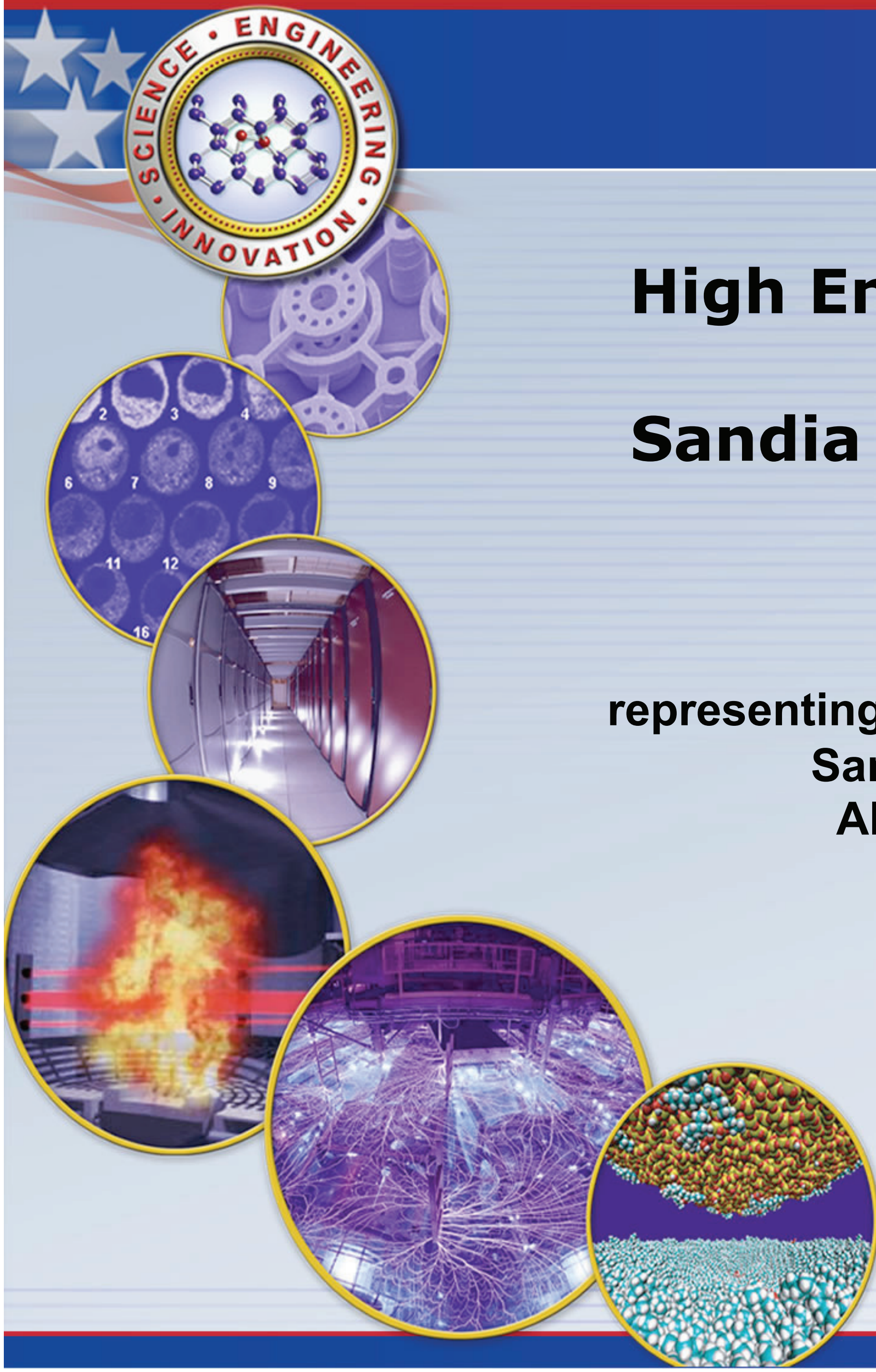


High Energy Density Physics Research at Sandia National Laboratories

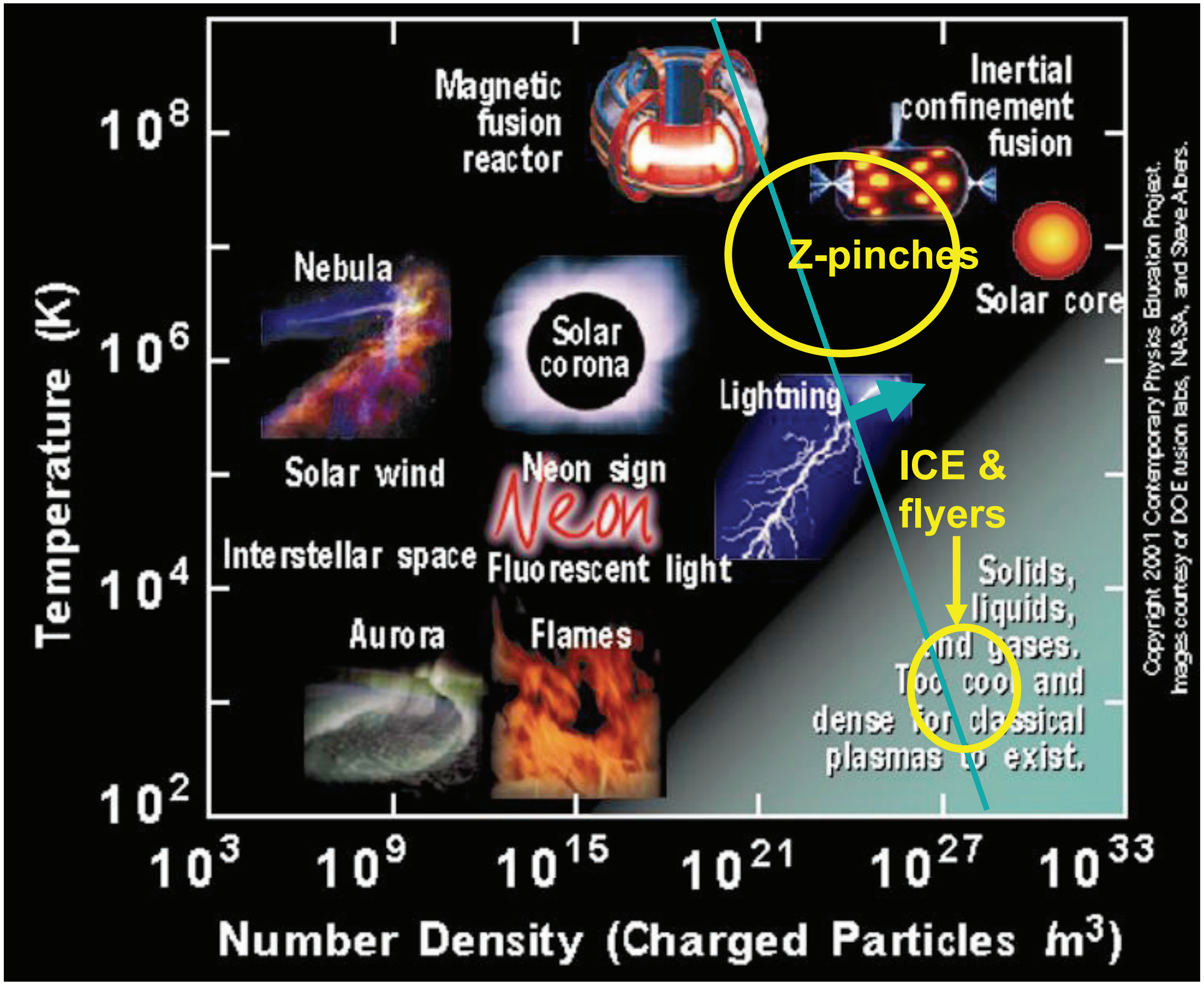
Ramon J. Leeper
representing the Pulsed Power Sciences Center
Sandia National Laboratories
Albuquerque, New Mexico

July 14, 2009

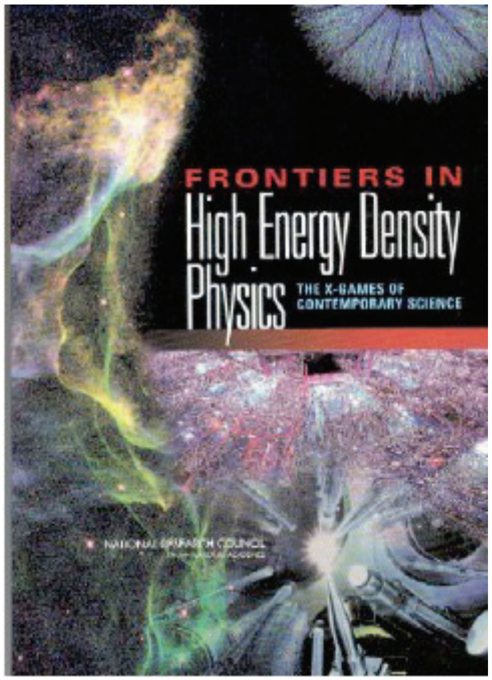
It's an exciting time to be working on the Z facility

- Refurbished Z is up and running
- Ever more extreme conditions are being reached in the dynamic materials program
- Several new concepts for pulsed power inertial confinement fusion look interesting
- Higher currents are enabling brighter x-ray sources and hotter and denser plasmas for astrophysical opacity research
- Particle In Cell (PIC) calculations of a gas puff Z-pinch reveal new insights into this "classic" plasma system

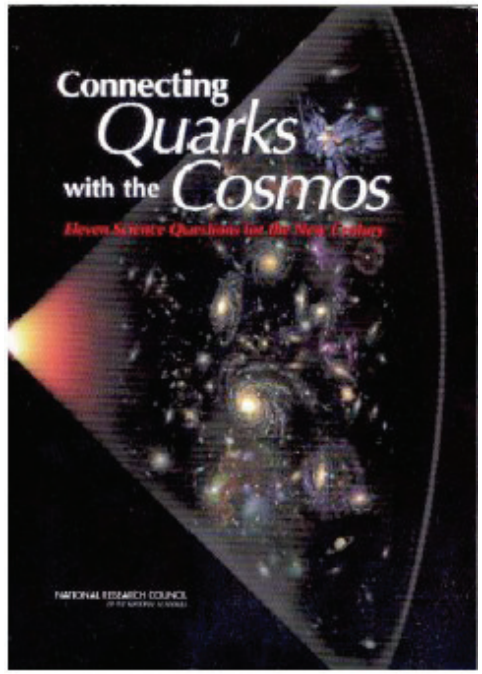
Regimes of high energy density are typically associated with energy density 10^5 J/cm^3 = 1 Mbar



Several recent studies have highlighted High Energy Density Science



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



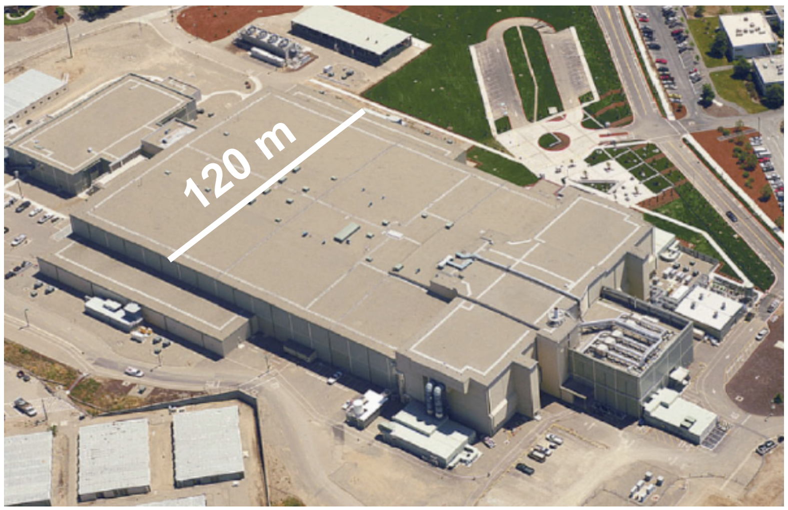
“Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century”,
M Turner et al. 2002

Science and Applications of Ultrafast, Ultraintense Lasers (SAUUL)

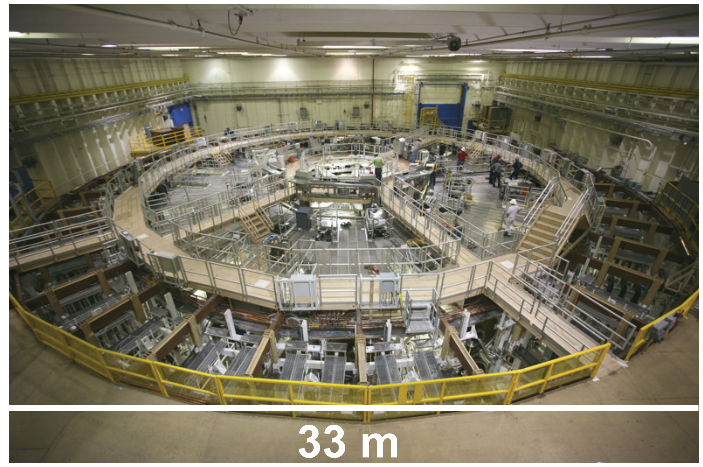
Sandia National Laboratories

Z has a unique role as one of the three major US facilities for High Energy Density Physics (HEDP) experiments

NIF (2009)
(1.8 MJ @ 0.35 µm)

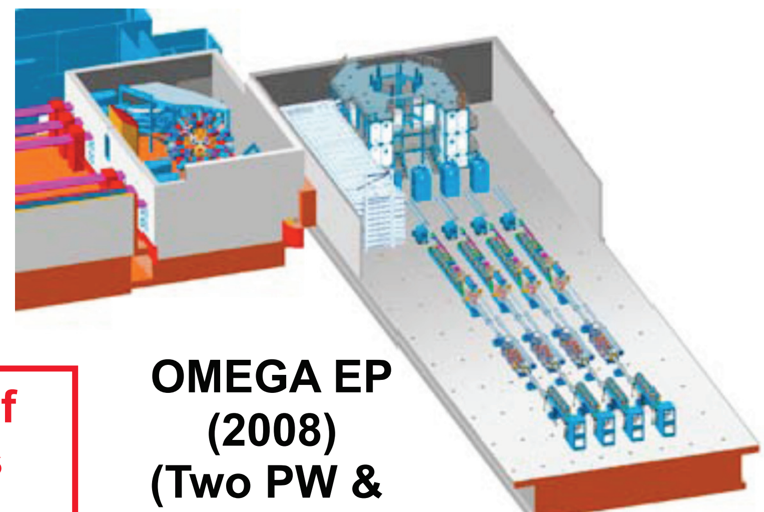


Refurbished Z (2007)
(3 MJ)



OMEGA

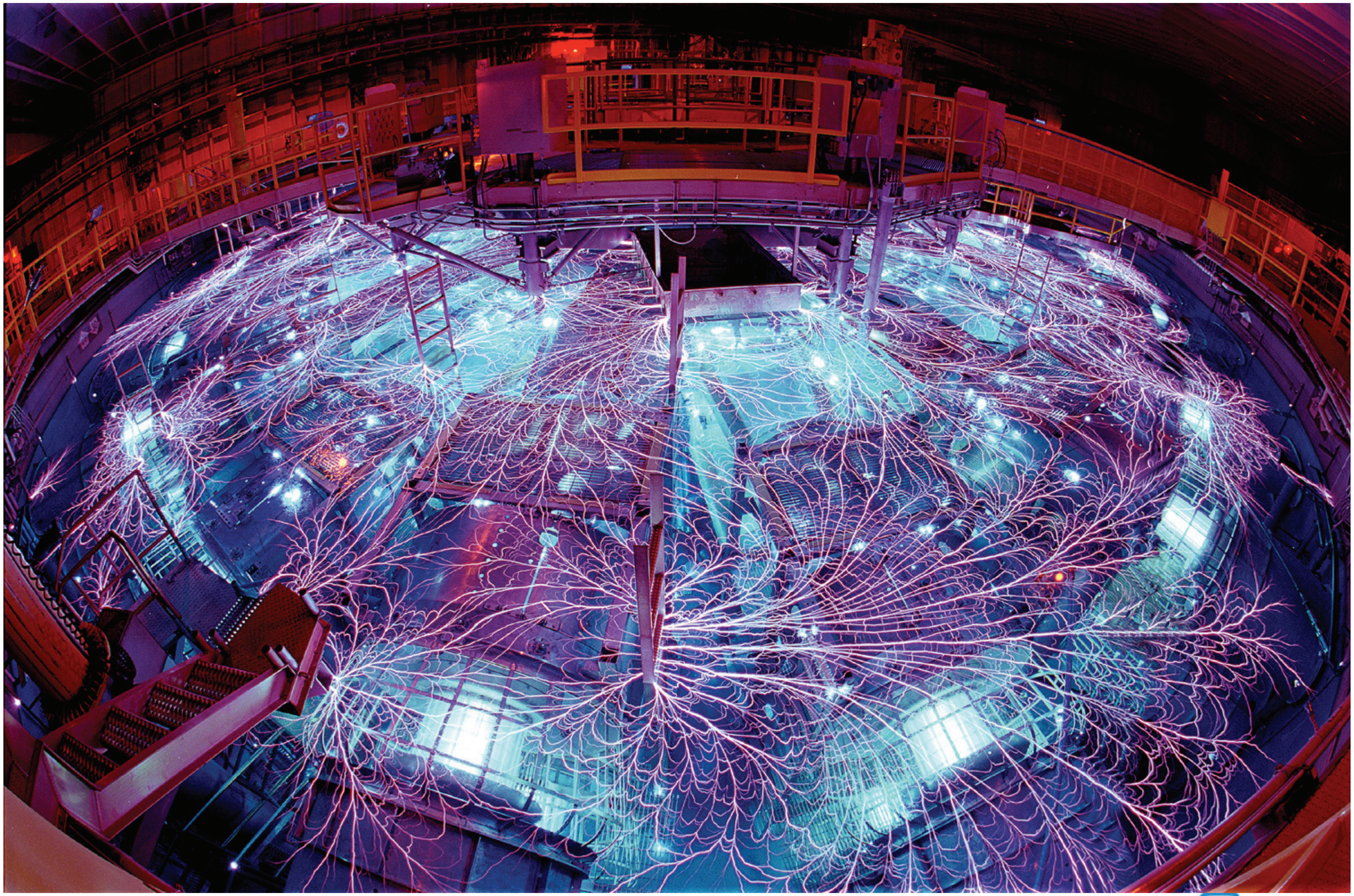
(30 kJ @ 0.35 µm)



