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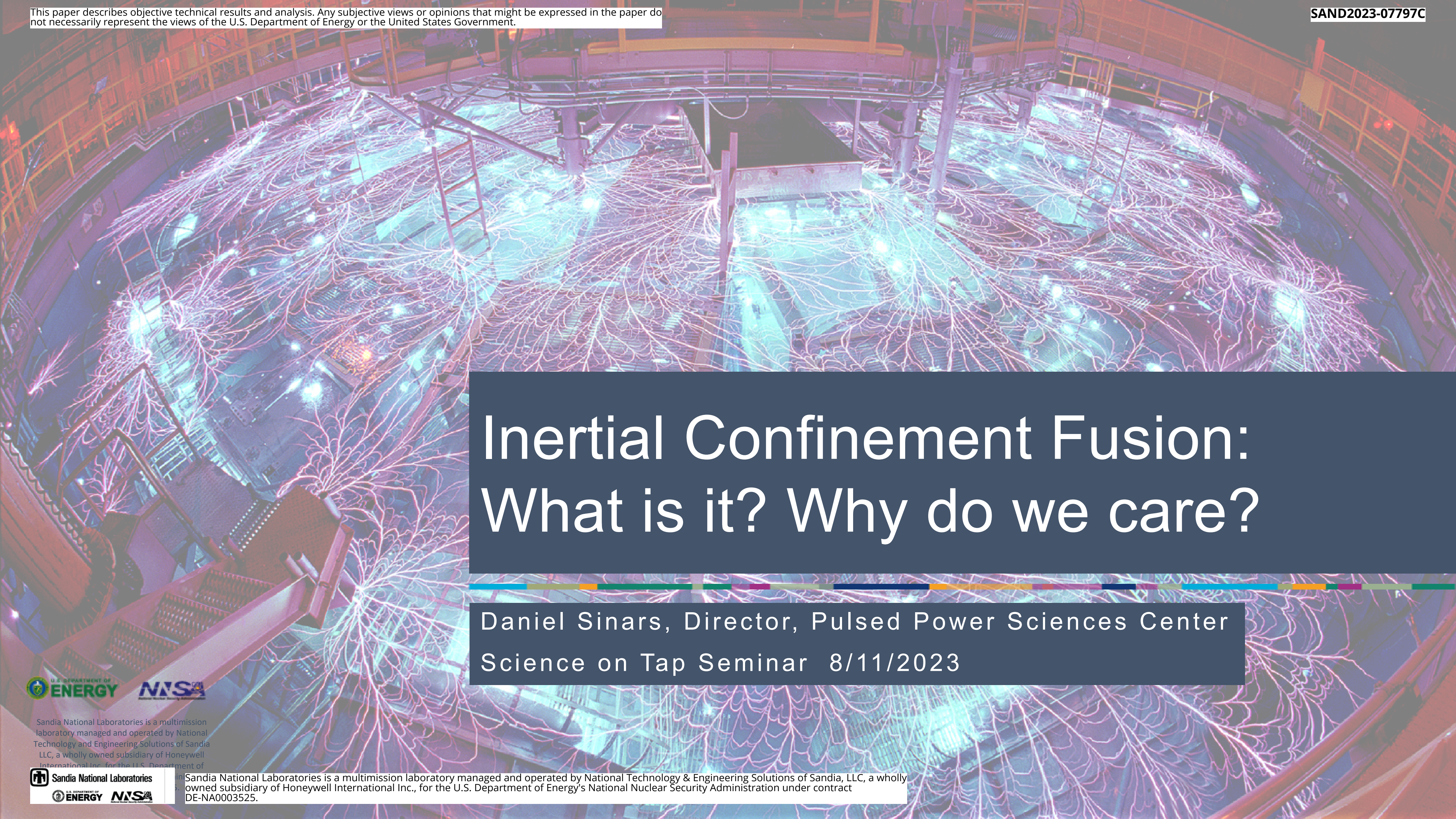

Inertial Confinement Fusion: What is it? Why do we care?

Daniel Sinars, Director, Pulsed Power Sciences Center

Science on Tap Seminar 8/11/2023

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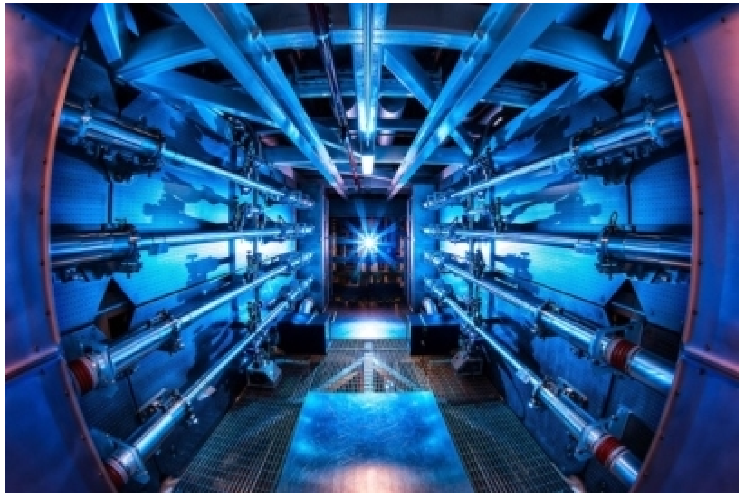

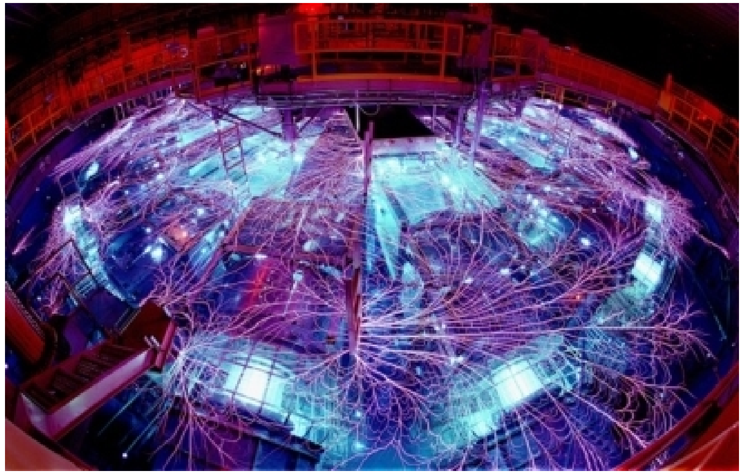

The world's largest laser and largest pulsed power machine

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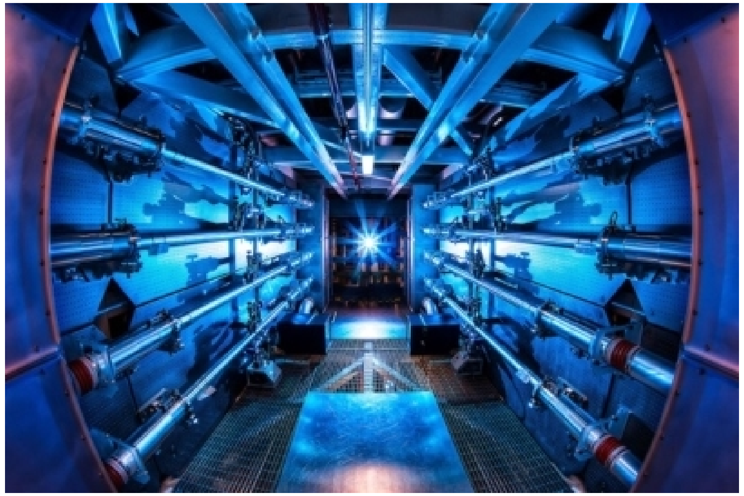

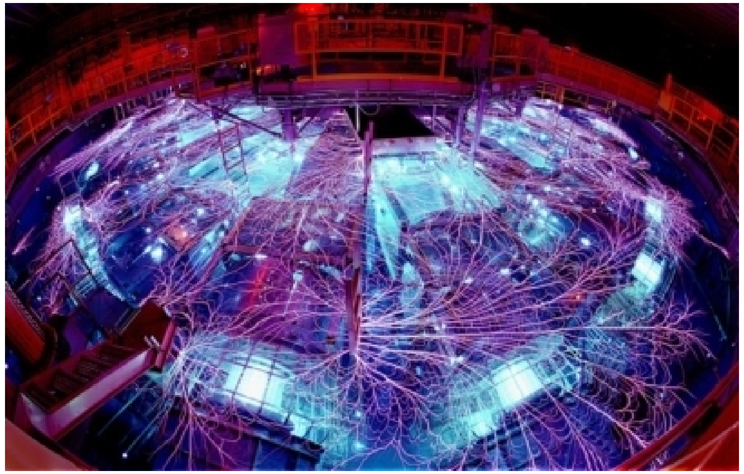

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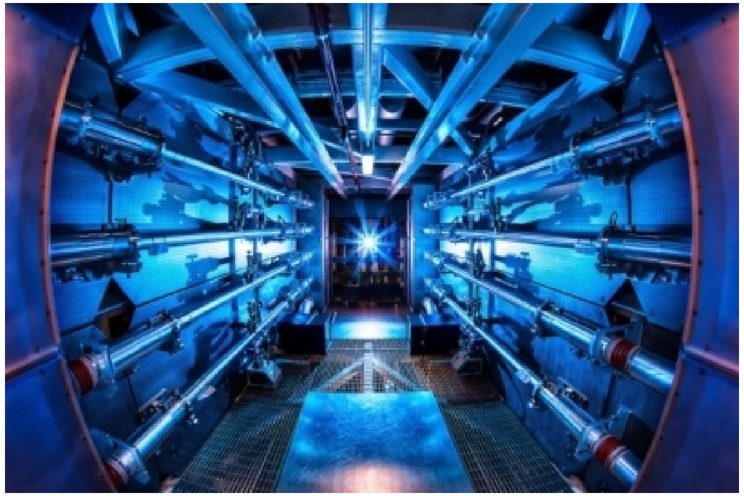

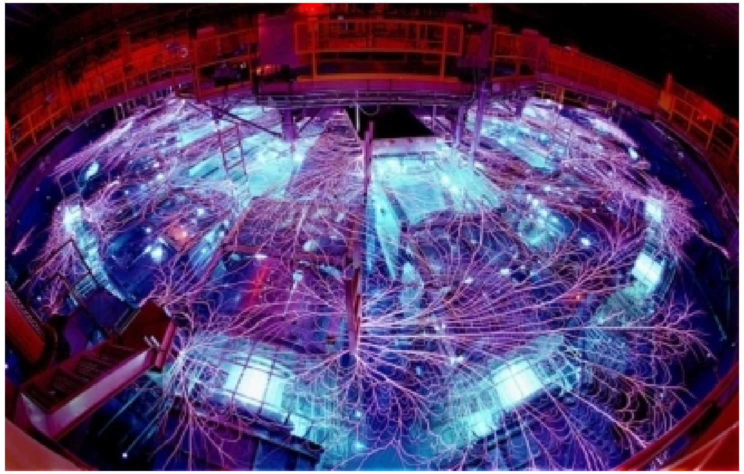

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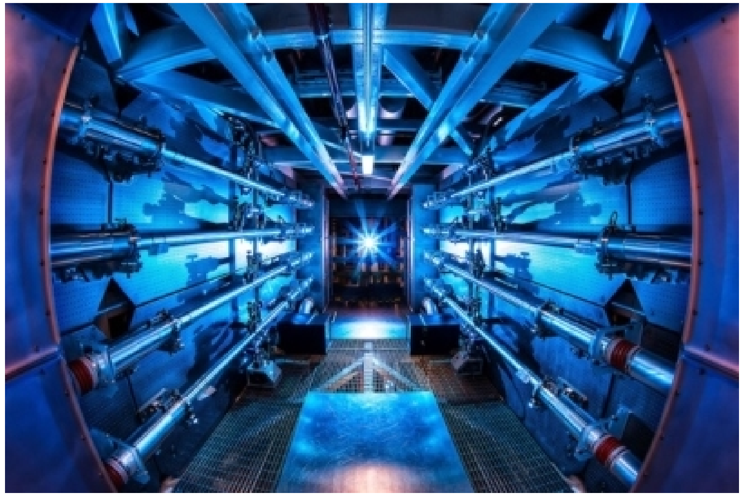

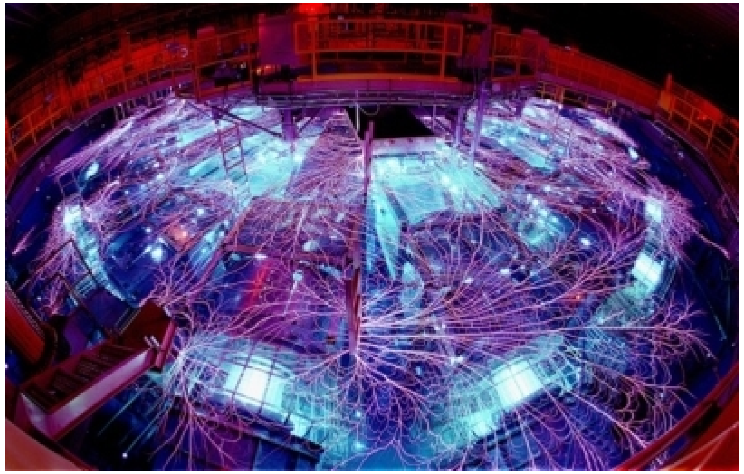

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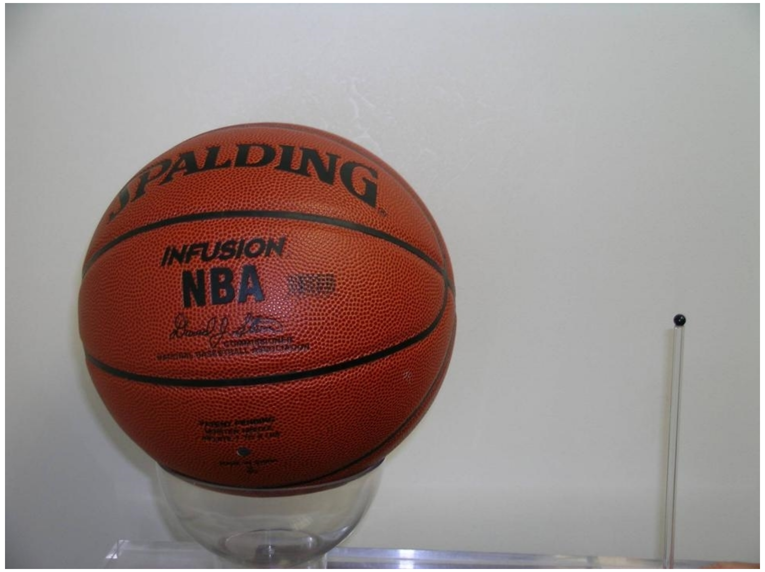
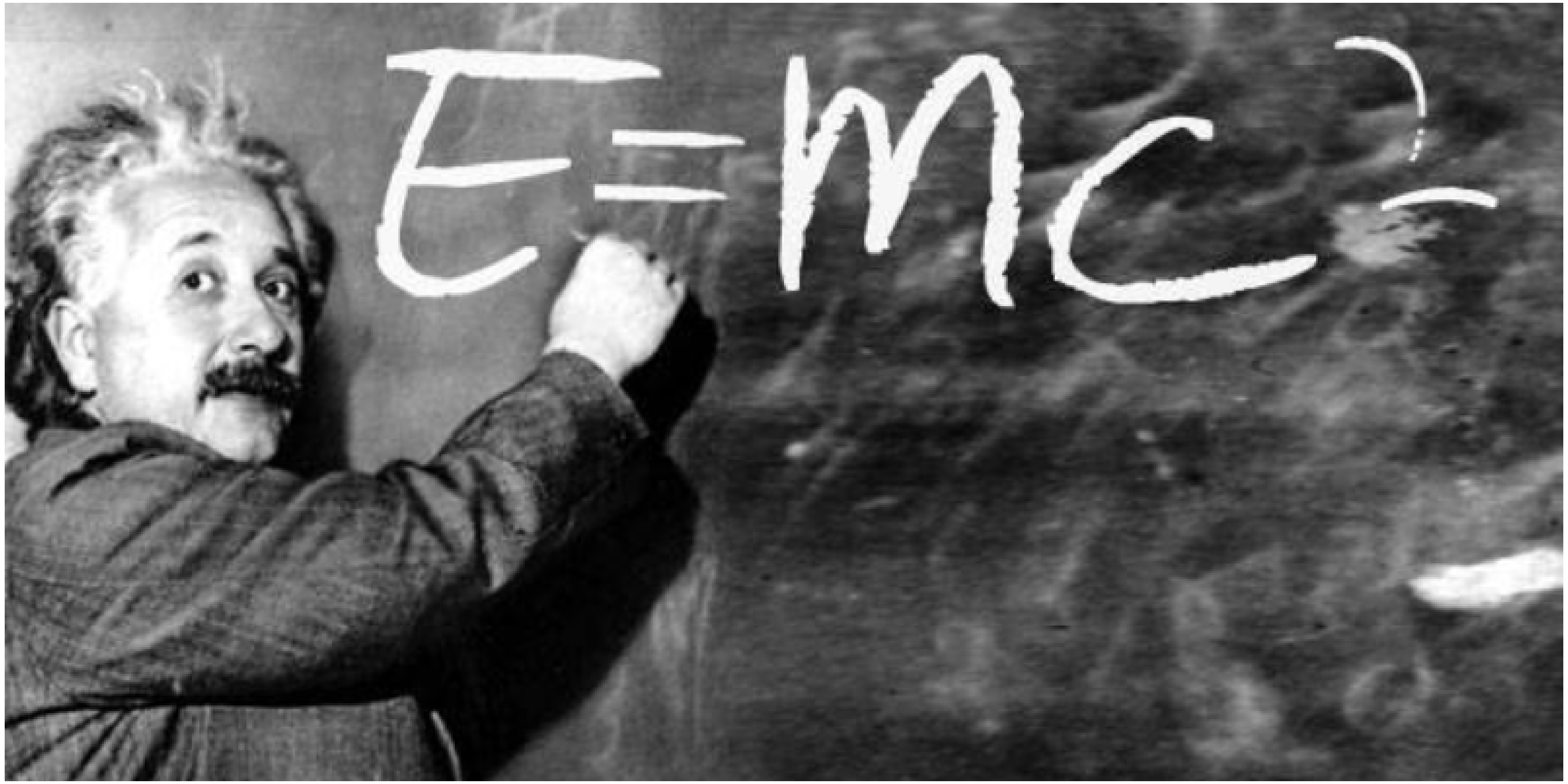


Basketballs & peas

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???

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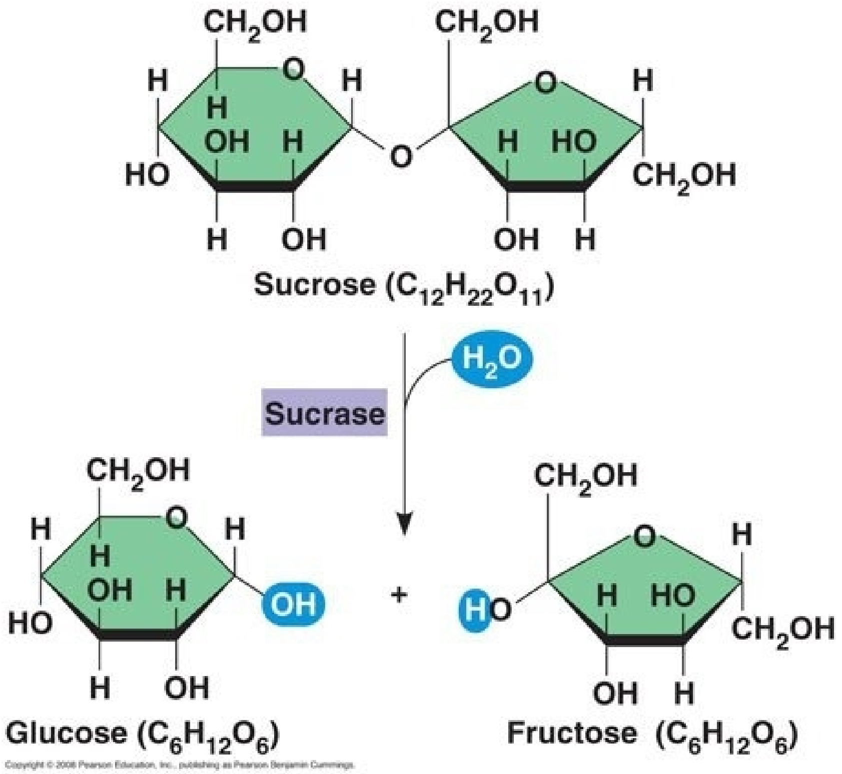
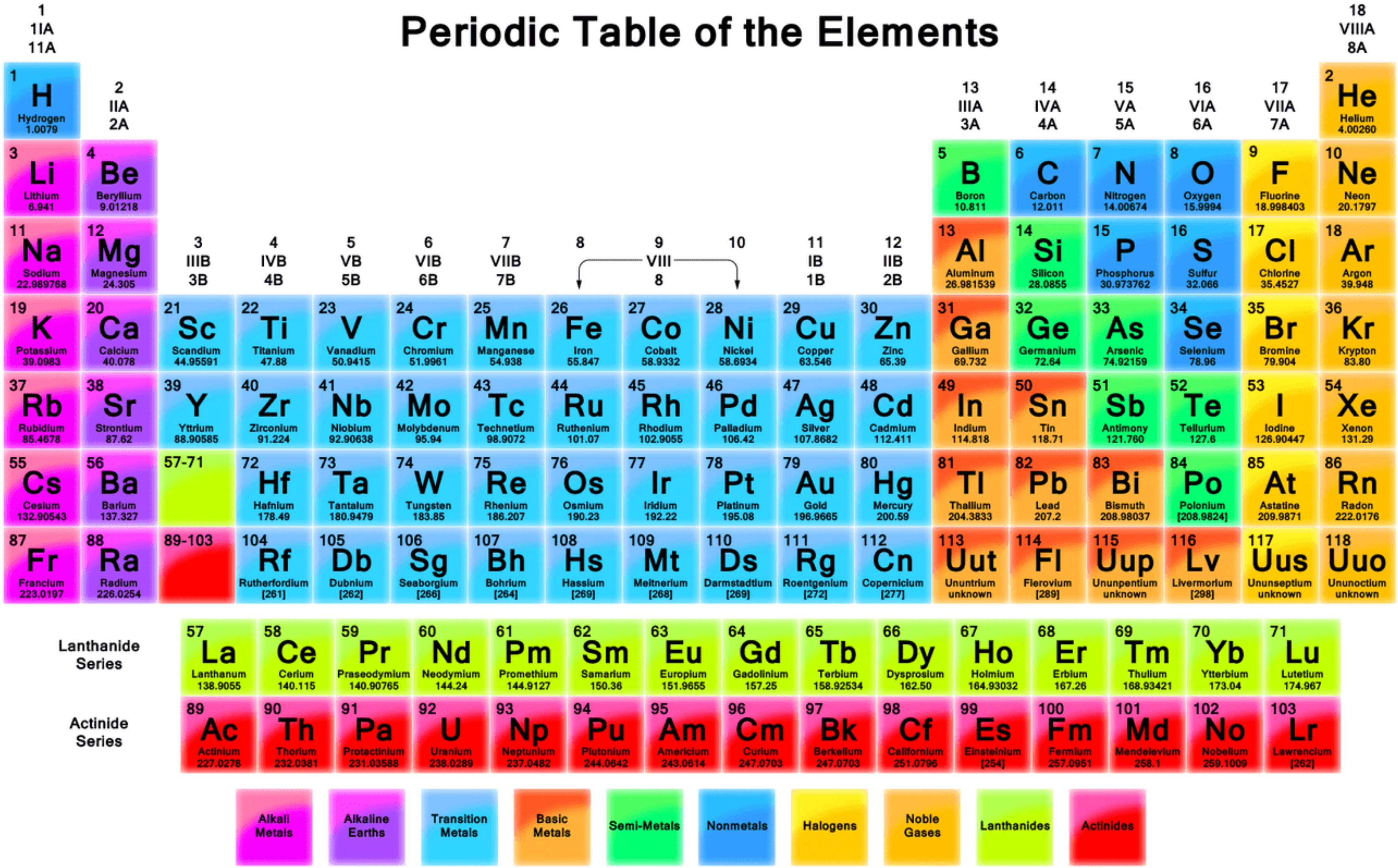
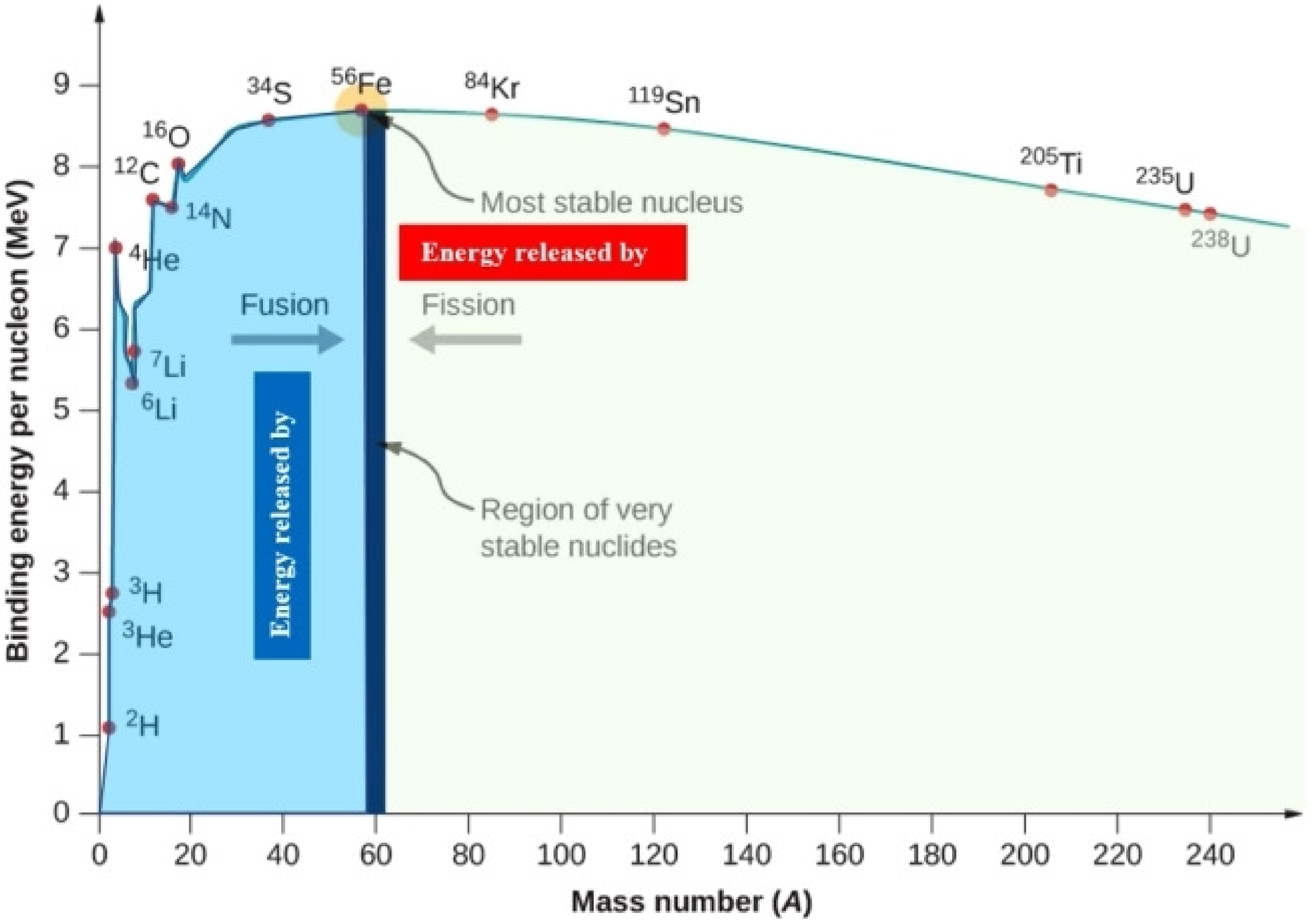


