SAND2014-3936C

Exceptional service in the national interest

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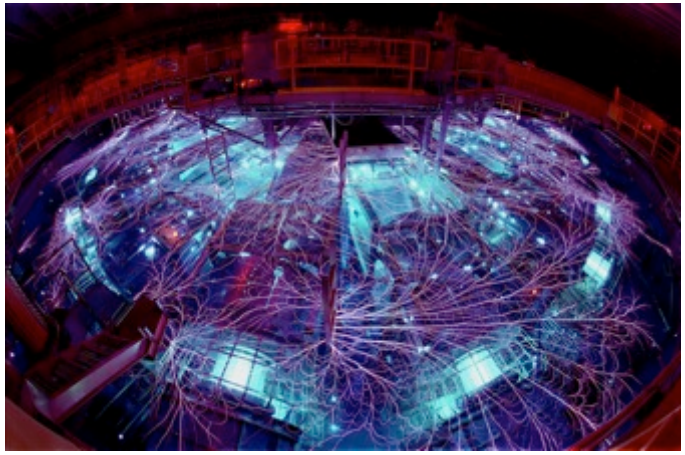
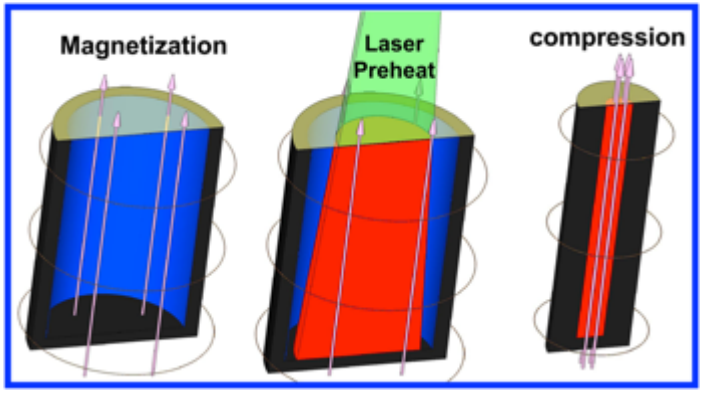


Using Magnetic Fields to Create and Control High Energy Density Matter



Mark C Herrmann

Pulsed Power Sciences Center

Sandia National Laboratories

George Washington University

May 8, 2014

U.S. DEPARTMENT OF ENERGY | NNSA

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It is an exciting time to be working in High Energy Density Science

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- The nation has made a large investment in facilities to create matter at high energy densities
- We use the Z facility, the world's largest pulsed power driver, to study high energy density matter
- We are applying the Z facility to better understanding material properties relevant to planetary science and astrophysics
- We have performed our first test of fusion concept called Magnetized Liner Inertial Fusion (MagLIF) on the Z facility. Initial results are promising.

The US has invested in three major experimental facilities for high energy density science

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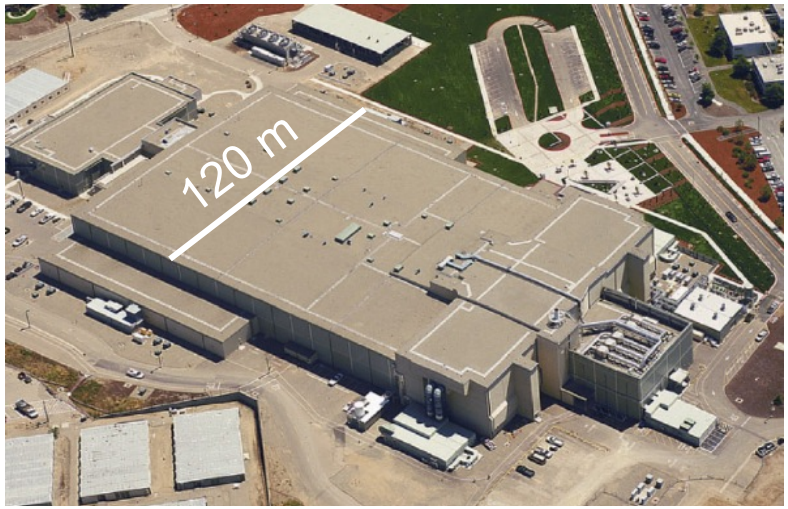
National Ignition Facility (2009)
Lawrence Livermore National Laboratory

(1.8 MJ @ 0.35 μm)



Refurbished Z facility (2007)
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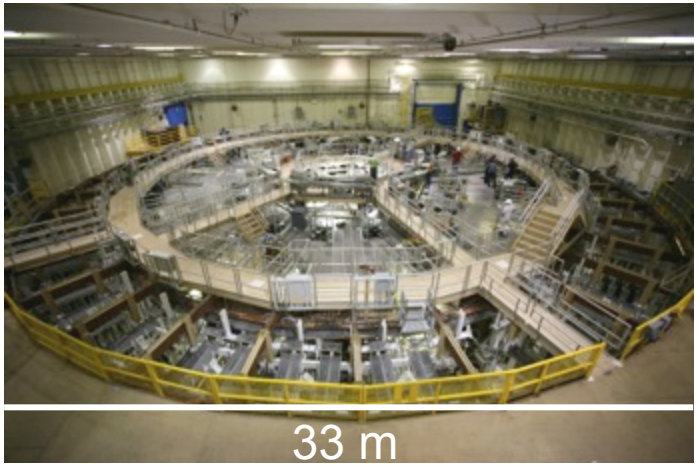
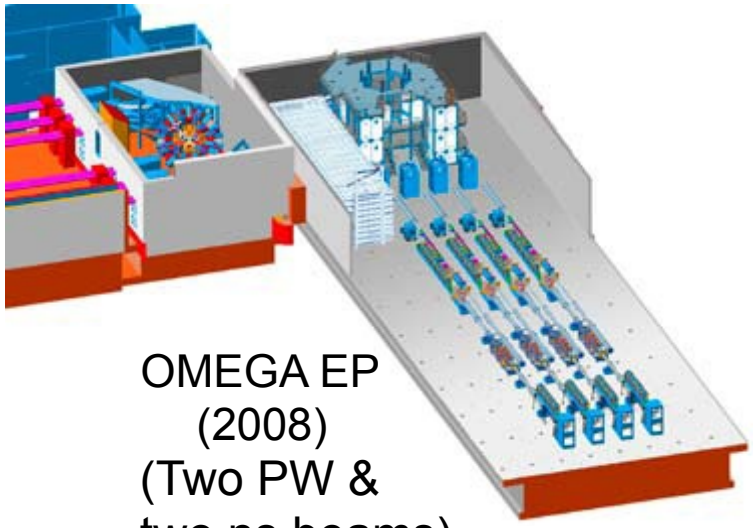
(3 MJ)



OMEGA

(30 kJ @ 0.35 μm)



OMEGA EP
(2008)
(Two PW &
two ns beams)

These facilities enable the study of matter at high energy densities for the stockpile stewardship program to ensure a safe, secure, and effective deterrent

What is high energy density science?

