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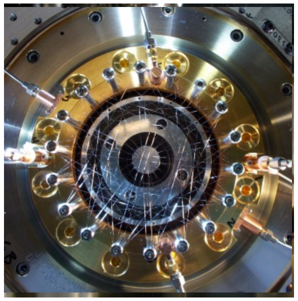

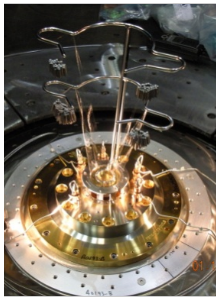

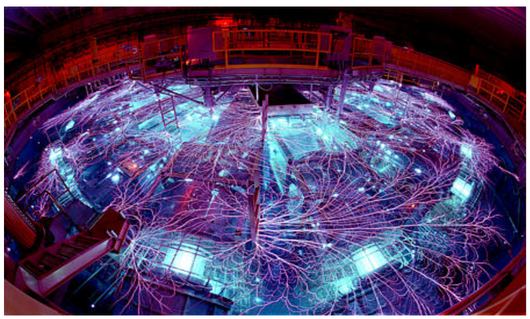

Sandia National Laboratories

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# High Energy Density Physics with Pulsed Power

Mike Cuneo

Senior Manager

Pulsed Power Science and Technology Group

mecuneo@sandia.gov

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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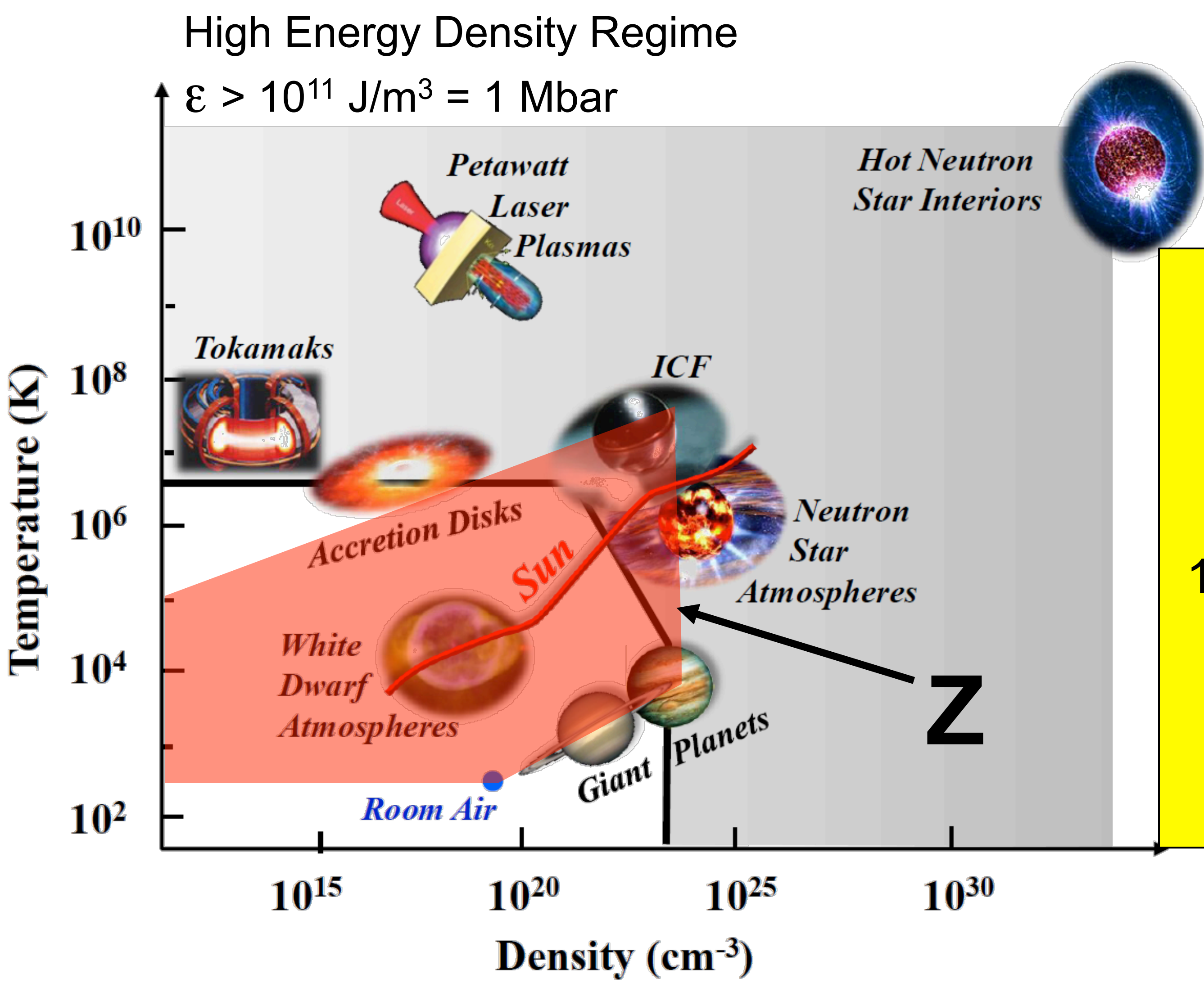
## Summary

- What is high energy density science?
- How do we generate high energy density conditions?
- What do we use high energy density for?
  - Discovery science at the forefront of what's possible in the laboratory
  - Developing and validating predictive models
  - Nuclear weapon relevant scientific work
  - Fundamental science
- Some example scientific results

Key takeaway: when we make measurements, ***almost without exception*** the measurements disagree with scientific predictions or expectations before the experiments

# High energy density is defined, somewhat arbitrarily, as a pressure of 1 Mbar




Pressure is equivalent to energy density

1 Mbar =
1.01e6 atmospheres =
1.e11 Pascals =
100 GPa =
5 MGauss
1.e11 J/m$^3$

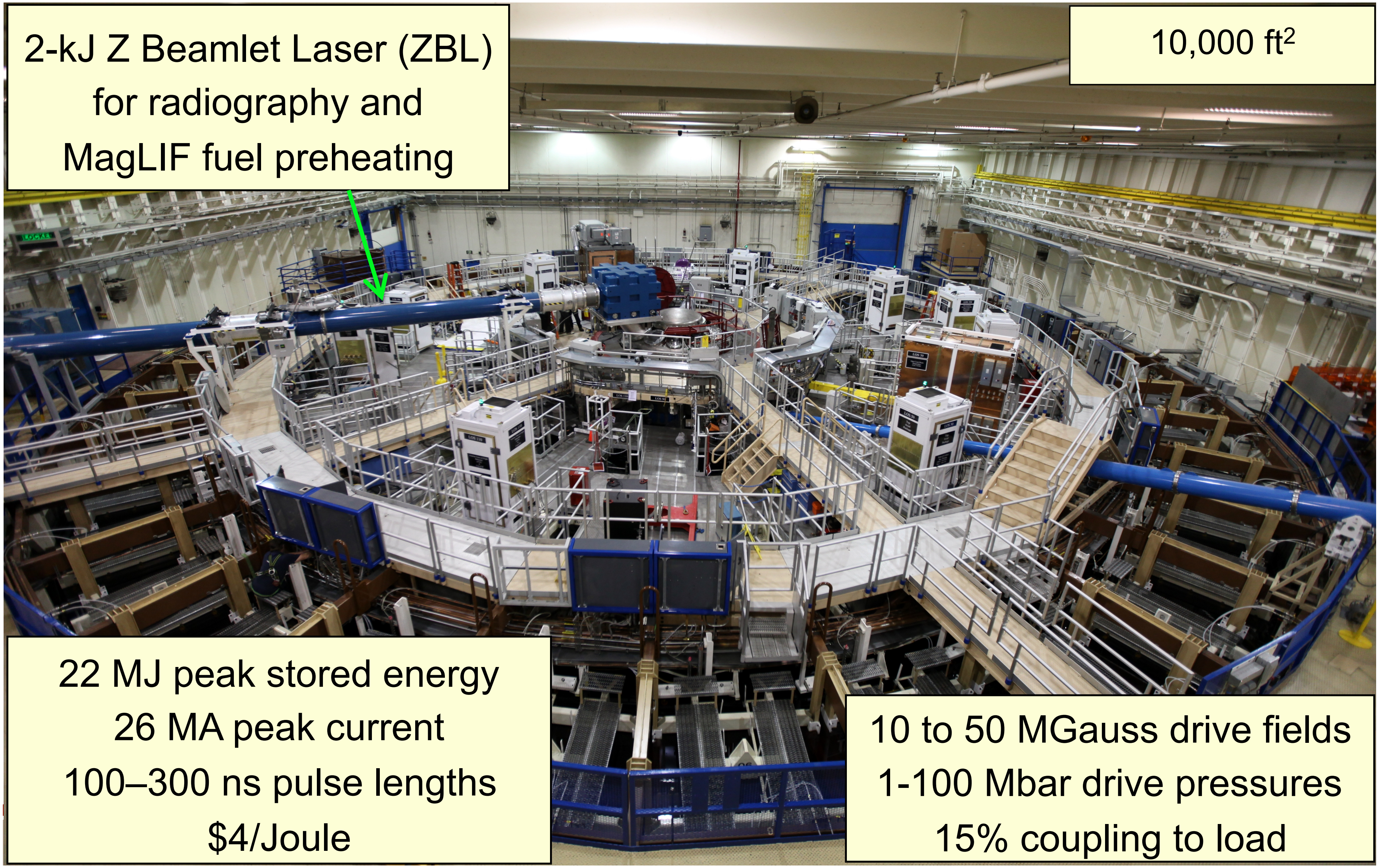
# Extreme conditions are present at pressures of 1 Mbar (100 GPa)

- Material strength
  - internal energy density of a hydrogen molecule
  - bulk moduli of solids (glass ~ 45 GPa, steel ~ 160 GPa, diamond ~ 440 Gpa)
- Energy density of electromagnetic field
  - photon intensity ~ 3e15 W/cm$^2$
  - thermal (blackbody) radiation field ~ 400 eV ~ 4.6e6 °K
  - electric field E ~ 1.5e11 V/m ~ 1.5e5 MV/m
  - magnetic field B ~ 500 T
- Plasma pressure
  - plasma density ~ 6e20 cm$^{-3}$ for 1 keV temperature
  - plasma density ~ 6e14 cm$^{-3}$ for 1 GeV particle energy
- Electron degeneracy pressure ~ 1.5e23 cm$^{-3}$ for cold plasmas
- Ablation (rocket) pressure
  - 1 µm laser ~ 4e12 W/cm$^2$
  - thermal radiation on plastic ~ 70 eV ~ 8.1e5 °K
- Magnetic pressure
  - 26 MA at 1 cm
  - 2.6 MA at 1 mm

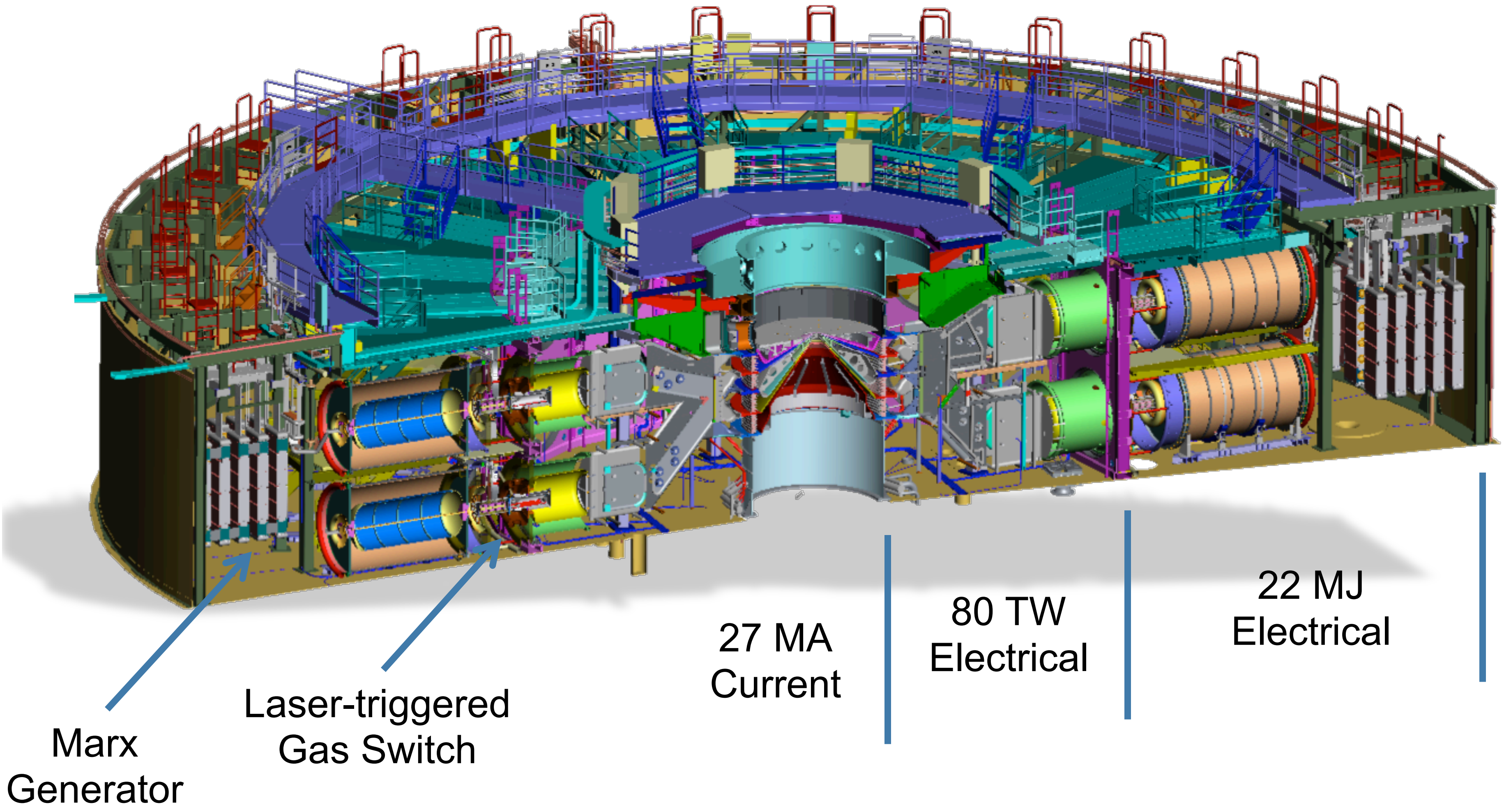


Reference: Frontiers of HEDP: The X-Games of Contemporary Science (2003)