Hold on! Eating food breaks down chemical bonds that join molecules together in your food, but it doesn't change the atoms. Einstein was talking about creating and destroying matter/atoms!

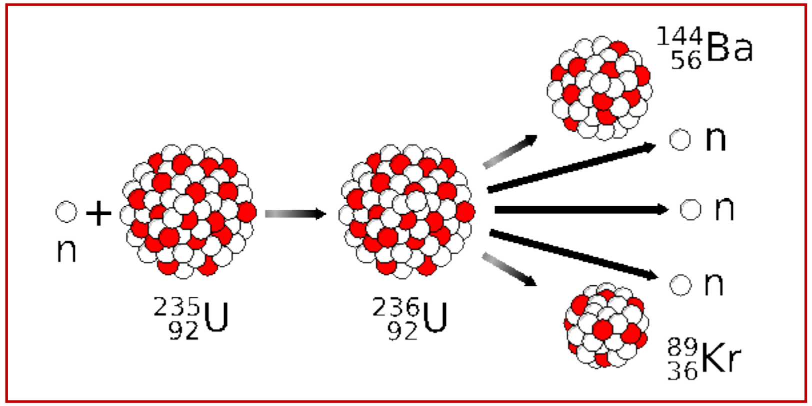
All matter is made up of atoms with different properties, masses, etc. Einstein's famous equation speaks about what happens when you create/destroy this matter



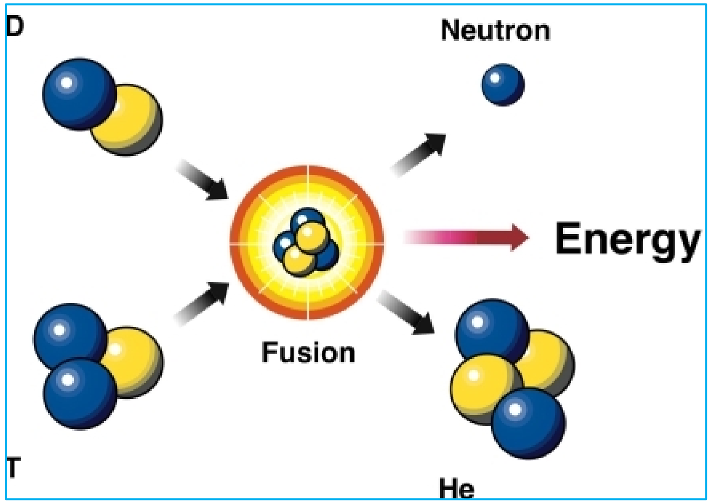
We can release and harness energy from matter through one of two processes



Fission

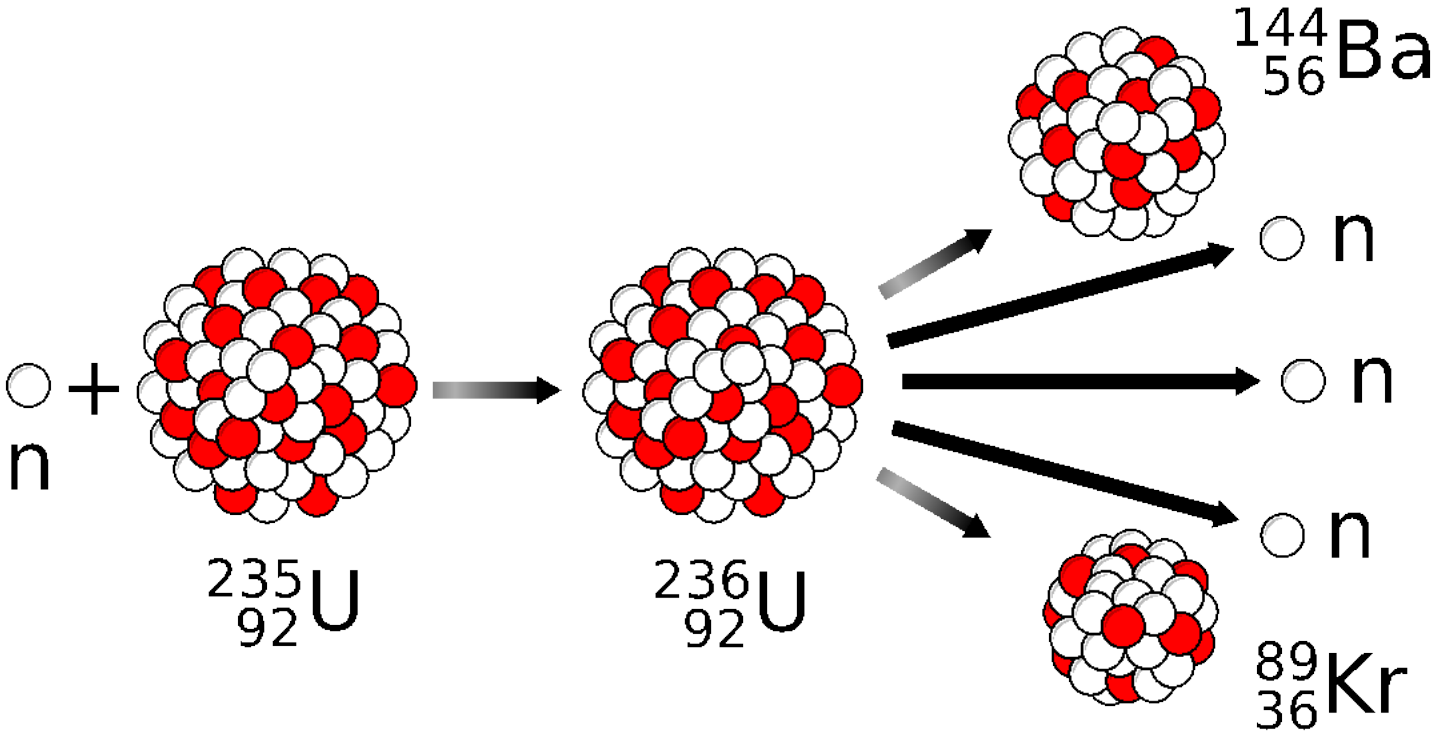


Fusion



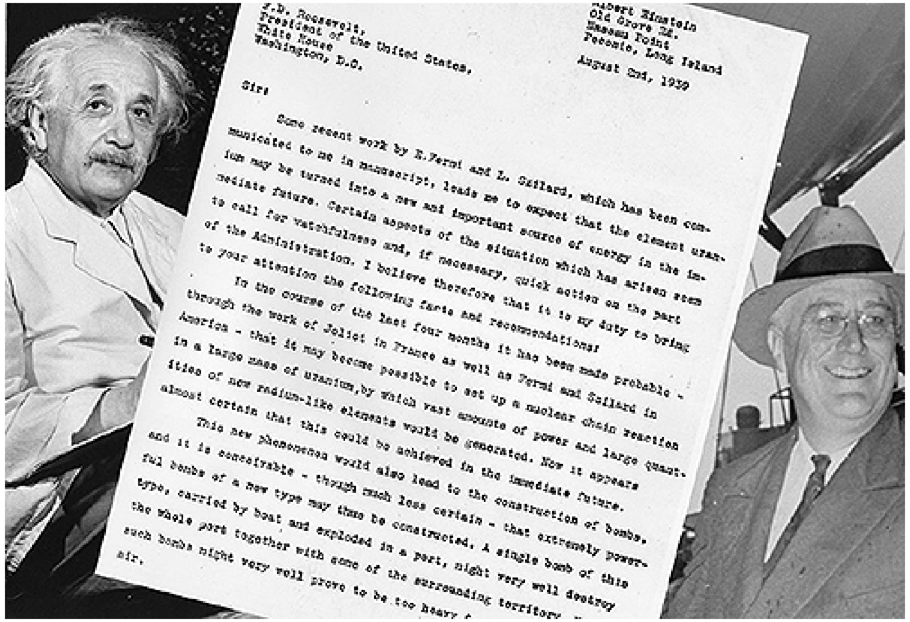
In December 1938, Lise Meitner and Otto Frisch built upon work by Meitner and Hahn, explaining that they had found evidence for a uranium nucleus splitting into lighter atoms and releasing energy in the process.

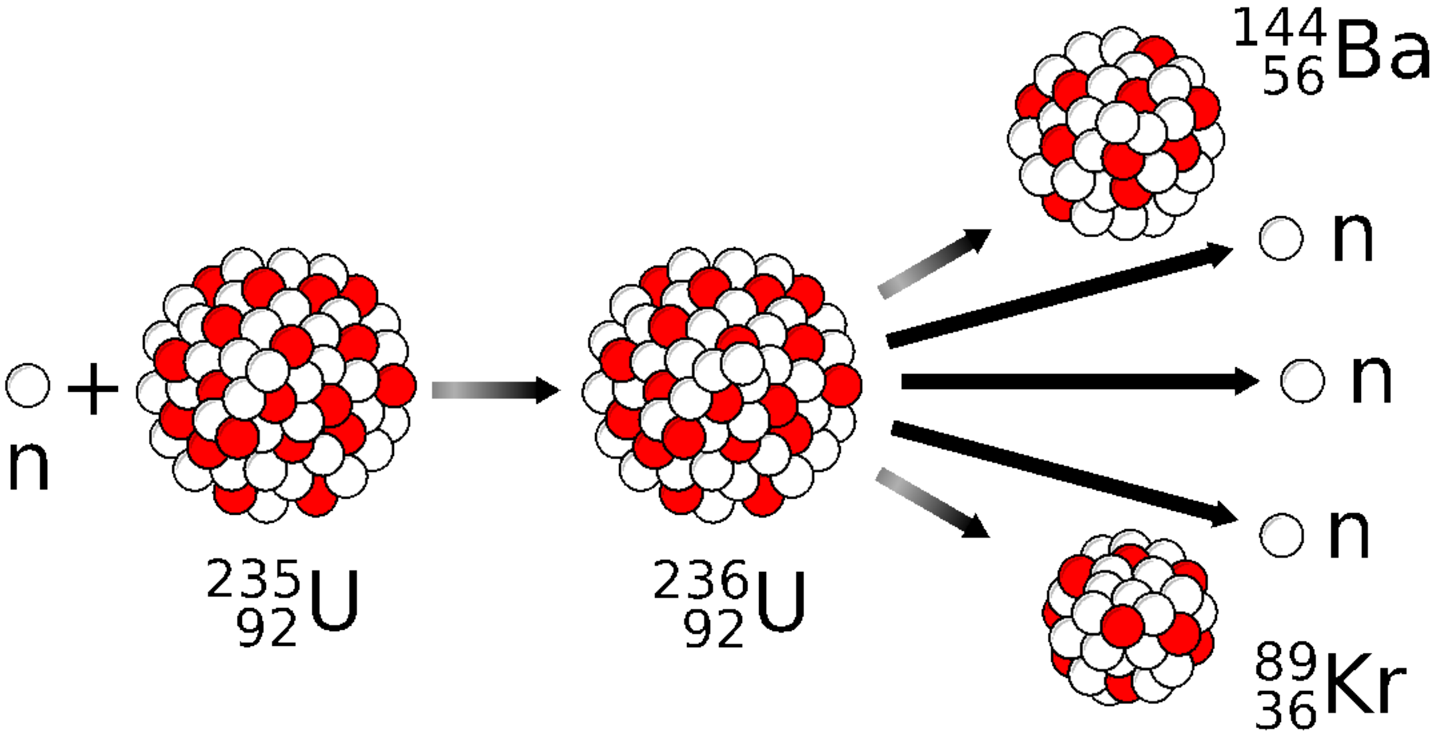
Lise Meitner and Otto Hahn,
Kaiser-Wilhelm Institute, Berlin



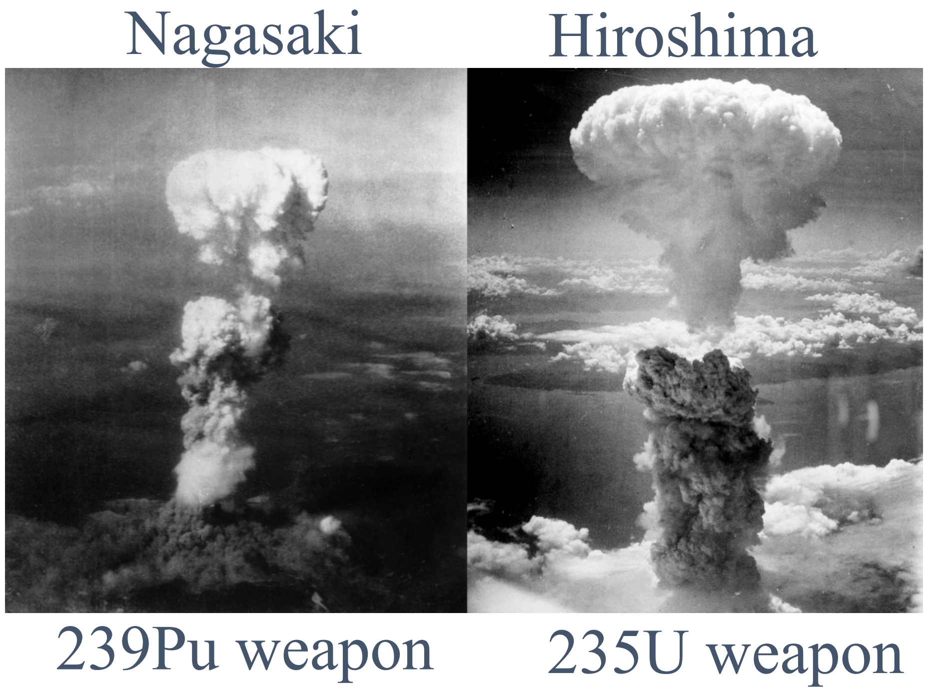
Note that this reaction starts with a neutron hitting the atom, and it produces three neutrons. It was soon recognized that this reaction had the potential for a runaway reaction process that could release energy.

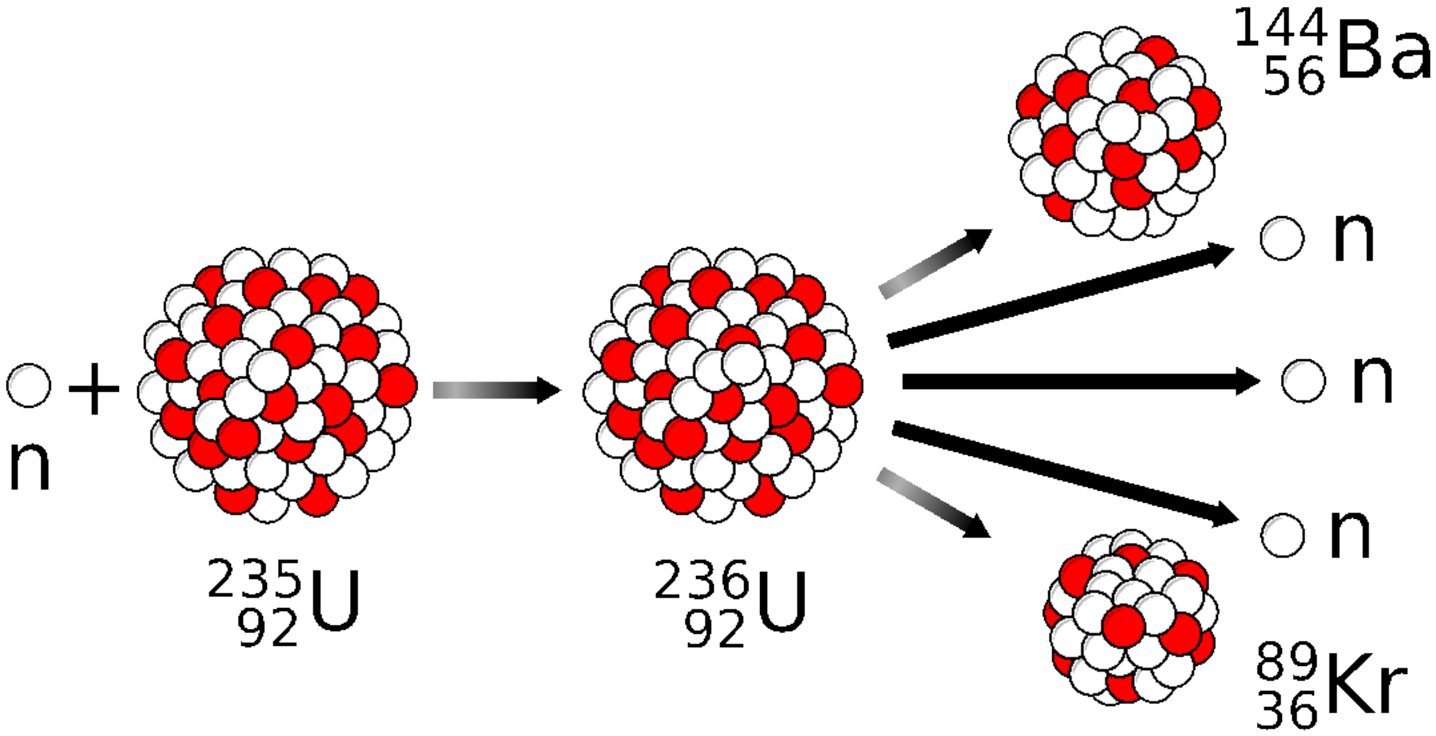
Einstein (remember him from 1905?) was worried enough by the potential of fission reactions for both energy production and weapons that he wrote to FDR in 1939 advising him that the U.S. needed to explore this research



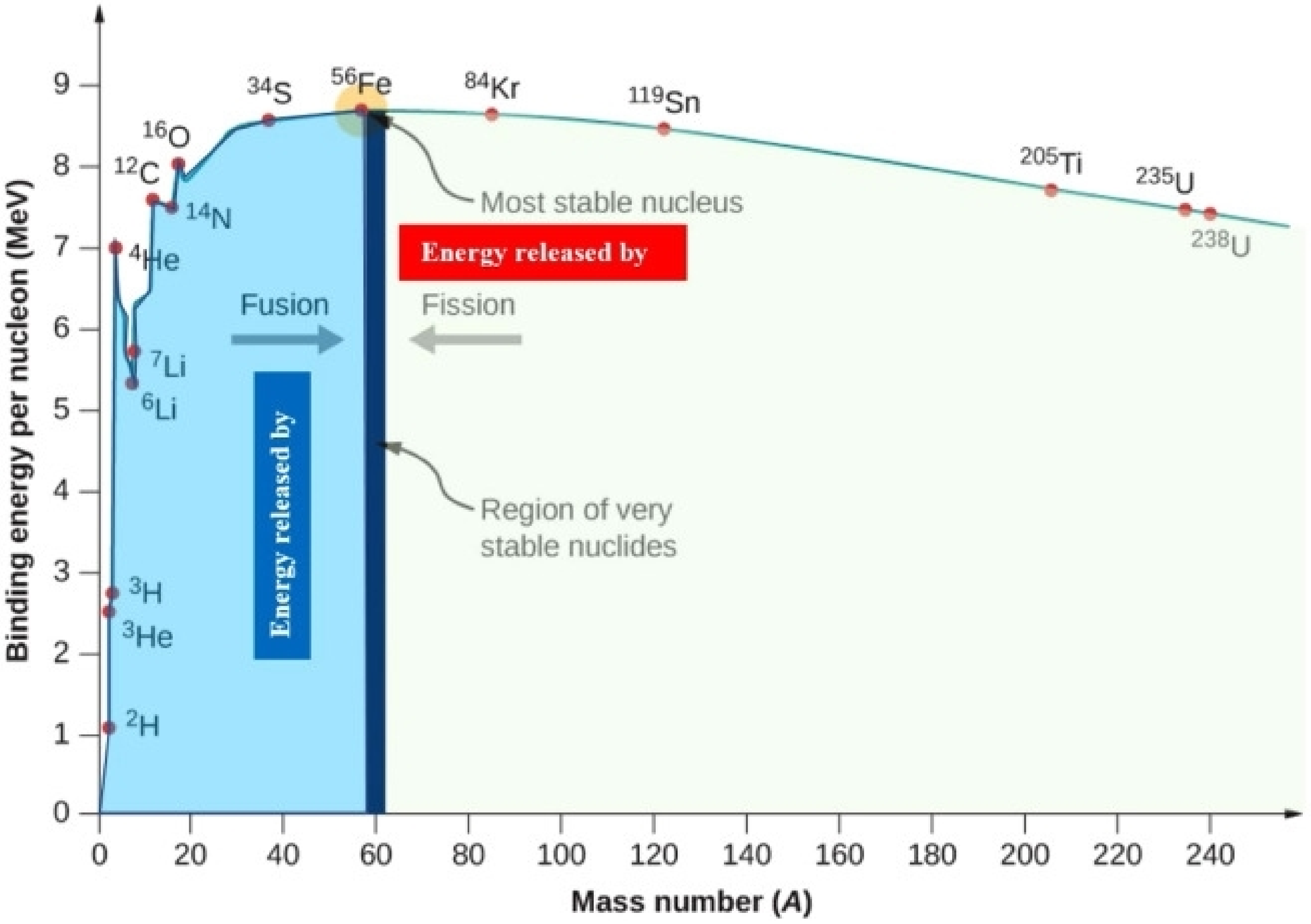


To make a long story short, nuclear fission played a key role in the development of nuclear weapons by the United States (and you are in the right place to learn more!)

