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Progress in High-Energy-Density Physics and Pulsed-Power ICF on the Refurbished Z Facility

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representing the Pulsed Power Sciences Center
Sandia National Laboratories

Many people contributed to this talk

Thanks to:

M.E. Cuneo, S. A. Slutz, J. E. Bailey, M.D. Knudson, M.P. Desjarlais, R. W. Lemke, R. A. Vesey, W. A. Stygar, D.B. Sinars, M. Jones, K. Peterson, T. A. Mehlhorn, M.K. Matzen, D. B. Sinars, D. Rovang, D. L. Hanson, C. Jennings, B. J. Jones, D. Ampleford, C. A. Coverdale, R. McBride, G. A. Rochau, J. E. Bailey, T. J. Nash, M. R. Lopez, P. VanDevender, T. Nash, J. L. Porter, E. M. Waisman, A. Sefkow and the Z and ZBL Team

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**
- **Higher currents are enabling brighter x-ray sources and hotter and denser plasmas for opacity research**
- **Magnetized concepts for pulsed power inertial confinement fusion look interesting**
- **We are working to grow a fundamental science effort on the refurbished Z**

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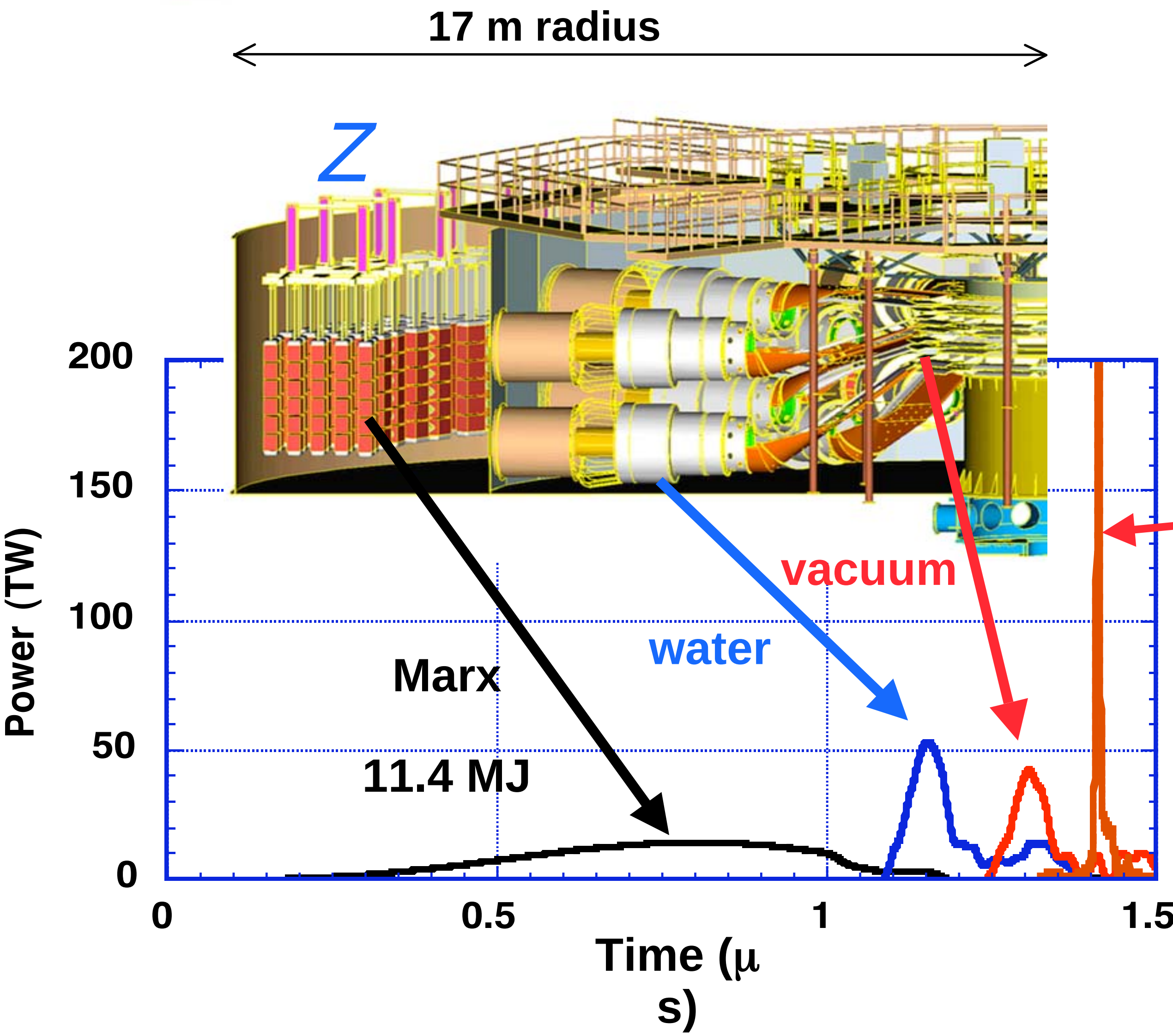
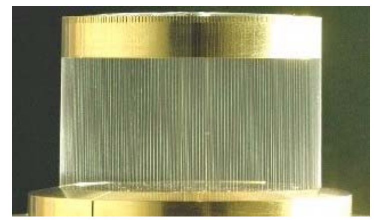
Z provided compact, efficient, power amplification



wire array implosion

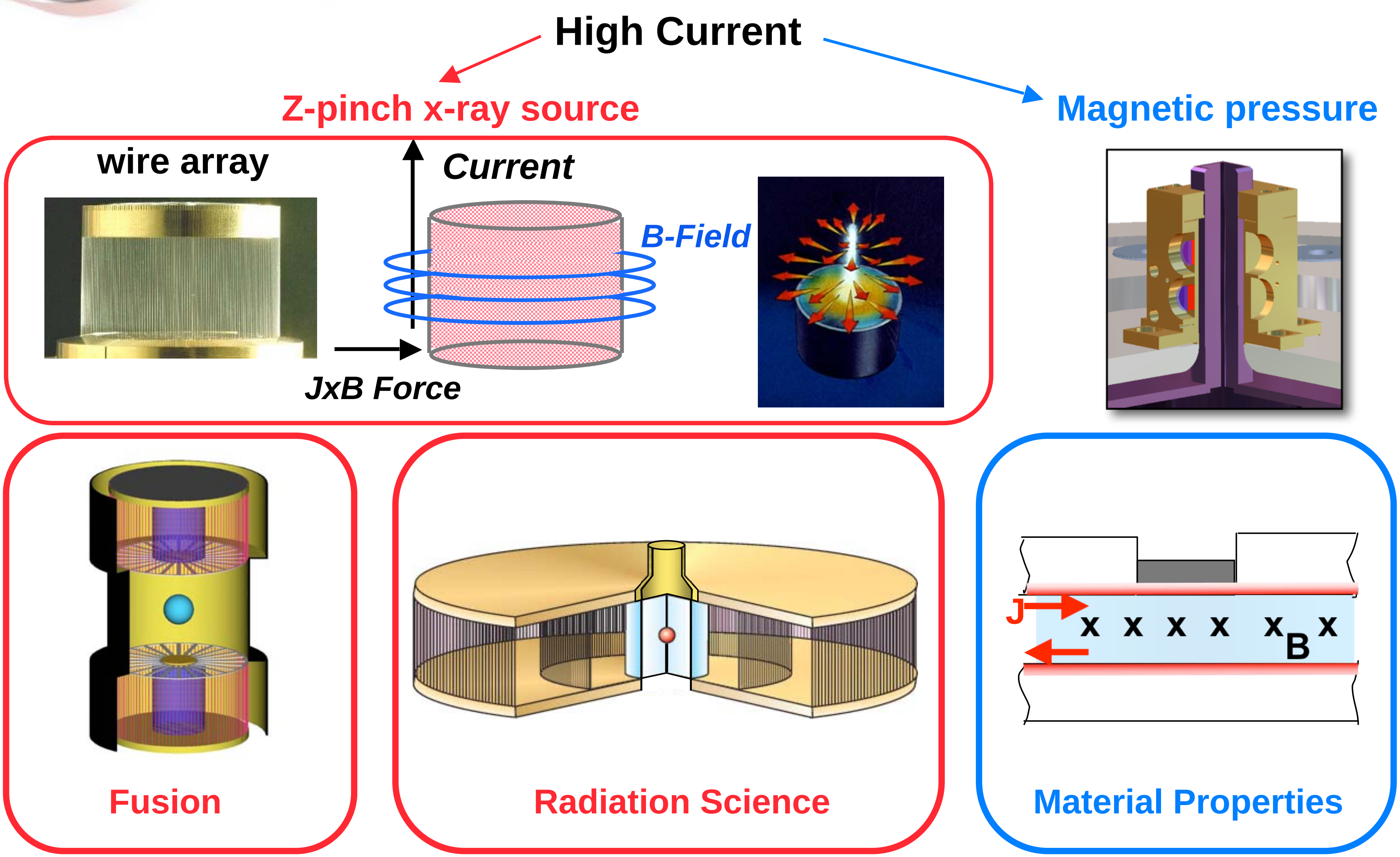


x ray output
~1.6 MJ
~200 TW

Electrical to x-ray energy
Conversion efficiency ~ 15%

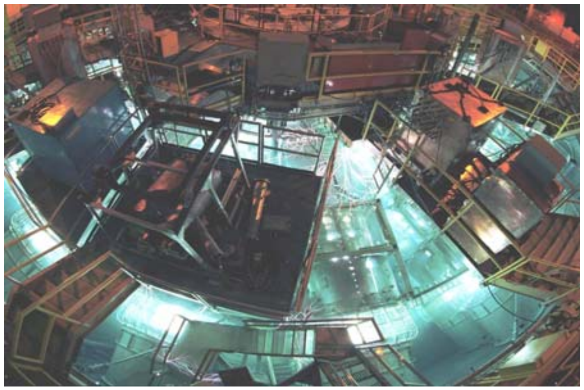
Efficiency ⇒ Low Cost

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



The five-year Z-Refurbishment project has been completed

Last Shot



July '06

Demolition Completed

Sept '06

Tank Modifications Completed

Jan '07

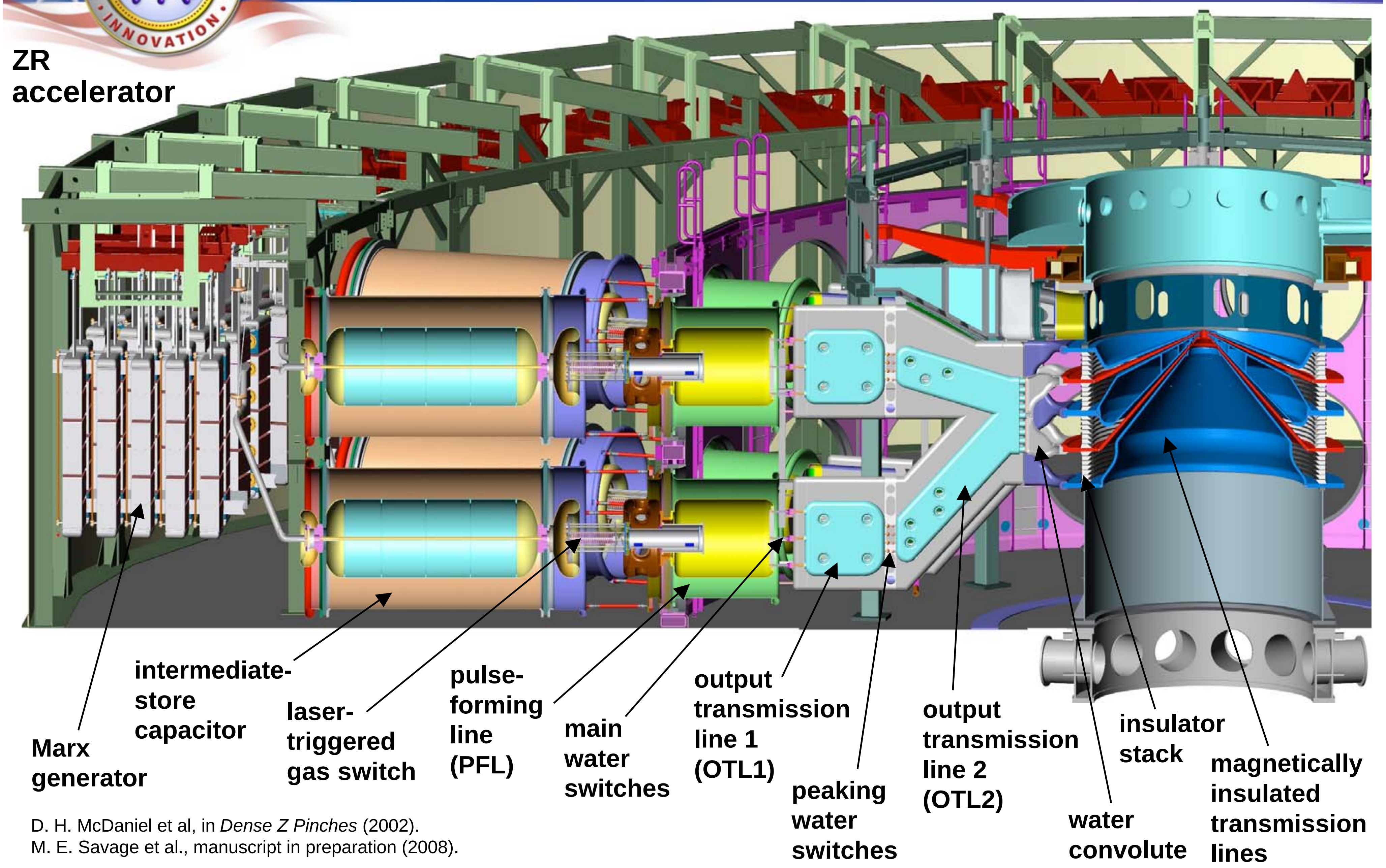
Installation Underway – Multiple Contractors