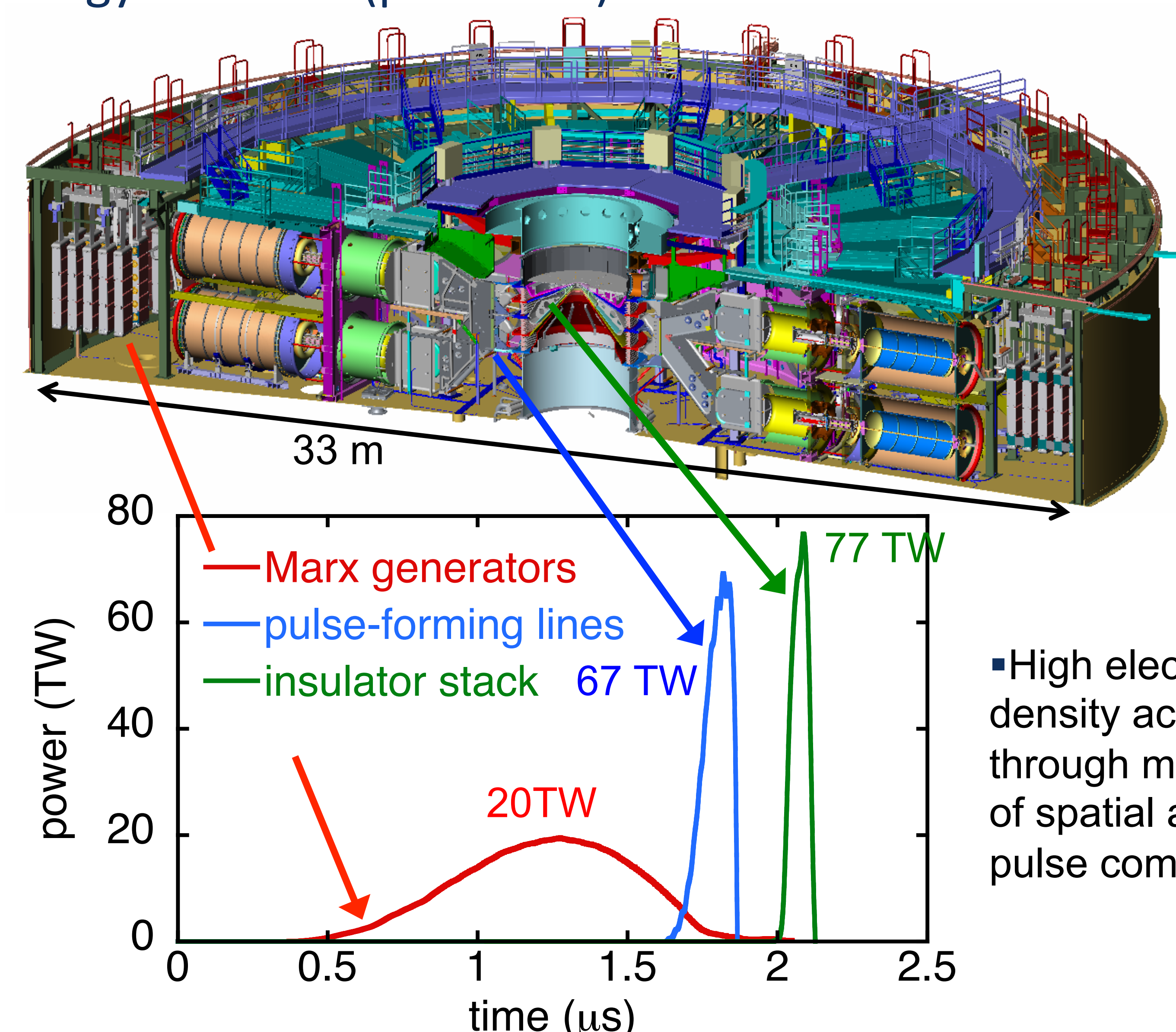
# The Z pulsed-power facility combines a compact MJ-class target physics platform (the Z accelerator) with a TW-class laser (ZBL)



# Cross section of the Z facility at Sandia National Laboratories



# Z works by compressing energy in space and time to reach high energy densities (pressures)



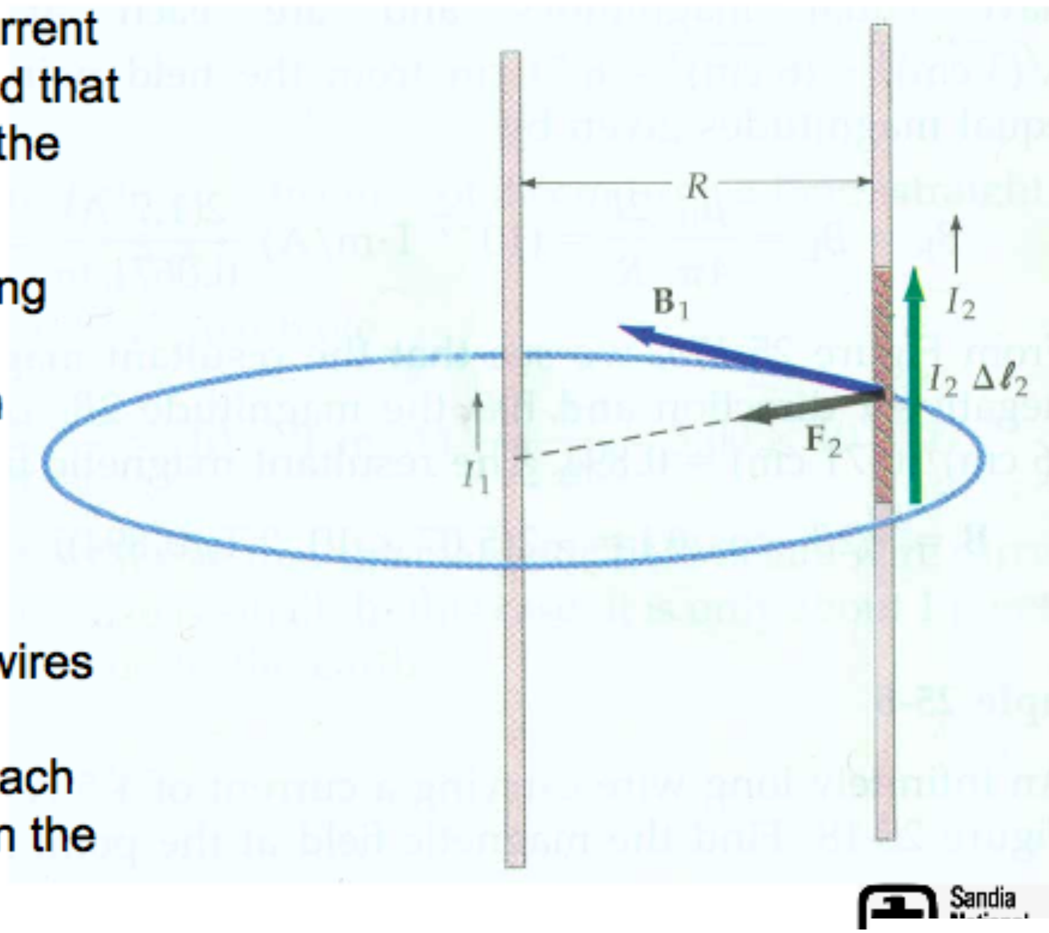

- High electrical power density achieved through multiple stages of spatial and temporal pulse compression

# 1st year physics refresher: the "pinch effect"

A single wire carrying current produces a magnetic field that encircles it according to the right-hand rule

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 force/length is 2e-7 N/m



## How strong is this pressure?

$N = kg\ m\ s^{-2}$ (mks) versus $dyne = g\ cm\ s^{-2}$ (cgs)

So $1\ N = 10^5\ dyne$, and, in pressure units:
$1\ N\ m^{-2}$ (Pa) $= 10\ dyne\ cm^{-2} = 10^{-5}\ bar$

$$P_m(dyne/cm^2) = \frac{B(G)^2}{8\pi}$$

A typical refrigerator magnet is 100 gauss ~ 400 dyne/cm$^2$

A 5000 G (0.5 T) magnetic field ~ $10^6$ dyne/cm$^2$ ~ 1 atmosphere ~ 1 Bar

A $5\text{x}10^6$ G (500 T) magnetic field ~ 1 Million atmospheres = 1 Megabar (MB)= High energy density physics ("HEDP")

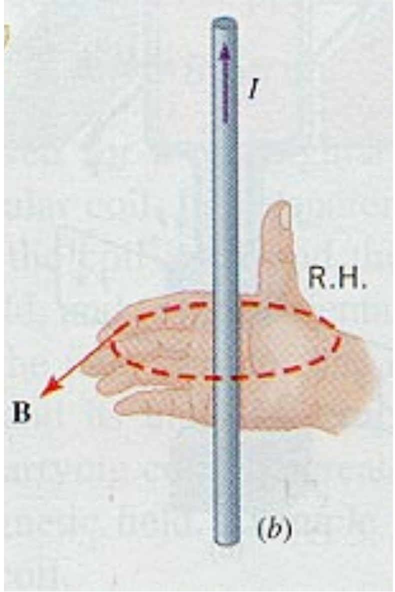
A $5\text{x}10^9$ G (500 kT) magnetic field ~ 1 Trillion atmospheres = 1 Terabar (TB) > pressure in the center of the sun

Note that high explosives have pressure ~ 100,000-300,000 atmospheres ~ 0.1-0.3 Mbar (not "HEDP") ~ equivalent ~50-150 T or $5\text{x}10^5$-$1.5\text{x}10^6$ G

# Large currents can create large B fields!

$$\nabla \times \mathbf{B} = \frac{4\pi \mathbf{J}}{c}$$

$$\oint_C \mathbf{B} \bullet dl = \frac{4\pi}{c} \iint_S \mathbf{J} \bullet d\mathbf{S}$$ Ampere's law




For an axial current I:

$$2\pi r B_\theta = \frac{4\pi}{c} I \qquad B_\theta = \frac{2}{c}\frac{I}{r} \quad (cgs)$$

$$B_\theta(G) = \frac{I(A)}{5\,r(cm)} \longrightarrow$$ **$P_{mag} \sim B^2 \sim I^2\, r^{-2}$**

100 A at 2 mm radius is 100 G

$1.0\text{x}10^7$ A (**10 MA**) at **4 mm** radius is $5\text{x}10^6$ G = **1 MBar** of pressure!

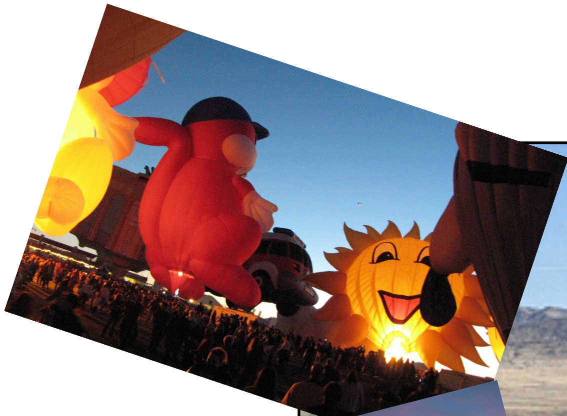
$2.5\text{x}10^7$ A (**25 MA**) at **1 mm** radius is $5\text{x}10^7$ G = **100 MBar** of pressure!! **← Z Machine**

*(~1000x more than high explosives)*

**LARGE CURRENTS → LARGE MAGNETIC FIELDS → LARGE PRESSURES!**

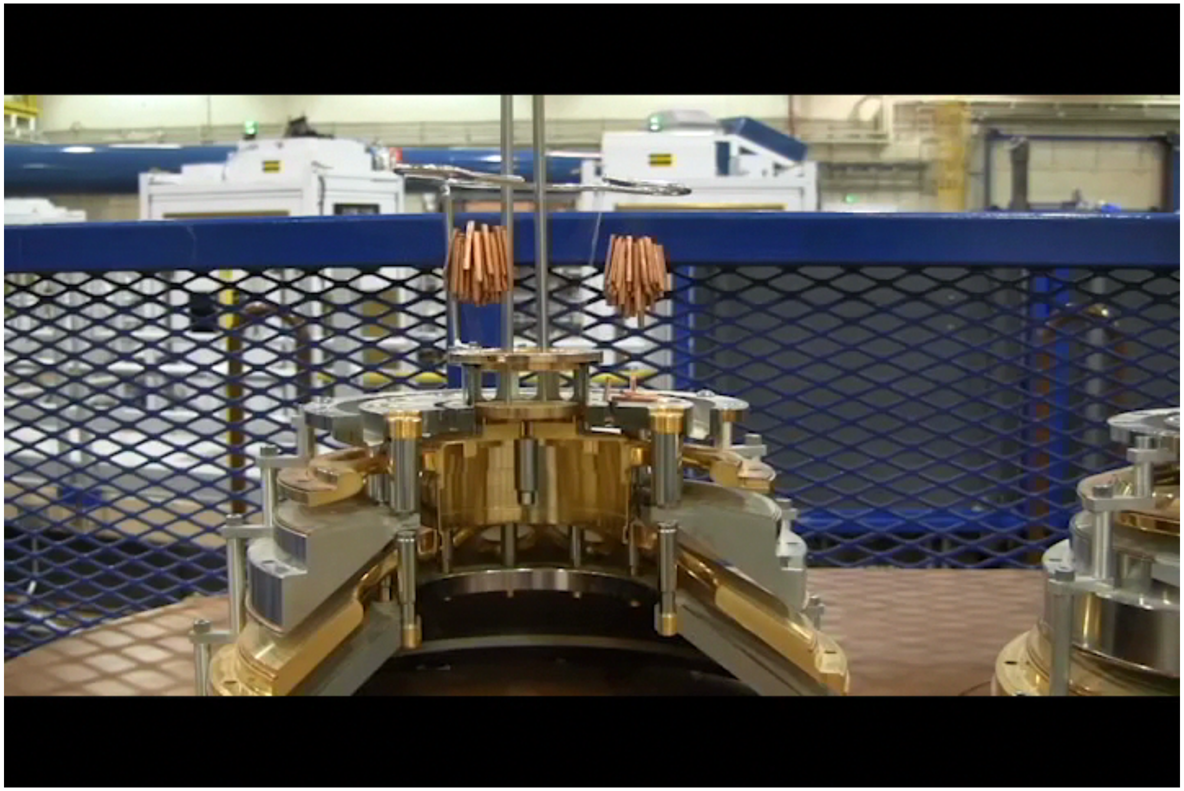
# The "Z" pulsed-power facility is located at Sandia National Laboratories in Albuquerque, New Mexico

Youtube.com: search for the BBC TV show:
"*Horizon: Can we make a star on earth*?"



