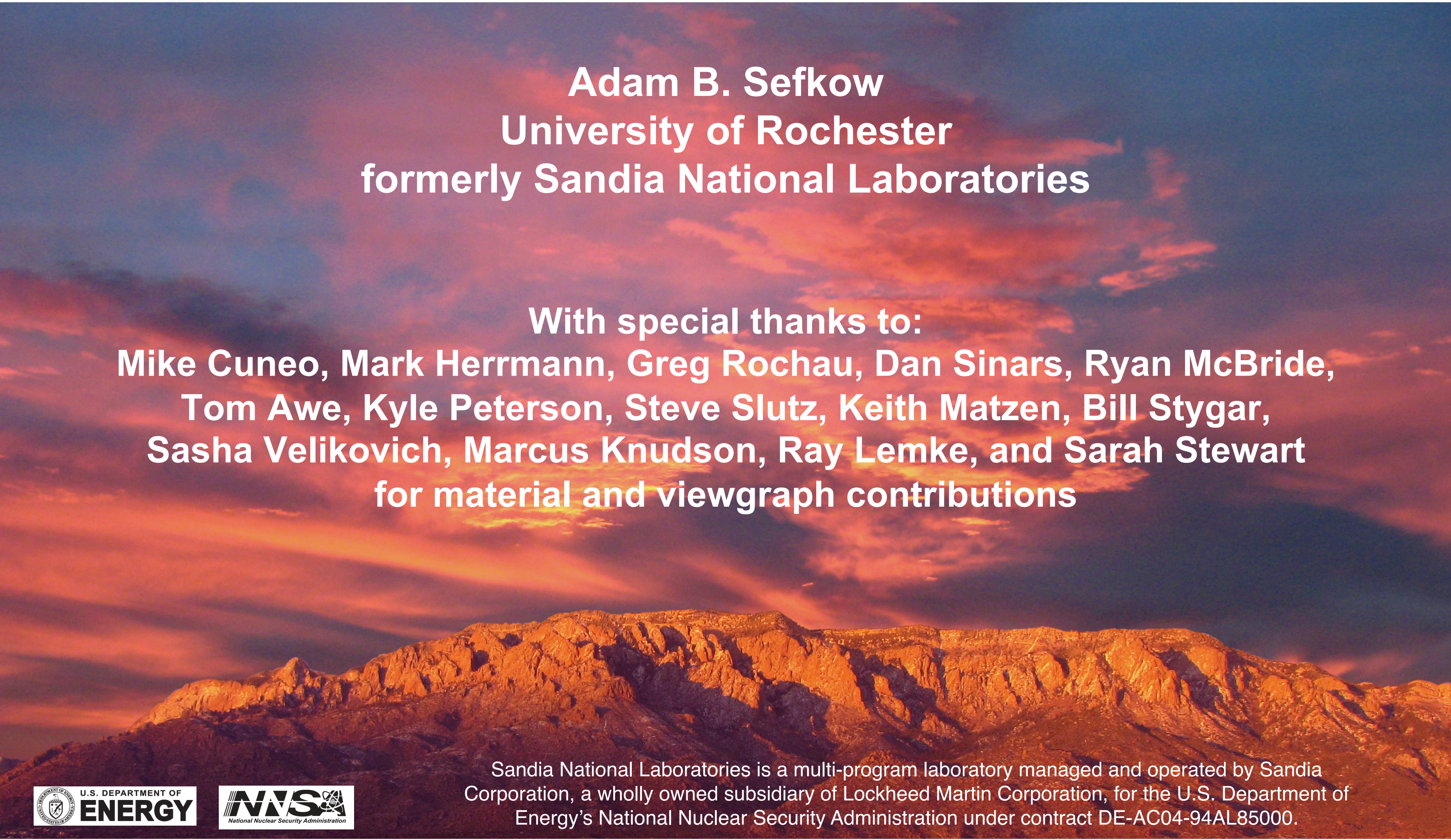
Pulsed power, Z-pinches, and Applications



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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

Outline

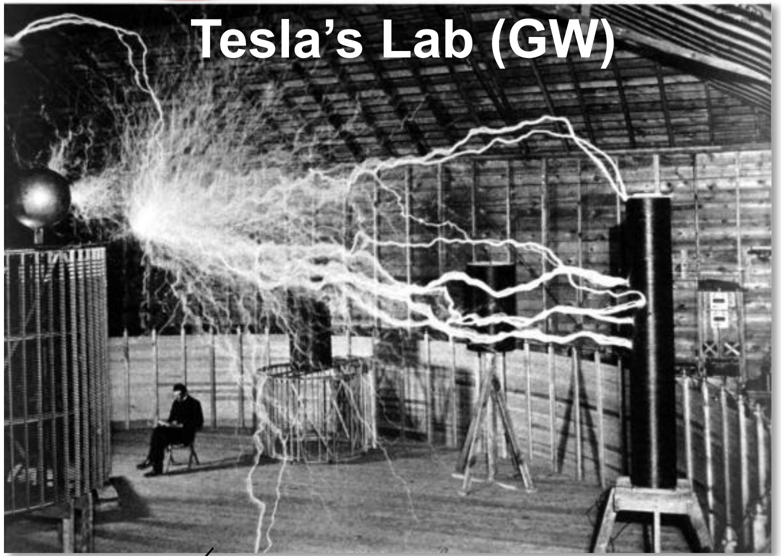
- Pulsed-power technology produces large currents (15-27 MA) in a short pulse (100-600 ns) on the Z machine

- Large currents generate large magnetic fields
  = tremendous pressure

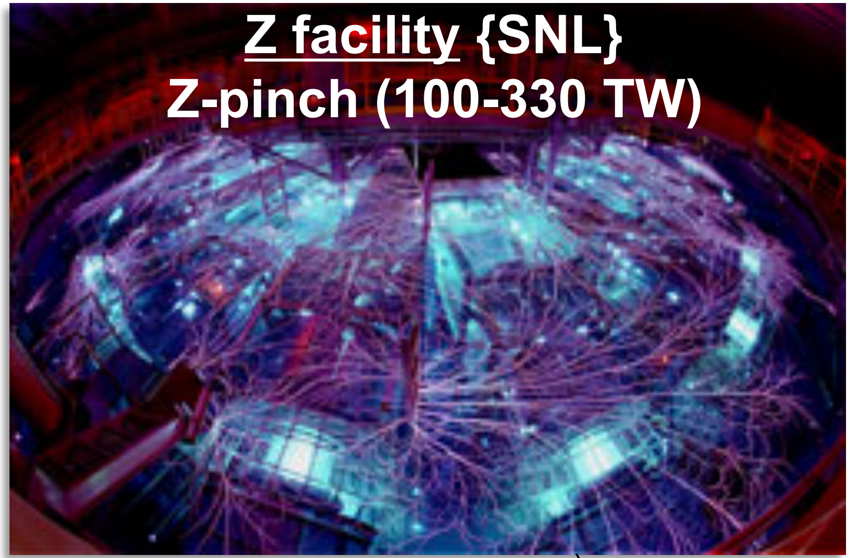
- Large pressures enable access to
  High Energy Density regimes (> ~10^{11} J m^{-3}, or > ~1 Mbar)

- There are many interesting applications

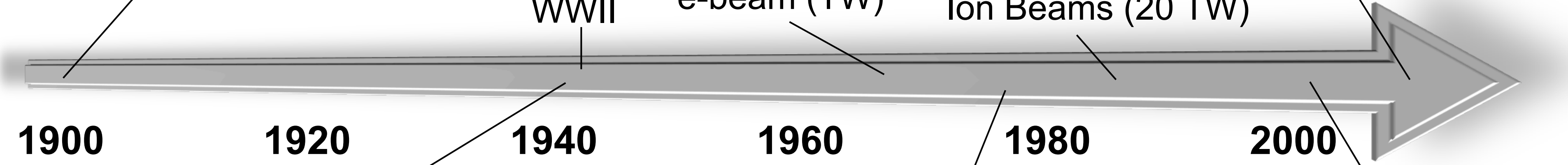
The accumulation and transmission of electromagnetic energy, called “pulsed power”, has been investigated for over a century



Tesla’s Lab (GW)



Z facility {SNL}
Z-pinch (100-330 TW)



WWII

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

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

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

Angara - II {Russia}
Simulator (TW)

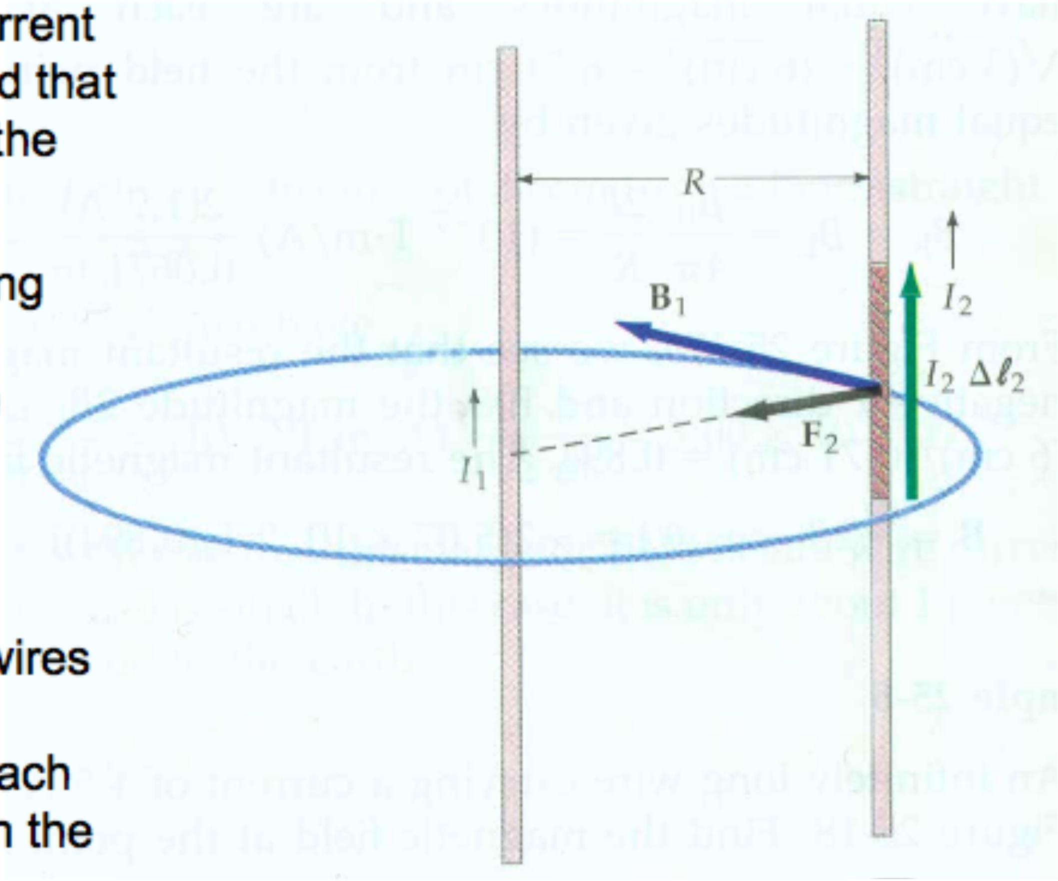
DARHT {LANL}
Radiography (10 GW)

1st 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

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

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

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

In the case of an axisymmetric z-directed current (B_θ 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

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

HED Matter P > 1 Mbar, B > 5 Megagauss

<u>Magnetic fields have some unique advantages when creating HED plasmas:</u>

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

<u>Magnetic fields have interesting contrasts with other ways of generating HED:</u>

- 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

<u>Magnetic fields change the way particles and energy are transported in a plasma</u>

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

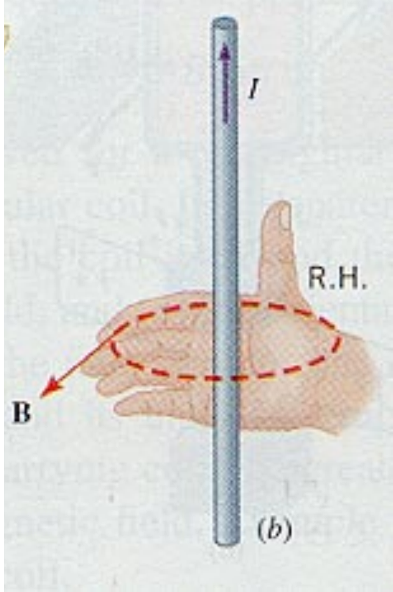
A 5000 G (0.5 T) magnetic field ~ 10^6 dyne/cm^2 ~ 1 atmosphere ~ 1 Bar

A 5×10^6 G (500 T) magnetic field ~ 1 Million atmospheres = 1 Megabar (MB)= High energy density physics (“HEDP”)

A 5×10^9 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 5×10^5-1.5×10^6 G

Large currents can create large B fields!



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

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

For an axial current I:

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

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

100 A at 2 mm radius is 100 G

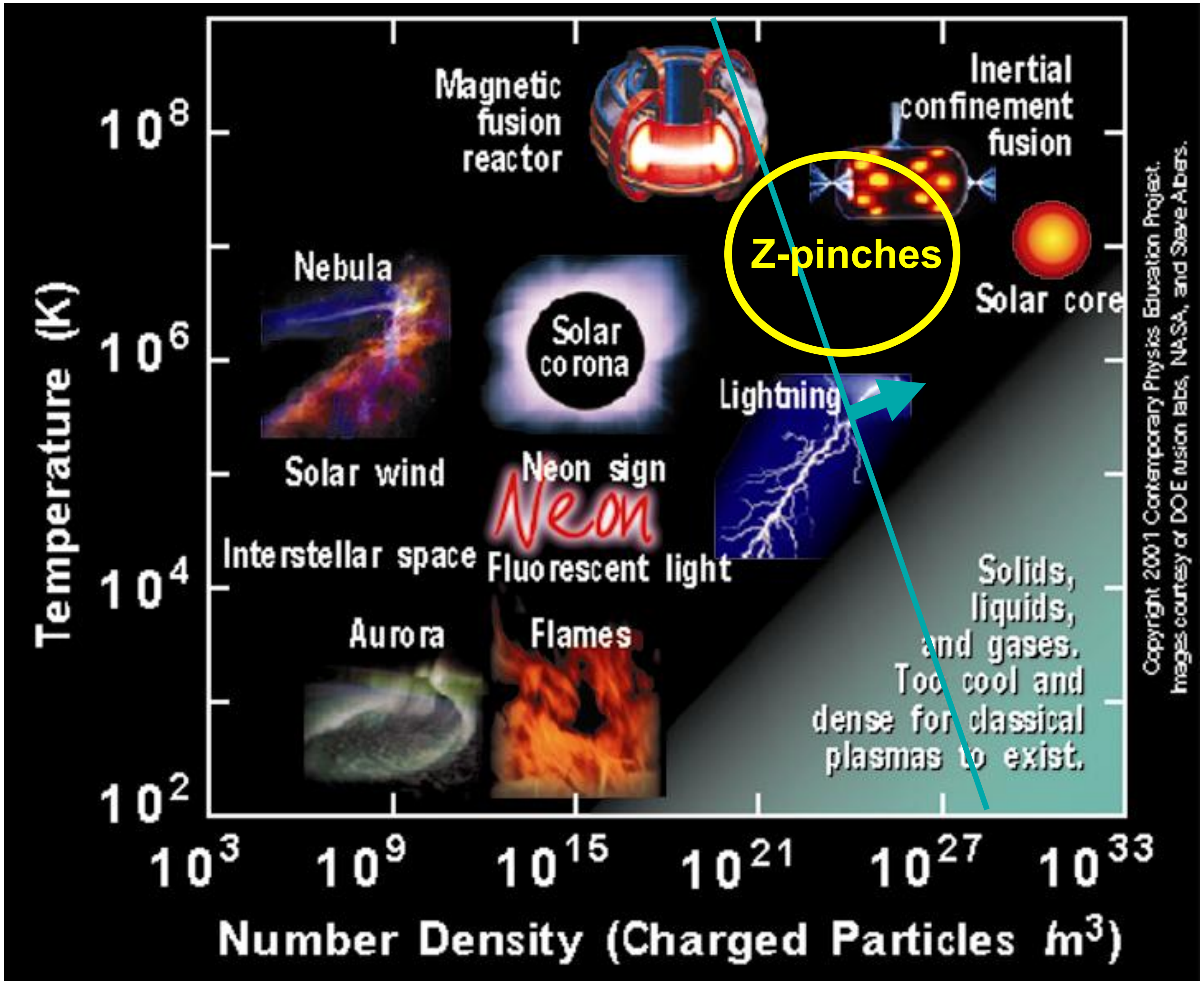
1.0x10^7 A (**10 MA**) at **4 mm** radius is 5x10^6 G = **1 MBar** of pressure!

2.5x10^7 A (**25 MA**) at **1 mm** radius is 5x10^7 G = **100 MBar** of pressure!! **←Z Machine**

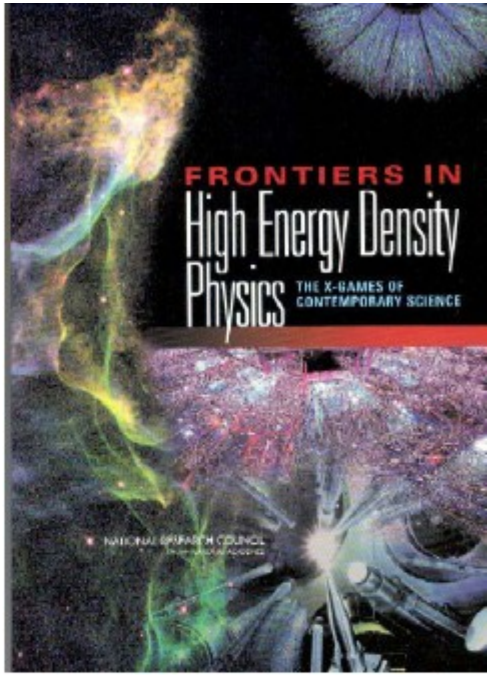
(~1000x more than high explosives)

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

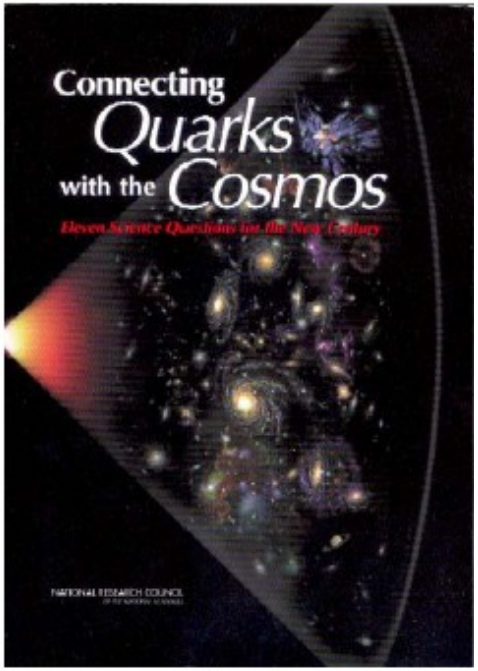


Several recent studies have highlighted High Energy Density Science



FRONTIERS IN
High Energy Density Physics
THE X-GAMES OF CONTEMPORARY SCIENCE

NATIONAL RESEARCH COUNCIL



Connecting
Quarks
with the Cosmos
Eleven Science Questions for the New Century

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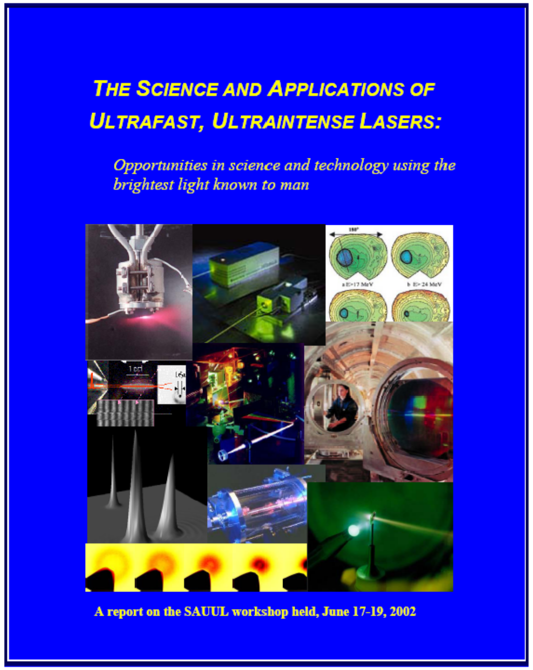


THE SCIENCE AND APPLICATIONS OF
ULTRAFAST, ULTRAINTENSE LASERS:

Opportunities in science and technology using the brightest light known to man

A report on the SAUUL workshop held, June 17-19, 2002

“Frontiers in High Energy Density Physics”, R. Davidson et al. 2004

“Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century”, M Turner et al. 2002

Science and Applications of Ultrafast, Ultraintense Lasers

Sandia National Laboratories

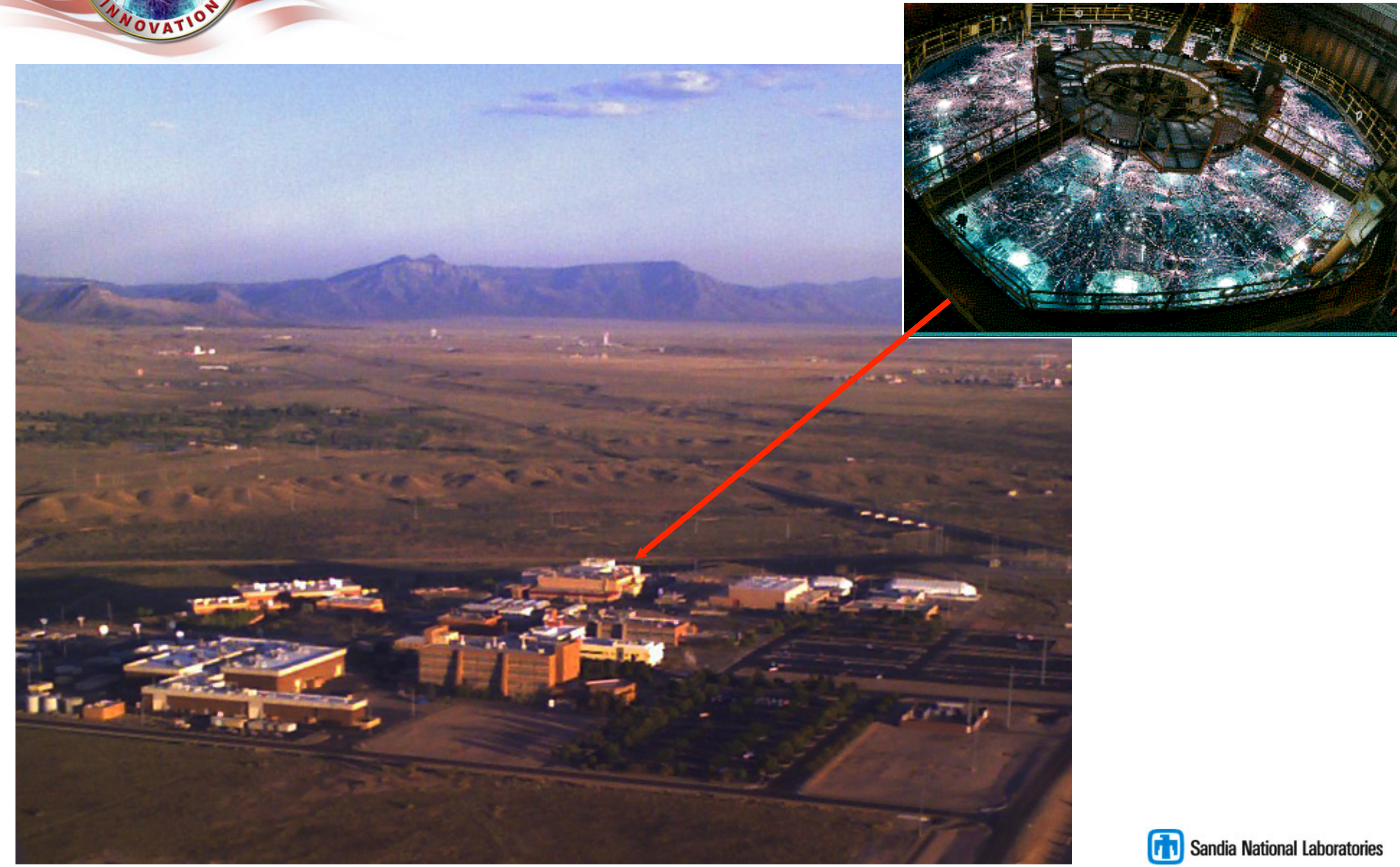
Scales of energy density

- 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)

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

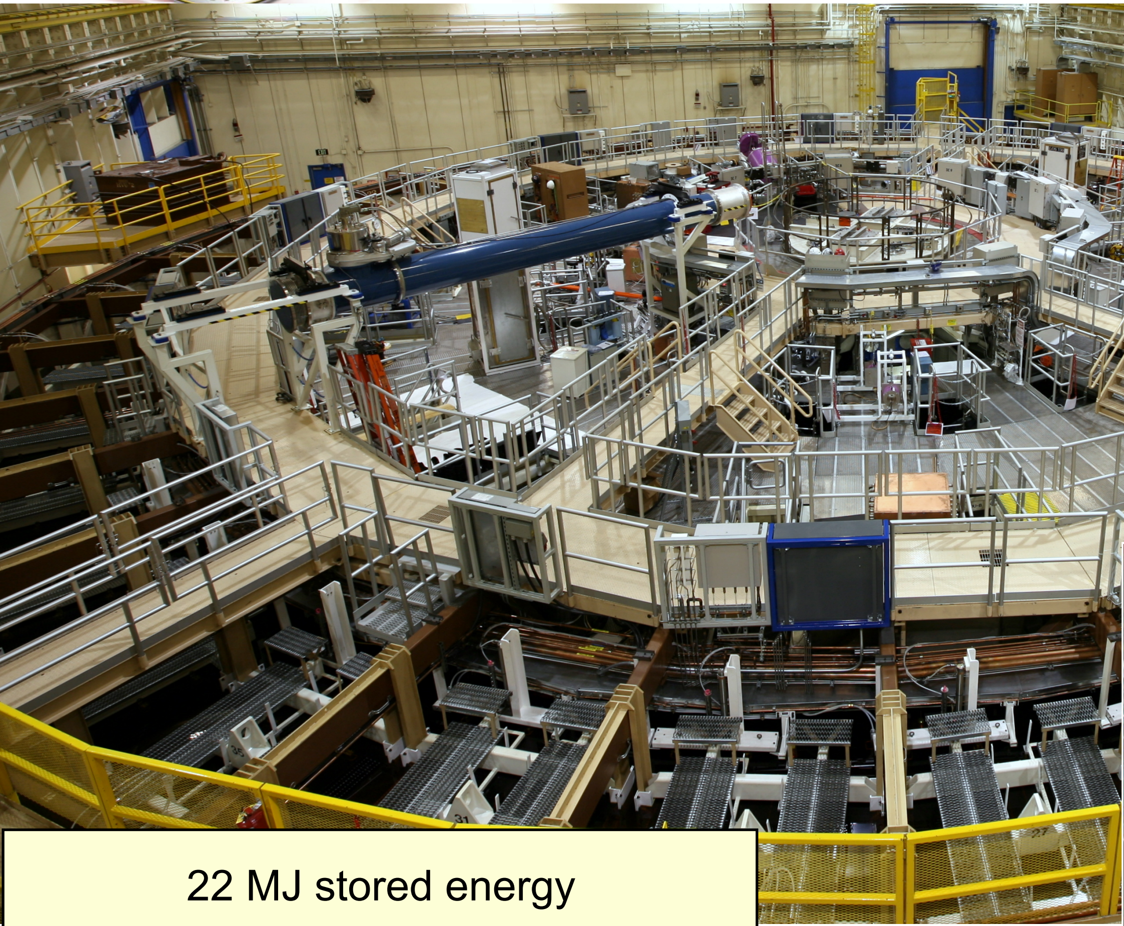
Youtube.com: search for the BBC TV show:
“*Horizon: Can we make a star on earth*?”

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



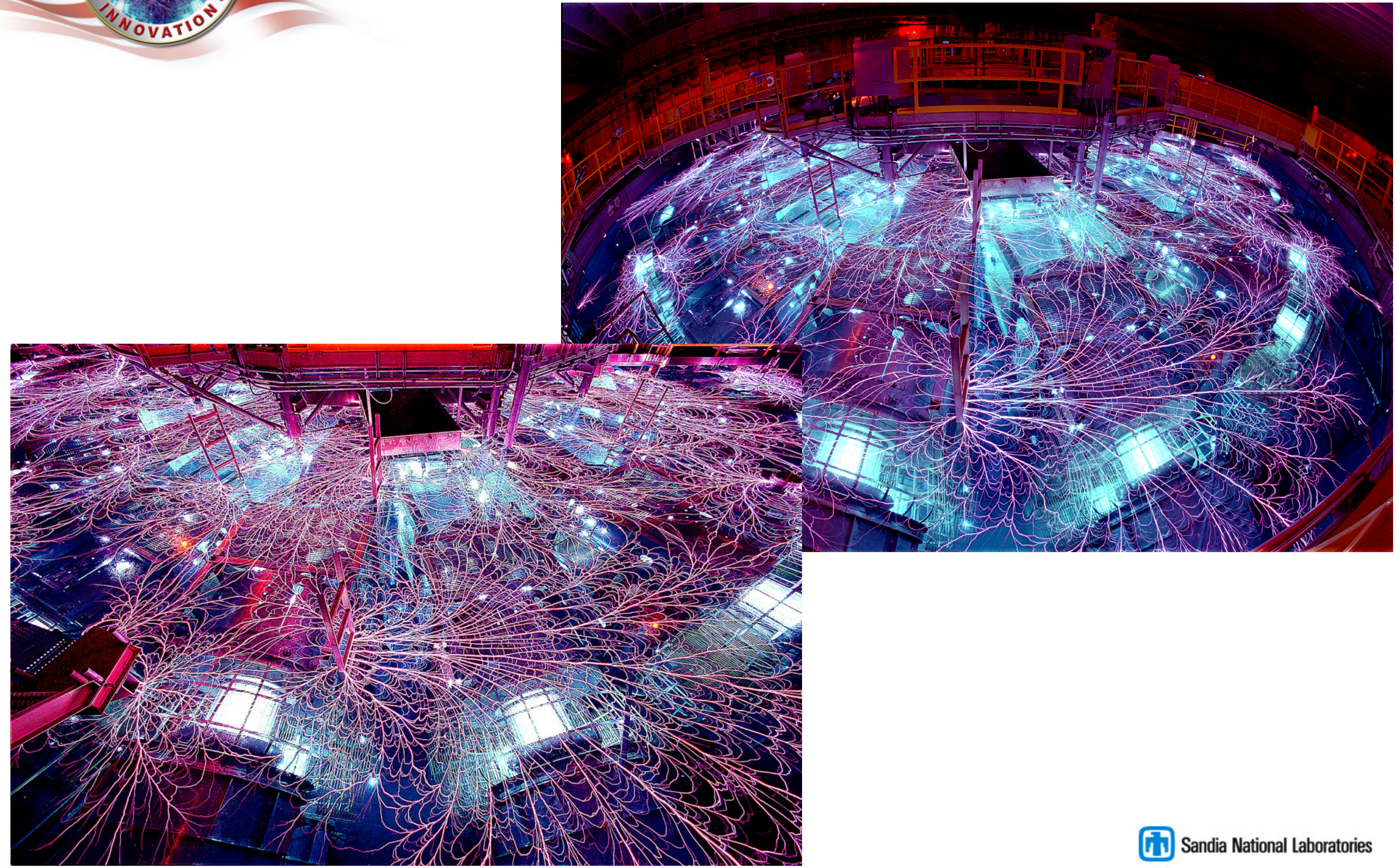
“Z” is the world’s largest pulsed-power facility

Tank~10,000 ft^2

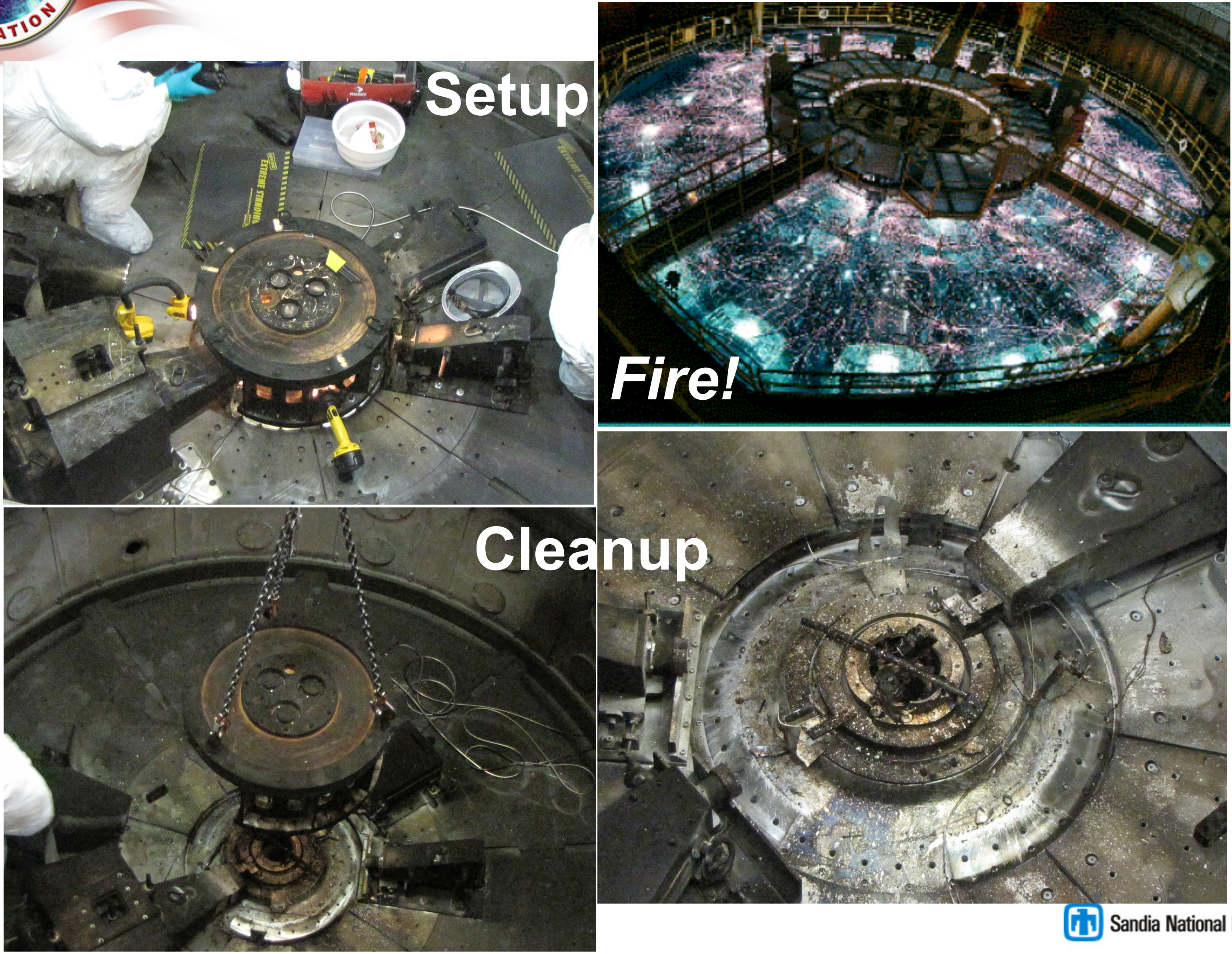


22 MJ stored energy
3MJ delivered to the load
27 MA peak current
5 – 50 Megagauss (1-100 Megabar)
100-600 ns pulse length

