Pulsed power, Z-pinches, and Applications

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Mike Cuneo, Mark Herrmann, Greg Rochau, Dan Sinars, Ryan McBride, Tom Awe, Kyle Peterson, Steve Slutz, Keith Matzen, Bill Stygar, Sasha Velikovich, Marcus Knudson, Ray Lemke, and Sarah Stewart for material and viewgraph contributions

About me (1 of 2)

- I was a SULI/NUF student in the summer of 2000.
- My research project that summer was on a tokamak at MIT for **magnetic confinement fusion** (MCF). *-- low density, long time scale*
- I also spent two summers at LLNL working on indirect-drive **inertial confinement fusion** (ICF). *-- high density, short time scale*
- Having been bitten by the fusion "bug", I went to graduate school at Princeton and had an office at PPPL.
- My dissertation research was on a sub-field of ICF called Heavy Ion Fusion (replaces the lasers with intense charged particle beams).
- The overall goal of my research career is to improve the predictive capability of simulation codes for plasma science. I consider myself a computational physicist who does numerical experiments.

About me (2 of 2)

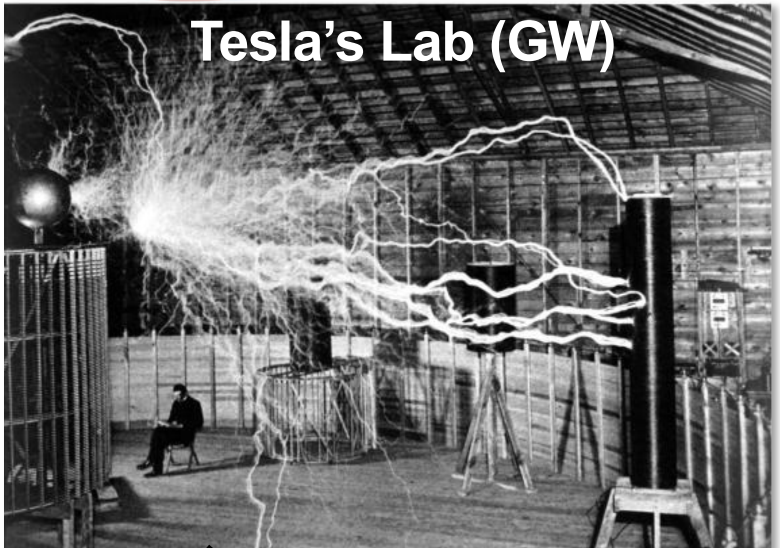
- After earning a Ph.D., I became a scientist at **Sandia National Laboratories** and designed the first successful Magnetized Liner Inertial Fusion (MagLIF) experiments you will hear about today.
- In 2016, I became a professor at the **University of Rochester** in New York. I also am a scientist at the **Laboratory for Laser Energetics.**
- In addition to laser-driven ICF, I also work on an innovative MCF concept called the Field Reversed Configuration (FRC) at PPPL (remotely).
- Three interesting facts about me:
  - I have conducted fusion research on all “mainline” approaches presently supported today by the US Dept. of Energy
  - I have designed experiments for the Z Machine (Sandia), NIF (LLNL), OMEGA (LLE), and many other accelerators and lasers.
  - I have lived in all four states whose names begin with the word “New”
- My group is The TriForce Center for Multiphysics Modeling, and we are accepting new graduate students. (It is being updated, but...) Please visit:

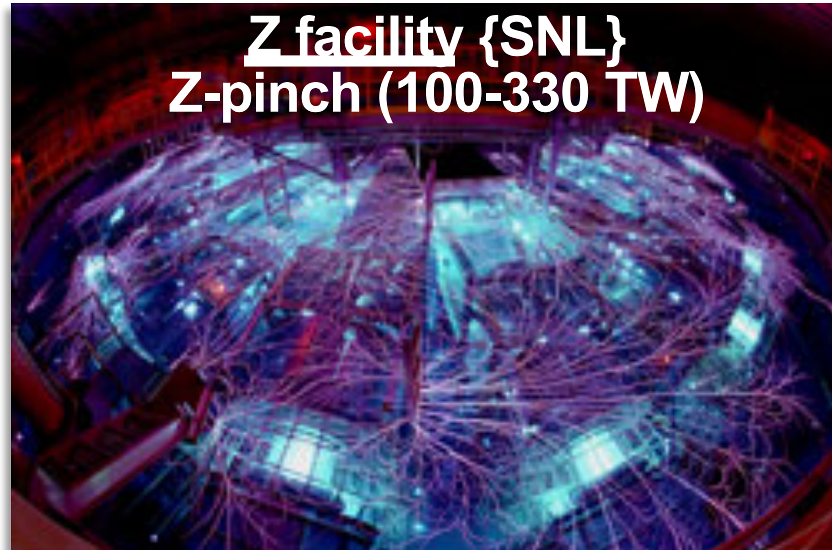
https://hajim.rochester.edu/me/sites/sefkow/index.html

Outline

- 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)
- There are many interesting applications

The accumulation and transmission of electromagnetic energy, called "pulsed power", has been investigated for over a century





1900 | 1920 | 1940 | 1960 | 1980 | 2000

WWII

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

Hermes - II {SNL}
e-beam (TW)

Angara - II {Russia}
Simulator (TW)

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

DARHT {LANL}
Radiography (10 GW)

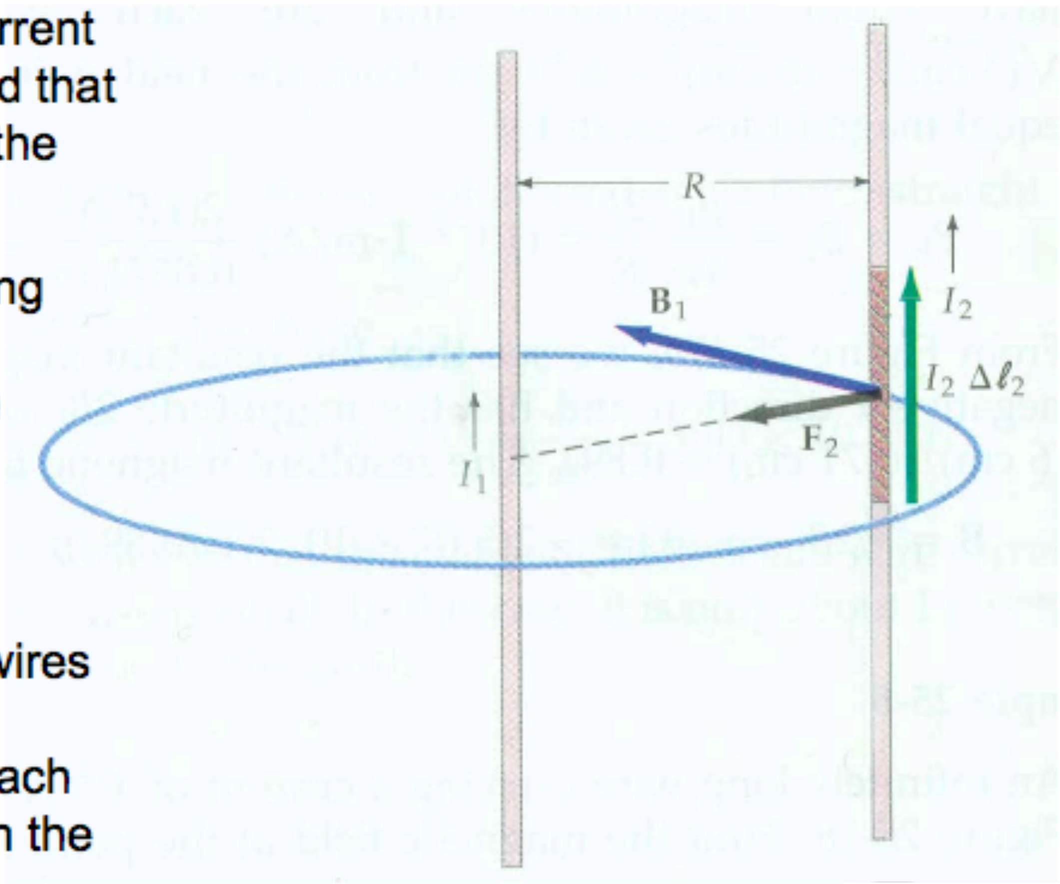
Sandia National Laboratories

1^{st} year physics refresher

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



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

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

mass conservation

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

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

magnetic tension — fluid pressure — magnetic pressure

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

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 create and manipulate high energy density (HED) matter

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

HED Matter P > 1 Mbar, B > 5 Megagauss

Magnetic fields have some unique advantages when creating HED plasmas:

- Magnetic fields are very efficient at creating HED matter, enabling large samples and energetic sources
- Magnetic fields have very interesting properties in converging geometry

Magnetic fields have interesting contrasts with other ways of generating HED:

- Magnetic fields can create high pressures without making material hot
- Magnetic fields can be generated over long time scales with significant control over the time history

Magnetic fields change the way particles and energy are transported in a plasma

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) = $10\ dyne\ cm^{-2} = 10^{-5}\ bar$

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

A 5000 G (0.5 T) magnetic field ~ 1 atmosphere ~ 1 Bar

A $5x10^6$ G (500 T) magnetic field ~ 1 Million atmospheres = 1 Megabar (MB)= High energy density physics ("HEDP")

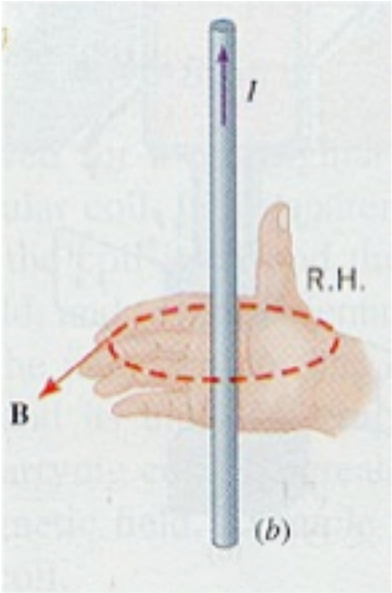
A $5x10^9$ G (500 kT) magnetic field ~ 1 Trillion atmospheres = 1 Terabar (TB) > pressure in the center of the sun

Note that high explosives have pressure ~ 100,000-300,000 atmospheres ~ 0.1-0.3 Mbar (not "HEDP") ~ equivalent ~50-150 T or $5x10^5$-$1.5x10^6$ G

Large currents can create large B fields!

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

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



For an axial current I:

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

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

100 A at 2 mm radius is 100 G

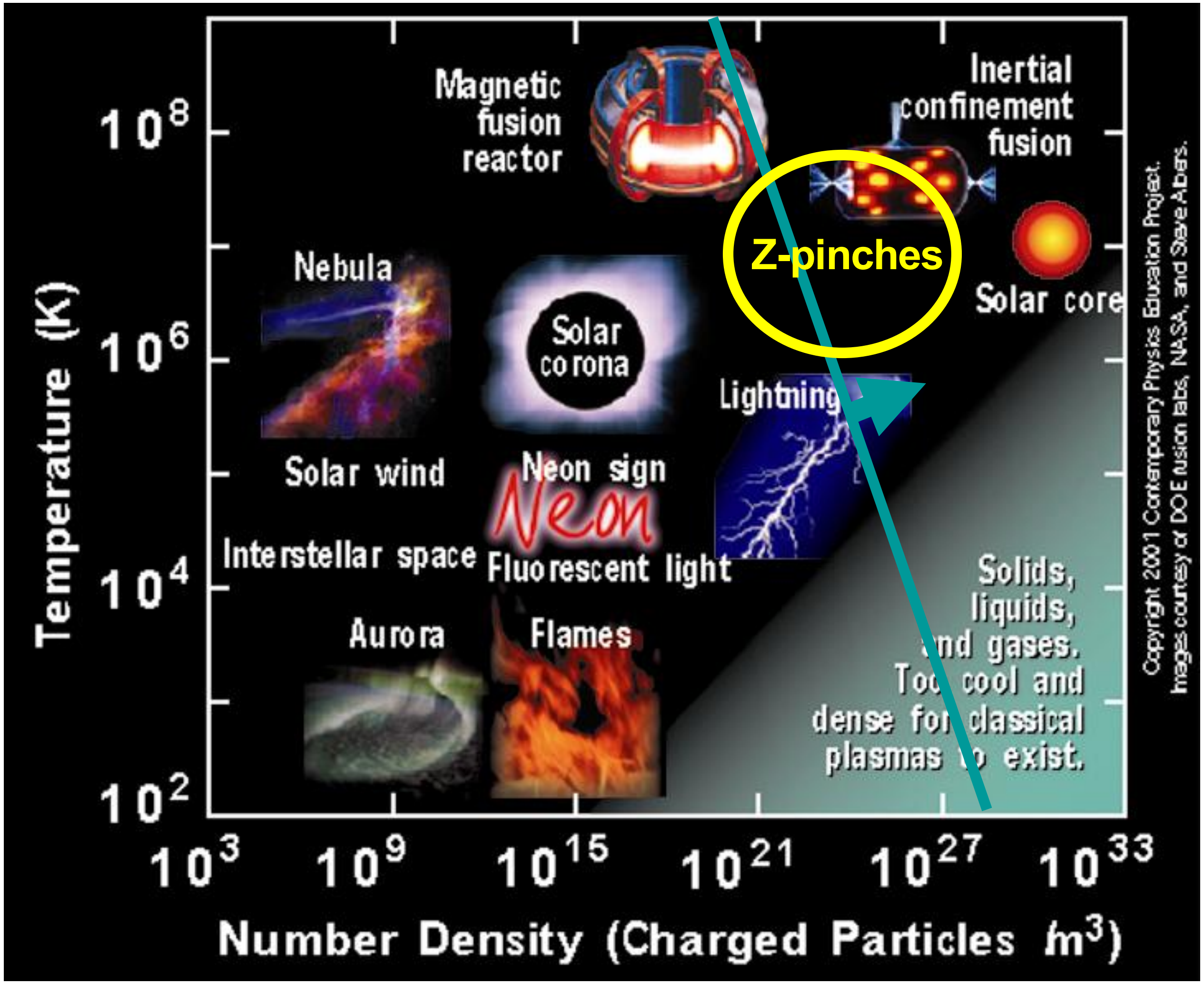
1.0×10^7 A (**10 MA**) at **4 mm** radius is 5×10^6 G = **1 MBar** of pressure!

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

(~1000x more than high explosives)

LARGE CURRENTS → LARGE MAGNETIC FIELDS → LARGE PRESSURES!

Regimes of high energy density are typically associated with energy density 10^{11} J/m^3 = 1 Mbar



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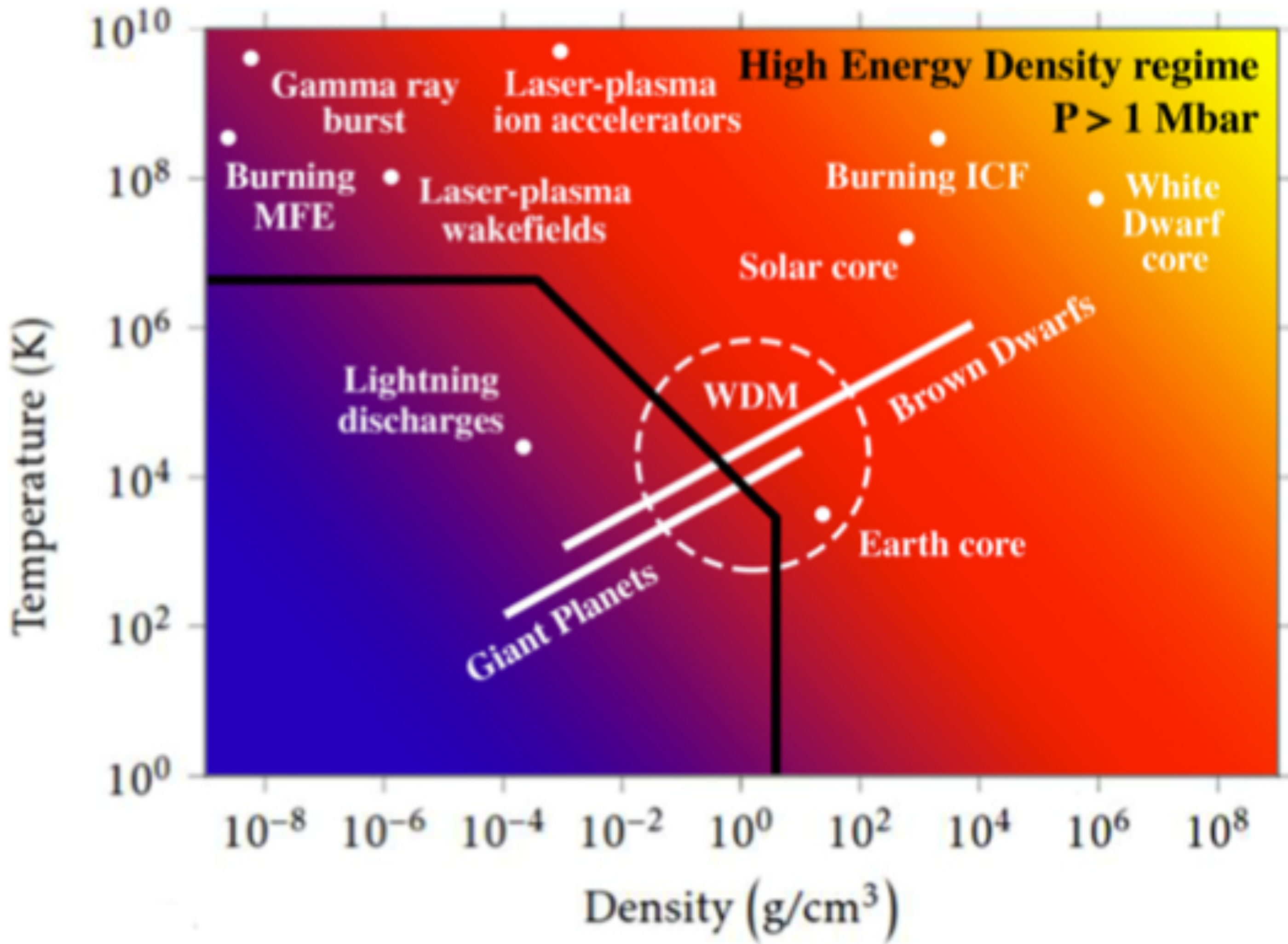

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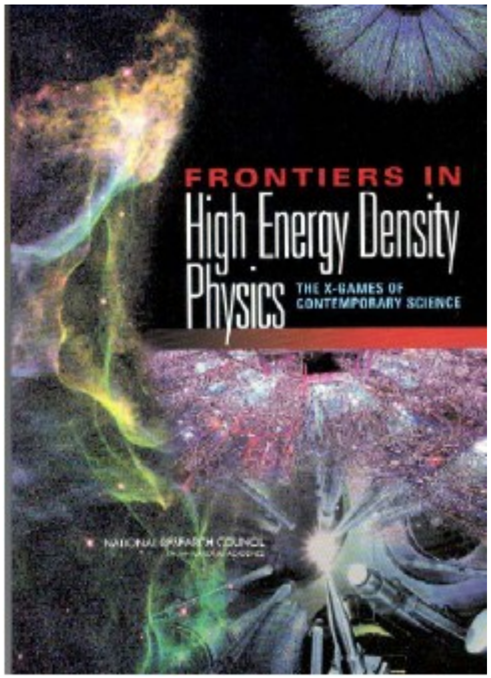
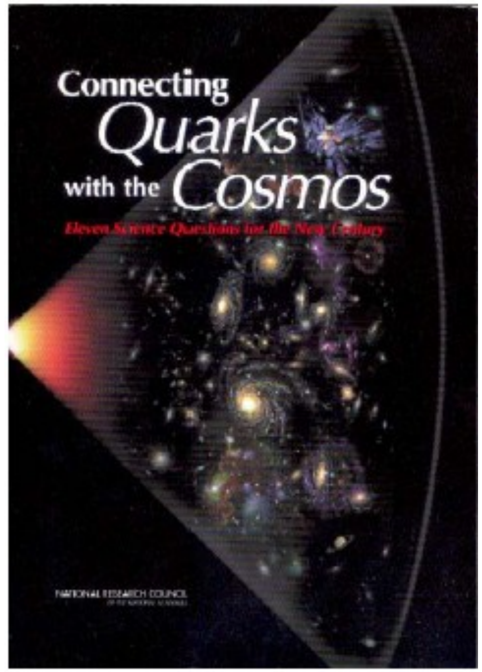
Several studies have highlighted High Energy Density Science



"Frontiers in High Energy Density Physics",
R. Davidson et al.



"Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century",
M Turner et al.

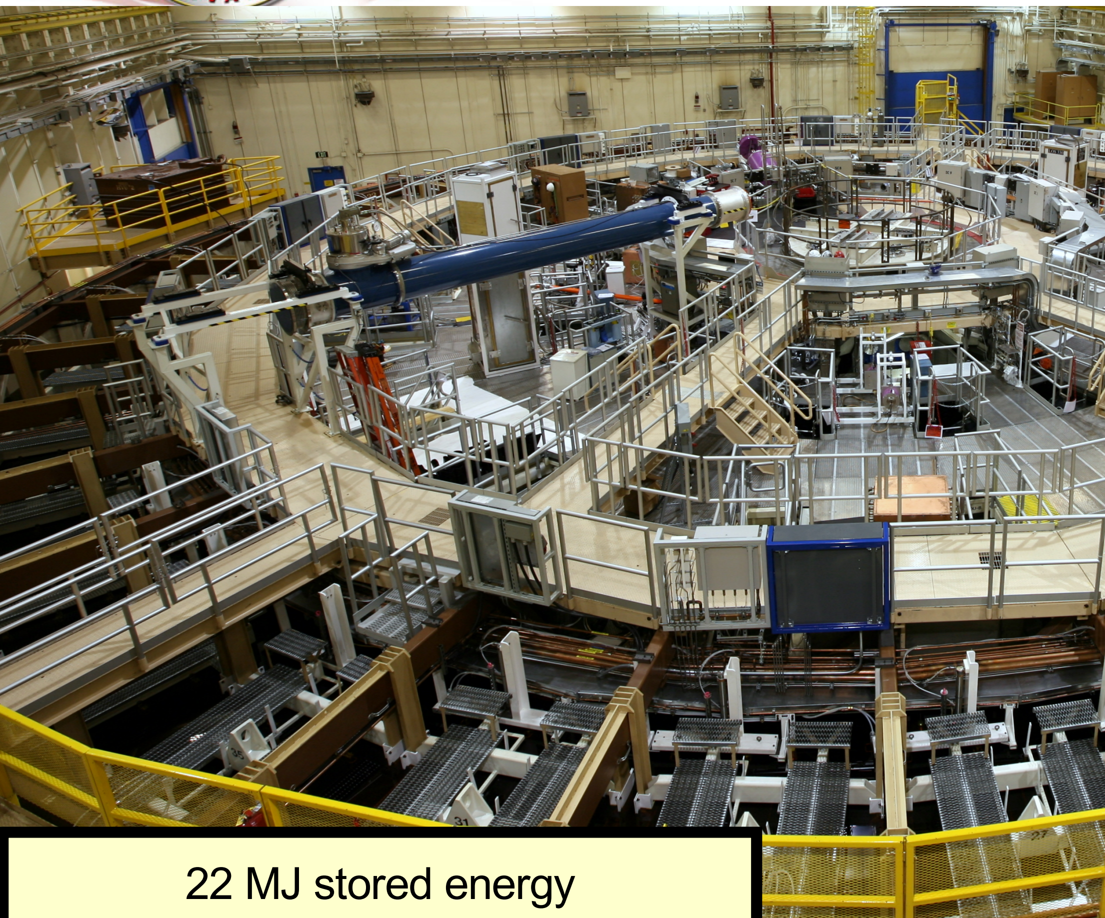
Science and Applications of Ultrafast, Ultraintense Lasers

Scales of energy density

- 0.001 MJ/kG water at 100 m dam height
- 0.5 MJ/kG Li ion battery
- 1.968 MJ/kG water
- 7.5 MJ/kG stick of dynamite
- 33 MJ/kG Low Earth Orbit
- 45 MJ/kG gasoline
- 310,000 MJ/kG typical z-pinch implosion at 27 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)

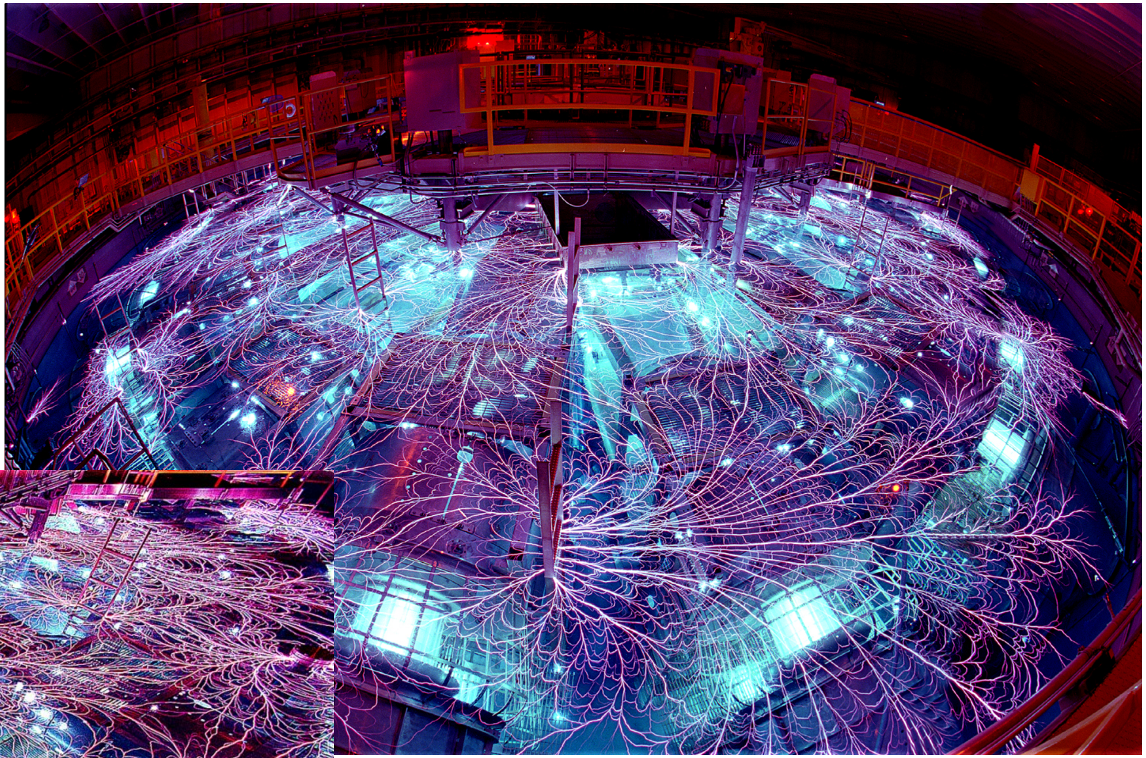
"Z" is the world's largest pulsed-power facility

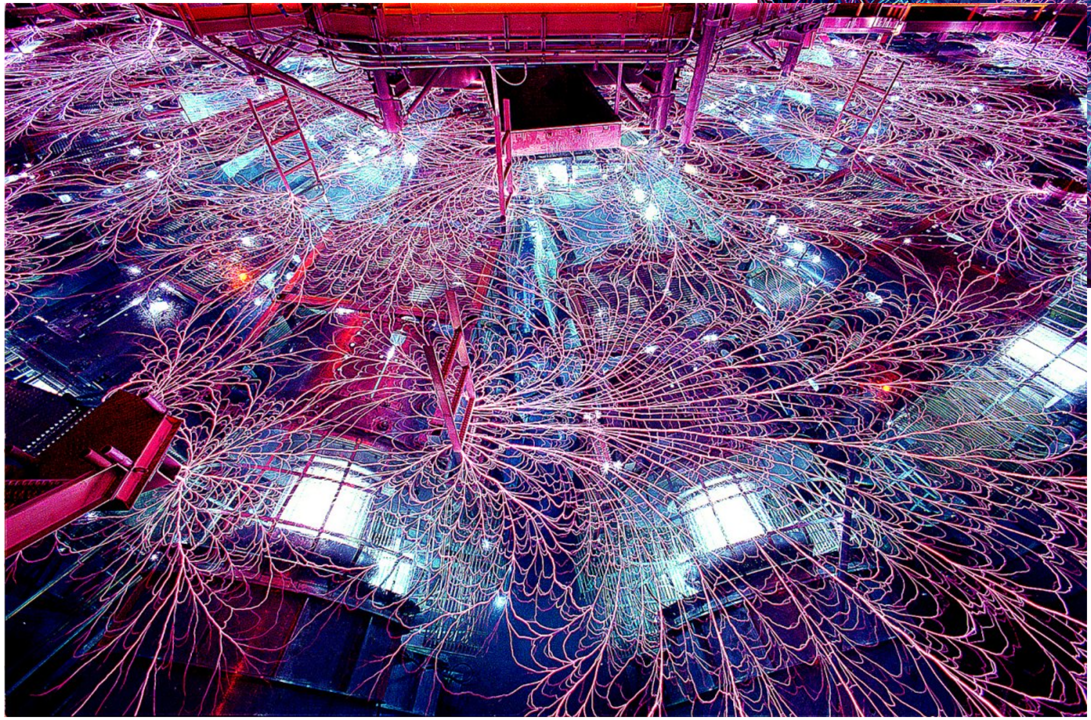
Tank~10,000 ft^2

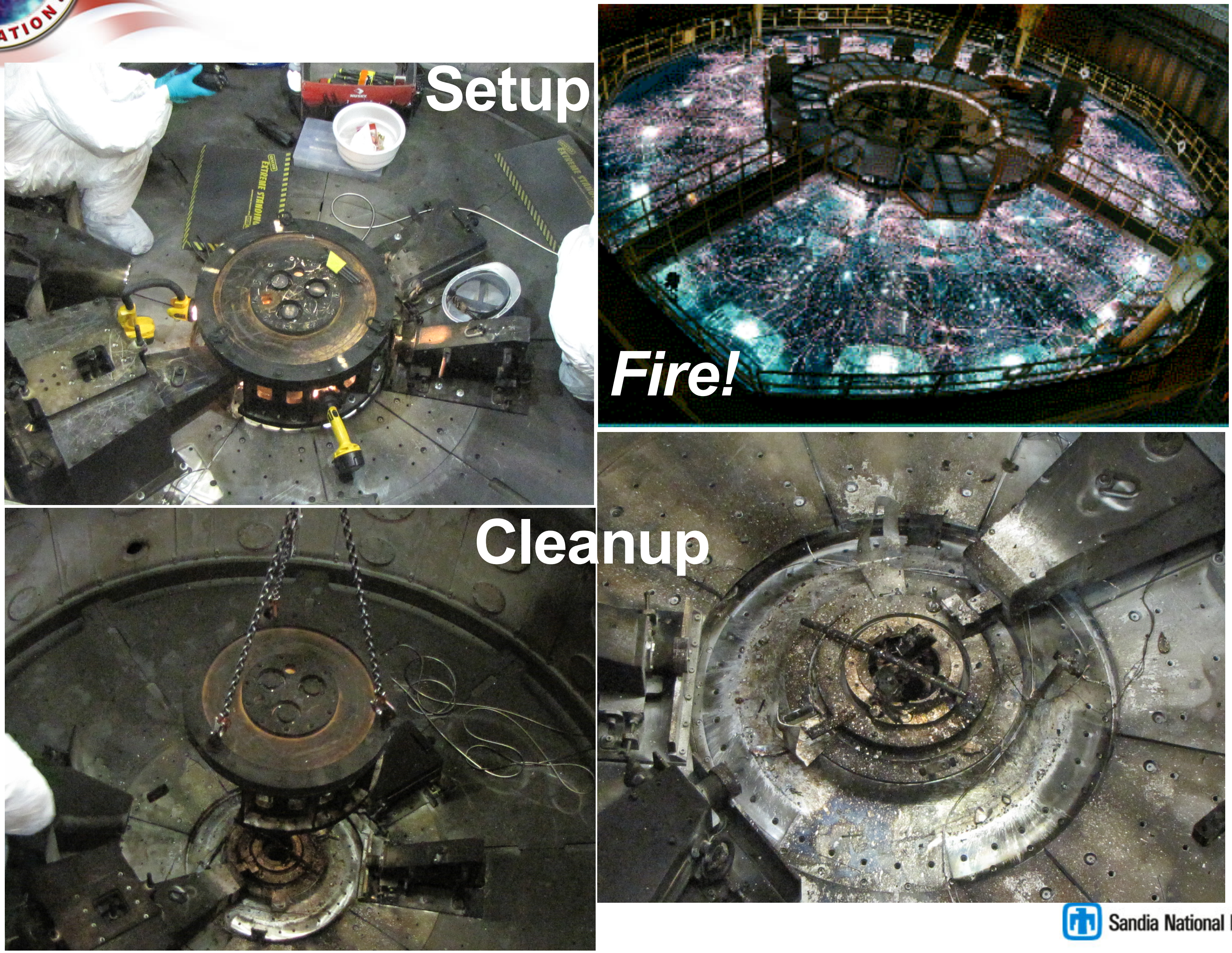


22 MJ stored energy
3MJ delivered to the load
27 MA peak current
5 – 50 Megagauss (1-100 Megabar)
100-600 ns pulse length

"Z" is the world's largest pulsed-power facility



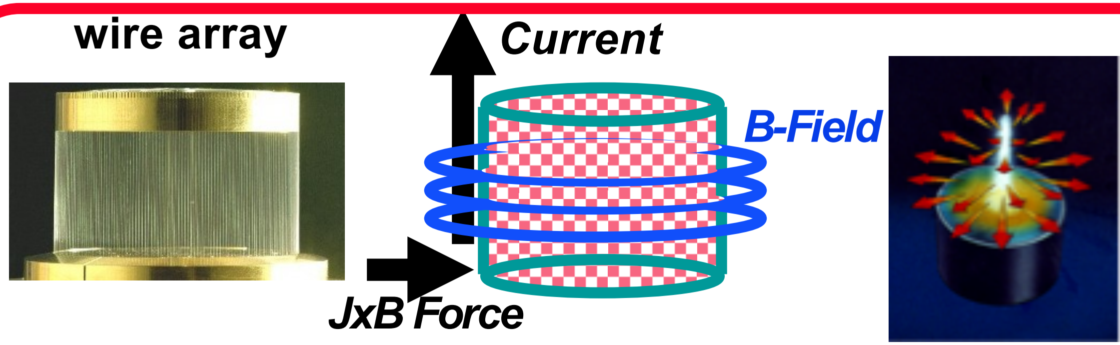



Setup
Fire!
Cleanup

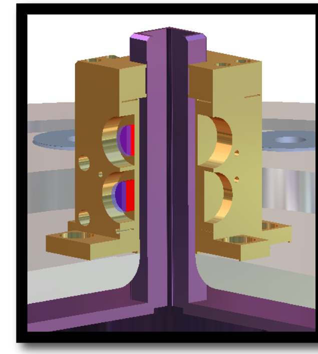
We can use high currents to push plasmas in different ways for different applications

High Current

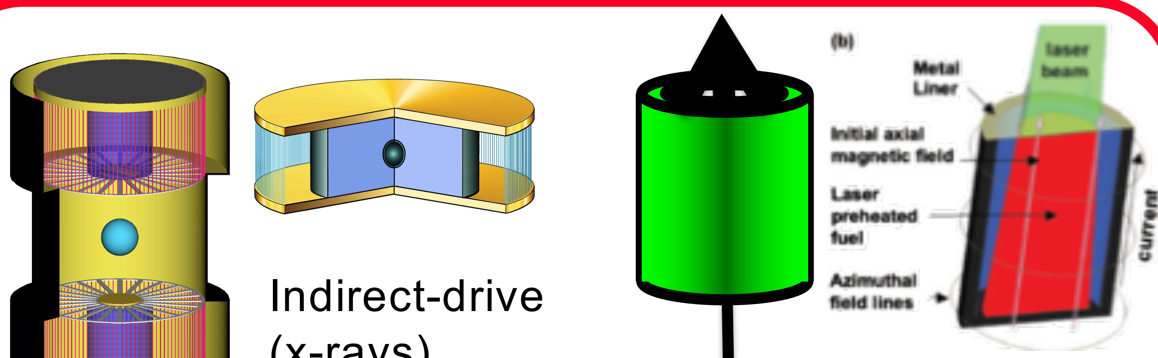
Z-pinch X-ray sources



Planar magnetic pressure



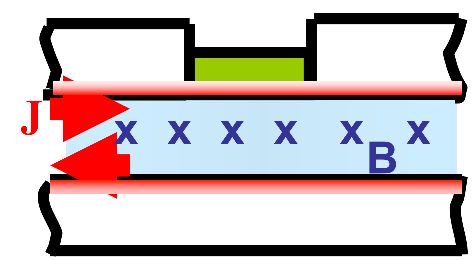
Inertial Confinement Fusion (ICF)



Indirect-drive (x-rays)

Direct-drive (magnetic field)

Material Properties



Experiments are well-diagnosed

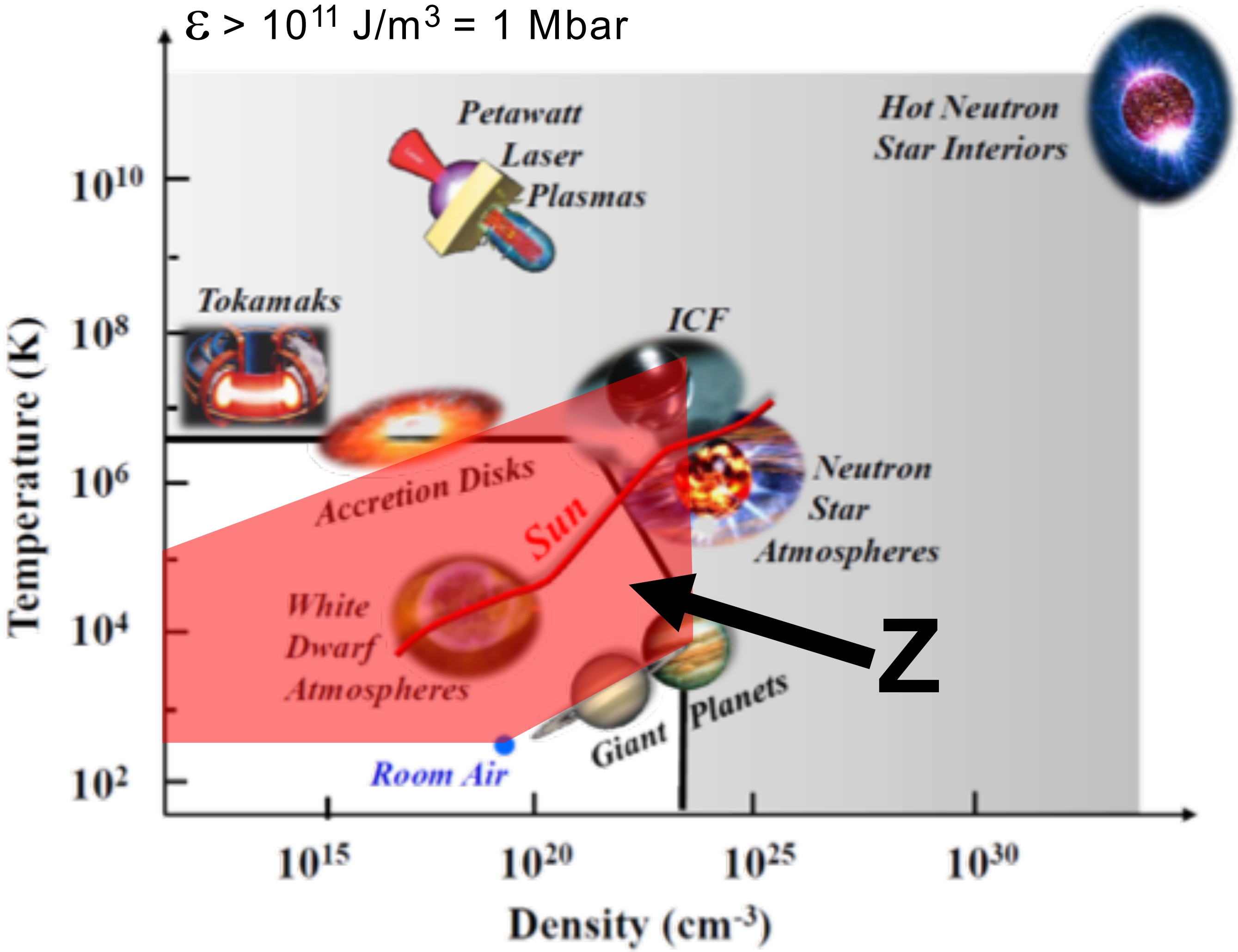
Z Target Diagnostics

- **Power & Energy**
  - X-ray Diodes
  - Photo Conducting Diamonds
  - Silicon Diodes
  - Bolometer
- **Spectroscopy**
  - Time-integrated 0.8-10 keV
  - Time-resolved 0.8-10 keV
  - Time-integrated 7-25 keV
  - Streaked Visible
- **X-ray Imaging**
  - 1.9 or 6.1 keV Backlighting
  - 277 or 528 eV Self-Emission
  - Filtered Self-Emission
- **Motion / Velocity**
  - VISAR
  - Photonic Doppler Velocimetry
  - Passive Shock Breakout
- **Neutrons**
  - D-D Activation
  - D-T Activation
  - Time-of-Flight
  - Imaging