- **Pressure (Pascals, bars) is equivalent to Energy Density (J/m^3)**
  - **1 Mbar = 10^6 atm = 10^{11} Pascals = 10^{11} J/m^3**
- **HED threshold is pressures >1 Mbar, which exceeds the internal energy density of molecules/atoms (solids become compressible, etc.)**

Object	Pressure (Mbar)
Atmosphere at sea level	1e-6
High pressure gas cylinder	1e-4
TNT	0.07
Internal energy of H atom	1.00
Pressure at the center of the Earth	3.5
Pressure at the center of Jupiter	30.00
Center of the sun	250,000.00

Currents create magnetic fields that in turn apply forces on other currents

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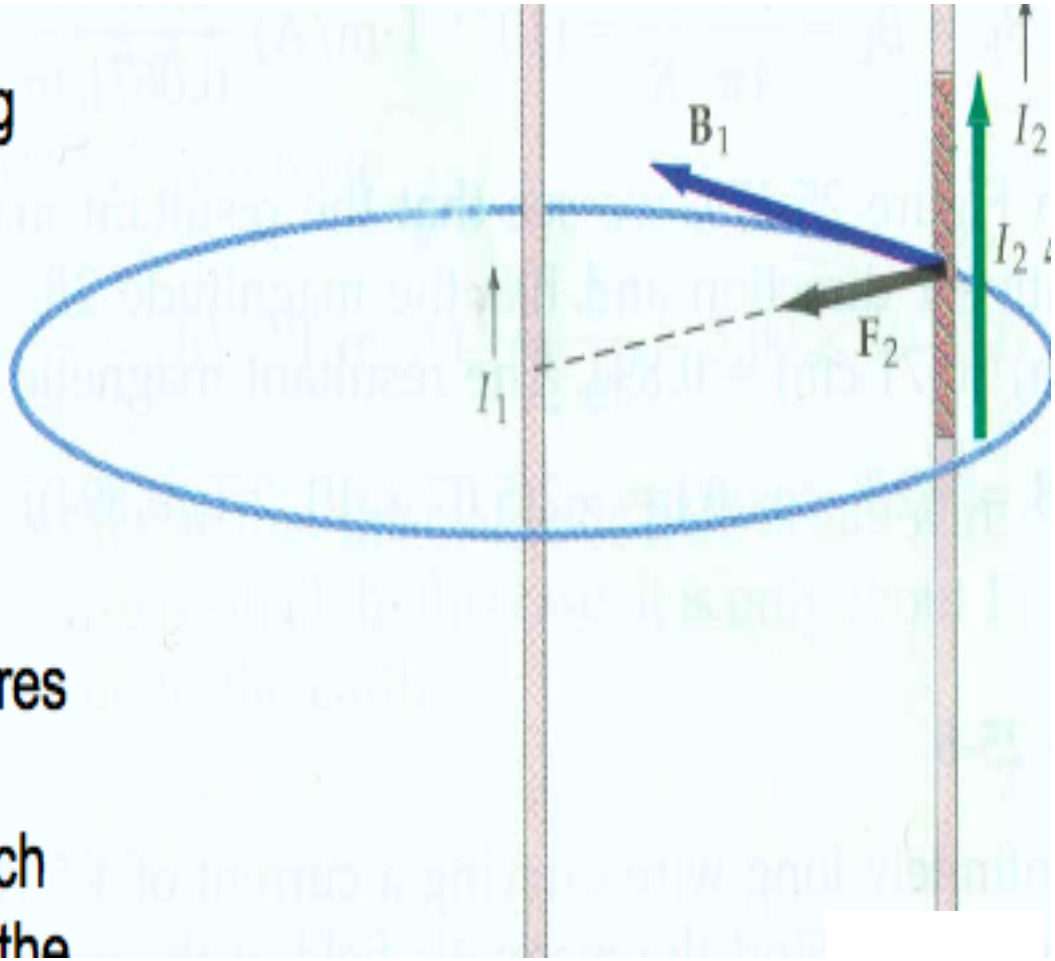
Two parallel wires carrying current along the same direction will attract each other (Biot-Savart Law, "JxB force")

Definition of an Ampere:
If two very long parallel wires 1 m apart carry equal currents, the current in each is defined to be 1 A when the



We use the Z pulsed power facility to generate large currents and large magnetic fields

