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Pulsed-power, Z-pinches, and Applications

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Mark Herrmann (SNL)

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Outline

- Pulsed-power technology produces large currents (15-26 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

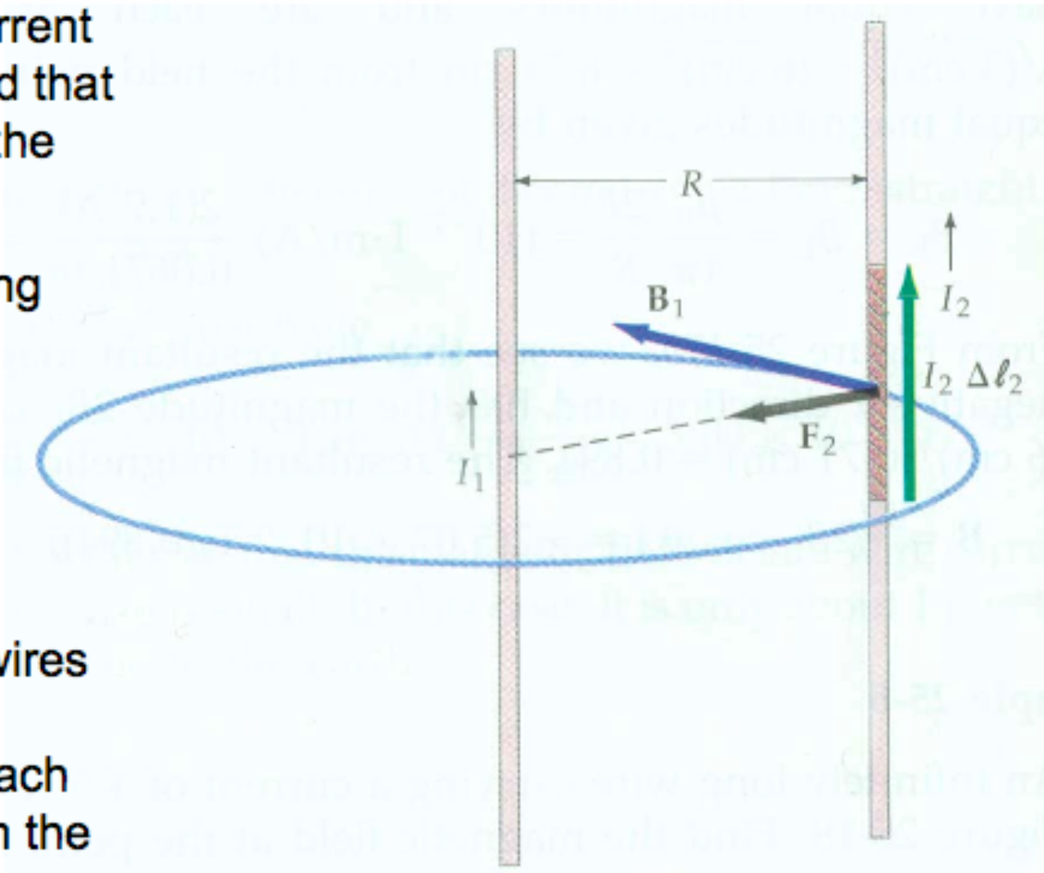
- There are several interesting applications

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 fluid equations

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

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:

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

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

The magnetic field can be included as an effective pressure

From vector identities

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

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

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

magnetic tension magnetic pressure

In the case of an axisymmetric Z current (theta field) the magnetic tension is zero

How strong is this pressure?

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

A typical refrigerator magnetic 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

A 5×10^9 G magnetic field ~ 1 Trillion atmospheres = 1 Terabar (TB) > pressure in the center of the sun

Note that high explosives have pressure ~ few 100,000 atmospheres

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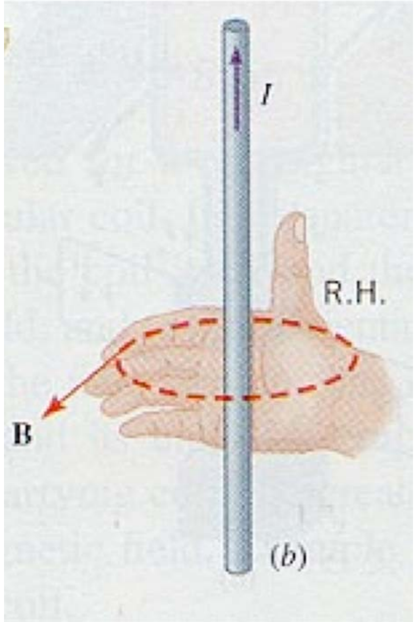
Large currents can create large fields!

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

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



For an axial current I:

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

$$B_\theta(G) = \frac{I(A)}{5\, r(cm)}$$

100 A at 2 mm radius is 100 G

10^7 A at 4 mm radius is 5 10^6 G = 1 MBar of pressure

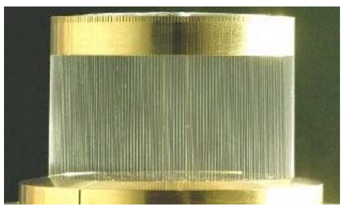
2.5x10^7 A at 1mm radius is 5x10^7 G= 100 MBar of pressure!!

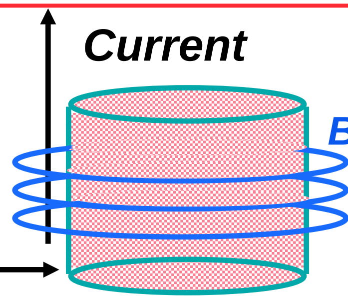
We can use high currents to push plasmas in different ways

High Current

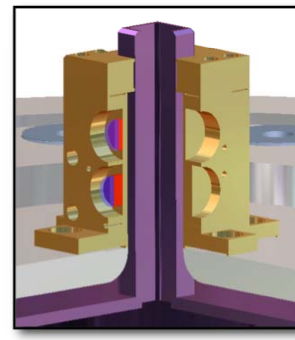
Cylindrical compression:
Z-pinch x-ray source

wire array



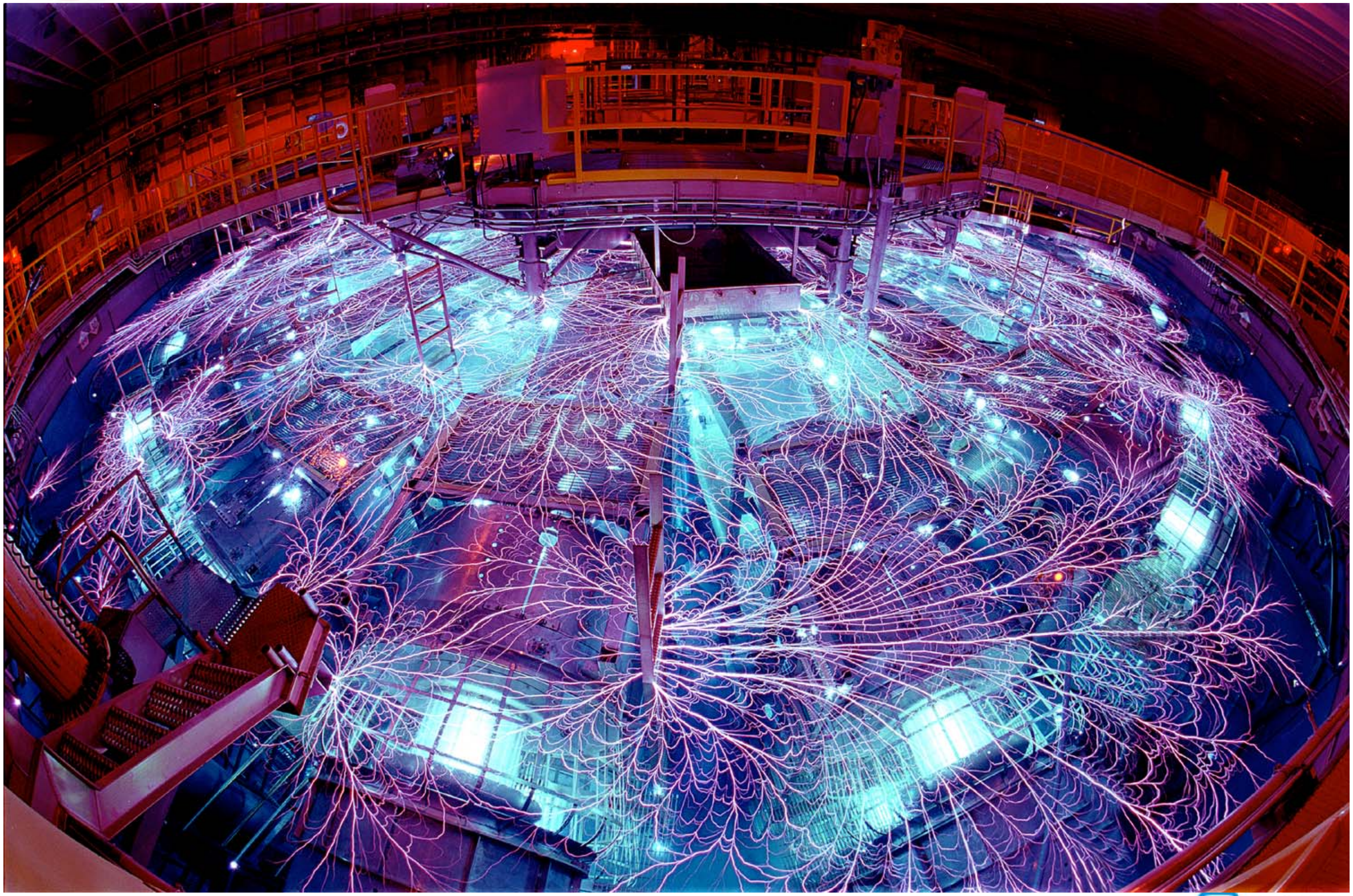


Planar compression:
Materials experiments



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

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



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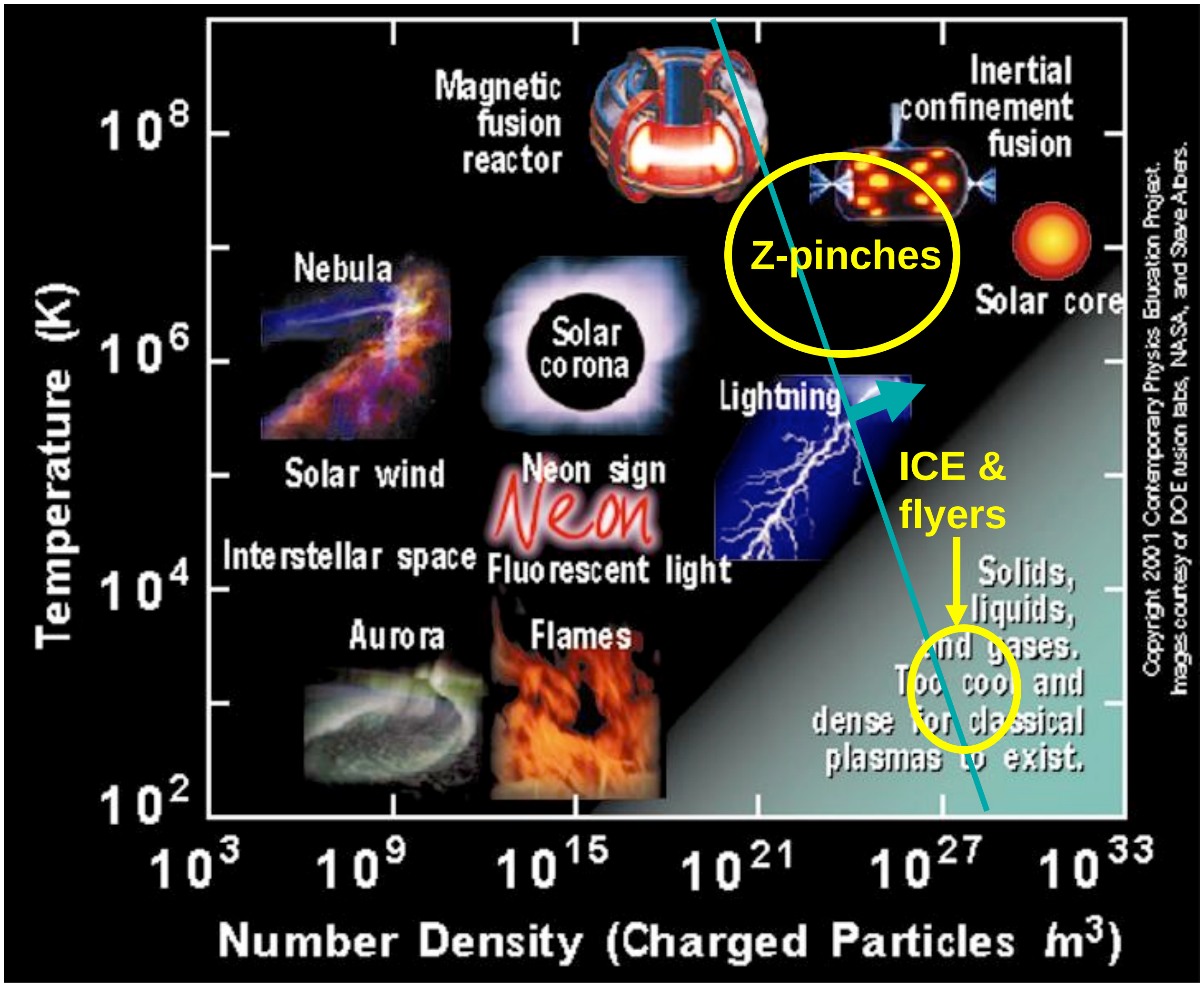
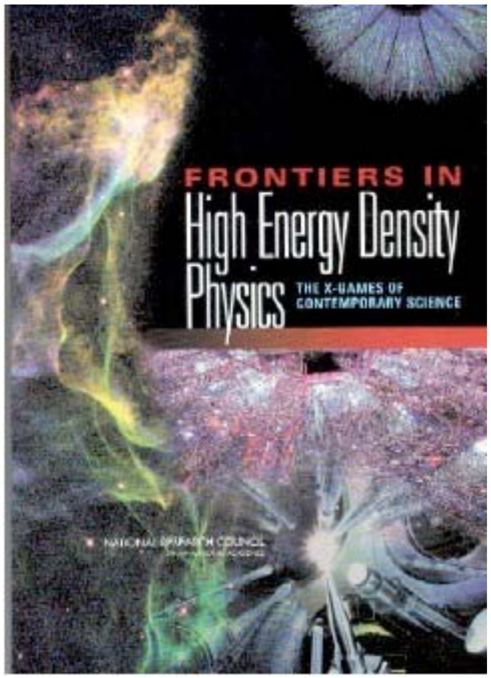
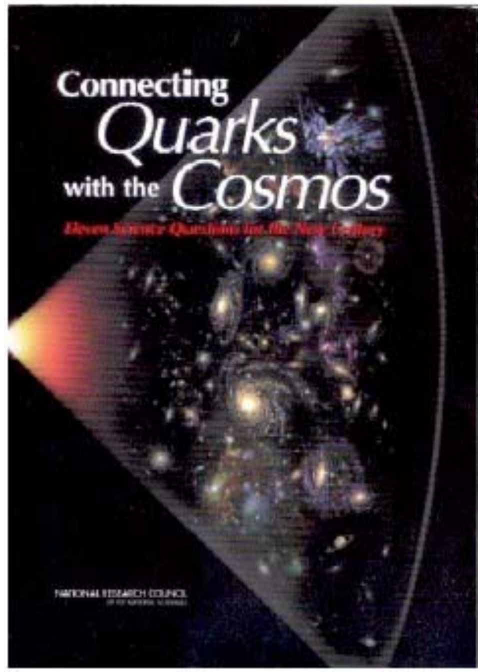
Regimes of high energy density are typically associated with energy density 10^5 J/cm^3 = 1 Mbar



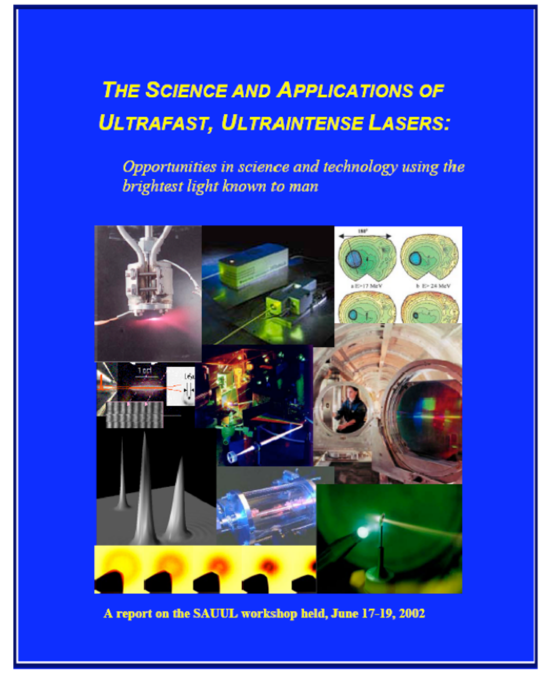
Several recent studies have highlighted High Energy Density Science



"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

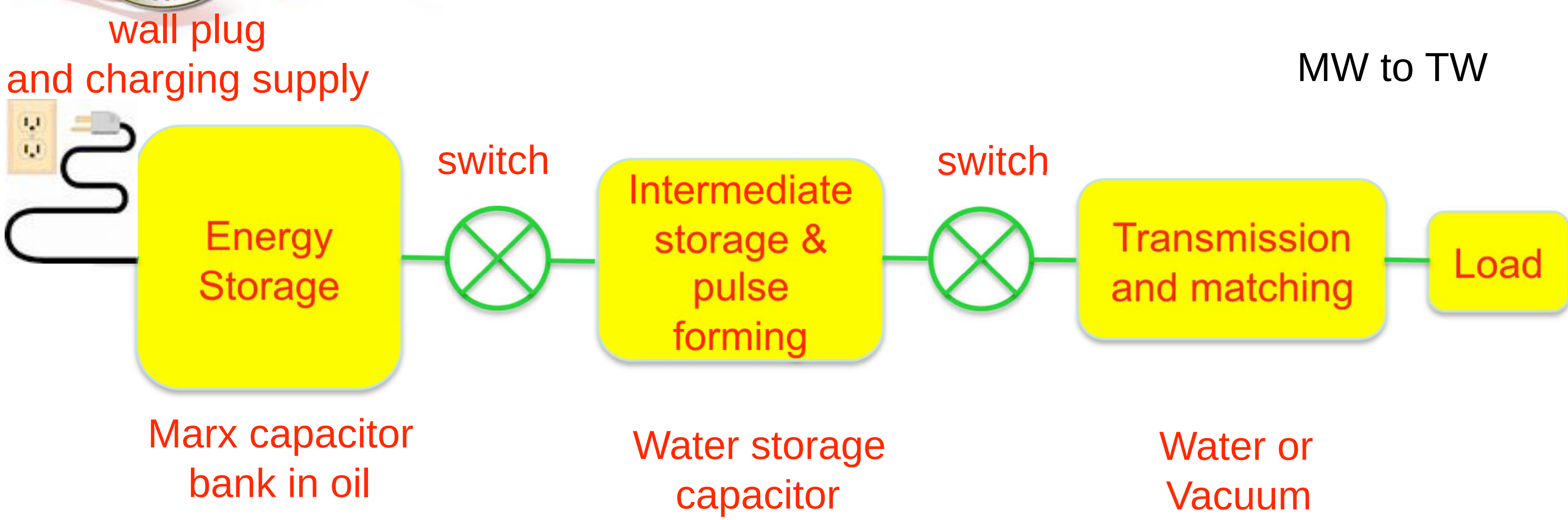


Science and Applications of Ultrafast, Ultraintense Lasers (SAUUL)