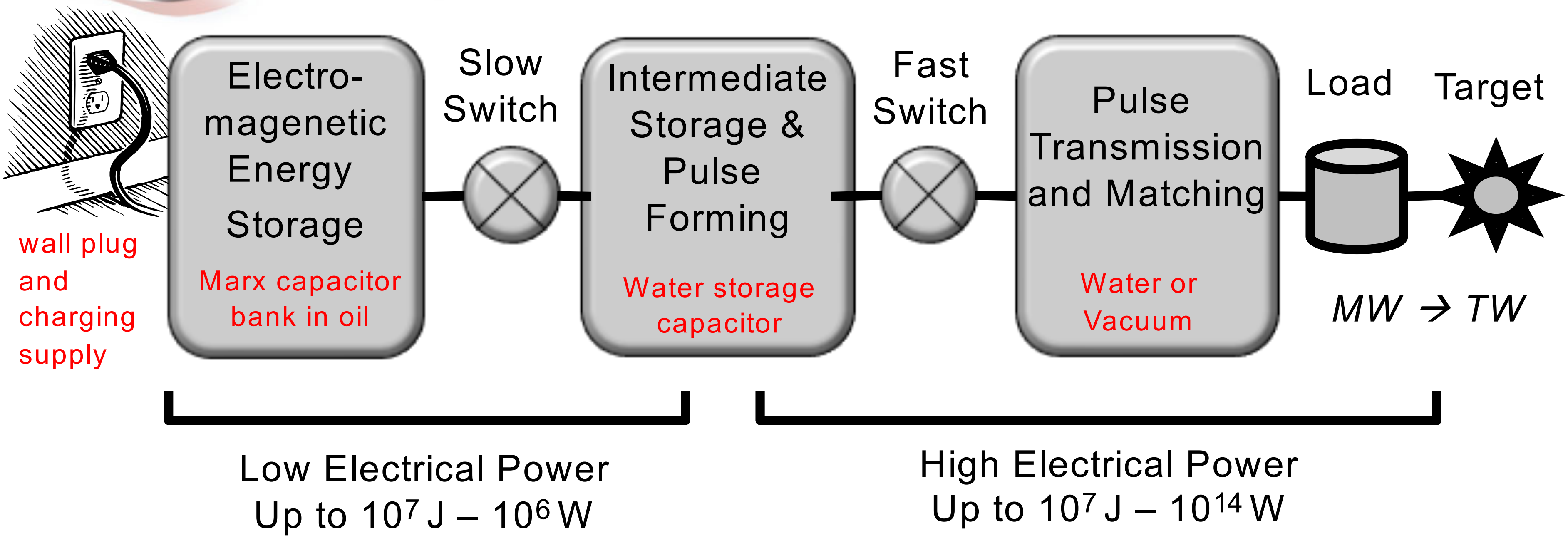
Experiments on Z access a large region of the energy density phase-space

High Energy Density Regime

$\varepsilon > 10^{11}$ J/m^3 = 1 Mbar



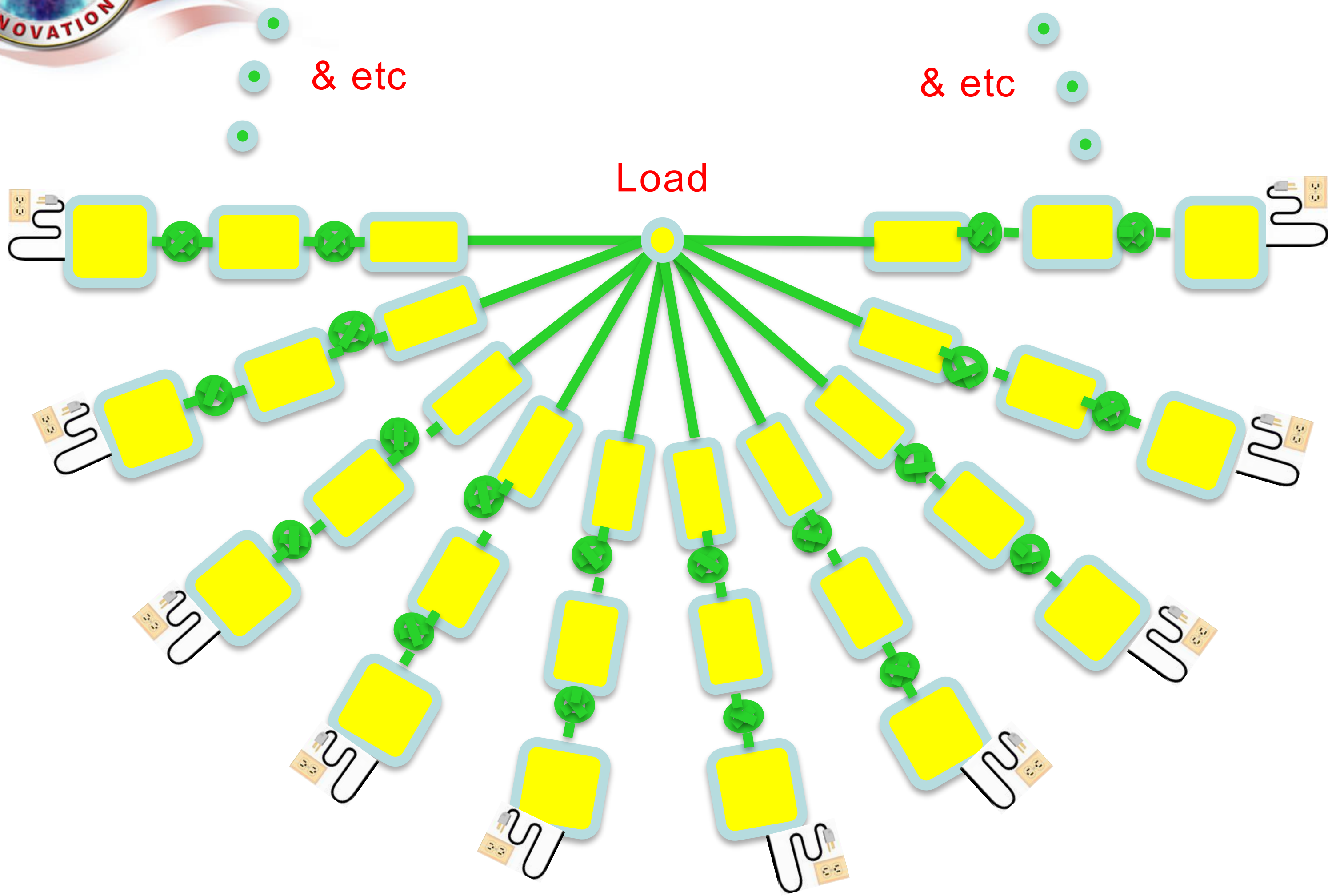
Pulsed-power technology produces high electrical power using fast switching and pulse compression



- Typically the pulse is compressed in both space and time
- The load produces the last step in pulse compression and power gain
- You can think of this as a complicated circuit

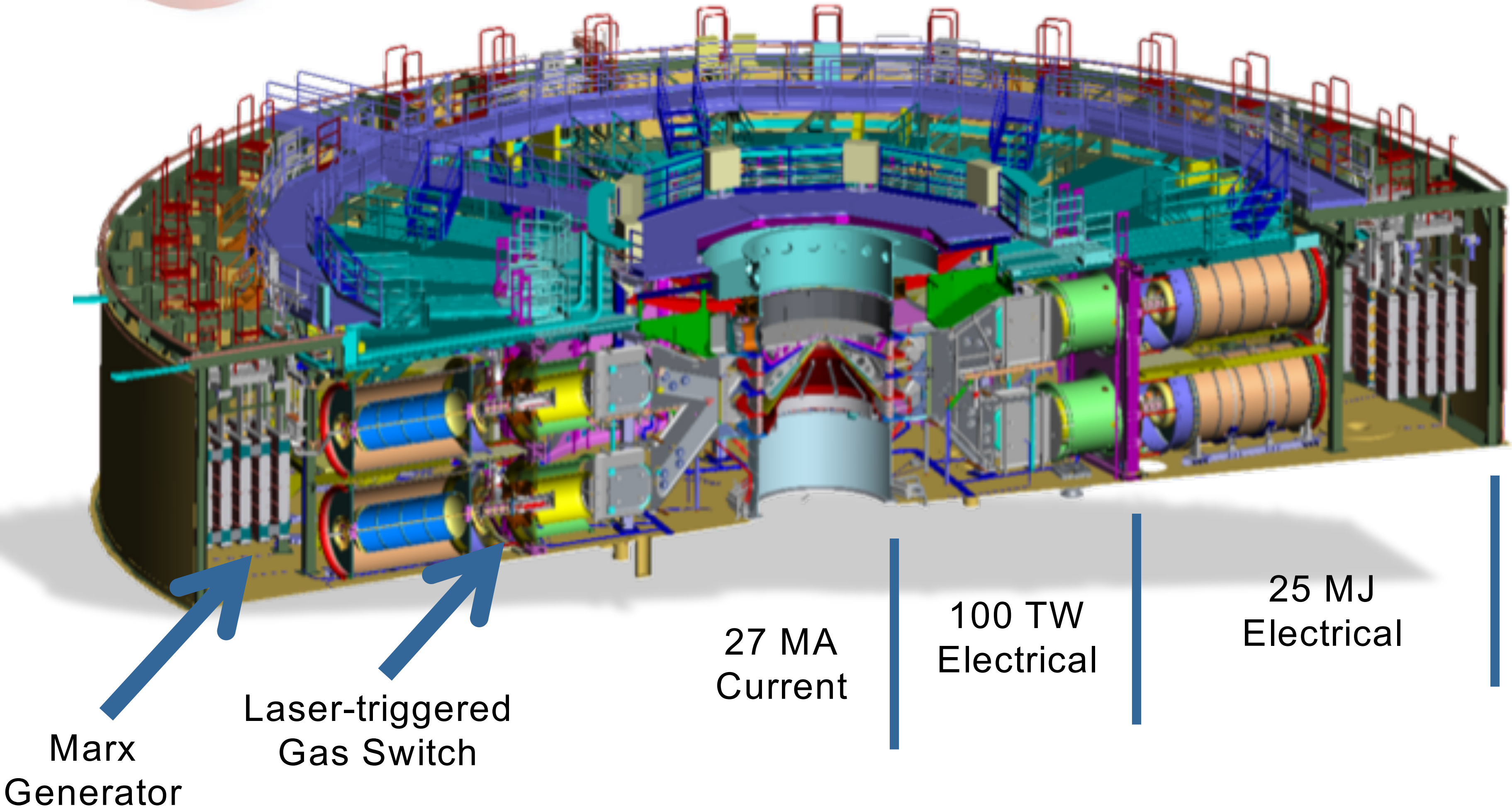
  (whose load is destroyed with each shot)

Multiple modules are used to achieve the highest powers

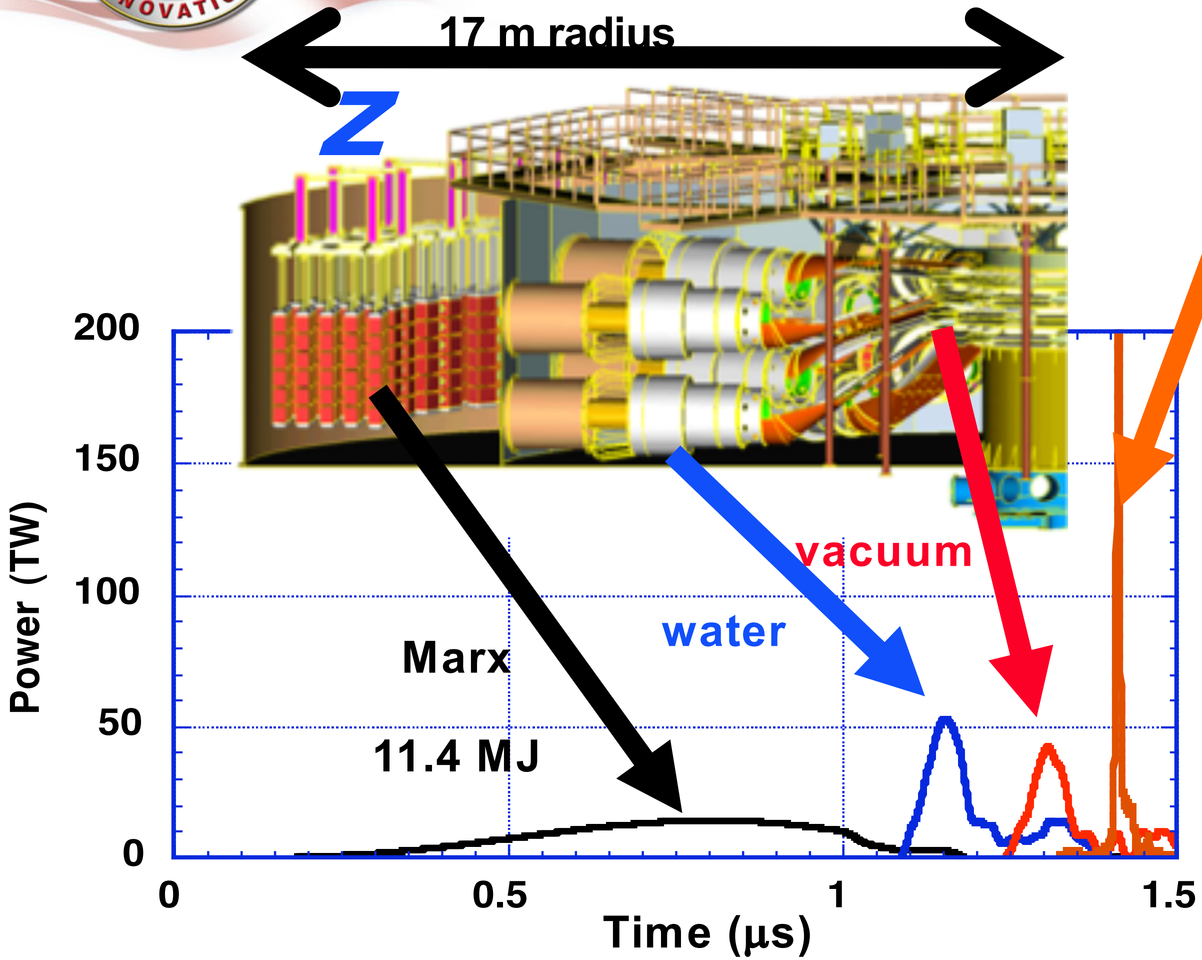


- Laser-triggered gas switches are used to synchronize the pulses (to within a few ns) from the individual modules

Cross section of the Z facility at Sandia National Laboratories



Pulsed-power provides compact, efficient, power amplification



x ray output
~2 MJ
~200 TW in ~5 ns

conversion efficiency
~15%
(wall-plug to x-rays)

at a velocity of c:
Current pulse: 100 ns (30 m)
x-ray pulse: 5 ns (150 cm)

This is akin to taking the equivalent electrical energy consumption in one evening's operation of a TV set (a few MJ) and compress it into more electrical power than provided by all the power plants in the world combined (~13-15 TW).

We employ kinetic 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 light bulb uses 1 MJ in 2.8 hours

A velocity of 50 cm/μsec:

- ~ 1,100,000 miles per hour
- Princeton 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

We compress energy in space *and* time on Z

- Compression in height X 625
  - 625 cm tank Marx height to 1.0 cm load height

- Compression in radius X 1375
  - 1650 cm in Marx tank radius to 1.2 cm load radius

- Compression in time X 2.4×10^{10}
  - 2 minute Marx charge to 5 ns pinch output

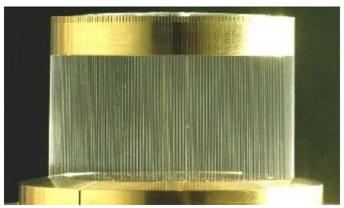
- Total power density compression factor ~8×10^{15}
  - (η x area x time, η~0.4)

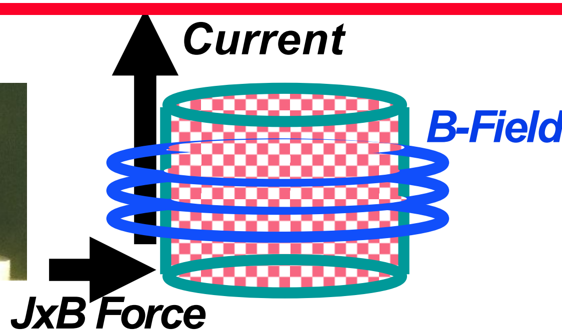
We can use high currents to push plasmas in different ways for different applications

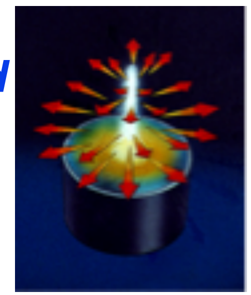
High Current

Z-pinch X-ray sources

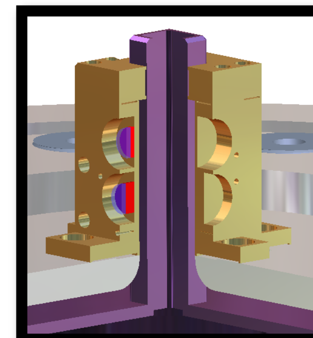
wire array



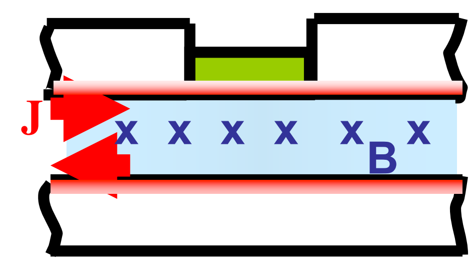




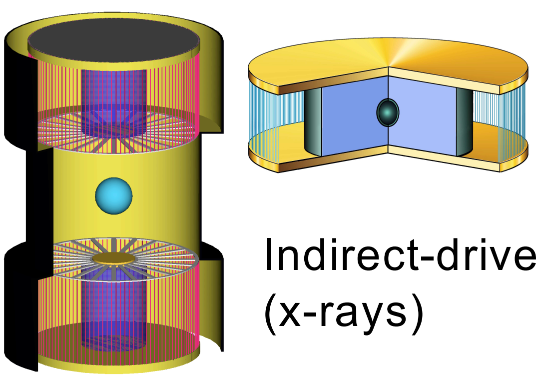
Planar magnetic pressure



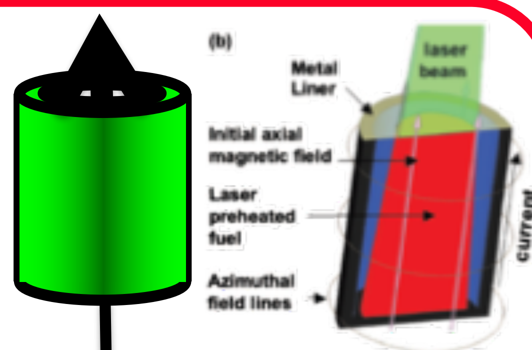
Material Properties



Inertial Confinement Fusion (ICF)



Indirect-drive (x-rays)



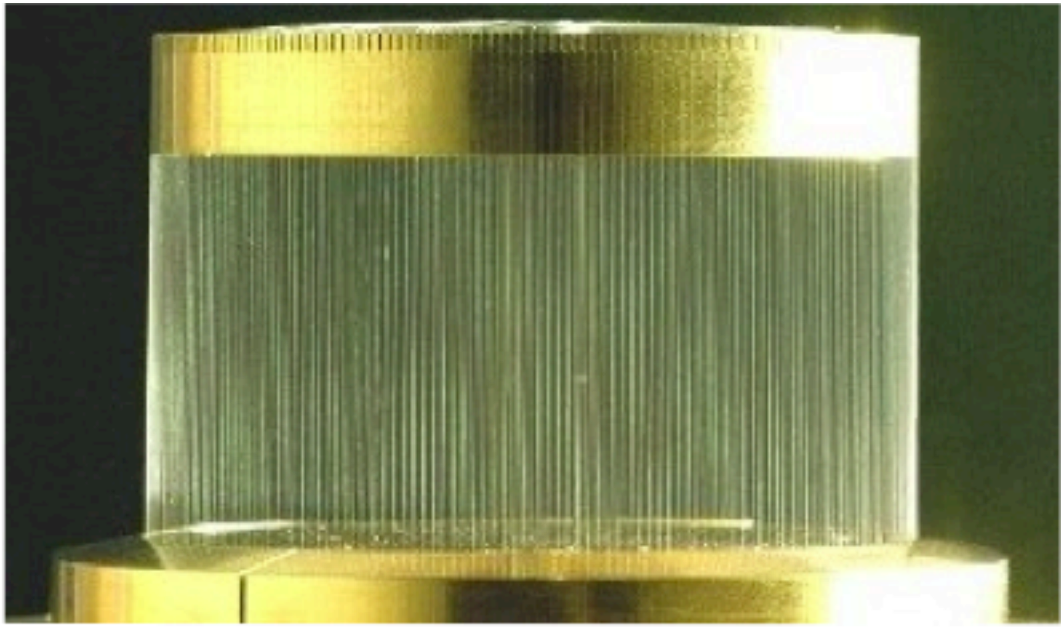
Direct-drive (magnetic field)

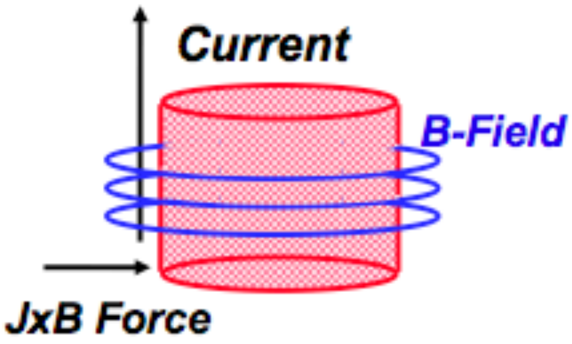
Wire arrays are a "simple" extension of the two wire problem

Instead of 2 wires, use ~300 wires in a cylindrical array. The JxB force accelerates the wires toward the array axis.