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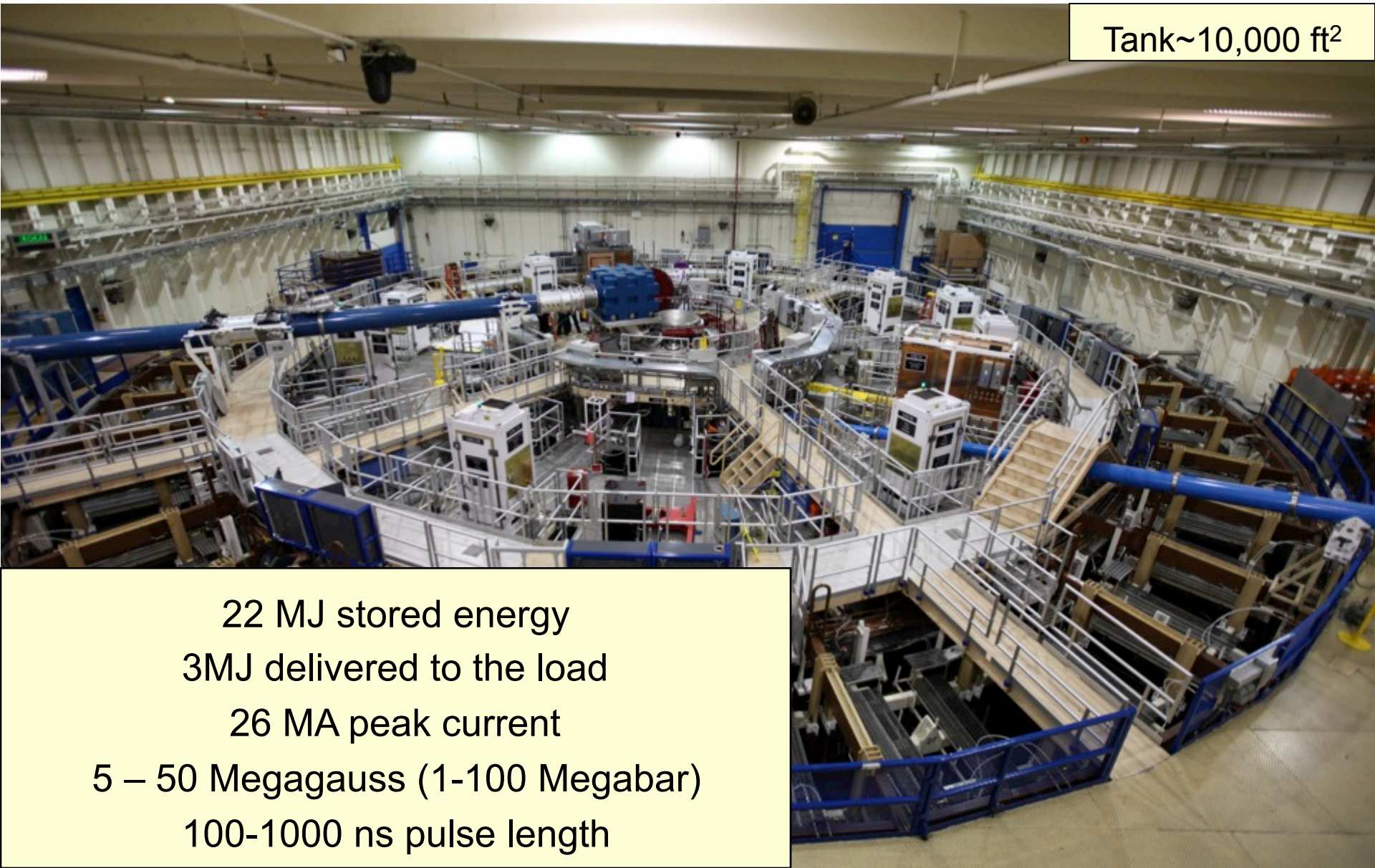


22 MJ stored energy

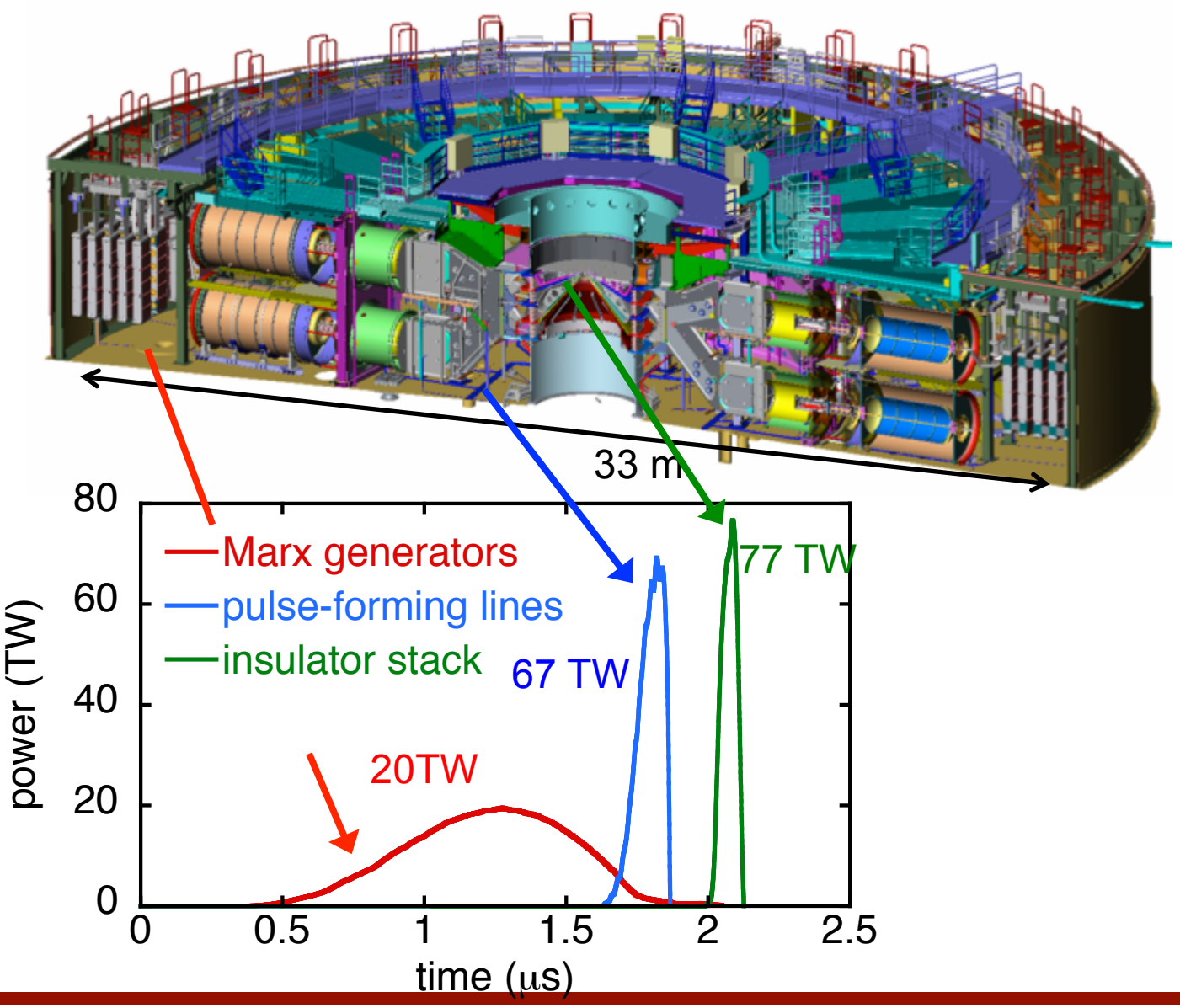
3MJ delivered to the load

26 MA peak current

5 – 50 Megagauss (1-100 Megabar)