OMEGA EP (2008)
(Two PW & two ns beams)

After 40 years of research, the components of simulations, drivers, diagnostics, and targets are in place to test ignition concepts

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

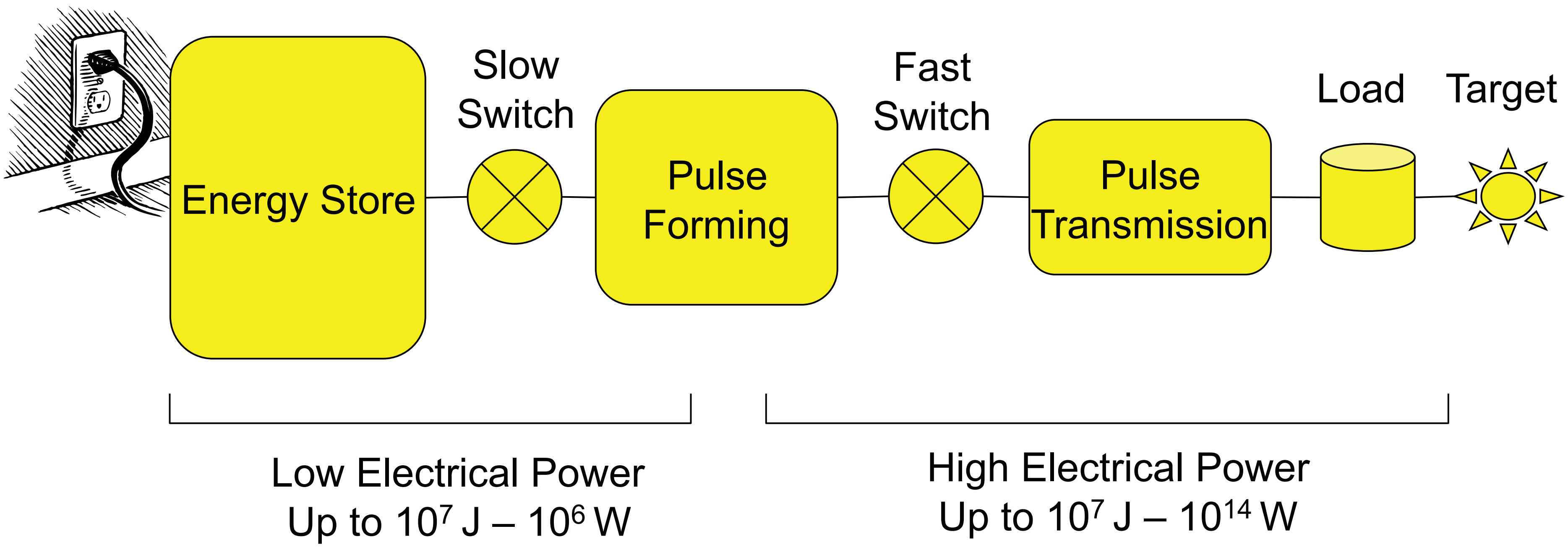


Sandia National Laboratories

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

BBC Horizon TV show: Can we make a star on earth?
http://www.youtube.com/watch?v=vpcDw255JP8

Z compresses electrical energy to produce short bursts of high power.



Goal: "Take the equivalent energy required to operate a TV for a few hours (1-2 MJ) and compress it into more electrical power than provided by all the power plants in the world combined (~15 TW)"

…S T Pai & Qi Zhang, "Introduction to High Power Pulse Technology," World Scientific Publishing Co., Singapore, 1995.

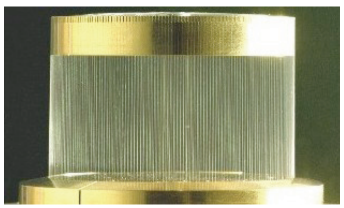
Sandia National Laboratories

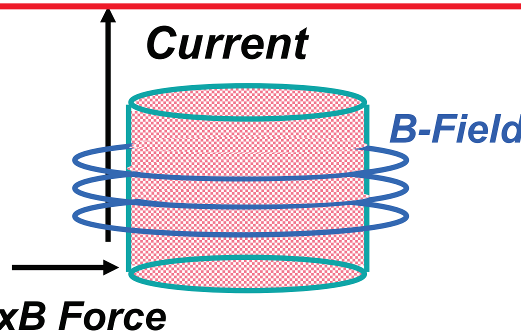
We use pulsed power drivers to create and study matter at high energy densities

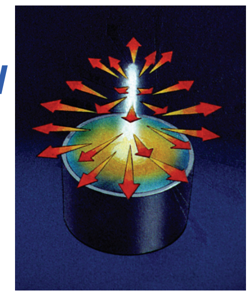
High Current

Z-pinch x-ray source

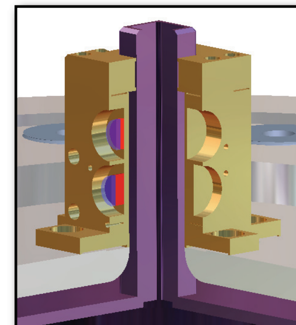
wire array

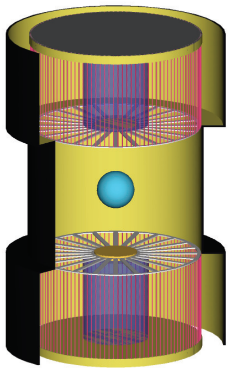




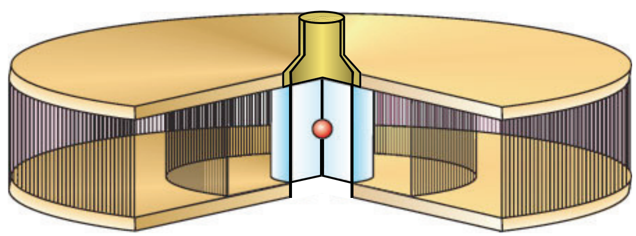


Magnetic pressure

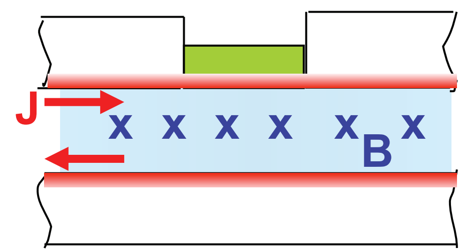




Fusion



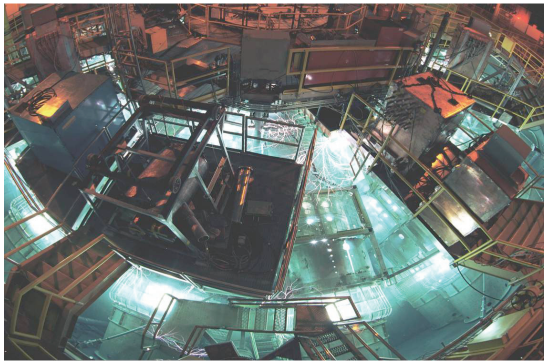
Radiation Science



Material Properties

The five-year Z-Refurbishment project has been completed

Last Shot



July '06

Demolition Completed

Sept '06

Tank Modifications Completed

Jan '07

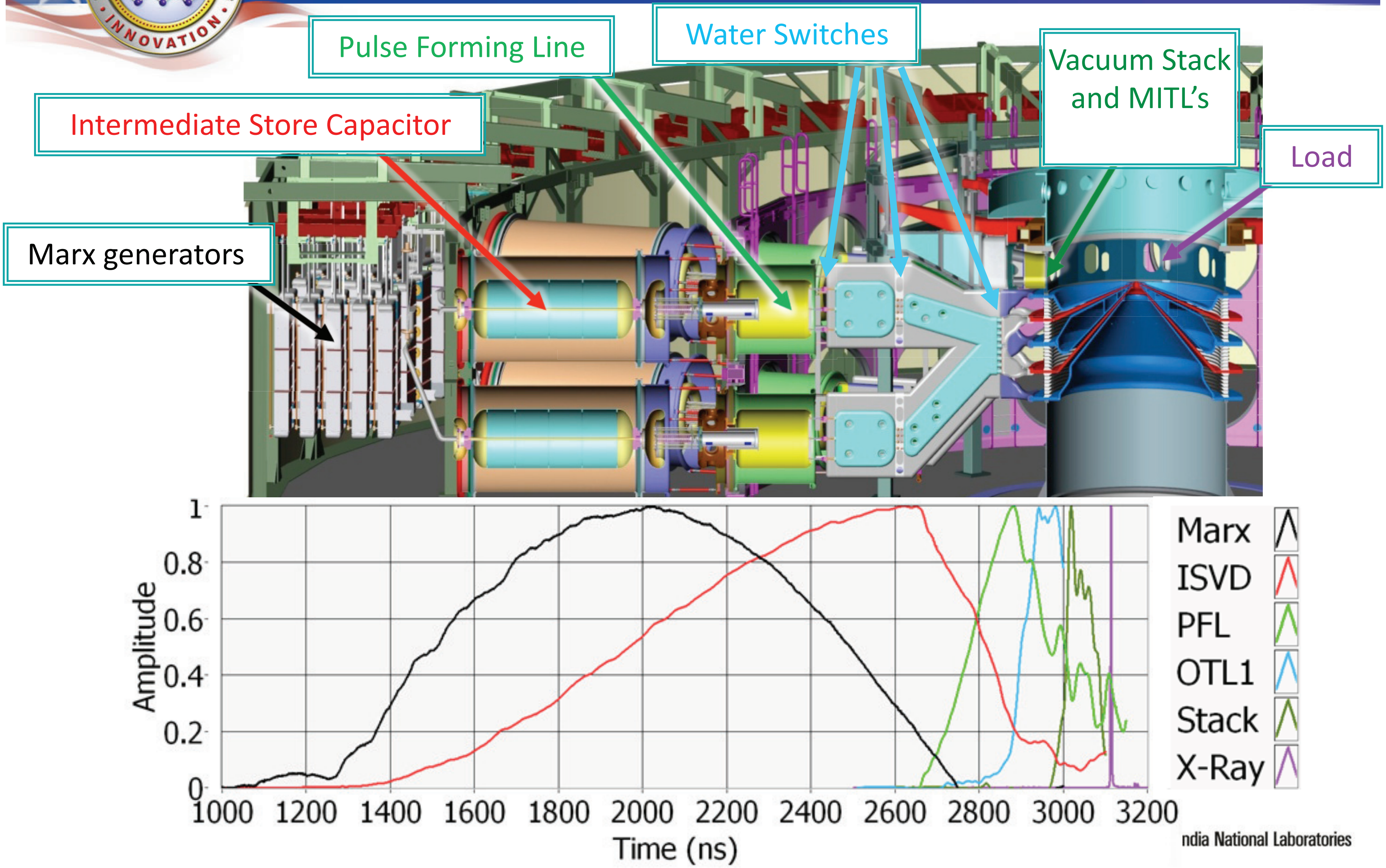
Installation Underway – Multiple Contractors

March '07

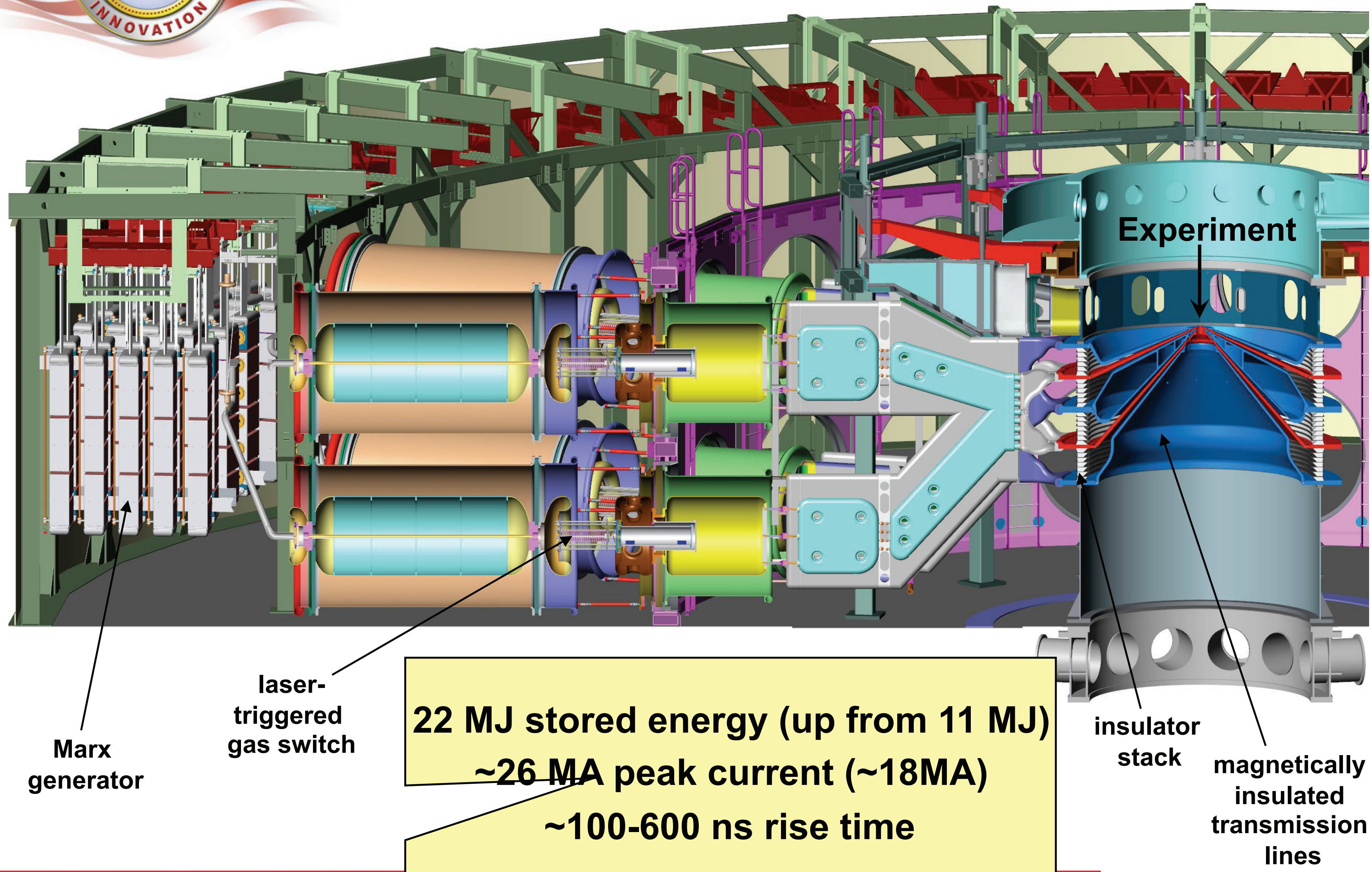
Installation Completed

August '07

A series of capacitors, transmission lines and switches achieves temporal and spatial compression on Z