Instead of 1 mA or 1 A, use 20,000,000 Amperes of current in the array, delivered in a ~100 ns current pulse.

The result is the creation of soft x rays (~0.1-10 keV) with 10-15% efficiency from the stored electrical energy

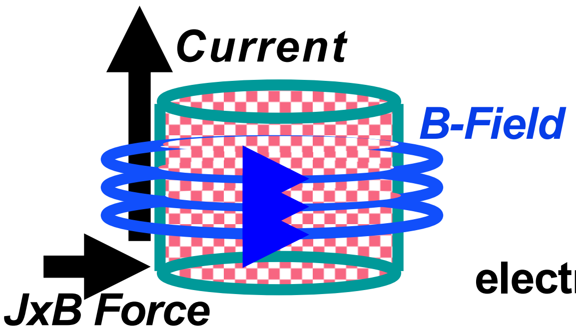




Z-pinch loads:

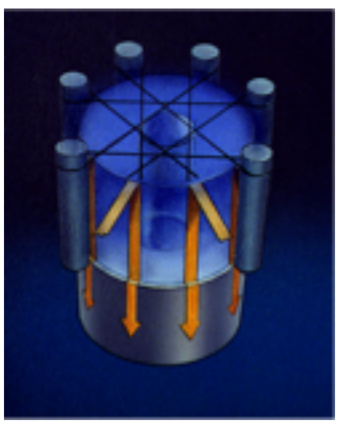
Wire Array
Gas Puffs
Foil/Liner
Foam

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



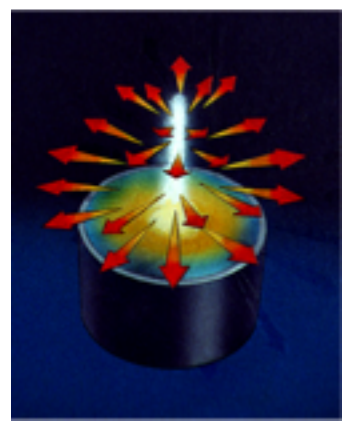
electrical energy → kinetic energy

kinetic and magnetic energy → internal energy → x rays



Ablation

Implosion



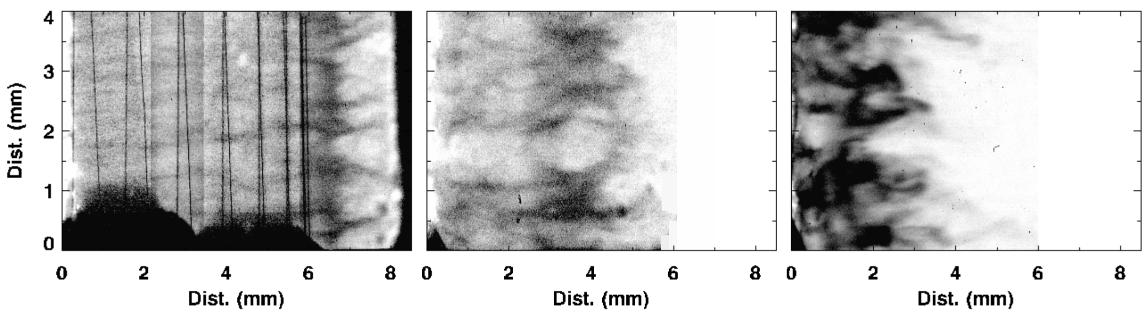
Stagnation

<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

Magneto-Rayleigh-Taylor (MRT) instability limits the quality of the implosion

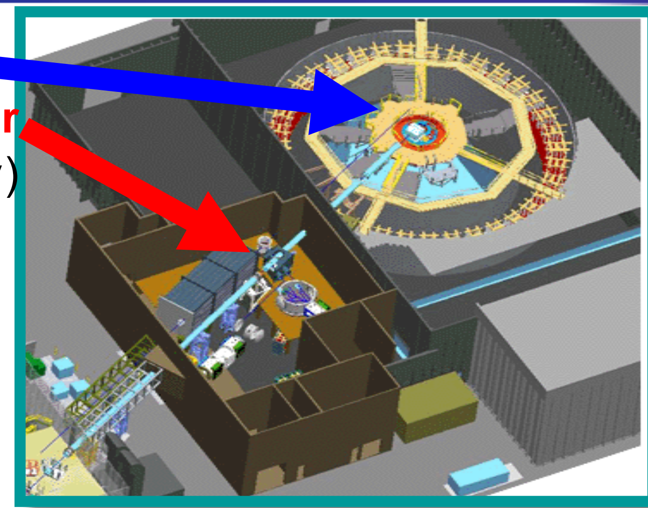
Xray images of a wire array during its implosion!

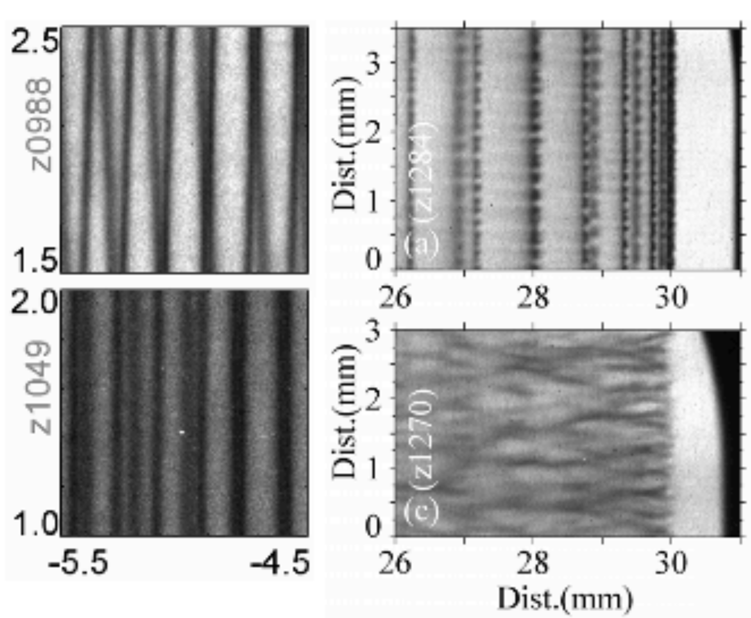


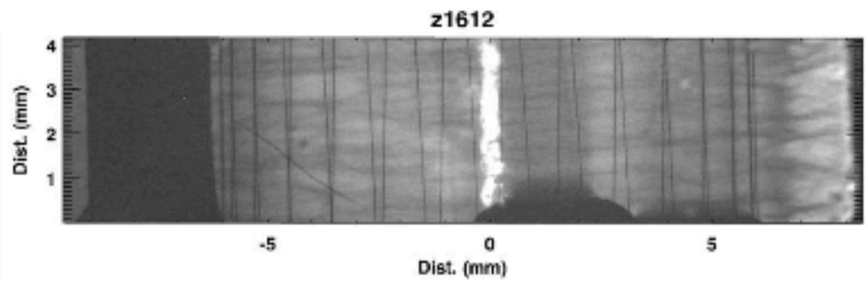
Z Machine

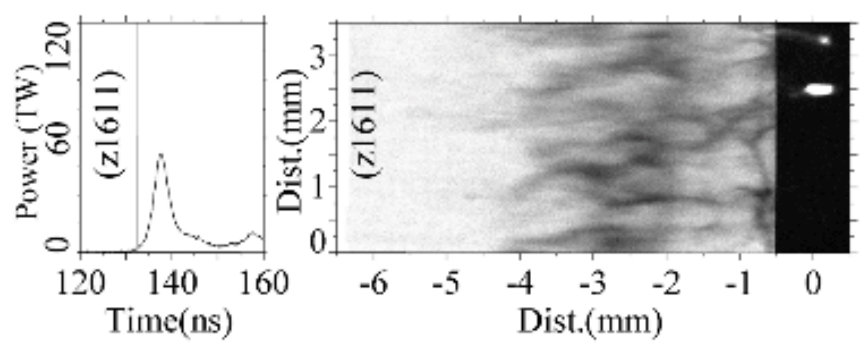
Z Beamlet laser

(for radiography)

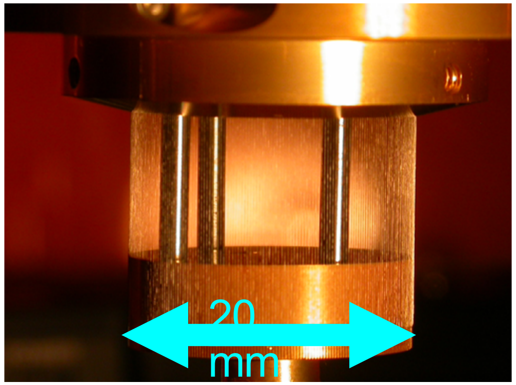


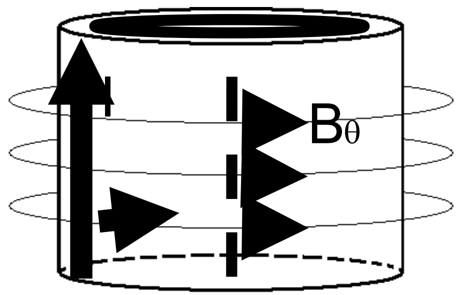


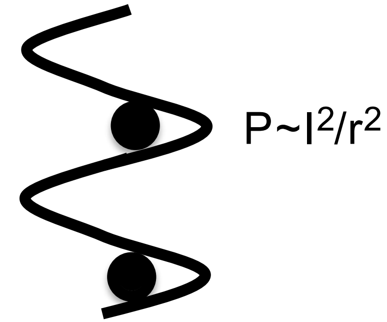


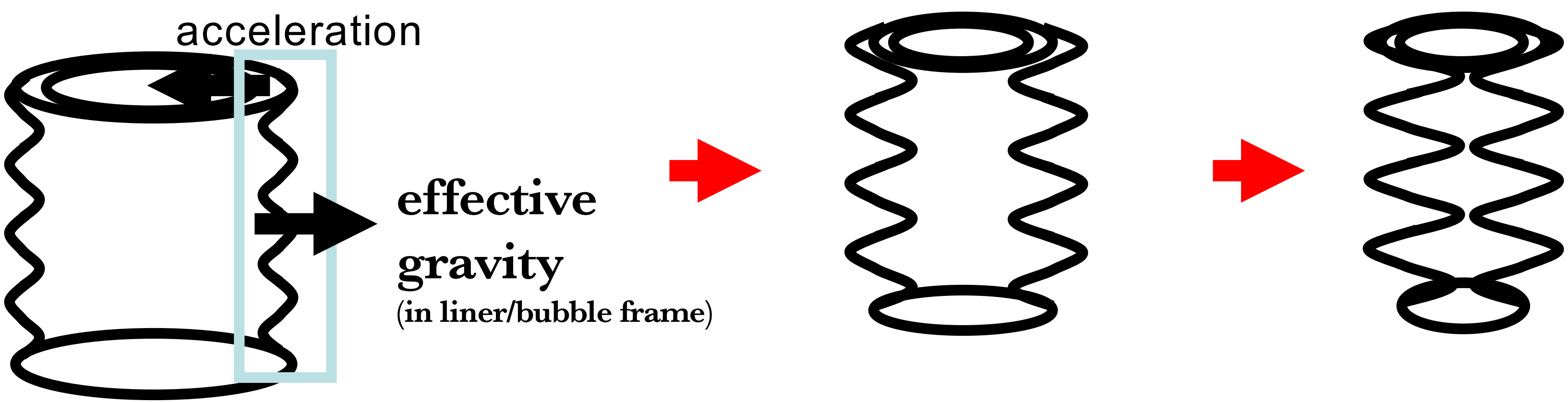


The plasma is the heavy fluid and the B field is the light fluid → *unstable* to the MRT



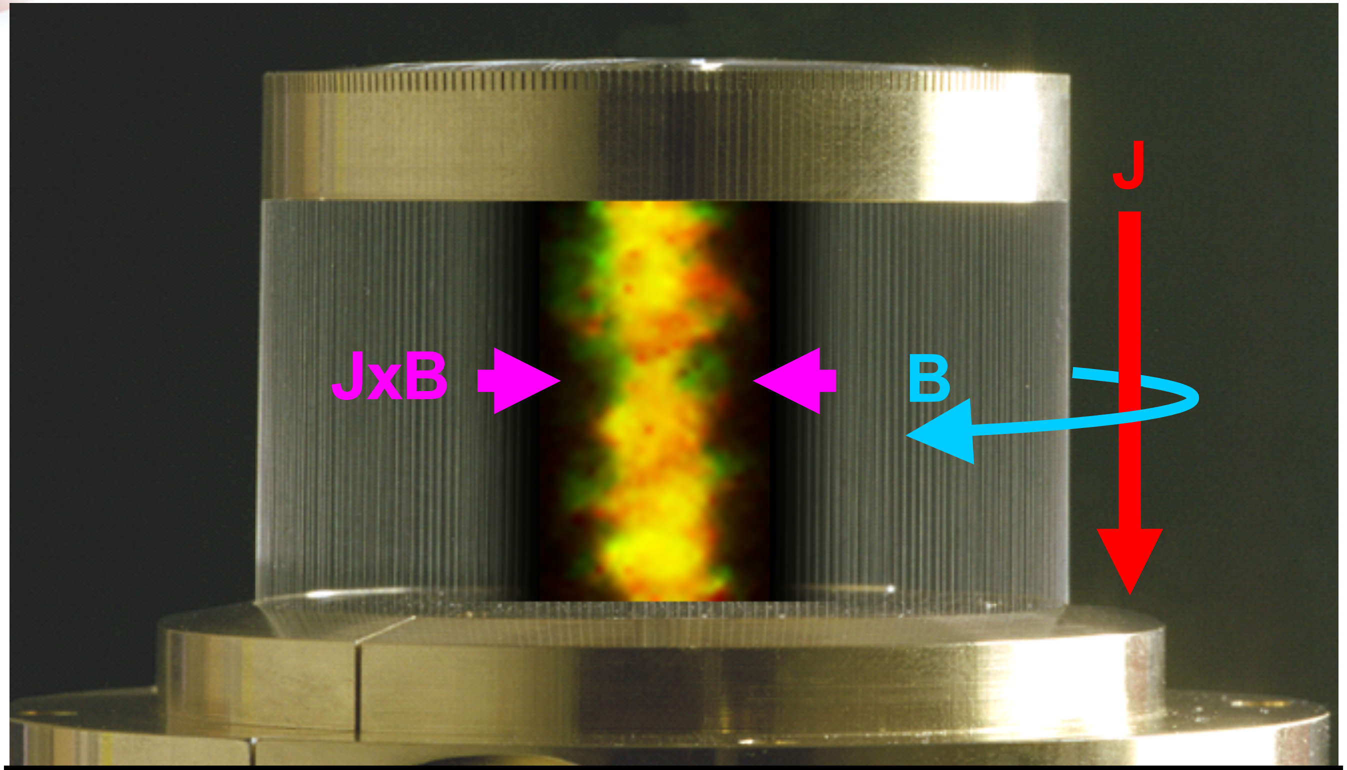






- Our z-pinches are termed “fast” because only the MRT grows during implosion

Summary: J x B force pinches wire array into a dense, radiating plasma column



Z-pinch wire array x-ray source summary:

E_{rad} ~ 2 - 3 MJ, ~15% wall plug efficiency

P_{rad} ~ 100-330 TW (~330 million million Watts)

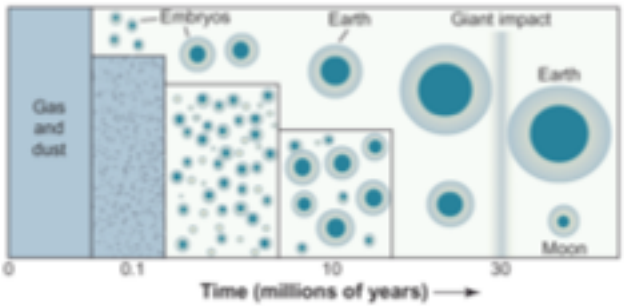
T_{rad} ~ 200 eV ~ 2,300,000 ° K

A power of 330 TW

- 25 x global annual power consumption [2008]
- 104 x US annual power consumption

- BUT, remember, it's just on for 5 ns……..light will only travel 4.9 feet in 5 ns

Sandia has a fundamental science program on Z and awards time to university users



Earth formation

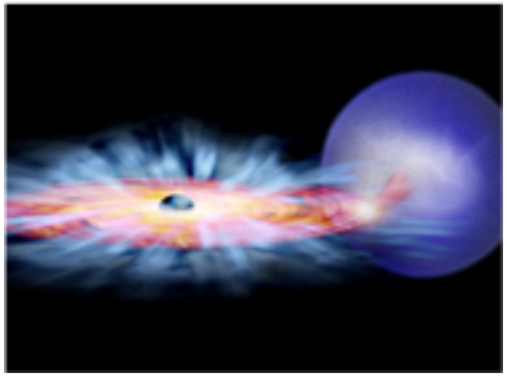
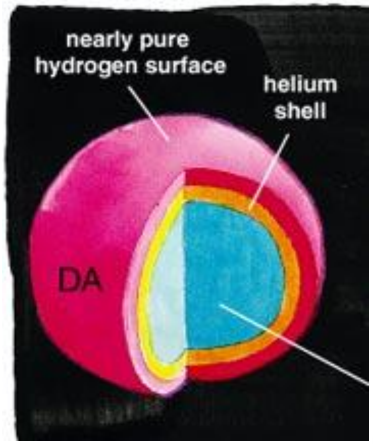
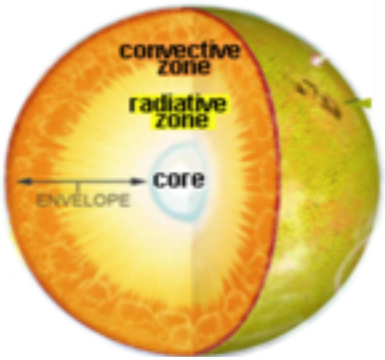


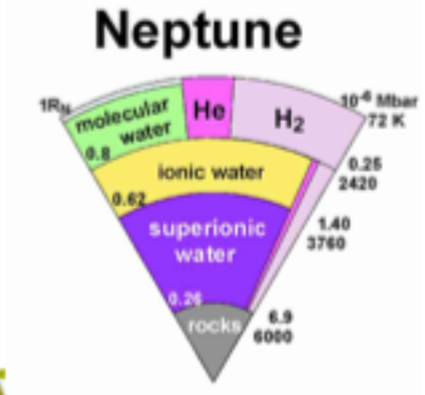
Photo-ionized plasmas



White Dwarfs



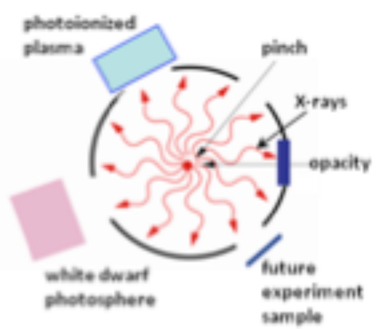
Solar Opacities



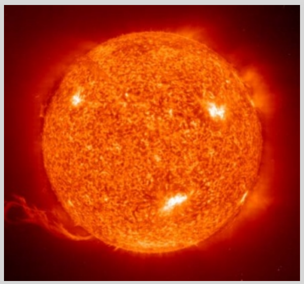
Planetary structure

- We use high magnetic pressures and intense x-ray bursts to create unique matter and plasmas that can help address astrophysical questions
- Proposals address exciting scientific issues:
  - Do we understand the structure of the sun?
  - Can we use white dwarfs as cosmic chronometers?
  - How does the accretion disk around a black-hole behave?
  - What is the structure of the planets in our solar system (and beyond)?
  - How did the Earth and the Moon form?

