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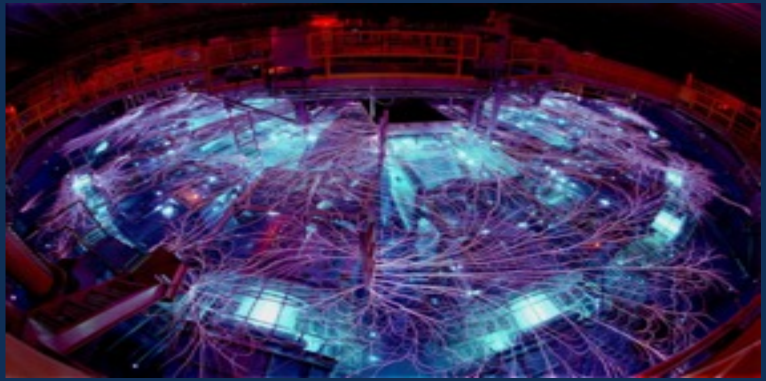

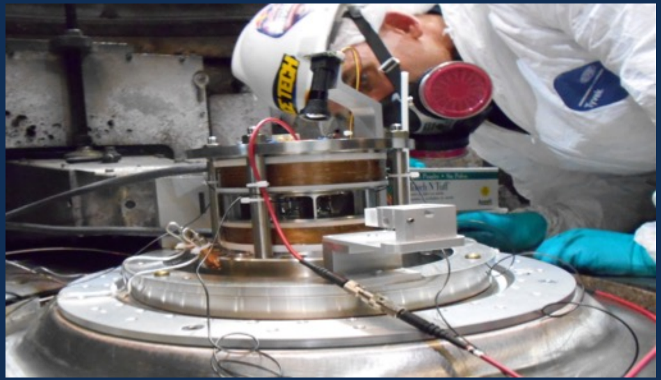

Progress in the Quest for Fusion in the Laboratory

Kyle Peterson

Manager, Radiation & Inertial Confinement Fusion Target Design

North Park University, October 27, 2017

U.S. DEPARTMENT OF ENERGY NNSA

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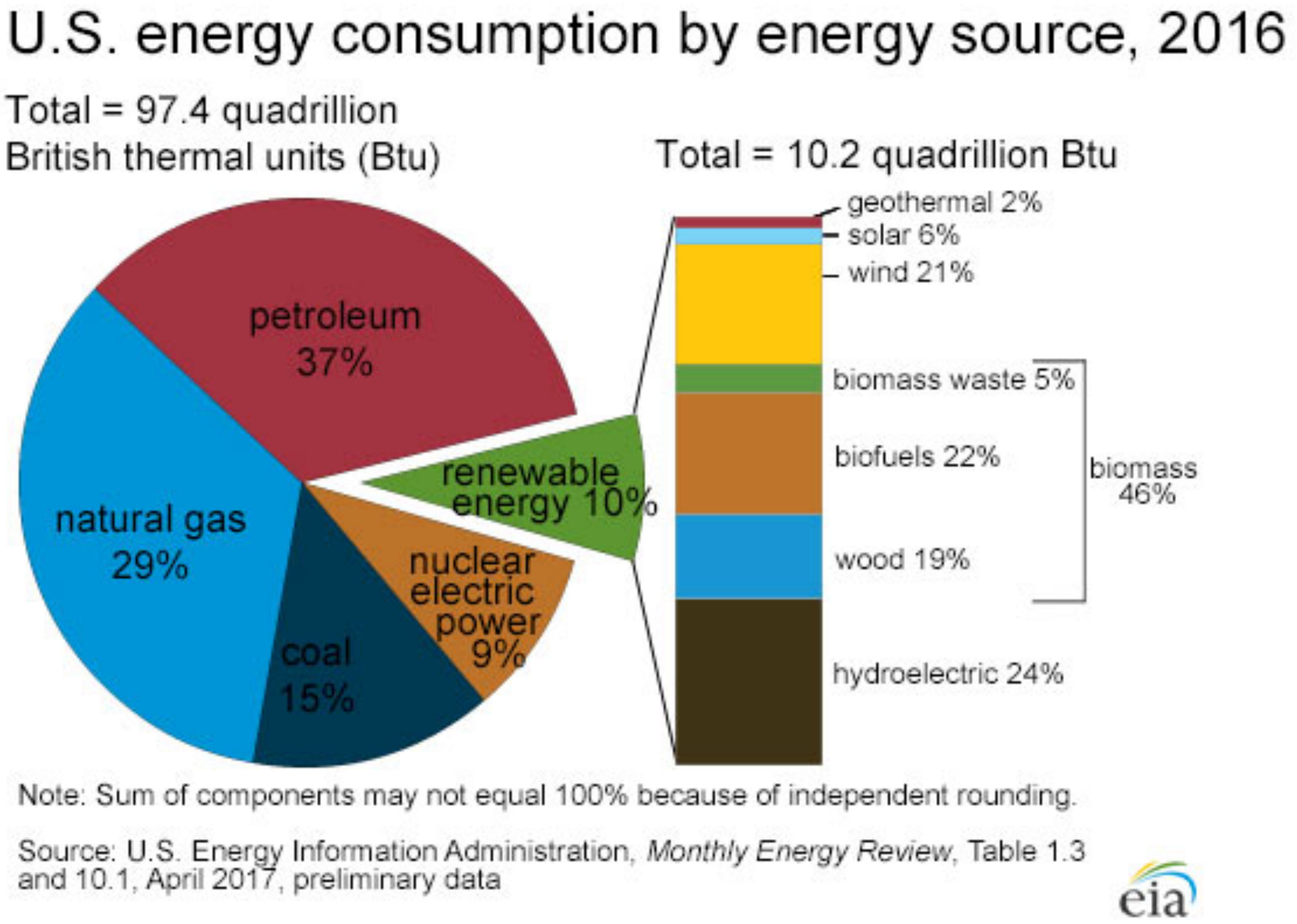
Outline

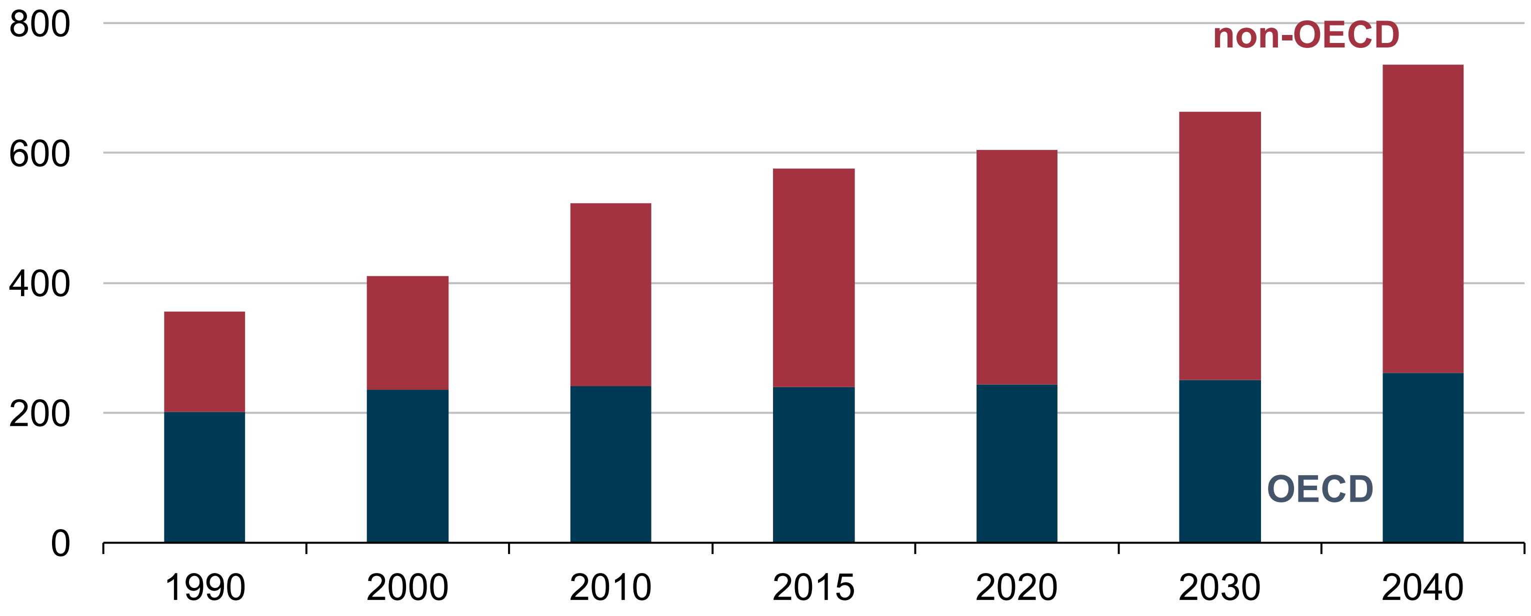
- Need for Nuclear Fusion
- Nuclear Fusion 101
- Approaches to Creating Fusion in the Laboratory
- Difficulties and Challenges
- Exciting Progress
- The Future of Inertial Confinement Fusion Research

Currently more than 80% of our energy comes from fossil fuels



World-wide energy consumption is predicted to rise 28% by 2040, mostly driven by China and India

Estimated World-wide energy consumption based on “reference” case (IEO2017)



Assumes economic development at similar rates and current energy conservation efforts and technological developments will continue to reduce average persons energy consumption

Thermonuclear fusion powers the galaxy. Can we use it to power earth?

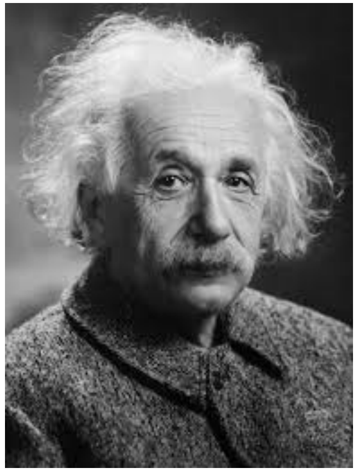
A galaxy of controlled fusion reactors

- Einstein's famous equation, **$E=mc^2$**, equates mass and energy

- Example: 1 gram raisin converted completely into energy *

$$\text{Energy} = (1\text{ gram}) \times (c^2)$$
$$= (0.001\text{ kg}) \times (3 \times 10^8\ \text{m/s})^2$$
$$= 9 \times 10^{13}\text{ joules}$$

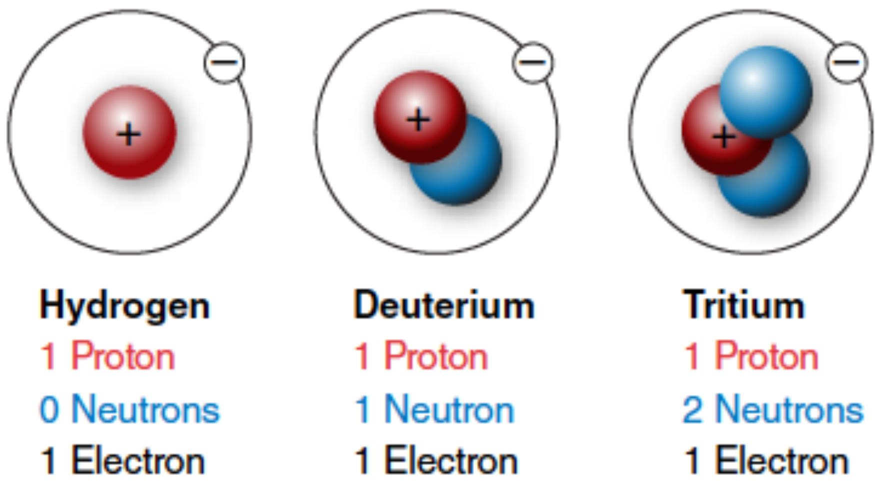
$$= 10{,}000\text{ tons equivalent of TNT!!!}$$



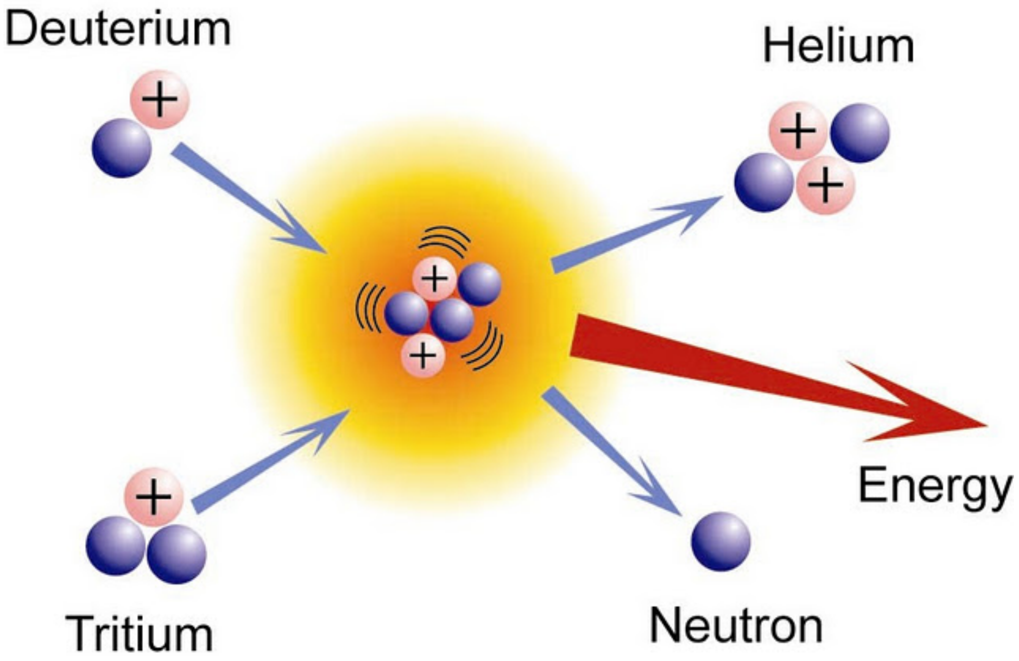
* Complete mass to energy conversion can only be achieved in matter-antimatter reactions

Nuclear fusion turns mass into energy by fusing two light elements together into a heavier one

Hydrogen Isotopes



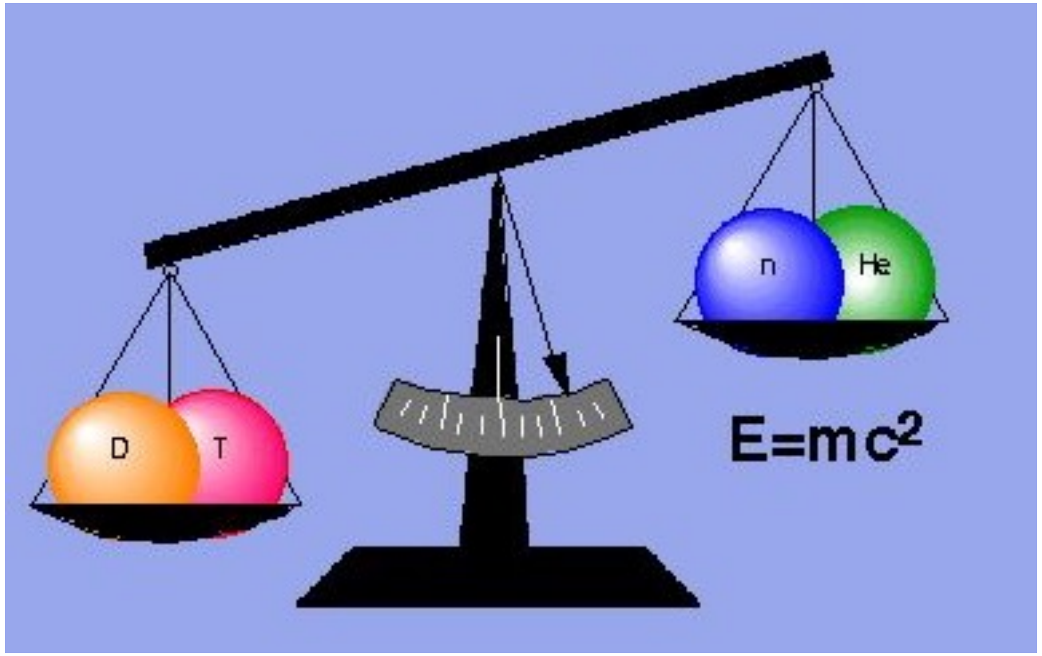
Fusion of DT



- **Virtually unlimited energy source!** Seawater contains 40 grams of deuterium and 0.1 grams of lithium per ton (lithium + neutron used to produce tritium)
- **Clean energy source**, carbon free

Nuclear fusion converts only a tiny portion of the mass into energy, but even that is significant!

