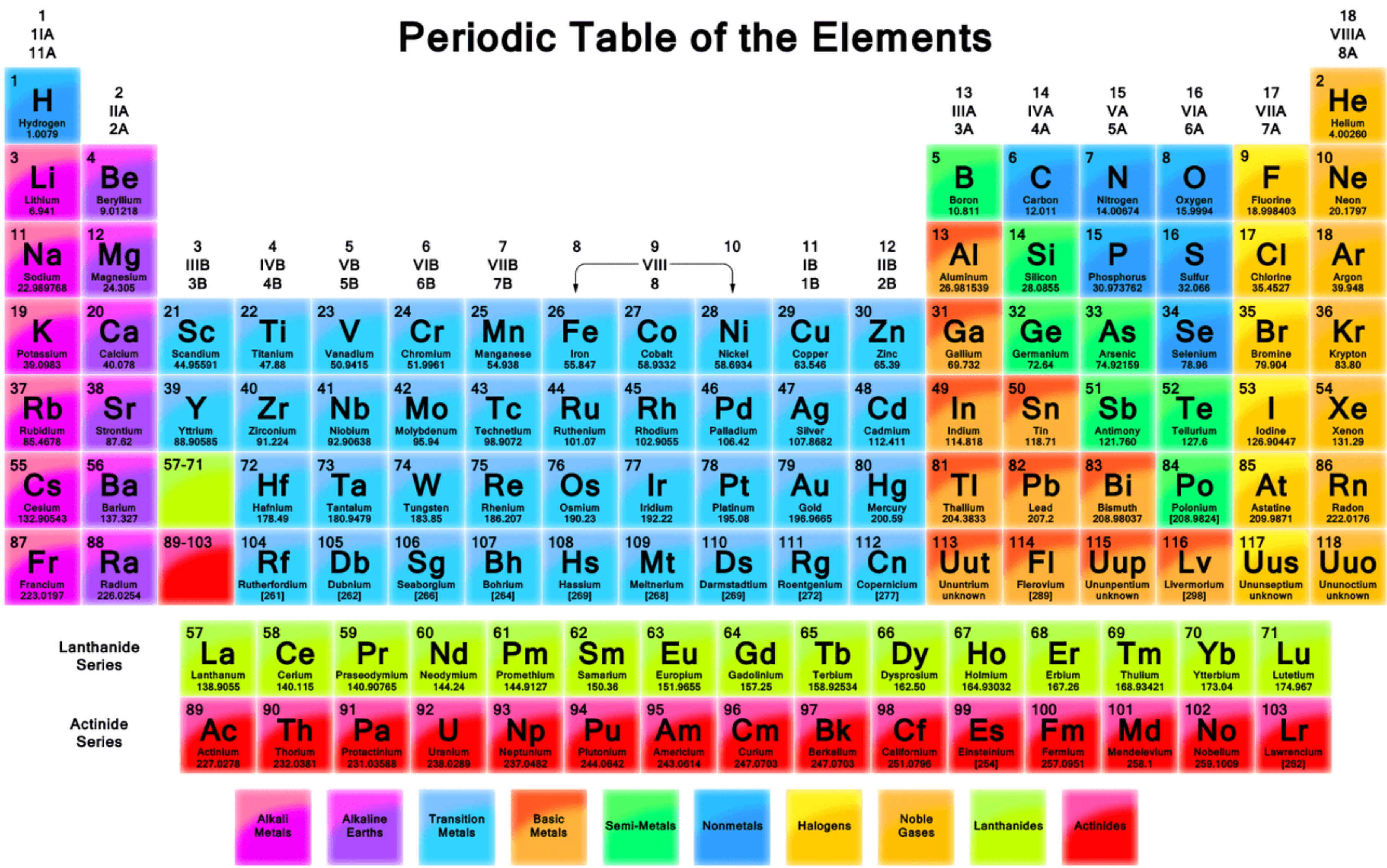
Published in 1905, this equation makes a powerful statement:
Mass and energy can be converted into one another

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

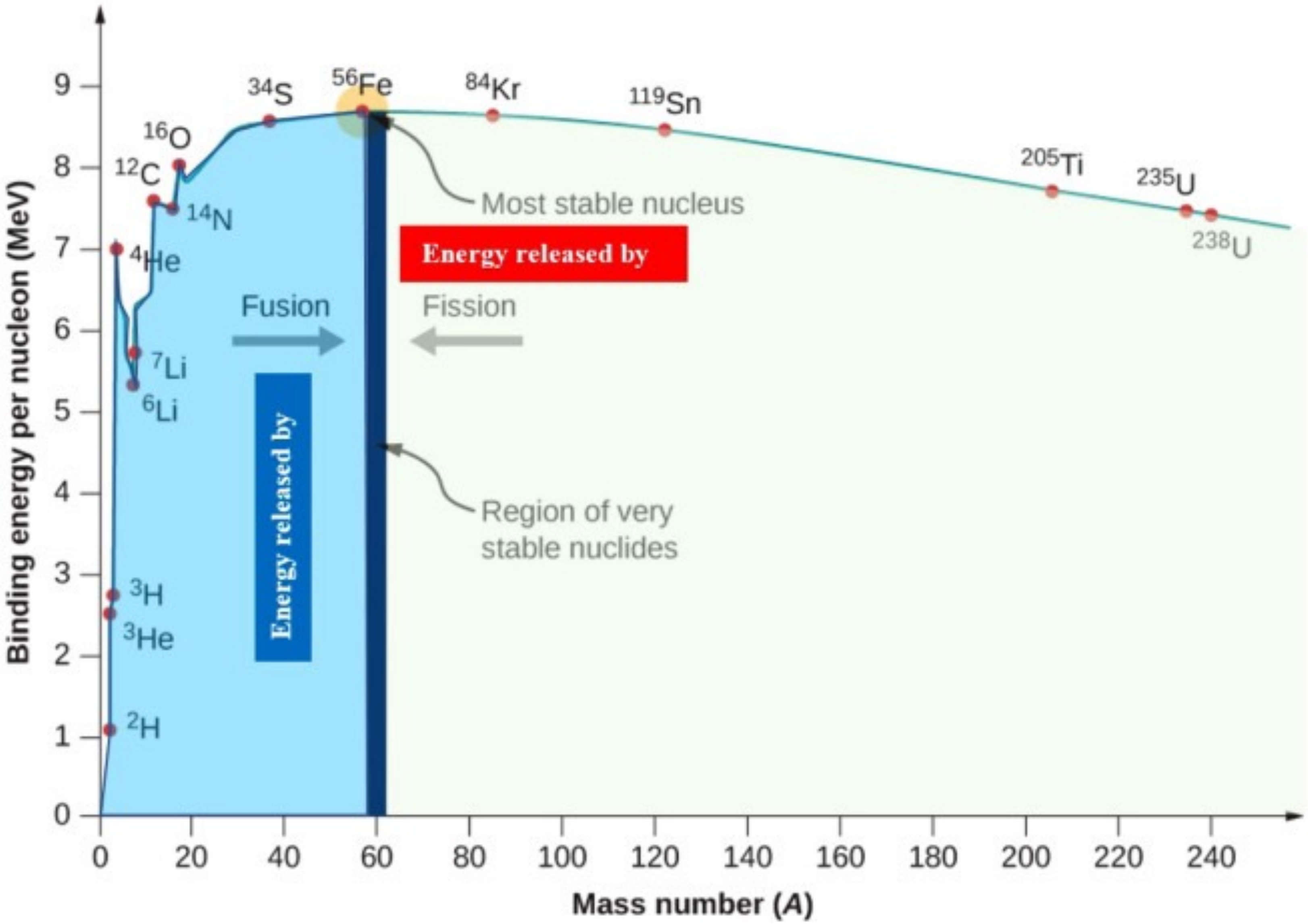


Hold on! Eating food breaks down chemical bonds that join molecules together in your food, but it doesn't change the atoms. Einstein was talking about creating and destroying matter/atoms!

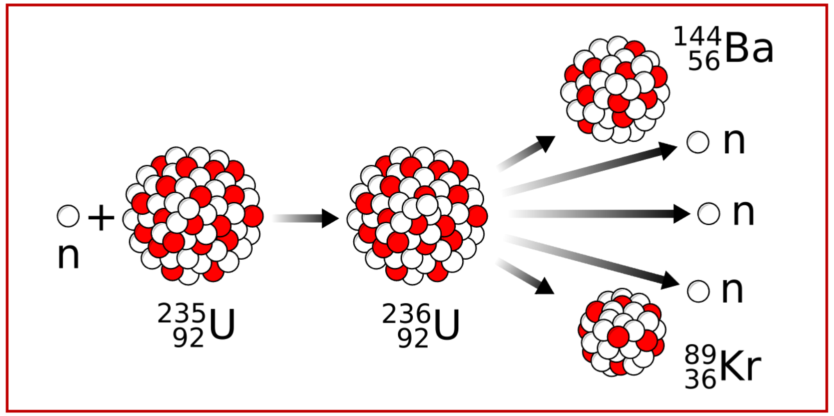
All matter is made up of atoms with different properties, masses, etc. Einstein's famous equation speaks about what happens when you create/destroy this matter.



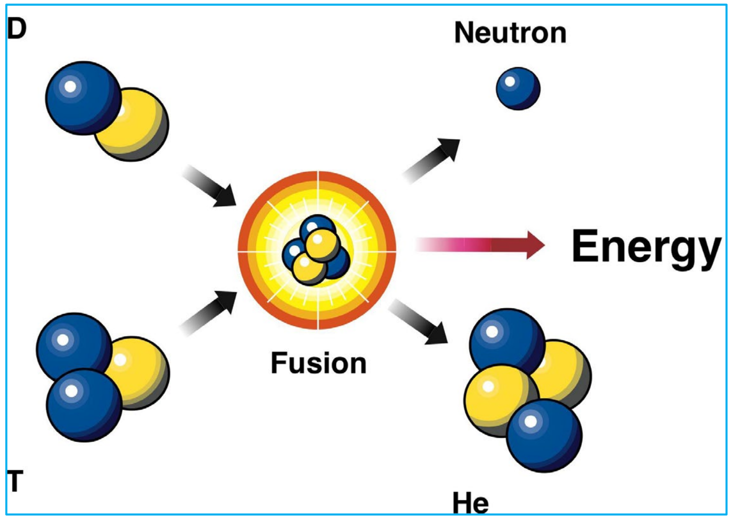
We can release and harness energy from matter through one of two processes



