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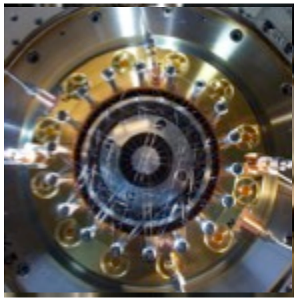

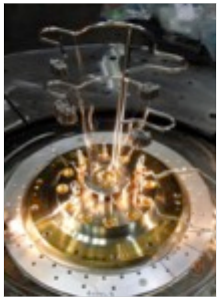

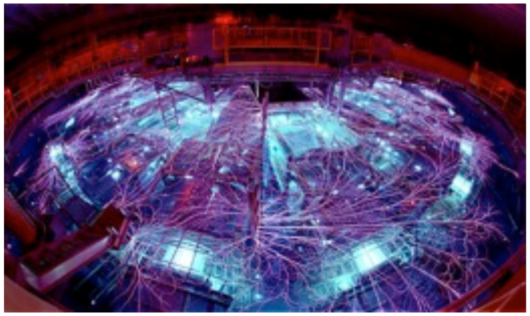

Sandia National Laboratories

*Exceptional service in the national interest*

# Pulsed Power Driven High Energy Density Plasmas

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HED Summer School
University of California, San Diego
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U.S. DEPARTMENT OF ENERGY

NNSA

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[2]*Laboratory of Plasma Studies, Cornell University, Ithaca, NY*

[3]*Lawerence Livermore National Laboratory, Livermore, CA*

[4]*General Atomics, San Diego, CA*

[5]*Raytheon Ktech, Albuquerque, NM*

[6]*Naval Research Laboratory, Washington, DC*

# Synopsis

- Pulsed-power technology produces large currents (15-27 MA) in a short pulse (100-600 ns) on the Z machine

- Large currents generate large magnetic fields
  = tremendous pressure

- Large pressures enable access to
High Energy Density regimes ( > ~$10^{11}$ J $m^{-3}$, or > ~1 Mbar)

- Magnetically-driven implosions and explosions of many types provide many interesting applications

- These applications go well beyond traditional concepts known colloquially as “z-pinches”

Pressure is equivalent to energy density

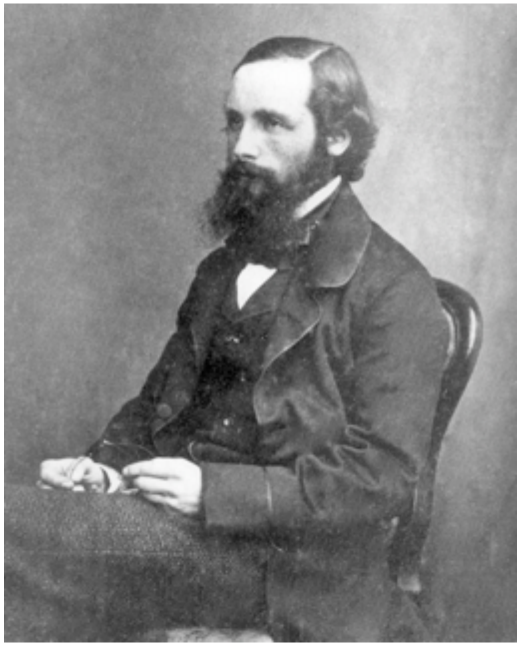
1 Mbar =
1.01e6 atmospheres =
1.e11 Pascals =
100 GPa =
5 MGauss =
1.e11 J/$m^3$

# Pulsed power is an amazing technology

Pulsed-power accelerators:

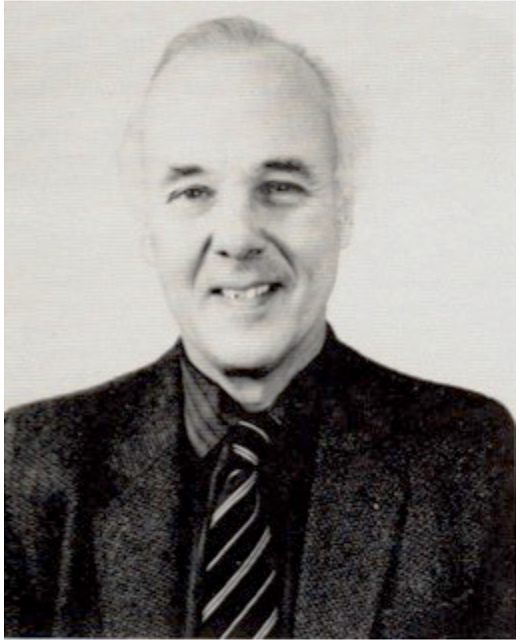
- Serve as precision scientific instruments
- Deliver megajoules of energy to milligrams of matter on a time scale of nanoseconds
- Achieve extreme states of matter over macroscopic volumes
- Drive a wide variety of high-energy-density-physics experiments in support of the U.S. national-security mission

Michael Faraday



James Clerk Maxwell

Erwin Otto Marx

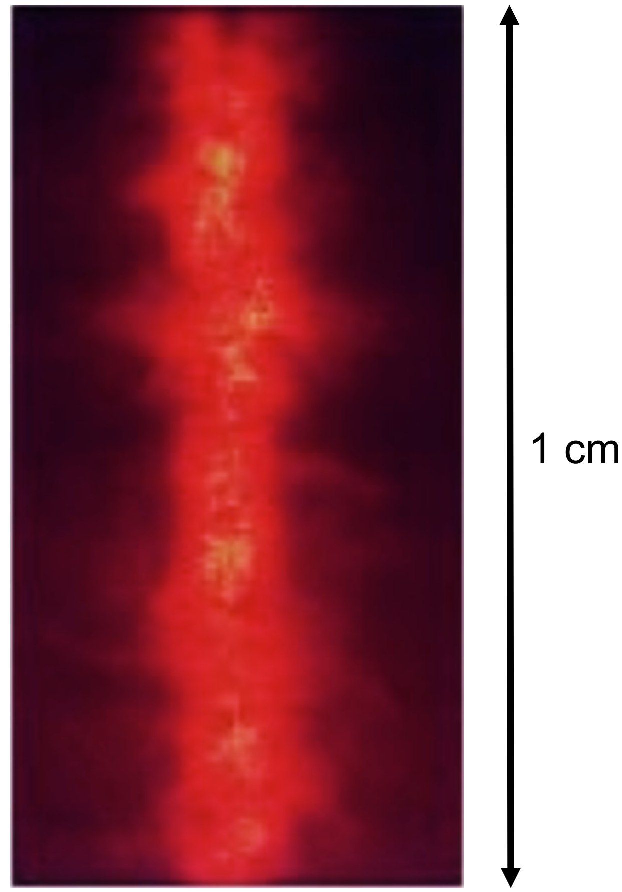


J. C. “Charlie” Martin

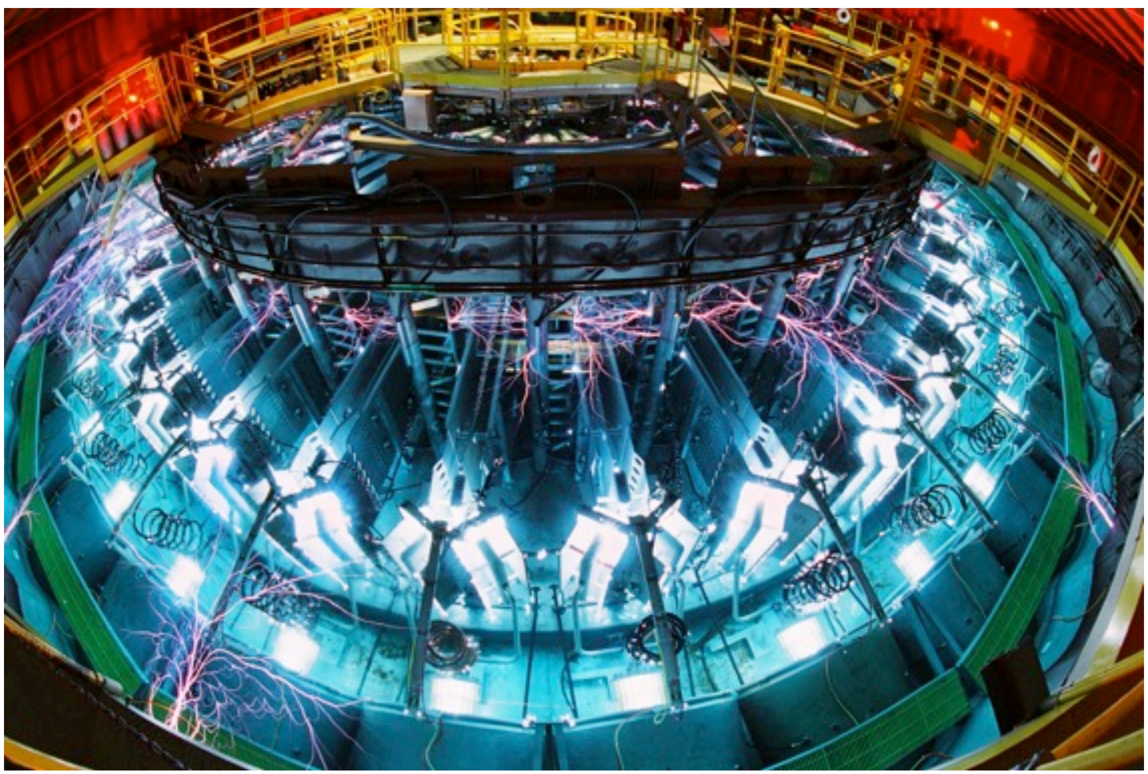
# Pulsed-power experiments presently deliver the following:

- Kinetic energy per atom: 1 MeV
- Implosion velocities: 100 cm/μs
- Shock velocities: 30 km/s
- Temperatures: 5 keV
- Magnetic pressures: 5 Mbar
- Energy radiated in K-shell x rays: 400 kJ
- Energy radiated in thermal x rays: 2.2 MJ
- Power radiated in thermal x rays: 330 TW

100-ps x-ray image of a 280-TW z pinch at stagnation




(Deeney, Douglas, Spielman, and colleagues, PRL, 1998.)



20-TW 33-m-diameter Saturn accelerator

(Bloomquist, Corcoran, Spielman, and colleagues.)

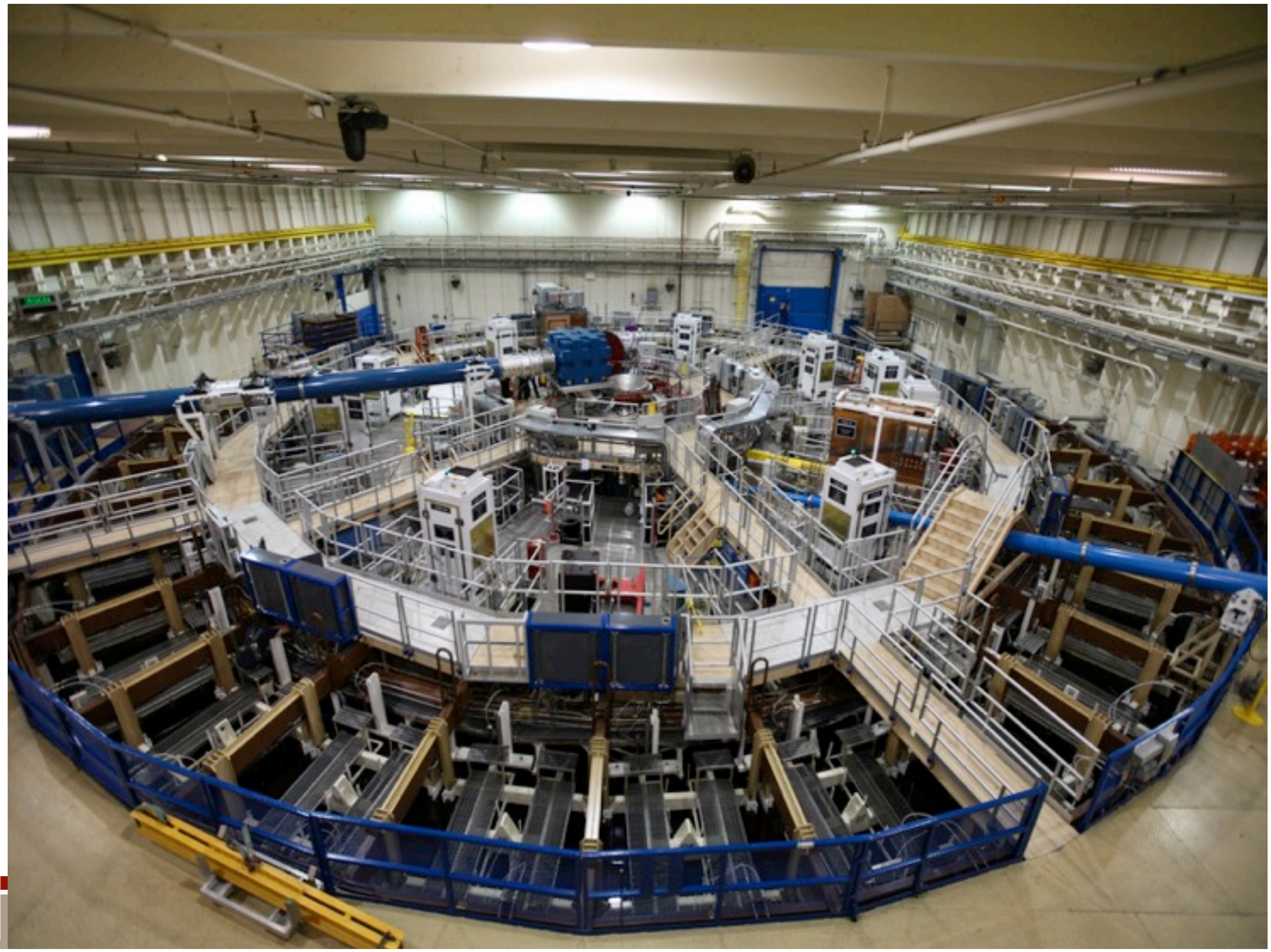
# Sandia's Z accelerator is *presently* the world's largest and most powerful pulsed-power machine

$E_{stored}$ = 20 MJ　$V_{stack}$ = 4 MV　$I_{load}$ = 26 MA　$E_{radiated}$ = 2.2 MJ

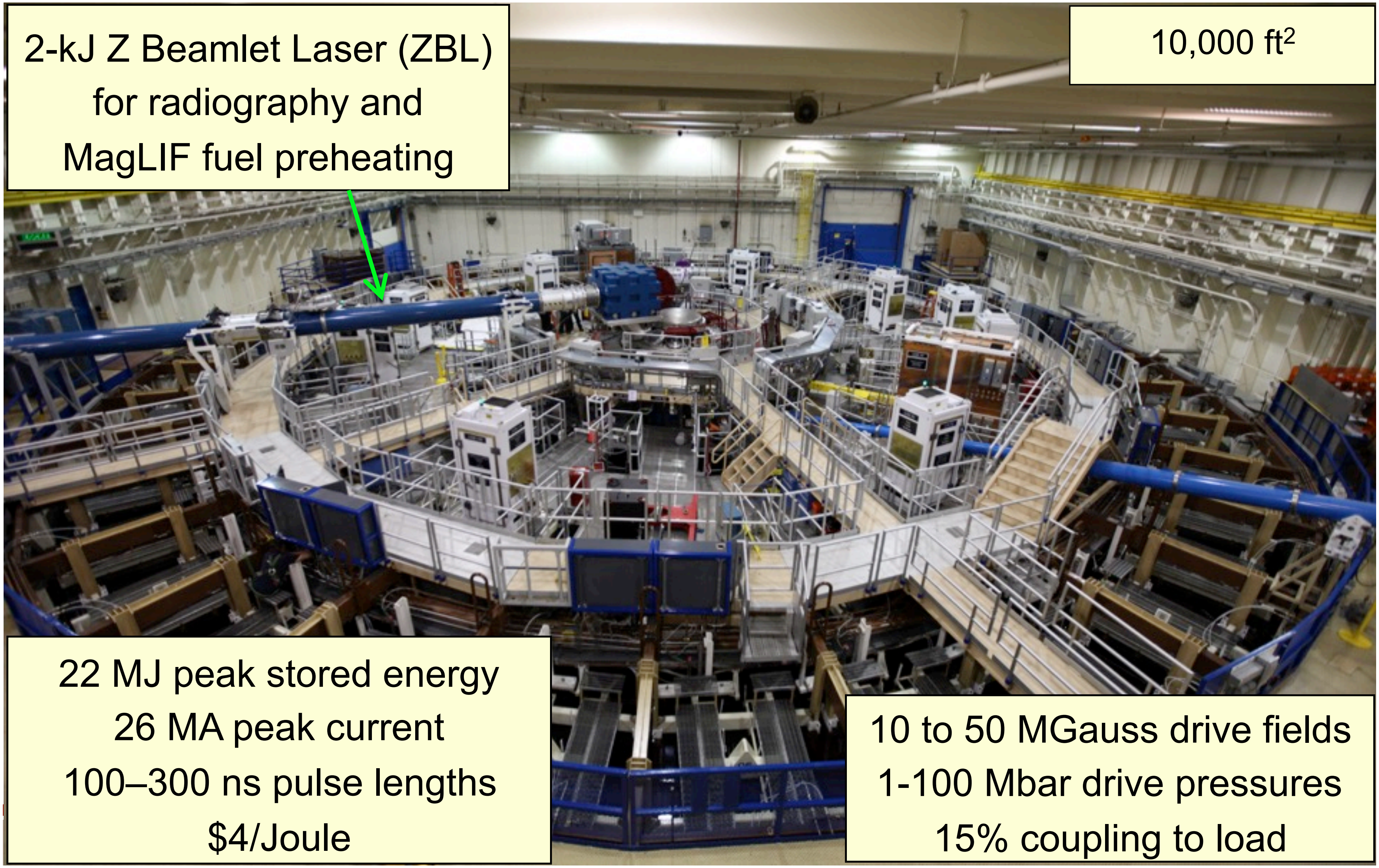
$P_{electrical}$ = 80 TW　$L_{vacuum}$ = 12 nH　$\tau_{implosion}$ = 130 ns　diameter = 33 m

- Since 1997 we have conducted, on average, 160 Z shots each year.
- To date, 2800 Z shots have been conducted altogether.

McDaniel, Bloomquist, Ives, Johnson, LeChien, Lehr, Maenchen, Savage, Spielman, Stoltzfus, Weed, and Weinbrecht.



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

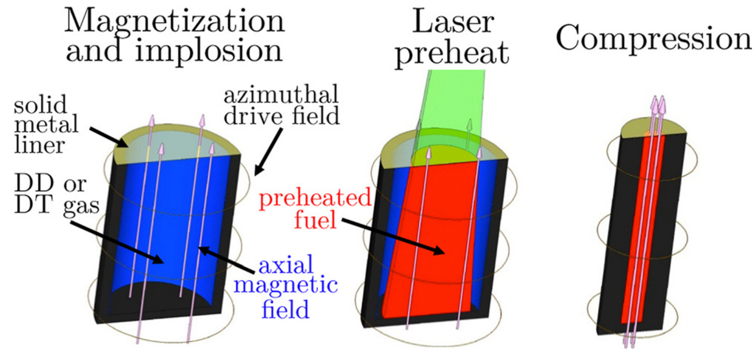


# Z drives a wide variety of experiments in support of the U.S. national-security mission

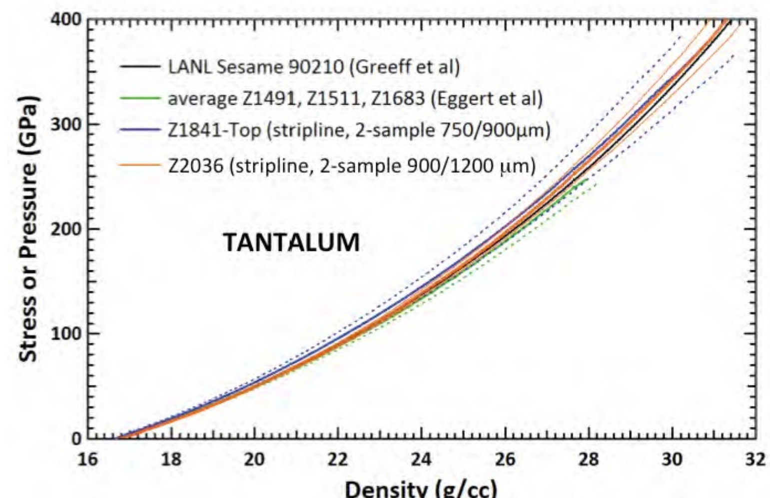
- Inertial confinement fusion
- Radiation physics
- Material physics
- Laboratory astrophysics

Results of experiments conducted on Z have been published in over 500 peer-reviewed journal articles.