Scales of energy density

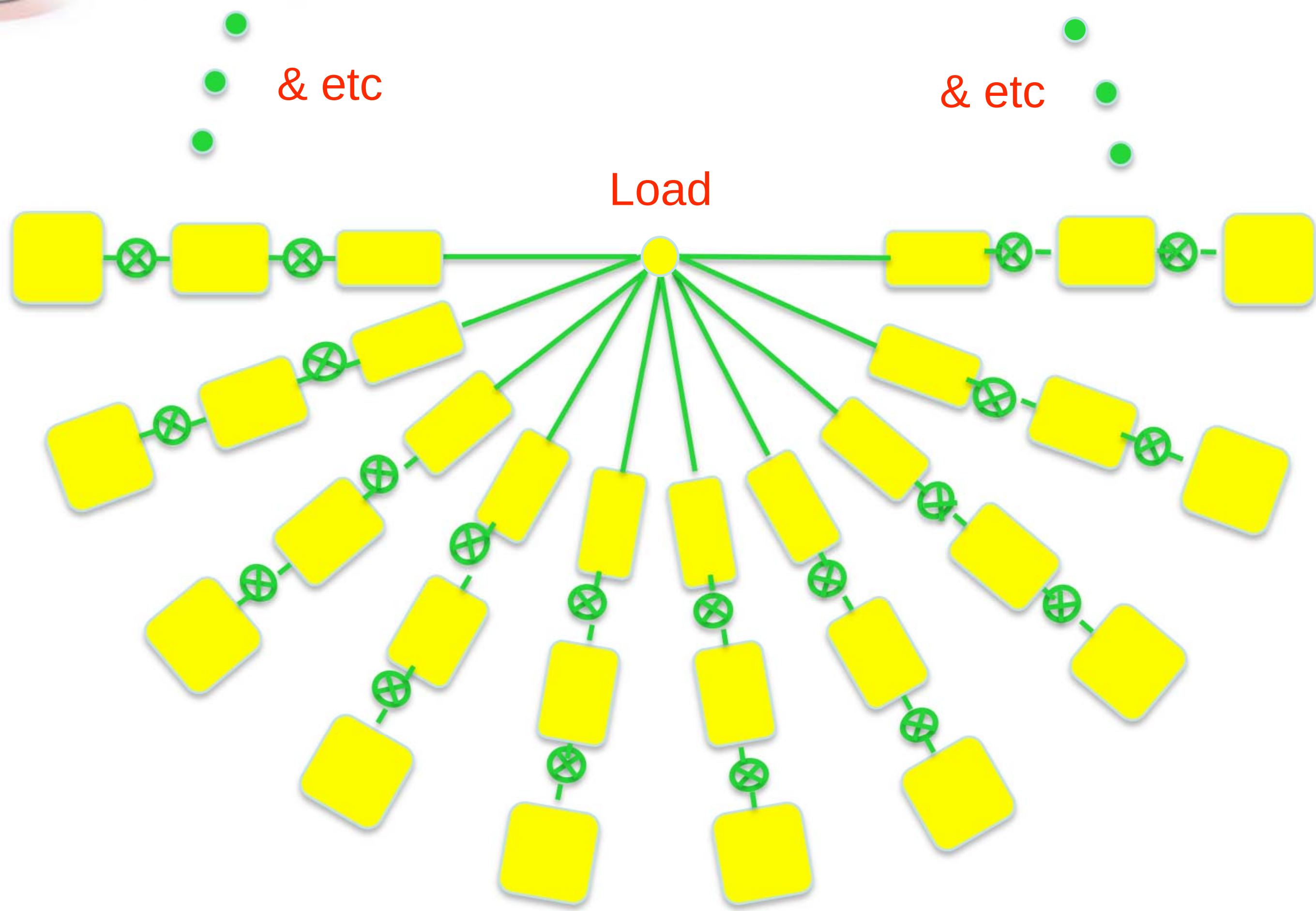
- 0.001 MJ/kG water at 100 m dam height
- 0.5 MJ/kG Li ion battery
- 1.968 MJ/kG water
- 7.5 MJ/kG stick of dynamite
- 33 MJ/kG Low Earth Orbit
- 45 MJ/kG gasoline
- 170,000 MJ/kG typical z-pinch implosion at 20 MA
- 3.5 million MJ/kG fission of 3.5% enriched U-235
- 337 million MJ/kG DT fusion
- 645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

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



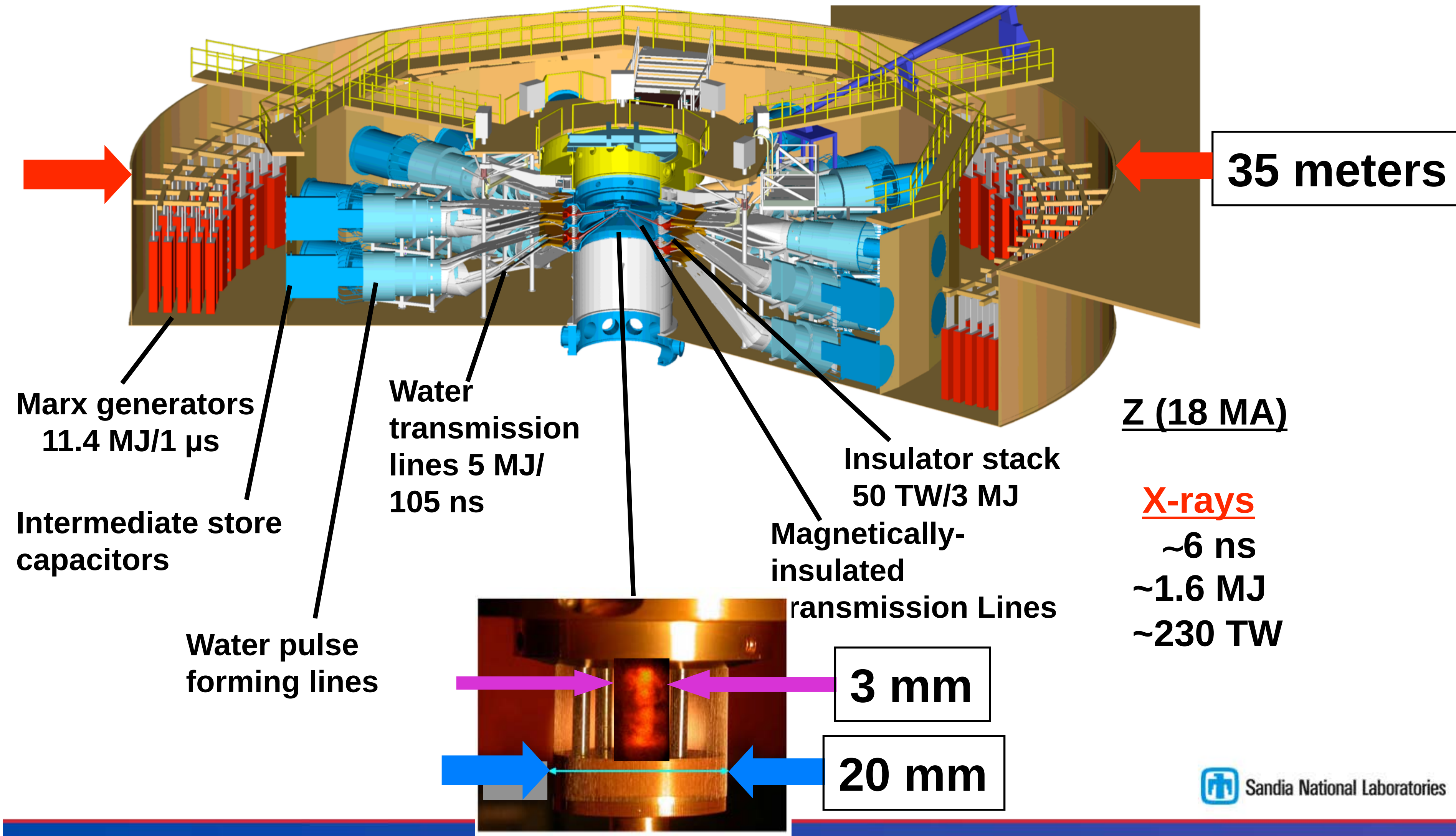
- Typically the pulse is compressed in both space and time
- The load produces the last step in pulse compression and power gain

Multiple modules are used to achieve the highest powers



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

Z creates a ~100 ns, ~25 MA pulse to drive the world's most energetic x-ray source



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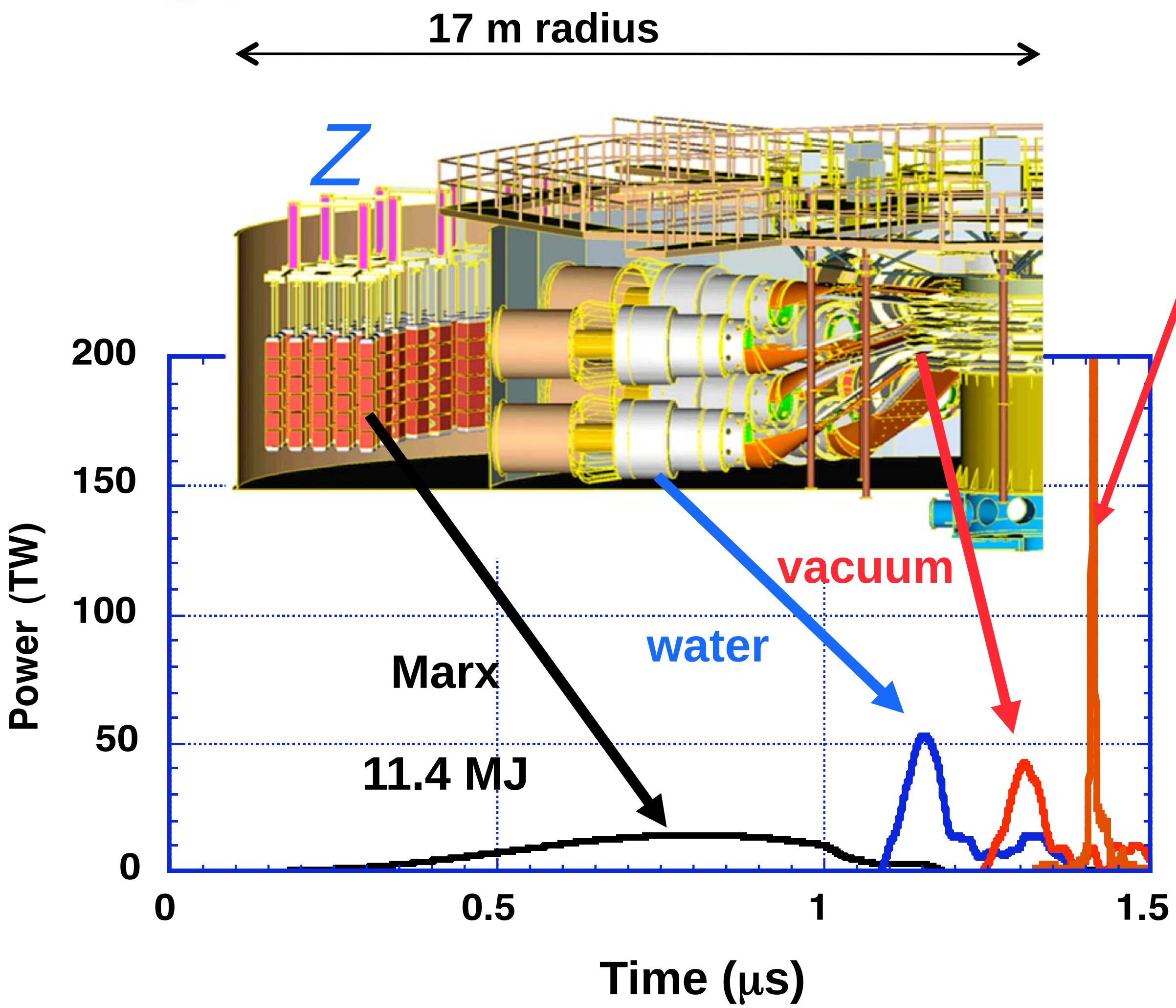
Pulsed-power provides compact, efficient, power amplification



x ray output
~1.6 MJ
~200 TW

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

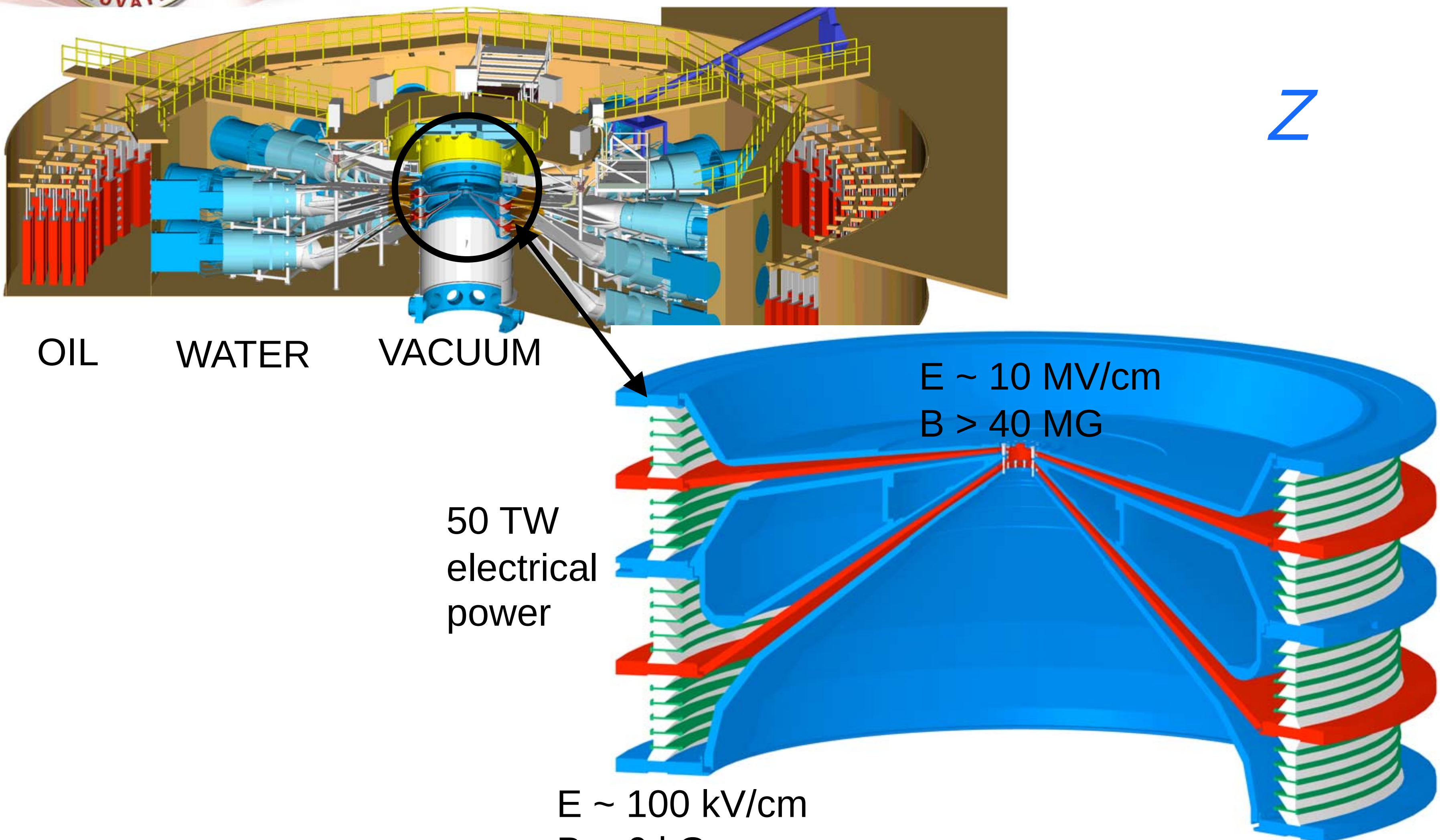
at a velocity of c:
100 ns (30 meters)
5 ns (150 cm)

We compress energy in space and time on Z

- Compression in height — X 625
  - 625 cm tank Marx height to 1.0 cm hohlraum height
- Compression in radius — X 1375
  - 1650 cm in Marx tank radius to 1.2 cm hohlraum radius
- Compression in time — X 1.7×10^{10}
  - 2 minute Marx charge to 7 ns pinch output
- Total power density compression factor — $\sim 1.5 \times 10^{16}$
  - (η x area x time, $\eta \sim 0.4$)

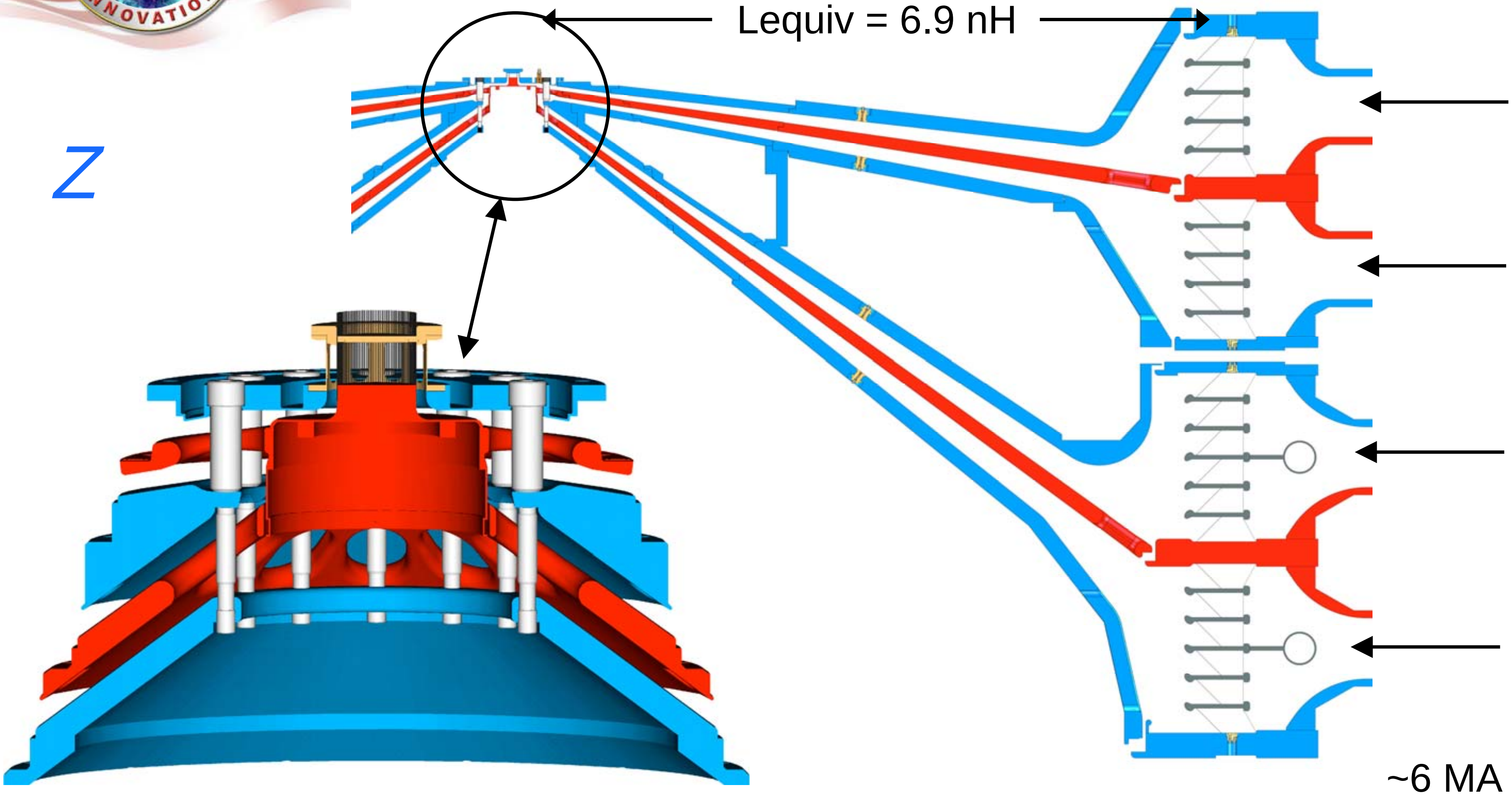
Self magnetically insulated transmission lines (MITLs) allow power flow at electric fields far above breakdown

Z



Vacuum Insulator Stack

High current is achieved by adding four low inductance conical transmission lines in parallel