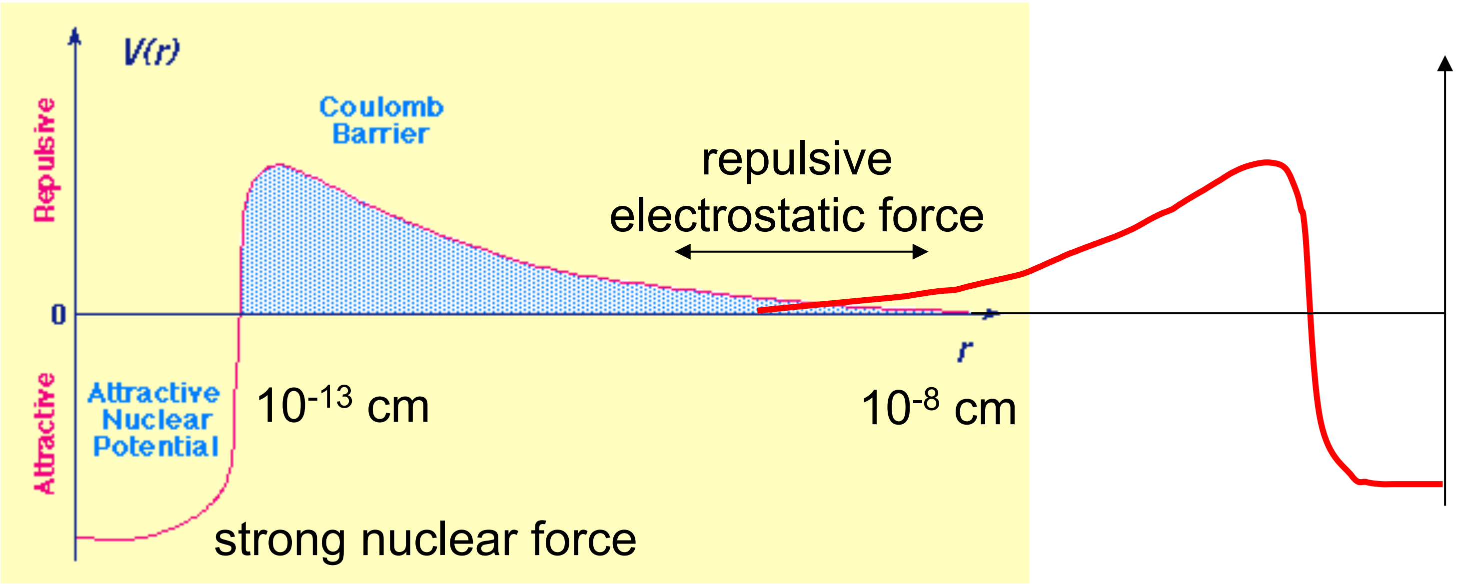
(0.04% mass converted into energy)

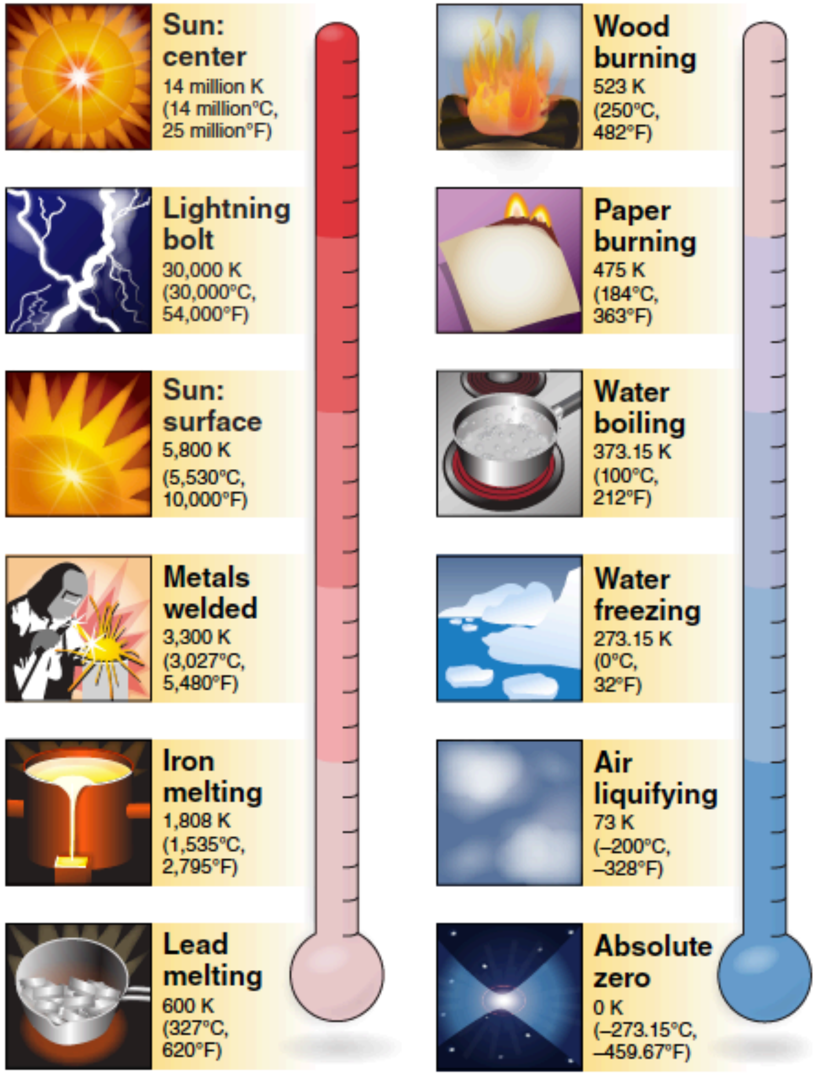


Fusion energy released from 1 gram of DT fuel is equivalent to the energy contained in 2400 gallons of oil !

In order for deuterium and tritium to fuse, a temperature of more than a 10 million degrees is required !

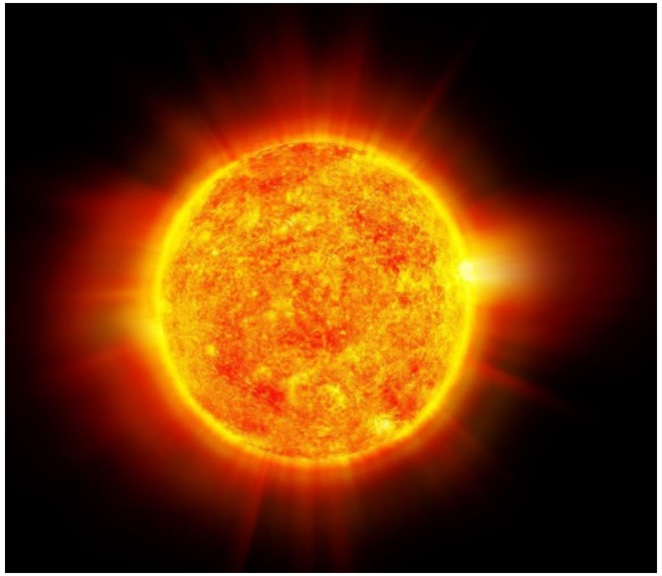
Fusion requires high particle energies to overcome the strong repulsion between the positive charge of the nucleus





But there is (at least) one other significant challenge… confinement!

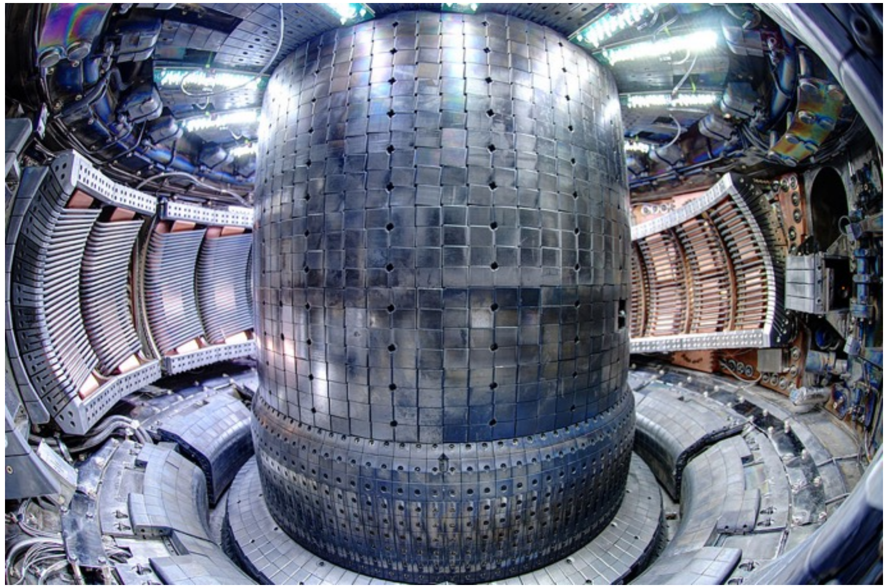
Gravitational



steady-state
controlled fusion reactor

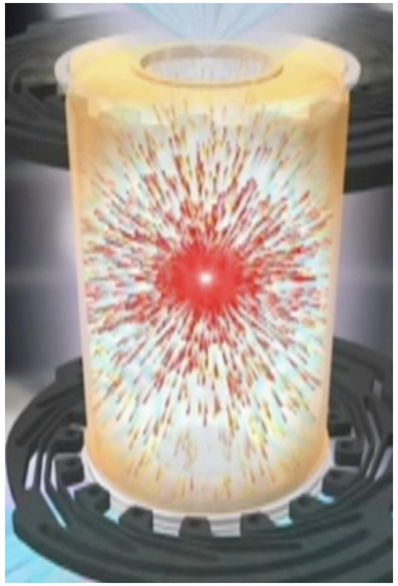
$\tau \sim \infty$

Magnetic



- magnetic confinement studied since 1950s
- Currently, the flagship project is ITER
- Ideally steady-state , τ ~ 300-500 s

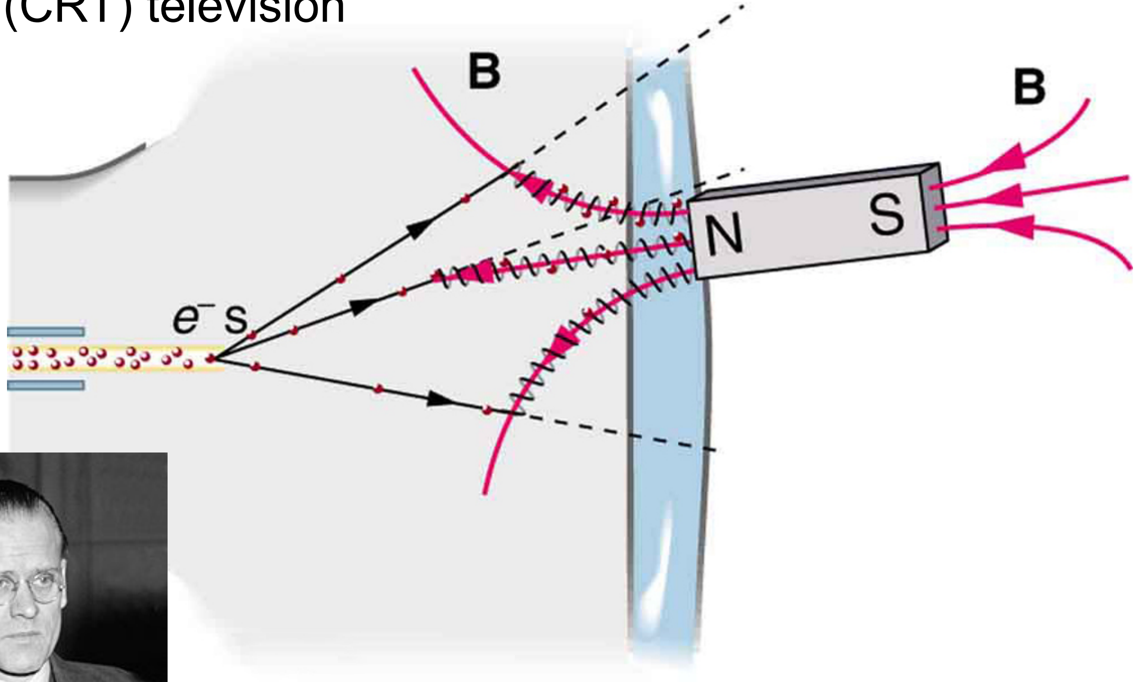
Inertial



- studied over 50 years with lasers
- Currently, the flagship is NIF
- Pulsed operation, τ ~ 10 ps

Since plasmas contain charged particles, magnetic fields can be used to confine them

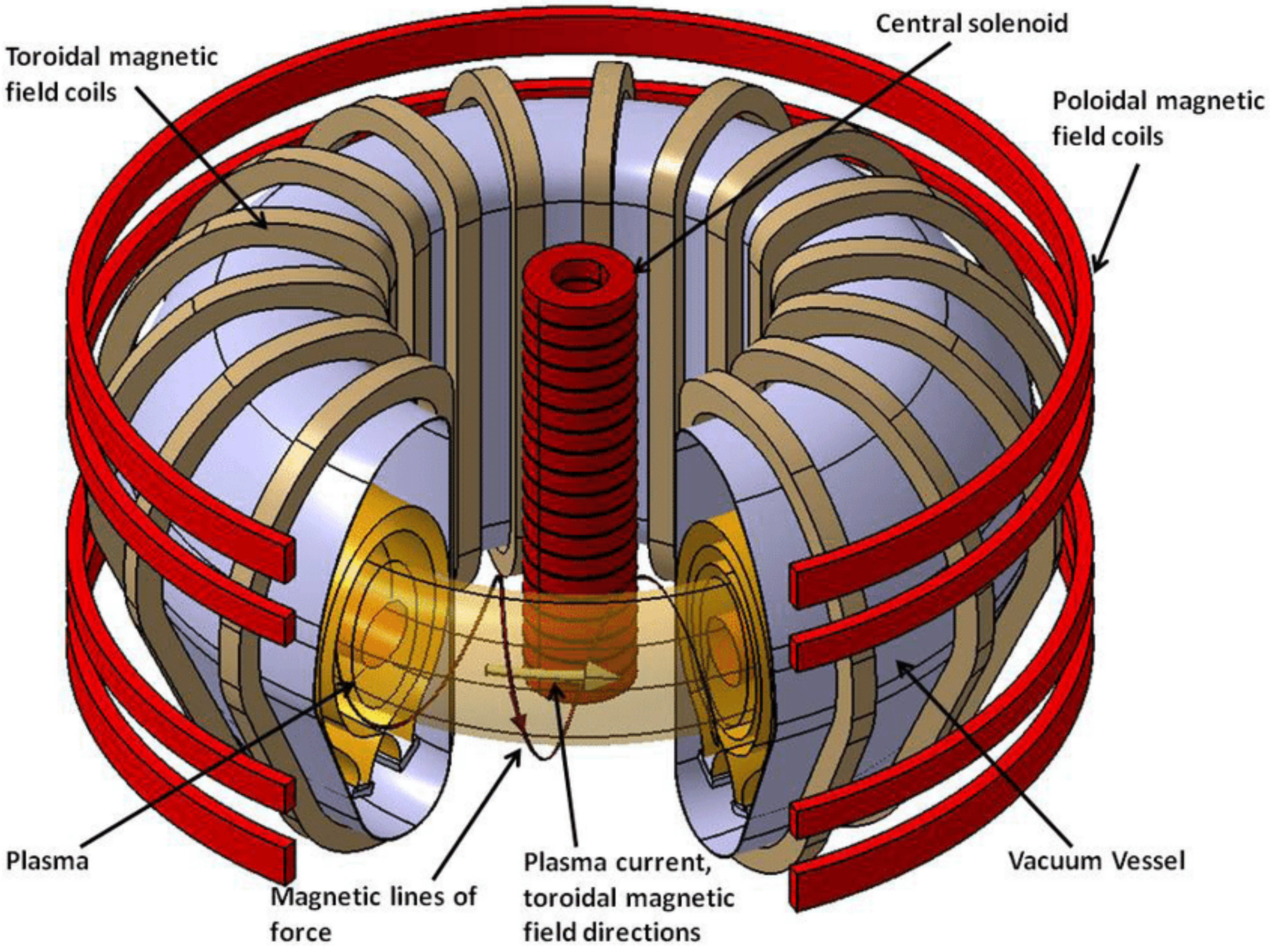
Example: Permanent magnetic redirecting electron beam in an old cathode ray tube (CRT) television



This is way more fun than watching a show on a LCD television!

Philo T. Farnsworth invented the television in high school! He also went onto develop a nuclear fusion device called the Farnsworth–Hirsch fusor

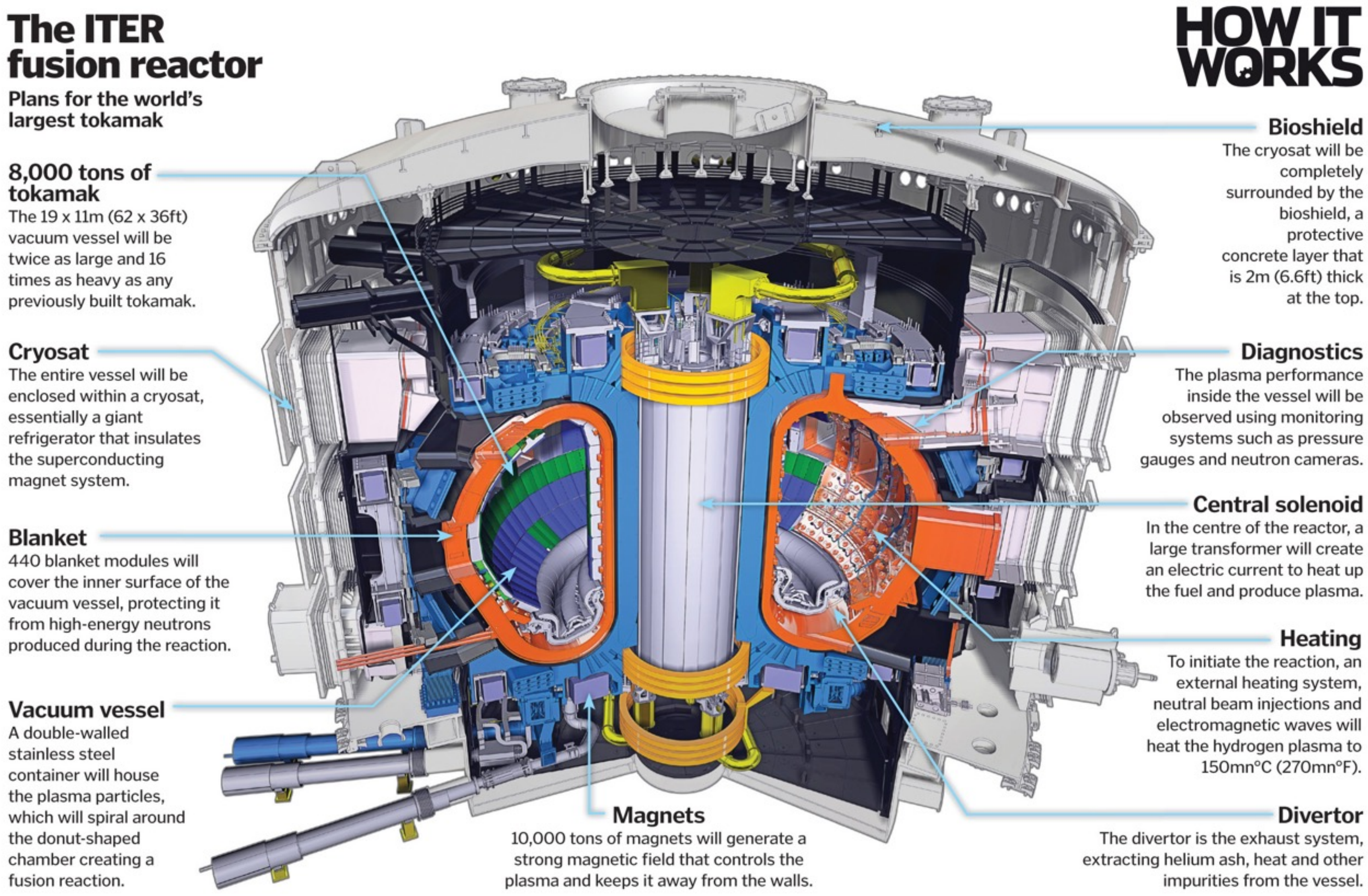
Magnetically confined fusion schemes use complex arrangements of magnetic fields



- Plasma confined to toroid and away from walls
- Low density plasmas confined for relatively long periods of time (τ ~ 300-500 s)
- Large research effort world-wide

<u>Heating Techniques</u>
Ohmic
EM waves
Neutral beams

Current estimate are that ITER will cost ~ $22 billion to complete and won't have a DT plasma until 2035



ITER fusion reactor has been designed to produce 500 megawatts of output power for around twenty minutes while needing 50 megawatts to operate

The internal combustion engine is an analogy for Inertial Confinement Fusion (ICF)

