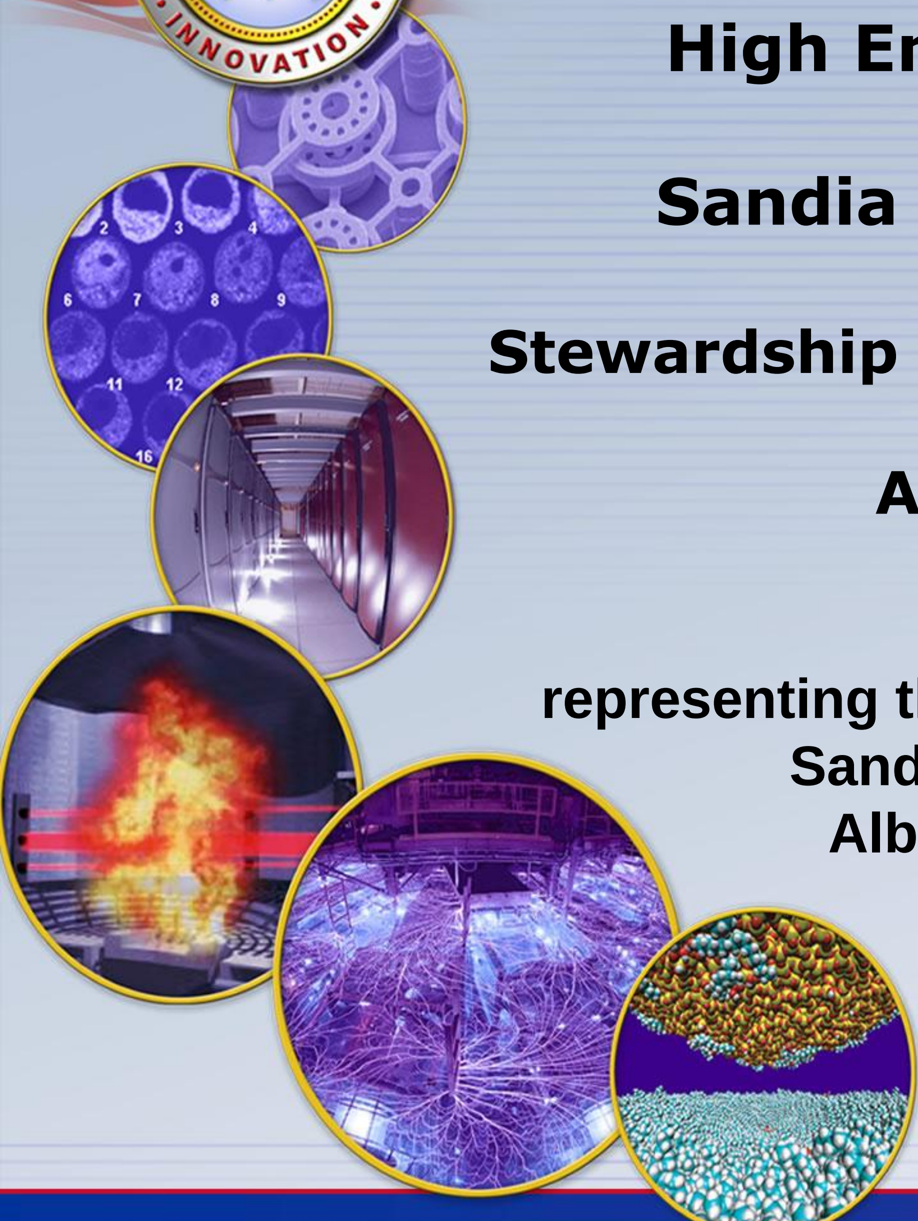


High Energy Density Physics Research at Sandia National Laboratories

Stewardship Science Graduate Fellowship Annual Meeting
Arlington, Virginia

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

July 27, 2012

Sandia National Laboratories

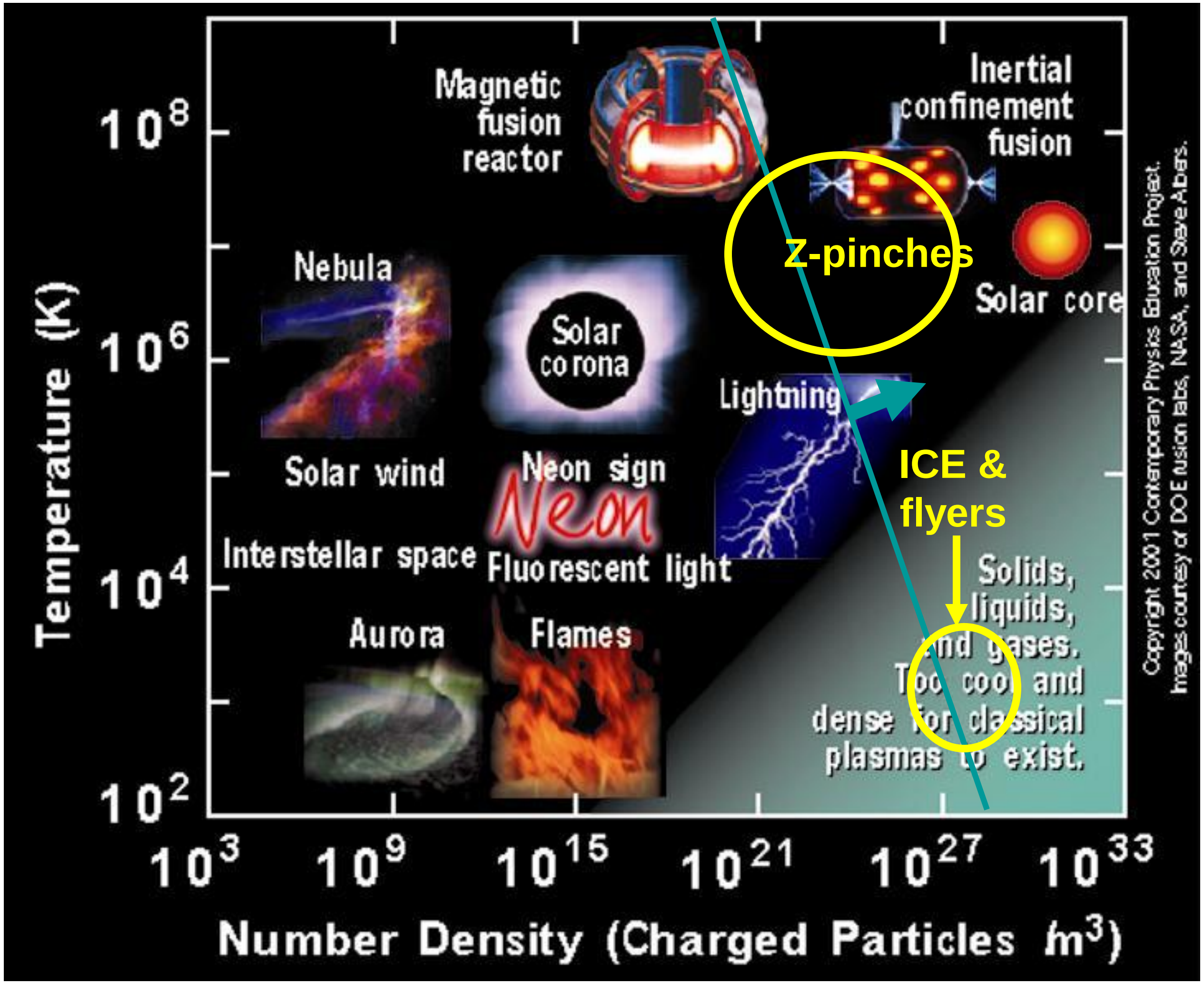
Sandia National Laboratories is one of three Department of Energy's NNSA laboratories

- Sandia National Laboratories is a government owned/contractor operated (GOCO) facility operated by Lockheed Martin Corporation
- Sandia currently has 8980 employees and a operating budget of approximately $2.5 billion
- Major locations include Albuquerque, New Mexico (~ 8055 employees) and Livermore, California (~925 employees)
- Sandia's precursor was Los Alamos National Laboratory's Z Division created in 1945 as part of the Manhattan Project
- Sandia separated from Los Alamos in 1949 and ATT took over its initial operation at the direct request of President Truman

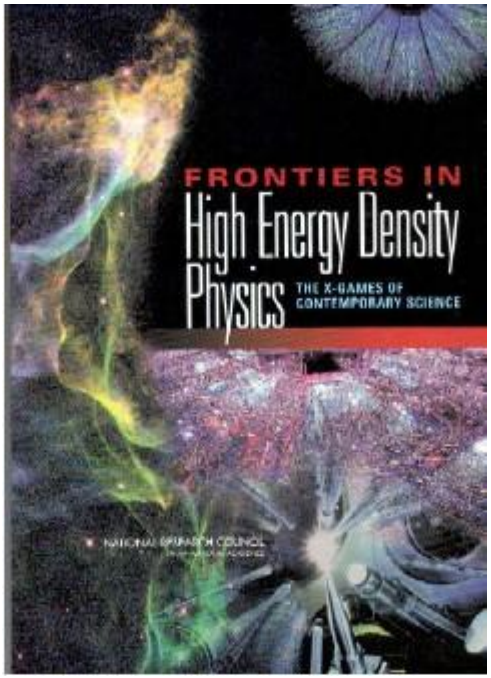
Sandia broadly contributes to the national HEDP and ICF programs in a number of important areas

- Sandia leads the national effort in pulsed power HEDP and ICF research
- Sandia operates the Z and Z-Beamlet laser facilities
- Since 1995, the Sandia program has participated and contributed to the NIF diagnostic effort
- Sandia is now actively engaged in the NIC physics efforts in the areas of ablator physics and shock timing
- The Sandia program is now actively developing a fundamental science user program on the Z and Z-Beamlet
- The Sandia HEDP and ICF program employs approximately 155 technologists and technical staff plus another 80 contractors

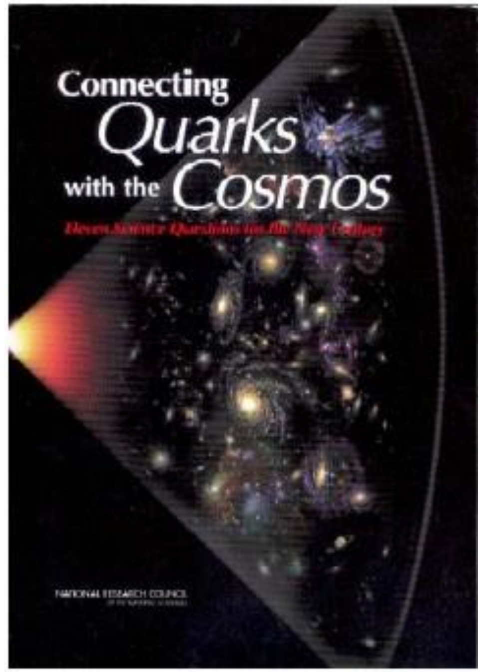
Regimes of high energy density are typically associated with energy density 10^5 J/cm^3 = 1 Mbar



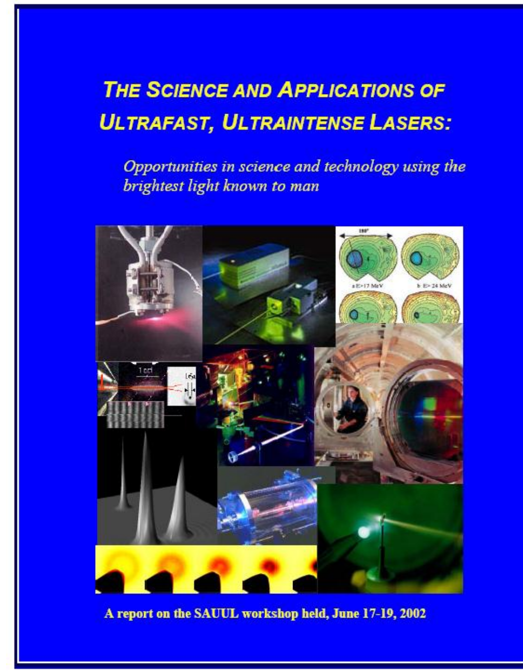
Several recent studies have highlighted High Energy Density Science



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



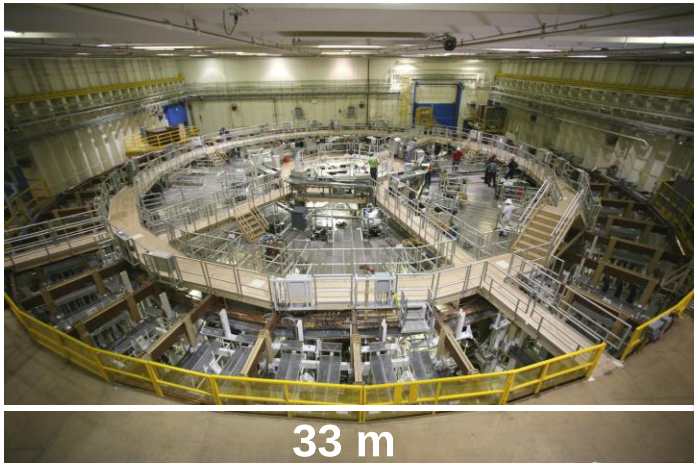
“Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century”, M Turner et al. 2002



Science and Applications of Ultrafast, Ultraintense Lasers (SAUUL)

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

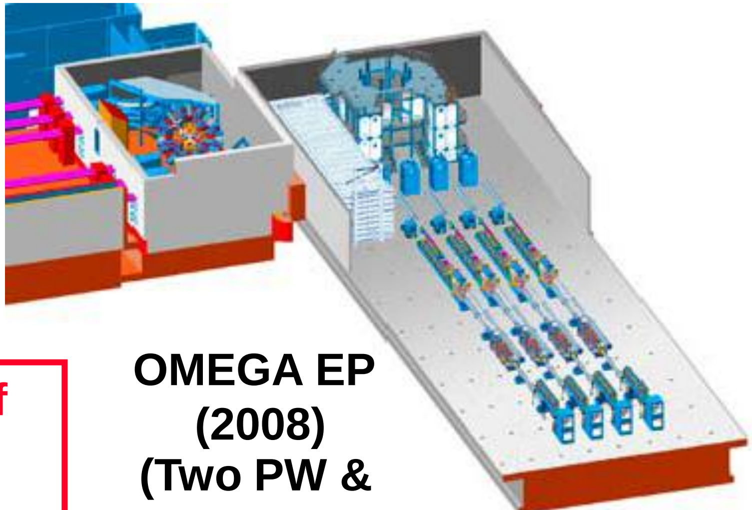
Refurbished Z (2007)
(3 MJ)



NIF (2009)
(1.8 MJ @ 0.35 μm)

OMEGA

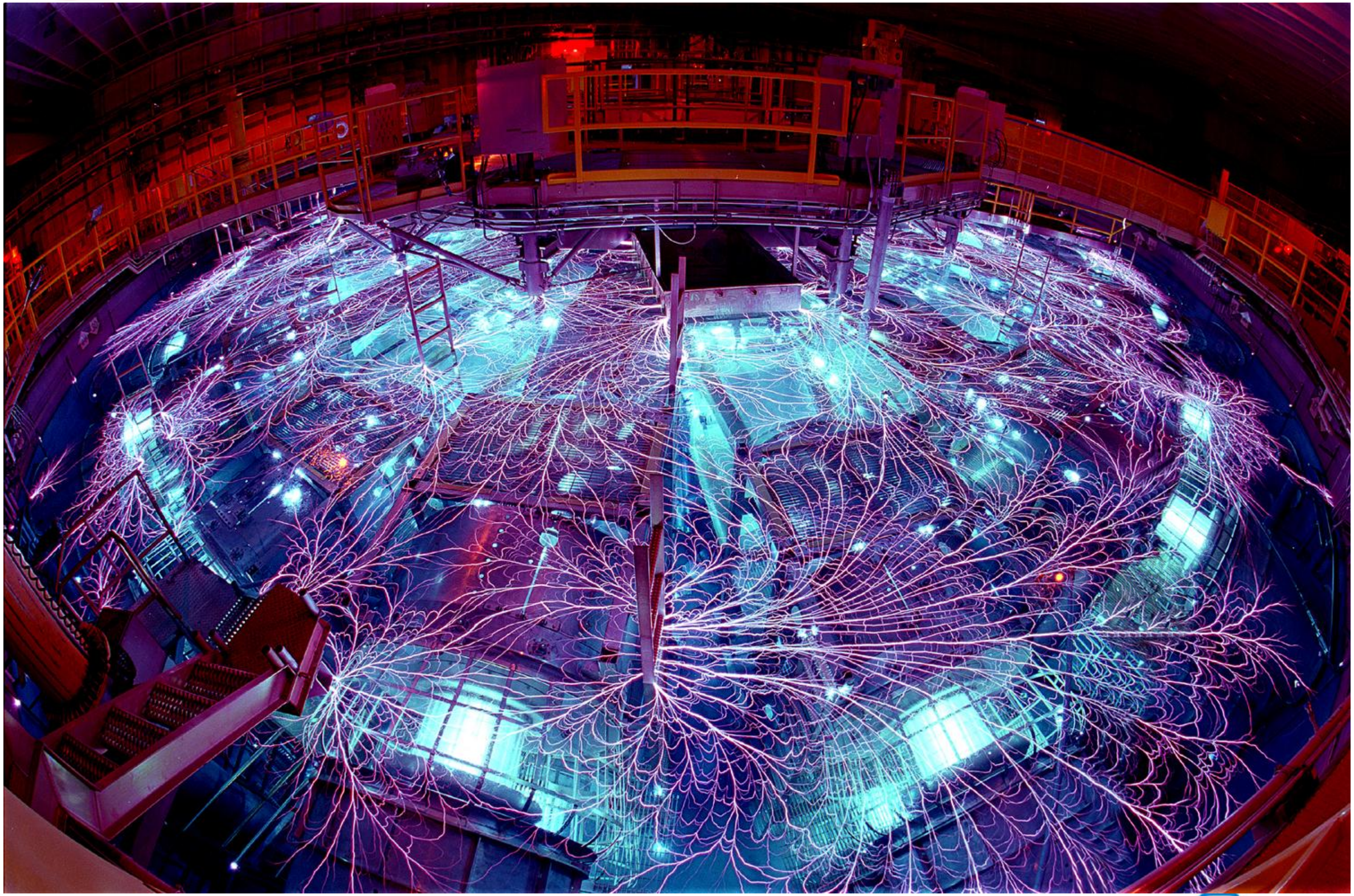
(30 kJ @ 0.35 μm)