Z Astrophysical Plasma Properties (ZAPP) project



Solar Opacity

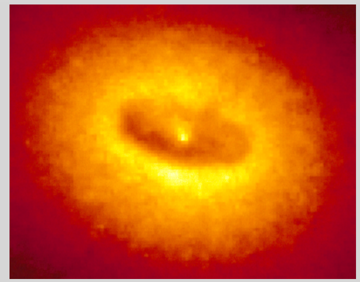


Collaborator:
Ohio State University

Purpose:
Test Fe opacity models at conditions relevant to the convection zone boundary in the Sun.

Required Conditions:
$T_e \sim 180$ eV, $n_e \sim 10^{23}$ cm^{-3}

Photoionized Plasma



Collaborators:
UNR / LLNL

Purpose:
Test photo-ionization models and atomic physics at conditions relevant to black hole accretion disks.

Required Conditions:
$T_e \sim 15$ eV, $n_e \sim 10^{18}$ cm^{-3}

White Dwarf Line-Shapes

Collaborator:
University of Texas

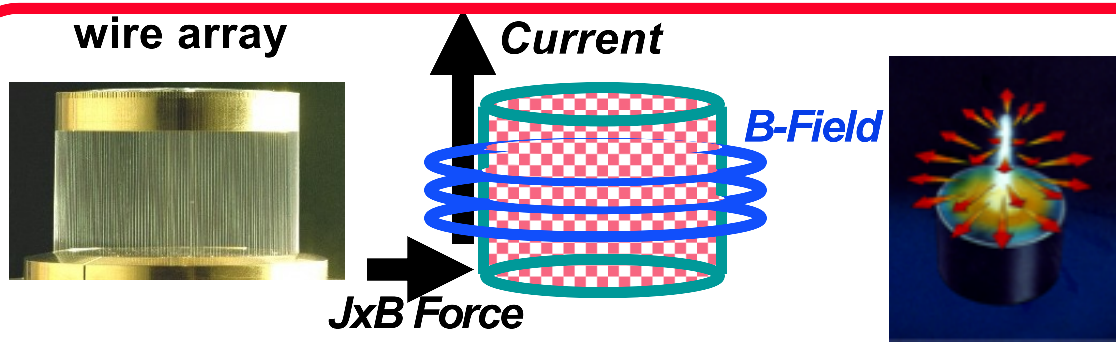
Purpose:
Test line-broadening theory of H at conditions relevant to White Dwarf photospheres.

Required Conditions:
$T_e \sim 1\text{-}4$ eV, $n_e \sim 10^{17\text{-}19}$ cm^{-3}

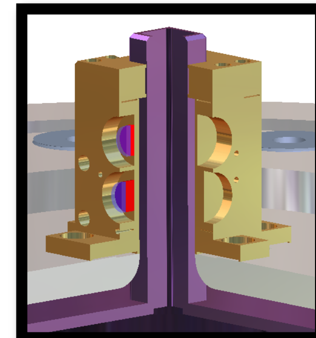
We can use high currents to push plasmas in different ways for different applications

High Current

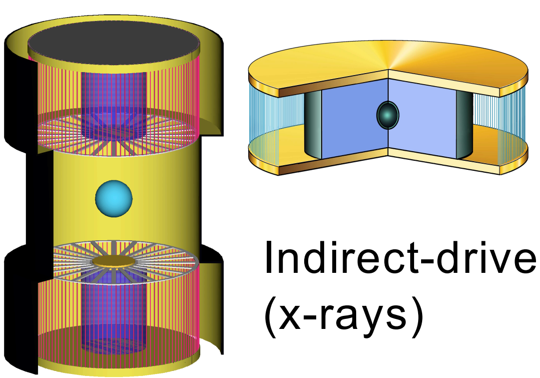
Z-Pinch X-ray Sources



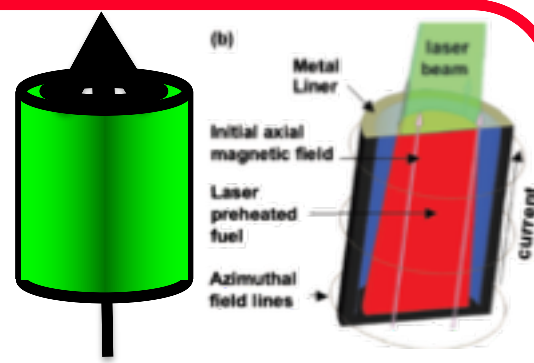
Planar magnetic pressure



Inertial Confinement Fusion (ICF)

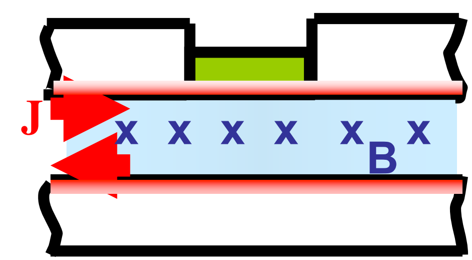


Indirect-drive (x-rays)



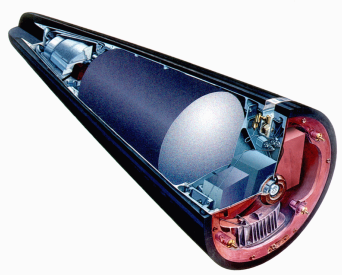
Direct-drive (magnetic field)

Material Properties

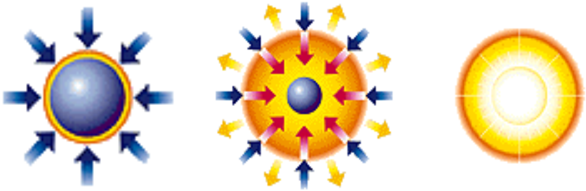


Understanding material properties at high pressure is important for Stockpile Stewardship, ICF, and understanding planets

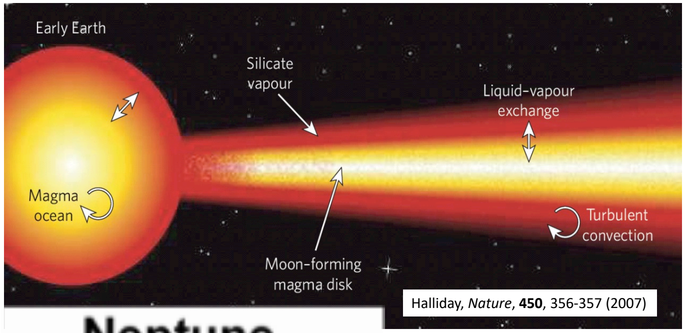
- Nuclear weapons materials
  - Behavior of plutonium, uranium, etc.



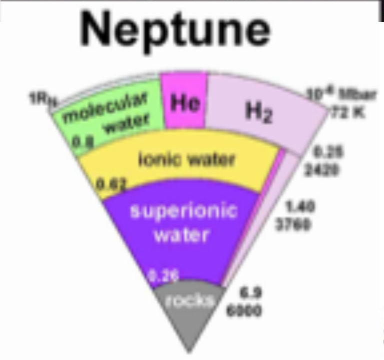
- Inertial confinement fusion (ICF) materials
  - Behavior of hydrogen, plastics, beryllium, diamond, etc.



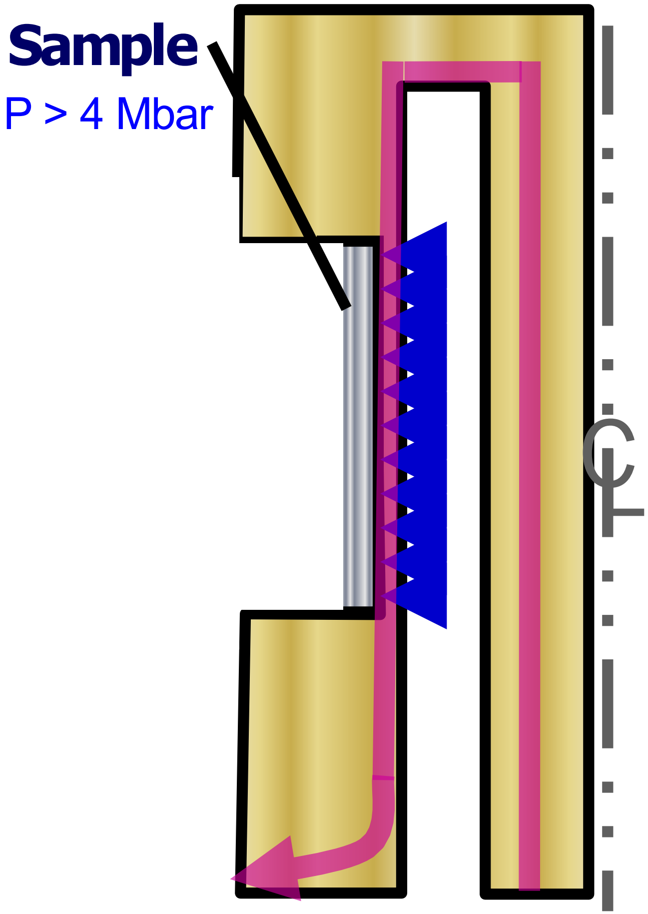
- Planetary science
  - Giant impacts (e.g. Moon Forming Event)
  - Earths and super-earths
    - Equation of state of *Mg, Fe, Si, C, O*, etc.
  - Giant Planets (e.g. Uranus & Neptune and exo ice-giants)
    - High-pressure mixtures of *H, He, C, O, N*

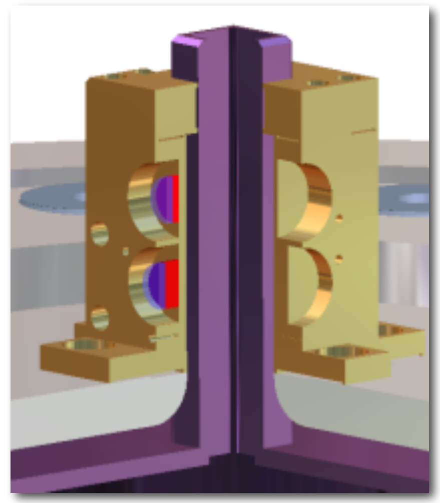


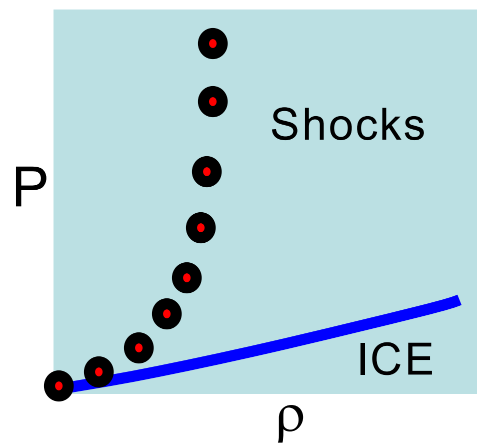
Halliday, *Nature*, **450**, 356-357 (2007)

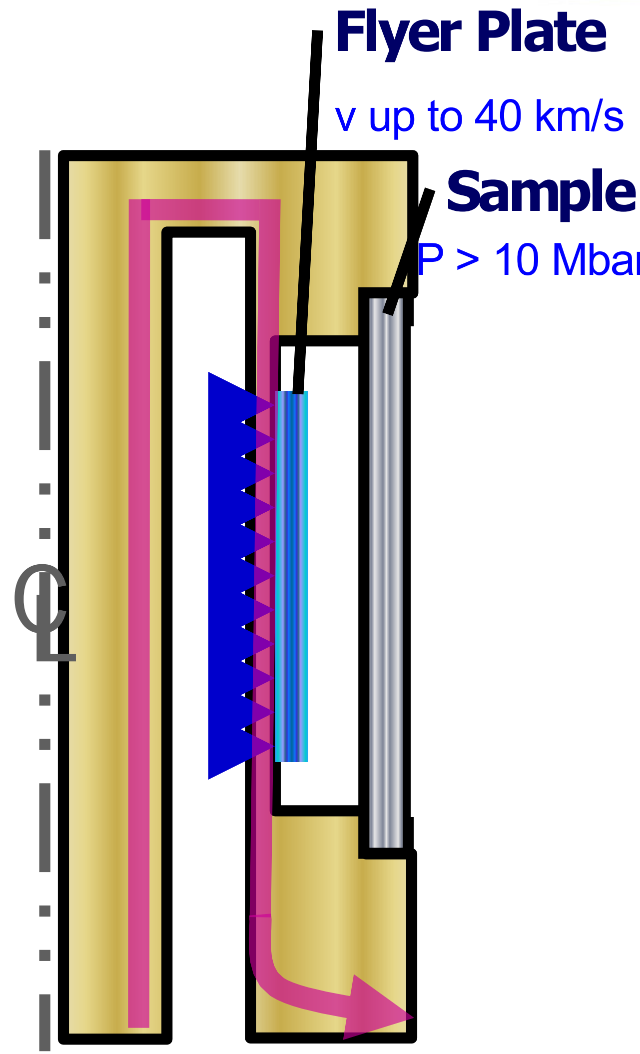


Isentropic compression and shock wave experiments map different regions of phase space





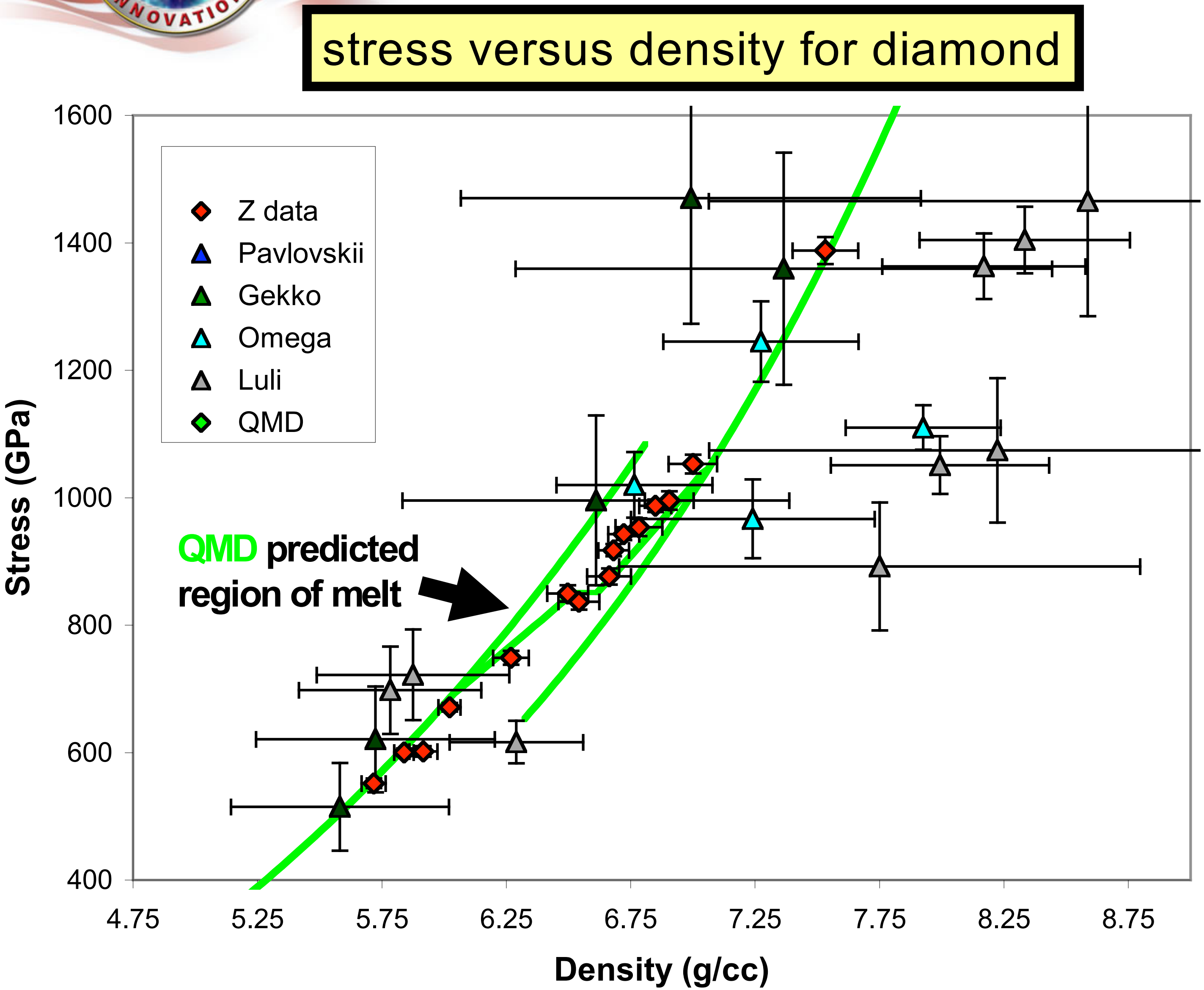




Isentropic Compression Experiments:
gradual pressure rise in sample

Shock Hugoniot Experiments:
shock wave in sample on impact

Z answered important questions about the properties of diamond at high pressure



- The Z data was obtained in 1 week
- Measurements on Z have an accuracy of ≤ 1%

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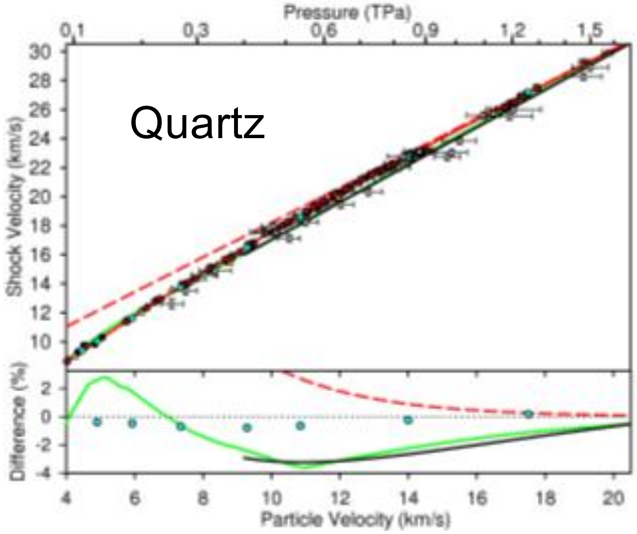
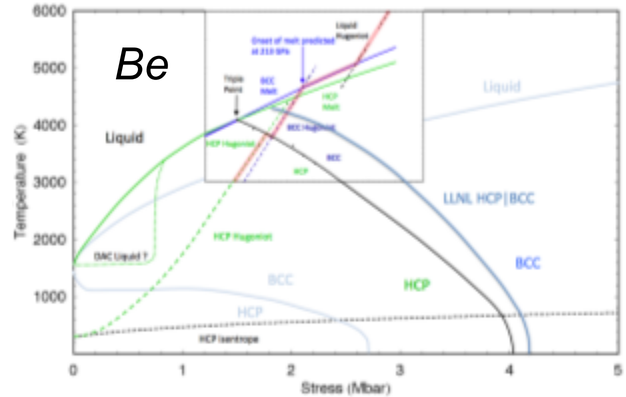
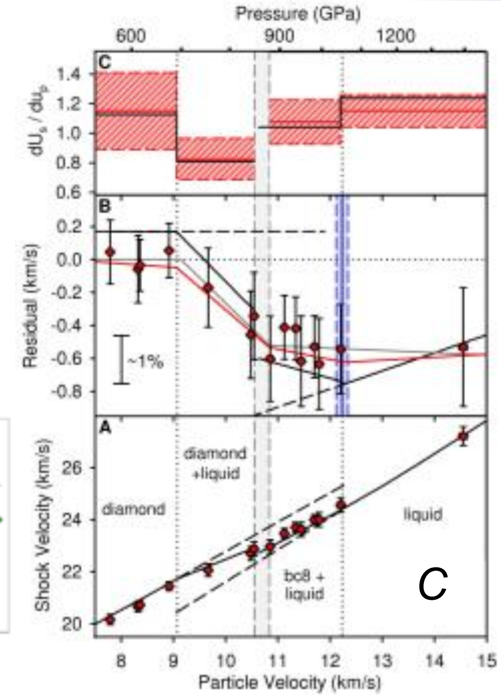
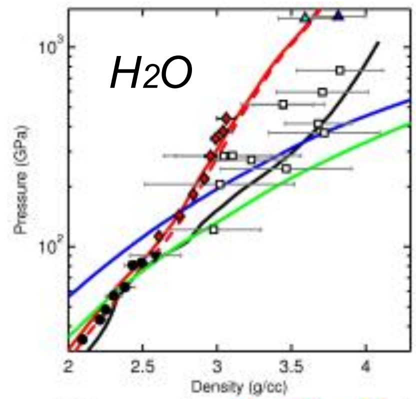
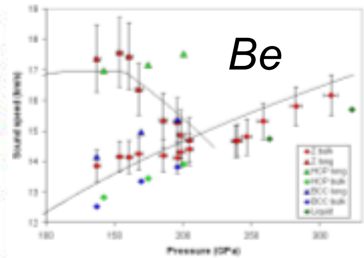
Z has been used to study material properties in the multi-Mbar regime for many materials