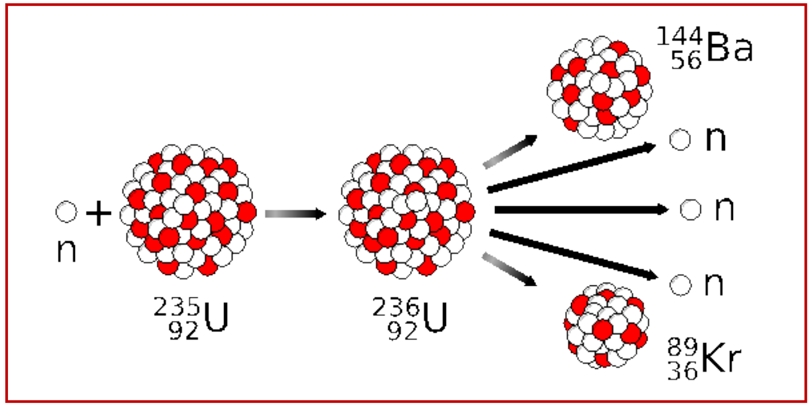




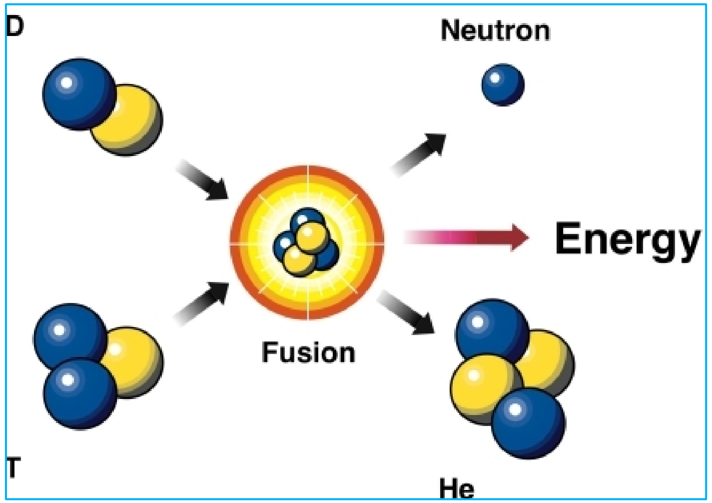
But what about the second method, nuclear fusion…?



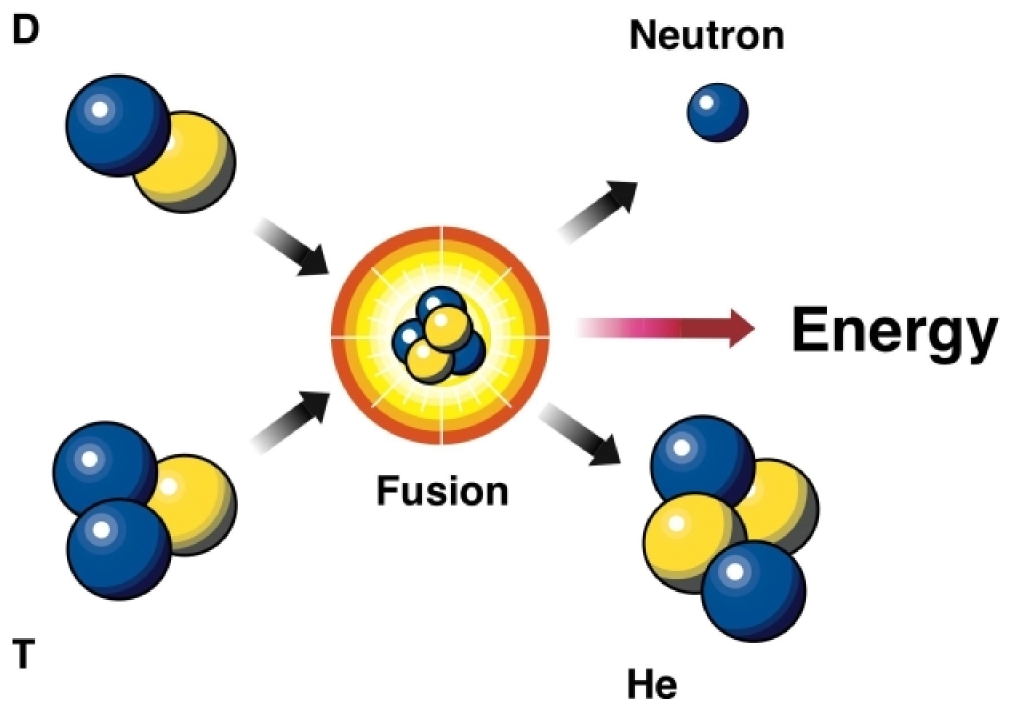
Fission

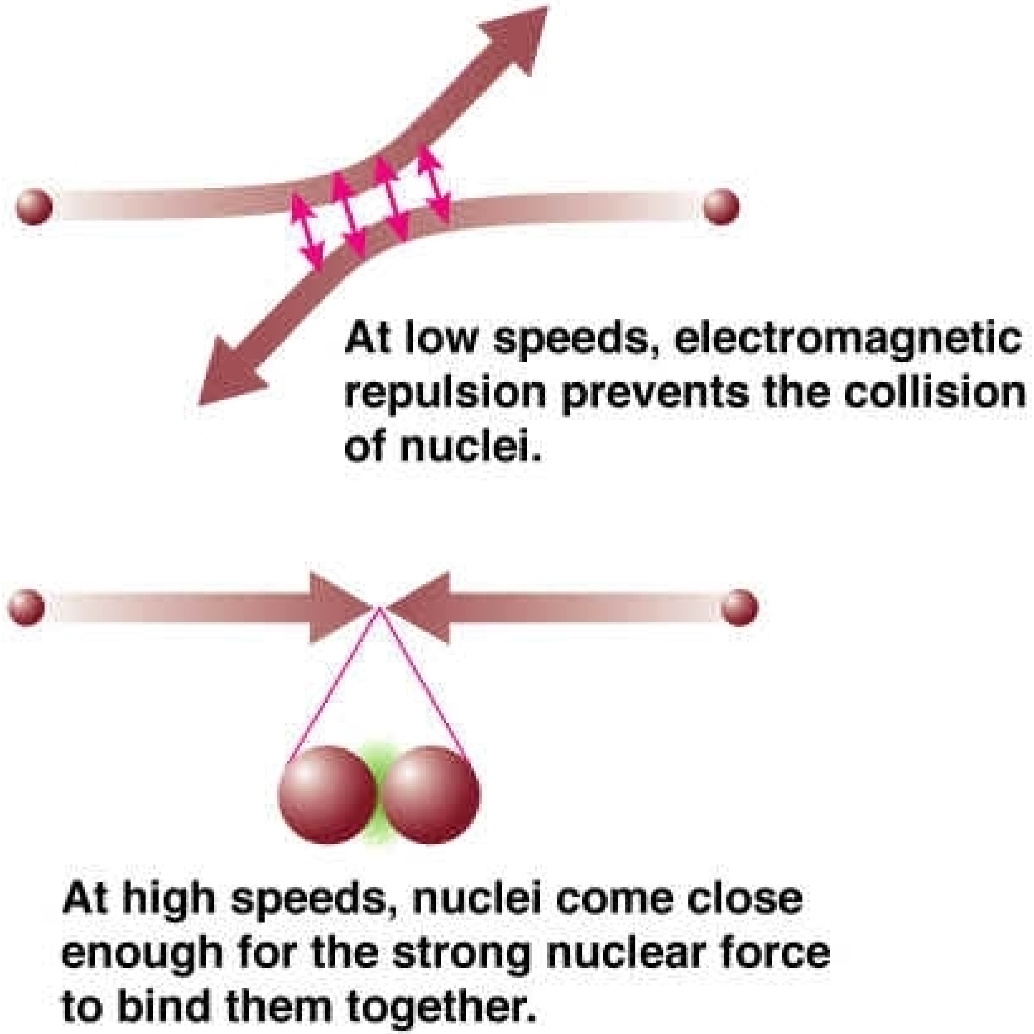


Fusion

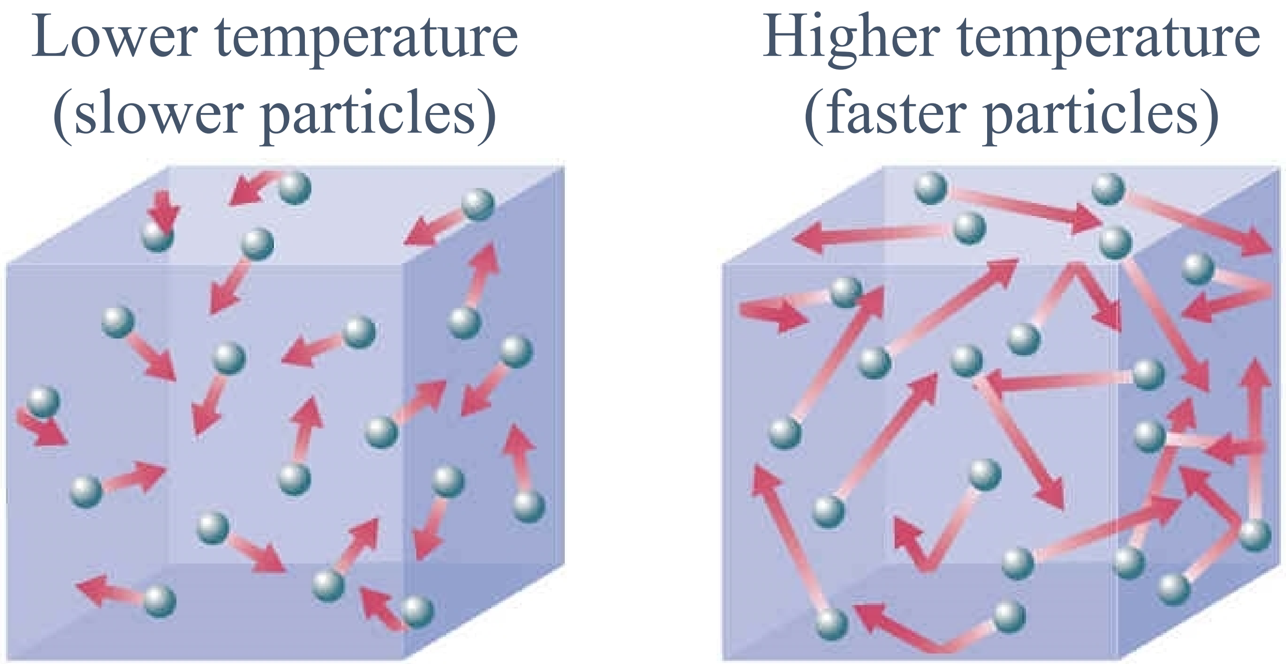


A key challenge for fusion is that the reacting particles are both positively charged, which will cause them to repel each other unless their velocities are high enough



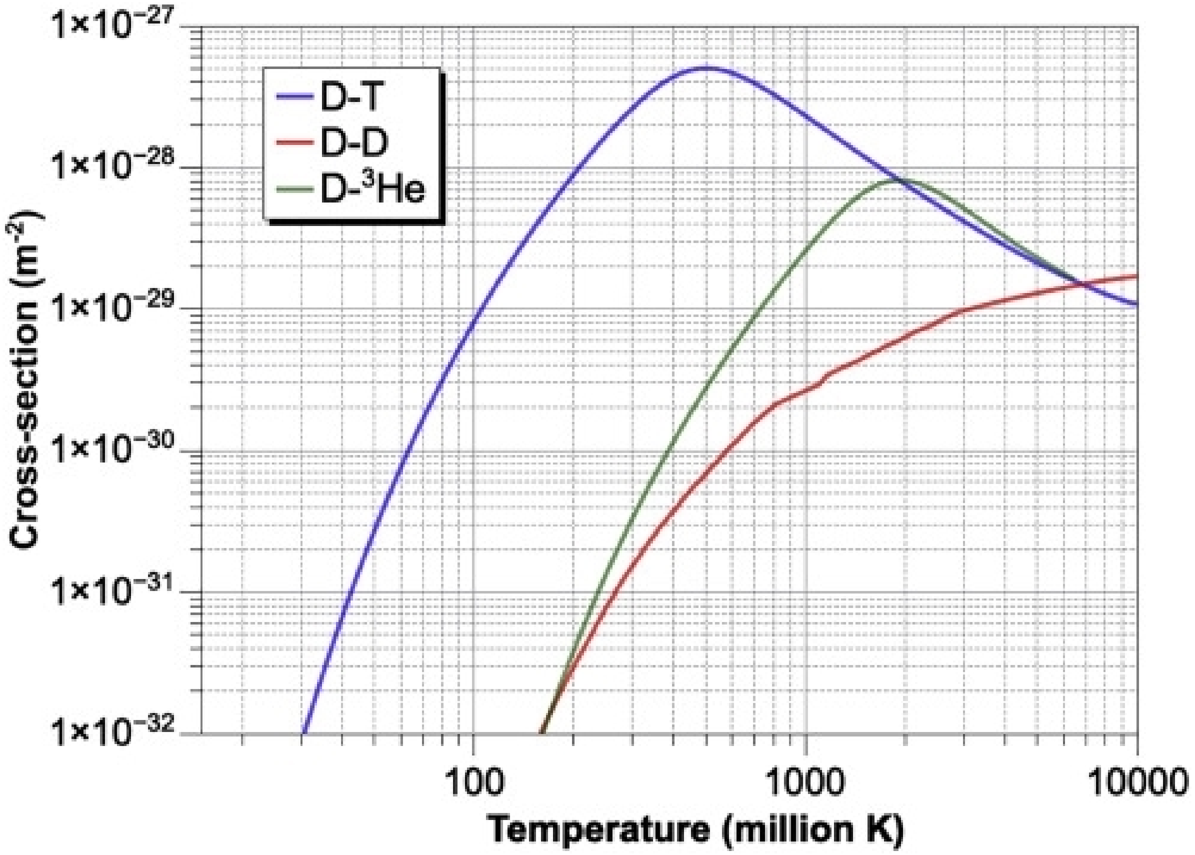


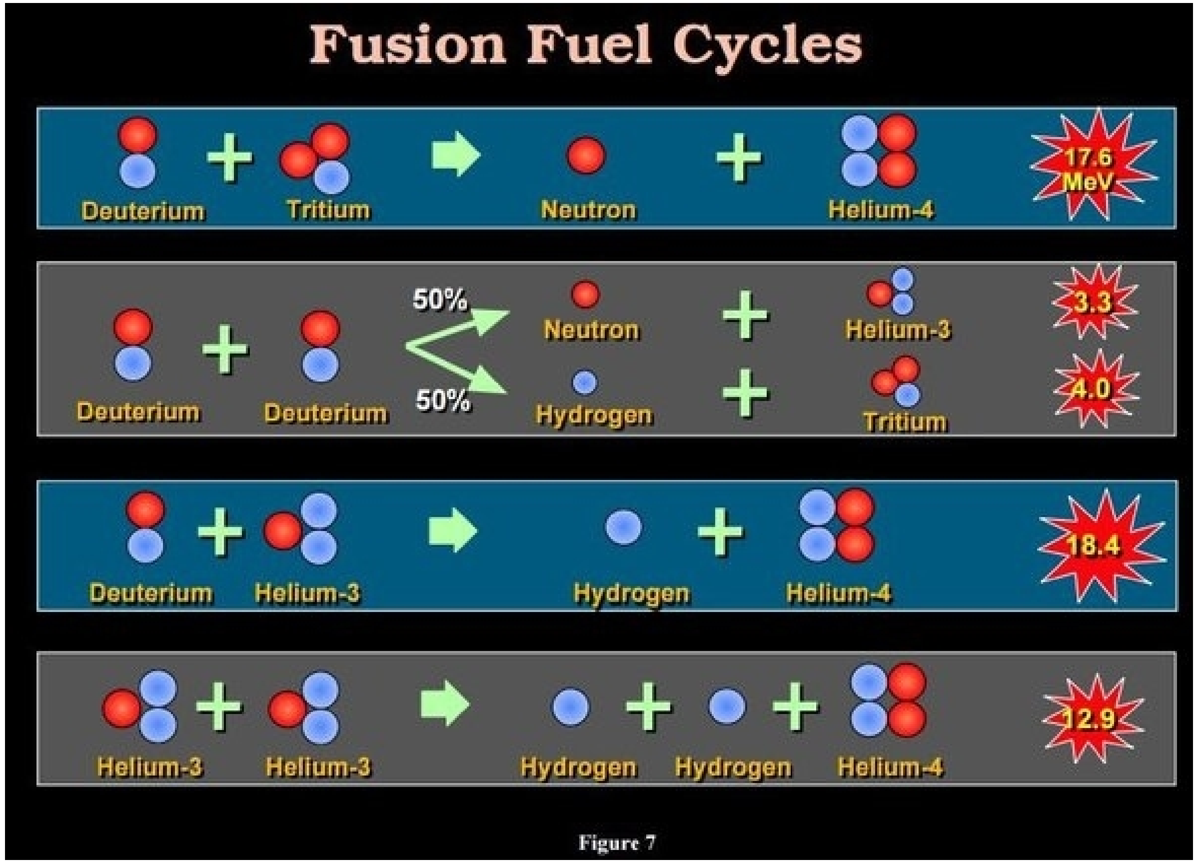
To enable the fusion reaction to occur, the particles must be moving at very high velocities, which corresponds to needing a very high temperature



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).

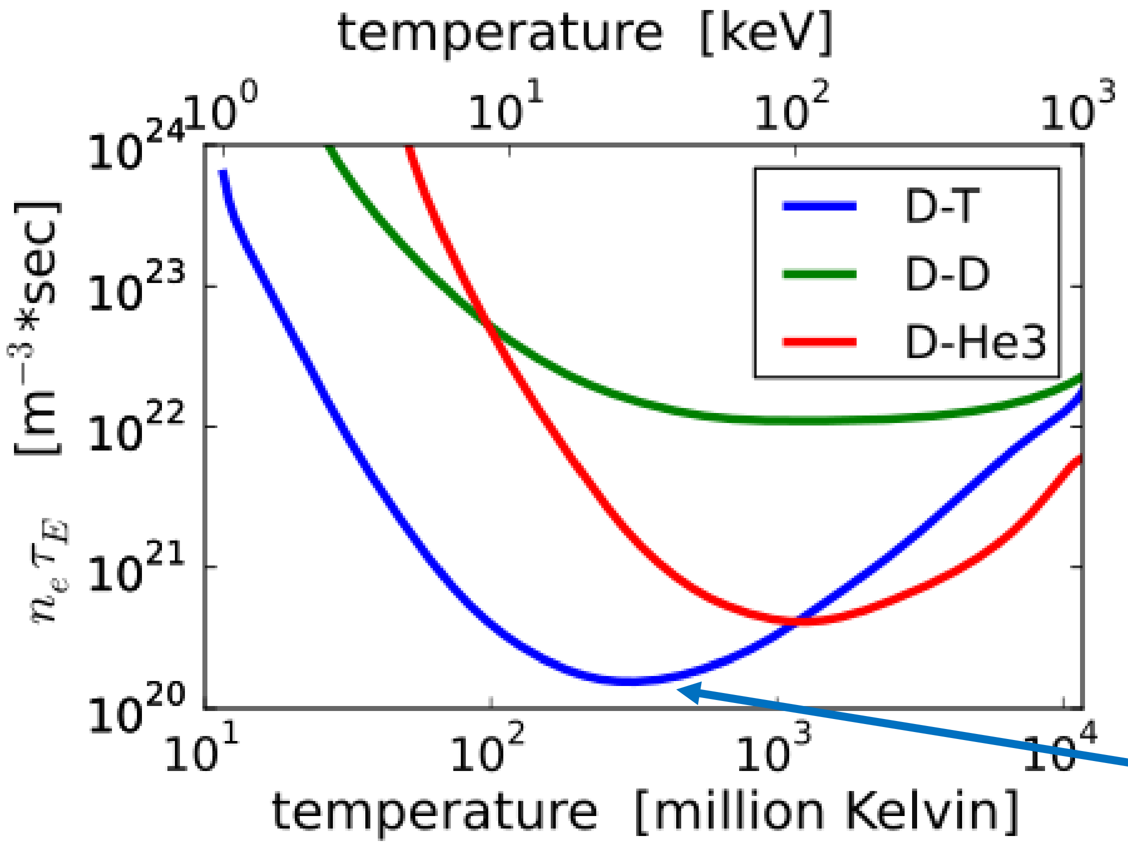


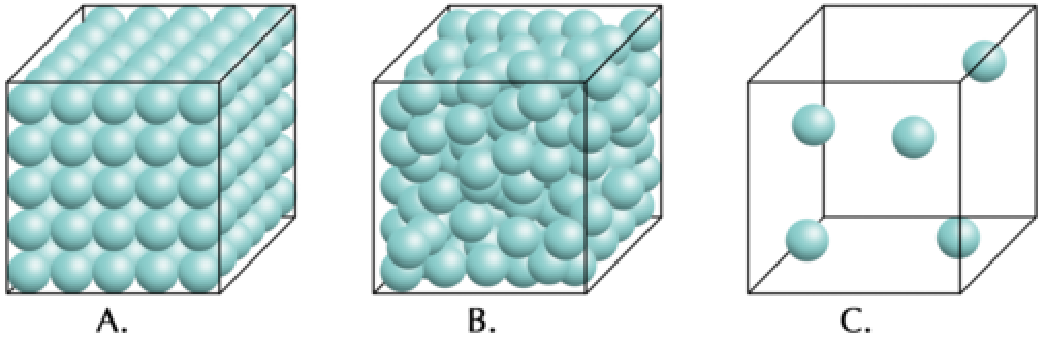


100 million Kelvin = 180 million degrees Fahrenheit
1 keV = 11.6 million K

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

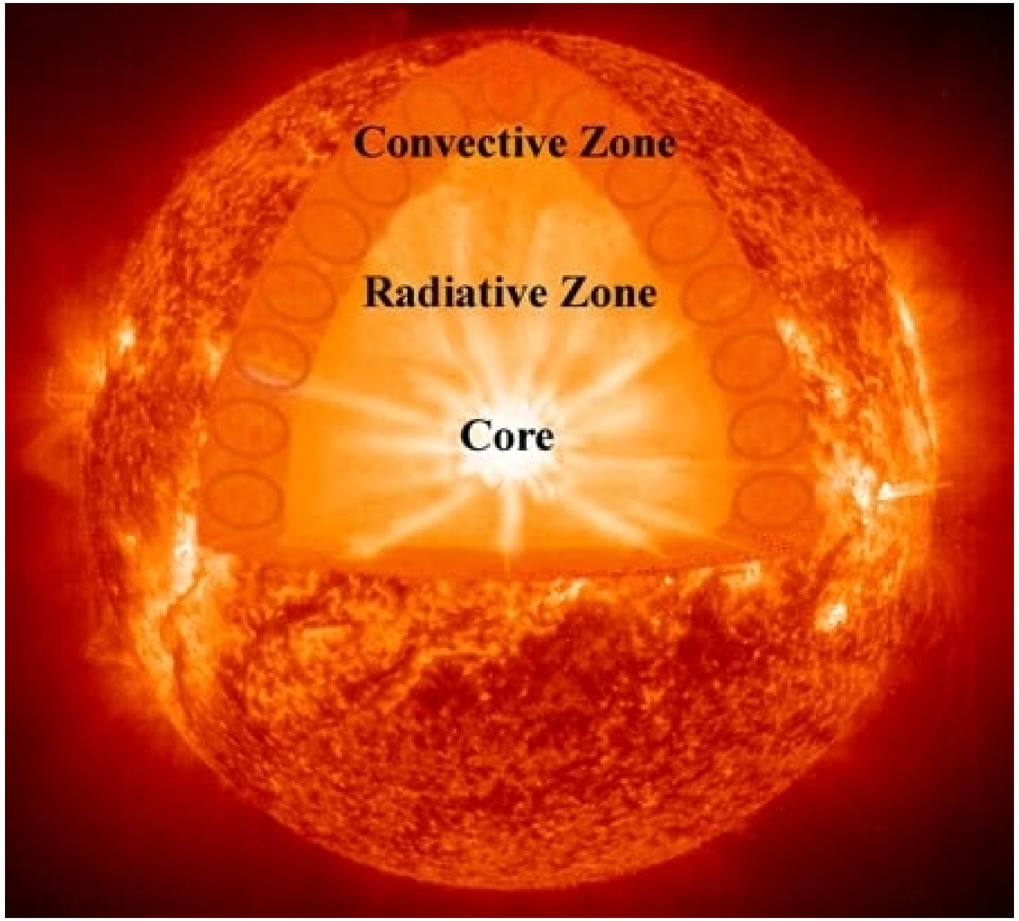
Number of particles/unit volume

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)