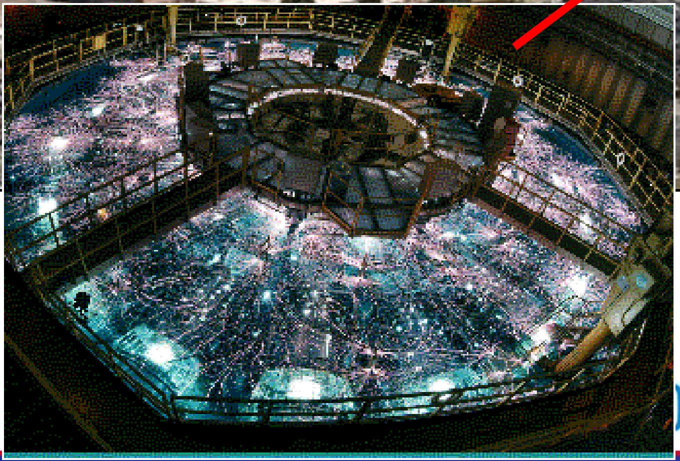
OMEGA EP (2008)
(Two PW & two ns beams)

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

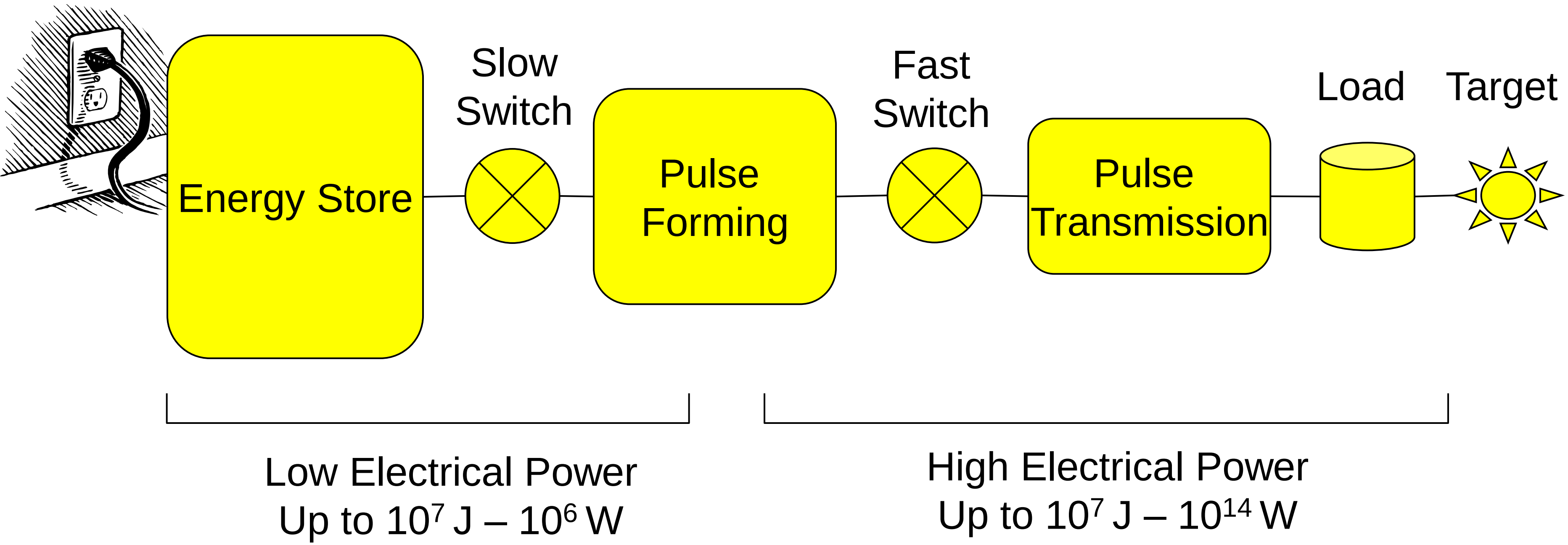


The "Z" pulsed power facility is located at Sandia National Laboratories in Albuquerque, New Mexico



Sandia National Laboratories

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.

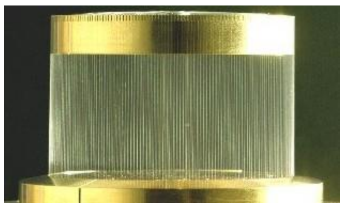
We use pulsed power drivers to create and study matter at high energy densities