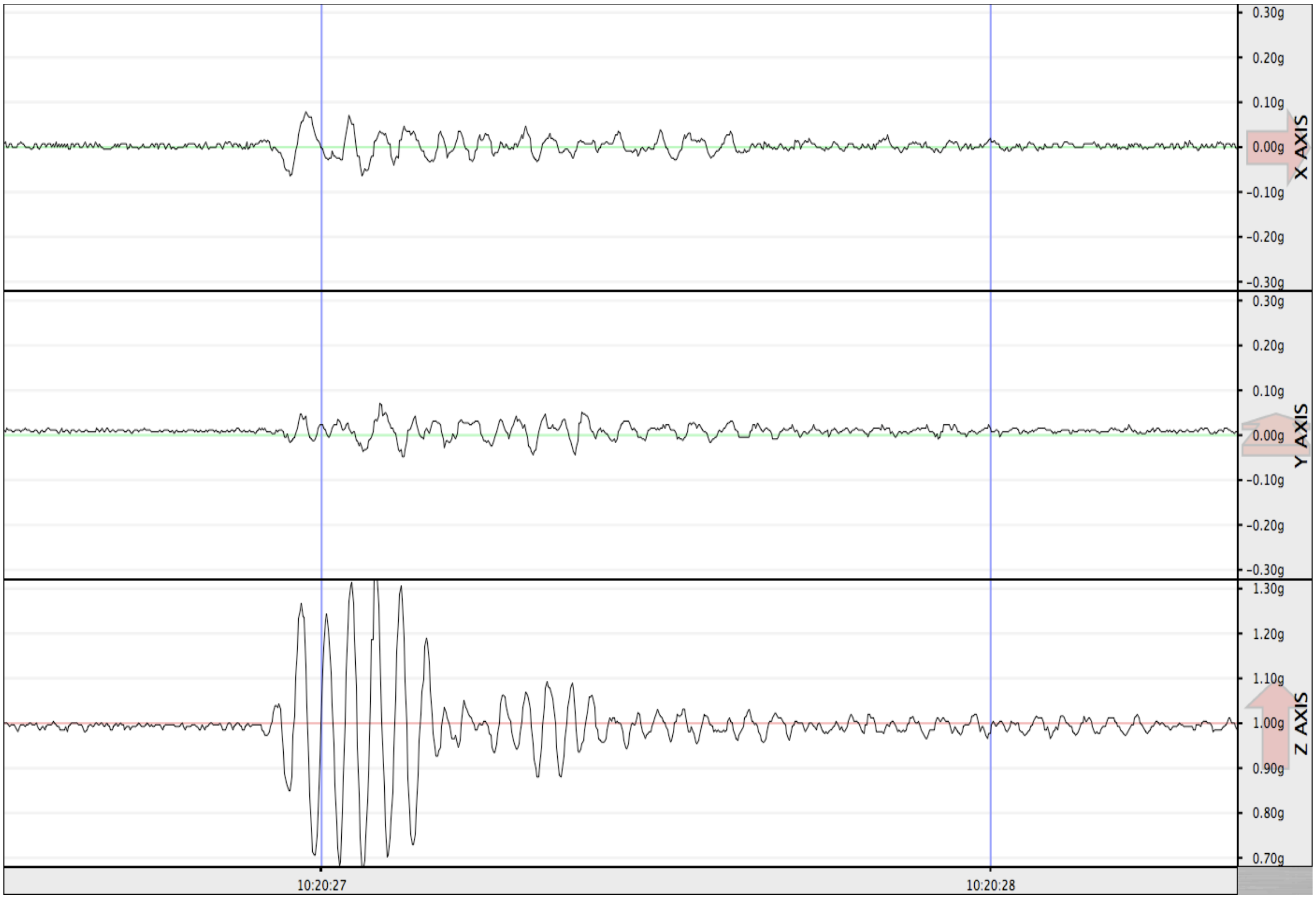
# The "Z" pulsed-power facility is located at Sandia National Laboratories in Albuquerque, New Mexico

# Z poses a challenging environment for experiments



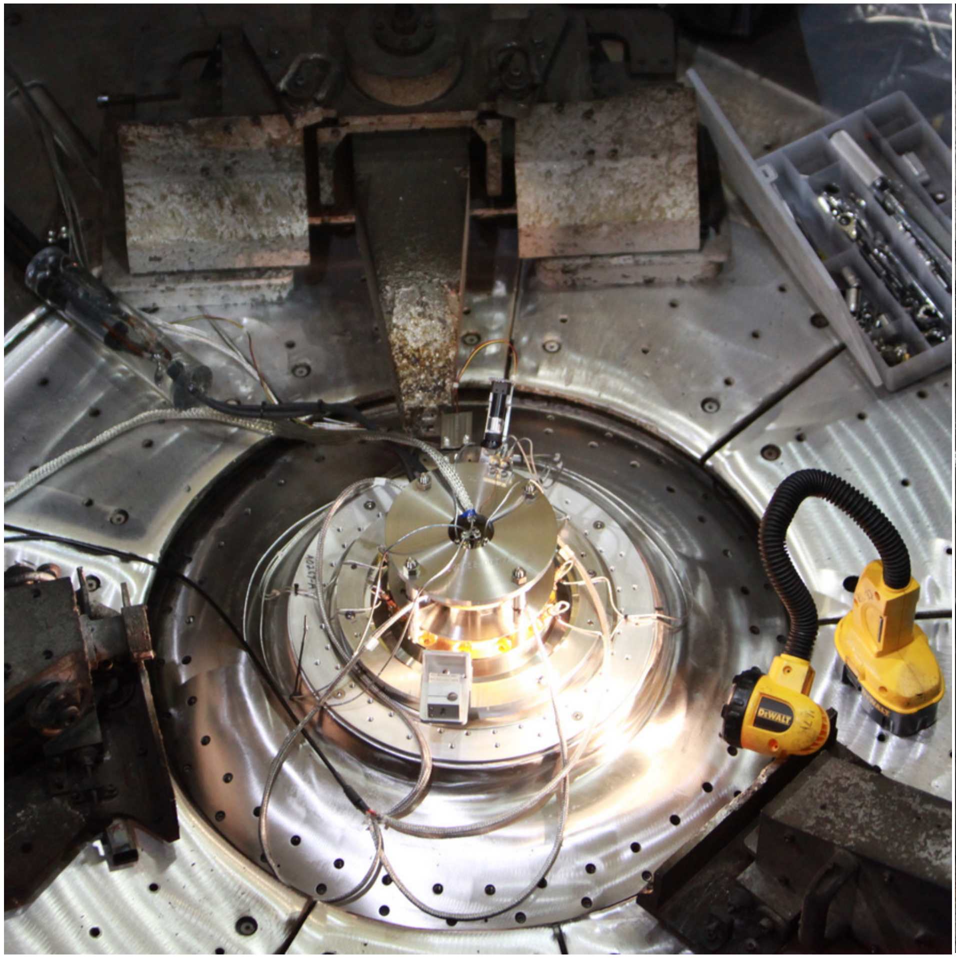
• 30 – 100 g instantaneous shock at center

# The ground shock is ±1g of acceleration over 200 ms




Seismac program

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

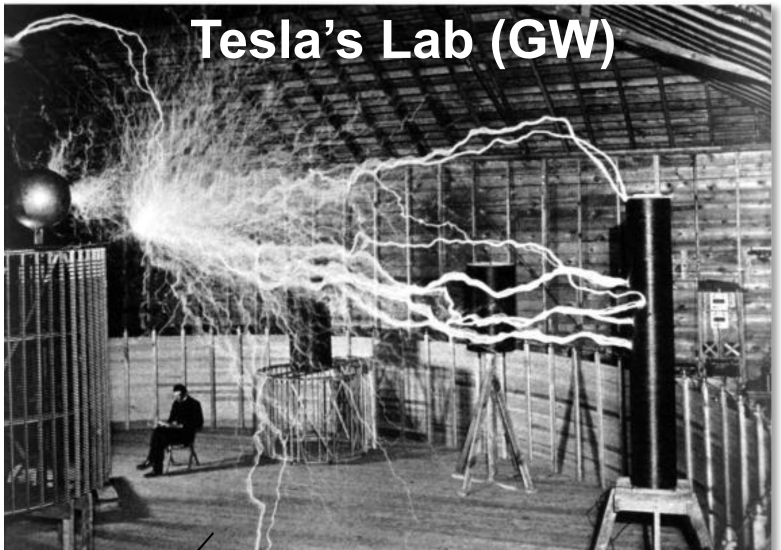


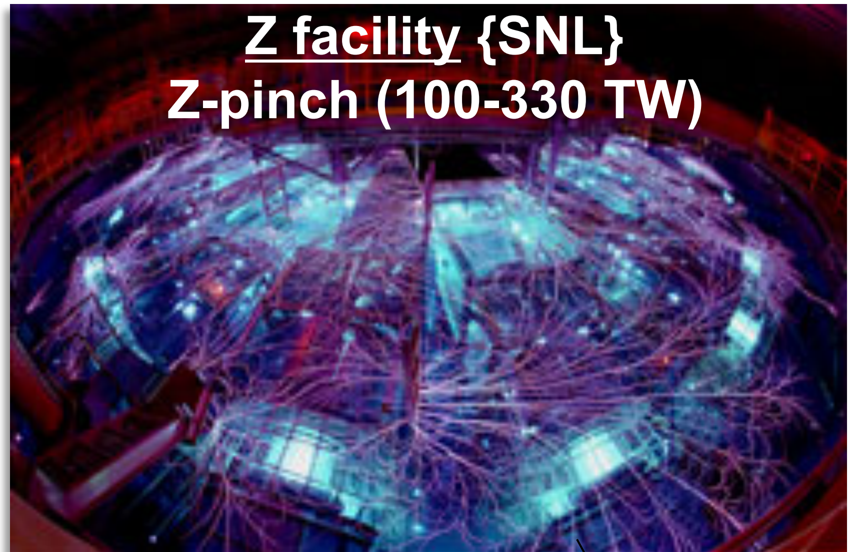
Pre-shot photo of coils & target hardware

Post-shot photo

**MagLIF Experiment**

# The accumulation and transmission of electromagnetic energy, called “pulsed power”, has been investigated for more than a century




Marx generator

WWII

Charlie Martin {AWE}
Hermes - II {SNL}
e-beam (TW)

PBFA - II {SNL}
Ion Beams (20 TW)

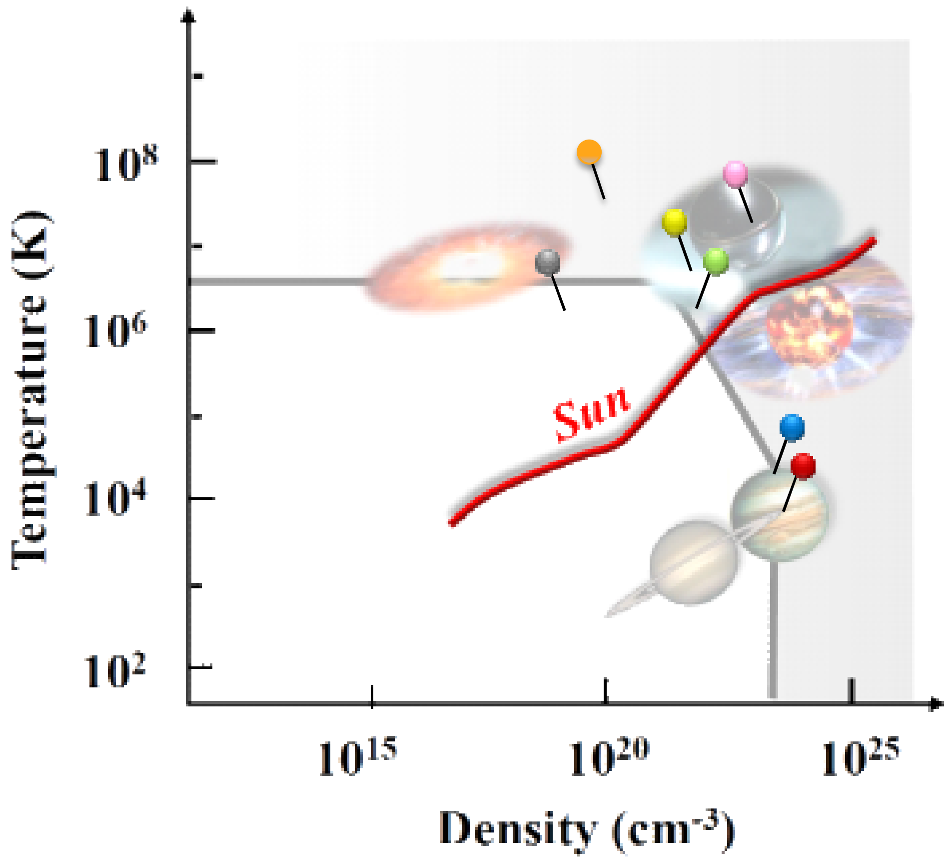
1900 | 1920 | 1940 | 1960 | 1980 | 2000

Radar (MW)
- Germany
- US
- Russia
- Great Britain

Angara - II {Russia}
Simulator (TW)

DARHT {LANL}
Radiography (10 GW)

# HED experiments on Z address issues of fundamental importance




- **Diamond at 10 Mbar**
  Knudson et al., Science 322 (2008)
- **$D_2$ EOS at 1 Mbar**
  Knudson et al., PRL 87 (2001)
- **Photoionized Plasmas**
  Foord et al., PRL 94 (2004)
- **Radiating Shocks**
  Rochau et al., PRL 100 (2008)
- **Opacity at $T_e$ > 150 eV**
  Bailey et al., PRL 99 (2007)
- **Fusing Plasmas**
  Bailey et al., PRL 93 (2004)
- **High-Z Ion Radiating Plasmas at 40 Mbar**
  Ampleford et al.. submitted PoP (2013)

# Pulsed power generates amazing conditions in the laboratory

Peak currents of 10 – 25 Mega Amperes

Electromagnetic energy of 1 – 2 Mega Joule

Magnetic fields of 0.1 – 5 Mega Gauss

Magnetic pressures of 1 – 100 Mega bar

Accelerations and decelerations of 1 Tera g's

Implosion velocities of 0.1 – 1 Mega meters/sec

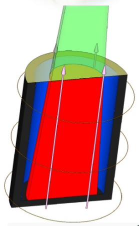
Plasma stagnation temperatures of 10 – 50 Mega kelvin

Plasma stagnation pressures of 1 Mega Bar to 1 Giga Bar

# The stockpile stewardship is divided into a broad portfolio of "science campaigns" with diverse requirements

Dynamic Materials Properties

Materials of interest at pressure and temperatures of interest

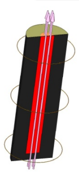


Inertial Confinement Fusion

Researching into creating "self-heating or burning plasmas"

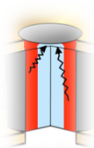
Radiation Effects Sciences

Study the impact of radiation on circuits and components?



Primary Assessment

Simulate and study process of importance in NW primaries



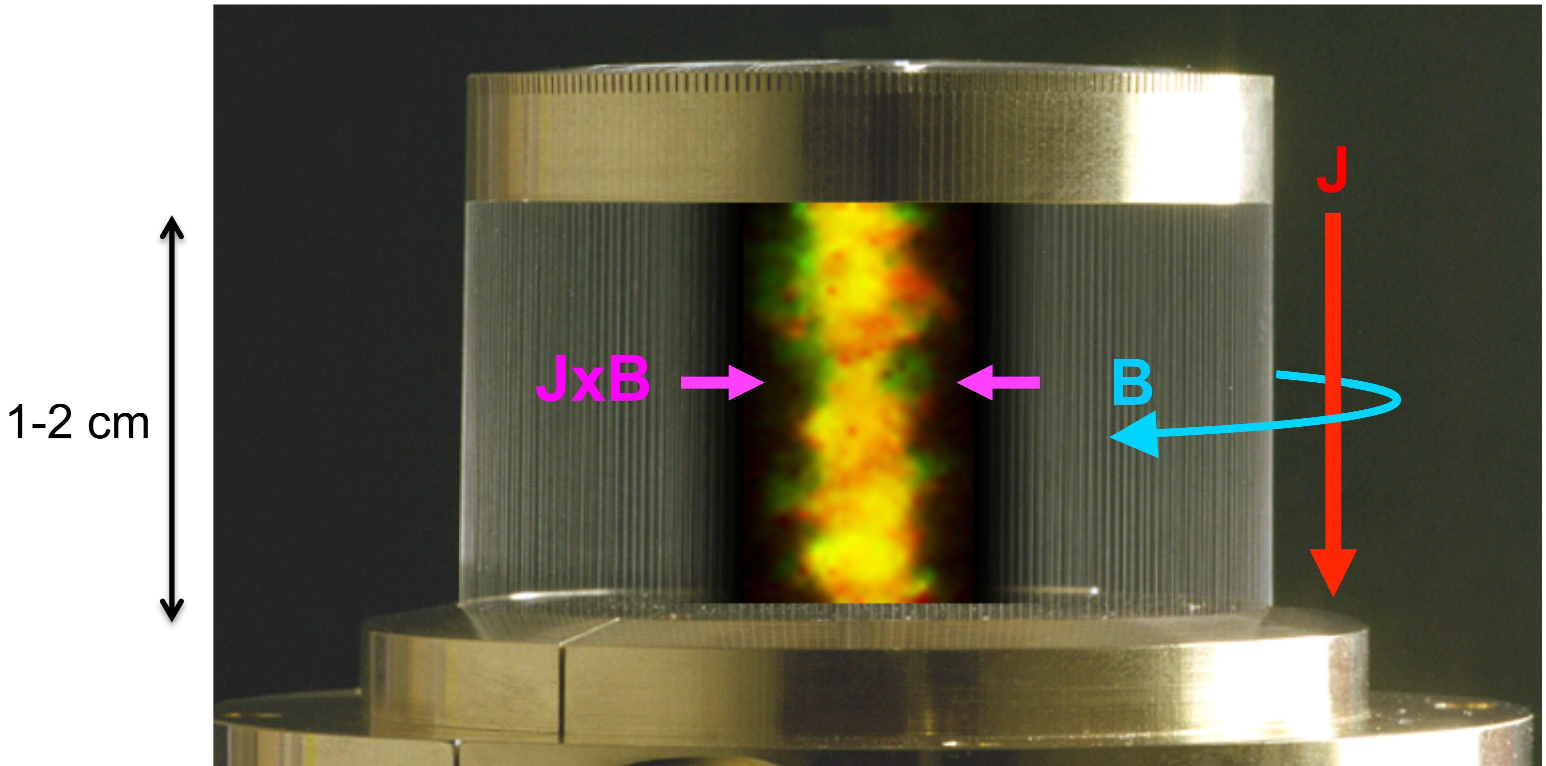
Secondary Assessment

Simulate and study process of importance in NW secondaries

Fundamental Science

Use the conditions to study basic science questions in astrophysics, geophysics, plasma, atomic physics