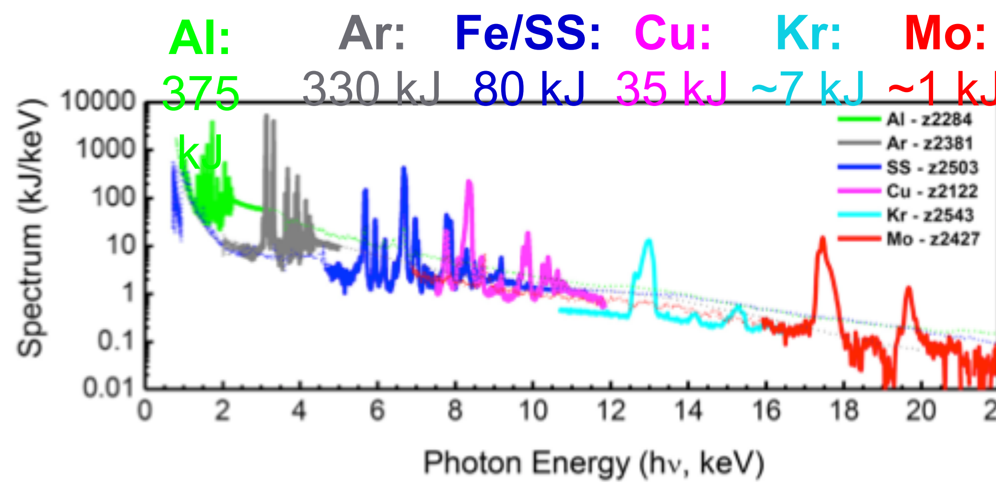
magnetized liner inertial fusion (MagLIF) concept



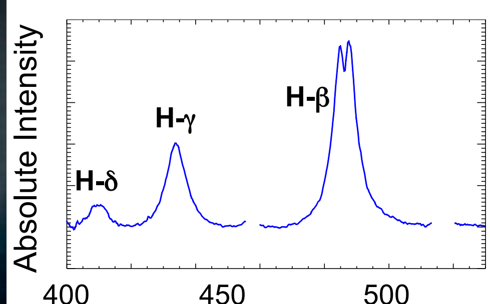

quasi-isentrope of tantalum to 4 Mbar



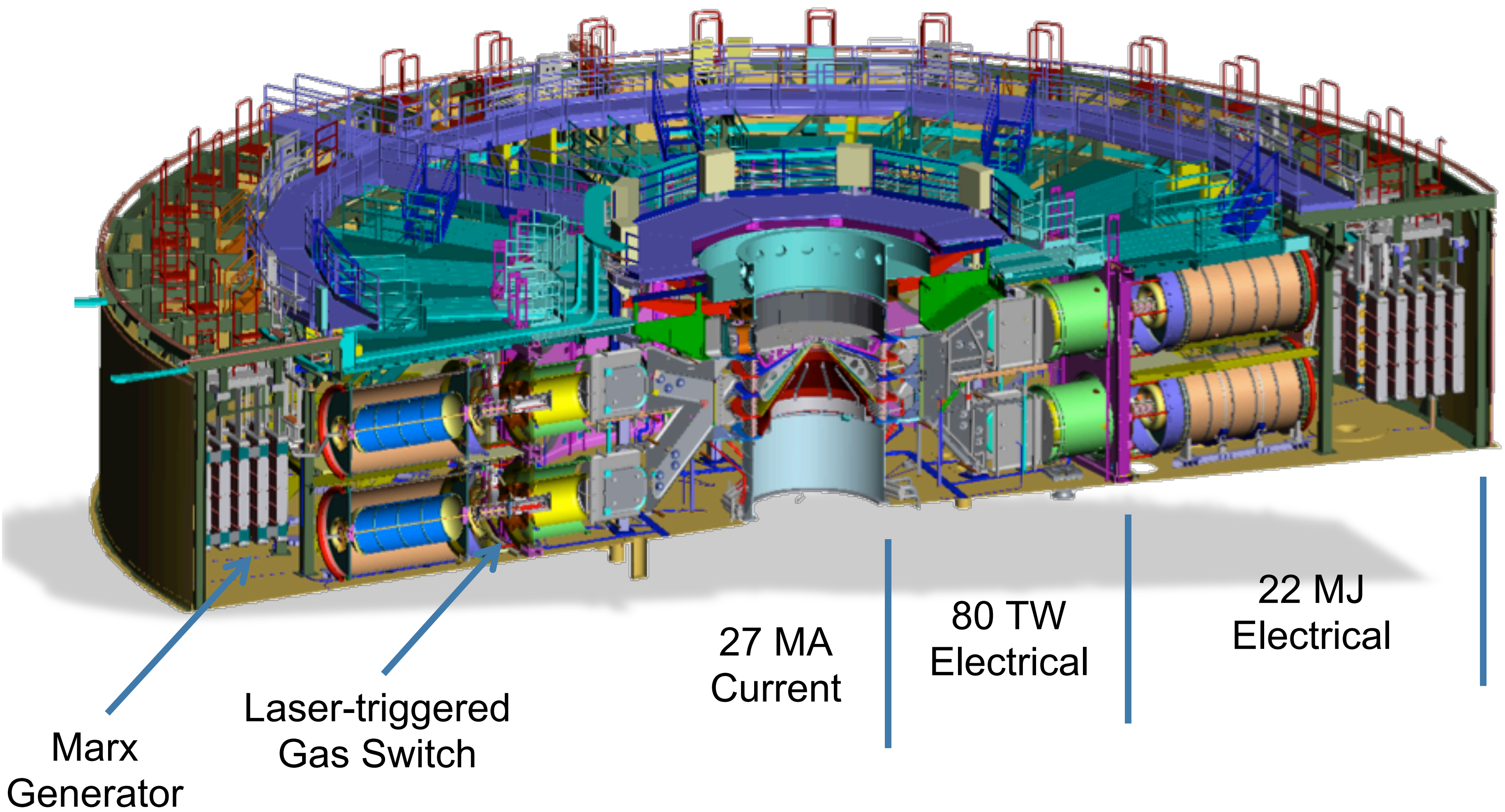

K-shell x-ray sources



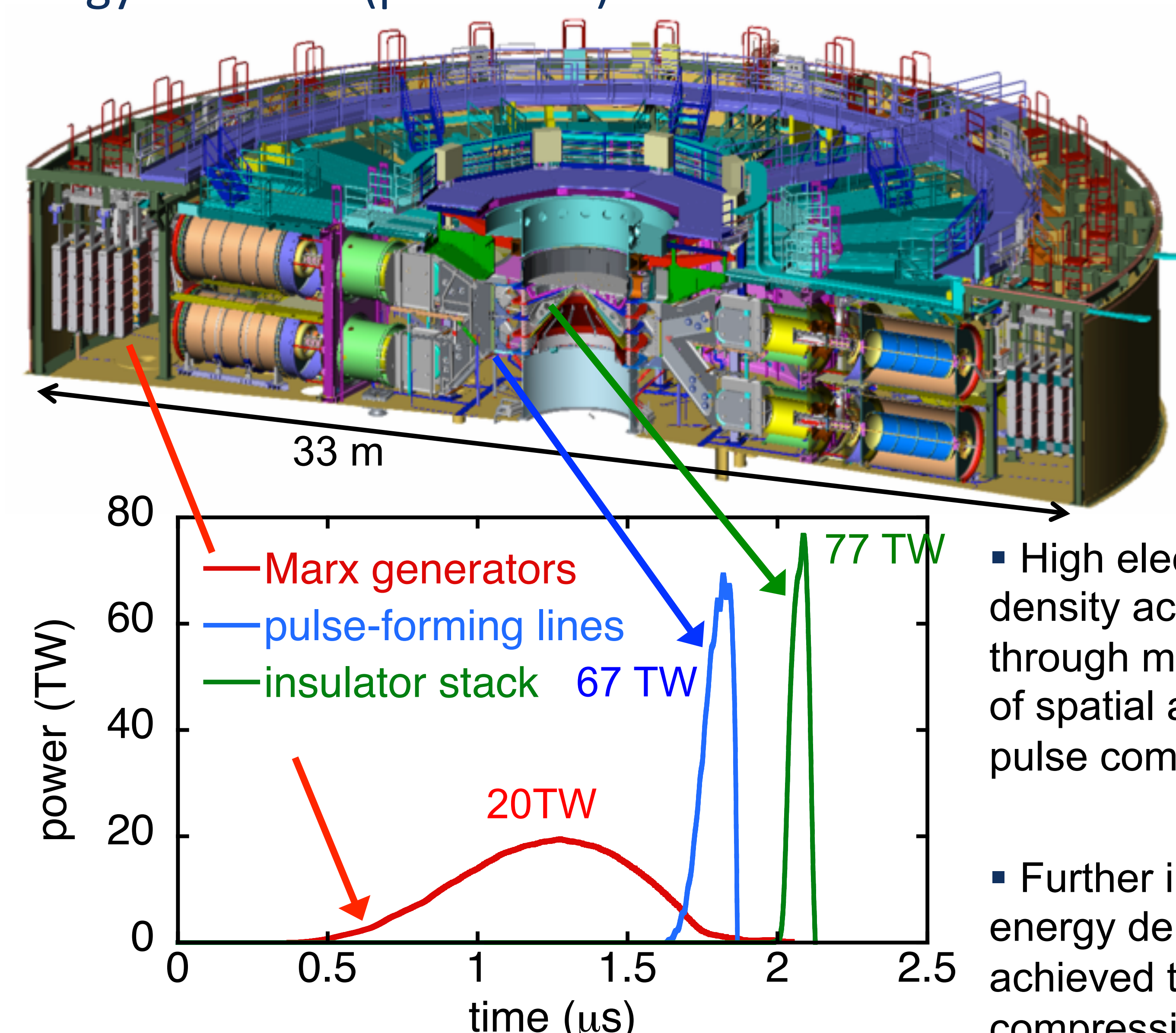

white-dwarf line shapes



# Cross section of the Z facility at Sandia National Laboratories



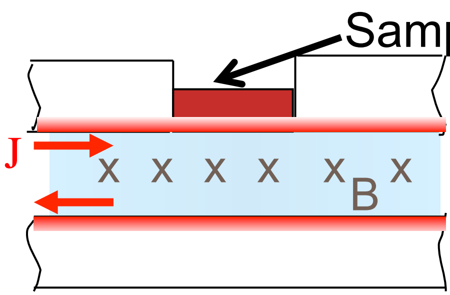
# Z works by compressing energy in space and time to reach high energy densities (pressures)

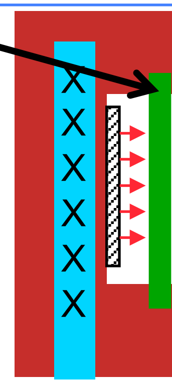



- High electrical power density achieved through multiple stages of spatial and temporal pulse compression
- Further increases of energy density are achieved through shock compression, implosion, stagnation

# We use magnetic fields on Z in several ways to create High Energy Density matter for stockpile stewardship applications

**Dynamic Material Properties**

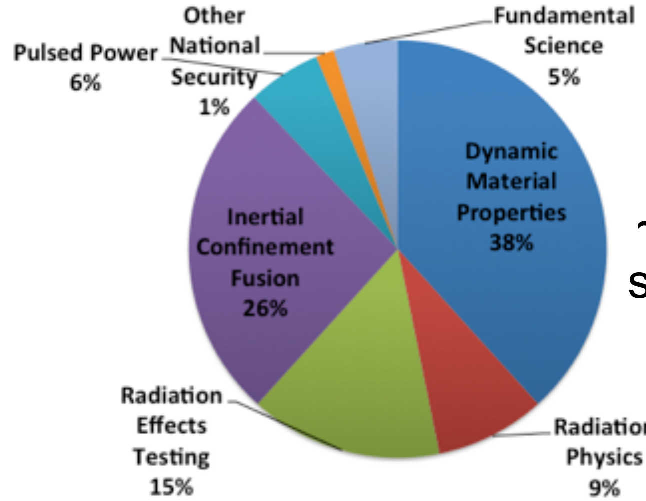


Isentropic Compression

Flyer Plate

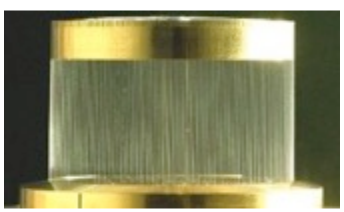
CY13 Z shot distribution

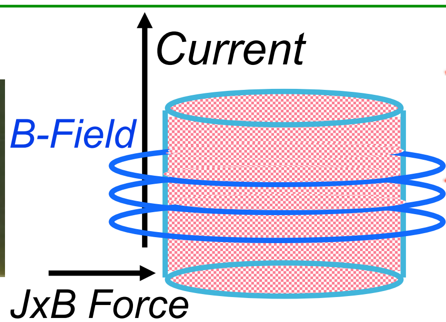


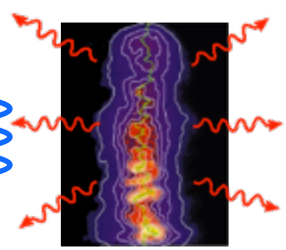

~150-200 shots/year

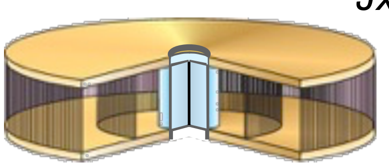
**Z-Pinch X-ray Sources (RES, Rad. Physics)**

wire array

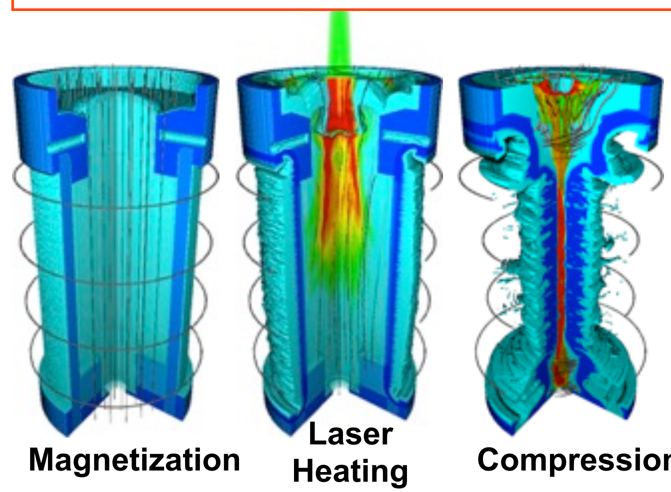






**Inertial Confinement Fusion**

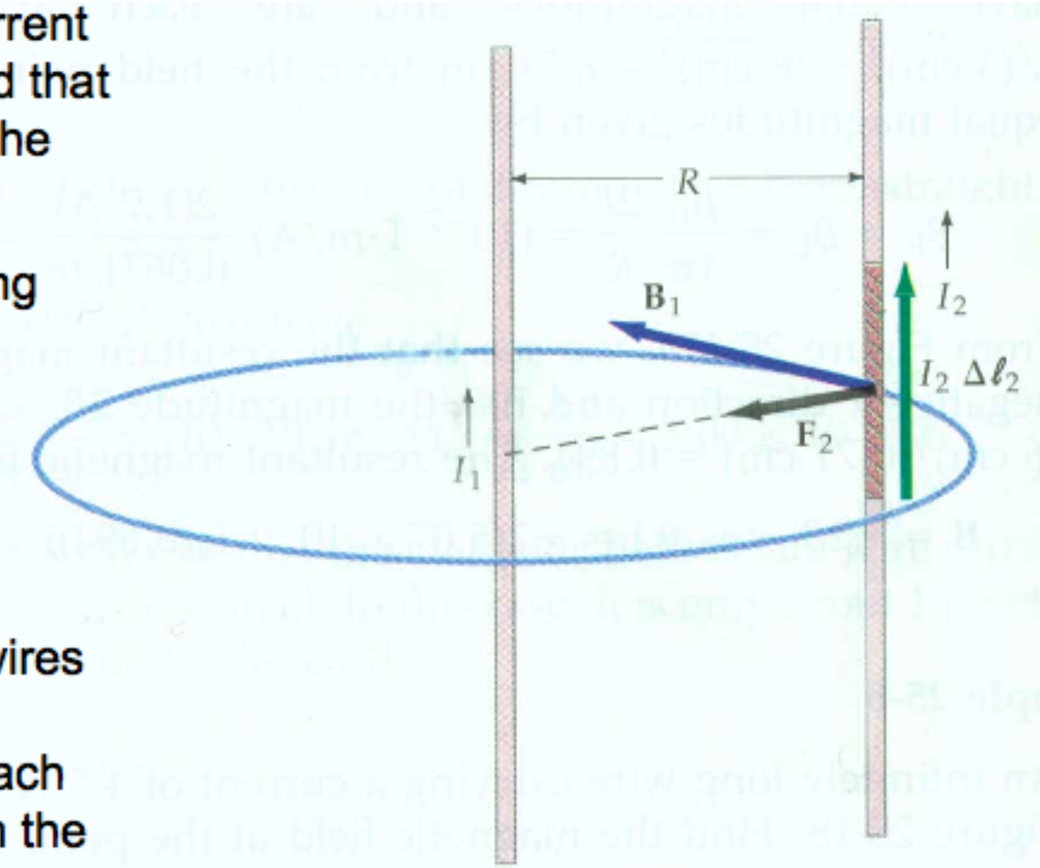


# 1st year physics refresher: the "pinch effect"

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

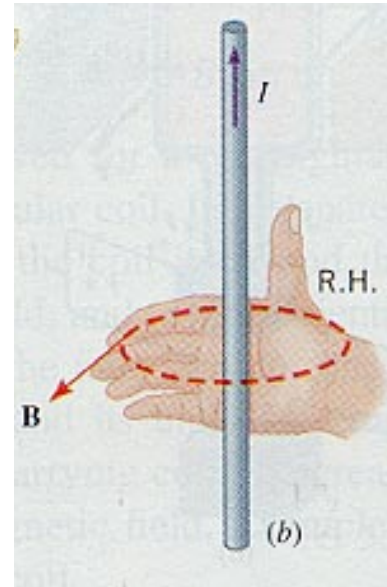



Sandia

# Large currents can create large B fields!

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

$$\oint_C \mathbf{B} \bullet d\mathit{l} = \frac{4\pi}{c} \iint_S \mathbf{J} \bullet d\mathbf{S}$$ 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

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

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

*(~1000x more than high explosives)*

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

# 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 $5 \times 10^6$ G (500 T) magnetic field ~ 1 Million atmospheres = 1 Megabar (MB)= High energy density physics ("HEDP")

A $5 \times 10^9$ 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 $5 \times 10^5$-$1.5 \times 10^6$ G

# We can incorporate the effect of magnetic fields into the plasma fluid equations as an effective pressure

$$\frac{\partial \rho}{\partial t} + \nabla \bullet \rho \mathbf{u} = 0$$ mass conservation

$$\boxed{\rho\left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u}\right)} = \frac{\mathbf{J}\times\mathbf{B}}{c} - \nabla P$$

**momentum conservation**
(F=ma) cgs

For slowly varying fields we can approximate: $\nabla \times \mathbf{B} = \frac{4\pi \mathbf{J}}{c}$ *(Ampere's law, ignoring displacement current)*

We re-write JxB as: $\mathbf{J}\times\mathbf{B} = \frac{c}{4\pi}(\nabla\times\mathbf{B})\times\mathbf{B} = -\frac{c}{4\pi}\mathbf{B}\times(\nabla\times\mathbf{B})$

From vector identities: $\mathbf{B}\times(\nabla\times\mathbf{B}) = \frac{1}{2}\nabla(\mathbf{B}\bullet\mathbf{B}) - \mathbf{B}\bullet\nabla\mathbf{B} = \nabla\left(\frac{B^2}{2}\right) - \mathbf{B}\bullet\nabla\mathbf{B}$

So JxB becomes: $\mathbf{J}\times\mathbf{B} = \frac{c}{4\pi}\left(\mathbf{B}\bullet\nabla\mathbf{B} - \nabla\left(\frac{B^2}{2}\right)\right)$

$$\boxed{\rho\left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u}\right)} = \frac{\mathbf{J}\times\mathbf{B}}{c} - \nabla P = \boxed{\frac{1}{4\pi}\mathbf{B}\bullet\nabla\mathbf{B}} - \nabla\left(P + \boxed{\frac{B^2}{8\pi}}\right)$$

**magnetic tension** — **fluid pressure** — **magnetic pressure**

*In the case of an axisymmetric z-directed current ($B_\theta$ field), the magnetic tension is zero*

***Plasma momentum is affected by magnetic fields***

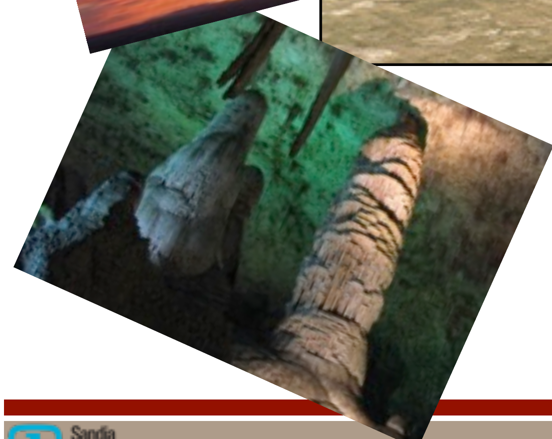
# Large currents and the corresponding magnetic fields can be used to create and control high energy density matter

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u}\right) = \frac{\mathbf{J}\times\mathbf{B}}{c} - \nabla P \approx \frac{1}{4\pi}\mathbf{B}\bullet\nabla\mathbf{B} - \nabla\left(P + \frac{B^2}{8\pi}\right)$$

- Magnetic pressure can be created efficiently over $cm^3$ volumes, enabling large samples and energetic sources
- Magnetic pressure increases in a converging geometry
- High pressures can be created *without making material hot*
- Magnetic fields can be generated over long time scales with significant control over the time history (pulse shaping)
- Energy density is increased through planar compression or cylindrical implosion
- Magnetic fields change the way particles and energy are transported in a plasma

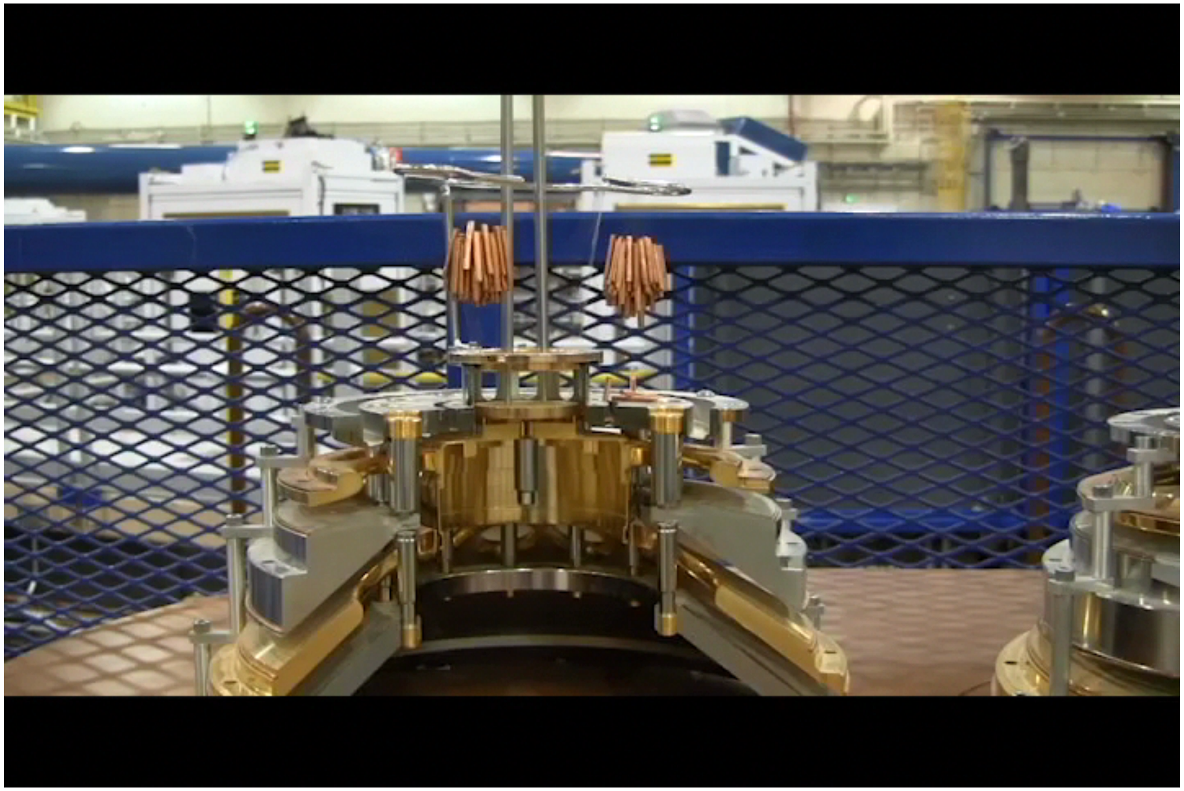
# The “Z” pulsed-power facility is located at Sandia National Laboratories in Albuquerque, New Mexico