Fission

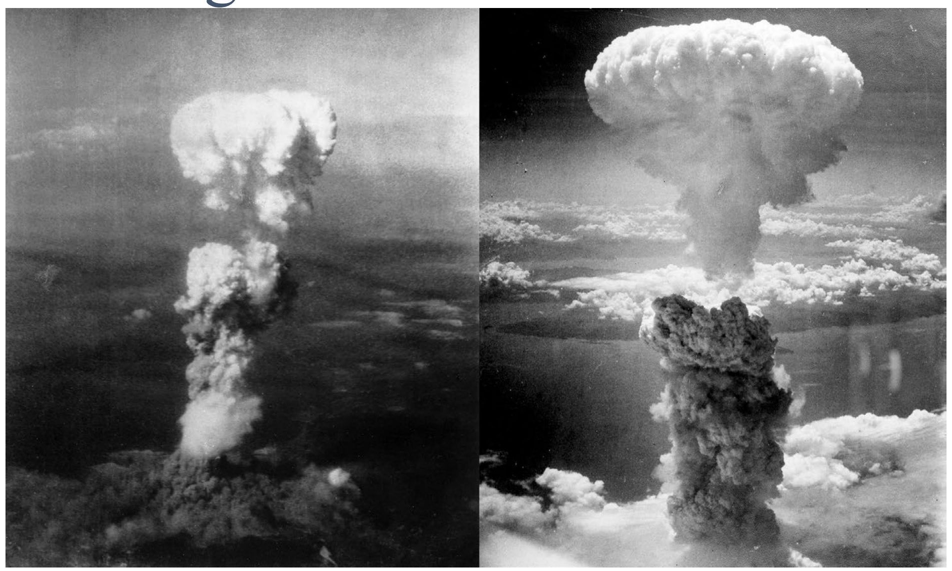


Fusion

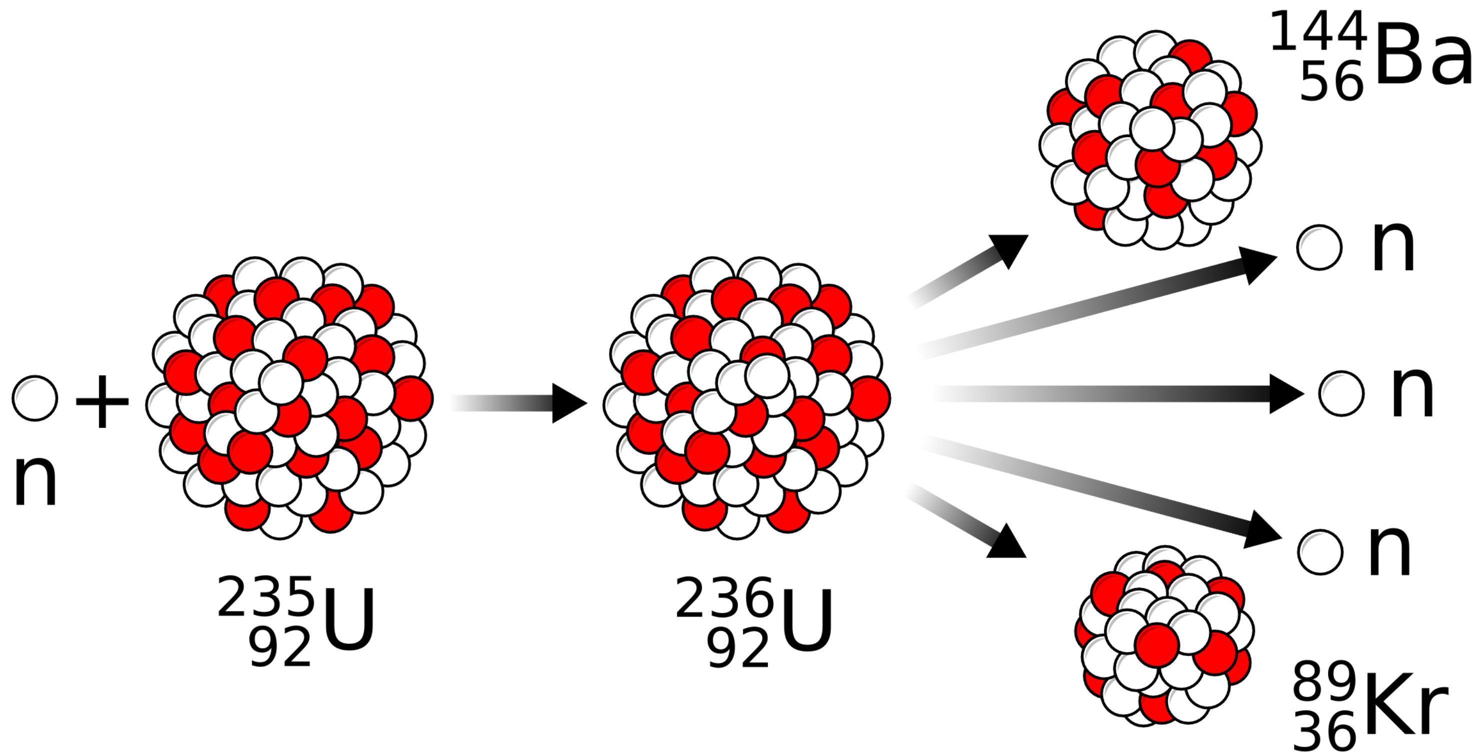


Nuclear fission played a key role in the development of the world's first nuclear weapons by the United States