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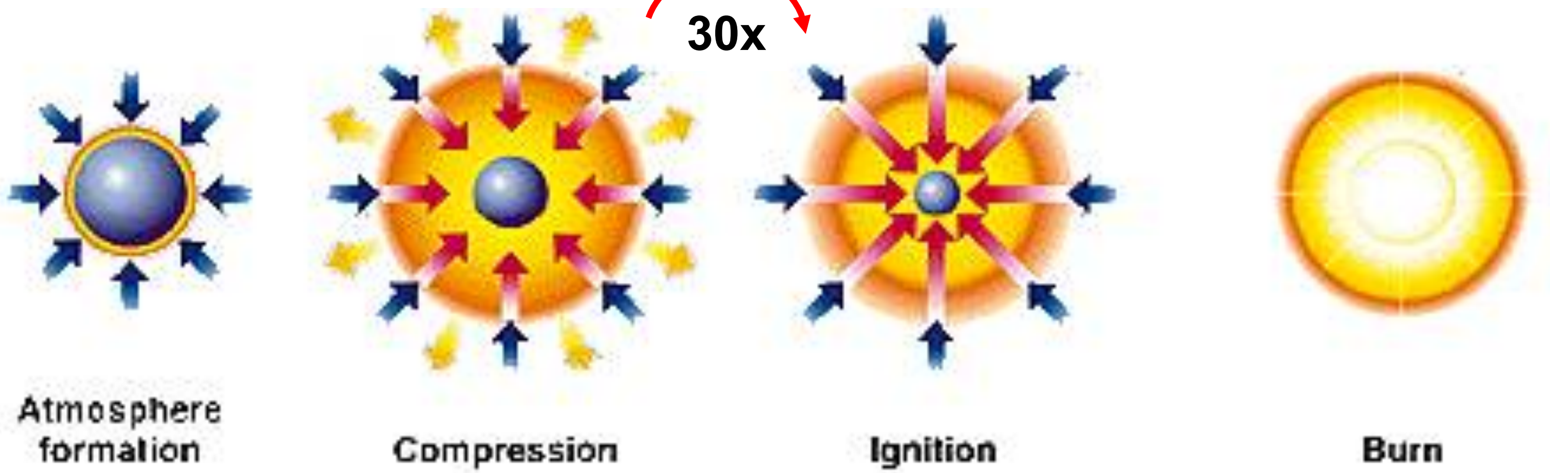
30x

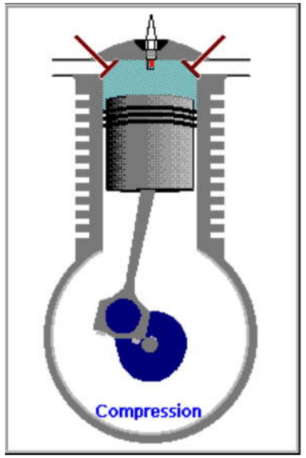


Fuel

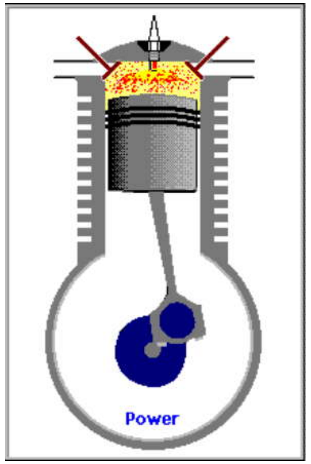
Hot spot

Nuclear Fusion

“Just squeeze real hard….. and stand back”

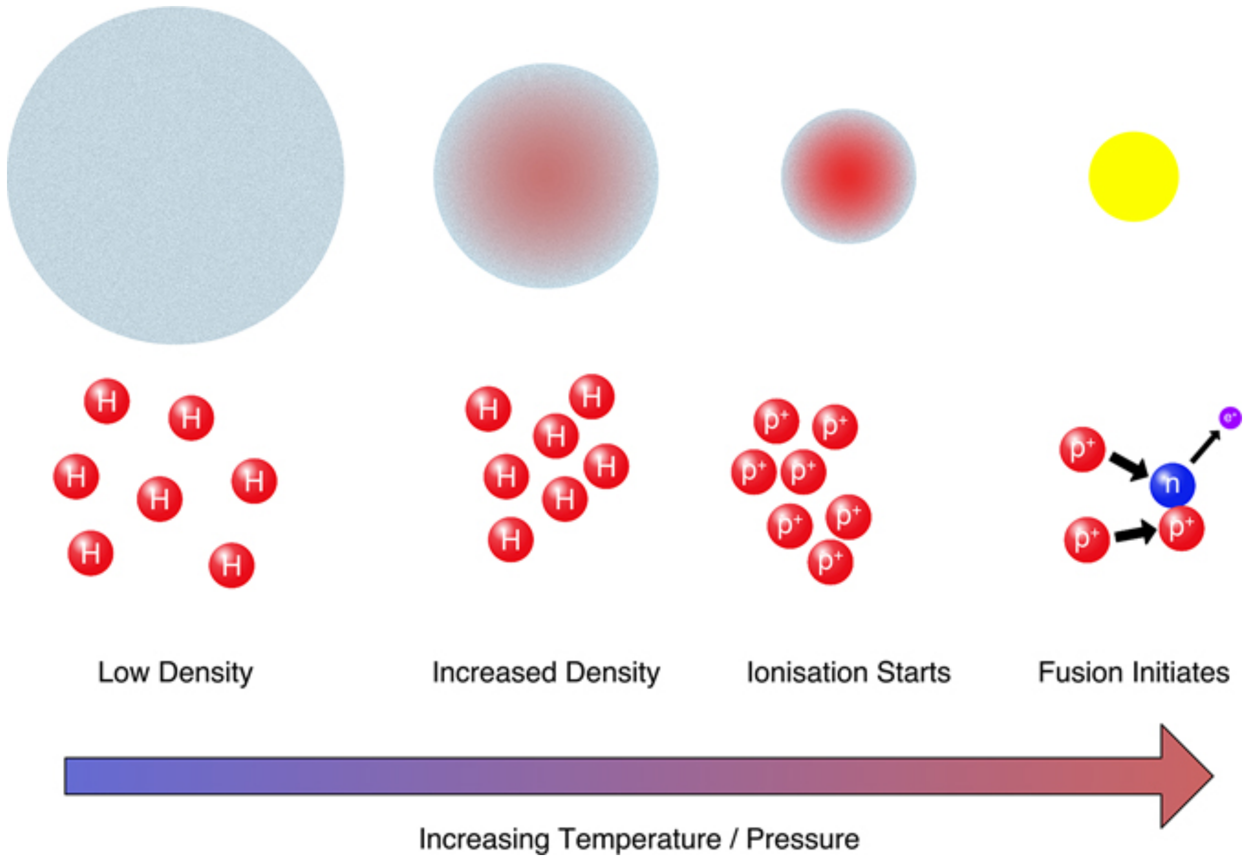


Fuel compression



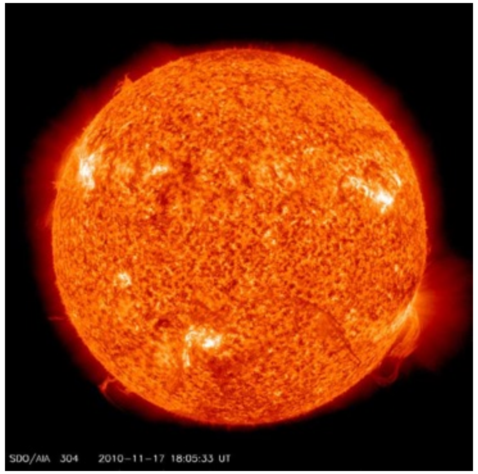
Spark ignition and chemical combustion burn

Inertial confinement fusion requires high fuel densities and enormous pressures



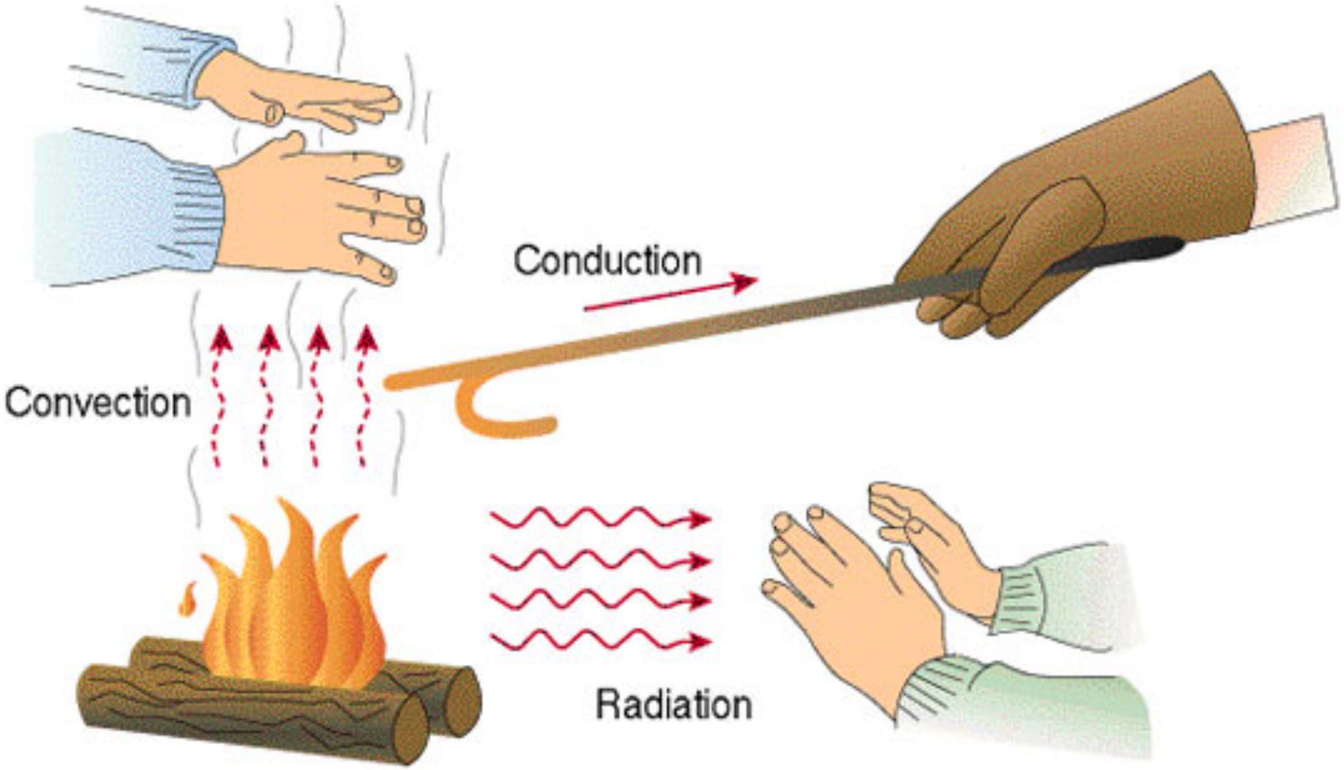
Amount of compression required depends on the amount of driver energy available - tradeoff between driver cost and difficulty

Pressure of Willis (Sears) tower upside down on antenna tip (1 cm^2) is **20 Mbar**

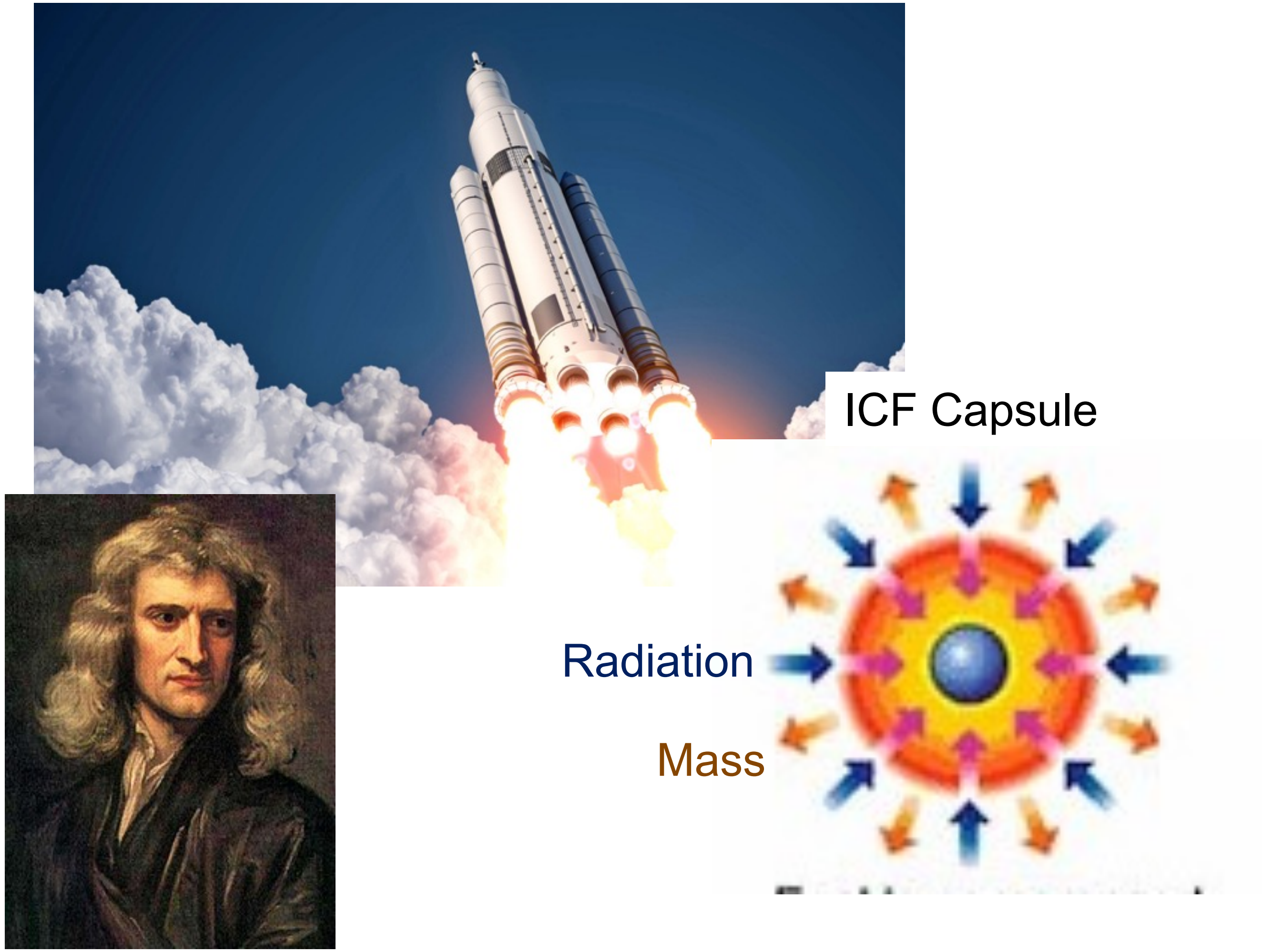


- **400 Gbar** pressure required for ICF
- Center of sun is about 250 Gbar!

In order to heat fuel to fusion temperatures, the fuel must be squeezed faster (heated) than heat conducts or radiates away



In order to achieve the necessary fusion temperature, we use rocket propulsion to compress the fuel with high velocities

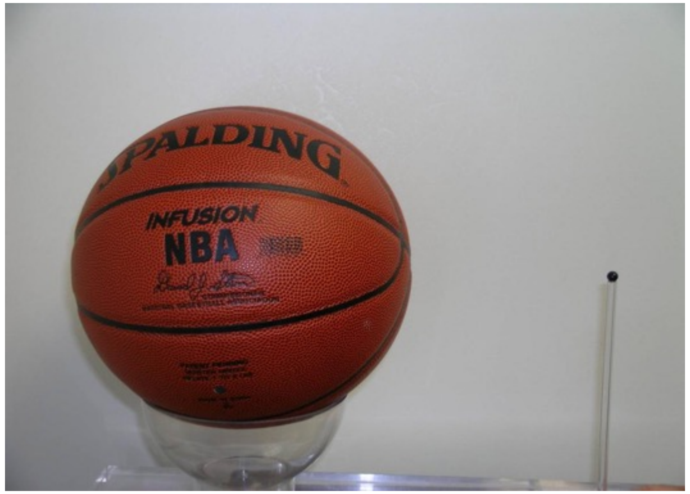


- **Newton's Third Law:** "every action has an equal and opposite reaction".
  - Burning fuel expels mass which pushes the rocket forward
  - In ICF, ablation of the outer shell mass is used to implode fuel

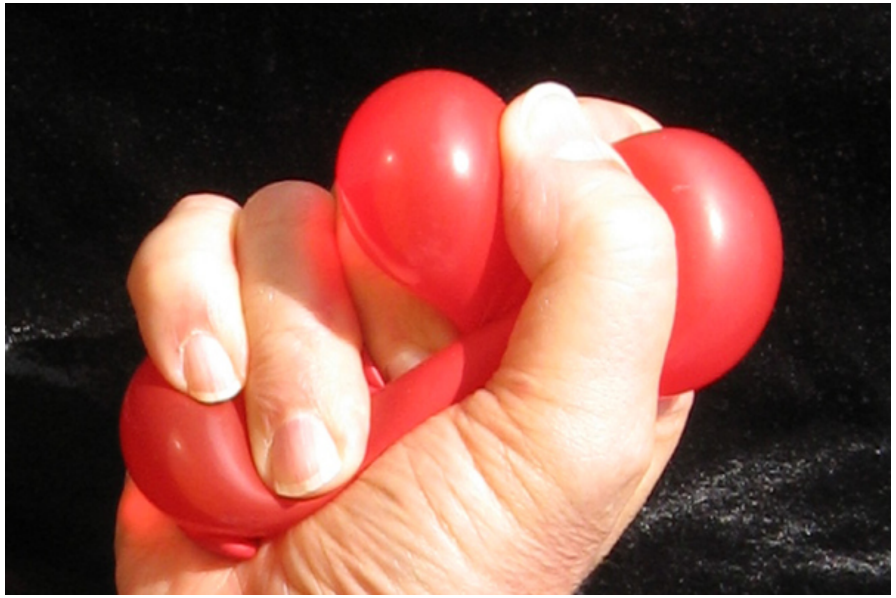
- Speed of rocket escaping the Earth's gravity: **about 8 km/s** (5 miles/second)
- ICF requires **350-400 km/s** !

ICF targets must be extremely smooth and compressed with exquisite control of symmetry

ICF Capsule



Balloon squeezed non-uniformly does not increase internal pressure!