March '07

Installation Completed

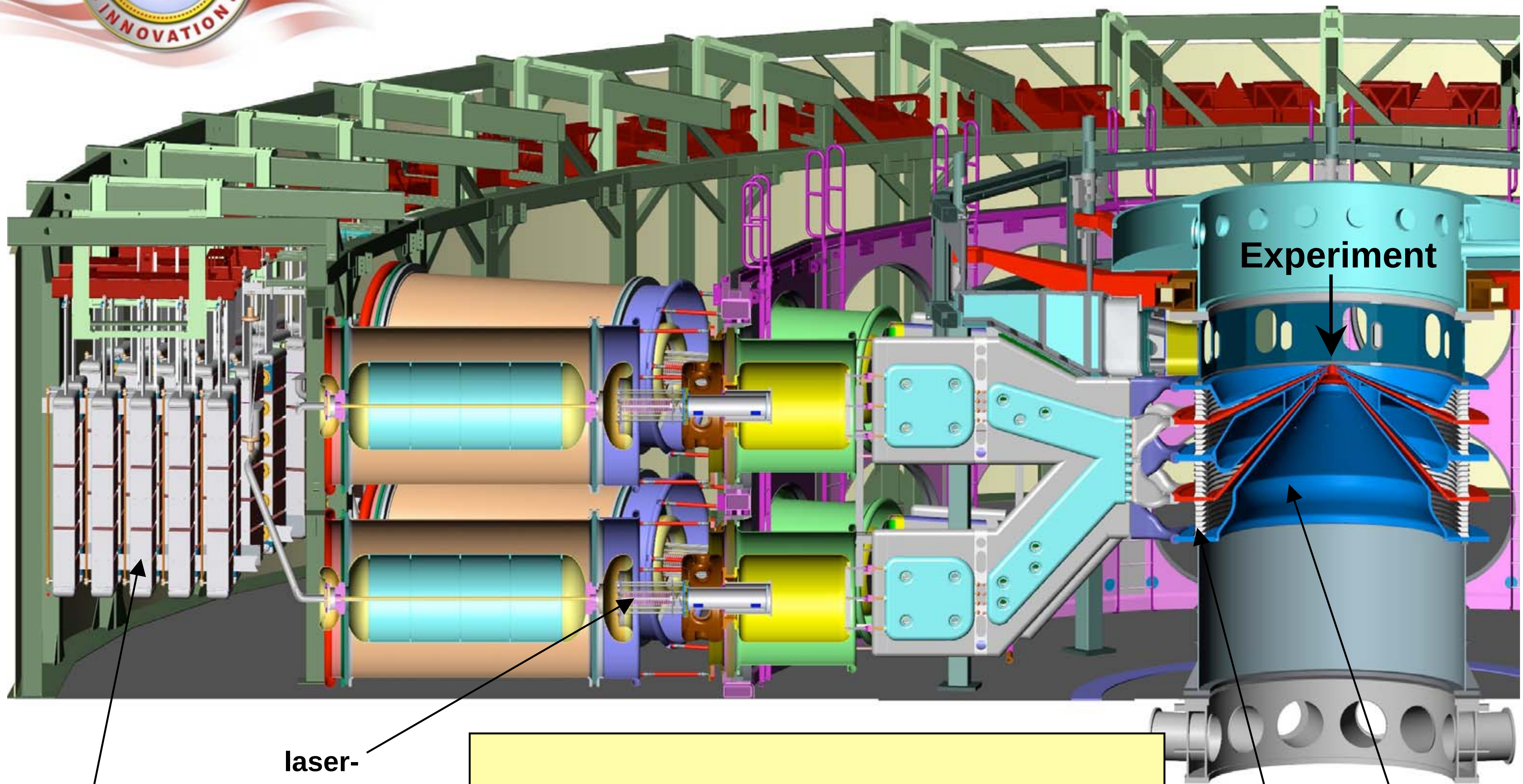
August '07

Everything inside the tank wall was replaced during the refurbishment



D. H. McDaniel et al, in *Dense Z Pinches* (2002).
M. E. Savage et al., manuscript in preparation (2008).

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

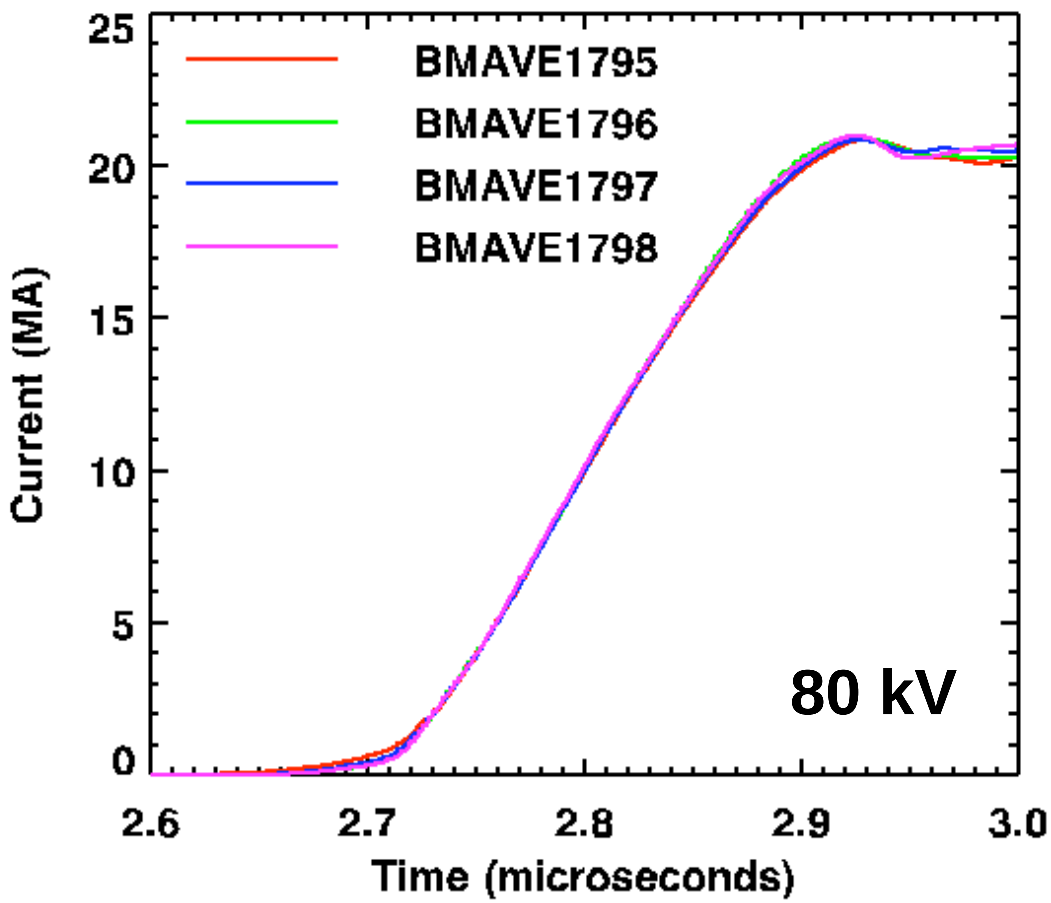


22 MJ stored energy (up from 11 MJ)

~26 MA peak current (~18MA)

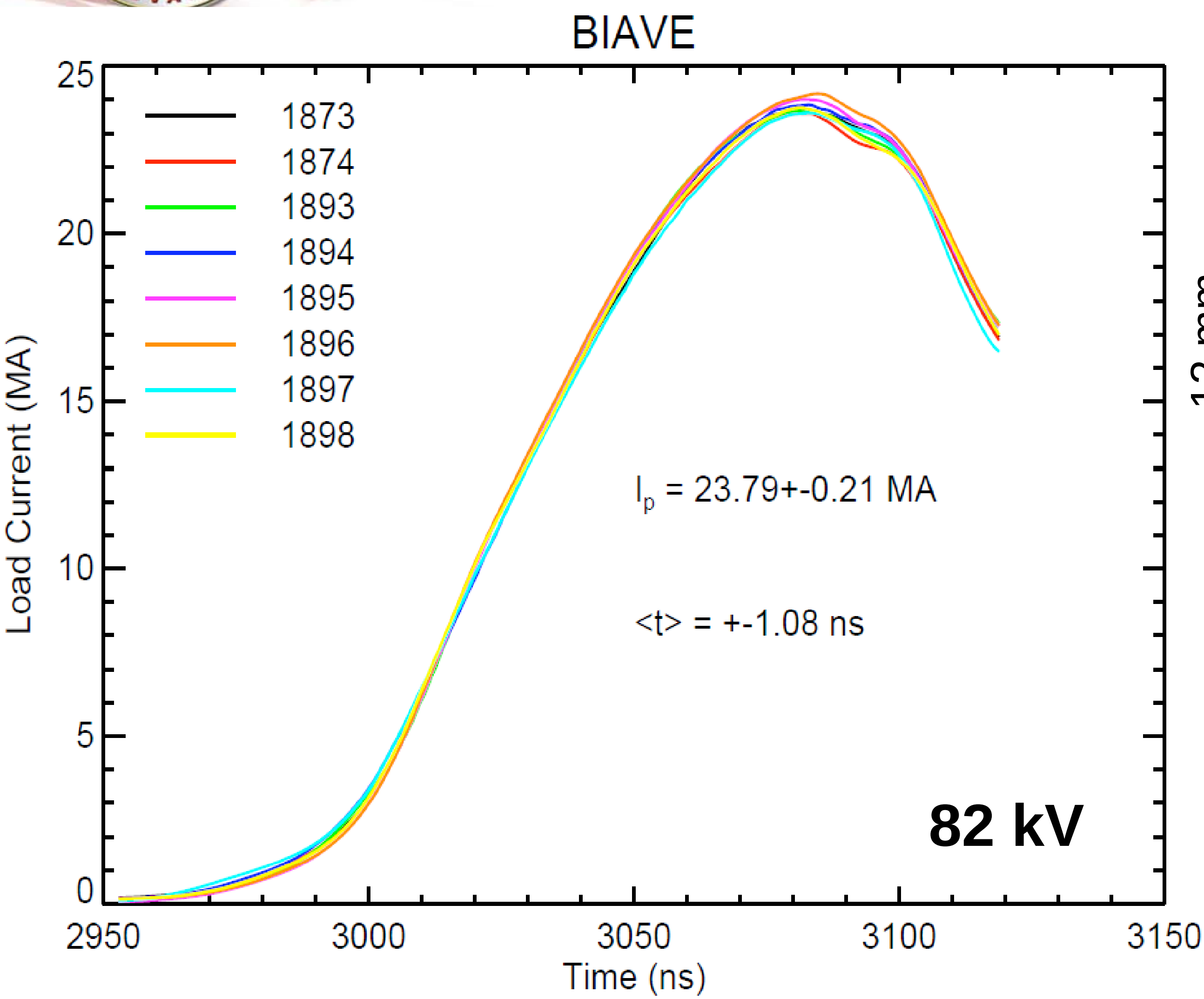
~100-600 ns rise time

Long pulse experimental currents are highly reproducible

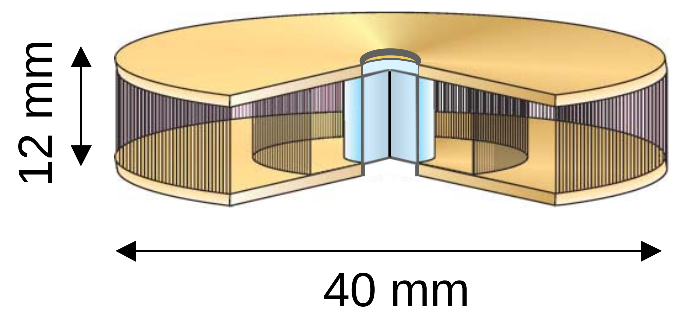


- Pulse lengths of up to 300 ns are possible
- Long pulse capability used for dynamic materials experiments