The Refurbished Z Machine has more energy and more pulse shape flexibility

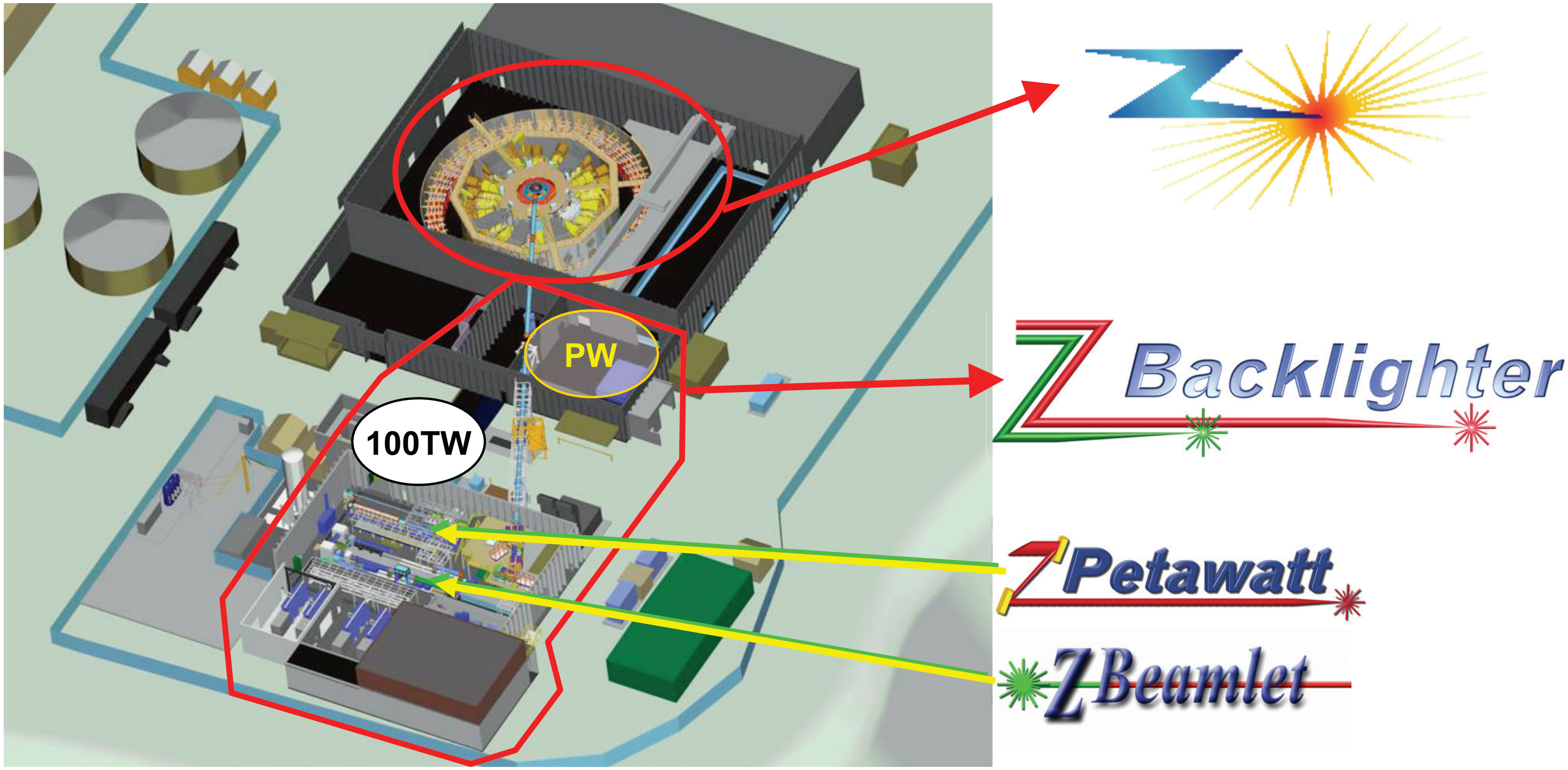


22 MJ stored energy (up from 11 MJ)

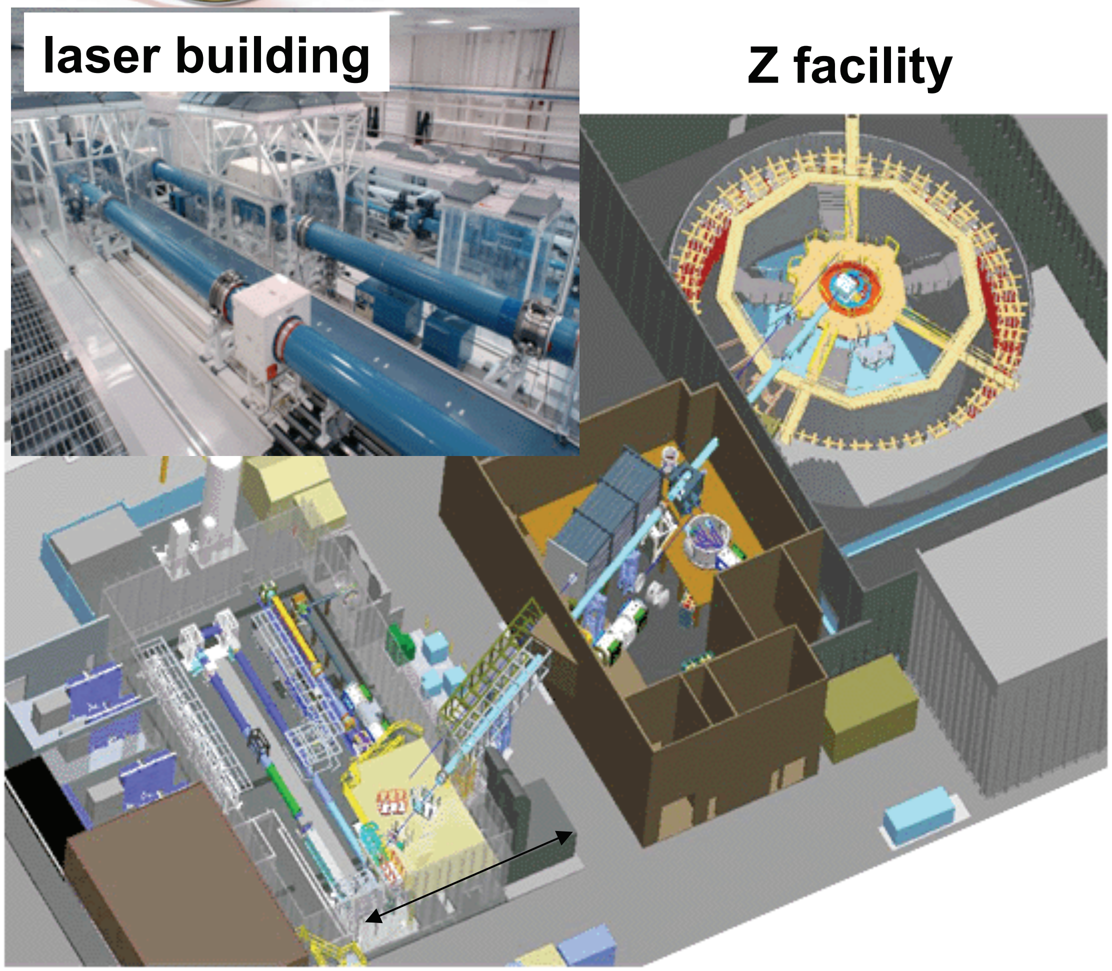
~26 MA peak current (~18MA)

~100-600 ns rise time

Z Facility Overview

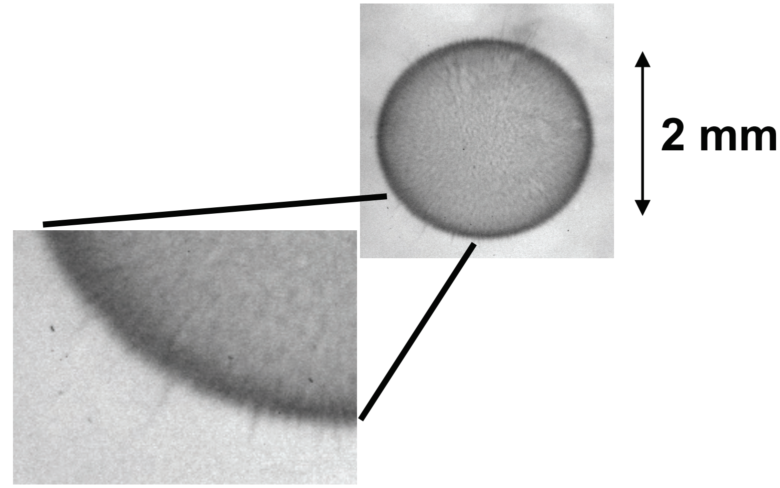


The Z-Beamlet and Z-Petawatt laser backlighters provide a powerful new capability for diagnosing Z experiments

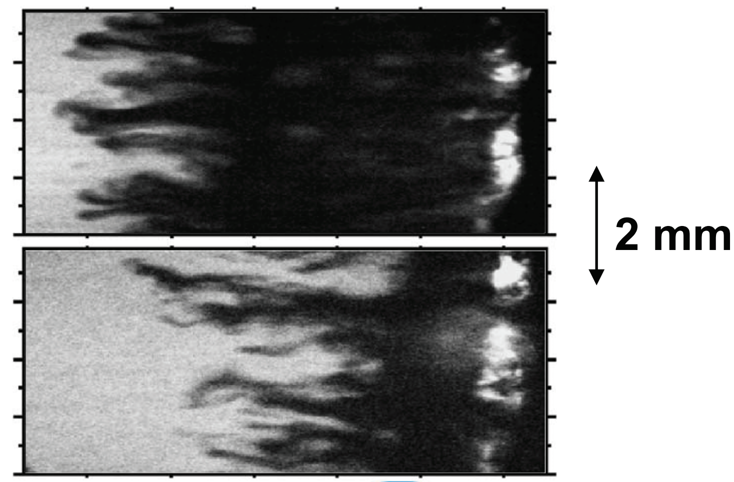


Z-Beamlet and Z-Petawatt lasers

imploding capsule



imploding z-pinch



It's an exciting time to be working on the Z facility

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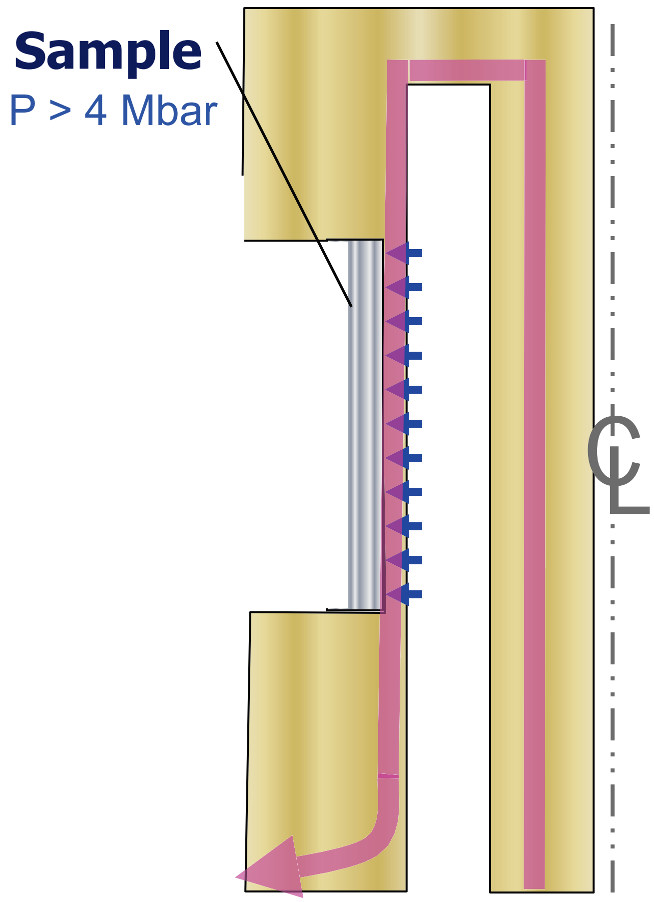
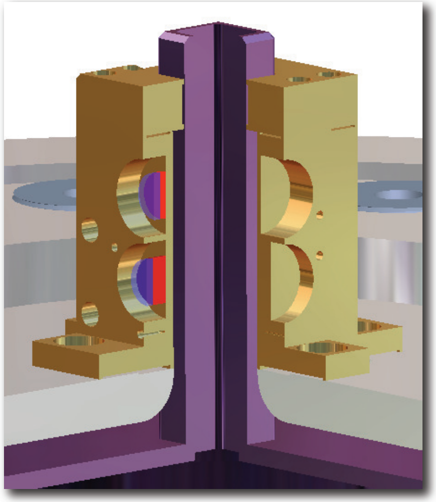
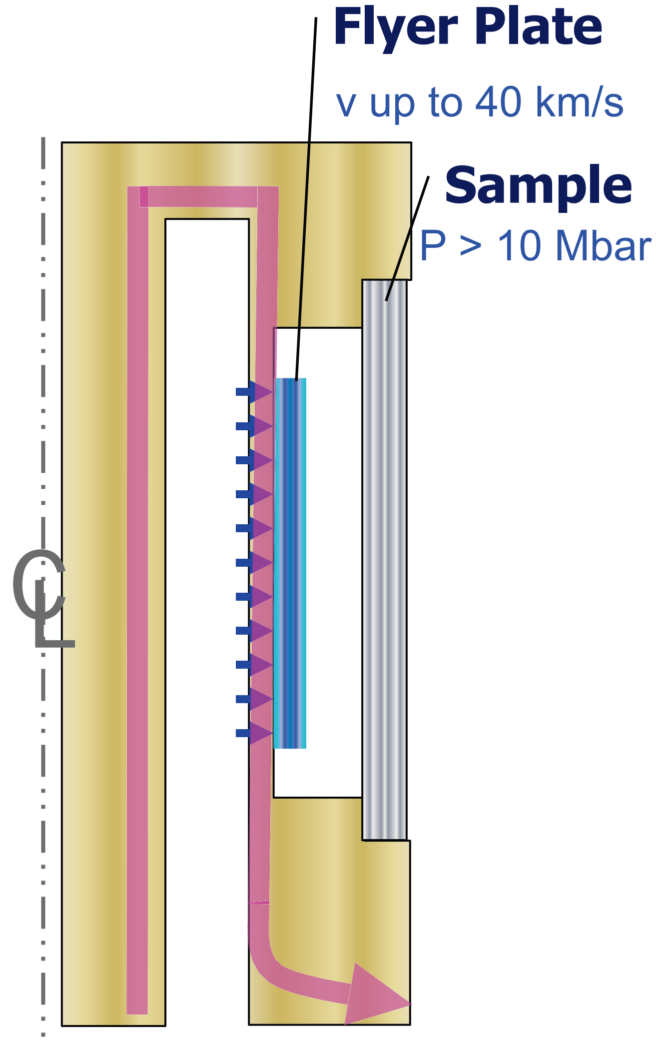
- **Several new concepts for pulsed power inertial confinement fusion look interesting**
- **Higher currents are enabling brighter x-ray sources and hotter and denser plasmas for astrophysical opacity research**
- **Particle In Cell (PIC) calculations of a gas puff Z-pinch reveal new insights into this "classic" plasma system**

Isentropic compression and shock wave experiments are both possible on Z



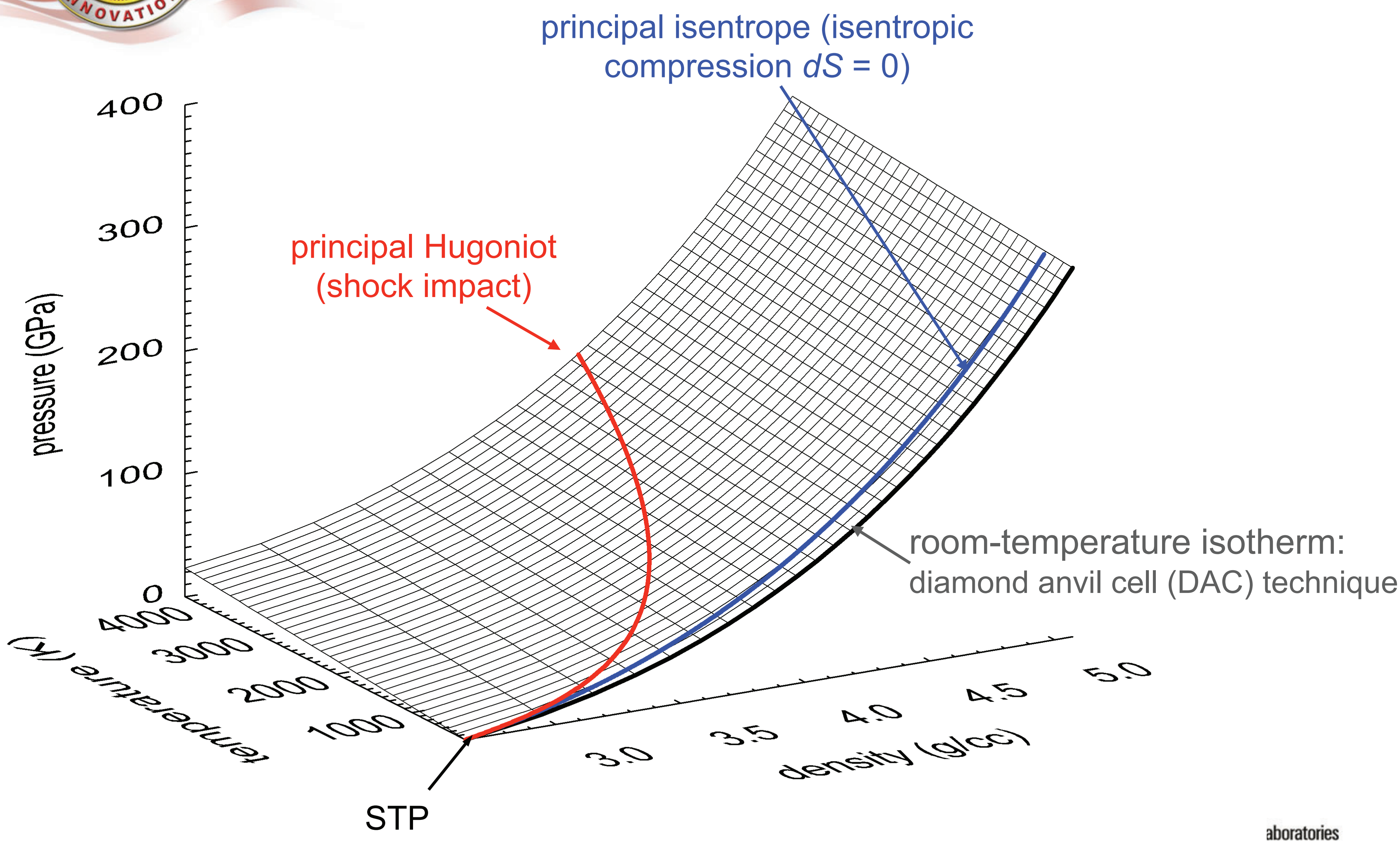




Isentropic Compression Experiments:
gradual pressure rise in sample

Shock Hugoniot Experiments:
shock wave in sample on impact

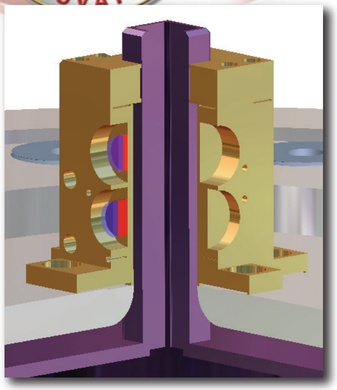
Magnetic pressure can be used to examine fundamental material properties at HEDP conditions