100-1000 ns pulse length

Z works by compressing electromagnetic energy in time and space



Not all of the electrical energy in the Z facility makes it to the load

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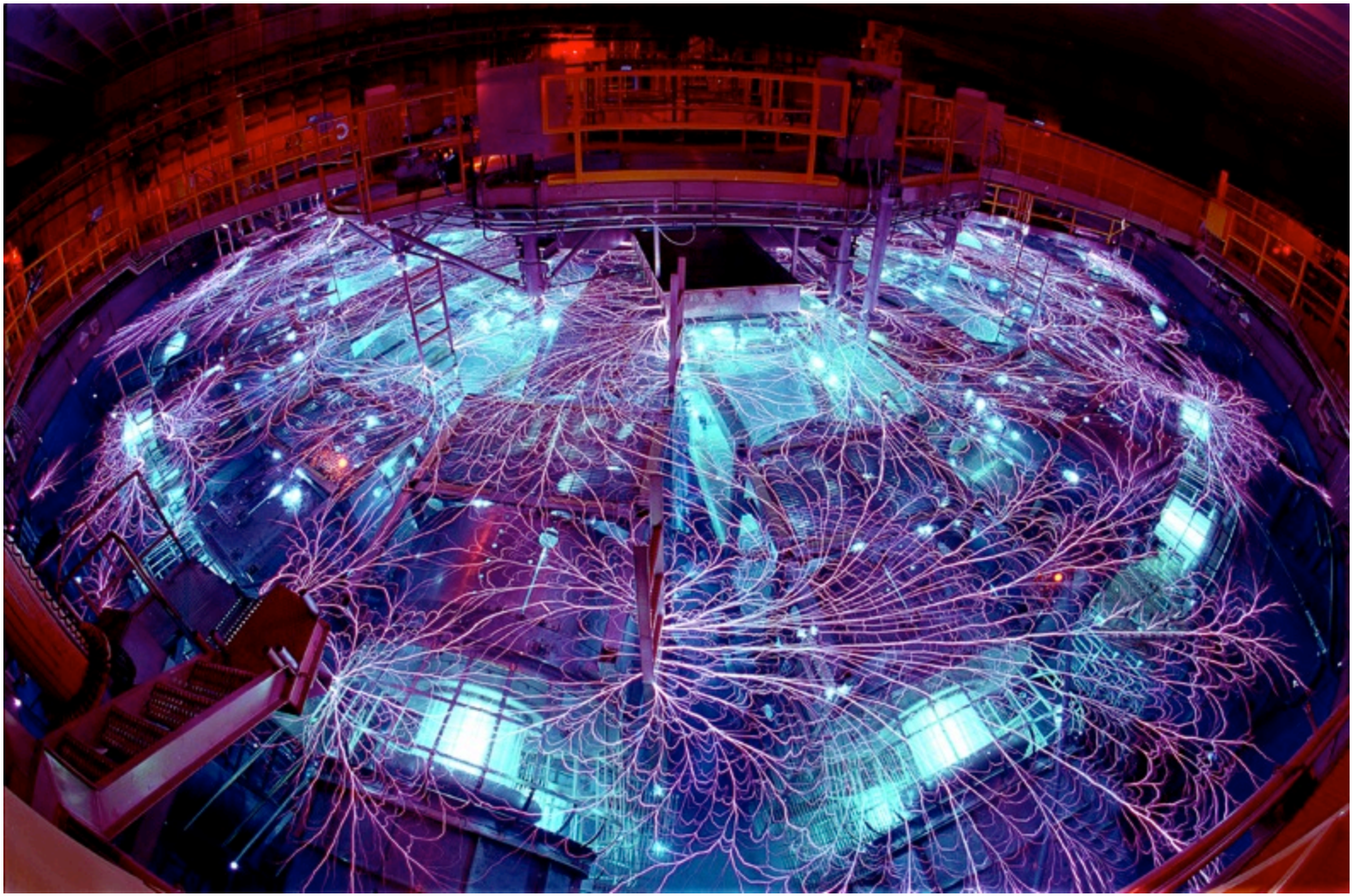


Z West High Bay Camera
CAUTION
2009/11/03 13:39:33.91
11-03-2009 13:39:33

We use magnetic fields to create HED matter in different ways for different applications

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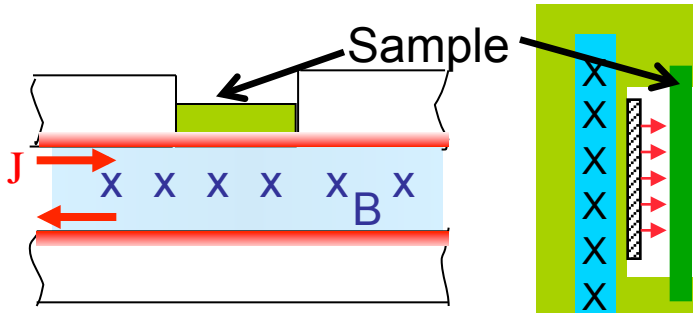
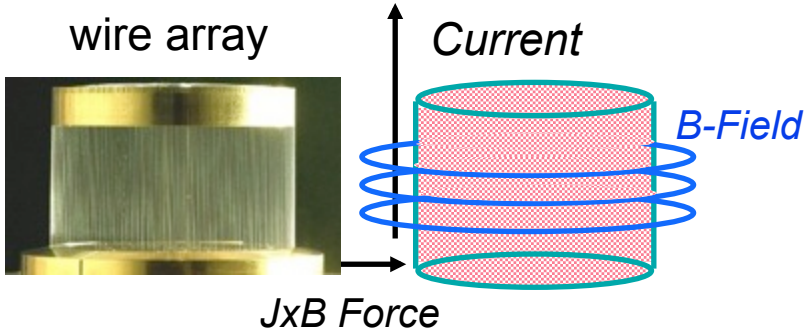
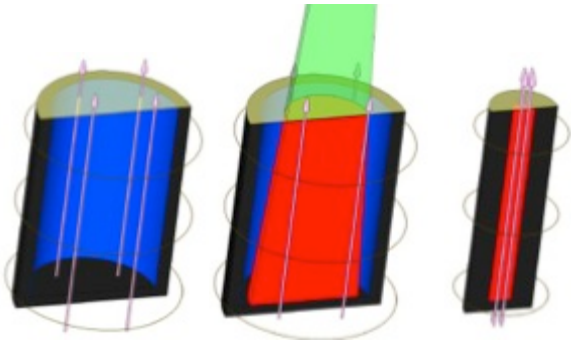
Materials Properties