- 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

Small scale instabilities increase with amount of convergence and ultimately limit the achievable pressure

- Key challenge for all Fusion concepts
- Rayleigh-Taylor (RT) instabilities occur along accelerating interfaces

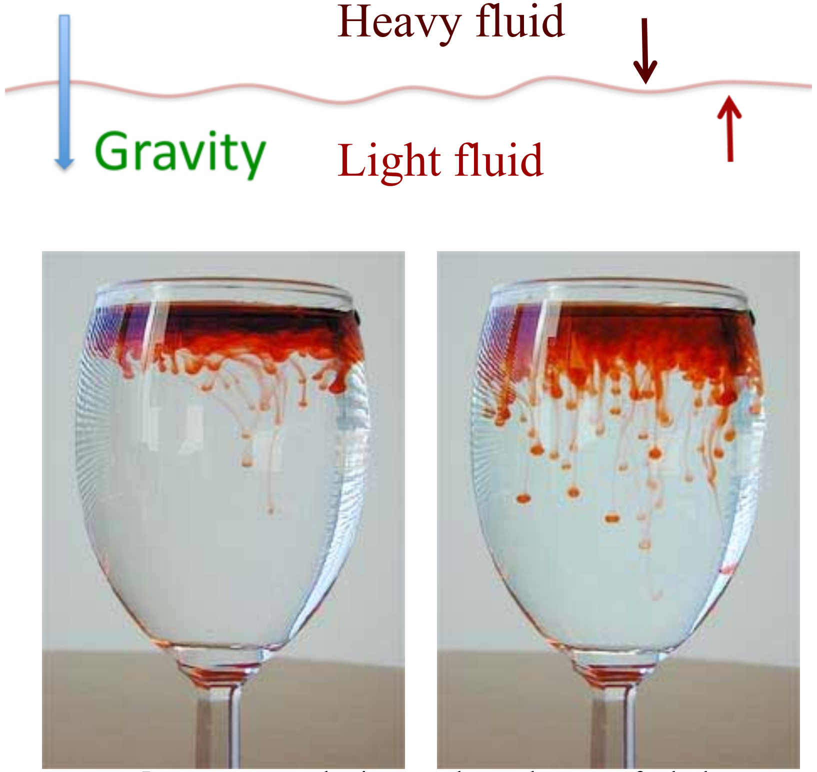


Image sources: physicscentral.com, large.stanford.edu

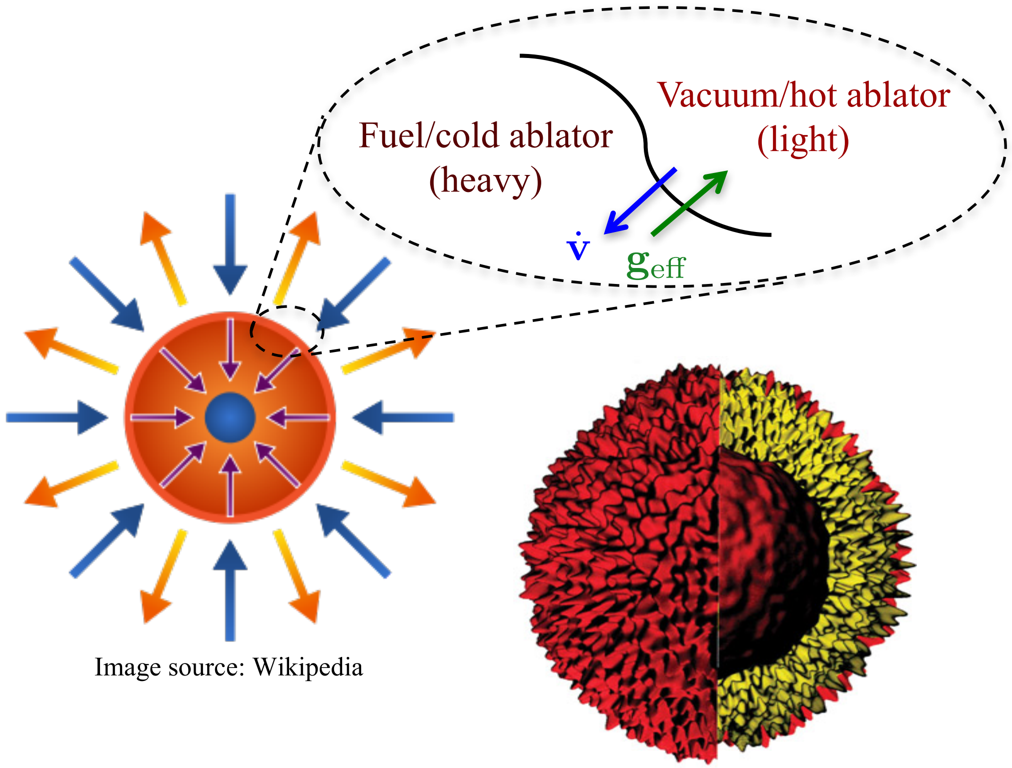


Image source: Wikipedia

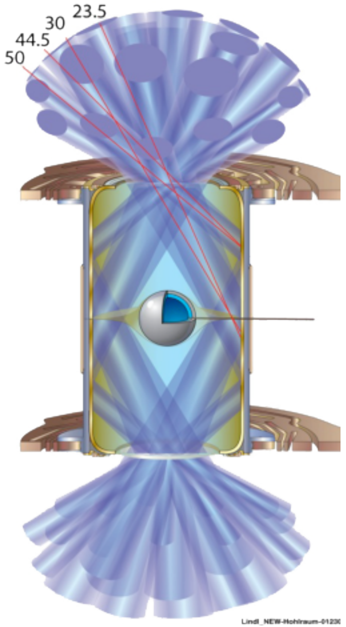
Image source: llnl.gov

Despite these challenges, ICF has been demonstrated to work

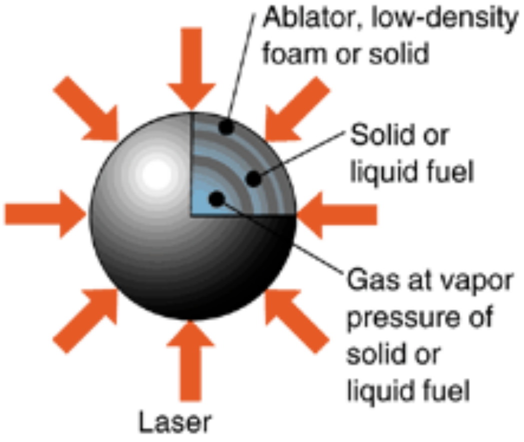
- The US Centurion/Halite program “put to rest fundamental questions about the basic feasibility of achieving high gain”

The US ICF program is studying three main approaches

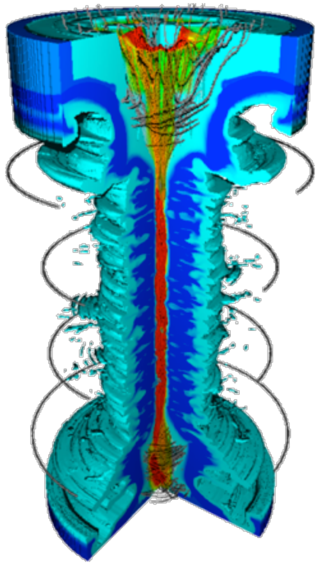
Laser Indirect Drive (LLNL)



Laser Direct Drive (LLE)



Magnetic Direct Drive (Sandia)



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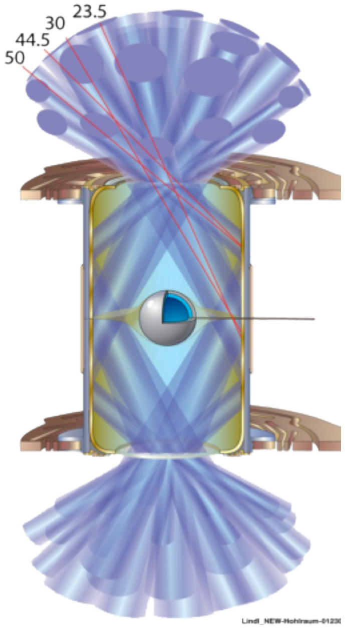
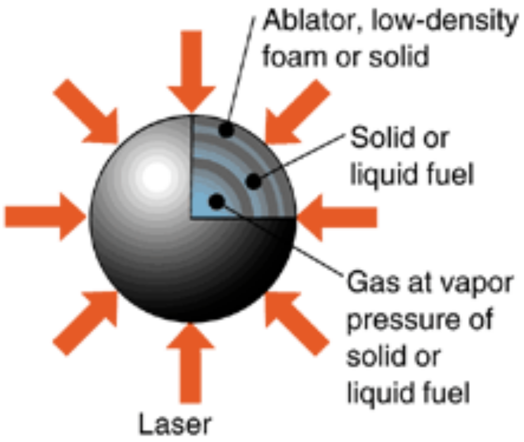
The US ICF program is studying three main approaches

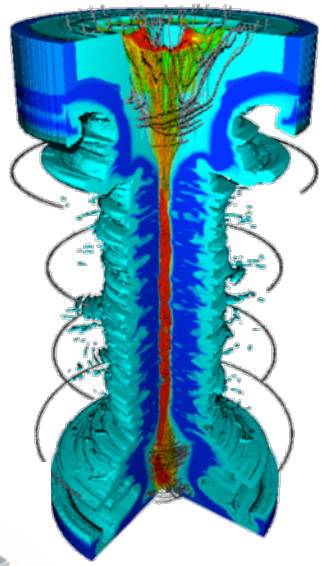
Laser Indirect Drive (LLNL)



Laser Direct Drive (LLE)



Magnetic Direct Drive (Sandia)



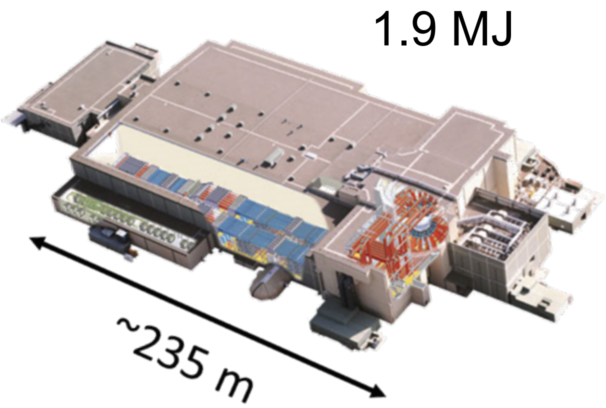
GENERAL ATOMICS UR LLE Los Alamos NATIONAL LABORATORY EST.1943 MIT PPPL National Security Technologies LLC Vision • Service • Partnership Schafer

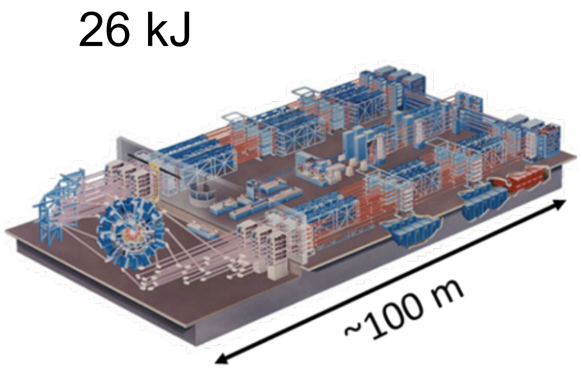
The US ICF program is studying three main approaches

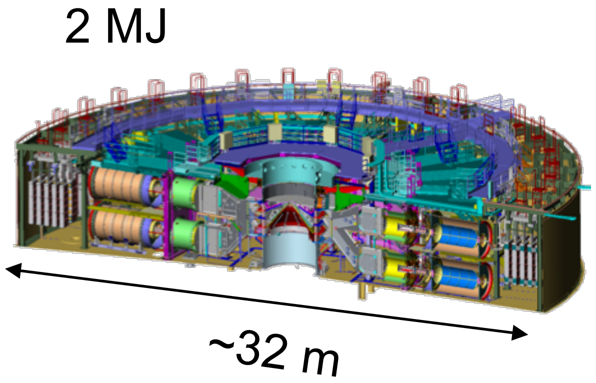
Laser Indirect Drive (LLNL)

Laser Direct Drive (LLE)

Magnetic Direct Drive (Sandia)





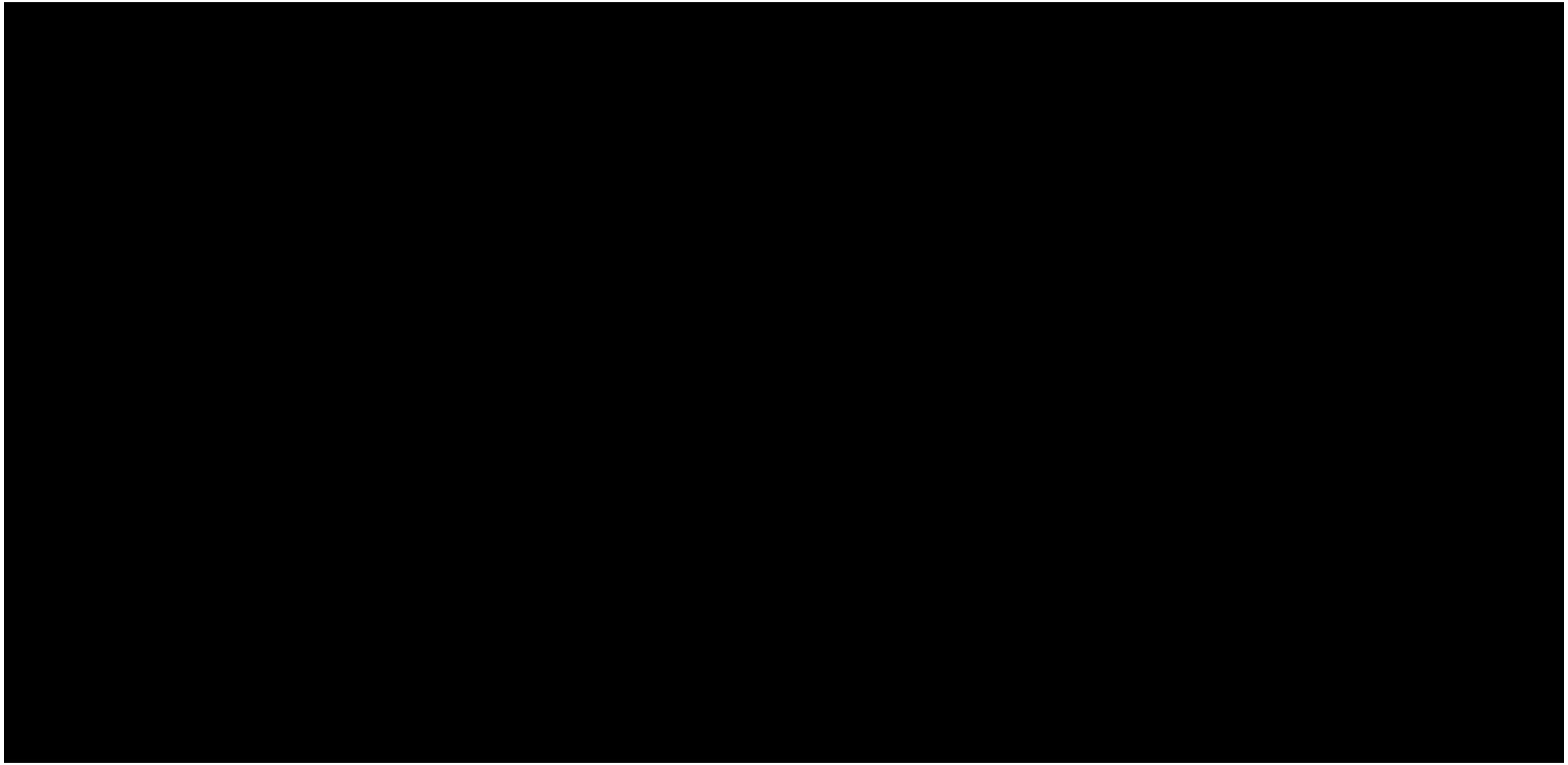


National Ignition Facility

Omega Facility

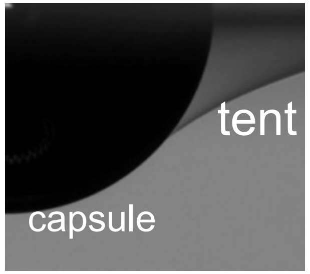
Z Facility

The National Ignition Facility (NIF), completed in 2010, was designed to achieve fusion ignition in the laboratory

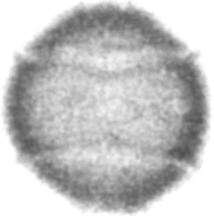


Why hasn’t NIF achieved ignition? Non-ideal target features and radiation symmetry have been difficult to control

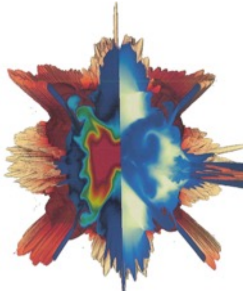
Capsule ‘Tent’