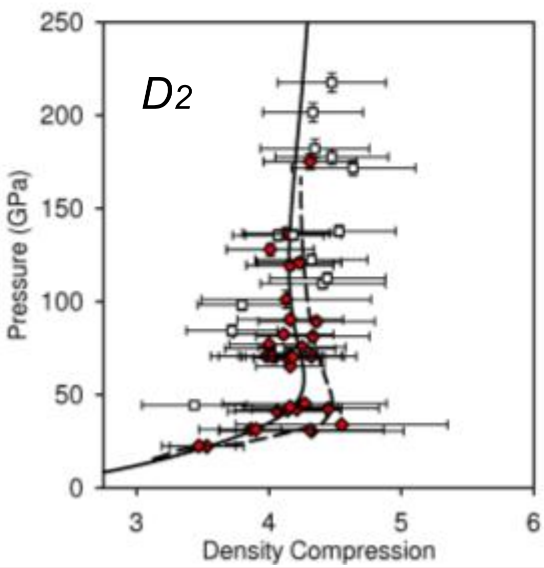


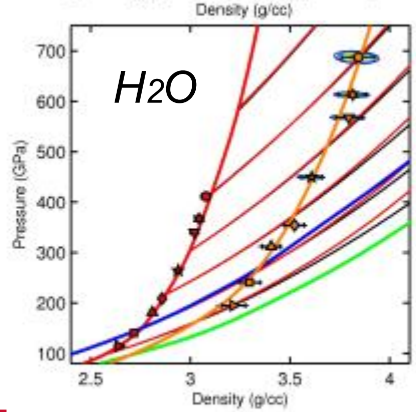


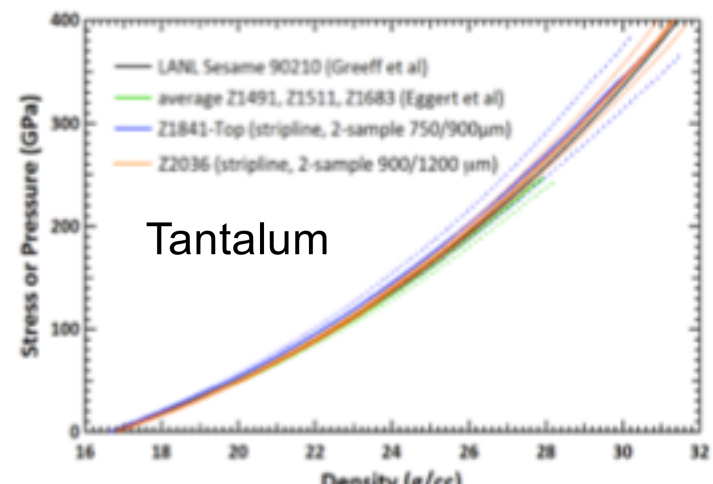






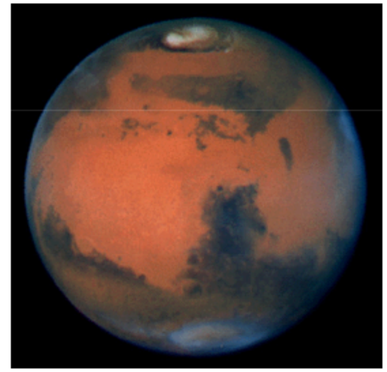




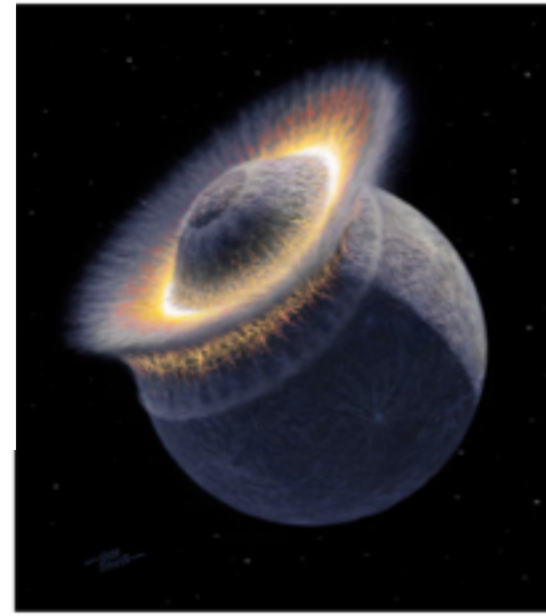


Giant Impacts:
unlocking the mysteries of satellites and planets

Europa Ganymede Callisto



Mars



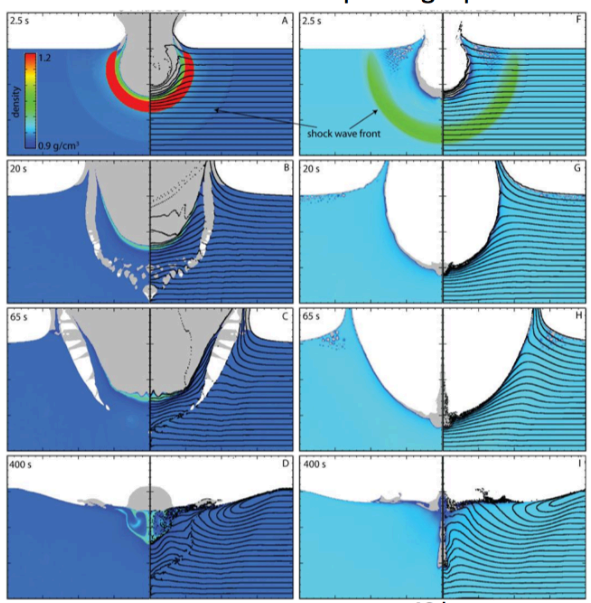
5-Phase EOS Simple single phase EOS

2.5 s

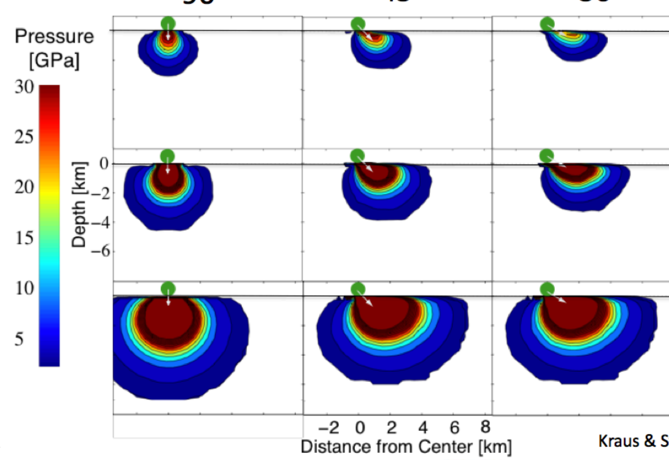
20 s

65 s

400 s



40 km



Kraus & Stewart, in prep.

Sandia National Laboratories

Credit: S. Stewart (Harvard)

Giant Impacts:
unlocking the mysteries of satellites and planets

Giant impacts:

- affect final physical and dynamical properties of a planet
- are invoked to explain the large core of Mercury, spin of Venus, crust asymmetry on Moon and Mars, etc.
- result in a diversity of features from possible outcomes

Physical properties of the planets and moons, and collisions among them, depend on thermodynamics models:

→ EOS (T, ρ, P, S), phase changes, mixtures, strength

The goals are to understand:

- planet and satellite formation, structure, and evolution
- effects of collisions on planets and satellites
- cratering mechanics and morphology

We use flyer plates on the Z machine to gather shock data on relevant materials, such as *MgO* and *Fe*, in support of this research

Credit: S. Stewart (Harvard)

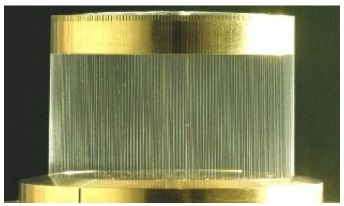
Sandia National Laboratories

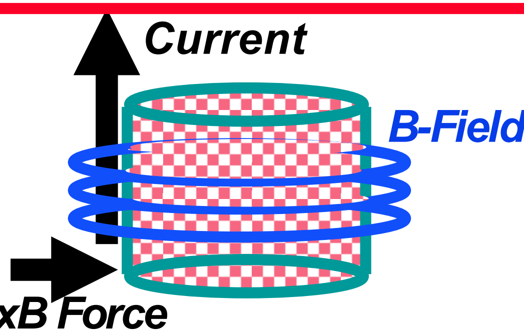
We can use high currents to push plasmas in different ways for different applications

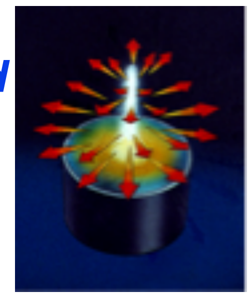
High Current

Z-pinch X-ray sources

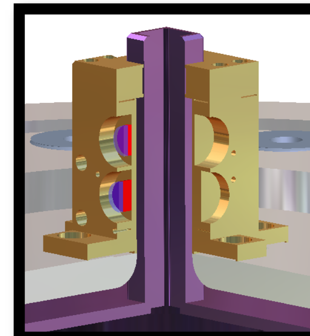
wire array



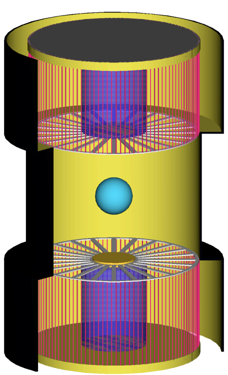


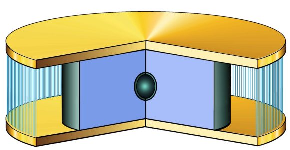


Planar magnetic pressure

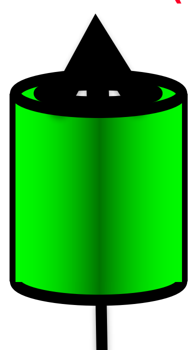


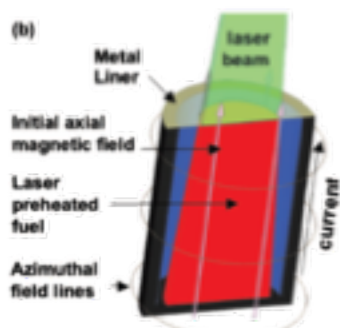
Inertial Confinement Fusion (ICF)





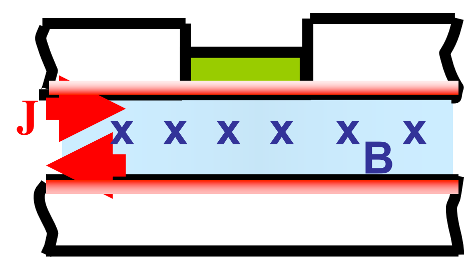
Indirect-drive (x-rays)





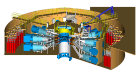
Direct-drive (magnetic field)

Material Properties

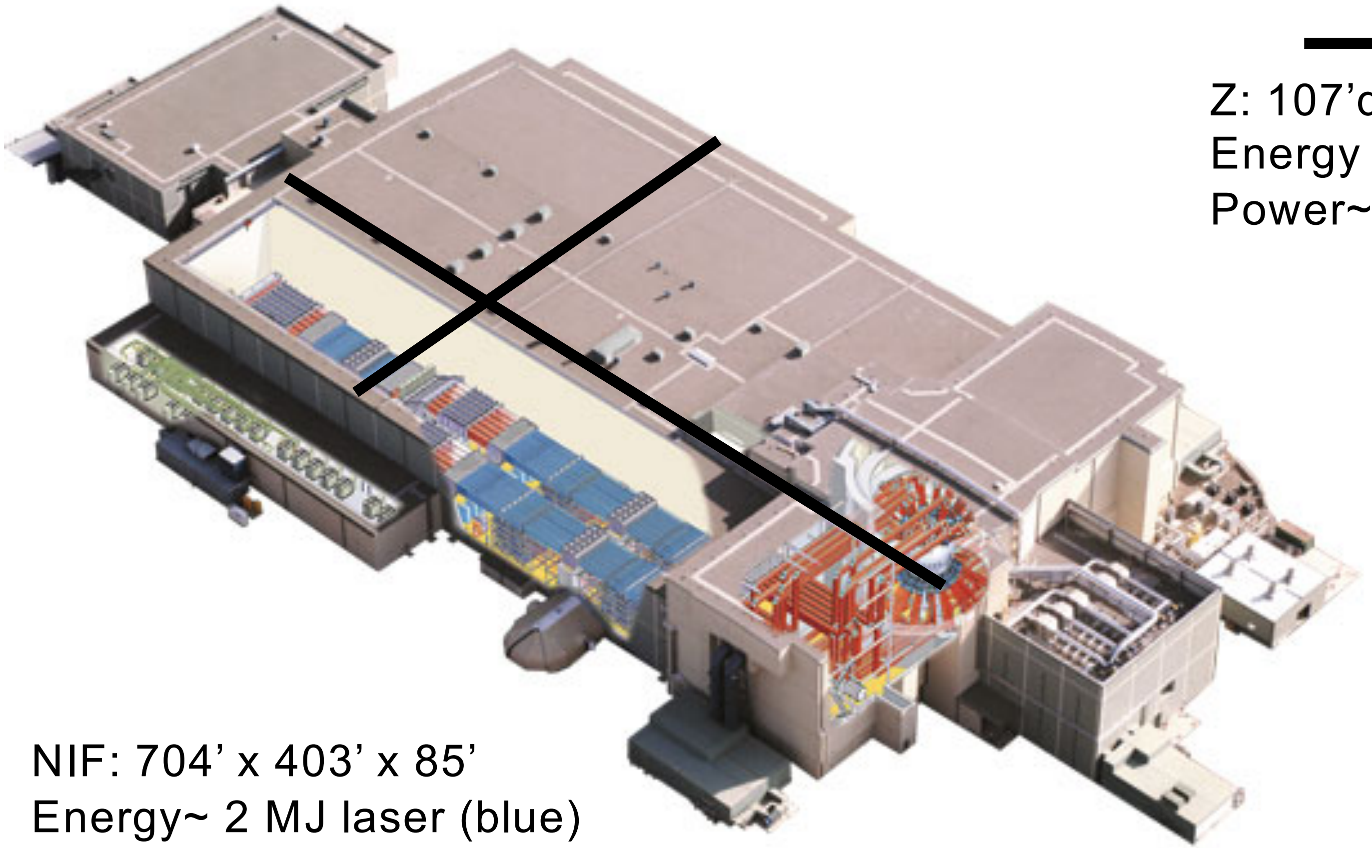


Pulsed power is a compact and efficient driver for high energy density physics experiments

The cost effectiveness and efficiency of pulsed power is evident from a size comparison of Z and NIF



Z: 107'diam x 20' high
Energy ~2 MJ x-rays
Power~100-330 TW

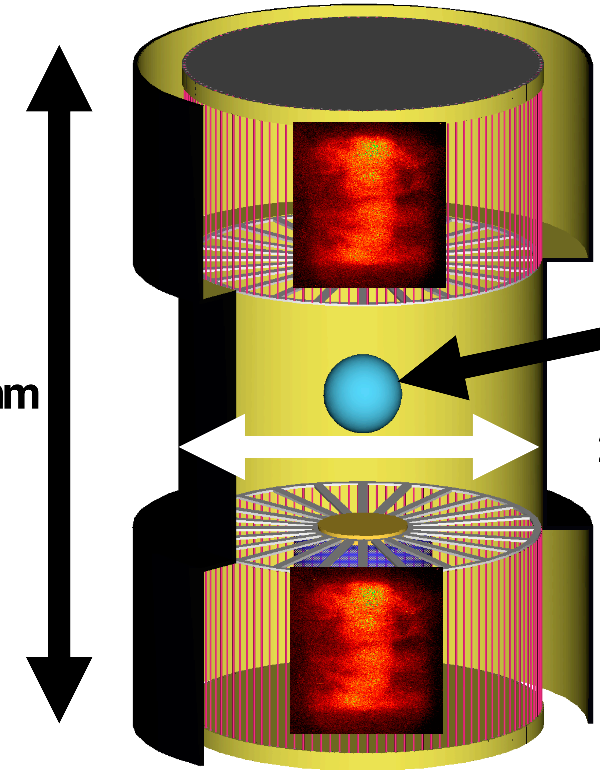


NIF: 704' x 403' x 85'
Energy~ 2 MJ laser (blue)
Power~ 500 TW

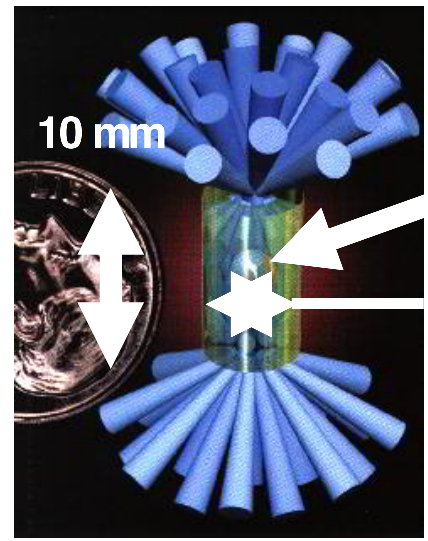
HOWEVER:

While Z pinches are more efficient radiators, they need more energy to reach ICF conditions...