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



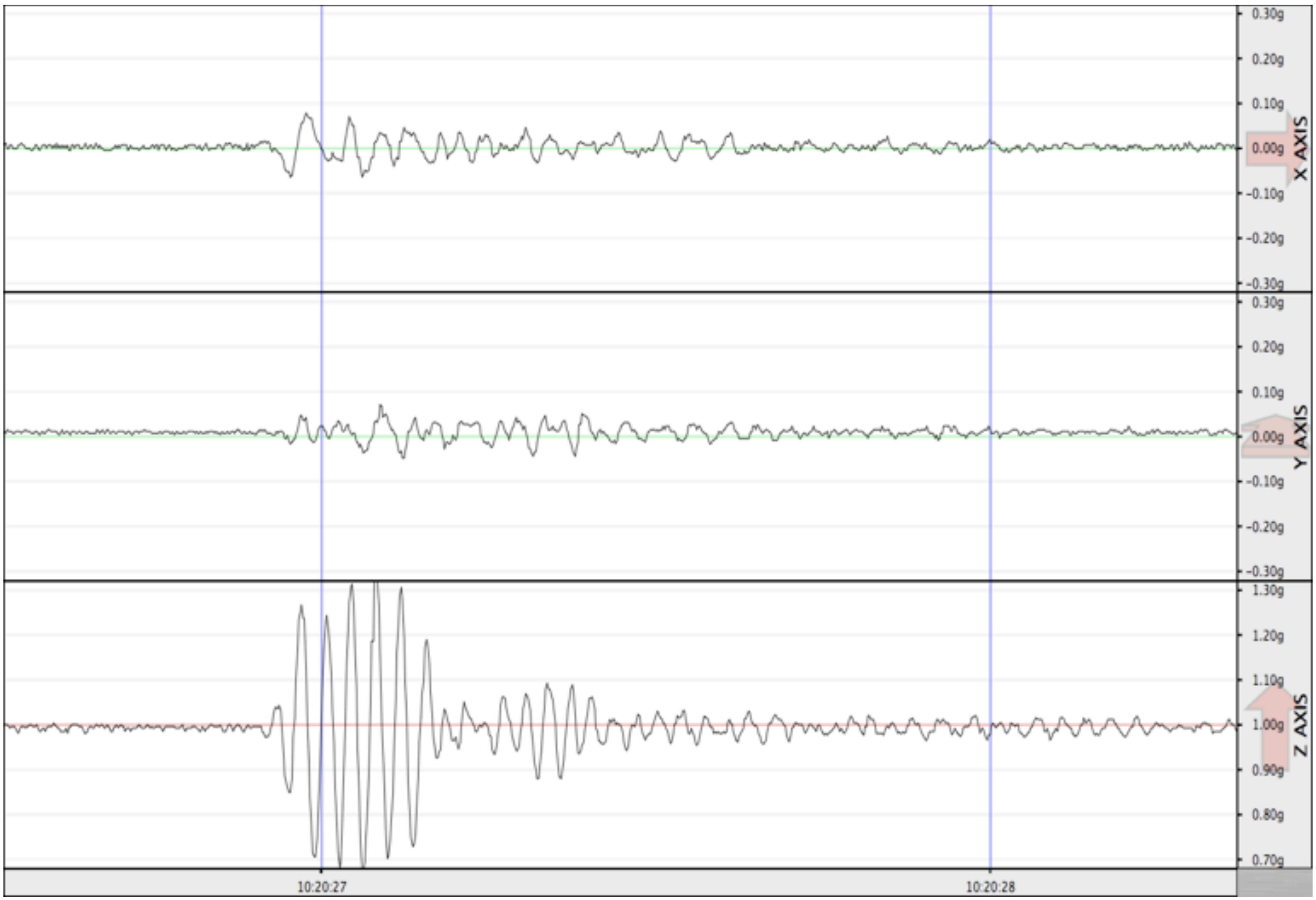
# The "Z" pulsed-power facility is located at Sandia National Laboratories in Albuquerque, New Mexico

# Z poses a challenging environment for experiments



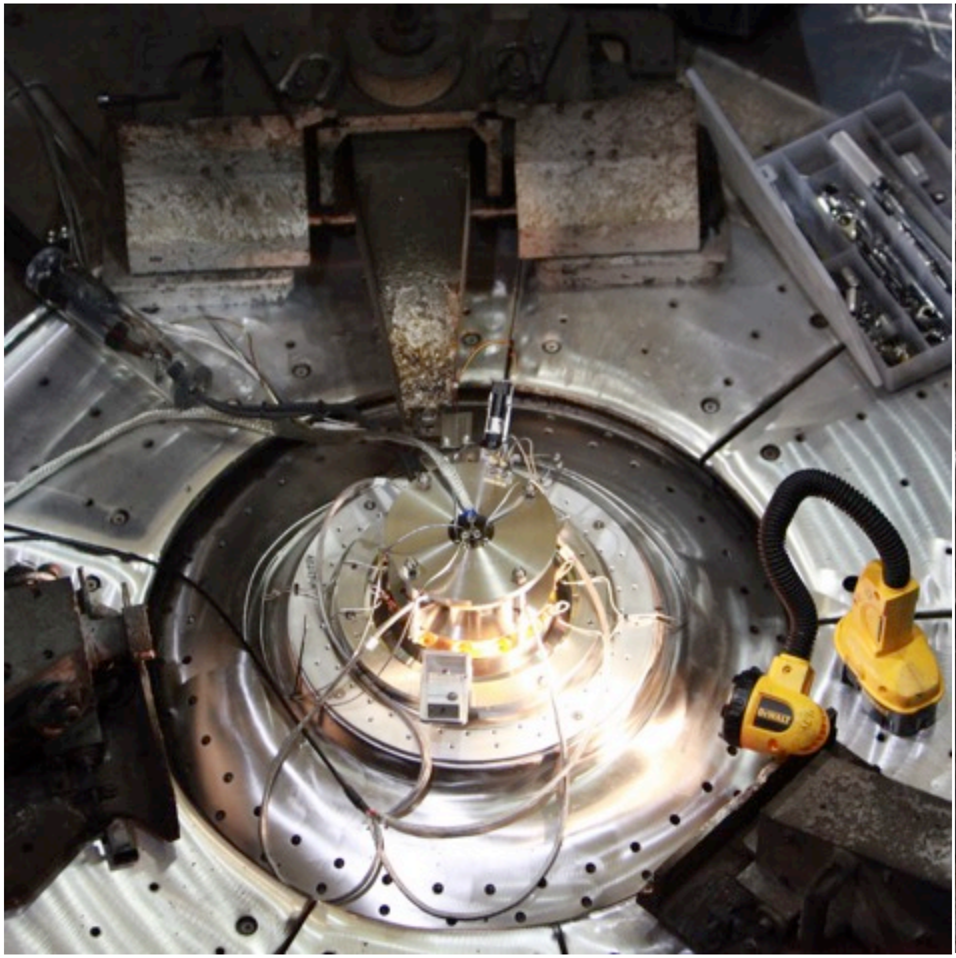
• 30 – 100 g instantaneous shock at center

# 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)

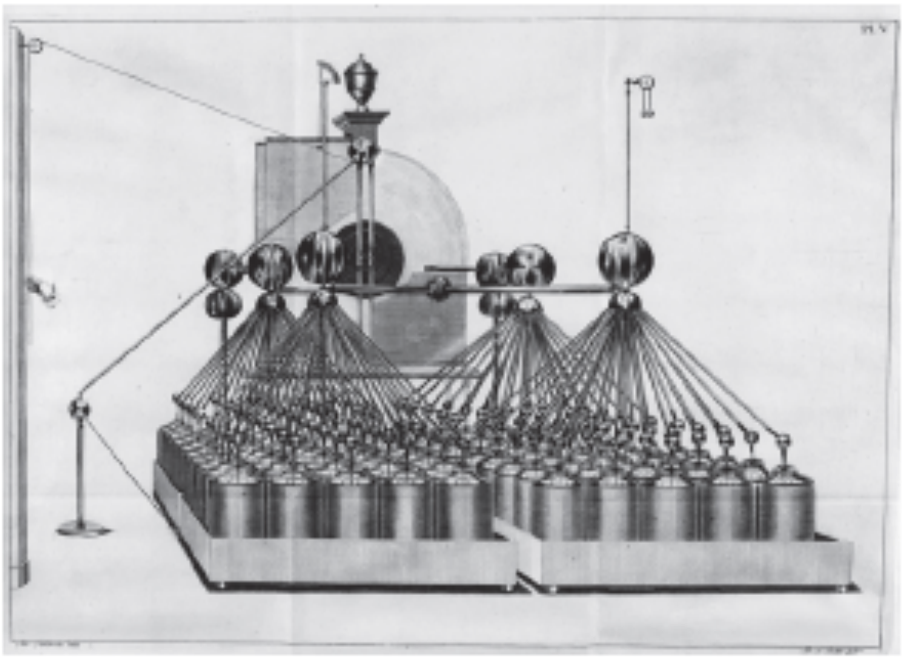


Pre-shot photo of coils & target hardware

Post-shot photo

**MagLIF Experiment**

# The earliest z-pinch experiment on record



Martinus van Marum

Location: Amsterdam

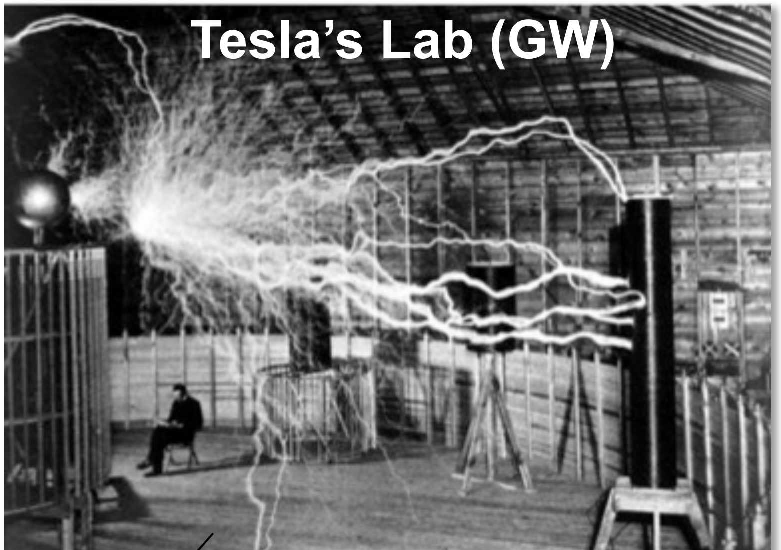
Date: 1790

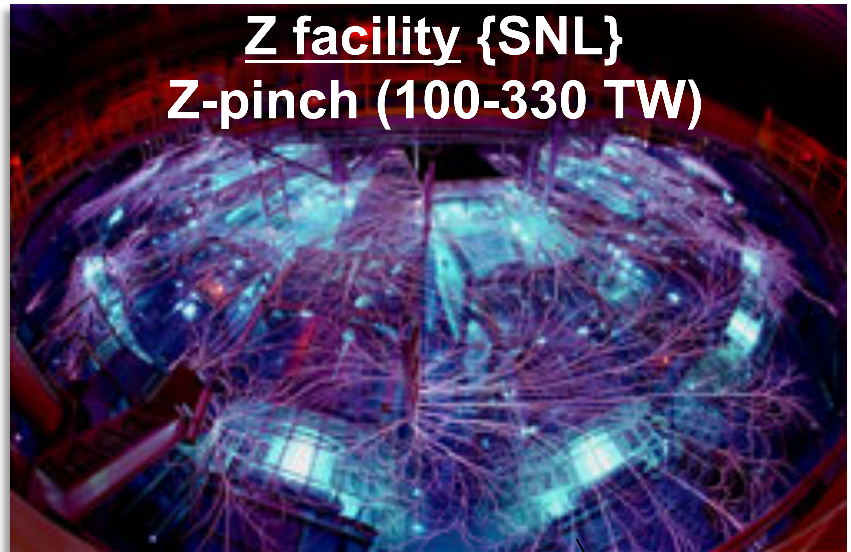
Parameters:
1 kJ energy storage

Technology:
100 Leyden jars

Application:
explosion and vaporization of 1 m long wire

# 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)

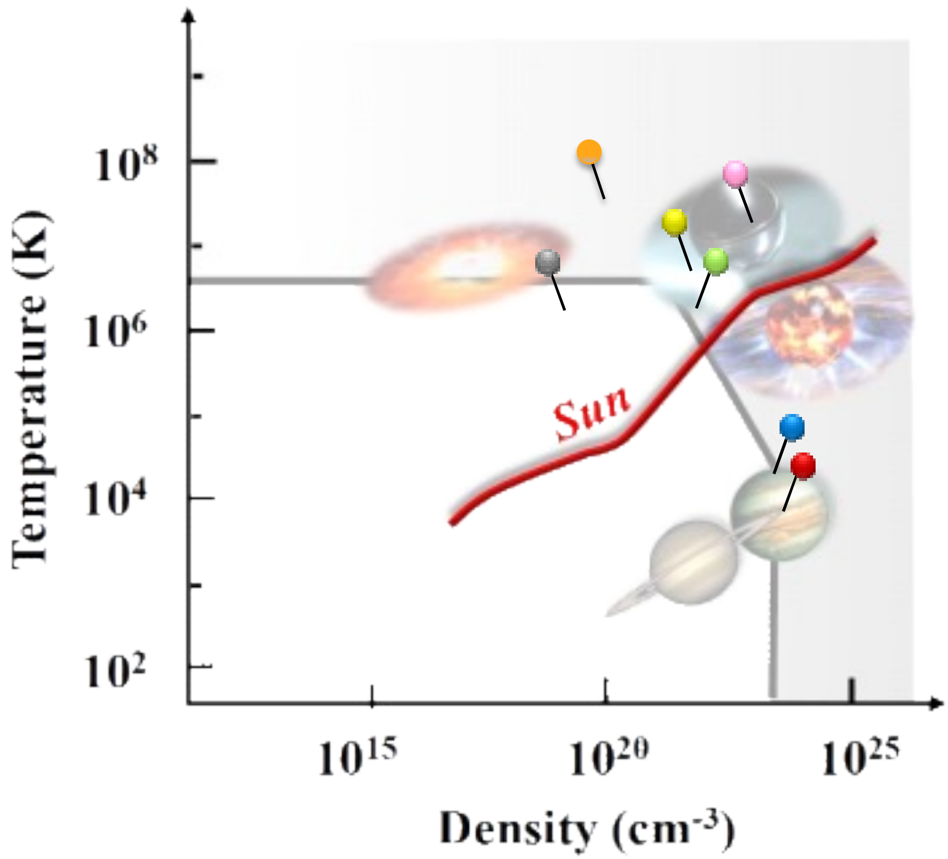
1900 1920 1940 1960 1980 2000

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)

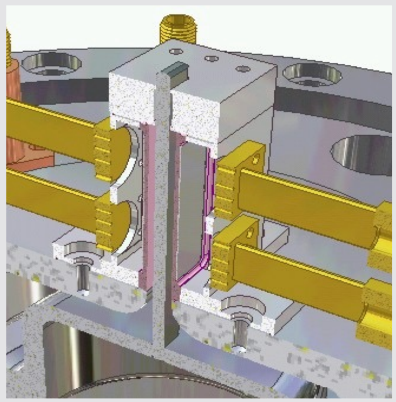
**Fusing Plasmas**
Bailey et al., PRL 93 (2004)

**High-Z Ion Radiating Plasmas at 40 Mbar**
Ampleford et al.. submitted PoP (2013)

# There are multiple ways to use the current on Z

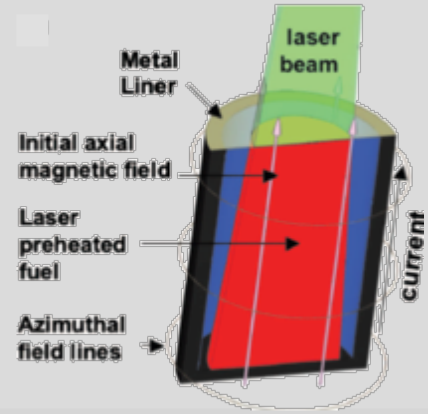
## Shock Compression

Velocities > 40 km/s



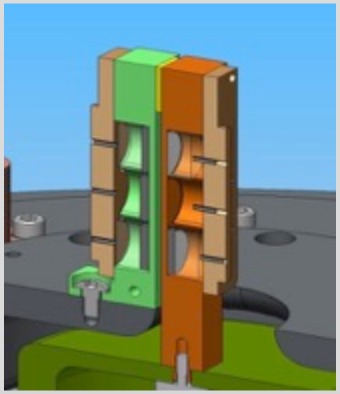
## Cylindrical compression

-Fusion (P up to 1 Gbar)
-EOS up to 6.5 Mbar



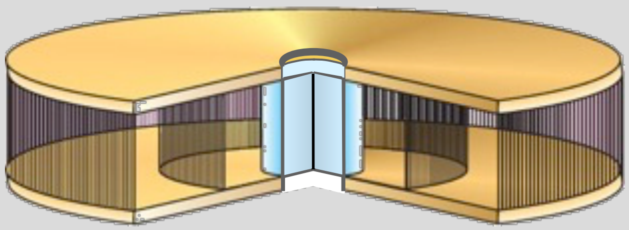

## Planar ramp-compression

continuous compression up to ~4 Mbar



## Z-pinch x-ray sources

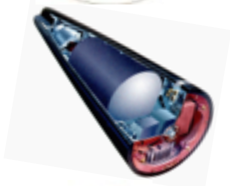
X-ray power up to 330 TW, 2.2 MJ



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

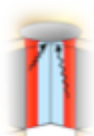
**Dynamic Materials Properties** — Materials of interest at pressure and temperatures of interest

**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

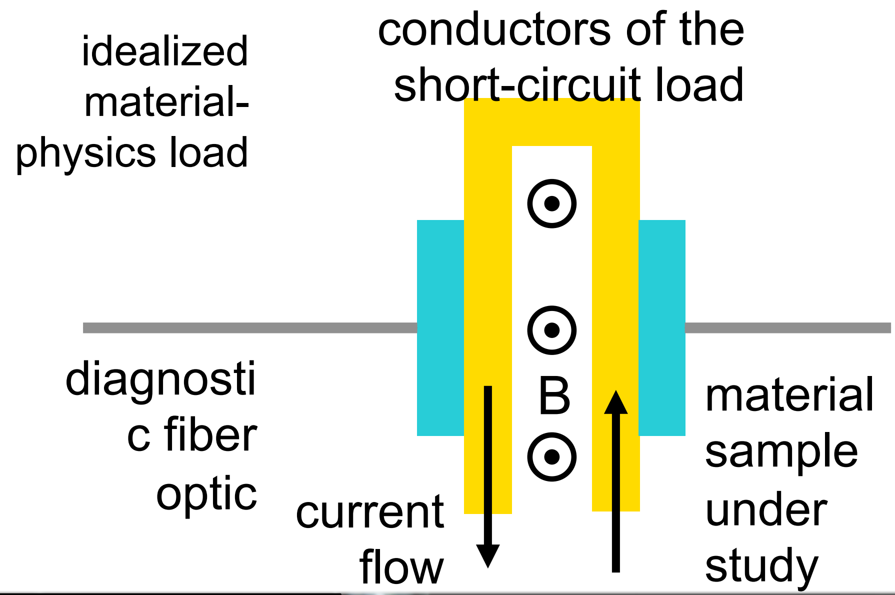
## Z and other pulsed-power machines are used to drive material-physics experiments

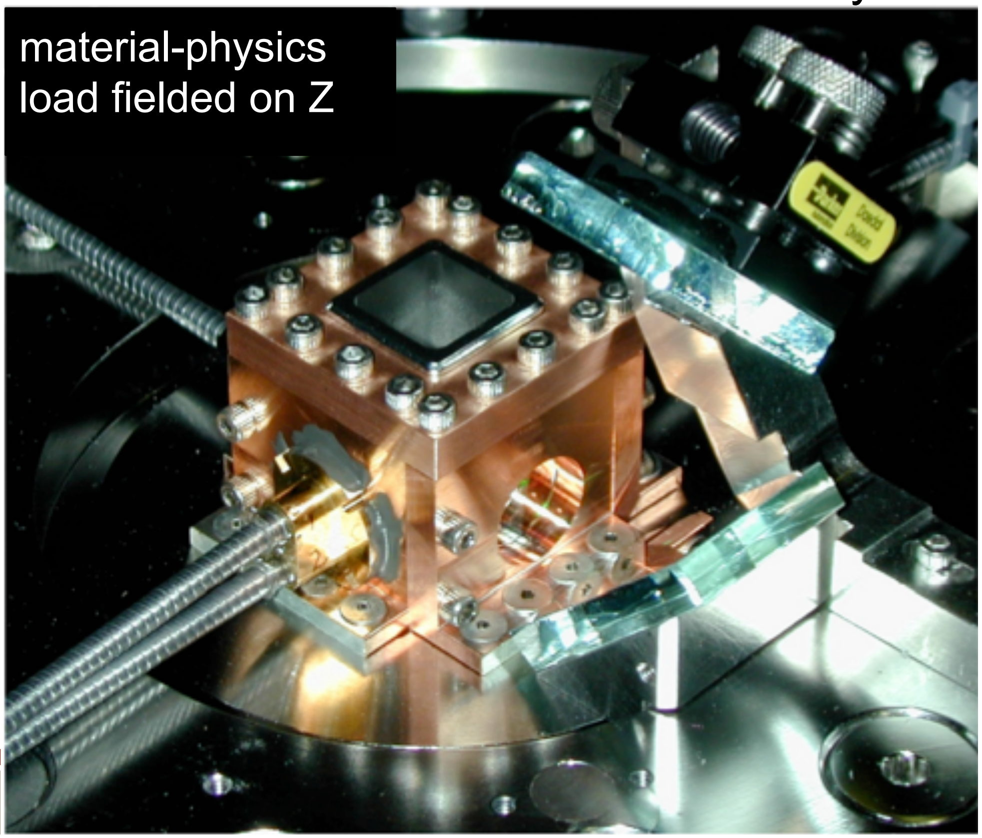
- This application is outlined in seminal publications by Reisman and colleagues (JAP, 2001) and Hall and co-workers (RSI, 2001).
- The magnetic pressure generated within a short-circuit load drives the experiment.