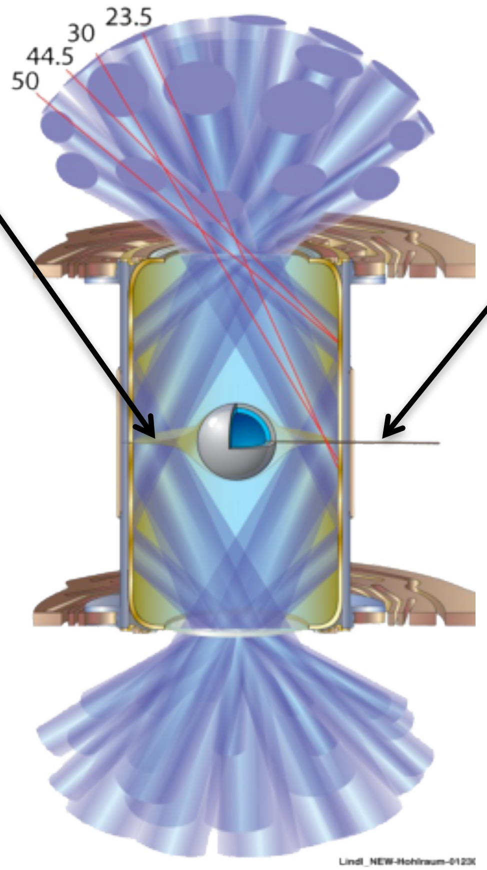


In-Flight Radiograph

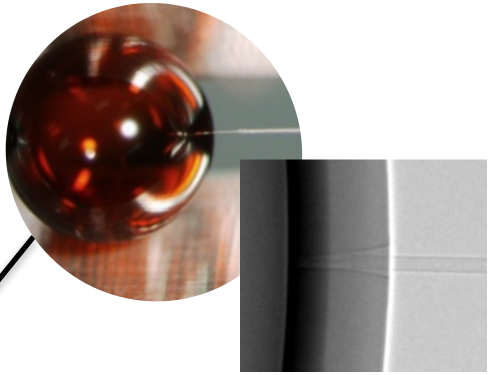


3-D Simulation

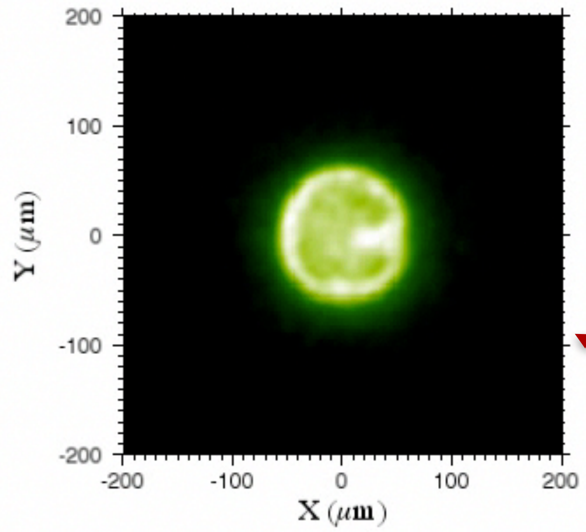




Fill Tube



X-ray Imaging

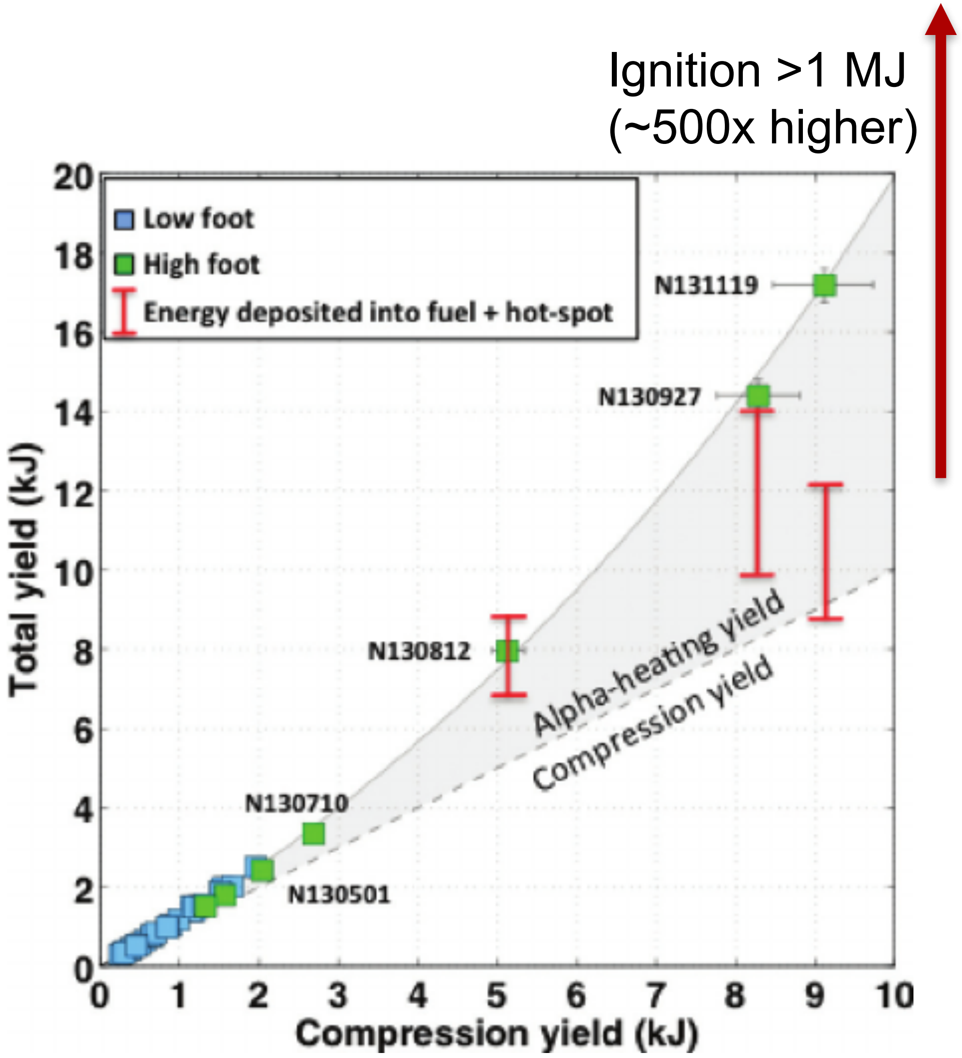


16 fps

20 billion fps

Although NIF has not yet obtained fusion ignition, it has demonstrated self heating of the fusion fuel!

Ignition >1 MJ
(~500x higher)

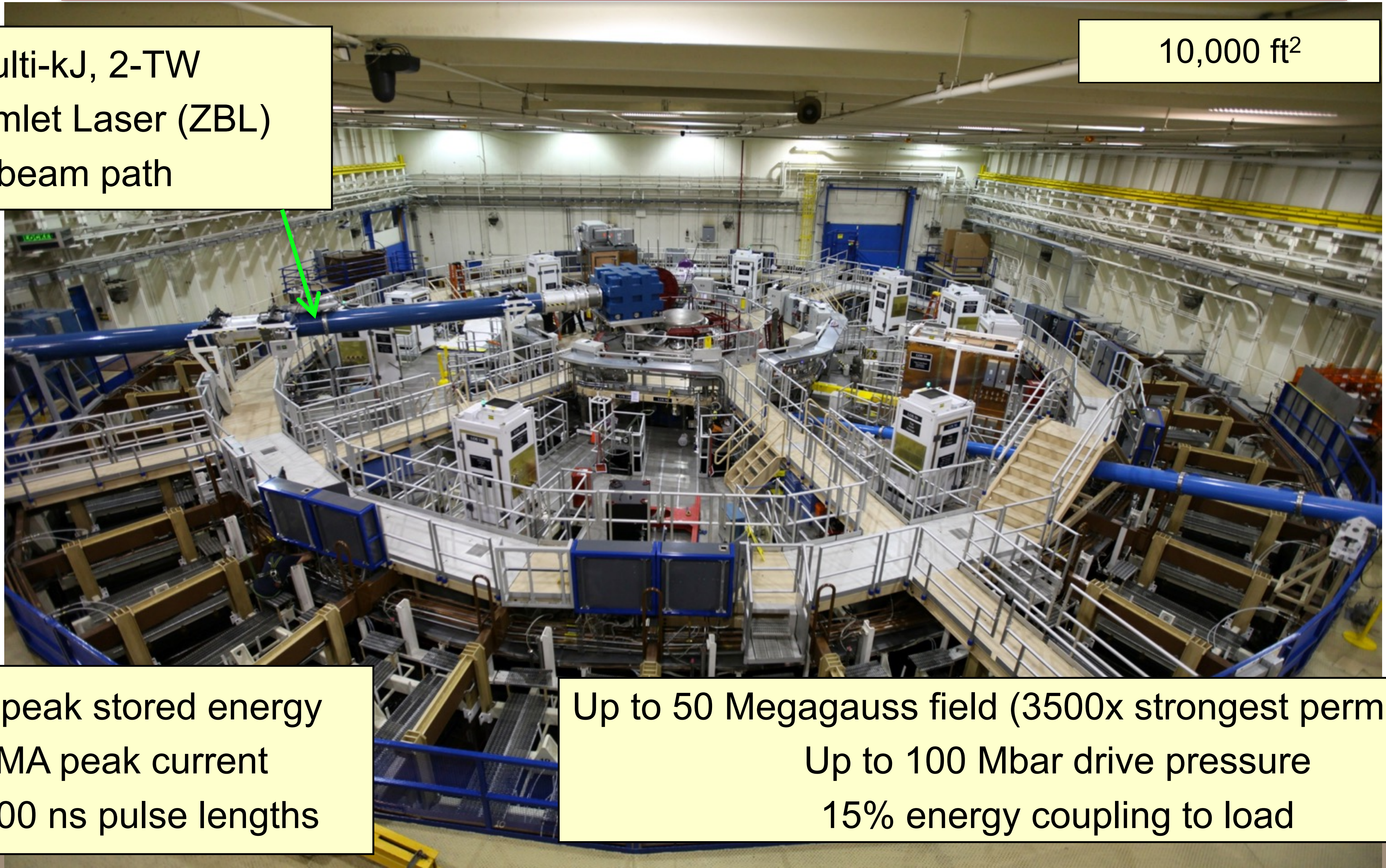


Analogy: NIF has produced a small fusion spark! However, the wood is still wet and still very difficult to ignite.

The Sandia Z pulsed power facility uses magnetic pressure to efficiently couple MJs of energy to "targets" at its center

Multi-kJ, 2-TW
Z-Beamlet Laser (ZBL)
beam path

10,000 ft^2

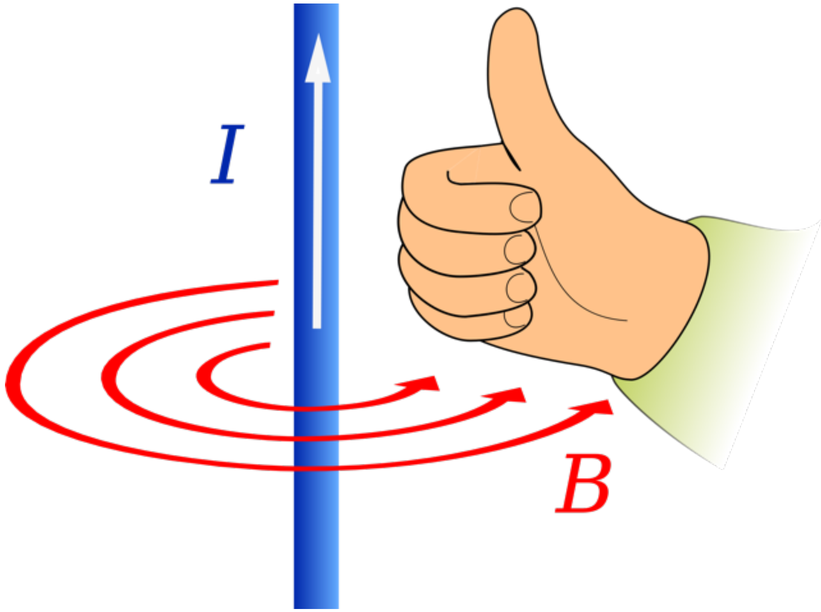


22 MJ peak stored energy
28 MA peak current
100–300 ns pulse lengths

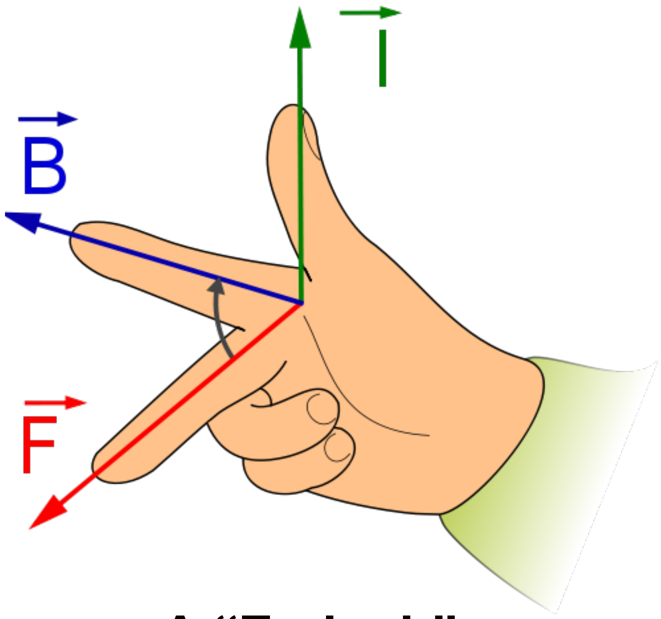
Up to 50 Megagauss field (3500x strongest perm. magnet)
Up to 100 Mbar drive pressure
15% energy coupling to load

Large currents create strong azimuthal magnetic fields, which results in a radially inward “JxB” force

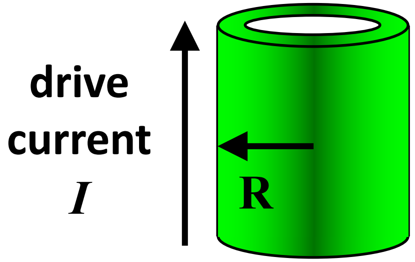
Current (I)



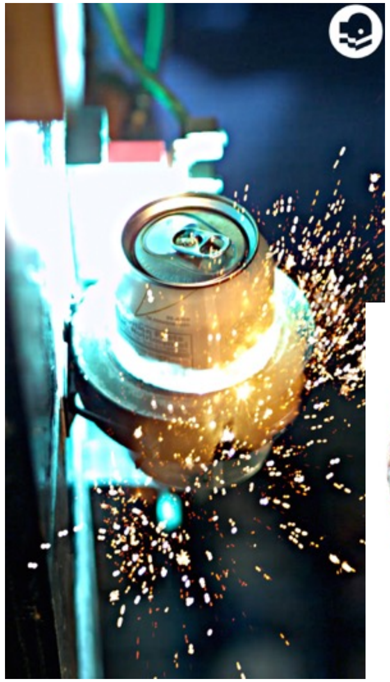
Magnetic Field (B)



A “Z-pinch”



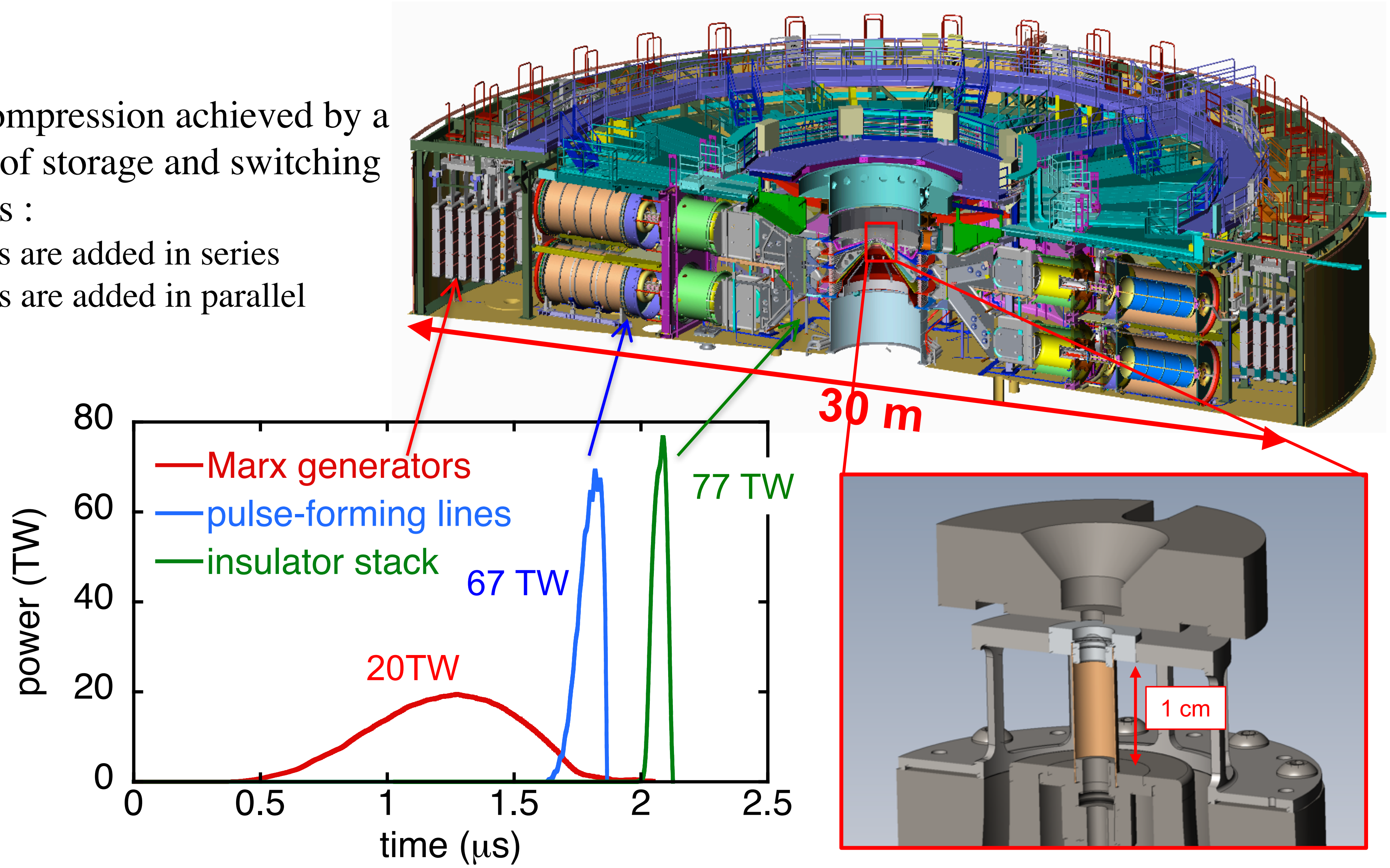
A “theta-pinch” can crusher



Pulsed-power is all about energy compression in both space and time

Energy compression achieved by a sequence of storage and switching techniques :

- Voltages are added in series
- Currents are added in parallel



For ~100 nanoseconds, Z generates more electrical power (~80 TW) than all the world’s power plants, combined.

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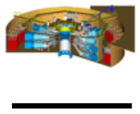
The total electrical-power-generating capacity installed worldwide is 4.7 TW:

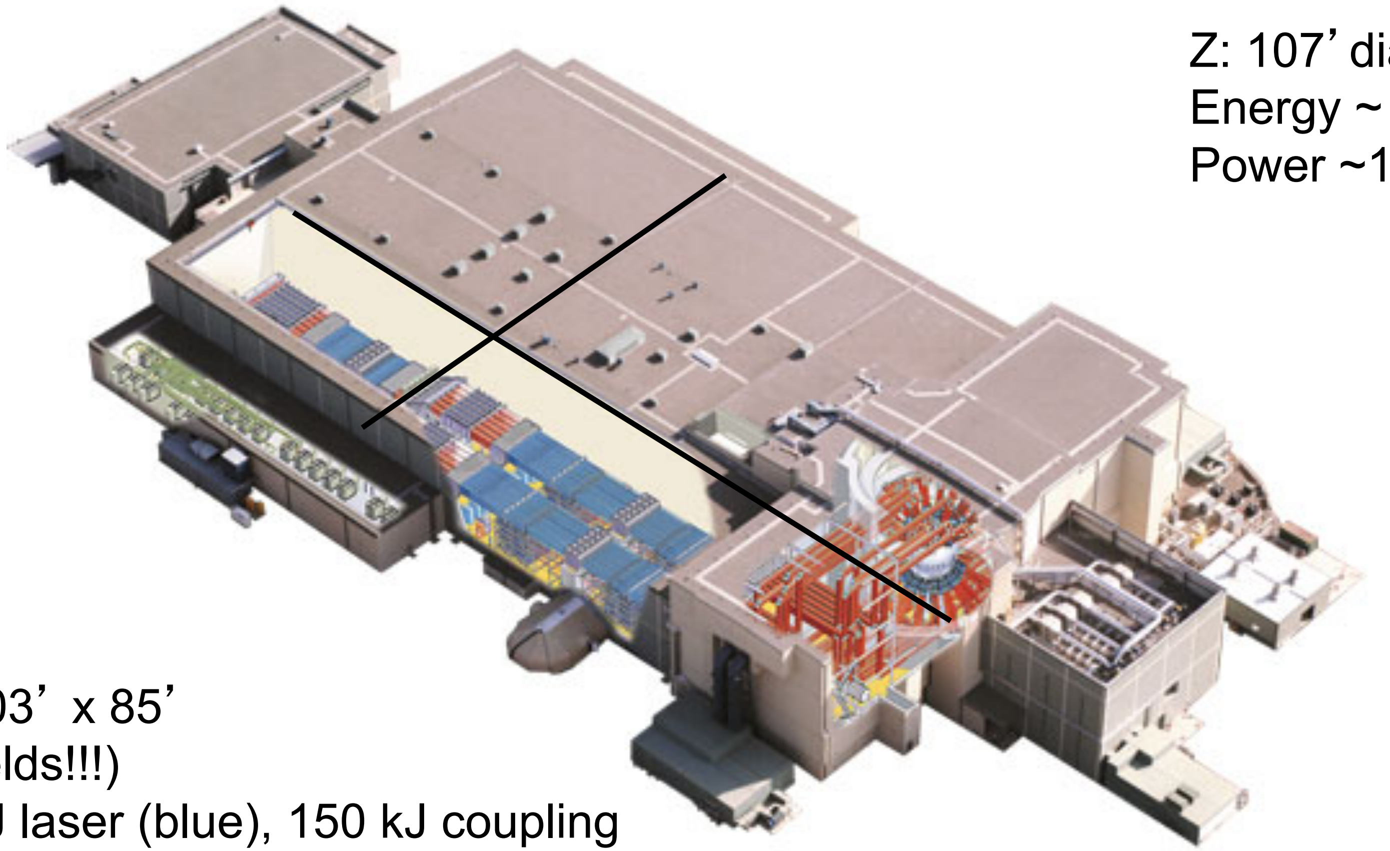
Conventional thermal	3.2 TW
Hydroelectric	0.9 TW
Nuclear	0.5 TW
Geothermal, solar, wind, and wood	0.1 TW
Total	4.7 TW

(International Energy Annual Report, DOE)

Compared to NIF, Z is a small facility but still capable of creating similar energy densities. Pulsed power is efficient!