“Z” is the world’s largest pulsed-power facility



“Z” is a great place to conduct experiments

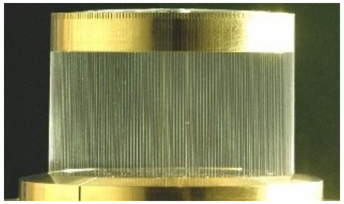


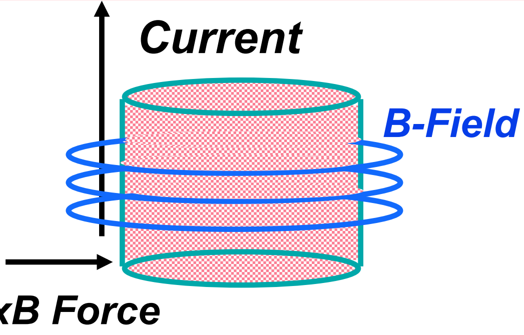
We can use high currents to push plasmas in different ways for different experiments

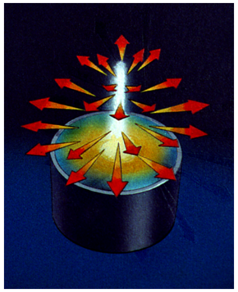
High Current

Cylindrical compression: Z-pinch x-ray source

wire array

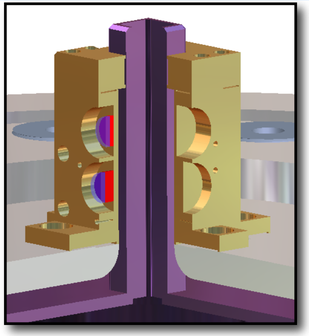






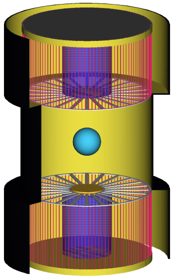
Produces intense x-ray sources:
~ few ns timescale, > 1 MJ energy, > 100 TW power

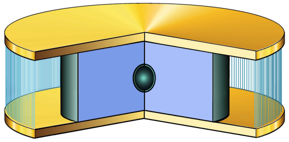
Planar magnetic pressure



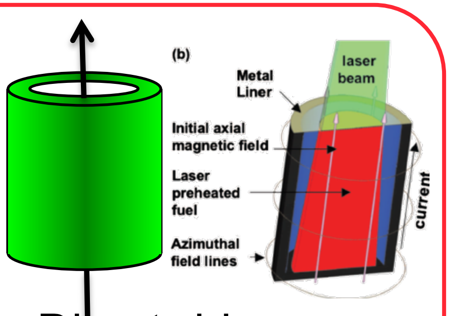
"ICE" and "flyer" plates: Accurately measure material properties, e.g. "Equation of State" *(how P relates to ρ and T in the fluid formalism)*

Inertial Confinement Fusion (ICF)

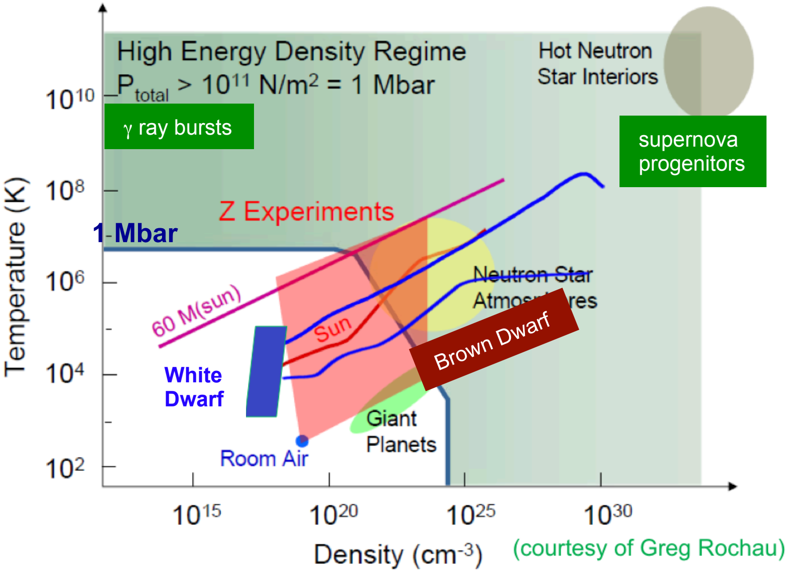




Indirect-drive
(x-rays)



Direct-drive
(magnetic field)



(courtesy of Greg Rochau)

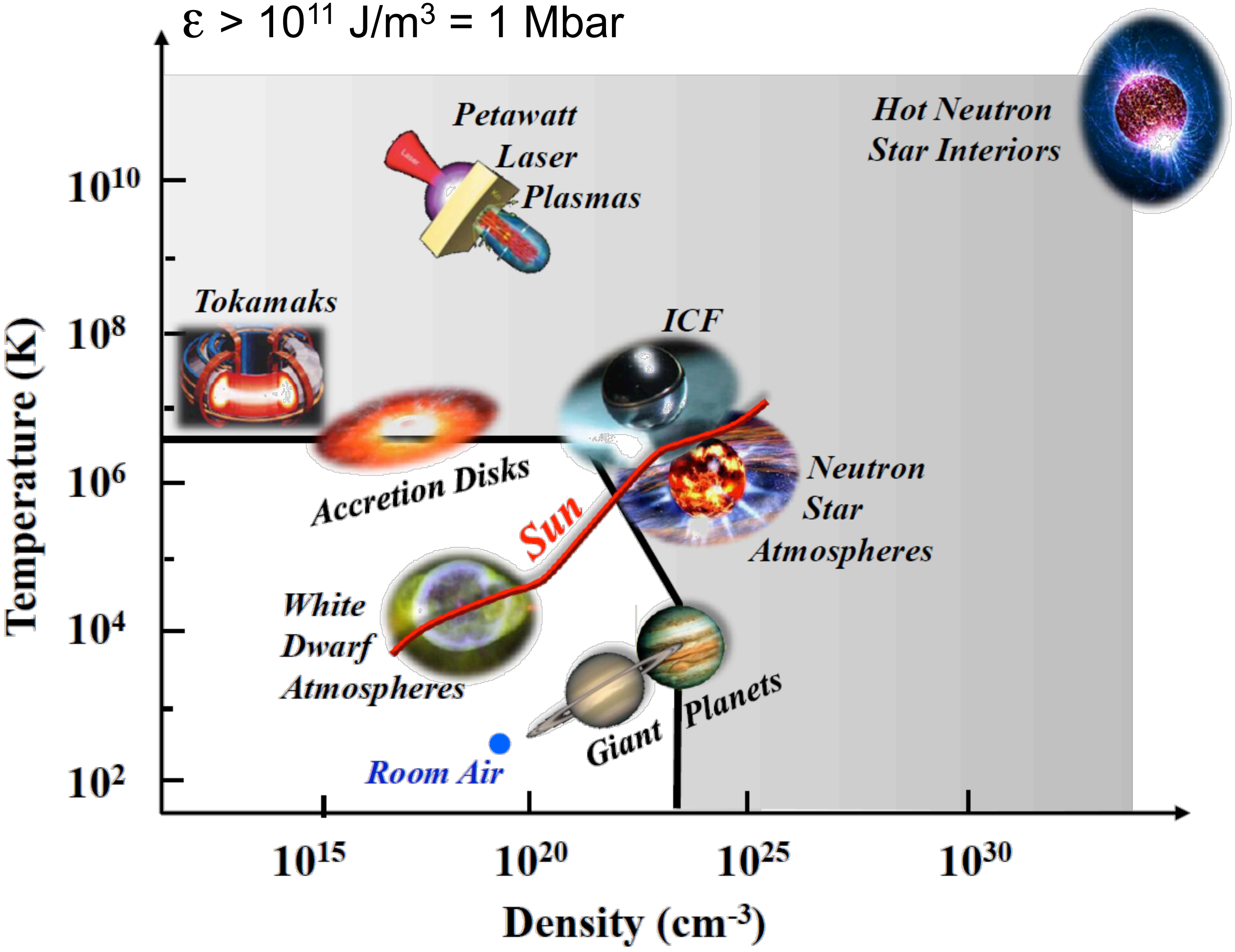
Our experiments are well-diagnosed

- 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



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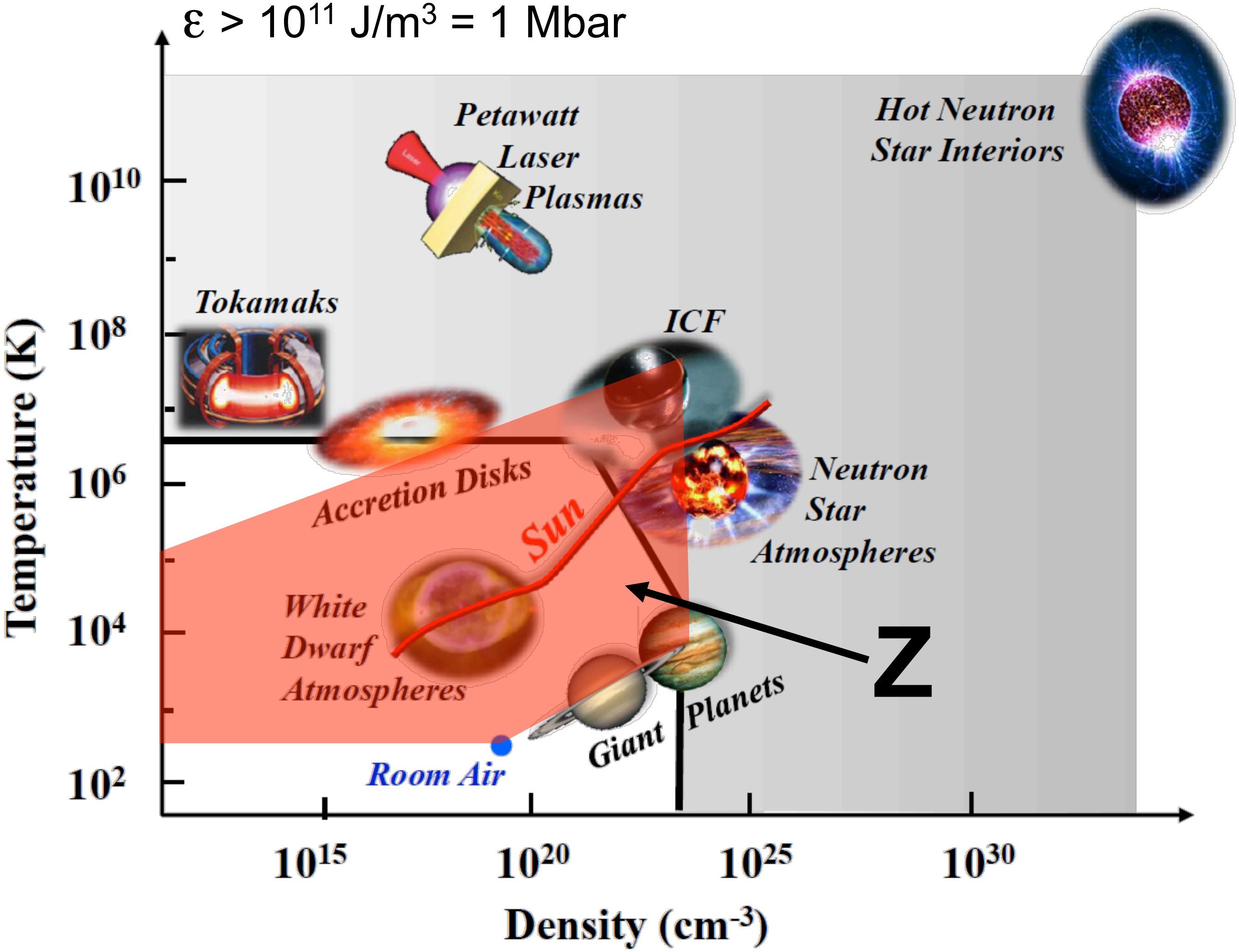
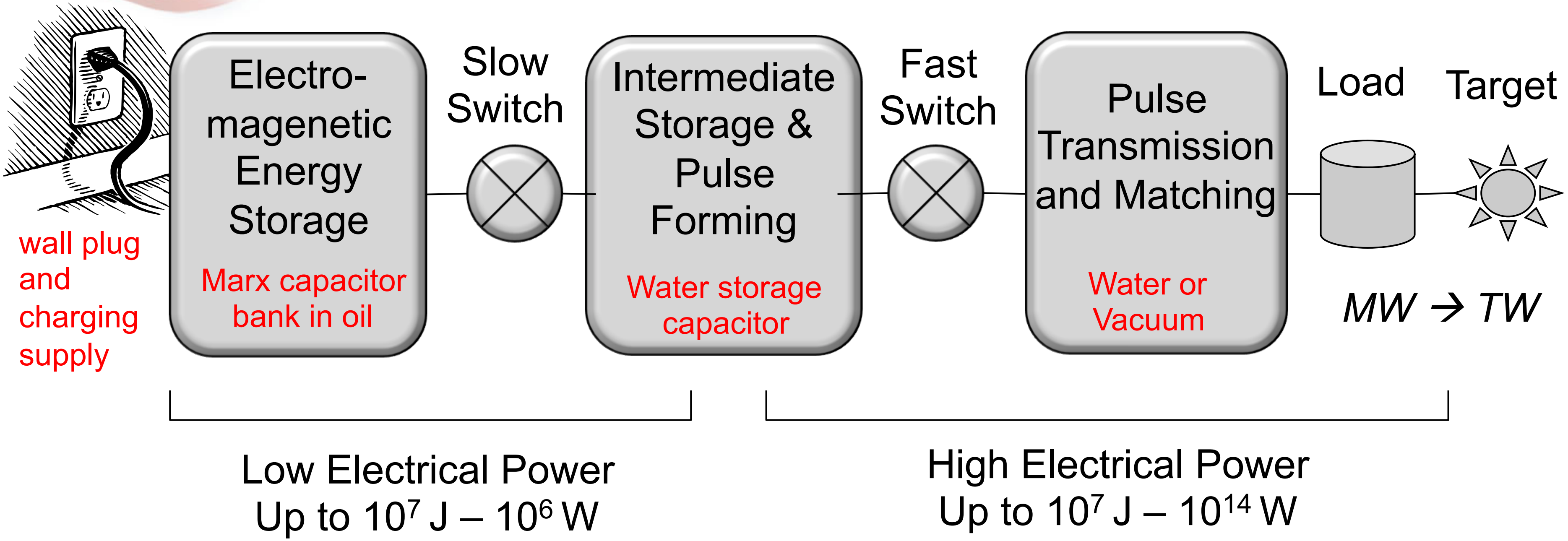


Pulsed-power technology produces high electrical power using fast switching and pulse compression



wall plug and charging supply

Electro-magenetic Energy Storage

Marx capacitor bank in oil

Slow Switch

Intermediate Storage & Pulse Forming

Water storage capacitor

Fast Switch

Pulse Transmission and Matching

Water or Vacuum

Load

Target

MW → TW

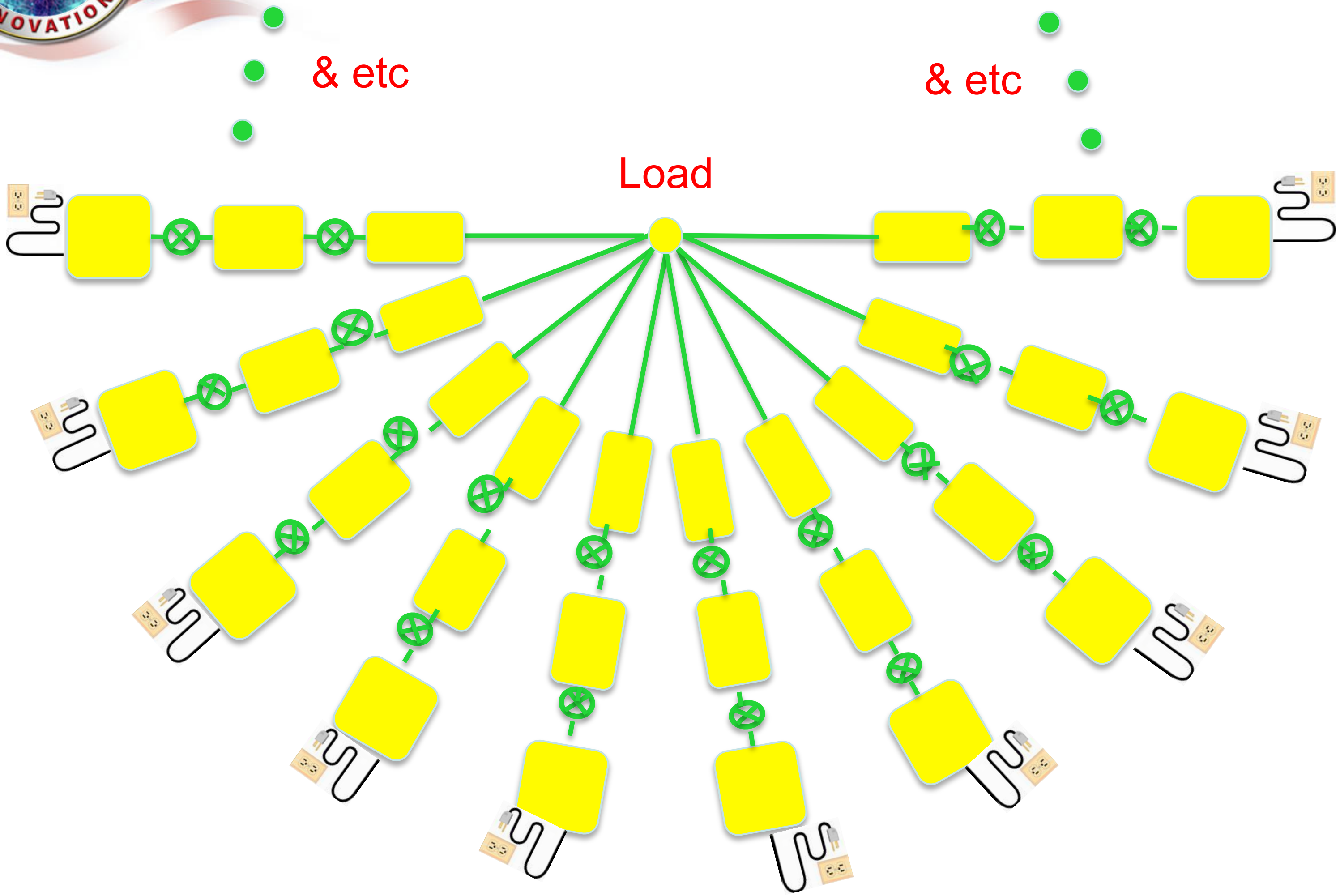
Low Electrical Power
Up to 10^7 J – 10^6 W

High Electrical Power
Up to 10^7 J – 10^{14} W

- 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

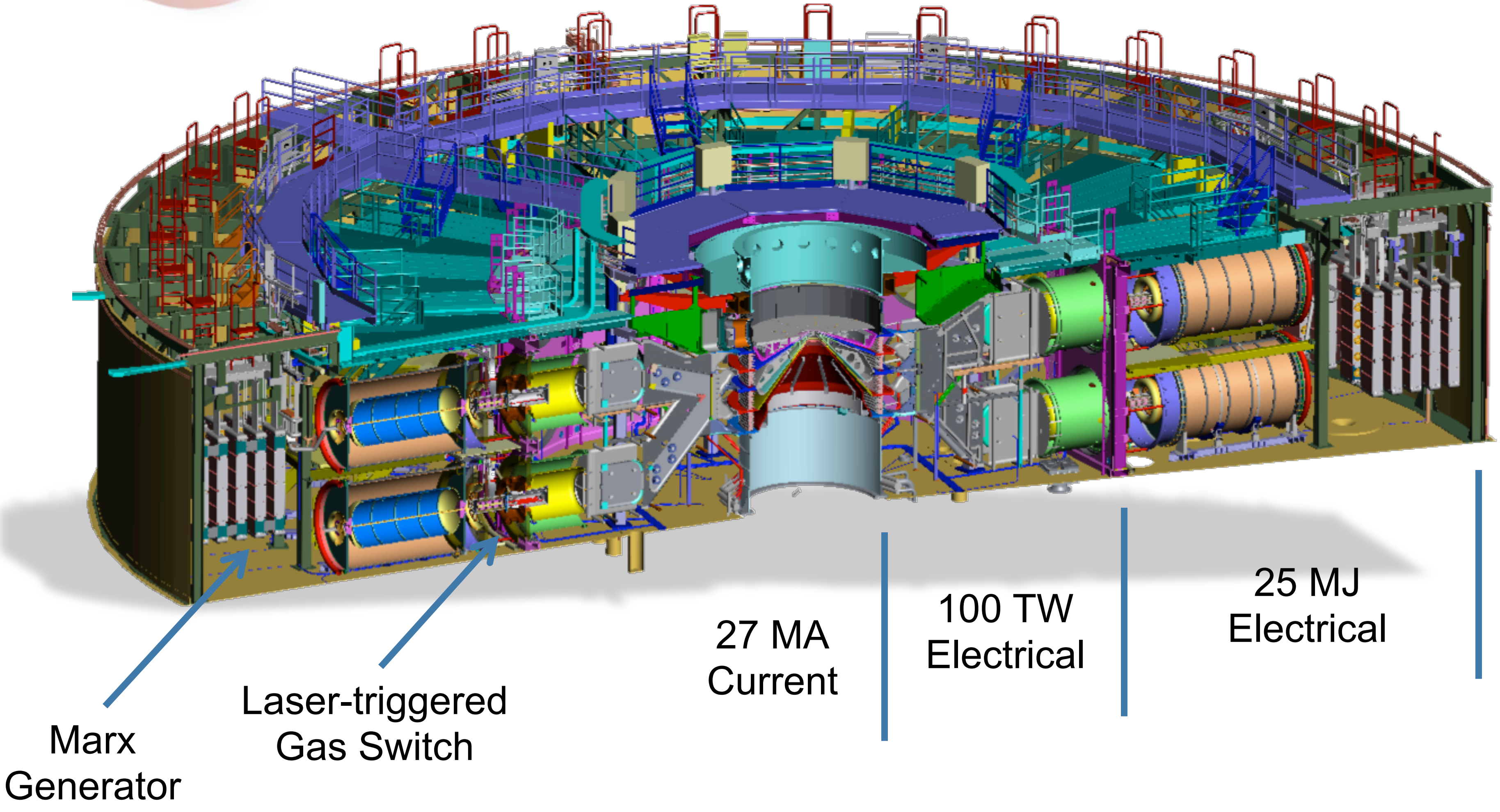
  (whose load is destroyed with each shot)

Multiple modules are used to achieve the highest powers

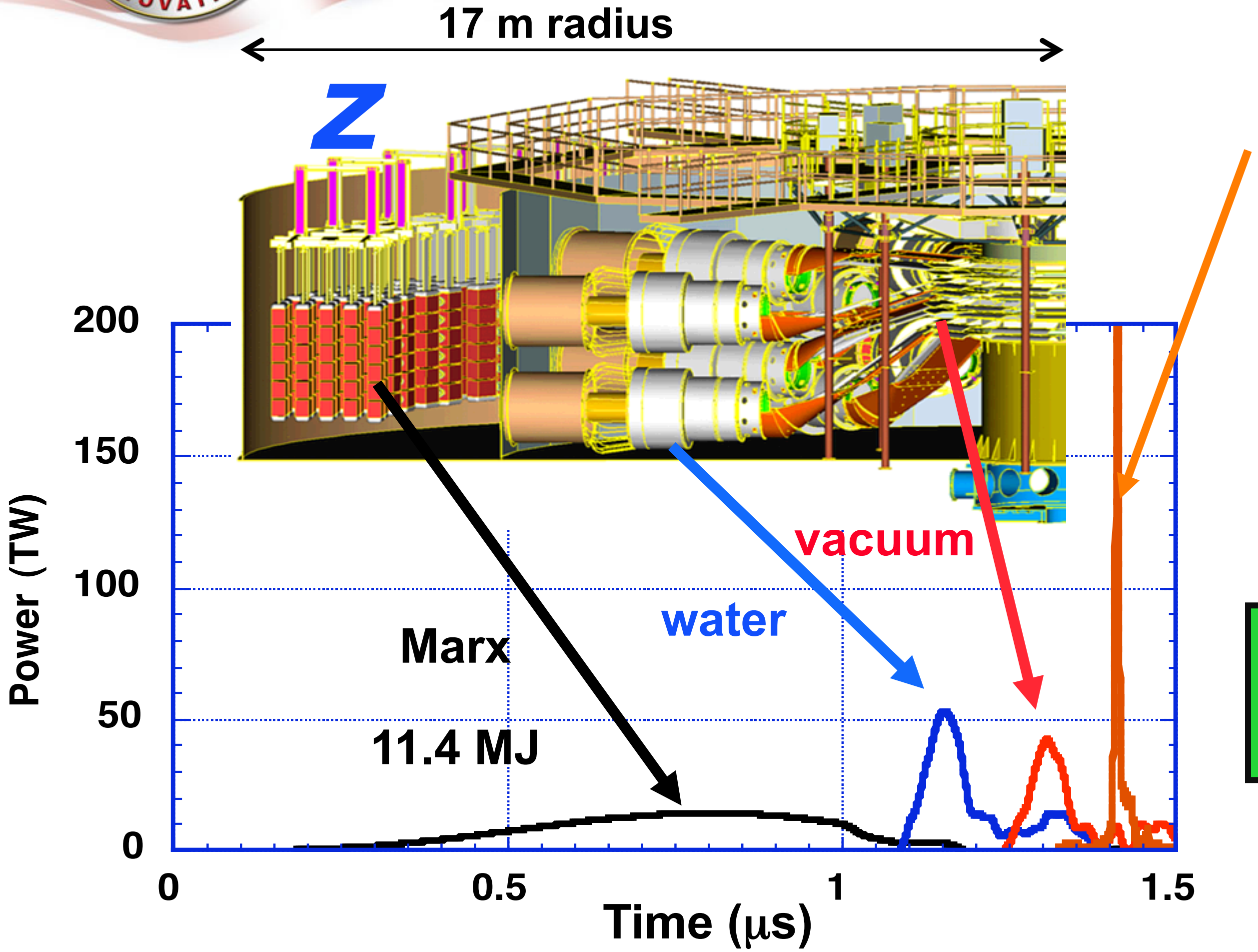


- Laser-triggered gas switches are used to synchronize the pulses (to within a few ns) from the individual modules

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 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

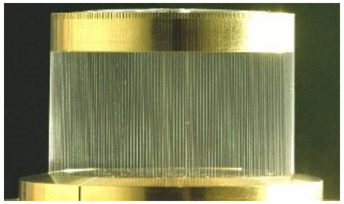
  - Total power density compression factor ~8×10^{15}
  - (η x area x time, η~0.4)

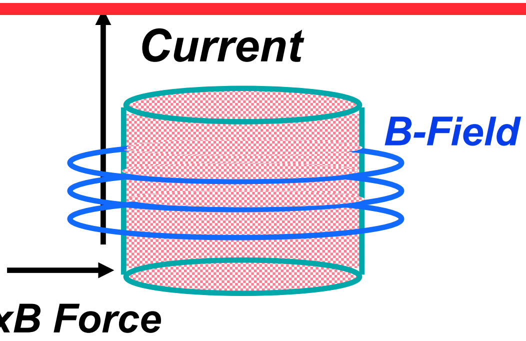
We can use high currents to push plasmas in different ways for different applications

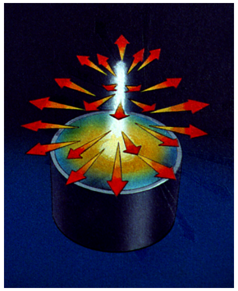
High Current

Z-pinch X-ray sources

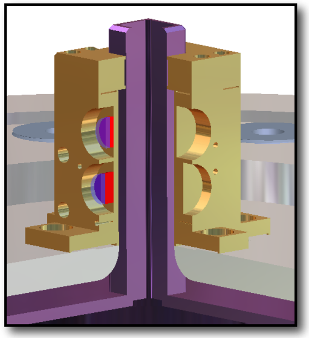
wire array



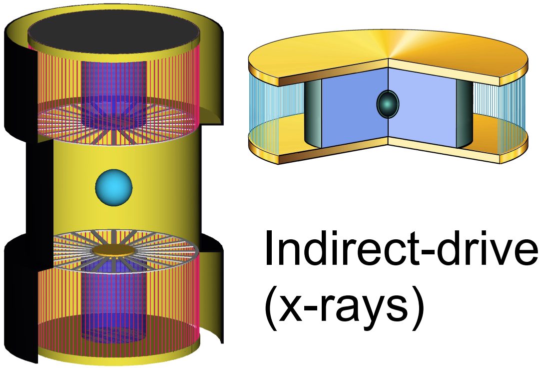




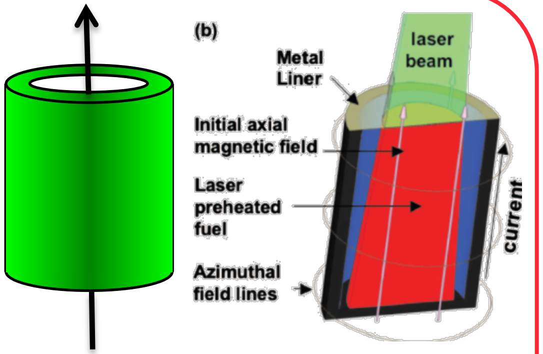
Planar magnetic pressure



Inertial Confinement Fusion (ICF)

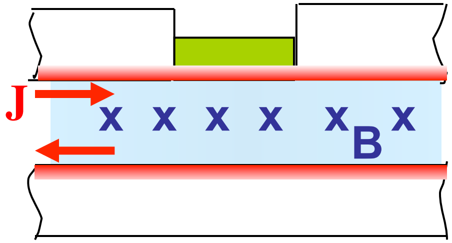


Indirect-drive (x-rays)



Direct-drive (magnetic field)

Material Properties

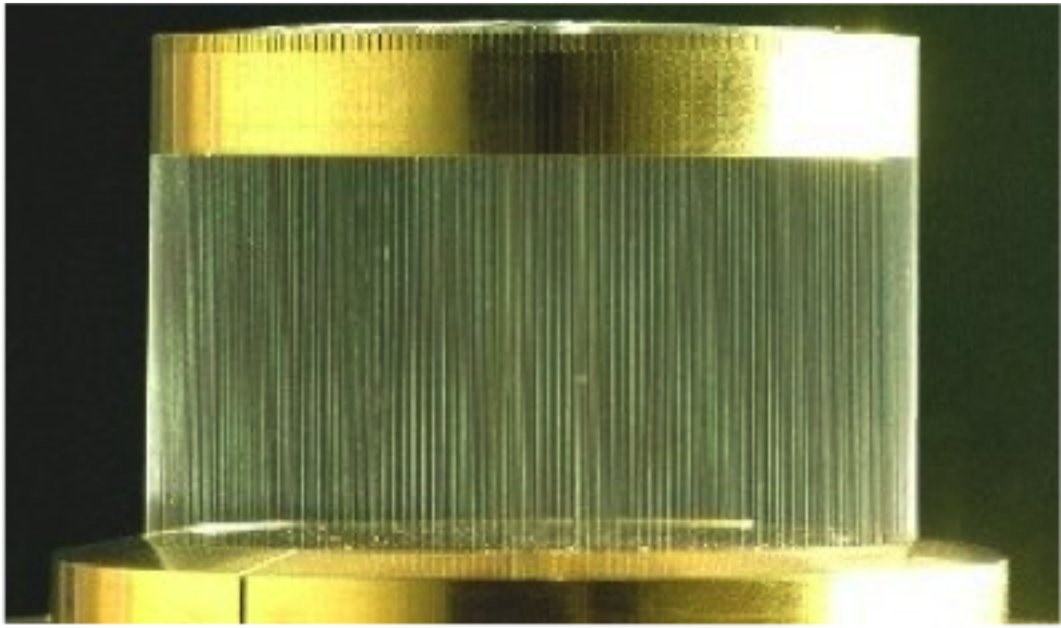


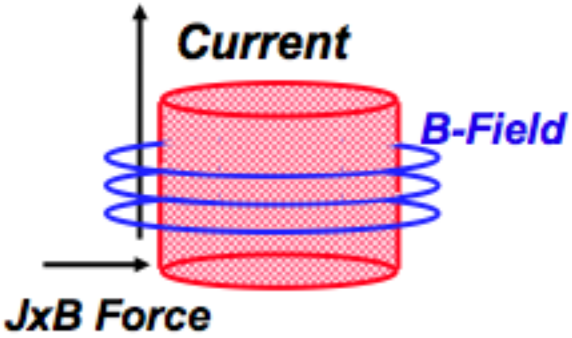
Wire arrays are a “simple” extension of the two wire problem

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

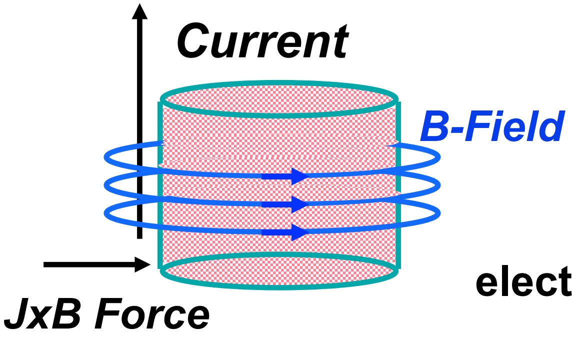




Z-pinch loads:

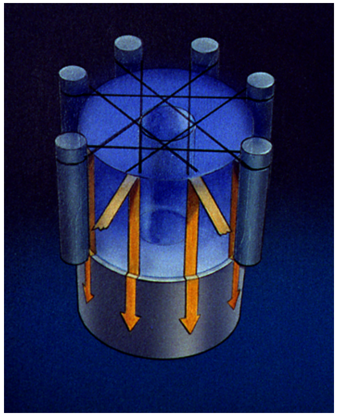
Wire Array
Gas Puffs
Foil/Liner
Foam

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

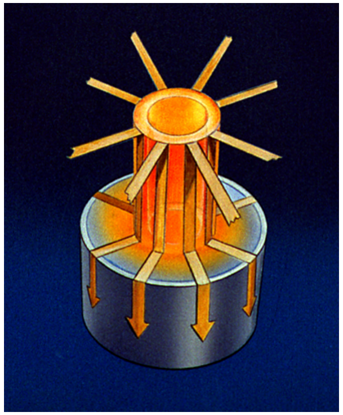


electrical energy
↓
kinetic energy

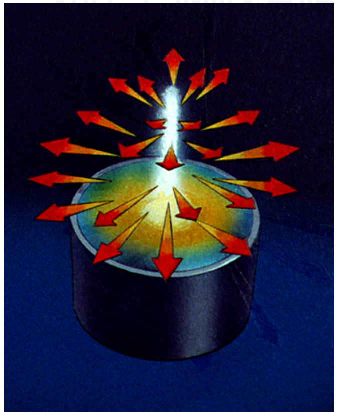
kinetic and magnetic energy
↓
internal energy
↓
x rays



Ablation



Implosion

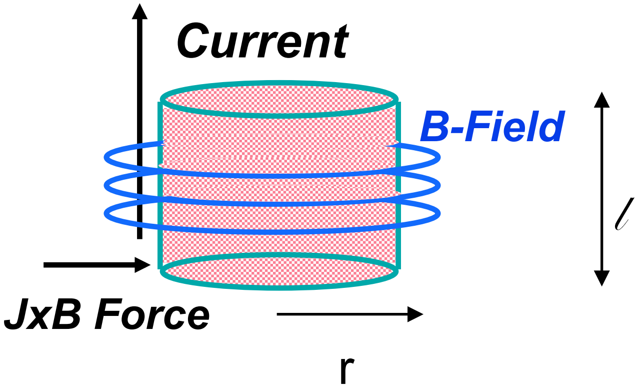


Stagnation

<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

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

$$ma = F$$

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

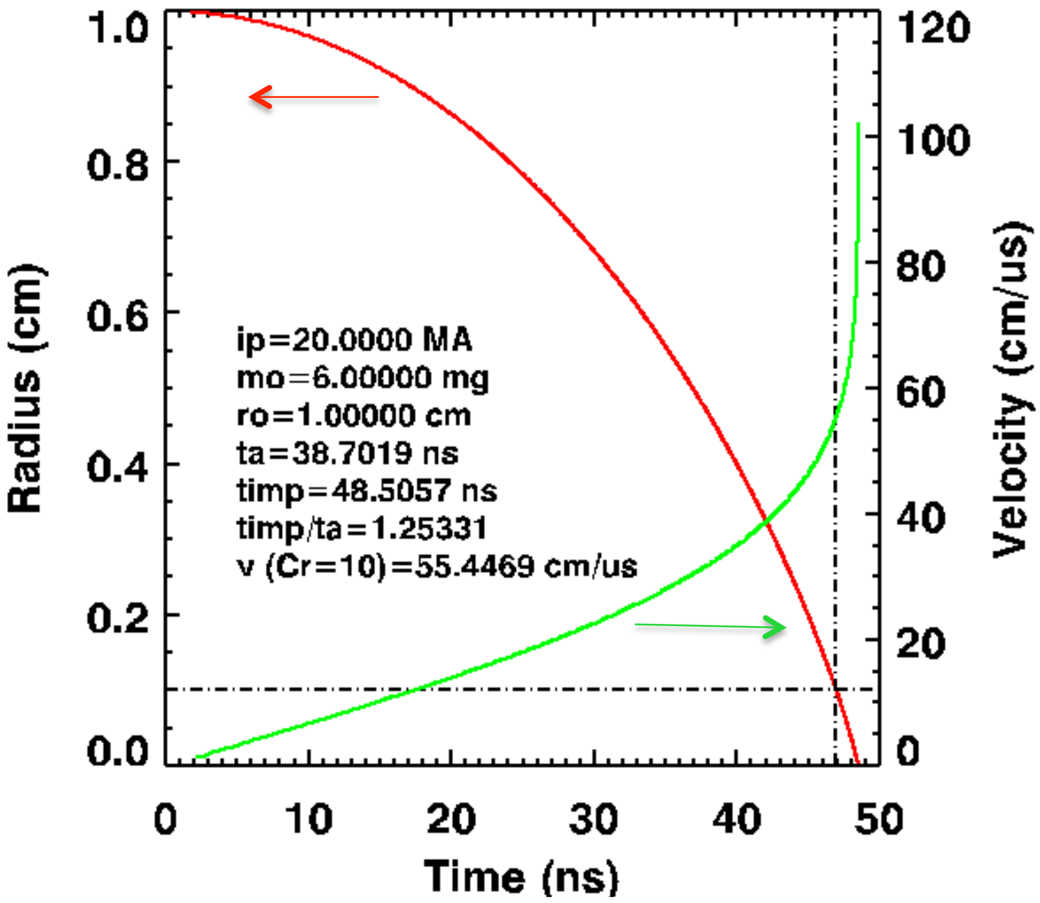
$$P = \frac{B^2}{2\mu_o} \sim \left(\frac{I}{r(t)}\right)^2$$

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

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

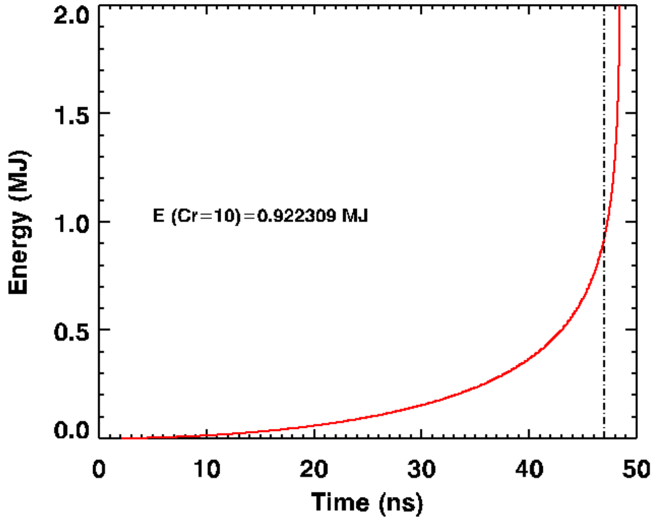
We can integrate this equation to get the kinetic energy given to the imploding shell

The analytic solution with **I ~ constant** shows rising magnetic pressure accelerates the pinch

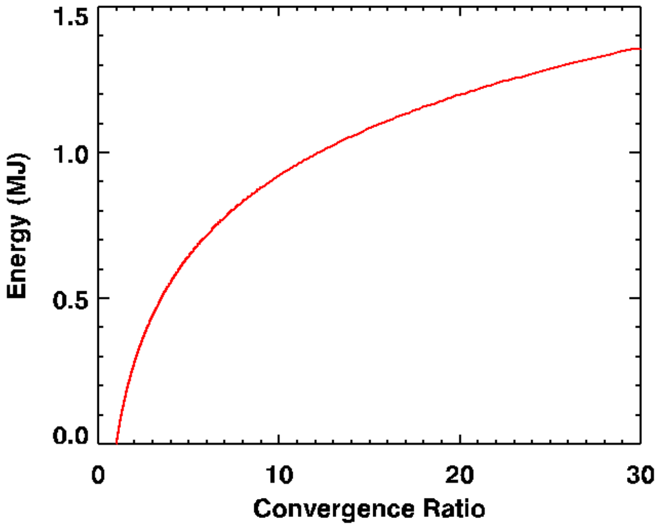


ip=20.0000 MA
mo=6.00000 mg
ro=1.00000 cm
ta=38.7019 ns
timp=48.5057 ns
timp/ta=1.25331
v (Cr=10)=55.4469 cm/us

Kinetic Energy (MJ)



E (Cr=10)=0.922309 MJ



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

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:

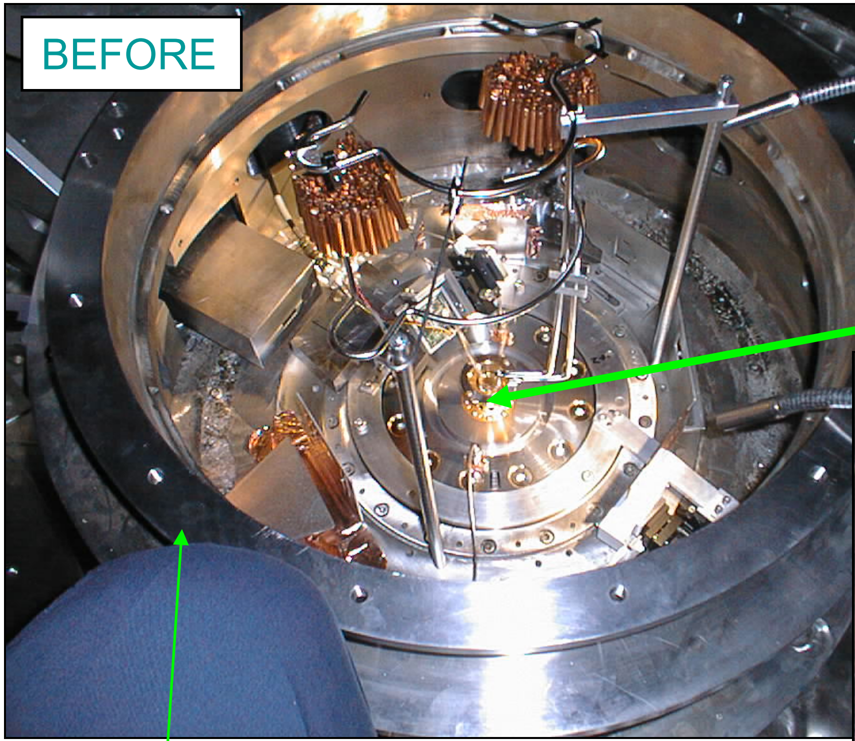
- ~ 1,100,000 miles per hour
- Princeton to LA in ~ 8 seconds
- 1/600 speed of light

- 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

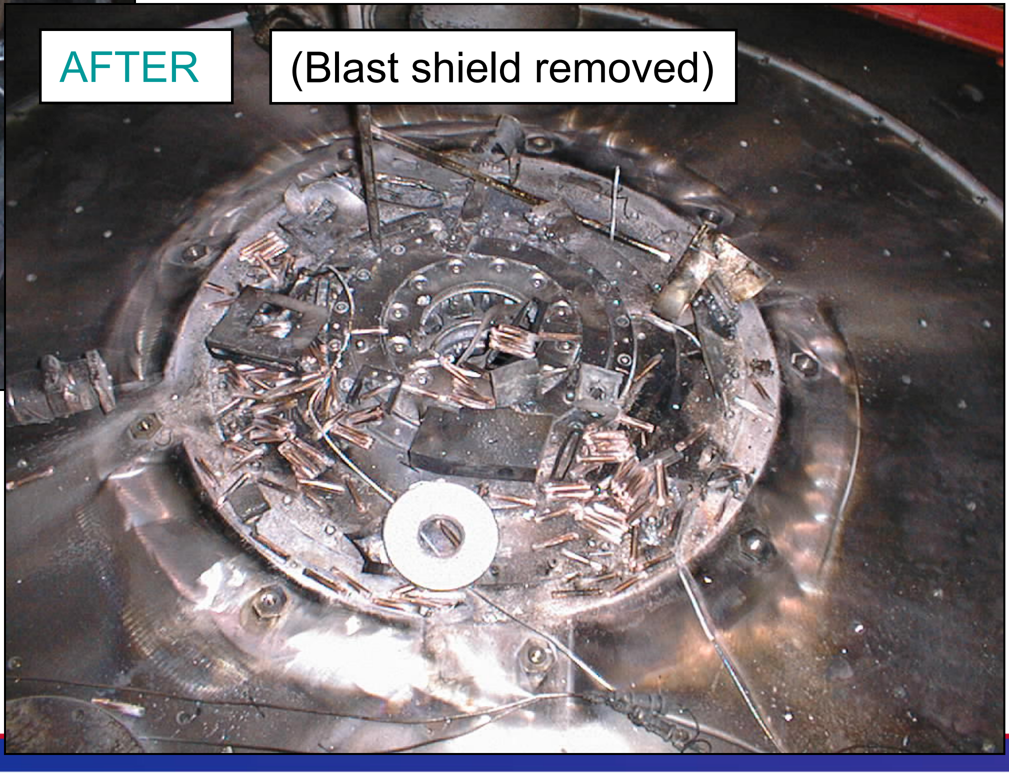
The 2-3 MJ of magnetic energy and radiation destroys the hardware following the pulse

“Hostile” environment

debris, electrical noise, photon background, plasma



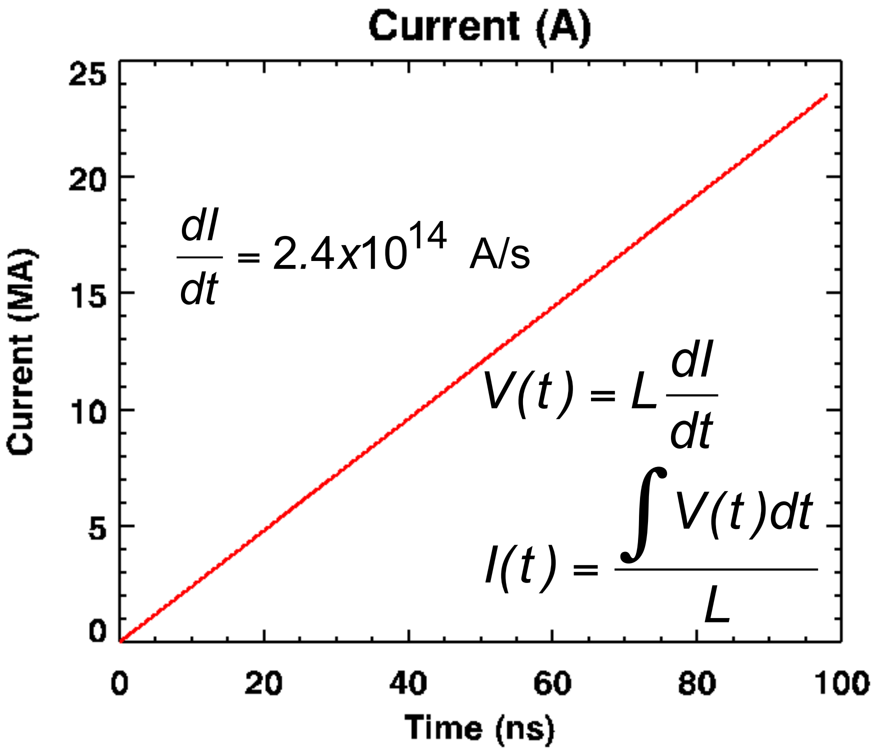
Wire array

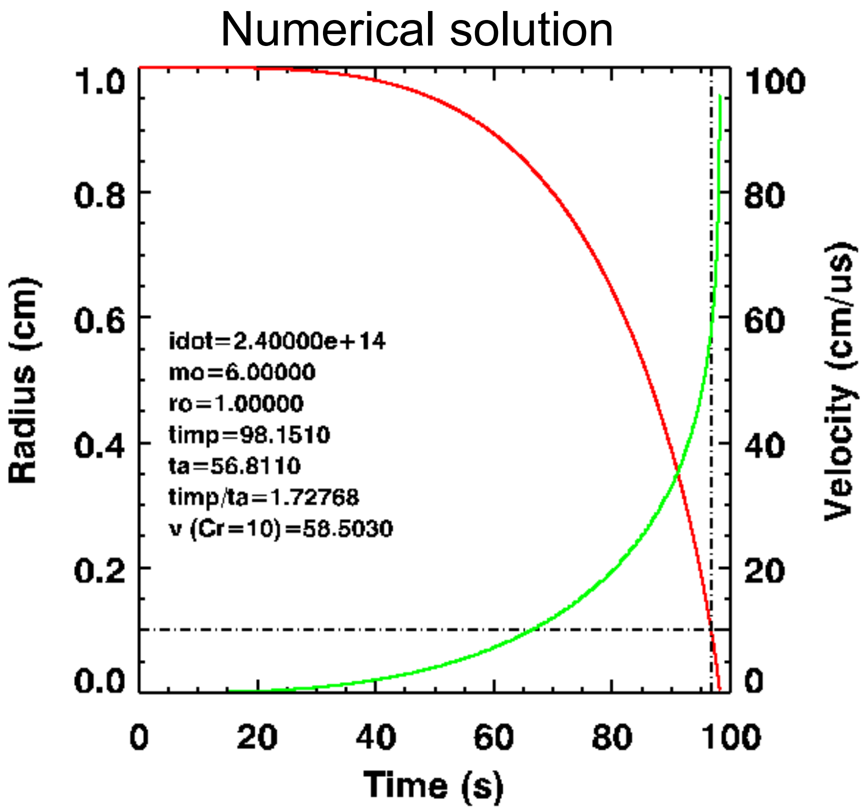


Blast shield

Equivalent to 2 lbs high explosive released in a few ns in <1 cm^3 volume!

A real pulsed power driver does not produce a constant current

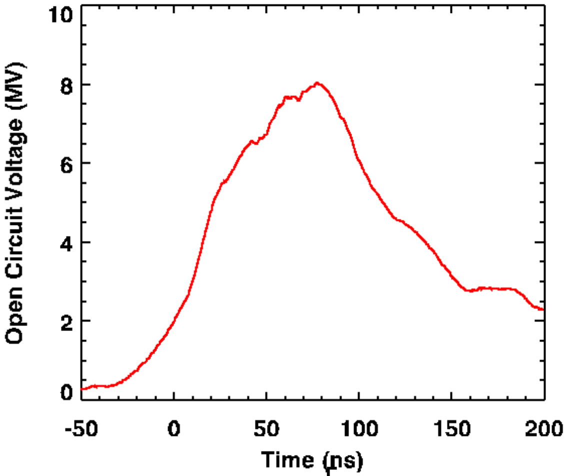


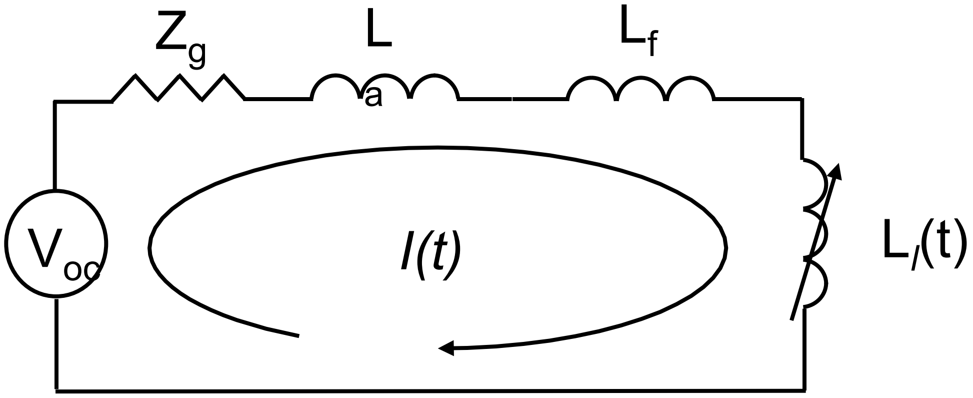


- A pulsed power driver is an **inductor** charging problem
- An element's ***inductance L*** determines the ***d/dt*** of I(t) / ϕ_{mag}(t)
- Typical current waveforms are linearly rising or ~ $\sin^2(\omega t)$

A large pulsed power driver can be represented by a simple equivalent circuit

$$V_{OC}(t) - I(t)Z_g - \frac{dI(t)}{dt}\left[L_a + L_f\right] - \frac{d}{dt}\left[I(t)L_l(t)\right] = 0$$





$$\frac{dI(t)}{dt} = \frac{\left[V_{OC}(t) - I(t)Z_g - I(t)\,{}^{dL_l(t)}\!/_{dt}\right]}{\left[L_a + L_f + L_l(t)\right]}$$

$$\frac{dL_l(t)}{dt} = -\frac{\mu\ell v(t)}{2\pi r(t)}$$

$$L_l(t) = \frac{\mu\ell}{2\pi}\ln\left(\frac{r_o}{r(t)}\right)$$

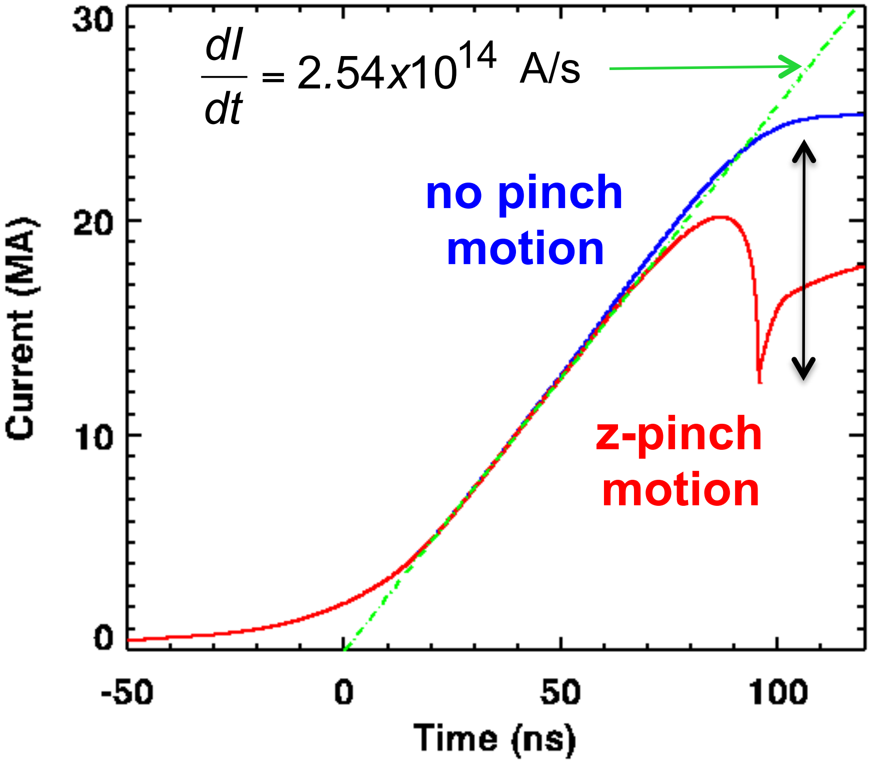
$$\frac{dv(t)}{dt} = -\frac{\mu\ell}{4\pi m}\frac{I^2(t)}{r(t)}$$

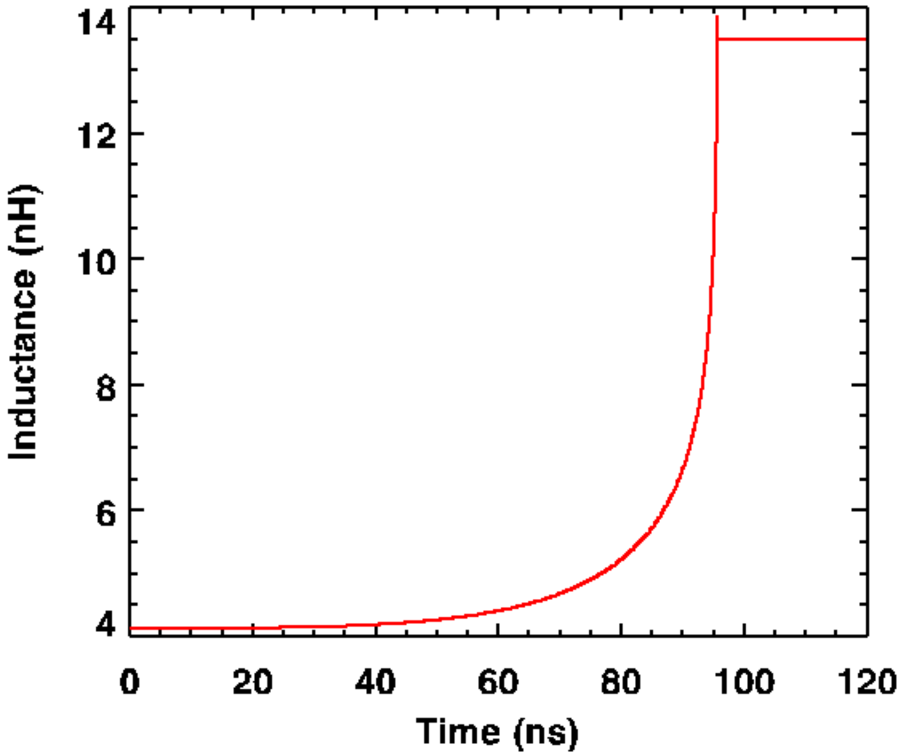
$$\frac{dr}{dt} = v(t)$$

- The z-pinch load has a ***dynamic* impedance** (like a “resistance” but for AC circuits)
- We want to **increase dI/dt** to **implode (dv/dt and r→0)** a load (“target”), but doing so **increases dL/dt** and, in turn, **limits dI/dt** (and can cause dI/dt < 0)

- This can be modeled, but the circuit must be self-consistently included

The z-pinch motion and dynamic impedance decreases the current that can be coupled





- The **“inductive dip” (dL/dt > 0)** represents magnetic energy conversion into work on the z-pinch implosion
- The larger the dip, the more efficient the coupling

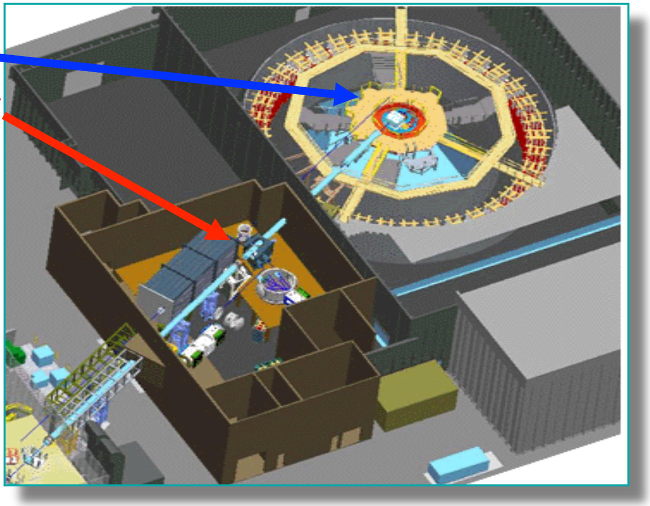
Magneto-Rayleigh-Taylor (MRT) instability limits the quality of the implosion

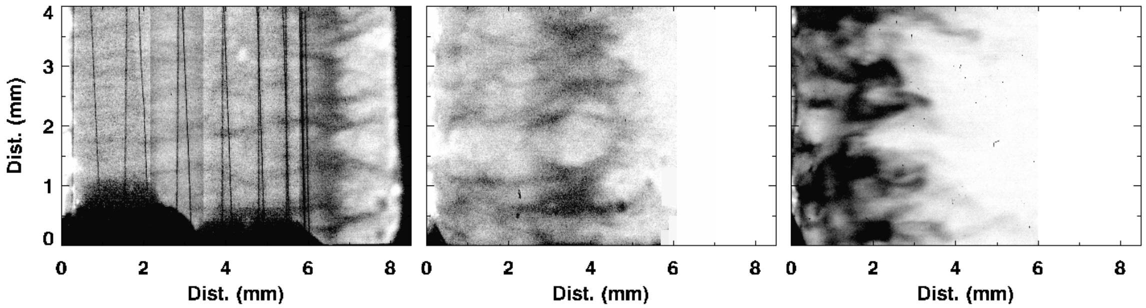
Xray images of a wire array during its implosion!

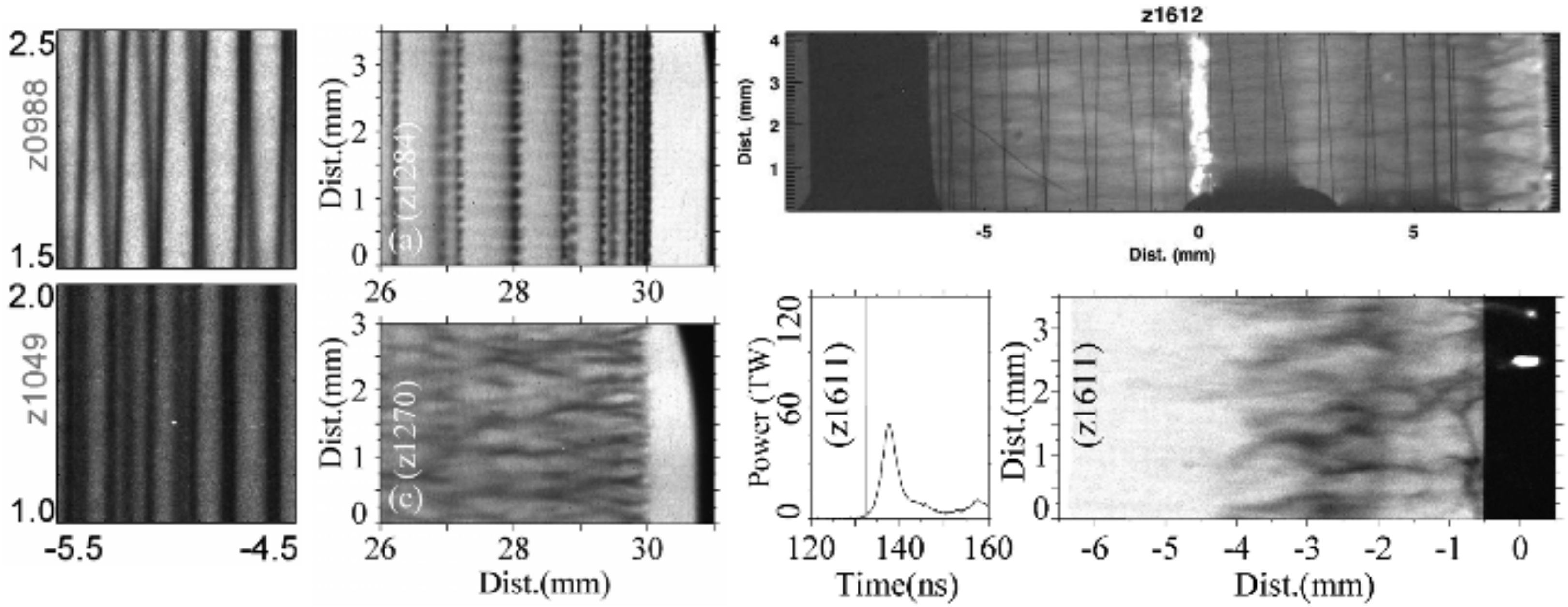
Z Machine

Z Beamlet laser

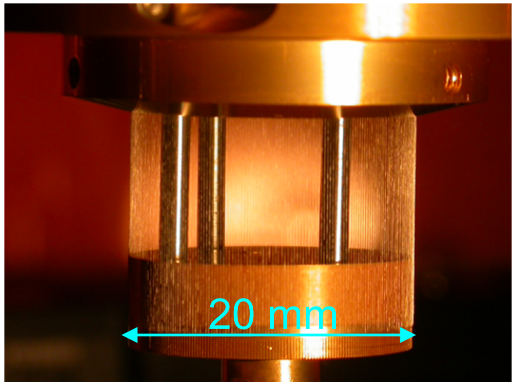
(for radiography)

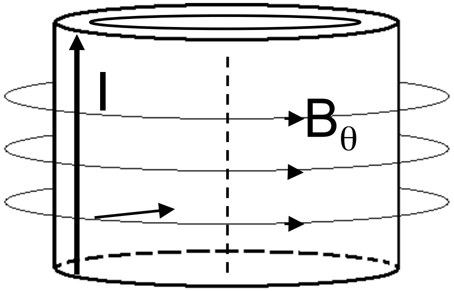


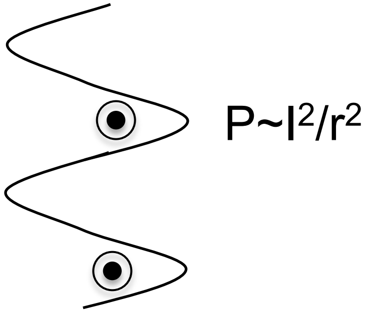


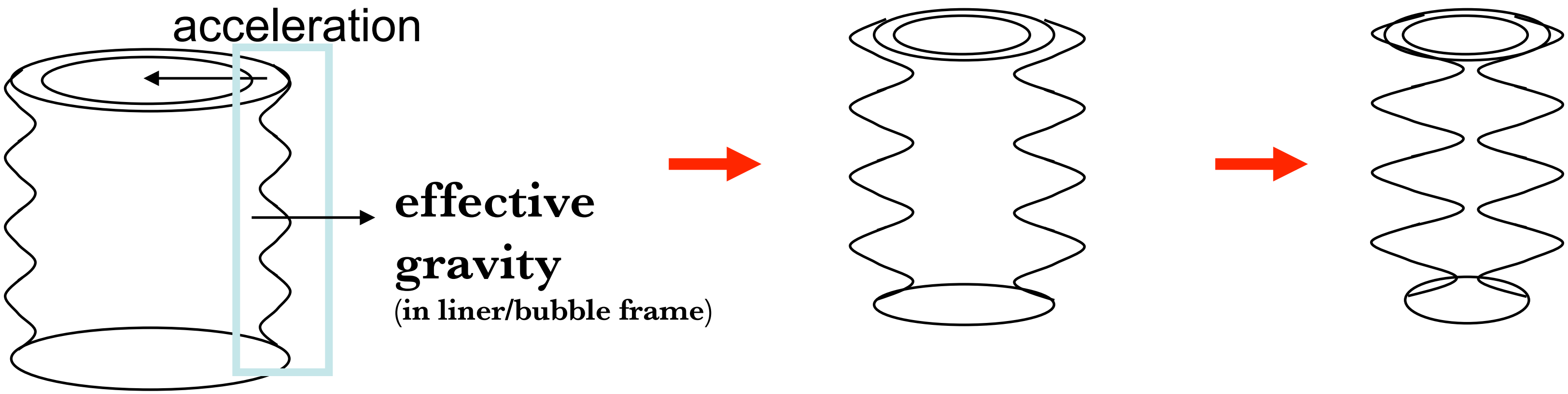


The plasma is the heavy fluid and the B field is the light fluid → *unstable* to the MRT