We delivered 24 MA to a Dynamic Hohlraum and the current and implosion time were reproducible to 1% over 8 experiments



Z-pinch Dynamic Hohlraum



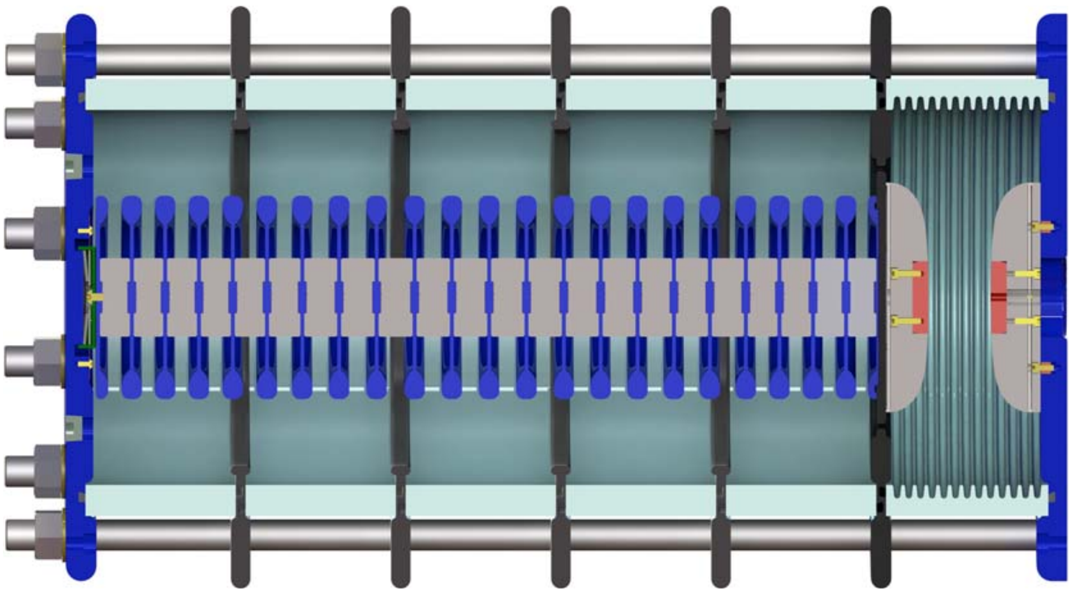
- 240 outer W wires
- 120 inner W wires
- Total W mass ~ 6.7 mg
- Initial Load Inductance ~ 2.7 nH

~1.6% is the published random uncertainty in these load Bdot measurements

J. Bailey, G. Rochau, T. Nash et al., manuscript in preparation (2009).

Over the last 1.5 years we have significantly improved the gas switch

performance parameter	original ZR gas switch (5 - 6 MV)	ZR-A-5 gas switch (5 - 6 MV)
prefire rate	7%	0.1%
jitter	13 ns	5 ns
flashover rate	5%	0.1%
replacement interval	10 shots	60 shots



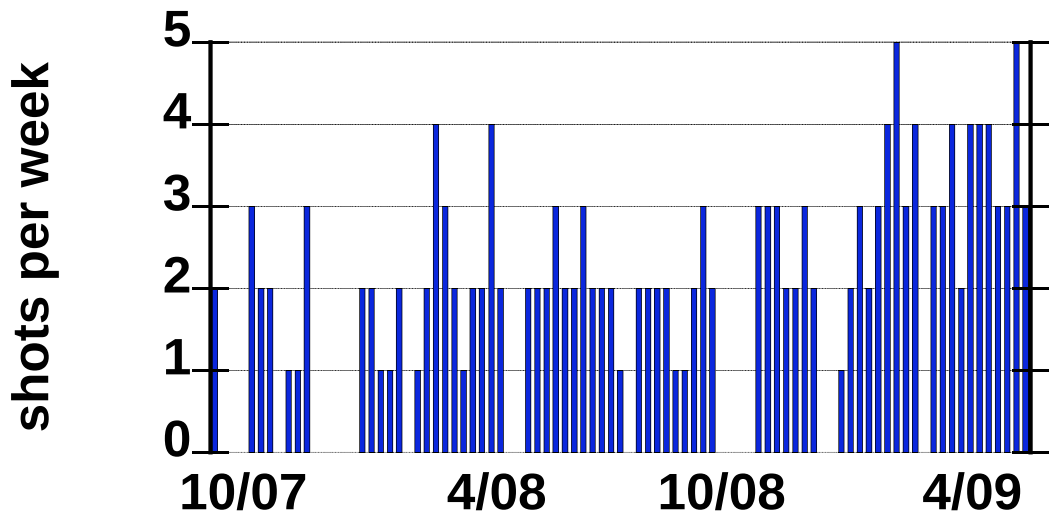
ZR-A-5 laser-triggered gas switch

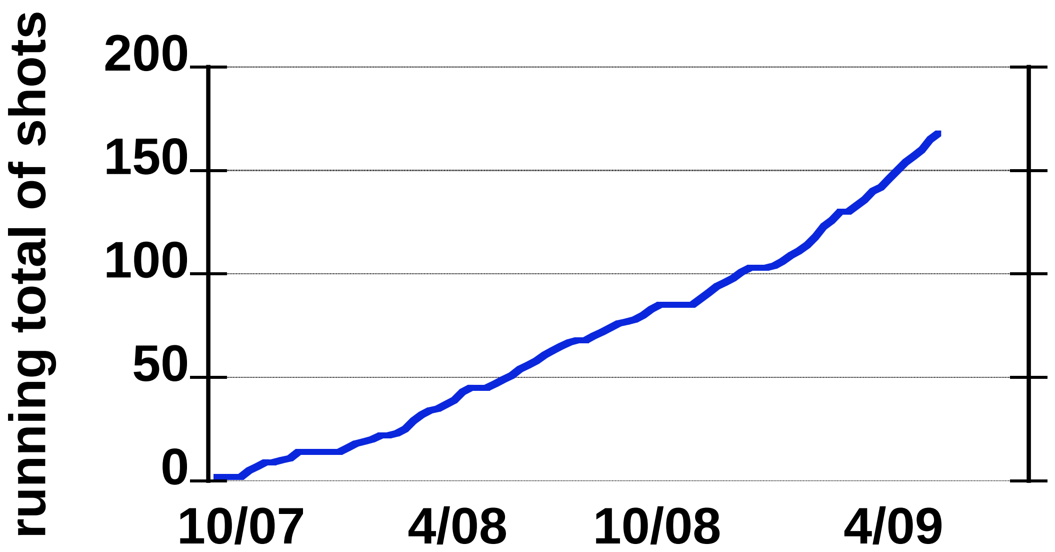
We have recently demonstrated 30 consecutive ZR shots (i.e., 1080 switch shots) without a single switch failure.

K. R. LeChien, M. E. Savage et al., Phys. Rev. ST Accel. Beams **11**, 060402 (2008).
K. R. LeChien, W. A. Stygar et al., manuscript in preparation (2009).

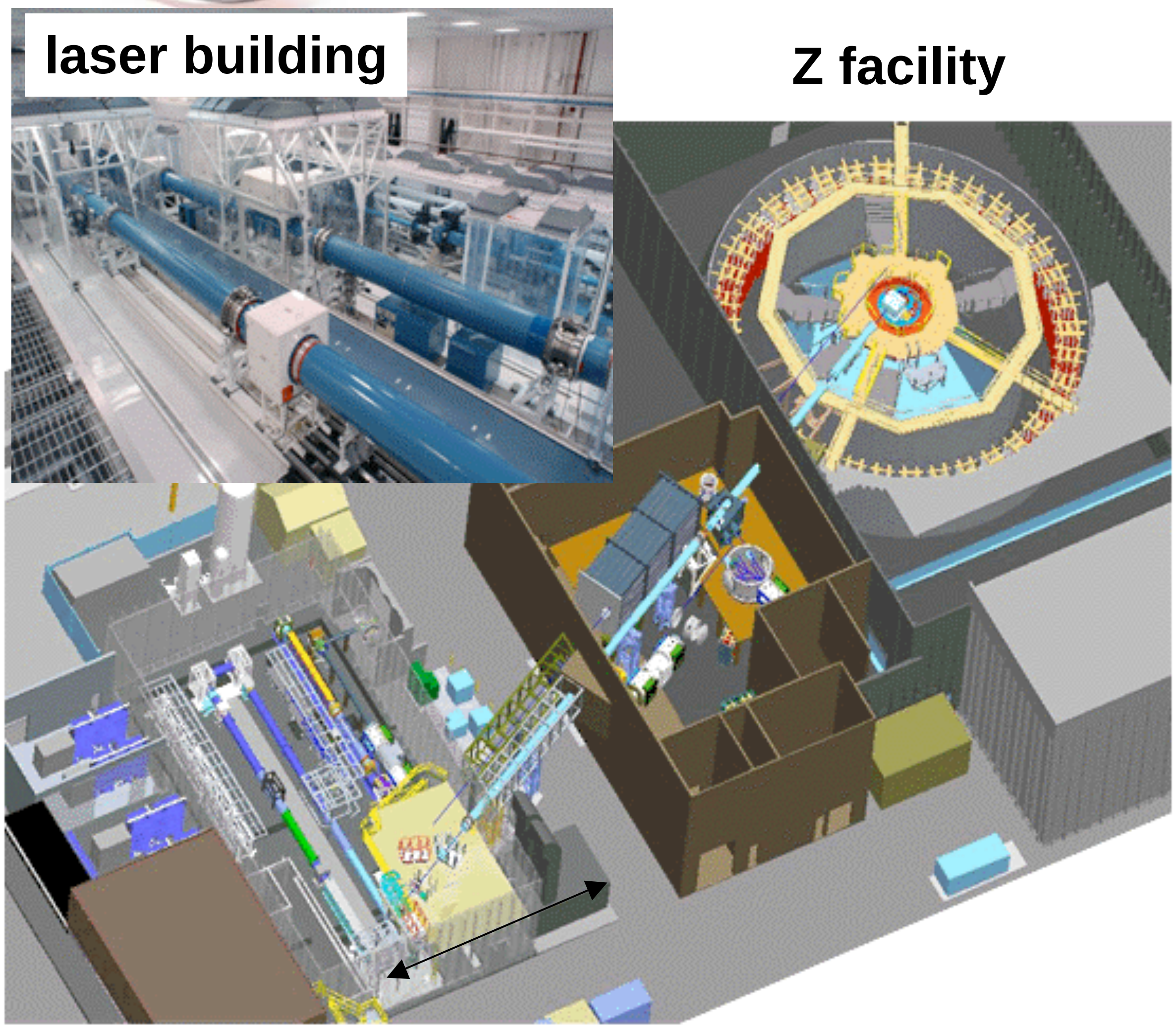
The shot rate on ZR continues to improve as we optimize the performance and reliability of the new accelerator systems

- **Improvements in accelerator reliability and operations efficiency are enabling us to steadily increase the shot rate.**
- **The first shot on ZR occurred in September 2007.**
- **We completed 81 shots in FY2008.**
- **We have completed 85 shots to date in FY2009 (73% more than during the same period last year).**
- **We are on track to perform 50 shots in Q4 FY2009.**