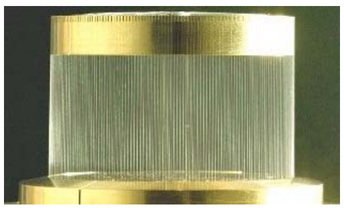
- Z produced currents up to 20 MA in 100 ns
- Z-R has produced currents up to 26 MA in 100 to 250 ns

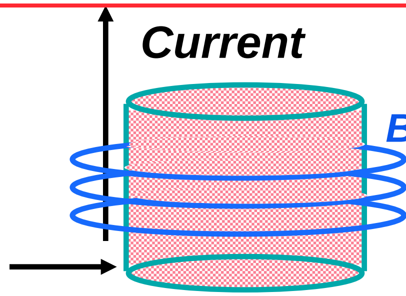
We can use high currents to push plasmas in different ways for different applications

High Current

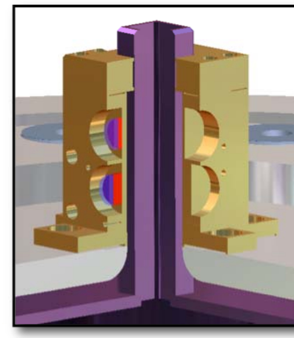
Cylindrical magnetic pressure

wire array

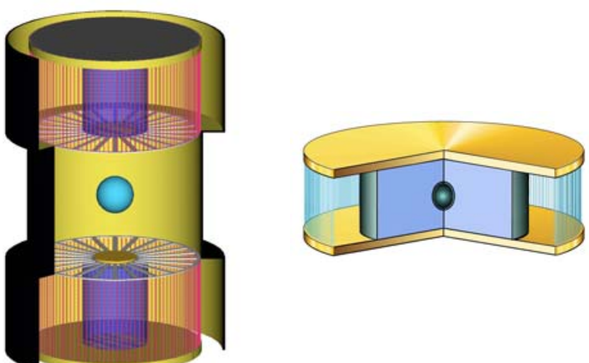




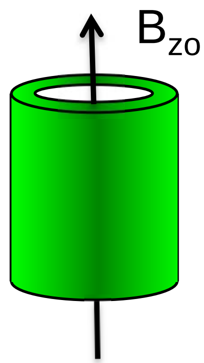
Planar magnetic pressure



Inertial Confinement Fusion (ICF)

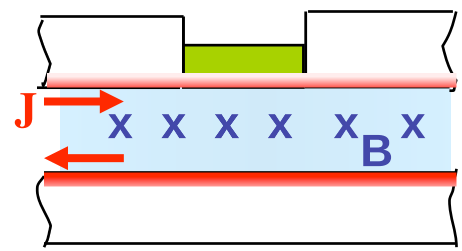


Indirect



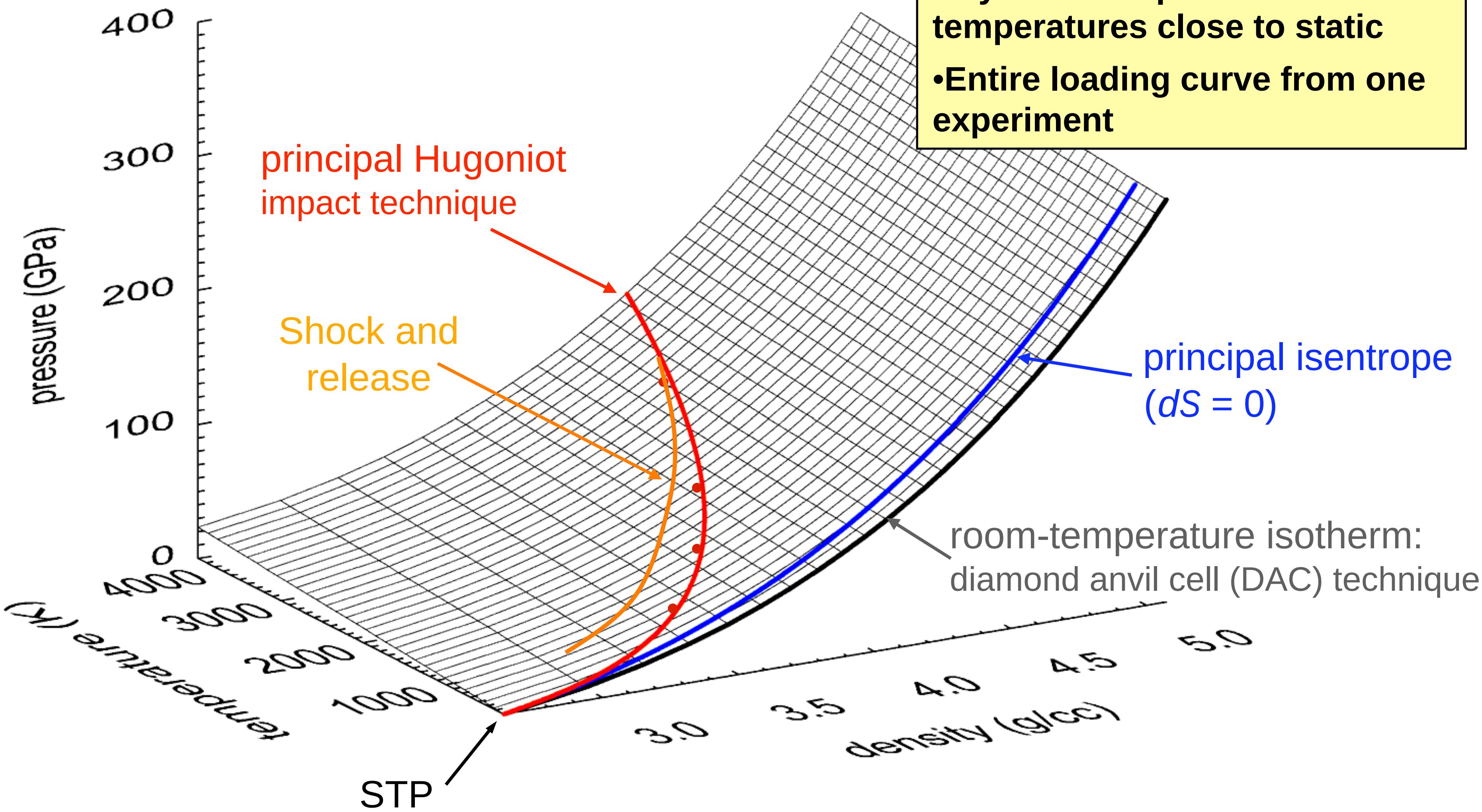
Direct (MTF)

Material Properties

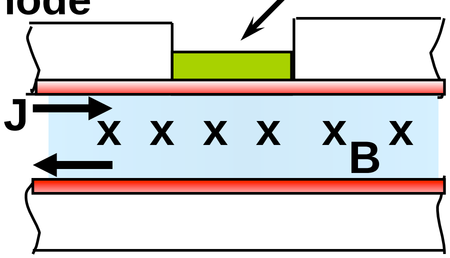


Magnetic pressure can be used to examine fundamental material properties at HED conditions

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



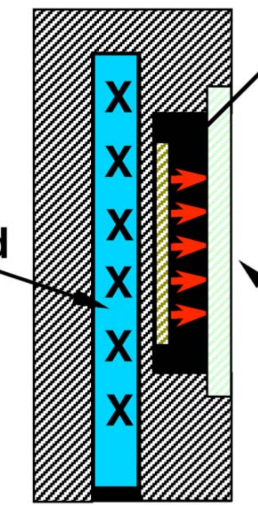
Techniques developed on Z have enabled major advances for accurate EOS studies



Isentropic Compression Experiments (ICE)*

Magnetically produced Isentropic Compression Experiments (ICE) to provide measurement of continuous compression curves to ~3 Mbar
- previously unavailable at Mbar pressures

* Developed with LLNL

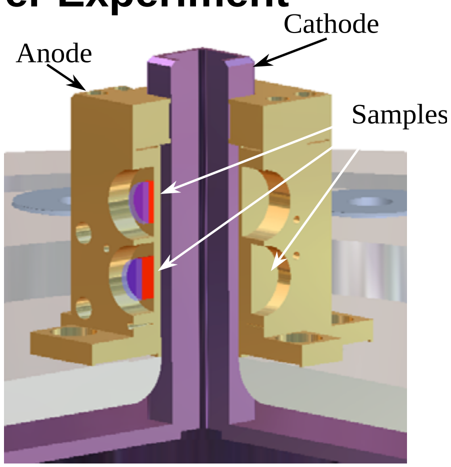


Magnetically launched flyer plates

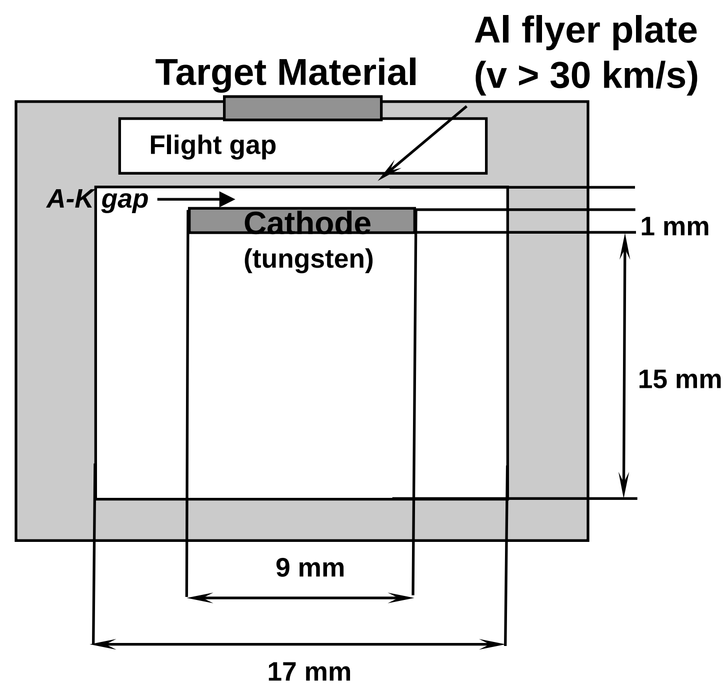
Magnetically driven flyer plates for shock Hugoniot experiments at velocities to ~ 34 km/s
- exceeds gas gun velocities by ~ 4X and pressures by ~ 7-8X with comparable accuracy

Numerical simulations enable the design of high velocity flyer plate experiments

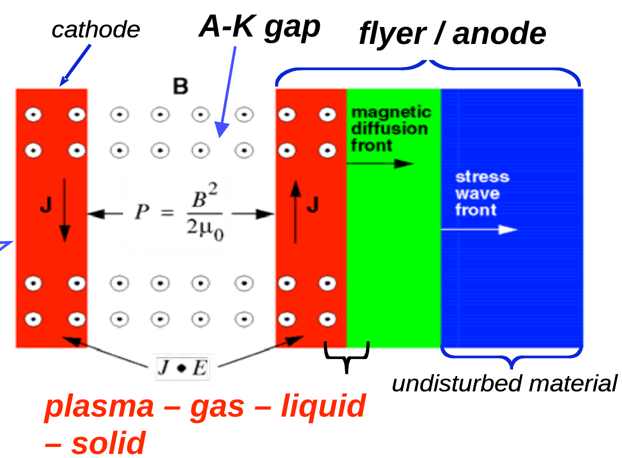
Setup for High Velocity Flyer Experiment



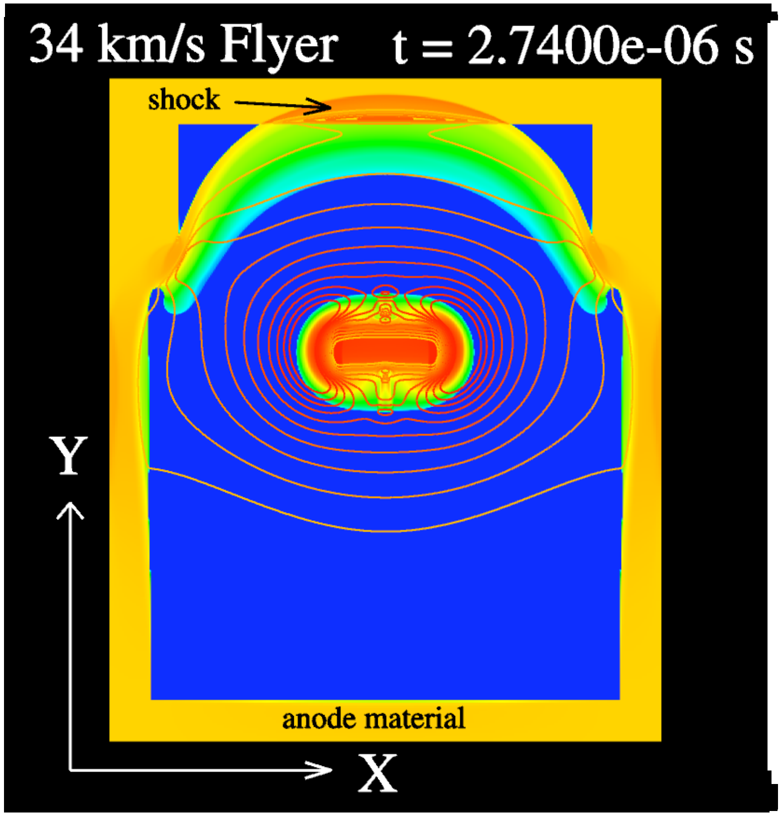
2D Model for Numerical Simulation

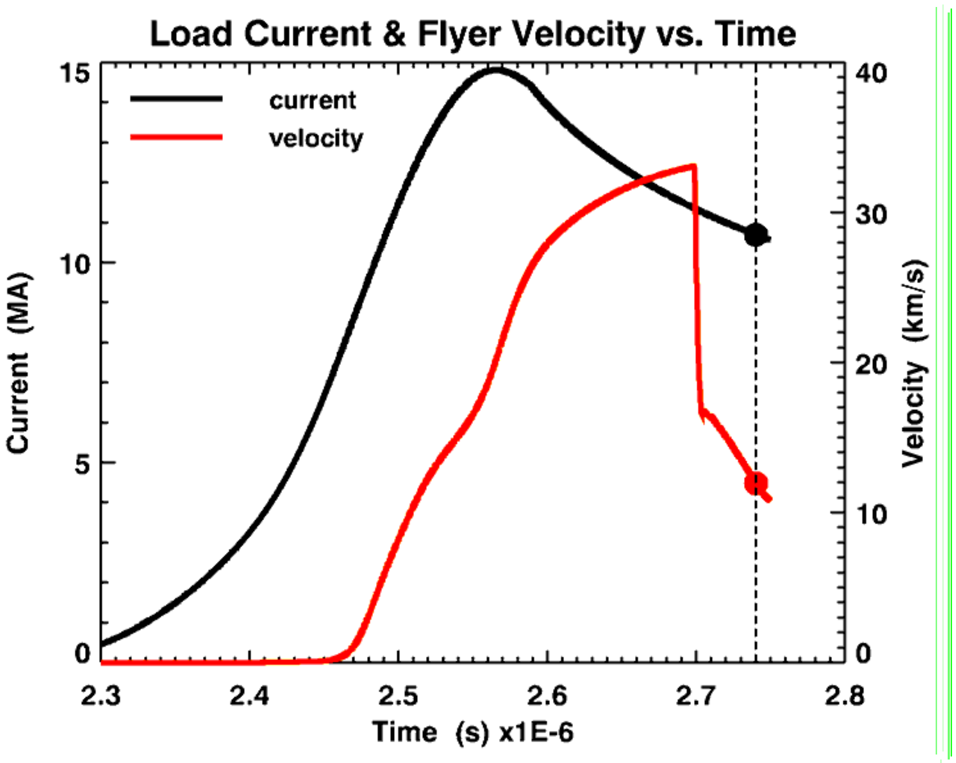


Physics of magnetically accelerated flyer in 1D.



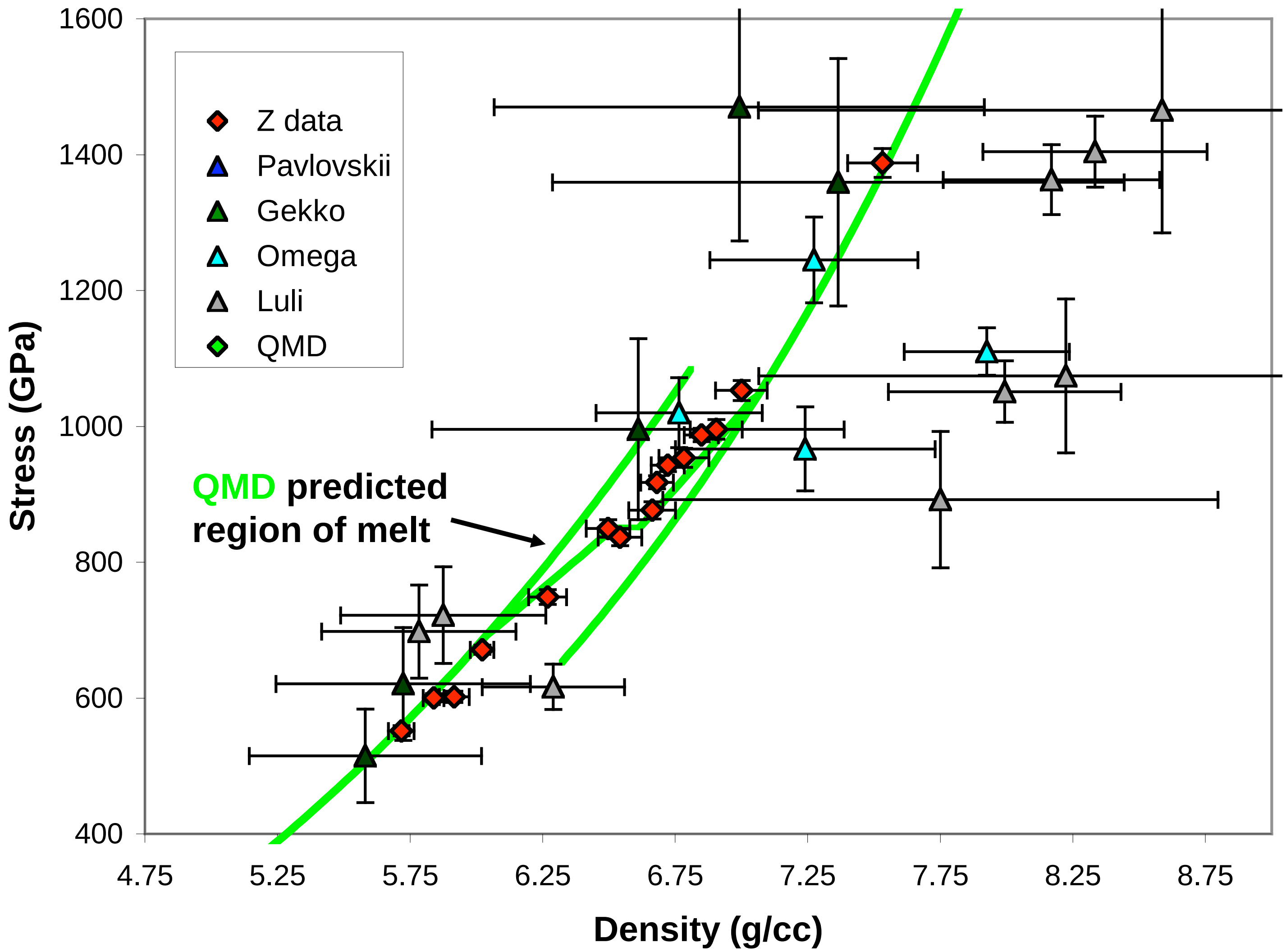
Snapshots from 2D numerical simulation show dynamics of flyer in high velocity





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

stress versus density for diamond



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

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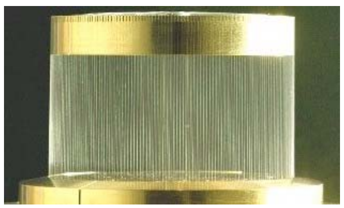
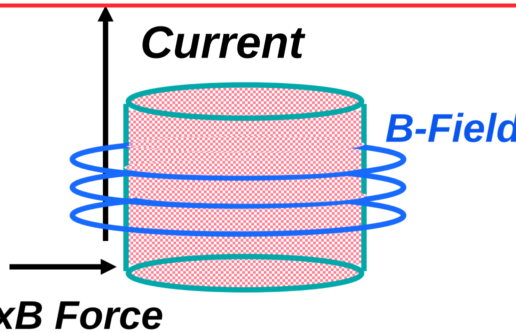
We can use high currents to push plasmas in different ways for different applications