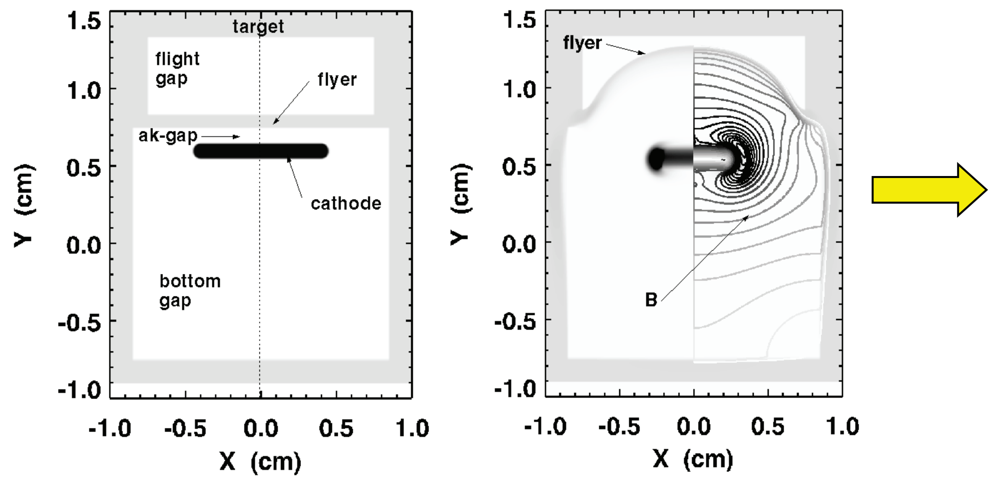


aboratories

Our MHD simulation capability is a powerful design tool

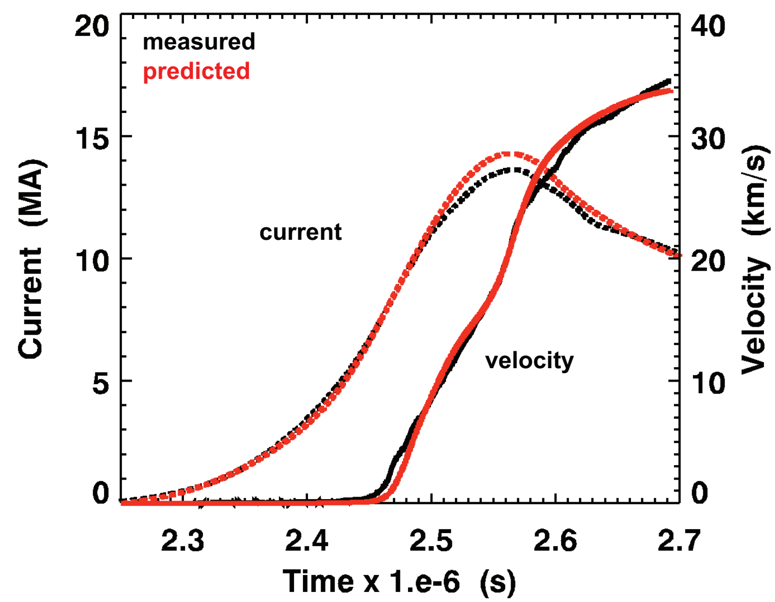
DFT based material models gave us predictive capability
ASC codes enable optimized experiments





R. W. Lemke *et al.*, *J. Appl. Phys.* **98**, 073530 (2005)

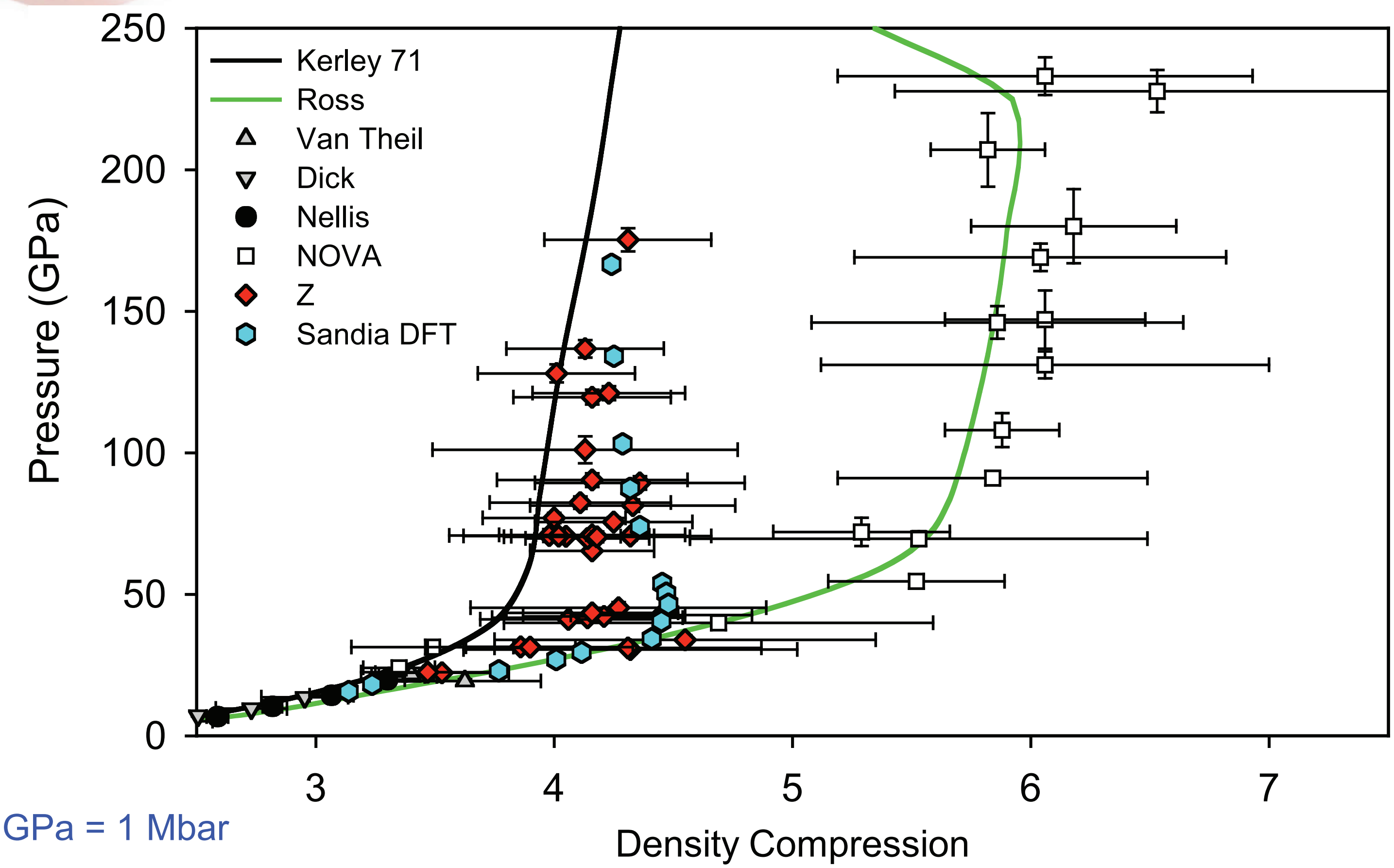
Measured / predicted current & flyer velocity (850 μm Al)



In 2-D, 160 CPUs, 4 hours (T-Bird)

In 3-D, 8192 CPUs, 300 hours (ASC Purple)

Deuterium experiments demonstrated the capabilities of Z as a platform for accurate EOS measurements



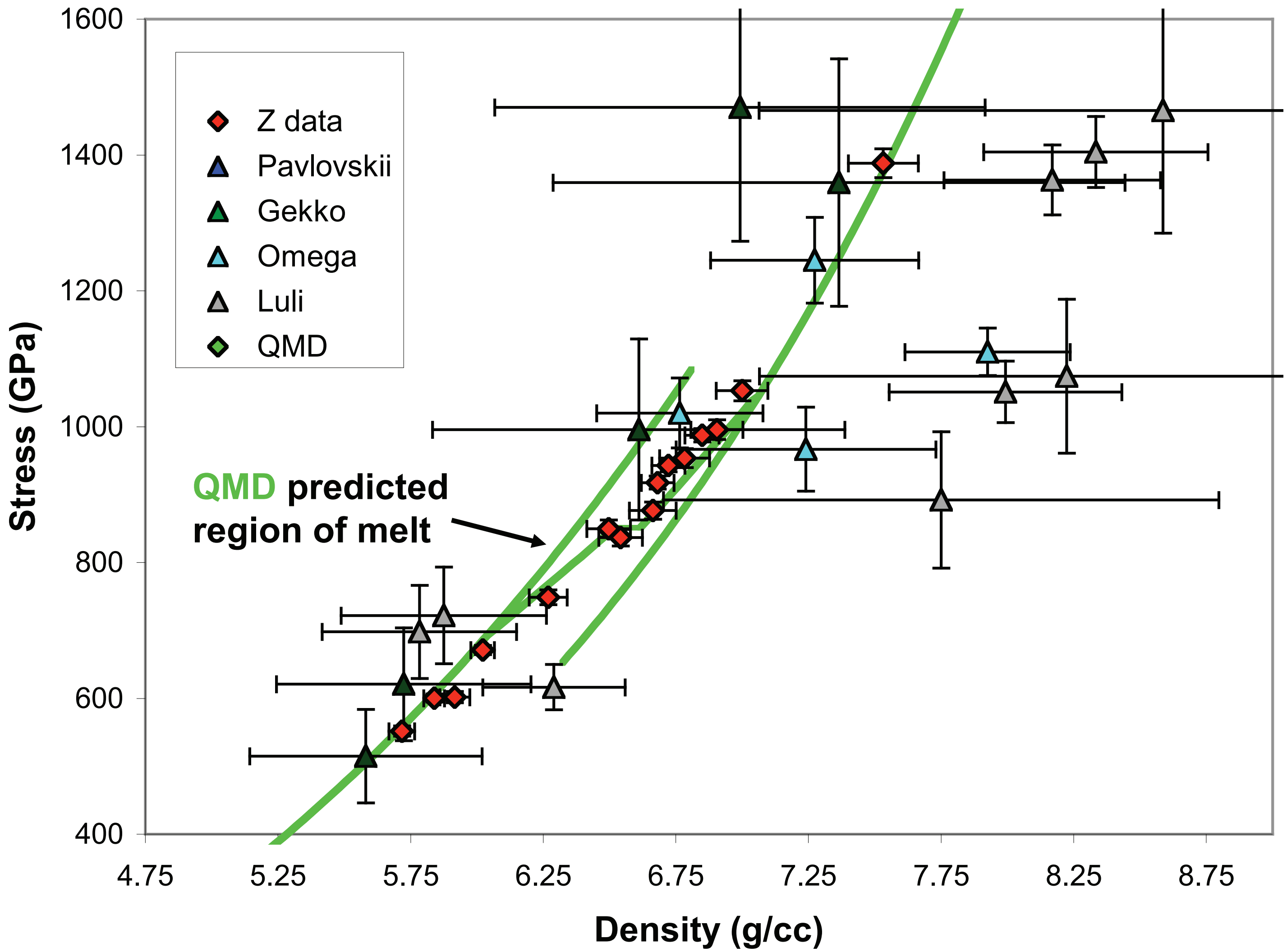
100 GPa = 1 Mbar

M. D. Knudson *et al.*, Phys. Rev. Lett. **87**, 225501 (2001)
M. P. Desjarlais, Phys. Rev. B **68**, 064204 (2003)

Impacts ICF and planetary models

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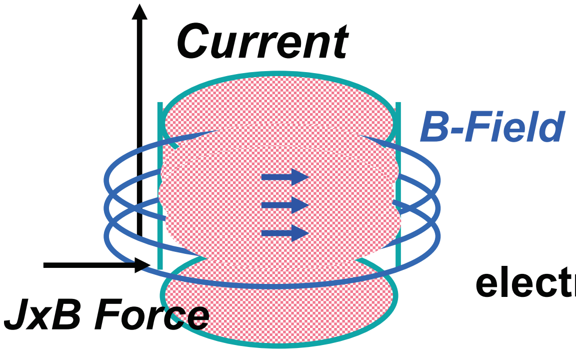
Magnetically-driven fast Z-pinch implosions efficiently convert electrical energy into radiation



kinetic and magnetic energy

↓

internal energy

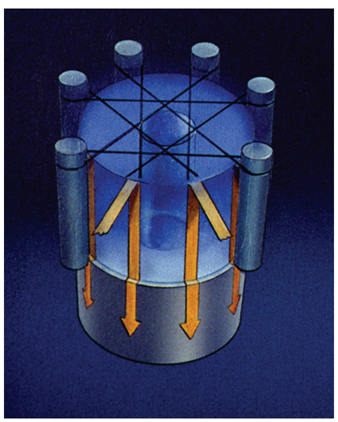
↓

x rays

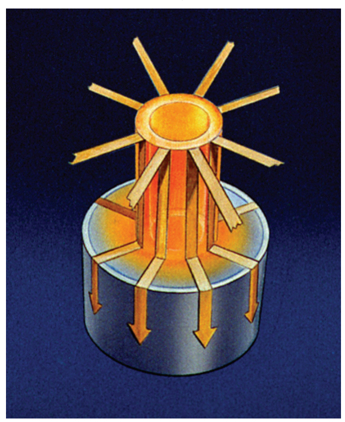
electrical energy

↓

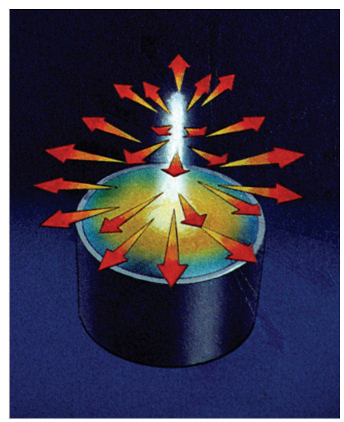
kinetic energy



Ablation



Implosion

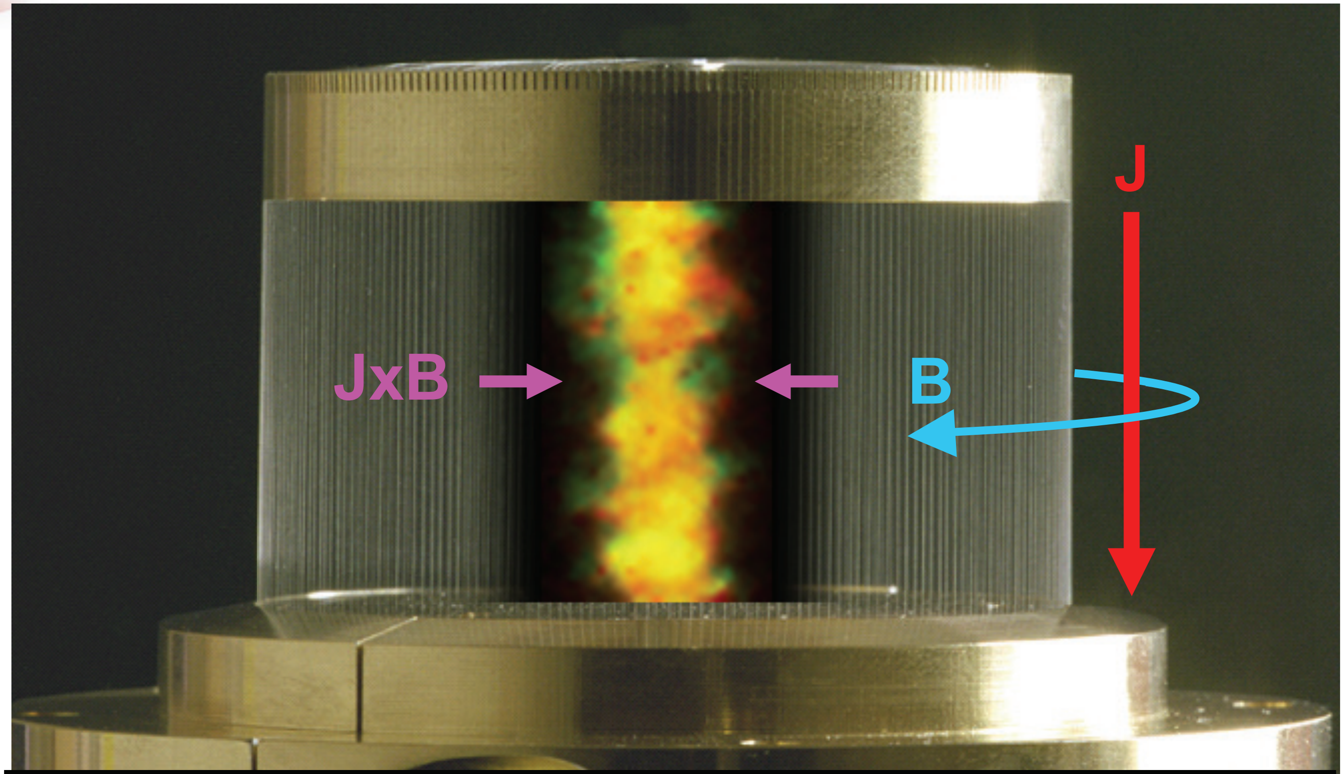


Stagnation

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

- **Z-pinches are imploded in 60 to 120 ns**
- **Energy: x-ray ≈ 15% of stored electrical**
- **Power: x-ray ≈ 2-5 x electrical**

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



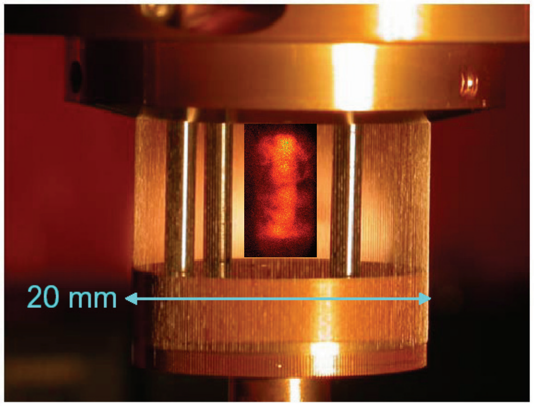
z-pinch sources

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

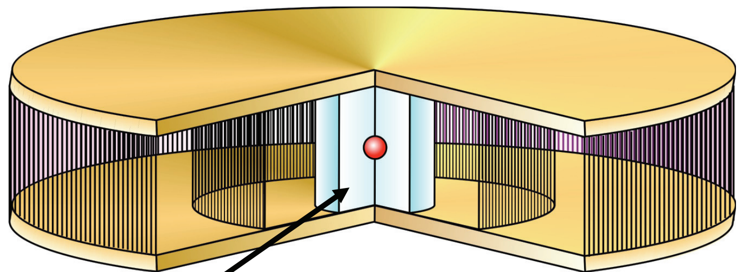
P_{rad} ~ 100-250 TW ~ 200 million million Watts

T_{rad} ~ 200 eV ~ 2,300,000 °K

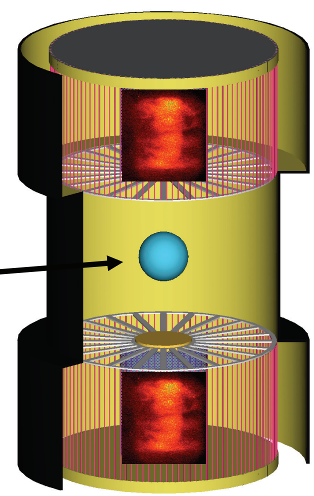
How can we use this efficient x-ray source to do ICF?