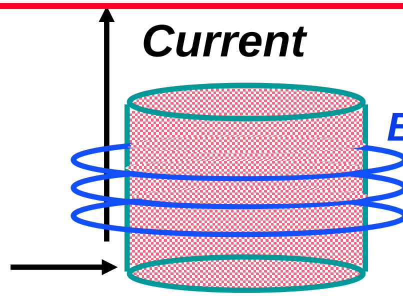
High Current

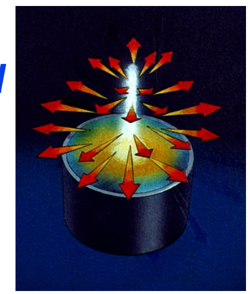
Z-pinch x-ray source

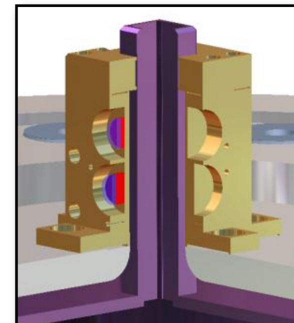
Magnetic pressure

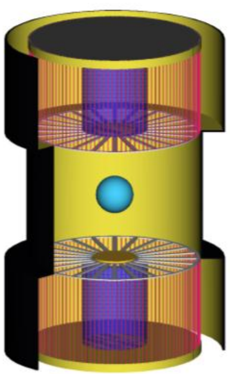
wire array



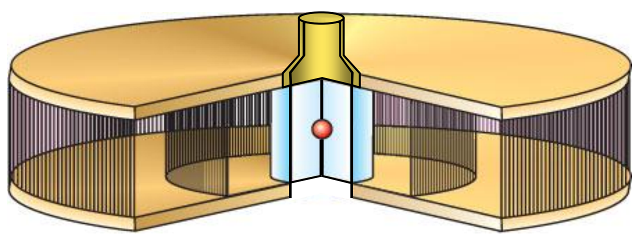




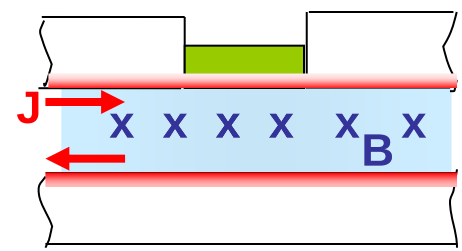




Fusion

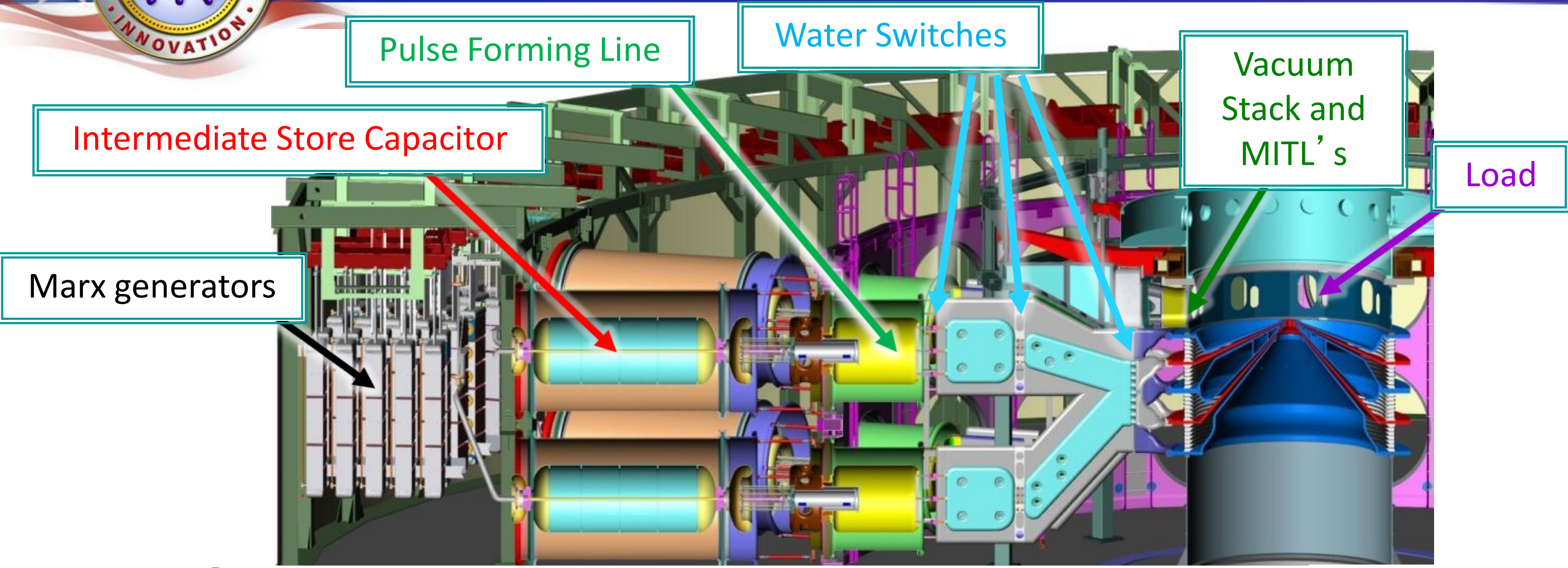


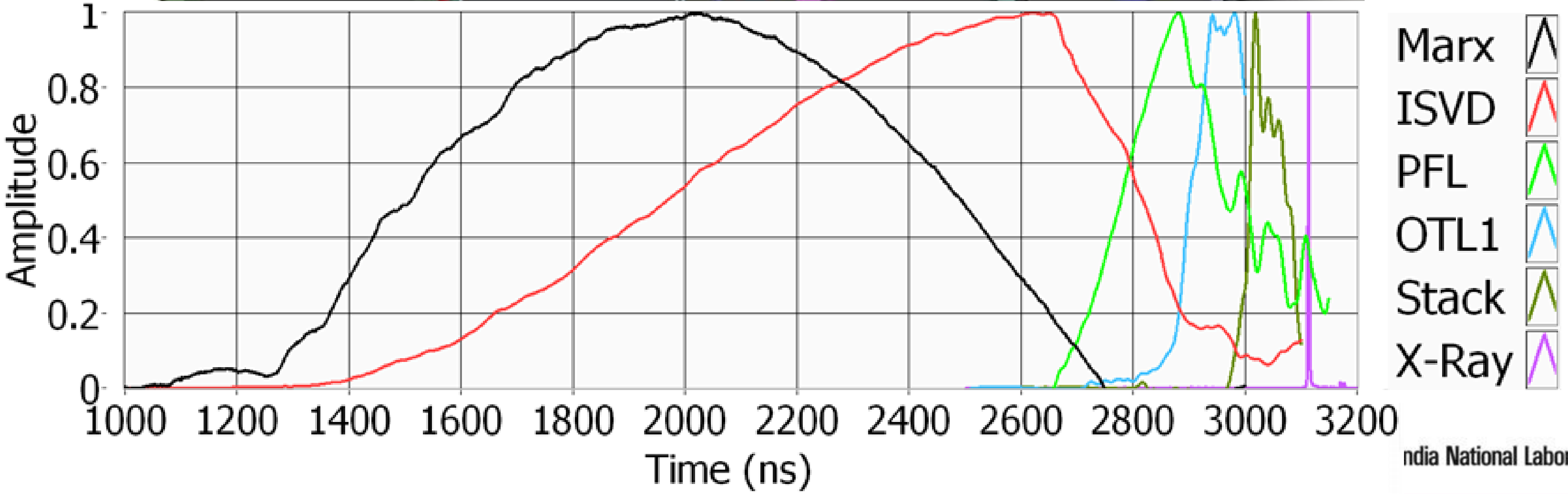
Radiation Science



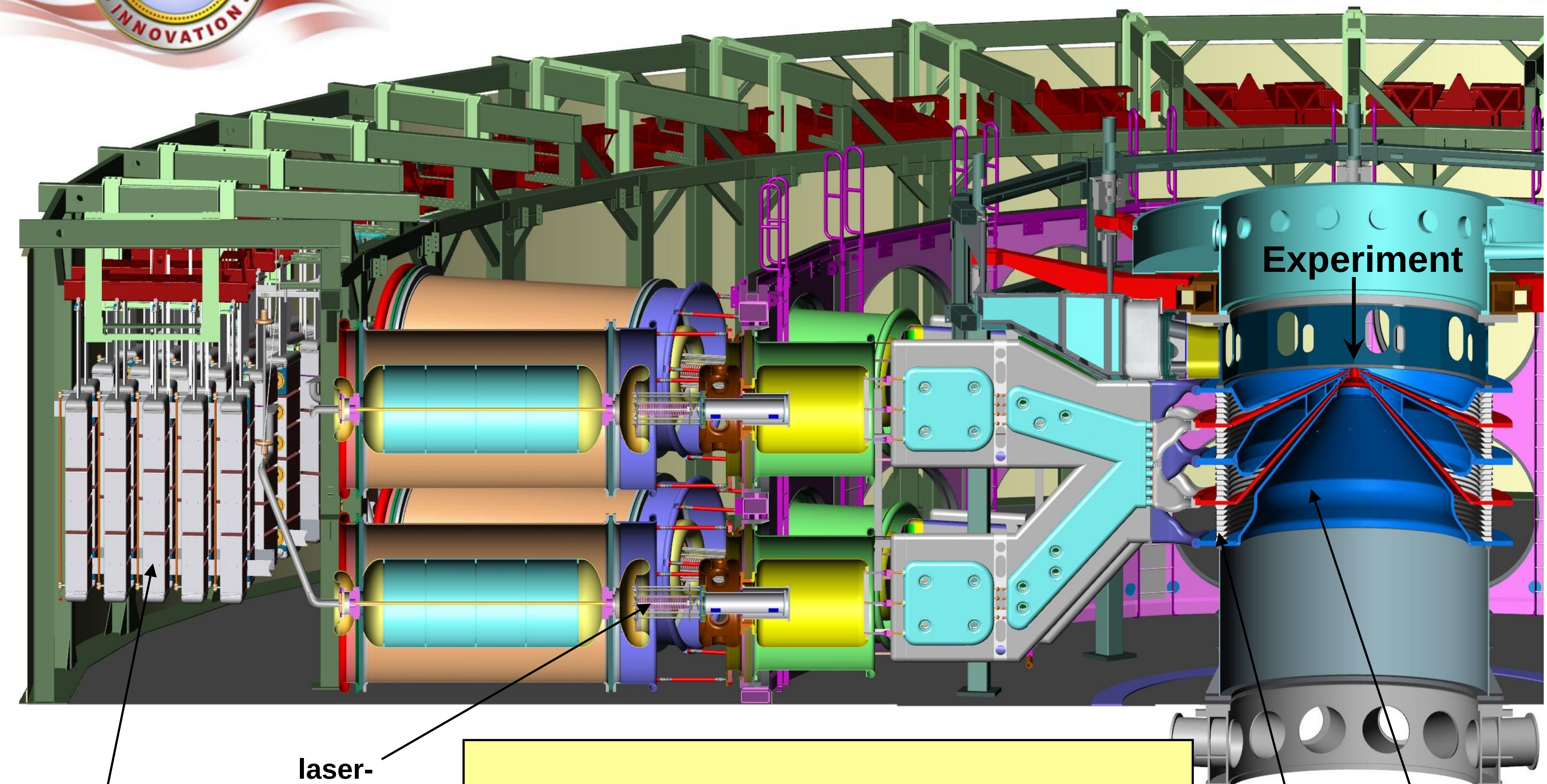
Material Properties

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



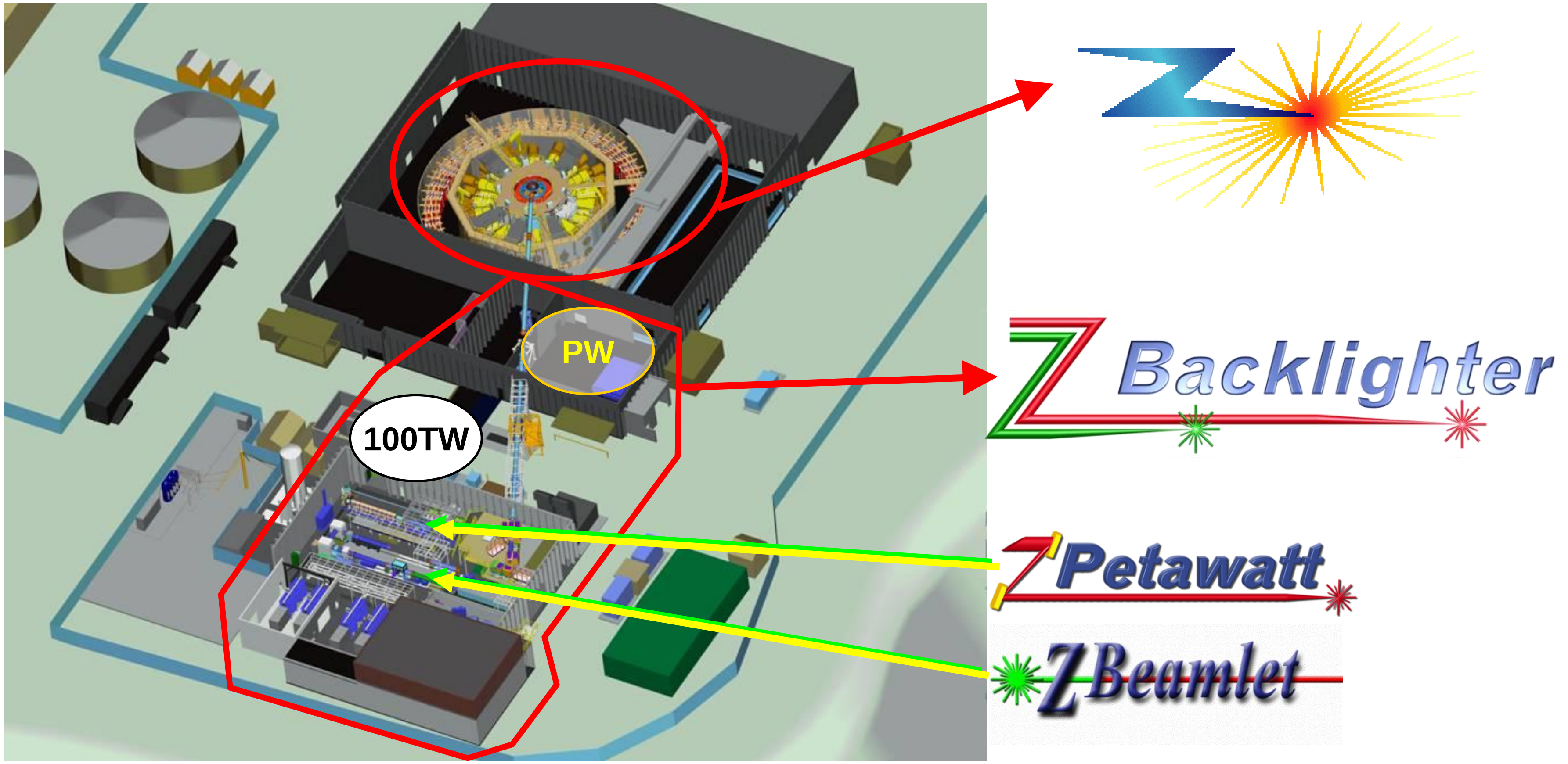


The Refurbished Z Machine has more energy and more pulse shape flexibility

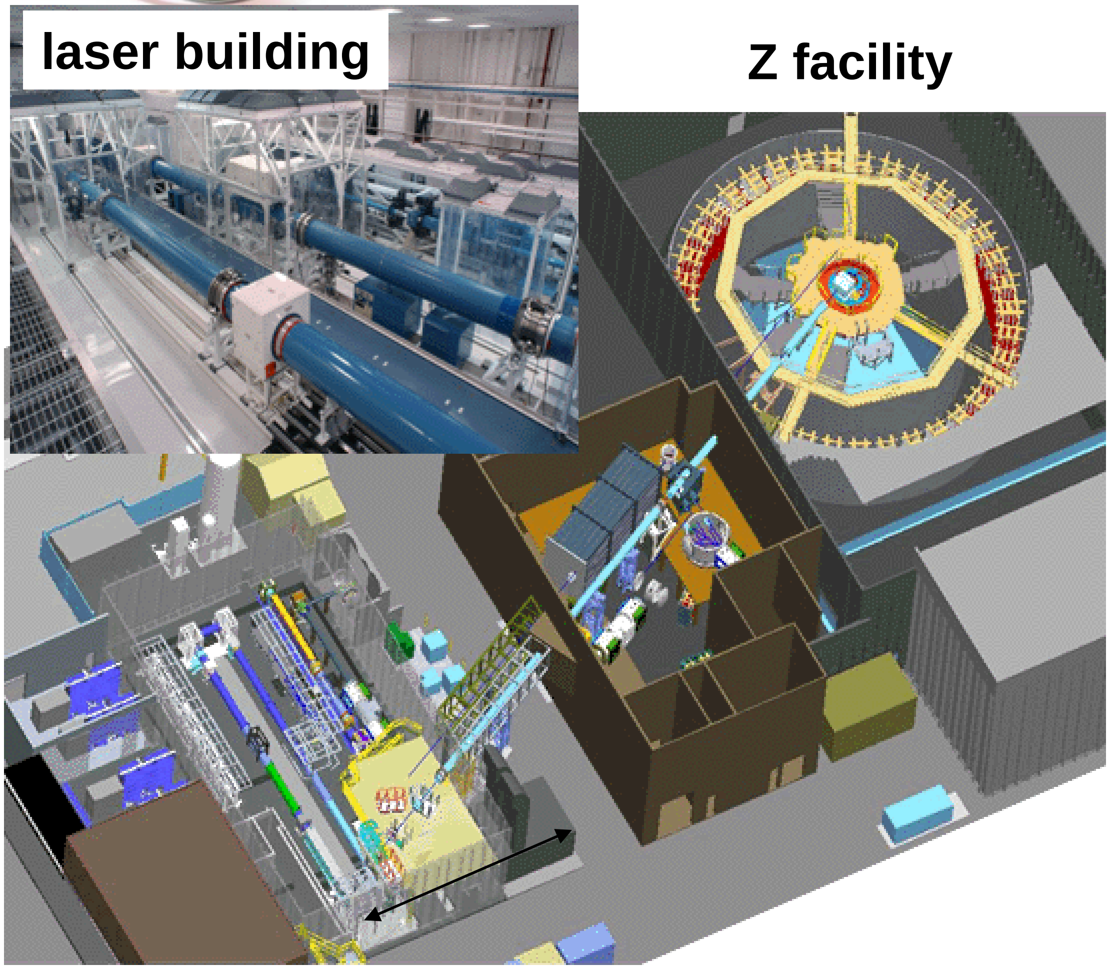


22 MJ stored energy (up from 11 MJ)
~26 MA peak current (~18MA)
~100-600 ns rise time

Z Facility Overview

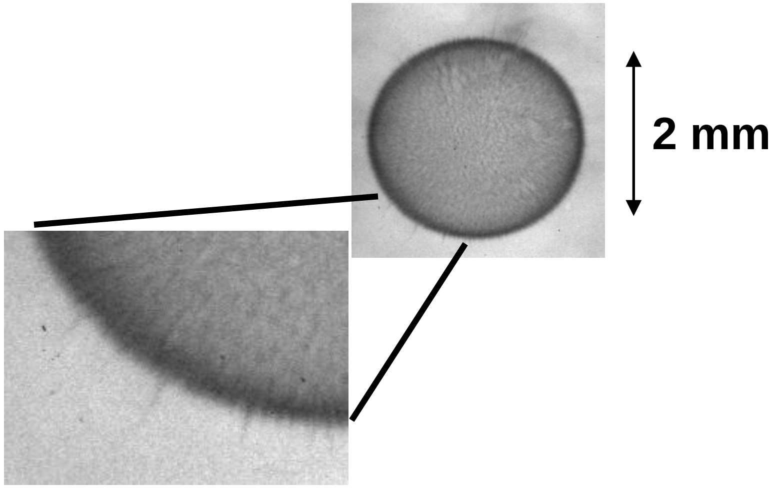


The Z-Beamlet and Z-Petawatt laser backlighters provide a powerful new capability for diagnosing Z experiments

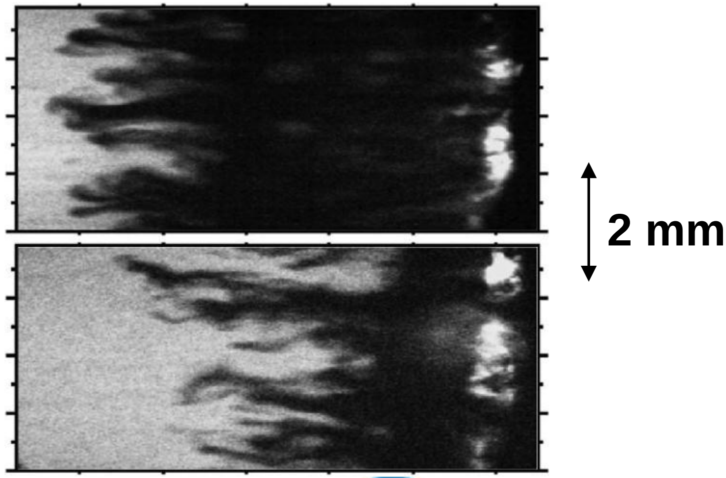


Z-Beamlet and Z-Petawatt lasers

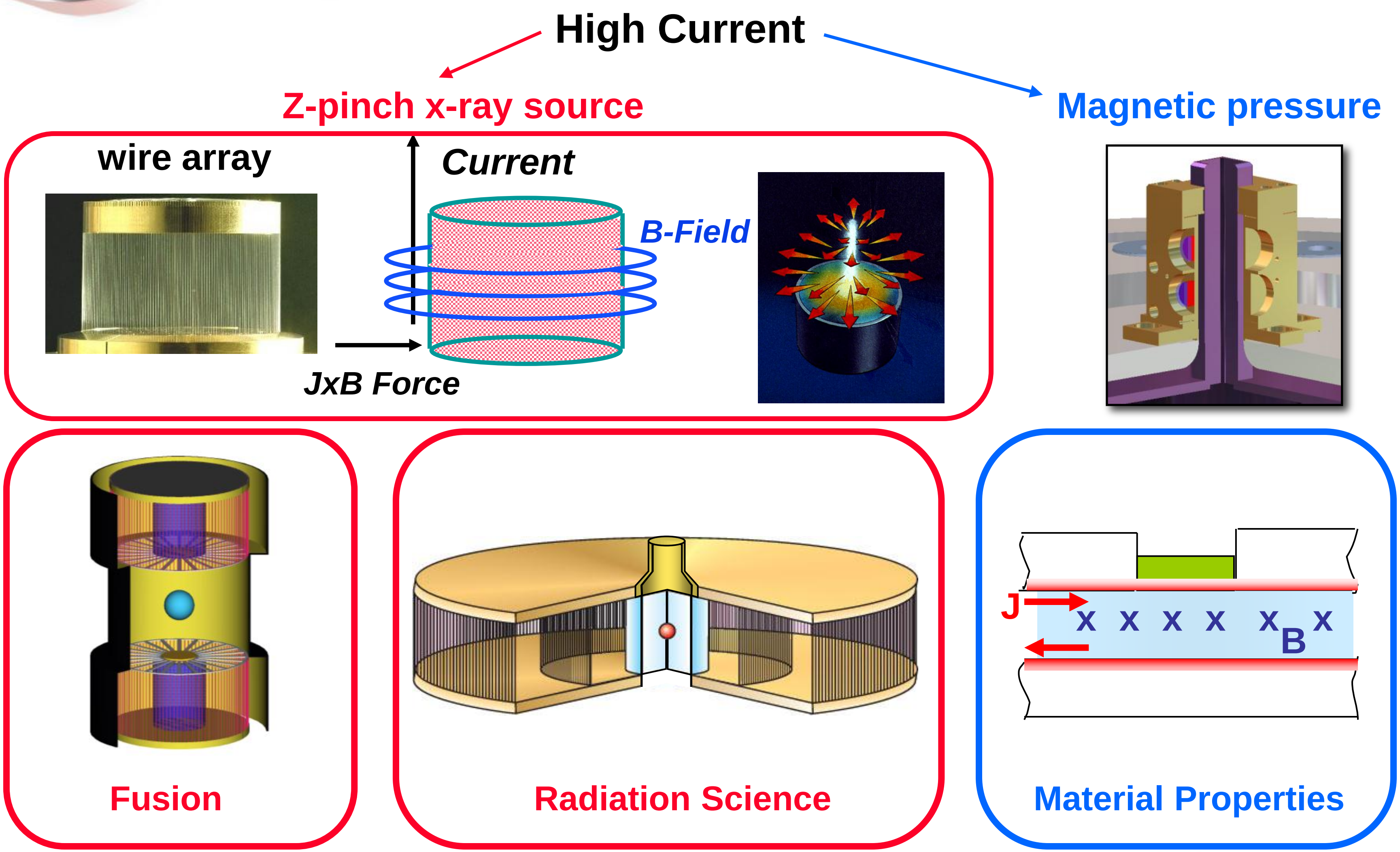
imploding capsule



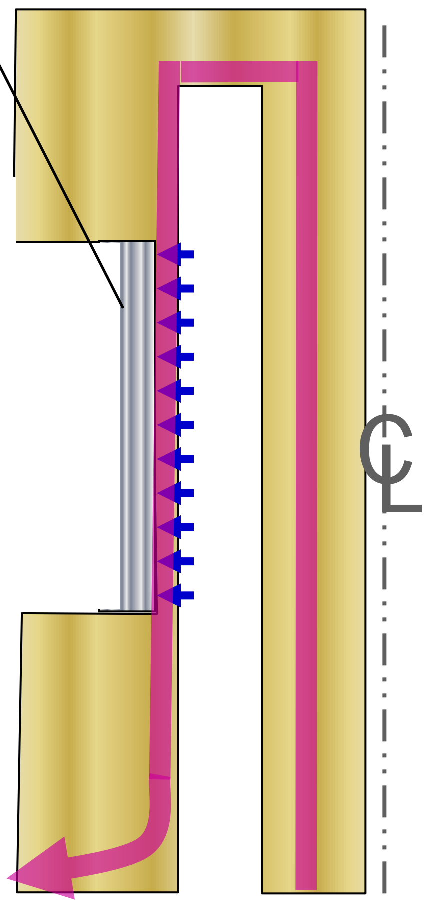
imploding z-pinch

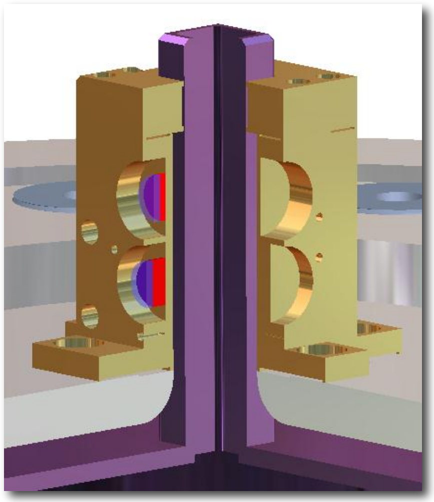


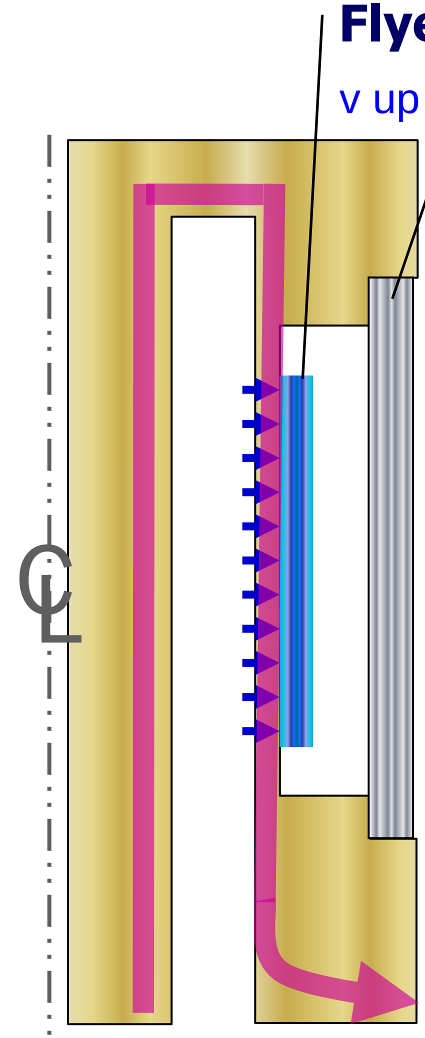
We use pulsed power drivers to create and study matter at high energy densities