$$P_{magnetic} = \frac{\mu_0 I^2}{2 w^2}$$

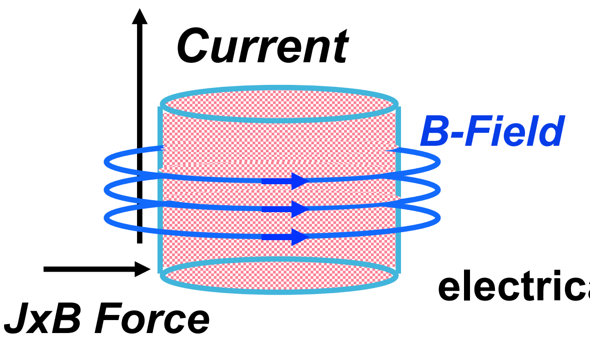
I = current

w = width of the conductor



# Magnetically-driven fast z-pinch implosions efficiently convert electrical energy into radiation




**electrical energy**

↓

**kinetic energy**

**kinetic and magnetic energy**

↓

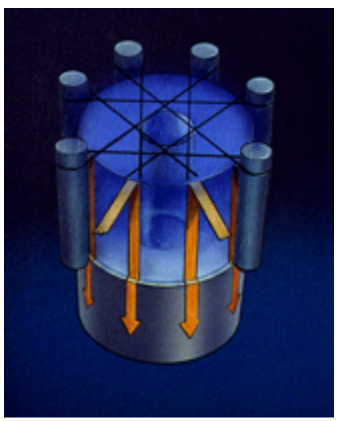
**internal energy (fast ions)**

↓

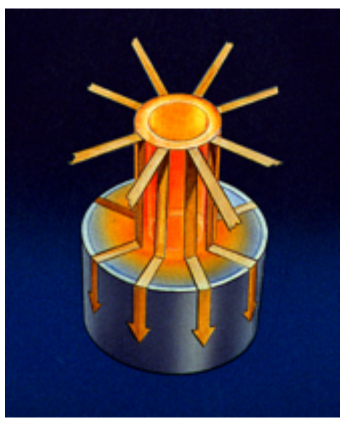
**internal energy (ions and electrons)**

↓

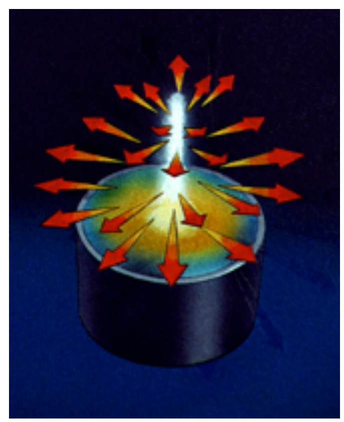
**x rays**



**Ablation**



**Implosion**

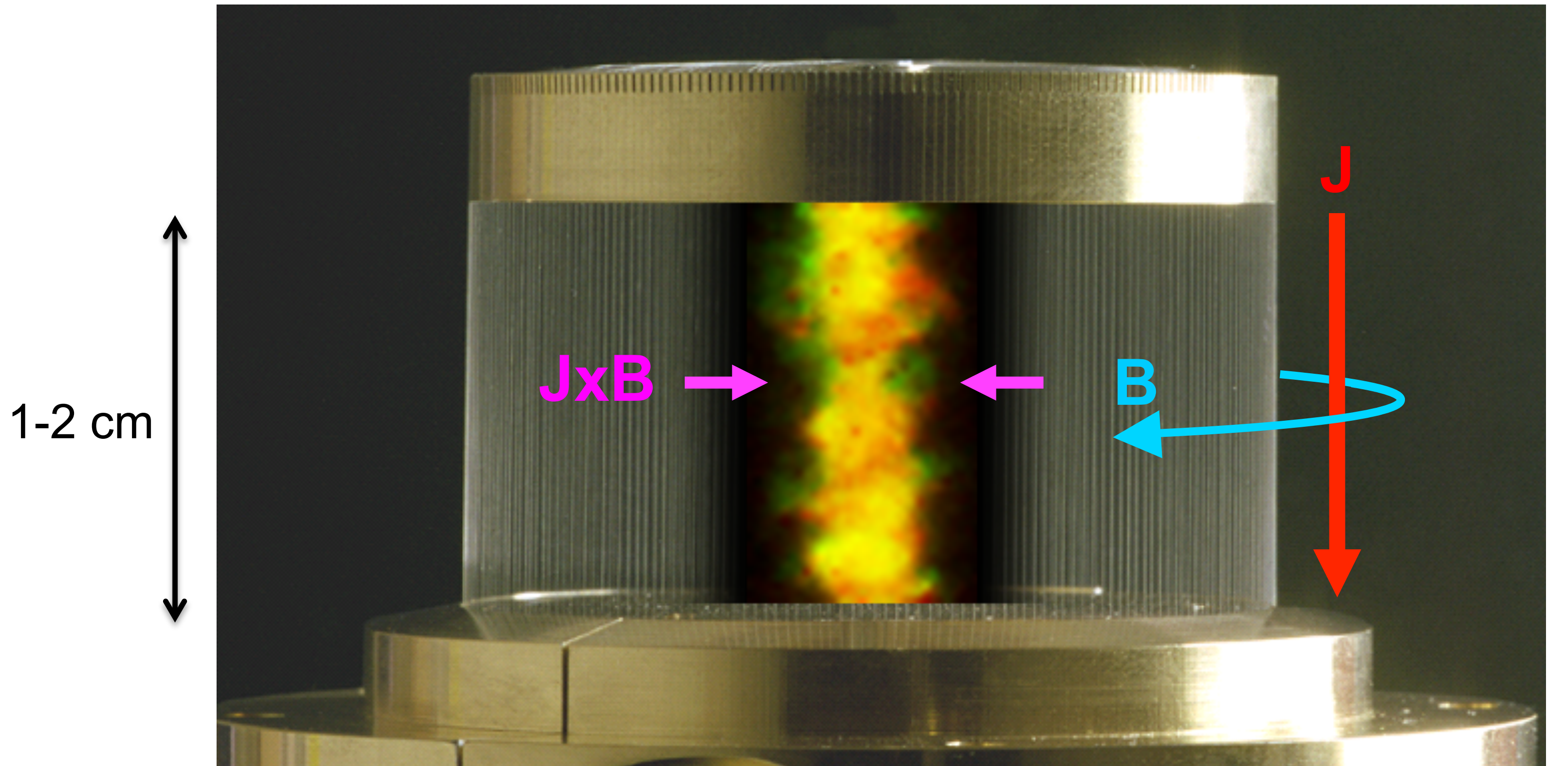


**Stagnation**

<u>Fast wire z-pinch loads:</u>

- Z-pinches are imploded in 60-120 ns, and radiate x-rays in 5 ns
- Energy: x-ray ~ 15% of stored electrical

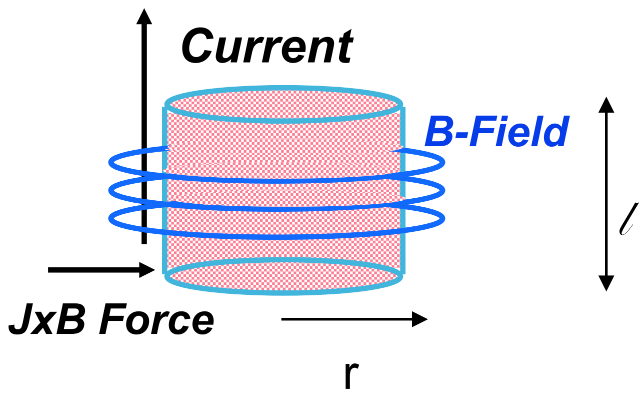
# Magnetically driven implosions are efficient, powerful, x-ray sources from 0.1 to 10 keV




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

~ 10-15% wall plug efficiency

# How much magnetic energy can we put into kinetic energy ?




According to the MHD equations we can treat the magnetic field working on the wires as a magnetic pressure $P_{mag} \sim B^2$

For a thin shell with all the current on the outside:

MKS units

$$ma = F$$

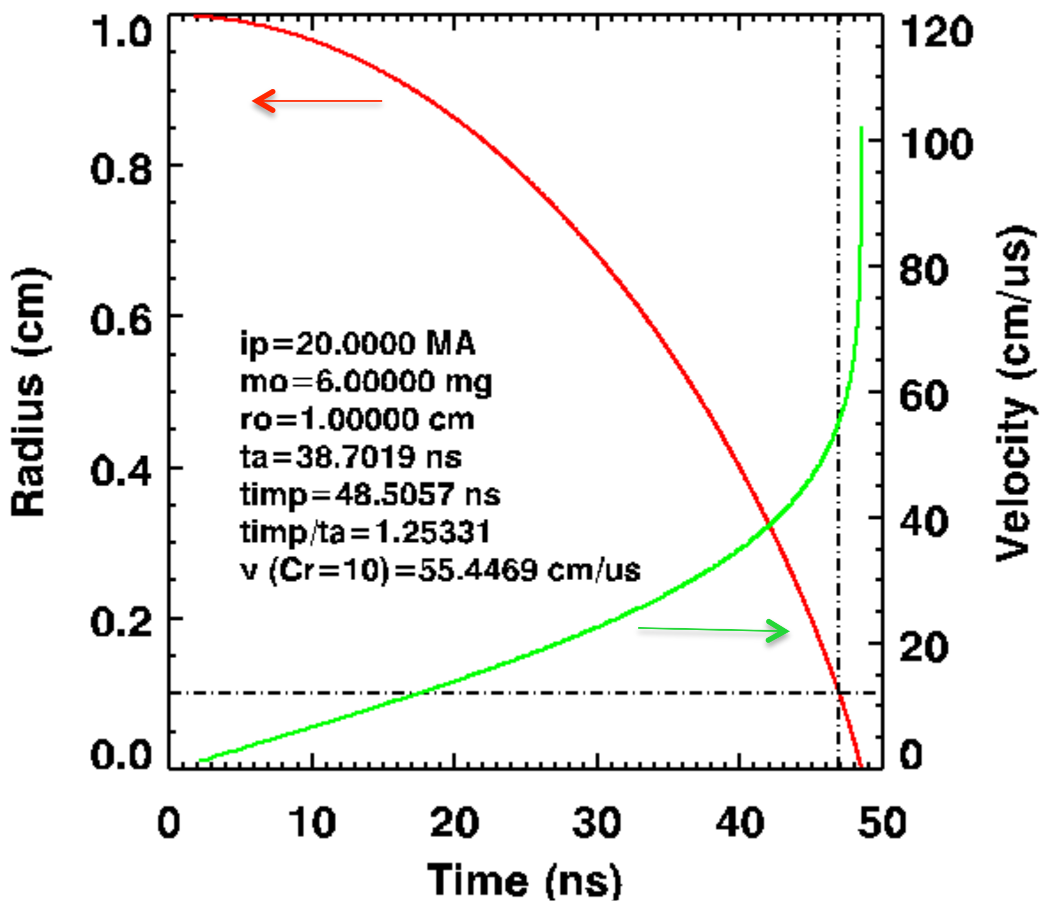
$$m(d^2r/dt^2) = PA \qquad A = 2\pi r l \qquad P = \frac{B^2}{2\mu_o} \qquad B = \frac{\mu_o I}{2\pi r}$$

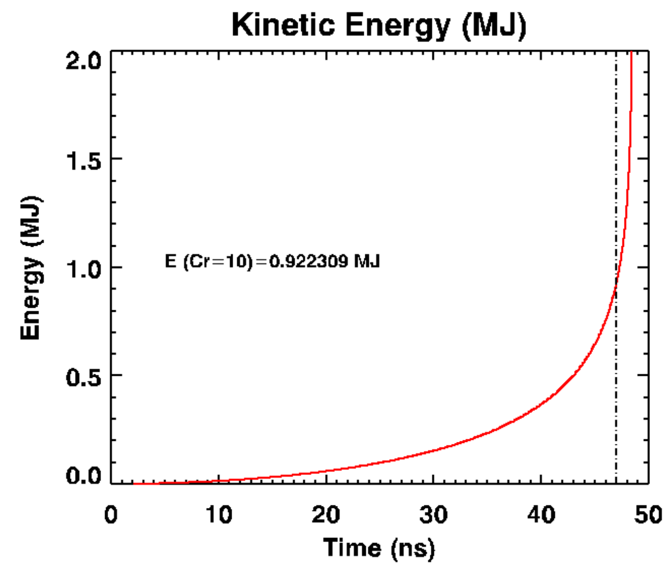
$$\frac{m}{\ell}\frac{d^2 r}{dt^2} = -\frac{\mu_o}{4\pi}\frac{I^2}{r}$$

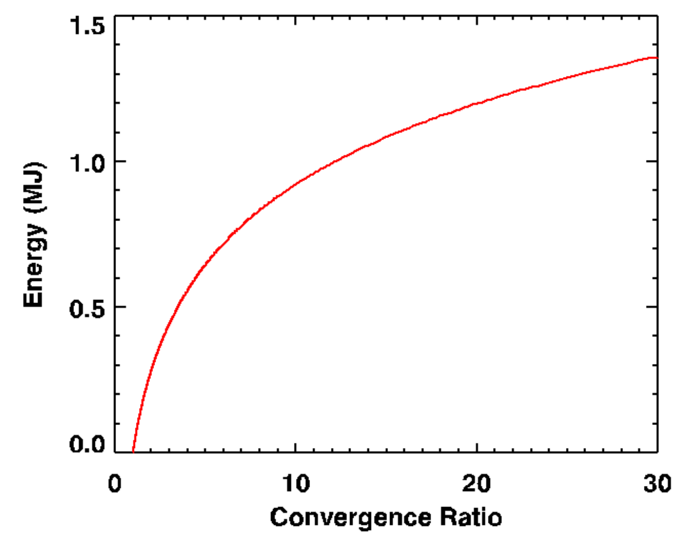
Acceleration increases with $I^2$, but it also **increases** *during* implosion ($r^{-1}$) !

**We can integrate this equation to get the kinetic energy given to the imploding shell**

# An analytic solution to the equation of motion with I ~ constant shows rising magnetic pressure accelerates the pinch




- Velocity at convergence ratio of 10 ~ 50 cm/μs ~ 500 km/s

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

An energy of 1 MJ:

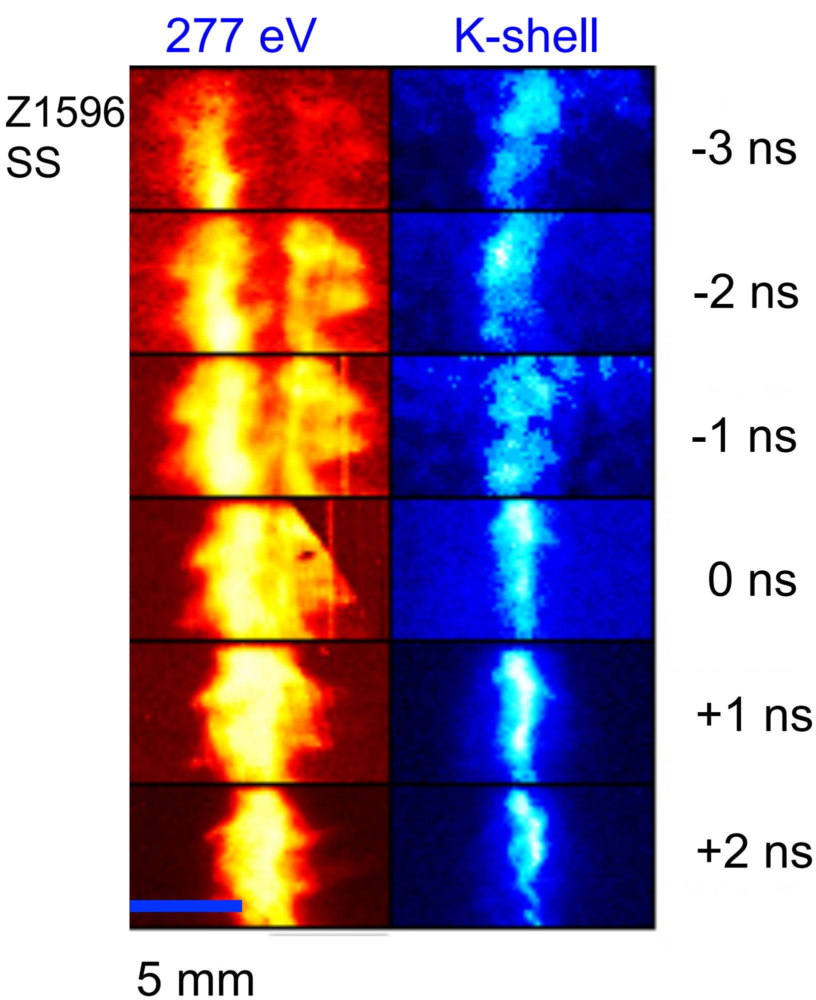
- Kinetic energy of F150 at ~60 mph
- 0.48 x energy in a stick of dynamite
- 100 W incandescent light bulb uses 1 MJ in 4.3 hours

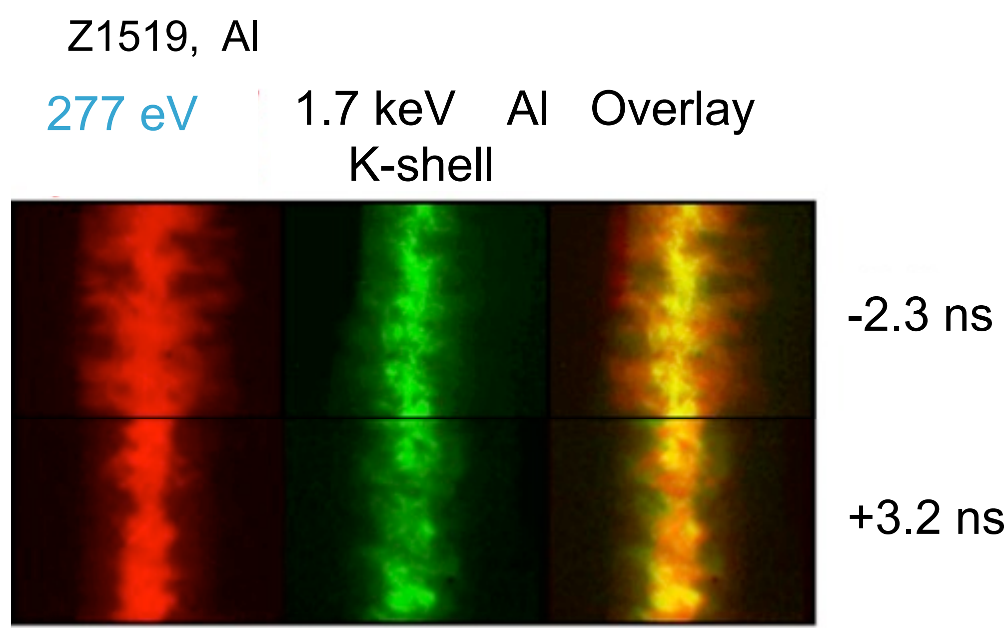
A velocity of 500 km/sec:

- ~ 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

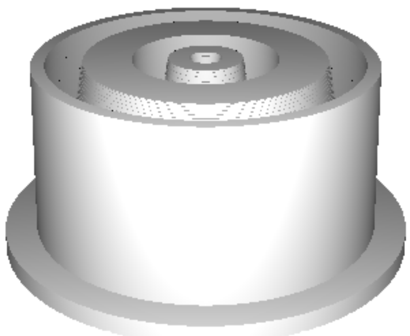



- As noted previously,
  - Evidence of instability at stagnation
  - Observed structure varies with atomic number
- Hot, dense column emitting K-shell on axis with colder material still imploding

# 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

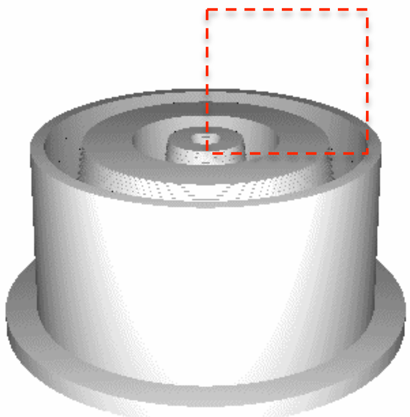


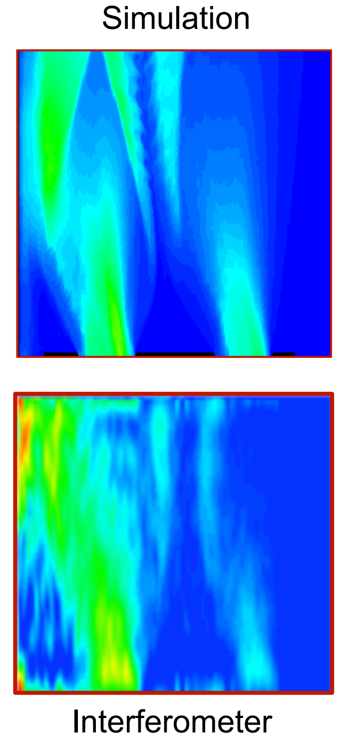
C.A. Jennings, SNL, GORGON

- 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



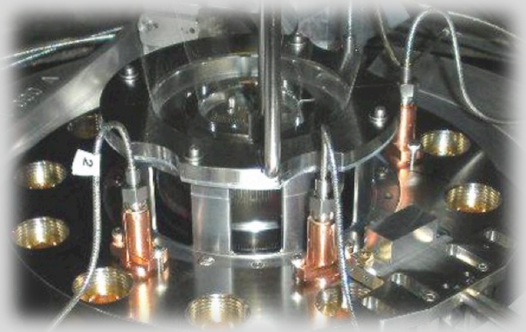



C.A. Jennings, SNL, GORGON

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

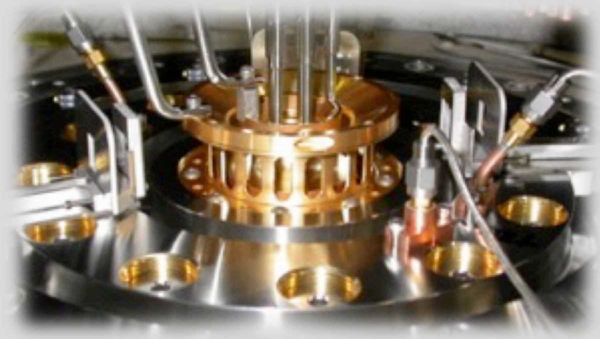
# Many x-ray experiments use just one of two types of routine, established wire array z-pinch sources