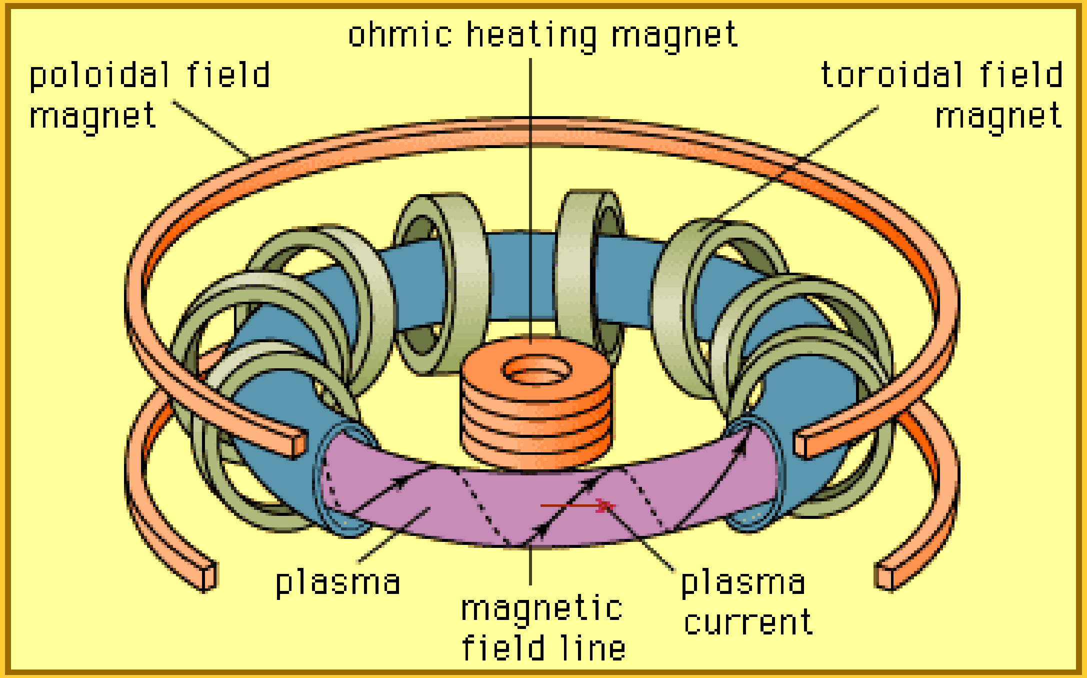
Fusion reactions occur naturally in stars, where immense gravitational forces and large sizes can confine plasmas at the high temperatures needed for fusion



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

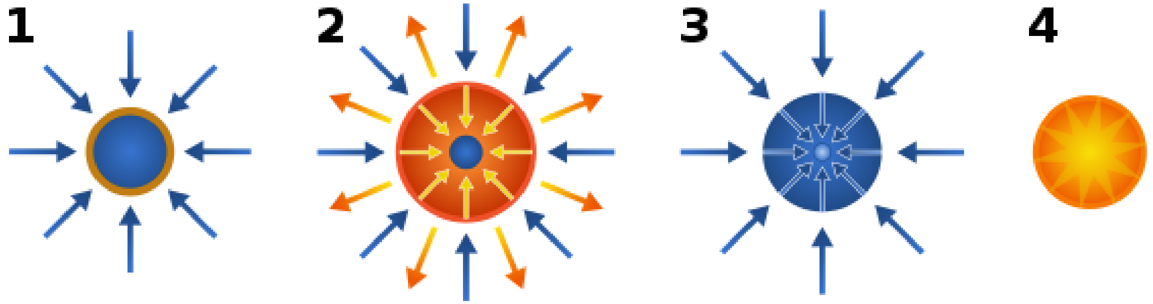
Magnetic Confinement Fusion



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

Inertial Confinement Fusion

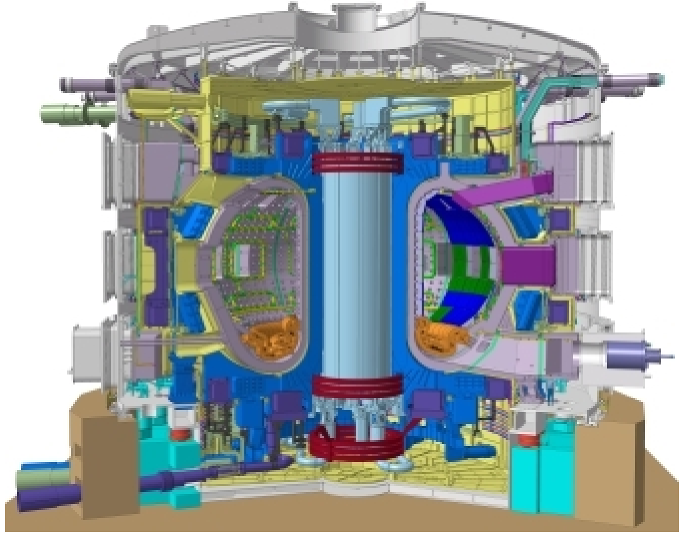
Lasers, particle beams, or electricity compress fusion fuel



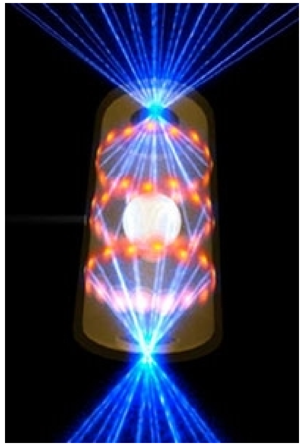
Compress fuel to very high densities for short periods of time—nothing touches the hot plasma

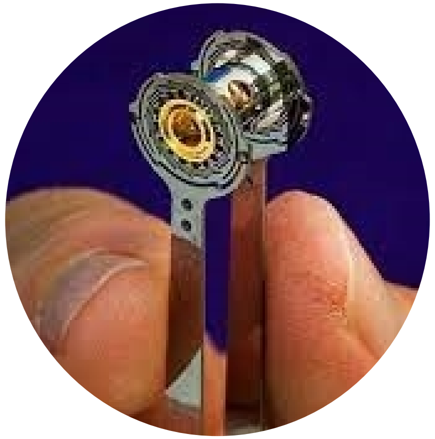
The largest laboratory fusion projects today are focused on magnetic or inertial confinement fusion, though there is growing interest in intermediate regimes

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	ICF
Density	1 x 10^{20} 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 kG	0 kG

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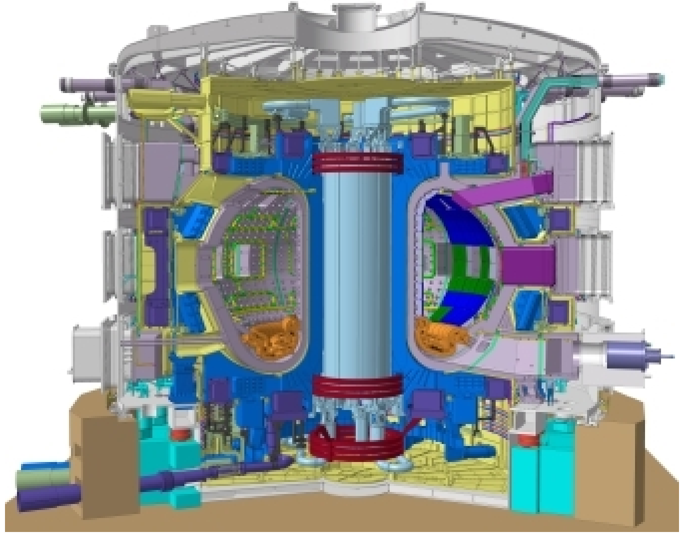

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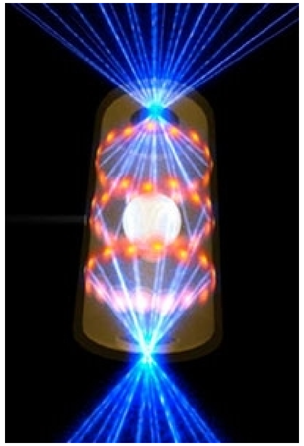

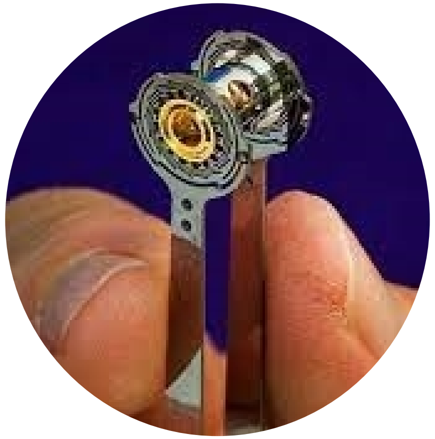

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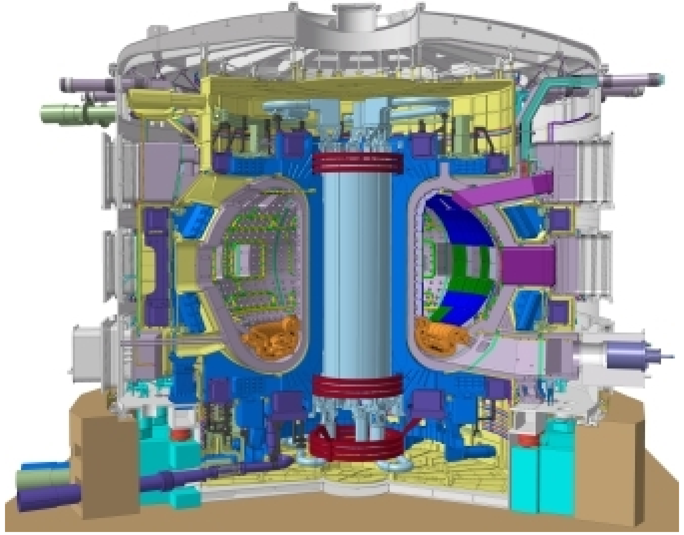
Magnetic field	100 kG		0 kG

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

Today's talk will focus on ICF!

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



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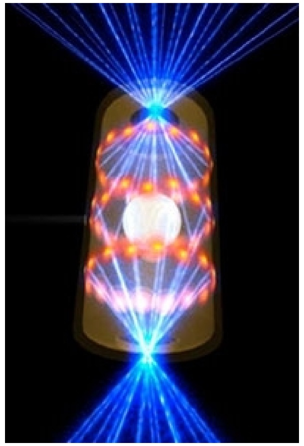

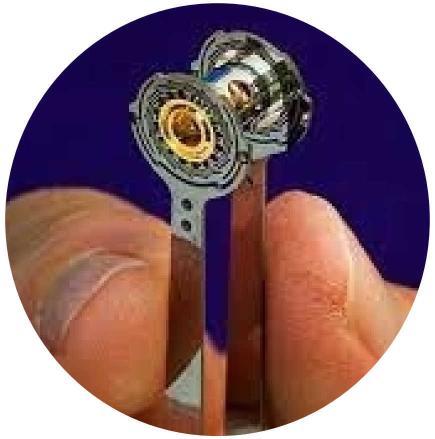

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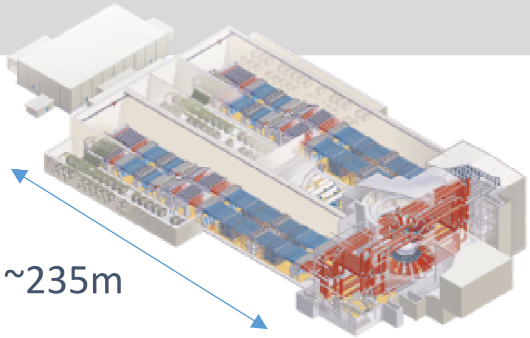
There are three major facilities in the United States' Inertial Confinement Fusion program, including the Z machine here in Albuquerque at Sandia

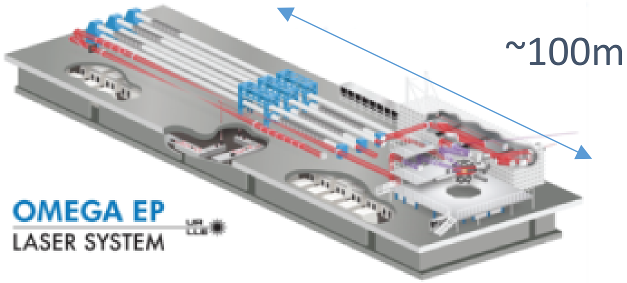
National Ignition Facility (NIF)

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



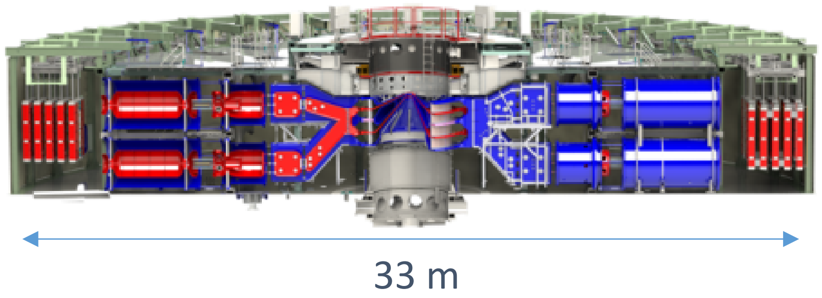
OMEGA Laser Facility

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

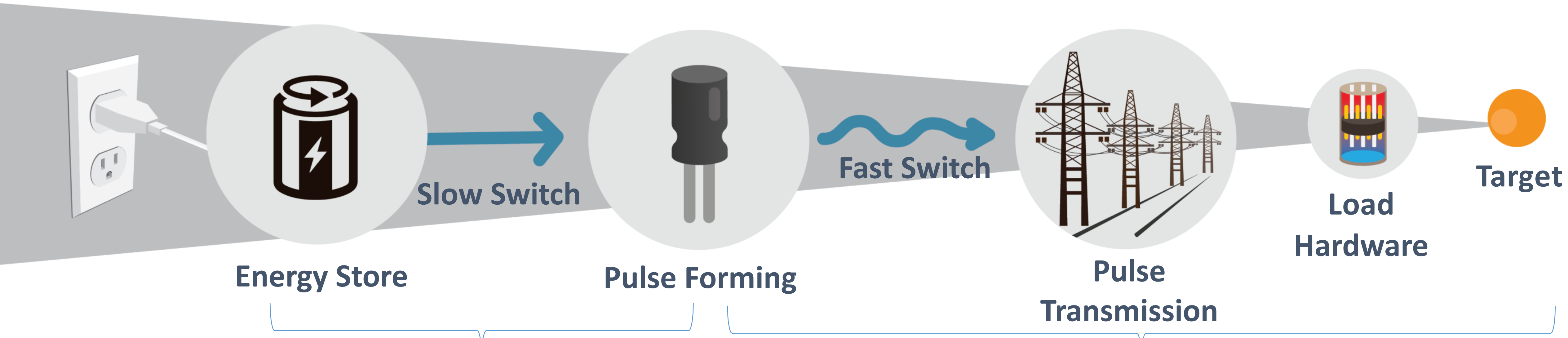


Z Facility

- 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?

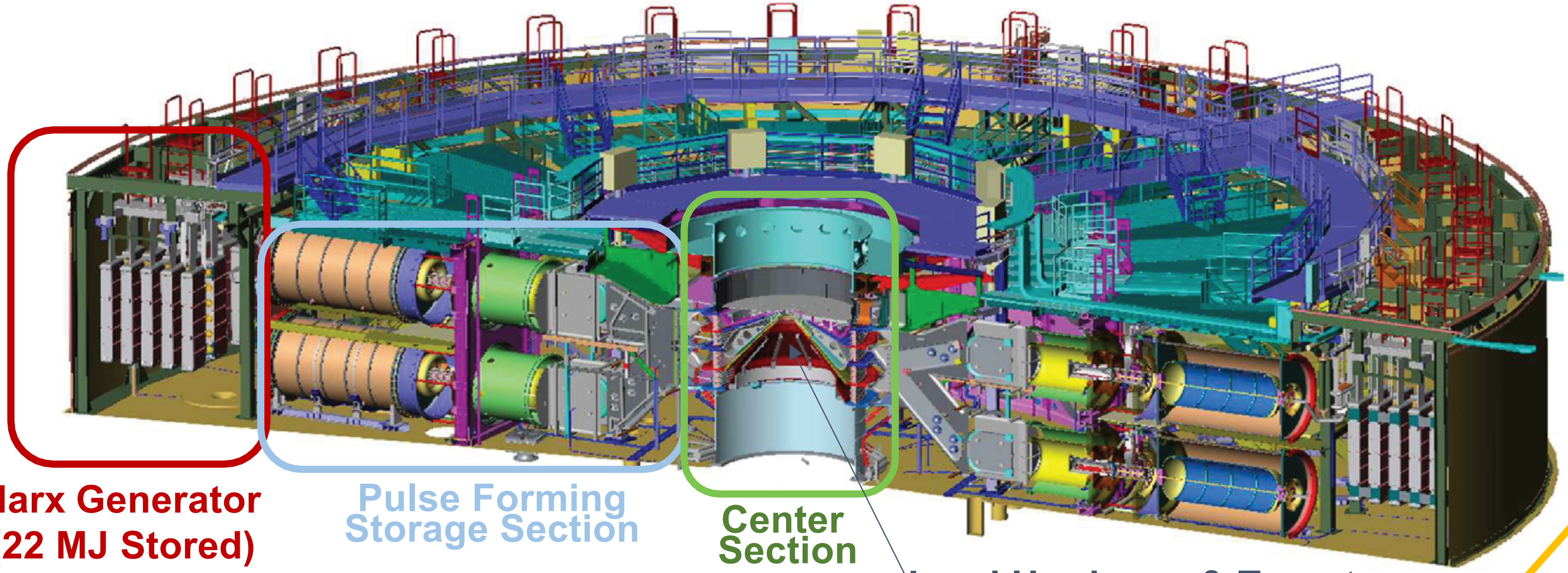


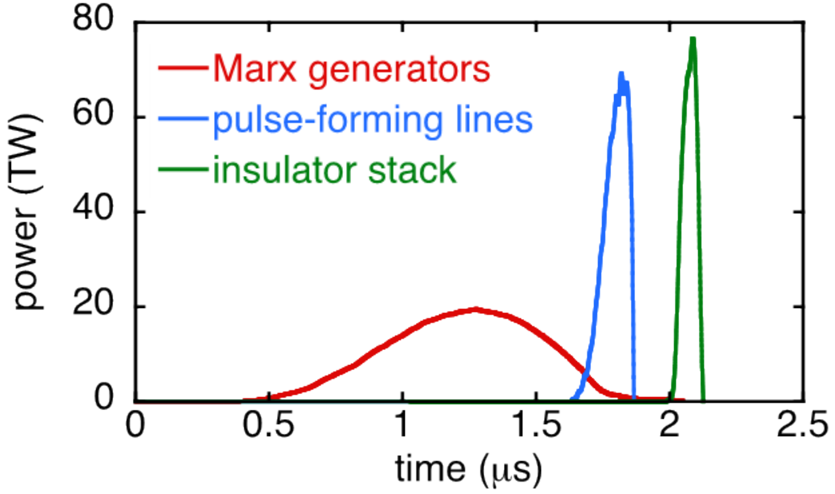
Low Electrical Power
Up to 10^7 J – 10^6 W

High Electrical Power
Up to 10^7 J – 10^{14} W

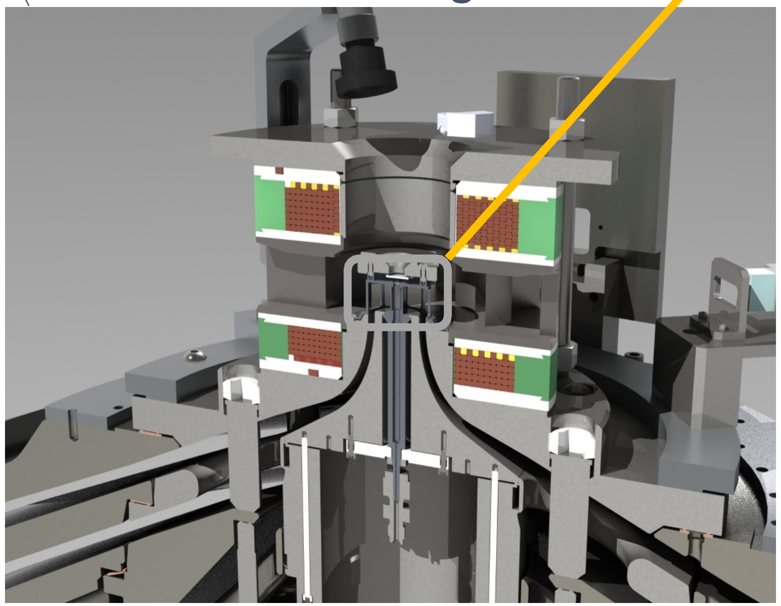
Pulsed power compresses electrical energy in both space and time to produce short bursts of high power.

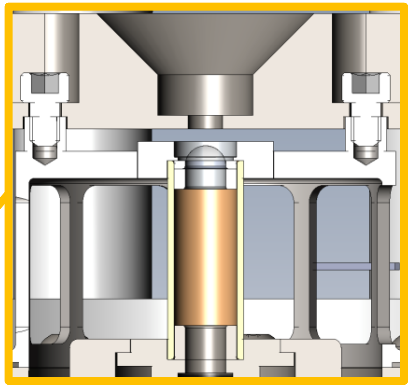
Z, the world's largest pulsed power machine, delivers 80 TW and 6 MJ of electrical energy to its center section





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

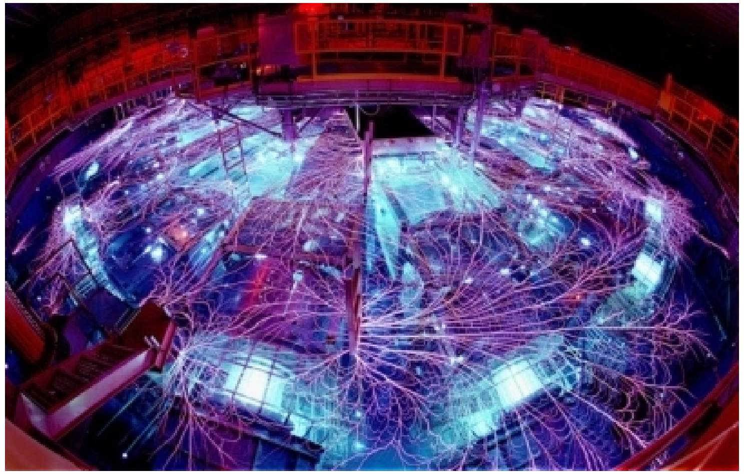
To understand the extreme nature of inertial confinement fusion, let's make sure we all understand the key concepts of energy, power, and energy density

Which of these releases the most energy?