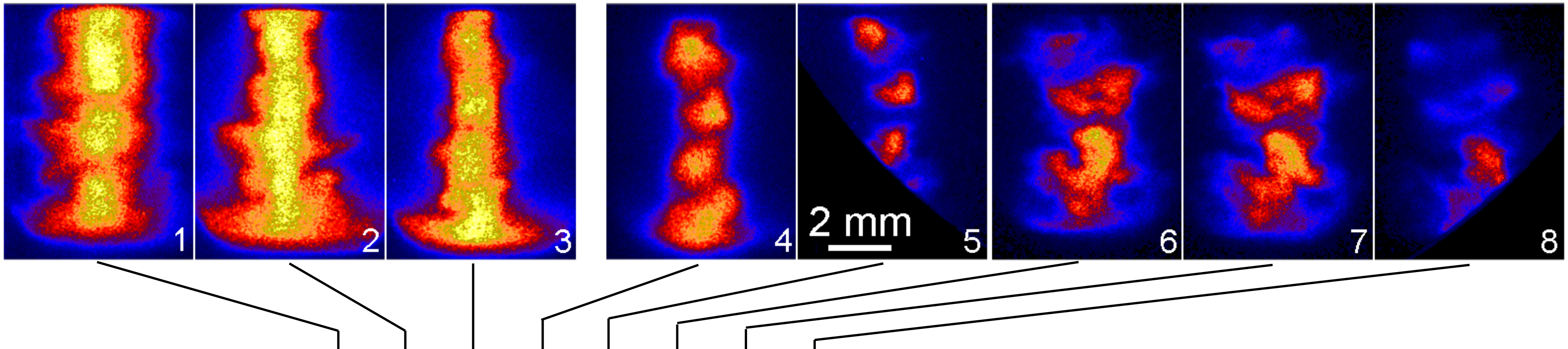


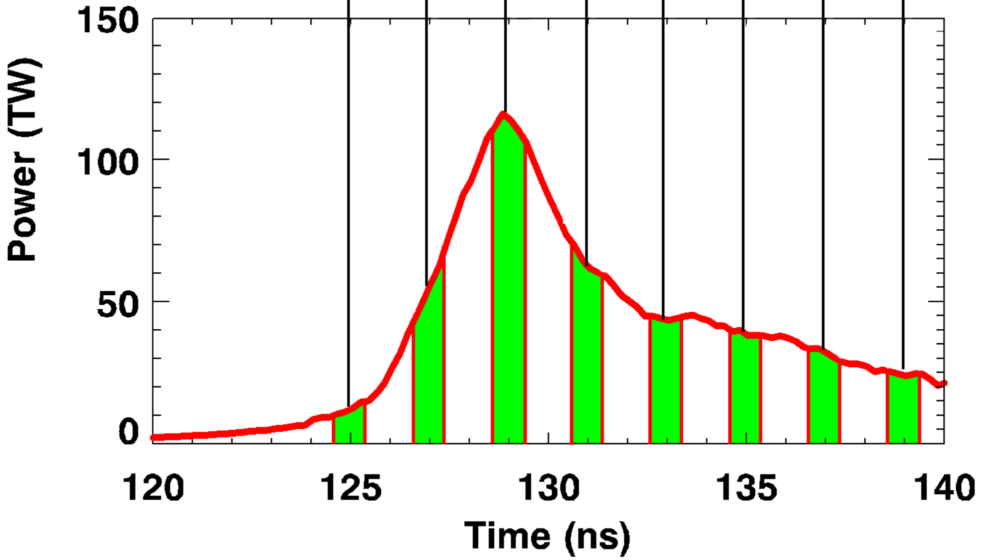




- Our z-pinches are termed “fast” because only the MRT grows during implosion

The plasma pinch convergence ratio is commonly estimated using x-ray self-emission imaging





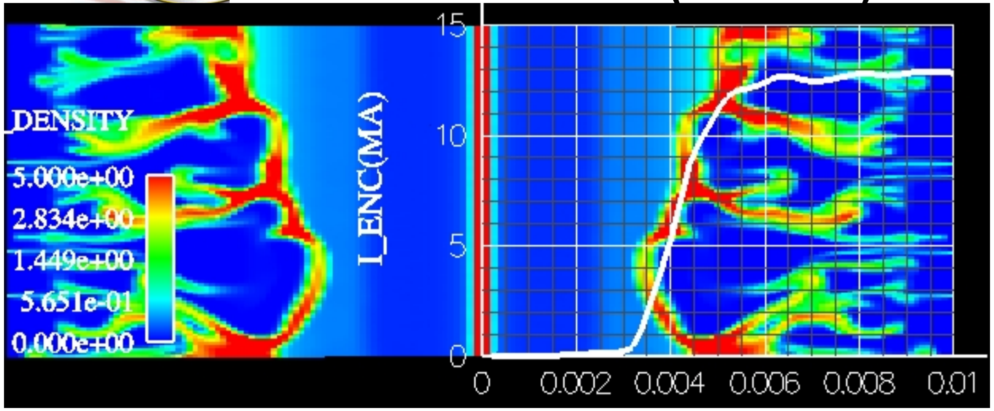
Plasma is relatively stable and axially uniform during main radiation pulse

Most work in literature estimates plasma CR using x-ray pinhole cameras

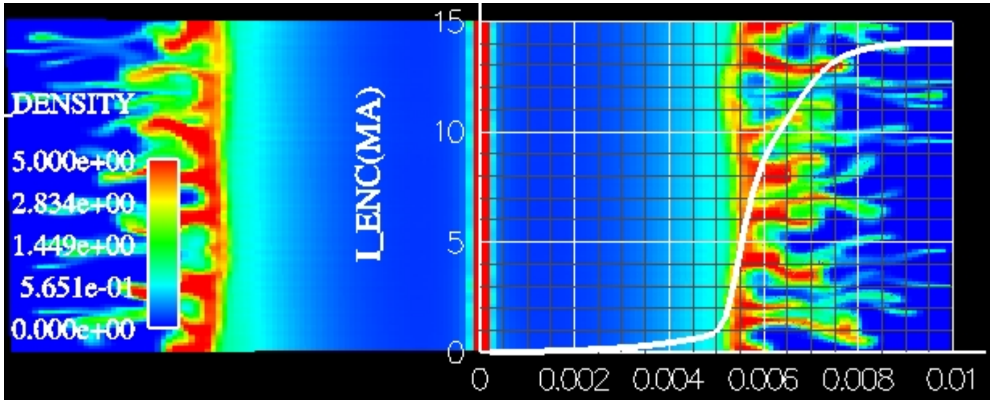
Instability bubble growth is reduced by 3D effects, current travels azimuthally and "self-regulates" bubble growth

Yu, et al., Phys. Plasmas (2008)

2D Case: C=100% (2520 ns)



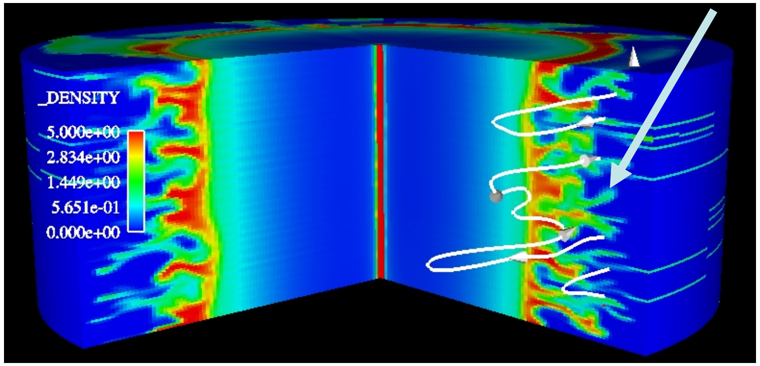
3D Case: C=3% (2520 ns)



2D(r,z) simulations exaggerate the correlation (to 100%) because azimuthal symmetry (θ) is enforced

In a 3% correlated problem in 3D, bubble growth is reduced because current can flow azimuthally.

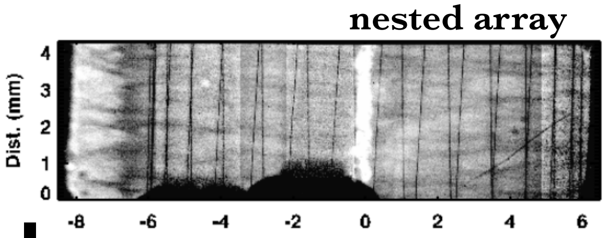
current streamline (in azimuth)



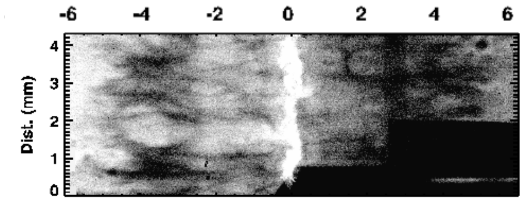
We perform simulations in order to understand, and *try* to predict, physical behavior

Experimental radiographs can constrain simulations

experiment:2.42 mg

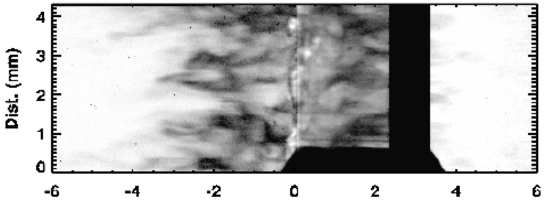


-19 ns before peak power



-10.5 ns before peak power

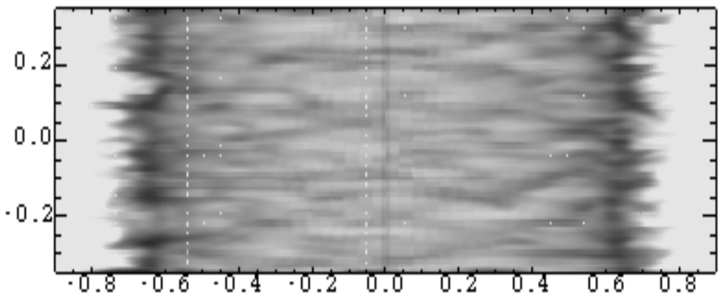
Time



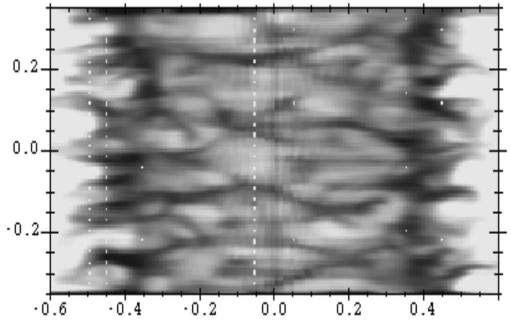
-4.7 ns before peak power

simulation(from Spect3d)

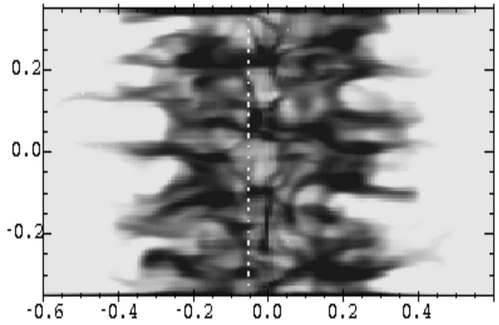
C=1.7%



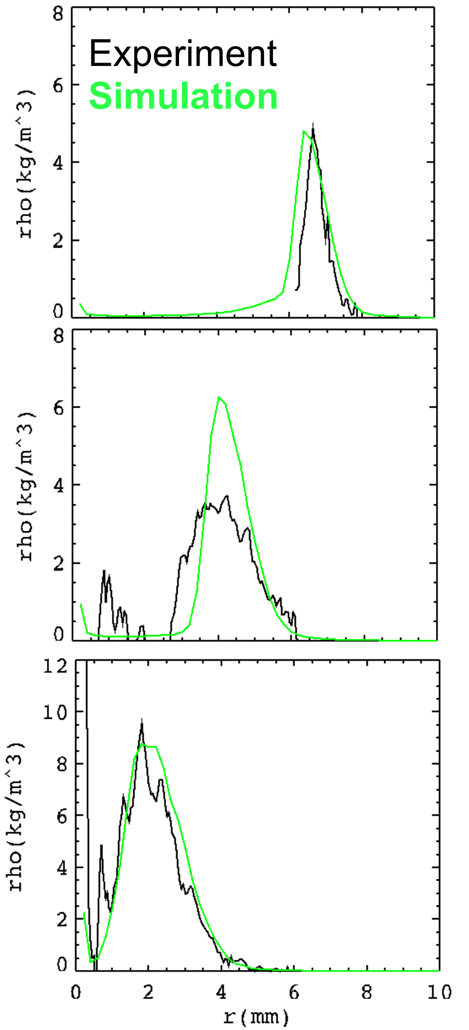
1.7%



1.7%

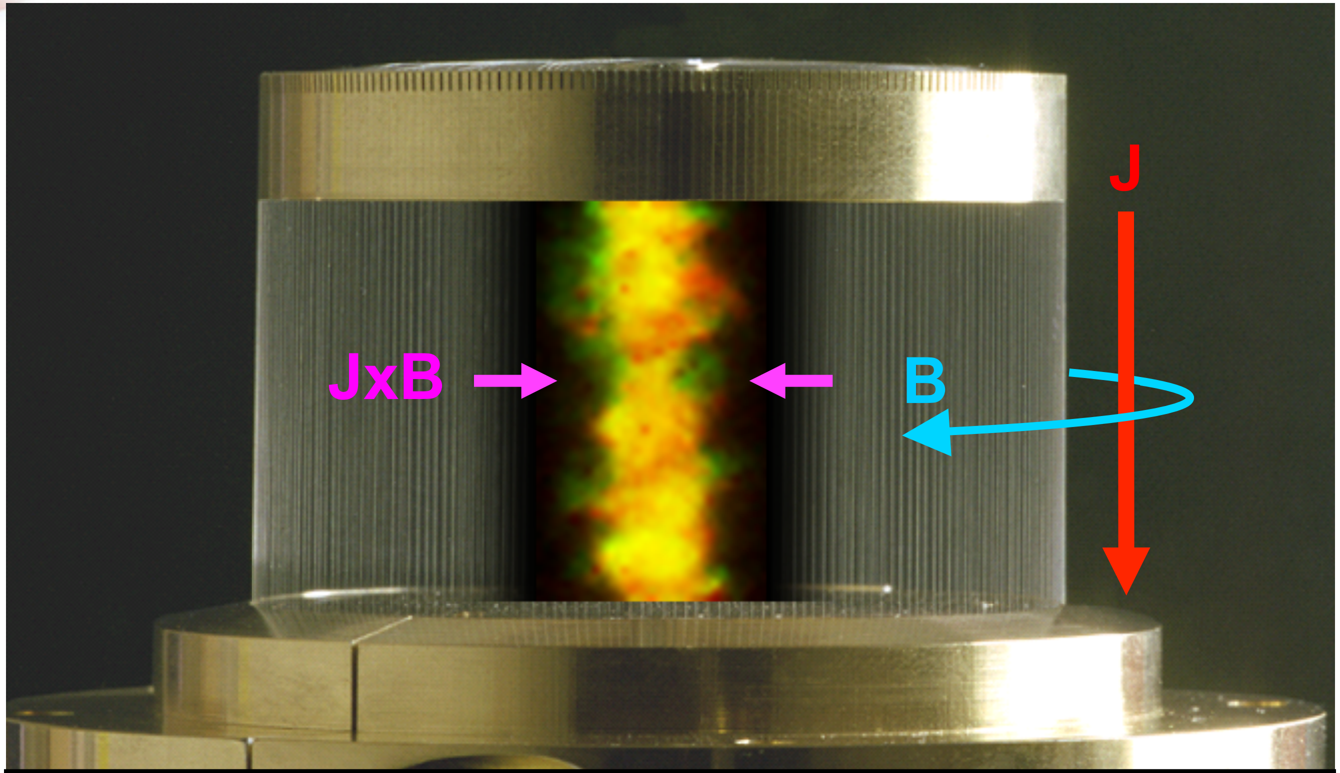


density profiles



Yu, et al., Phys. Plasmas (2008)

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)

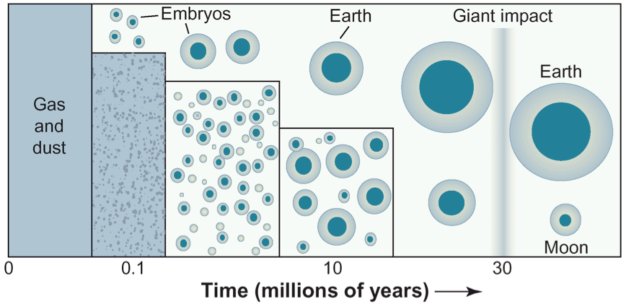
T_{rad} ~ 200 eV ~ 2,300,000 °K

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

We have established a fundamental science program on Z and have awarded time to university users



Earth formation

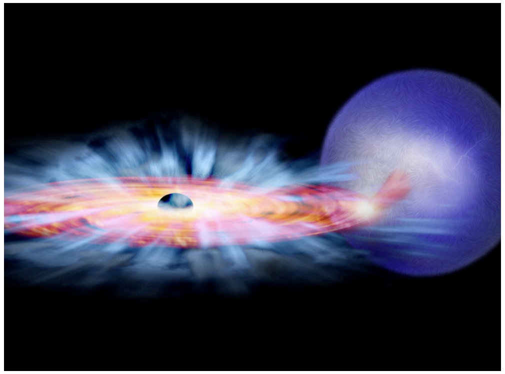
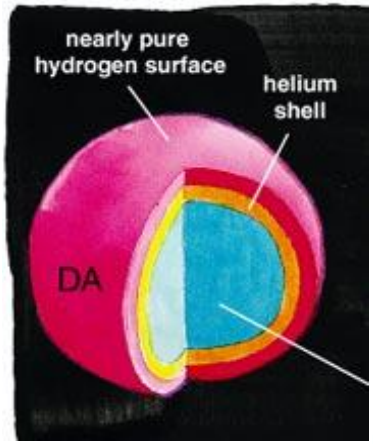
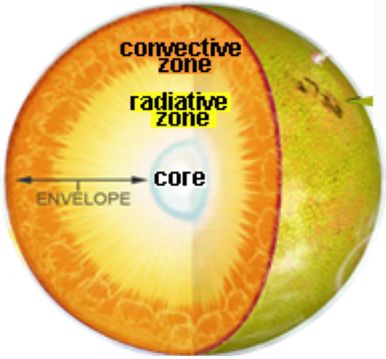


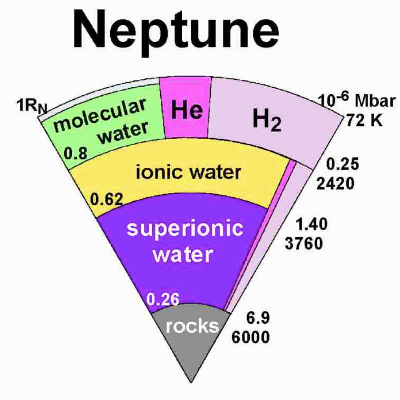
Photo-ionized plasmas



White Dwarfs



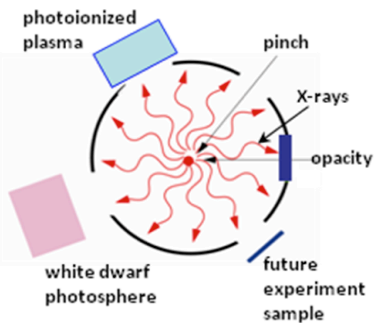
Solar Opacities



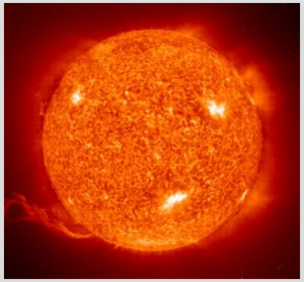
Planetary structure

- 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

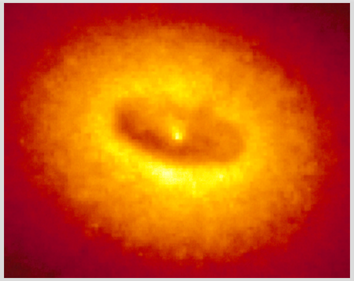


Collaborator:
Ohio State University

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.

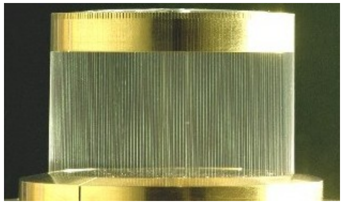
Required Conditions:
$T_e \sim 1\text{-}4$ eV, $n_e \sim 10^{17\text{-}19}$ cm^{-3}

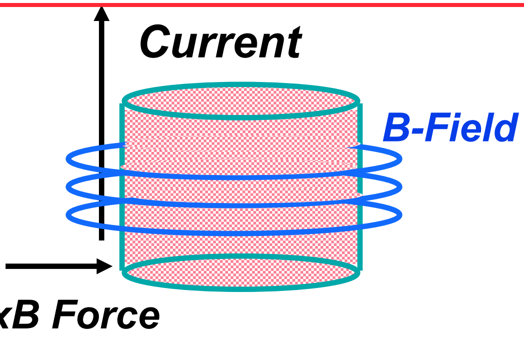
We can use high currents to push plasmas in different ways for different applications

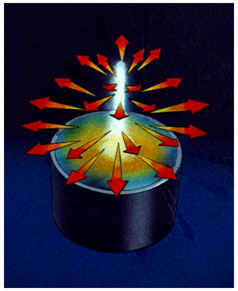
High Current

Z-Pinch X-ray Sources

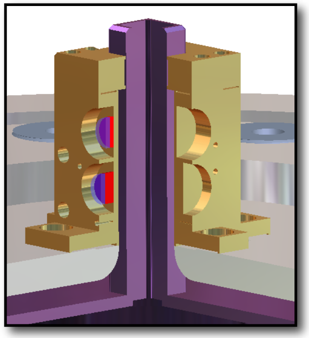
wire array



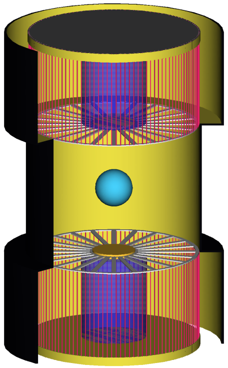


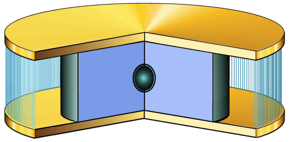


Planar magnetic pressure

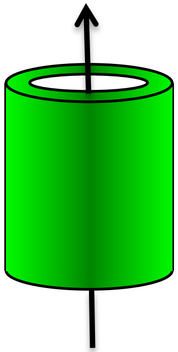


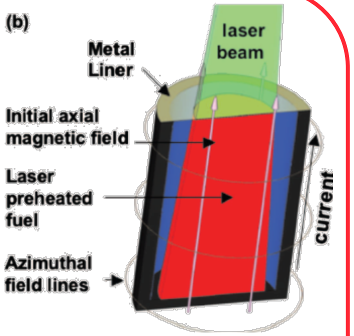
Inertial Confinement Fusion (ICF)





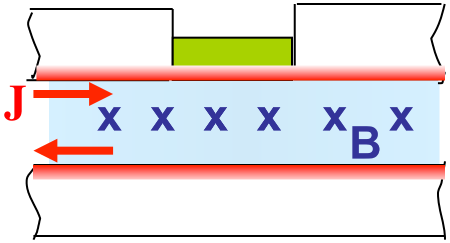
Indirect-drive
(x-rays)





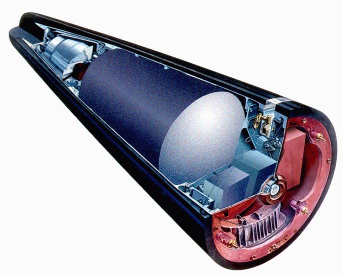
Direct-drive
(magnetic field)

Material Properties

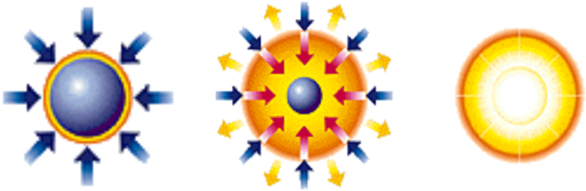


Understanding material properties at high pressure is important for Stockpile Stewardship, ICF, and understanding planets

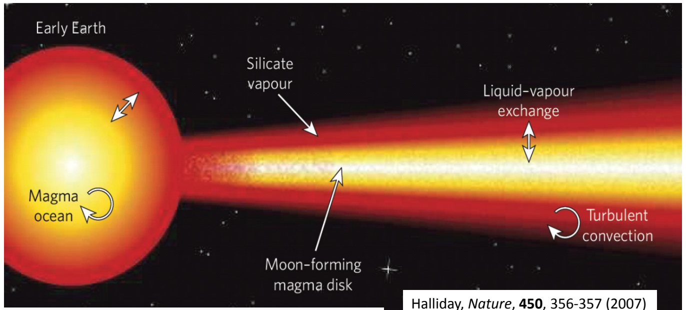
- Nuclear weapons materials
  - Behavior of plutonium, uranium, etc.



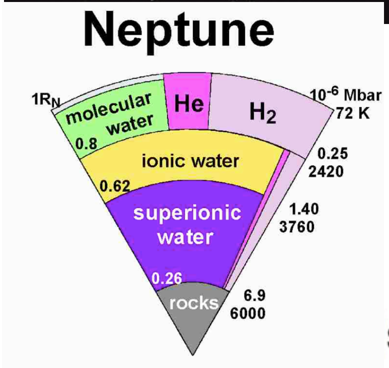
- Inertial confinement fusion (ICF) materials
  - Behavior of hydrogen, plastics, beryllium, diamond, etc.



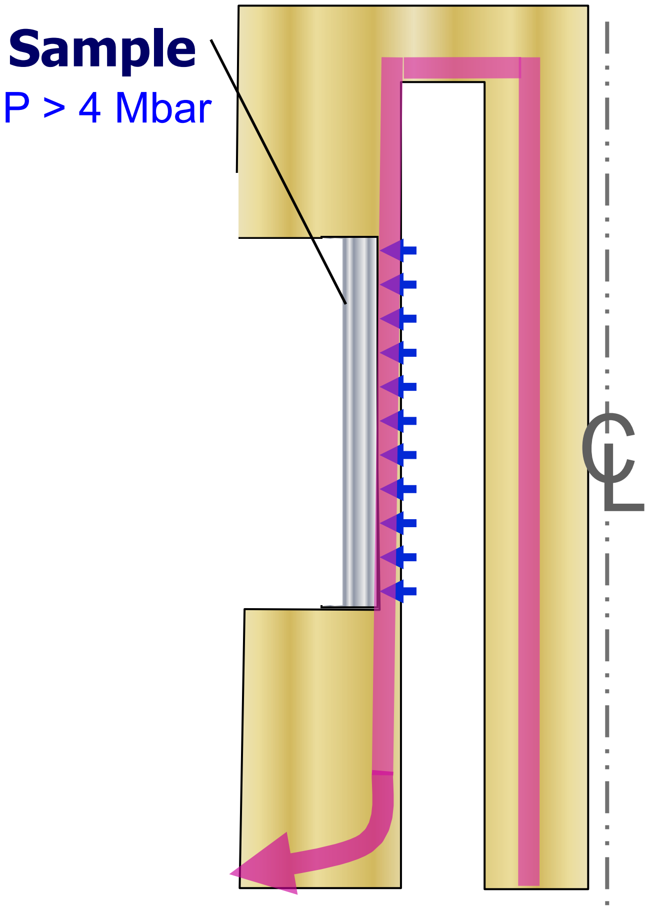
- Planetary science
  - Giant impacts (e.g. Moon Forming Event)
  - Earths and super-earths
    - Equation of state of *Mg, Fe, Si, C, O*, etc.
  - Giant Planets (e.g. Uranus & Neptune and exo ice-giants)
    - High-pressure mixtures of *H, He, C, O, N*

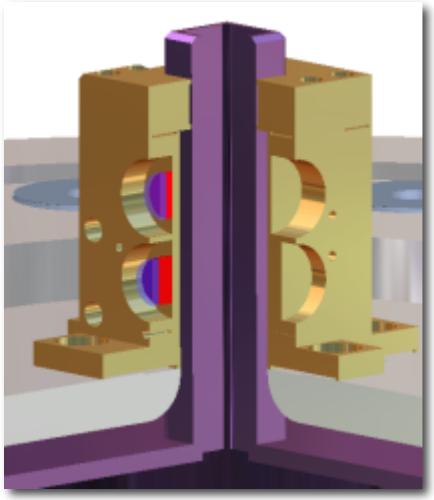


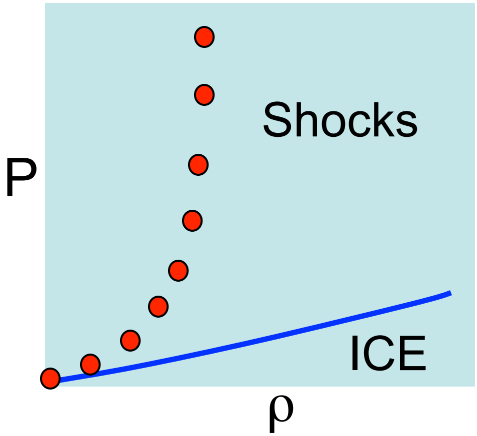
Halliday, *Nature*, **450**, 356-357 (2007)

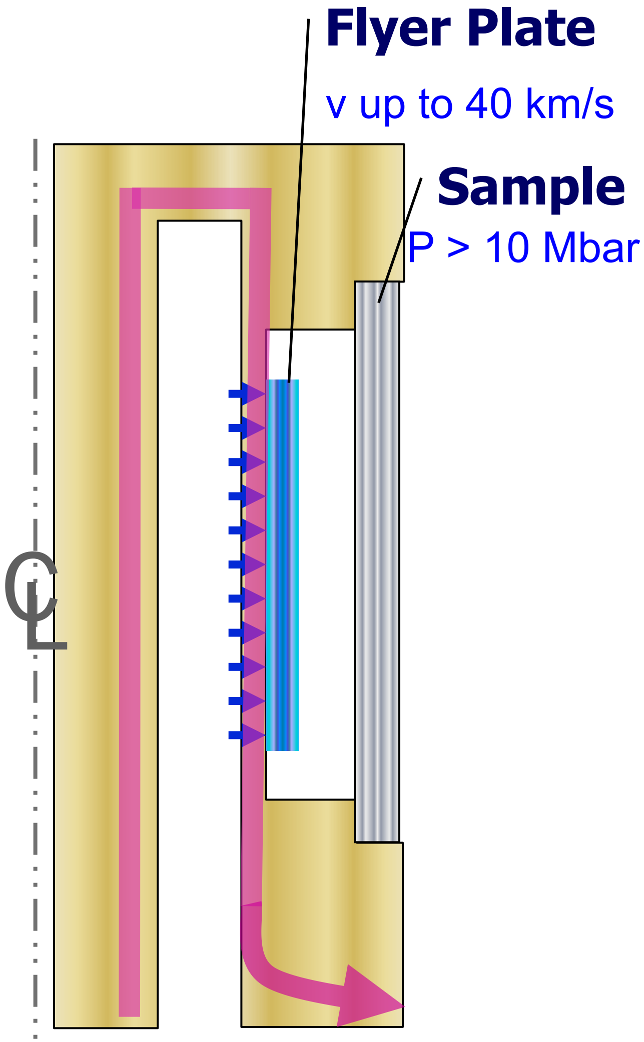


Isentropic compression and shock wave experiments map different regions of phase space







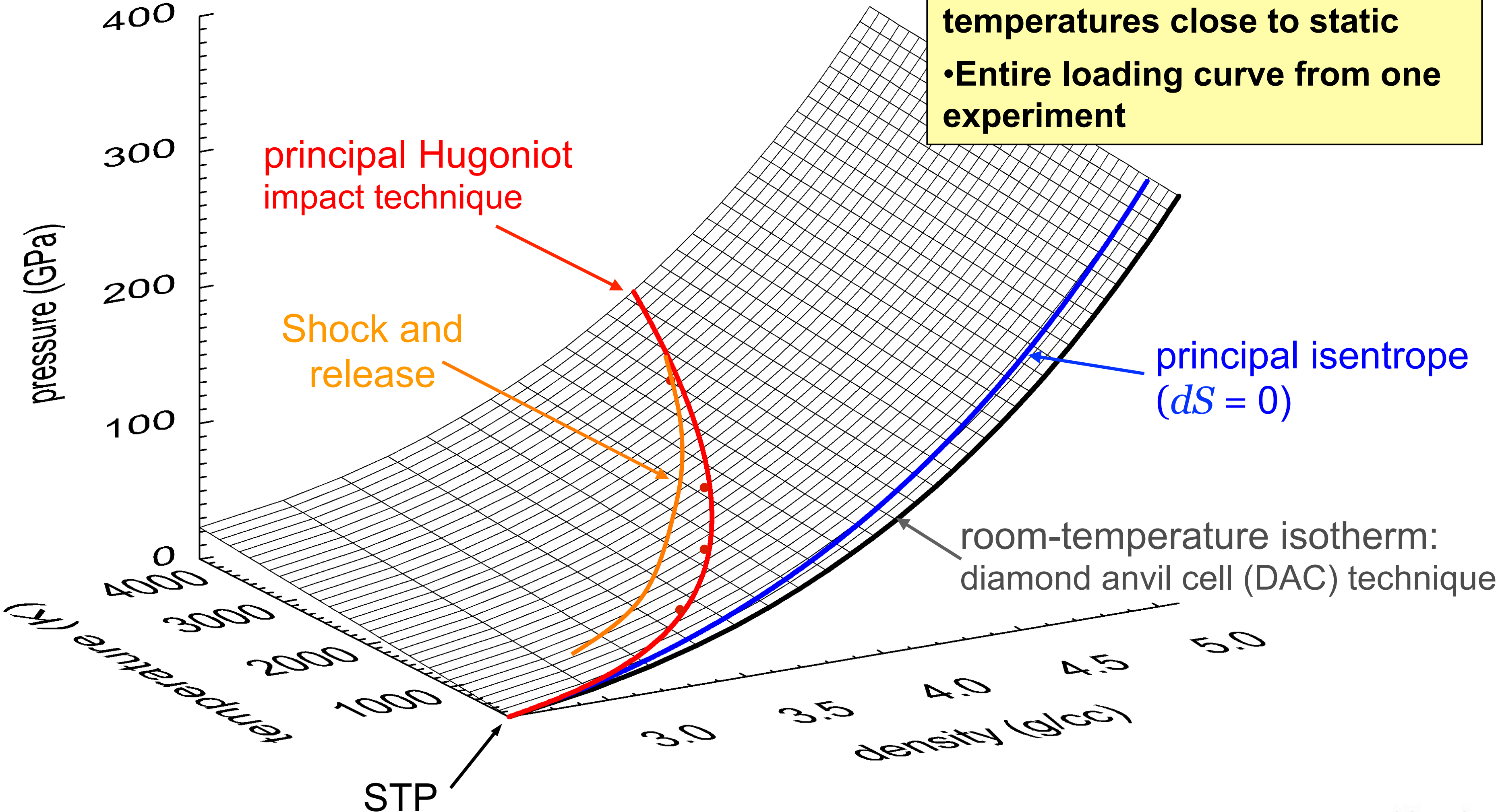


Isentropic Compression Experiments:
gradual pressure rise in sample

Shock Hugoniot Experiments:
shock wave in sample on impact

Magnetic pressure can be used to examine fundamental material properties at HED conditions