High Current

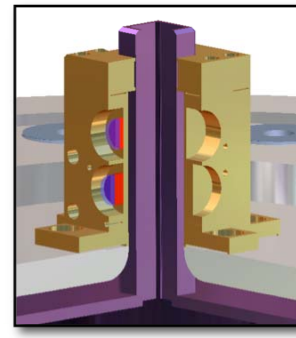
Cylindrical magnetic pressure

wire array

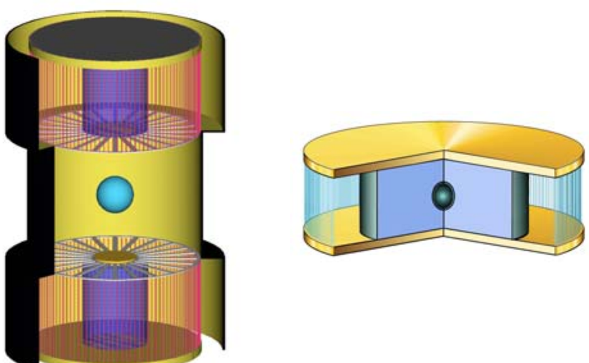




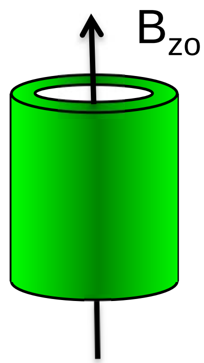
Planar magnetic pressure



Inertial Confinement Fusion (ICF)

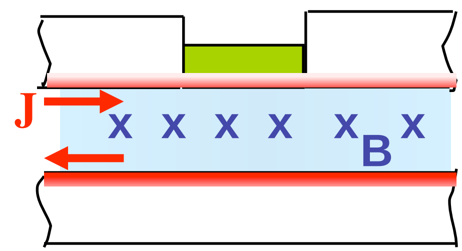


Indirect



Direct (MTF)

Material Properties

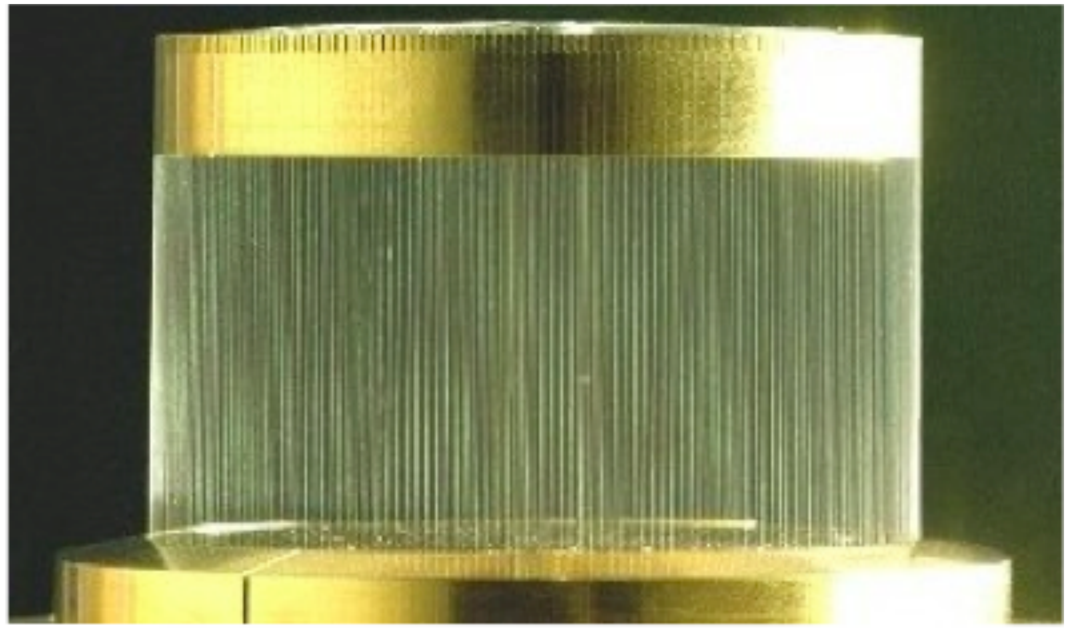


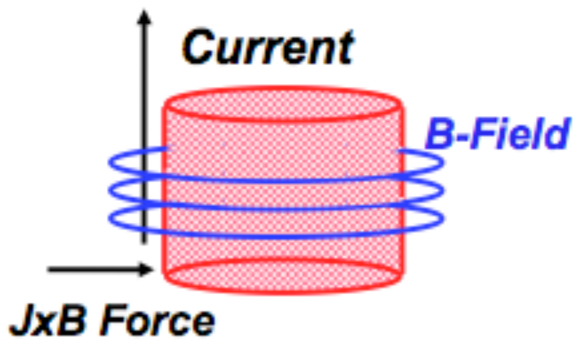
Wire arrays are a "simple" extension of the two wire problem

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

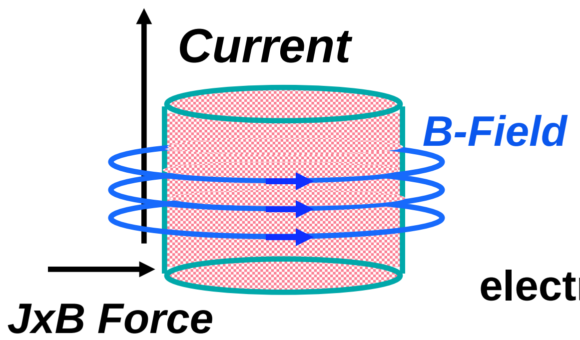




Z-pinch loads:

Wire Array
Gas Puffs
Foil/Liner
Foam

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

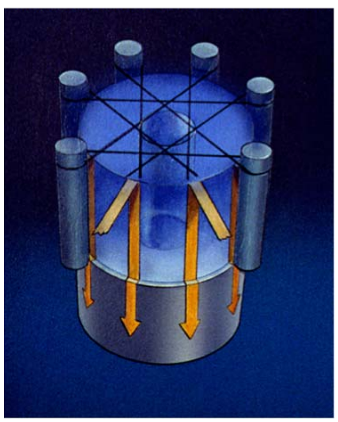


kinetic and magnetic energy

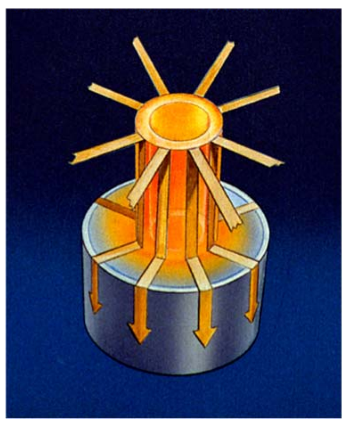
↓

electrical energy → kinetic energy

internal energy → x rays



Ablation



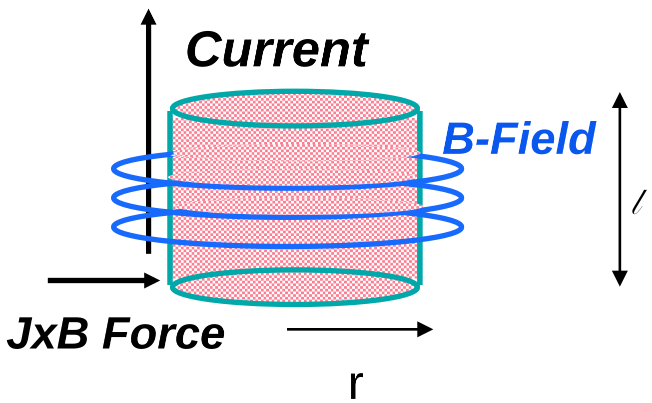
Implosion

Stagnation

Wire z-pinch loads:

- Energy: x-ray ≈ 15% of stored electrical
- Power: x-ray ≈ 2-5 x 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~B^2
For a thin shell with all the current on the outside:

$$ma = F$$

$$m\ddot{r} = PA \qquad A = 2\pi r l \quad P = \frac{B^2}{8\pi} \quad B \approx \frac{I}{5r}$$

cgs units

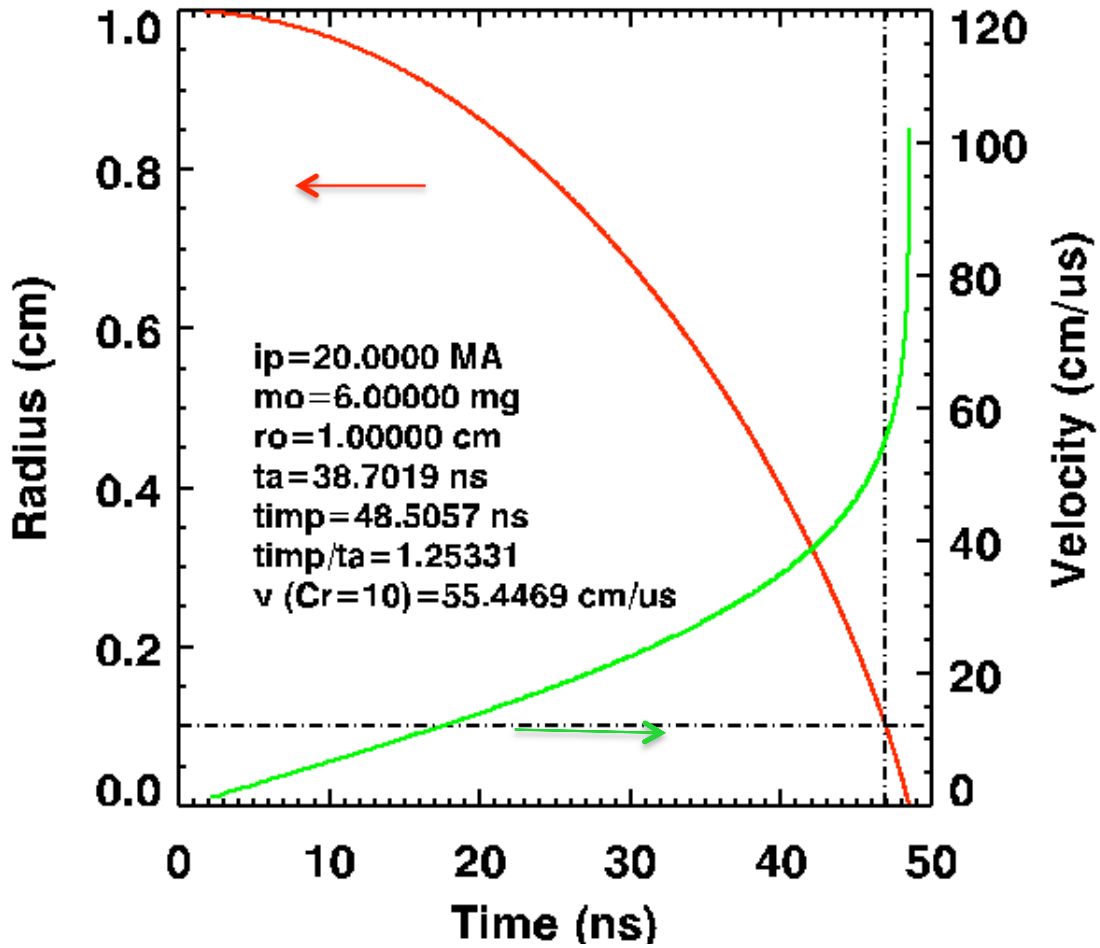
$$\frac{m}{l}\ddot{r} \approx \frac{I^2}{100r}$$

Note magnetic pressure increases for decreasing r

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

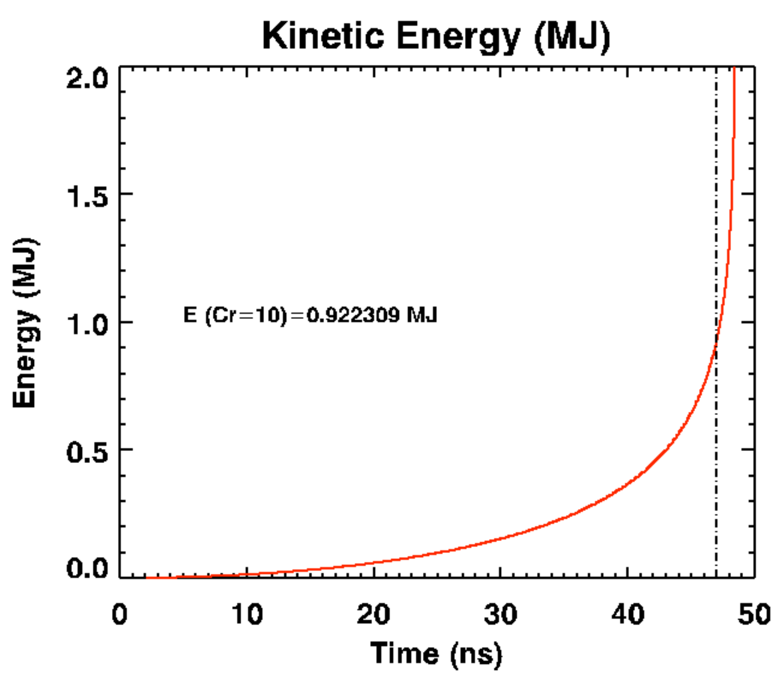
The analytic solution with I ~ constant shows increasing magnetic pressure accelerating the pinch

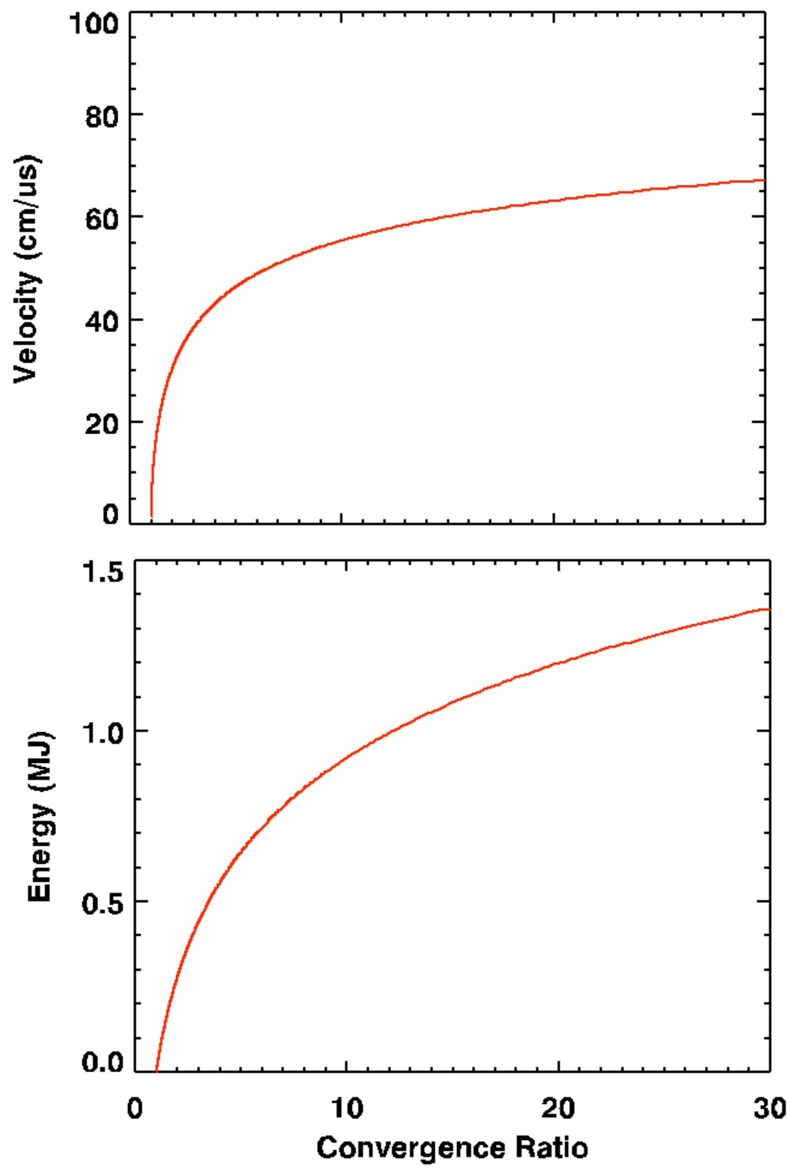
$$P = \frac{B^2}{8\pi} \sim \left(\frac{I}{r(t)}\right)^2$$



- Velocity at convergence ratio of 10 ~ 50 cm/μs ~ 1,100,000 mph
- Princeton to LA in 8 seconds
- 1/600th of the speed of light

Significant kinetic energies are coupled to the axis





l Laboratories

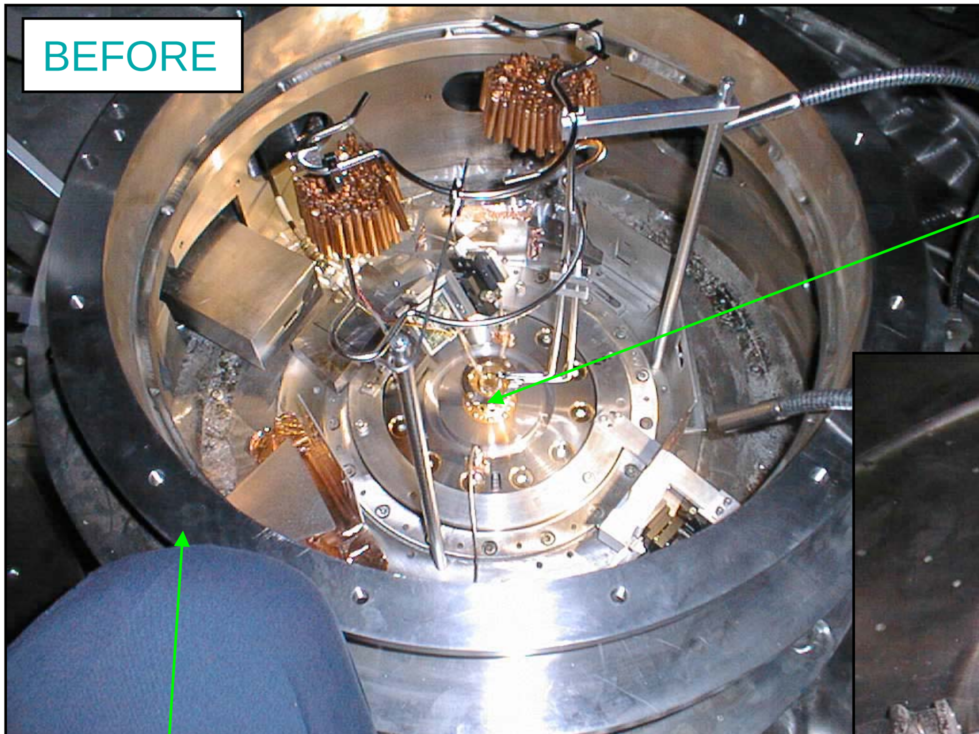
We employ kinetic energies of ~ 1 MJ in every day objects