Isentropic compression and shock wave experiments are both possible on Z



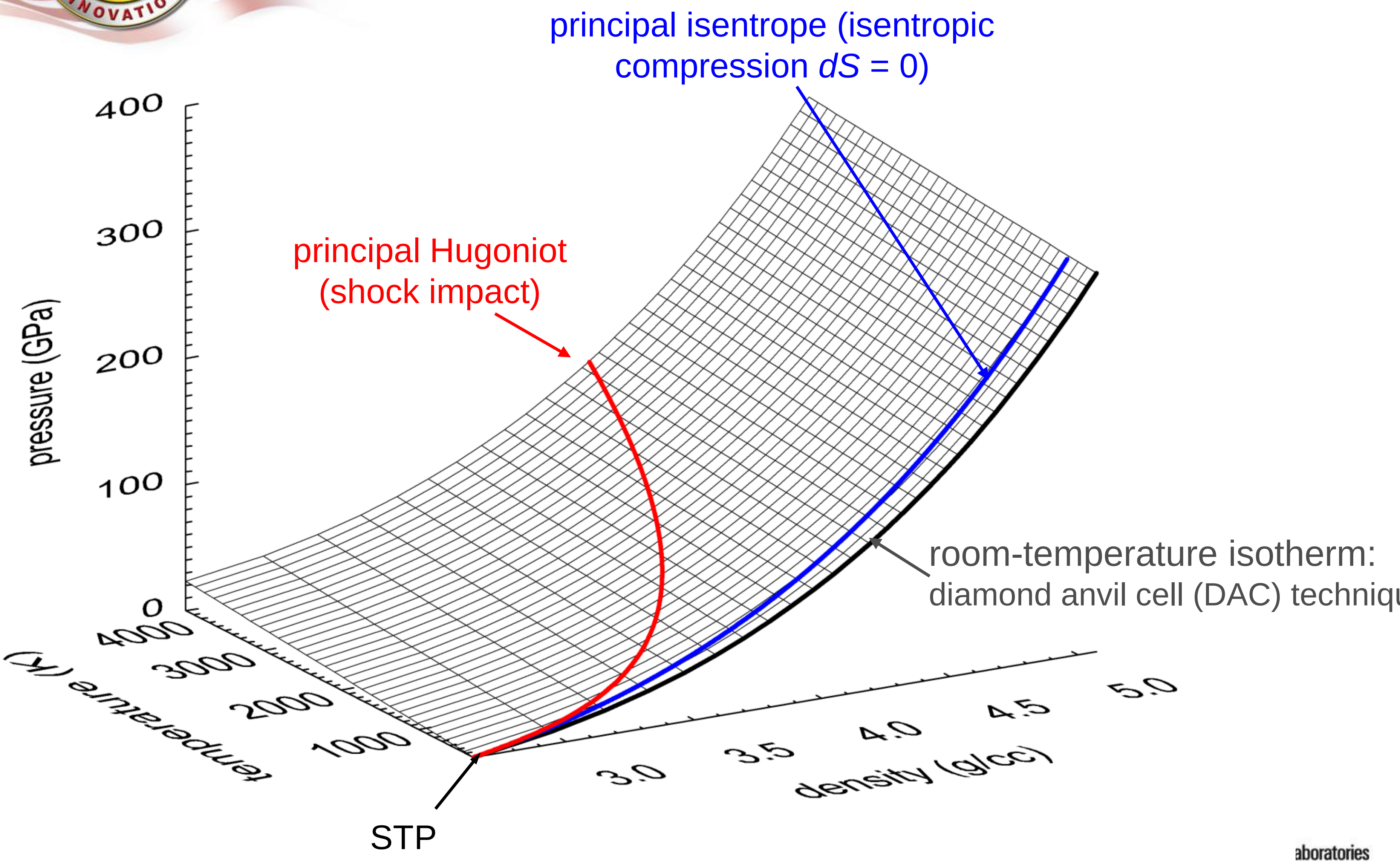




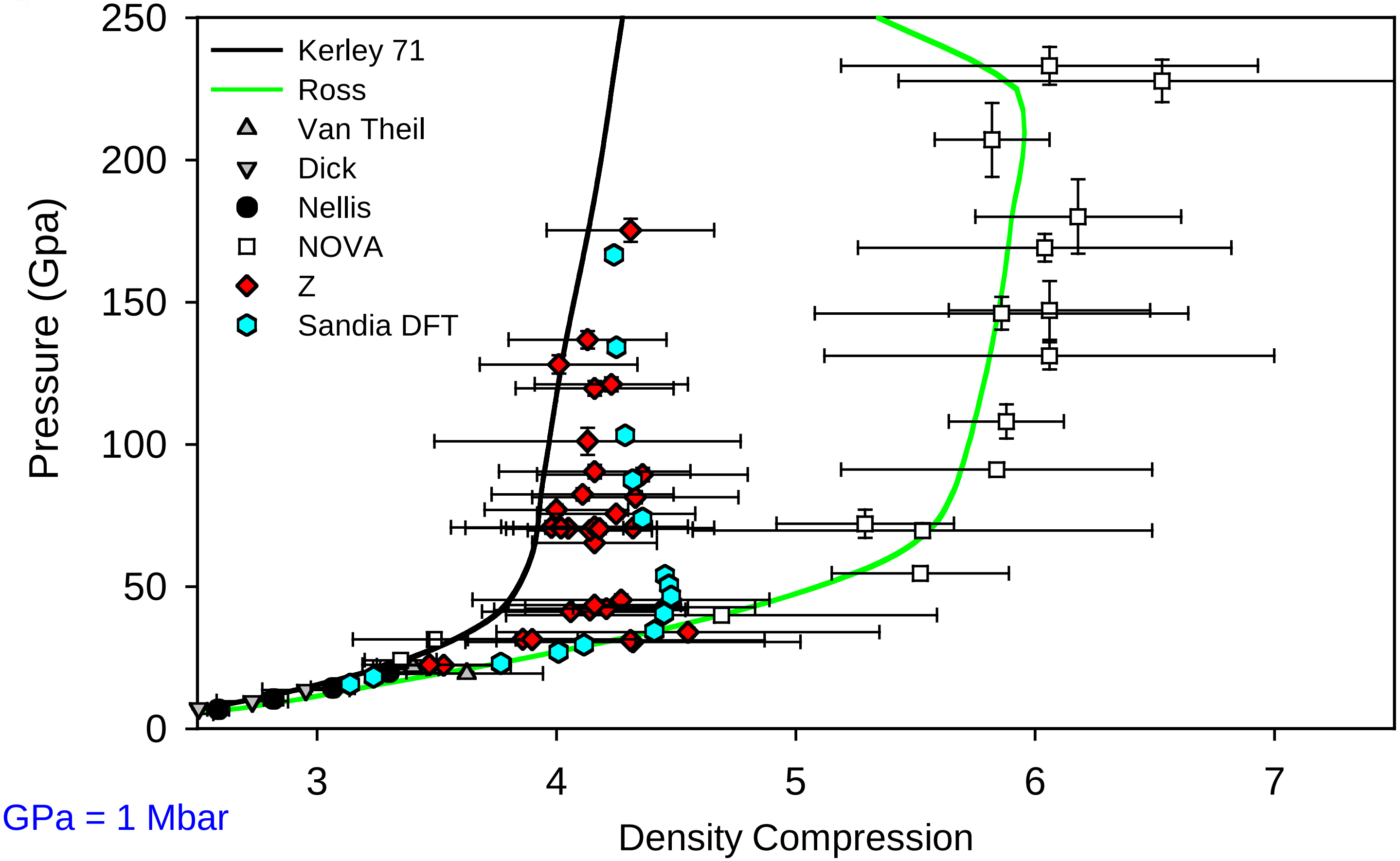
Isentropic Compression Experiments:
gradual pressure rise in sample

Shock Hugoniot Experiments:
shock wave in sample on impact

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



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

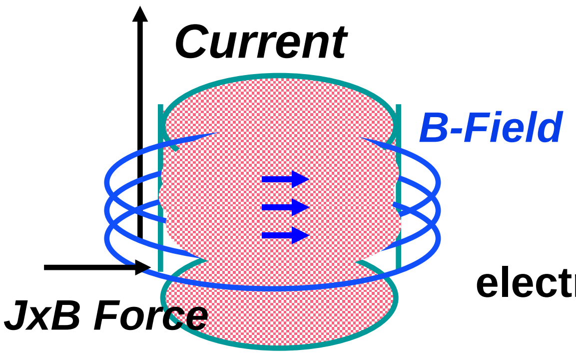


100 GPa = 1 Mbar

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

Impacts ICF, primary physics, planetary models

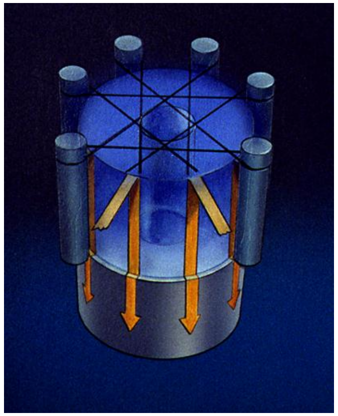
Magnetically-driven fast Z-pinch implosions efficiently convert electrical energy into radiation



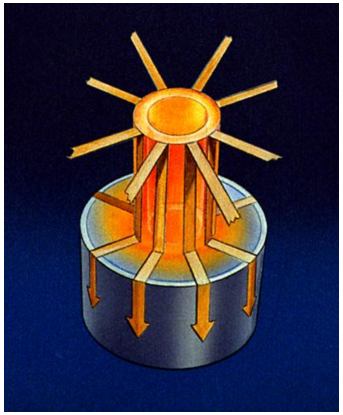
kinetic and magnetic energy

electrical energy → kinetic energy

internal energy → x rays



Ablation



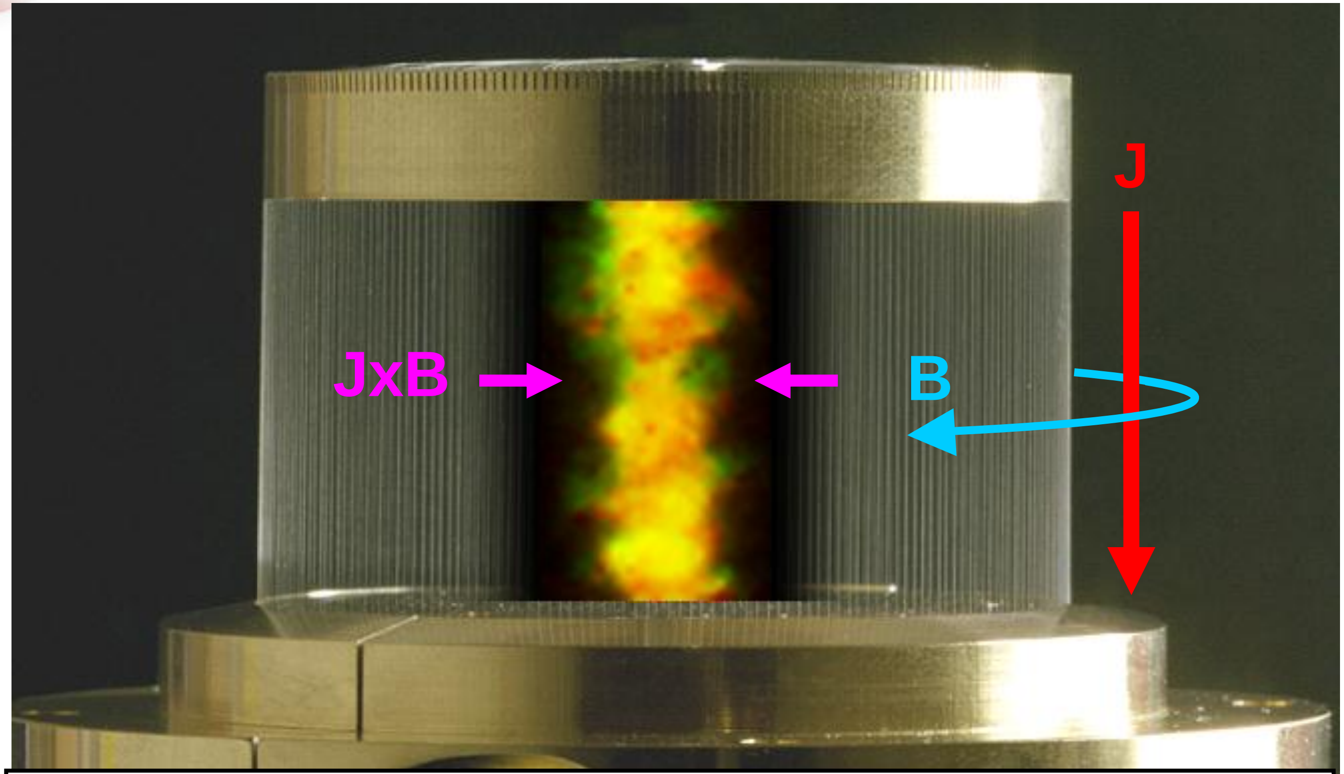
Implosion

Stagnation

Fast wire z-pinch loads:

- 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



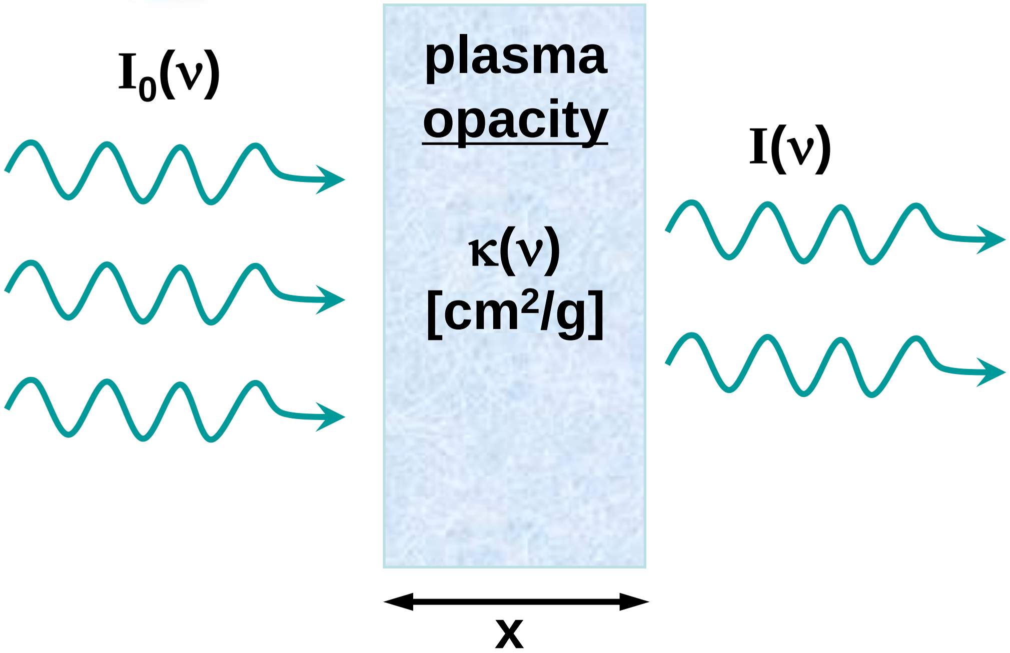
z-pinch sources

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

Opacity quantifies how transparent or opaque a plasma is to radiation



Transmission

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

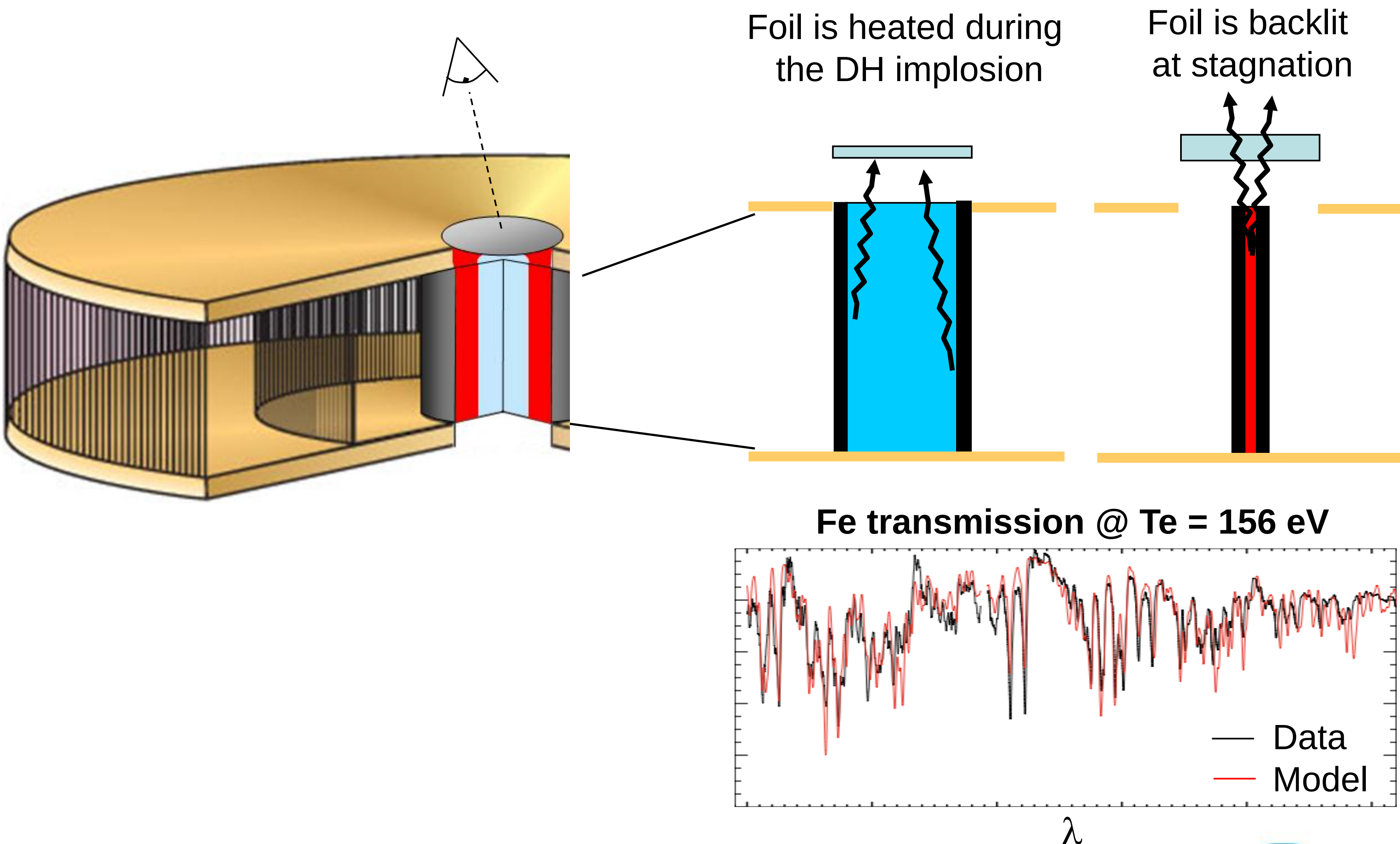
Optical depth

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

Stellar structure depends on opacities that have never been measured

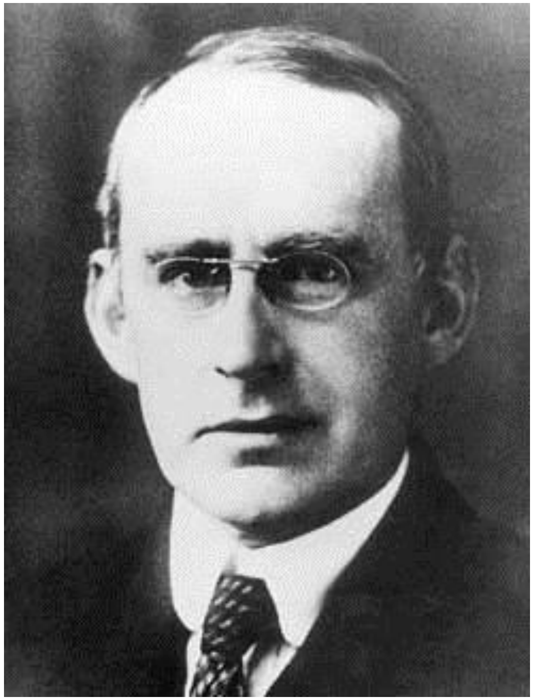
Challenge: create and diagnose stellar interior conditions on earth