Calories in a Krispy Kreme raspberry jelly doughnut

A stick of dynamite

Energy delivered by Z to a fusion target



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

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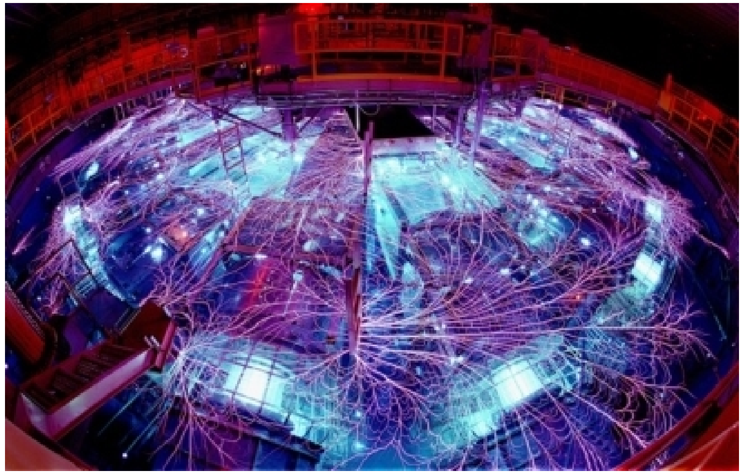
Calories in a Krispy Kreme raspberry jelly doughnut

290 Calories = 1.2 MJ

A stick of dynamite

About 1 MJ

Energy delivered by Z to a fusion target



About 1 MJ

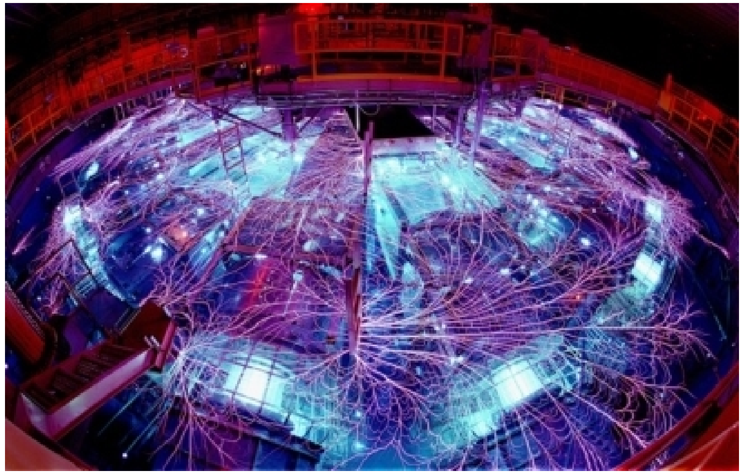
To understand the extreme nature of inertial confinement fusion, let's make sure we all understand the key concepts of energy, power, and energy density

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

A Krispy Kreme raspberry jelly doughnut

An electric power plant

Power delivered by Z to a fusion target



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

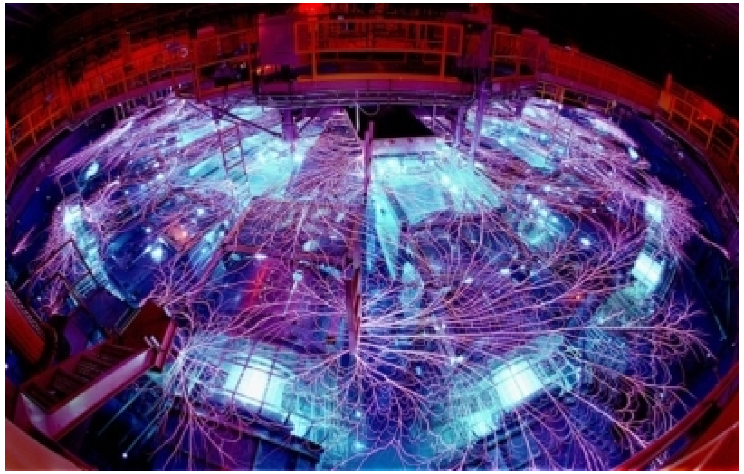
A Krispy Kreme raspberry jelly doughnut

290 Calories = 1.2 MJ
It takes your body roughly 60 minutes to digest
1,200,000 J / 3,600 sec = 330 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



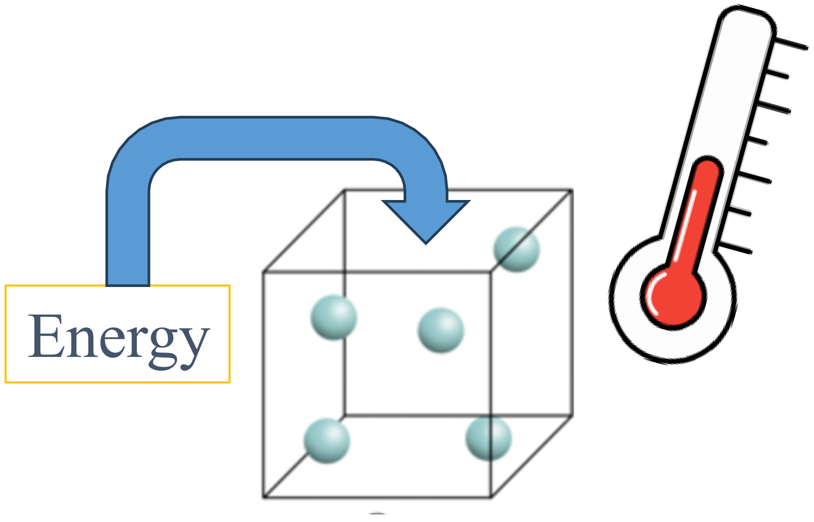
Power entering the insulator stack is 80 TW, i.e.,
80,000,000,000,000 Watts

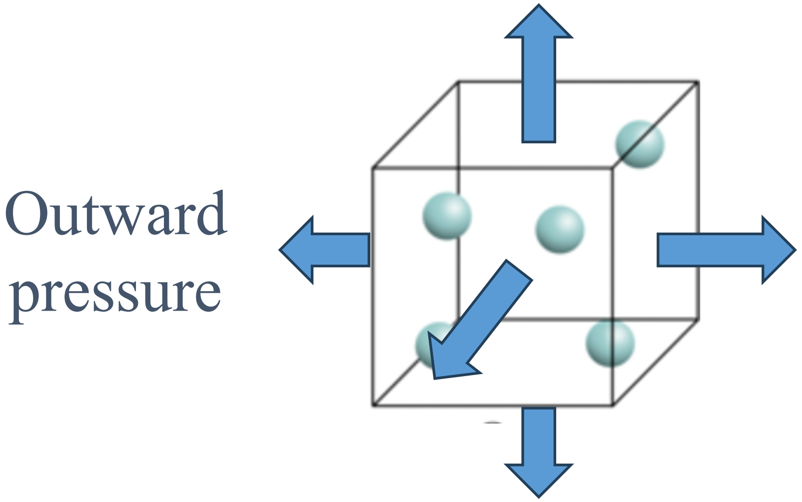
To understand the extreme nature of inertial confinement fusion, let's make sure we all understand the key concepts of energy, power, and energy density

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).



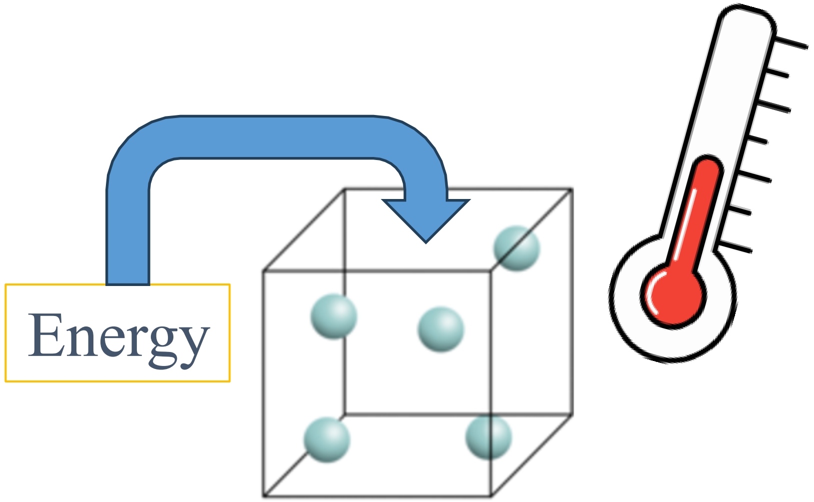


To understand the extreme nature of inertial confinement fusion, let's make sure we all understand the key concepts of energy, power, and energy density

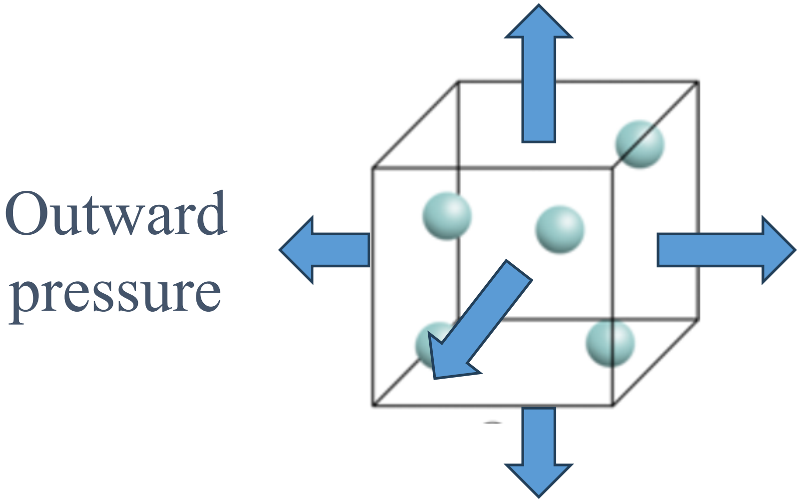
Energy corresponds to how much work you can do.

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

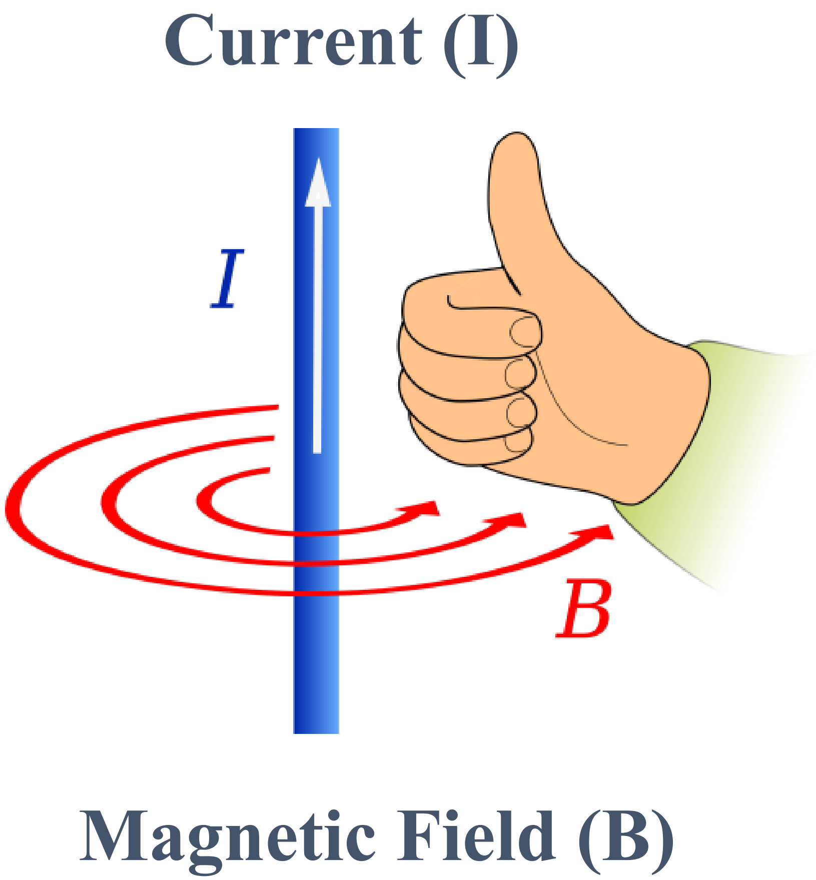
Energy density is the energy per unit volume, which is equivalent to a pressure (force per unit area).

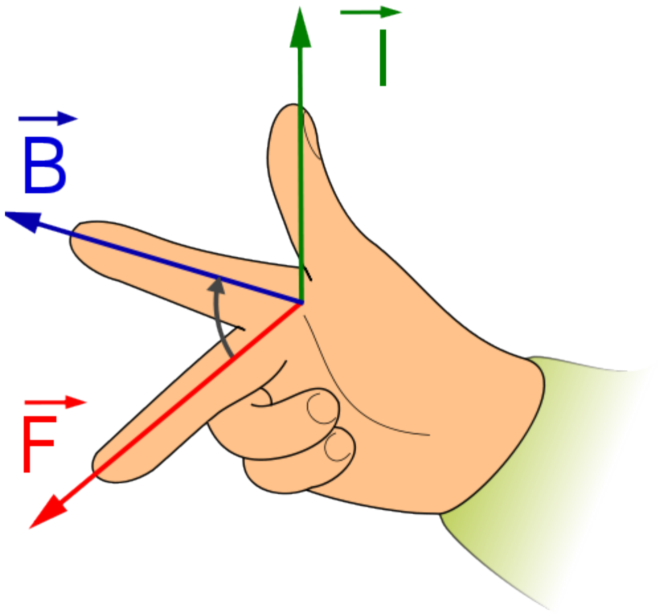


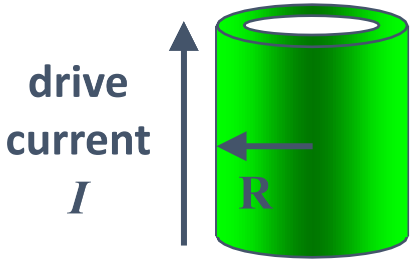
15psi = 1 bar = 100,000 J/m^3



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







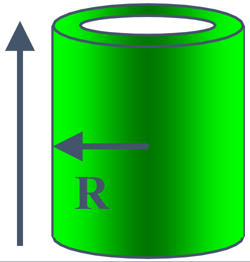
A "Z-pinch"

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



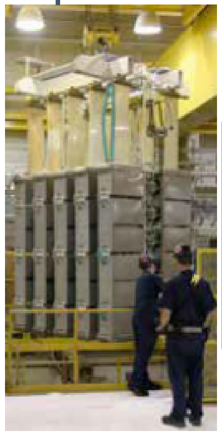
100 MBar at 26 MA and 1 mm

100 GPa = 1 Mbar ≈ 10^6 atmospheres

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

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

Z Storage capacitor

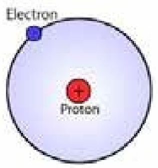


2e-6 Mbar

TNT

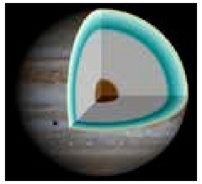
0.07 Mbar

Internal Energy of H atom



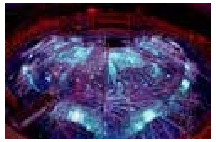
1 Mbar

Metallic H in Jupiter's core



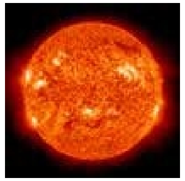
30 Mbar

Z Magnetic Drive Pressure



~100 Mbar

Center of Sun



250,000 Mbar

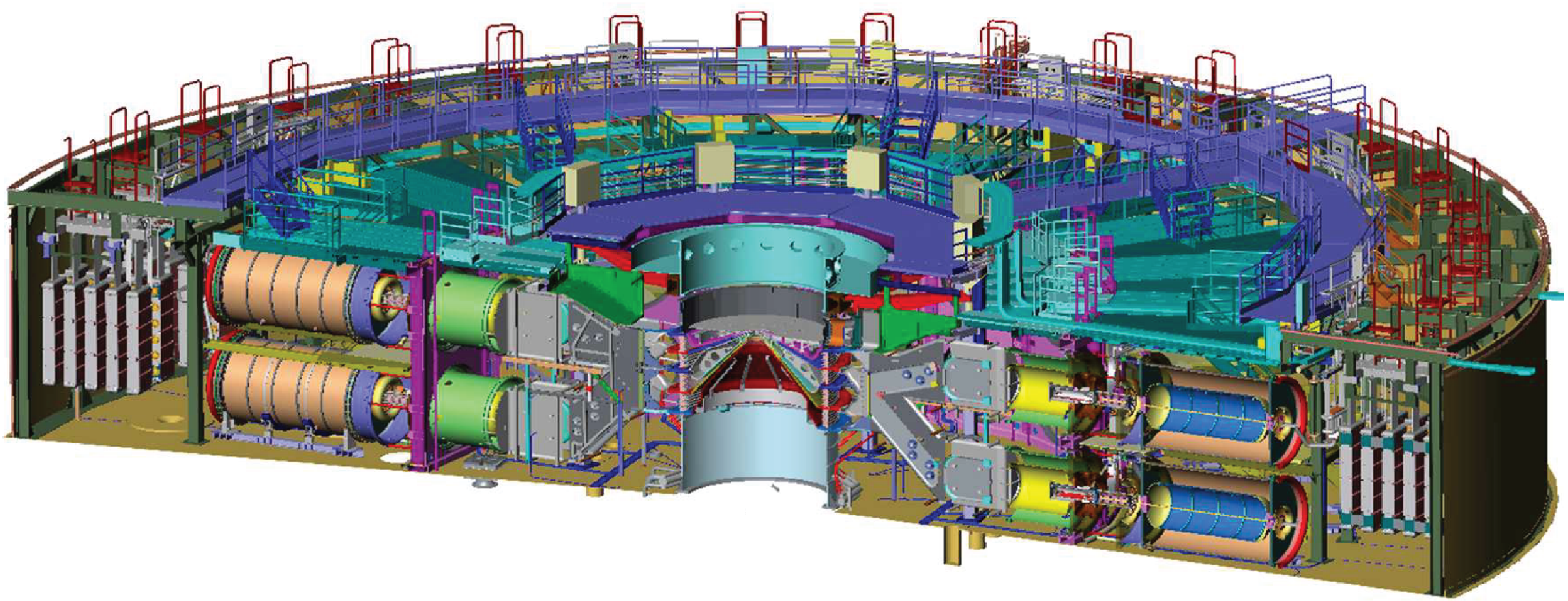
Burning ICF plasma

800,000 Mbar

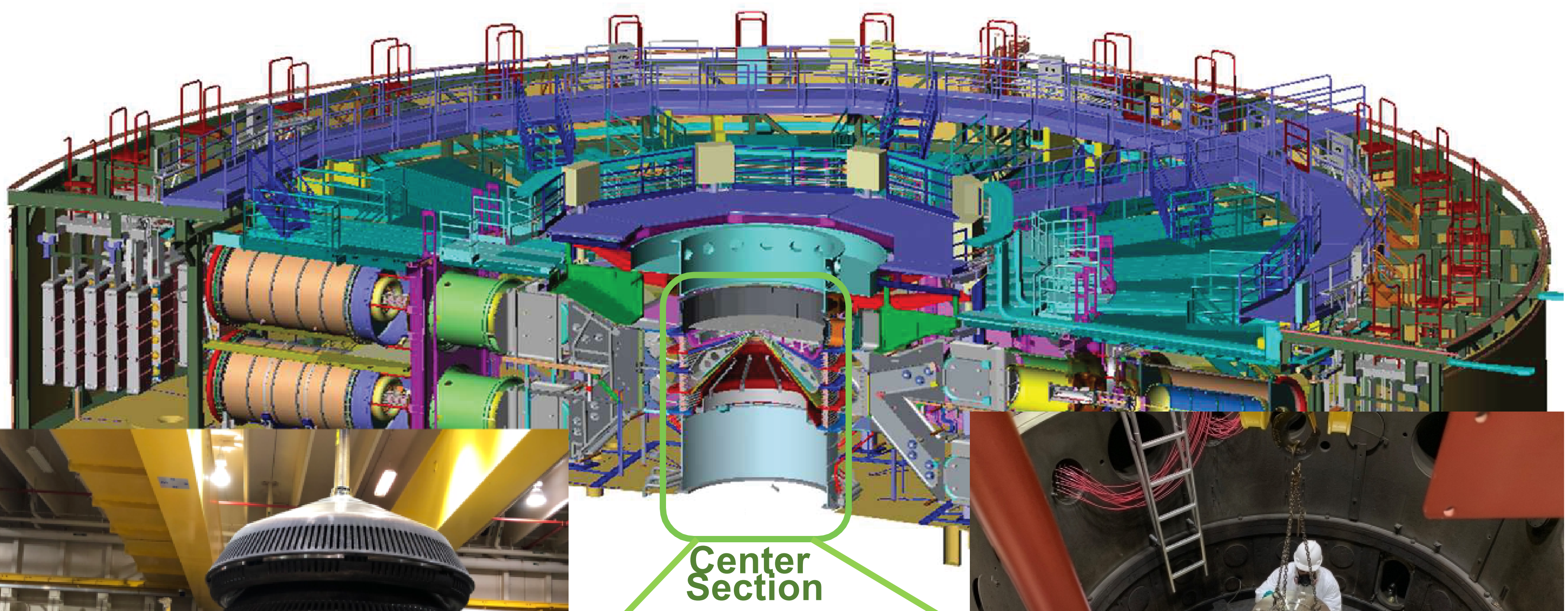
Push on samples

Compress fuel at high velocity

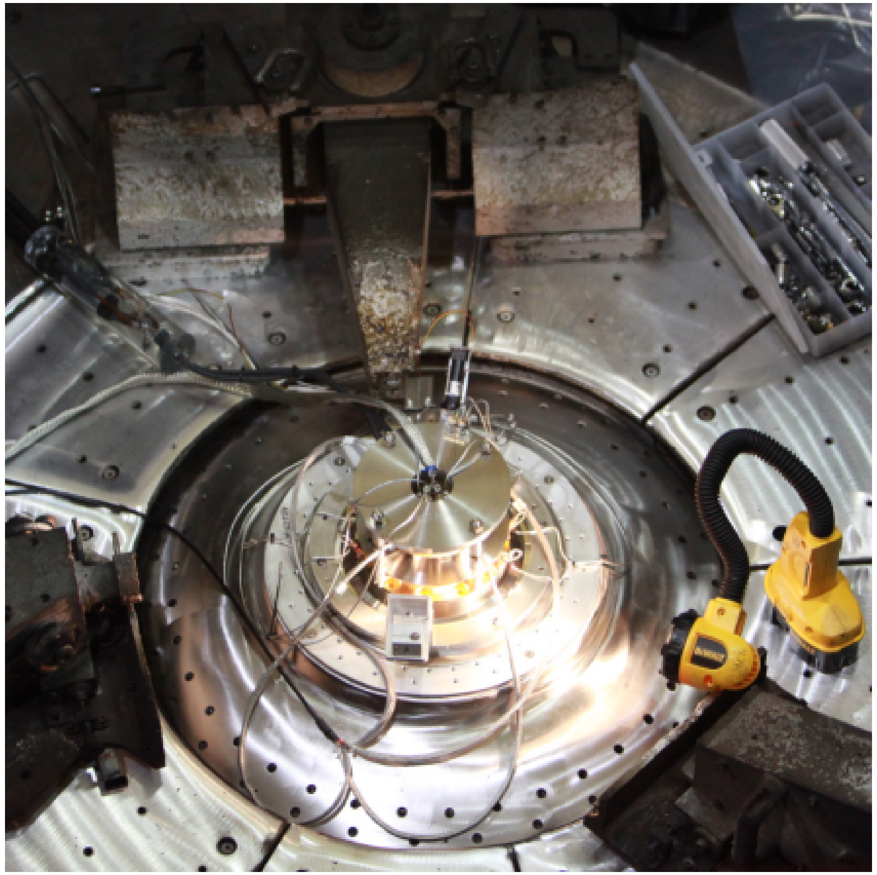
The purpose of the Z machine (and the National Ignition Facility, etc.) is to compress energy in both space and time to create extremely high energy density conditions at the focal point!