- 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

An energy of 1 MJ

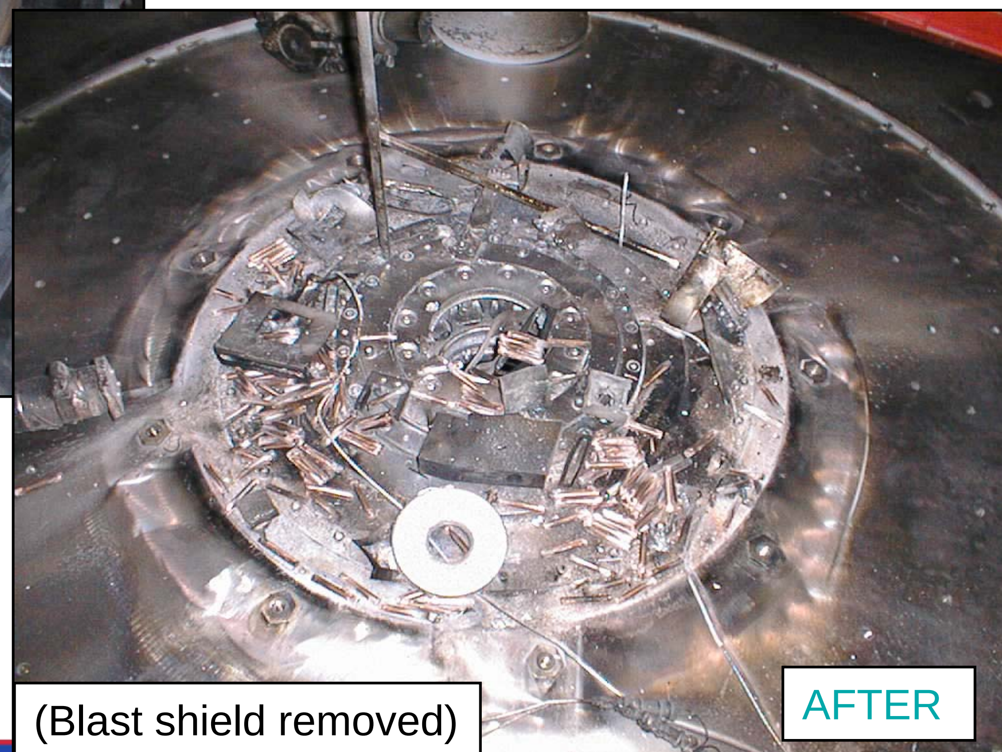
- Kinetic energy of F150 at 60 mph
- 0.48 x energy in a stick of dynamite
- 100 W light bulb uses 1 MJ in 2.8 hours

The 2-3 MJ of magnetic energy and radiation destroys by the debris following the radiation burst



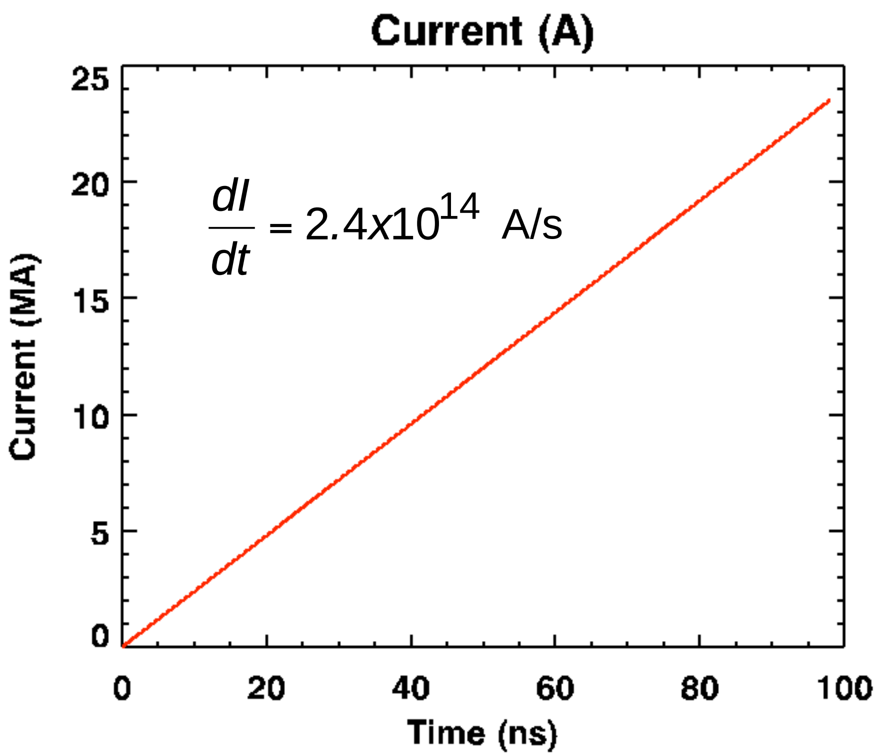
Wire array

Blast shield

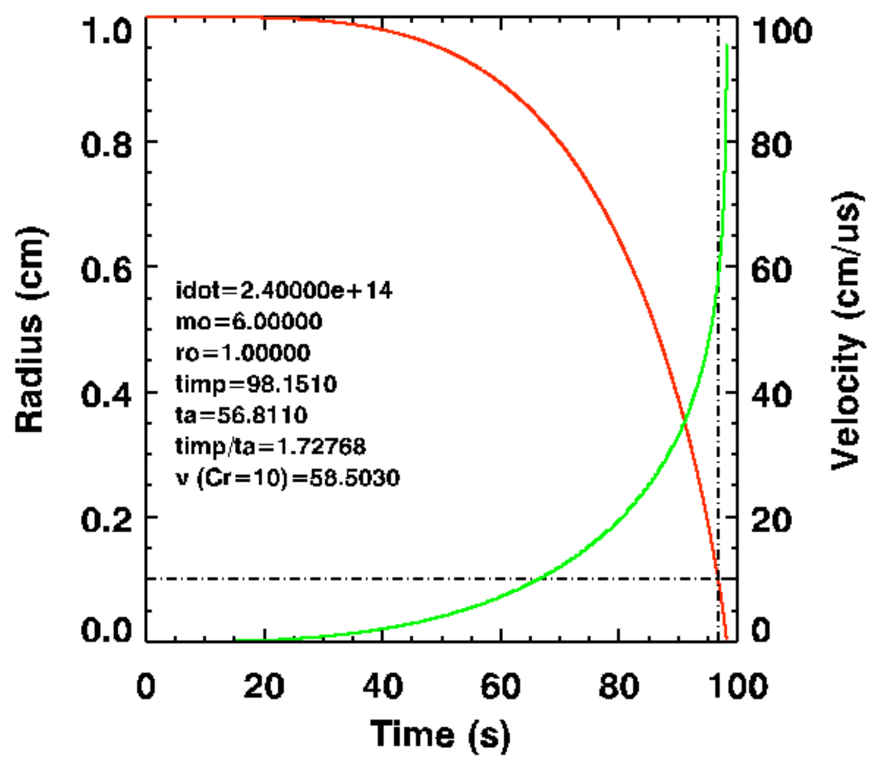


Equivalent to 2 lbs high explosive released in a few ns in <1 cc volume!

A real pulsed power driver does not produce a constant current



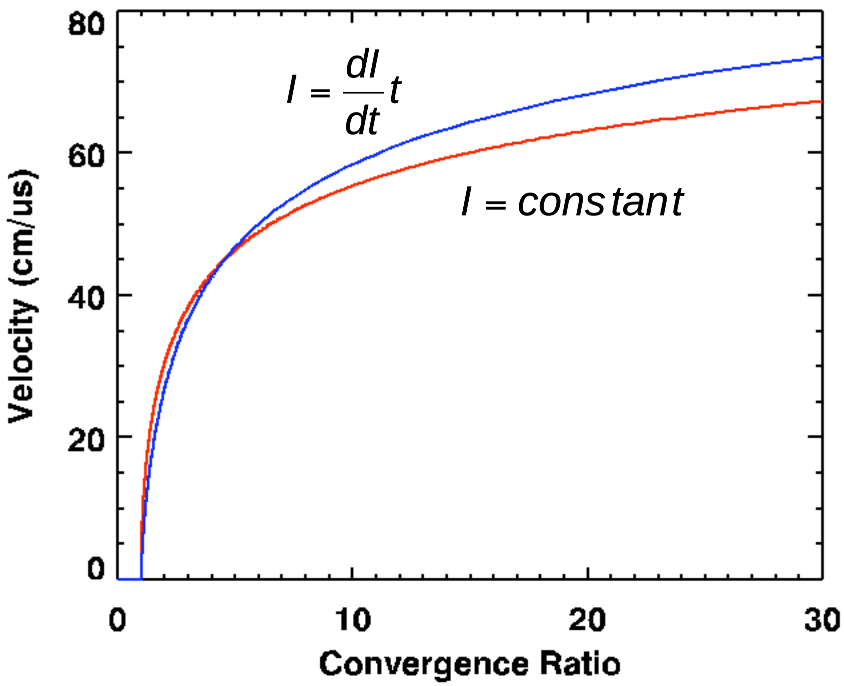
Numerical solution

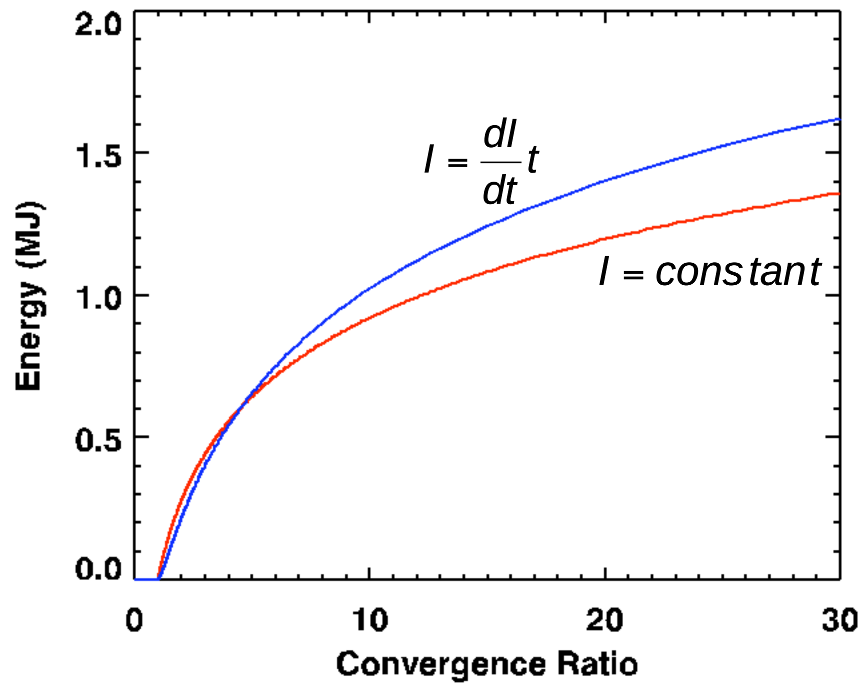


- A pulsed power driver is an inductor charging problem
- Typically current waveforms are linearly rising or ~ sin(ωt)

$$I(t) = \frac{\int V(t)dt}{L}$$

The kinetic energy just depends on the peak current and the convergence: insensitive to shape of I(t)





$$KineticEnergy = \frac{1}{2}mv^2 \sim f\ell I_{max}^2 \ln\left(\frac{r_o}{r_{fin}}\right)$$

$$ConvergenceRatio = \frac{r_o}{r_{fin}}$$

The plasma is an efficient radiator at stagnation

- The wire arrays are made out of a high Z material like tungsten (Z=74) .
- Because of this wire arrays are very good radiators of their kinetic energy (E_{KE}) at stagnation
- The magnetic field does additional work on the plasma at stagnation, some of which is radiated during the main radiation pulse (E*)
- So we know how much energy will be radiated by a wire array, but the issue for ICF is power density

$$P = \frac{E_{KE} + E^*}{\tau}$$

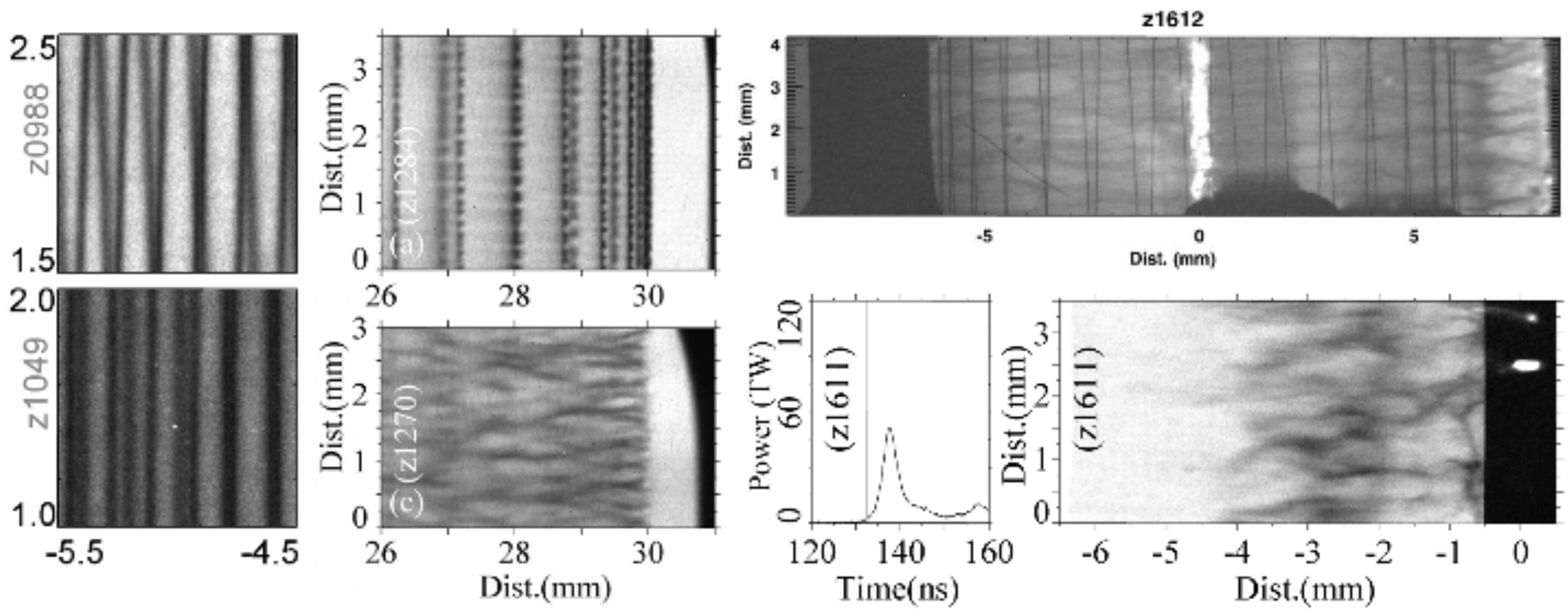
The shorter τ the higher the power will be! What determines τ?

The magneto-Rayleigh-Taylor instability limits how short τ can be

A good guess for τ:

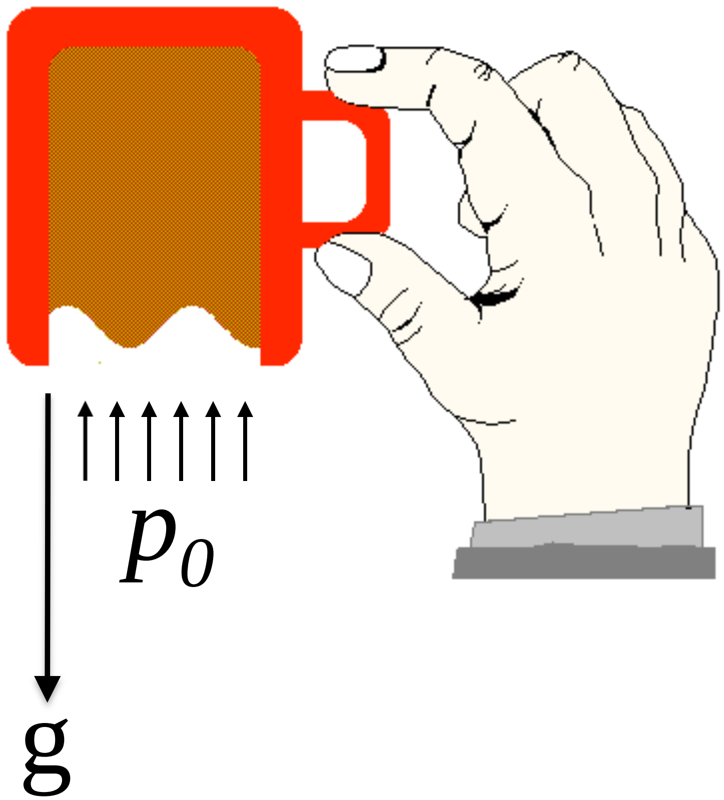
$$\tau \sim \frac{\delta r}{v}$$

Xray images of a wire array during its implosion!



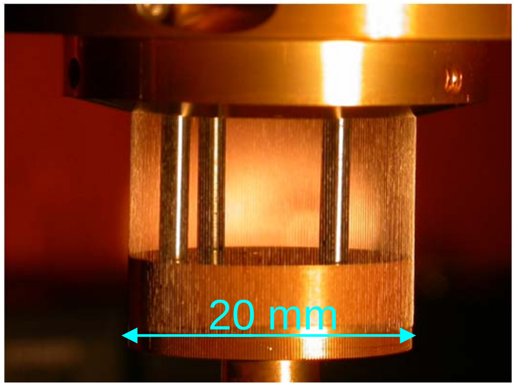
A heavy fluid supported by a light fluid is unstable

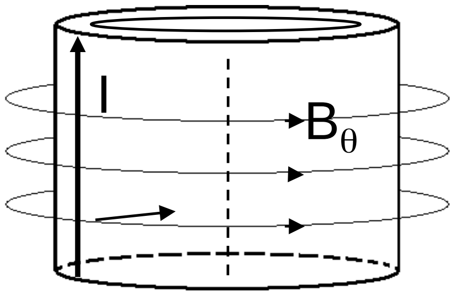
Atmospheric pressure p_0 is sufficient to support a coffee column 33 feet high against gravity. The RT instability helps us daily!