Dynamic Hohlraum



Double-Ended Hohlraum



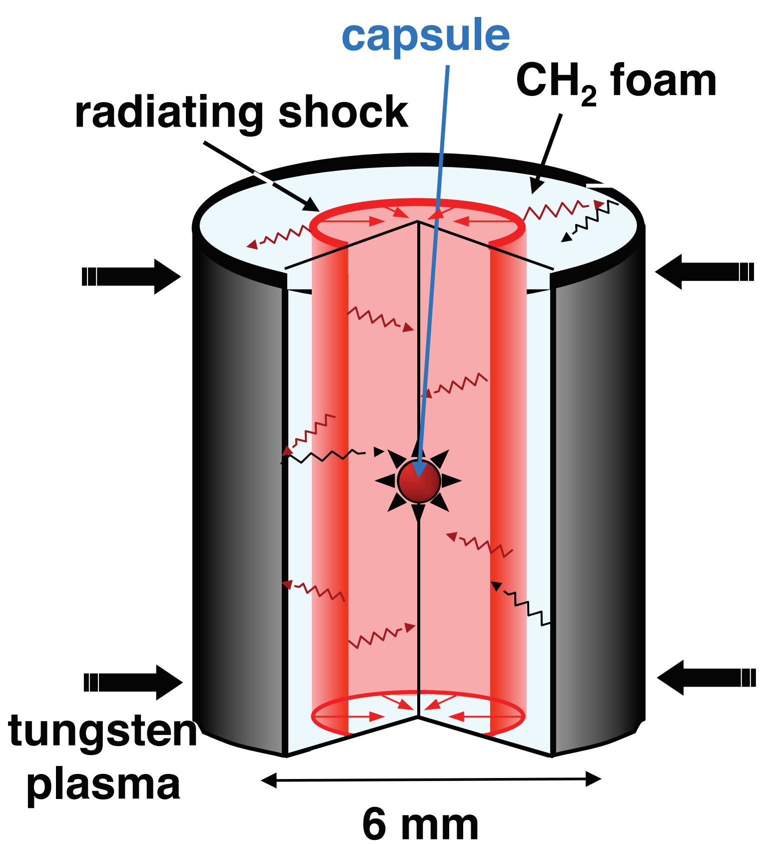
Where do we put the capsule?

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

This approach is the most conservative

Dynamic hohlraums efficiently couple x-rays to capsules

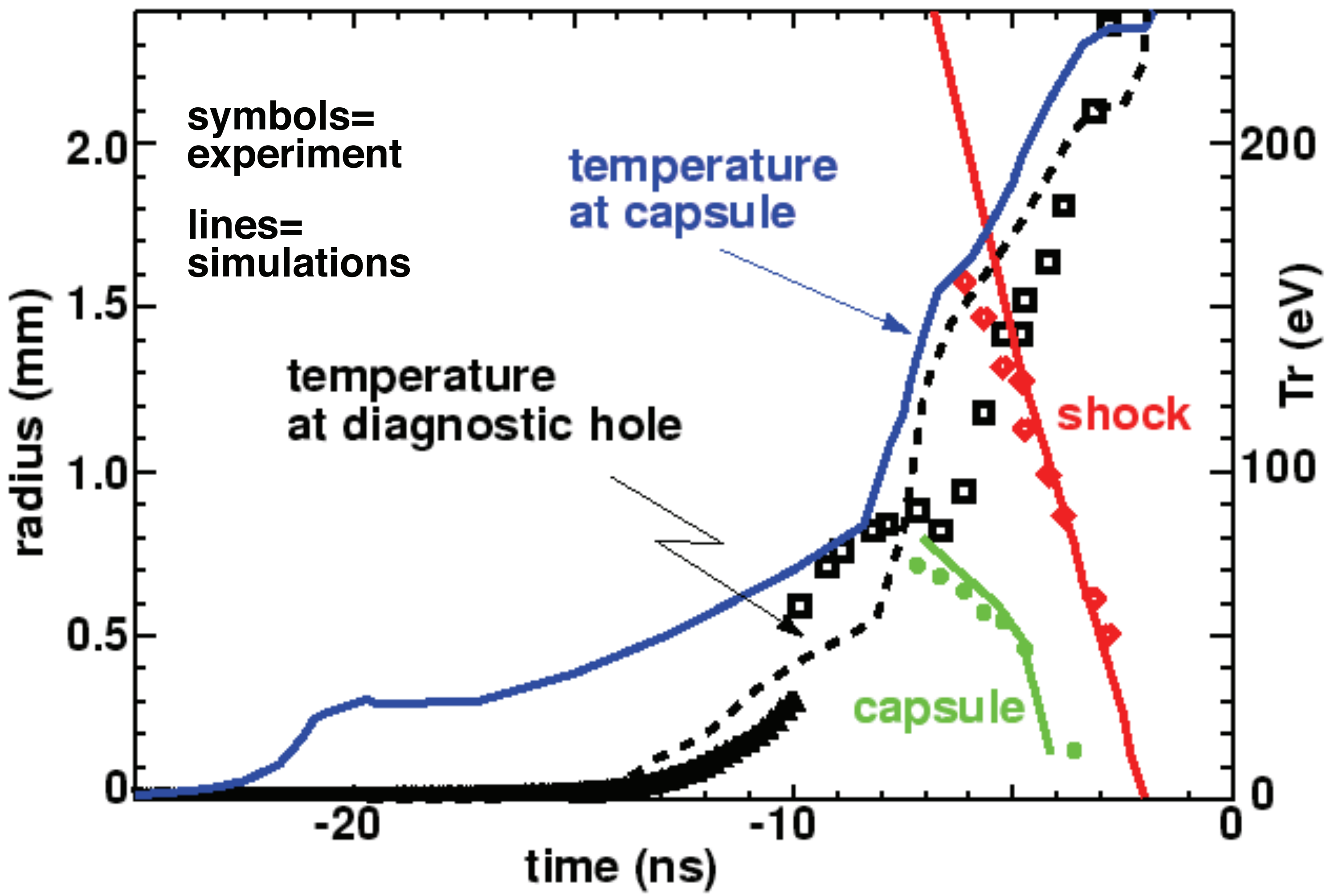


- Z-pinch plasma impacts foam converter
- The impact launches shocks in foam and tungsten
- The foam shock is a main radiation source
- The z-pinch confines the radiation
- Capsule heated mainly by re-emission from tungsten hohlraum wall

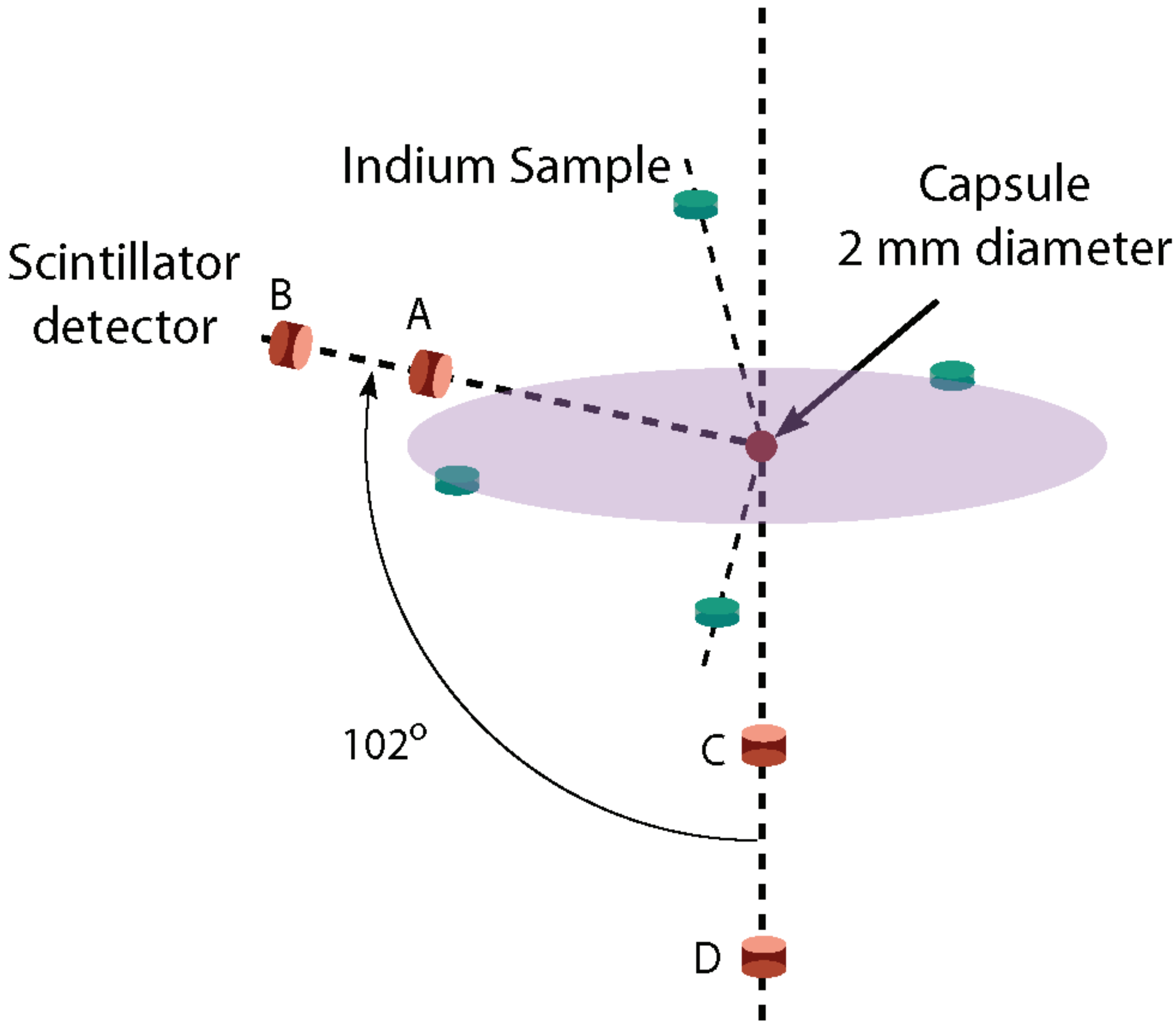
physics issues:

1. interior diagnostics
2. symmetry
3. radiation production
4. radiation transport
5. radiation confinement
6. preheat

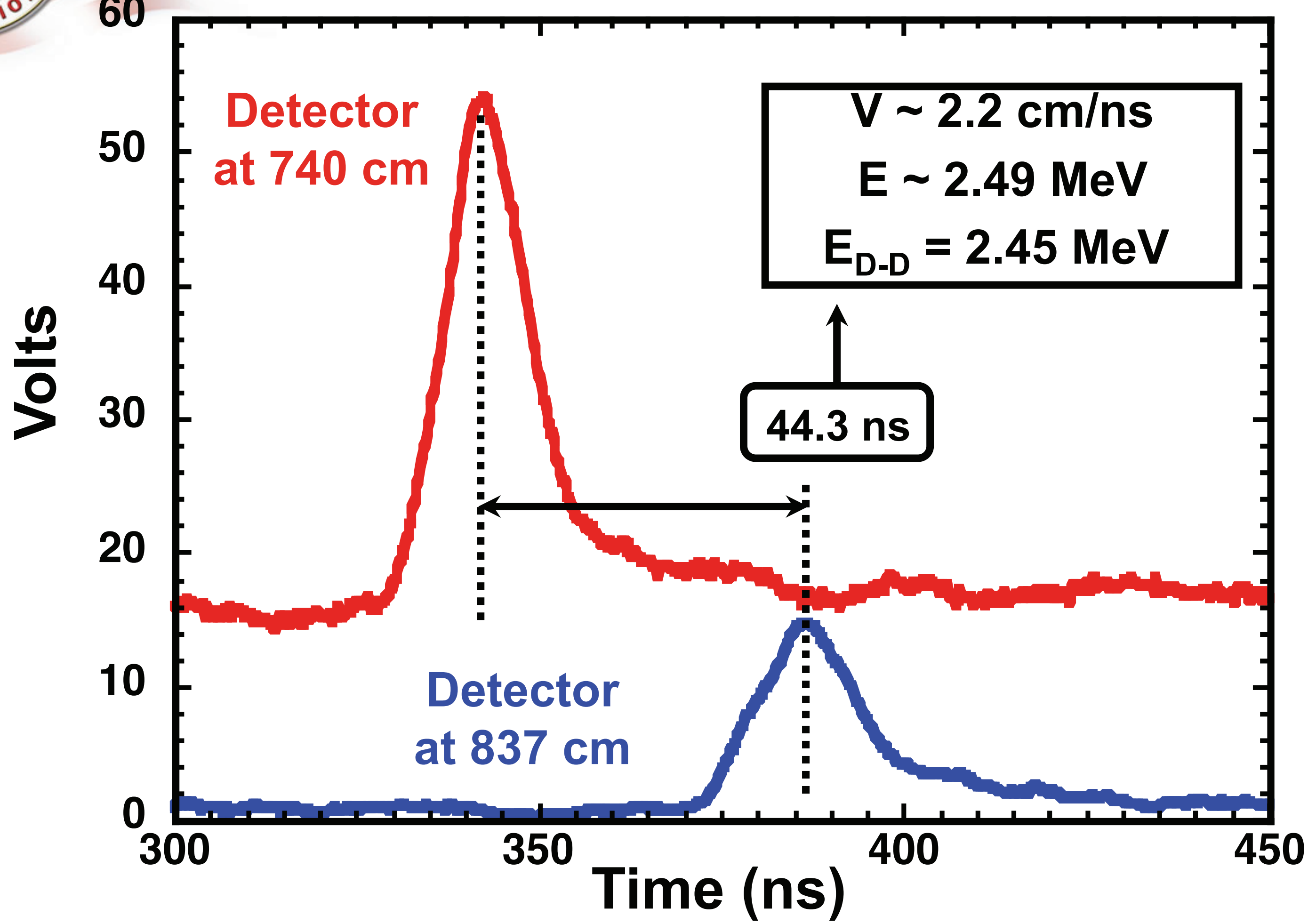
Dynamic hohlraums drive capsule implosions with 180-220 eV drive radiation temperature



Schematic of the neutron diagnostic arrangement used in these capsule experiments is shown here