- **Dynamic response at temperatures close to static**
- **Entire loading curve from one experiment**



principal Hugoniot
impact technique

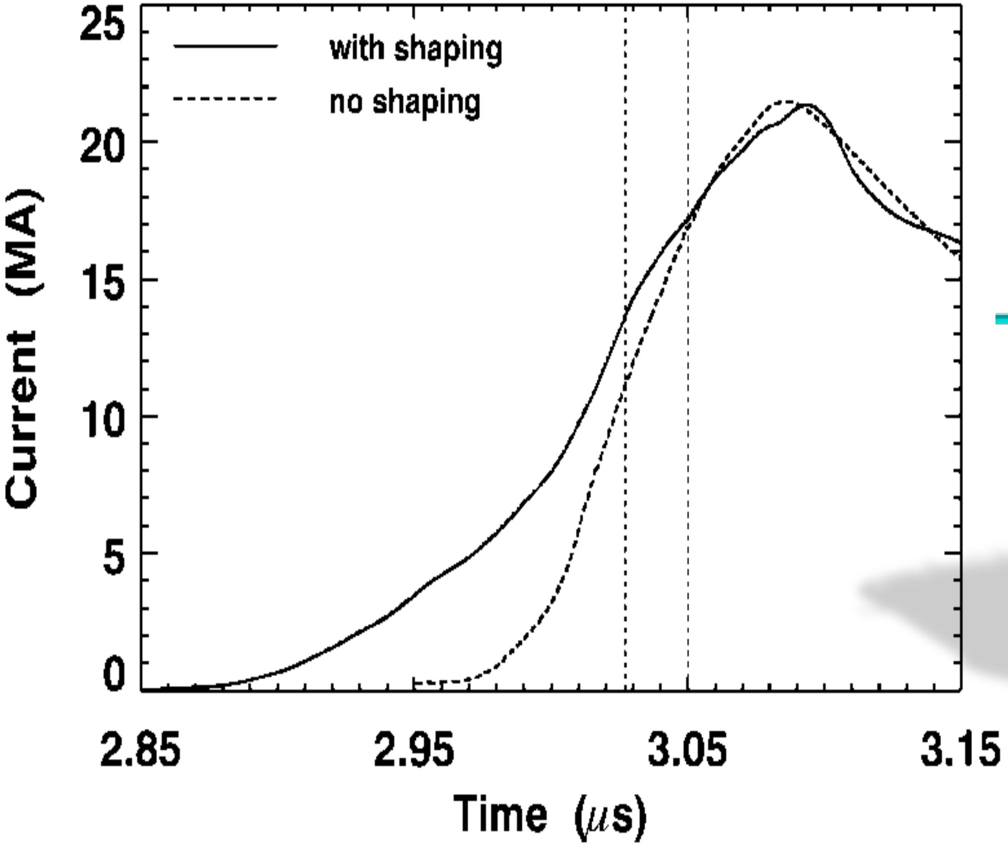
Shock and release

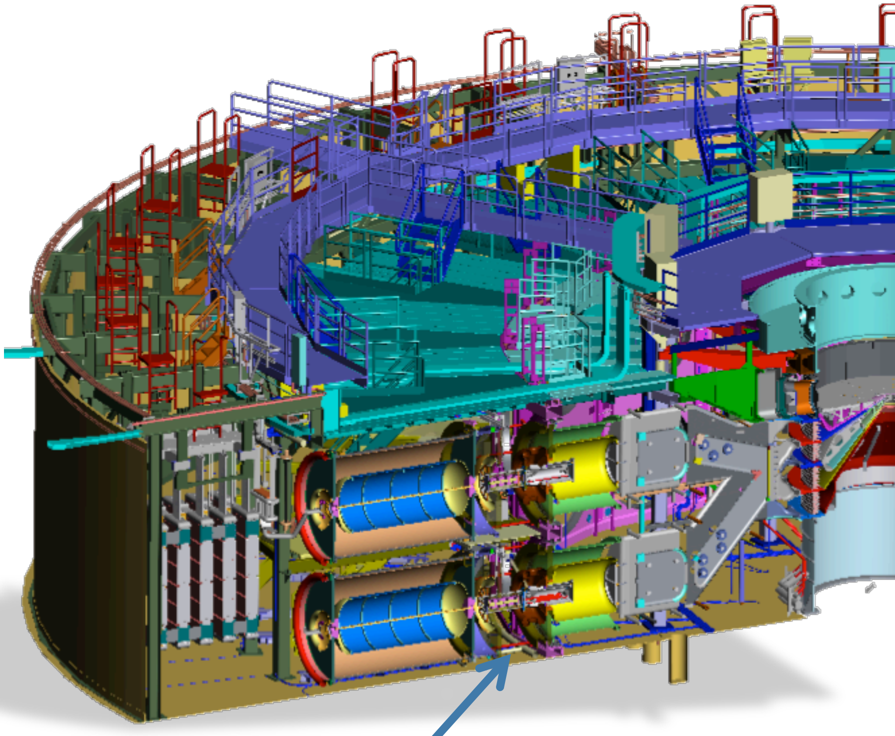
principal isentrope
($dS = 0$)

room-temperature isotherm:
diamond anvil cell (DAC) technique

STP

Current pulse-shaping is a key element for accurate and precise dynamic materials experiments on Z

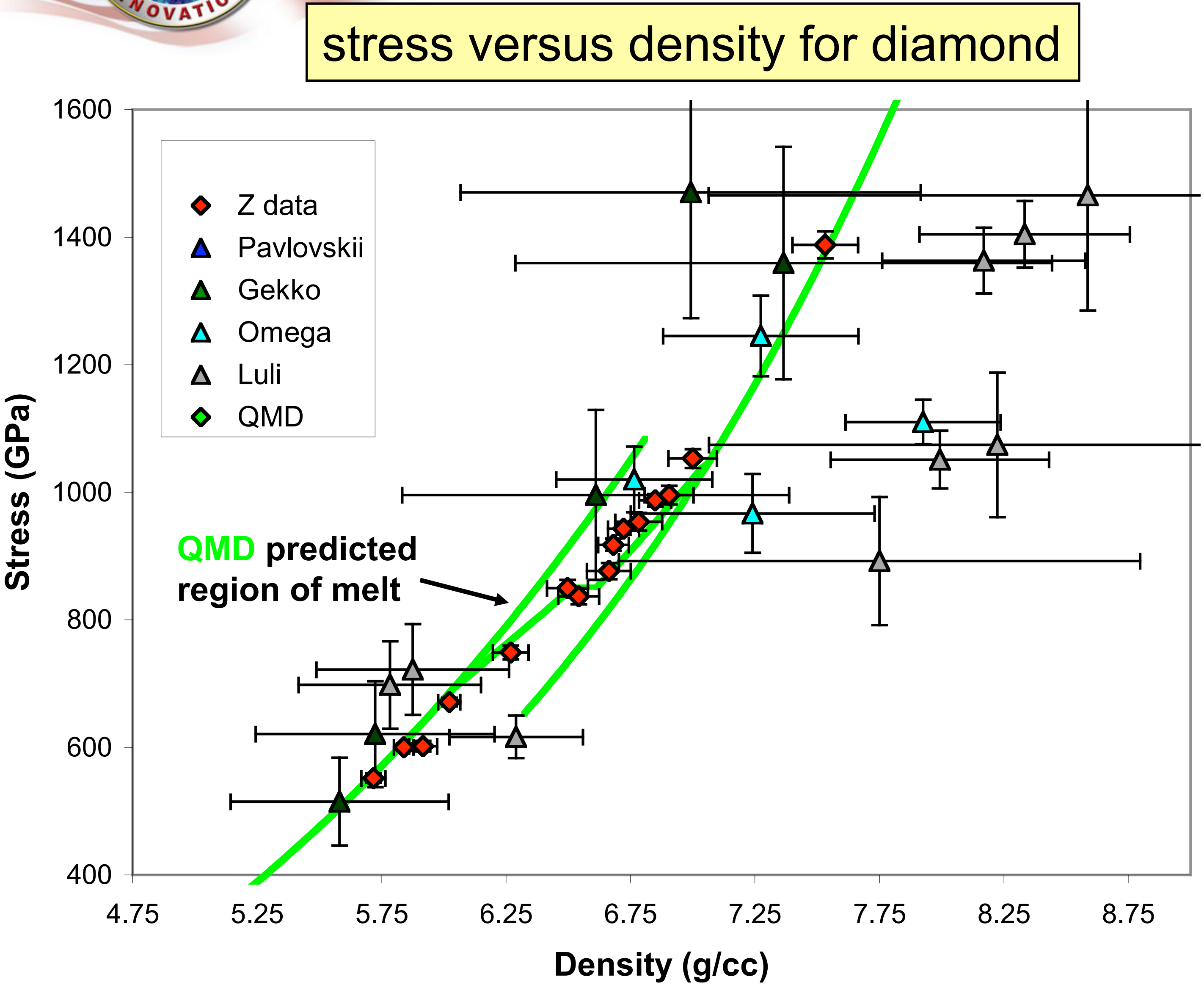




18 Independent Groups of Laser-Triggered Gas Switches

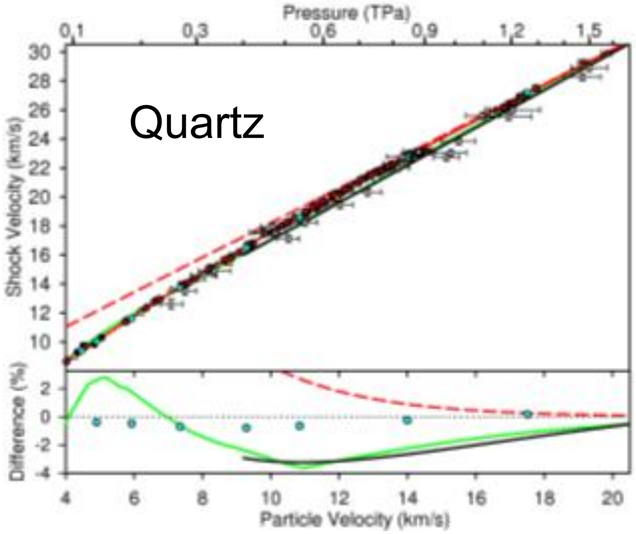
- Tailor ramp-compression to prevent shocks
- Optimize flyer velocity and characteristics

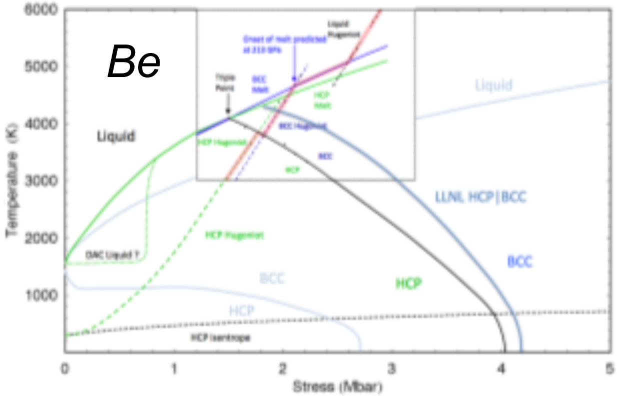
Z answered important questions about the properties of diamond at high pressure

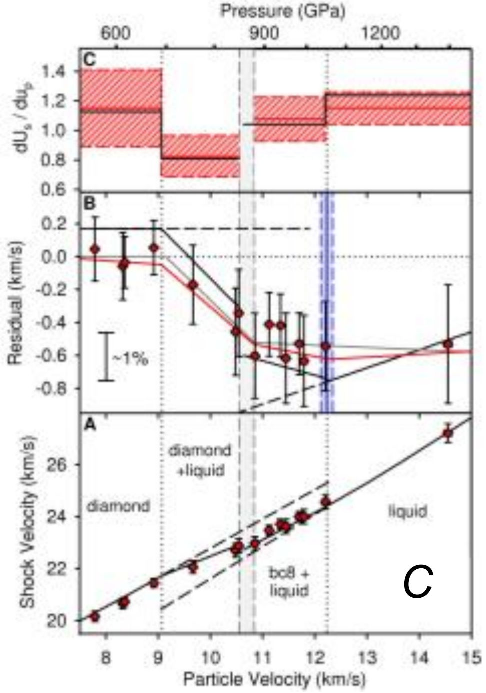


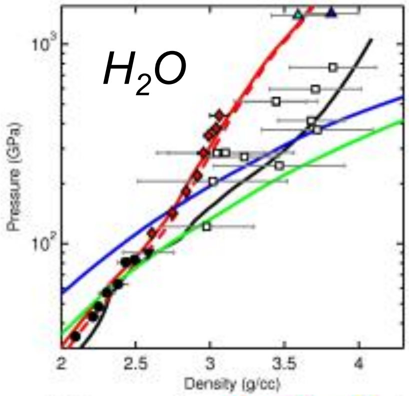
- **The Z data was obtained in 1 week**
- **Measurements on Z have an accuracy of ≤ 1%**

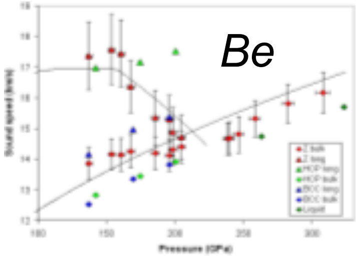
Z has been used to study material properties in the multi-Mbar regime for many materials

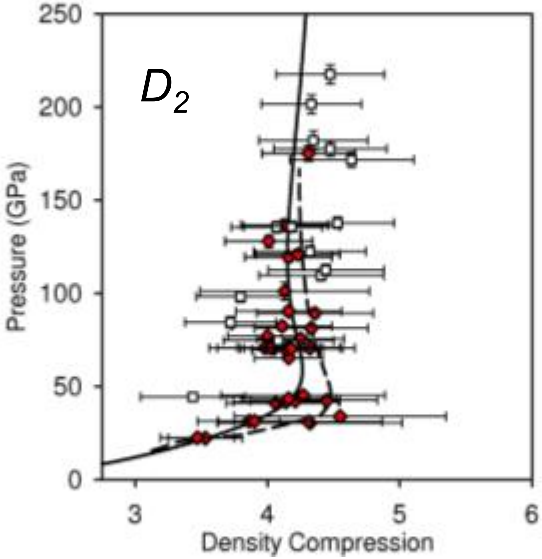


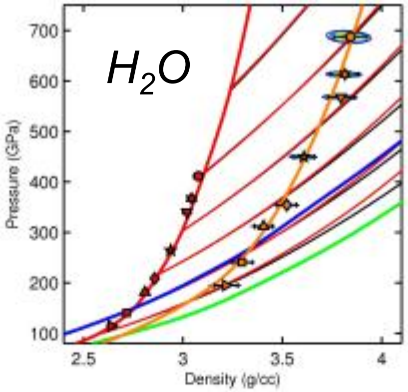


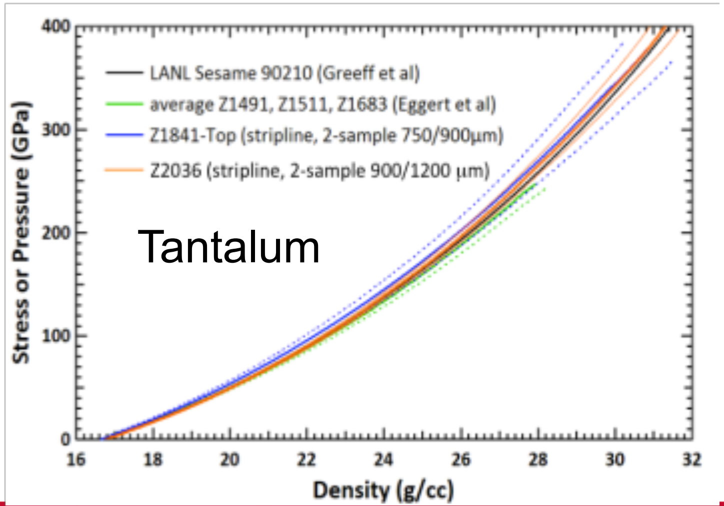












Giant Impacts:

unlocking the mysteries of satellites and planets

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:

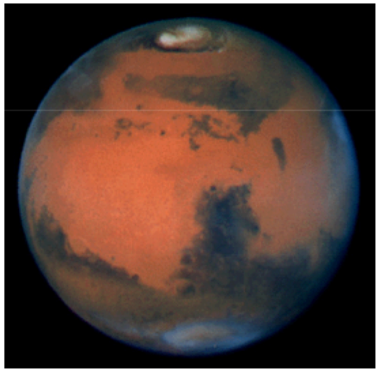
- planet and satellite formation, structure, and evolution
- effects of collisions on planets and satellites
- cratering mechanics and morphology

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

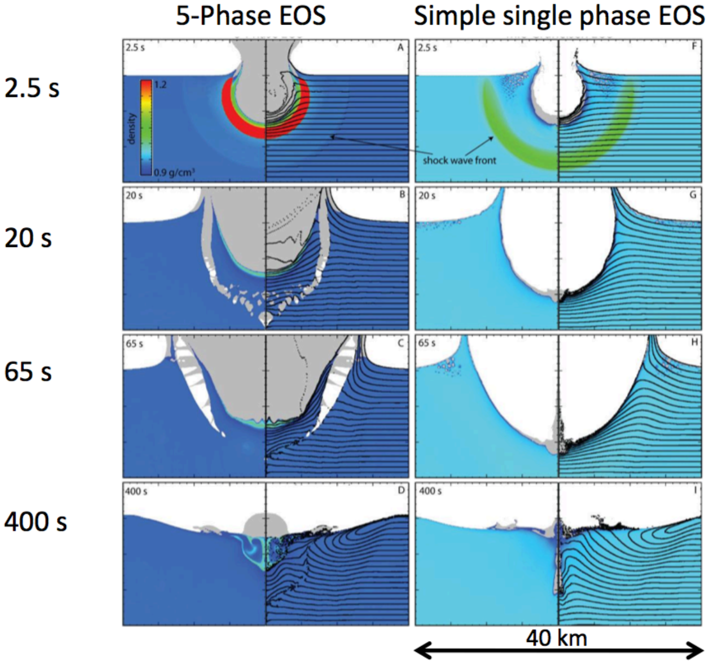
Credit: S. Stewart (Harvard)

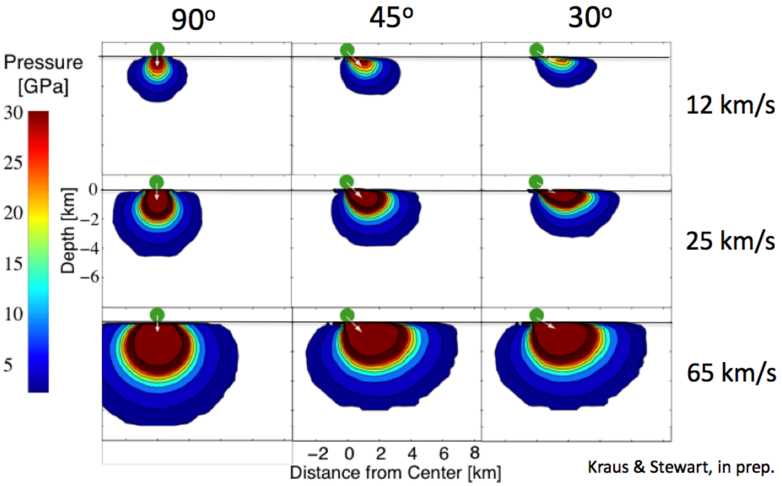
Giant Impacts:
unlocking the mysteries of satellites and planets

Europa Ganymede Callisto



Mars





Kraus & Stewart, in prep.

Sandia National Laboratories

Credit: S. Stewart (Harvard)

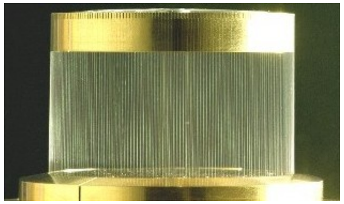
We can use high currents to push plasmas in different ways for different applications

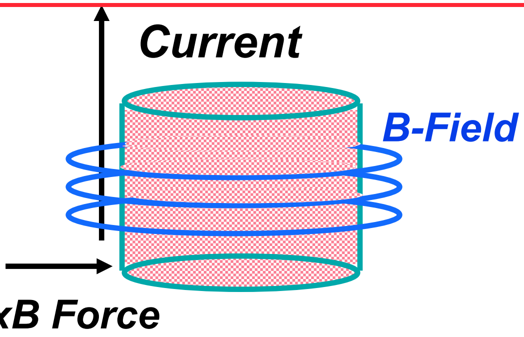
High Current

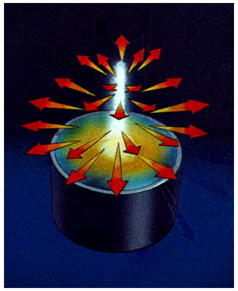
Z-pinch X-ray sources

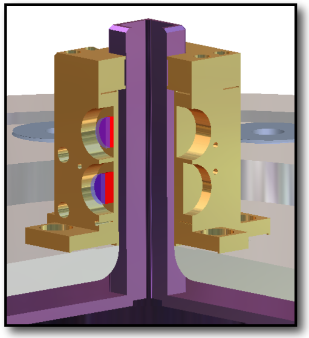
Planar magnetic pressure

wire array

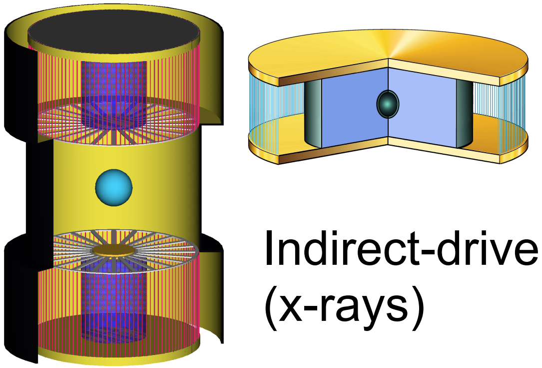




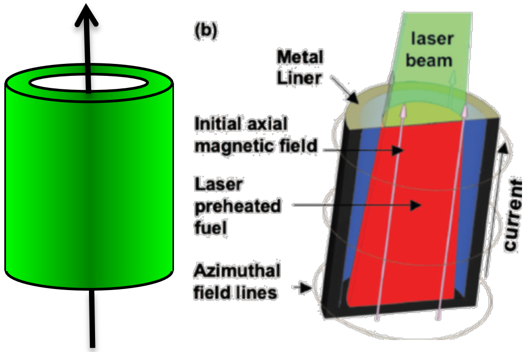




Inertial Confinement Fusion (ICF)

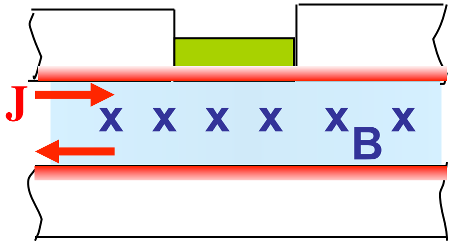


Indirect-drive
(x-rays)

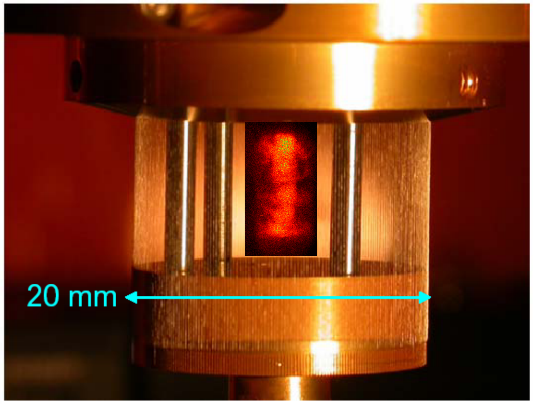


Direct-drive
(magnetic field)

Material Properties



Indirect drive: how can we use this efficient x-ray source to do ICF?



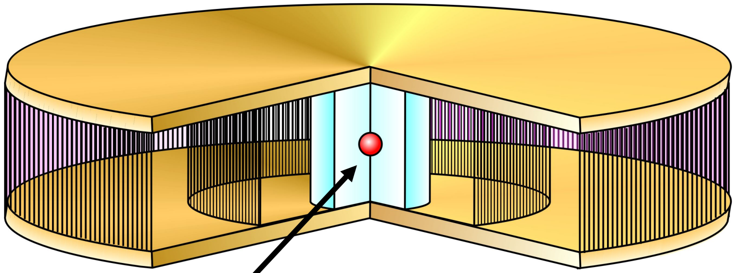
Two methods were proposed

Where do we put the capsule?

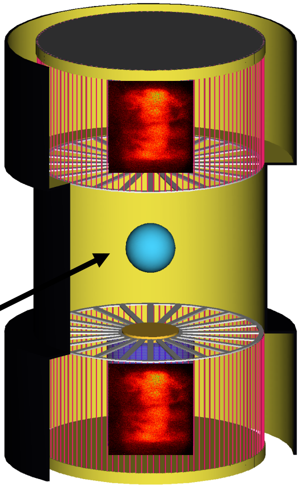
We want high intensity (high T_r) for high ablation pressure
→ *let the capsule see the pinch*

Capsule needs high uniformity (~1%) in x-rays for symmetry
→ *hide the capsule from the pinch*

Dynamic Hohlraum

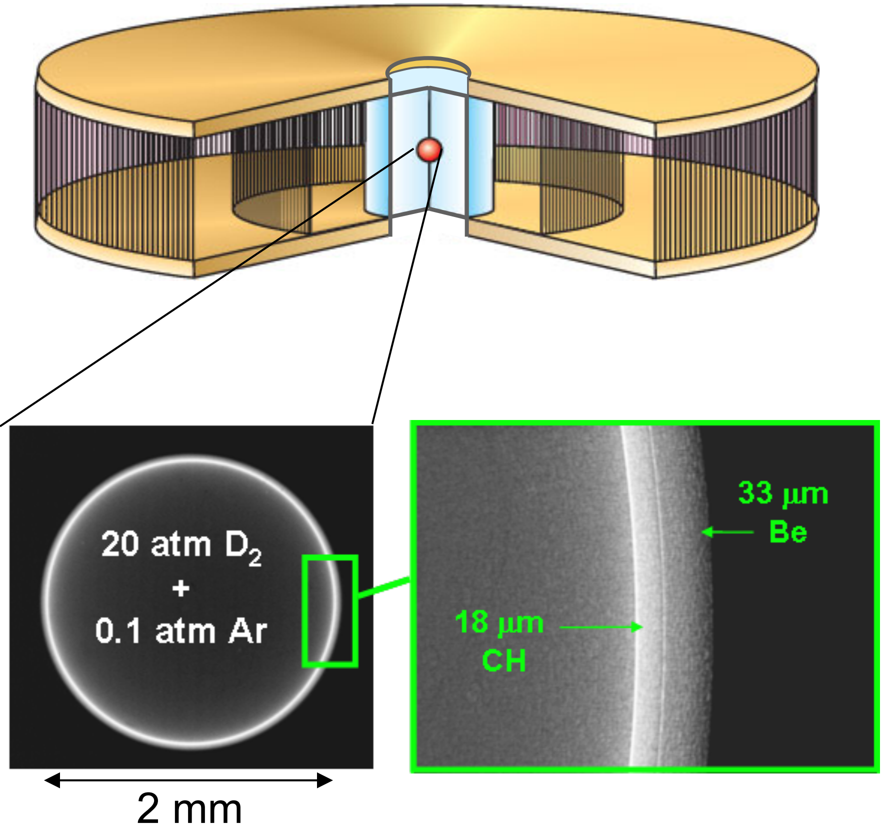


Double-Ended Hohlraum

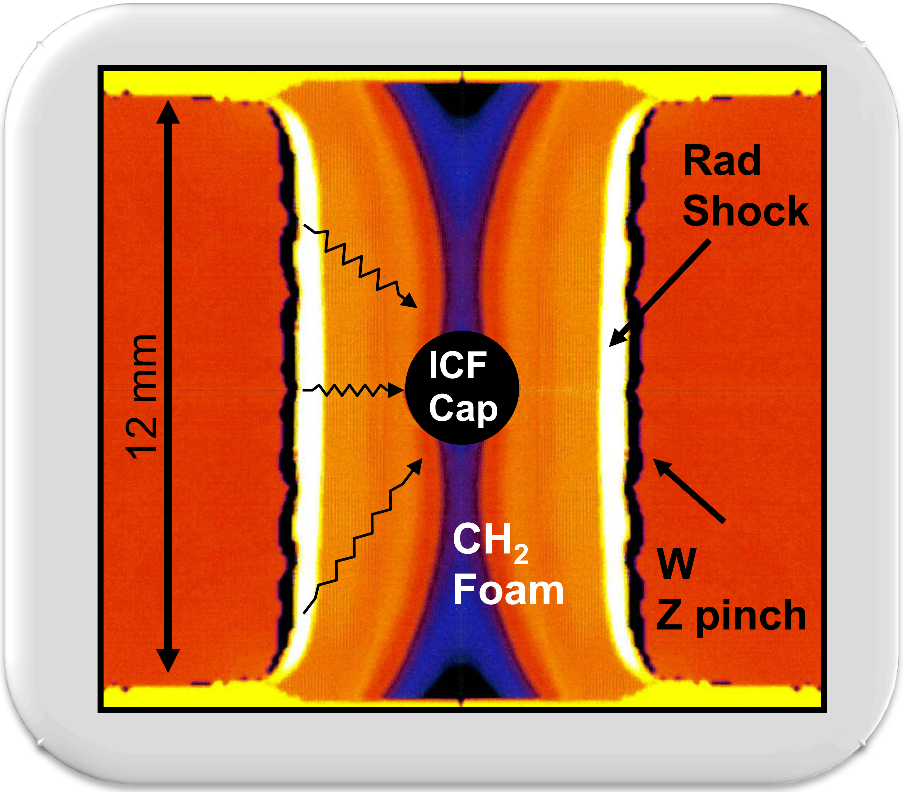


This approach is the most conservative

The ZPDH drives ICF capsules at T_r > 200 eV and up to 50 kJ absorbed energy.