Z: 107’ diameter x 20’ high
Energy ~ 22MJ, 0.5 -1 MJ coupling
Power ~100 - 200 TW

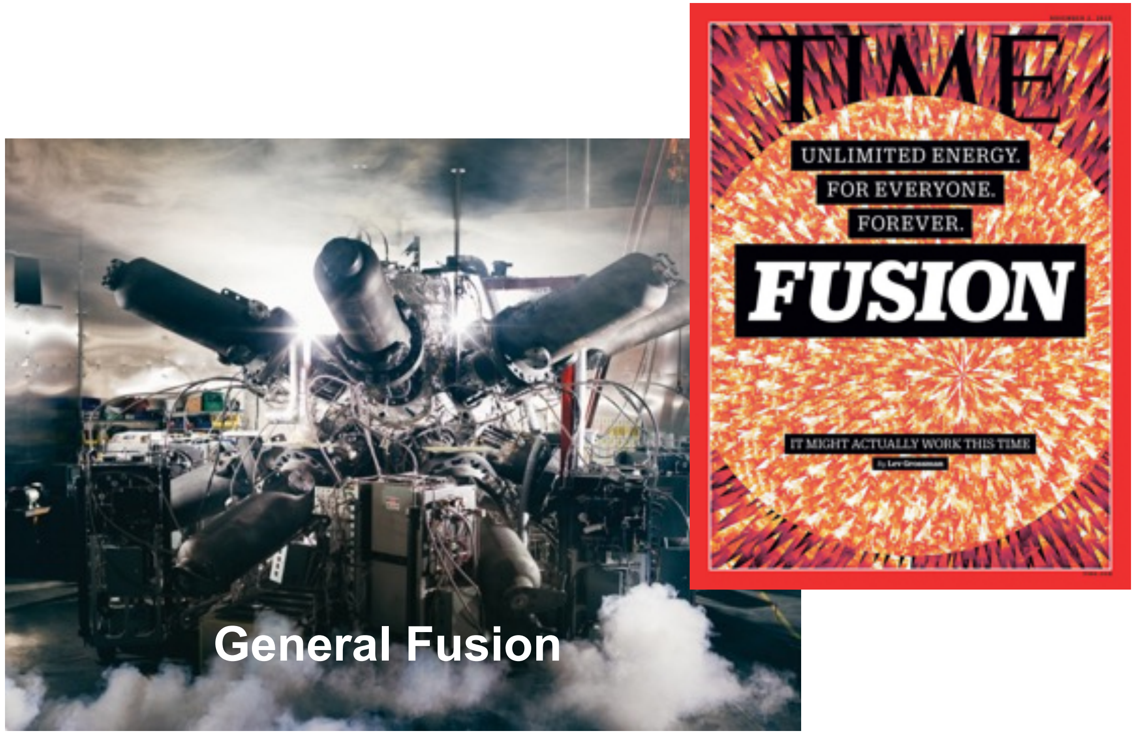


NIF: 704’ x 403’ x 85’
(3 Football Fields!!!)
Energy ~ 2 MJ laser (blue), 150 kJ coupling
Power ~ 500 TW

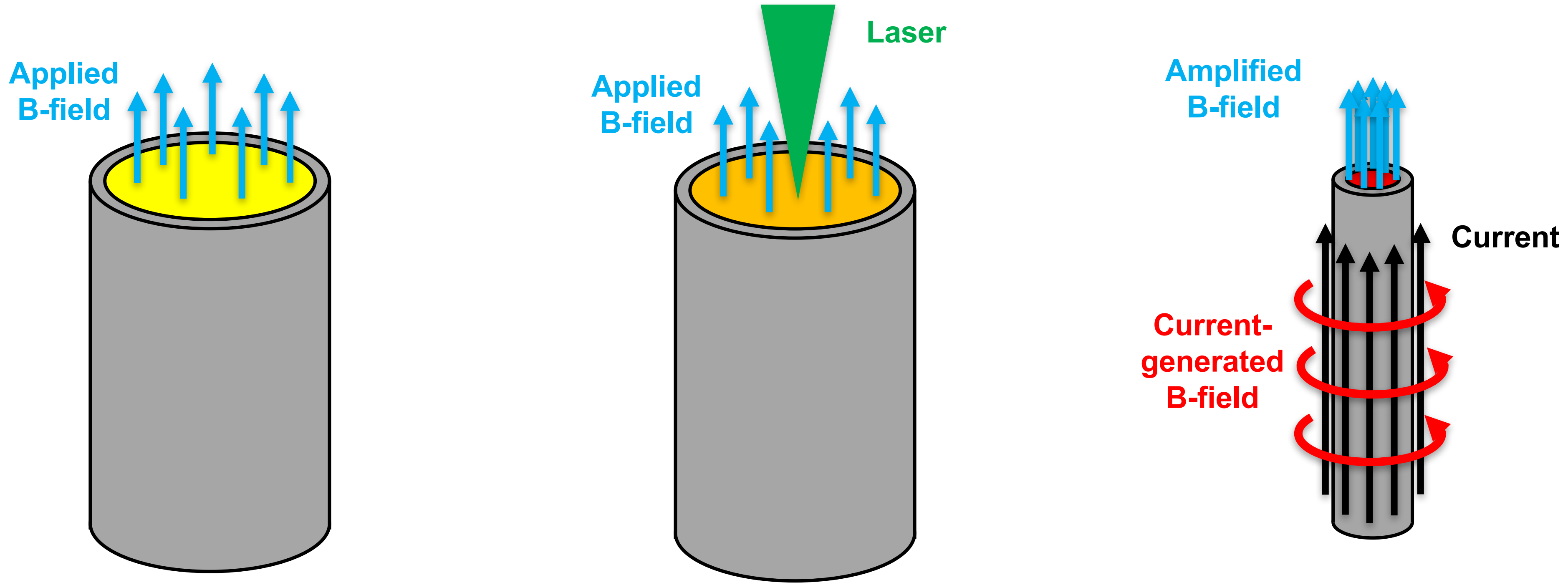
Magneto-inertial fusion attempts to operate in an intermediate fuel density space between MCF and ICF

- Strategy:
  - Try to make fusion conditions easier to obtain
  - **Reduce** fuel density to suppress radiation losses
  - Use a magnetic field to **suppress** the thermal conduction losses during compression
  - **Reduce** required target convergence
  - Longer fusion burn times required, i.e. more confinement

There are a number of start-up companies employing this approach that are receiving a great deal of press!



Magnetized Liner Inertial Fusion relies on three stages to produce fusion relevant conditions



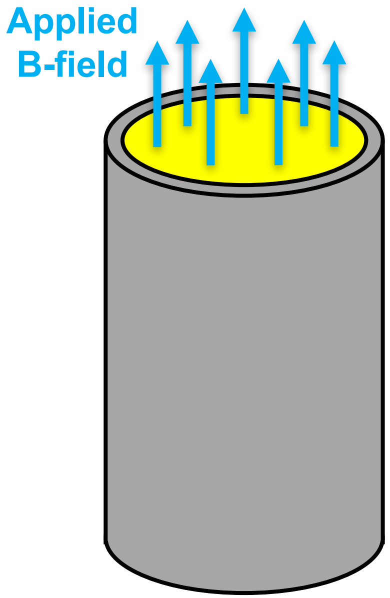
Apply axial magnetic field

Laser-heat the magnetized fuel

Compress the heated and magnetized fuel

S. A. Slutz, et al., Phys. Plasmas 17, 056303 (2010).

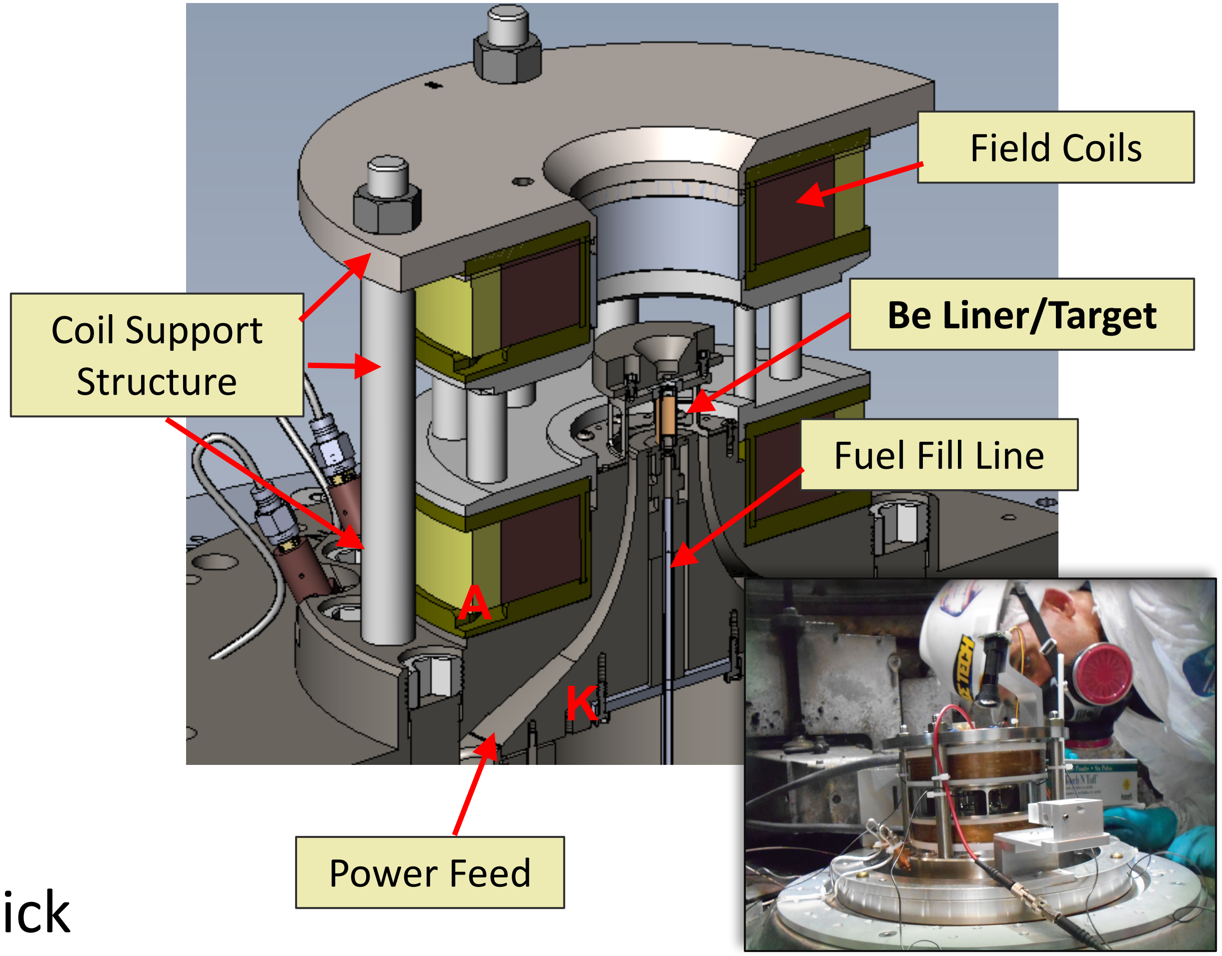
An axial magnetic field is applied with external field coils before the implosion occurs



Apply axial magnetic field

- Metal cylinder contains 0.7 mg/cm^3 of deuterium gas
- 10 mm tall, 5 mm diameter, 0.5 mm thick

Helmholtz-like coils apply 10-30 T in 3.5 ms



The current from the Z machine is used to implode the target

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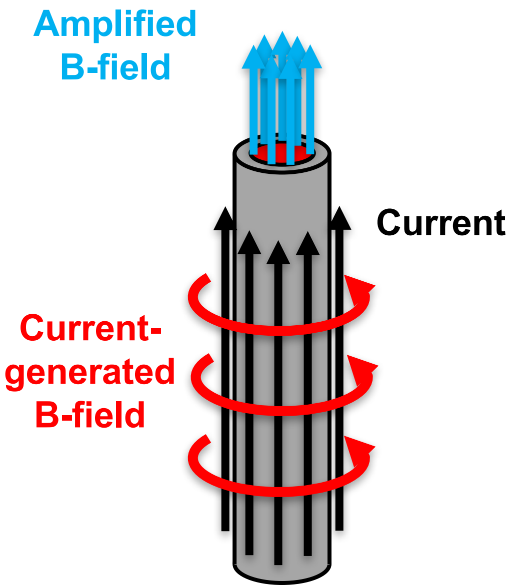
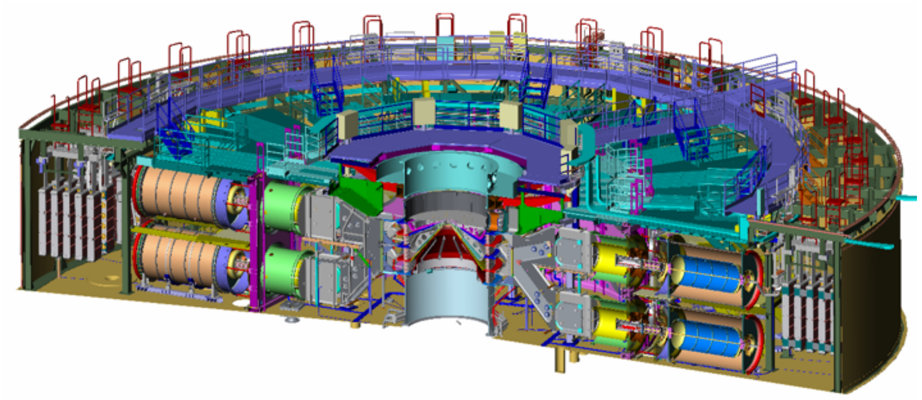
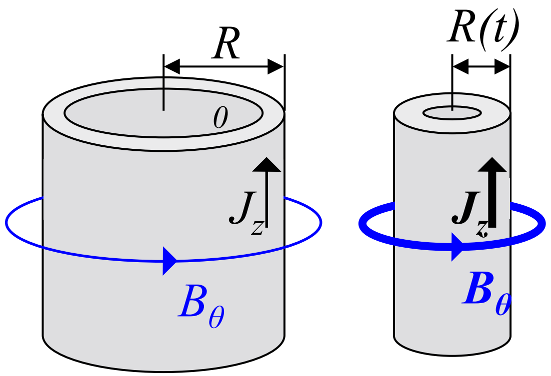


Compress the heated and magnetized fuel

Z drives axial ~17 MA axial current, risetime is 100 ns

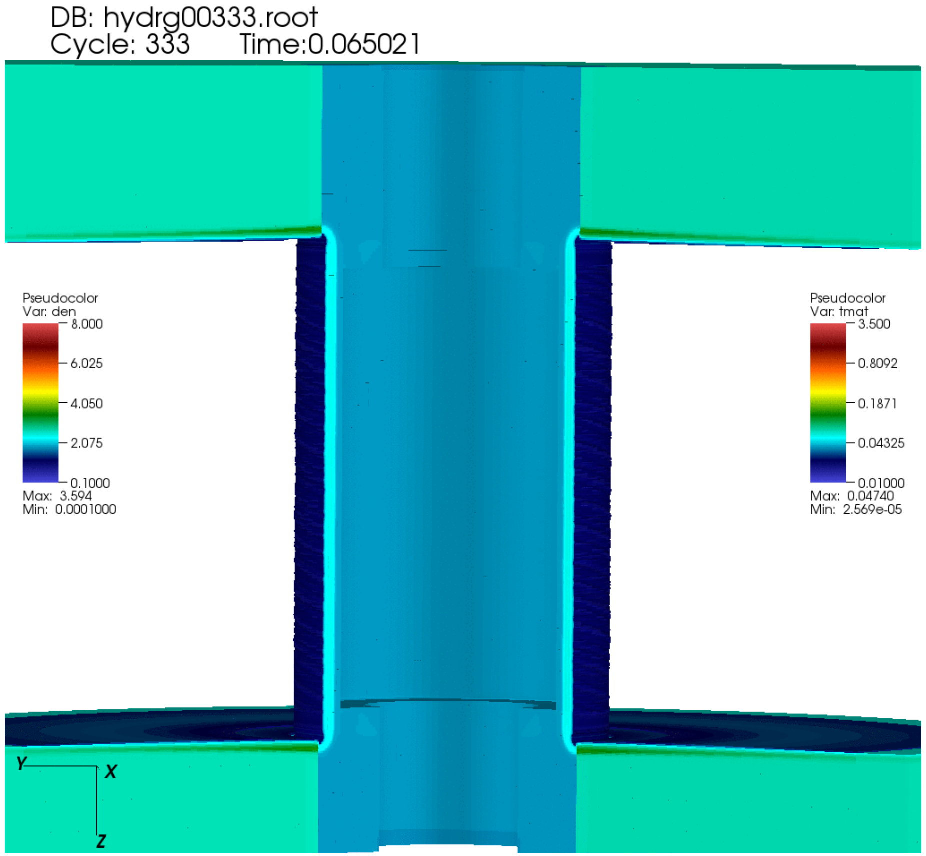




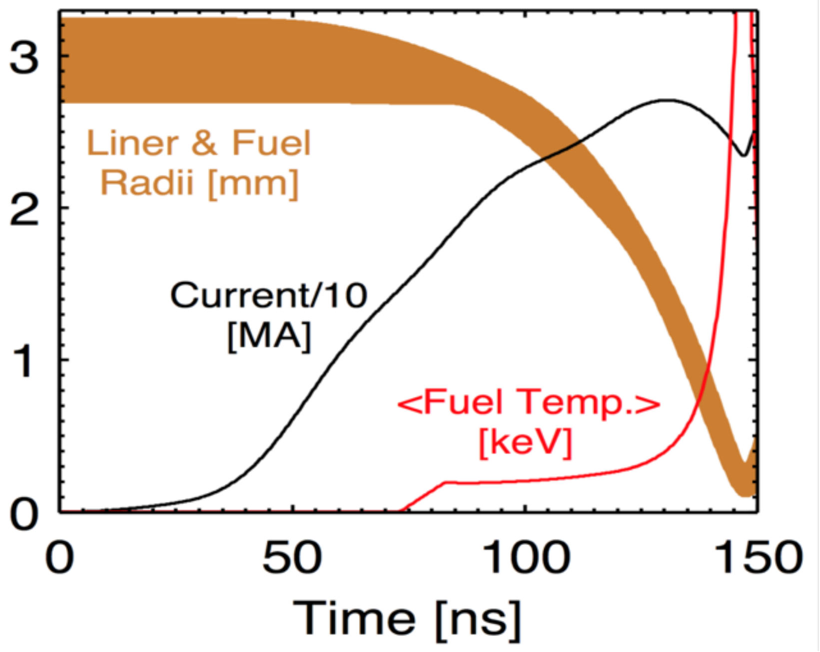
$$P = \frac{B^2}{8\pi} = 105\left(\frac{I_{MA}/26}{R_{mm}}\right)^2 \text{ MBar}$$