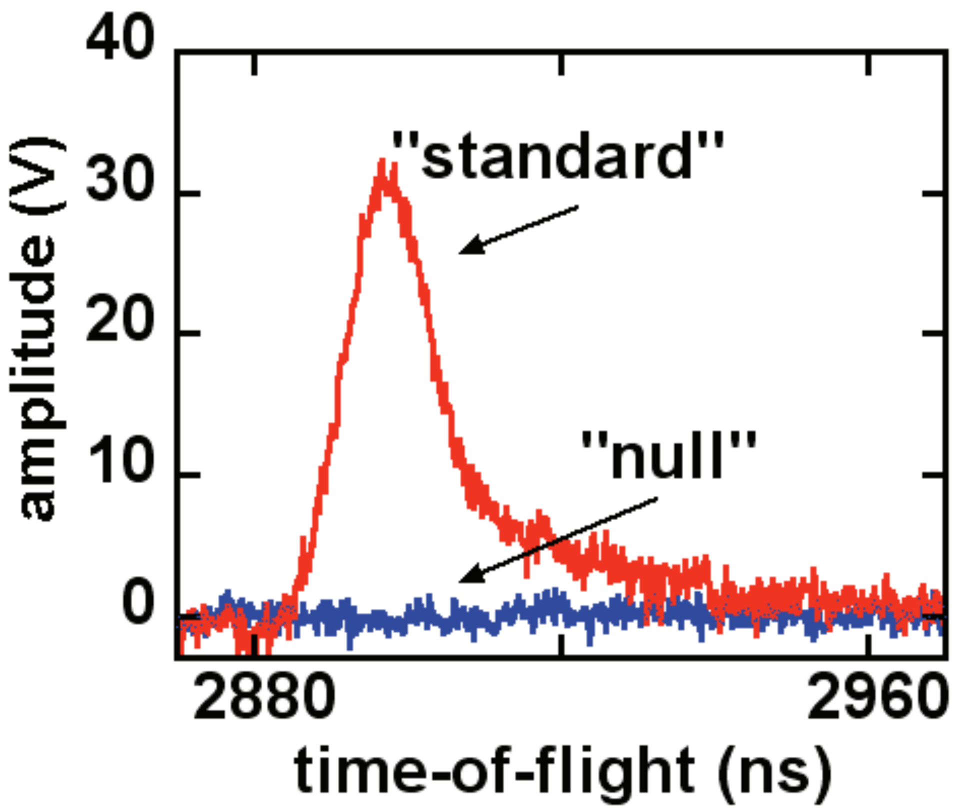
Side-on neutron time-of-flight data showing the detection of DD neutrons on a Be capsule shot



Data from 2-mm Be capsule with 33-μm Be wall on 18-μm plastic filled with ~16 atm DD

Total DD neutron yield was 2.7 x 10^{11} into 4π

Neutron time-of-flight signal dramatically decreases when Xe fill gas is added to “null” the production of thermonuclear neutrons

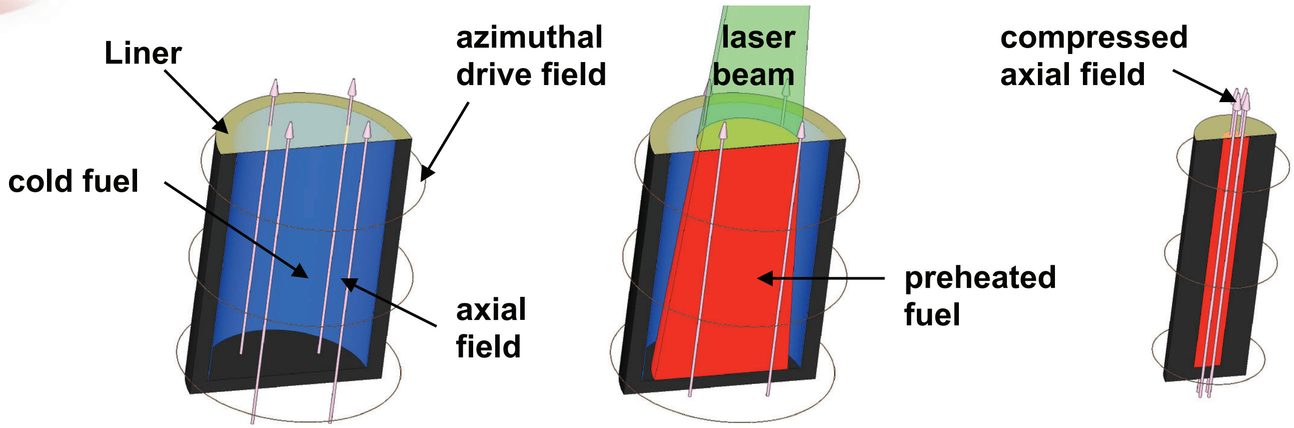


C. L. Ruiz et al., Phys. Rev. Lett. 93, 015001 (2004)
R. J. Leeper et al., J. Phys. IV 133, 175 (2006)

Z1031 “standard” fill (24 atm D_2 + 0.085 atm Ar)
Z1032 “standard” fill + 0.6 atm Xe

- On “null shots,” neutron yield measured by Be activation decreased by more than an order of magnitude

Magnetized Liner Inertial Fusion (MagLIF) provides beneficial effects for pulsed power 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**
  - **allows relatively low velocity implosions (5-10 cm/μs)**
  - **calculations indicate this could be done by the Z Beamlet laser**
- **Simulations indicate significant yields on ZR with modest convergence ratios**
- **The Z Beamlet backlighter will enable studies of the evolution of the Magneto-Rayleigh-Taylor instability in Beryllium liners**

Magnetized Liners on Z show promise, much work remains to be done to assess this concept

- Stability of the liner implosions is the key issue
    - We need to study the development of MRT in solid liners and bench mark our codes against experimental data
    - What Convergence Ratio is achievable?

- More Computational Work needs to be done:
    - 1D mix models to study fuel/liner interface
    - 2D simulations to assess stability
    - 3D effects
    - Laser heating for preheat
    - What is the effect of an axial magnetic field on the current delivery to the load?

- We hope to perform the first experiments on liner stability next year

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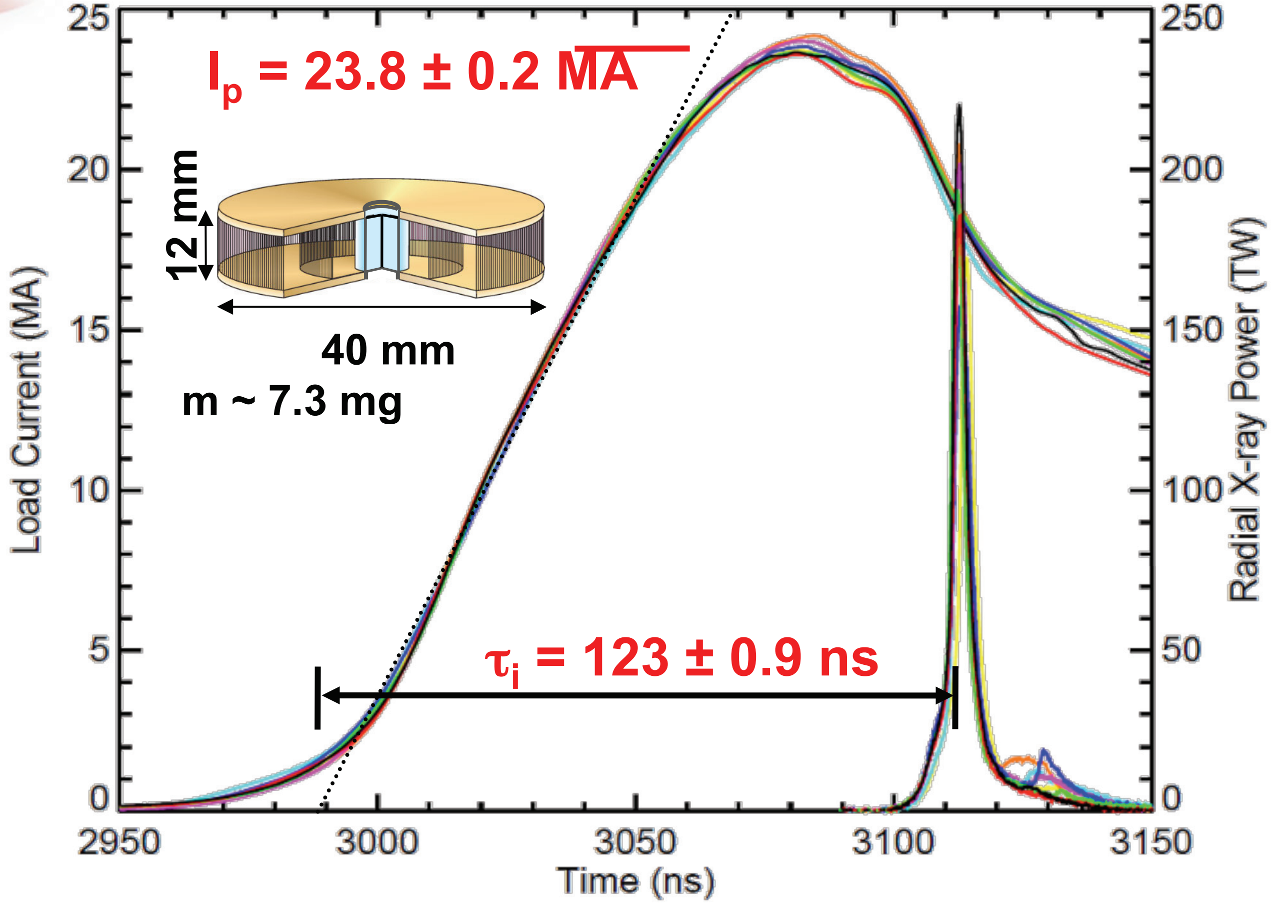
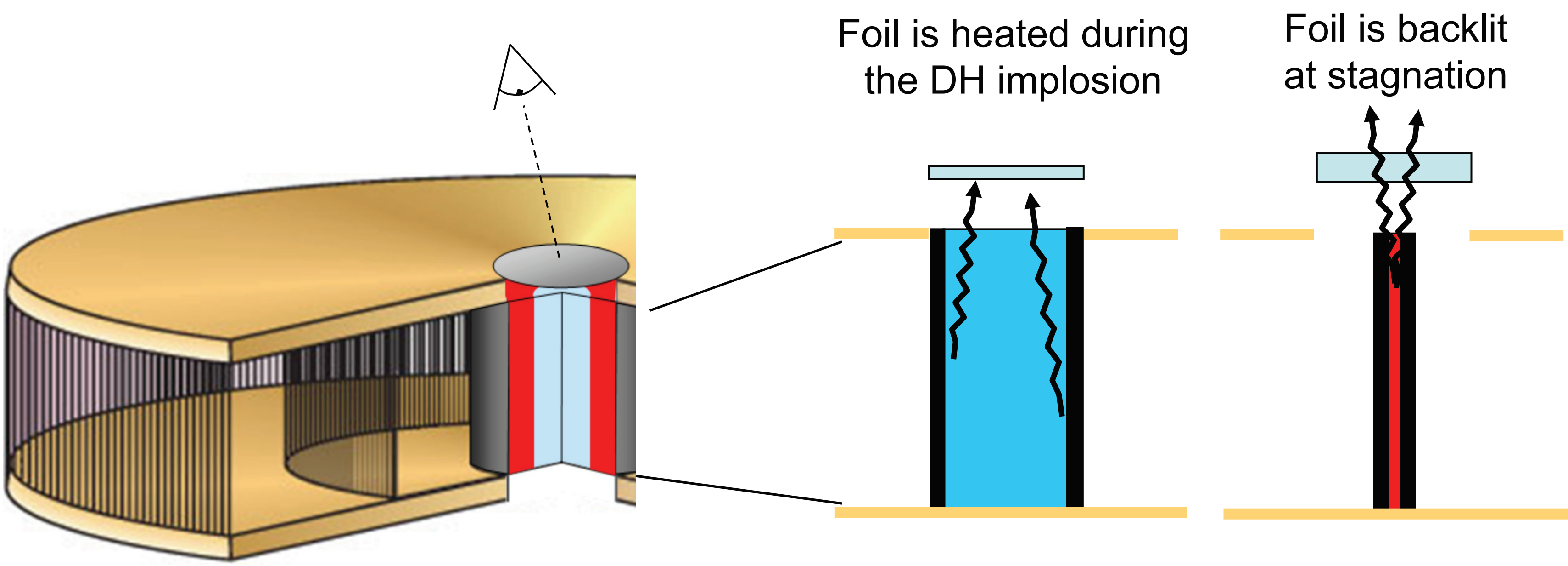
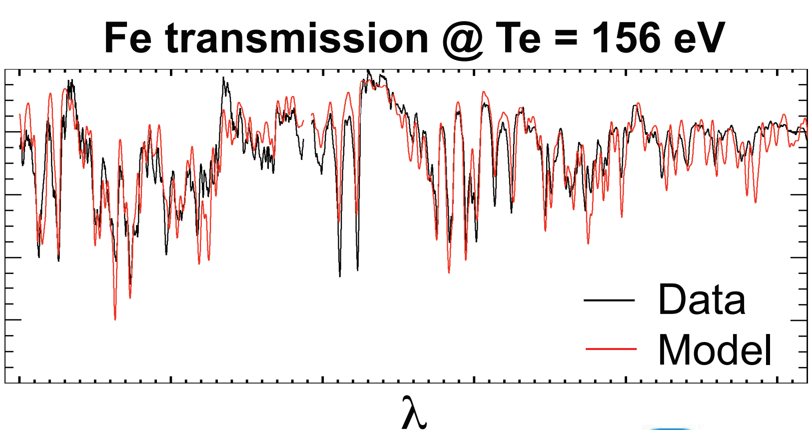
Refurbished Z has delivered world-record currents to Dynamic Hohlraum Z-pinch loads with < 1% shot-to-shot variation



This reproducible, bright (~200 TW) source is ideal for opacity experiments

Z dynamic hohlraums are used to make opacity measurements for comparison with models





"… the deep interior of the sun and stars is less accessible to scientific investigation than any other region of the universe….What appliance can pierce through the outer layers of a star and test the conditions within? "

A.S. Eddington ***The internal constitution of the stars***
Cambridge, 1926

~~exterior observations~~

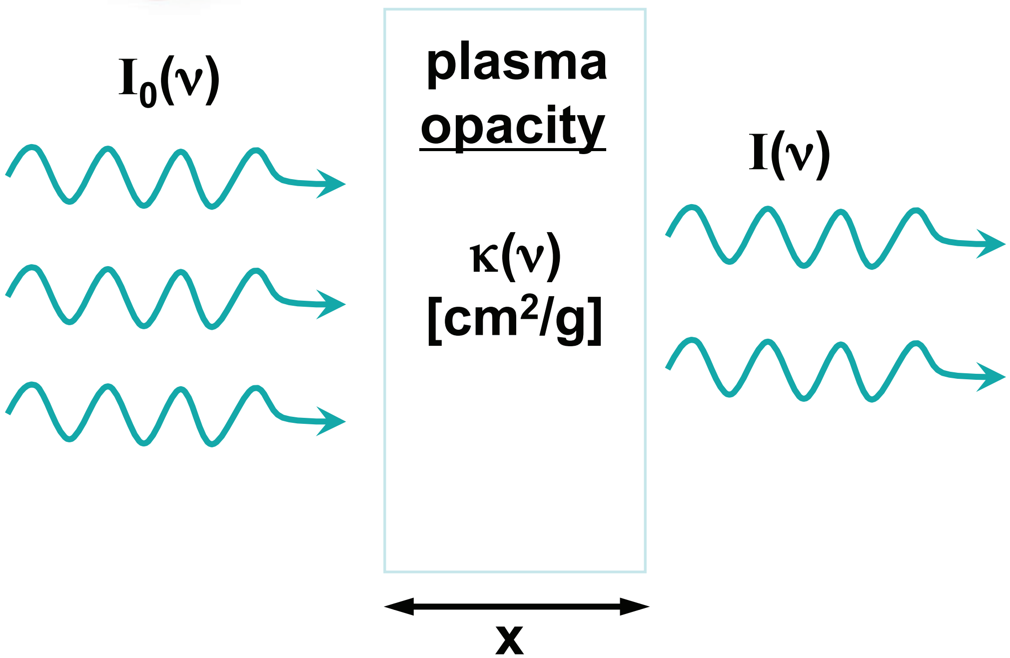
+

interior plasma property models

= understanding

model reliability requires laboratory experiments

Opacity quantifies how transparent or opaque a plasma is to radiation



Transmission

$T = I(\nu) / I_0(\nu) = \exp\{-\tau(\nu)\}$

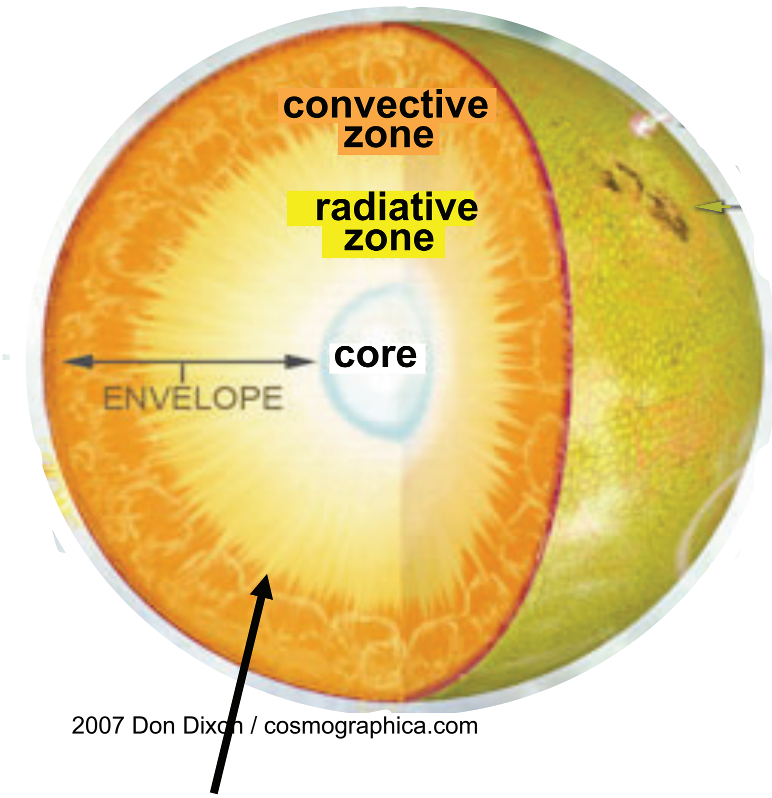
Optical depth

$\tau(\nu) = \kappa(\nu)\rho x$

Stellar structure depends on opacities that have never been measured

Challenge: create and diagnose stellar interior conditions on earth

Z experiments test opacity models that are crucial for stellar interior physics



Solar CZ boundary
193 eV, 1 x 10^{23} cm^{-3}

Predictions of solar structure do not agree with observations

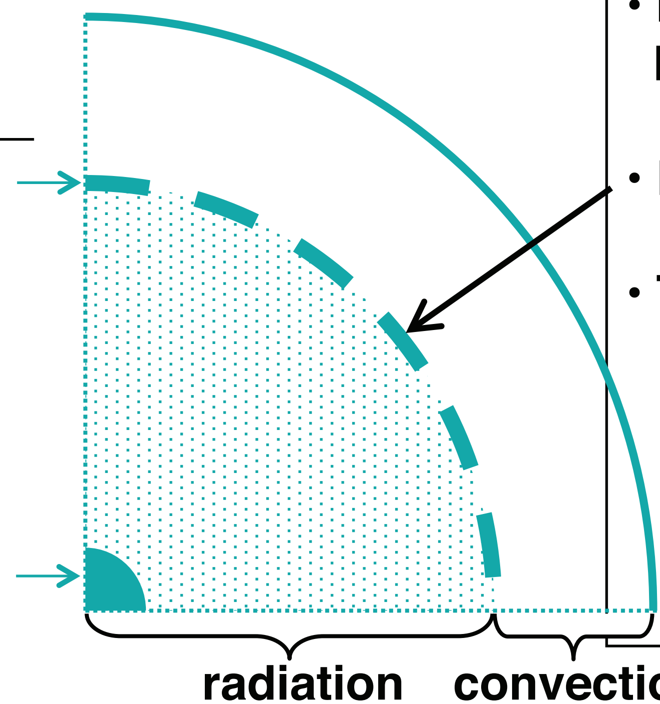
Solar structure depends on opacities that have never been measured

Challenge: create and diagnose stellar interior conditions on earth

High T enables first studies of transitions important in stellar interiors

Solar structure predictions disagree with helioseismic data. Why?