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




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

~ 10-15% wall plug efficiency

# We employ energies of ~ 1 MJ in every day objects

An energy of 1 MJ:

- Kinetic energy of F150 at ~60 mph
- 0.48 x energy in a stick of dynamite
- 100 W incandescent light bulb uses 1 MJ in 4.3 hours

A velocity of 500 km/sec:

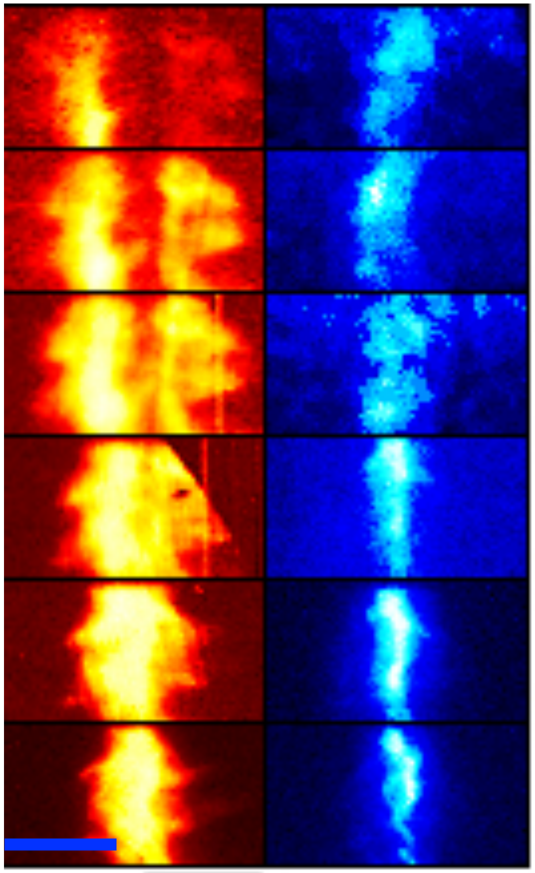
- ~ 1,100,000 miles per hour
- New York to LA in ~ 8 seconds
- 1/600 speed of light

- $m_{F150}$ = 2950 kg
- $v_{F150}$=94 km/hour (58 mph)
- E = 1 MJ
- In a typical z-pinch, this 1 MJ is released in 5 ns

# Self-emission x-ray imaging shows that magnetically driven implosion generates large volumes (10 to 100 mm$^3$) of hot plasma

Z1596 SS

277 eV | K-shell

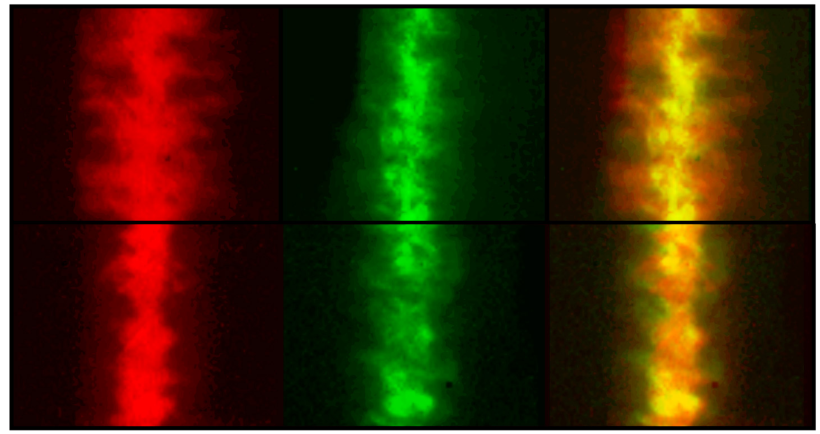


-3 ns
-2 ns
-1 ns
0 ns
+1 ns
+2 ns

5 mm

Z1519, Al

277 eV | 1.7 keV Al K-shell | Overlay



-2.3 ns
+3.2 ns

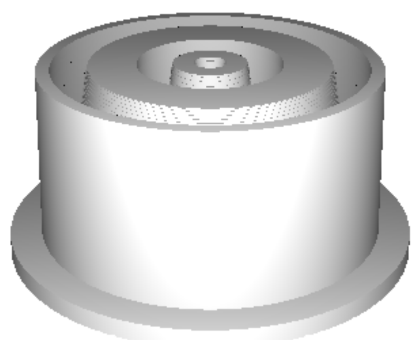
- As noted previously,
  - Evidence of instability at stagnation
  - Observed structure varies with atomic number
- Hot, dense column emitting K-shell on axis with colder material still imploding

# Numerical modeling tools are mature and complement Z gas puff experiments

- Cold gas flow models may be validated using experimental interferometer data

- Benchmarked simulated profiles can be used to initiate MHD simulations

- Tabulated atomic data are used to estimate K-shell x-ray outputs



C.A. Jennings, SNL, GORGON

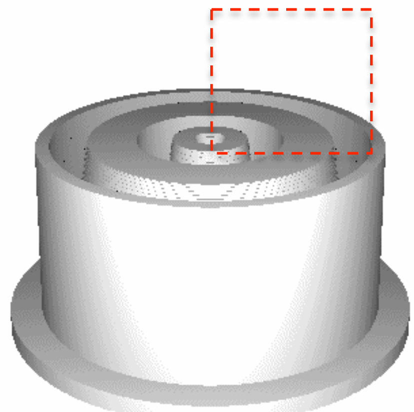
- Pre-shot NRL modeling [Thornhill *et al*., HEDP **8**, 197 (2012)] was consistent with SNL Gorgon simulations (Jennings)

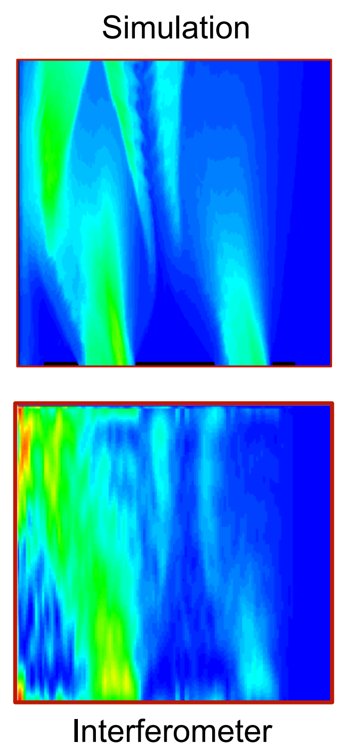
# Numerical models are being used to design experiments and benchmarked post-shot to gain physics insight

- Cold gas flow models may be validated using experimental interferometer data

- Benchmarked simulated profiles can be used to initiate MHD simulations

- Tabulated atomic data are used to estimate K-shell x-ray outputs

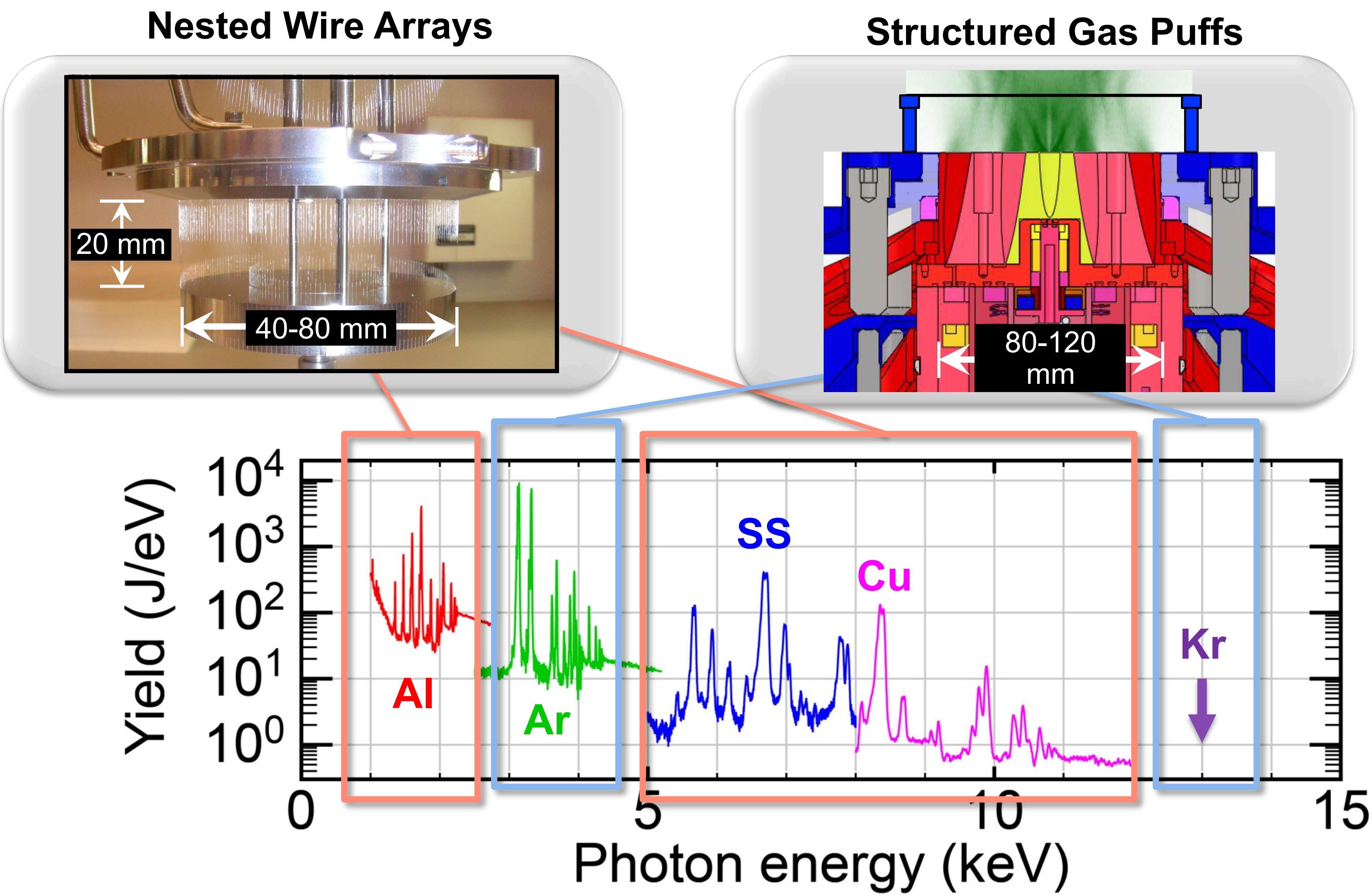





C.A. Jennings, SNL, GORGON

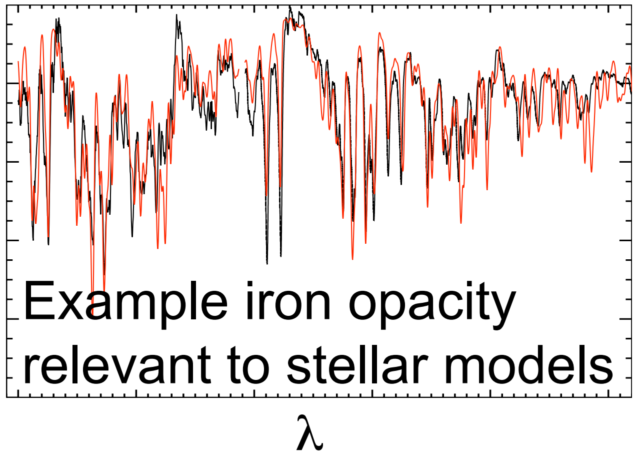
- Pre-shot NRL modeling [Thornhill *et al*., HEDP **8**, 197 (2012)] was consistent with SNL Gorgon simulations (Jennings)

# Magnetically-driven implosions to ~500–1000 km/s are used to access K-shell emissions from different materials

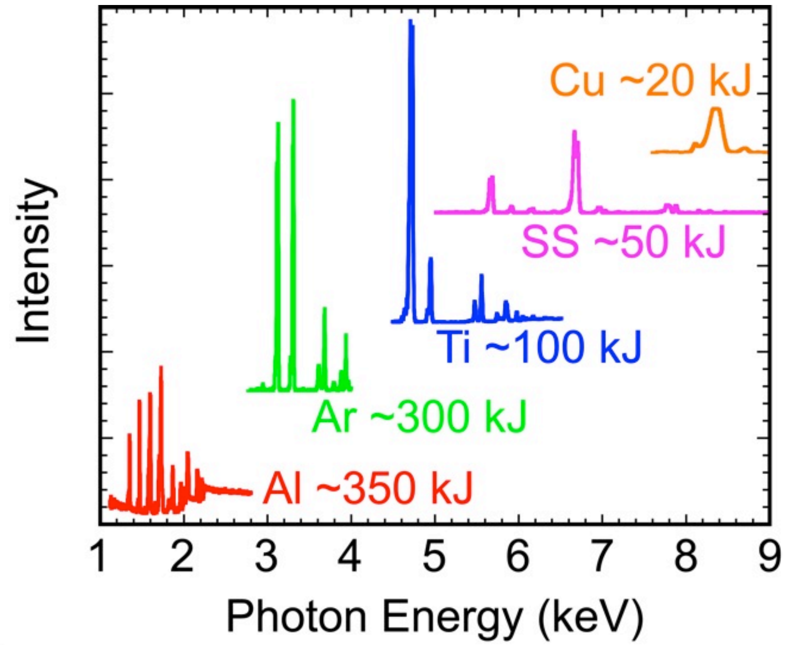


# Magnetically-driven x-ray sources are being used for a variety of fundamental and applied science applications

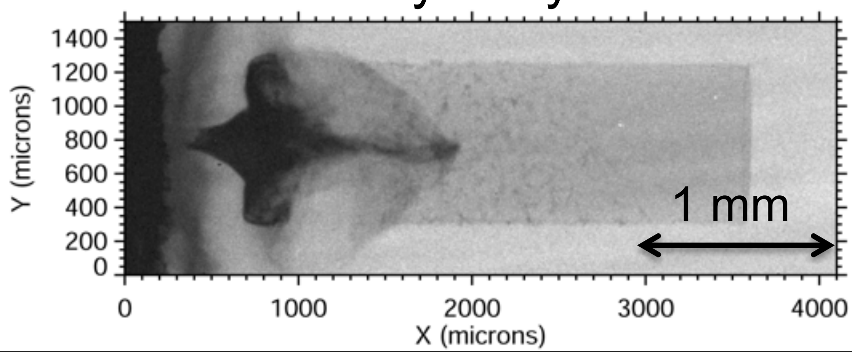
## Opacity Measurements and Photo-ionized plasmas [1]