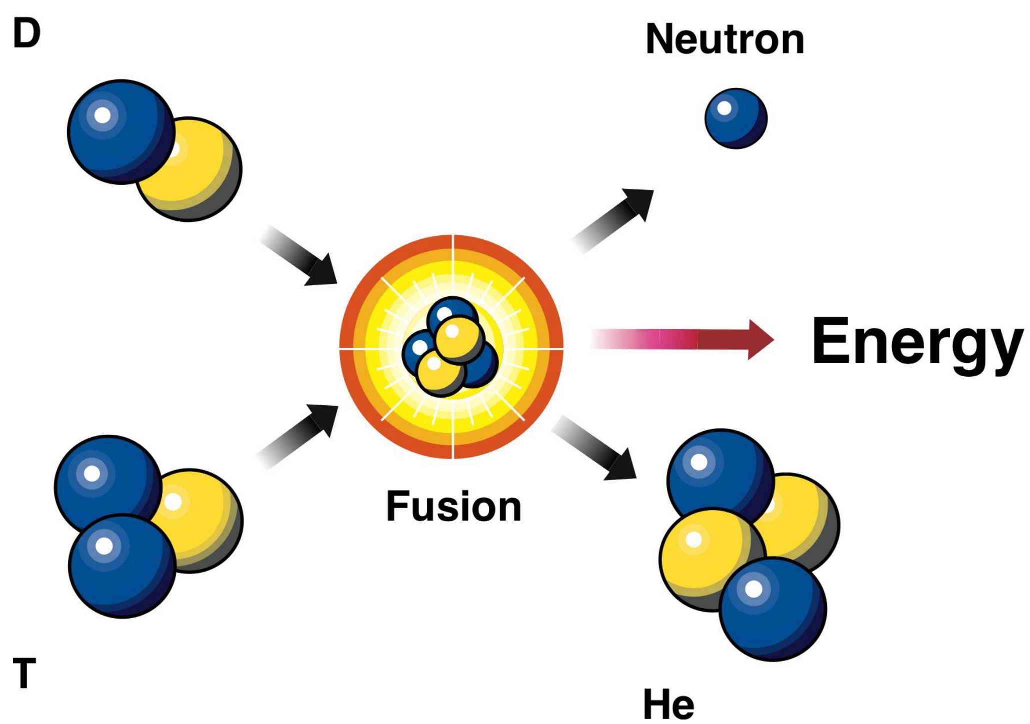
Nagasaki Hiroshima

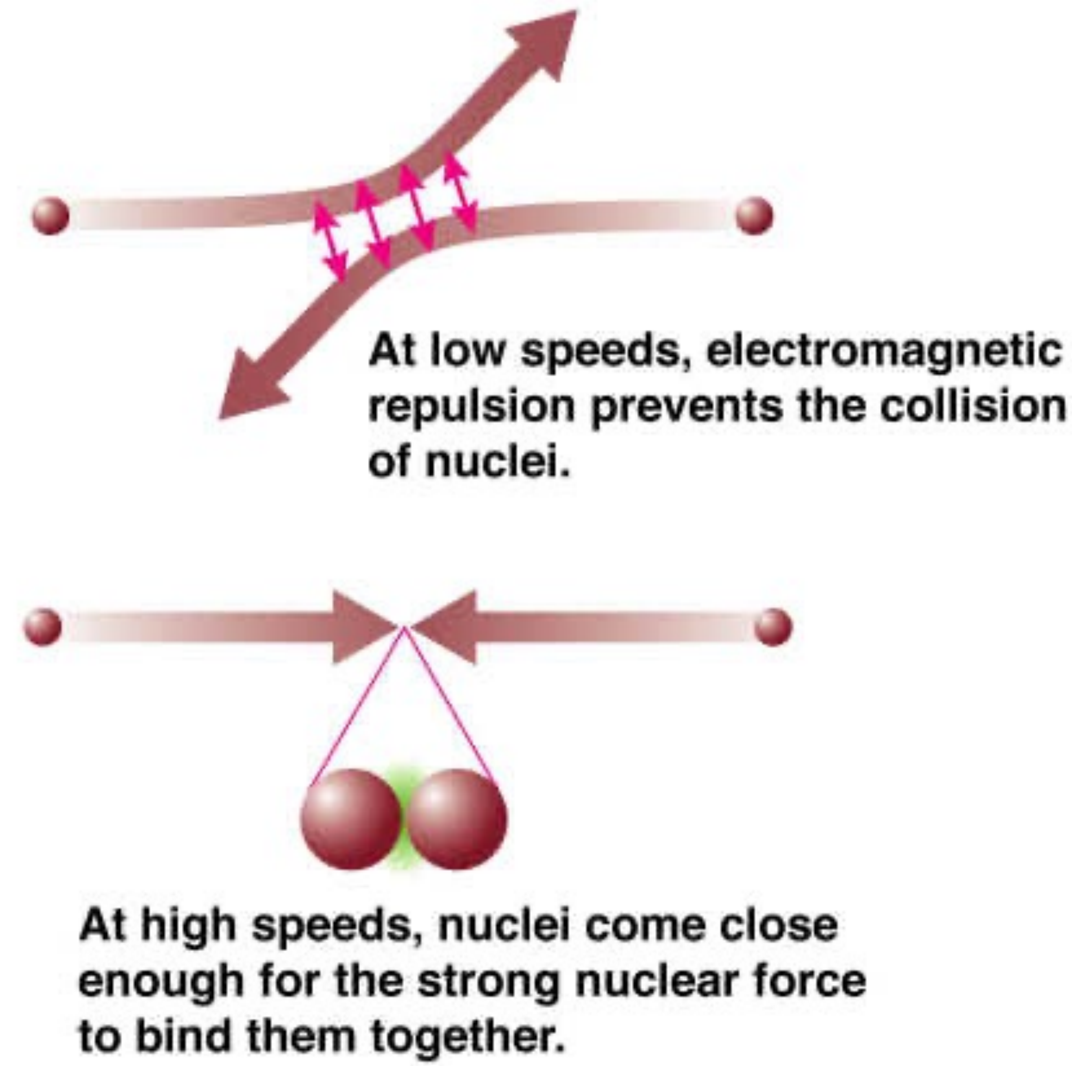


239Pu weapon 235U weapon

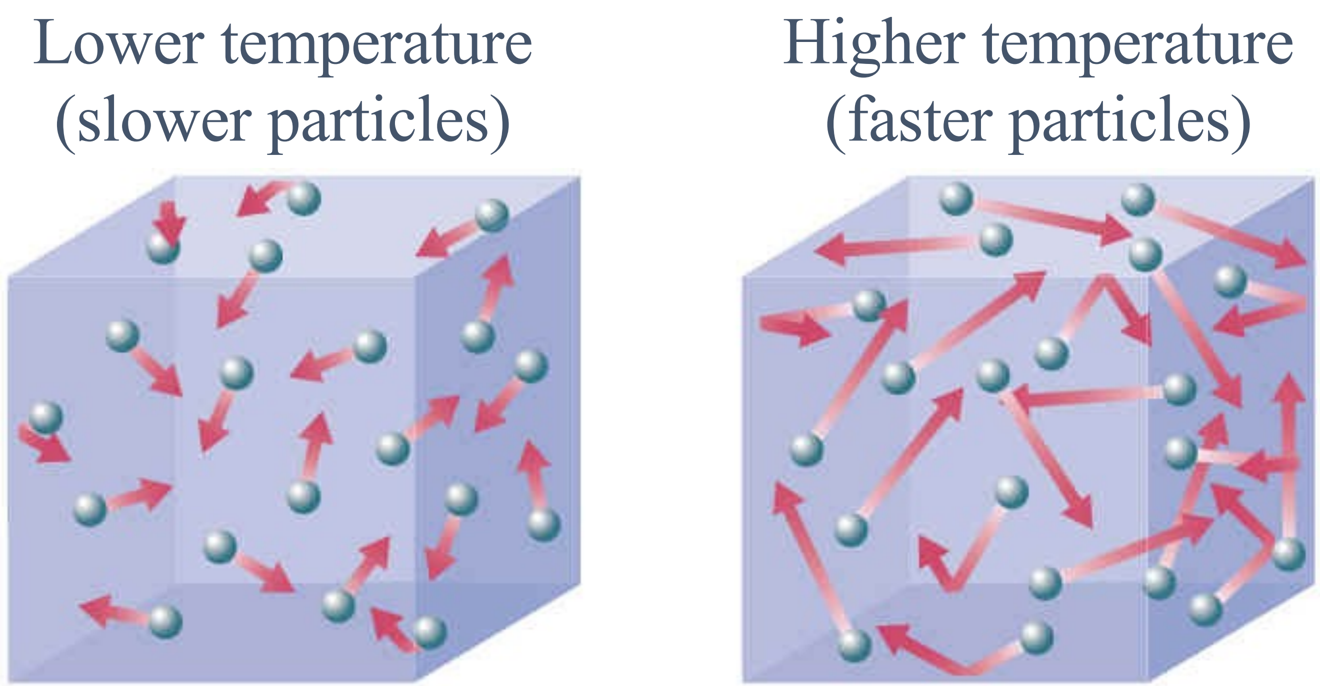


A key challenge for fusion is that the reacting particles are both positively charged, which will cause them to repel each other unless their velocities are high enough



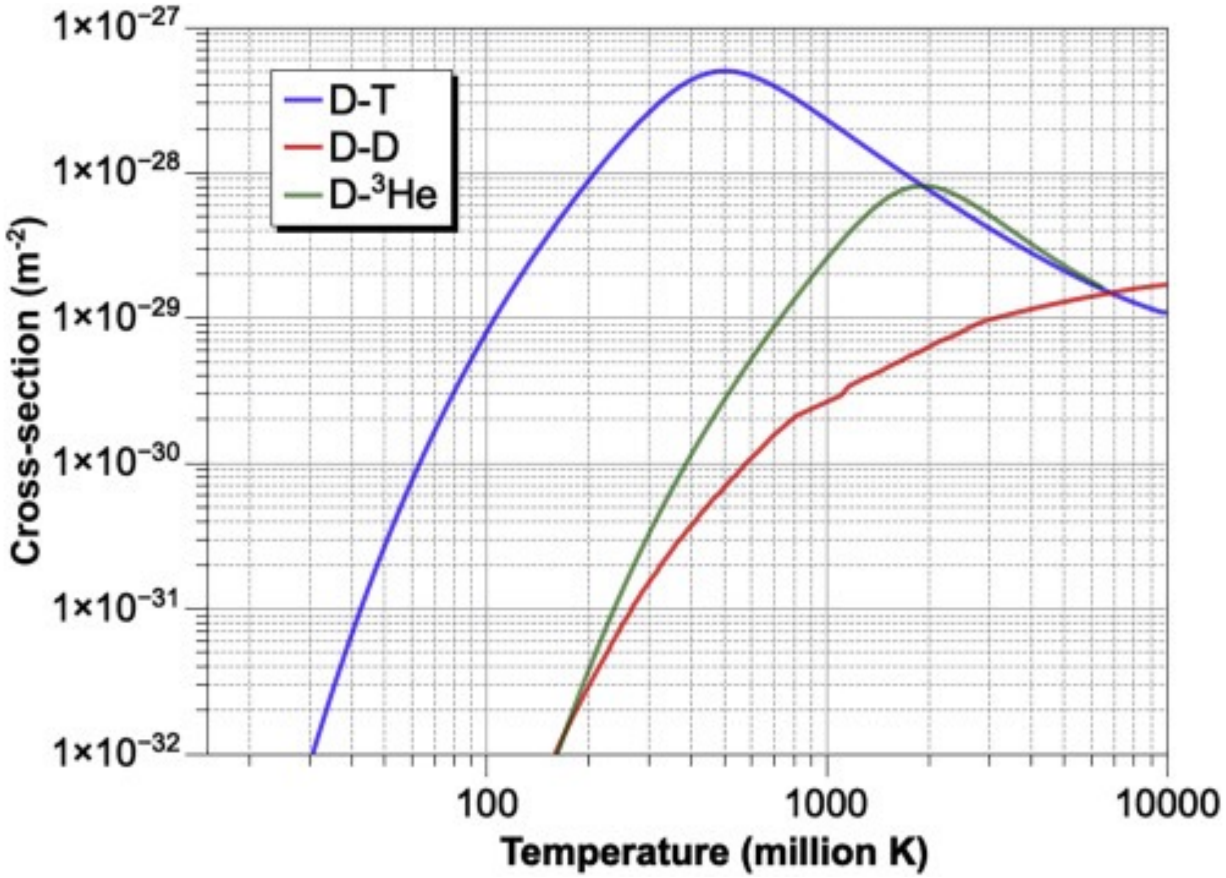


To enable the fusion reaction to occur, the particles must be moving at very high velocities, which corresponds to needing a very high temperature

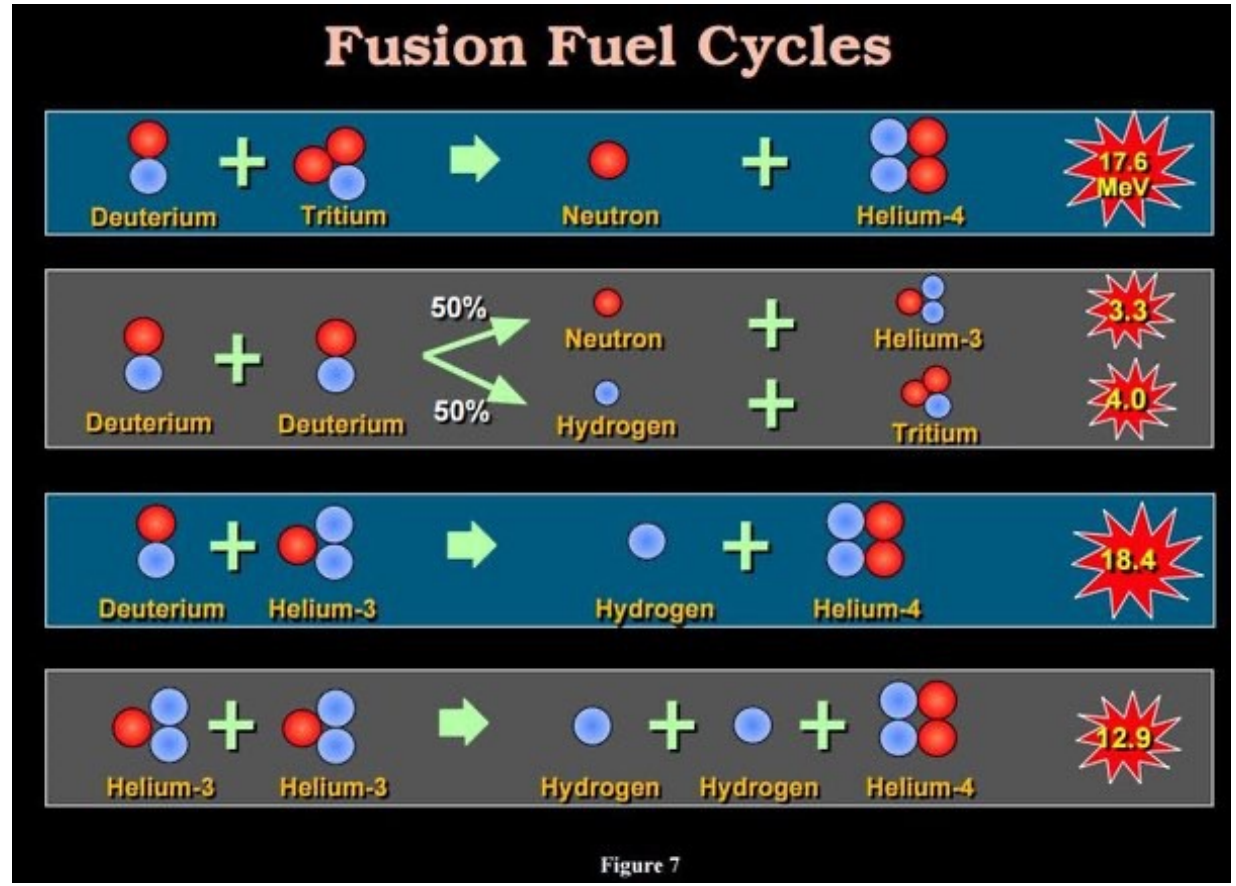


Longer arrows mean higher average speed.

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).