**Large-diameter K-shell sources**



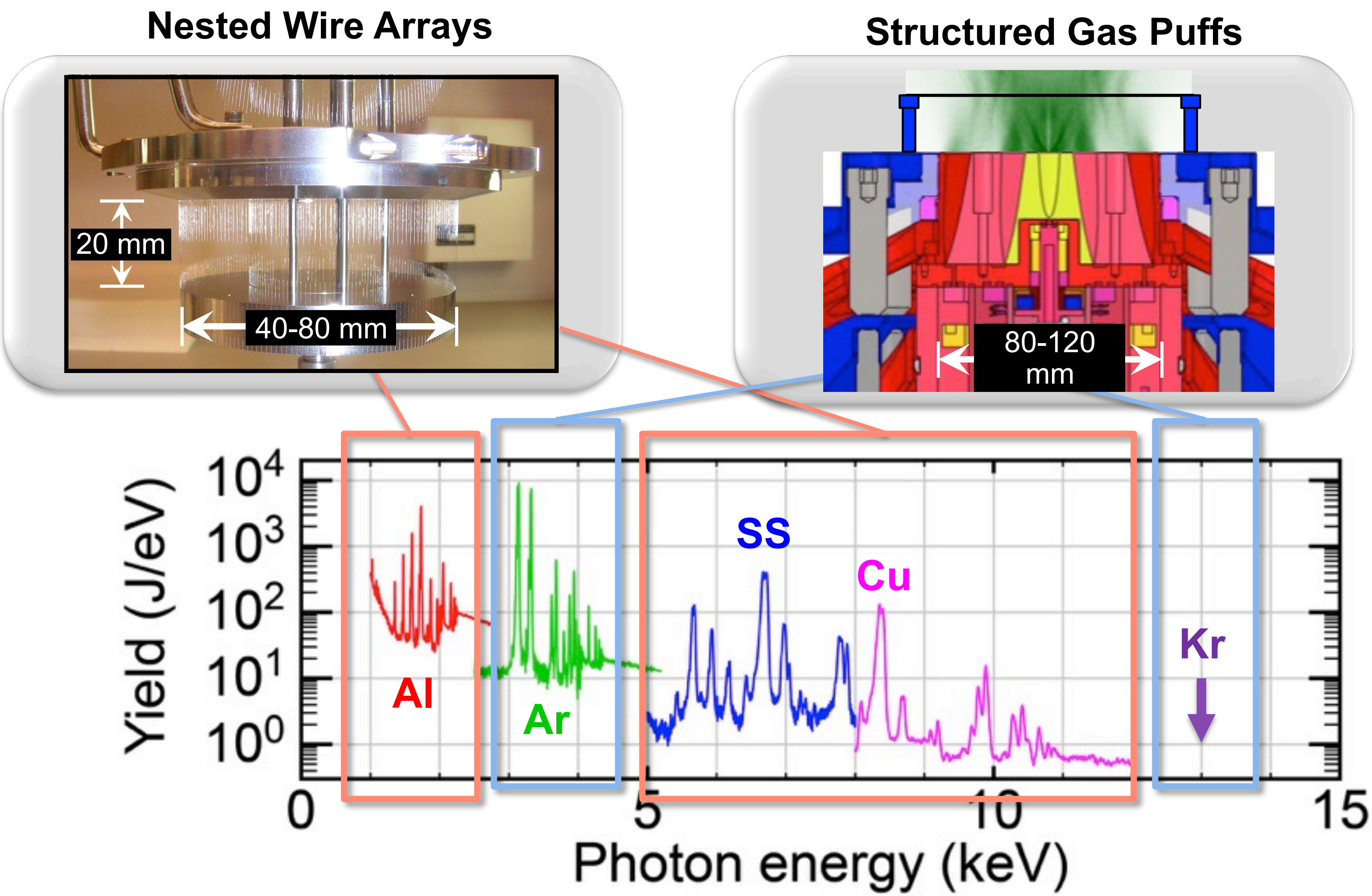
- Diameter: 4-8 cm
- Height: 2 cm
- Radial Beamlines: 9
- Axial Beamlines: 1
- Optimized for K-shell emission
- Spectrum/Power/Energy depends on wire material: Al, SS, Cu

**Z-pinch dynamic hohlraum**



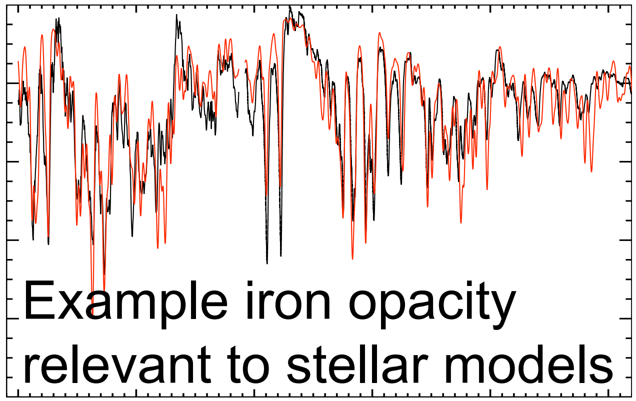
- Diameter: 4 cm
- Height: 1.2 cm
- Radial Beamlines: 9 or 18
- Axial Beamlines: 1
- Near-Planckian emission spectrum
- Broadband Energy Emission: 1 MJ
- Peak Power: 170 TW
- Power FWHM: 3 ns

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

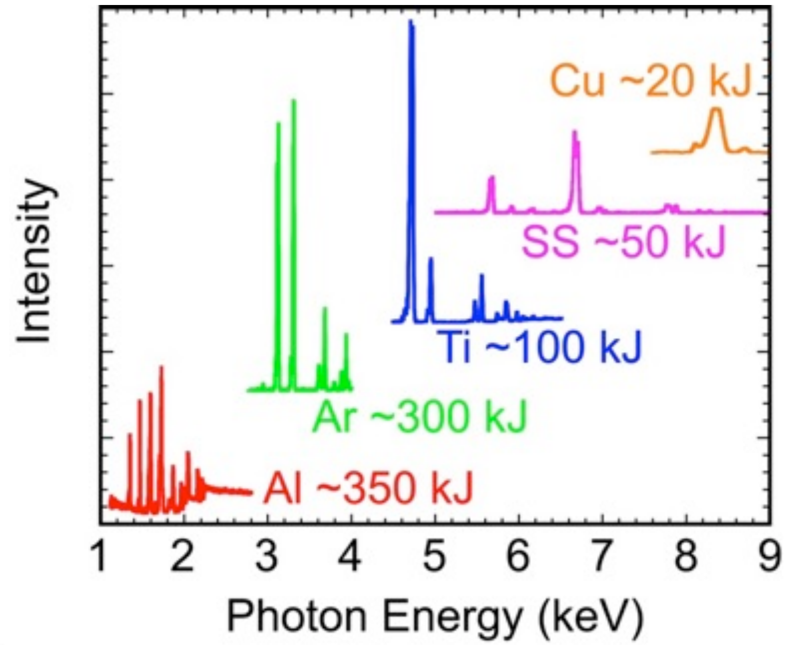


# Magnetically-driven x-ray sources are being used for a variety of fundamental and applied science applications

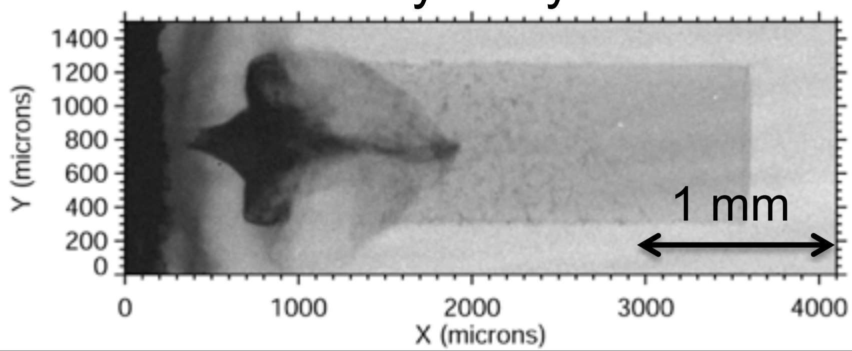
## Opacity Measurements and Photo-ionized plasmas [1]

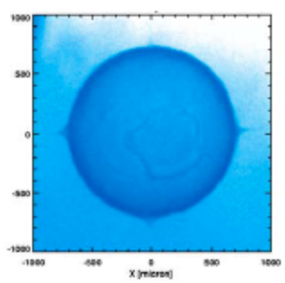



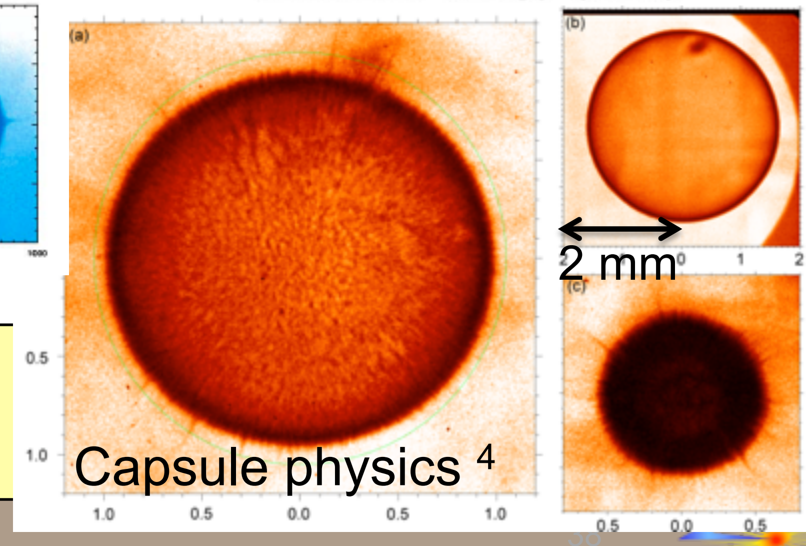

## K-Shell Sources [3]




## Radiation Hydrodynamics [2]





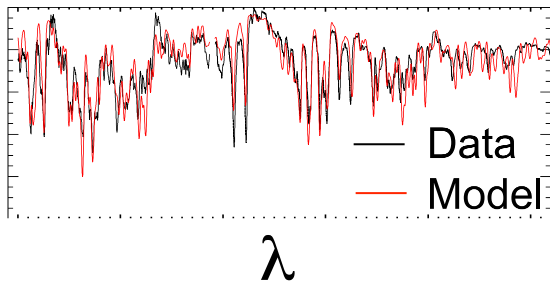


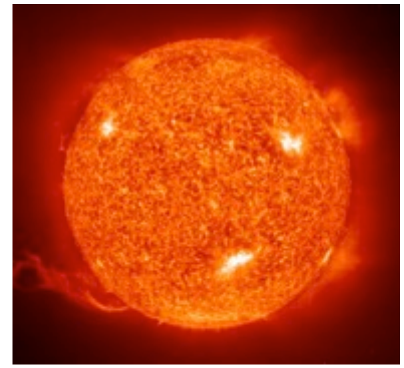
[1] J.E. Bailey, et al, Phys. Rev. Lett. 99, 265002 (2007).
[2] G.R. Bennett, et al., Phys. Rev. Lett. 205003 (2007).
[3] C. A. Coverdale et al., IEEE T. Plas. Sci. 35, 582 (2007).
[4] M.E. Cuneo et al., IEEE T. Plas. Sci. 40, 3222 (2012).

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

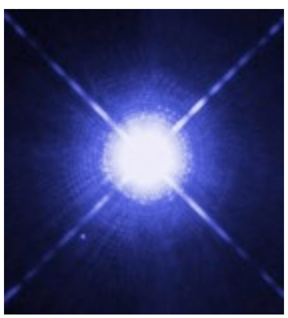
**Solar opacity at $T_e$ > 150-170**

Bailey et al., PRL 99 (2007)



**White dwarf physics**



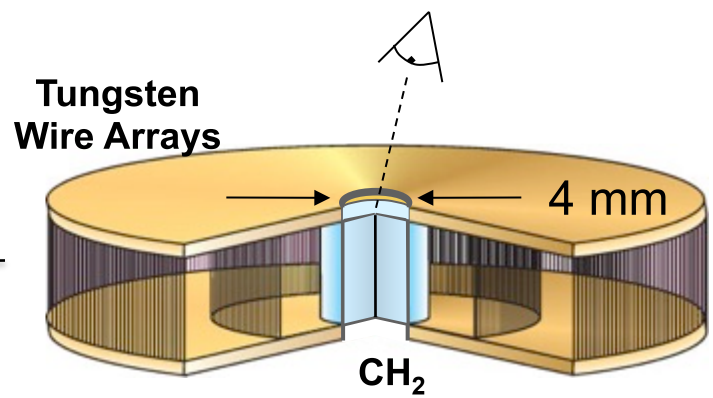
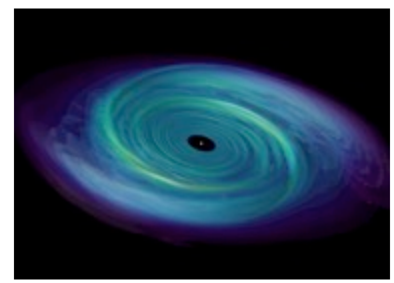
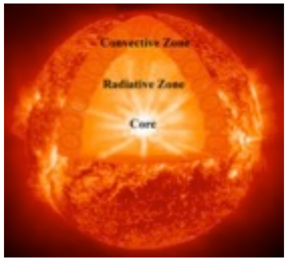


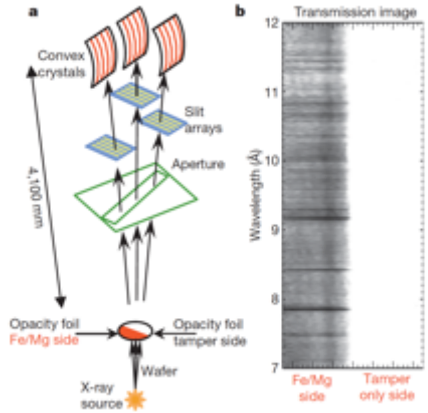

**Photo-ionized plasmas**



- 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

# We are making fundamental discoveries in Astrophysics and Planetary Science within the Z Fundamental Science Program




**A higher opacity of iron at solar conditions explains contradictions between helioseismic observations and established solar models**

*A higher-than-predicted measurement of iron opacity at solar interior temperatures*

- Jim Bailey, et. al., Nature 517, 14048 (2015)
- Sandia, Ohio State University, University of Nevada Reno, PRISM, LANL, LLNL, and CEA
- High-precision measurements at the almost unreachable conditions of the radiation/convection boundary in the sun

LETTER

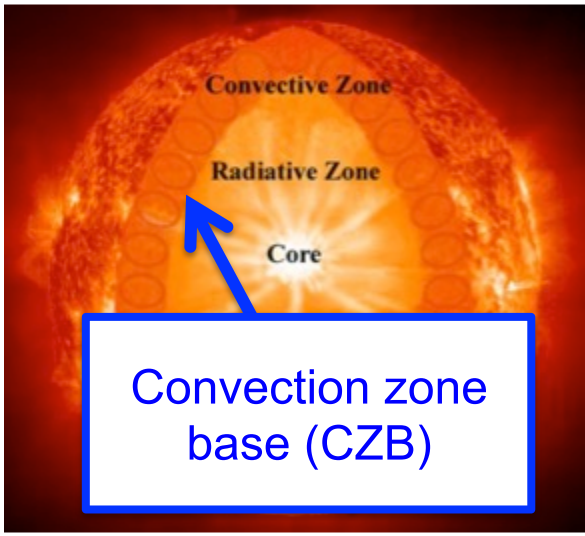
doi:10.1038/nature14048

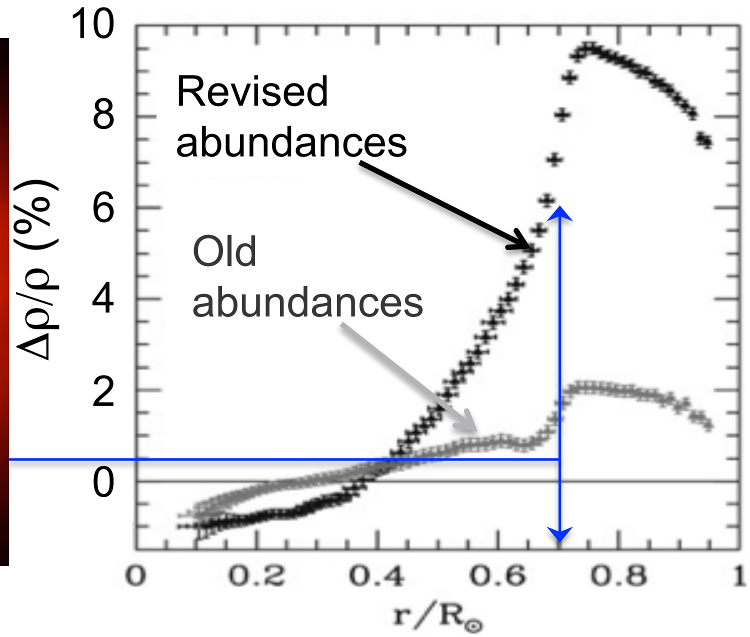
**A higher-than-predicted measurement of iron opacity at solar interior temperatures**

J. E. Bailey[1], T. Nagayama[1], G. P. Loisel[1], G. A. Rochau[1], C. Blancard[2], J. Colgan[3], Ph. Cosse[2], G. Faussurier[2], C. J. Fontes[3], F. Gilleron[2], I. Golovkin[4], S. B. Hansen[1], C. A. Iglesias[5], D. P. Kilcrease[3], J. J. MacFarlane[4], R. C. Mancini[6], S. N. Nahar[7], C. Orban[7], J.-C. Pain[2], A. K. Pradhan[7], M. Sherrill[3] & B. G. Wilson[5]

# 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

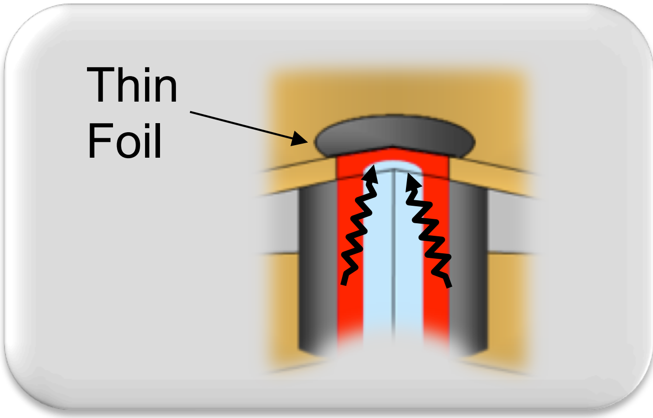
Stellar composition and opacity are intertwined

Problem resolved if mean opacity ~15% higher than predicted

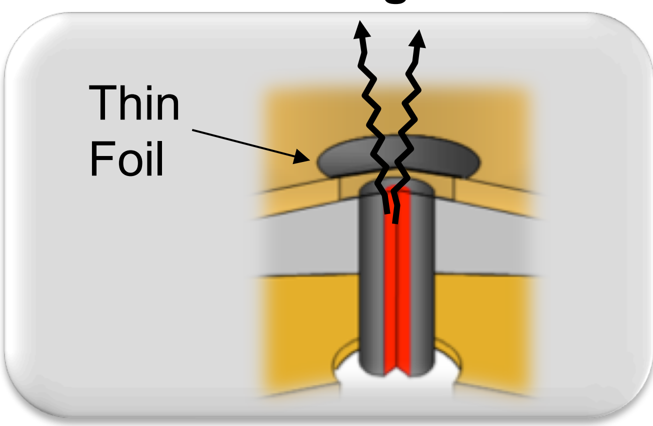
- **Conditions at the solar CZB : 182 eV, 9e22 electrons/cc**
- **Similar conditions exist in many astrophysical and laboratory plasmas**
- **Thus, solar opacity model refinements have far-reaching implications**

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

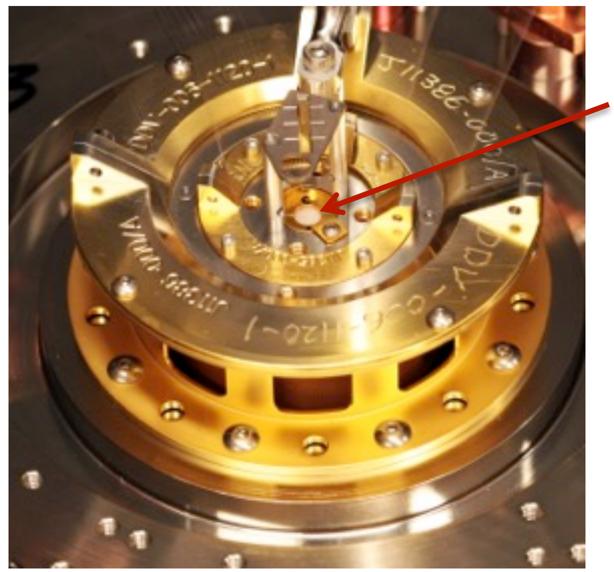
**Foil is heated during the ZPDH implosion**