Z 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~~

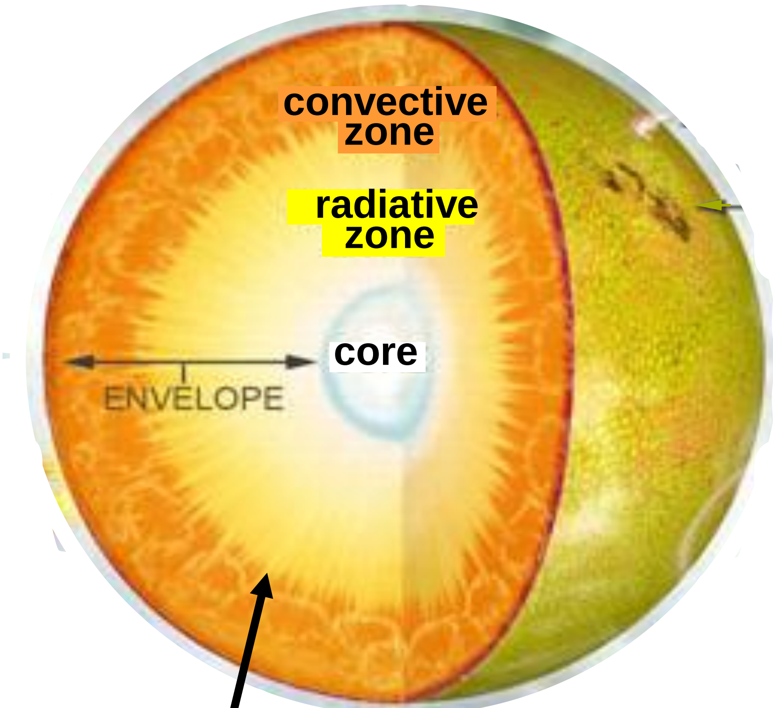
+

interior plasma property models

= understanding

model reliability requires laboratory experiments

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



2007 Don Dixon / cosmographica.com

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

Predictions of solar structure do not agree with observations

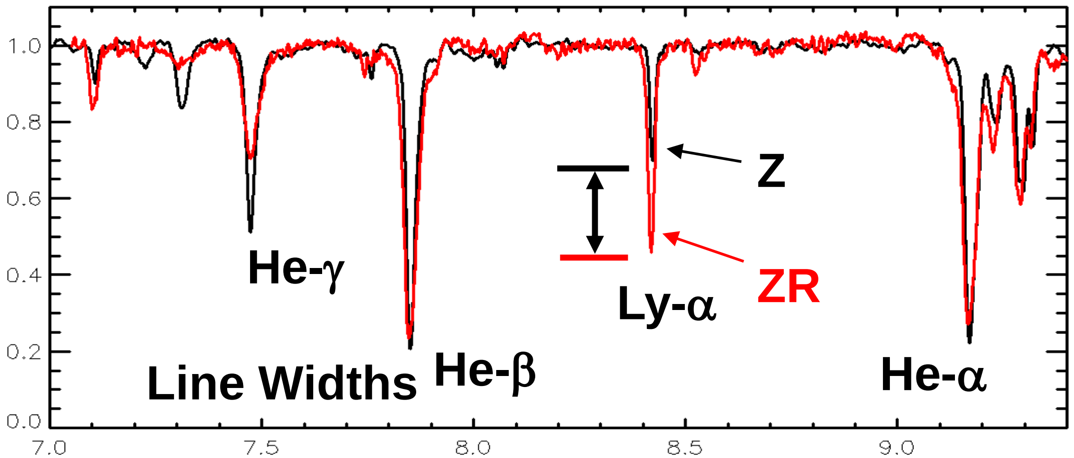
Solar structure depends on opacities that have never been measured

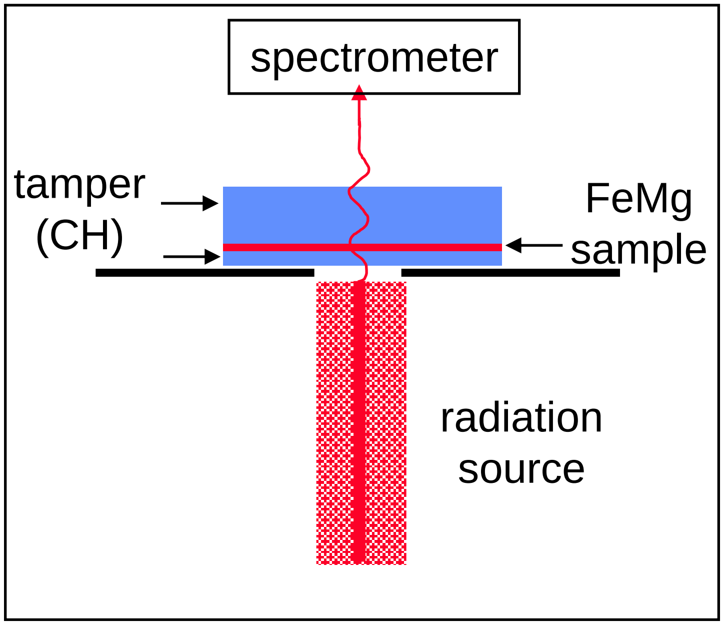
Challenge: create and diagnose stellar interior conditions on earth

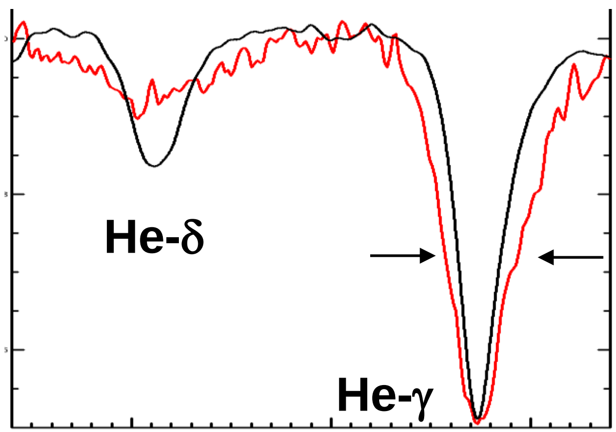
High T enables first studies of transitions important in stellar interiors

Opacity measurements on Z are close to replicating solar interior matter

Mg K-shell absorption from a Mg/Fe foil



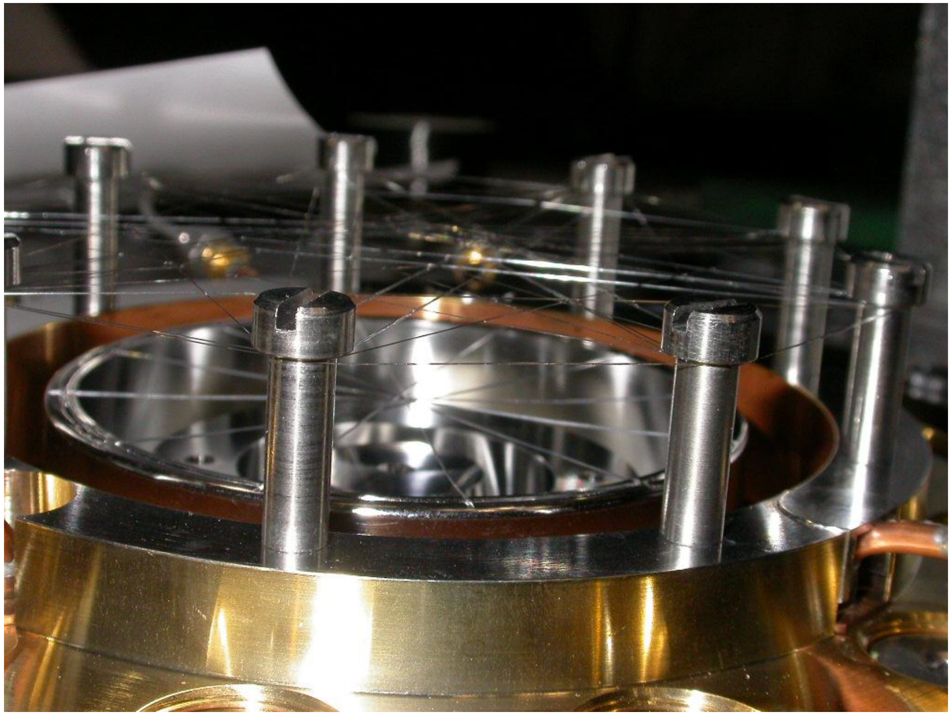




- **Higher Ly/He ratios indicate ~20% increase in T_e ~190 eV**
- **Broader high-n lines indicate thicker tamper led to ~300% increase in n_e**

This is much closer to Fe conditions in the Sun

3.9 x 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
- Recent Publications:

D. R. Welch et al., Phys. Rev. Lett. 103, 255002 (2009)

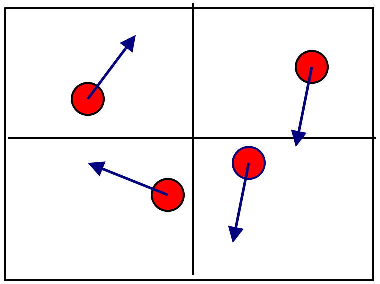
D. R. Welch et al., Phys. Plasmas 17, 072702 (2010)

D. R. Welch et al., Phys. Plasmas 18, 056303 (2011)

*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, n, v, interpolated to grid; fields back to particles



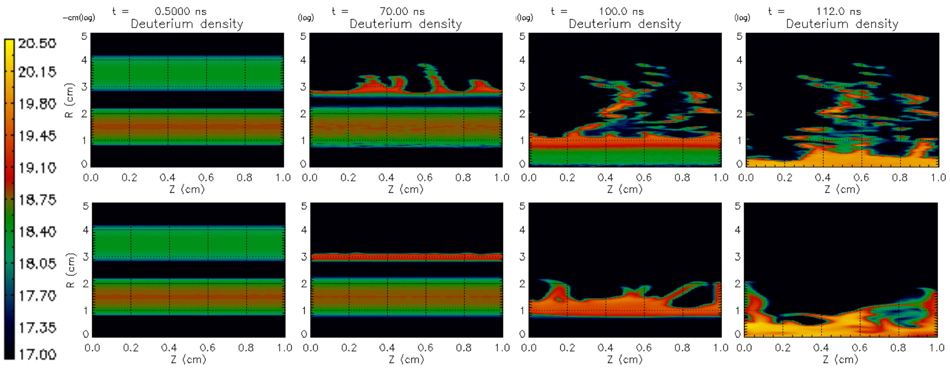
EM Fields, pressure, etc. calculated on grid

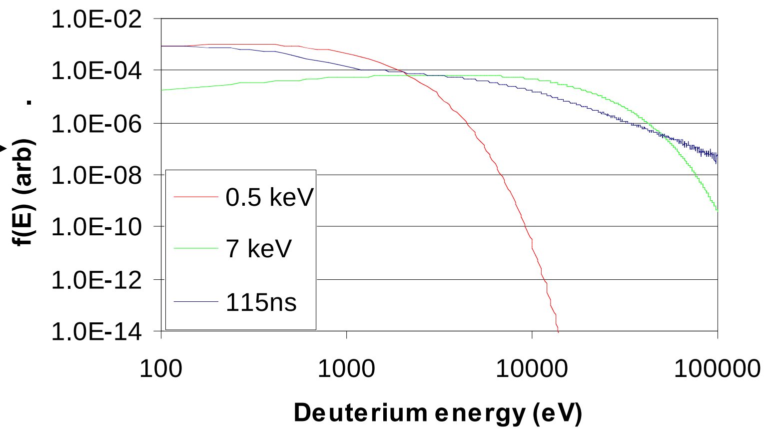
- **PIC follows macroparticles with each representing many real ones**
  - **Particle currents J (or charges ρ) are interpolated to a grid**
  - **Maxwell's (or Poisson's) equations are advanced on the grid using J or ρ**
  - **The electric E and magnetic B fields are interpolated to particles**
  -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

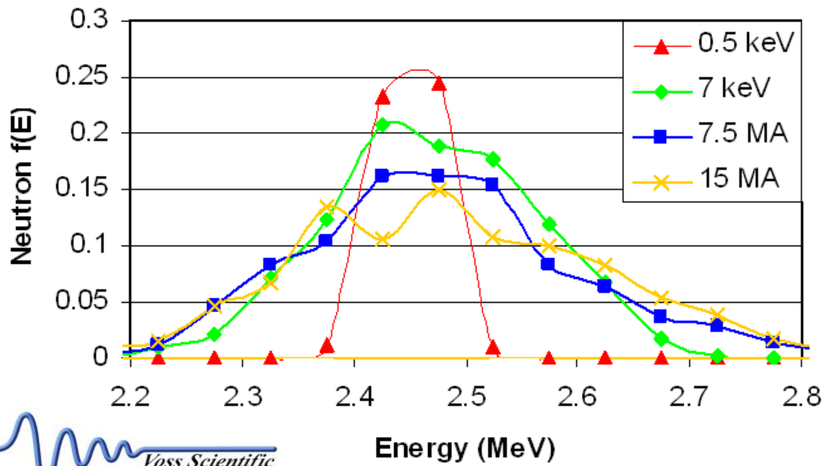
2D 15 MA LSP simulation



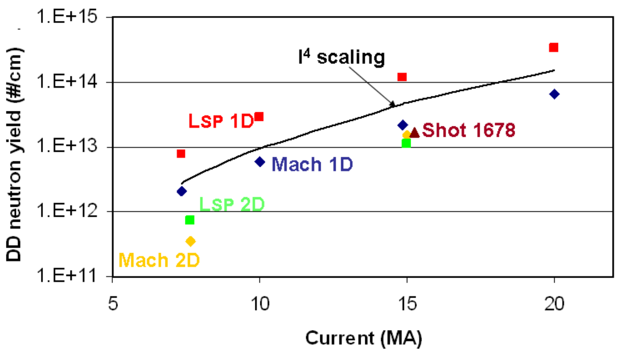


High energy tail accounts for half neutron production by 115 ns, broadens neutron energy spectrum.

2D 15 MA MHD (Mach2) simulation

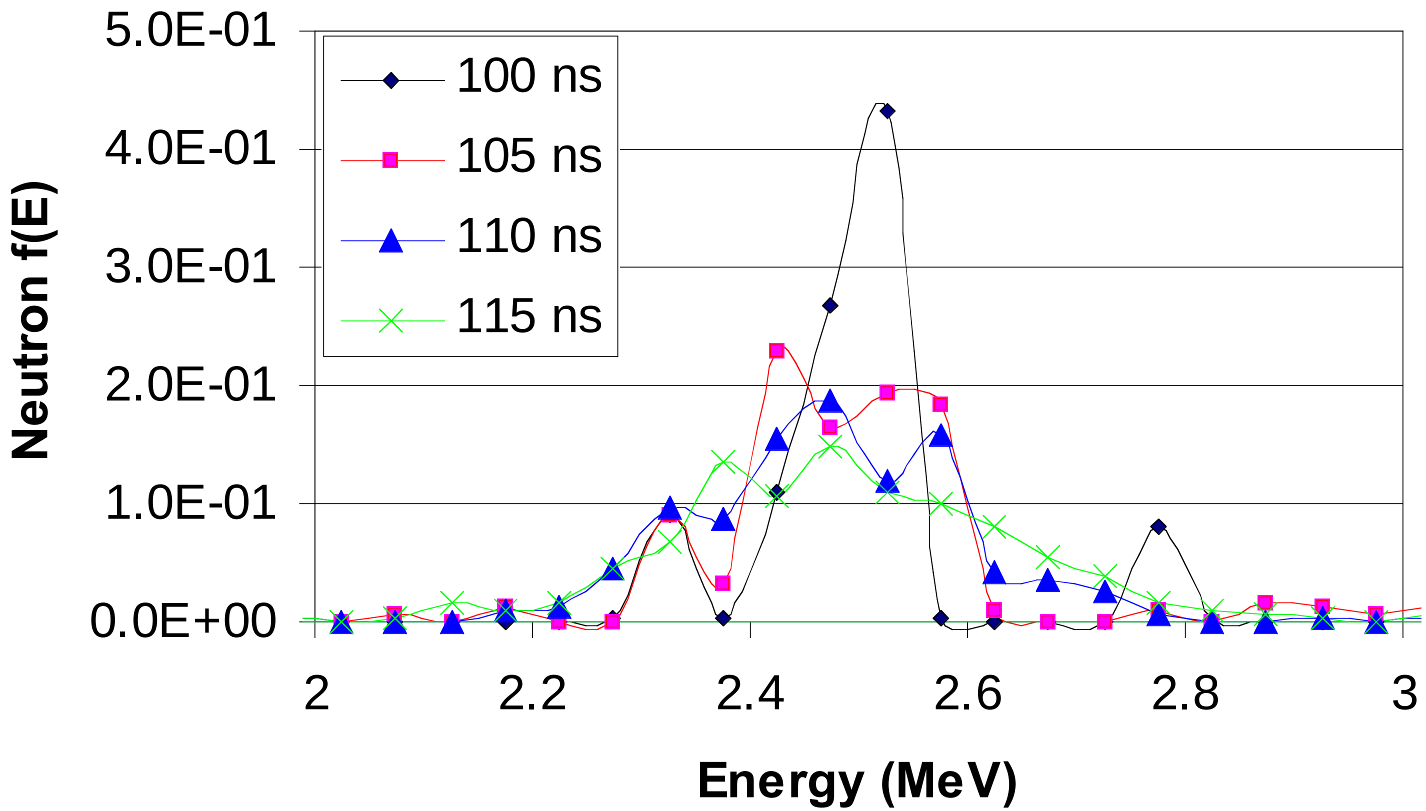


Favorable neutron yield production with pinch current!