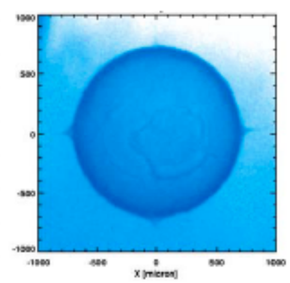



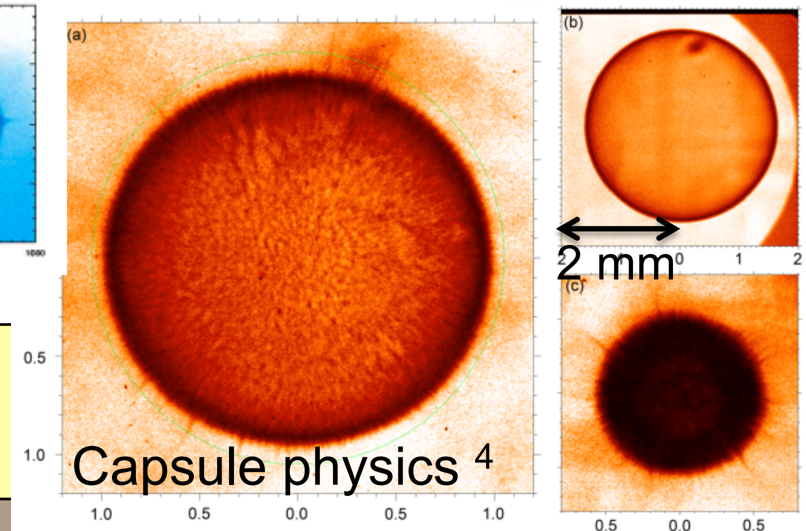

## K-Shell Sources [3]




## Radiation Hydrodynamics [2]



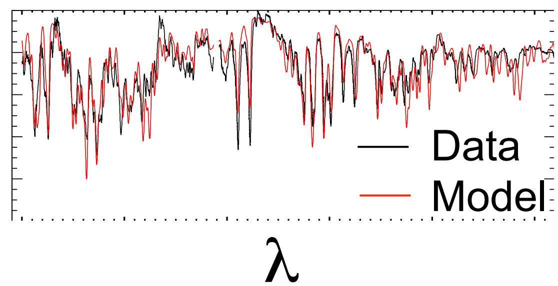


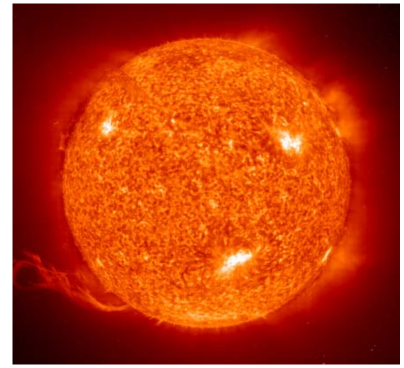

[1] J.E. Bailey, et al, Phys. Rev. Lett. 99, 265002 (2007).
[2] G.R. Bennett, et al., Phys. Rev. Lett. 205003 (2007).
[3] C. A. Coverdale et al., IEEE T. Plas. Sci. 35, 582 (2007).
[4] M.E. Cuneo et al., IEEE T. Plas. Sci. 40, 3222 (2012).

# Magnetically-driven x-ray sources are being used for a variety of fundamental and applied science applications

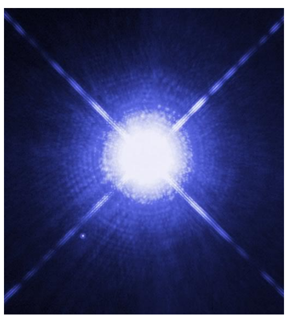
**Solar opacity at $T_e$ > 150-170**

Bailey et al., PRL 99 (2007)



**White dwarf physics**



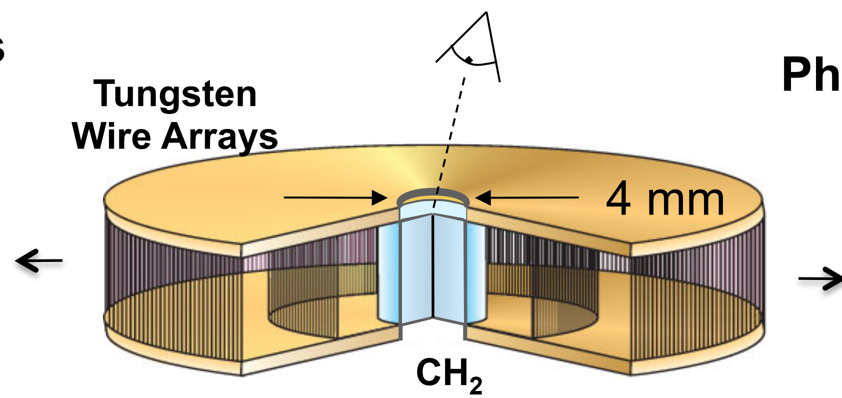
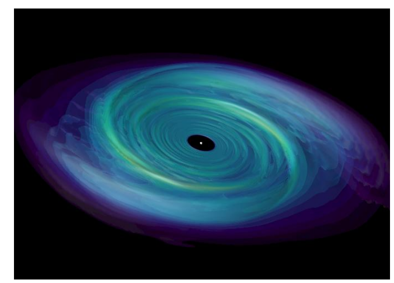


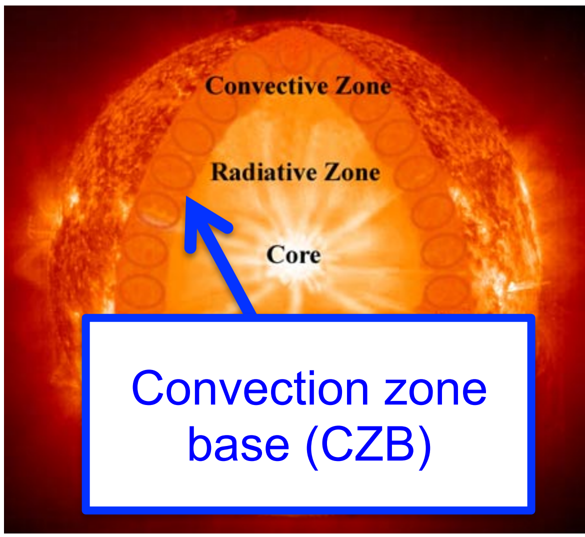

**Photo-ionized plasmas**

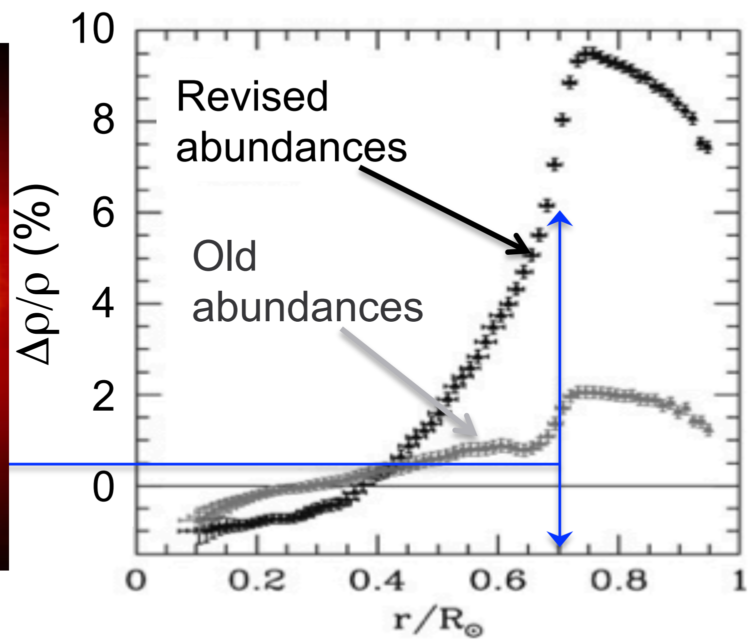


- 1 μg of stellar interior at R ~ 0.7Rsol
- $10^{-3}$ liters of accretion disk at R ~ 100 – 1000 km from black hole
- ~0.1 liters of white dwarf photosphere
- weapons science

# Z iron opacity experiments refine our understanding of the sun, stars, and laboratory HED systems

- Opacity is the fundamental property that controls photon absorption in matter
- Opacity model uncertainty has been proposed as an explanation for the decade old problem that solar models do not match helioseismic observations




Solar problem arose with abundance revision in ~ 2000

Stellar composition and opacity are intertwined

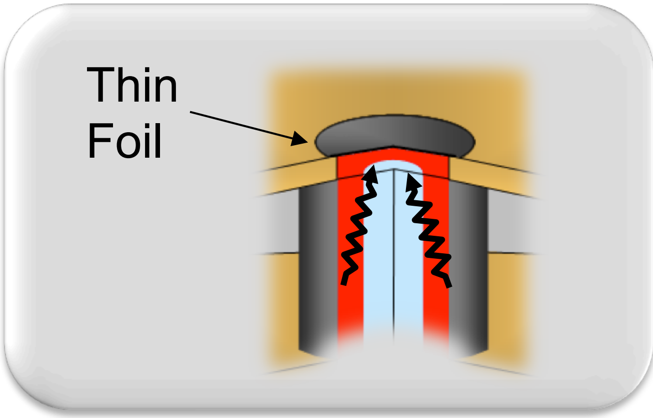
Problem resolved if mean opacity ~15% higher than predicted

- **Conditions at the solar CZB : 182 eV, 9e22 electrons/cc**
- **Similar conditions exist in many astrophysical and laboratory plasmas**
- **Thus, solar opacity model refinements have far-reaching implications**

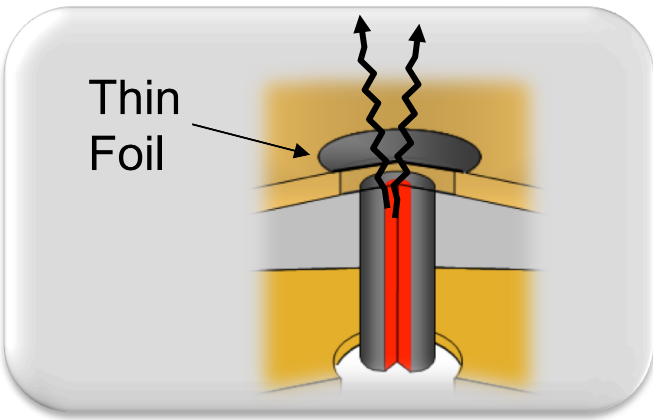

Basu *et al*, Physics Reports (2008). Asplund *et al*, Annu. Rev. Astro. Astrophys. (2005).

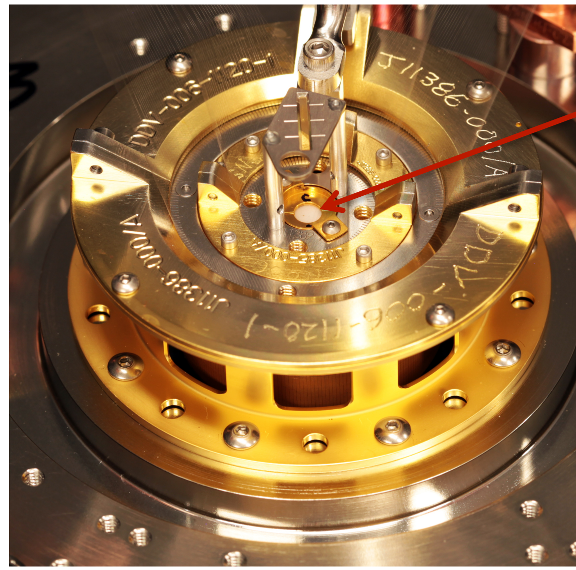
# The ZPDH radiating shock is used to both heat and backlight samples to stellar interior conditions.