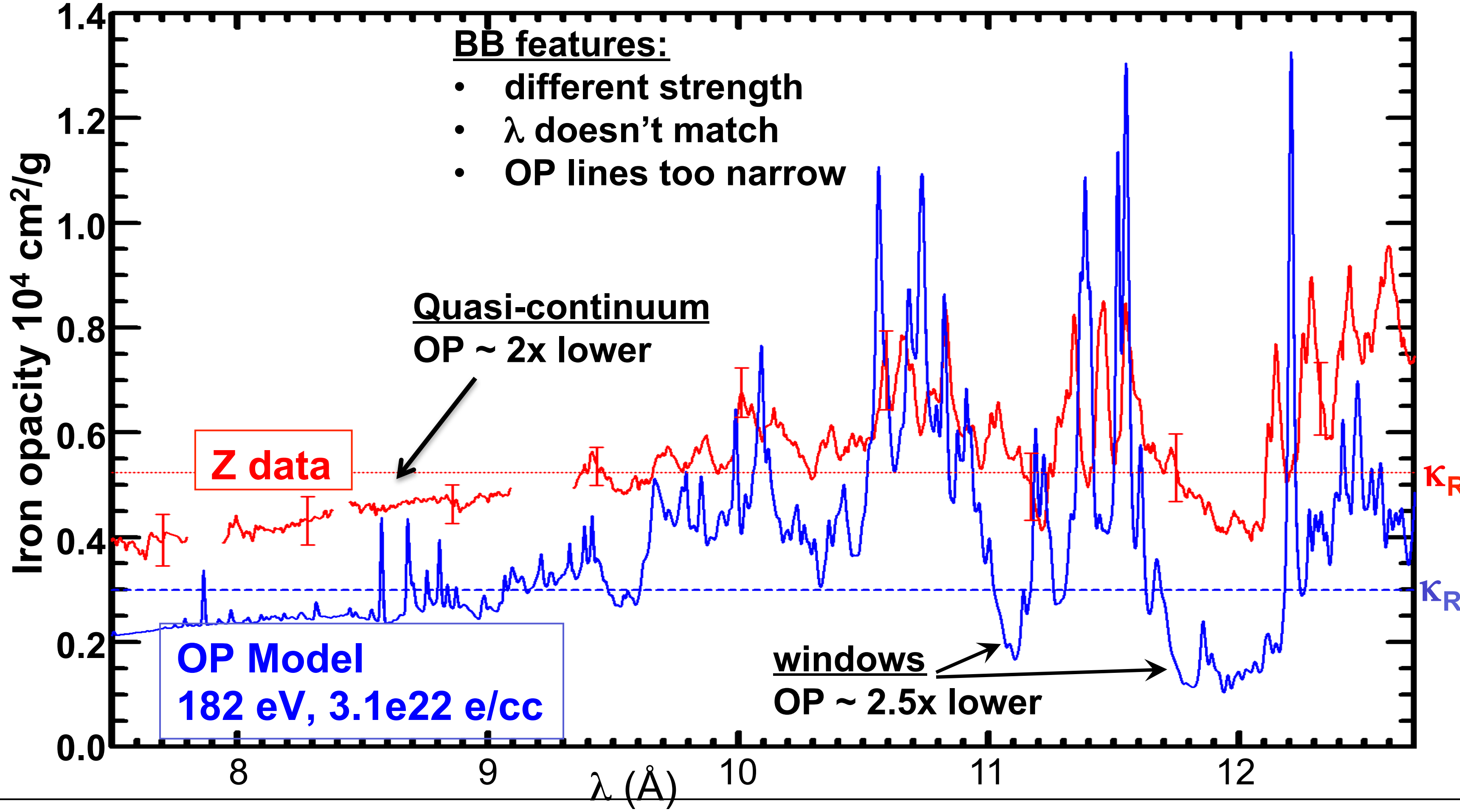

**Foil is backlit at shock stagnation**




Bailey et al., *Nature* 2015

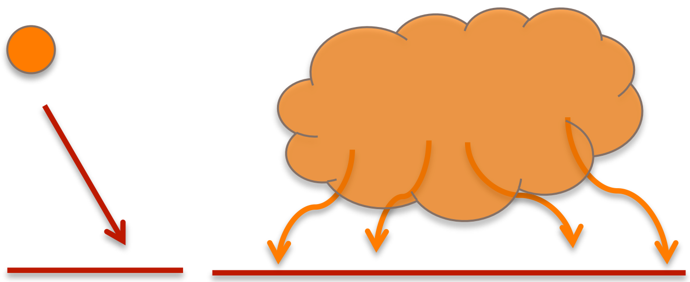


# Opacity model discrepancy at solar-interior conditions implies photon absorption in HED matter is different than previously believed




- **Calculated Rosseland mean for iron is 1.75x lower than measured**
- **This difference accounts for roughly half the opacity change needed to resolve the solar problem**

# We are making fundamental discoveries in Astrophysics and Planetary Science within the Z Fundamental Science Program



**Iron rain following a meteor impact explains the iron-enriched mantle of the earth and a key earth/moon difference**

*Impact vaporization of planetesimal cores in the late stages of planet formation*

- Richard D. Kraus, et. al., Nature Geoscience, DOI: 10.1038/NGEO2369 (2015)
- Sandia, Harvard, UC Davis, and LLNL
- Multi-Mbar dynamical material experiments to measure properties of vaporized iron at conditions of planetary impacts

nature geoscience

LETTERS

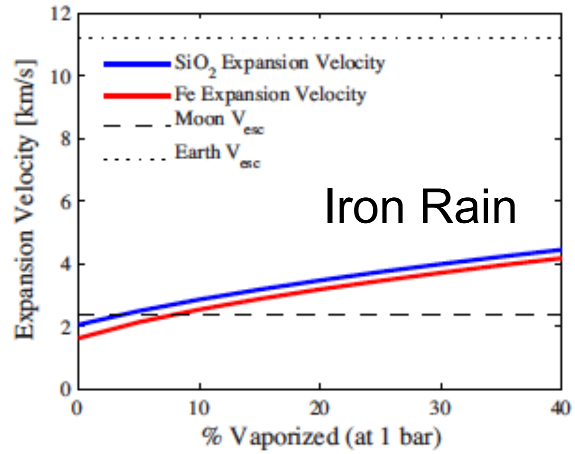
PUBLISHED ONLINE: 2 MARCH 2015 | DOI: 10.1038/NGEO2369

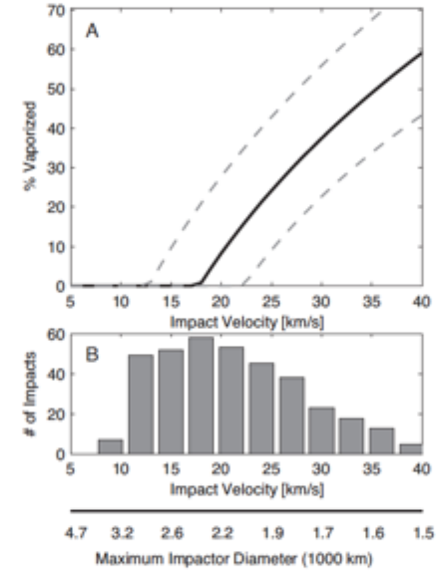
## Impact vaporization of planetesimal cores in the late stages of planet formation

Richard G. Kraus[1,2]*, Seth Root[3], Raymond W. Lemke[4], Sarah T. Stewart[1,5], Stein B. Jacobsen[1] and Thomas R. Mattsson[4]

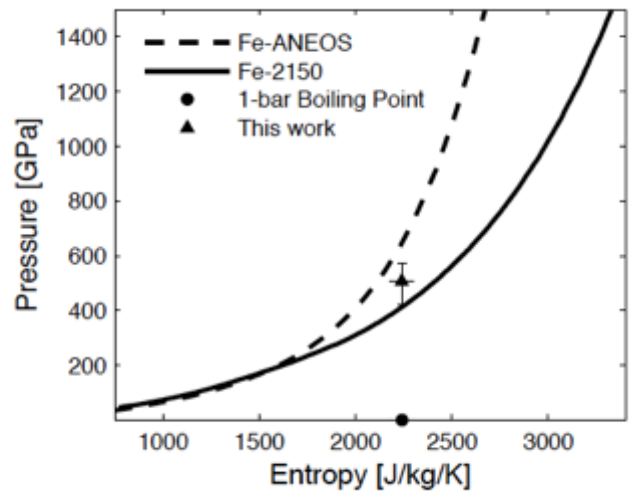
# Planetesimal impacts played an important role in shaping the solar system

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

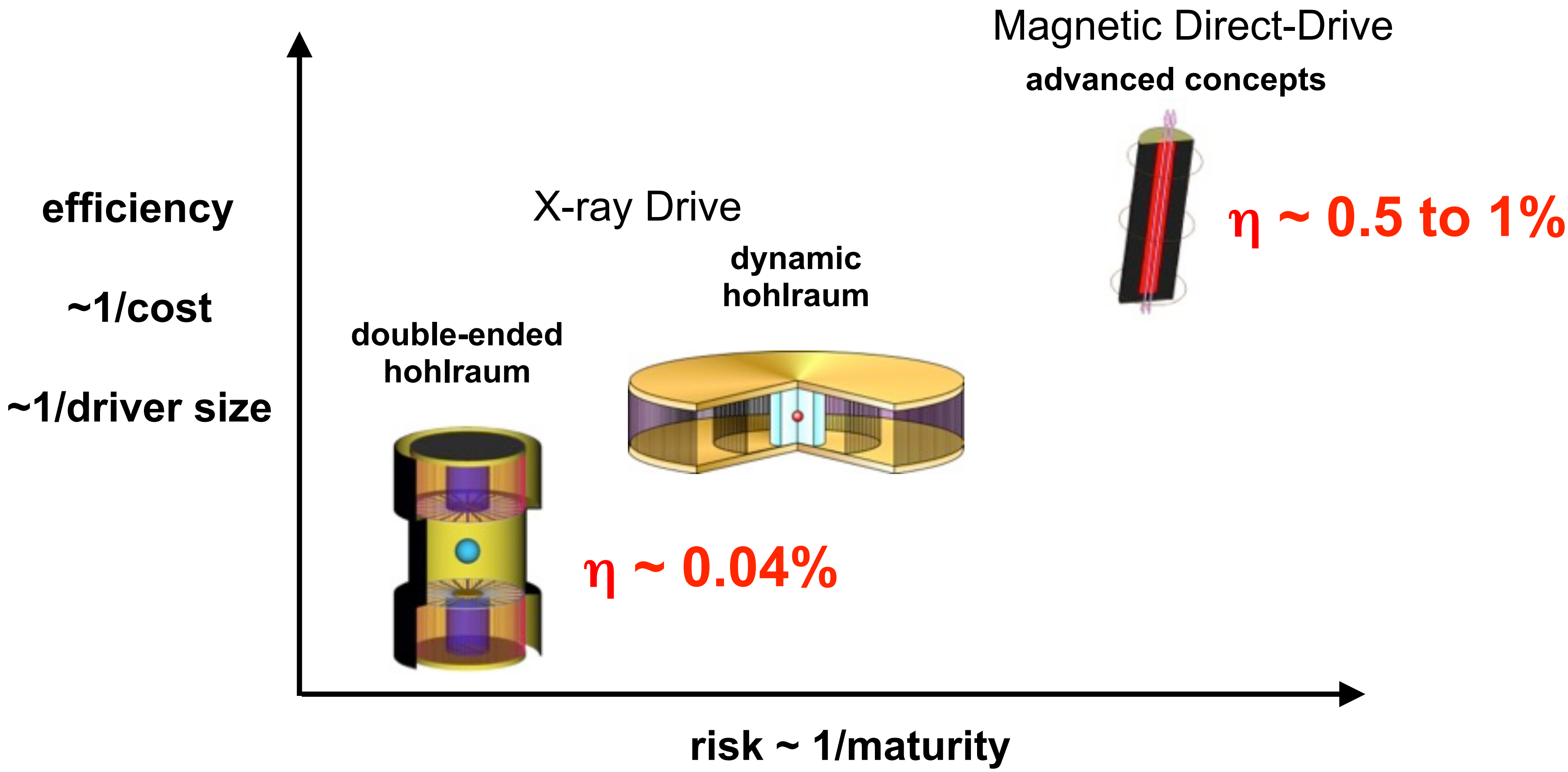



A significantly lower shock pressure (500 GPa) is required to vaporize iron upon release than previously used in planetary modeling  (890 GPa)

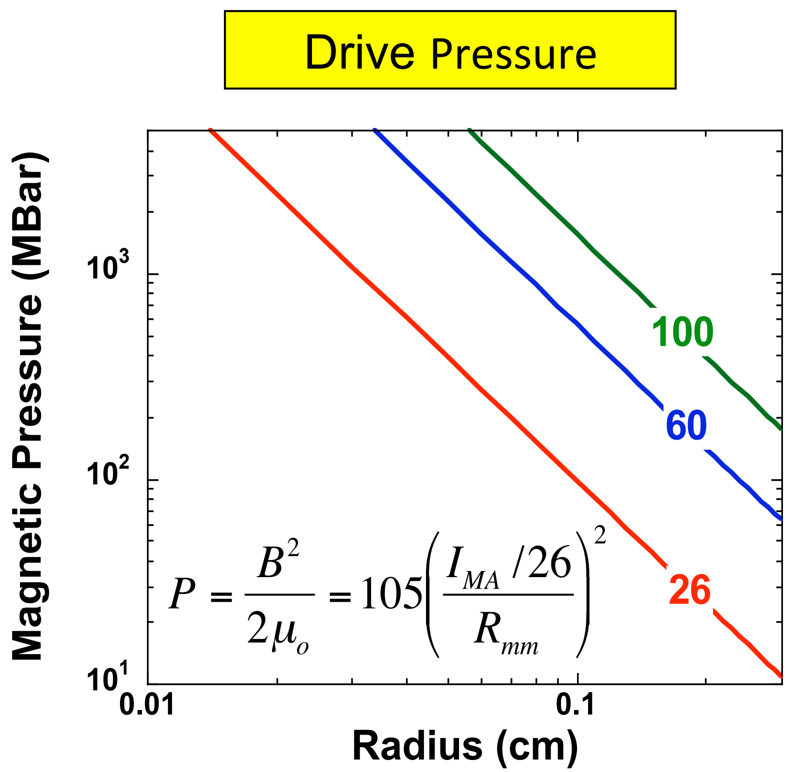


# Are there more efficient pulsed power methods for heating and compressing fusion fuel?




- Pulsed power can flexibly drive many target types
- Direct fuel compression and heating with the magnetic field could be up to 20X more efficient

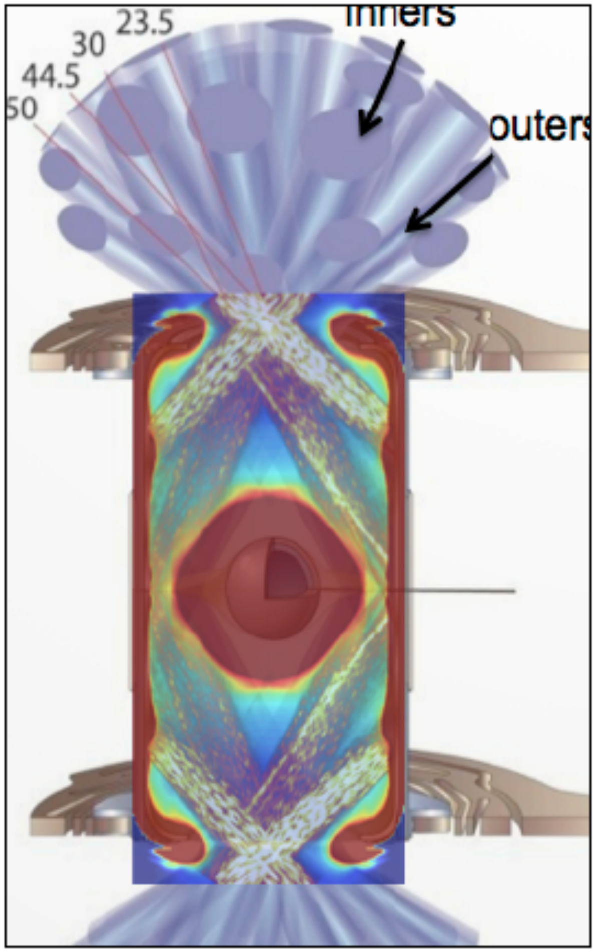
# Direct-magnetically-driven targets efficiently absorb large energies



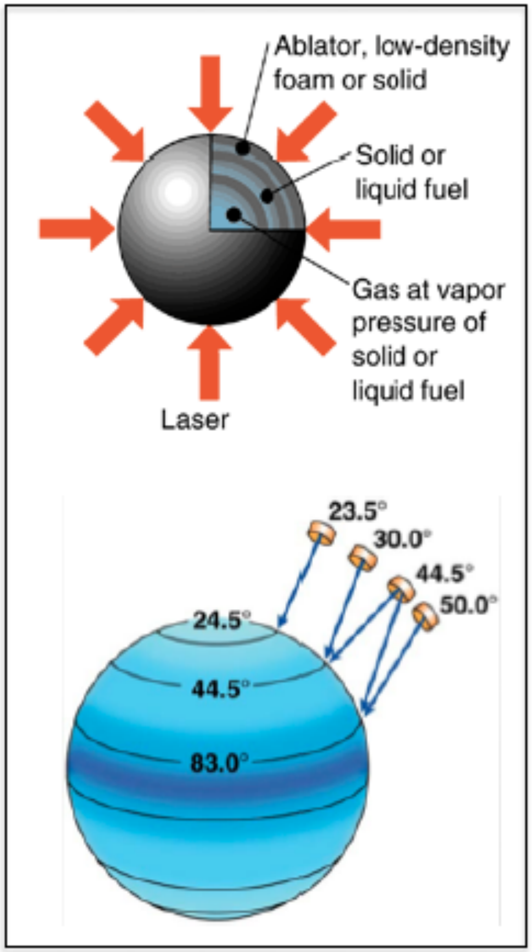

- Large drive pressures:
  - 100 MBar on Z at 26 MA
  - >500 MBar at > 60 MA
- Efficient. No energy is wasted on:
  - Heating target
  - Hohlraum heating
  - Conversion to x-rays
- Energy rich:
  - 100kJ into fusion fuel (~0.5%) on Z
  - 7 MJ into target (~5%) at 60 MA