Z-Pinch X-ray Sources

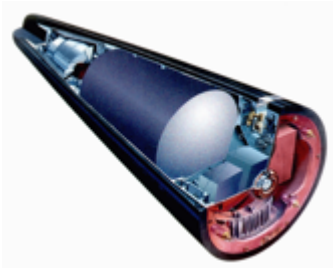


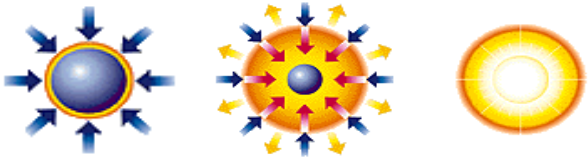
Inertial Confinement Fusion

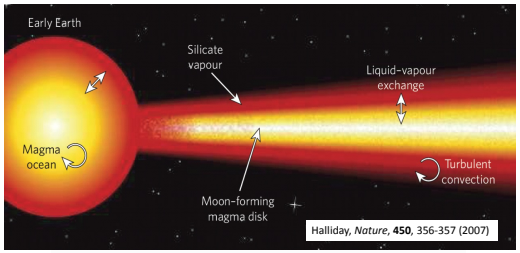


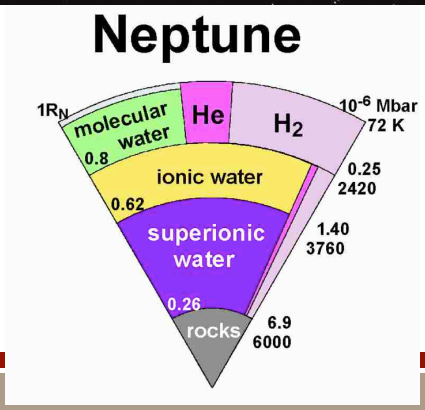
Understanding material properties at high pressure is important for Stockpile Stewardship and understanding planets

- **Nuclear Weapons materials**
  - **In the absence of underground testing we need a predictive capability**
  - **Material properties are a key input to nuclear weapons simulations**
- **Inertial confinement fusion (ICF) materials**
  - **Behavior of hydrogen, plastics, beryllium, diamond**
- **Planetary science**
  - **Giant impacts (e.g. Moon Forming Event)**
  - **Earths and super-earths**
    - **Equation of state of Mg, Fe, Si, C, O and related compounds**
  - **Giant Planets (e.g. Uranus & Neptune and exo ice-giants)**
    - **High-pressure mixtures of H, He, C, O, N**

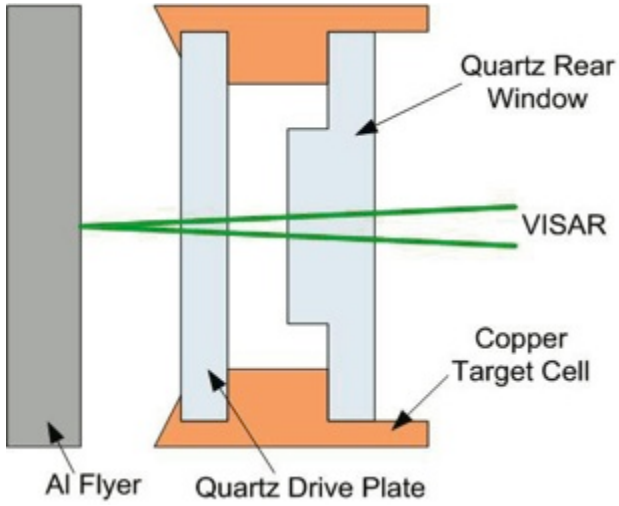


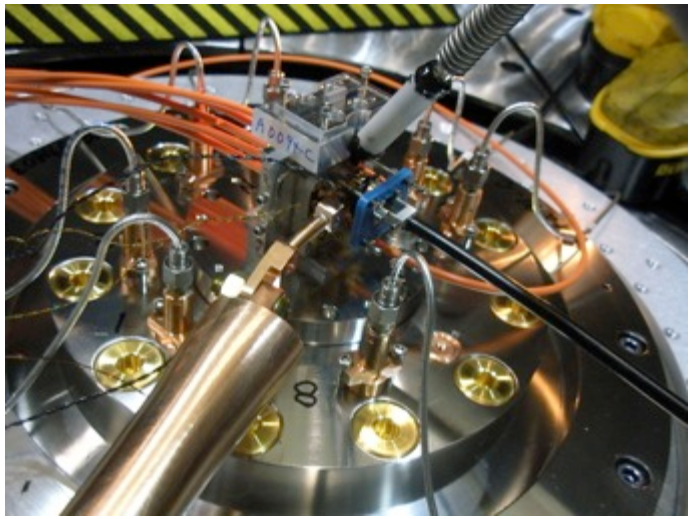


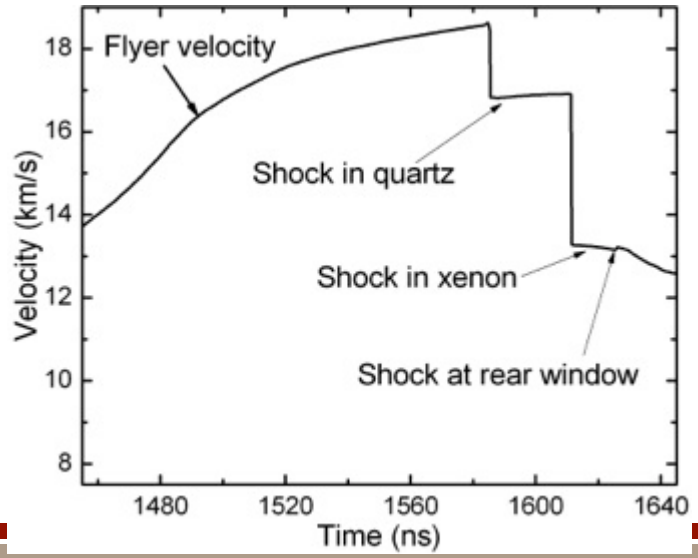


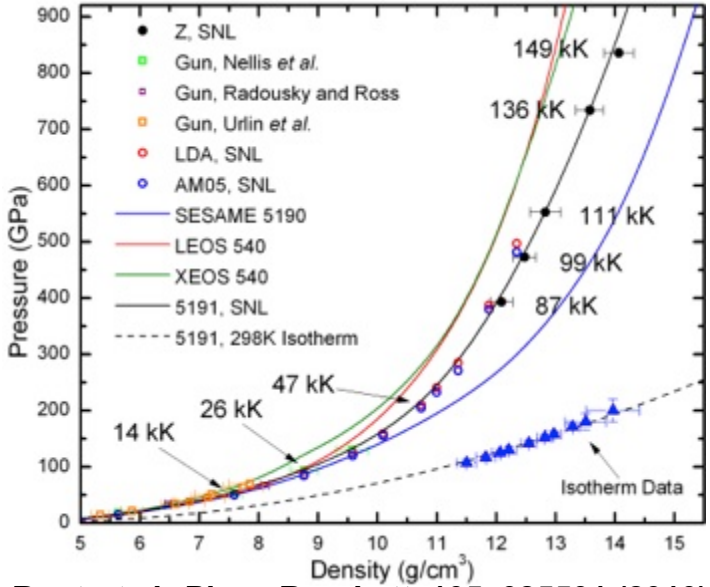


Large sample sizes and "long" time scales enable sub-percent accuracy at record pressures