- Metal cylinder implodes at ~70 km/s
- Fuel is nearly adiabatically compressed
- Axial magnetic field is compressed to 1-10 kT

Fully-integrated (Bz+Laser+Z) 3-D HYDRA calculations illustrate the stages of a MagLIF implosion



1-D picture*



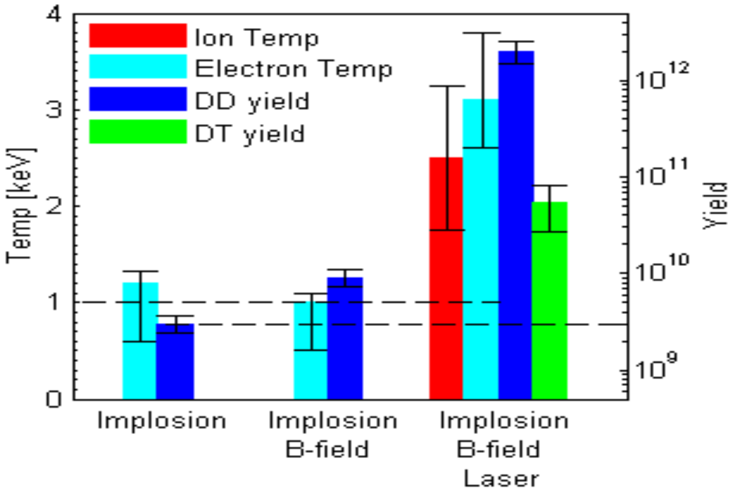
A. B. Sefkow et al., Phys. Plasmas, 21 072711 (2014), *R. D. McBride and S. A. Slutz, PoP 22, 052708 (2015)

We have demonstrated the principles of magneto-inertial fusion work and have achieved interesting fusion yields!

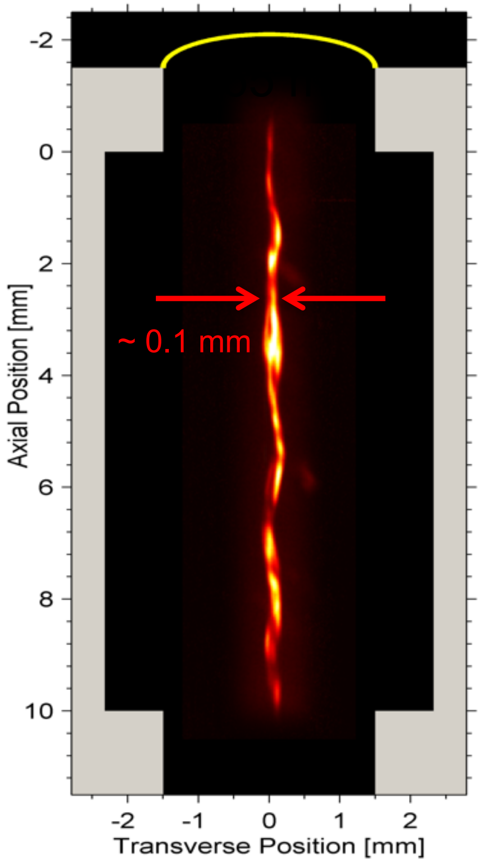
Significant yields and temperatures only w/ applied B_z and preheat

	No B-field	B-field
No Laser Heating	$3x10^9$	$1x10^{10}$
Laser Heating	$4x10^{10}$	$3x10^{12}$

DD Neutron yield



High Convergence Implosion



$3x10^{12}$ is a DT-equivalent yield of ~0.6 kJ

No spark yet, but there is smoke!

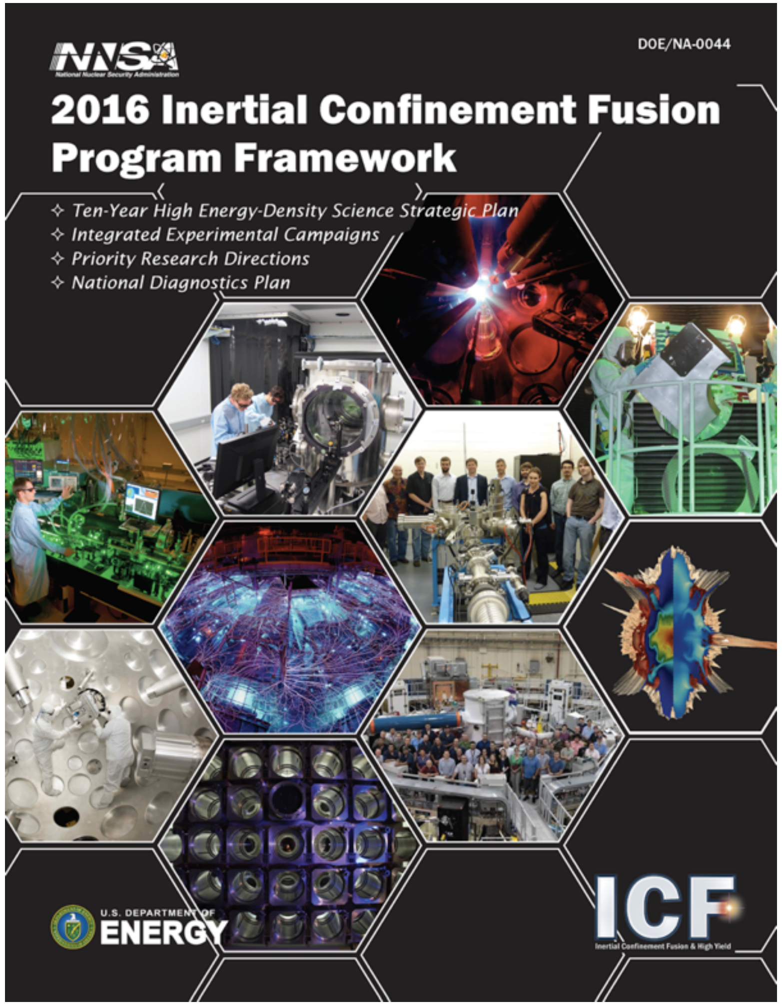
The goal of the US ICF program is to achieve multi-MJ fusion yields.

US National Program Goal: Determine the efficacy of reaching ignition on the NIF and of achieving credible physics scaling to multi-megajoule fusion yields for each of the three major ICF approaches

Organized around four framework elements:

- 10-year strategic plan for High Energy Density Science
- Integrated experimental campaigns
- Focused science experiments
- Transformative diagnostics

Search 'ICF Framework NNSA' on Google



Laser indirect drive is currently focused on improving implosion quality and assessing if additional energy is needed for MJ-yields

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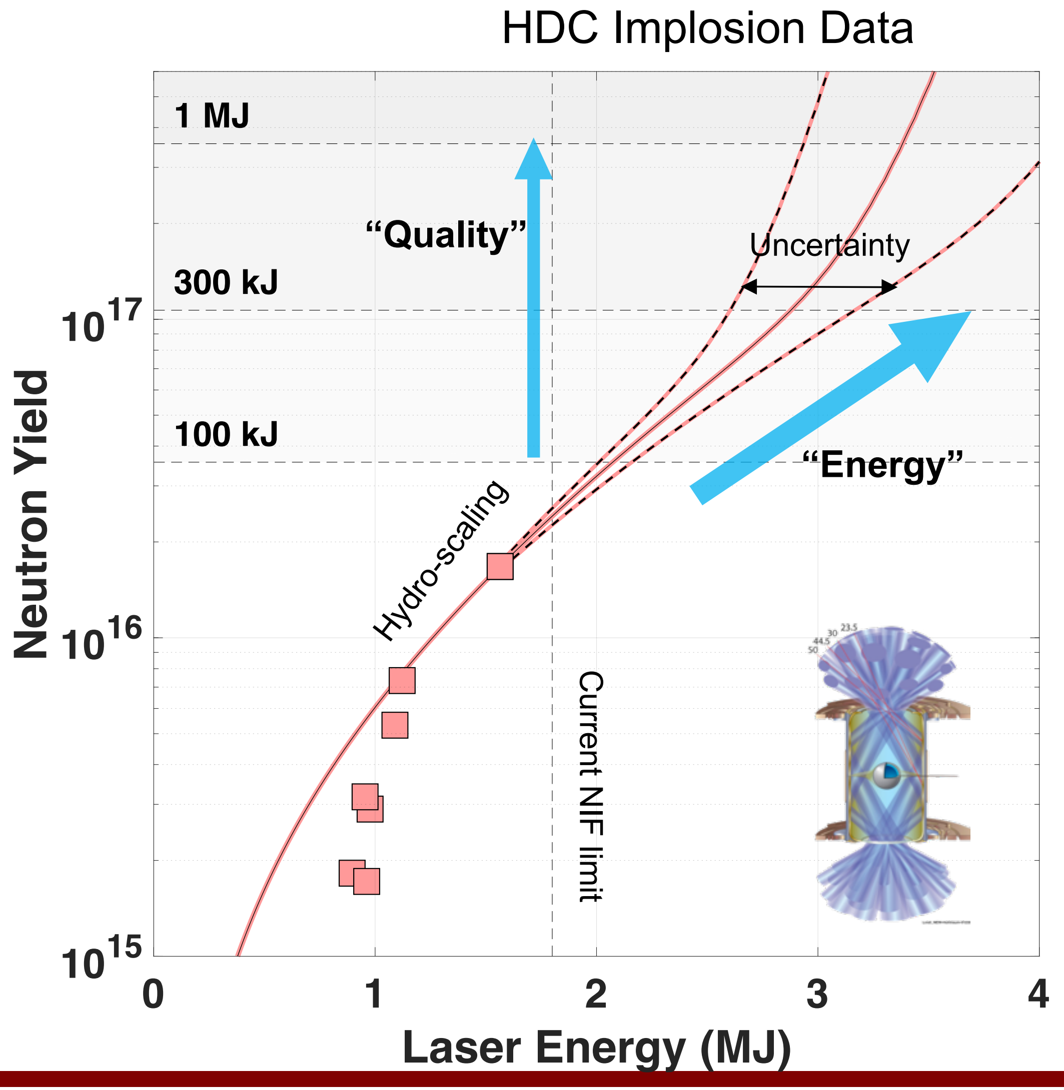
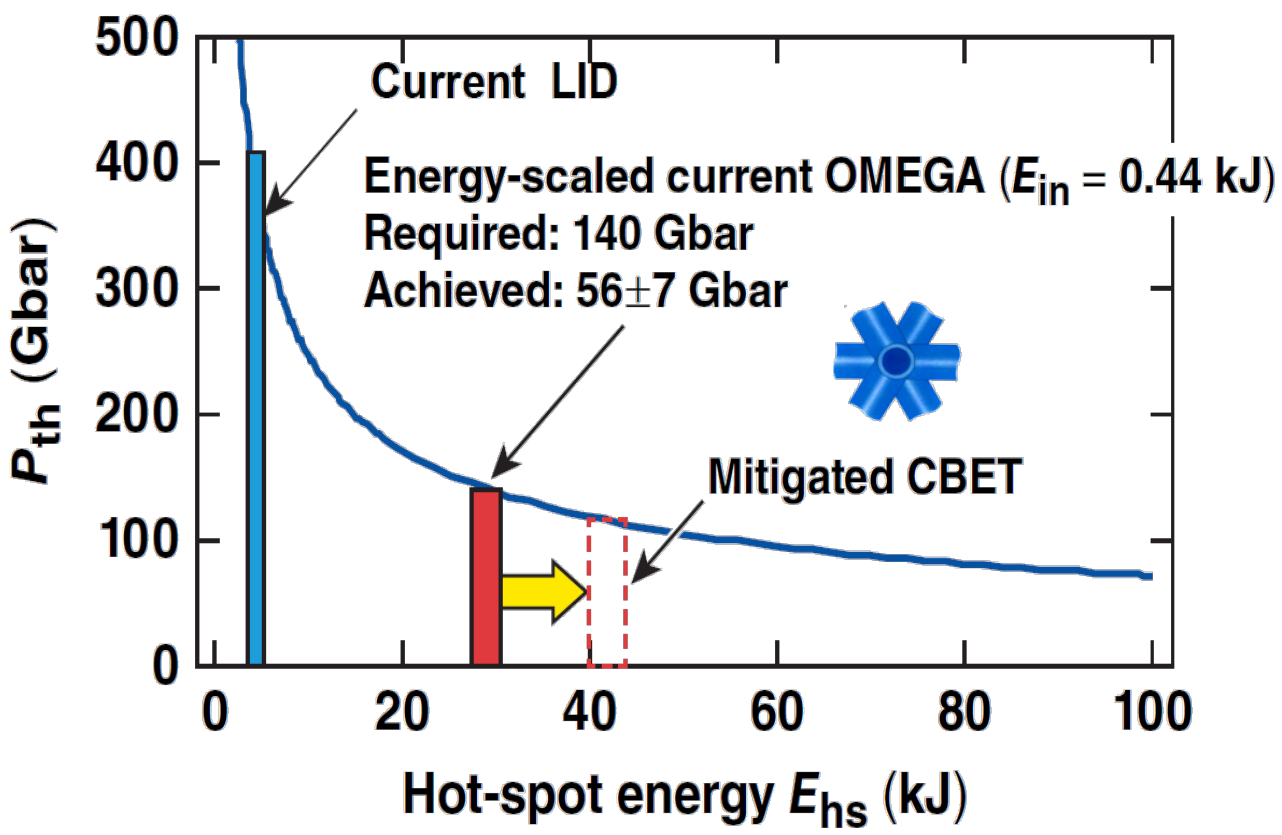


1. Can we achieve ignition on NIF? —Improving implosion **"quality"**
2. If not, how much more **"energy/power"** is needed?

The laser direct drive effort is focusing on defining the requirements for achieving credible and robust ignition

Ignition Pressure vs. Hot Spot Energy



100 Gbar Campaign on OMEGA

- Demonstrate 80-100 Gbar in ignition-scaled designs on OMEGA

MJ Direct Drive Campaign on NIF

- Demonstrate understanding and control of LPI at the 1.8 MJ scale

1-D Campaign on OMEGA

- Test understanding in low-convergence implosions

MagLIF efforts are focused on improved performance at lower convergence, increasing capabilities for testing scaling, and defining what is required to produce >10MJ fusion yields

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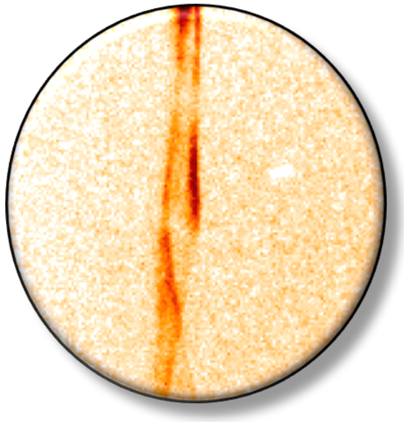
Implosion & Stagnation

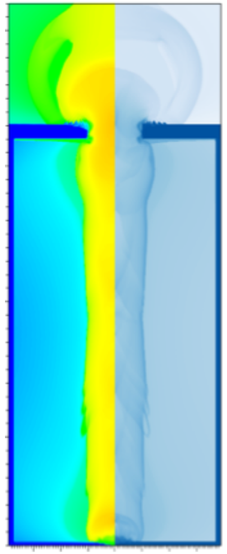
- Decrease CR to ~35 for a less structured and more repeatable stagnation.



- Achieve >10 kJ DT yield with $T > 4$ keV and $BR > 0.5$ MG-cm

Laser Preheat

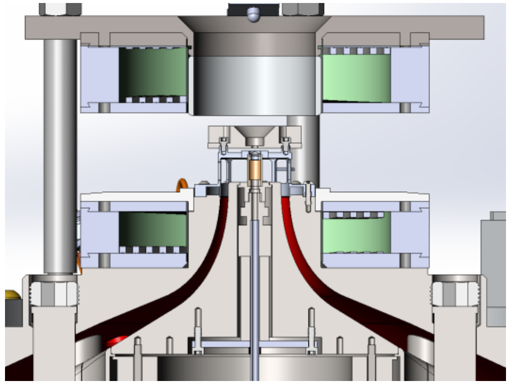
- Develop methods and validated models for more efficient laser preheat.