.... because they radiate in *bigger volumes*

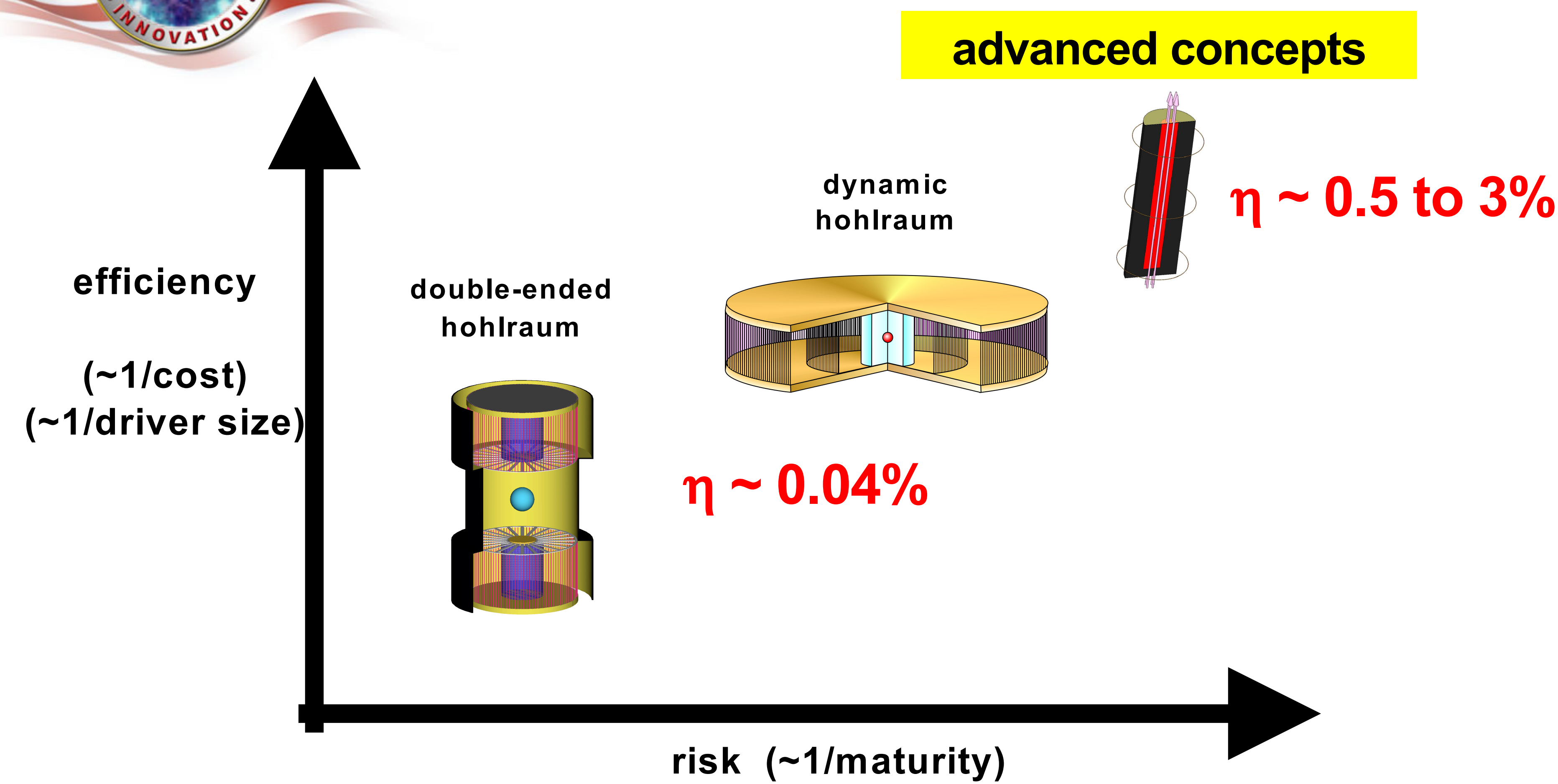


Z-pinch driven hohlraum (2 Z-pinches)
Z: 2 MJ X-ray source
High Yield requirement ~ 16 MJ x-ray source



NIF Laser (192 laser beams)
1-2 MJ X-ray source

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 ~20-50 times more efficient than x-ray indirect drive

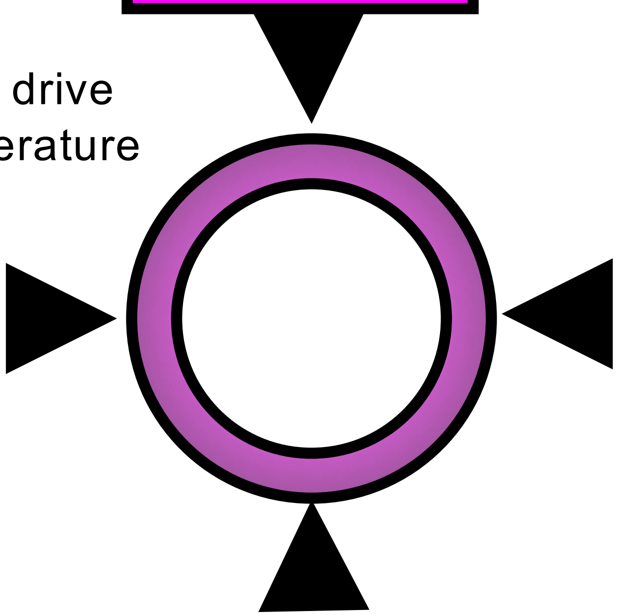
Magnetic direct-drive implosions generate high pressures just like radiation indirect-drive implosions

Radiation-driven spherical implosion (spherical rocket), ***indirect drive***

$$P = \frac{(2/5)(1-\alpha)\sigma T_r^4}{C_s} = 3e-7 * T_r[eV]^{3.5} \text{ MBar}$$

140 MBar
at T_r = 300 eV

X-ray drive temperature T

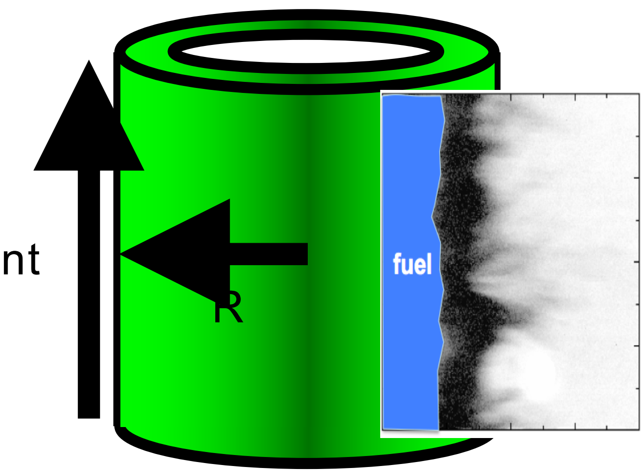


Magnetically-driven cylindrical implosion, ***direct drive***

$$P = \frac{B^2}{2\mu_o} = 1.57e-3\left(\frac{I_{MA}}{R_{cm}}\right)^2 \text{ MBar}$$

~458 MBar
at I = 27 MA, R = 0.05 cm

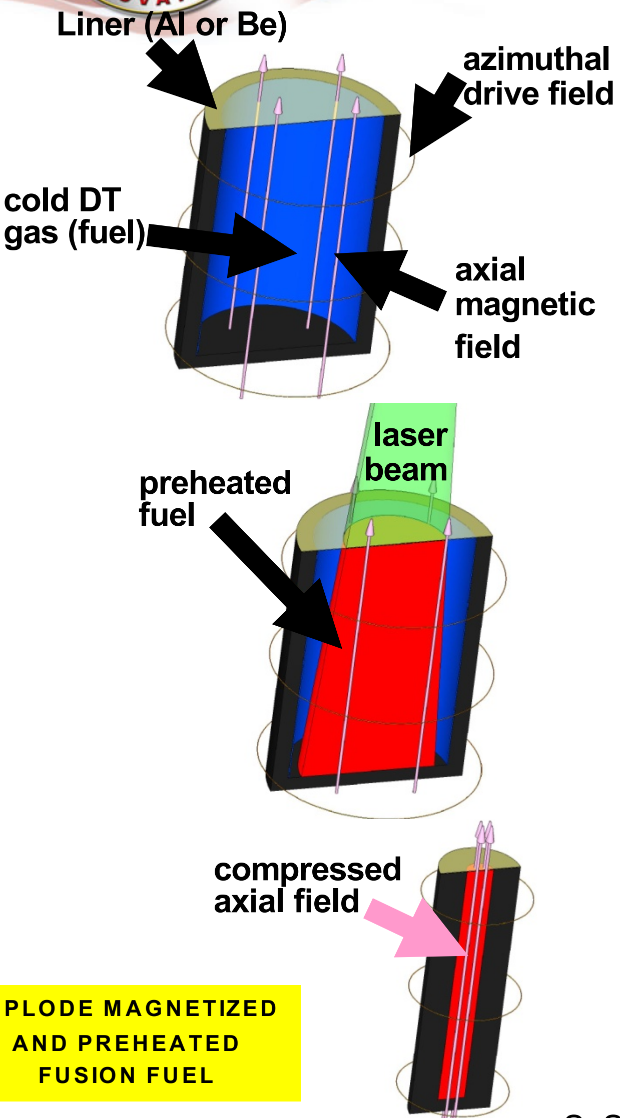
Drive current I



~2.26 GBar
at I = 60 MA, R = 0.05 cm

Need fuel pressures of ~100s Gbar and fuel ρr of ~1 g/cm^2 for ignition

The ICF program is evaluating a **direct-drive** concept called Magnetized Liner Inertial Fusion (MagLIF)

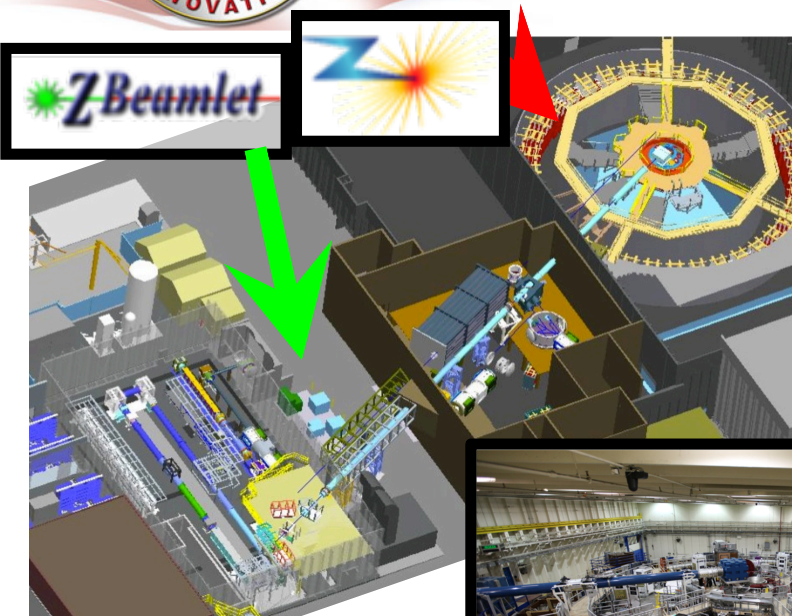


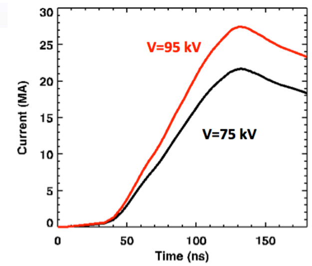
IMPLODE MAGNETIZED AND PREHEATED FUSION FUEL

- An initial B_z~10-50 T magnetic field is applied
  - Inhibits thermal conduction losses
  - Enhances alpha particle energy deposition
  - May help stabilize implosion at late times
- During implosion, the fuel is heated using the Z-Beamlet laser (up to 10 kJ needed)
  - Preheats fuel to 100 – 500 eV
  - Reduces the compression needed to obtain ignition temperatures to 20-30 on Z
  - Reduces the necessary implosion velocity to 100 km/s (slow for ICF)
- Z provides pressure to implode at ~100 km/s and compress B_z field to ~100 MG
- Scientific breakeven may be possible on Z (fusion yield = energy into fusion fuel)

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

MagLIF uses the Z facility to compress a liner containing pre-magnetized and pre-heated D_2 gas

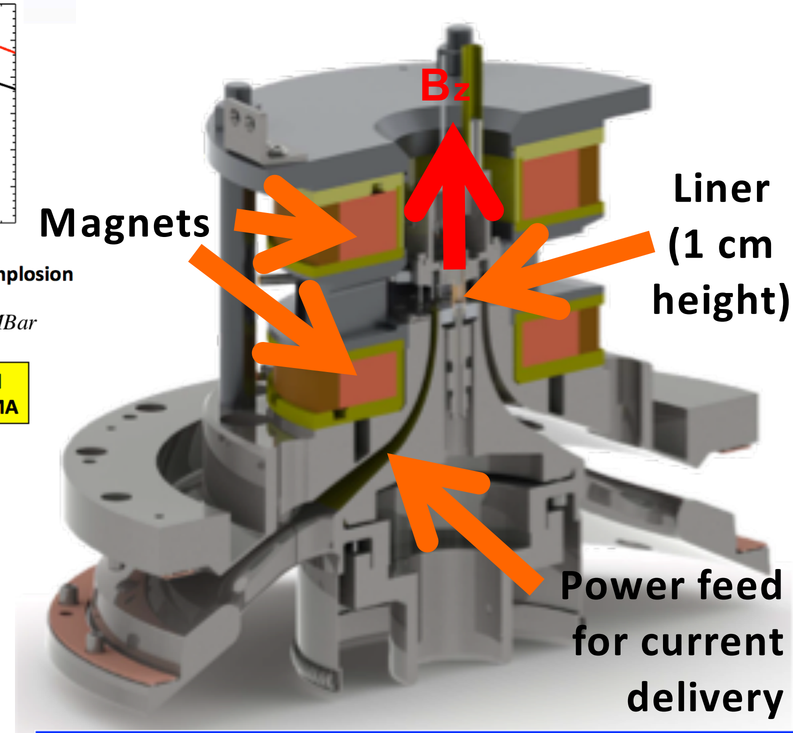


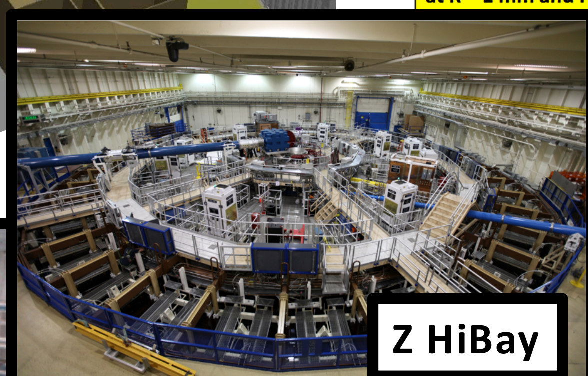


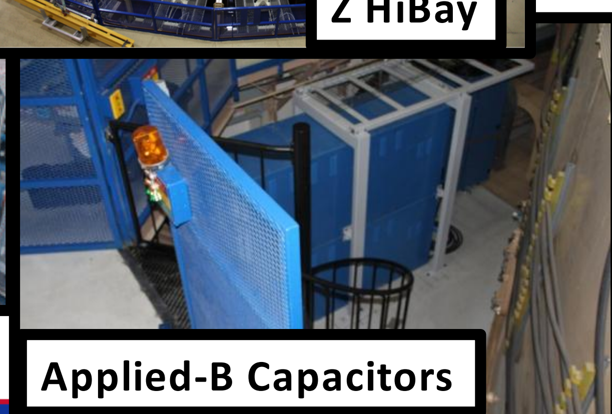
Magnetically-Driven Cylindrical Implosion

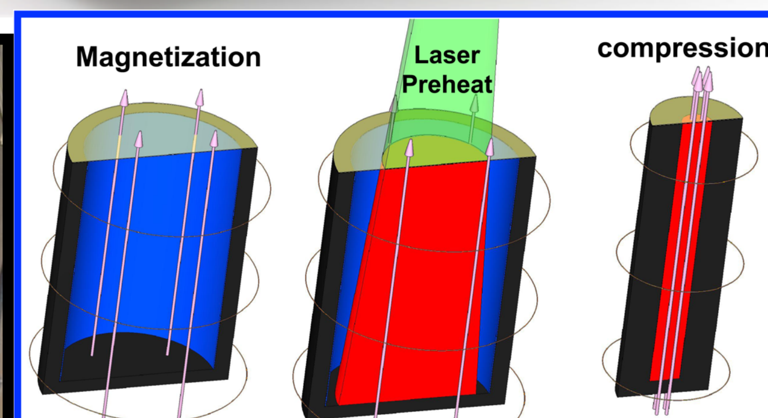
$$P = \frac{B^2}{2\mu_o} = 140\left(\frac{I_{MA}/30}{R_{mm}}\right)^2 MBar$$