Workers on Z fire ~150 shots per year under challenging working conditions



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



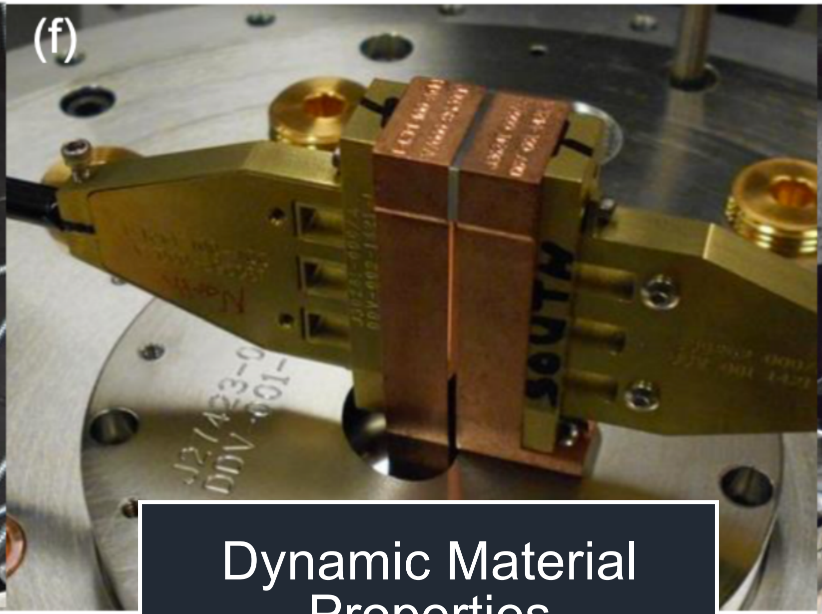
Pre-shot photo of coils and target hardware

Post-shot photo

Harsh debris, shock, and radiation environment make fielding experiments unique and challenging

Z is a precision tool for high energy density science in three broad areas

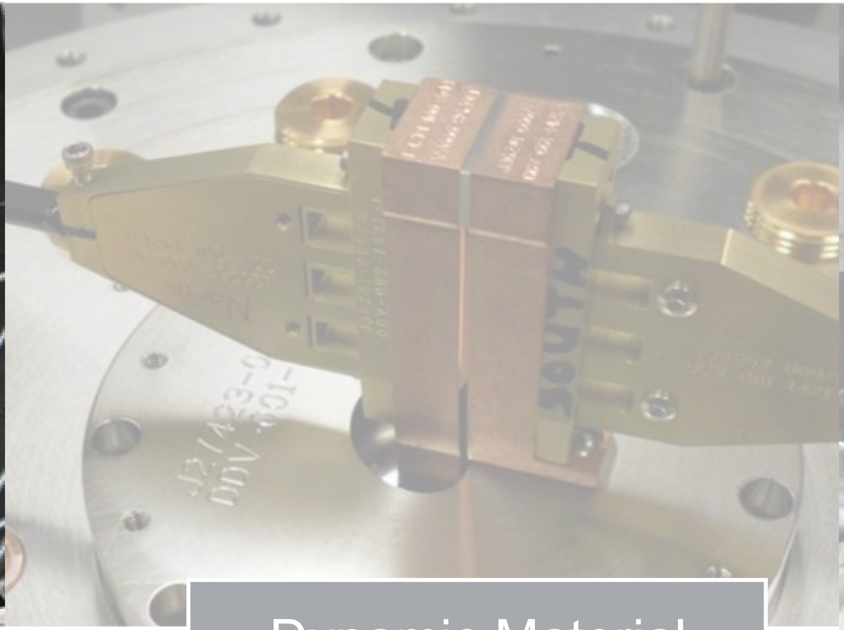
Radiation Science



Dynamic Material Properties

Inertial Confinement Fusion

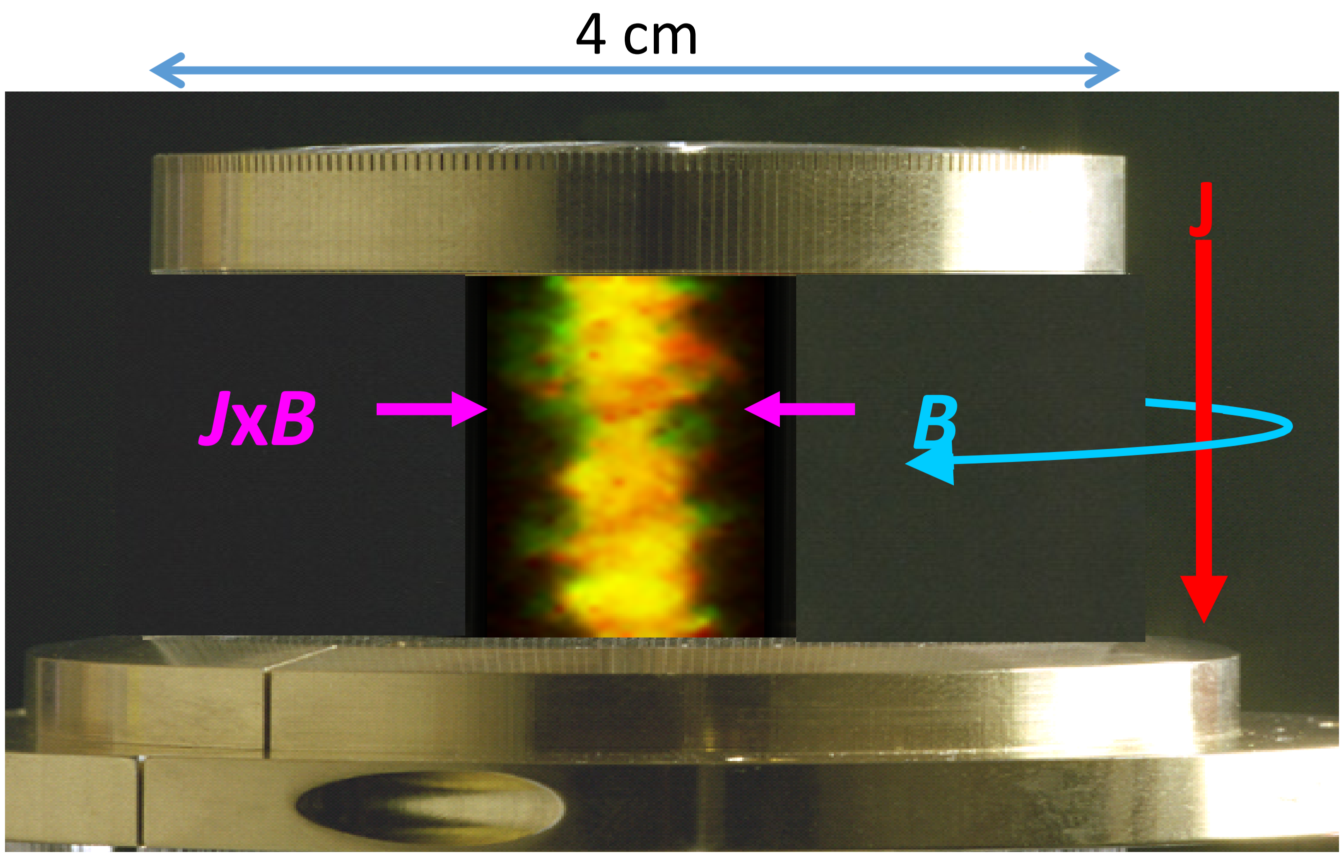
Radiation Science



Dynamic Material Properties

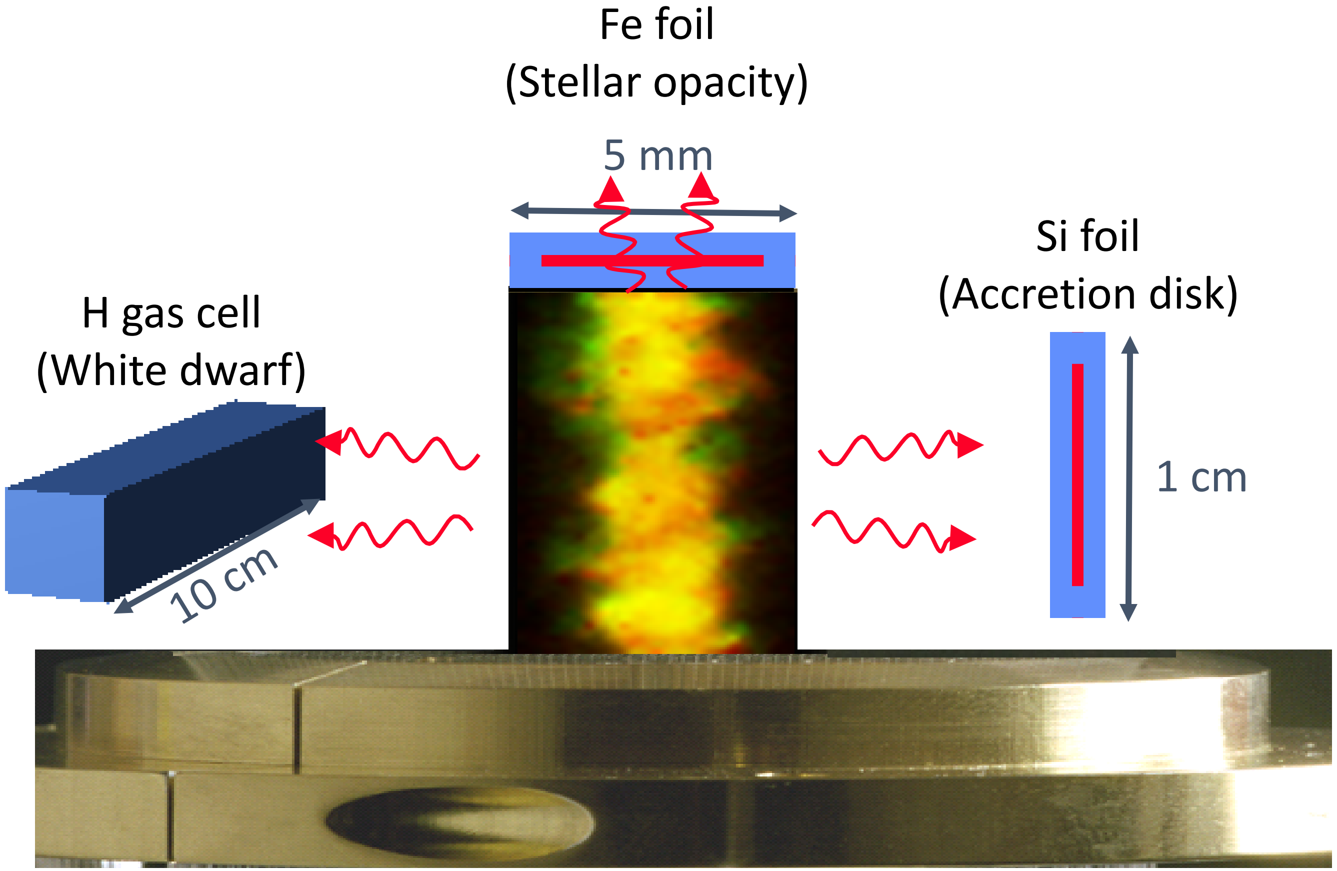
Inertial Confinement Fusion

Wire-array implosions on Z use 26 MA of current to create >1 MJ of x rays, which can be used to drive multiple experiments on a single Z shot



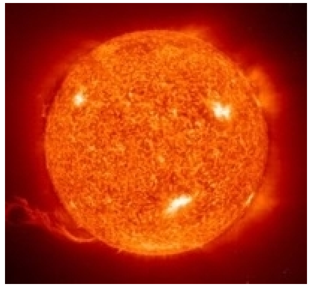
Marx Energy	20.3 MJ
Ipeak	25.8 MA (1.5%)
Peak Power	220 TW (10%)
Radiated Energy	1.6 MJ (7%)

Wire-array implosions on Z use 26 MA of current to create >1 MJ of x rays, which can be used to drive multiple experiments on a single Z shot



Partners: LLNL, LANL, University of Texas, Ohio State, West Virginia U., U. Nevada-Reno, CEA

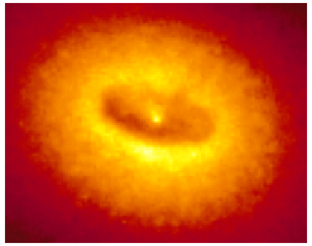
Stellar opacity



Question:
Why can't we predict the location of the convection zone boundary in the Sun?

Achieved Conditions:
T_e ~ 200 eV, n_e ~ 10^{23} cm^{-3}

Accretion disk



Question:
How does ionization and line formation occur in accreting objects?

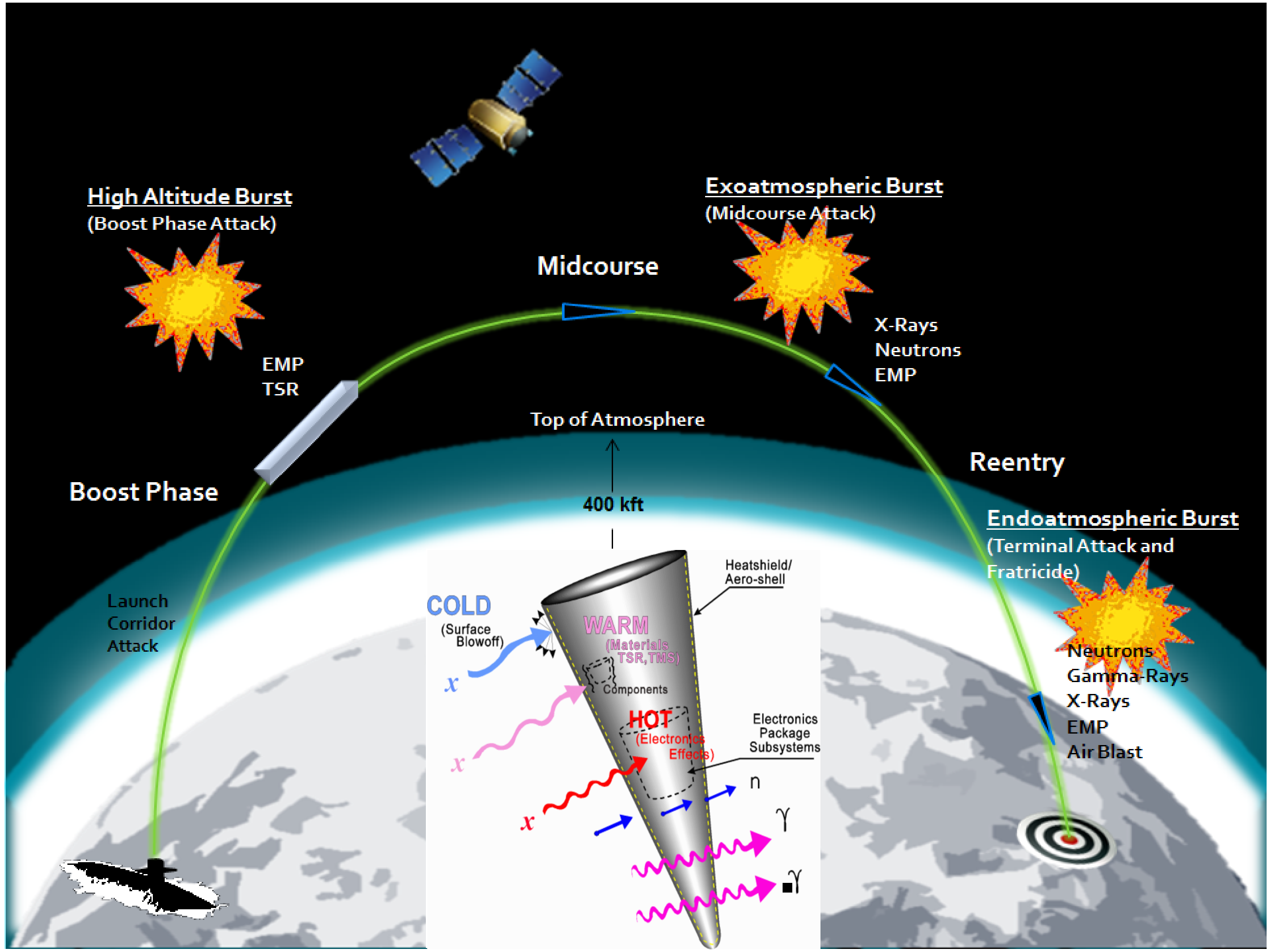
Achieved Conditions:
T_e ~ 20 eV, n_e ~ 10^{18} cm^{-3}

White dwarf

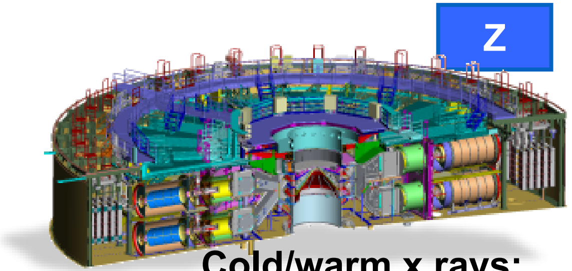
Question:
Why doesn't spectral fitting provide the correct properties for White Dwarfs?

Achieved Conditions:
T_e ~ 1 eV, n_e ~ 10^{17} cm^{-3}

Z is also one of several facilities that Sandia uses to address radiation environment threats in the Stockpile-to-Target Sequence (STS)



Hot x rays

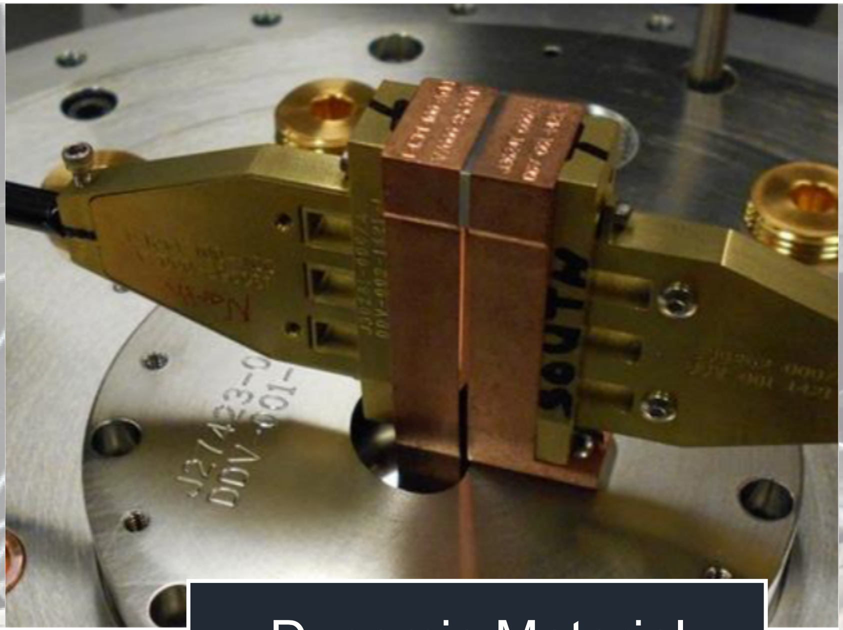


Cold/warm x rays; fast fusion neutrons

Gamma rays

Thermal neutrons

Radiation Science



Dynamic Material Properties

Inertial Confinement Fusion

The Z machine is also used to study the properties of materials used in weapons, such as plutonium and uranium

Z is a unique platform for dynamic materials research

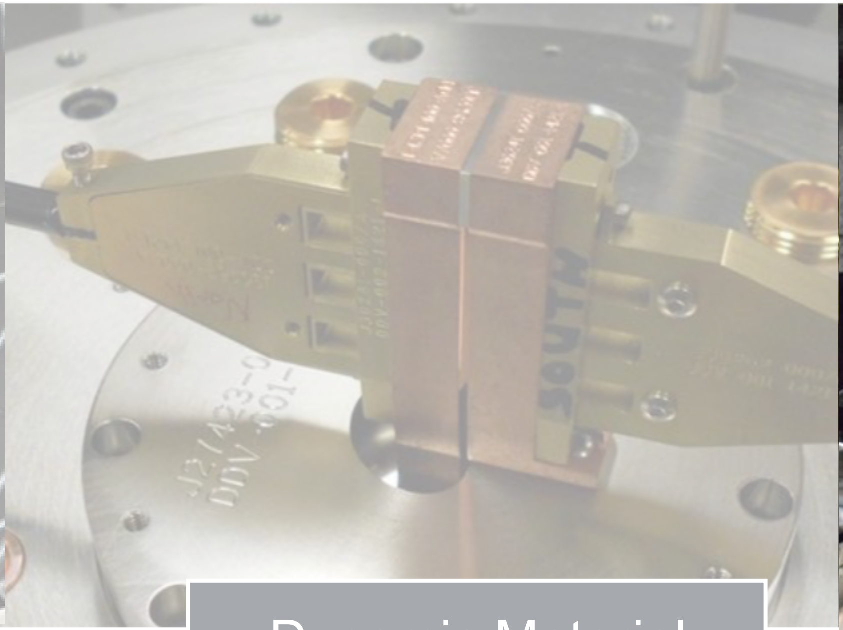
- Large samples, high pressures, and relevant loading paths
- Containment capability allows us to field a wide range of hazardous materials without relying on surrogacy

Compared response of 5- and 52-year-old Pu samples to improve pit aging analysis for certification models