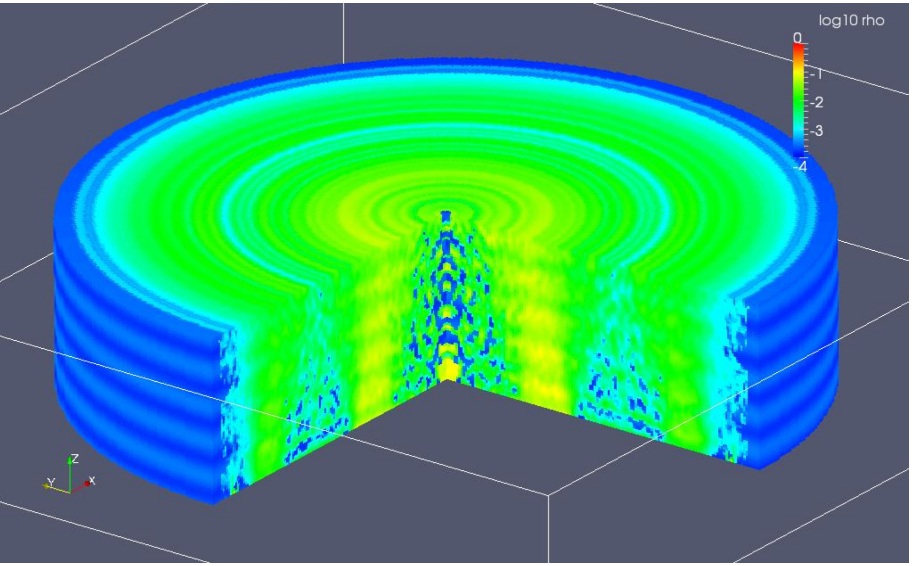
Voss Scientific

Neutron spectrum reflect higher reactant energies as pinch progresses

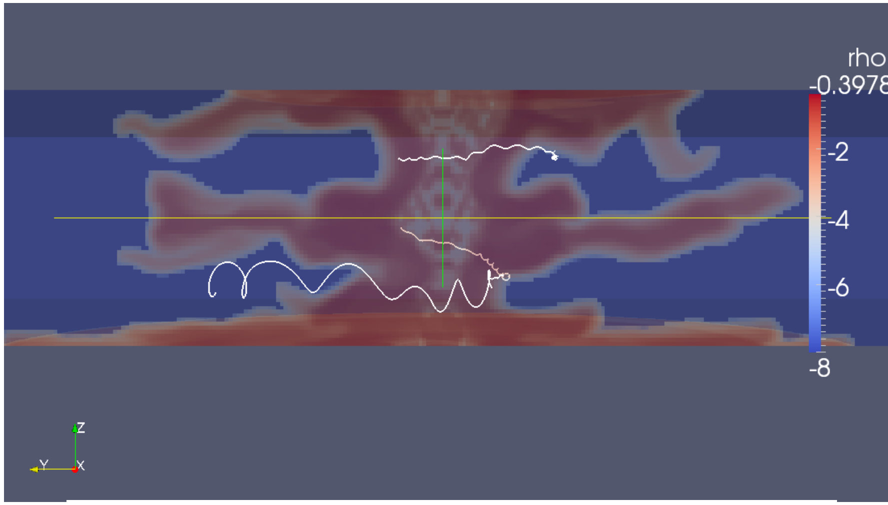


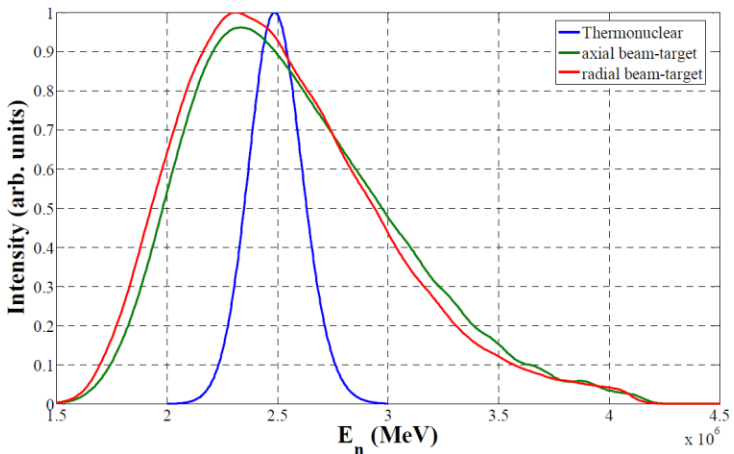
- **FWHM of distribution increases from 80 to 300 keV**
- **These neutron spectra suggest that both "thermal" and "non-thermal" neutrons are produced in pinch plasma systems**

Combined MHD and PIC simulations model implosion, particle acceleration and fusion reaction kinetics



MHD code of gas puff Z-pinch on Z, using measured deuterium density profile plus 3D helical twist thermonuclear yield of 4×10^{13} D-D

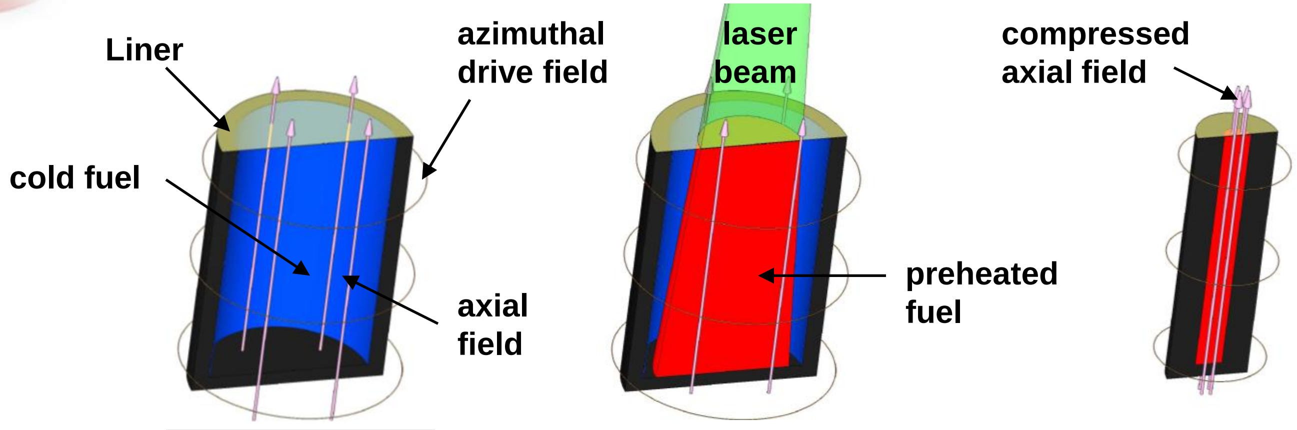




Neutron spectrum is dominated by thermonuclear reactions, but has a broad range of energies due to accelerated and magnetized beam of deuterons

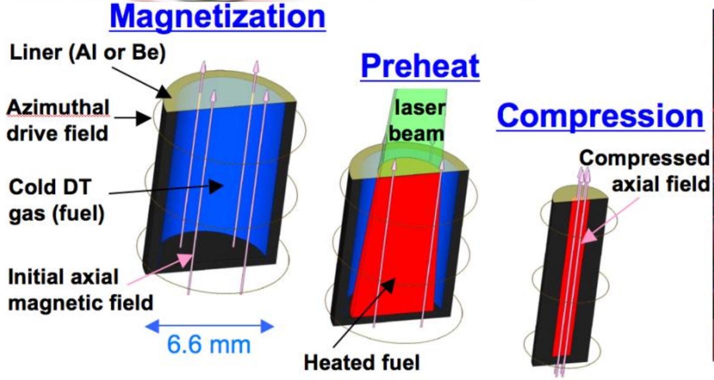
Imperial College London

Magnetized Liner Inertial Fusion (MagLIF) provides beneficial effects for pulsed power driven ICF

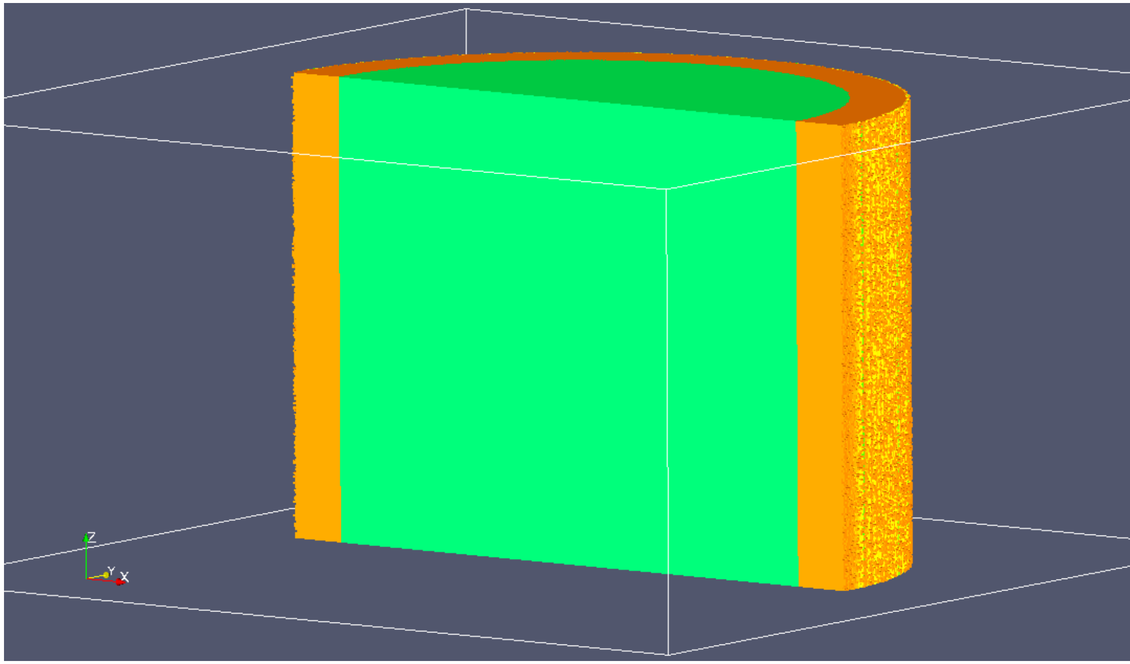


- **A magnetic field inhibits thermal conduction and enhances alpha particle deposition within the fuel**
- **Preheating the fuel reduces the compression needed to obtain ignition temperature**
  - **allows relatively low velocity implosions (5-10 cm/μs)**
  - **calculations indicate this could be done 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**

Similar combined MHD & PIC techniques are being used to model liner fusion schemes such as MagLIF



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



Rayleigh Taylor instability grows in the aluminum liner during implosion, but is unable to penetrate into fuel before a fusion yield of 100 kJ is obtained

Unique explicit formalism of Imperial College's MHD code 'Gorgon' enables efficient parallel scaling - demonstrated on up to 13,000 processors on AWE's Blackthorn computer - with 13×10^9 computational elements in simulations of SNL wire arrays and liner fusion schemes

Imperial College London

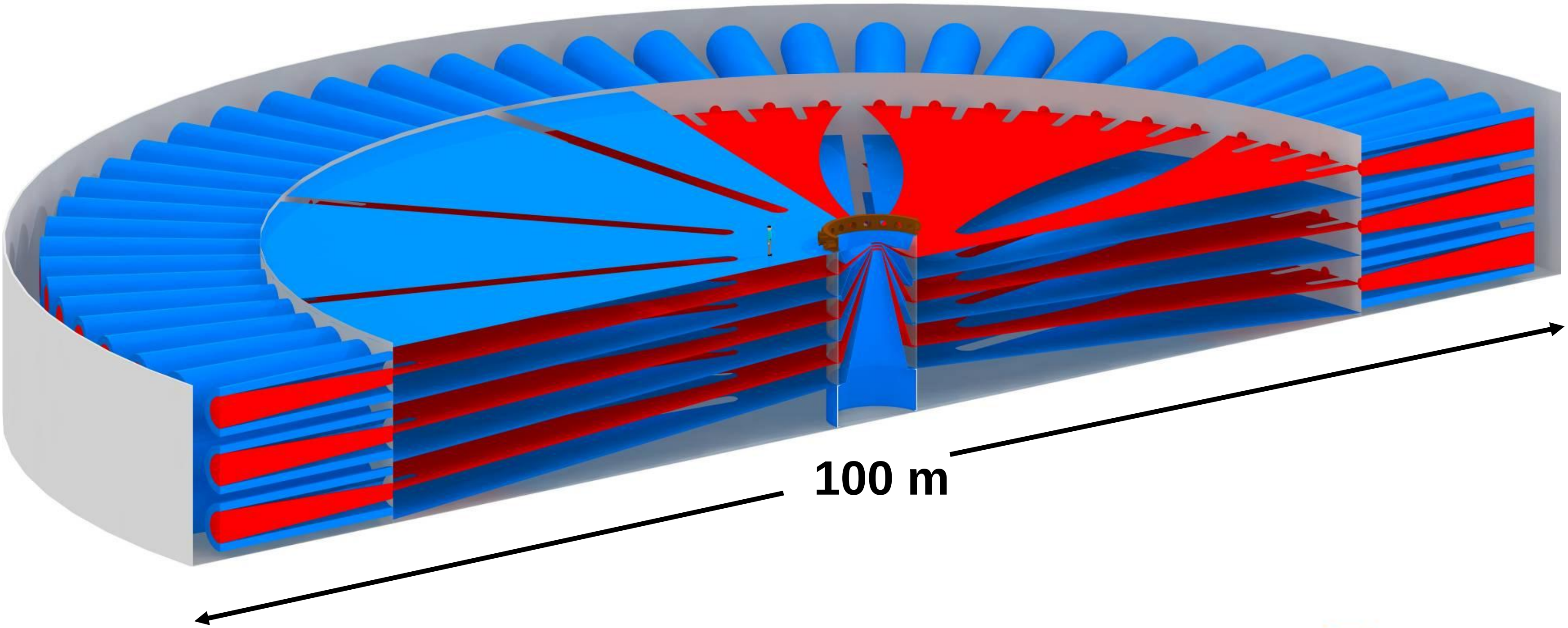
Sandia National Laboratories

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)

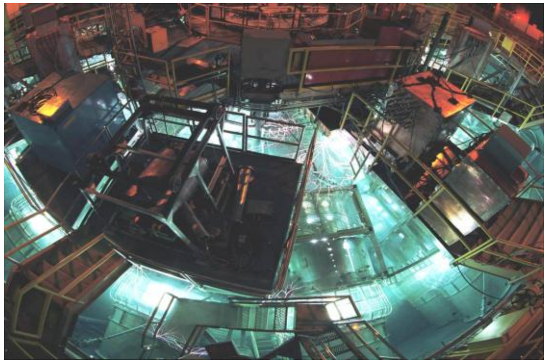


It's an exciting time to be working on the Z facility

- 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

The five-year Z-Refurbishment project has been completed

Last Shot



July ‘06

Demolition Completed

Sept ‘06

Tank Modifications Completed

Jan ‘07

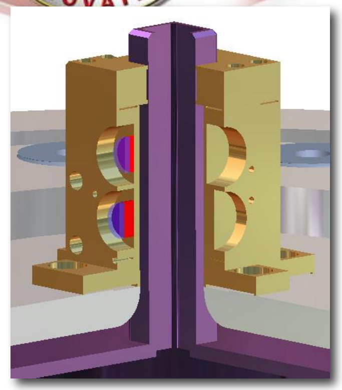
Installation Underway – Multiple Contractors

March ‘07

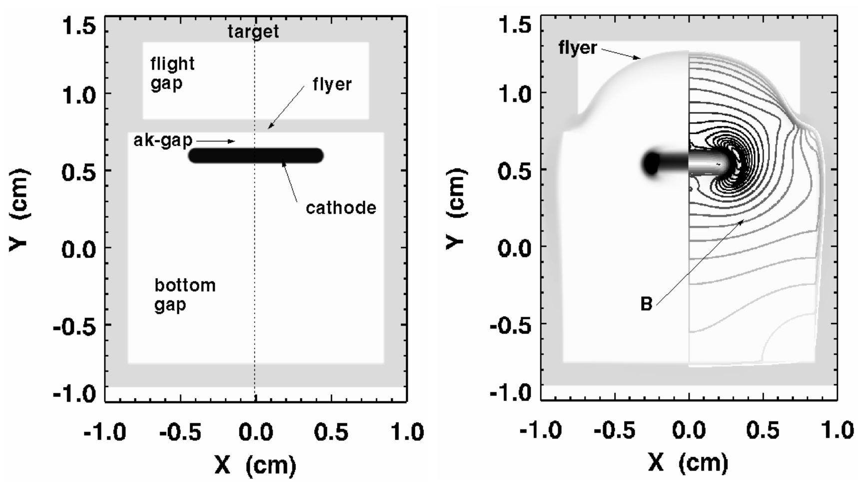
Installation Completed

August ‘07

Our MHD simulation capability is a powerful design tool

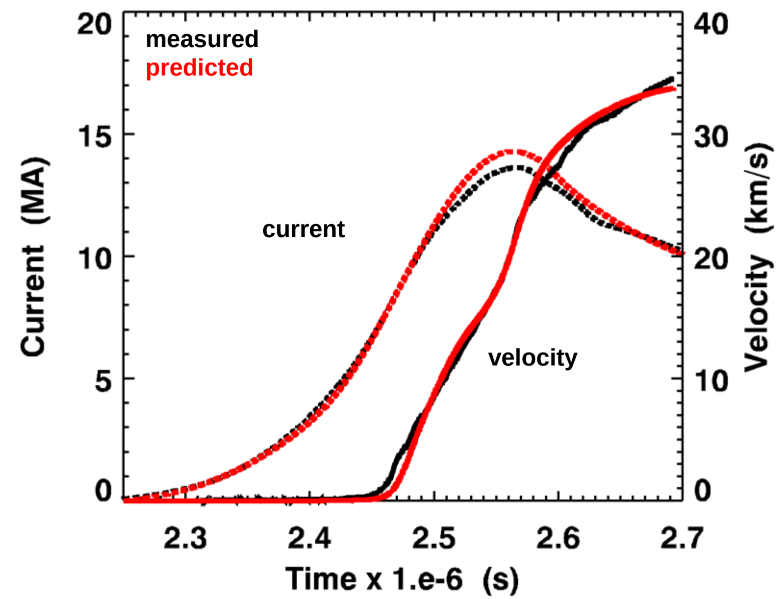


DFT based material models gave us predictive capability
ASC codes enable optimized experiments



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

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

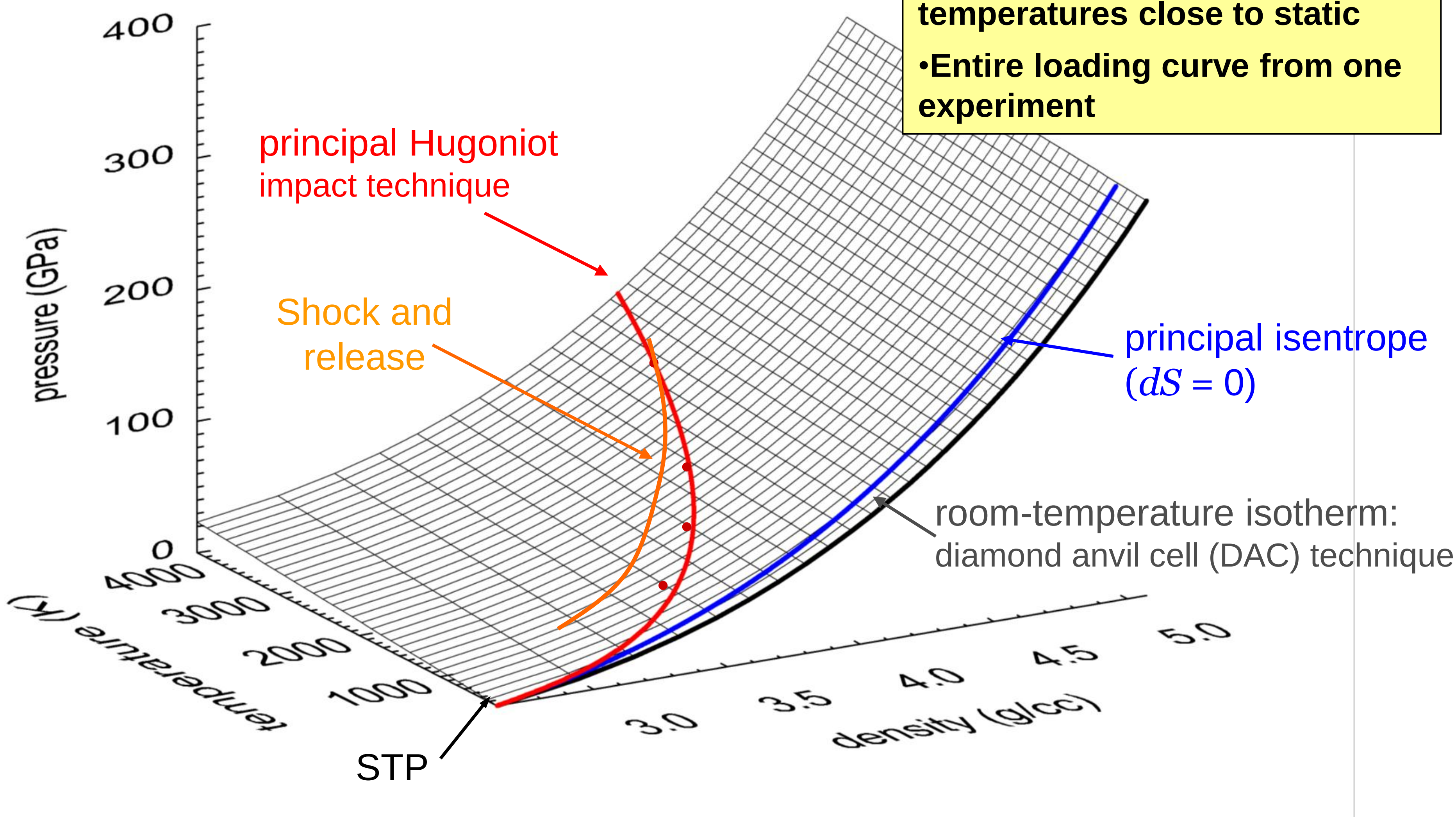


In 2-D, 10^6 elements, 160 CPUs, 4 hours (T-Bird)