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

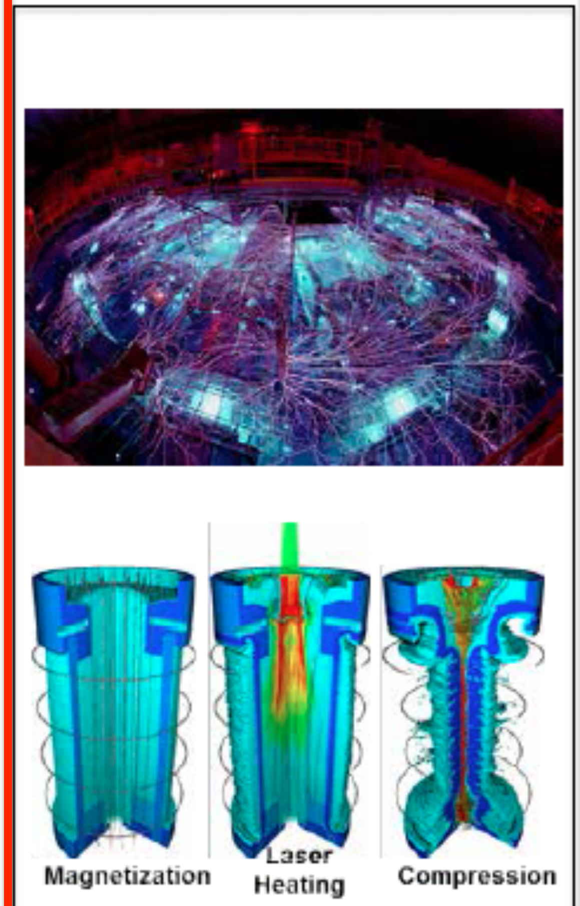
## Radiation-driven implosions




## Laser-driven implosions

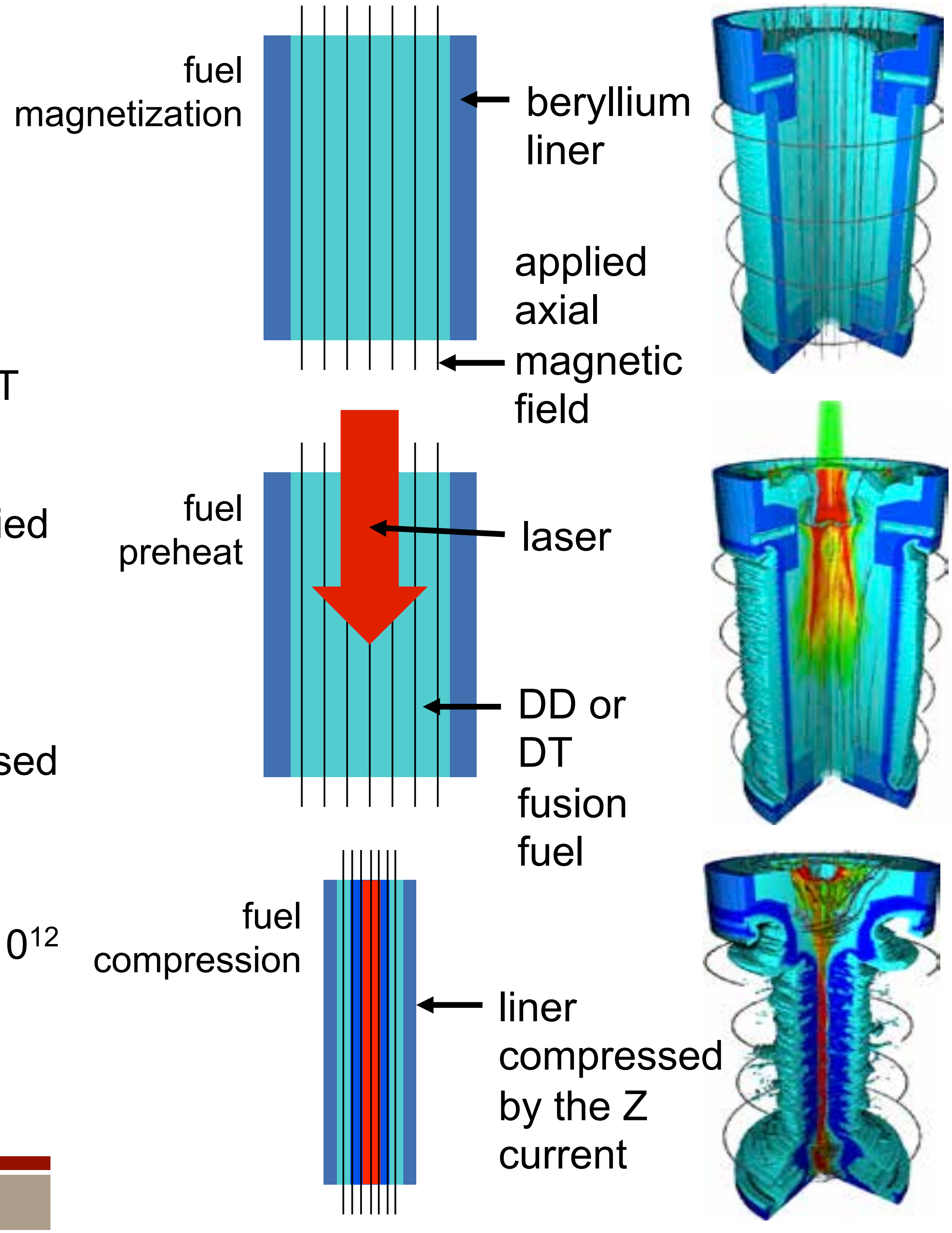



## Magnetically-driven implosions

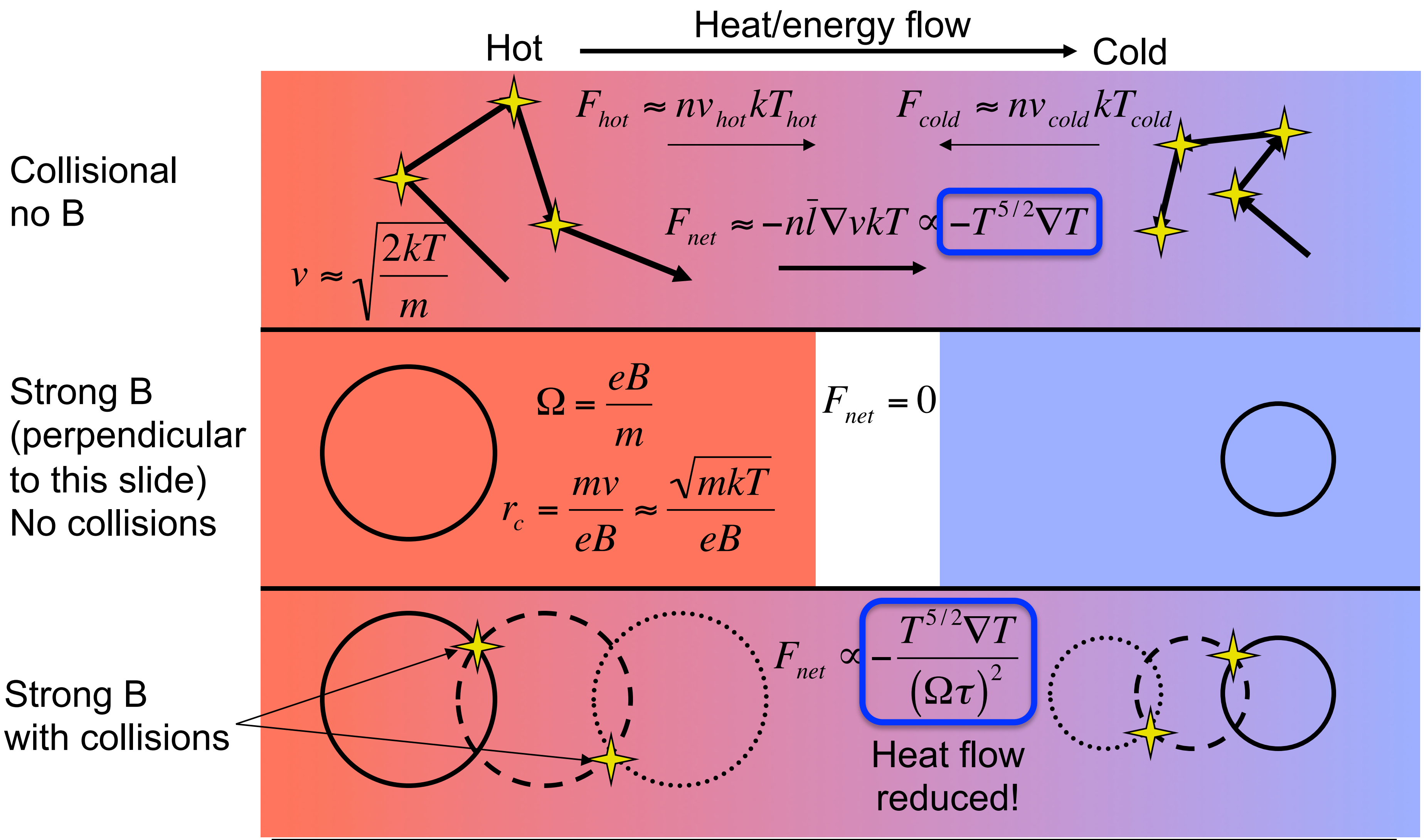


# Sandia is conducting magnetized-liner interial-fusion (MagLIF) experiments on Z

- A beryllium liner contains DD or DT fusion fuel
- The fuel is magnetized by an applied axial magnetic field
- The fuel is preheated by a laser
- The fuel is subsequently compressed by the Z-accelerator current
- To date, the MagLIF concept has achieved DD neutron yields ~2 x $10^{12}$

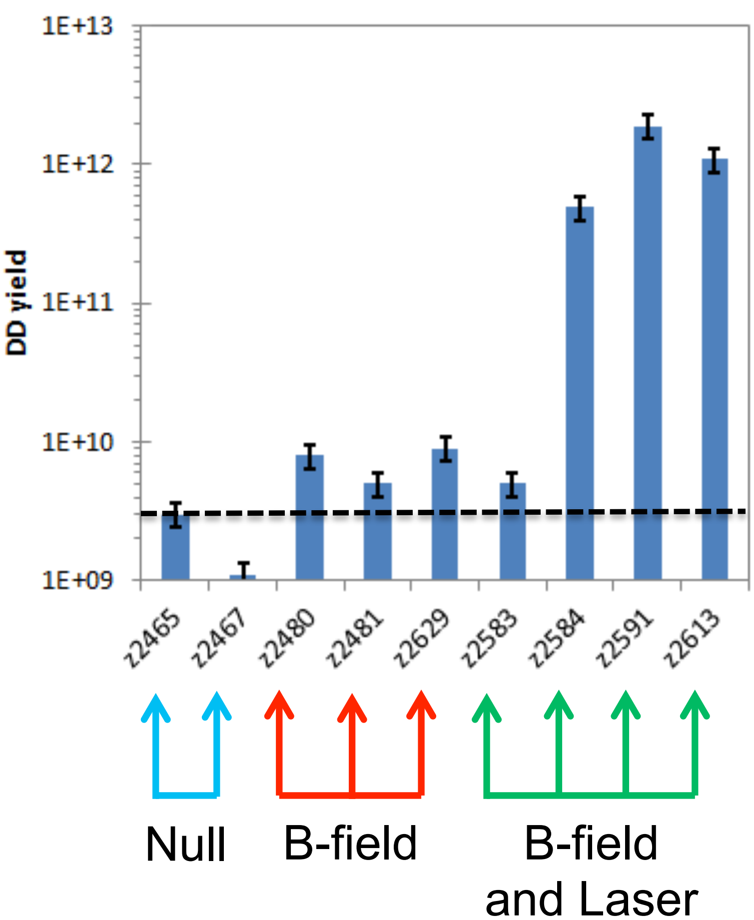


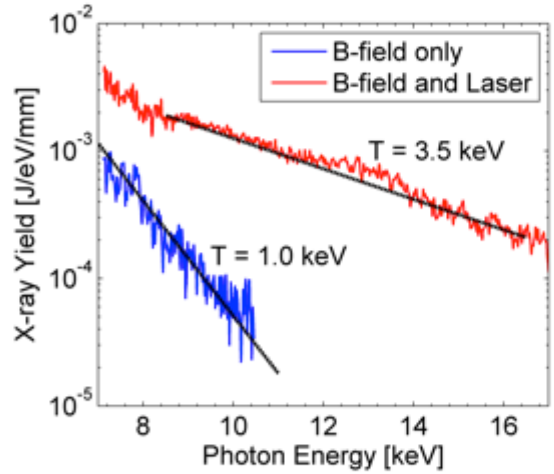
# The presence of a magnetic field can strongly affect transport properties, e.g. electron heat conduction

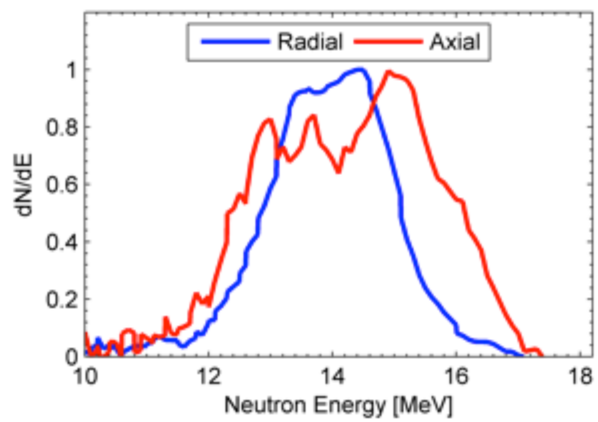


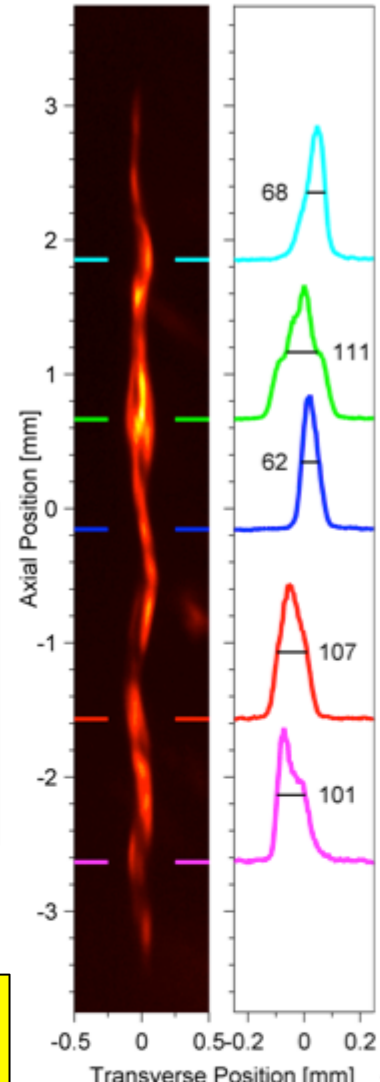

"Anomalous" heat transport can reduce the benefit of magnetic fields (e.g., in tokamaks) but there remains a significant benefit

# We have obtained promising initial results with MagLIF



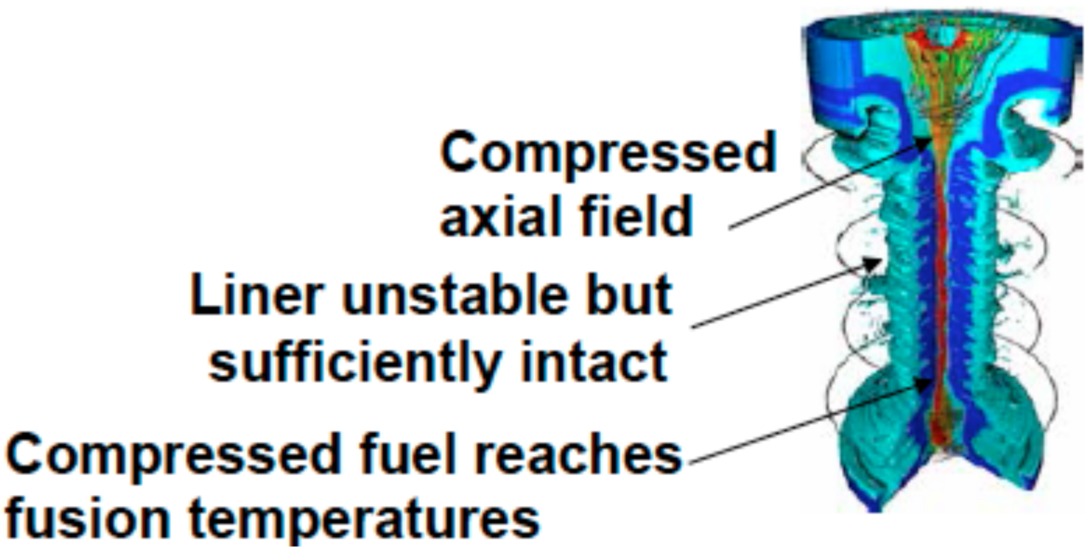




Sefkow, Slutz, et al., Phys. Plasmas (2014)
Gomez et al. Phys. Rev. Lett. (2014), Phys. Plasmas (2015)
Schmit et al. Phys. Rev. Lett. (2014)
Knapp et al. Phys. Plasmas (2015)

## MagLIF is a concept well suited to pulsed power and may lower requirements for plasma self-heating



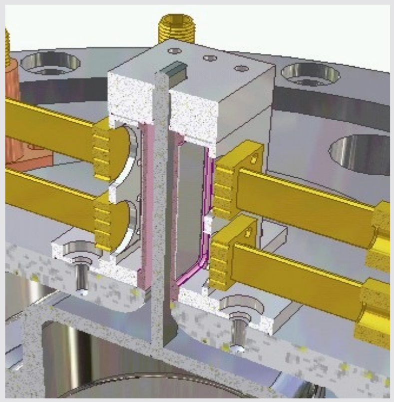

**Vimp ~ 7 to 10 cm/μsec**
**Telectron ~ Tion ~ 3 keV**
**DD Neutron Yield ~ 2.e12**
**DT Neutron Yield ~ 5.e10**
**P ~ 1 GBar**
**BR ~ 0.4 MGauss-cm**
**$\rho R_{fuel}$ ~ 1.5 mg/cm$^2$**
**$\rho R_{liner}$ ~ 0.9 g/cm$^2$**

**See Ryan McBride's talk on Thursday**

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

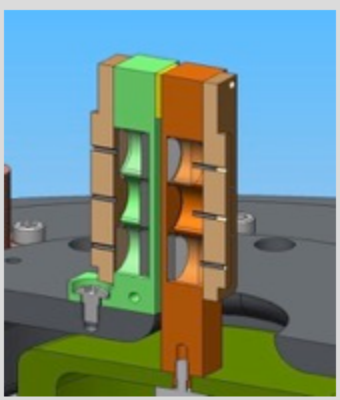
**Shock Compression**

Velocities > 40 km/s



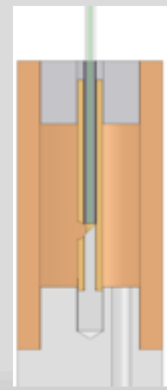
**Planar Ramp-Compression**

continuous compression up to ~4 Mbar



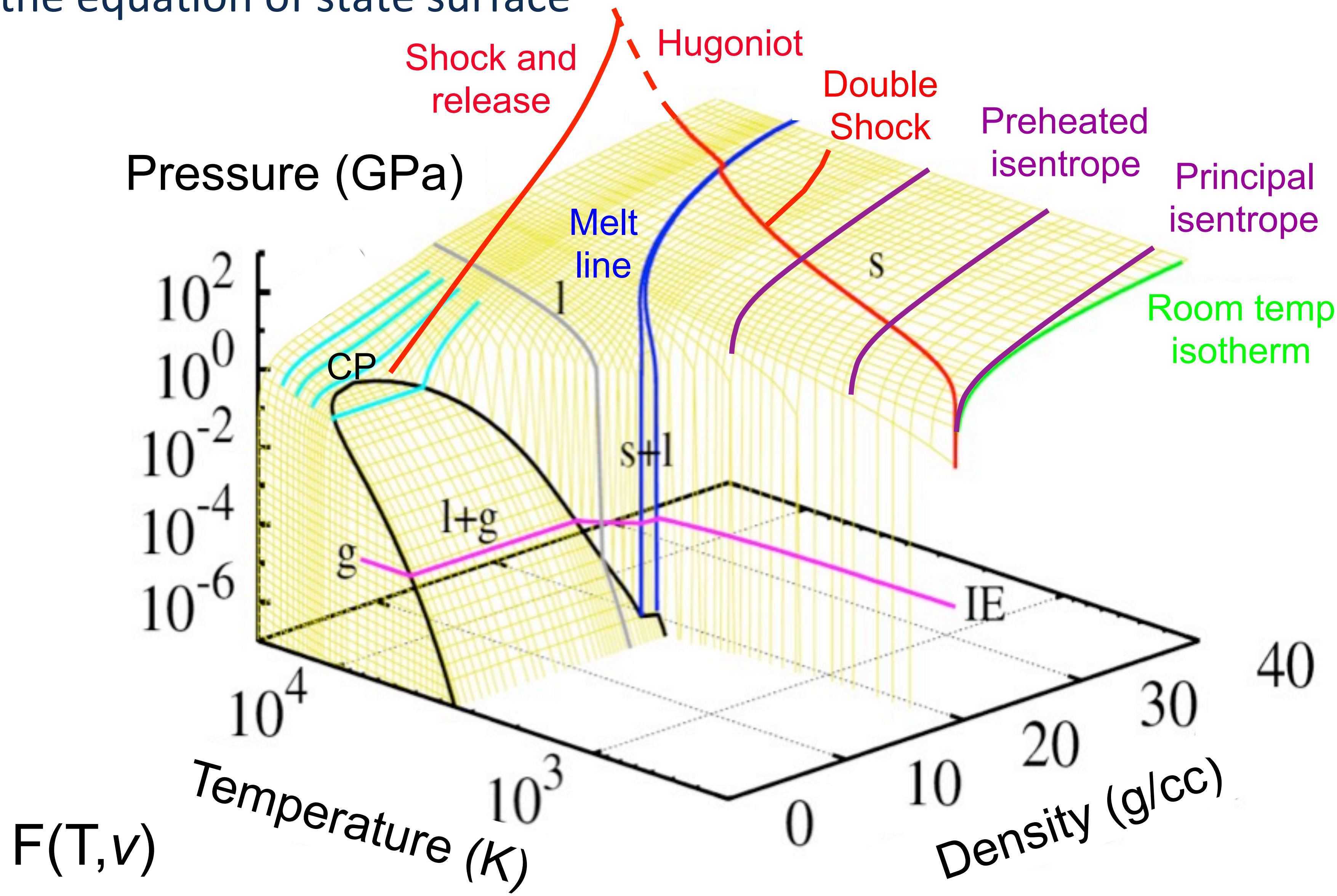
**Cylindrical Ramp-Compression**

Possibly continuous compression up to ~10-20 Mbar

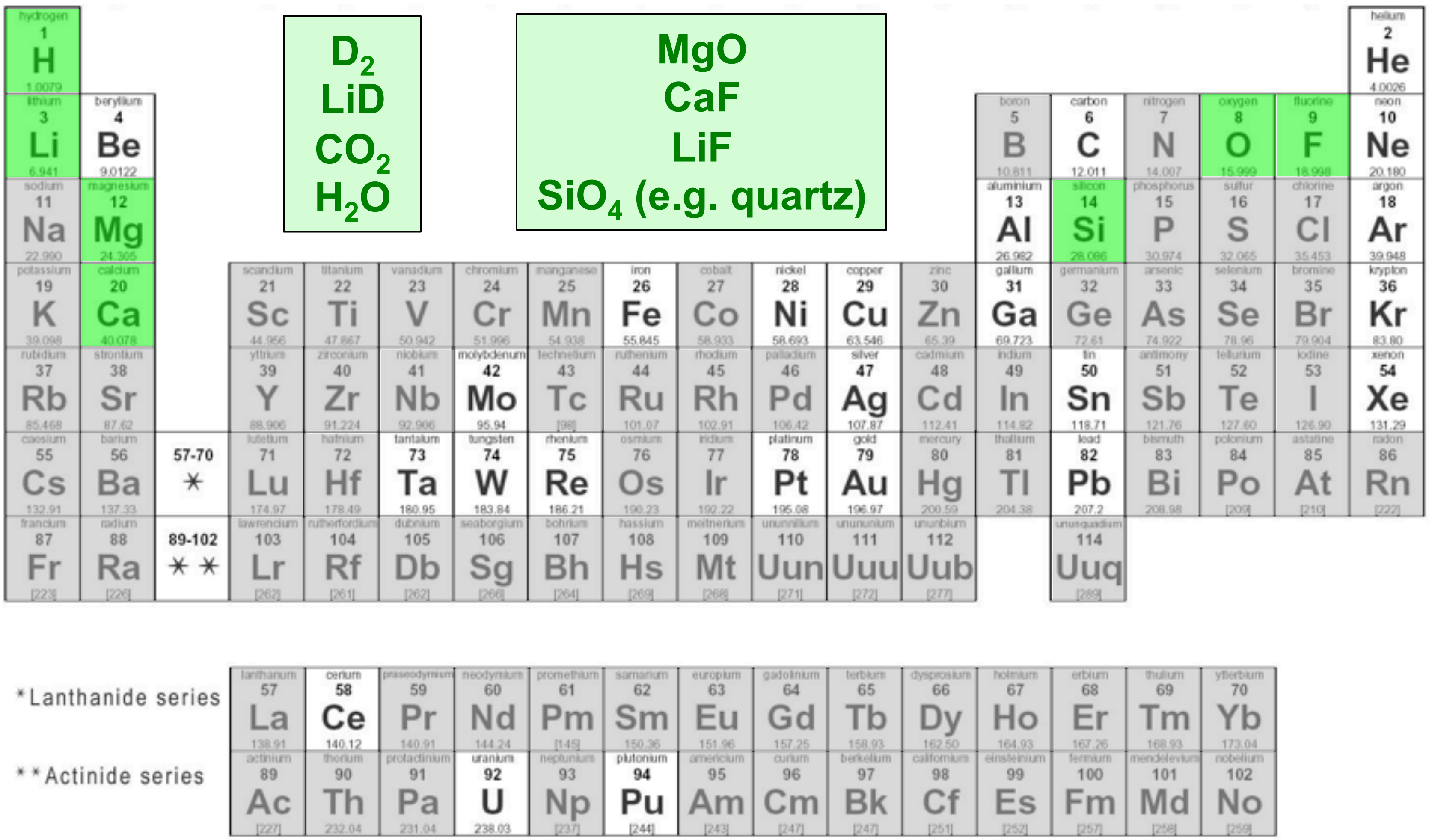


- Shock or ramp compression of materials increases densities by 2 to ***10:1***

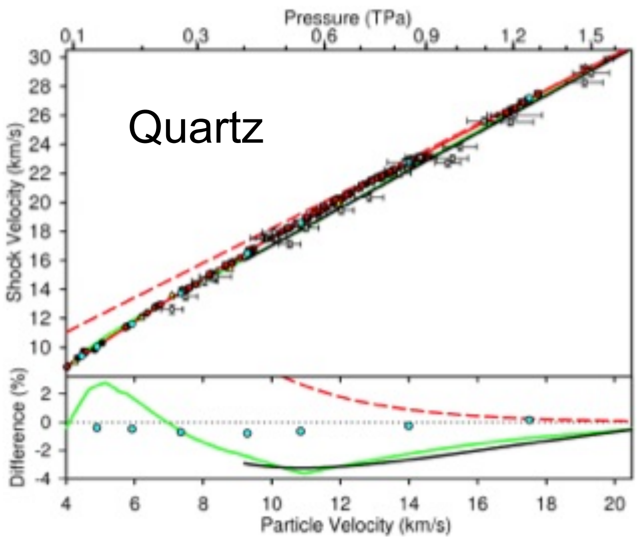
# Magnetic pressure on Z allows access to a large region of the equation of state surface