S. Root *et al.*, Phys. Rev. Lett. 105, 085501 (2010).

VISAR trace from a xenon experiment with 18.5 km/s impact velocity

Magnetically driven implosions are efficient, powerful, x-ray sources from 0.1 to 10 keV

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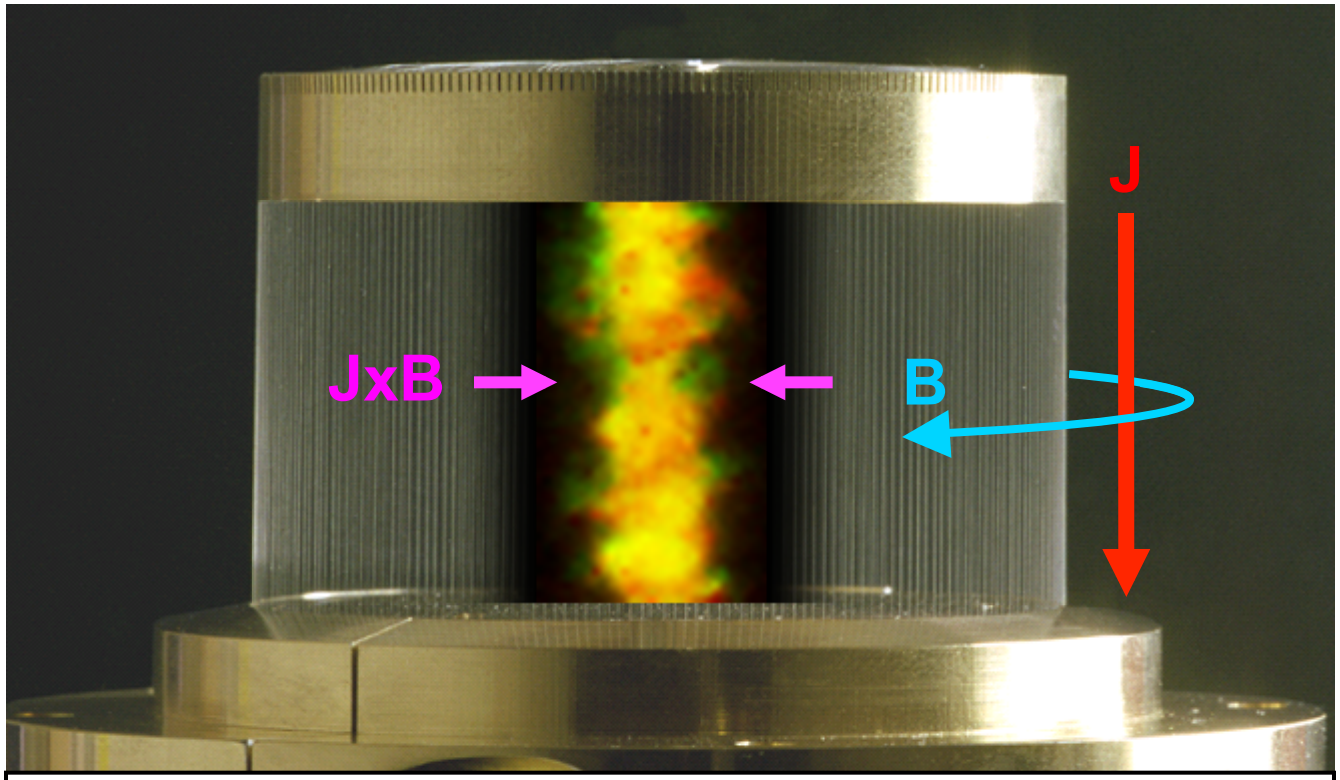

P_{rad} ~ 400 TW, Y_{rad} ~ 2.5 MJ

~ 10-15% wall plug efficiency

We are using the intense x-ray bursts from Z to create unique plasmas that can help address astrophysical questions

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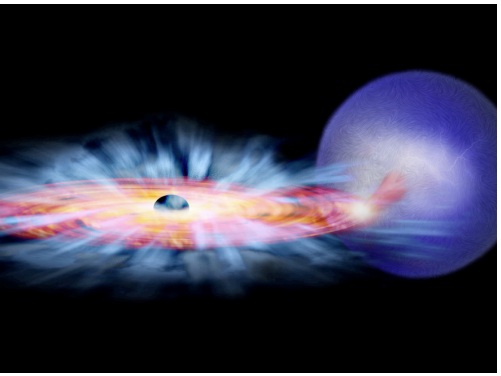
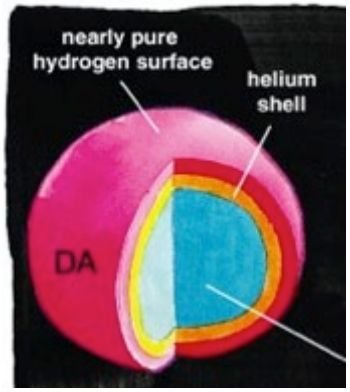
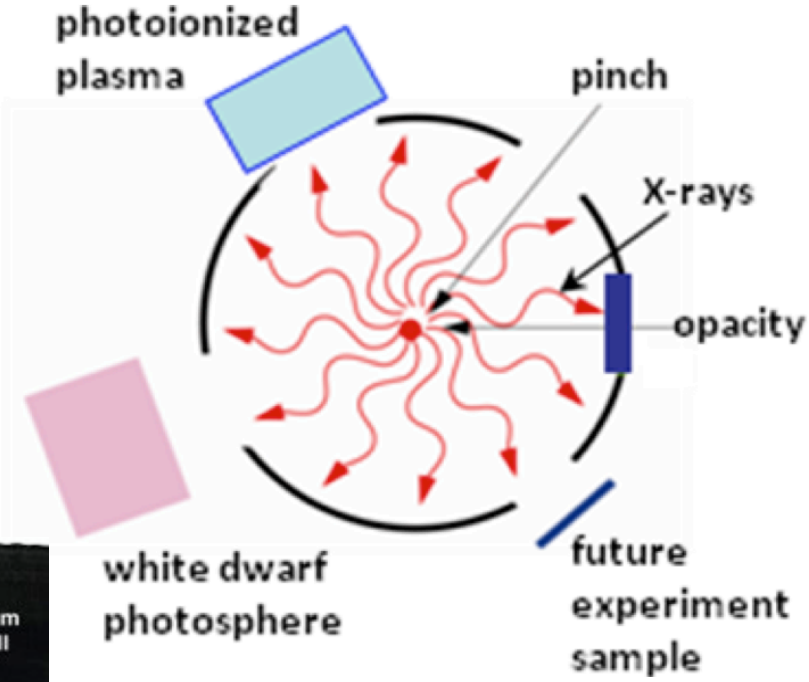


Photo-ionized plasmas

How does the accretion disk around a black-hole behave?