T(eV)	$n_e(cm^{-3})$	r/R_0
193	$1x10^{23}$	0.7133
1360	$6x10^{25}$	0



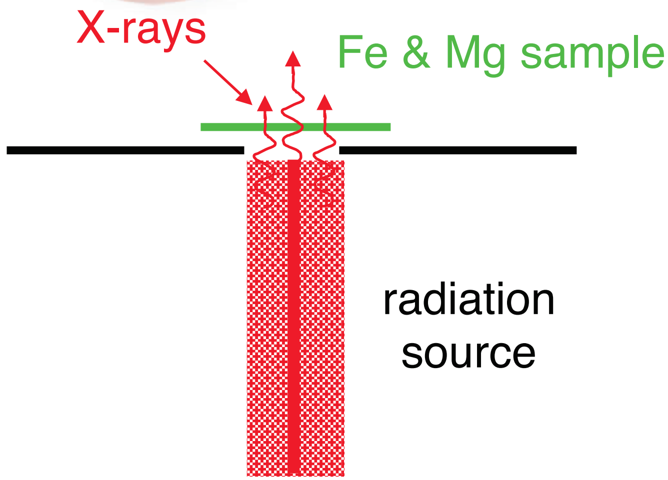
- measured boundary R_{CZ} = 0.713 ± 0.001
- Predicted R_{CZ}= 0.726
- Thirteen σ difference

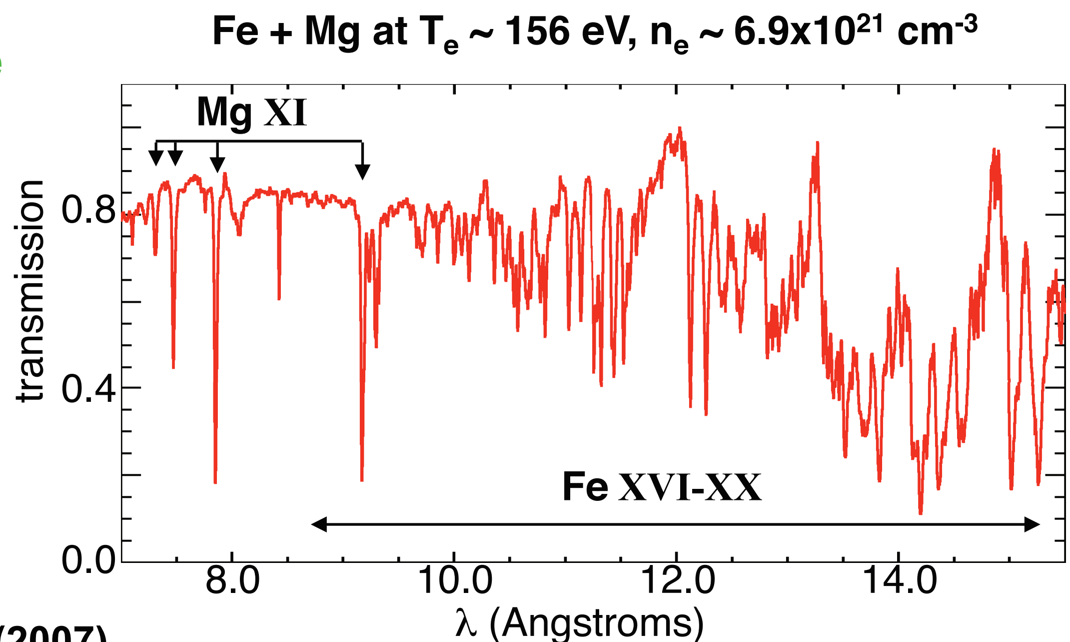
"The CZ problem"

Bahcall et al, ApJ 2004
Basu & Antia
Physics Reports 2008

- Boundary location depends on radiation transport
- A 10-20% opacity change solves the CZ problem.
- This accuracy is a challenge – experiments are needed to know if the solar problem arises in the opacities or elsewhere.

Z opacity experiments reached T ~ 156 eV, two times higher than in prior Fe research

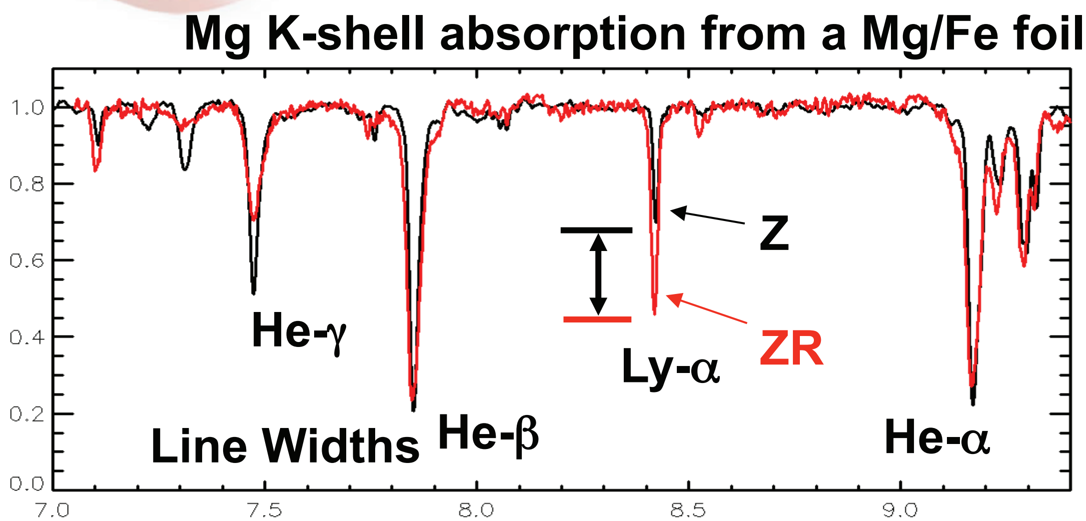


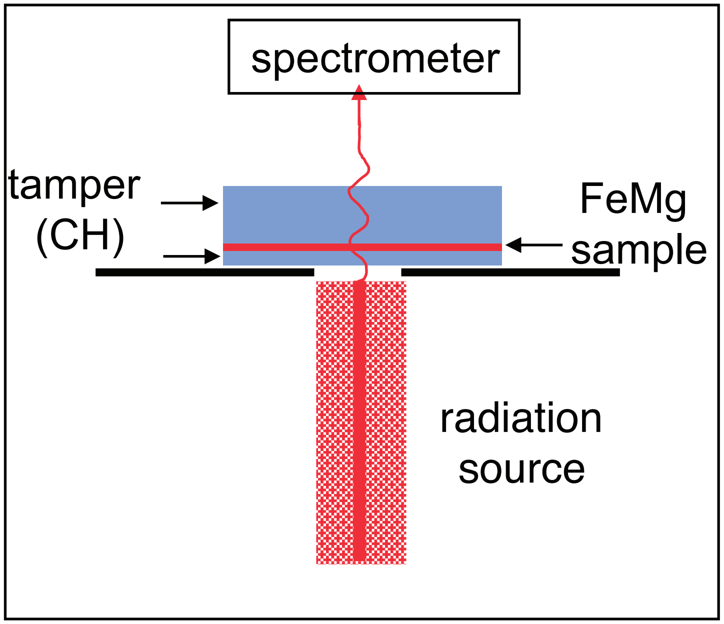


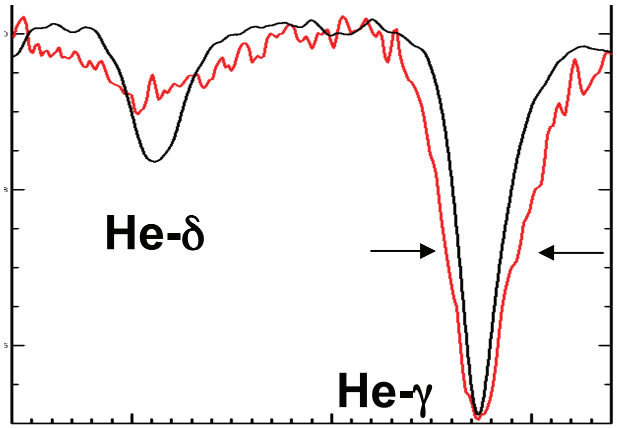
J.E. Bailey et al., PRL 99, 265002 (2007)

• Mg is the "thermometer", Fe is the test element

Opacity measurements on the refurbished Z are close to replicating solar interior matter







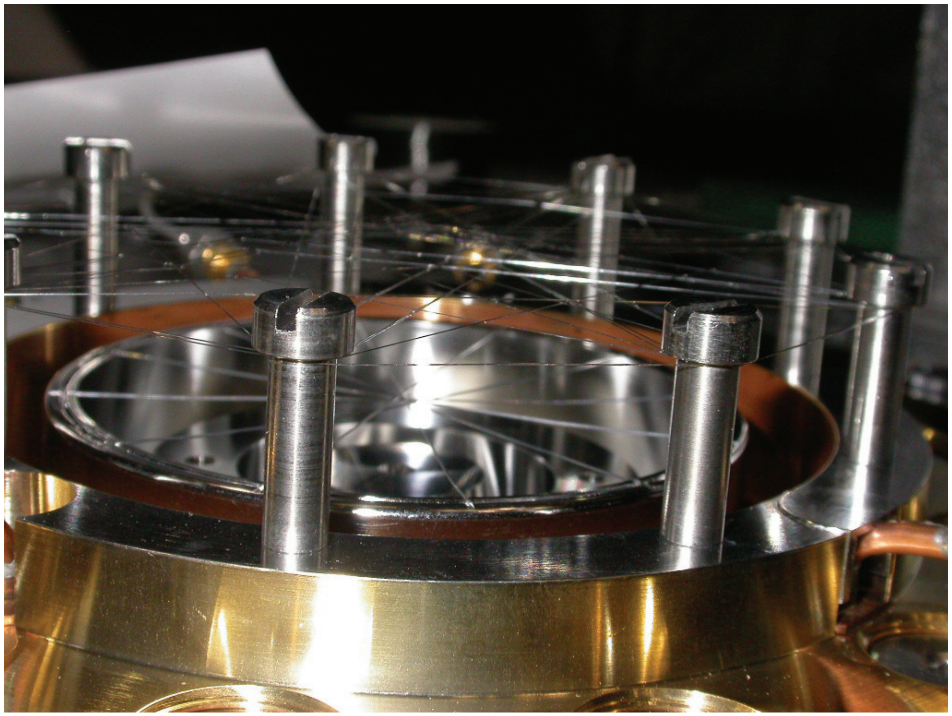
- Higher Ly/He ratios indicate ~20% increase in T_e ~190 eV
- Broader high-n lines indicate thicker tamper led to ~300% increase in n_e

This is much closer to Fe conditions in the Sun

It's an exciting time to be working on the Z facility

- Refurbished Z is up and running
- Ever more extreme conditions are being reached in the dynamic materials program
- Several new concepts for pulsed power inertial confinement fusion look interesting
- Higher currents are enabling brighter x-ray sources and hotter and denser plasmas for astrophysical opacity research
- Particle In Cell (PIC) calculations of a gas puff Z-pinch reveal new insights into this "classic" plasma system

3.9×10^{13} D-D neutrons have been produced in deuterium gas puff experiments on Z at 17.7 MA



Gas puff nozzle

- Yield follows approximately I^4 scaling
  - In agreement with previous assessments for neutron scaling from pinch systems
- Origin of these neutrons is still being assessed experimentally
- 1D, 2D, and 3D MHD calculations reproduce measured outputs
- Particle In Cell (PIC) calculations of this system are revealing new insights into this system

C. A. Coverdale, C. Deeney et al., Phys. Plasmas 14, 022706 (2007)
A. L. Velikovich et al., Phys. Plasmas 14, 022701 (2007)

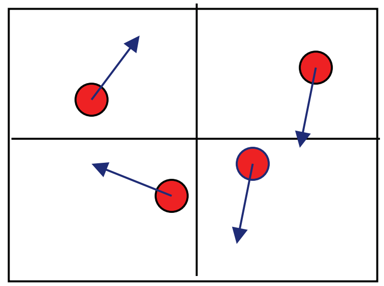
PIC calculations provide insight to the 50 year old issue of the neutron production mechanism in Z-pinch plasmas

- **Neutron production scaling as I^4 is quite promising***
- **Deuterium Z-pinch systems have been examined experimentally for many years**
  - **Significant neutron production is observed**
  - **Early conclusions had been that the majority of neutron yield is from non-thermal deuterium population that does not scale favorably**
- **Fully kinetic electromagnetic modeling is now possible that includes both nonthermal and thermal processes to address this fundamental issue**
- **Recent PIC calculations of this fundamental plasma system are providing new understanding in how neutrons are produced in pinched plasma systems**

*J. Ise, Jr. and R. V. Pyle, in Conference on Controlled Thermonuclear Reactions, Princeton Univ., 17-20 October 1955 (TID-7503, USAEC, 1955), p.218; Velikovich, et al. Phys. of Plasmas 14 022701 (2007).

Particle-In-cell (PIC) modeling is a natural way to describe Z-pinch plasmas

Particle currents and ρ interpolated to grid; fields back to particles



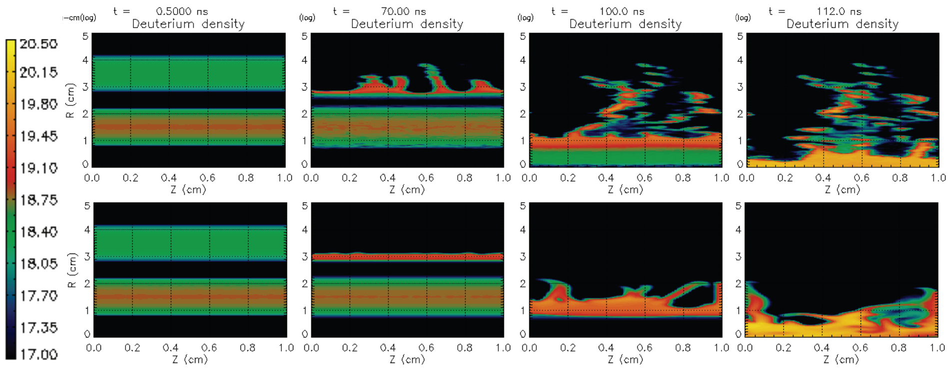
EM Fields, pressure, etc. calculated on grid

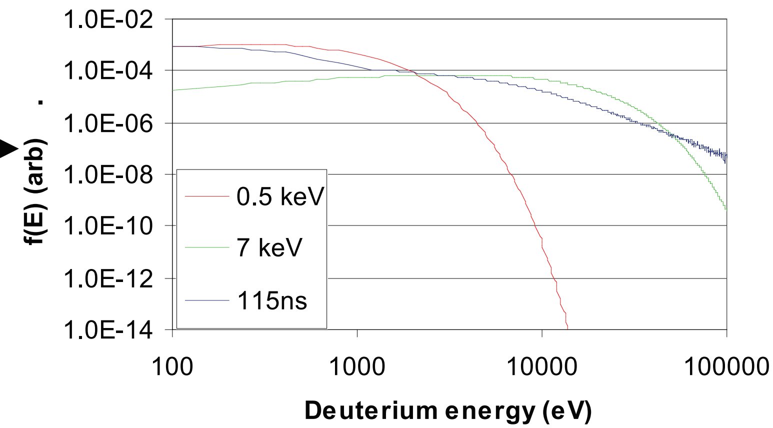
- **PIC follows macroparticles with each representing many real ones**
  - **Particle currents J (or charges ρ) are interpolated to a grid**
  - **Maxwell's (or Poisson's) equations are advanced on the grid using J or ρ**
  - **The electric E and magnetic B fields are interpolated to particles**
  - **The particle momentum p and position x are advanced with new E and B**

D. R. Welch, D. V. Rose, W. A. Stygar, and R. J. Leeper, "Electromagnetic Kinetic Simulations of a Deuterium Gas Puff Z-pinch", 36th International Conference on Plasma Science, San Diego, CA, June 3, 2009.