In 3-D, up to 10^8 elements, 8192 CPUs, 300 hours (ASC Purple)

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



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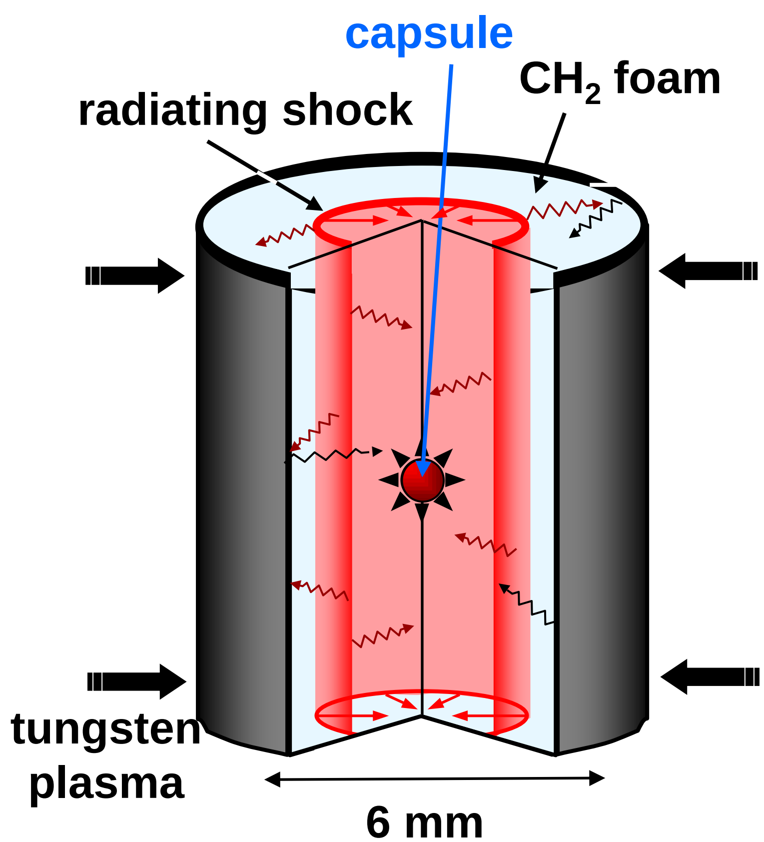
Dynamic hohlraums efficiently couple x-rays to capsules

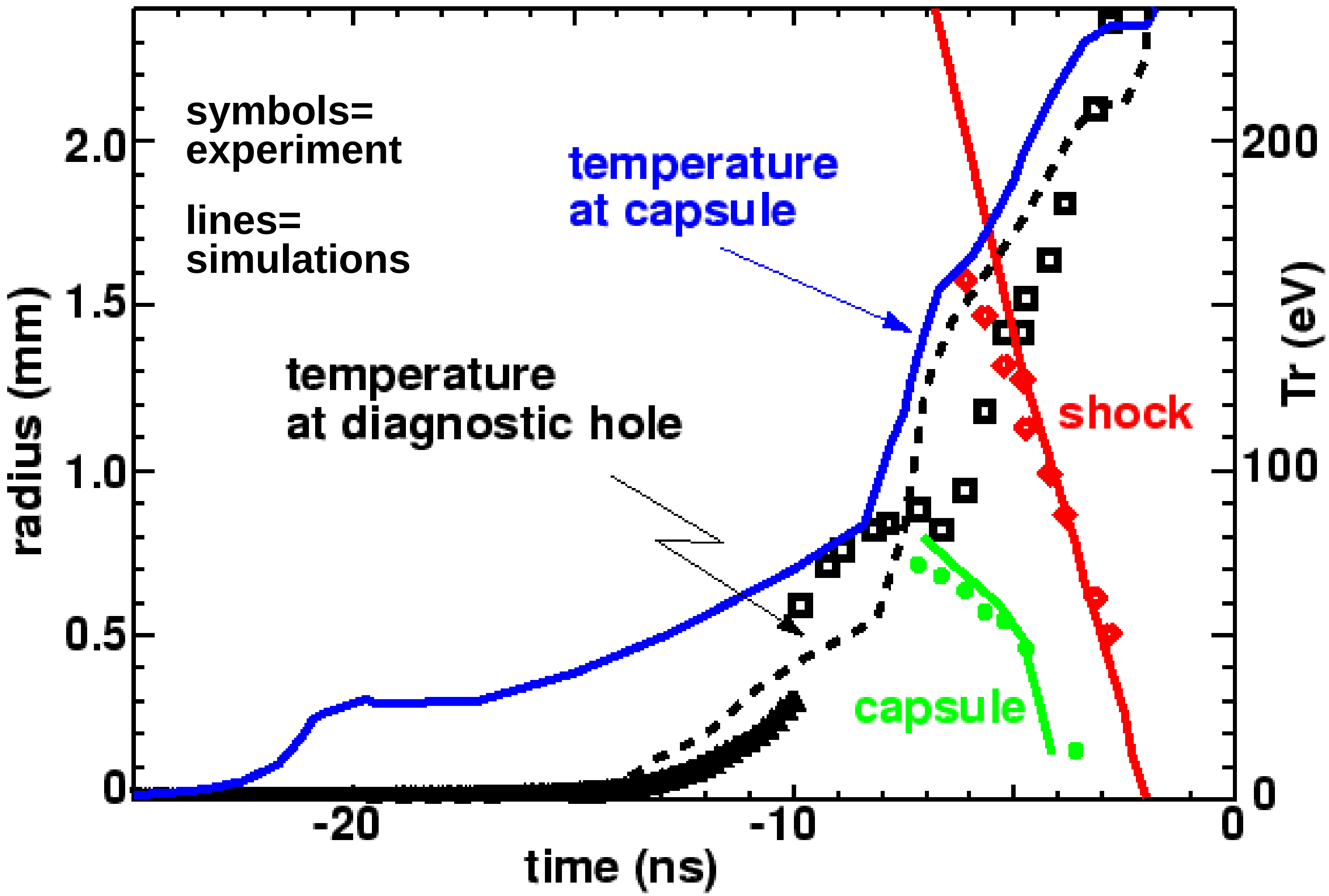


- Z-pinch plasma impacts foam converter
- The impact launches shocks in foam and tungsten
- The foam shock is a main radiation source
- The z-pinch confines the radiation
- Capsule heated mainly by re-emission from tungsten hohlraum wall

physics issues:

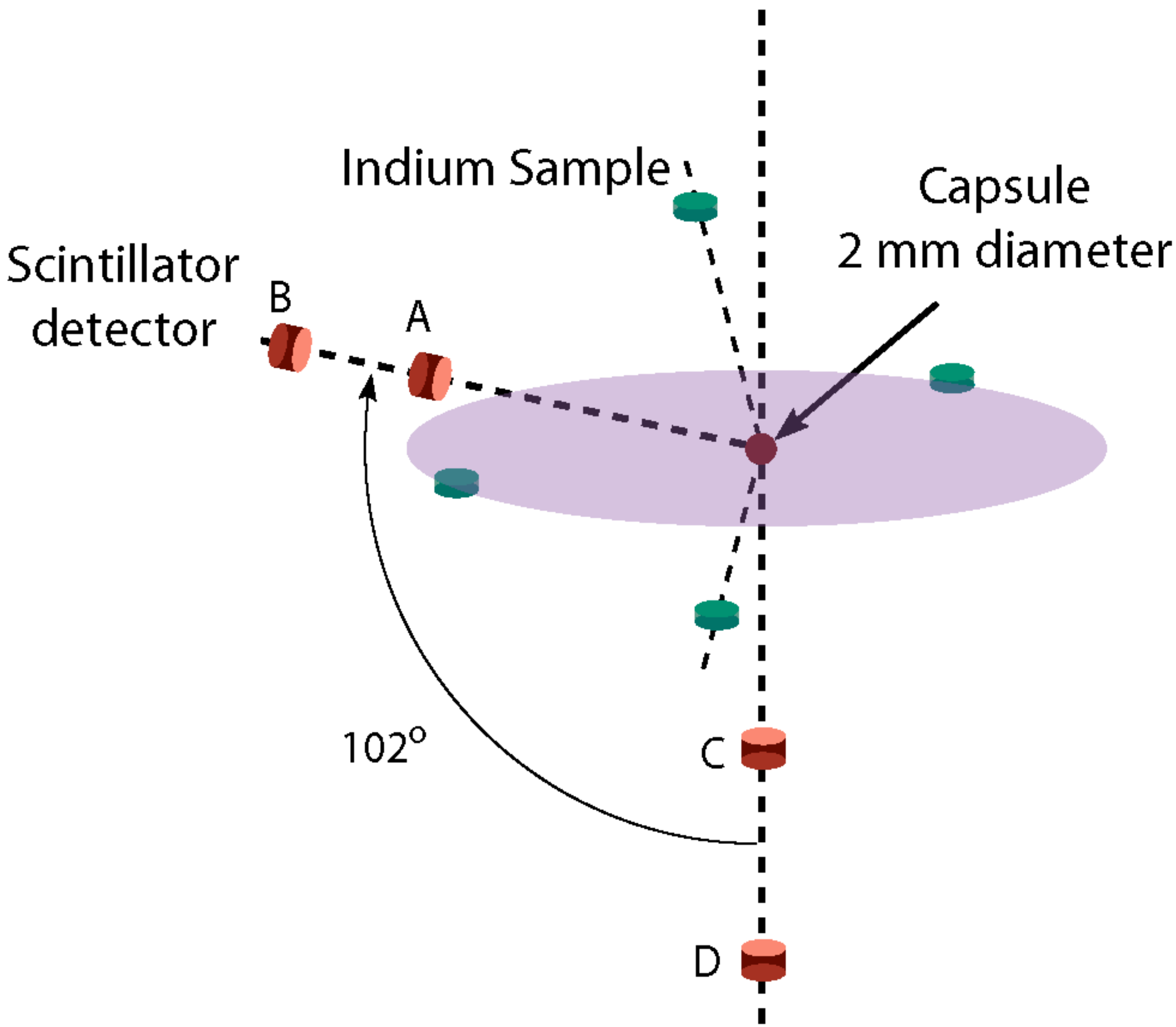
1. interior diagnostics
2. symmetry
3. radiation production
4. radiation transport
5. radiation confinement
6. preheat

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

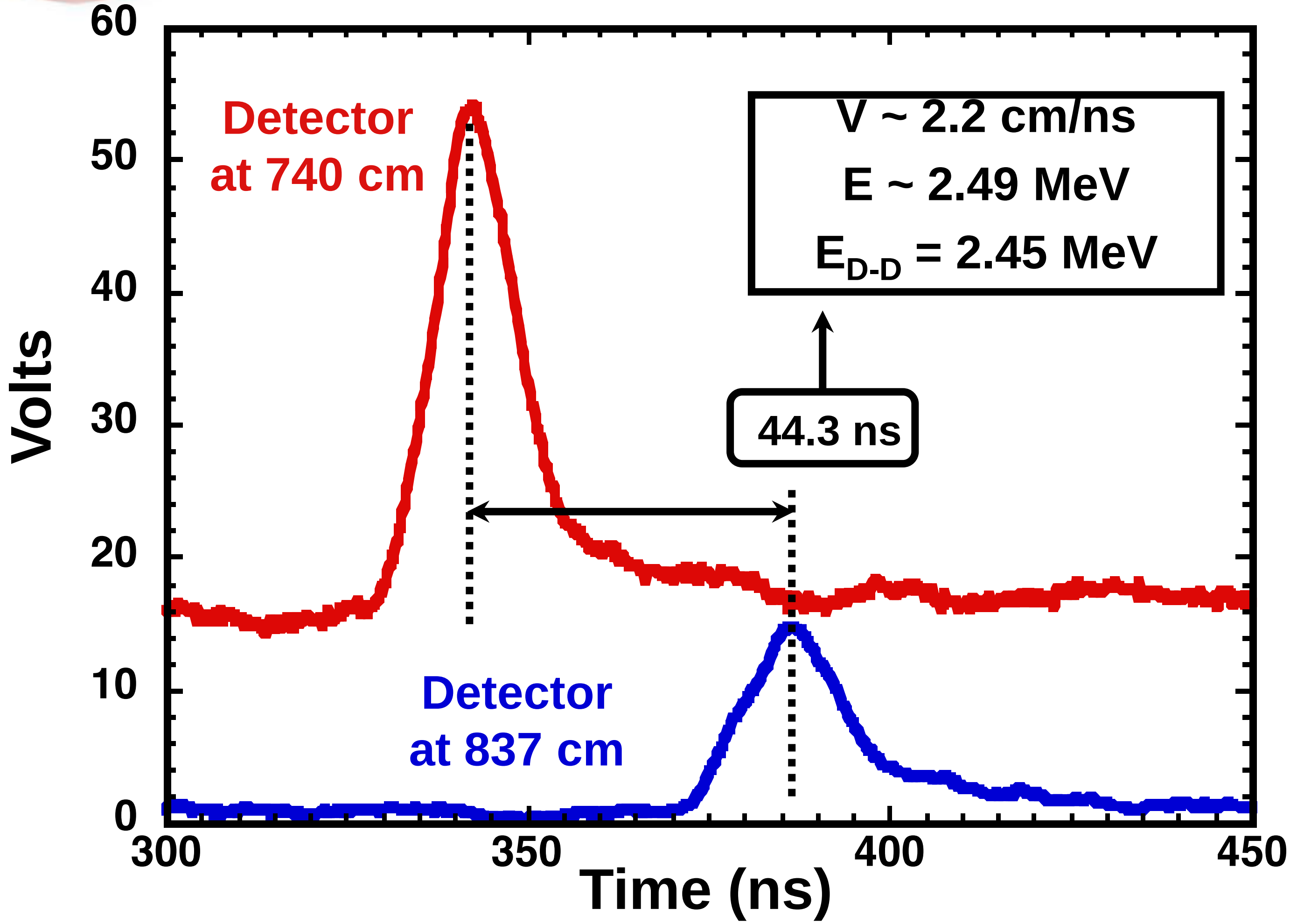


Sandia National Laboratories

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

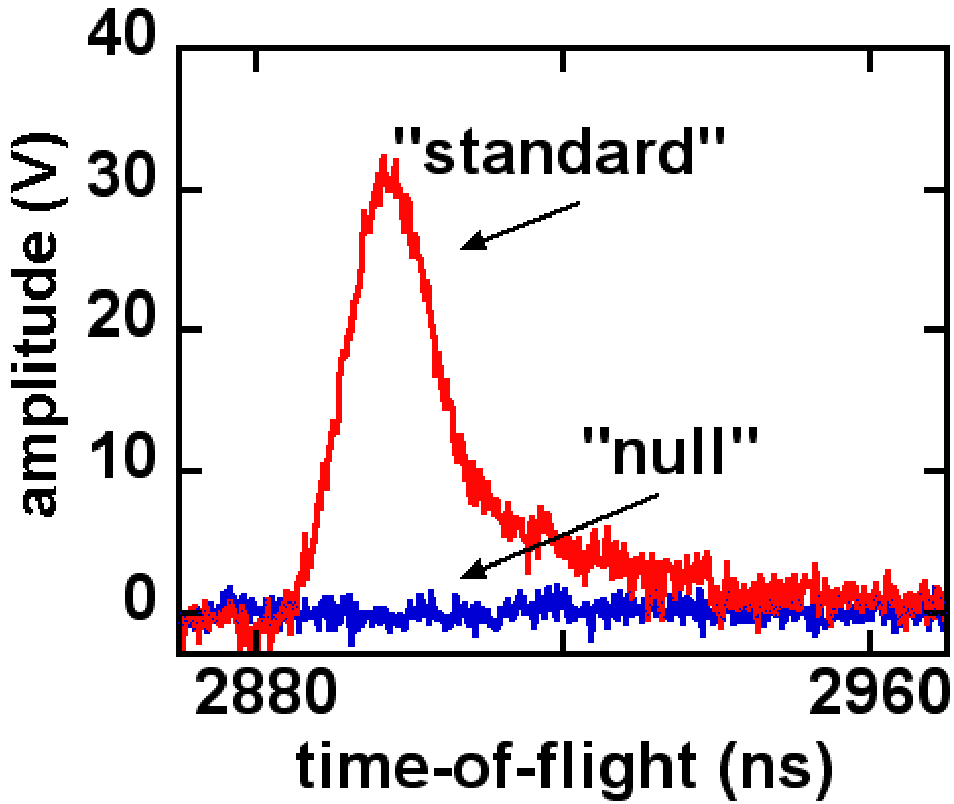


Side-on neutron time-of-flight data showing the detection of DD neutrons on a Be capsule shot