White Dwarfs

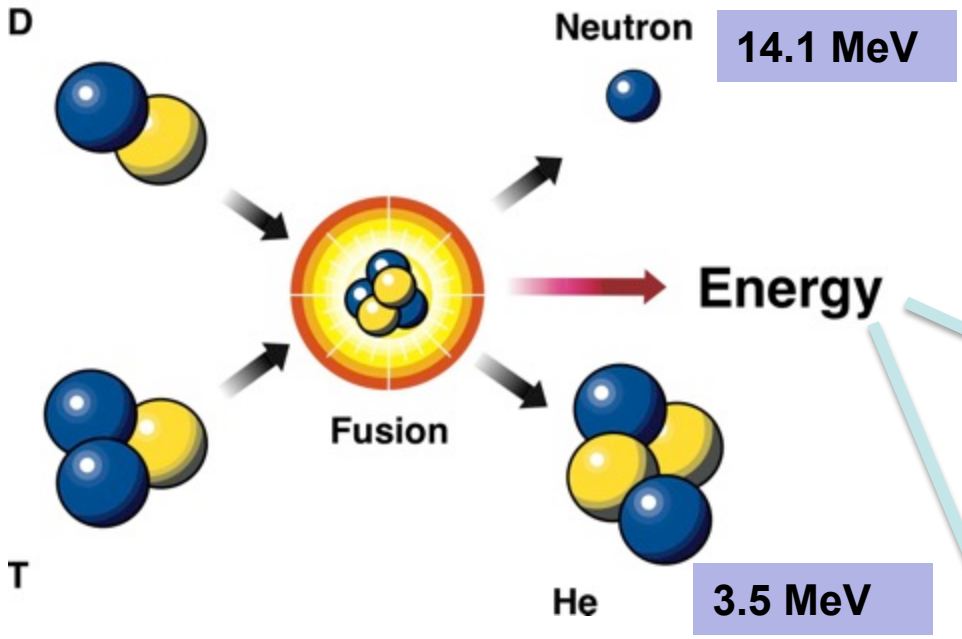


Can we use white dwarfs as cosmic chronometers?

Solar Opacities

Do we understand the structure of the sun?

The Fusion of 1 gram of Deuterium (D) and Tritium (T) results in the release of 340 GJ* of energy



Near term: National Security (Stockpile Stewardship (SSP) and avoid "technology surprise")

Longer term (~multiple decades) Inexhaustible "environmentally friendly " energy

~0.04% of DT mass converted into energy

*340 GJ ~ 80 tons of TNT

All fusion approaches require ≥ 50,000,000 °K, and there are two main approaches to plasma confinement

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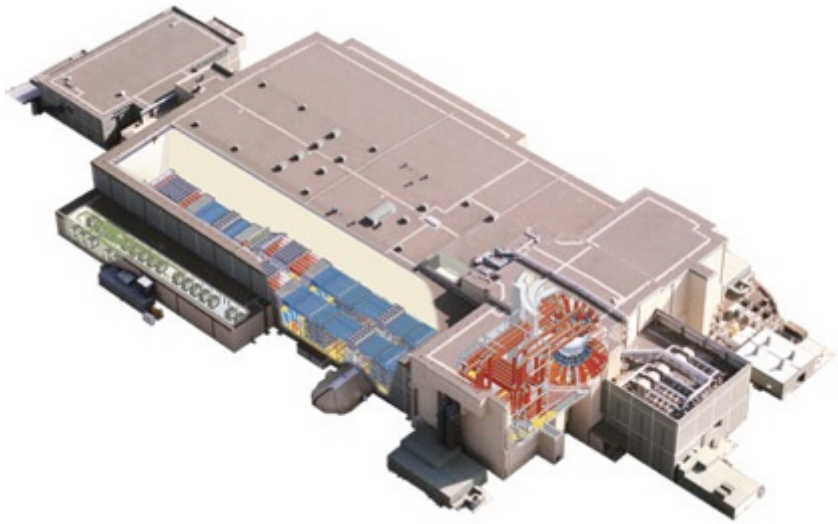
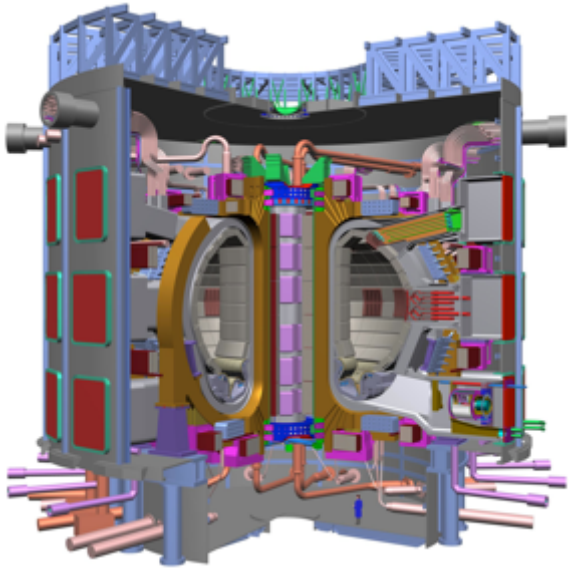
Inertial Confinement Fusion (ICF)
(United States dominant)



- Confinement: Plasma Inertia
  - Confinement time: ~ 10^{-10} sec
- Plasma Pressure: 5-300 Gbars
- Mission : National Security
  - Sponsor: DOE-NNSA
- Experiments: ongoing
- Capital cost: ~$3.5B+
- Operating cost ~$400M/yr

Magnetic Confinement Fusion (MFE)
(Europe and Asia dominant)