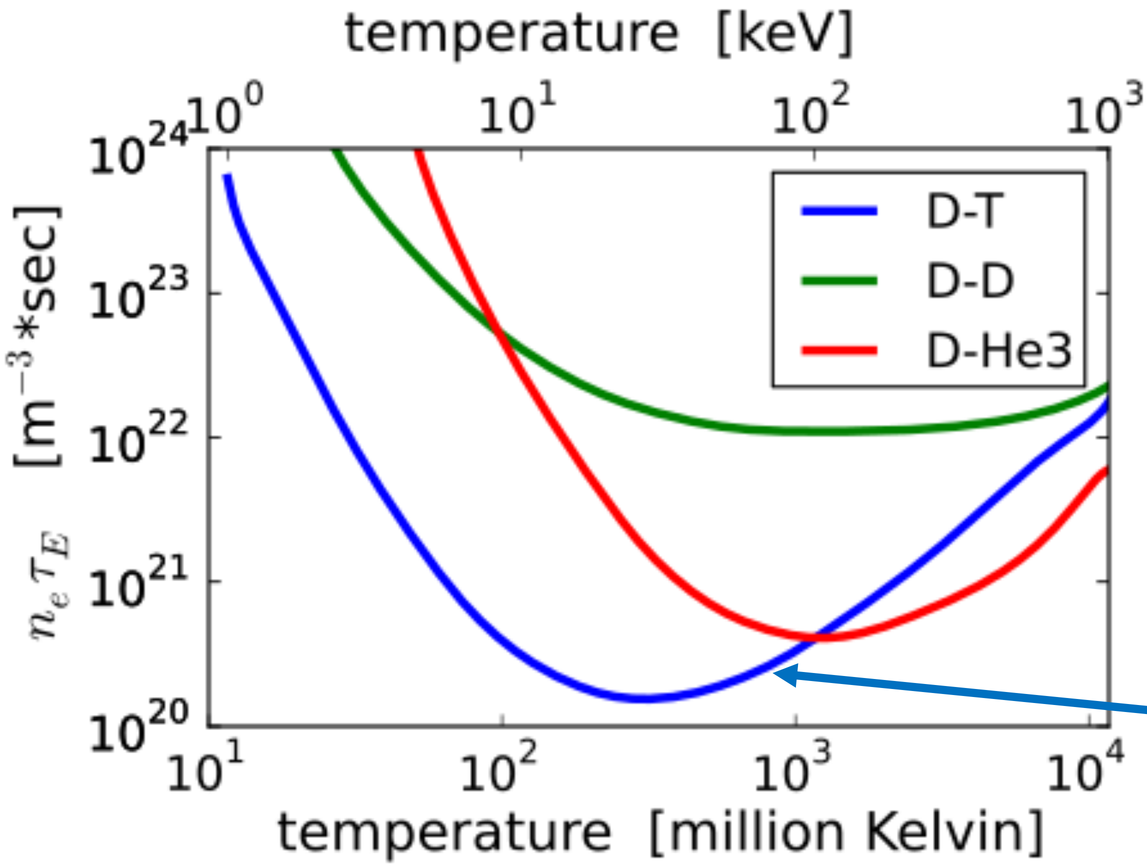


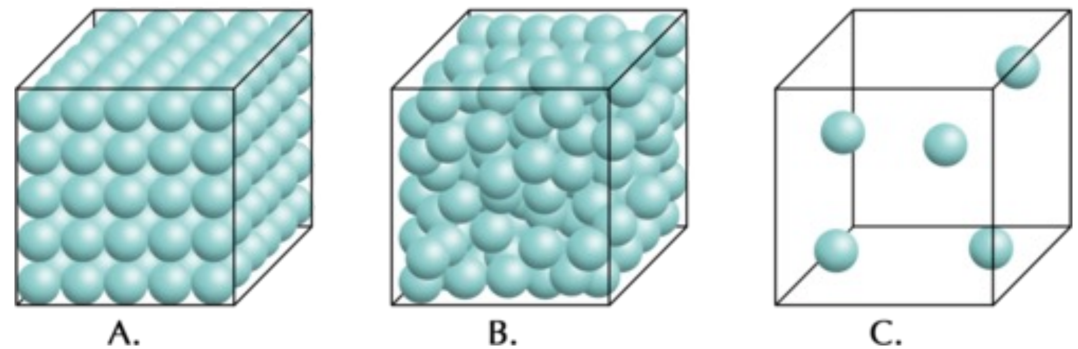
100 million Kelvin = 180 million degrees Fahrenheit
1 keV = 11.6 million K



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 ⟷ Lower

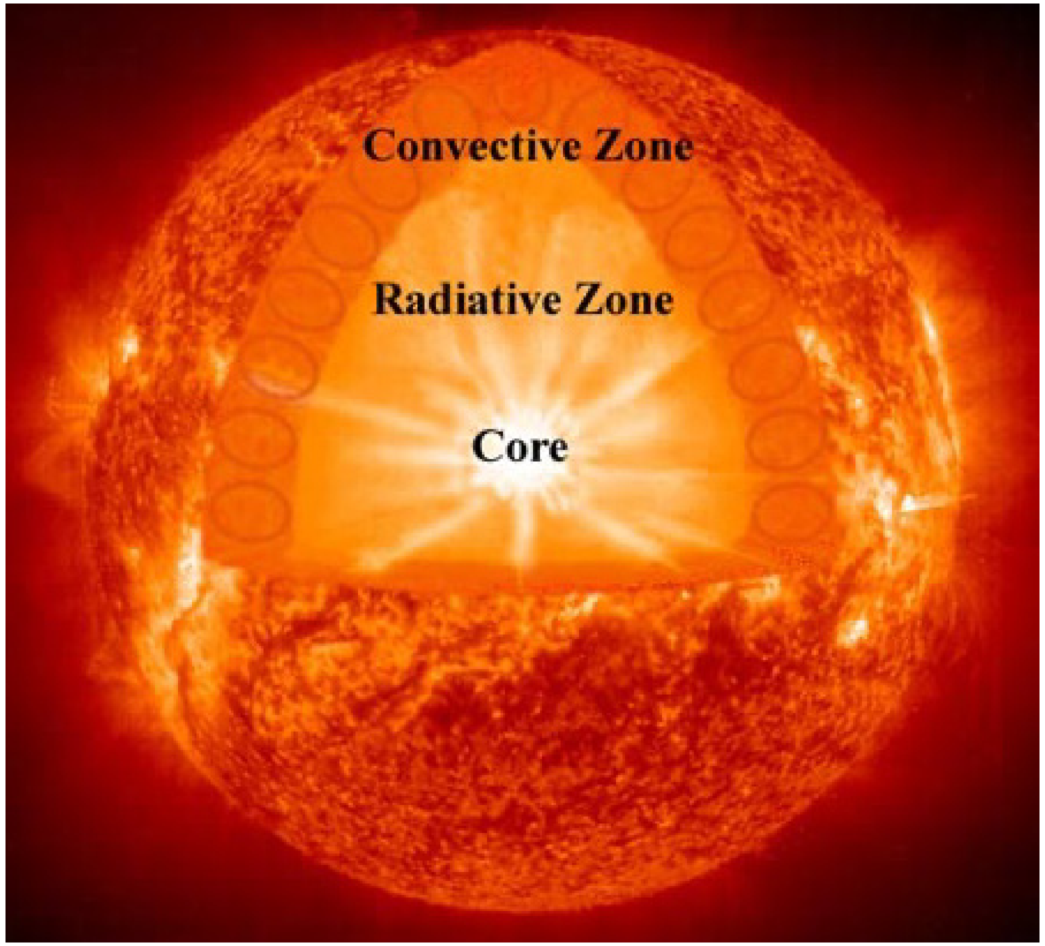
Number of particles/unit volume

Lawson criterion (DT)

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

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

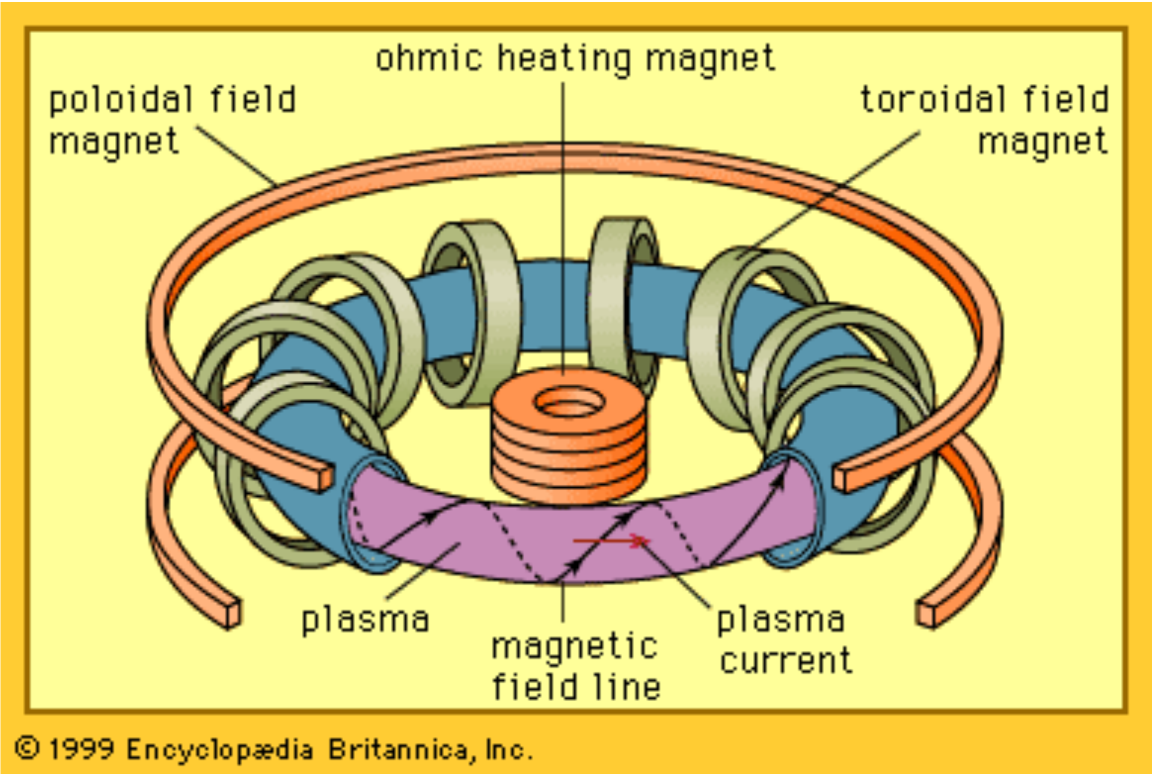
Fusion reactions occur naturally in stars, where immense gravitational forces and large sizes can confine plasmas at the high temperatures needed for fusion



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

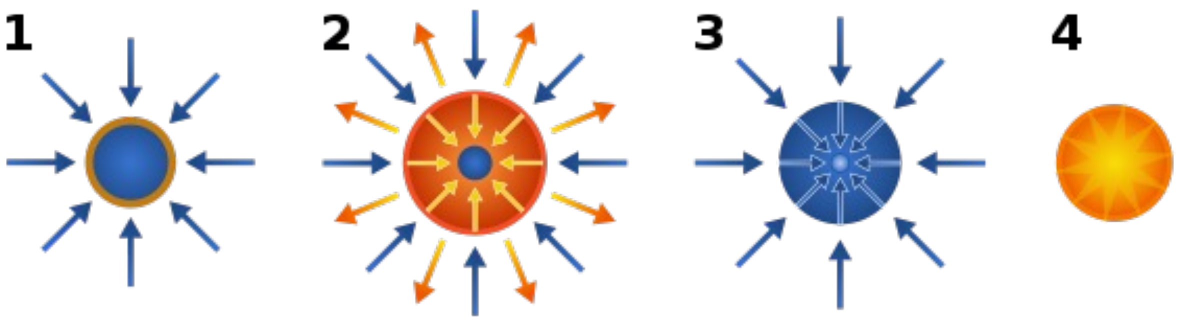
Magnetic Confinement Fusion



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

Inertial Confinement Fusion

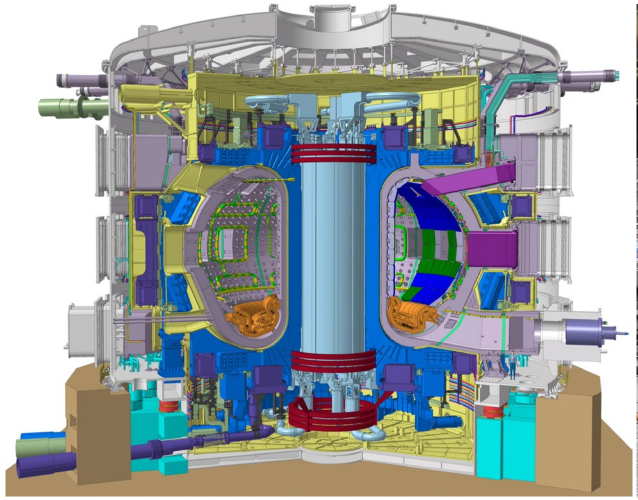
Lasers, particle beams, or electricity compress fusion fuel