Kinetic PIC model of a D Z-pinch is revealing physics not seen in MHD calculations

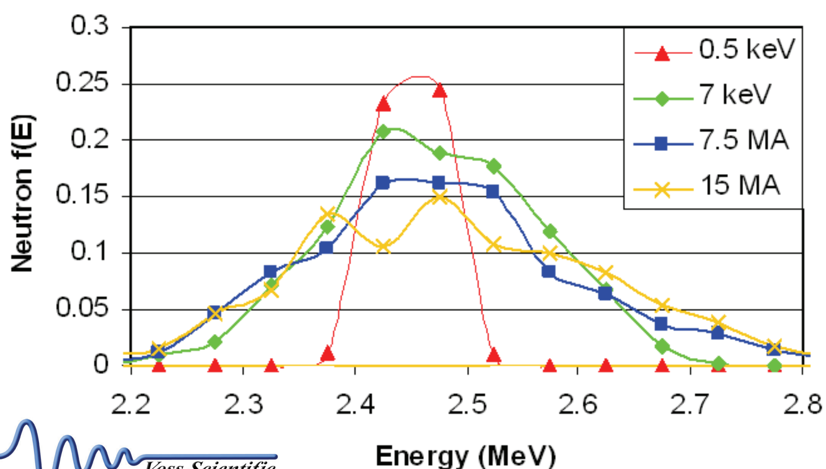
2D 15 MA LSP simulation



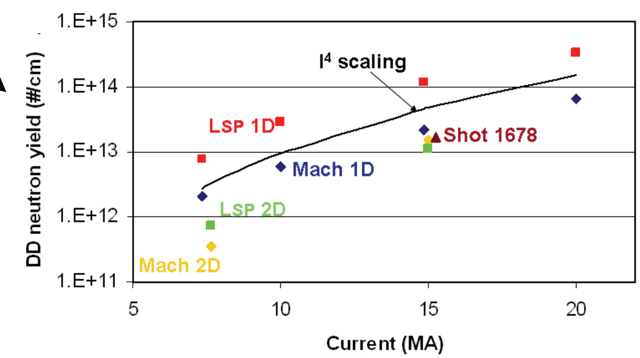


2D 15 MA MHD (Mach2) simulation

High energy tail accounts for half neutron production by 115 ns, broadens neutron energy spectrum.



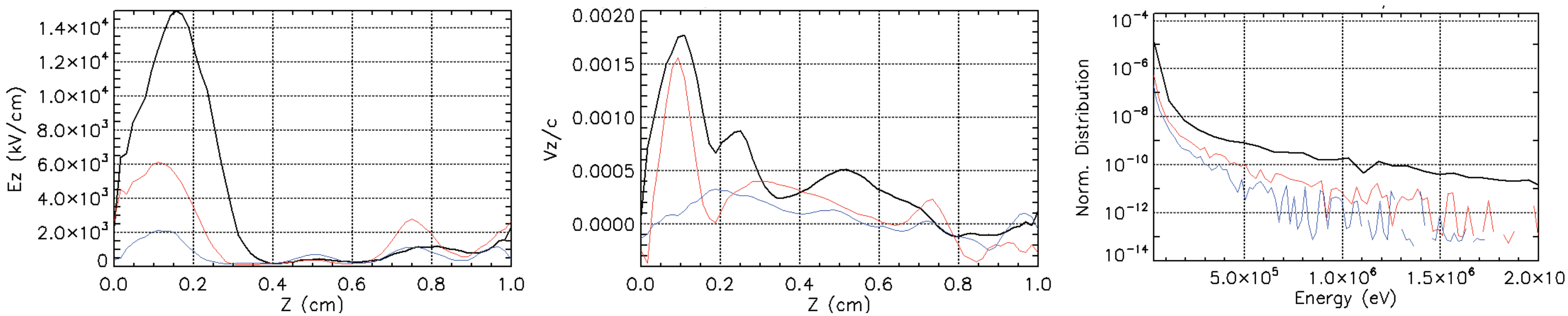
Favorable neutron yield production with pinch current!



Voss Scientific

PIC calculations are the first pinch calculations to predict a power law ion distribution $E^{-\alpha}$ that has been observed in experiment

105 ns 110 ns 115 ns



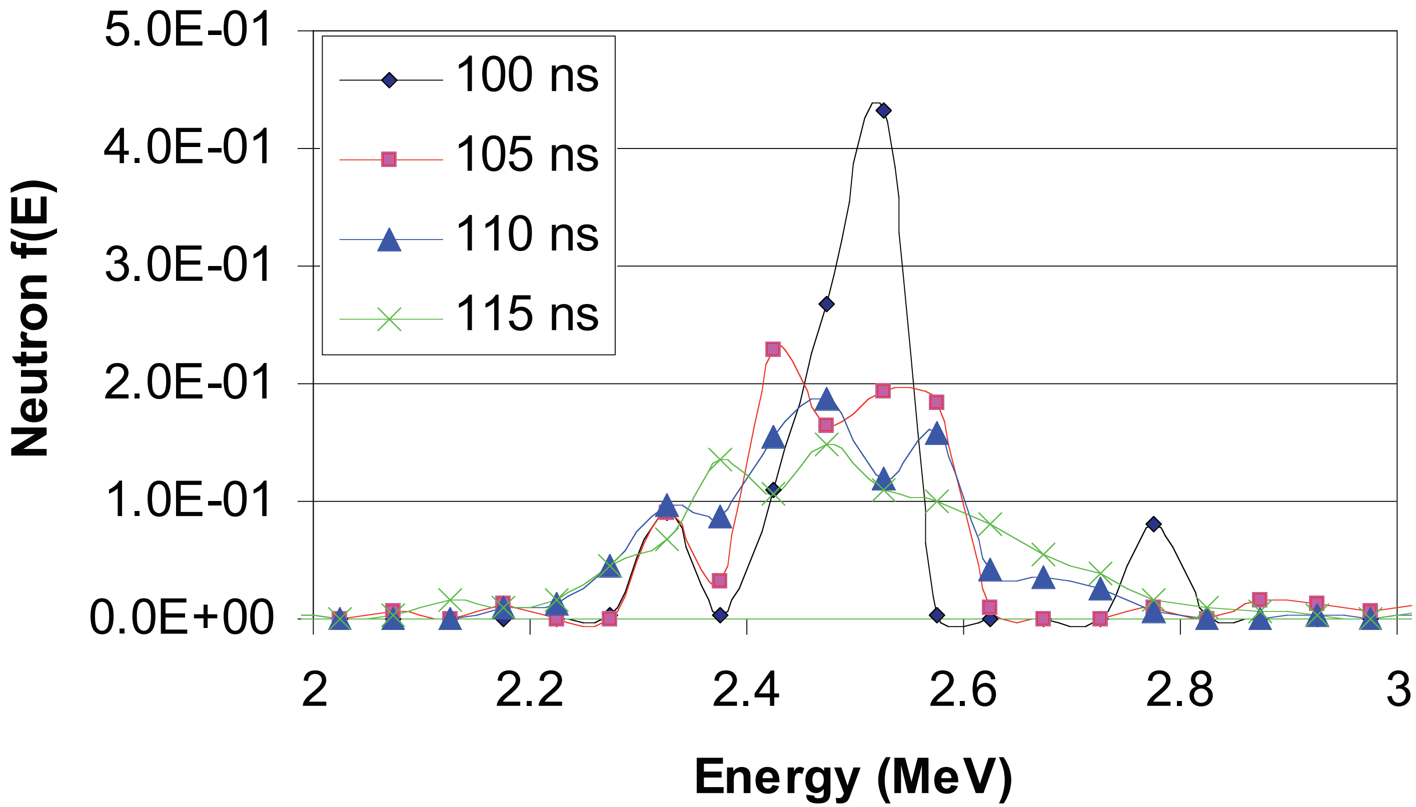
Average E_z within 1.5 cm radius

Average ion V_z within 1.5 cm radius

Deuterium energy distribution

H. L. L. Paasen et al., Phys. Fluids 13, 2606 (1970)
J. H. Lee et al., Plasma Phys. 13, 347 (1971)
W. A. Stygar et al., Nuclear Fusion 22, 1161 (1982)

Neutron spectrum reflect higher reactant energies as pinch progresses



- **FWHM of distribution increases from 80 to 300 keV**
- **These neutron spectra suggest that both “thermal” and “non-thermal” neutrons are produced in pinch plasma systems**

We are developing new pulsed power architectures for a next generation z-pinch facility

$E_{stored} = 180$ MJ

$P_{electrical} = 1100$ TW

$L = 29$ nH

$\eta_{electrical} = 70\%$

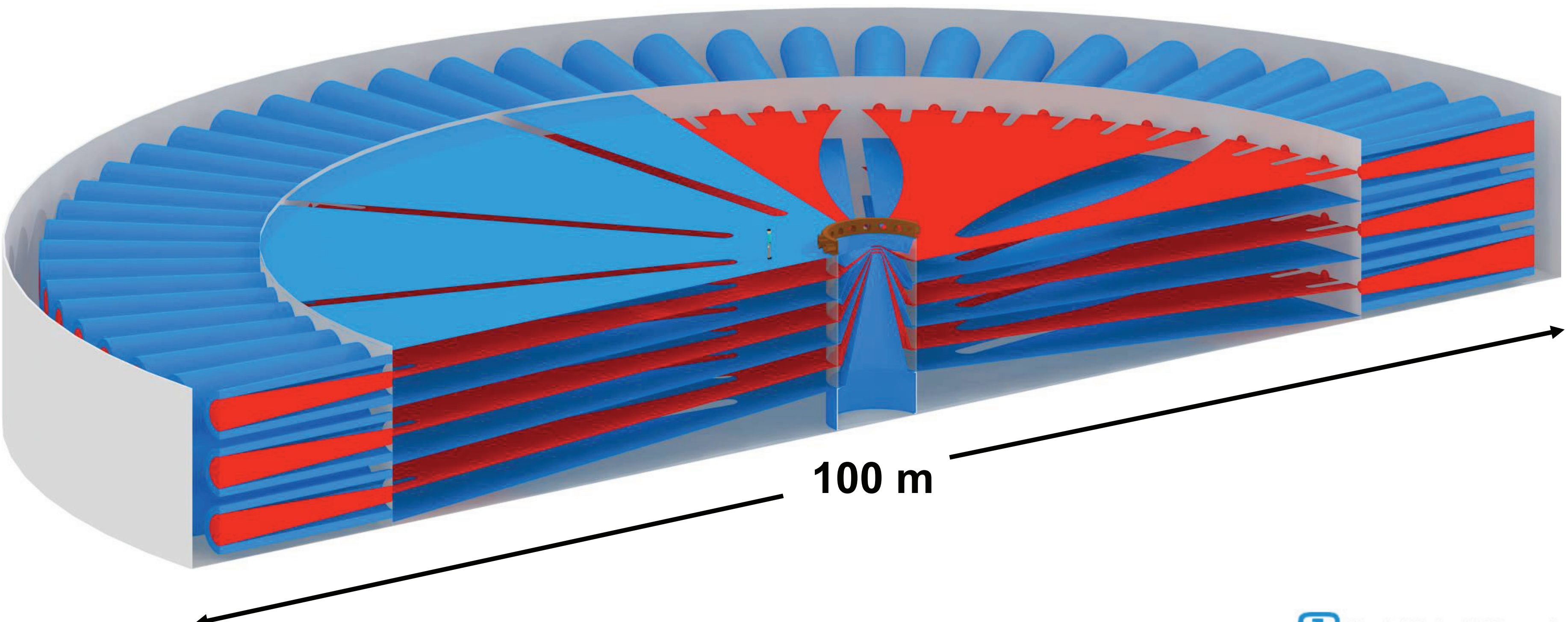
$V = 24$ MV

$I = 68$ MA

$\tau_{implosion} = 95$ ns

diameter = 100 m

W. A. Stygar, *et. al.*, "Architecture of petawatt-class z-pinch drivers", Phys. Rev. ST Accel. Beams 10, 03040 (2007)



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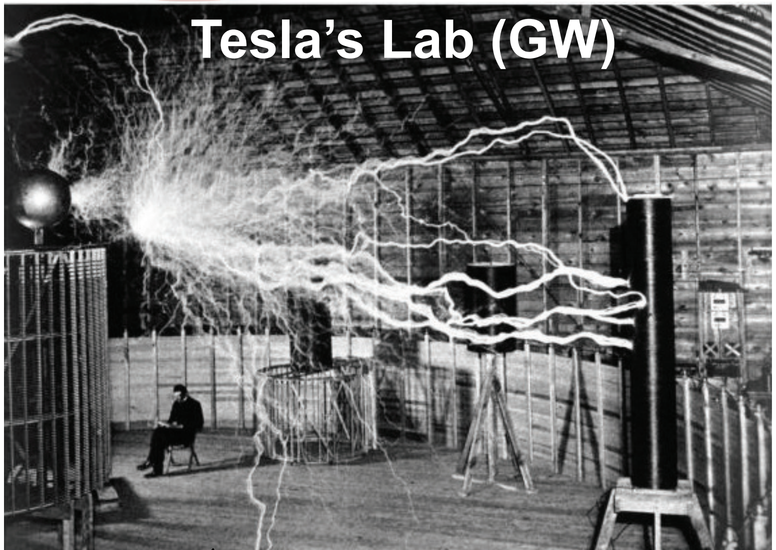
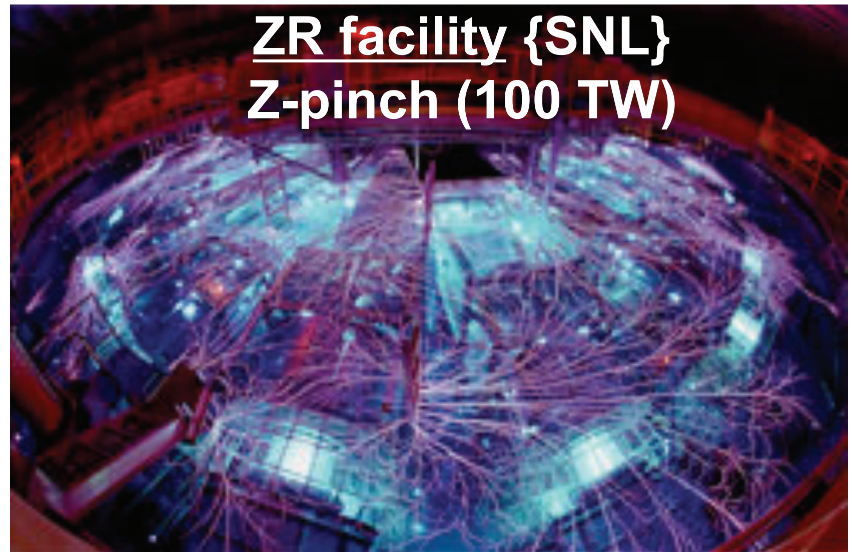
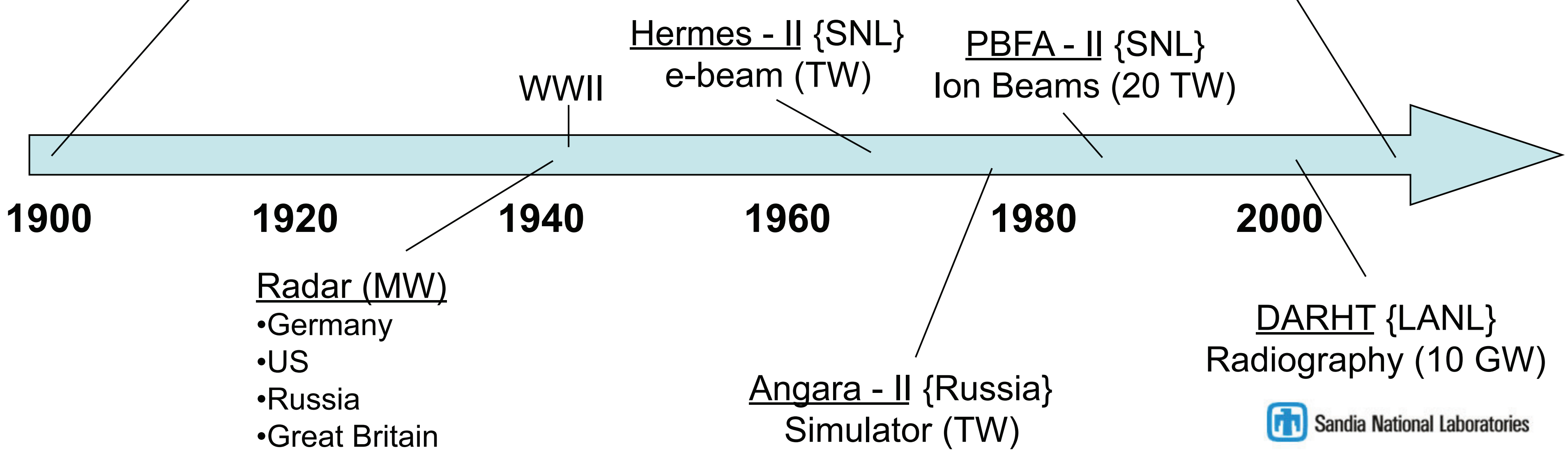
Pulsed power has been investigated for over a century.







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