**Foil is heated during the ZPDH implosion**




**Foil is backlit at shock stagnation**

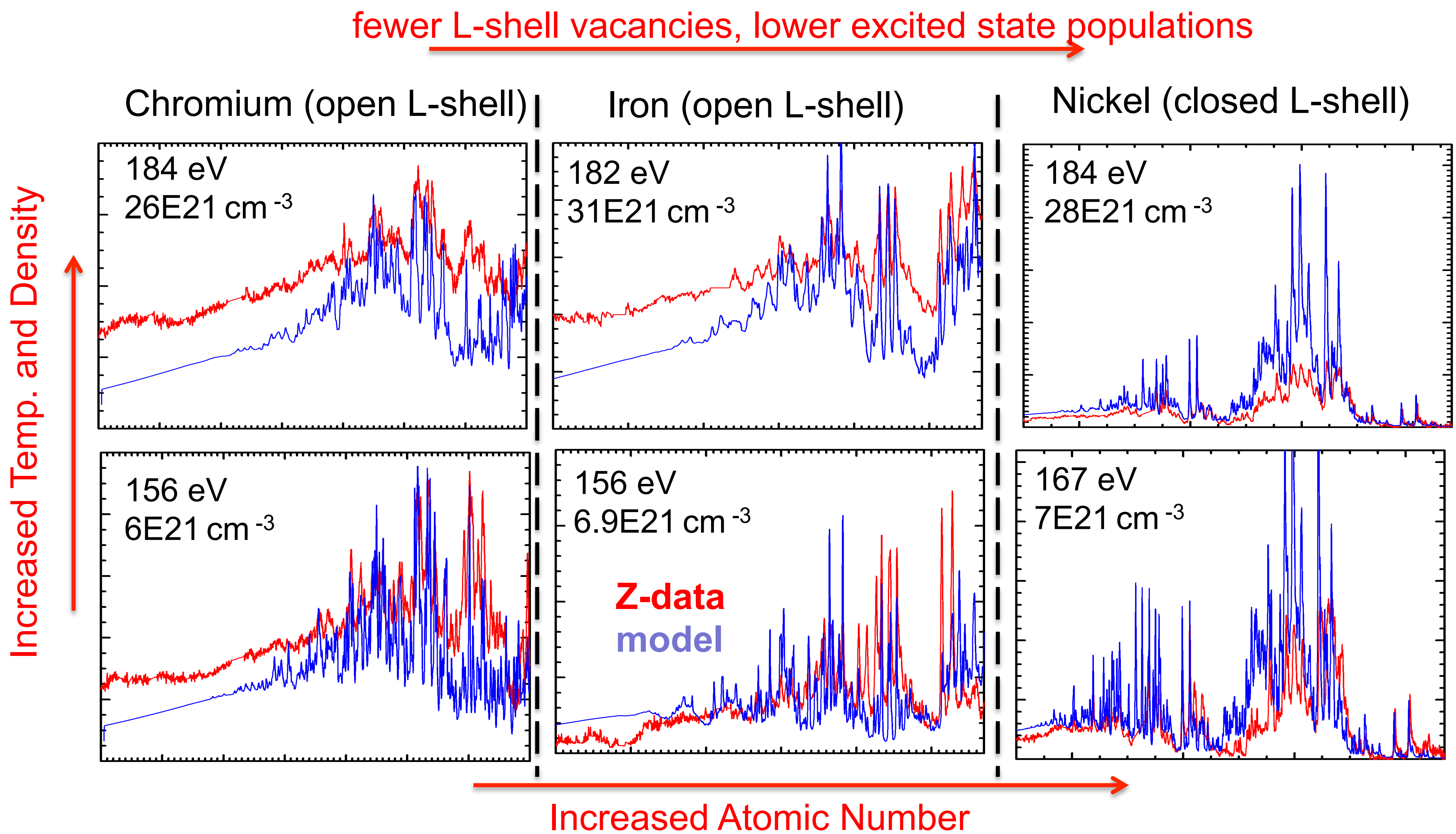




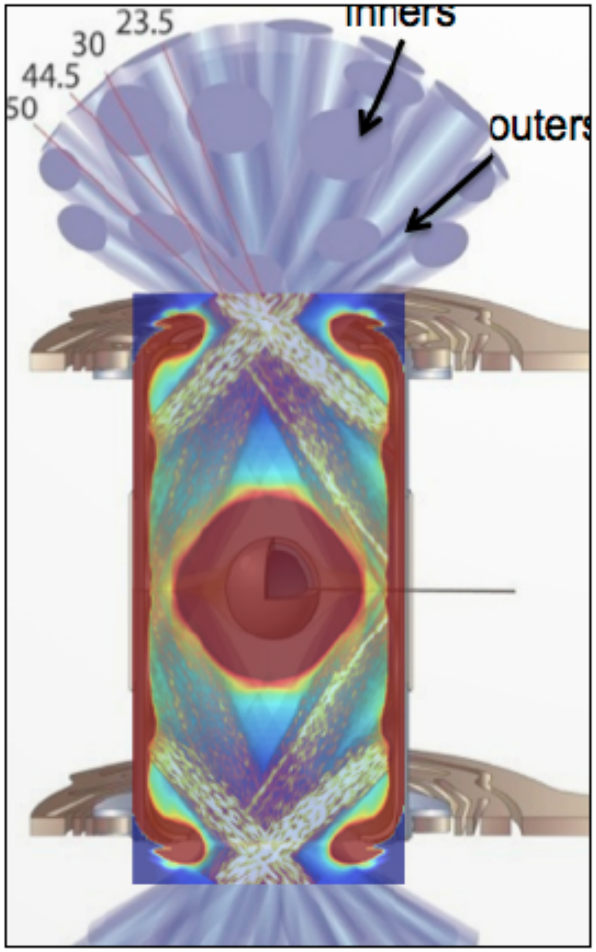

Bailey et al., *Nature* 2015

# Photon absorption in HED matter is different than expected: atomic physics models must be improved

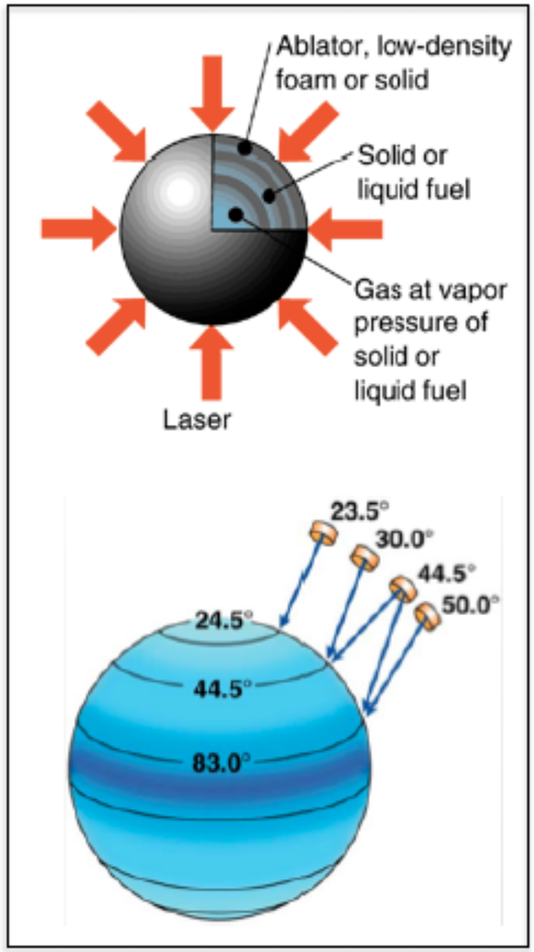


# The United States ICF program has focused on three main approaches

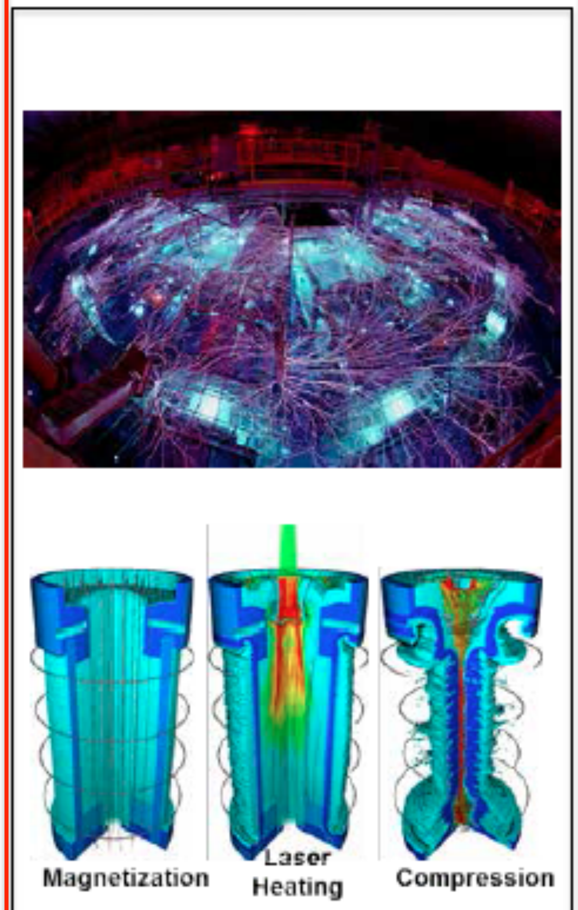
**Radiation-driven implosions**



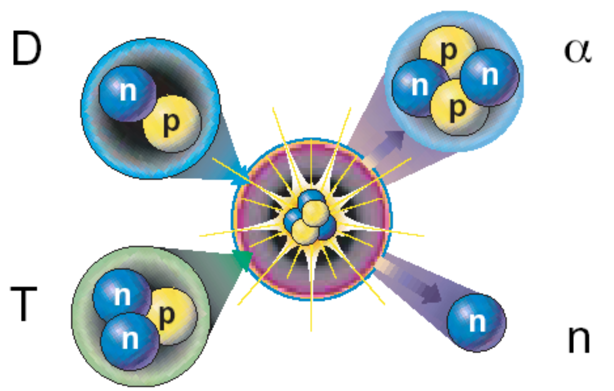

**Laser-driven implosions**




**Magnetically-driven implosions**

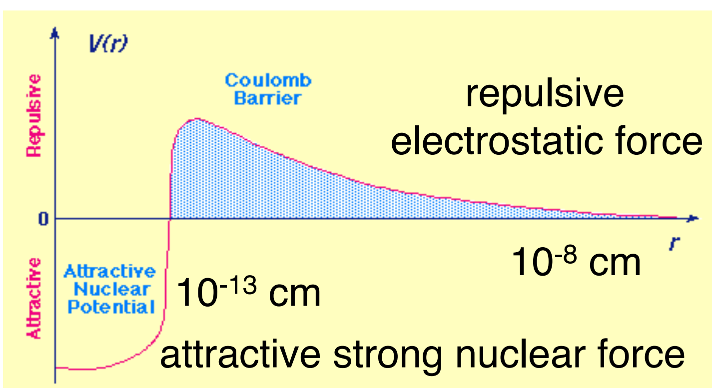


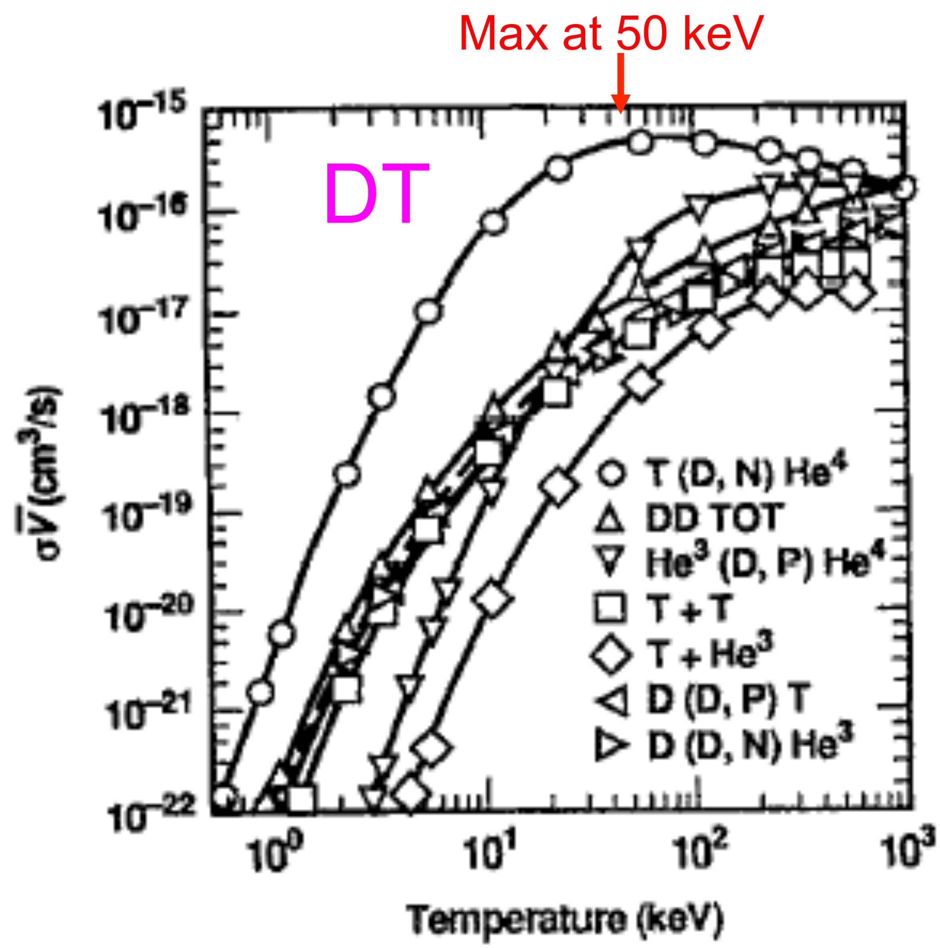
# Thermonuclear fusion requires high temperatures to overcome the Coulomb barrier