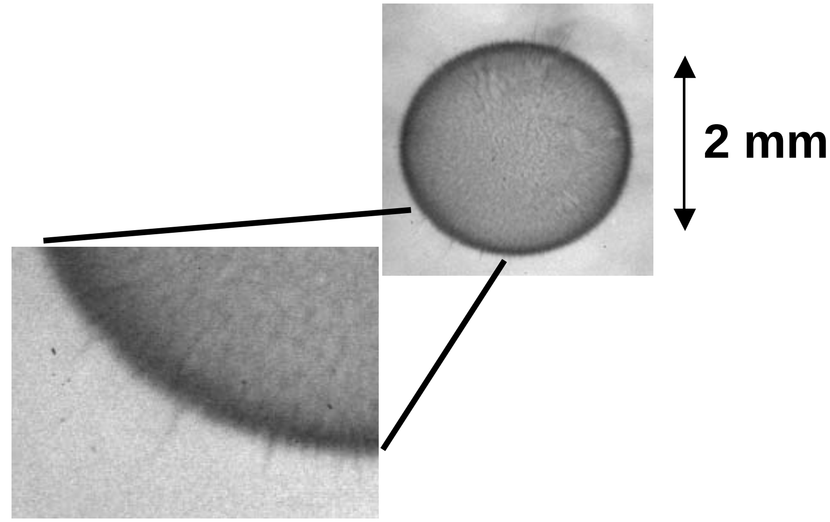


The Z-Beamlet and Z-Petawatt laser backlighters provide a powerful new capability for diagnosing Z experiments

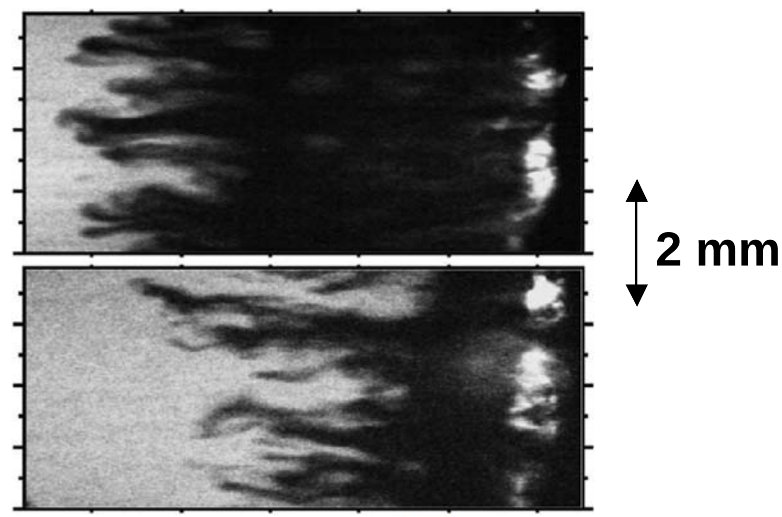


Z-Beamlet and Z-Petawatt lasers

imploding capsule



imploding z-pinch



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Magnetically-driven systems reach high energy density (1MB) at 5 Megagauss

The magnetic field acts like a pressure in the momentum equation:

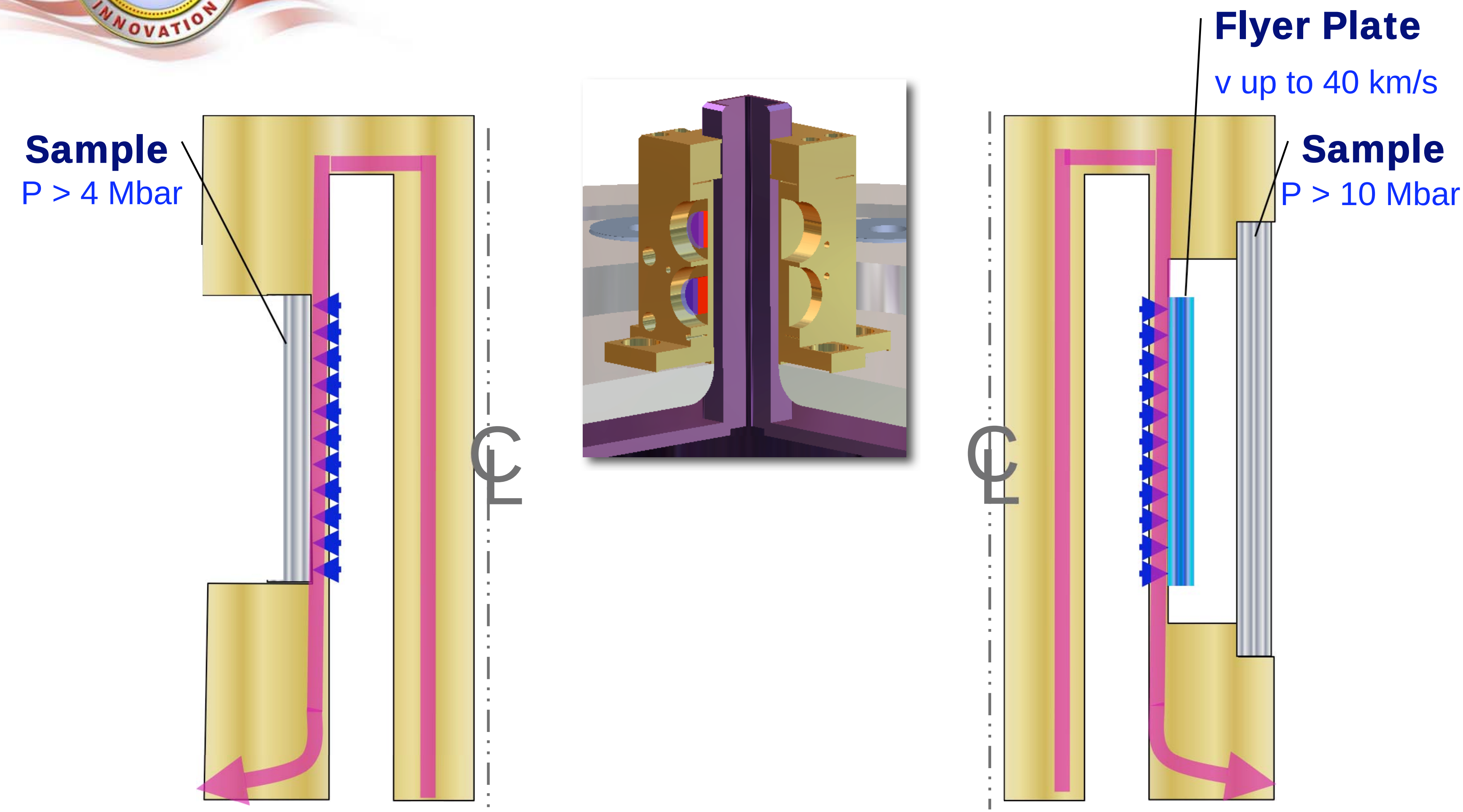
$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u}\right) = \frac{\mathbf{J}\times\mathbf{B}}{c} - \nabla P = \frac{1}{4\pi}\mathbf{B}\bullet\nabla\mathbf{B} - \nabla\left(P + \frac{B^2}{8\pi}\right)$$

For cylindrically symmetric Zpinches this term is zero

A 5 Megagauss (500 T) magnetic field applies a pressure of 1 MB to a conductor

A current of 25 MA at 1cm radius is 5 10^6 G= 1 Mbar of pressure

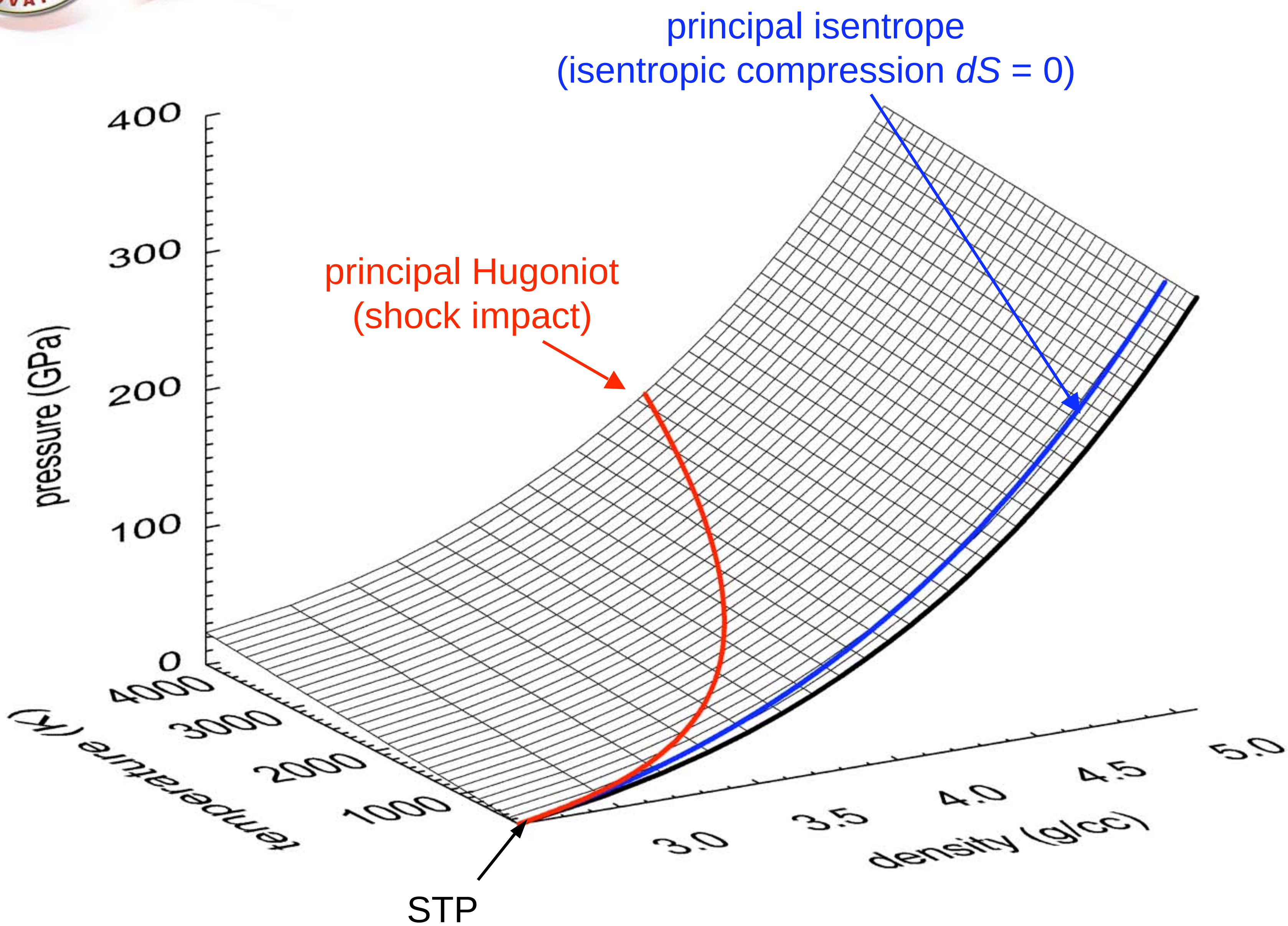
Isentropic compression and shock wave experiments are both possible on Z



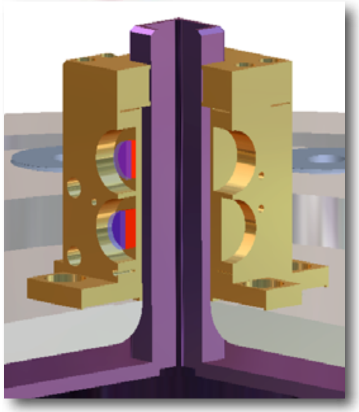
Isentropic Compression Experiments:
gradual pressure rise in sample

Shock Hugoniot Experiments:
shock wave in sample on impact

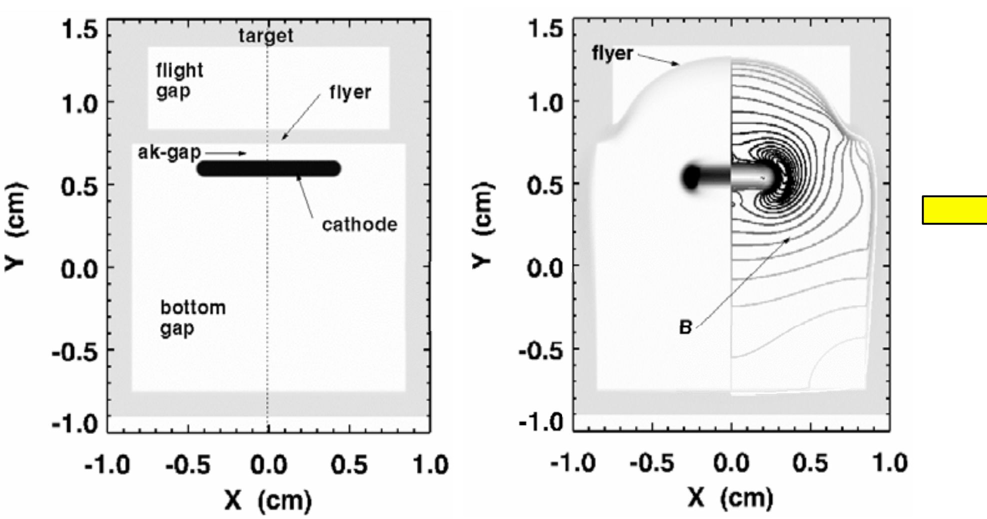
Isentropic compression and shock impact allow us to map out material properties at different densities and temperatures