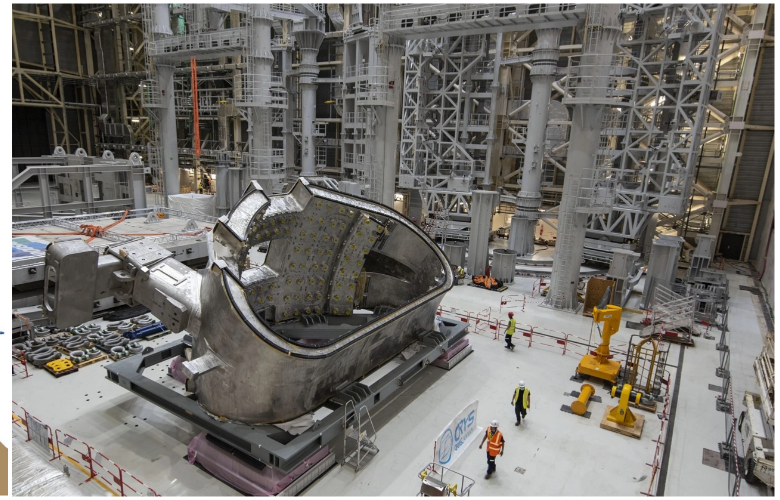


Compress fuel to very high densities for short periods of time—nothing touches the hot plasma

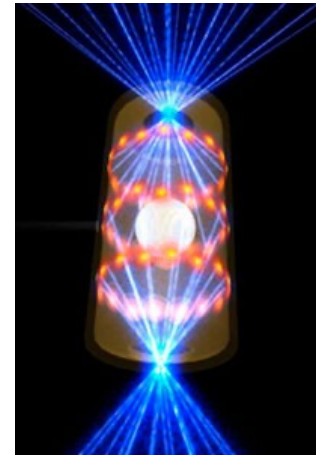
The largest laboratory fusion projects today are focused on magnetic or inertial confinement fusion, though there is growing interest in intermediate regimes

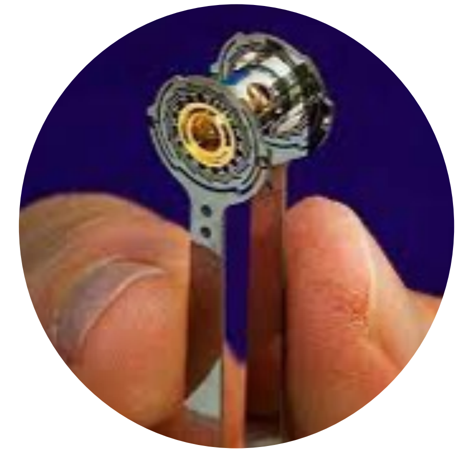
Magnetic Confinement Fusion (e.g., ITER)
Large volumes, low density, long confinement





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





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

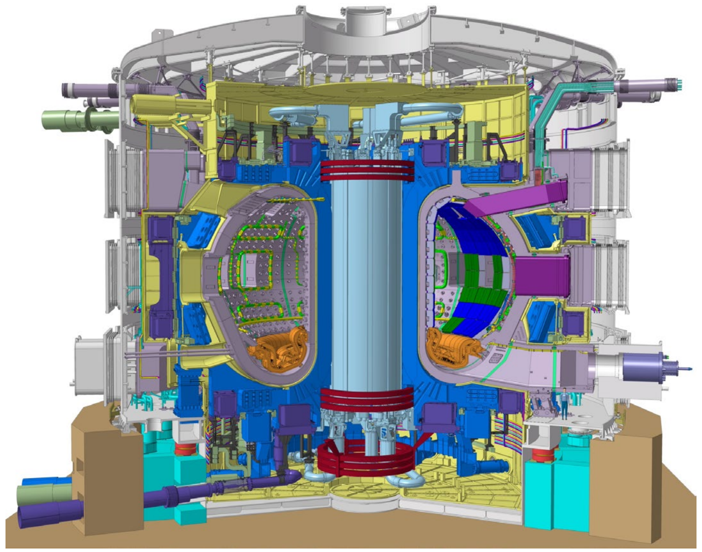
Note: A refrigerator magnet is ~50 G

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

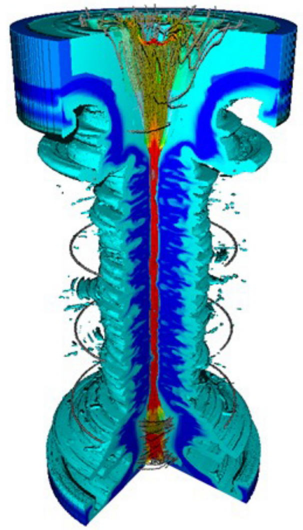
Fusion concepts at intermediate densities and confinement times are also possible. Many fusion startups operate in between these extremes.

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

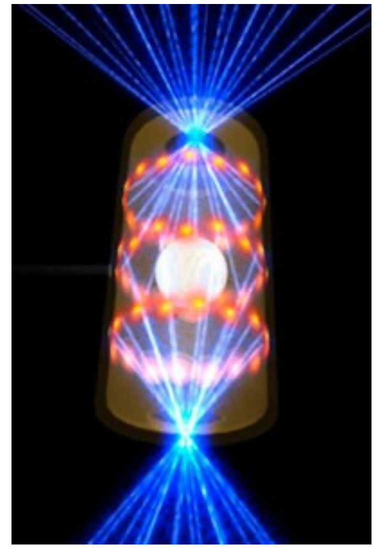
MCF (e.g. ITER)



MIF (e.g. MagLIF)



ICF (e.g. NIF)



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

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

*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 ~10^{27}-10^{31} m^{-3}, i.e., far closer to inertial fusion than magnetic fusion

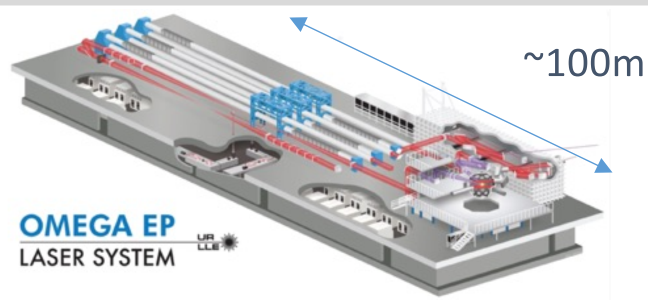
The NNSA funds Inertial Confinement Fusion research on three major facilities, including the Z machine here in Albuquerque at Sandia

National Ignition Facility (NIF)