140 MBar is generated at R = 1 mm and I = 30 MA

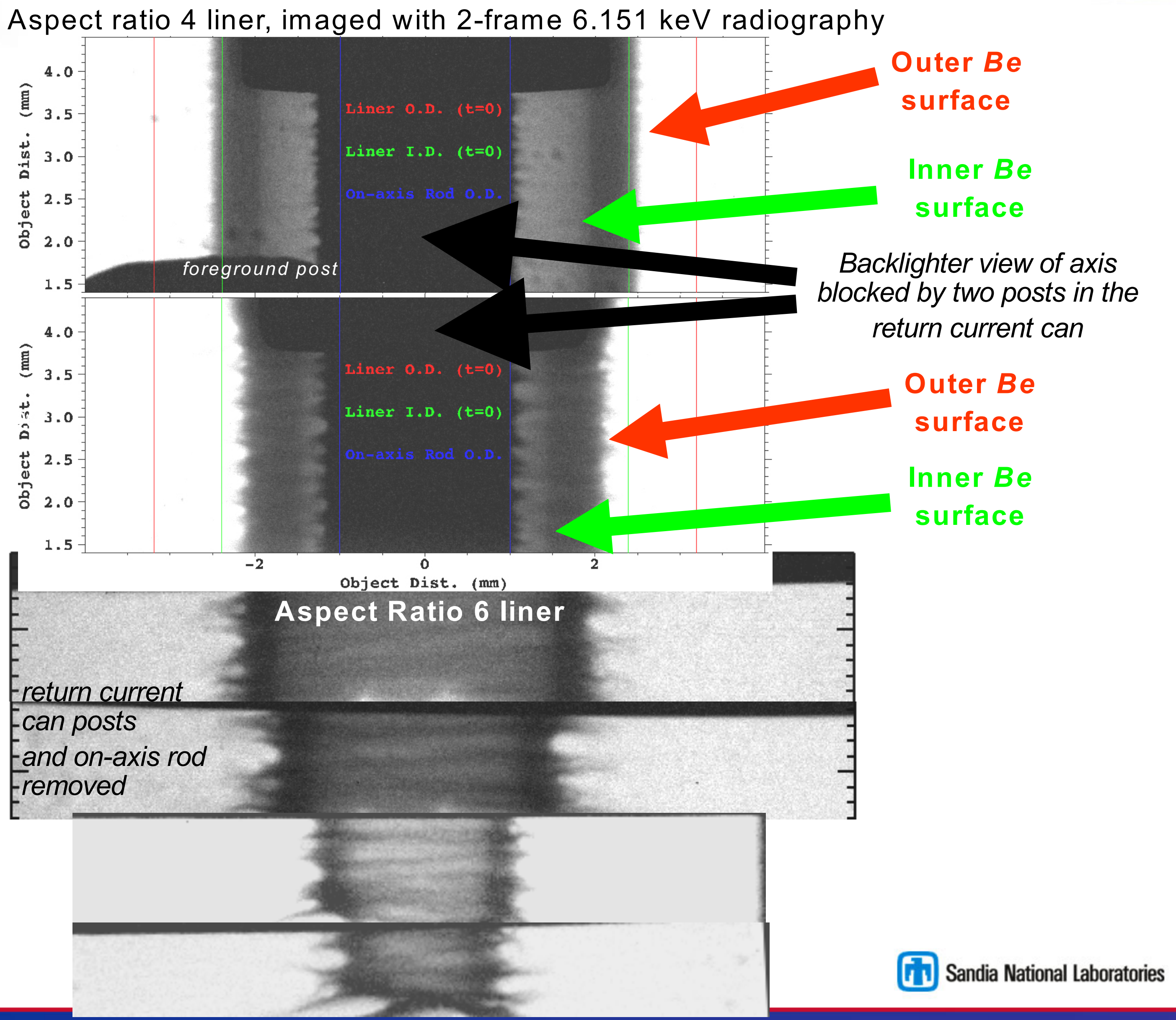


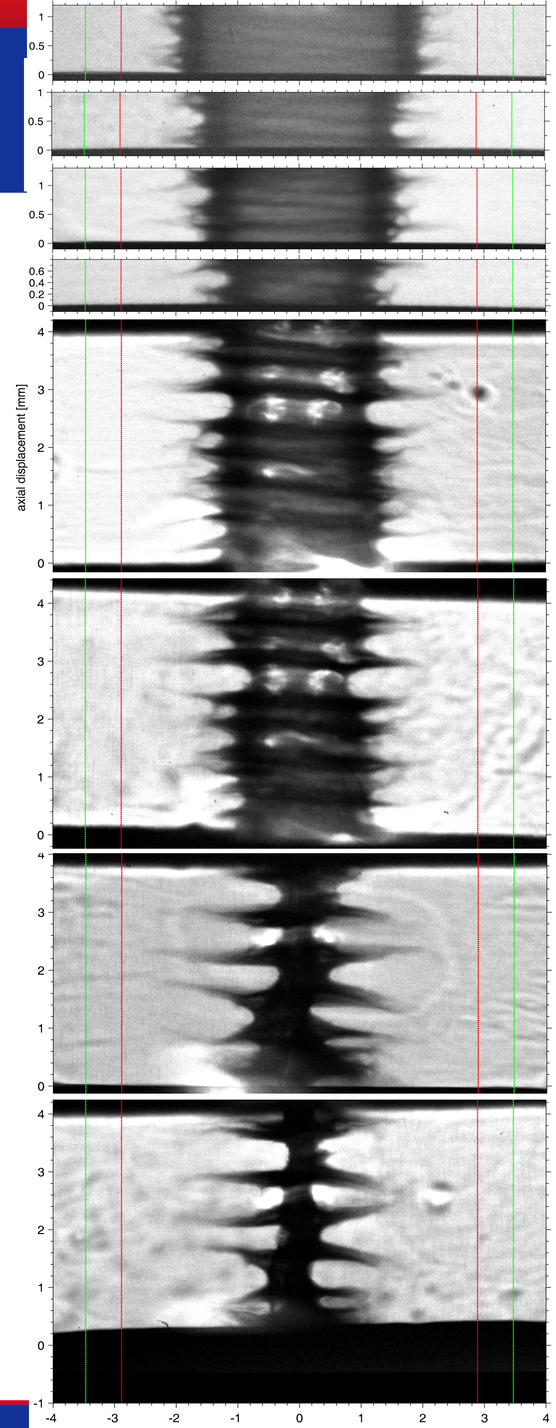




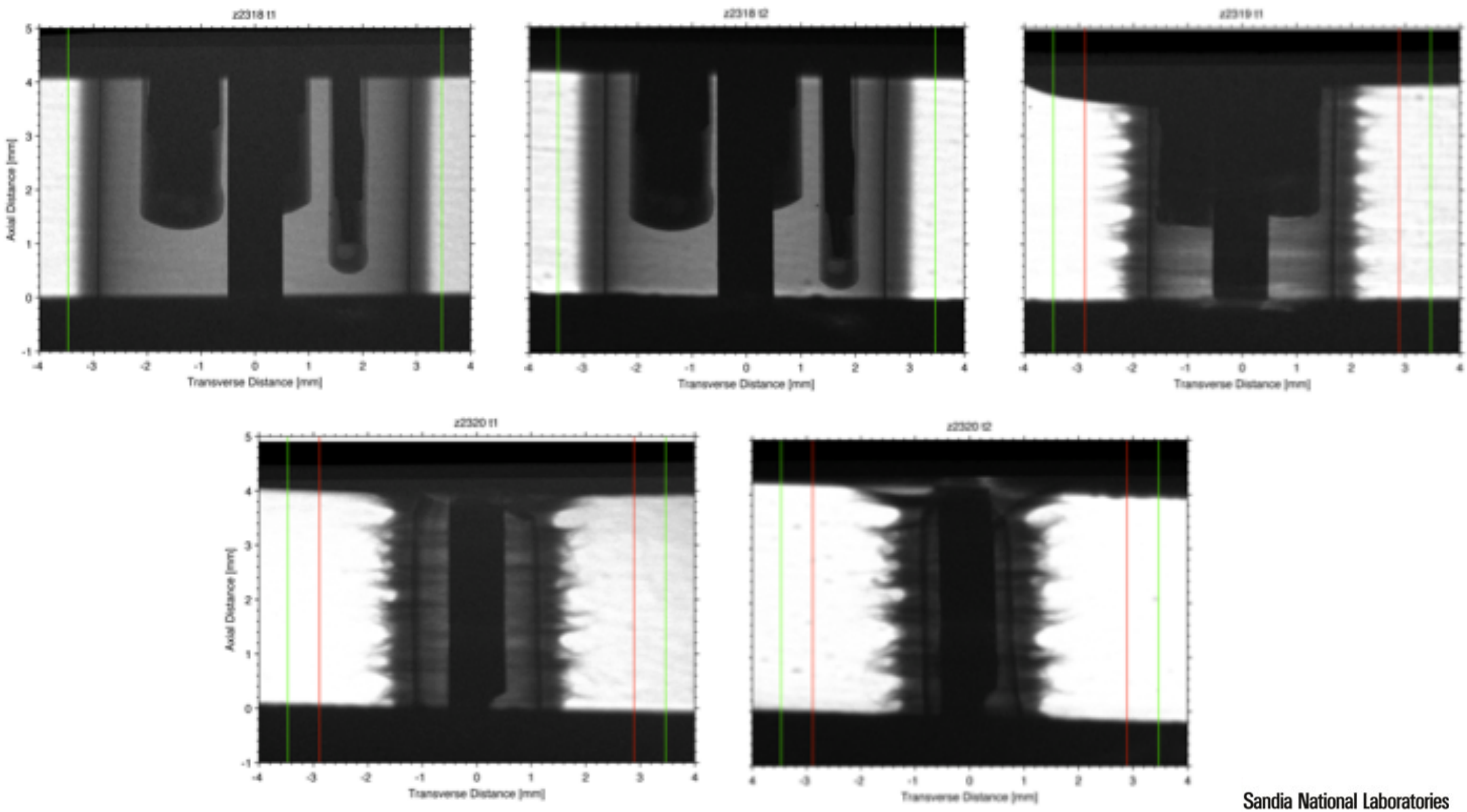


The inner surface of a thick *Be* liner is observable with 6 keV x-rays generated by the Z-Beamlet laser




axial displacement [mm]
transverse displacement [mm]
-4
-3
-2
-1
0
1
2
3
4
0.5
0.6
0.4
0.2

Recent studies examined a thin *Al* sleeve placed inside a *Be* liner to study the integrity of the inner surface



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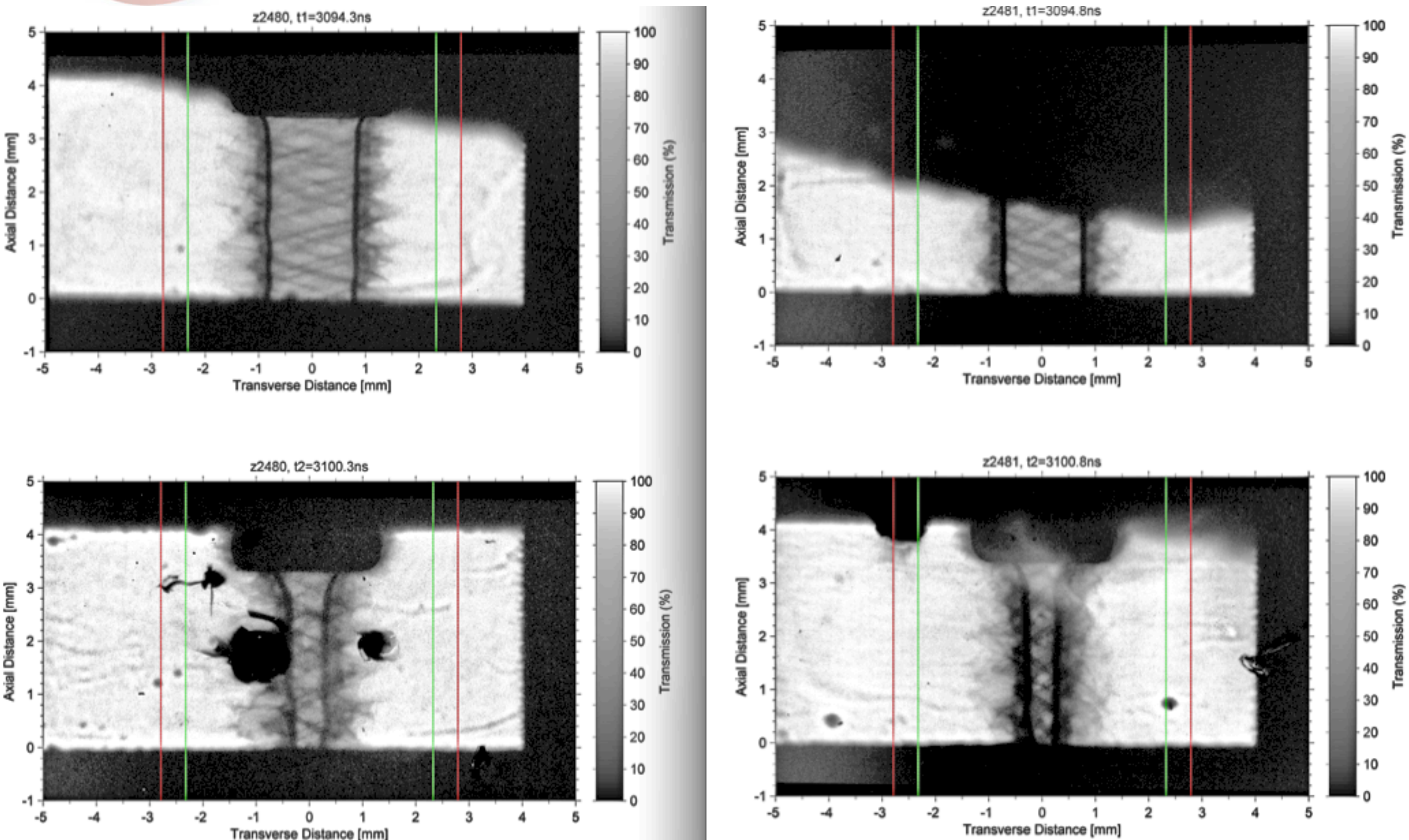
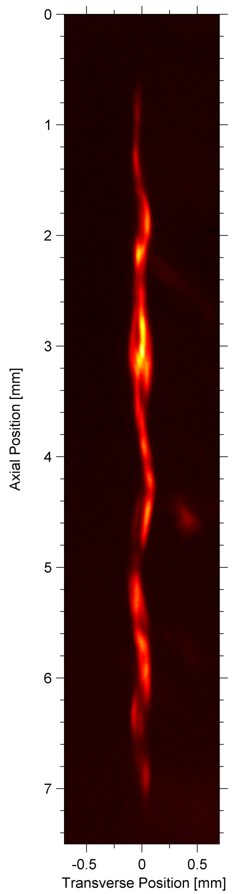
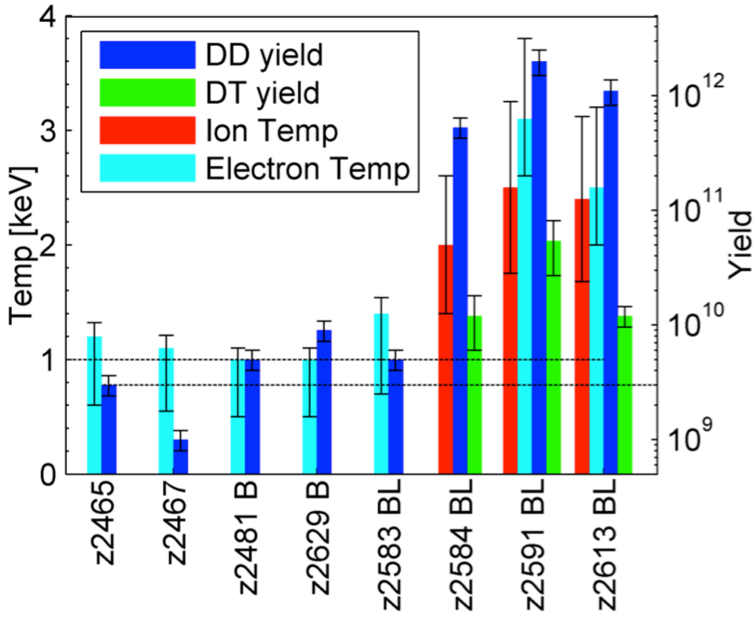
Recent experiments with B_z^0=7 T and 10 T, and I_{max}~17 MA, demonstrate excellent inner surface integrity at CR ~ 7

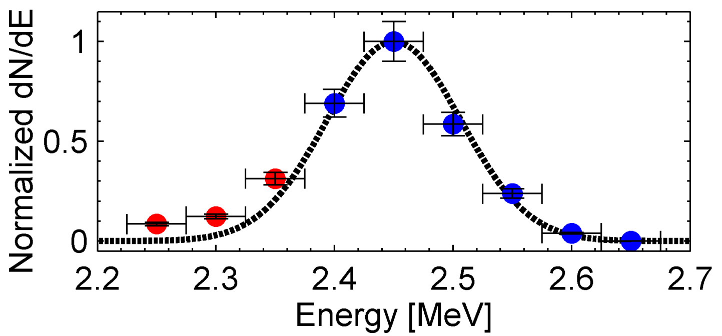


The first integrated MagLIF experiments successfully demonstrated the concept



- Thermonuclear DD neutron generation up to ~1e13 (~1e15 DT equivalent)
- Fusion-relevant stagnation temperatures
- Stable pinch with narrow emission column at stagnation
- Successful flux compression





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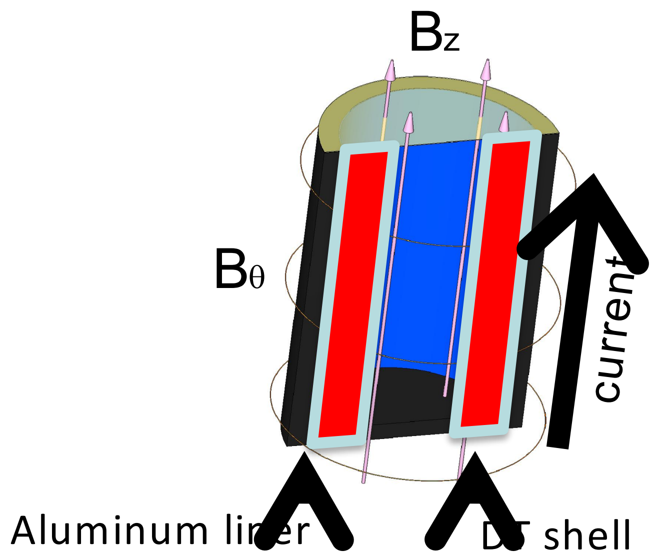
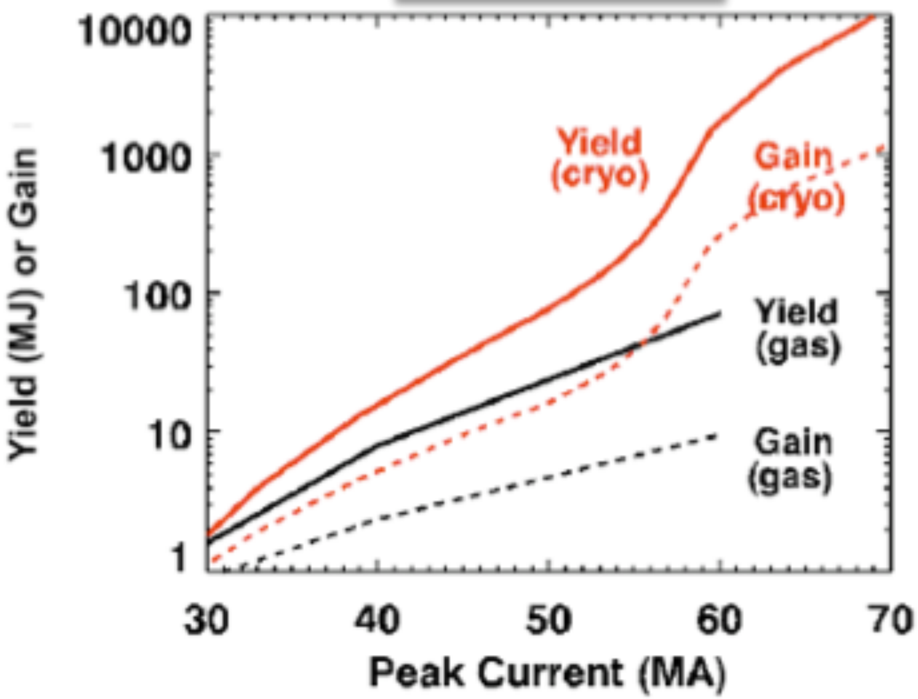
This was the first time slow implosions achieved such good performance!

Direct-magnetically-driven targets give high yields (>1 GJ) at 60 MA in simulations

Magnetized Cryogenic Levitated Shell



Yield and Gain



- Reduce difficulty of ignition and high yield
  - Large energies to target (> 1 MJ)
  - Magnetized fuel
  - Pre-heated fuel

S. A. Slutz *et al.*, *Phys. Plasmas*, 17, 056303 (2010).
S. A. Slutz, R. A. Vesey, *Phys. Rev. Lett.* 108, 025003 (2012)

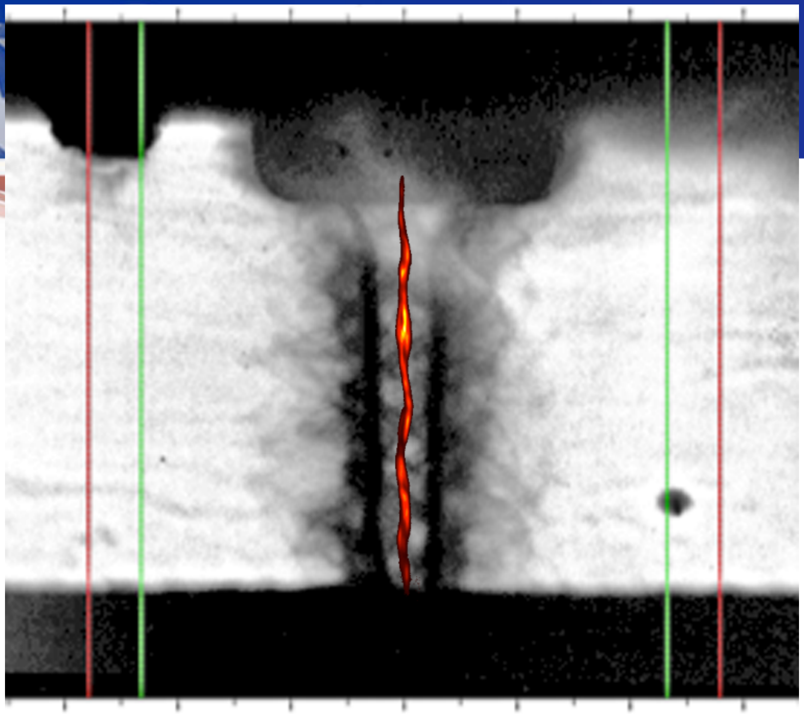
Large yields and low rep-rate may be an attractive path for Inertial Fusion Energy

The logic of the integrated system is compelling

- Compact, efficient, low cost, long-lifetime, repetitive driver
- Advanced, efficient, low cost, robust targets, that are simple to fabricate
- Large stored energies, efficient coupling
- $\Longrightarrow$ Very large absorbed target energies
- $\Longrightarrow$ Very large fusion yields
- $\Longrightarrow$ Allows low rep-rate using recyclable transmission lines (RTL)
- $\Longrightarrow$ RTL coupling is feasible, engineering development required
- $\Longrightarrow$ RTL allows thick-liquid-wall (TLW) and vaporizing blanket
- $\Longrightarrow$ TLW provides long lifetime chamber

Key enabling physics: **magnetically-driven-targets**
Key enabling technologies: **LTD's and RTL's, Fusion Engineering**

MagLIF Summary



MagLIF enables ICF yields
on pulsed-power accelerators
using slow < 100 km/s implosions

Integrated calculations provide realistic design requirements for MagLIF experiments, as well as predictions for improvements

Integrated experiments provided evidence for thermonuclear neutrons and magnetized fuel

Detailed comparisons between simulations and experimental results are excellent

There are many applications of pulsed power technology – we've only discussed some

(and there are more than just these….)

- Pulsed electric fields
  - Electroporation
  - Bacterial decontamination
  - Discharges through solids and liquids
- Pulsed magnetic fields
  - Equation of state measurements
  - High energy density physics
  - Ultra high field production
- High power beams
  - Electron beams
  - Ion beams
- Intense radiation sources
  - Laser flashlamps
  - Microwave generation
  - Z-pinch soft X-ray sources (< 5 keV)
  - Z-pinch warm x-ray sources (5-10 keV)
  - Hard X-ray sources (>100 keV)
- Pulsed power inertial confinement fusion
  - Indirect-drive wire arrays
    - Dynamic and double ended hohlraum
  - Direct-drive magnetically-driven implosions
    - Magnetized Liner Inertial Fusion
  - Liner stability experiments
  - Inertial Fusion Energy
    - High gain targets, linear transformer drivers, chambers, recyclable transmission lines
- Fundamental science
  - Laboratory astrophysics
  - Earth and planetary Sciences

Summary

- **Large currents** create large magnetic fields, and large magnetic fields **create large pressures**, which are needed to access high energy density regimes

- Pulsed power can inexpensively, efficiently, and flexibly drive many different kinds of experiments at **large currents** and high voltages

- The Z machine creates large currents (and is the world's largest x-ray source), allowing us to address fundamental issues in HED science, laboratory astrophysics, and inertial fusion energy

- Lasers have more control than Z-pinches regarding "where", "how", and "how long" energy is deposited.

  However, Z-pinches are **much cheaper** and **more efficient** than lasers, and so provide an attractive option for inertial fusion energy

- **The upper limits on Z-pinch performance in achieving high energy densities are not known.**

  There is a lot of room for innovation! (esp. direct drive concepts for fusion)

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  - "Inertial Confinement Fusion" by J.D. Lindl, Springer Verlag, NY (1998) ; Phys. Plasmas 2, 3933 (1995)
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