Partners: LANL, LLNL

Los Alamos NATIONAL LABORATORY EST. 1943

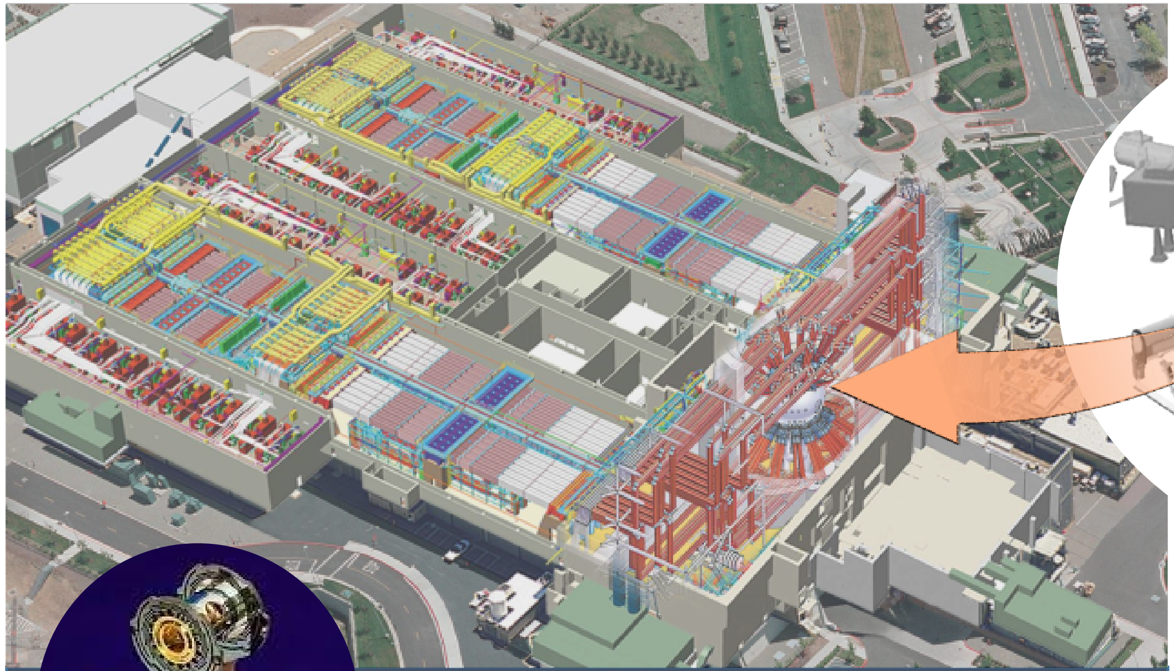
Radiation Science

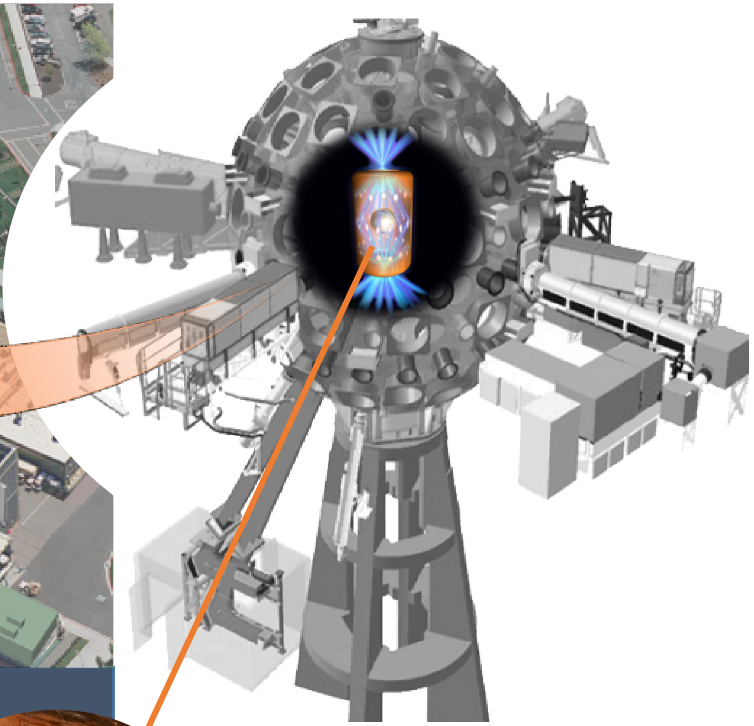


Dynamic Material Properties

Inertial Confinement Fusion

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



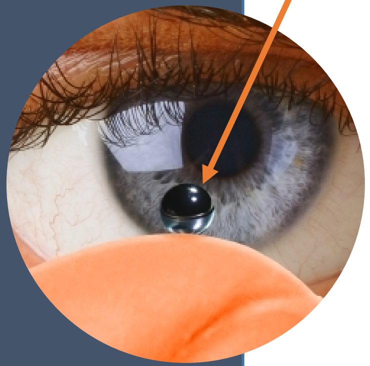


NIF lasers

500 trillion watts for

> 4 nanoseconds (ns)

> 1.9 million joules (MJ)



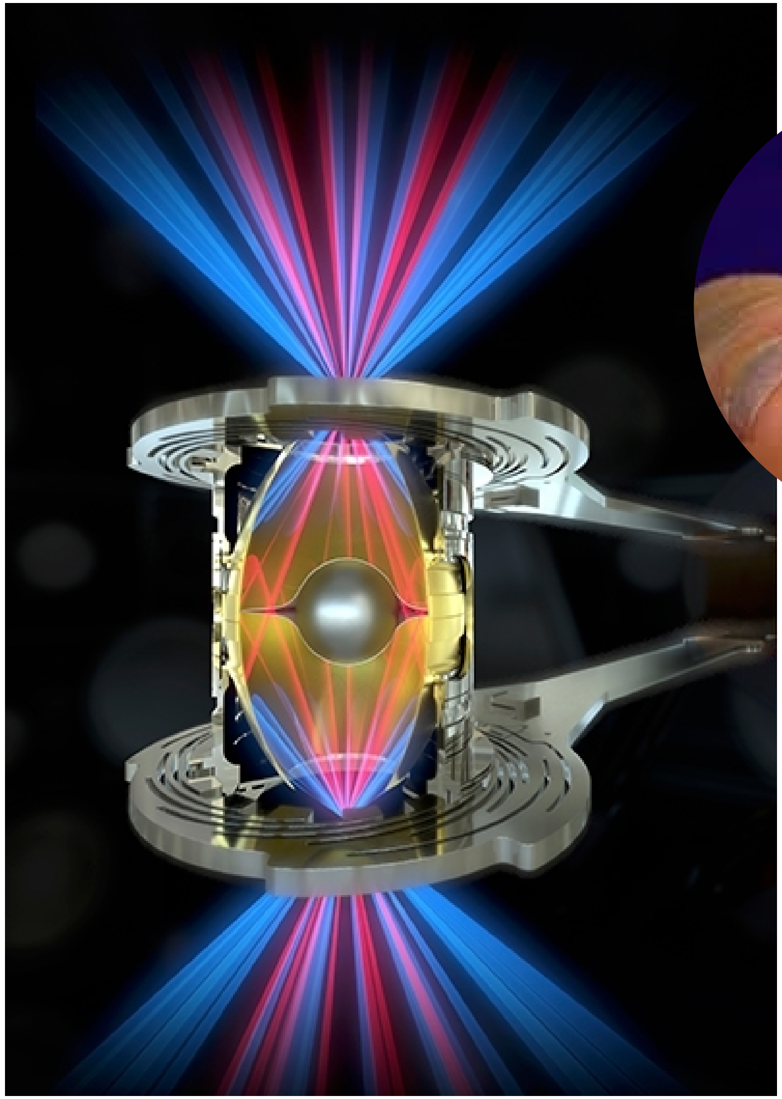
Target

~ 1 cm

Temperature

~3,000,000 K

Research on NIF uses lasers to make tiny x-ray ovens!

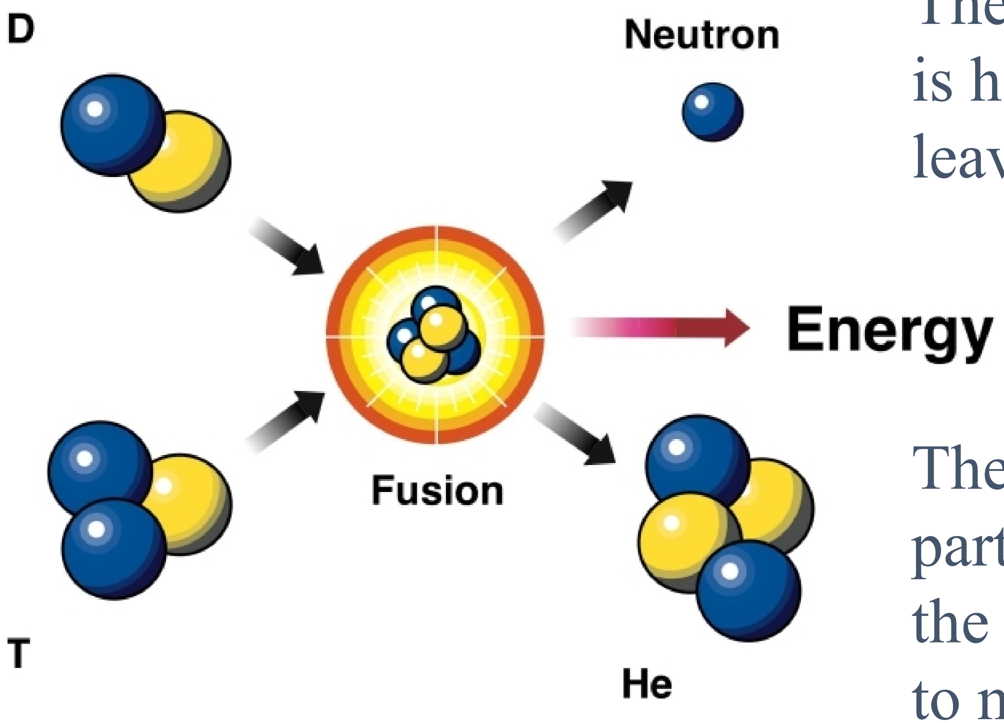


Up to 500 TW of laser light enters a “hohlraum”

192 laser beams hit the hohlraum walls and create an x-ray oven that bakes away (ablates) the outer surface of a spherical capsule target containing fusion fuel

If done symmetrically, the radially outward motion of the outer layer drives the inside of the capsule radially inward to create the extreme conditions needed for fusion

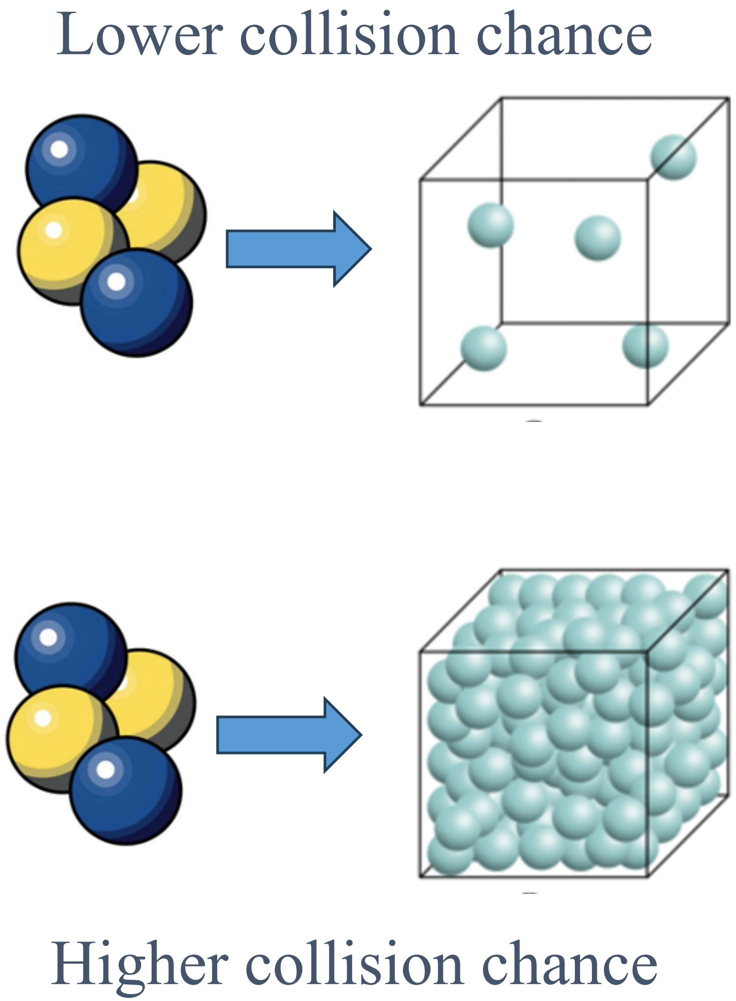
To release significantly more energy from a DT plasma than was needed to heat it up to the extreme temperatures needed for fusion, we must stop alpha particles

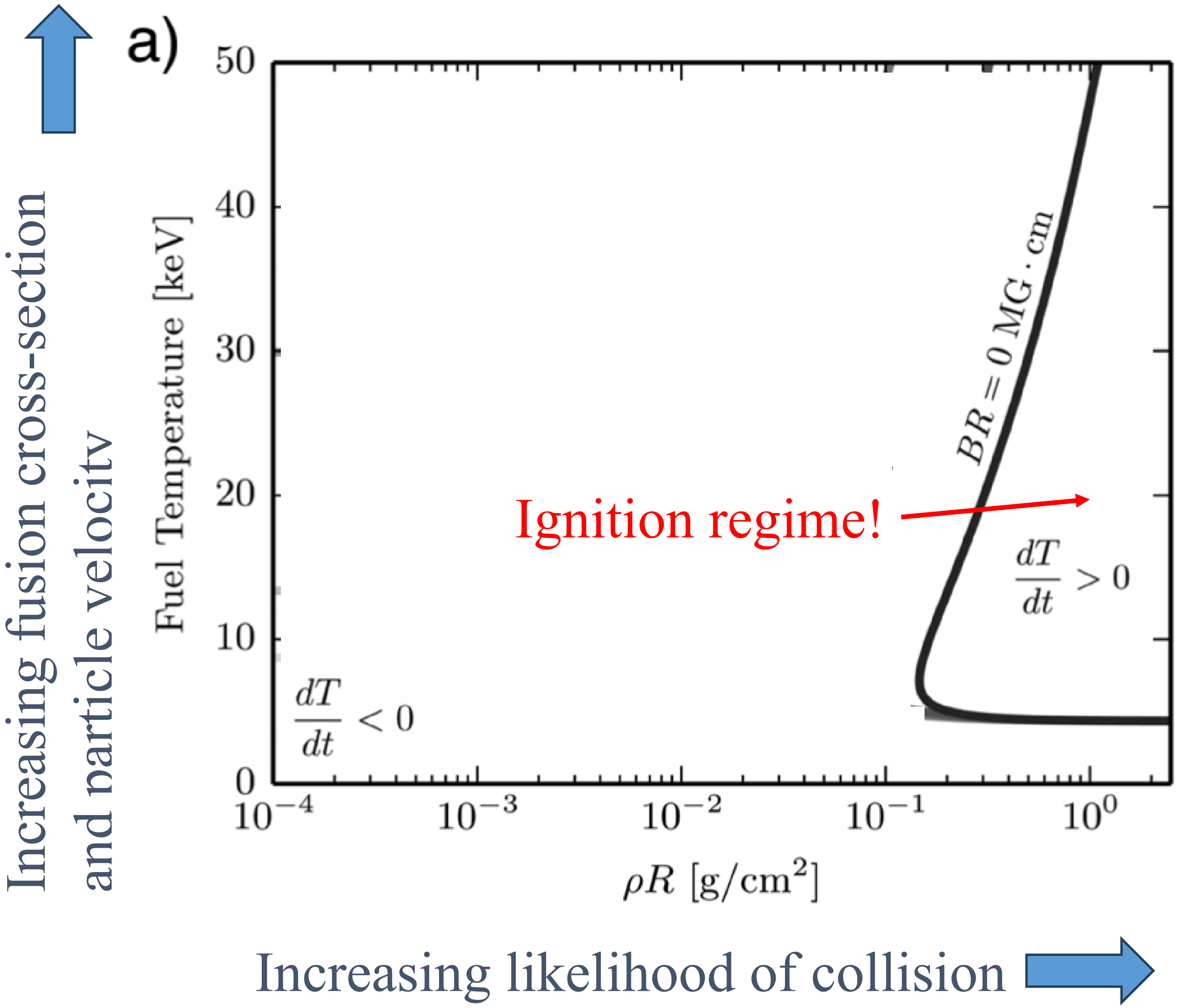


The high energy neutron is hard to stop and will leave the plasma

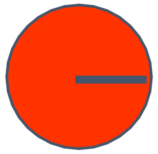
The helium nucleus (alpha particle) can be stopped if the plasma is dense enough to make a collision with another particle very likely

To release significantly more energy from a DT plasma than was needed to heat it up to the extreme temperatures needed for fusion, we must stop alpha particles





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

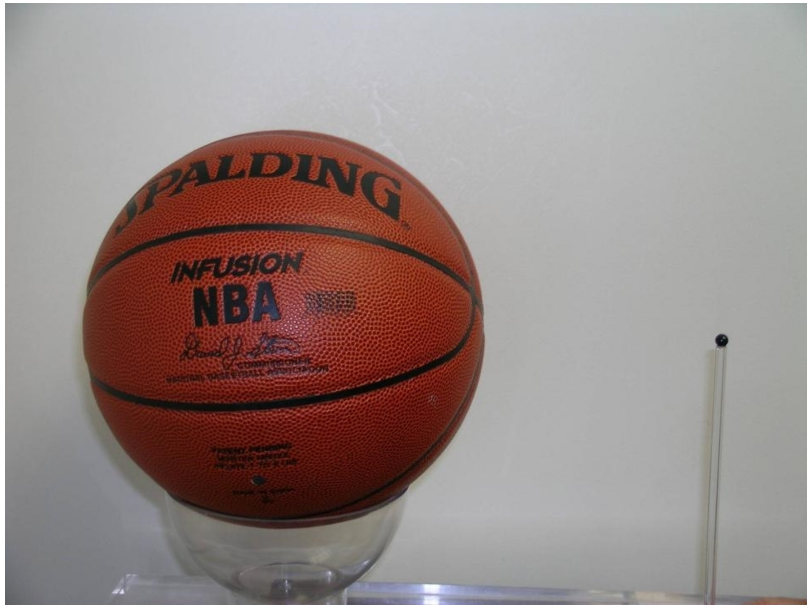


ρ, R, T

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

$E_{NIF} \sim 15\,\mathrm{kJ} \Rightarrow P \sim 400$ GBar

$R \sim 30\,\mu\mathrm{m} \Rightarrow$ and $\rho \sim 130\, g/cm^3$

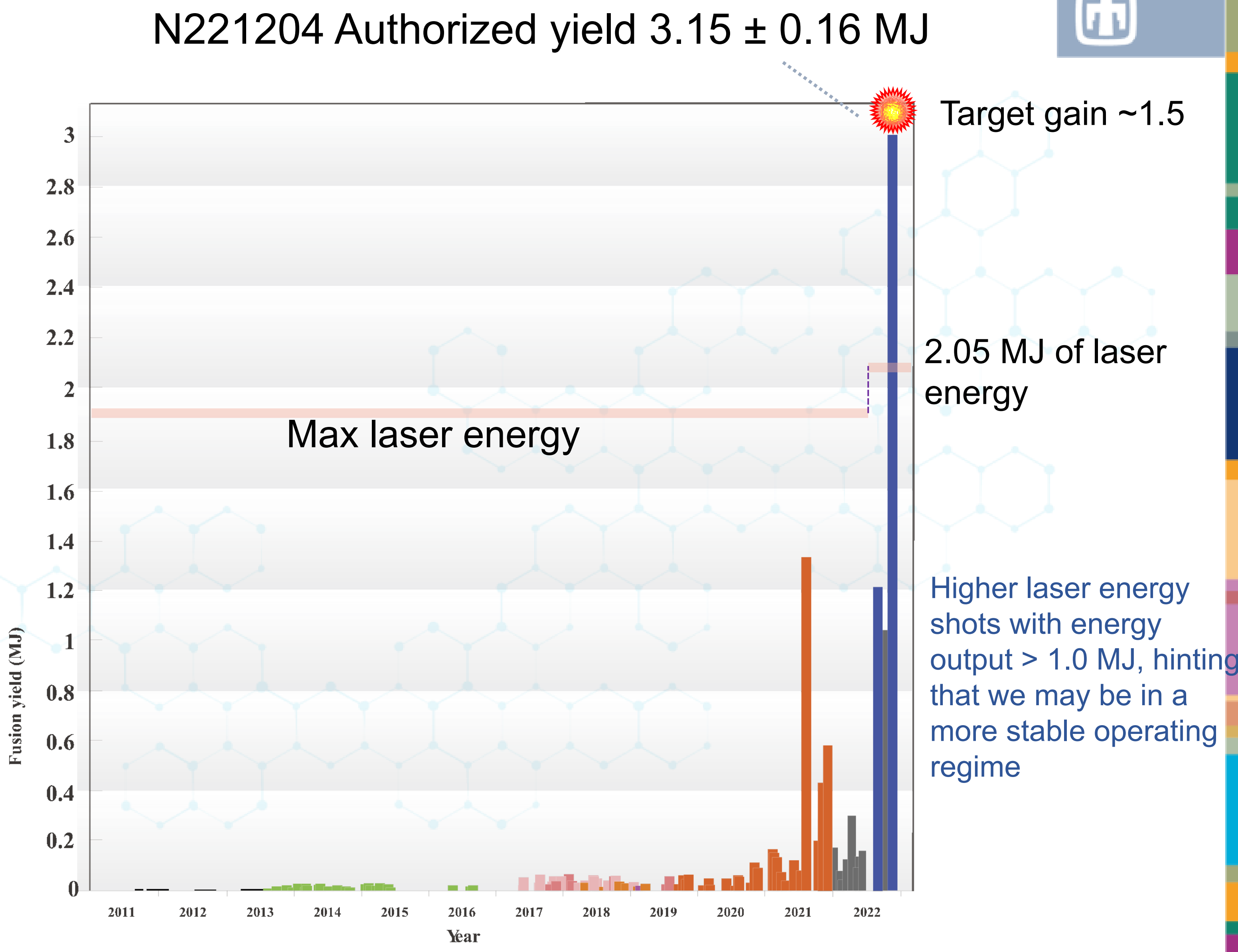


- 35:1 convergence ratio
- Basketball to pea
- Need <1—2% deviation from a perfect sphere
- If capsule scaled to size of earth, it would have to be smoother than earth
- Volume compression >40,000x

- 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!

In an experiment on 12/5/2022, **NIF exceeded the threshold* for fusion ignition**

…opening up new regimes of weapons physics and setting the stage for new fusion energy possibilities

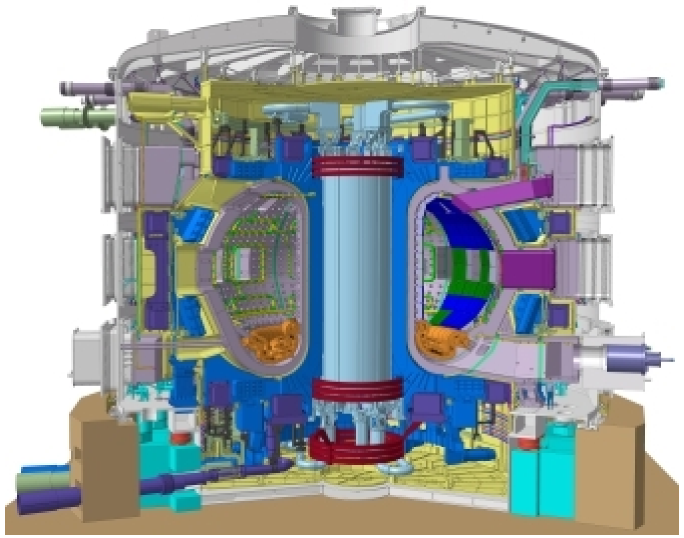


*National Academy of Sciences 1997 definition for ignition

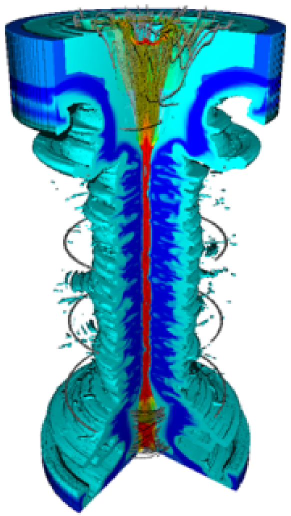
This result was just repeated in July with 3.88 ± 0.31 MJ!