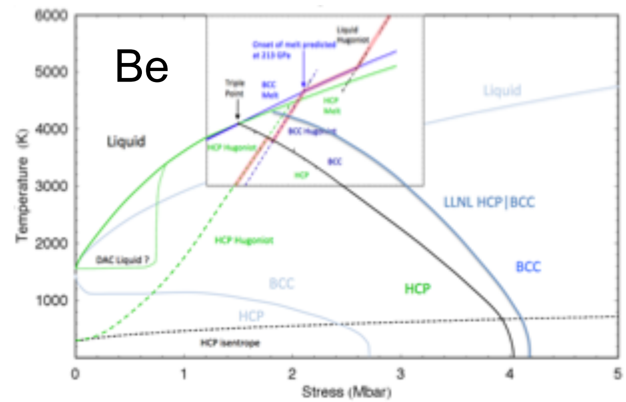


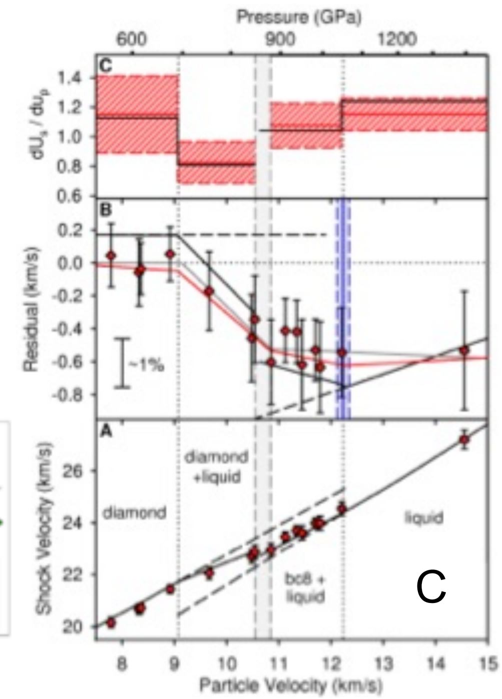
# The dynamic materials program measures equations of state and other properties (strength) for elements and compounds of interest

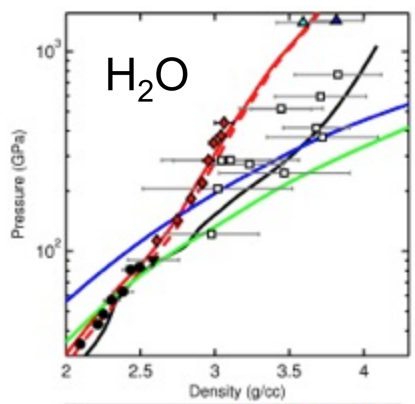


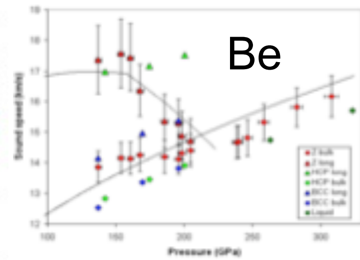
# Z has been used to address several interesting problems in the multi-Mbar regime

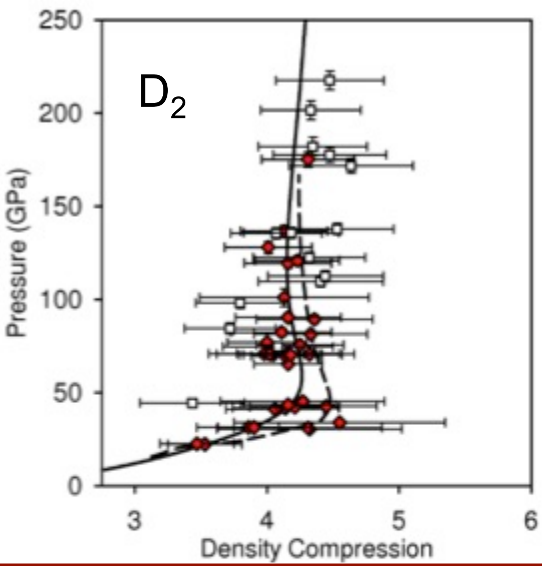


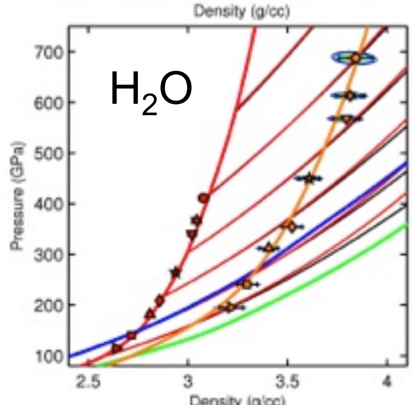



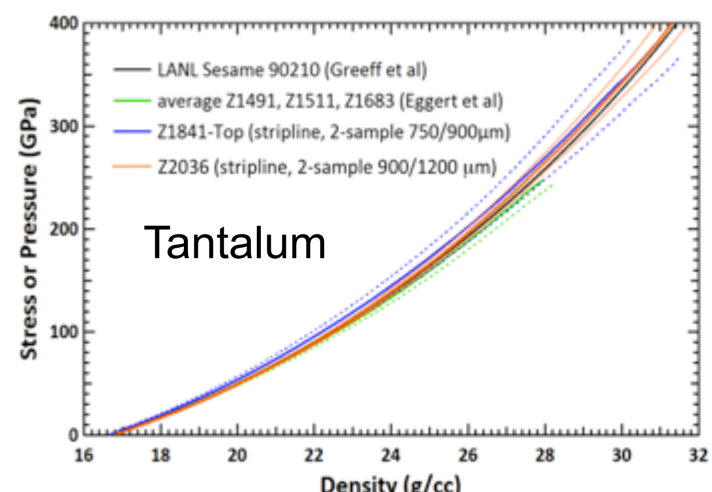



## There is a need for facilities that achieve thermonuclear ignition and high-yield fusion

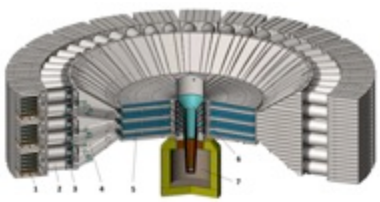
- The U.S. conducted its last underground nuclear test 23 years ago (in 1992)
- Since then, the U.S. has not conducted thermonuclear-ignition or high-fusion-yield experiments
- There will soon be no full-time scientists with direct experimental ignition or high-yield experience

It's clear the U.S. needs a thermonuclear-burn facility

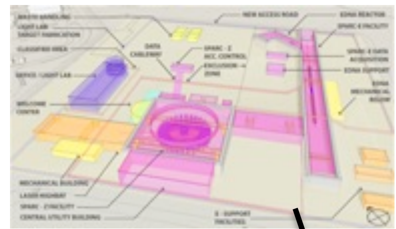
The second U.S. underground nuclear test was a 1-kiloton explosion (1955).

Preparation for an underground test at the Nevada Test Site in the 1990s.

# We have a long-term vision to achieve ignition and high-yield fusion in the future



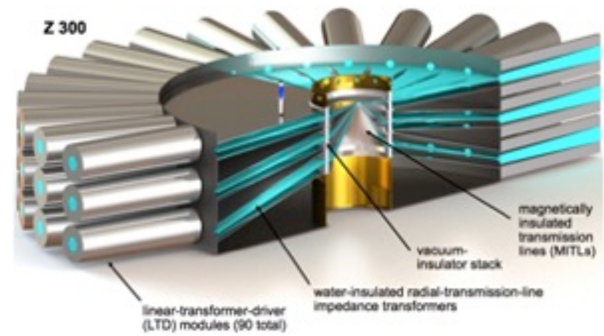
2019: Baikal operations begin (50 MA Russian fusion facility)




SPARC-Z operations begin

CD-0 for SPARC-Z High-Yield Facility

Z-300 demonstrates ignition and high-gain scaling




Z-300 operations begin

Review of Ignition on Z-300; CD-0 for Z300

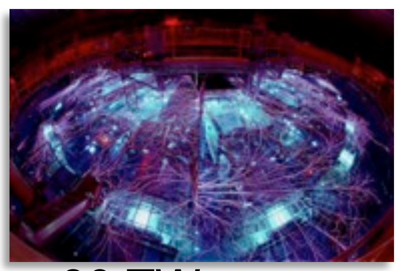
Demonstrate LTD module prototypes (e.g., radiography)

2015: National ICF program review

2013: First integrated tests of new MagLIF idea on Z

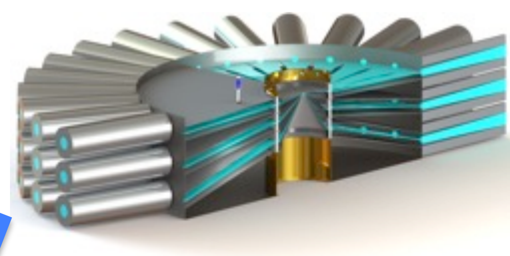
## We are currently exploring target designs and pulsed power architectures that may be on the path to 0.5-1 GJ yields that also meet the needs of the science campaigns

**Z Goal**
**Yield = Efuel**



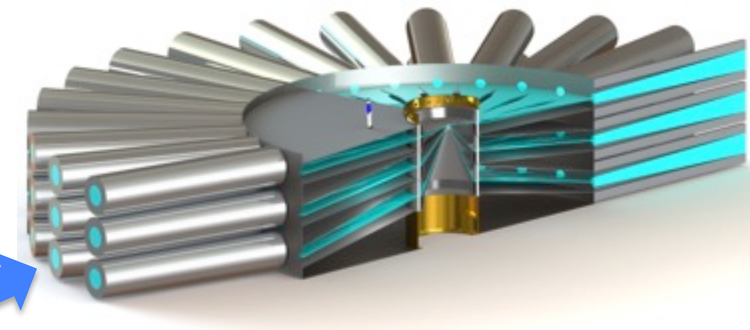
- 80 TW
- 33 m diameter
- 22 MJ stored energy
- 26 MA peak current

**Z-300 Goal**
**Yield = Etarget**



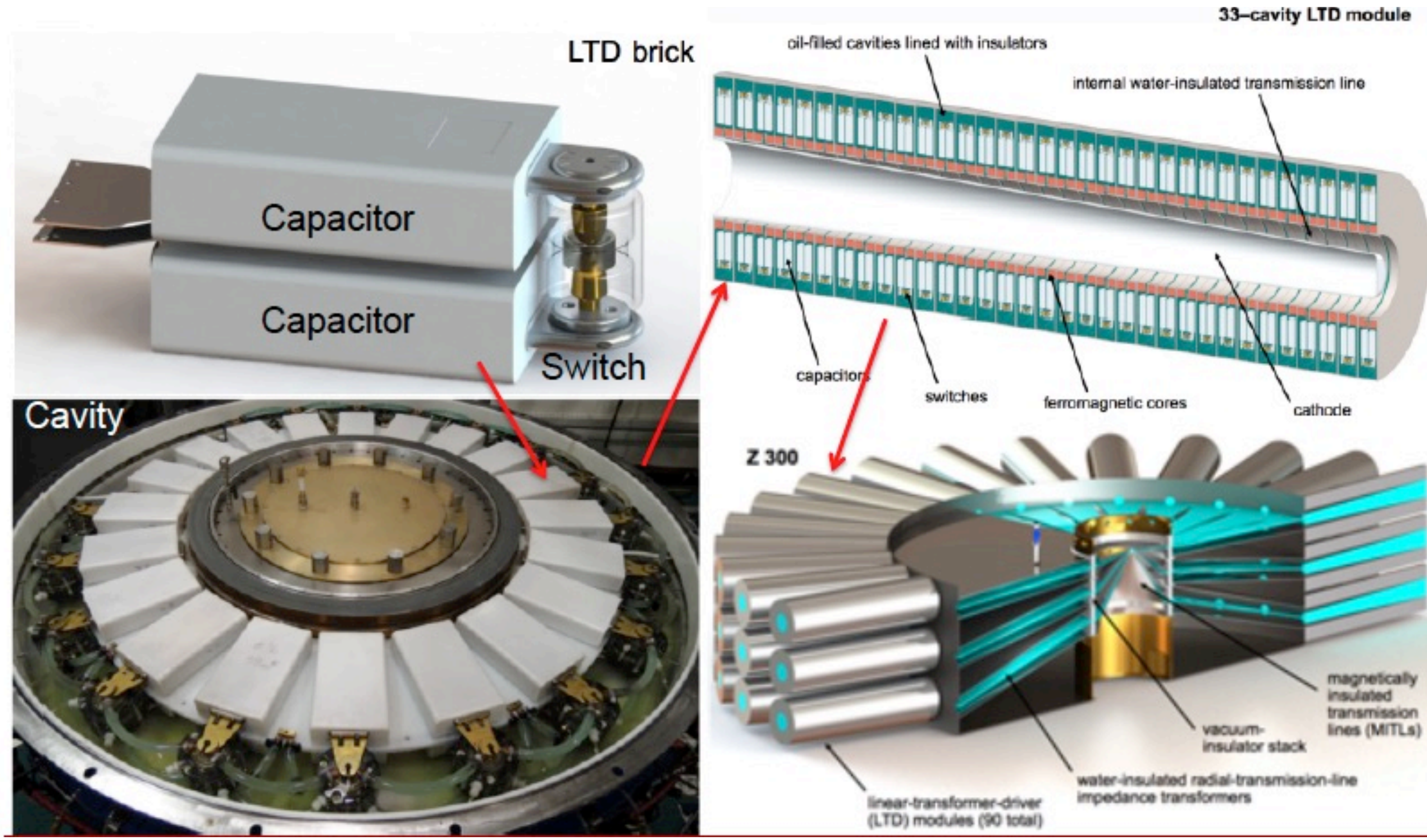
- 320 TW
- 35 m diameter
- 47 MJ stored energy
- 49 MA

**Z-800 Goal**
**Yield = Emachine**



- 890 TW
- 52 m diameter
- 130 MJ stored energy
- 66 MA

# 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



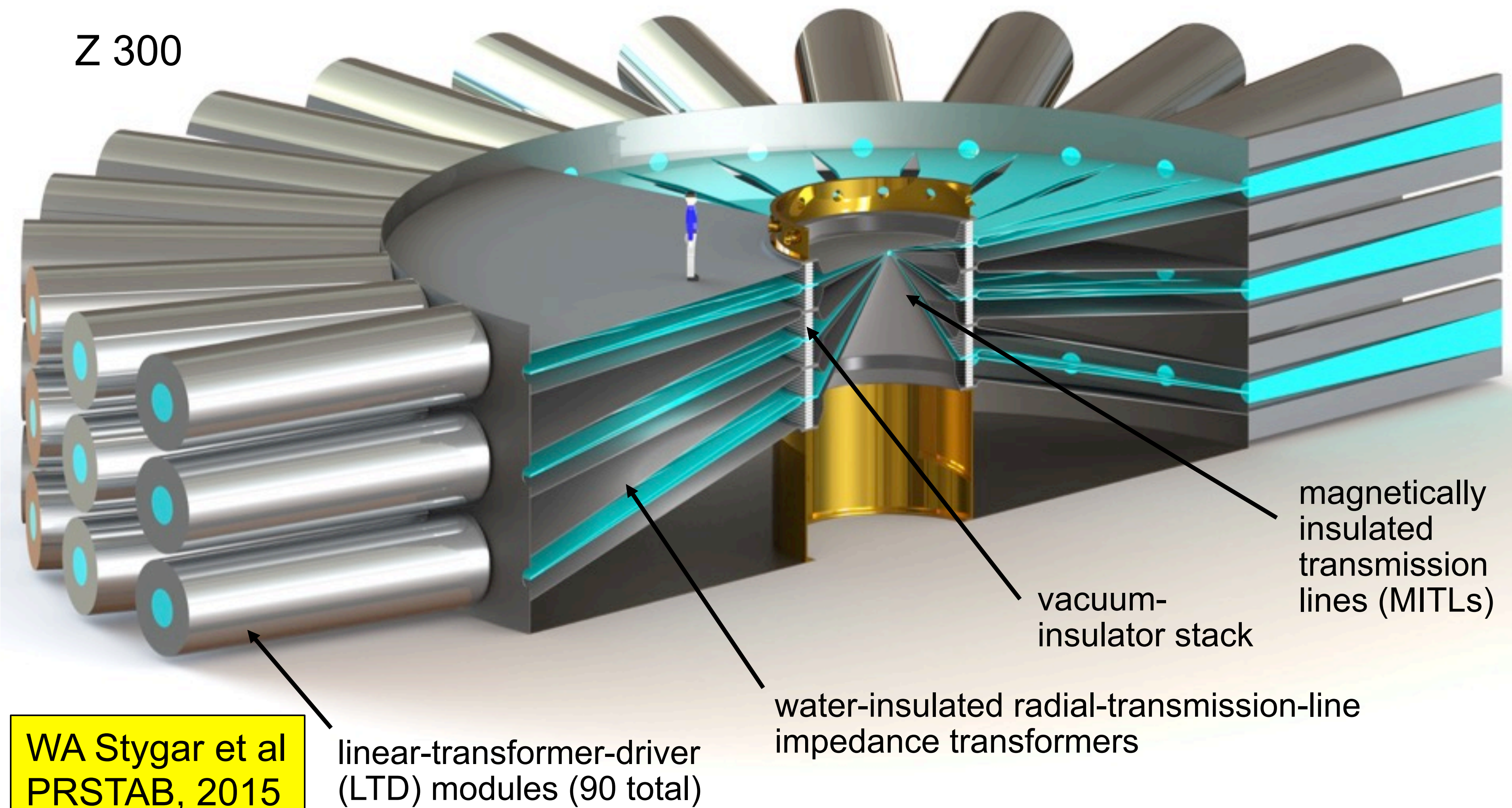
# Z 300 will deliver 49 MA to a MagLIF load.
# The goal: thermonuclear ignition (i.e., a liner gain of ~1)

$E_{LTDs}$ = 47 MJ
$P_{LTDs}$ = 320 TW

$V_{stack}$ = 7.7 MV
$L_{vacuum}$ = 15 nH

$I_{load}$ = 49 MA
$\tau_{implosion}$ = 150 ns

diameter = 35 m
fusion yield ~5 MJ




WA Stygar et al
PRSTAB, 2015

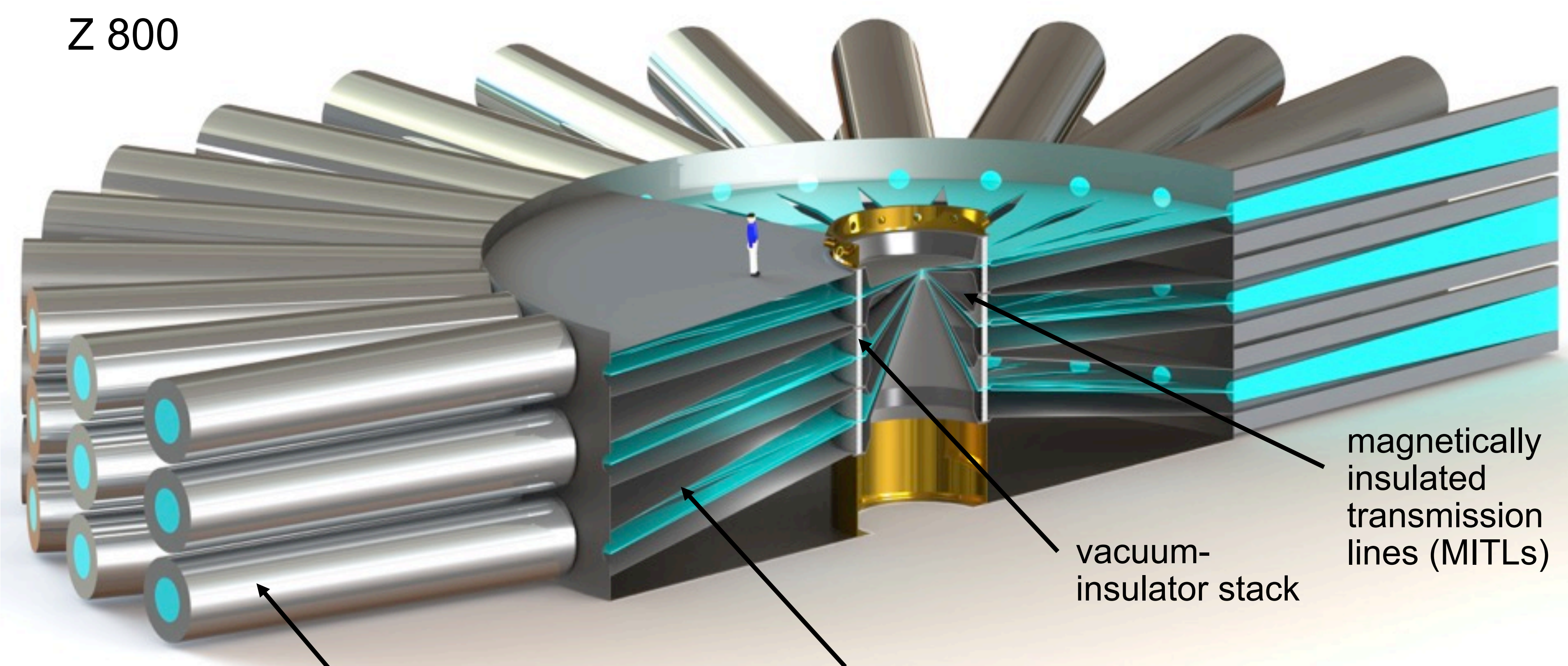
# Z 800 will deliver 66 MA to a MagLIF load.
# The goal: ~500 MJ of fusion yield (i.e., a machine gain of ~4)

$E_{LTDs}$ = 130 MJ
$P_{LTDs}$ = 890 TW

$V_{stack}$ = 15 MV
$L_{vacuum}$ = 20 nH

$I_{load}$ = 66 MA
$\tau_{implosion}$ = 114 ns

diameter = 52 m
fusion yield ~500 MJ




WA Stygar et al PRSTAB, 2015

## 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
- When we make measurements in the HED field, ***quite often*** the measurements disagree with scientific predictions or expectations before the experiments → experiments are needed to validate our models

## Summary

- Large currents create large magnetic fields, and large magnetic fields create large pressures, which are needed to access high energy density regimes
- The Z machine creates large currents, allowing us to address fundamental issues in HED science, dynamic materials, and inertial confinement fusion
- Pulsed power can inexpensively, efficiently, and flexibly drive many different kinds of applications at large currents and high voltages
- These applications go well beyond traditional concepts known colloquially as "z-pinches"
- Magnetic drive is a low cost and efficient way to generate high energy density conditions over large volumes
- The upper limits on magnetically-driven performance in achieving high energy densities are not known
- There is a lot of room for innovation!