Our MHD simulation capability is a powerful design tool

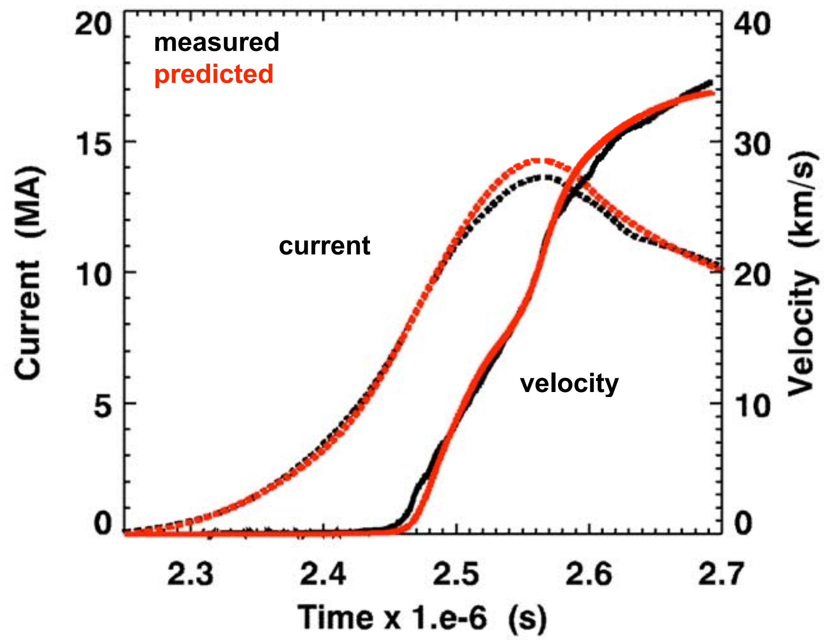


DFT based material models gave us predictive capability
ASC codes enable optimized experiments



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

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

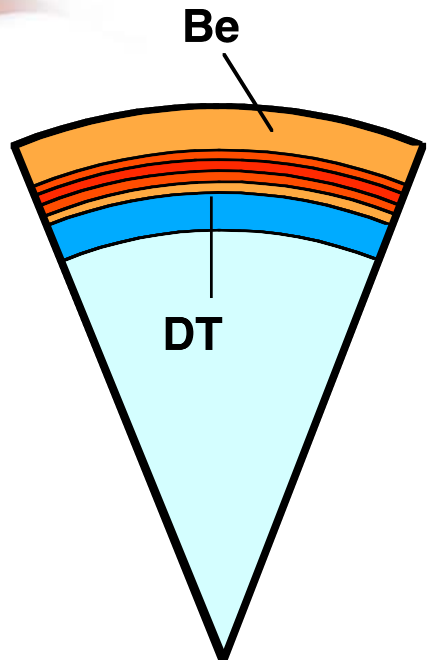


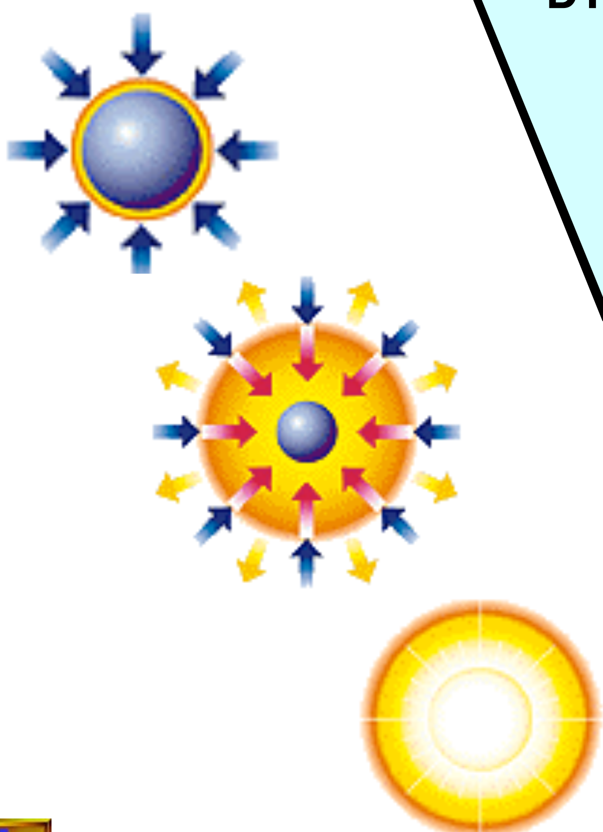
In 2-D, 10^6 elements, 160 CPUs, 4 hours (T-Bird)

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

Sandia was asked to perform melt studies in support of the National Ignition Campaign (NIC)

300 eV graded-doped Be design:

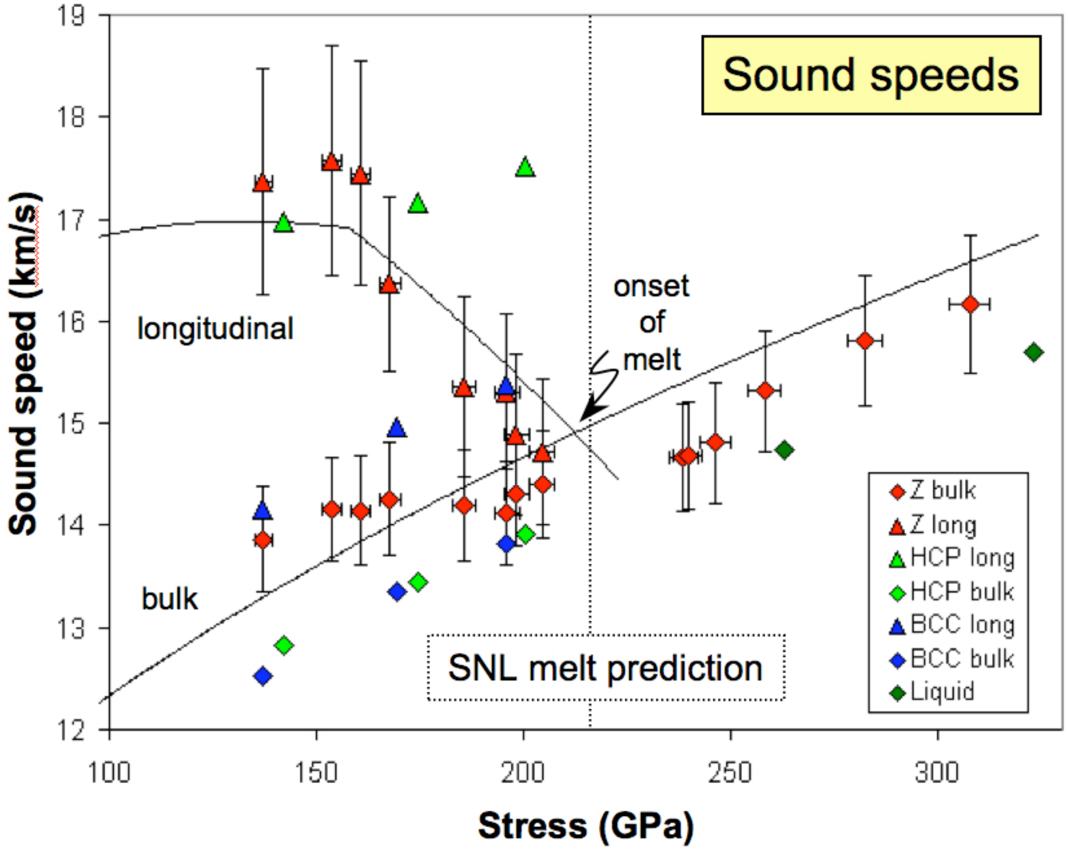


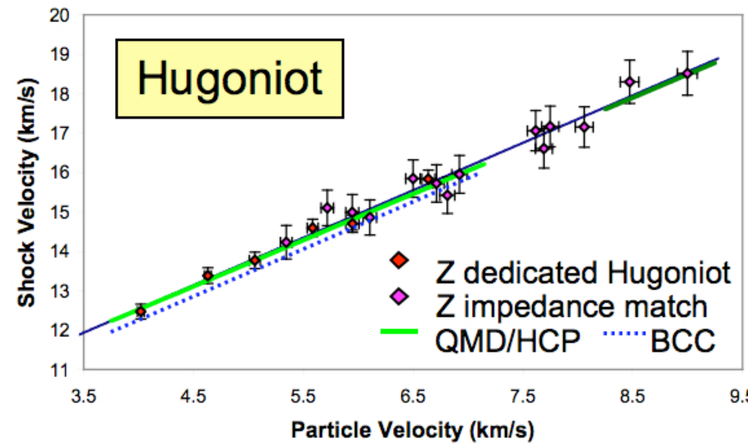


- Beryllium and diamond are being considered as ablator materials for ICF capsules
- Capsule implosion is an inherently unstable process
- Goal is to avoid any heterogeneities that may seed instability growth during implosion
- Detailed knowledge of the equation of state, in particular the melt properties of the ablator material is critical
  - For Beryllium the goal is to melt on the first shock (thus need to know at what shock strength Be melts)
  - For Diamond, melting on first shock would raise entropy of DT too much, must instead melt on the second shock

Beryllium experiments were performed in support of the National Ignition Campaign

NIC question: At what pressure would a Be ablator melt under shock loading?



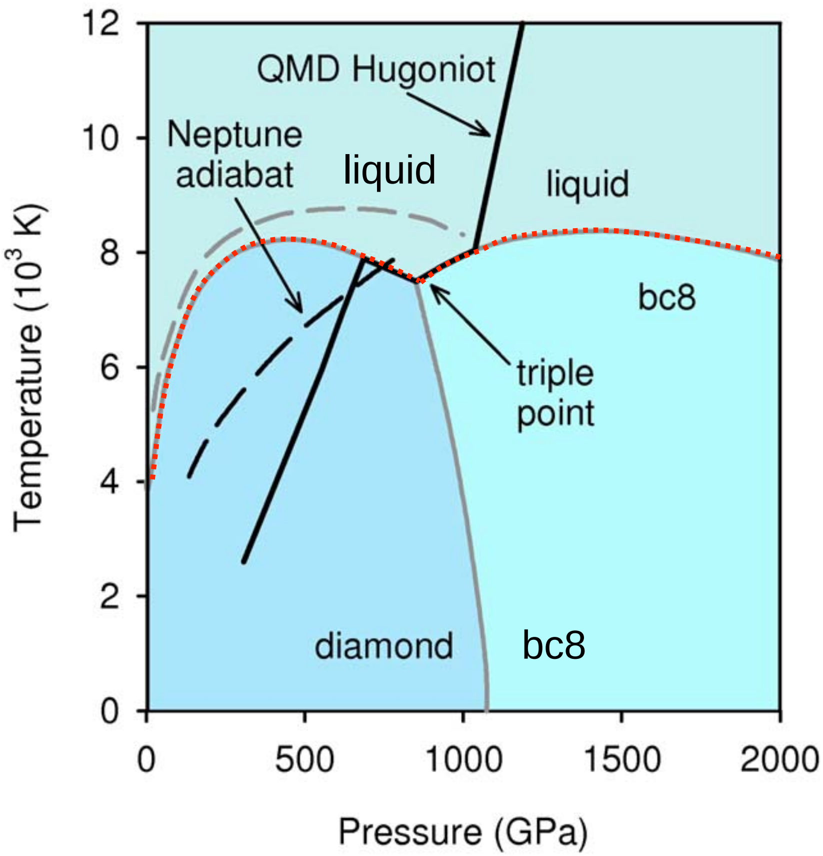


- QMD HCP Hugoniot in better agreement with experiment
- QMD HCP longitudinal sound speed in much better agreement with experiment