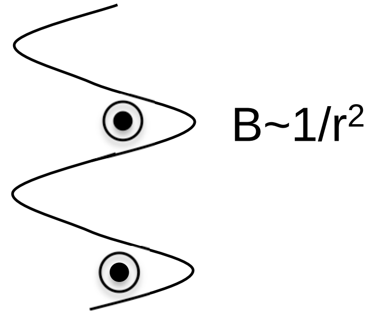


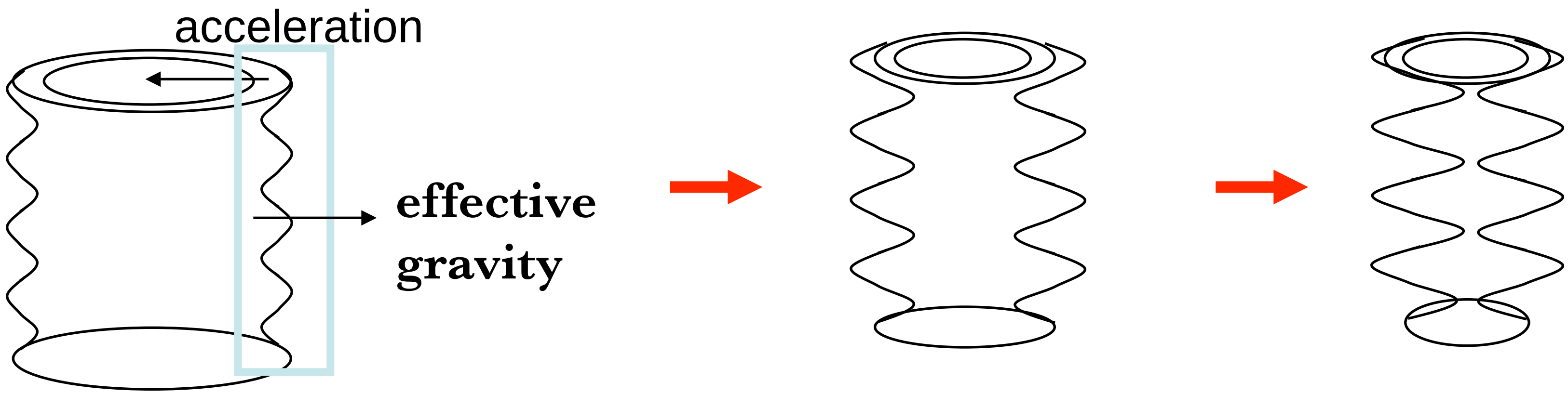
- This instability is the classical Rayleigh Taylor instability

The plasma is the heavy fluid, the magnetic field is the light fluid





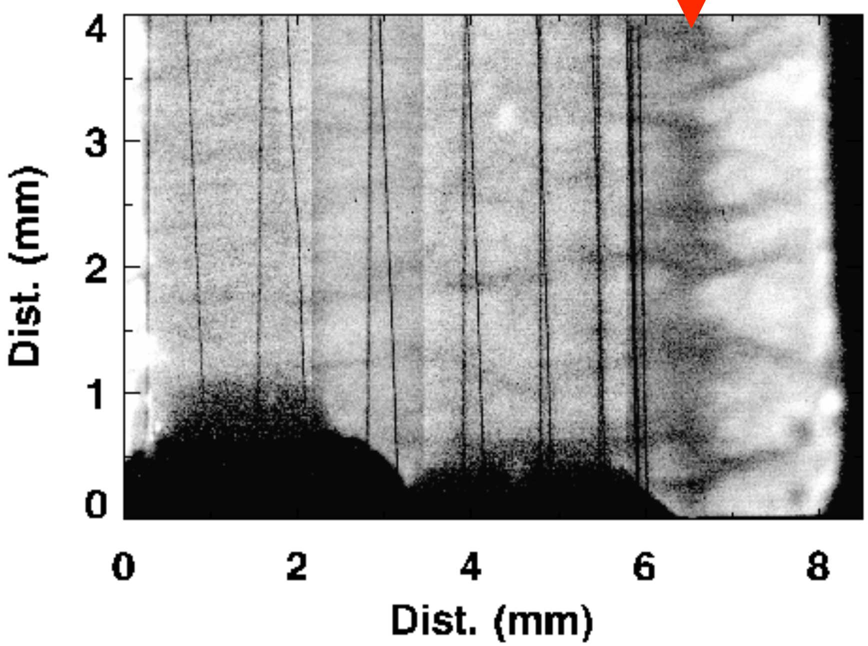




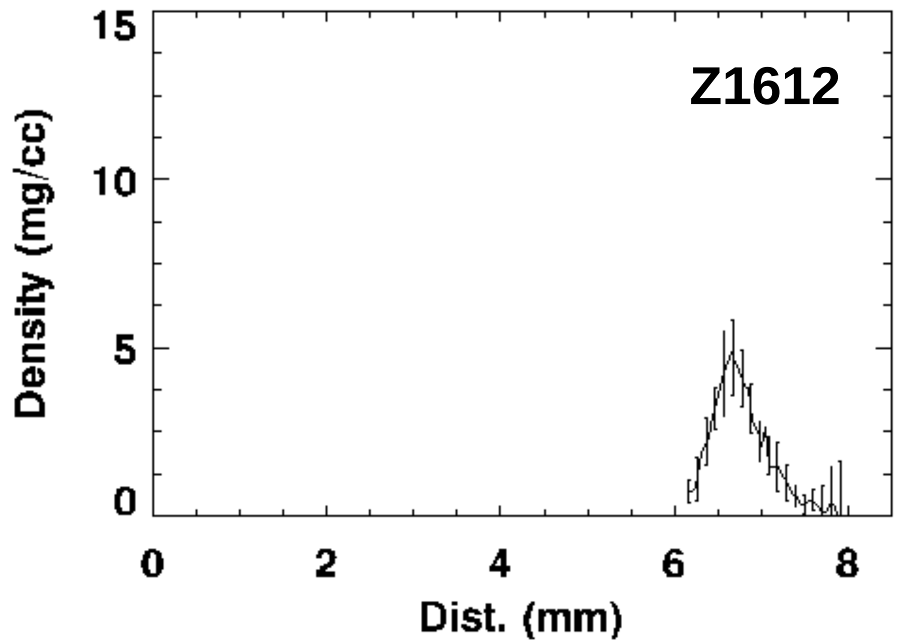
- The increase of $B \sim 1/r^2$ at the bubble position with respect to the spikes might be thought to increase the growth, but …

The magneto-Rayleigh-Taylor instability limits how short the pulsewidth τ can be

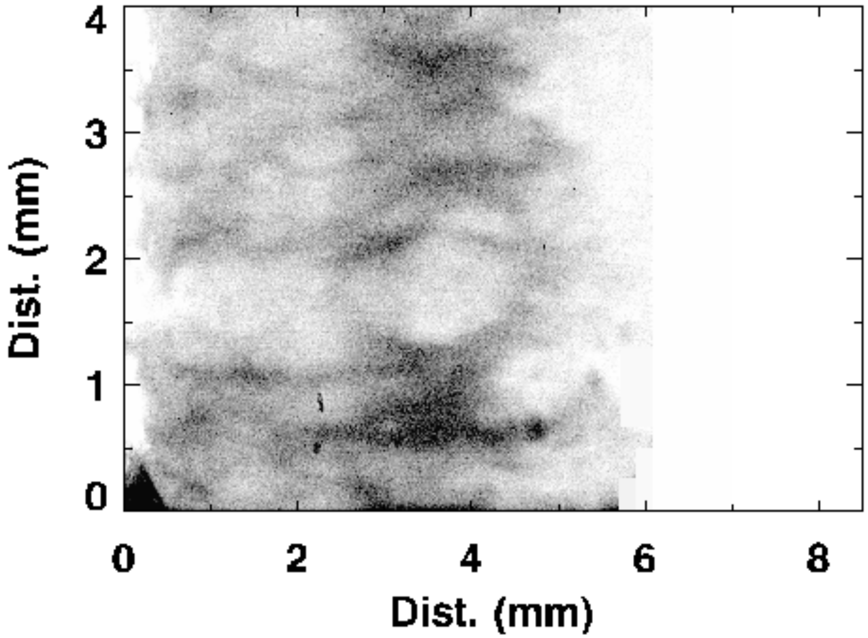
Mass profile of outer = profile of single



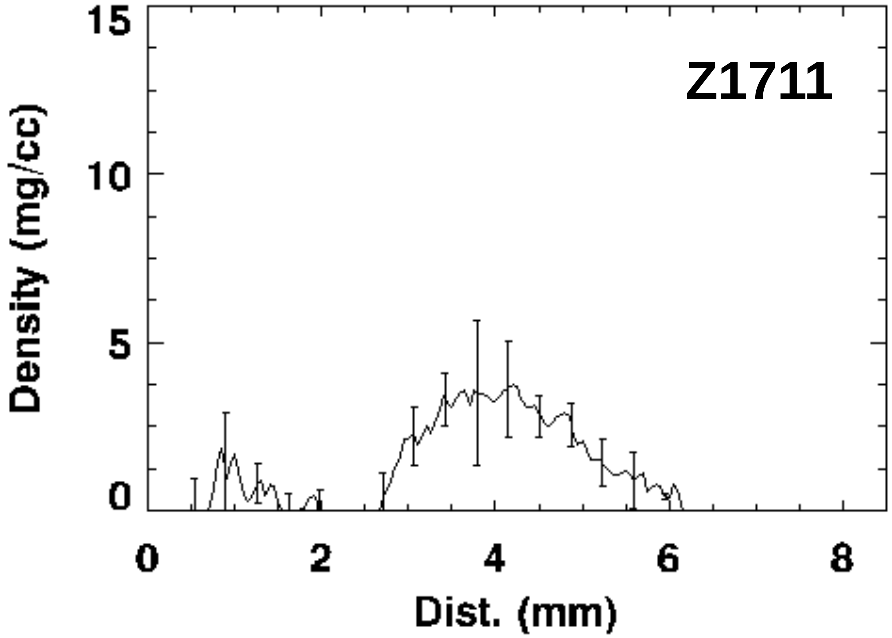
Abel inverted density profiles



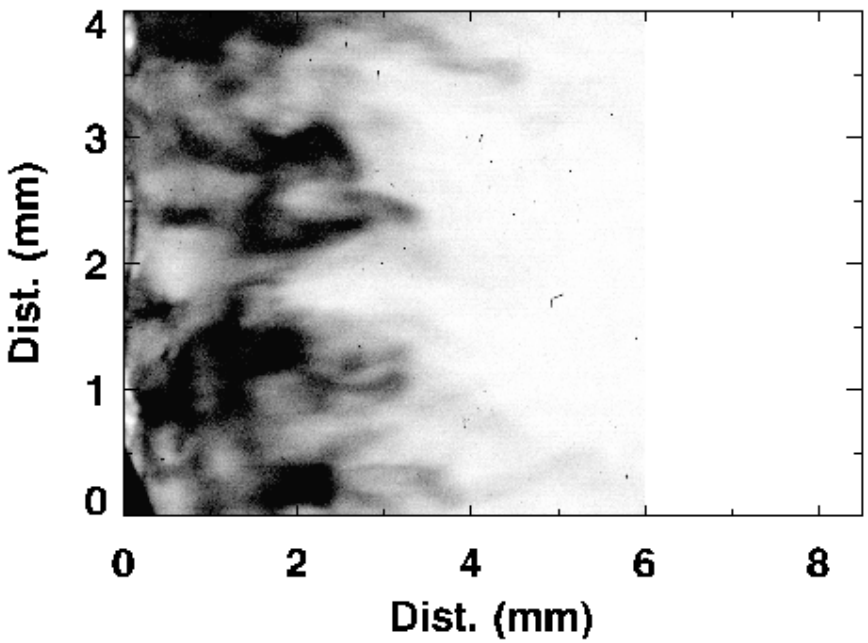
The magneto-Rayleigh-Taylor instability limits how short the pulsewidth τ can be



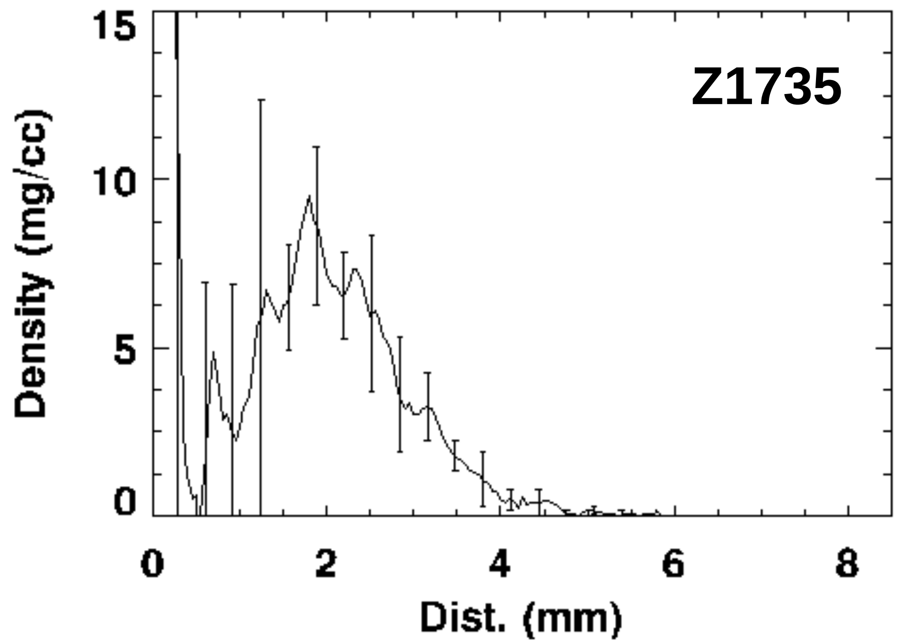
Abel inverted density profiles



The magneto-Rayleigh-Taylor instability limits how short the pulsewidth τ can be

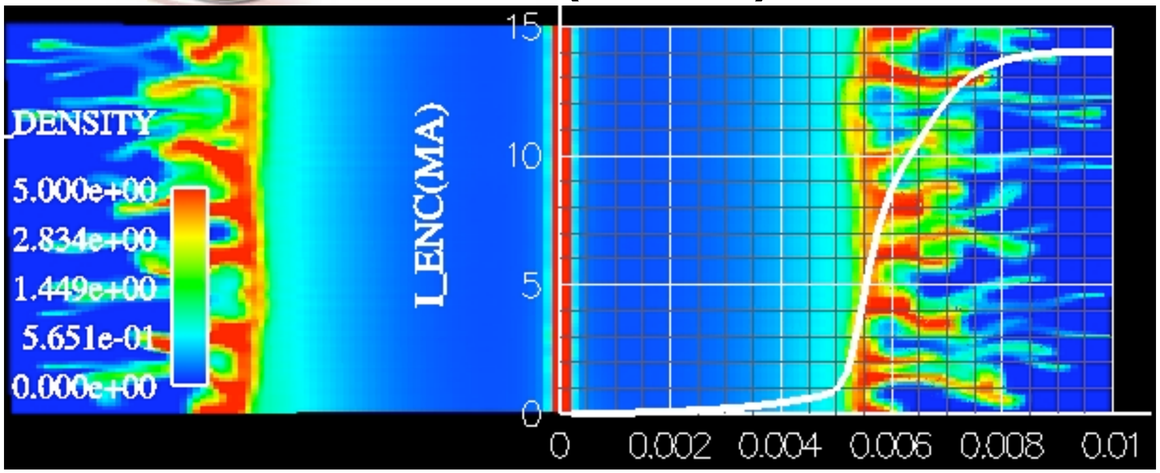


Abel inverted density profiles

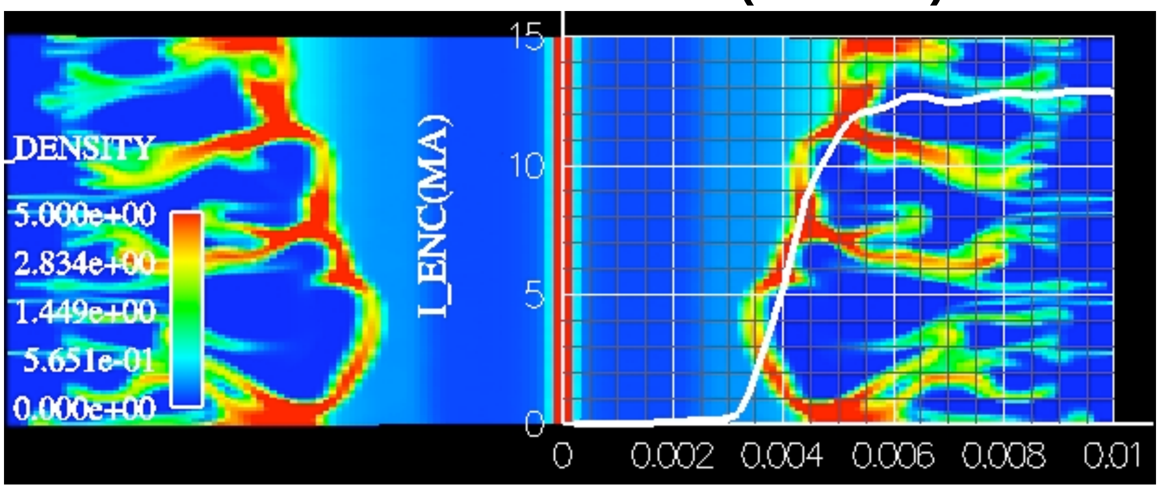


Instability bubble growth is reduced by 3D effects

C=3% (2520 ns)



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

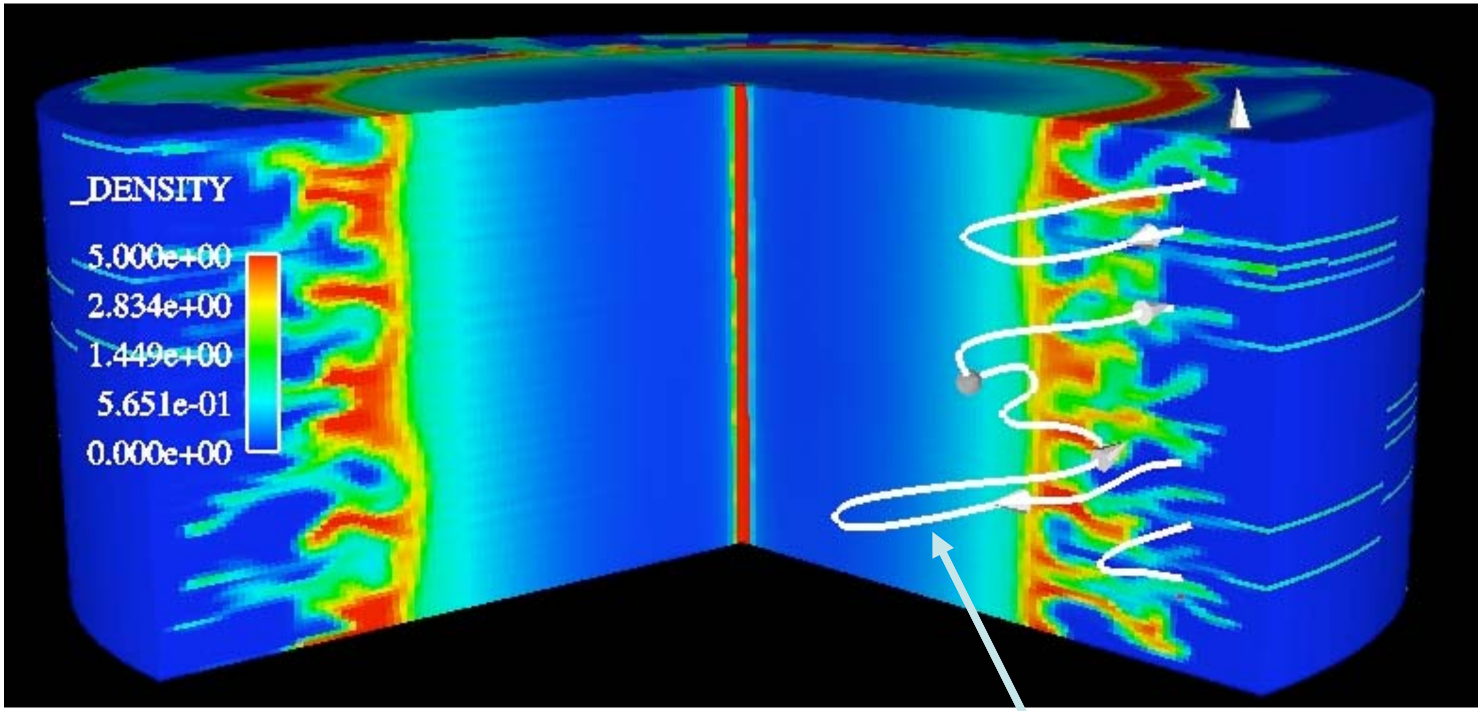


- **In 3% correlated problem, bubble growth is reduced because current can flow azimuthally.**
- **Mass distribution is left to right asymmetric as observed in radiographs**

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

In 3D, current can travel azimuthally, “self -regulating” bubble growth

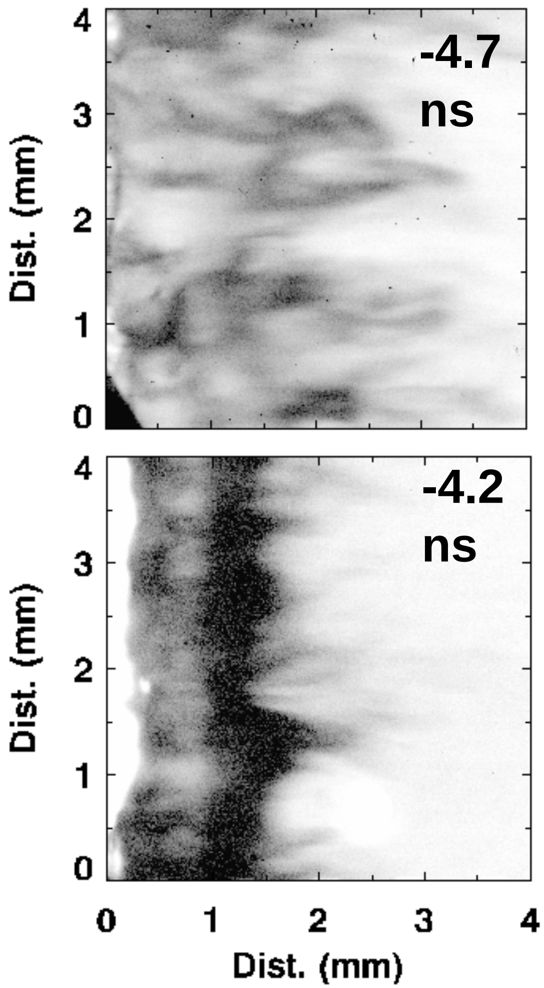
C=3%, t=2518 ns



current streamline

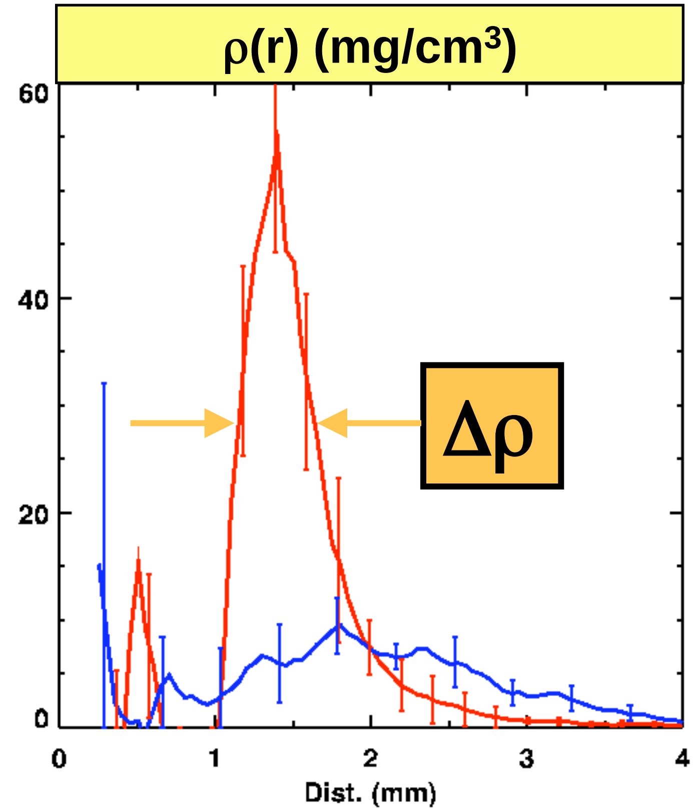
Yu, et al., Phys. Plasmas (2008)