- Confinement: Magnetic Fields
  - Confinement time: ~ secs
- Plasma Pressure: ~1-3 Bars
- Mission: Energy
  - Sponsor: International
- Experiments: ~2030 (DT)
- Capital cost: ~$40-60B (US ~ $4.0-6.0B)
- Operating cost (est.) ~$2-3B/yr

We are studying a hybrid approach to achieving fusion on the Z facility, using both inertial confinement and magnetic fields called MagLIF

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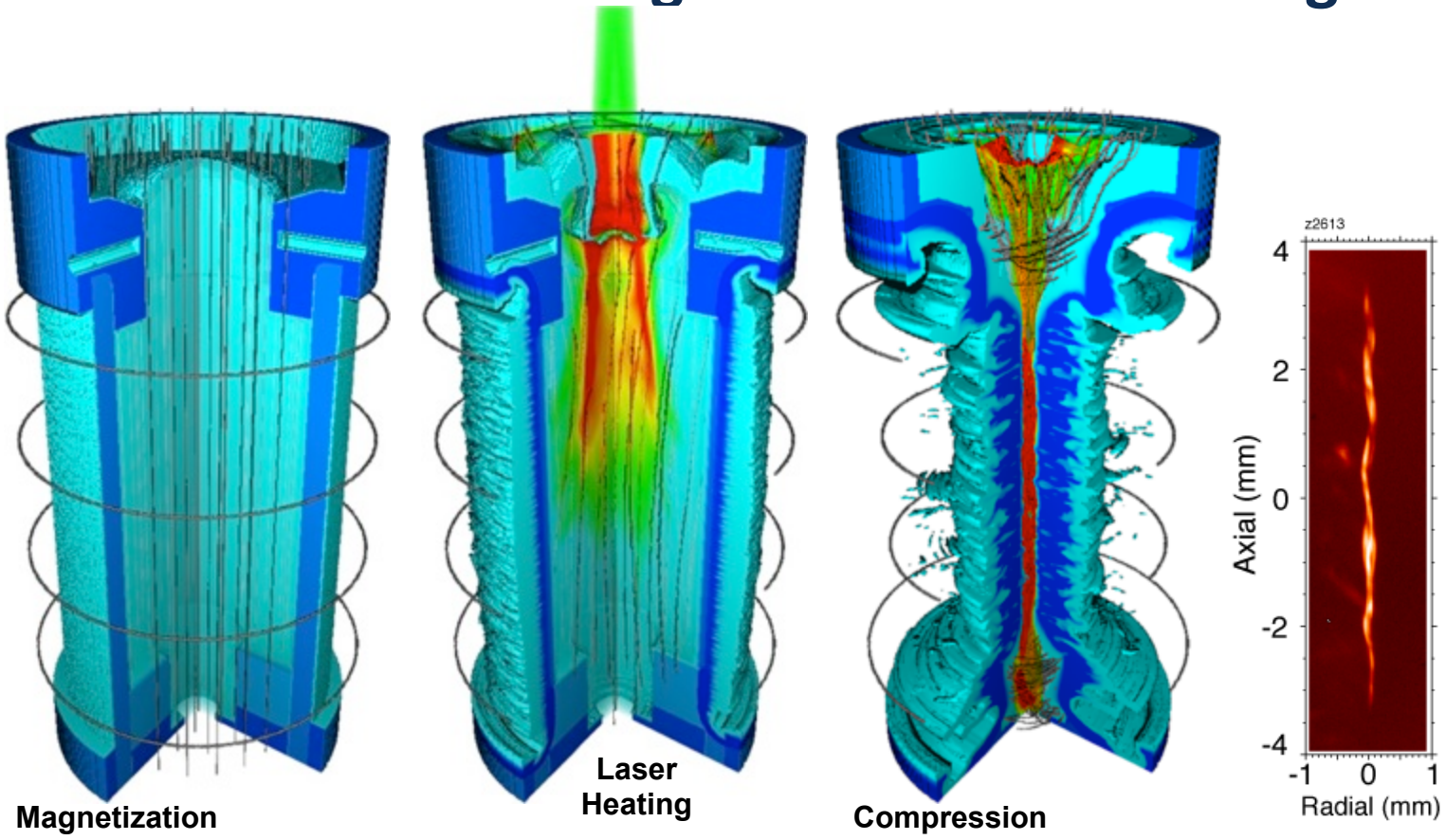

Initial experimental results are promising. Much more remains to be done.

A recent simulation of a MagLIF implosion illustrates the concept

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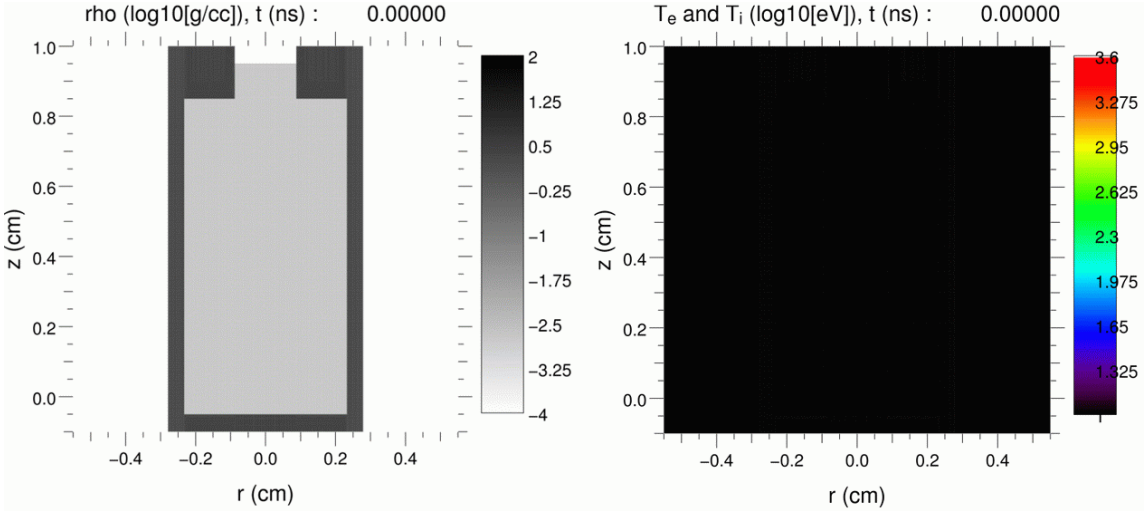
Log Density Map

Log Temperature Map



Log Pressure Map

Material Map

Example calculations by A. Sefkow, DD fuel, I=18MA, B_Z=10T, E_{LASER}=2.6 kJ

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