$$D + T \rightarrow \alpha + n$$

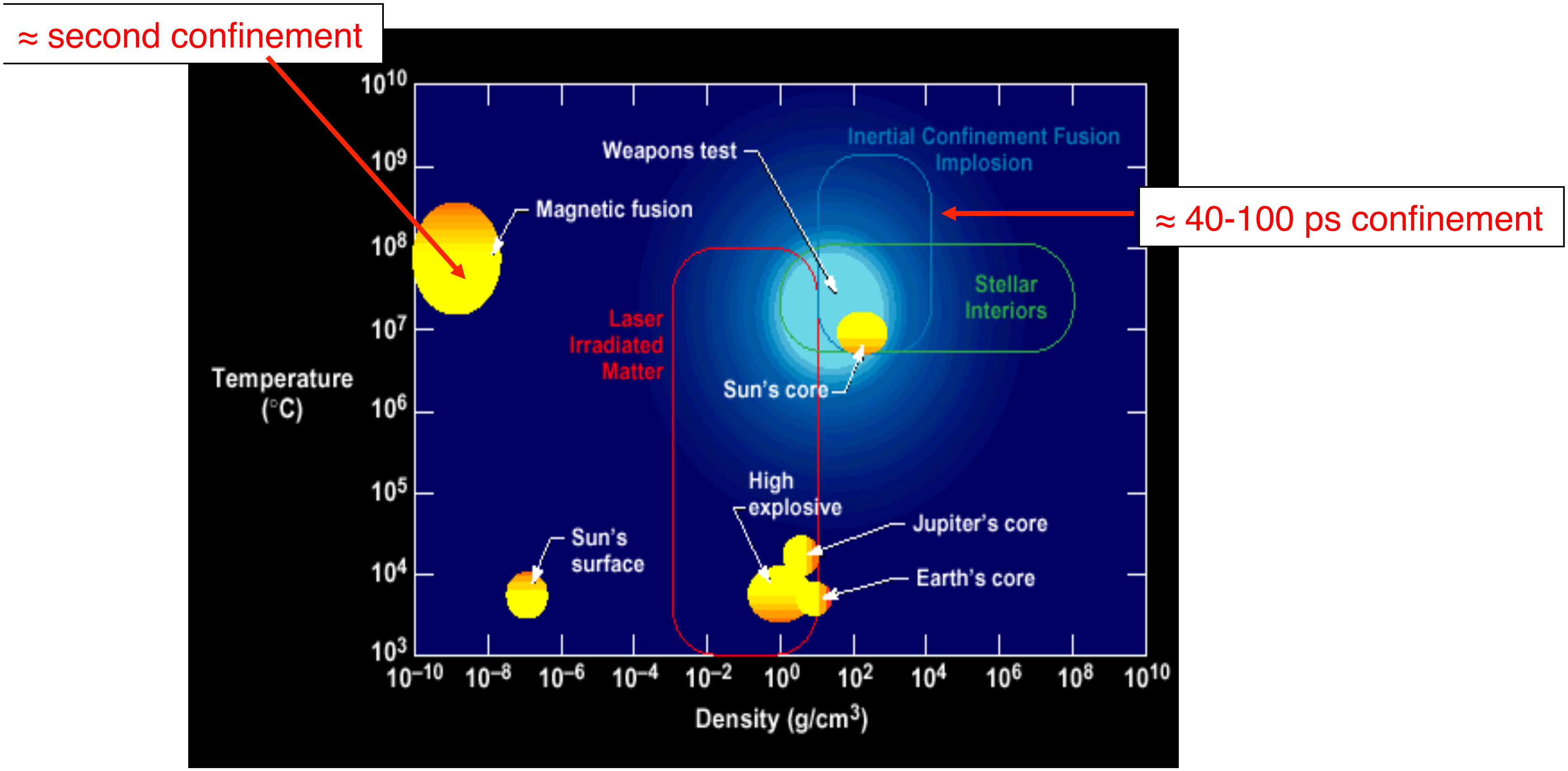
3.5 MeV 14.1 MeV




- $Q_{DT\ fusion}$ = 17.6 MeV/5 AMU = 3.3 x $10^{11}$ J/g

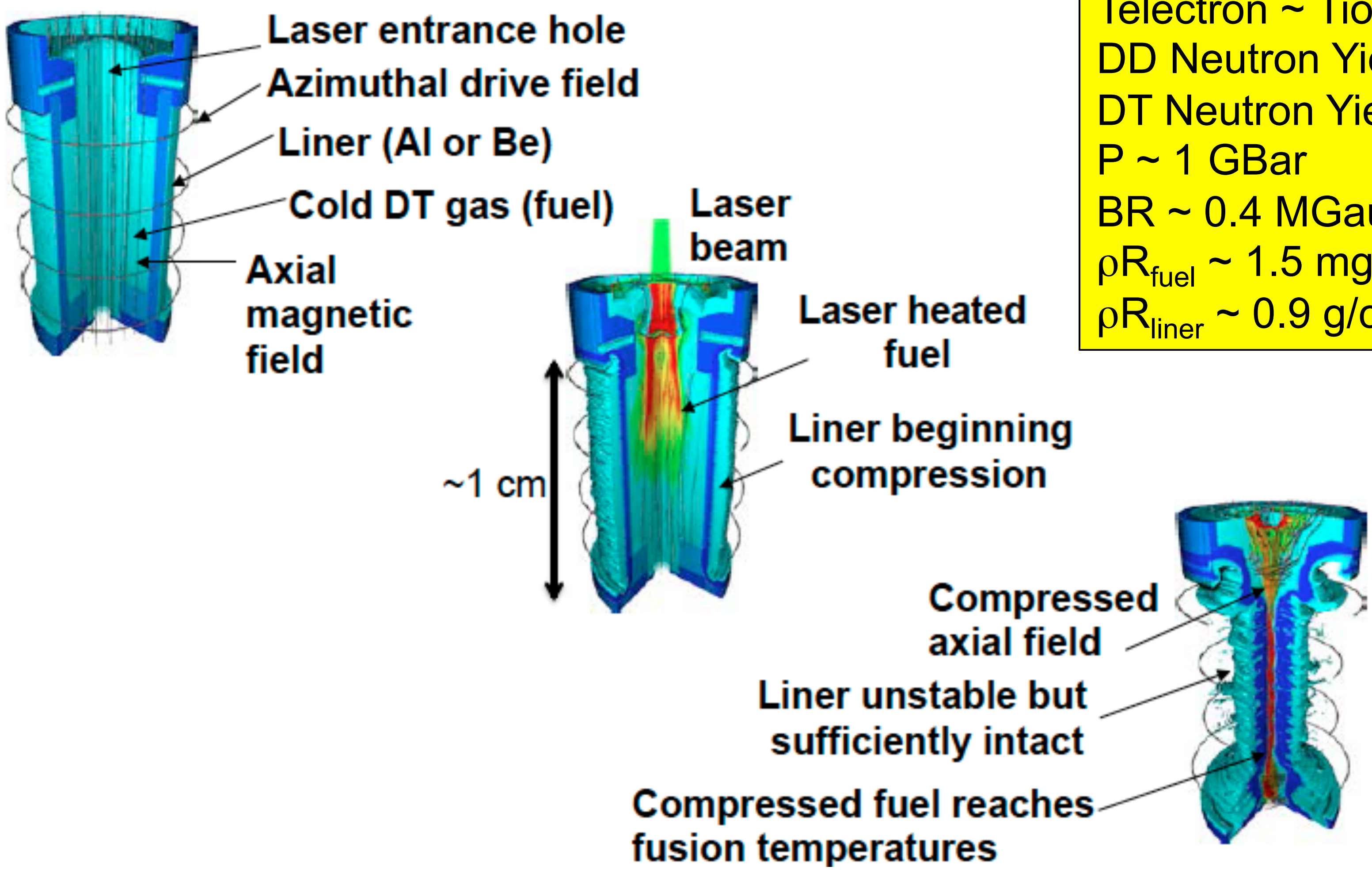
# Fusion can produce net energy with sufficient plasma density and confinement time at temperatures > 10 keV




- $n\tau > 2.e14\ cm^{-3}s^{-1}$ at T~20 keV for magnetic confinement (Lawson criterion)
- $\rho r > 0.3\ gcm^{-2}$ for ignition of ICF hot spot, equivalent to $n\tau > 2.5e14\ cm^{-3}s^{-1}$
- $\rho r > 3.0\ gcm^{-2}$ for ~30% fuel burn-up at 30 keV, equivalent to $n\tau > 2.5e15\ cm^{-3}s^{-1}$

# We are evaluating Magnetized Liner Inertial Fusion (MagLIF) – a concept well suited to pulsed power and that may lower requirements for plasma self-heating

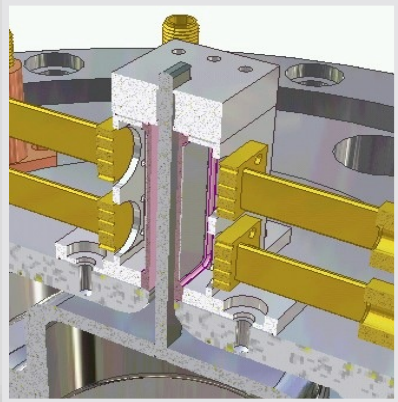
Telectron ~ Tion ~ 3 keV
DD Neutron Yield ~ 2.e12
DT Neutron Yield ~ 5.e10
P ~ 1 GBar
BR ~ 0.4 MGauss-cm
$\rho R_{fuel}$ ~ 1.5 mg/cm$^2$
$\rho R_{liner}$ ~ 0.9 g/cm$^2$



# Magnetically-driven planar and cylindrical geometries are used for the dynamic materials program

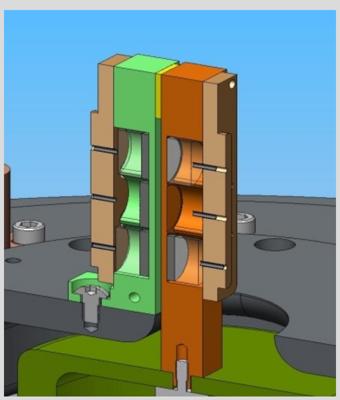
**Shock Compression**

Velocities > 40 km/s



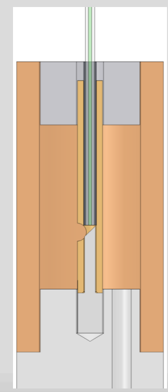
**Planar Ramp-Compression**

continuous compression up to ~4 Mbar



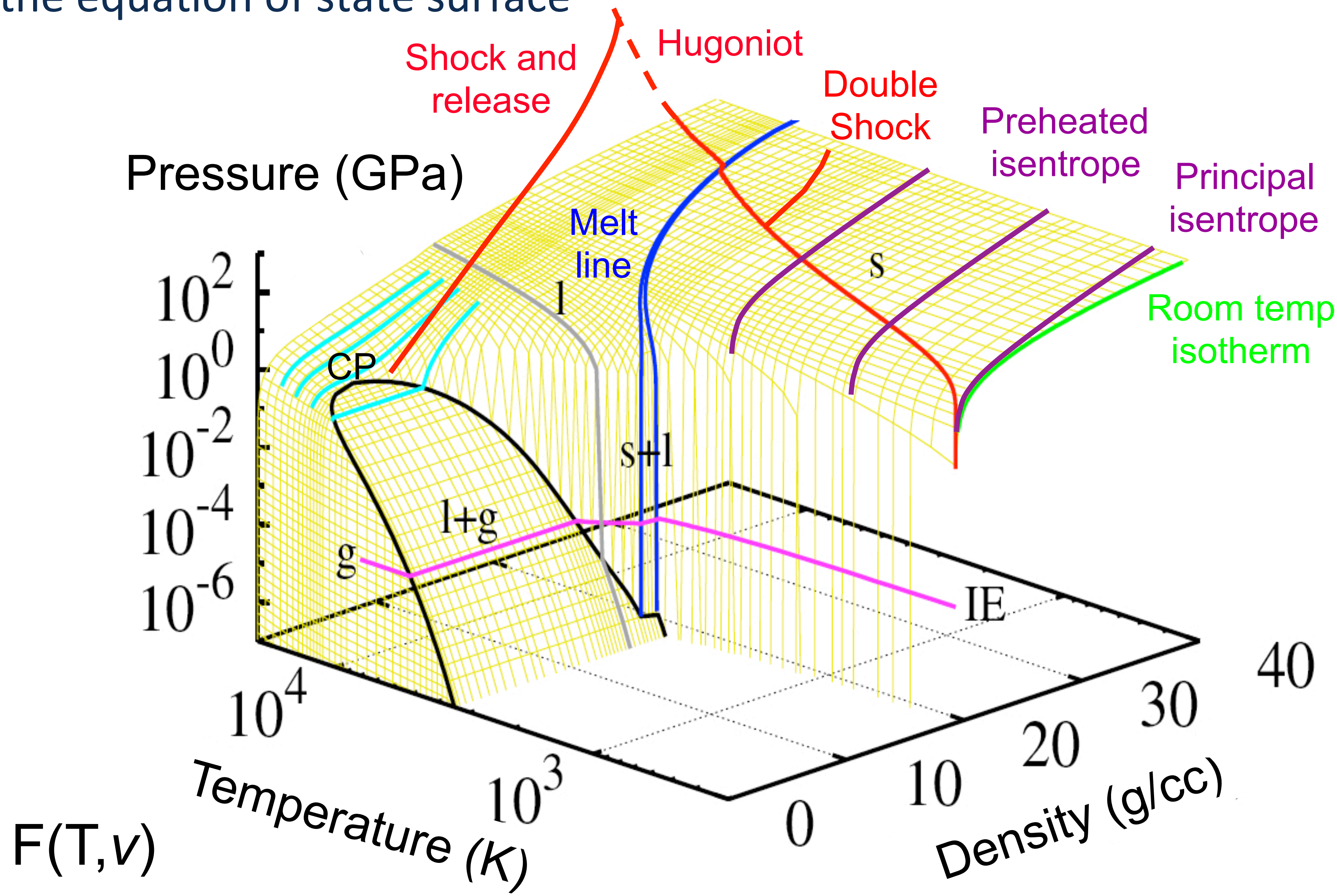
**Cylindrical Ramp-Compression**

Possibly continuous compression up to ~10-20 Mbar

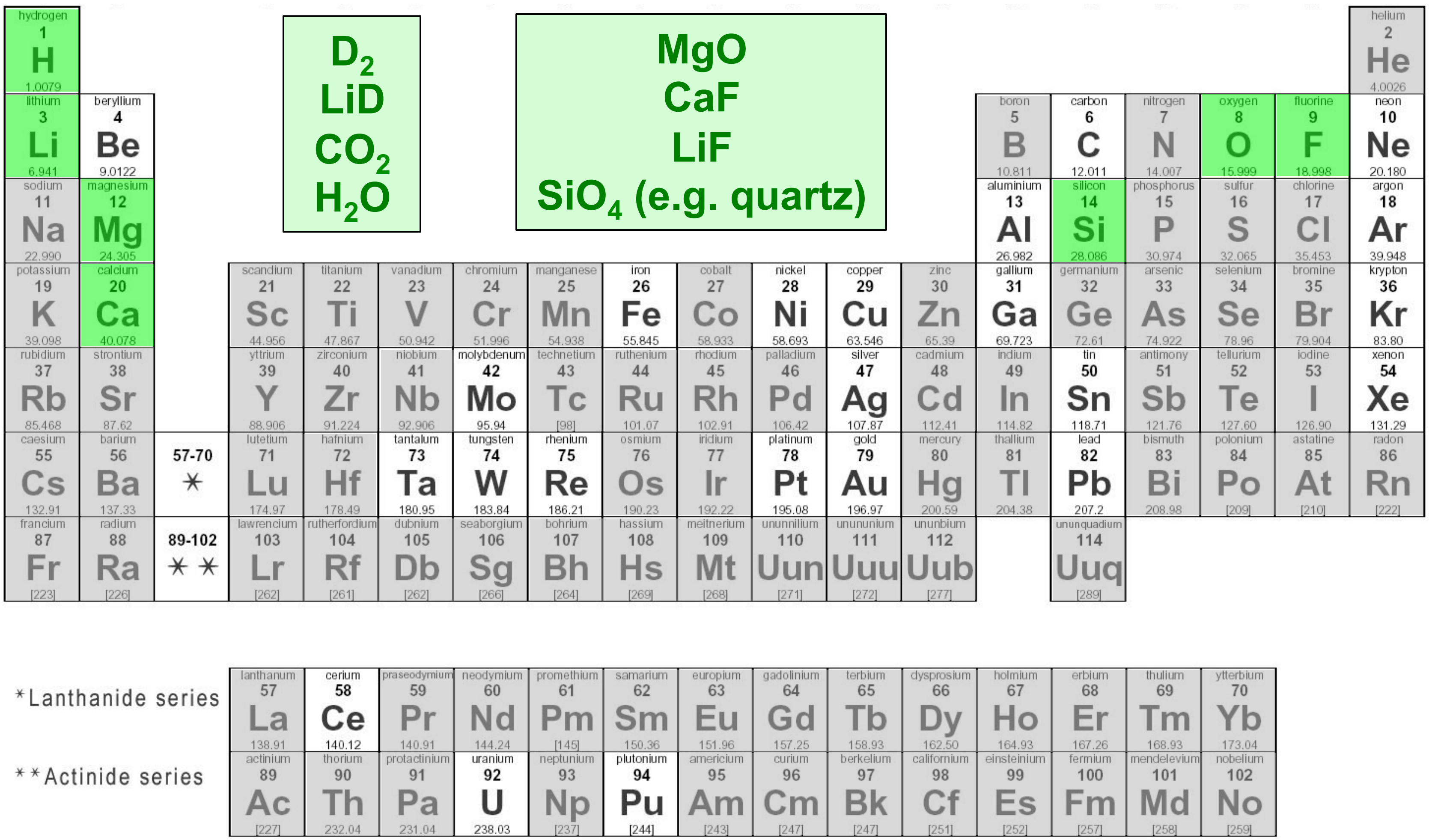


- Shock or ramp compression of materials increases densities by 2 to ***10:1***

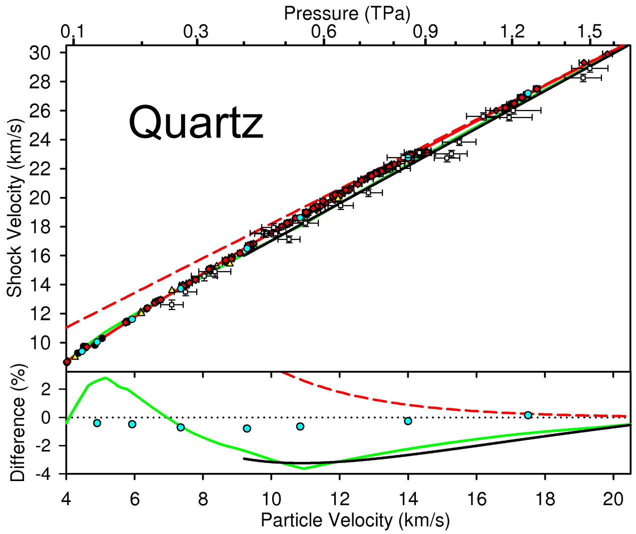
# Magnetic pressure on Z allows access to a large region of the equation of state surface