RMHD Simulation



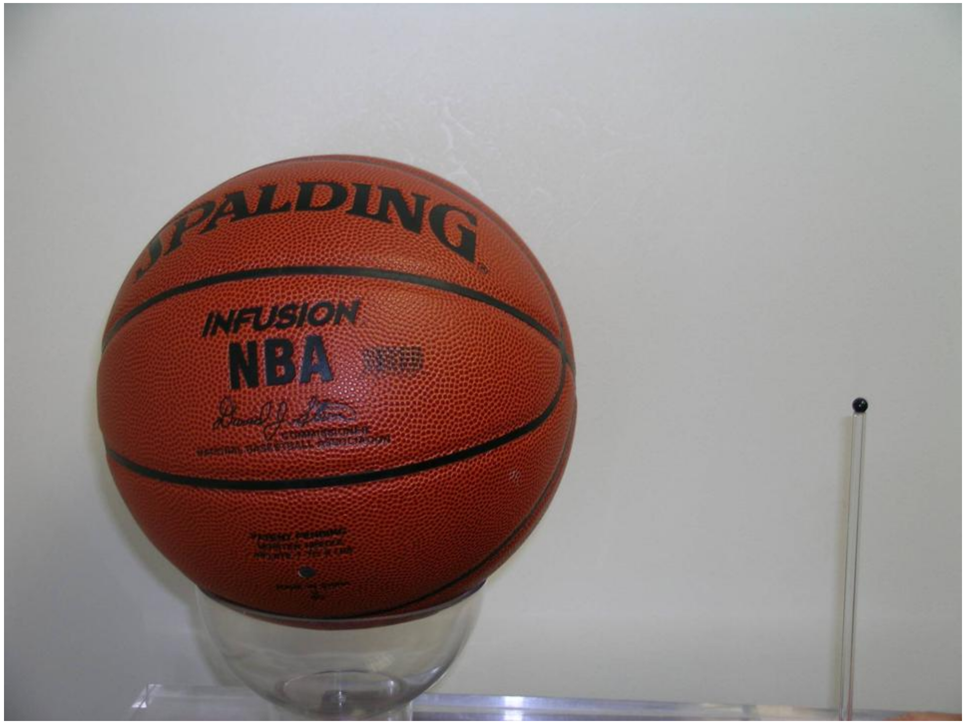
Produced record (at the time) indirect-drive DD neutron yields of > $3*10^{11}$

Bailey et al., PRL 89 (2002); Slutz et al., POP 13 (2006); Rochau et al., PPCF 49 (2007)

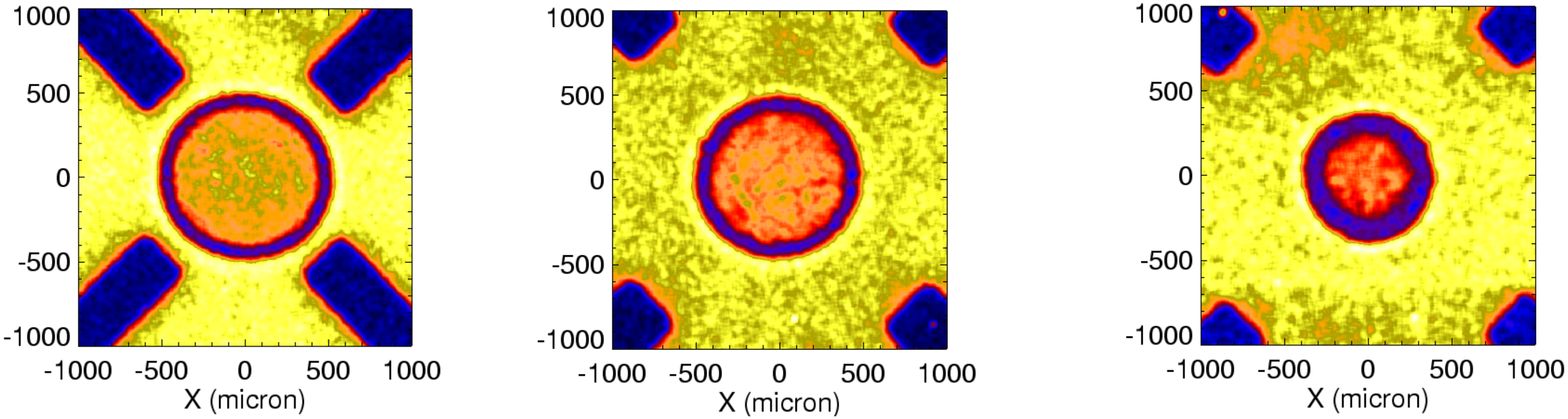
Spherical convergence is used to reach the high densities and pressures needed for ICF

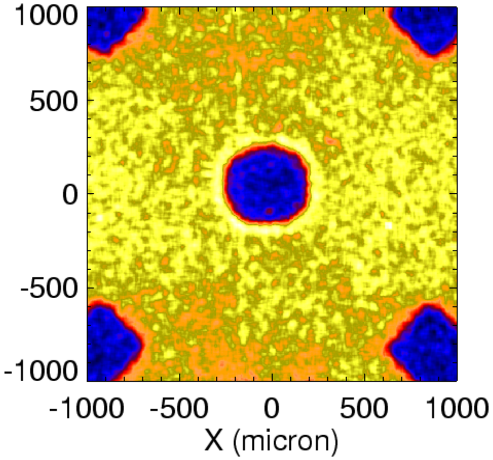
30 to 1 convergence ratio is required

- One requirement is 1-2% deviation from perfect sphere
- This means excellent pressure symmetry
- In turn this means excellent radiation symmetry

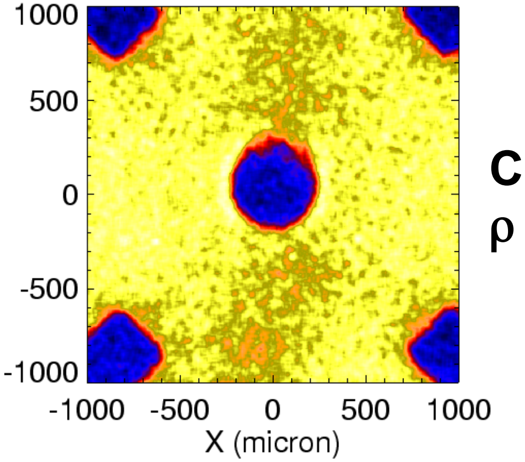


The double pinch has produced very symmetric capsule implosions





near peak CR
absolute transmission
~ 0 near center



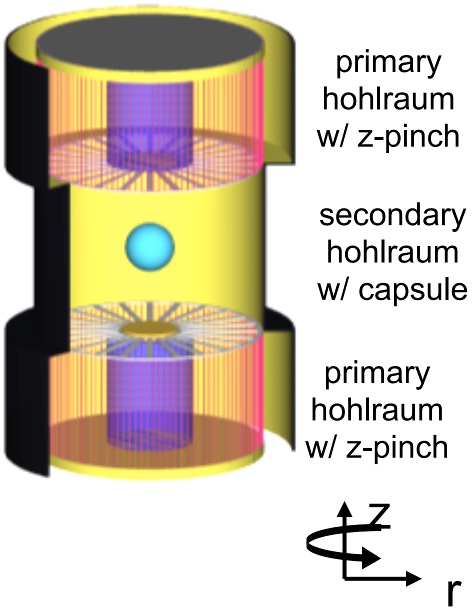
CR~ 13-20
ρ ~ 40 g/cc

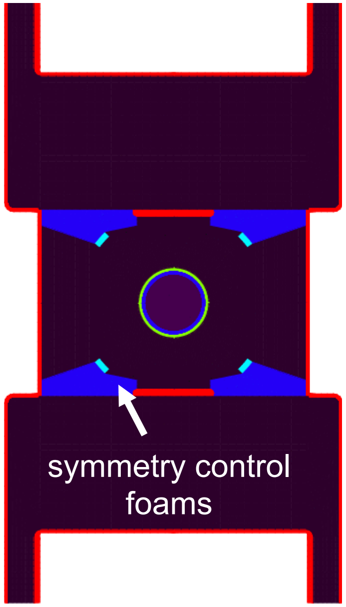
- Record convergence ratios for pulsed-power systems

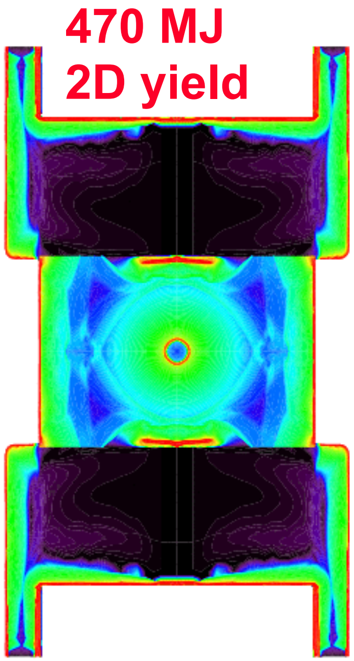
Integrated simulations demonstrate 400+ MJ fusion yield in a z-pinch driven hohlraum

Double z-pinch hohlraum fusion concept

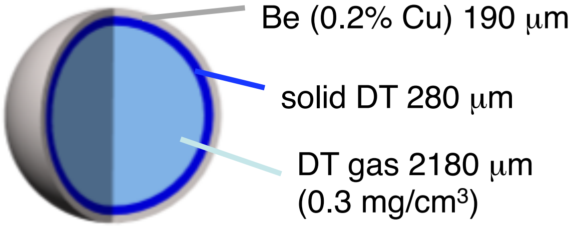
R. A. Vesey, M. C. Herrmann, R. W. Lemke *et al.*,
Phys. Plasmas (2007)



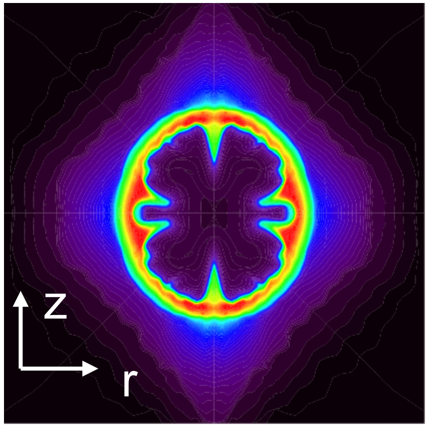




High yield capsule design



Fuel density at ignition

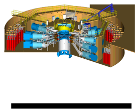


1D capsule yield 520 MJ
2D integrated yield 470 MJ

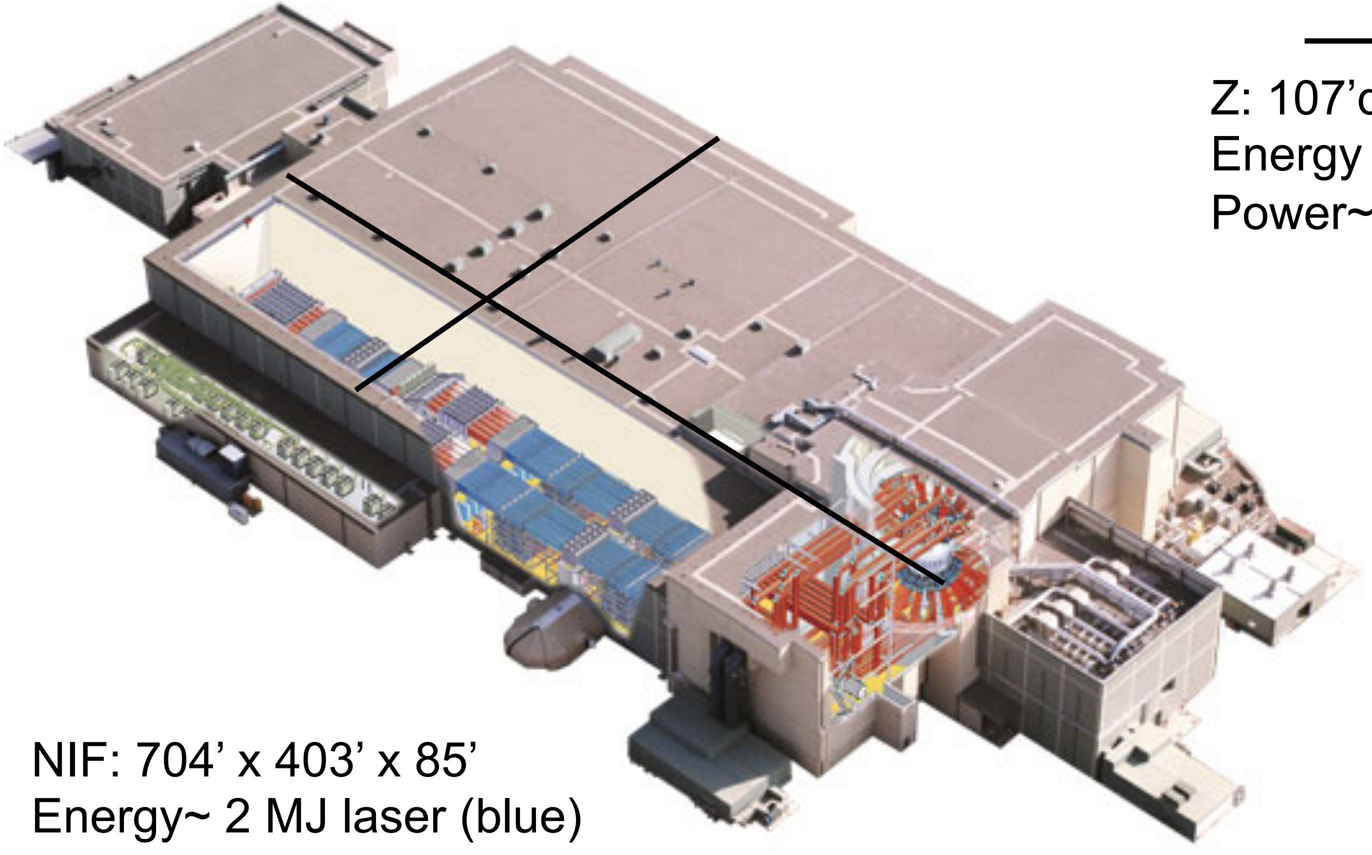
- Two z-pinches, each with 9 MJ x-ray output
- Symmetry control to 1% via geometry, shields
- Capsule absorbs 1.2 MJ, yields 400-500 MJ

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

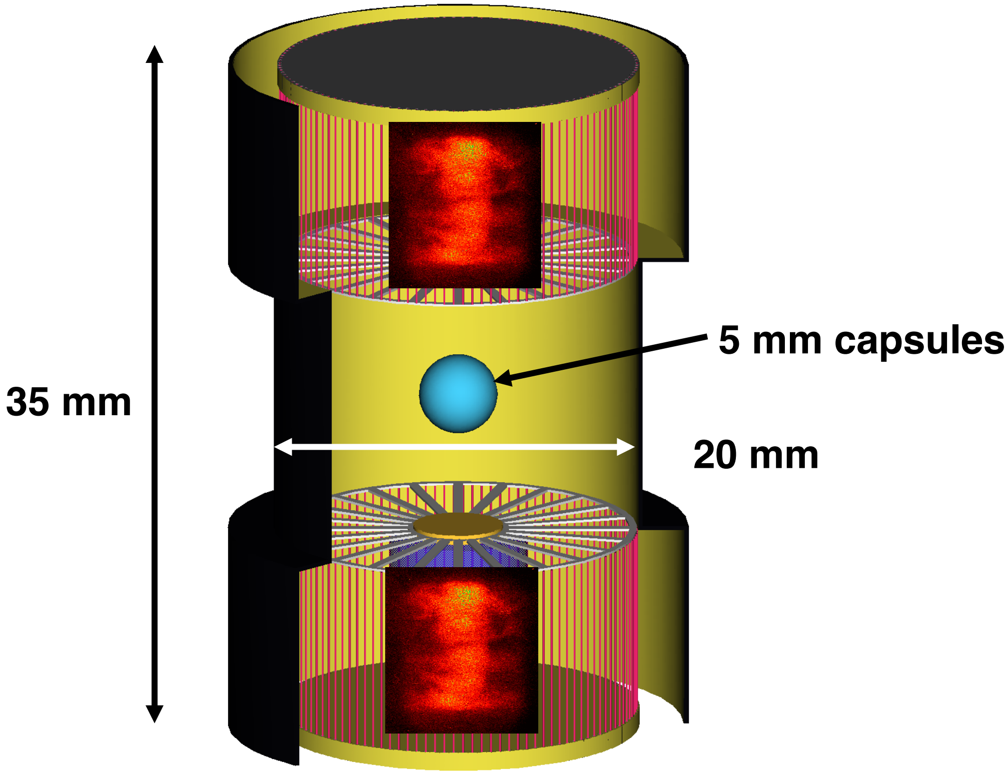


NIF: 704' x 403' x 85'
Energy~ 2 MJ laser (blue)
Power~ 500 TW

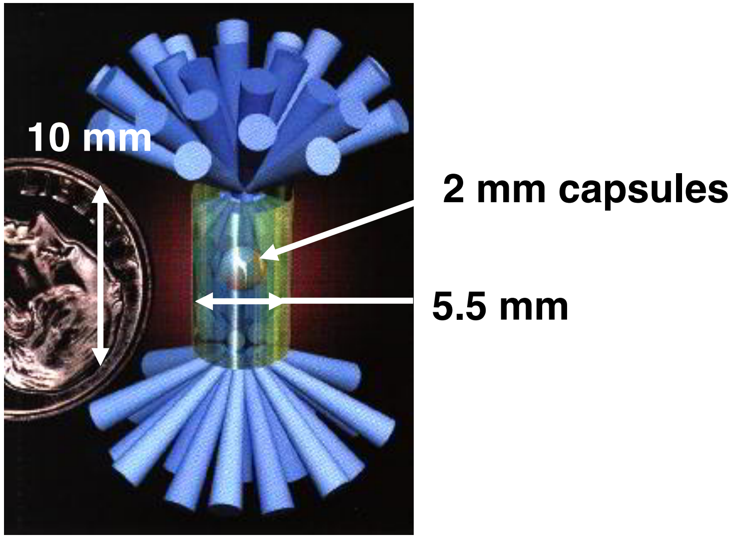
HOWEVER:

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

…. because they radiate in *bigger volumes*

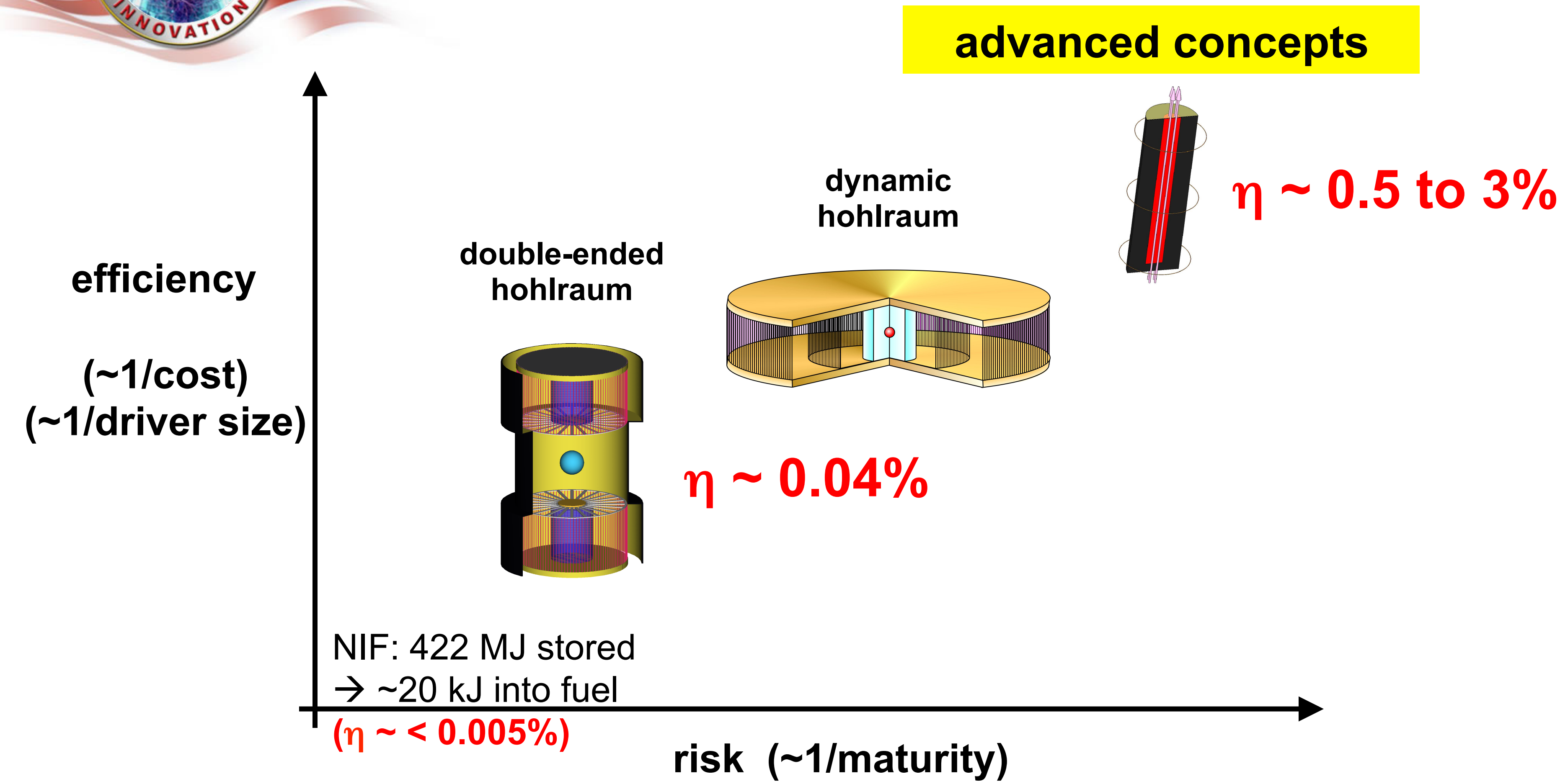


Z-pinch driven hohlraum (2 Z-pinches)
Z: 2 MJ X-ray source
High Yield requirement ~ 16 MJ x-ray source
$50 per Joule of x-rays



NIF Laser (192 laser beams)
1-2 MJ X-ray source
$4000 per Joule of x-rays

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



advanced concepts

efficiency

(~1/cost)
(~1/driver size)

risk (~1/maturity)

NIF: 422 MJ stored
→ ~20 kJ into fuel
(η ~ < 0.005%)

double-ended hohlraum

η ~ 0.04%

dynamic hohlraum

η ~ 0.5 to 3%

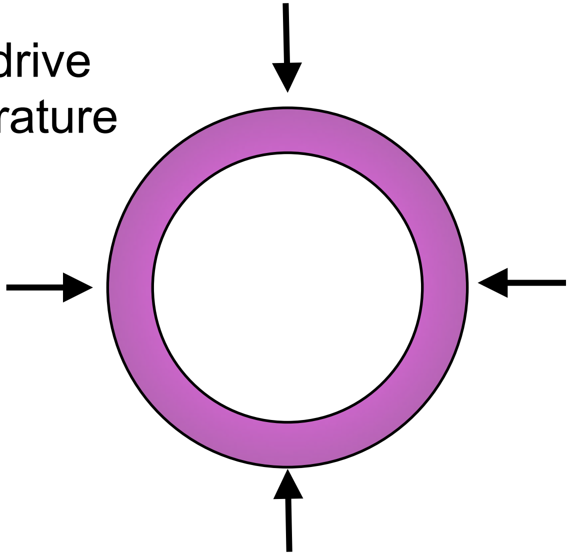
- Pulsed power can flexibly drive many target types
- **Direct fuel compression** and heating with the magnetic field could be ~20-50 times more efficient than x-ray indirect drive

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

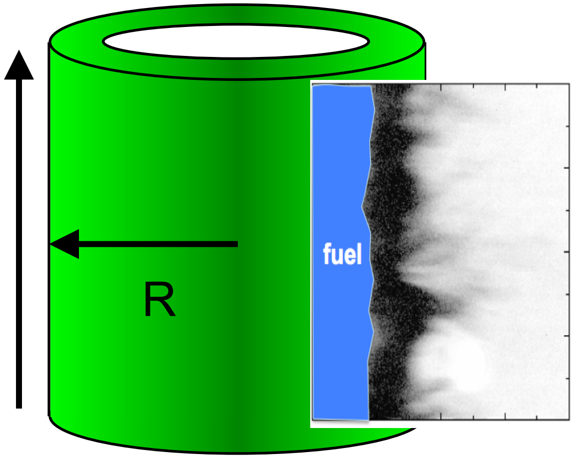


X-ray drive temperature T

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



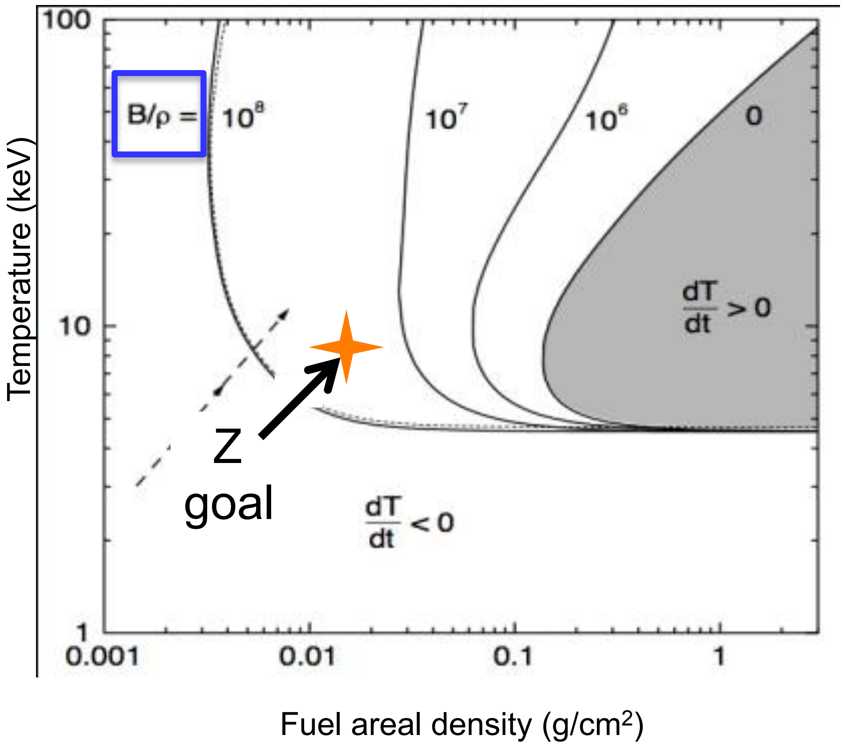
Drive current I

~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

Magnetization significantly reduces the self heating (ignition) requirements for inertial confinement fusion

*Basko et al. *Nuc. Fusion* 40, 59 (2000)



The ρr needed for ignition can be significantly reduced by the presence of a strong magnetic field, which:

- inhibits electron conduction (plasma stays hotter)
- enhances confinement of alpha particles

Lower ρr means lower densities are needed (~1 g/cc)

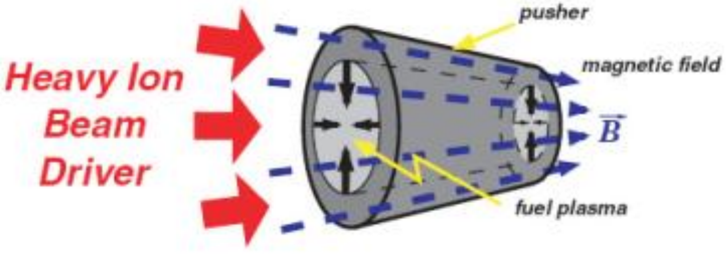
Pressure required for ignition can be significantly reduced to ~5 Gbar (<< 500 Gbar for hotspot ignition)

Large values of B/ρ are needed.

B_f~ 50-150 MG >> B_0 (0.1-1 MG aka 10-100 T)
→ flux compression is needed

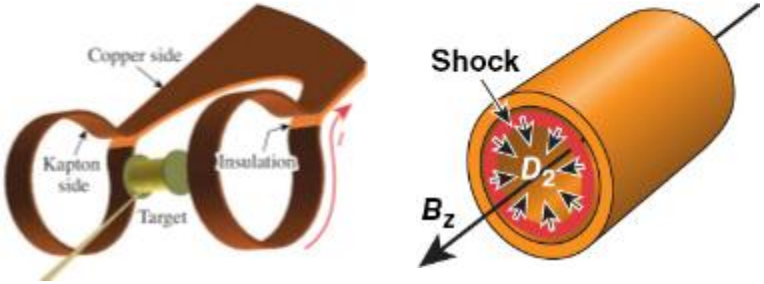
The parameter space for magnetized ICF is large, allowing for a diverse set of approaches

Max Planck / ITEP



Basko, Kemp, Meyer-ter-Vehn, *Nucl. Fusion* 40, 59 (2000)
Kemp, Basko, Meyer-ter-Vehn, *Nucl. Fusion* 43, 16 (2003)

U. Rochester LLE

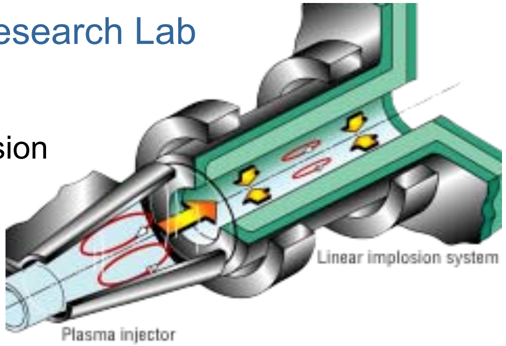


Direct drive laser implosion of cylinders
-- shock pre-heating, high implosion velocity

Gotchev *et al.*, *Bull. Am. Phys. Soc.* 52, 250 (2007)
Gotchev *et al.*, *Rev. Sci. Instr.* 80, 043504 (2009)
Gotchev *et al.*, Phys. Rev. Lett. 103, 215004 (2009)
Knauer *et al.*, *Phys. Plasmas* 17, 056318 (2010)

Los Alamos / Air Force Research Lab

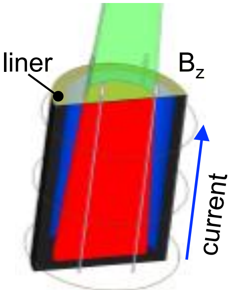
Field Reversed Configuration
Shiva Star generator
~20 μs, 0.5 cm/μs liner implosion

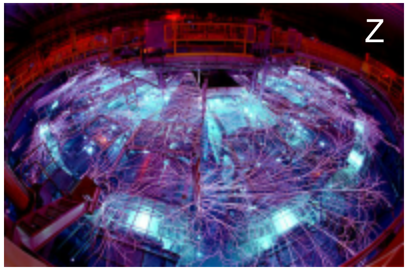


Taccetti, Intrator, Wurden *et al.*, *Rev. Sci, Instr.* 74, 4314 (2003)
Degnan *et al.*, *IEEE Trans. Plas. Sci.* 36, 80 (2008)

Sandia National Laboratories

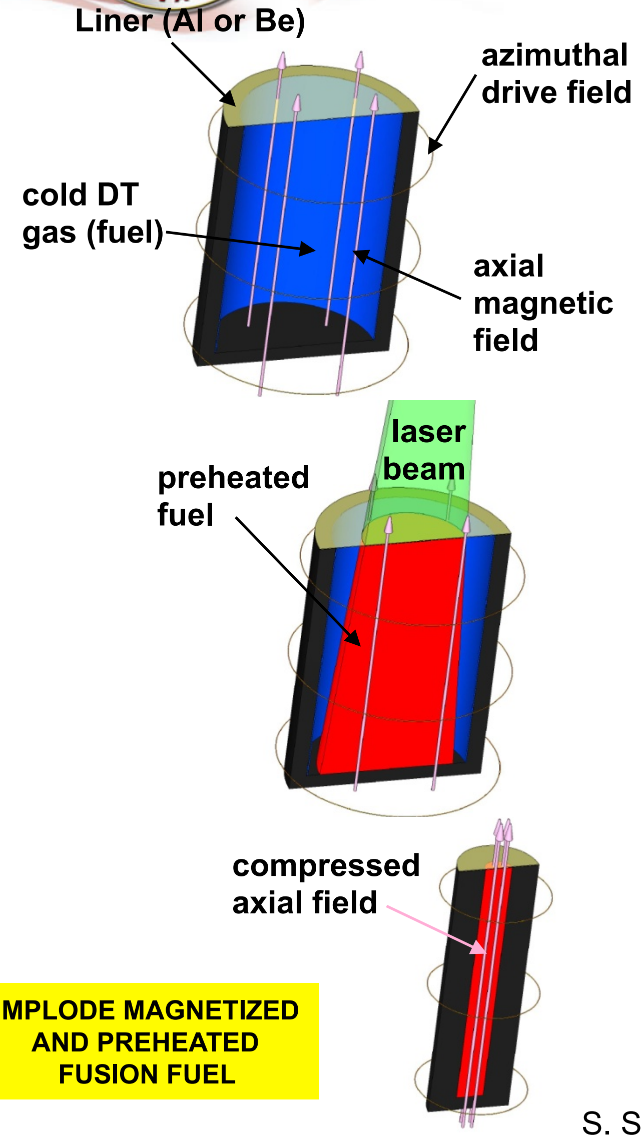
Magnetized Liner Inertial Fusion (MagLIF)





S. A. Slutz *et al.*, *Phys. Plasmas*, 17, 056303 (2010).
D.B. Sinars *et al.*, Phys. Rev. Lett. 105, 185001 (2010)

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



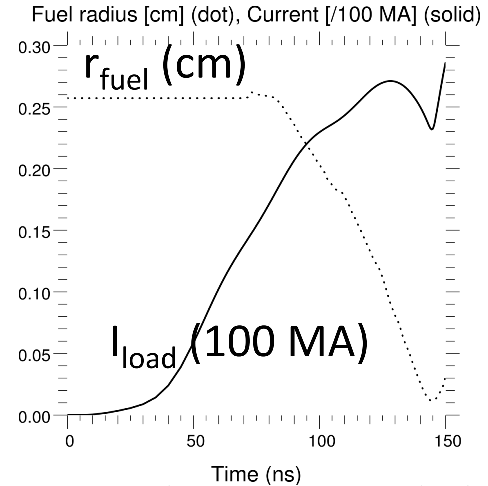
IMPLODE MAGNETIZED AND PREHEATED FUSION FUEL

- An initial ~10-50 T axial 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 Bz 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).