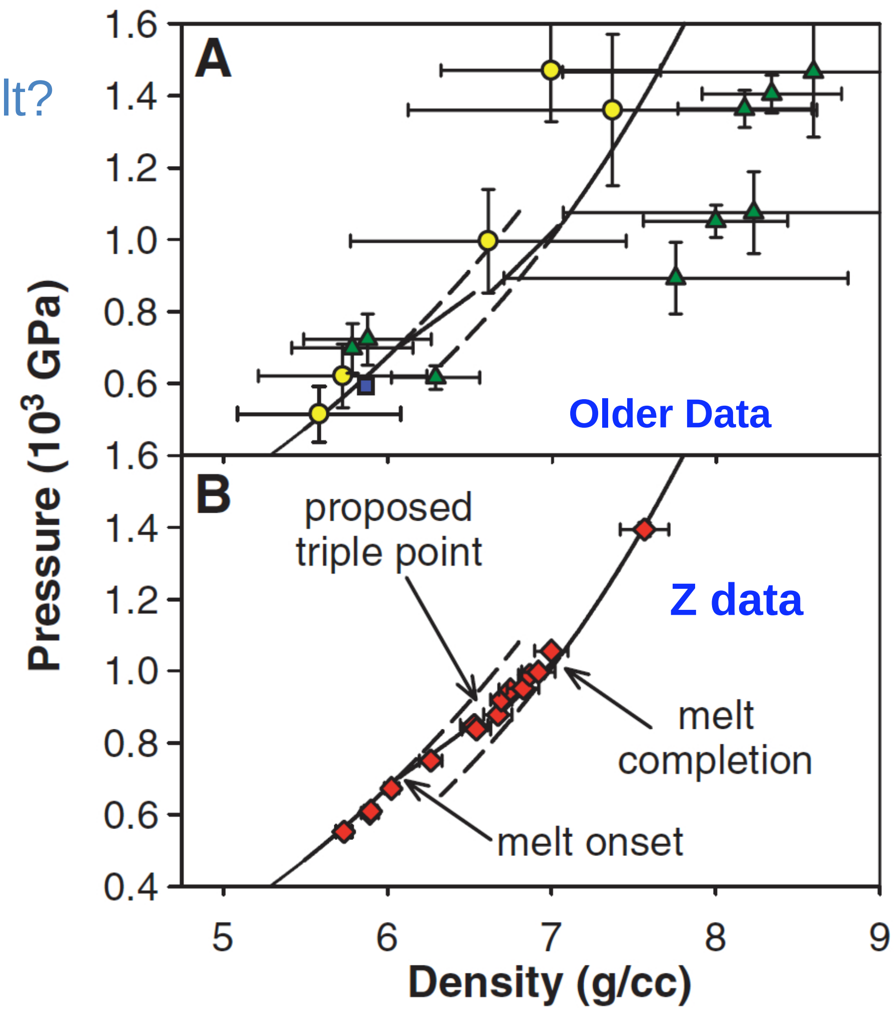
Onset of melt at 210 GPa in good agreement with QMD prediction of 213 GPa

Experiments on Z explored the shock melting of diamond as well

At what shock pressure does diamond melt?

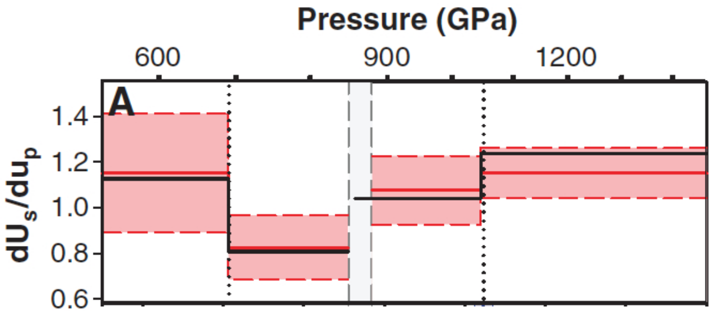


1000 GPa = 10 Mbar

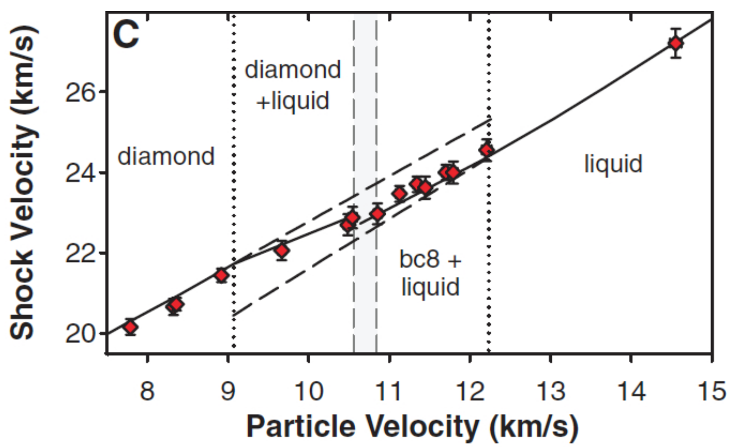


Our Z experiments achieved unprecedented accuracy for shocked diamond

QMD calculations predicted measurable changes in the shock velocity at the phase boundaries



QMD predictions in black
Z data in red



Shock-Wave Exploration of the High-Pressure Phases of Carbon

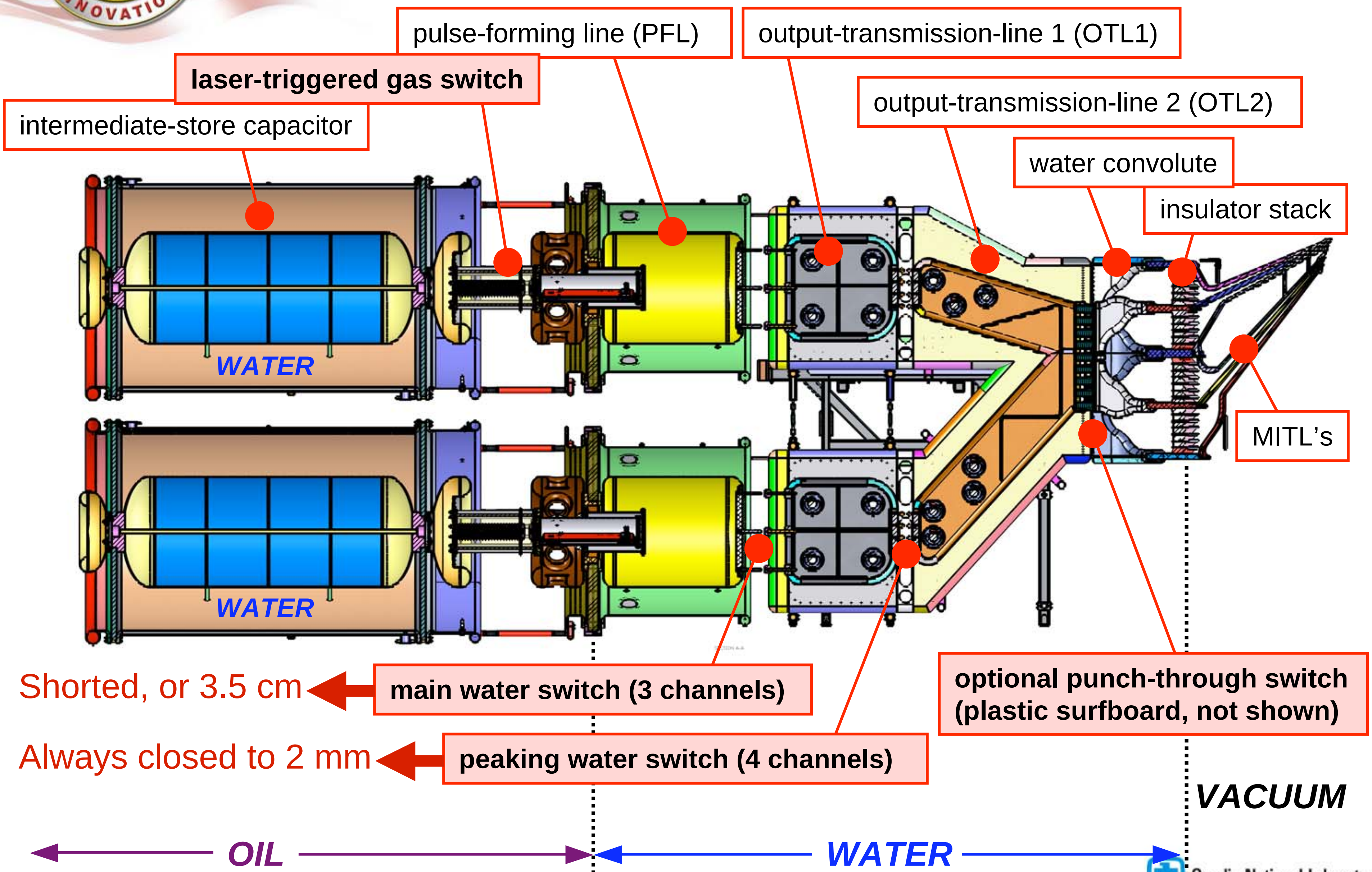
M. D. Knudson,* M. P. Desjarlais, D. H. Dolan

19 DECEMBER 2008 VOL 322 SCIENCE

Melt onset: 6.9 Mbar
Melt completion: 10.4 Mbar
First experimental evidence for BC8 phase in carbon

Impacts ICF and planetary science, validates theory

ZR was designed to enable shaped pulses, which will enable higher velocity flyers and higher pressure ICE



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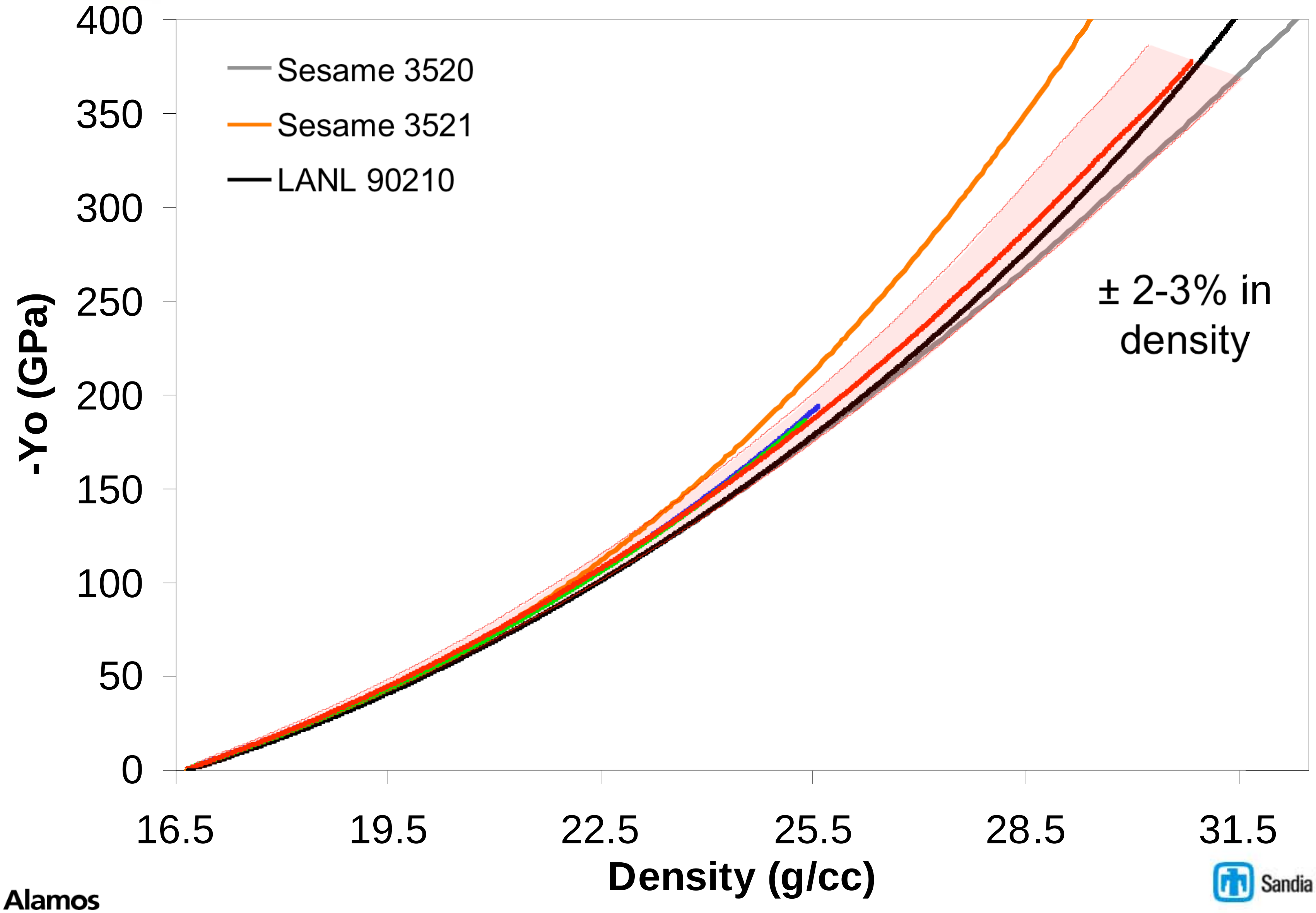
This capability was put to the test in recent experiments studying the isentrope of Ta to 4MB