Magnetic inertial fusion (MIF) bridges the gap between magnetic confinement fusion (MCF) and inertial confinement fusion (ICF)

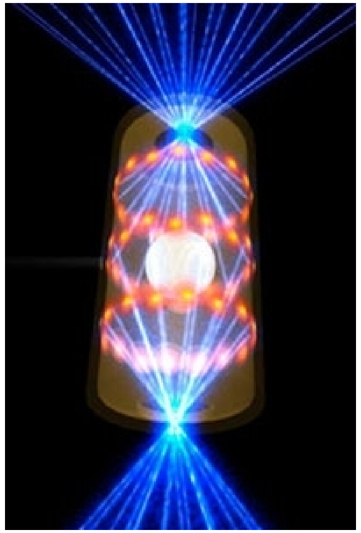
MCF (e.g. ITER)



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 kG	50-100 MG*	0 kG

MCF
- B field confines plasma

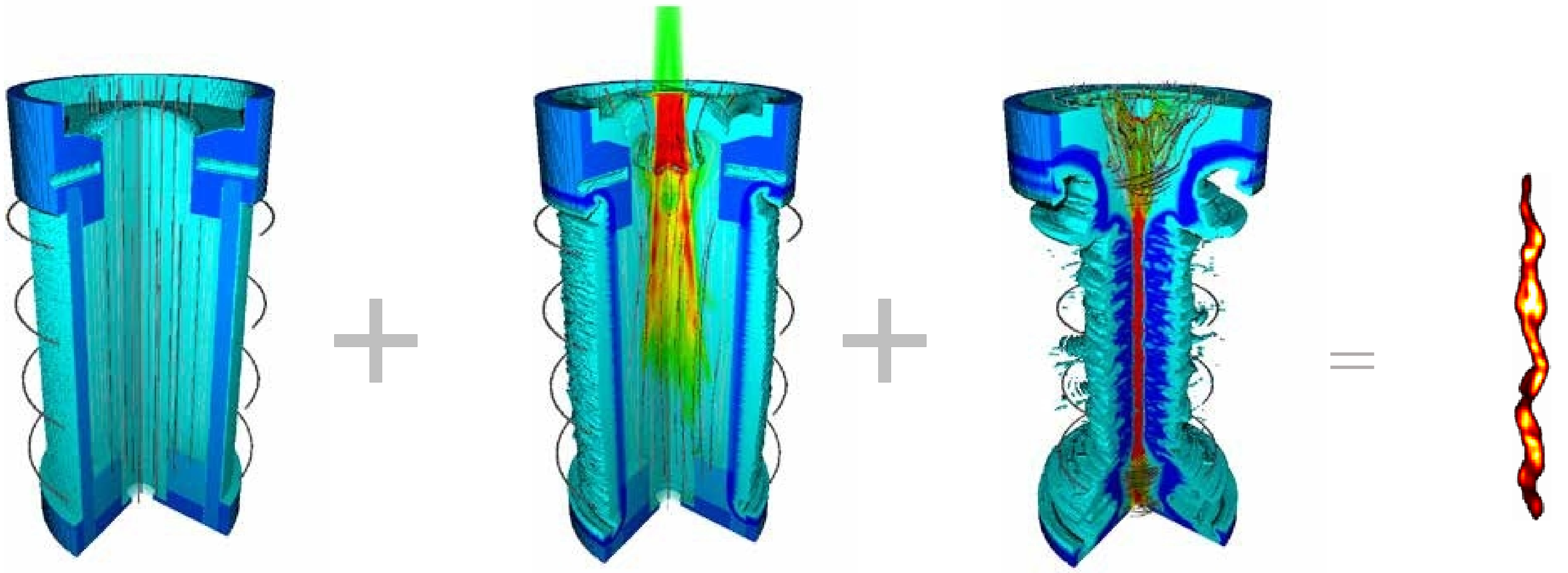
MIF
- B field reduces conduction losses during implosion
- B field increases path length of α's, reducing

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

*Achieved by flux compression

MagLIF is a Magneto-Inertial Fusion (MIF) concept

Relies on three components to produce fusion conditions at stagnation



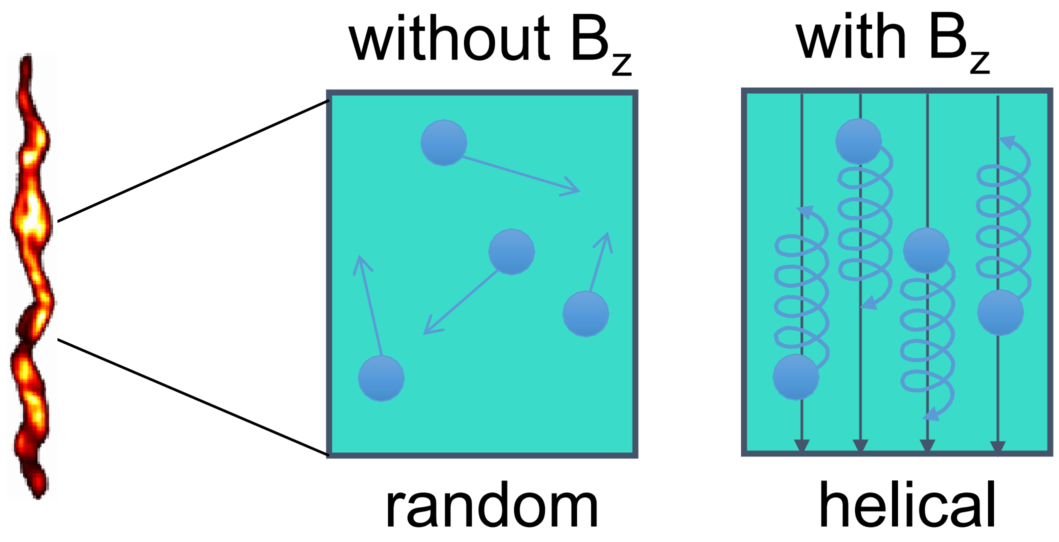
Magnetization
- Suppress radial thermal conduction losses
- Enable slow implosion with thick target walls

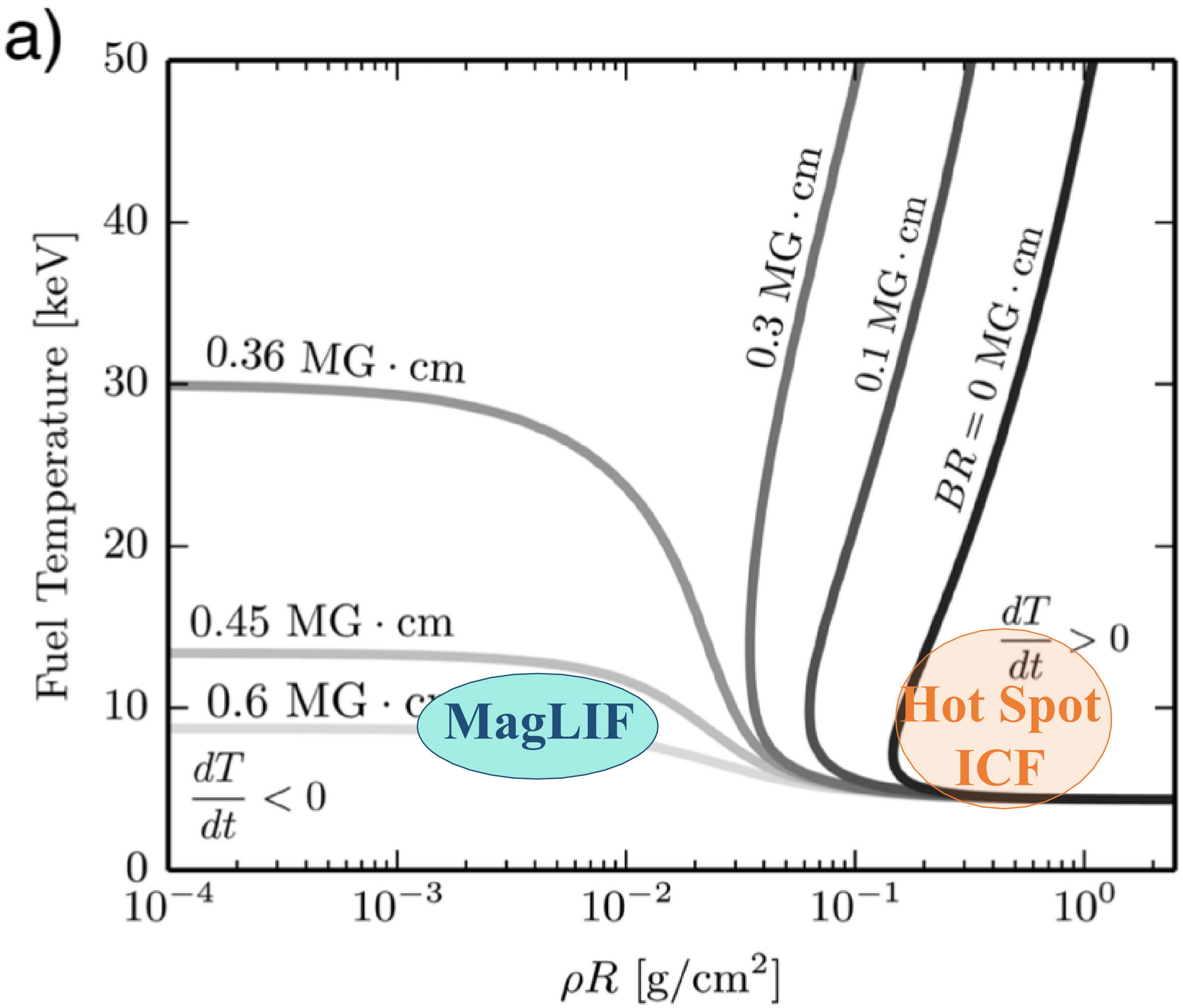
Preheat
- Ionize fuel to lock in B-field
- Increase adiabat to limit required convergence

Implosion
- PdV work to heat fuel
- Flux compression to amplify B-field

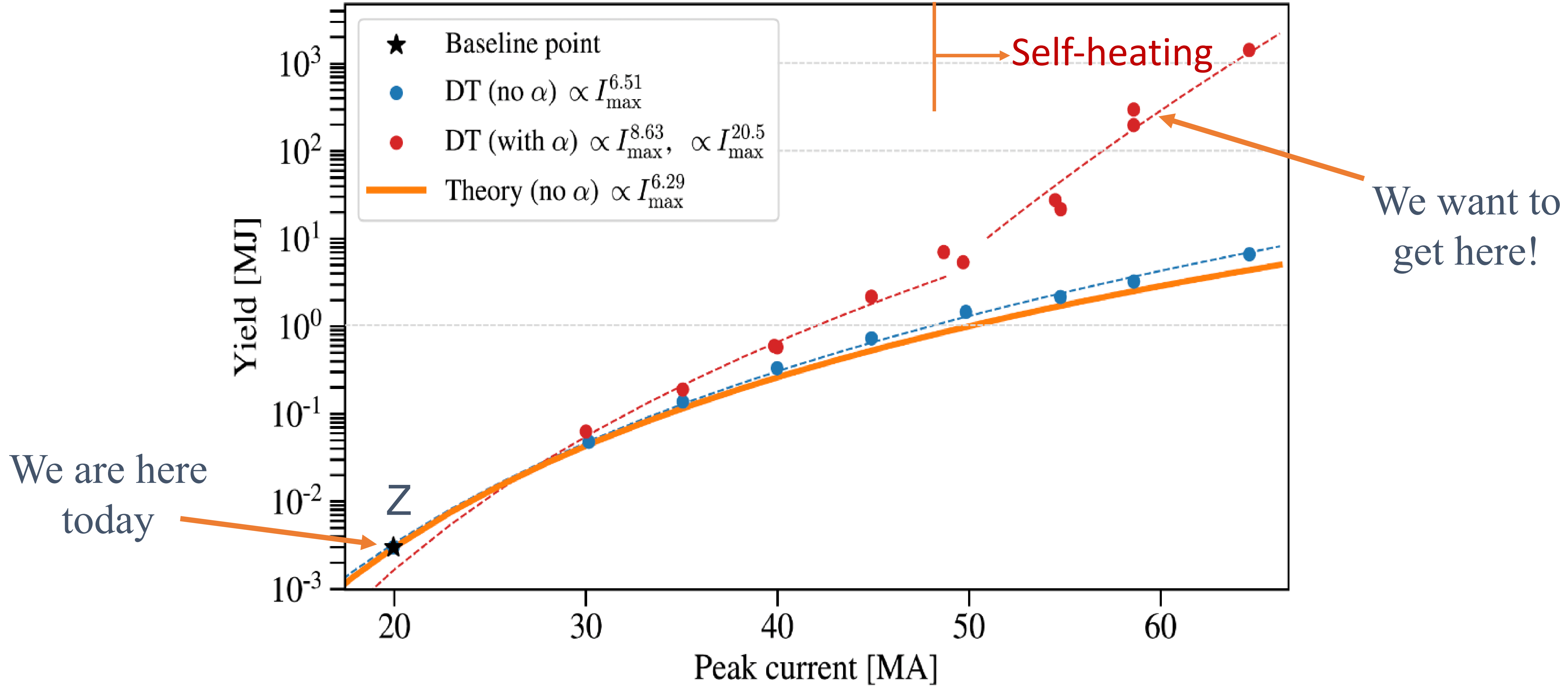
Stagnation
- Several keV temperatures
- Several kT B-field to trap charged fusion products

Combining magnetic fields with inertial confinement fusion can relax the extreme velocity and density requirements to reach fusion conditions!



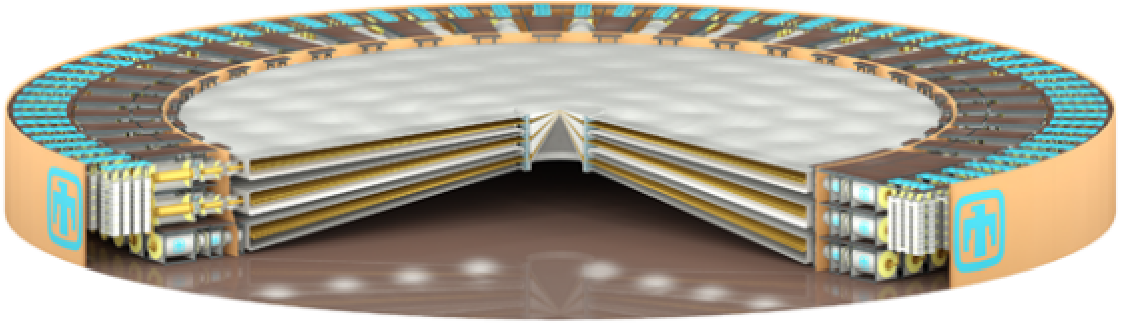


We are keenly interested in validating paths to ~100 MJ yields on future facilities with magnetic direct drive fusion targets



Sandia is working with the NNSA on a Next Generation Pulsed Power (NGPP) project

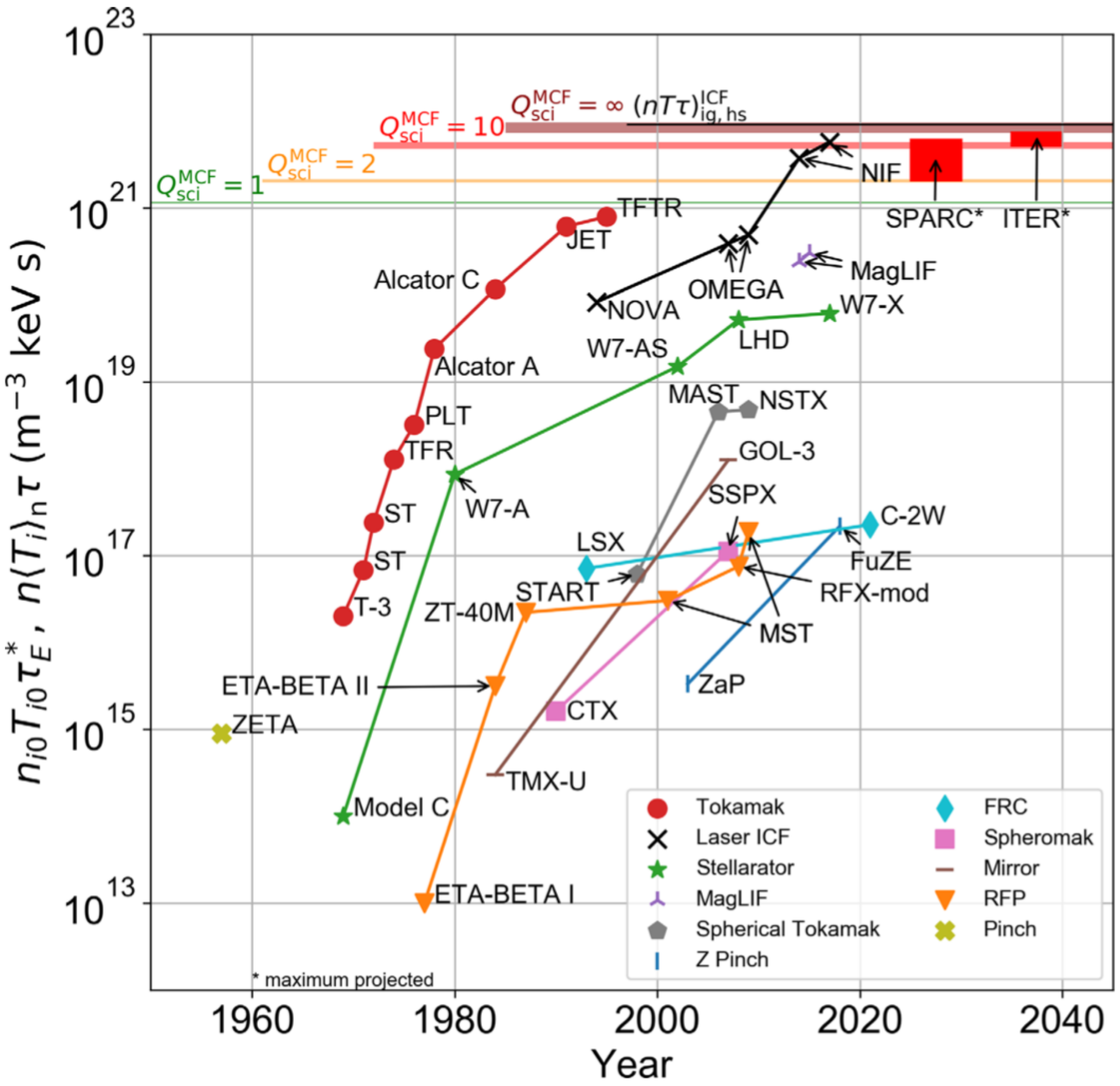
One example concept that would deliver 50-70 MA of electrical current depending on target



Parameter	Z	Ex. NGPP Option
Diameter	108’	300’
Marxes	36 @ 600 kJ (22 MJ)	75 @ 2400 kJ (180 MJ)
Capacitors	2,160 @ 2.65 μF	13,500 @ 2.95 μF
Power at Stack	85 TW	602 TW
Forward Energy at Stack	6 MJ (short pulse)	54 MJ (short pulse)
Energy to target	1-2 MJ	9-18 MJ

There has been tremendous progress in fusion research worldwide and many orders of magnitude improvement has been realized. What does the future hold?

Fusion “triple product”, a parameter that combines the Lawson criterion and the fusion temperature requirements



Plot from Wurzel & Hsu, “Progress toward fusion energy breakeven and gain as measured against the Lawson criterion”, Phys. Plasmas (June 2022).

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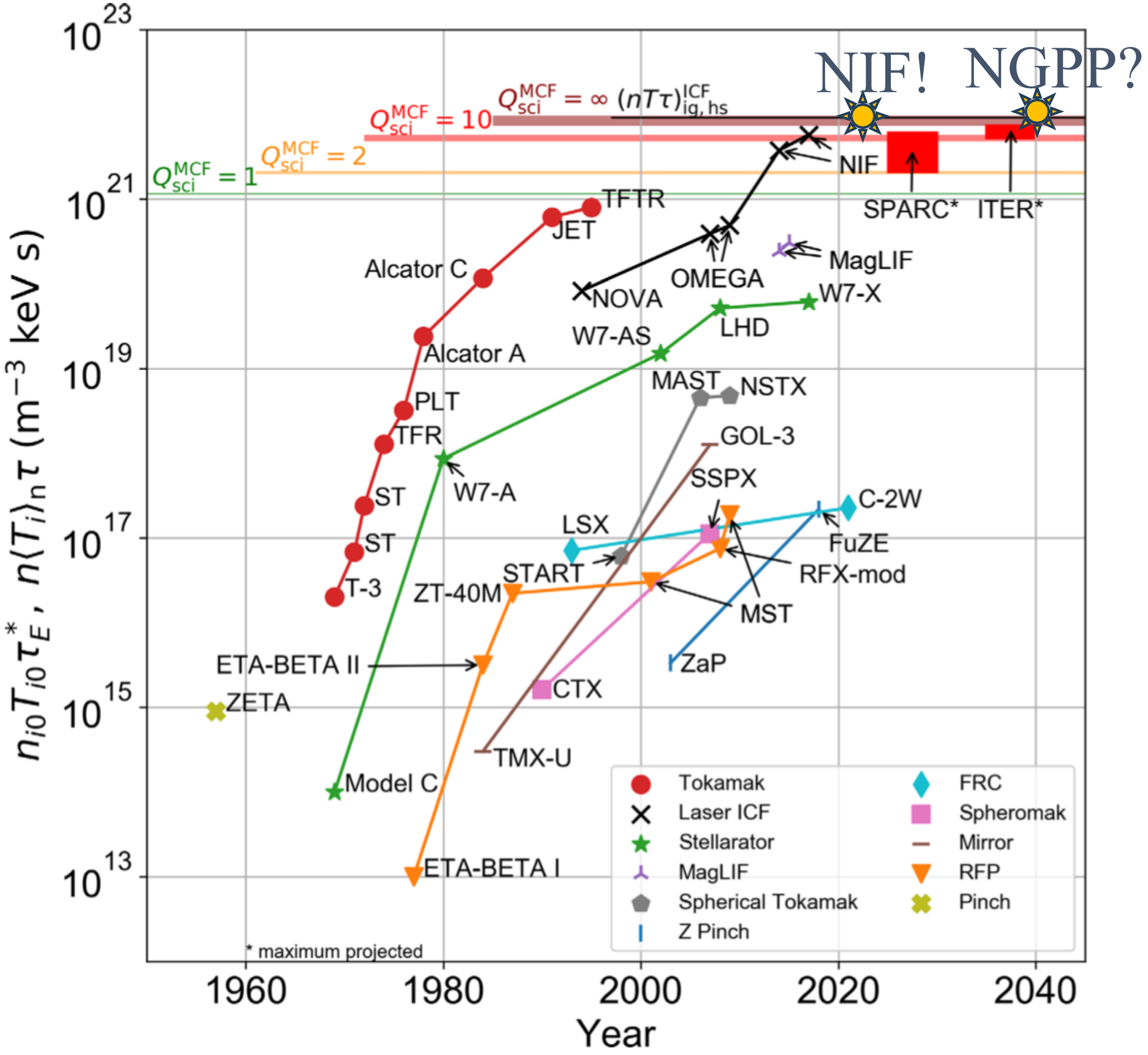
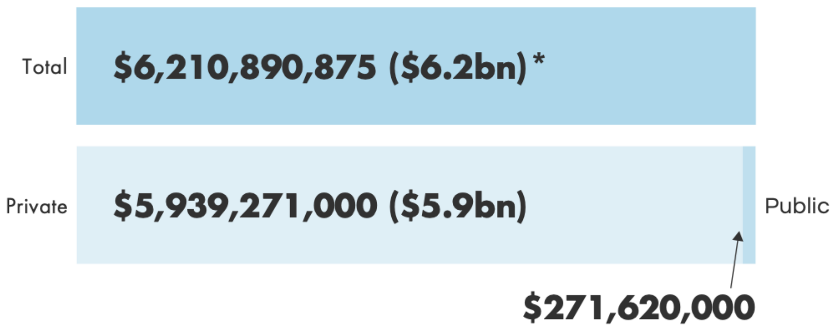


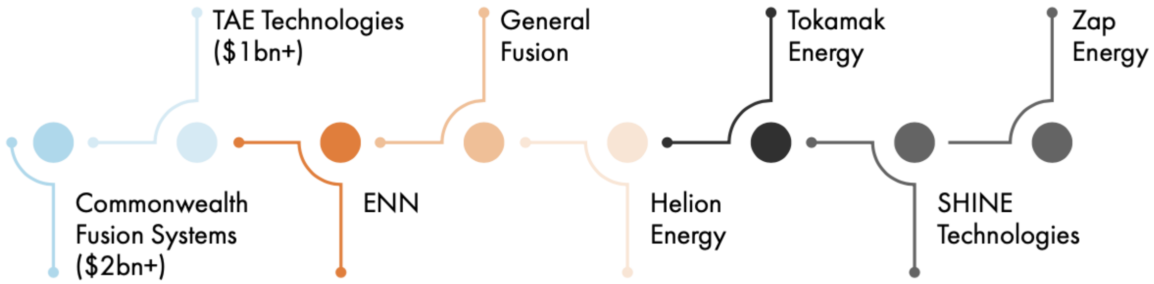
Plot from Wurzel & Hsu, "Progress toward fusion energy breakeven and gain as measured against the Lawson criterion", Phys. Plasmas (June 2022).

According to the Fusion Industry Association, there are at least 43 fusion energy companies worldwide and $6.2B of investment to date. Lots of ideas out there!

1. Funding for fusion companies



4. Companies with $200m investment or more



5. Location

By primary HQ

Have you had your fill of Inertial Confinement Fusion yet?

Questions?