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

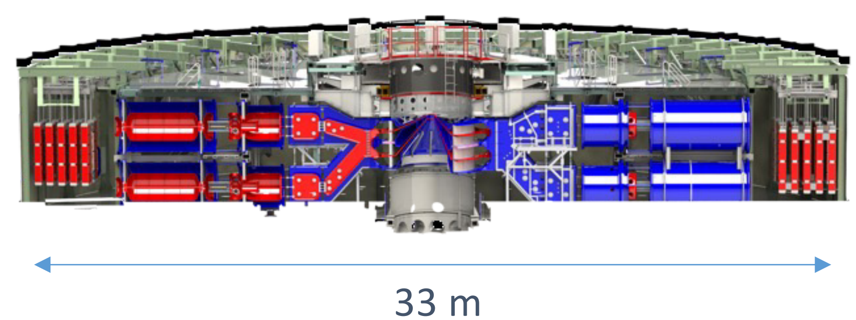
OMEGA Laser Facility

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

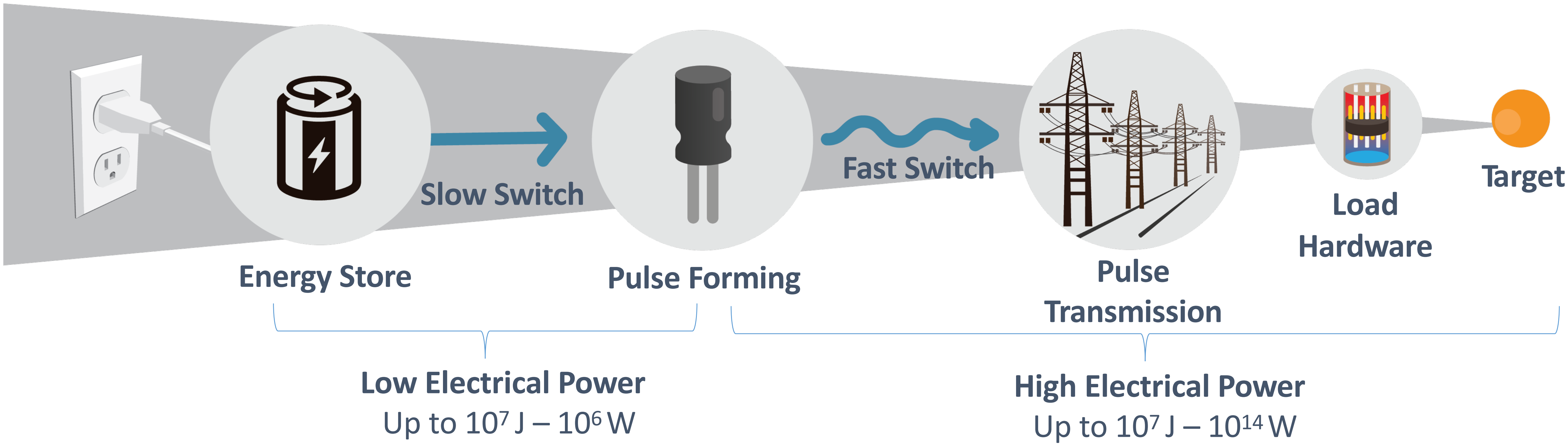


Z Facility

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

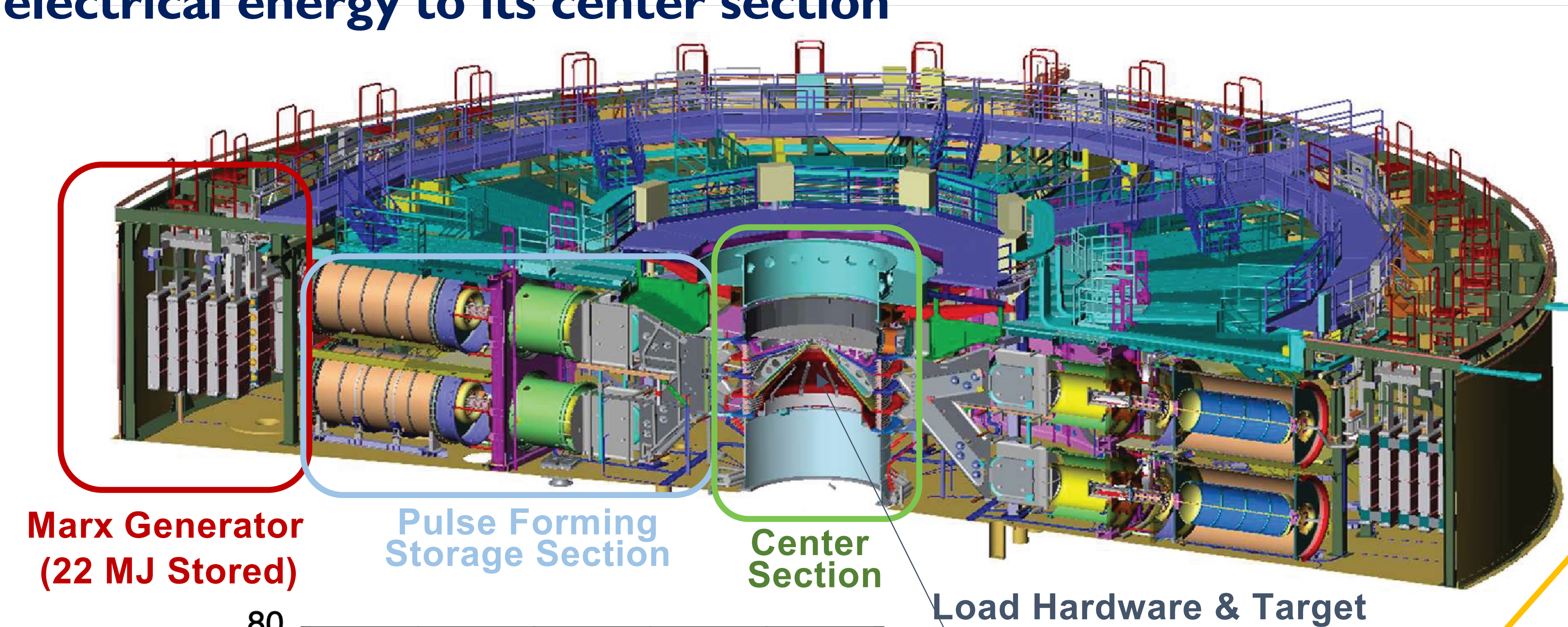


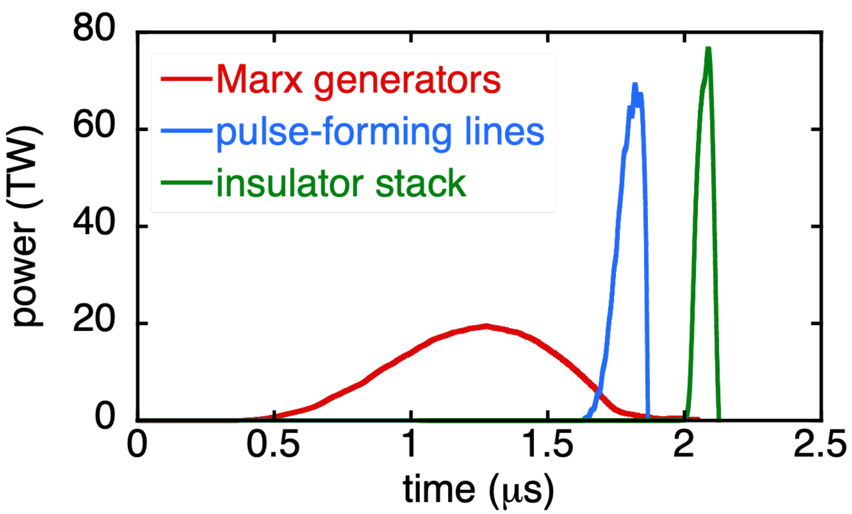
How does pulsed power work?

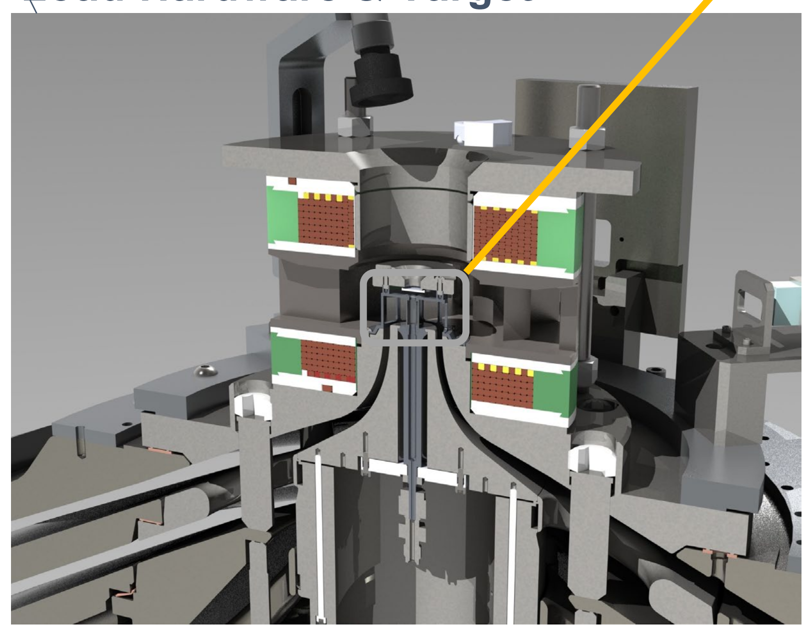


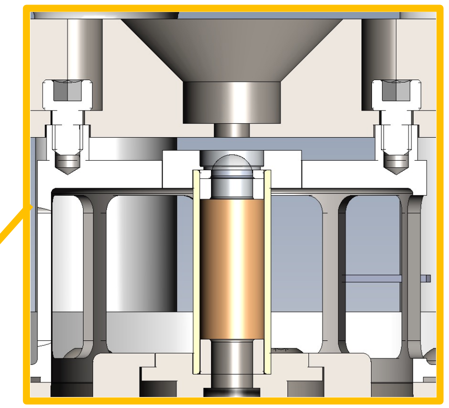
Pulsed power compresses electrical energy in both space and time to produce short bursts of high power.

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









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?

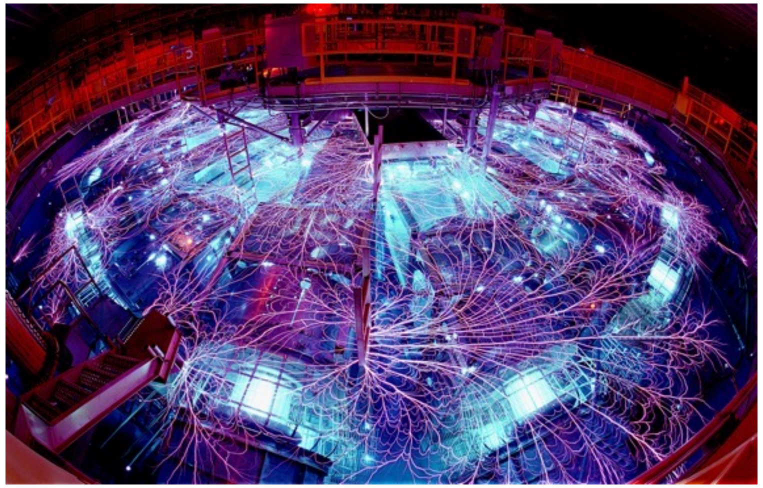
Calories in a Krispy Kreme raspberry jelly doughnut

290 Calories = 1.2 MJ

A stick of dynamite

About 1 MJ

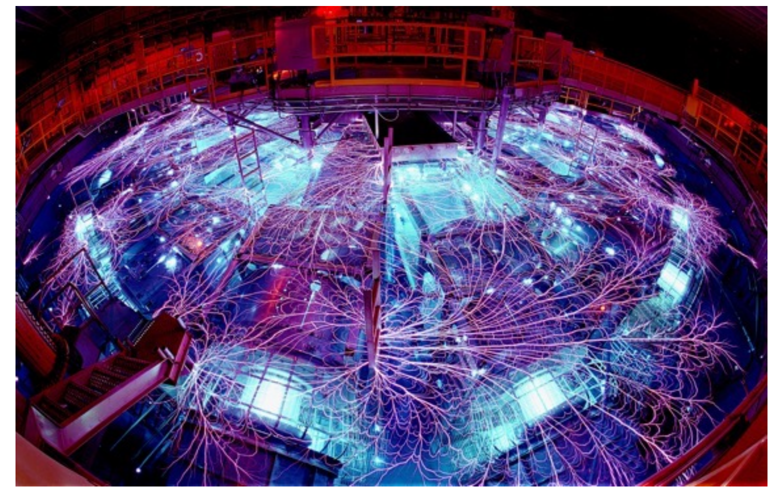
Energy delivered by Z to a fusion target



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)?

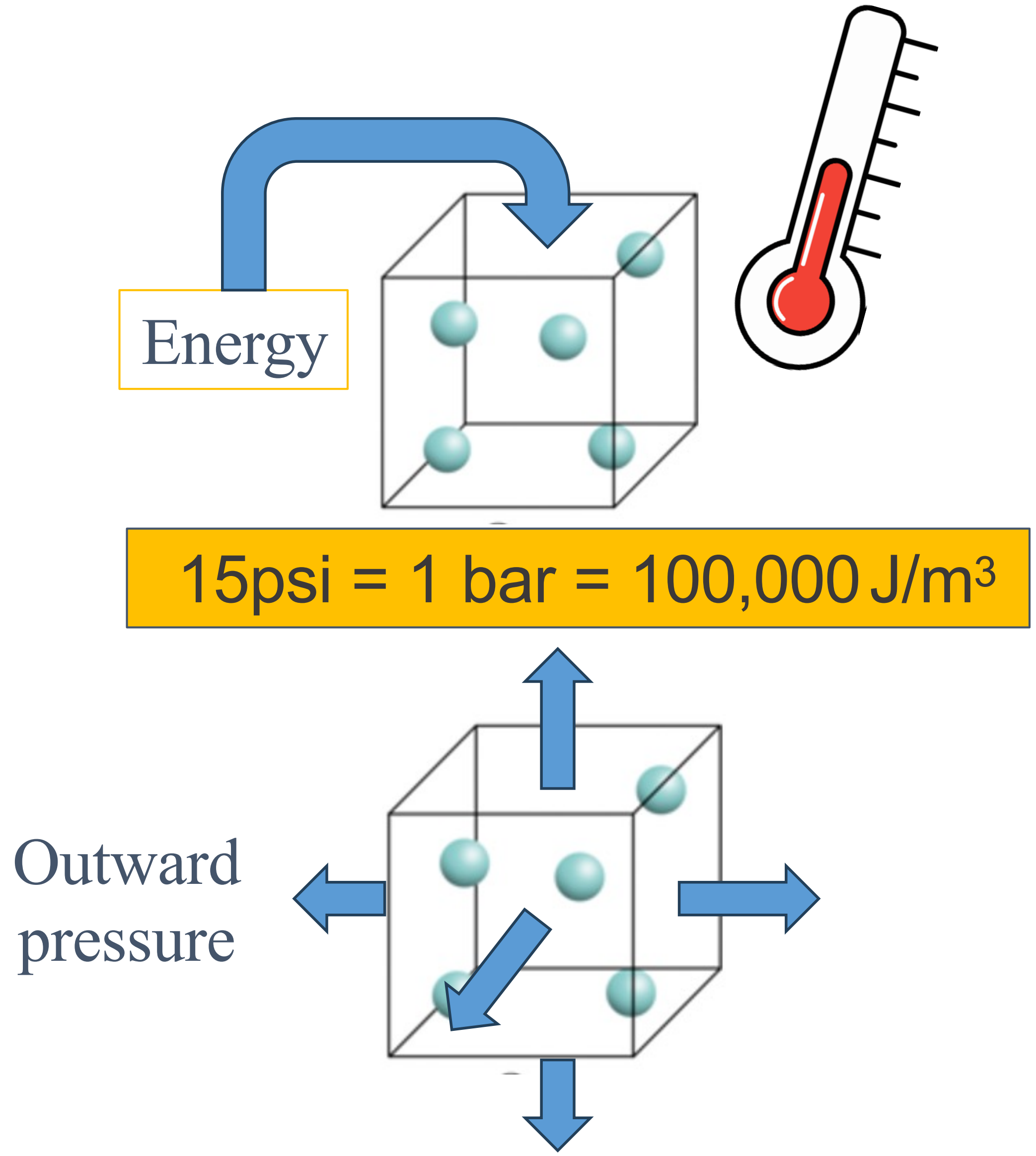
Eating a Krispy Kreme raspberry jelly doughnut	An electric power plant	Power delivered by Z to a fusion target
		
290 Calories = 1.2 MJ It takes your body roughly 60 minutes to digest 1,200,000 J / 3,600 sec = 330 Watts	Vary from 1 MW to 2 GW, i.e., up to 2,000,000,000 Watts	Power entering the insulator 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.