We can stabilize the magneto-Rayleigh-Taylor instability and decrease the width of the mass by 3X

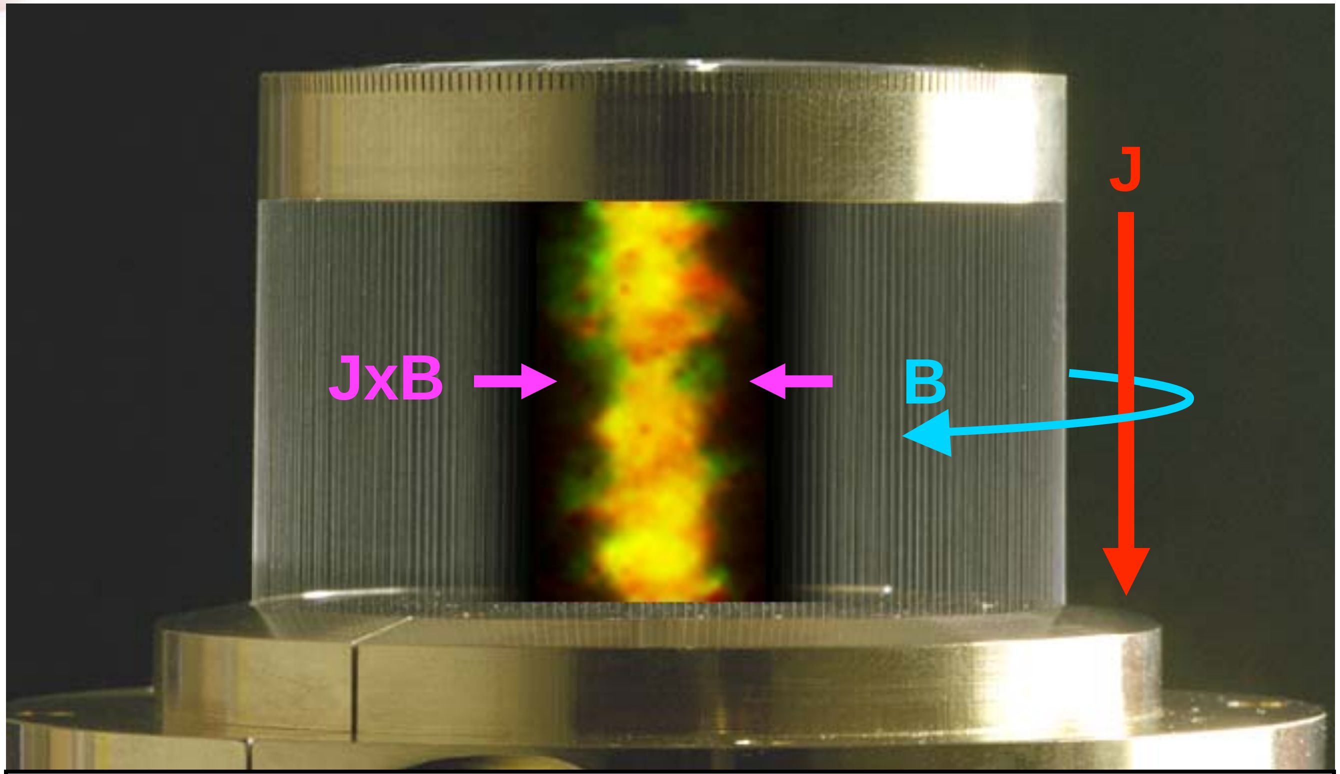


Single
Δρ=1.58 mm P=160 TW τ_w=3.9 ns

Nested+foam
Δρ= 0.51 mm P=260 TW τ_w= 1.7 ns



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



z-pinch sources

n_i ~ 1 - 5 x 10^{20} cm^{-3}, Y_{rad} ~ 1 - 2 MJ

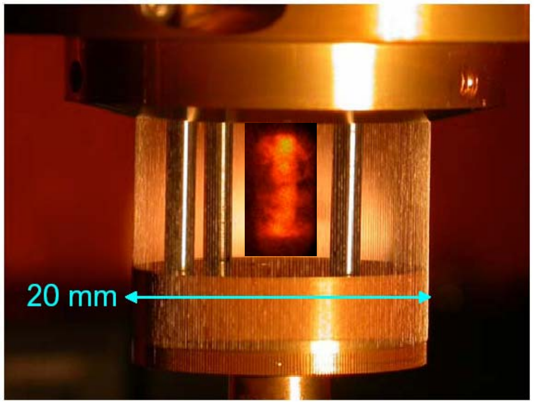
P_{rad} ~ 100-250 TW ~ 200 million million Watts

T_{rad} ~ 200 eV ~ 2,300,000 °K

A power of 200 TW

- 15 x global power consumption
- 63 x US annual power consumption
- http://www.wolframalpha.com/

How can we use this efficient x-ray source to do ICF?

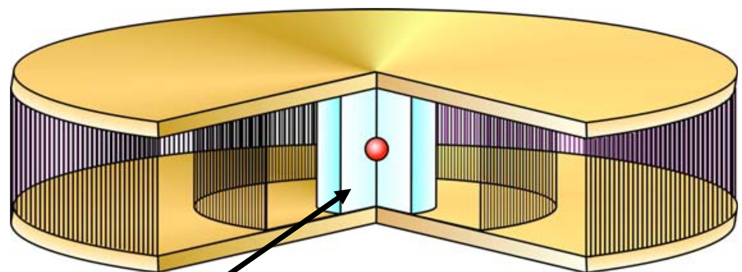


Where do we put the capsule?

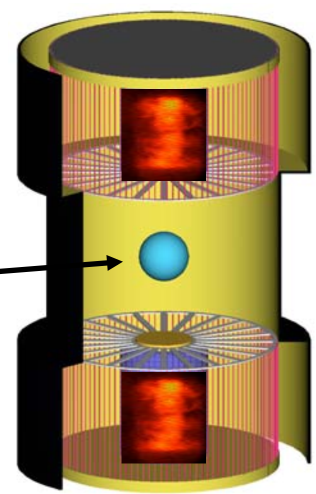
We want high intensity (high Tr)
for high ablation pressure
-> let the capsule see the pinch

We need high uniformity (~1%) in
x-rays the capsule sees for symmetry
-> hide the capsule from the pinch

Dynamic Hohlraum



Double-Ended Hohlraum

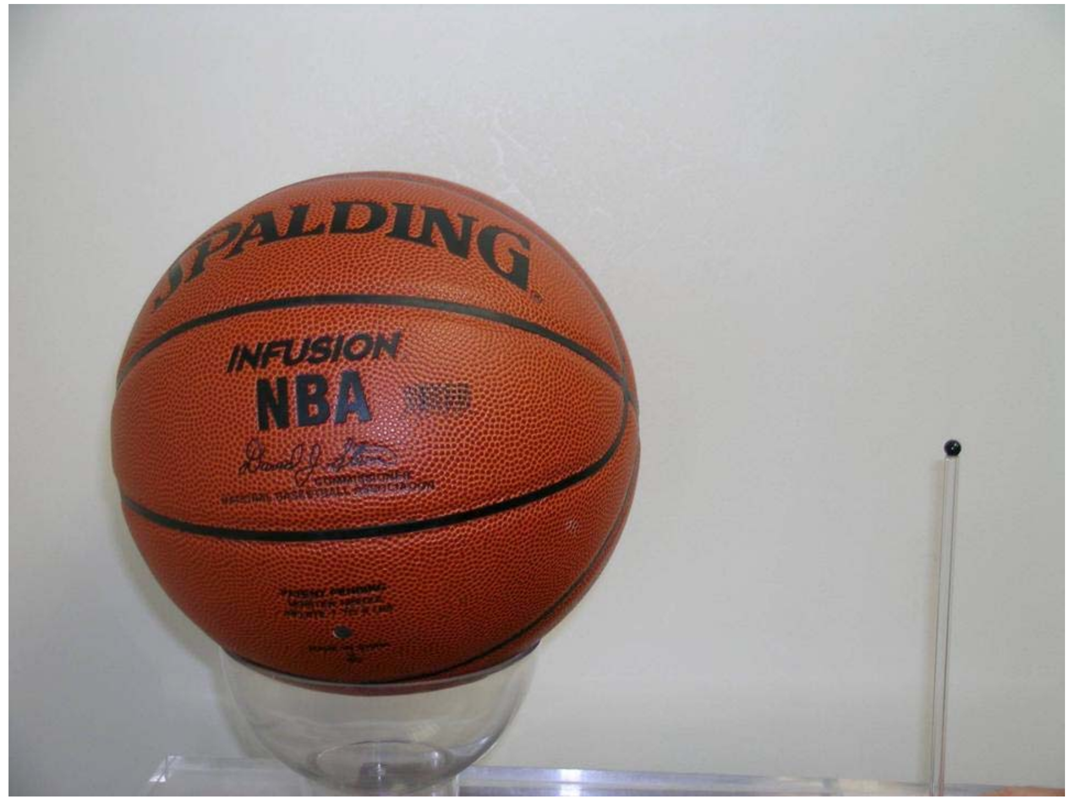


This approach is the most conservative

Spherical convergence is used to reach the high densities and pressures

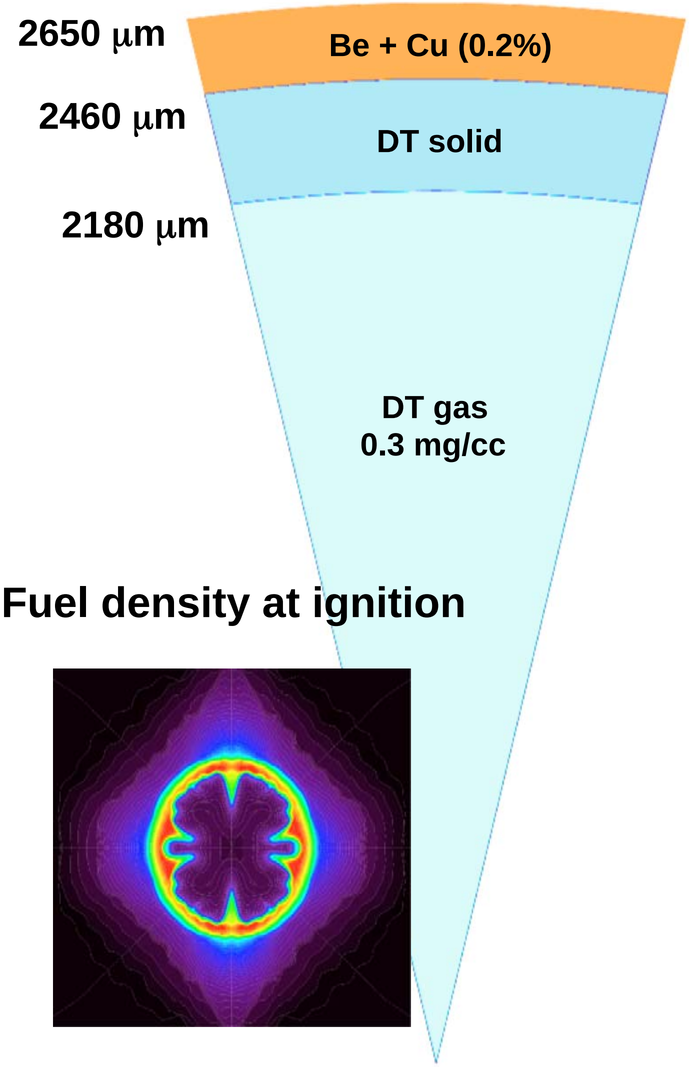
30 to 1 convergence ratio is required

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

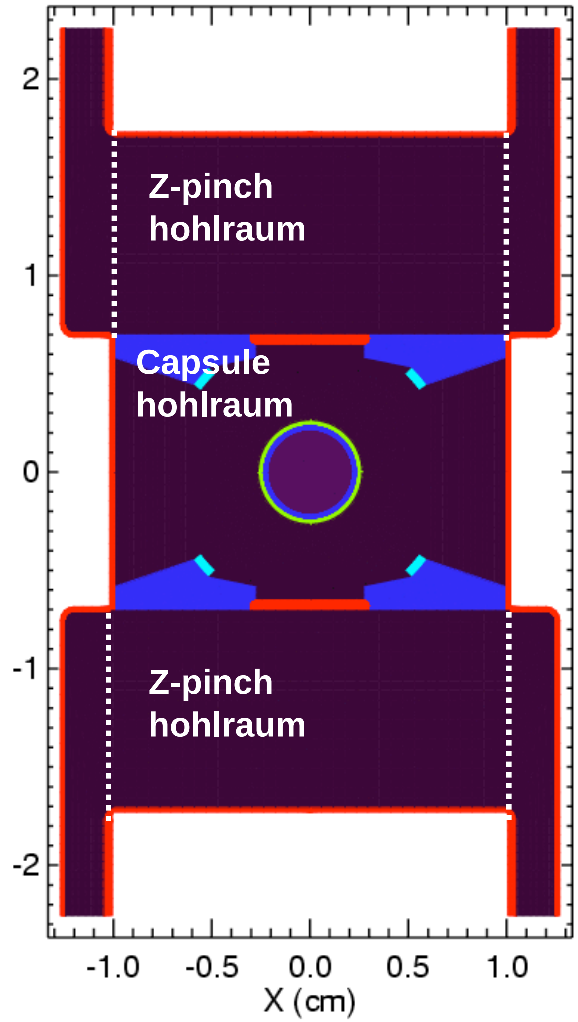


Integrated simulations demonstrate 400+ MJ fusion yield in a pulsed-power z-pinch driven hohlraum

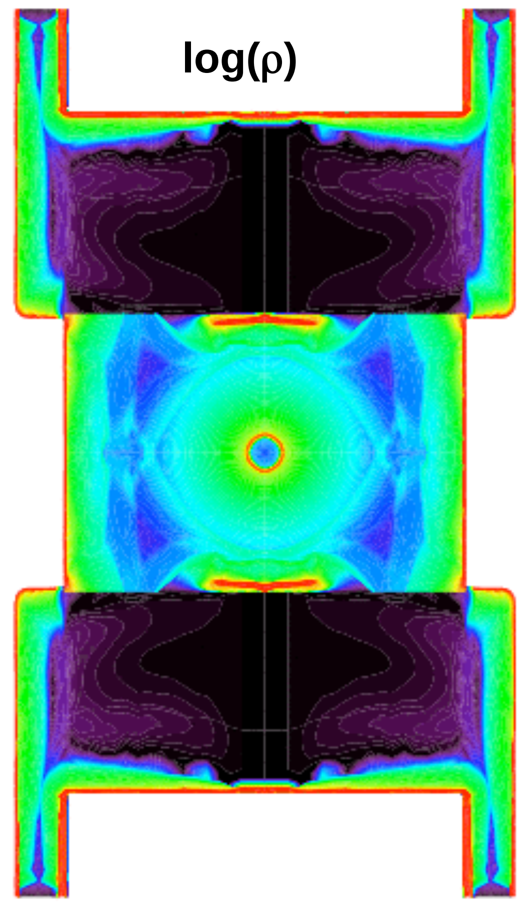
R. A. Vesey et al., Phys. Plasmas (2007)



Fuel density at ignition



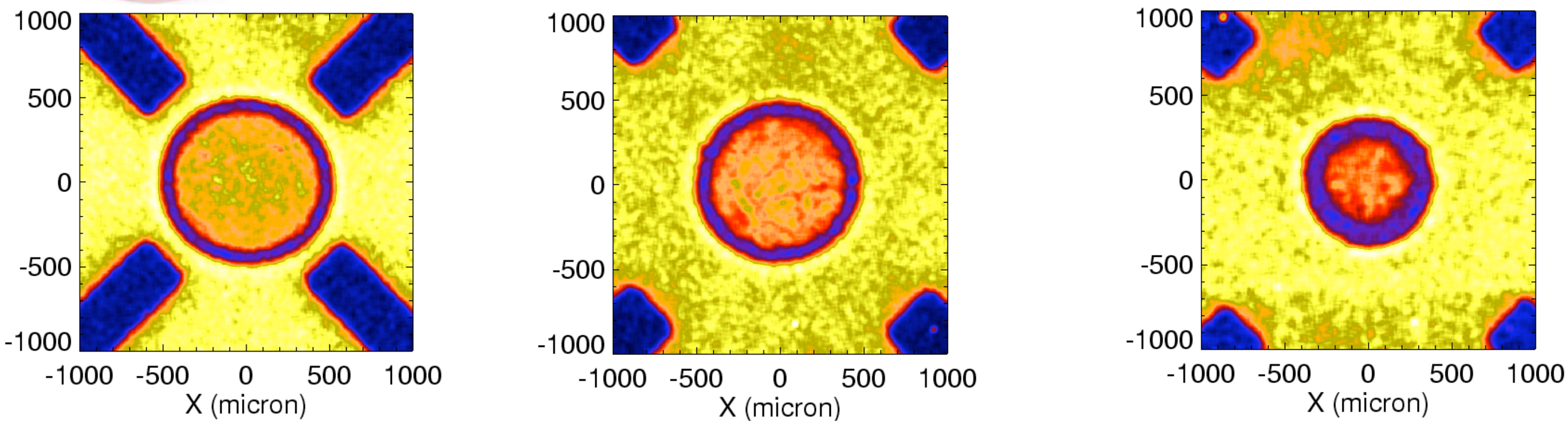
470 MJ 2D yield

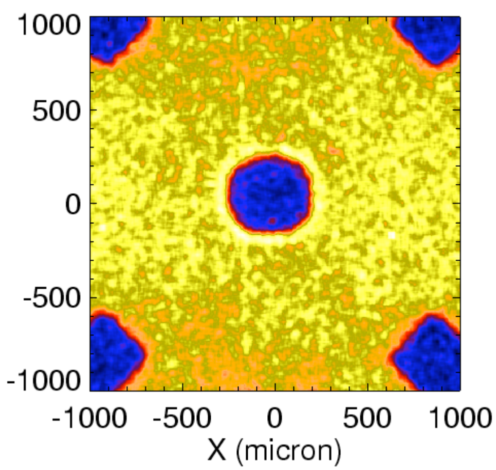


37 papers in 7 years

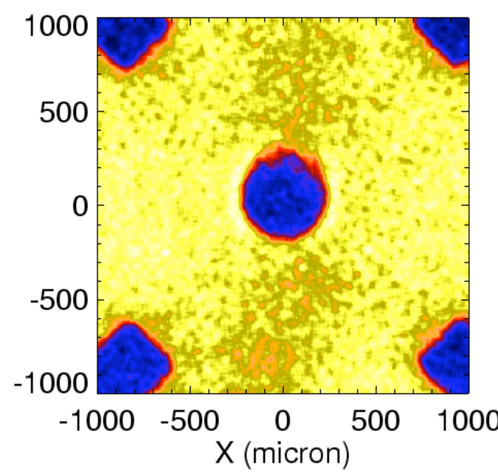
Sandia National Laboratories

The double pinch has produced some of the most symmetric capsule implosions, for any driver