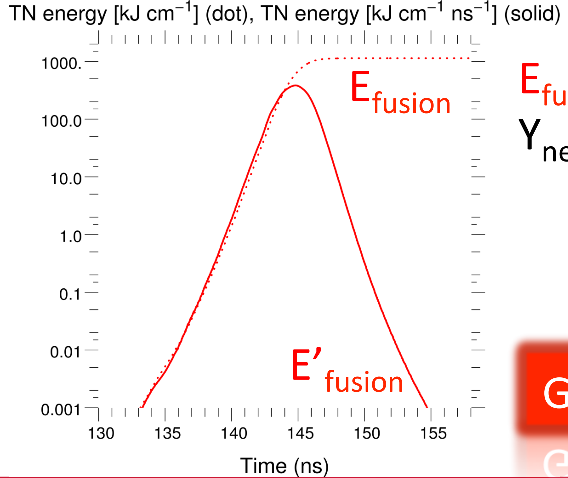
MagLIF appears to be a very exciting concept in ideal 1D HYDRA simulations

Preliminary 1D point design:
Be liner, A.R.= 6, 180 mg/cm
DT gas at 3 mg/cc, 250 eV preheat, B_z^0=30 T
95 kV charge voltage on Z (27 MA)

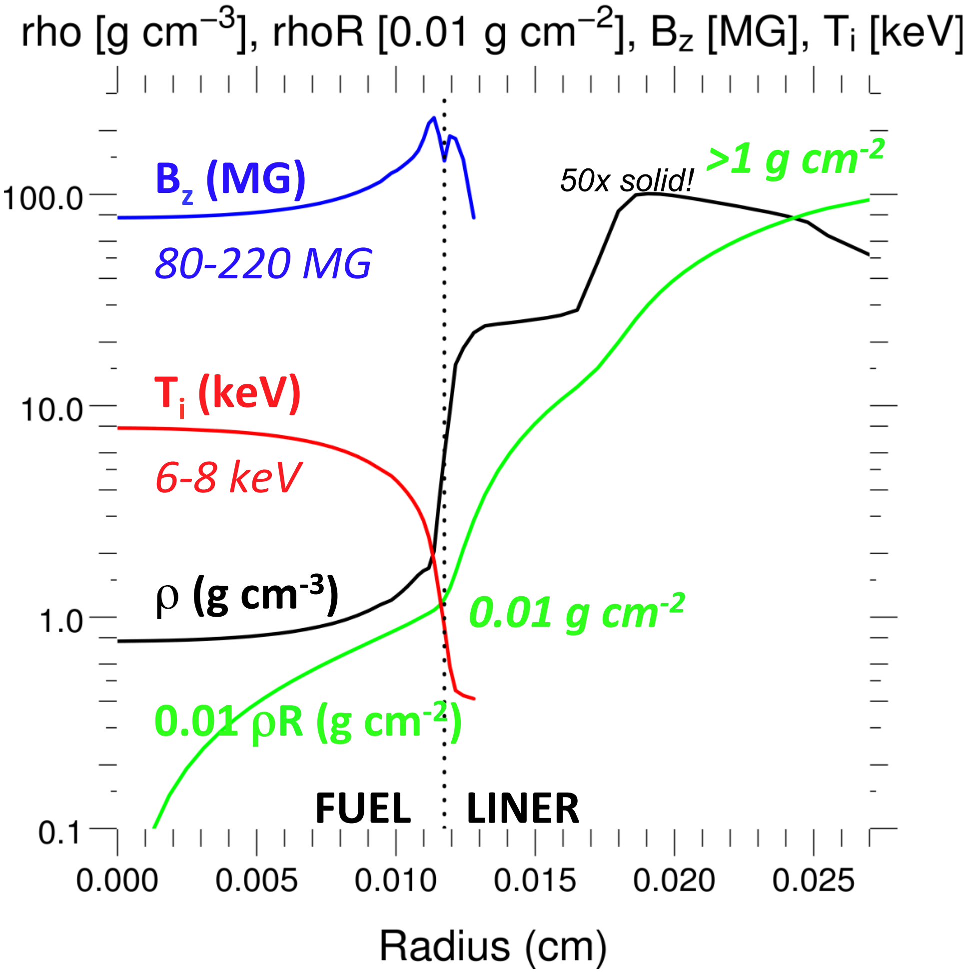


$\langle v_{imp}\rangle^{max}$ = 83 km s^{-1}
E_{fuel}^{abs} = 113 kJ cm^{-1}
E_{targ}^{abs}= 1026 kJ cm^{-1}

$E_{targ}^{abs}/E_{mag}^{load}$ = 47%
(drive efficiency)



E_{fusion}= 1130 kJ cm^{-1}
Y_{neut} = 4e17 cm^{-1}


Stagnation parameters (t = 145 ns)

Gain = 10.0 (fuel), 1.1 (target)

C.R. = 22, P_{stag} = 5 Gbar

MagLIF appears to be a very exciting concept in ideal 1D HYDRA simulations

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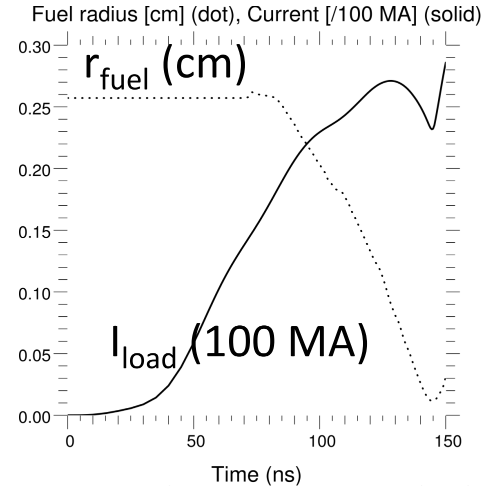

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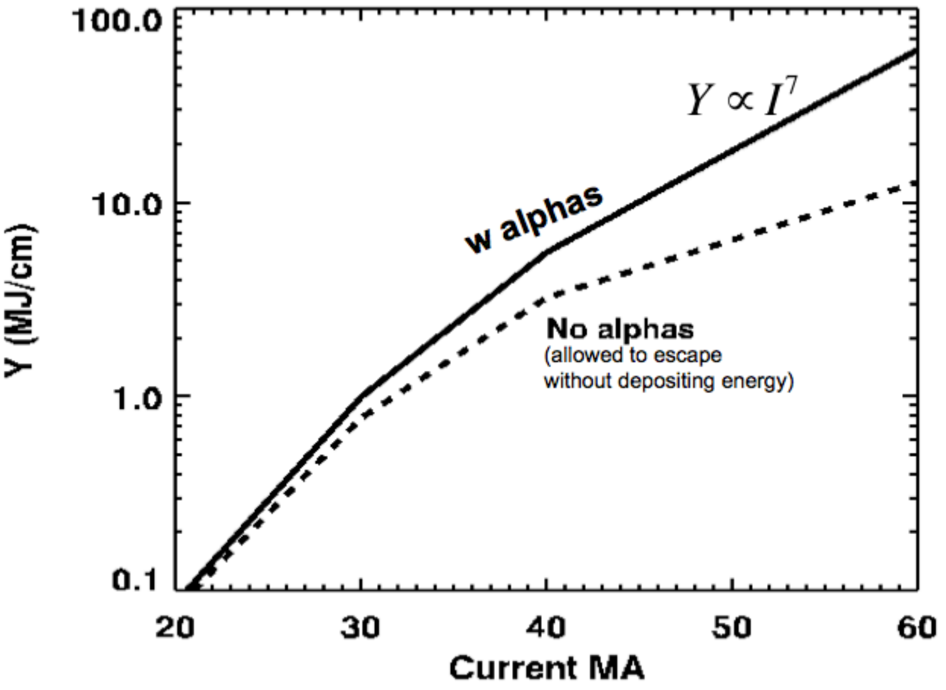

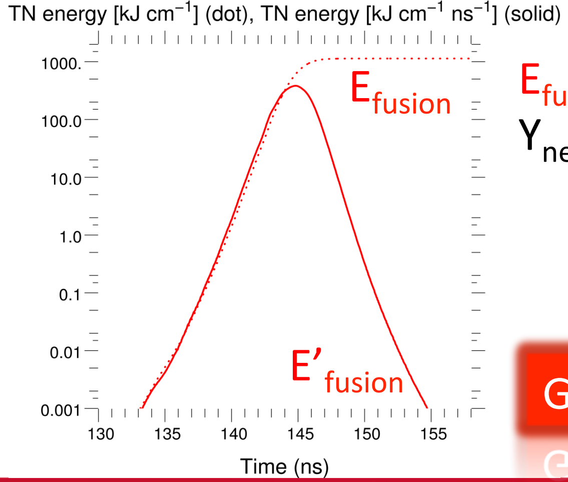

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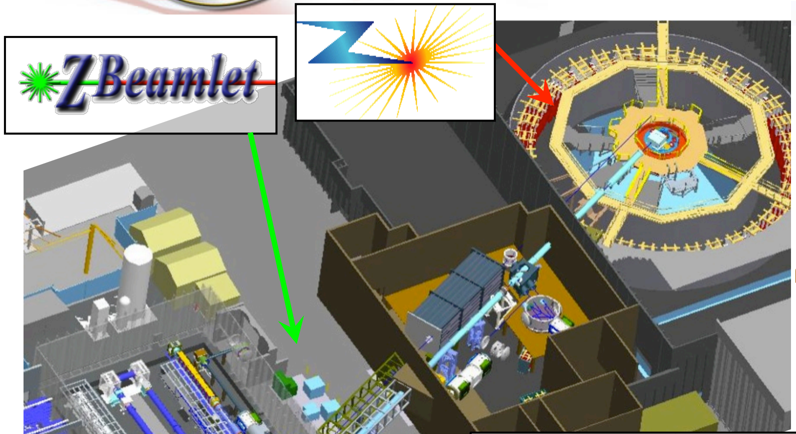
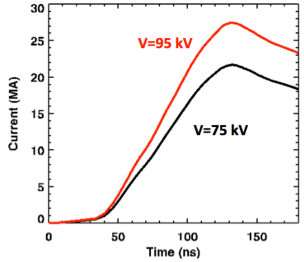
Gain = 10.0 (fuel), 1.1 (target)

C.R. = 22, P_{stag} = 5 Gbar

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

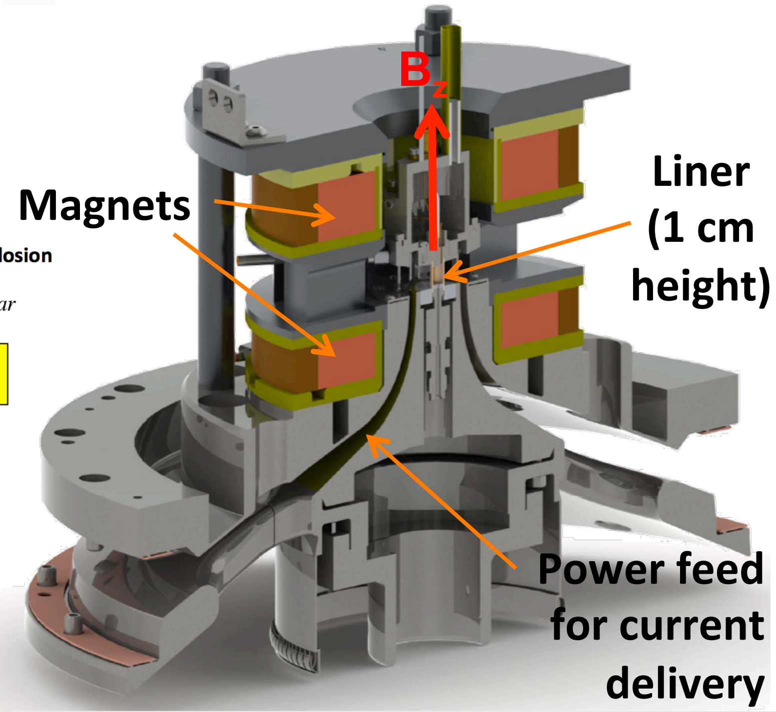




Magnetically-Driven Cylindrical Implosion

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

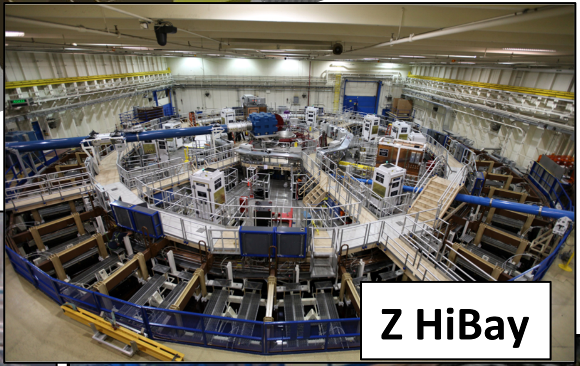
140 MBar is generated at R = 1 mm and I = 30 MA



Magnets

Liner (1 cm height)

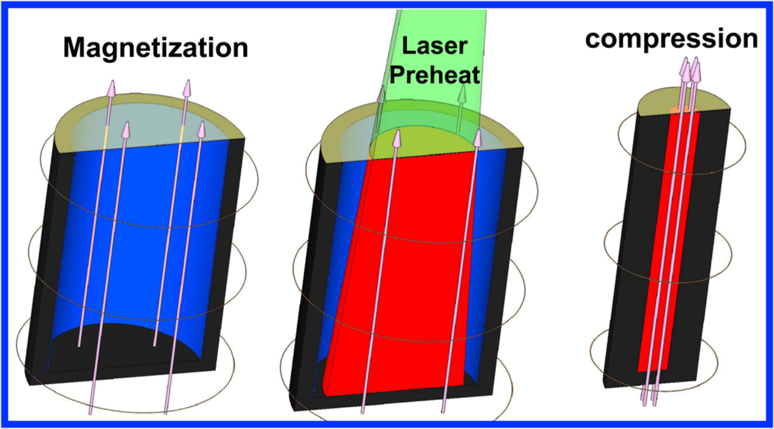
Power feed for current delivery



Z HiBay

Z-Beamlet HiBay

Applied-B Capacitors



Magnetization

Laser Preheat

compression

An integrated 2D model seeks to realistically simulate experiments as they would occur on Z

A number of parameters and constraints must be self-consistently included and integrated into one simulation:

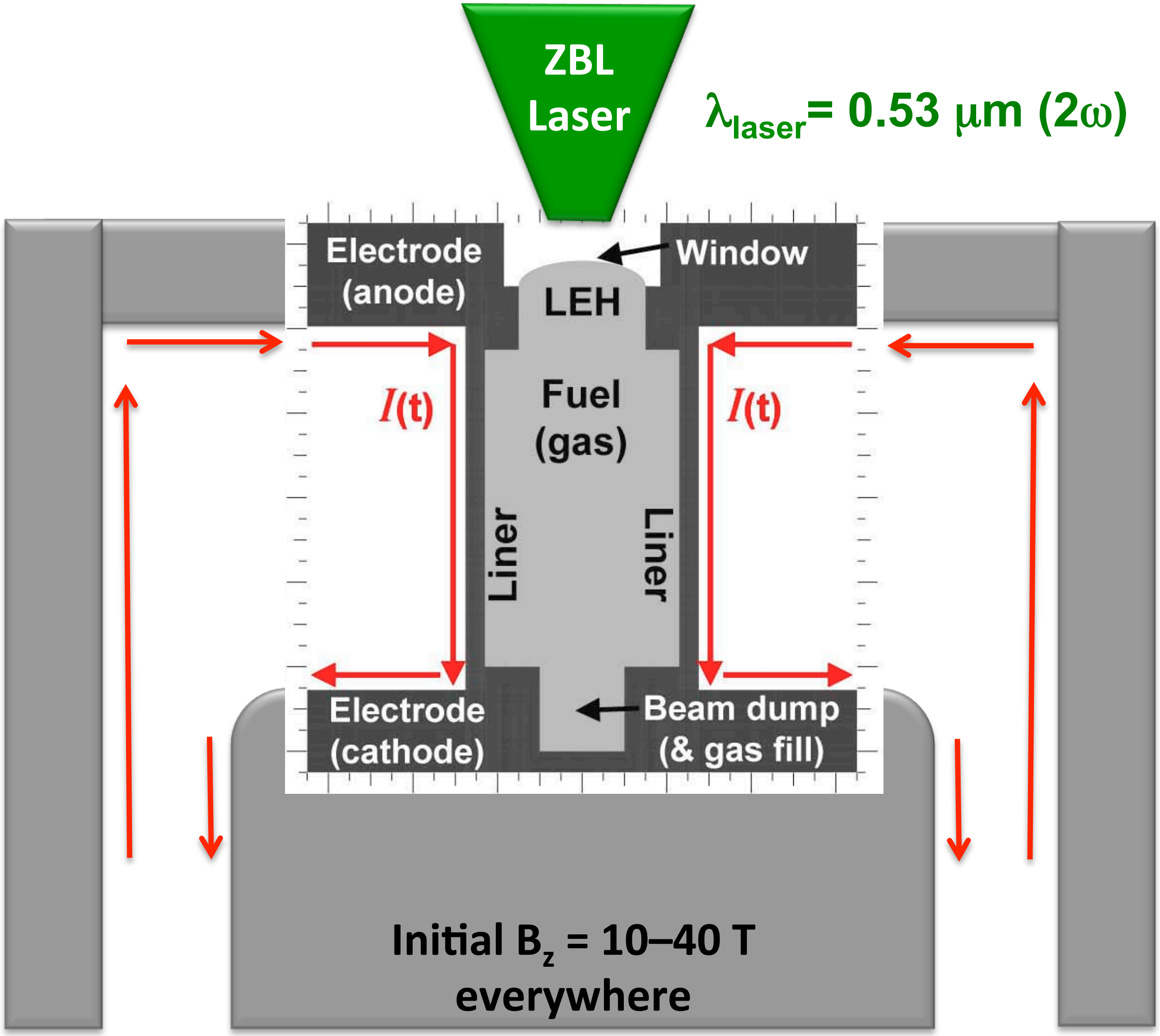
(1) Laser

(2) Laser entrance hole (LEH) and window

(3) Liner and circuit

(4) Electrode end caps

(5) Component interactions, timing, and optimization



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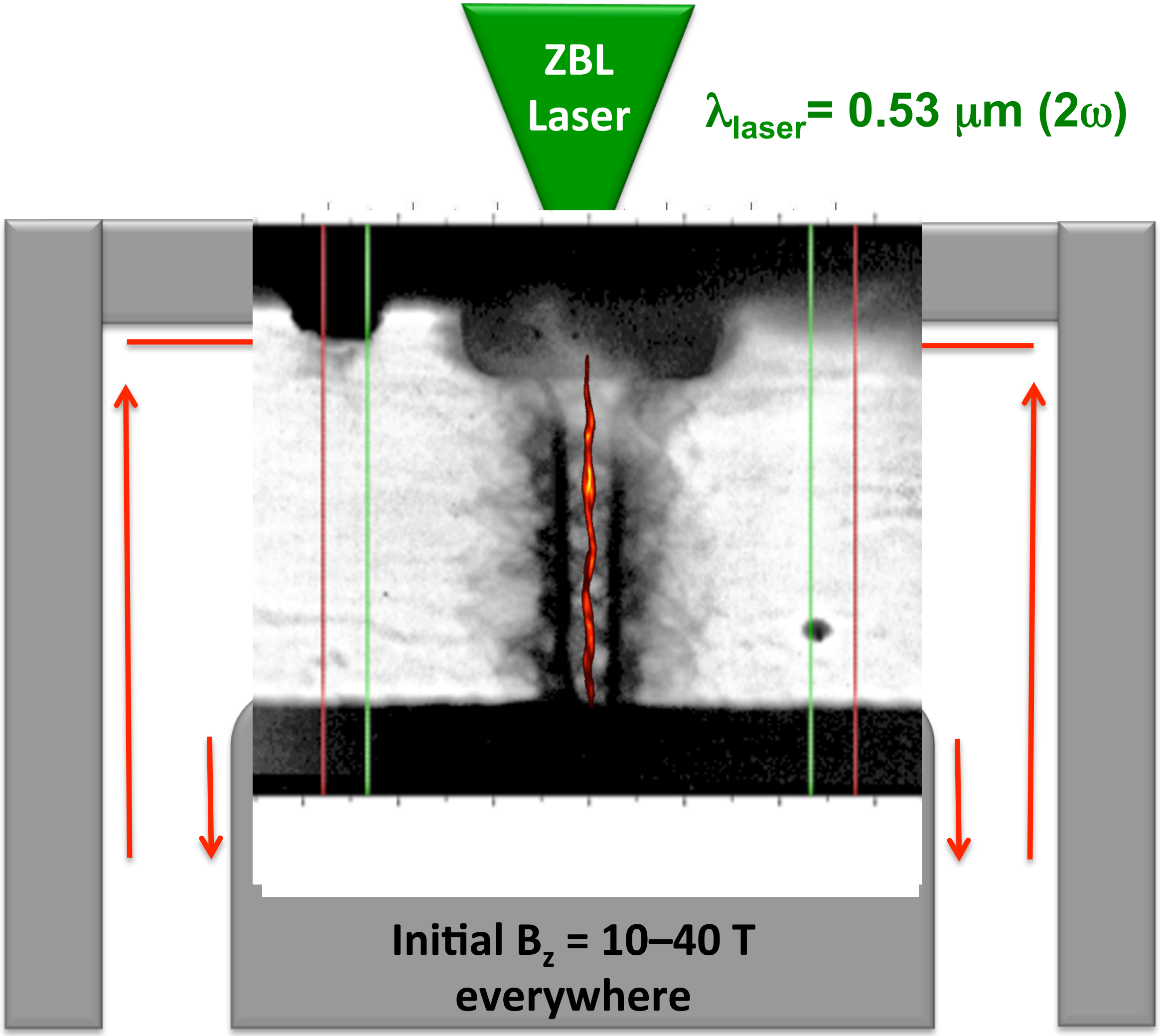
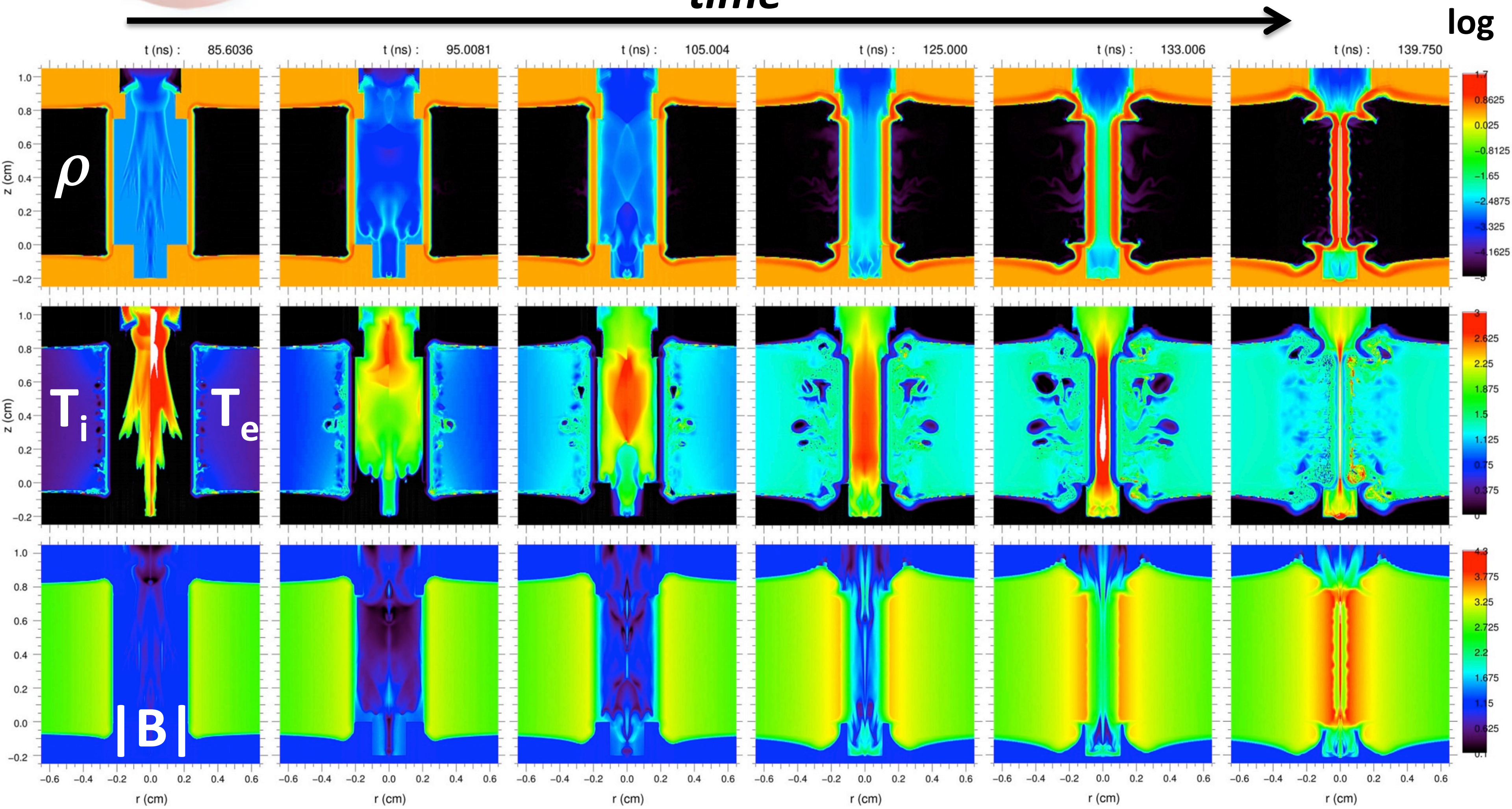


Integrated 2D HYDRA simulation of near-term experiments on Z using available parameters

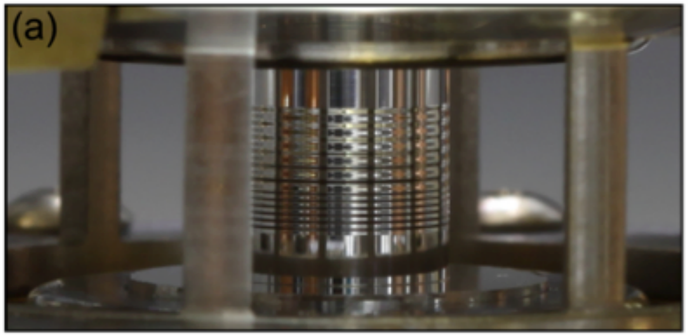
time



Comparison between ideal 1D and integrated 2D simulation using available parameters

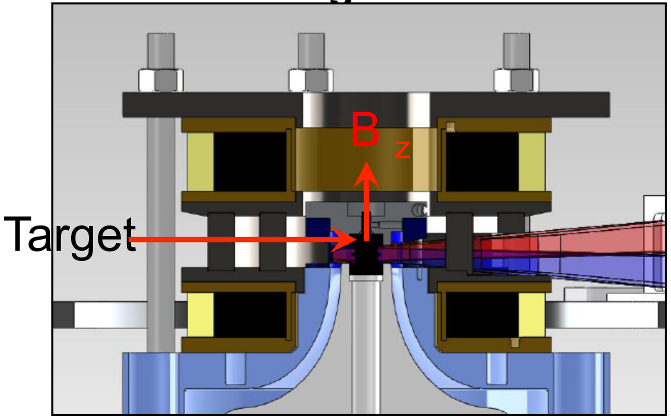
Parameter	1D ideal	2D integrated
E_{gas}^{abs}	2.20 kJ	1.74 kJ
m_{loss}	0%	43%
Φ_{loss}	36%	38%
CR_{2D}	28 (r_{stag} 84 μm)	37 (r_{stag} 63 μm)
T_i^{peak}	5.0 keV	6.5 keV
$\langle T_i \rangle^{DD}$	2.9 keV	3.2 keV
ρ_{gas}^{stag}	0.6 g cm^{-3}	0.5 g cm^{-3}
ρR_{liner}^{stag}	1.0 g cm^{-2}	0.9 g cm^{-2}
P^{stag}	2.5 Gbar	2.2 Gbar (peak in bottle)
$B_z^f r_{stag}$	4.1e5 G cm (r_{stag}/r_{α} 1.5)	5.3e5 G cm (r_{stag}/r_{α} 2.0)
Y_n^{DD}	2.6e14 (in 7.5mm)	6.1e13 (24% of 1D)
Y_n^{DD}/Y_n^{DT}	23	44
t_{burn}^{FWHM}	3.2 ns	2.1 ns

All the necessary capabilities for MagLIF have been commissioned, and experiments are happening now



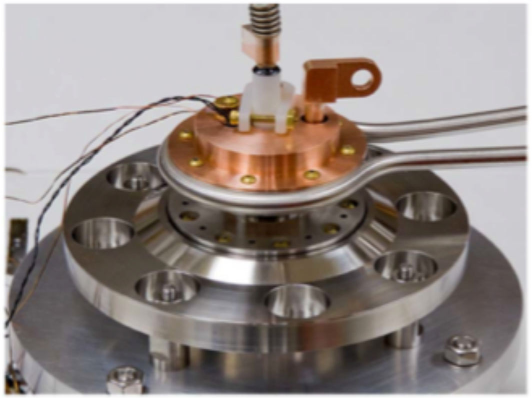
High-quality target fabrication on site

Externally-Applied Axial Magnetic Fields



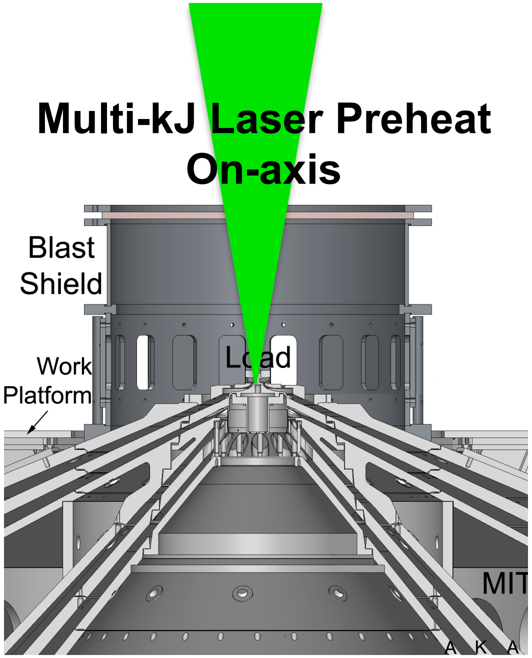
Challenges

- Maintain magnetic insulation in feeds
- Allow diagnostic access
- Measure B-field compression



Cryogenic cooling of liner targets has been demonstrated (liquid D2)

Multi-kJ Laser Preheat On-axis

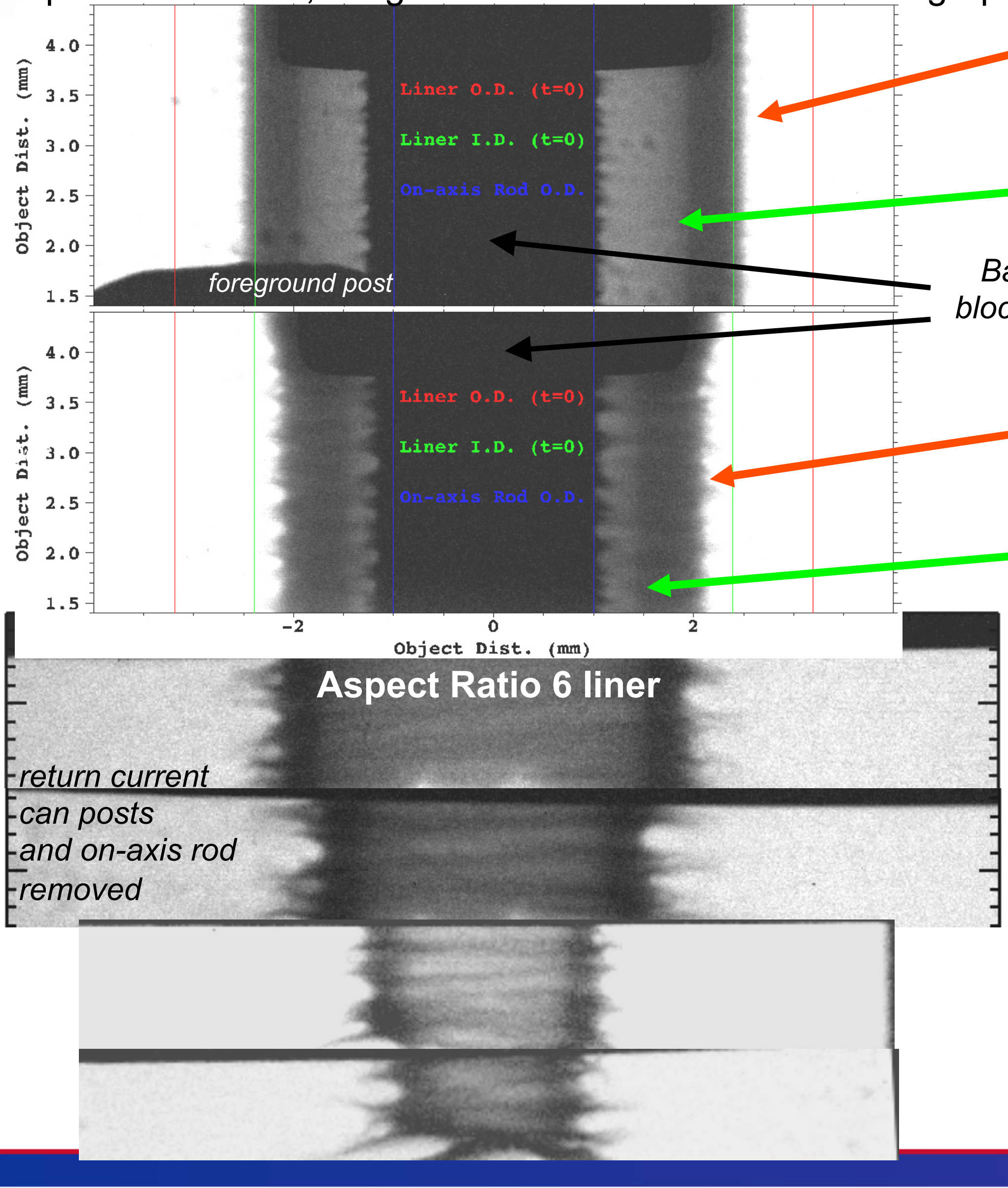


Challenges

- Maximize laser energy on target
- Protect final optics from debris
- Measure preheated fuel conditions

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

Aspect ratio 4 liner, imaged with 2-frame 6.151 keV radiography



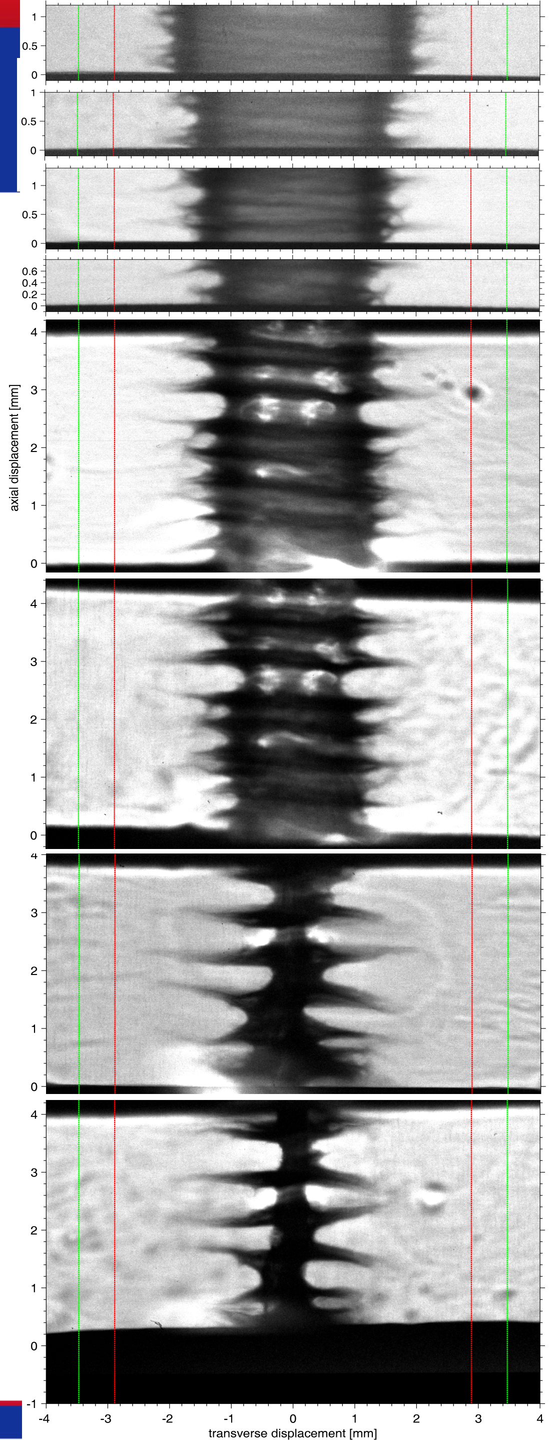
Outer *Be* surface

Inner *Be* surface

Backlighter view of axis blocked by two posts in the return current can

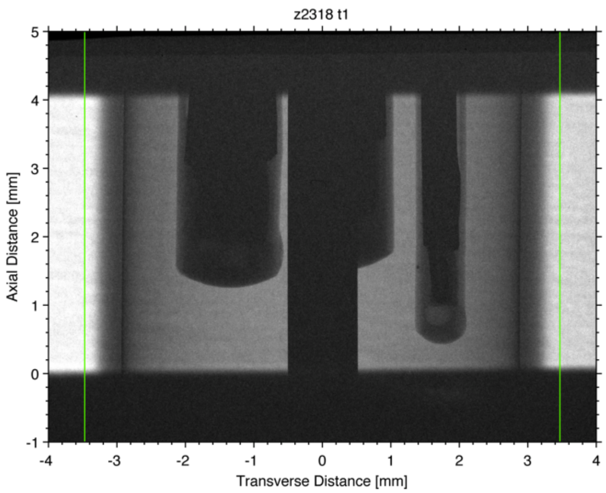
Outer *Be* surface

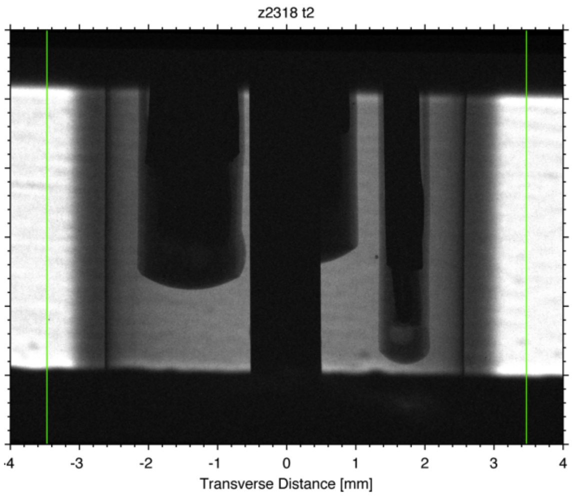
Inner *Be* surface

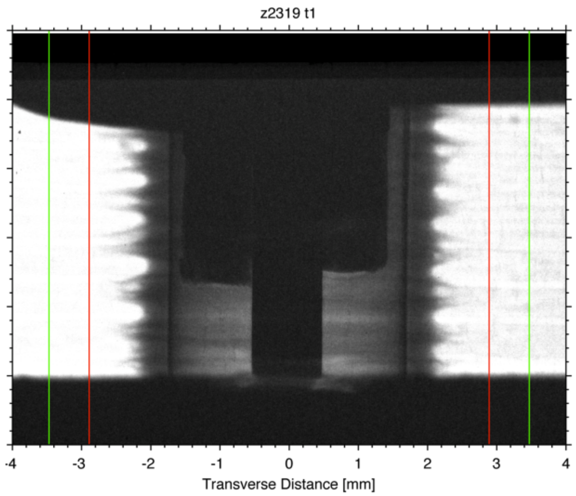


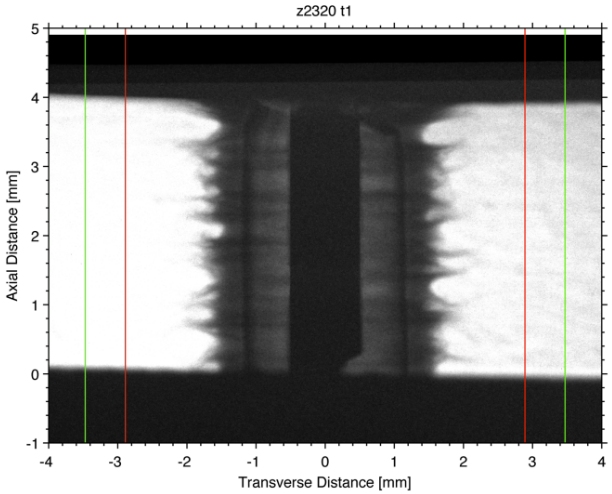
axial displacement [mm]
transverse displacement [mm]
-4
-3
-2
-1
0
1
2
3
4
0.5
0.6
0.4
0.2