Los Alamos

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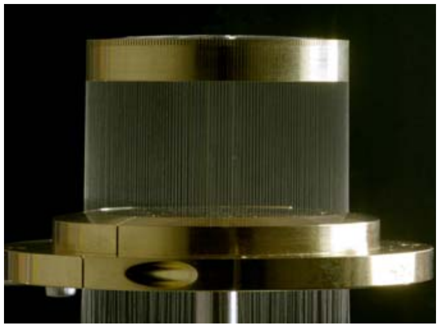
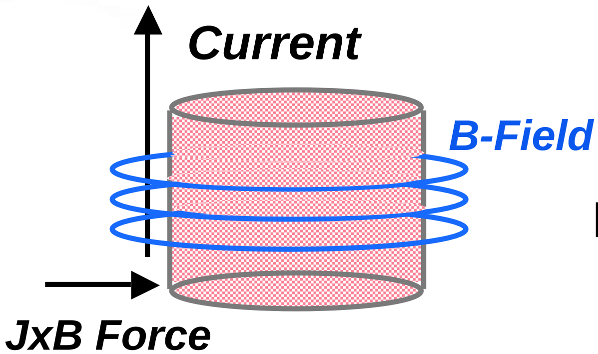
Wire Arrays efficiently convert energy from electrical to radiation

wire array



2 cm



kinetic and electrical energy

↓

internal (shock heating)

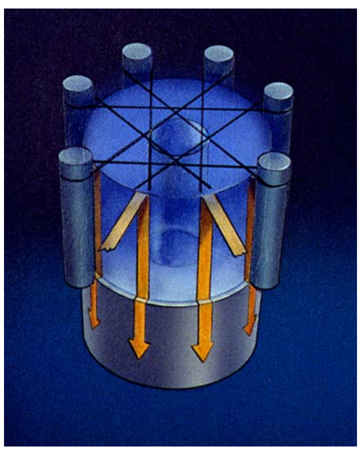
↓

x rays

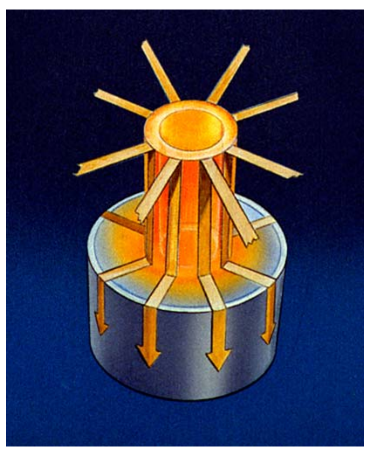
electrical energy

↓

kinetic energy



Initiation



Implosion

Stagnation

Z

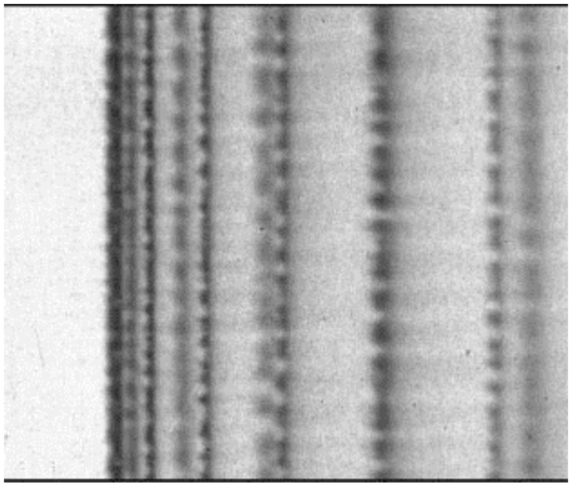
x rays
6 ns
~1.6 MJ
~200 TW

electrical to
x-ray ~15%
efficient

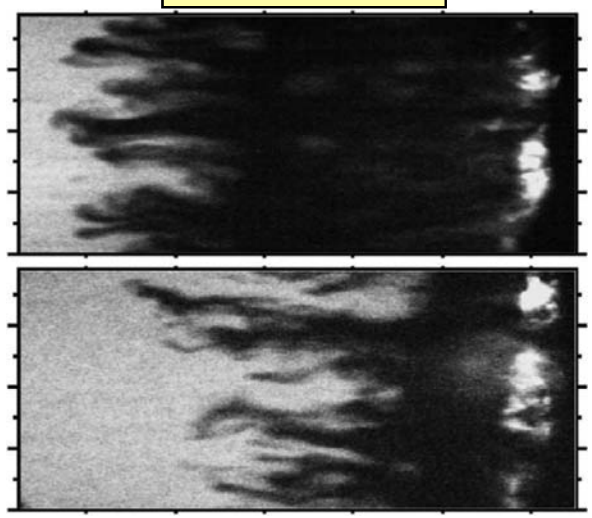
X-ray backlighting has enabled the study of wire array implosions so that we can further optimize them

Tungsten Wire Array implosions radiographed at 6.151 keV

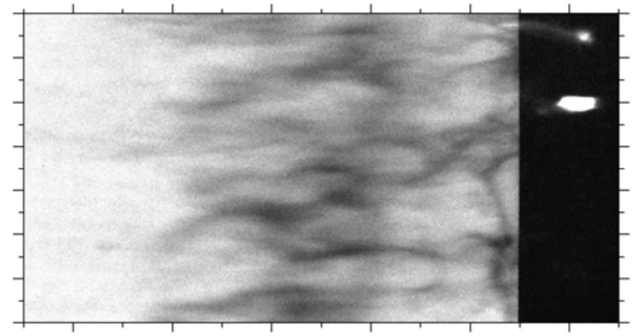
Ablation



Implosion



Stagnation & X-ray production

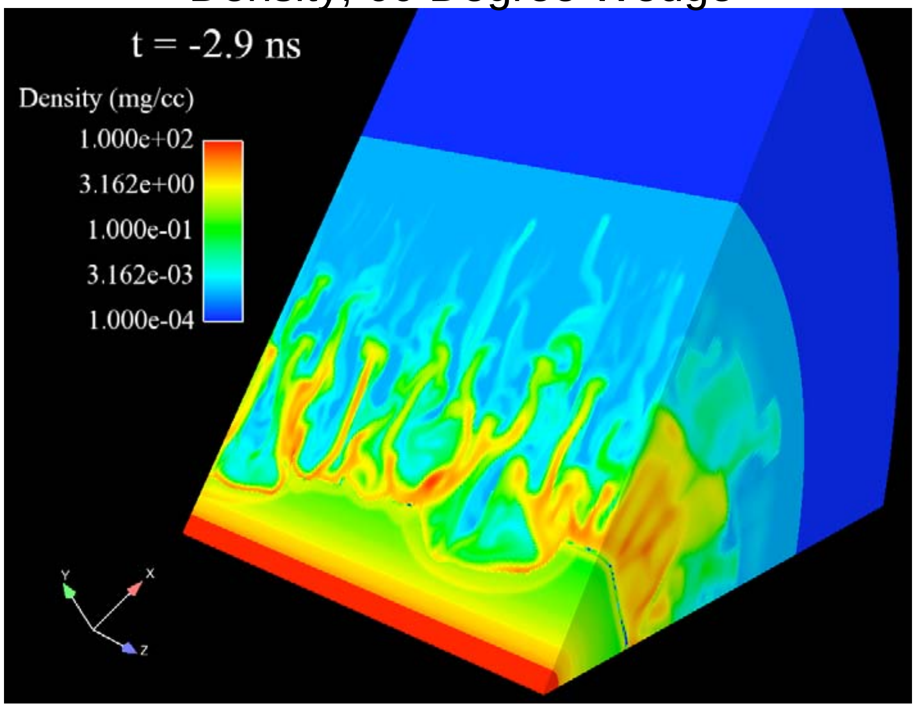


Magnetic Rayleigh-Taylor and other instabilities strongly affect wire array zpinches from the very beginning

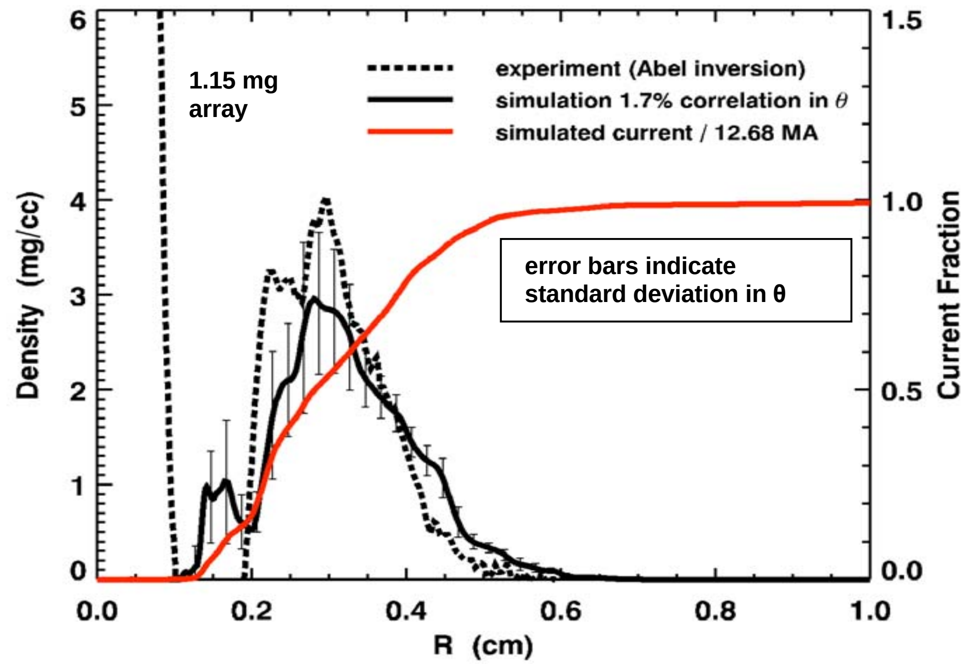
More work is needed to optimize these sources on the refurbished Z

3D Rad/MHD simulations are becoming essential tools in understanding magnetically-driven implosions

Density, 60 Degree Wedge



Z-Pinch Plasma Density vs. R



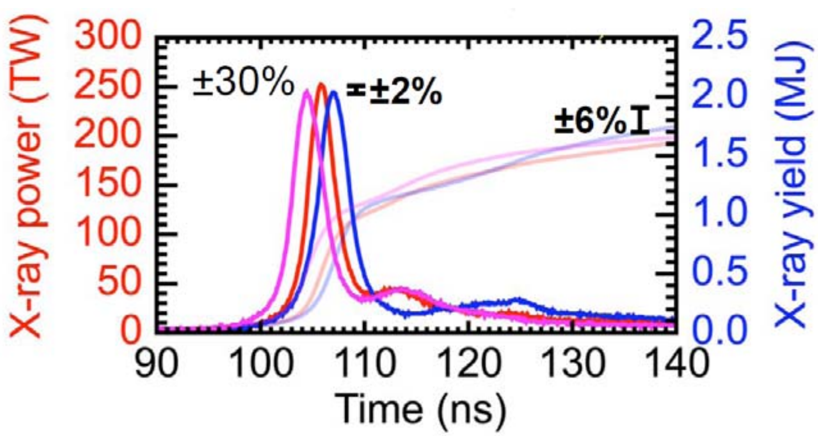
3D (and even 2D!) Rad/MHD codes are essential tools. Many issues remain to be worked through and benchmarked with experimental data.