near peak CR
absolute transmission
~ 0 near center

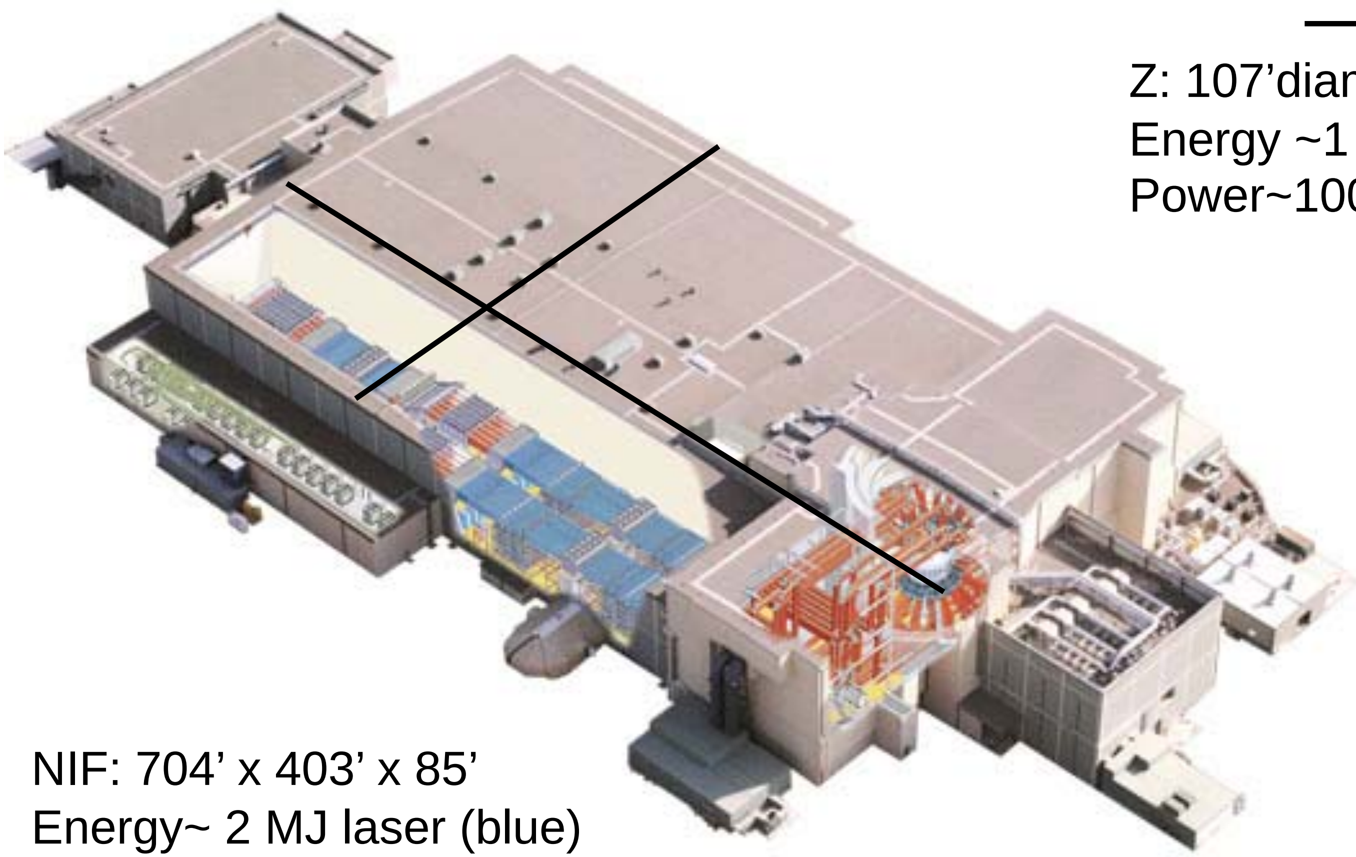


ρ > 40 g/cc

- Record convergence ratios for pulsed power systems

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

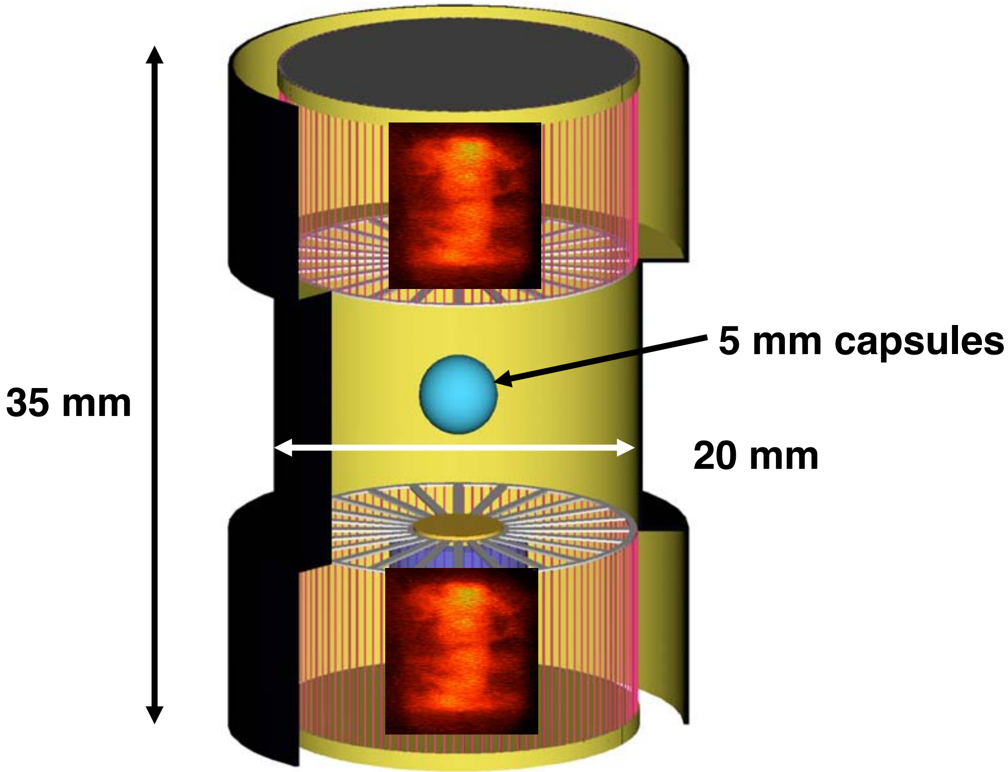
Z: 107’diam x 20’ high
Energy ~1 MJ “useable “x-rays
Power~100-200 TW



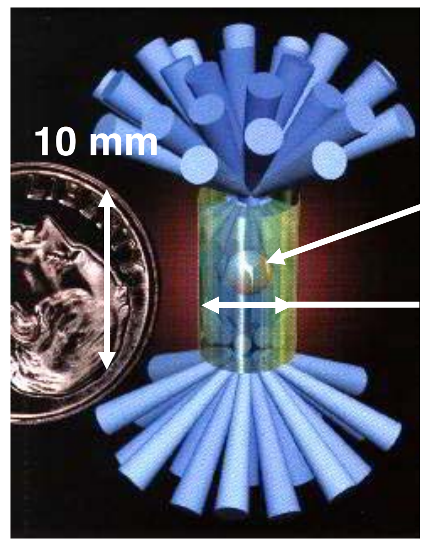
NIF: 704’ x 403’ x 85’
Energy~ 2 MJ laser (blue)
Power~ 500 TW

HOWEVER:

While Z pinches are more efficient radiators, they need more energy to reach ICF conditions because they radiate in bigger volumes

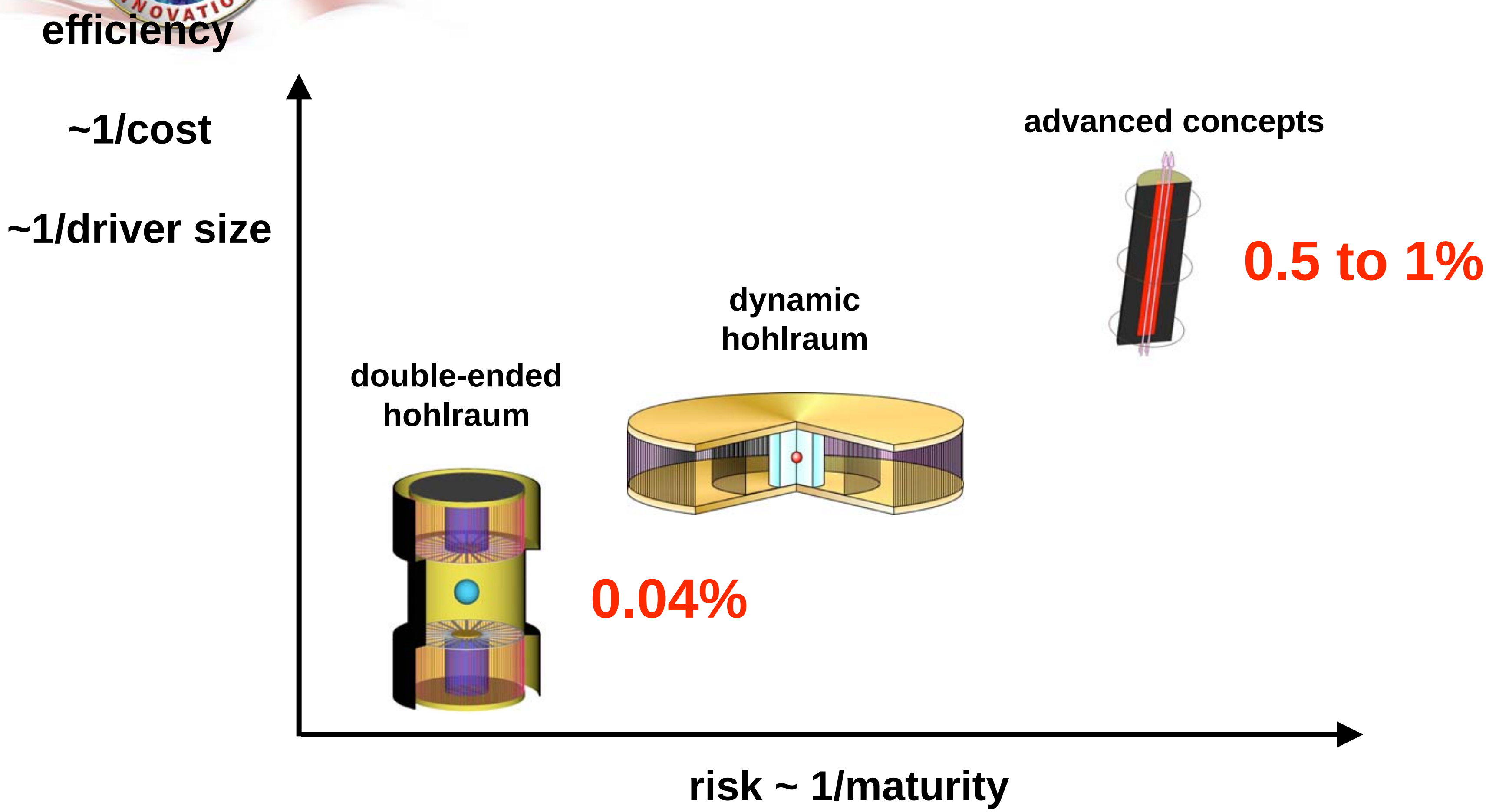


Z-pinch driven hohlraum (2 Z-pinches)
Z: 1-2 MJ X-ray source
High Yield requirement ~ 16 MJ x-ray source



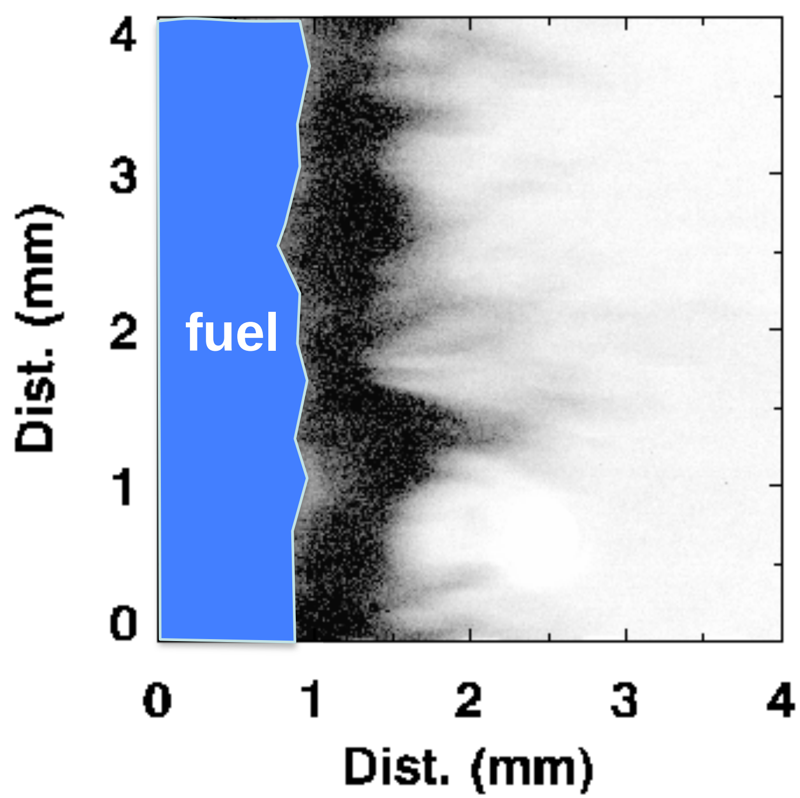
NIF Laser (192 laser beams)
1-2 MJ X-ray source

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



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

Direct magnetic compression of fuel could increase coupling efficiency by 20X!



Use stabilized cylindrical implosion to compress fuel

CR ~ 10:1

Magnetic presure at I=16 MA and r=1.5 mm
P ~ 18 Mbar

Ultimate convergence ratio of this pinch ~20:1 with
P ~ 160 Mbars

At 60 MA, P ~ 2.25 GBars

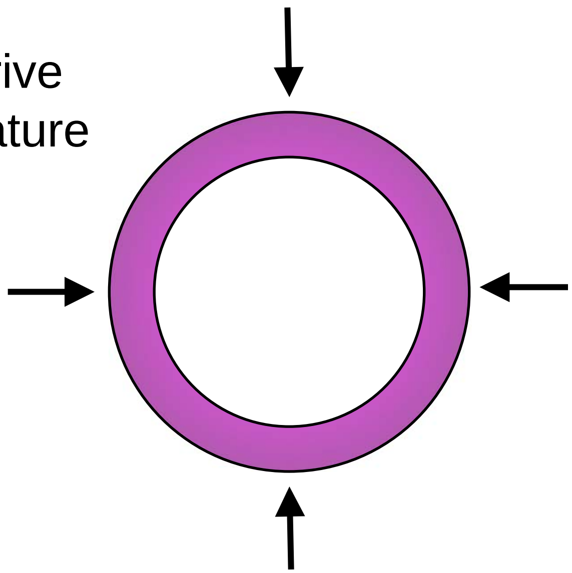
Spherical and cylindrical implosions are used to create high energy density conditions

Radiation-Driven Spherical Implosion (spherical rocket)

$$P = \frac{(2/5)(1-\alpha)\sigma T^4}{C_s} = 3T^{3.5} \quad \text{MBar}$$

140 MBar ≈ 2e9 psi
at T = 300 eV

X-ray drive
temperature
T

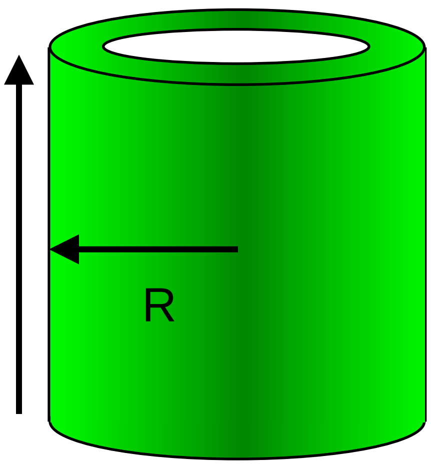


Magnetically-Driven Cylindrical Implosion

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

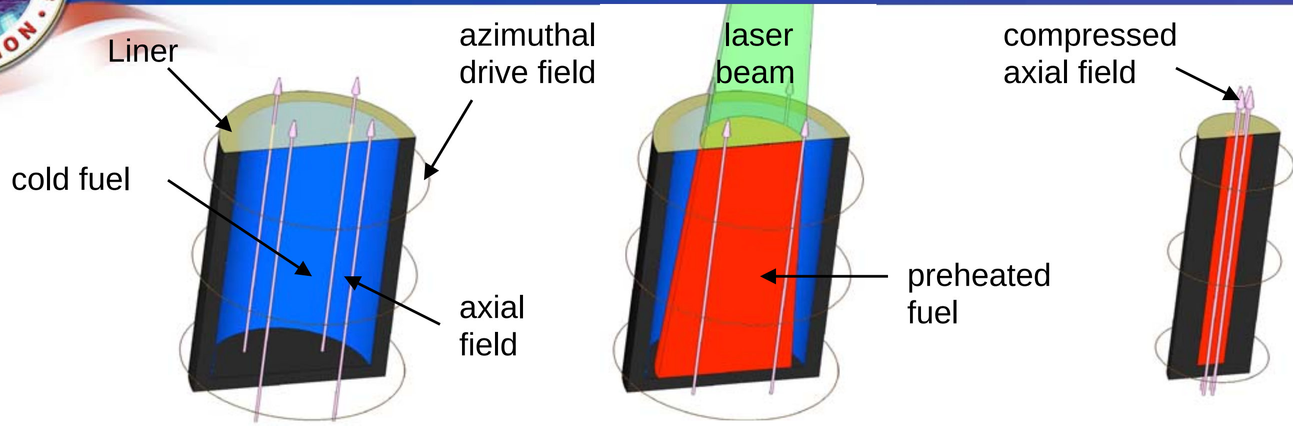
97 MBar ≈ 1e9 psi
at I = 25MA, R = 0.1 cm

Drive
current
I



Need fuel pressures of 500 Gbar and fuel ρr of 1 g/cm^2 for ignition

Fuel magnetization and preheat provide beneficial effects for liner driven ICF



A magnetic field inhibits thermal conduction and enhances alpha particle deposition within the fuel

Preheating the fuel reduces the compression needed to obtain ignition temperature

…calculations indicate this could be done by the Z Beamlet laser

Simulations indicate significant yields on ZR with modest convergence ratios and implosion velocities

The Magneto-Rayleigh-Taylor instability will be a key issue for this concept

S. Slutz, M. Herrmann

There are many applications of pulsed power technology

- Pulsed electric fields
  - Electroporation
  - Bacterial decontamination
  - Discharges through solids and liquids
- Pulsed magnetic fields
  - Equation of state measurements
  - High energy density physics
- 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 Systems" by H. Bluhm, Springer, (2006)

Summary

- Pulsed power can flexibly drive many different kinds of experiments at high currents and high voltages
- Large magnetic fields create large pressures. Large currents create large fields
- Large pressures are needed to access high energy density regimes
- The Z machine creates large currents and is the world's largest x-ray source
- Lasers have more control than Z-pinches regarding where/how/how long energy is deposited. However Z-pinches are cheaper than lasers.
- The upper limits on Z-pinch performance in achieving high energy densities are not known. There is a lot of room for innovation! (Direct drive)

Some References

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  - “High-Energy-Density Physics” by R.P. Drake, Springer, (2006).
  - "Inertial Confinement Fusion" by J.D. Lindl, Springer Verlag, NY (1998) ; Phys. Plasmas 2, 3933 (1995)
  - M. D. Rosen, Phys. Plasmas 6, 1690 (1999)
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  - HEDP Summer School, August, 2005 and August 2007 (see http://meetings.lle.rochester.edu/FSCschool)
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  - “Pulsed Power Systems” by H. Bluhm, Springer, (2006)
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