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

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



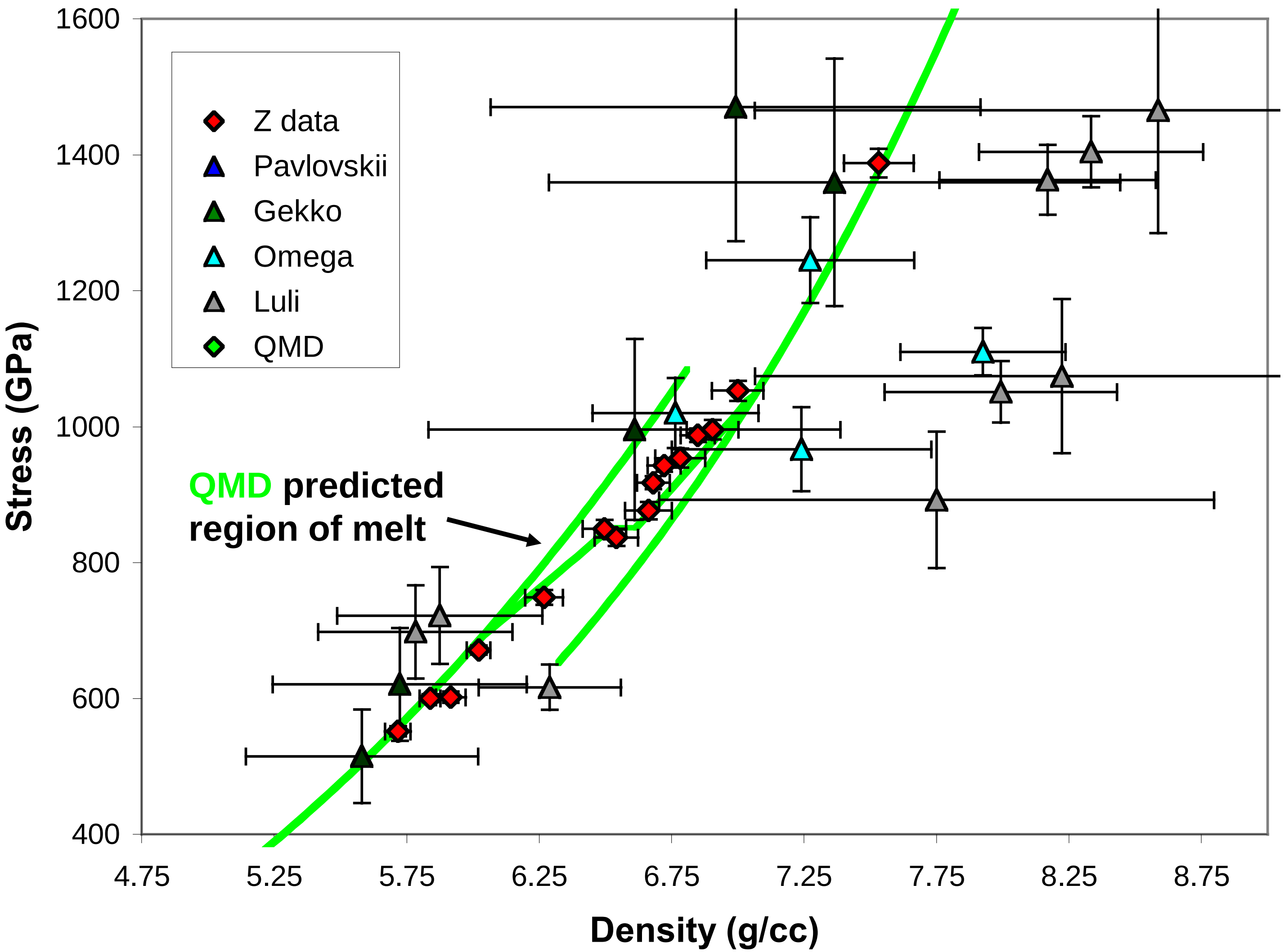
C. L. Ruiz et al., Phys. Rev. Lett. 93, 015001 (2004)
R. J. Leeper et al., J. Phys. IV 133, 175 (2006)

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

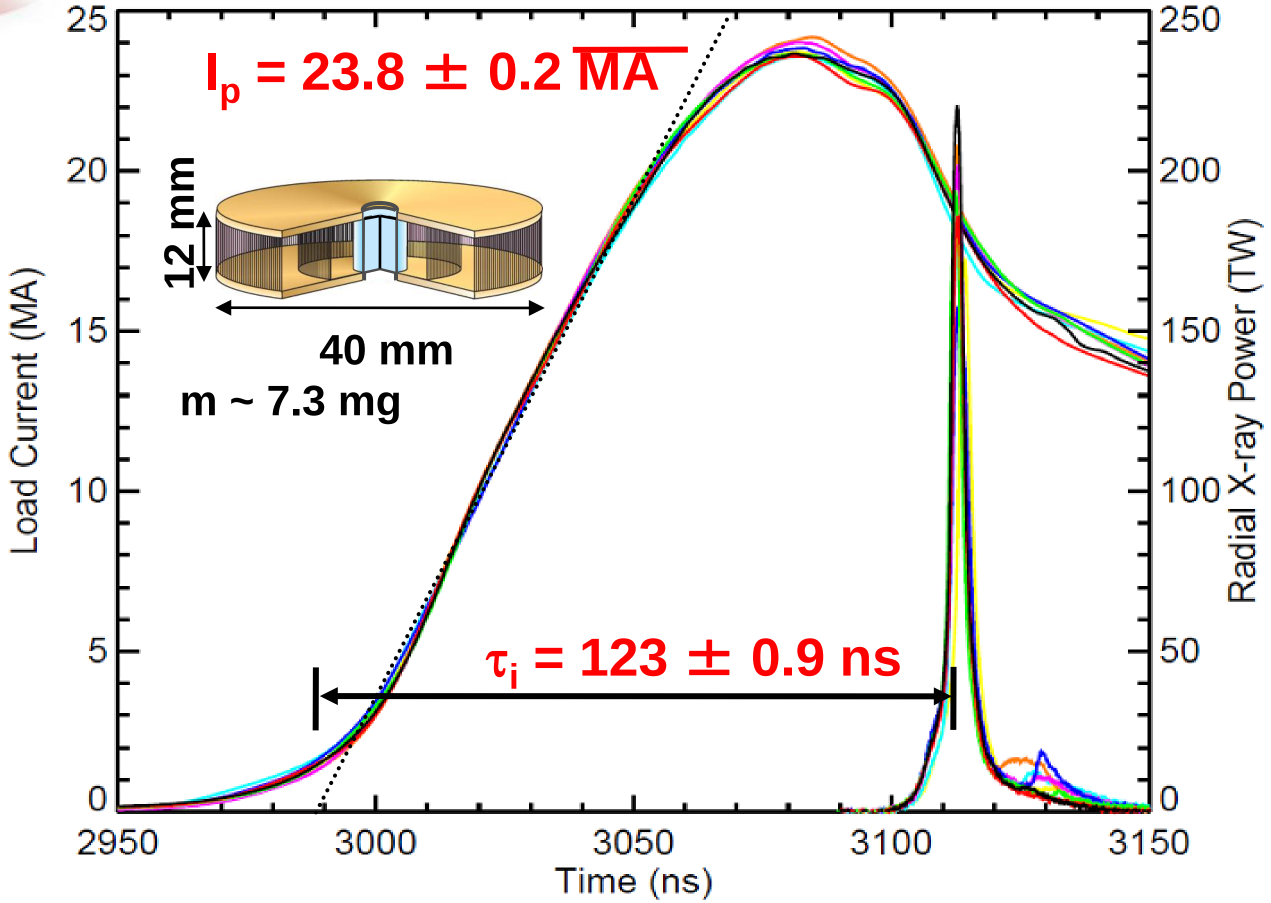
Z answered important questions about the properties of diamond at high pressure

stress versus density for diamond



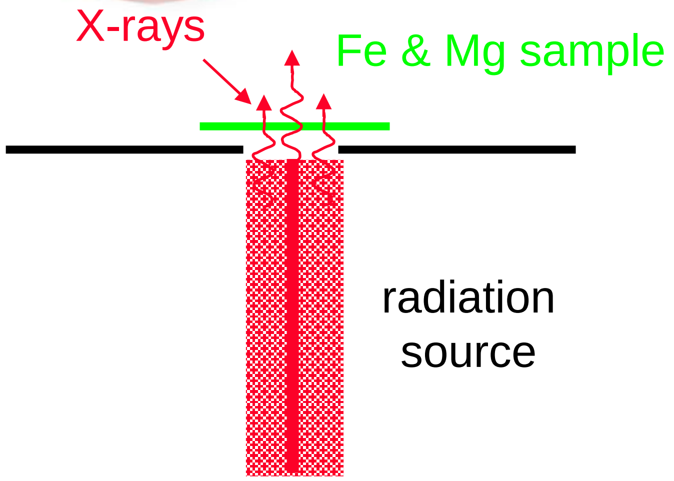
- **The Z data was obtained in 1 week**
- **Measurements on Z have a accuracy of ≤ 1%**

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

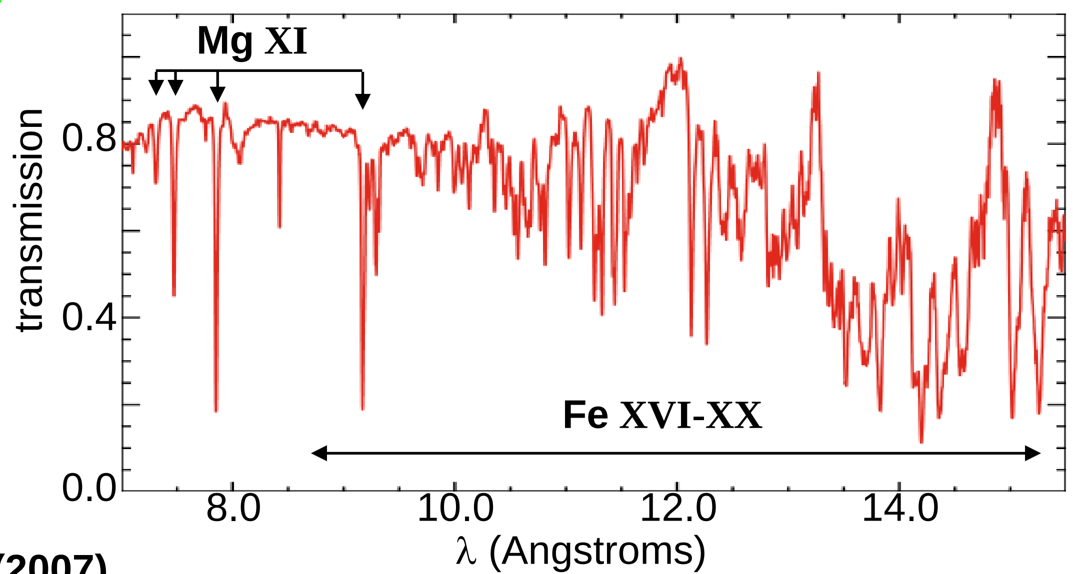


This reproducible, bright (~200 TW) source is ideal for opacity experiments

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



Fe + Mg at T_e ~ 156 eV, n_e ~ 6.9x10^{21} cm^{-3}

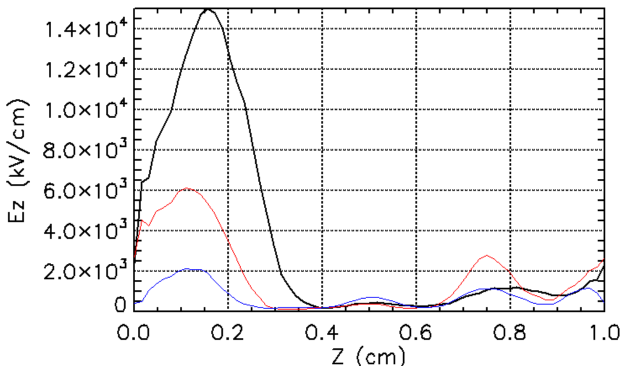


J.E. Bailey et al., PRL 99, 265002 (2007)

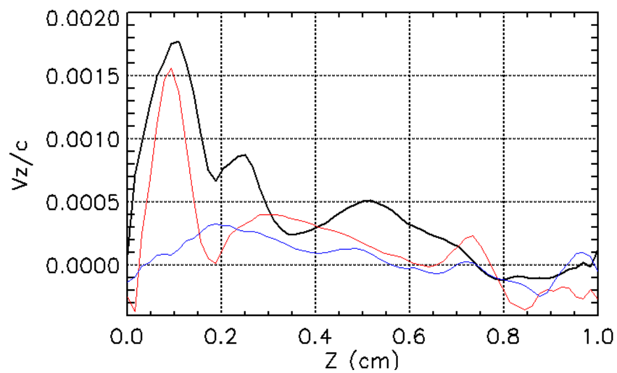
- **Mg is the “thermometer”, Fe is the test element**

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

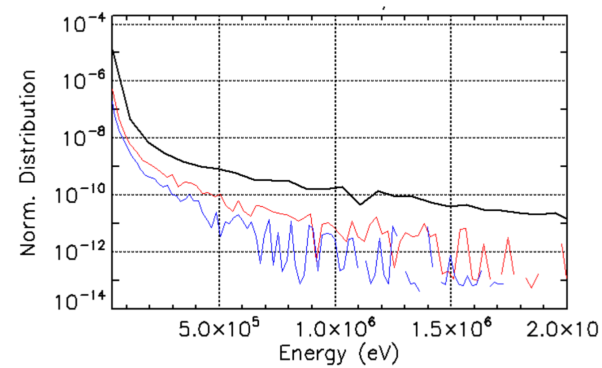
105 ns 110 ns 115 ns



Average E_z within 1.5 cm radius



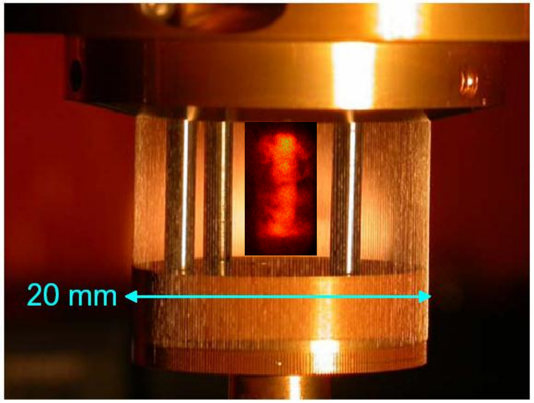
Average ion V_z within 1.5 cm radius



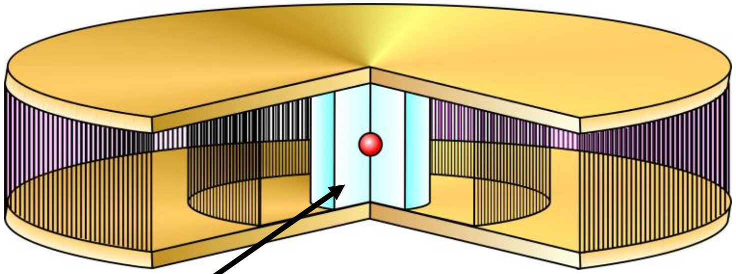
Deuterium energy distribution

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)

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



Dynamic Hohlraum

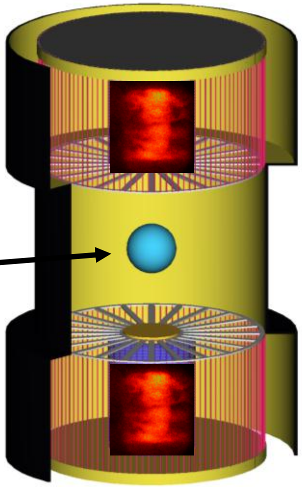


Where do we put the capsule?

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

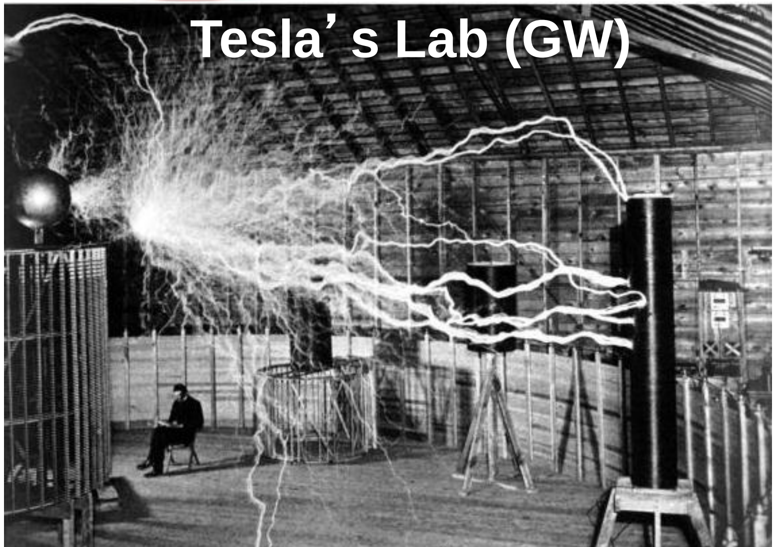
We need high uniformity (~1%) in x-rays the capsule sees for symmetry
-> hide the capsule from the pinch

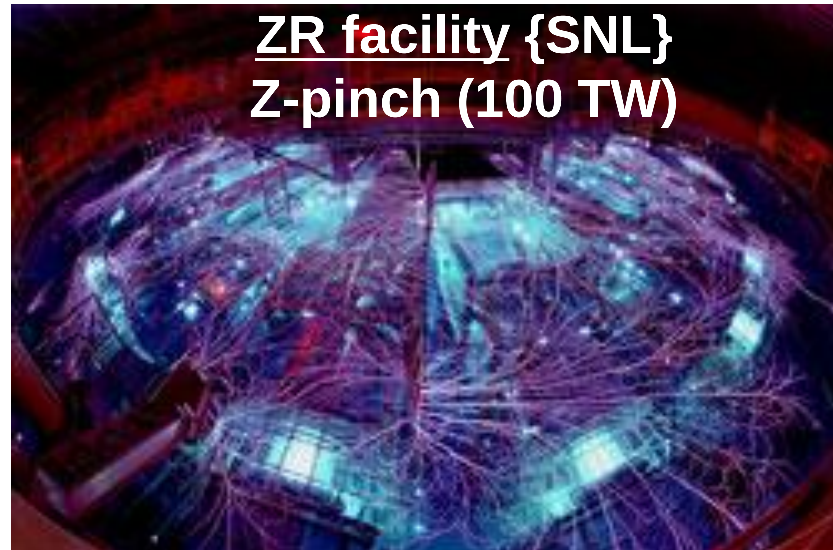
Double-Ended Hohlraum



This approach is the most conservative

Pulsed power has been investigated for over a century.





WWII

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

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

1900 1920 1940 1960 1980 2000

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

Angara - II {Russia}
Simulator (TW)

DARHT {LANL}
Radiography (10 GW)

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