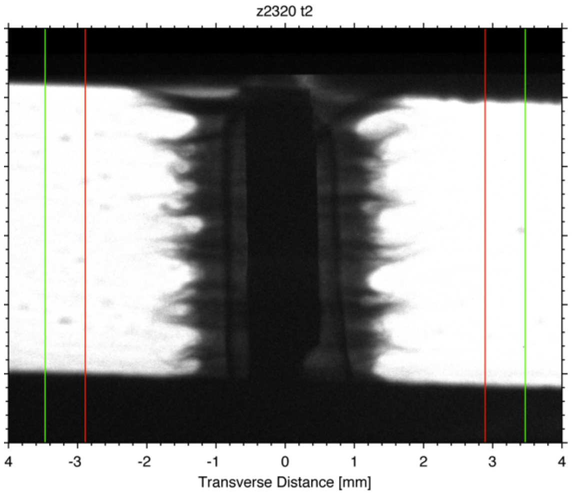
Recent studies examined a thin *Al* sleeve placed inside a *Be* liner to study the integrity of the inner surface


z2318 t1

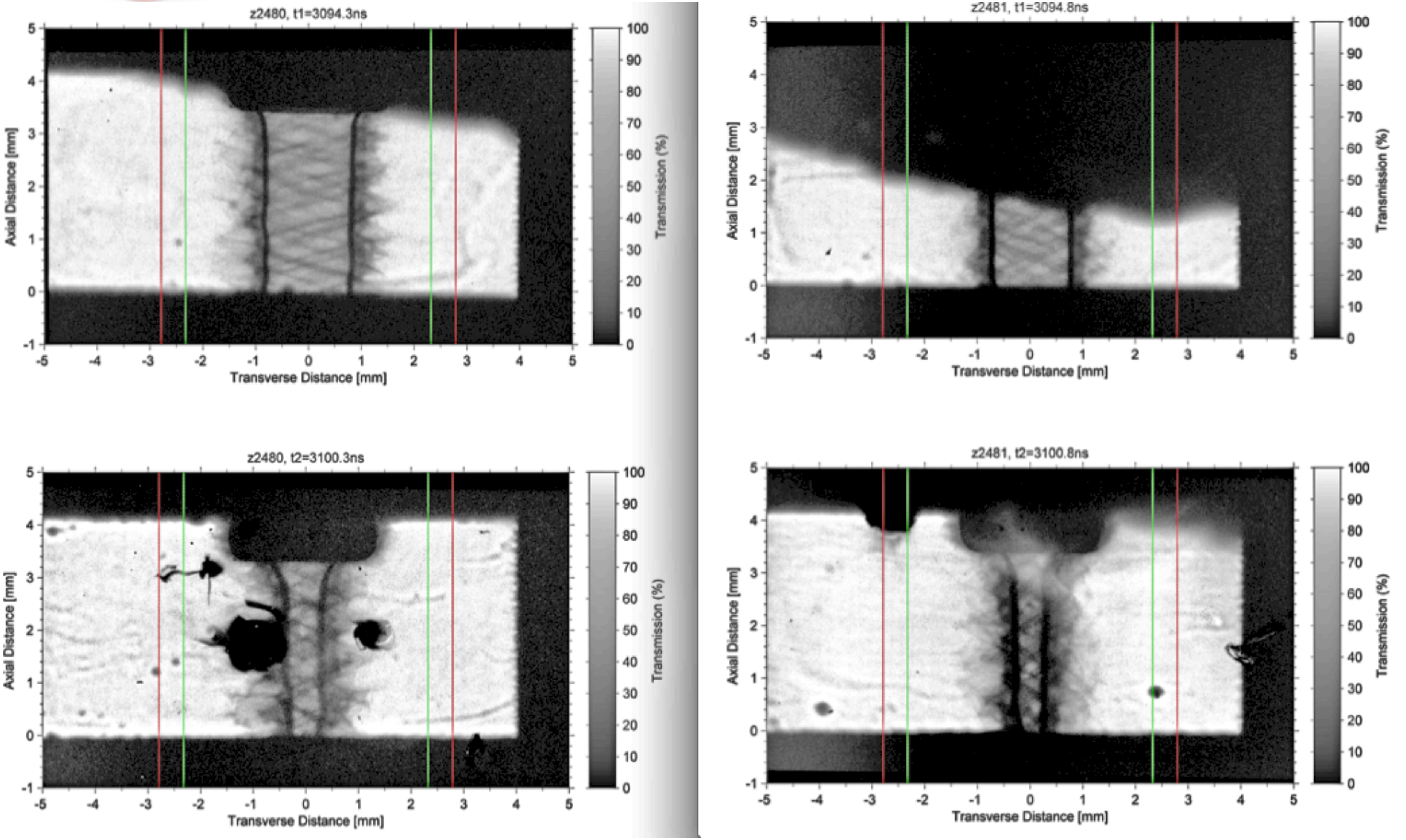

z2318 t2


z2319 t1

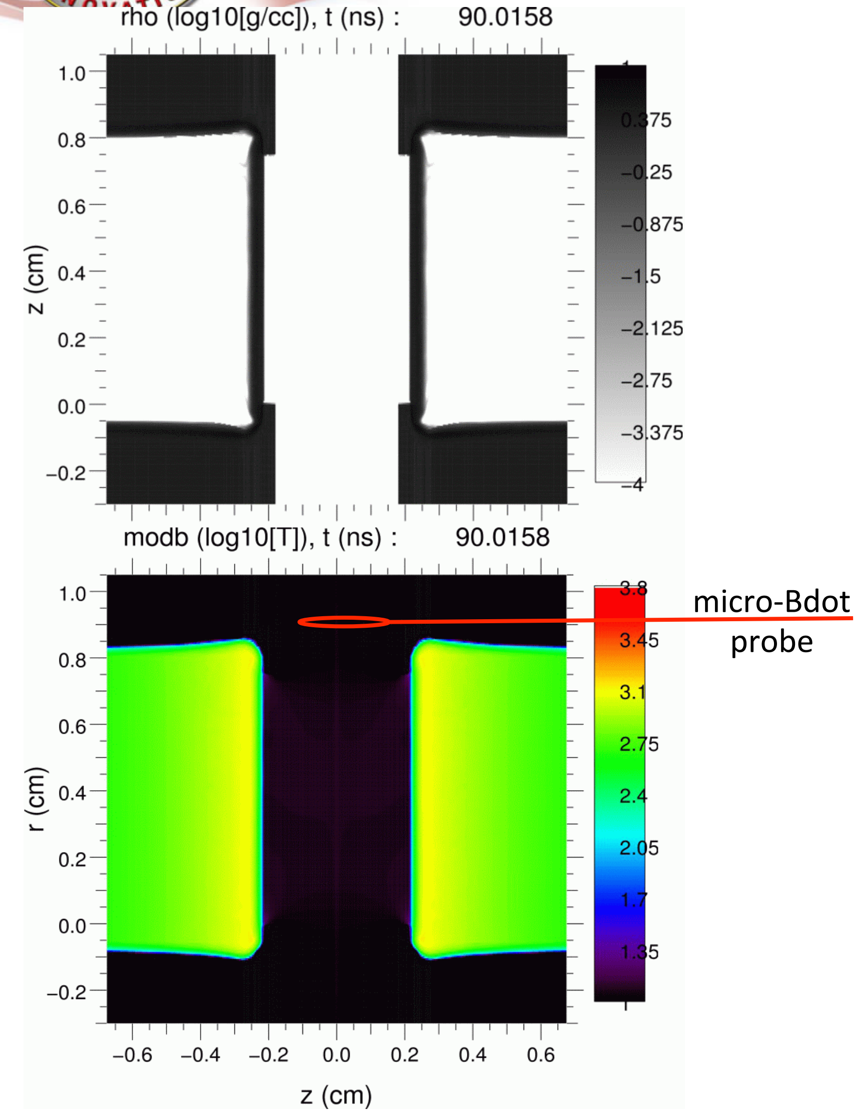

z2320 t1

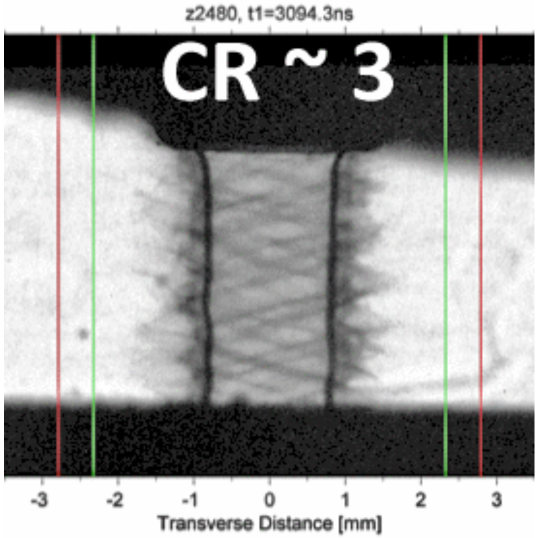

z2320 t2

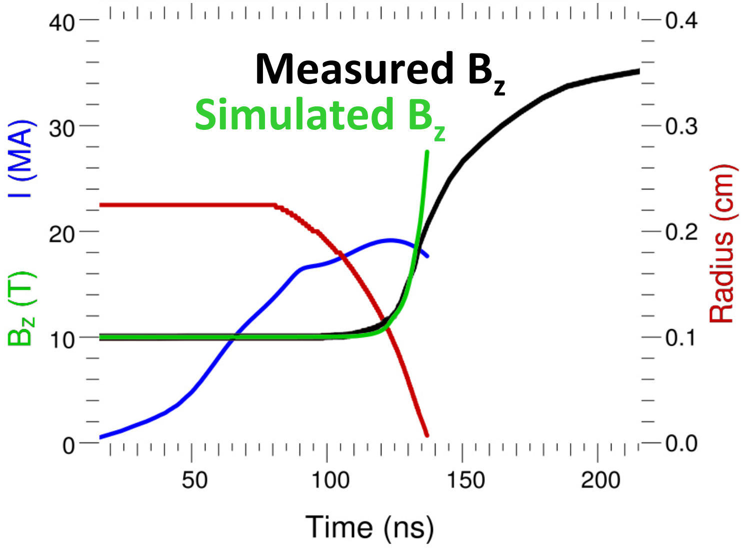
Recent experiments with B_z^0=7 T and 10 T, and I_{max}~17 MA, demonstrate excellent inner surface integrity at CR ~ 7



Liner-only flux compression experiments (with B_z, without laser) measure $B_z(t)$ and $r_{inner}(t)$







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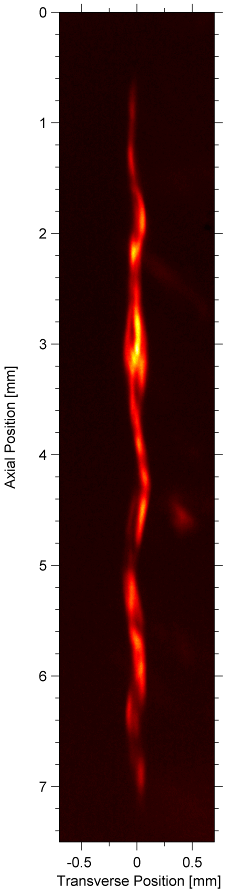
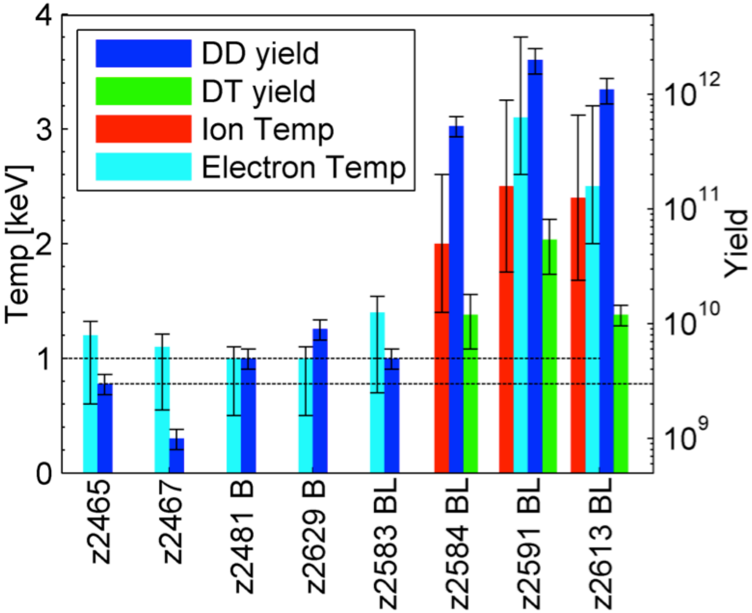
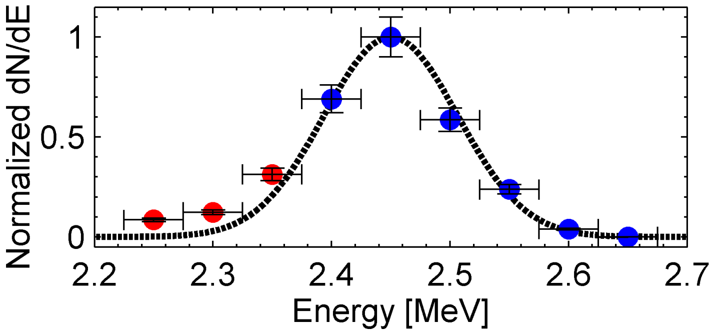
First integrated (with laser) MagLIF experiments successfully demonstrated the concept



- **Thermonuclear neutron generation up to 2e12**
- **Fusion-relevant stagnation temperatures**
- **Stable pinch with narrow emission column at stagnation**
- **Successful flux compression**





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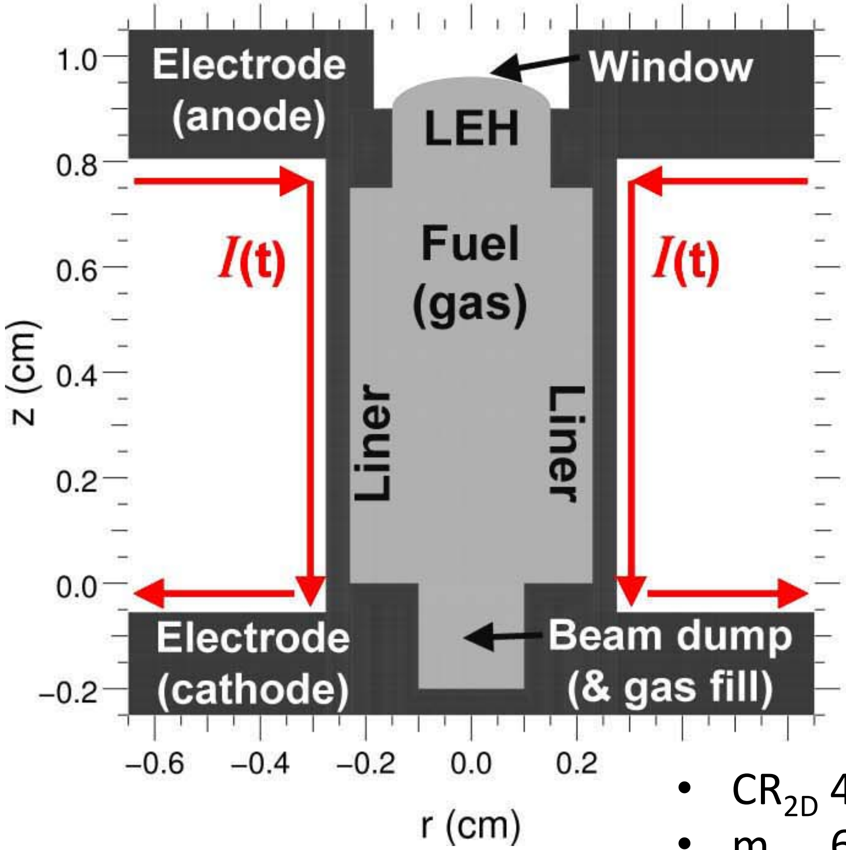
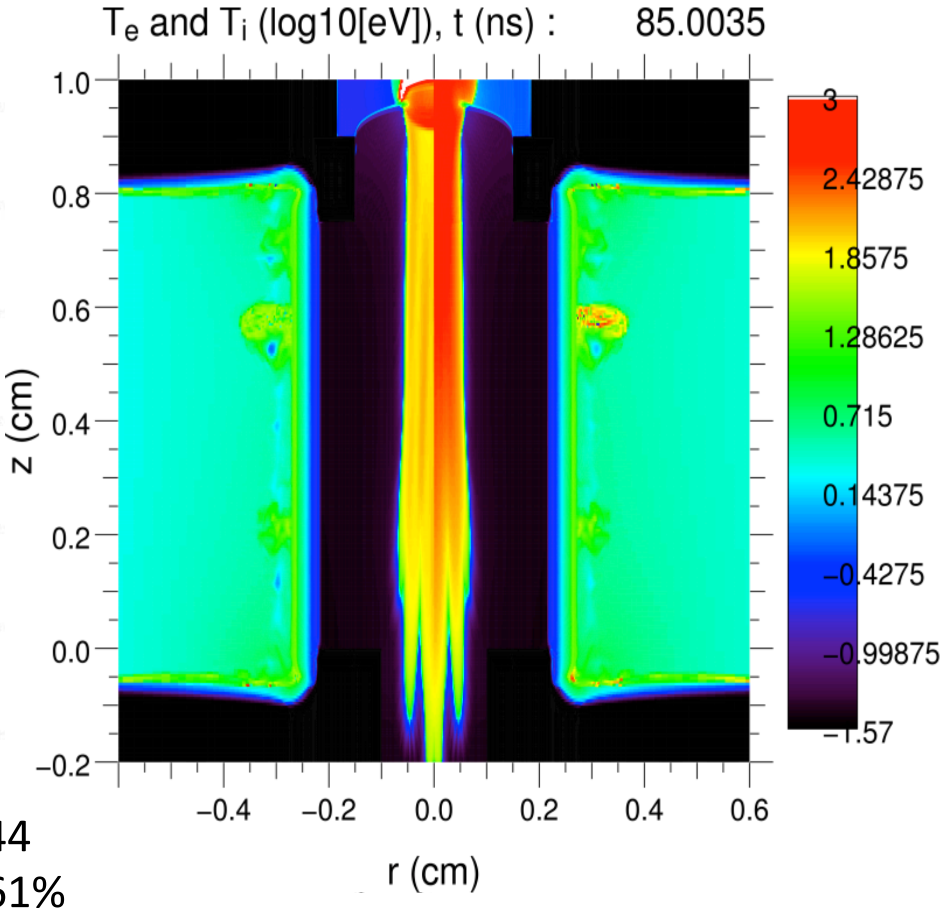
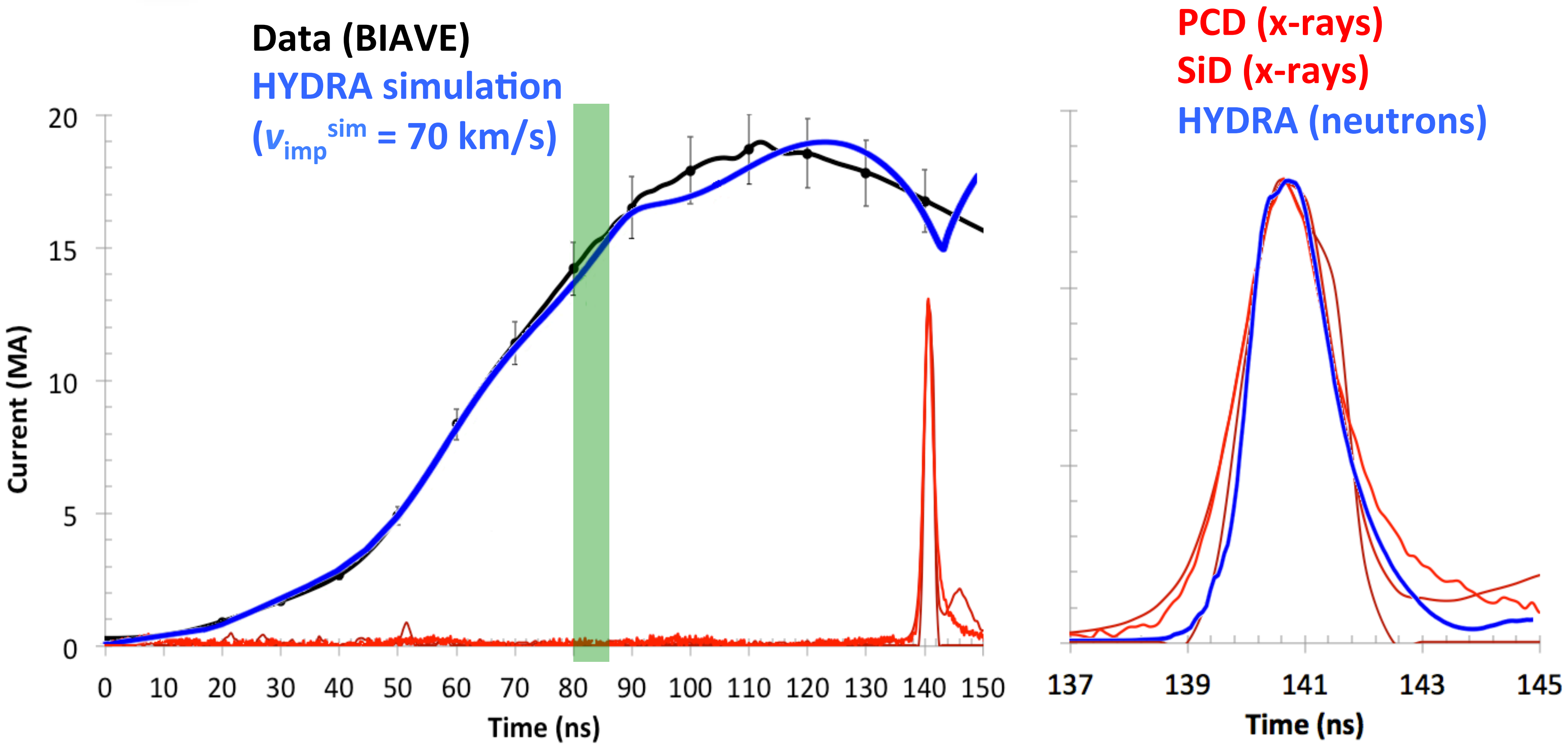
Estimate for laser energy transmission is FWHM~450±150 μm gaussian beam with 150±50 J



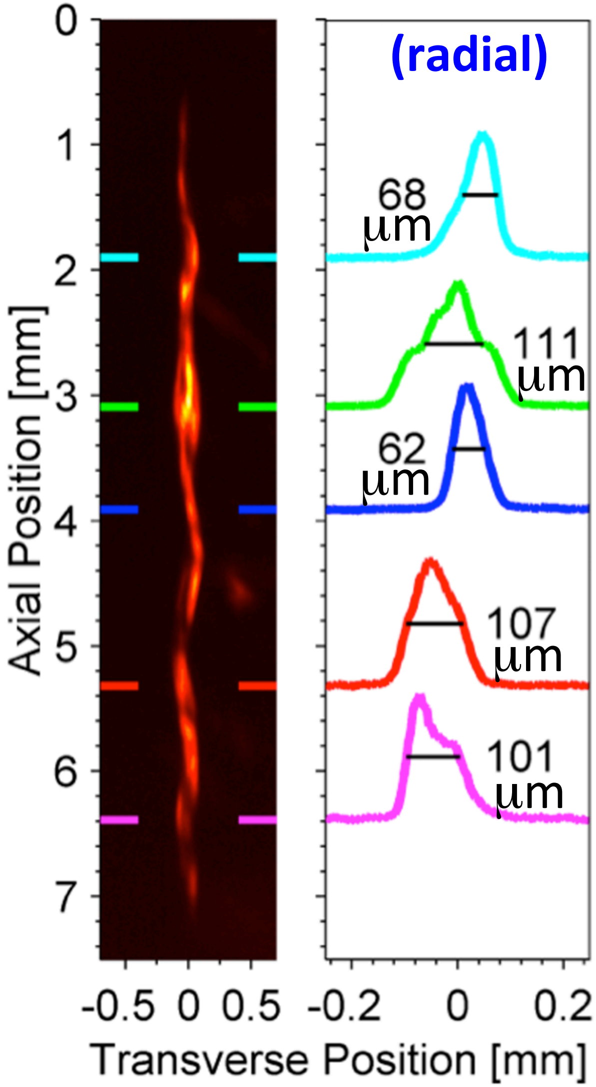


- CR_{2D} 44
- m_{loss} 61%
- Φ_{loss} 53%
- $\langle T_i \rangle^{DD}$ 3.0 keV
- $\langle T_{e/i} \rangle$ 2.7 keV

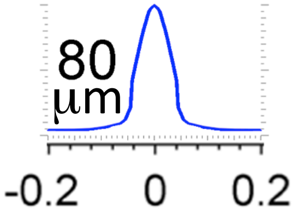
Current and implosion time agree within error

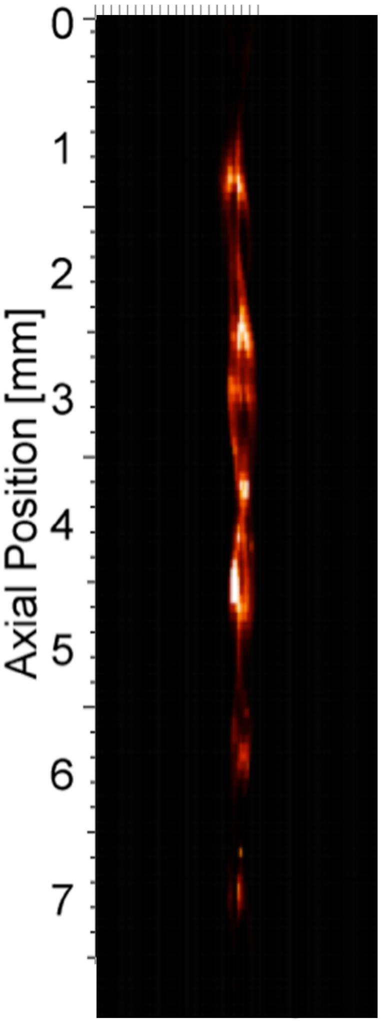


Comparison of stagnation column shape



HYDRA (radial)





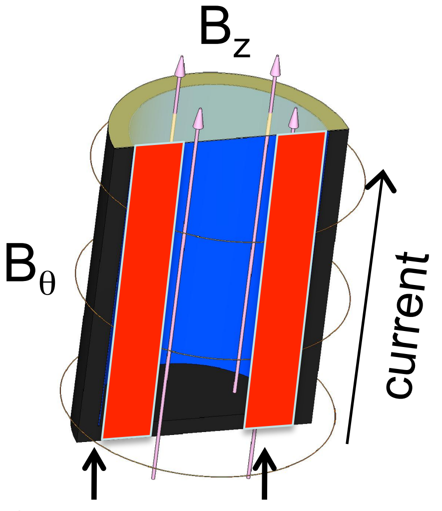
HYDRA Simulation

Comparison between observables and post-shot degraded simulations

Parameter	Measured/inferred [z2591]	Post-shot HYDRA simulations
I_{max}	19 ± 1.5 MA	19 MA
t_{imp}^{5MA}	+90 ± 1 ns	+90 ns (~70 km/s)
r_{laser}	450 ± 150 μm	450 ± 150 μm
E_{gas}^{abs}	~100-600 J	150 ± 50 J
r_{stag}^{hot}	44 ± 13 μm	40 μm (r_{stag}^{liner} 53 μm, CR_{2D}^{liner} 44)
$\langle T_i \rangle^{DD}$, $\langle T_{i,e}^{spec} \rangle$	2.5 ± 0.75, 3.0 ± 0.5 keV	3.0 ± 0.5, 2.7 ± 0.5 keV
ρ_{gas}^{stag}	0.3 ± 0.2 g cm^{-3}	0.4 ± 0.2 g cm^{-3}
ρR_{gas}, ρR_{liner}^{stag}	2 ± 1, 900 ± 300 mg cm^{-2}	2.6 ± 1.0, 900 mg cm^{-2}
$\langle P^{stag} \rangle$, E_{gas}^{stag}	1.0 ± 0.5 Gbar, 4 ± 2 kJ	1.5 ± 0.3 Gbar, 7 ± 2 kJ
$\langle B_z^f r_{stag} \rangle$	(4.5±0.5)e5 G cm ($r_{stag}/r_{L,\alpha}$ 1.7)	4.8e5 G cm ($r_{stag}/r_{L,\alpha}$ 1.8) ($\langle B_z^f \rangle$ 91 MG)
Y_n^{DD}	(2.0±0.4)e12	(2.5±0.5)e12
Y_n^{DD}/Y_n^{DT}	40 ± 20	41-57
DD, DT spectra	isotropic, asymmetric	isotropic, asymmetric
t_{burn}^{FWHM}	2.3 ± 0.6 ns (x-rays) [z2591, Y_n^{DD}=2e12] 1.5 ± 0.1 ns (x-rays) [z2613, Y_n^{DD}=1e12]	1.6 ± 0.2 ns (neutrons)
Liner emission	bounce & peak emission: t_{stag}+5 ns	bounce & peak emission: t_{stag} +5 ns
Δz_{burn} shape	5 ± 1 mm, asymmetric	Similar (but no helix or liner attenuation)
mix	0 - 10 %, not ≥ 20%	0% (by design)

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

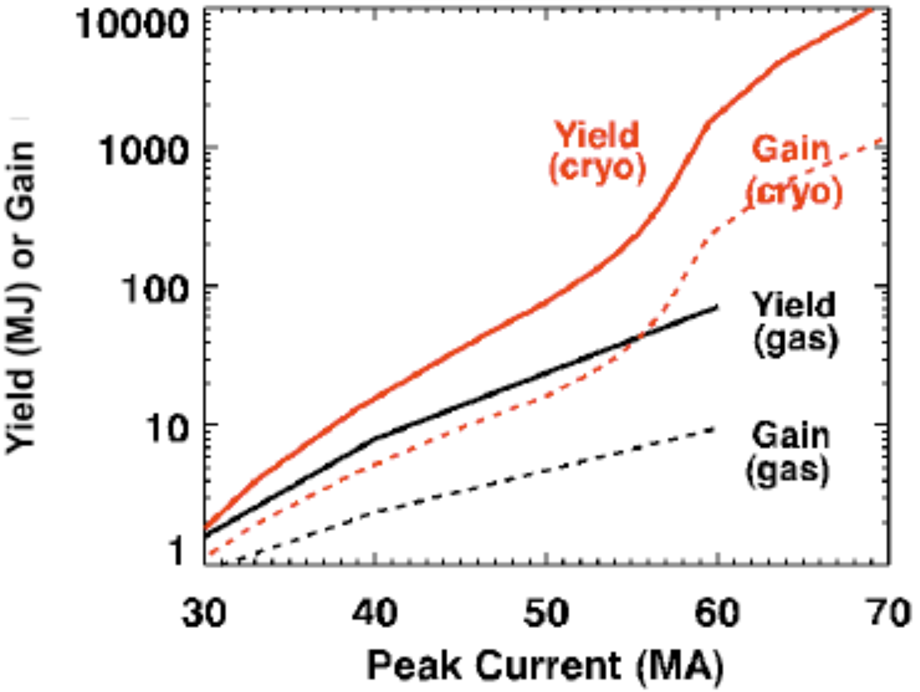
Magnetized Cryogenic Levitated Shell



Aluminum liner

DT 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).

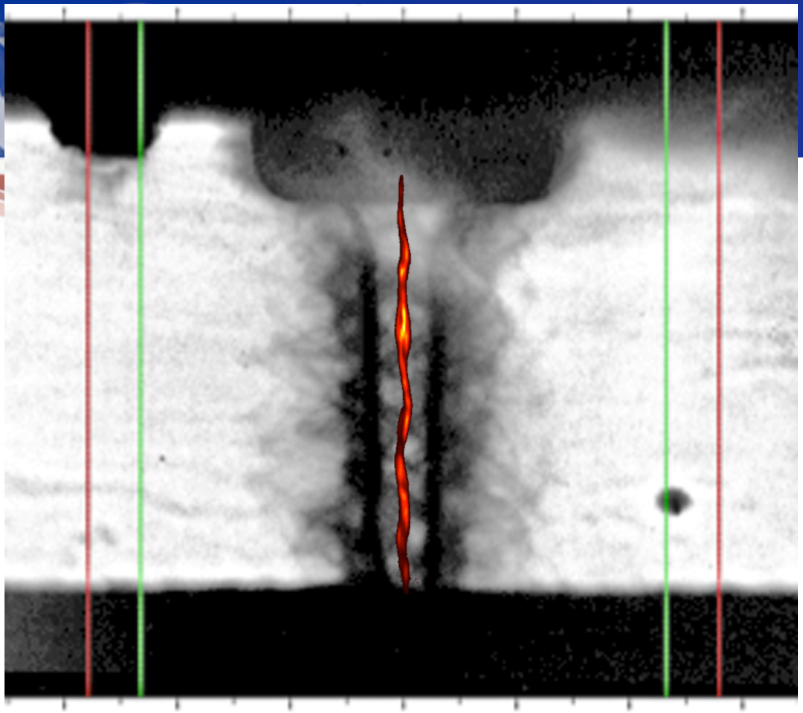
Large yields and low rep-rate may be an attractive path for Inertial Fusion Energy

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
- $\Longrightarrow$ 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 "clean 2D" predictions

Integrated experiments show strong evidence for thermonuclear neutrons and magnetized fuel

Detailed comparisons between "post-shot, degraded" simulations and experimental results are promising and ongoing

Sandia National Laboratories

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)

Some References

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  - M. D. Rosen, Phys. Plasmas 6, 1690 (1999)
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  - "The physics of fast z-pinches," D. Ryutov et al., Rev. Modern Physics, 72, 167 (2000).

Thanks for your attention!

Any questions?