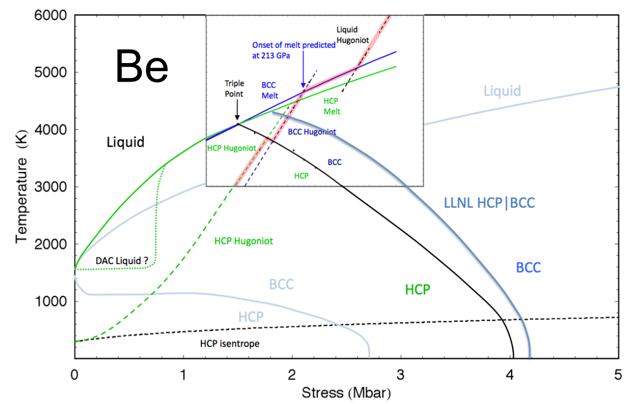


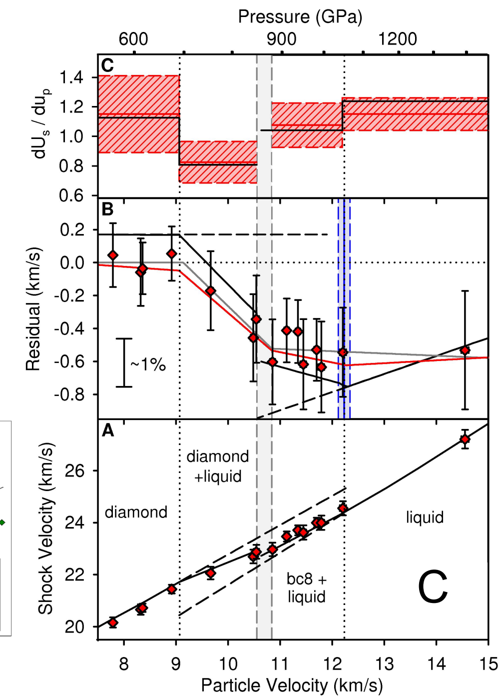
# The dynamic materials program measures equations of state and other properties (strength) for elements and compounds of interest

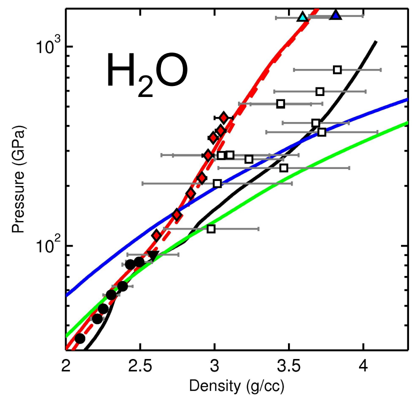


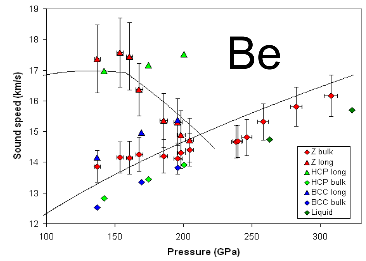
# Z has been used to address several interesting problems in the multi-Mbar regime

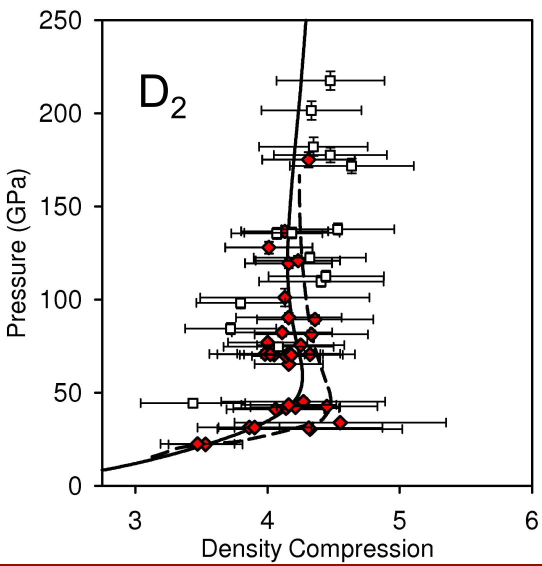


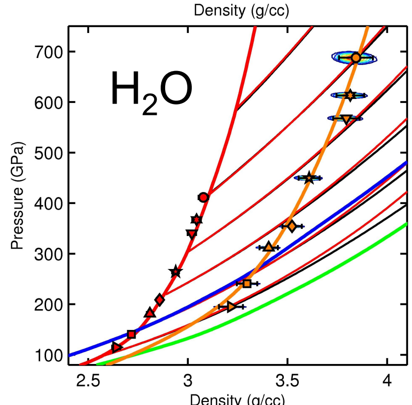



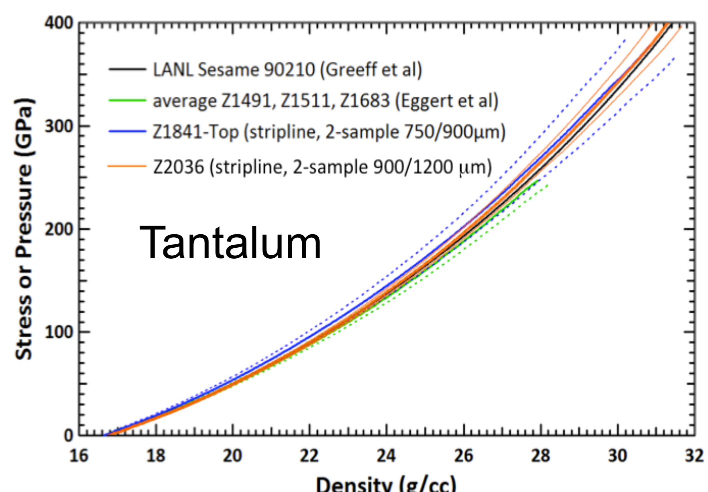



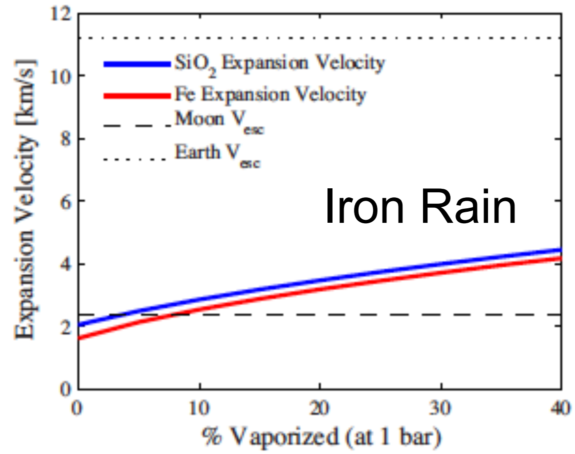



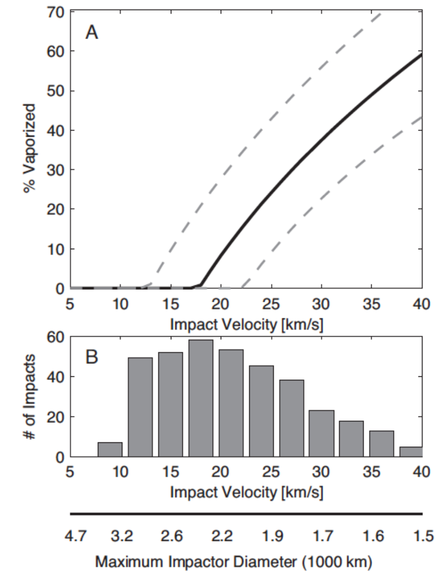



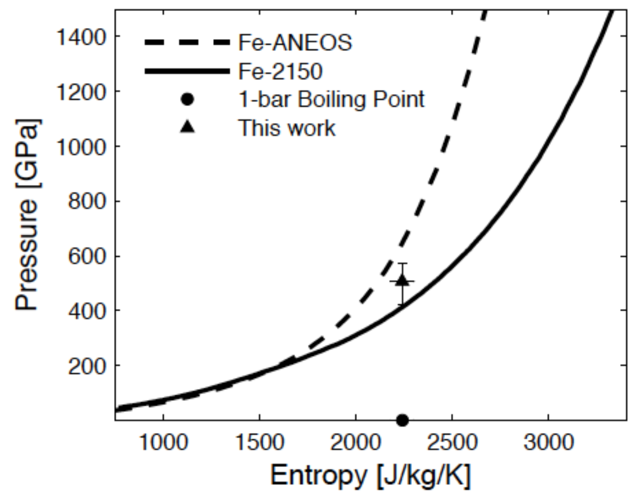
# Planetesimal impacts played an important role in shaping the solar system

R. G. Kraus et al., Nature Geoscience 04/2015; 8(April):269-272

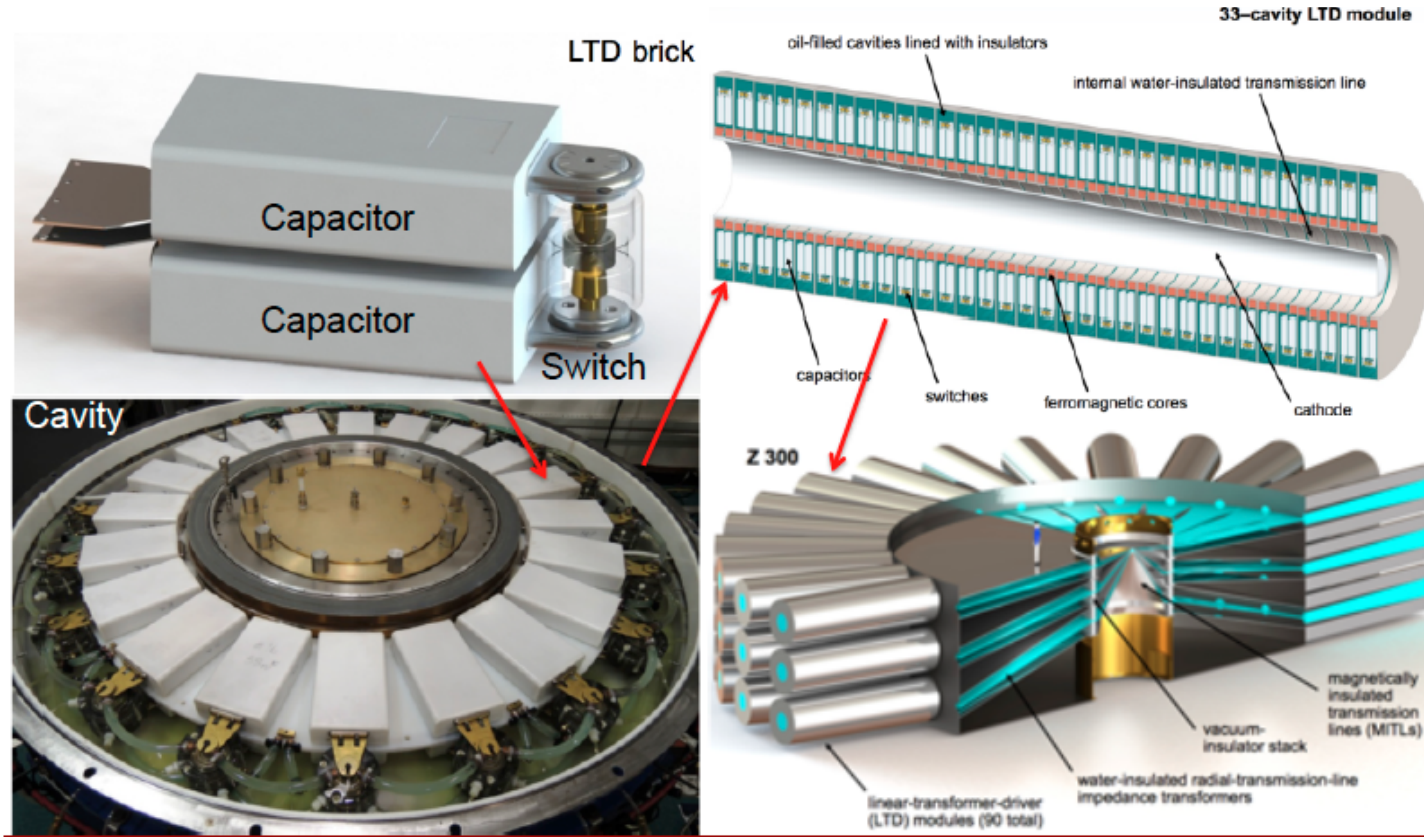



A significantly lower shock pressure (500 GPa) is required to vaporize iron upon release than previously used in planetary modeling (890 GPa)

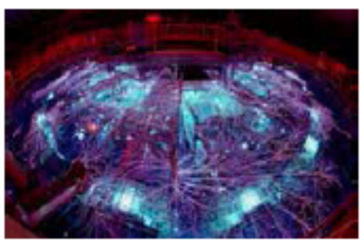


# We have developed a linear transformer driver architecture that can scale to 800-1000 TW and that is twice as efficient and twice as compact as Z



# We are currently exploring target designs and pulsed power architectures that may be on the path to 0.5-1 GJ yields that also meet the needs of the science campaigns

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



**Z**

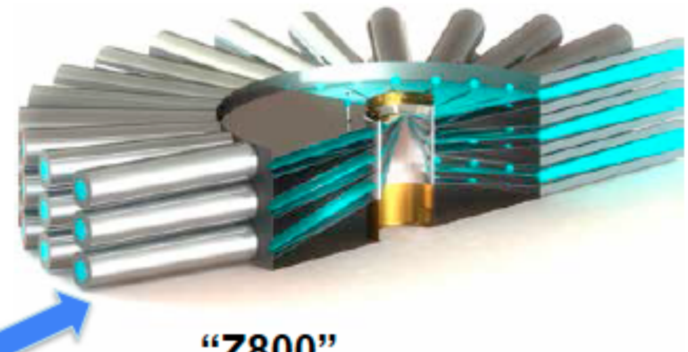
- 80 TW
- 33 Meter diameter
- 26 MA
- 22 MJ Stored Energy

**Yield = Etarget?**
**(About 3-4 MJ)**
**$\alpha$-dominated plasmas**

**"Z300"**

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

**Fusion Yield 0.5-1 GJ?**
**Burning plasmas**

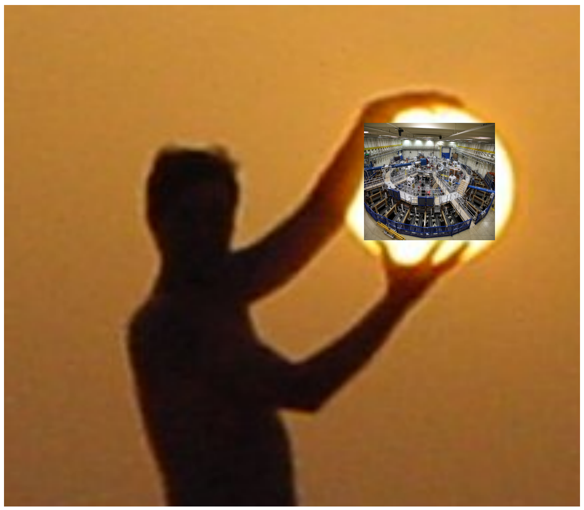


**"Z800"**

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

The "bold outcome" of the First to High Yield Fusion Research Challenge

## Large HED facilities are as close as we can get to "holding the Sun" on Earth



- We make sufficient enough macroscopic quantities of high energy density, hot-dense matter to allow accurate study
- Pulsed power, in particular, allows large energy delivery to the largest samples or targets, generating large scale size, hot, dense plasmas with large volume-to-surface area ratios, and at low cost per shot
- We may someday be able to "create a star" in the laboratory

# Backup

# Scales of energy density found in nature

- 0.001 MJ/kG water at 100 m dam height
- 0.7 MJ/kG Li ion battery
- 1.968 MJ/kG water
- 7.5 MJ/kG stick of dynamite
- 33 MJ/kG Low Earth Orbit
- 46 MJ/kG gasoline
- ~100 MJ/kG internal energy of the hydrogen molecule
- ~100 MJ/kG 1 MBar on unshocked plastic
- ~170,000 MJ/kG stagnation energy density typical z-pinch implosion at 20 MA
- 3.5 million MJ/kG fission of 3.5% enriched U-235
- 337 million MJ/kG DT fusion
- 645 million MJ/kG hydrogen fusion (Sun)
- 89.9 billion MJ/kG ($E=mc^2$, antimatter-matter annihilation)
- (see http://en.wikipedia.org/wiki/Energy_density)