- Achieve >2 kJ preheat w/ minimal laser-induced mix

Power Flow

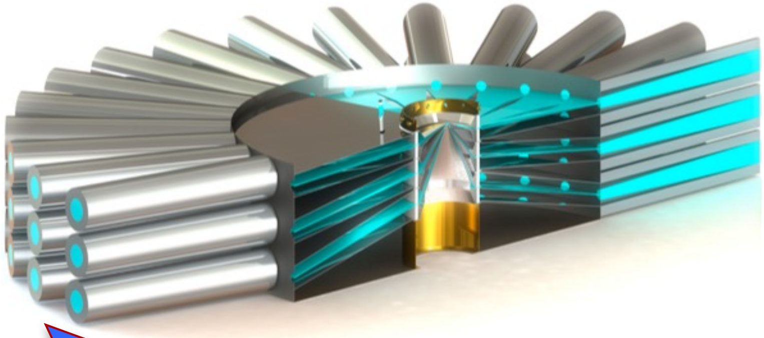
- Develop platforms and validated models for more efficient power flow compatible with High B_z



- Achieve >20 MA peak current w/ $B_z \sim 25$ T

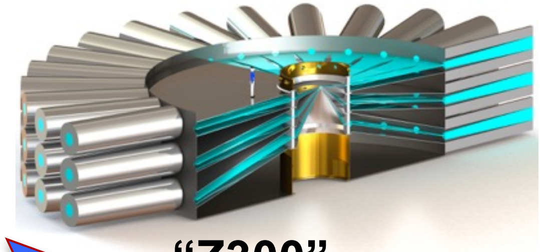
We are currently exploring target designs and pulsed power architectures that may be on the path to 0.5-1 GJ fusion yields

Fusion Yield 0.5-1 GJ?
Burning plasmas



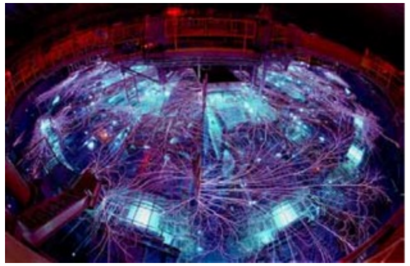
"Z800"
- 800 TW
- 52 Meter diameter
- 61 MA
- 130 MJ Stored Energy

Yield = Etarget?
(About 3-4 MJ)
α-dominated plasmas



"Z300"
- 300 TW
- 35 Meter diameter
- 47 MA
- 47 MJ Stored Energy

Yield = E_{fuel}?
(~100kJ$_{DT\ eq}$)
Physics Basis for Z300



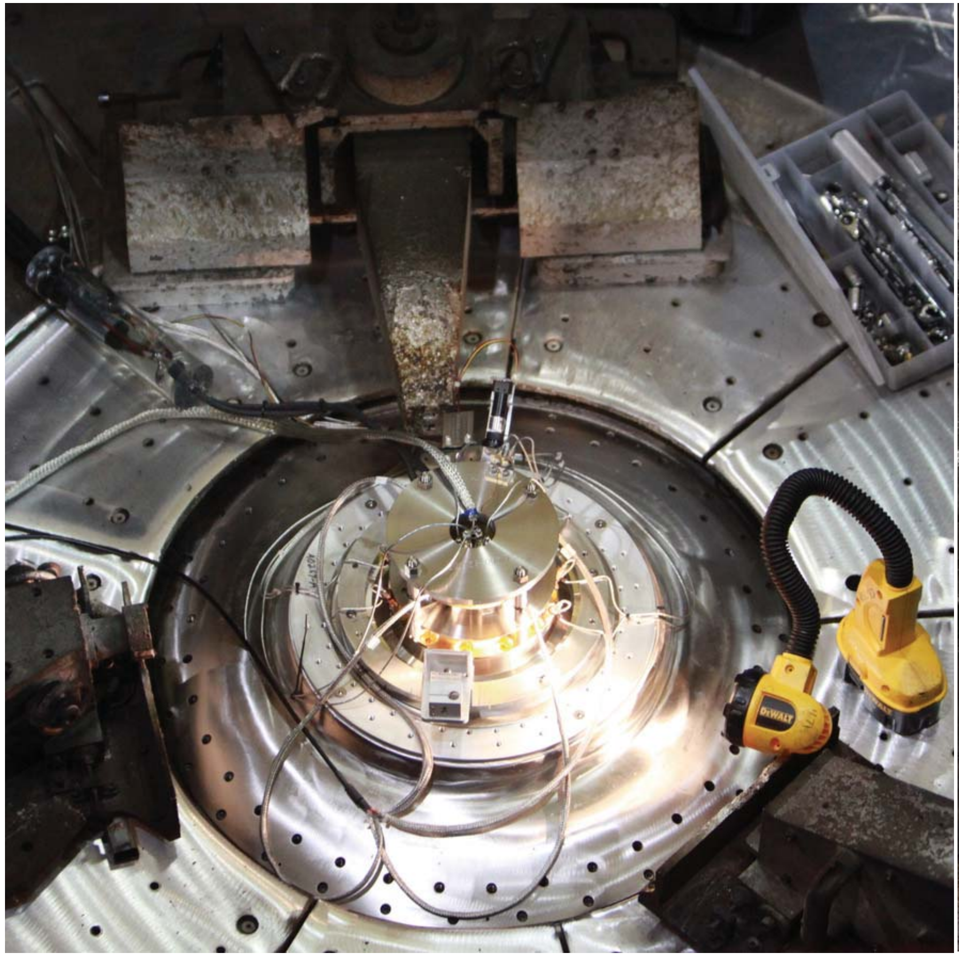
Z
- 80 TW
- 33 Meter diameter
- 26 MA
- 22 MJ Stored Energy

Note that 1 GJ ~ 0.25 tons TNT and there will be significant radiation and activation issues, so Z800 is "bold"!

W.A. Stygar *et al.*, Phys. Rev. STAB 18, 110401 (2015).

Backups

Debris from MagLIF experiments must be carefully managed (several MJ energy release equivalent to few sticks of dynamite)

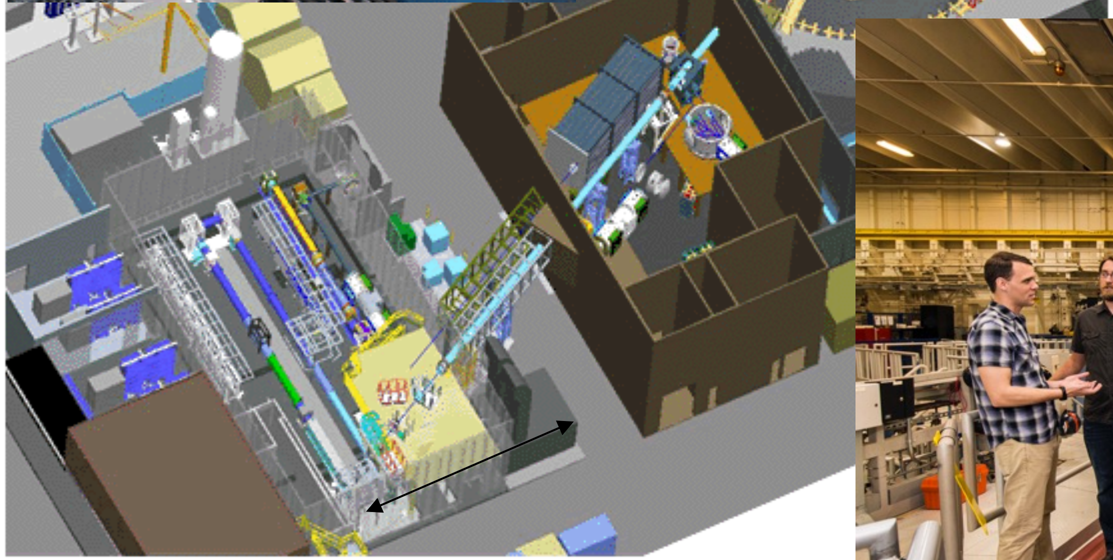


Pre-shot photo of coils & target hardware

Post-shot photo

The Z-Beamlet laser at Sandia* is being used to radiograph liner targets and heat fusion fuel

Z facility



Z-Beamlet and Z-Petawatt lasers

Z-Beamlet (ZBL) is now routinely used to deliver up to 4.5 kJ of 2ω light in a 6 ns time window

An advantage of laser heating is that it can be studied and optimized without using Z

* P. K. Rambo *et al.*, Applied Optics 44, 2421 (2005)

Sandia's history dates back to World War II

Sandia National Laboratories

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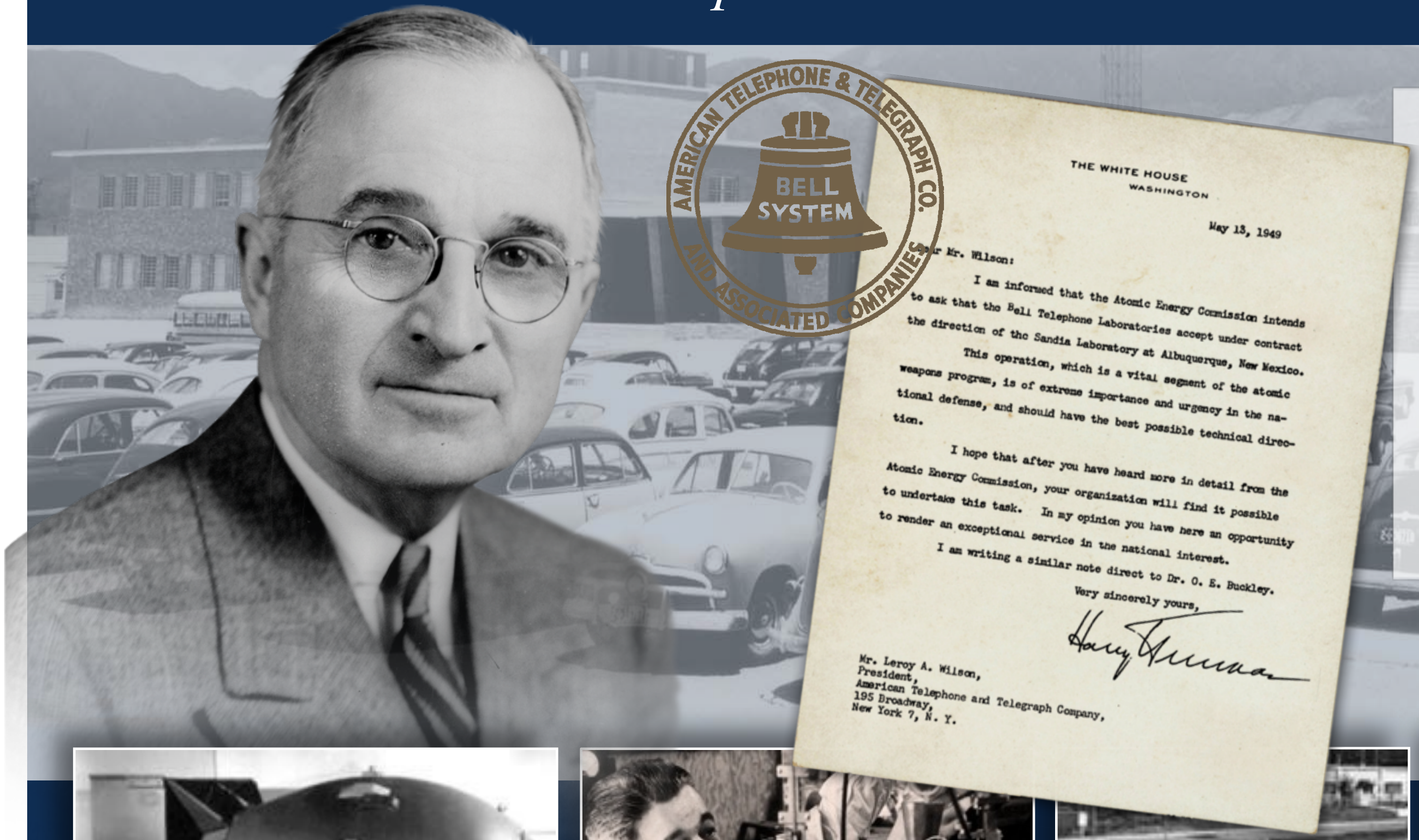
Exceptional service in the national interest



THE WHITE HOUSE
WASHINGTON

May 13, 1949

Dear Mr. Wilson:

I am informed that the Atomic Energy Commission intends to ask that the Bell Telephone Laboratories accept under contract the direction of the Sandia Laboratory at Albuquerque, New Mexico.

This operation, which is a vital segment of the atomic weapons program, is of extreme importance and urgency in the national defense, and should have the best possible technical direction.

I hope that after you have heard more in detail from the Atomic Energy Commission, your organization will find it possible to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.

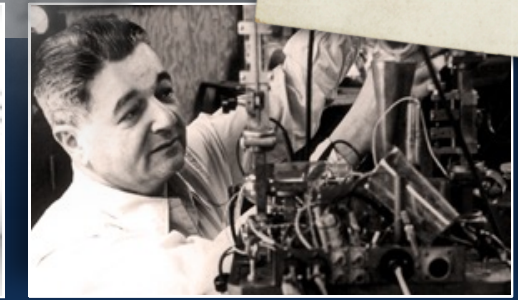
I am writing a similar note direct to Dr. O. E. Buckley.

Very sincerely yours,

Harry Truman

Mr. Leroy A. Wilson,
President,
American Telephone and Telegraph Company,
195 Broadway,
New York 7, N. Y.

- **July 1945:** Los Alamos creates Z Division
- Nonnuclear component engineering
- **November 1, 1949:** Sandia Laboratory established
- **1949–1993:** AT&T
- **1995–Present:** Lockheed Martin Corporation (contract extended through April 30, 2016, with an option of an additional year.)



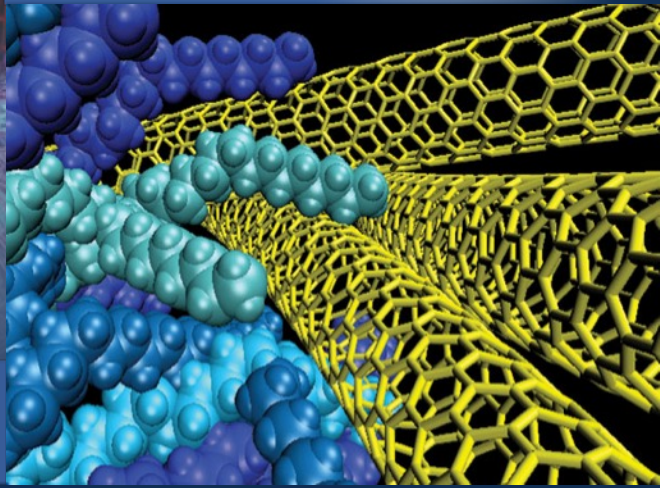
Sandia has sites across the United States, but the majority of its employees are in New Mexico

Sandia has "Research Foundations" that span a wide range of science, engineering, and technologies

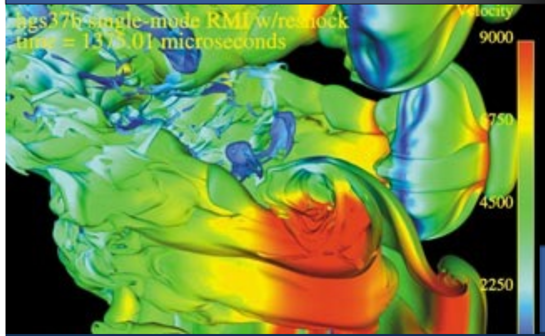
Computing & Information Sciences

Radiation Effects & High Energy Density Science

Materials Science

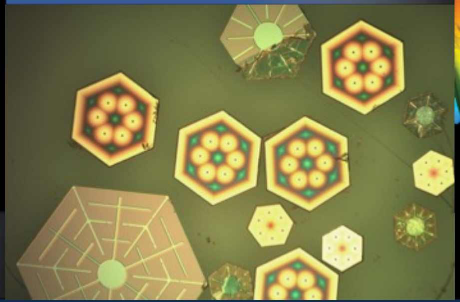


Engineering Sciences

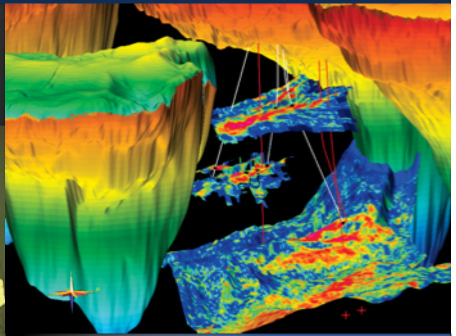


Bioscience

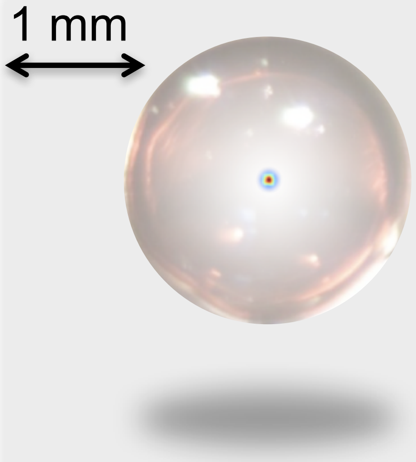
Nanodevices & Microsystems



Geoscience



Laser Indirect Drive On NIF

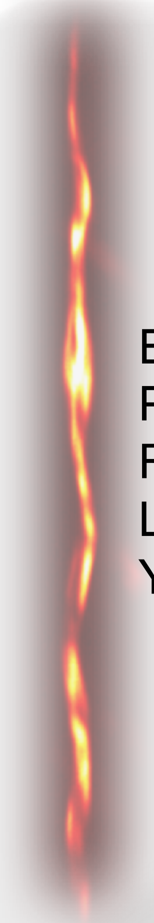


E_{driver} ~ 1.9 MJ
P_{HS} ~ 250 Gbar
R_{HS} ~ 40 um
Y_{DT} ~ 1E16

Laser Direct Drive On OMEGA

E_{driver} ~ 26 kJ
P_{HS} ~ 55 Gbar
R_{HS} ~ 20 um
Y_{DT} ~ 5E13

MagLIF On Z



E_{driver} ~ 2 MJ
P_{HS} ~ 1 Gbar
R_{HS} ~ 100 um
L_{HS} ~ 10 mm
Y_{DD} ~ 4E12

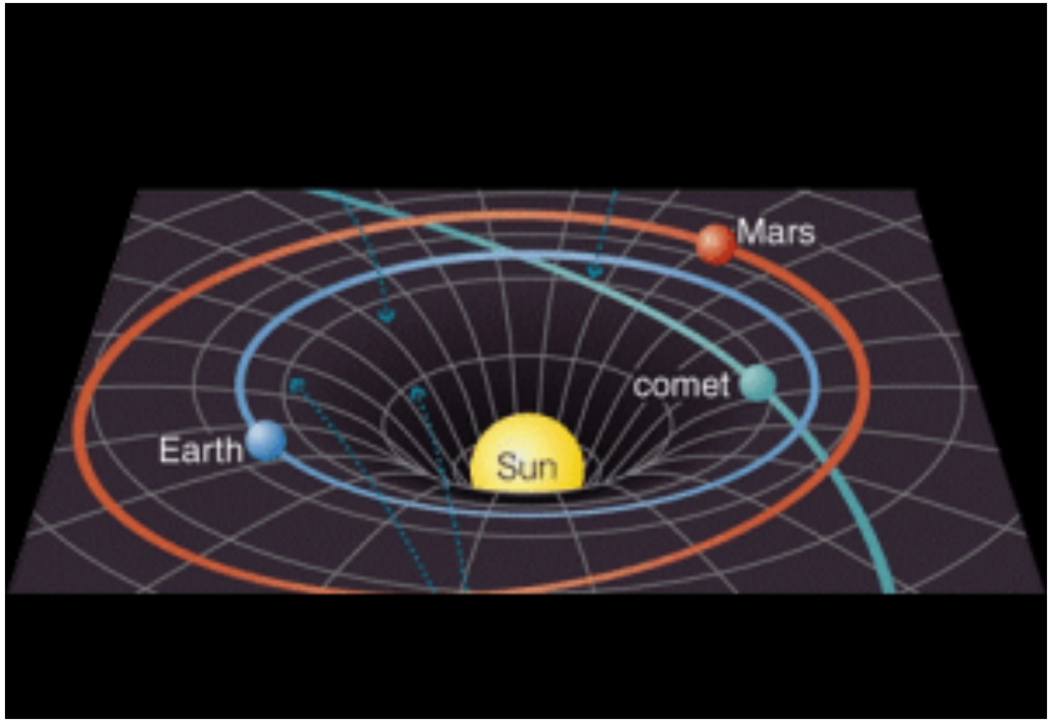


Image Credit: abovetopsecret.com