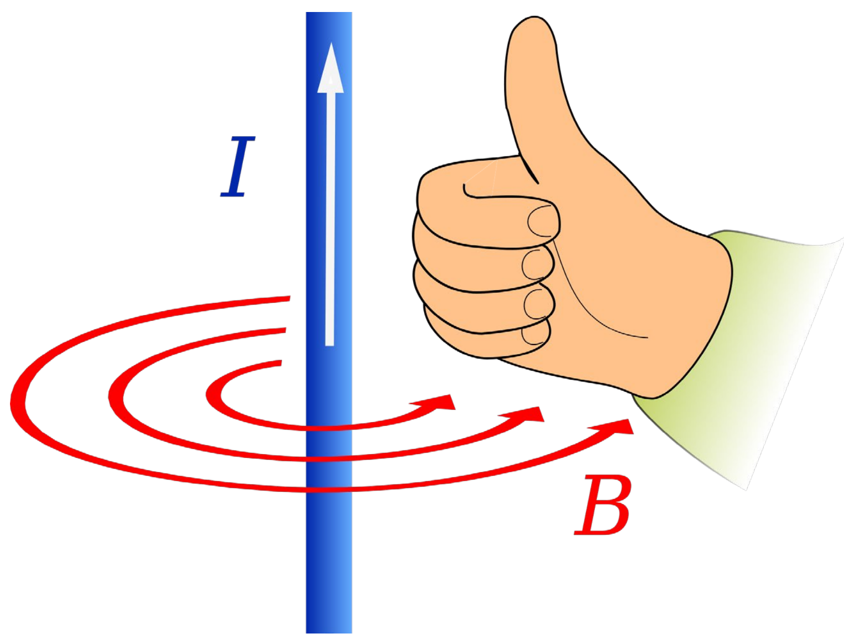
Power is energy per unit time, which corresponds to how quickly you can do work.

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

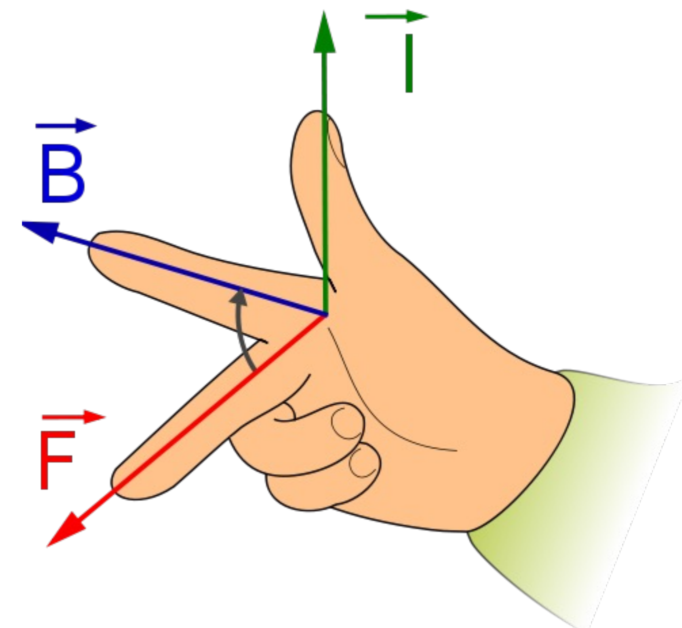


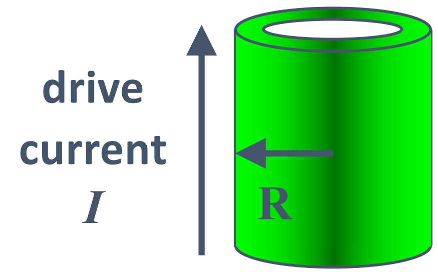
The Z machine can create large currents, which create a strong azimuthal magnetic fields, which results in a radially inward force

Current (I)



Magnetic Field (B)





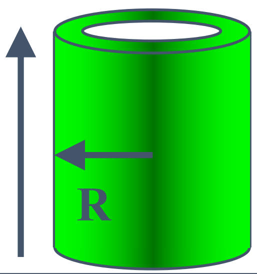
A “Z-pinch”

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

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

drive current ***I***



100 MBar at 26 MA and 1 mm

100 GPa = 1 Mbar ≈ 10^6 atmospheres

Pressure equivalent to Energy Density (J/m³)

1 Mbar = 10^{11} J/m³, threshold of High Energy Density regime

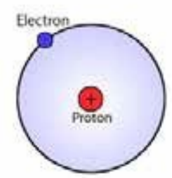
Z Storage capacitor

2e-6 Mbar

TNT

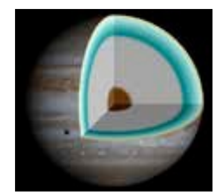
0.07 Mbar

Internal Energy of H atom



1 Mbar

Metallic H in Jupiter's core

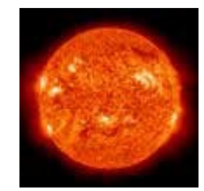


30 Mbar

Z Magnetic Drive Pressure

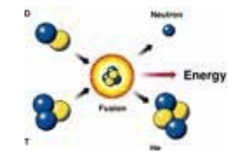
~100 Mbar

Center of Sun



250,000 Mbar

Burning ICF plasma

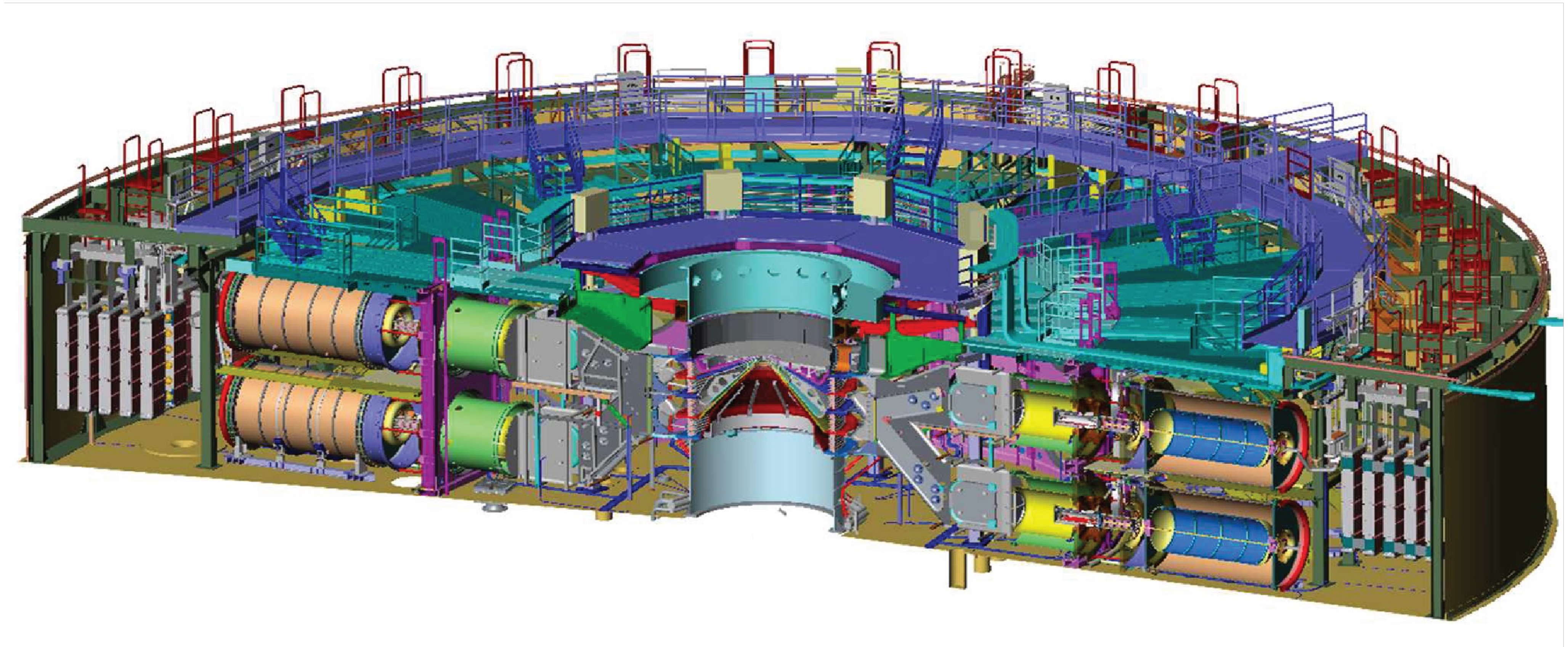


800,000 Mbar

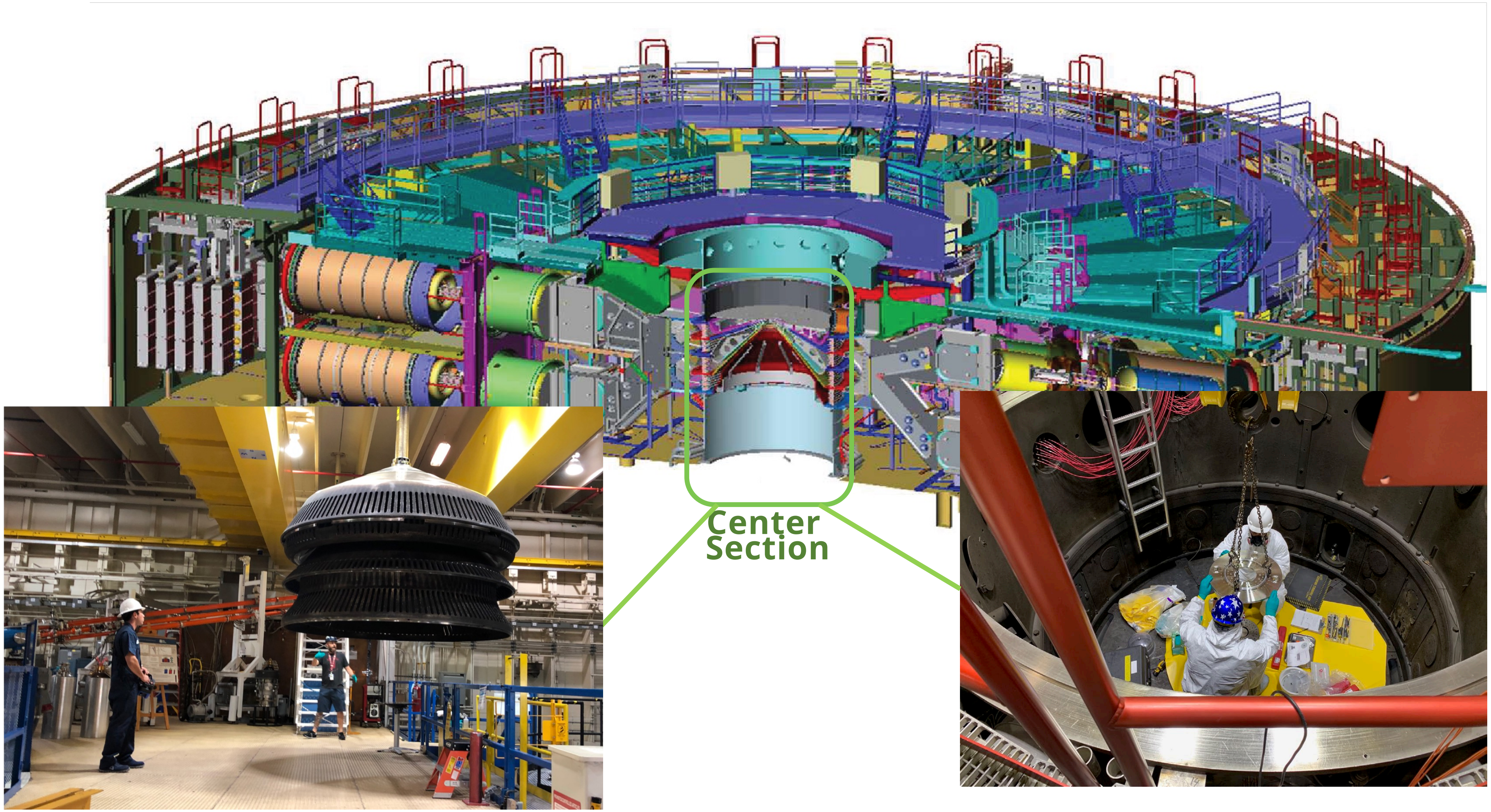
Push on samples

Compress fuel at high velocity

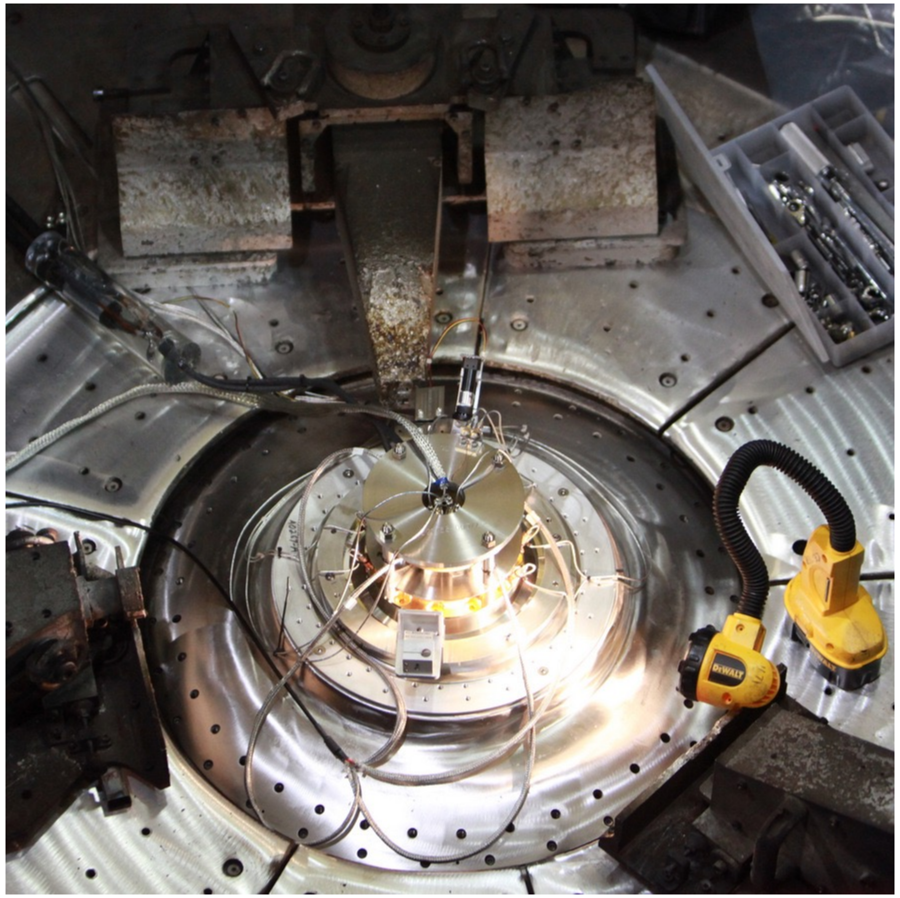
The purpose of the Z machine is to compress energy in both space and time to create extremely high energy density conditions at its focal point, creating conditions similar to those within or produced by a nuclear weapon



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.

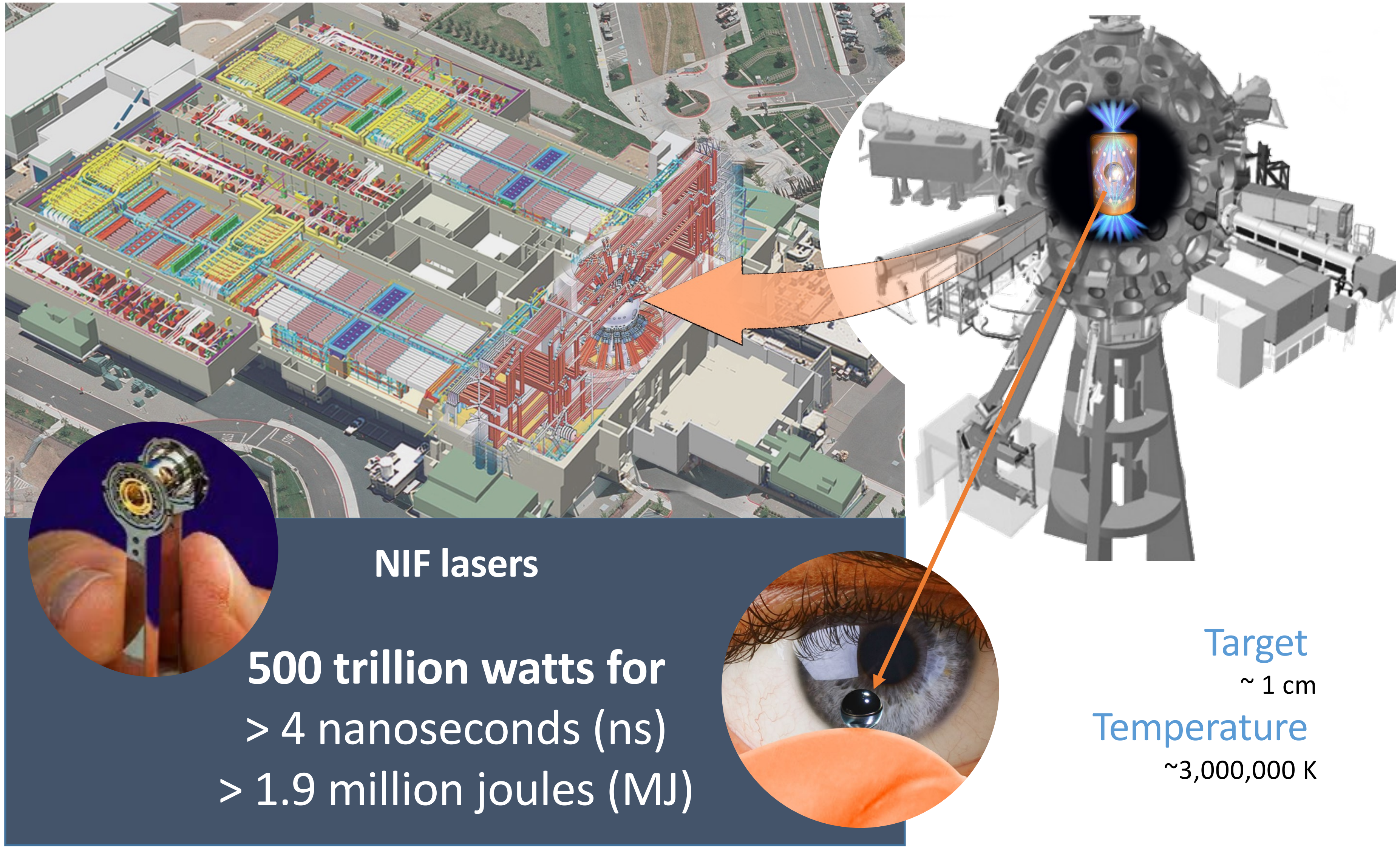
- A nominal ~1 GW power plant based on DT reactions would consume the world's supply of civilian tritium in just a few days
  - It is possible to "breed" tritium in a fusion plant once it gets started, but this remains to be demonstrated at scale
  - Alternative fuels are possible, but each option has 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!

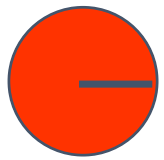
Have you had your fill of Fusion yet?

Questions?

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



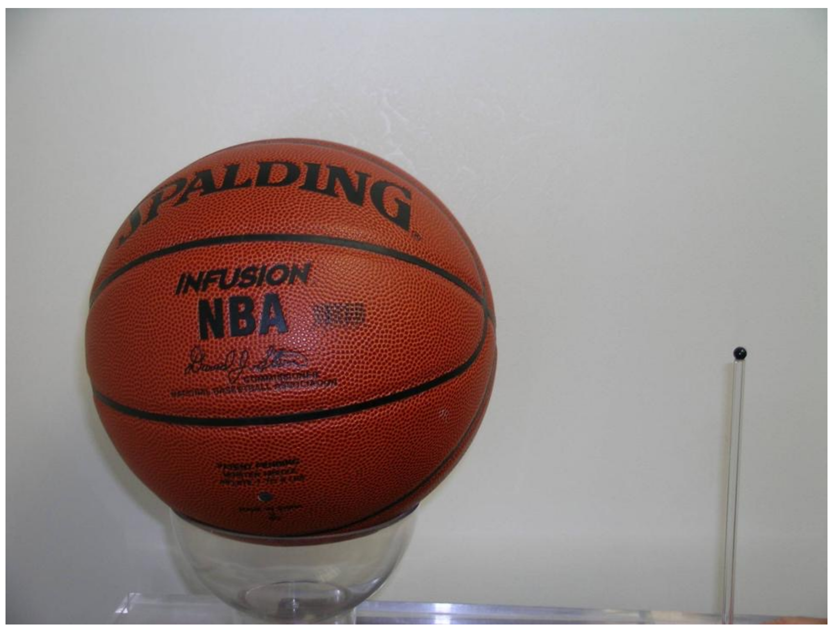
For hot-spot ignition, the fusion fuel must be brought to a pressure of a few hundred billion atmospheres, quickly & symmetrically



ρ, R, T

For ignition conditions: $\left\{ \begin{array}{l} \rho R \approx 0.4\,\mathrm{g/cm^2} \\ T \approx 5\,\mathrm{keV} \end{array} \right\}$

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



- 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!