The physics of shorting/current delivery is important to study and understand

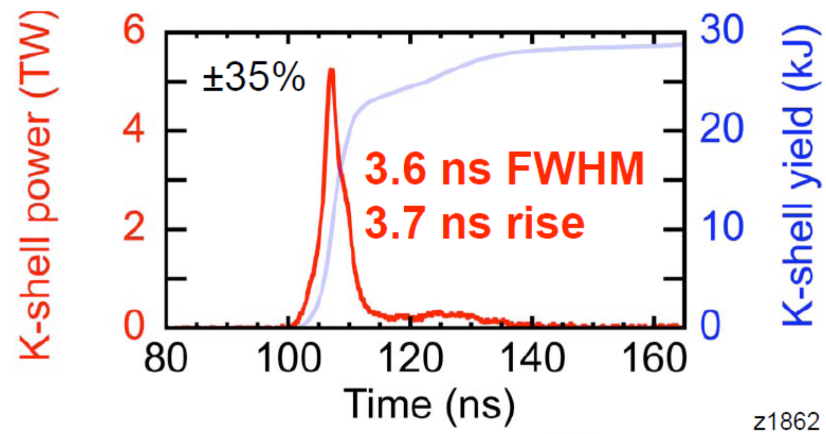
Simulations can help optimize arrays for different objectives

Large diameter wire arrays have achieved 250 TW peak total powers and 30 kJ of Cu K-shell on ZR

65 mm stainless steel arrays have for first time reproducibly achieved 250TW



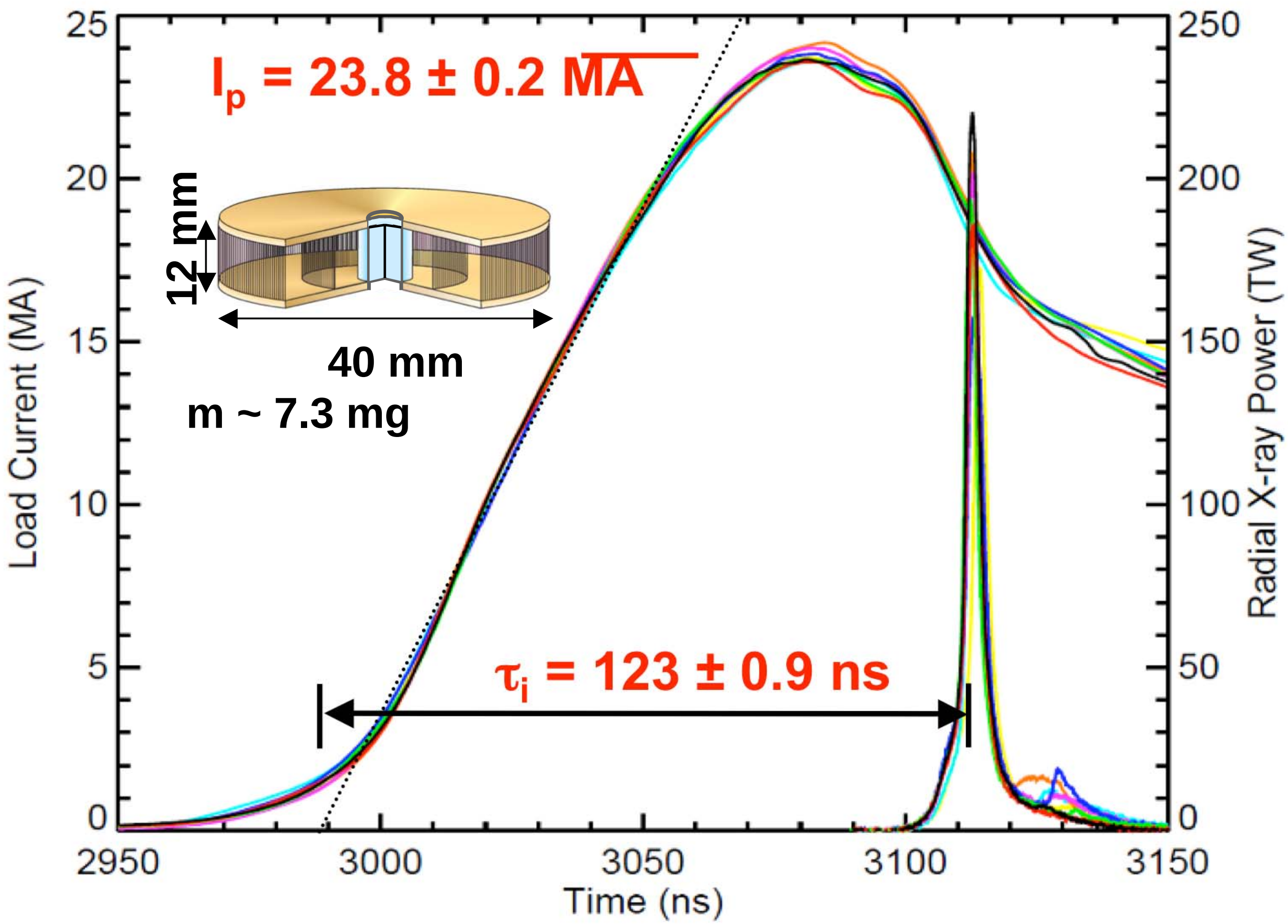
65 mm copper arrays have achieved 30 kJ at 8.4 keV



Upcoming plans include

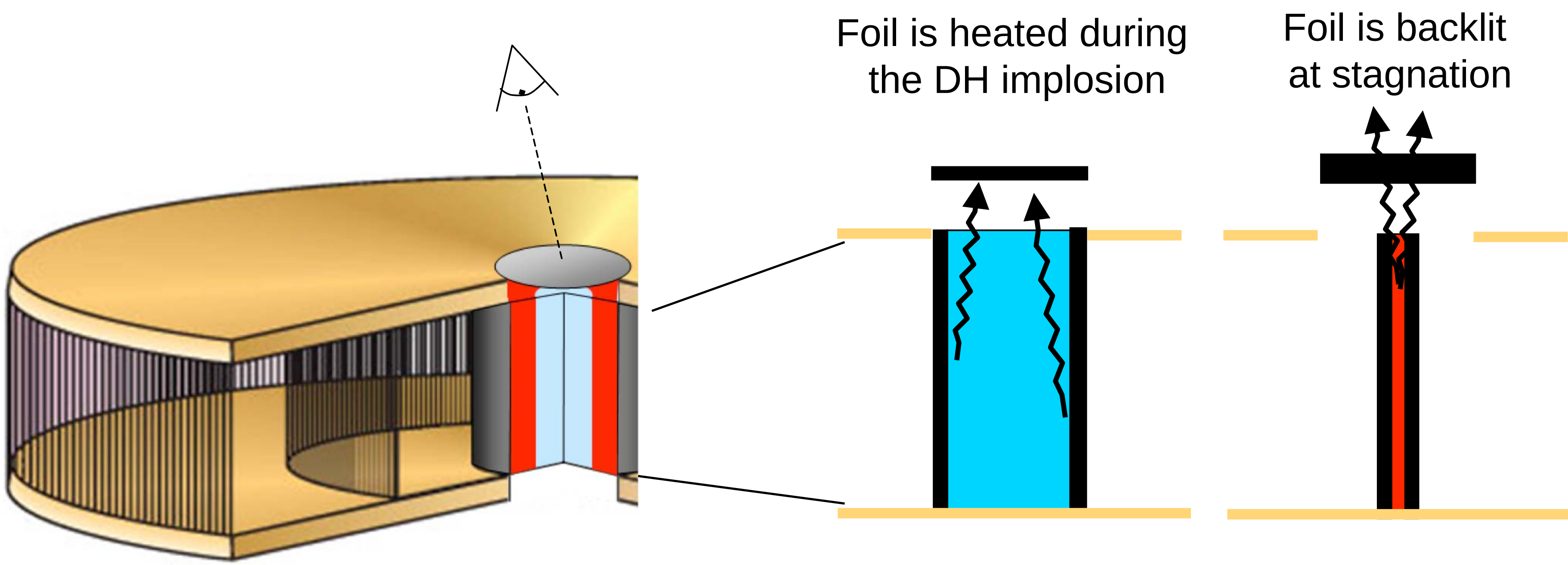
- Further optimization of SS (6.7keV) & Cu (8.4kev) loads based on
  - Detailed atomic modeling
  - 3D MHD modeling
  - Optimization of convolute and feed configurations
- Reestablishing Al (1.7 keV) wire array sources
- Begin investigations of Ar (3 keV) gas puffs on Z (FY10)

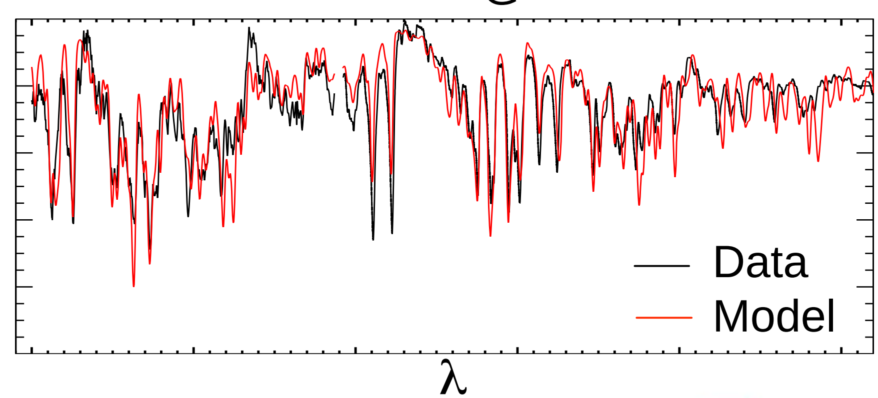
Refurbished Z has delivered world-record currents to Dynamic Hohlraum Z-pinch loads with < 1% shot-to-shot variation



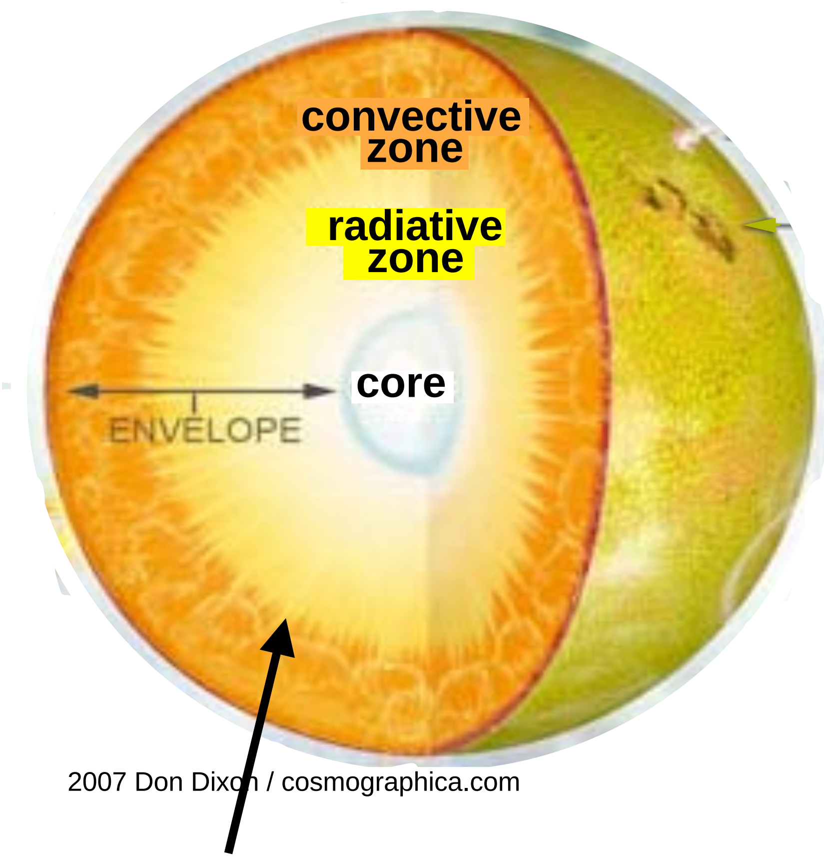
This reproducible, bright (~200 TW) source is ideal for opacity experiments

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





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}

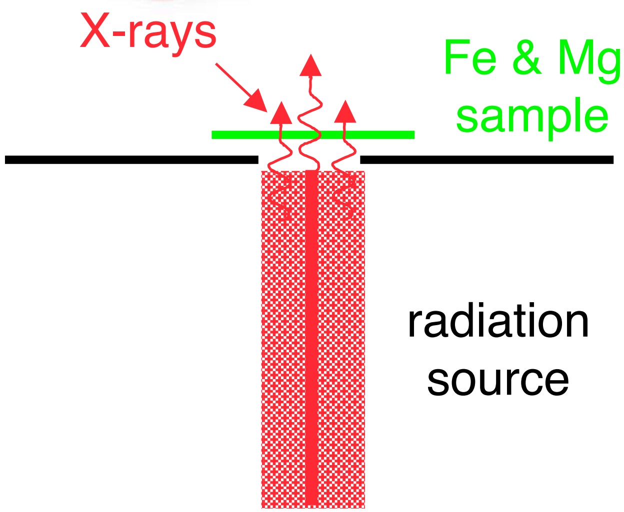
Predictions of solar structure do not agree with observations

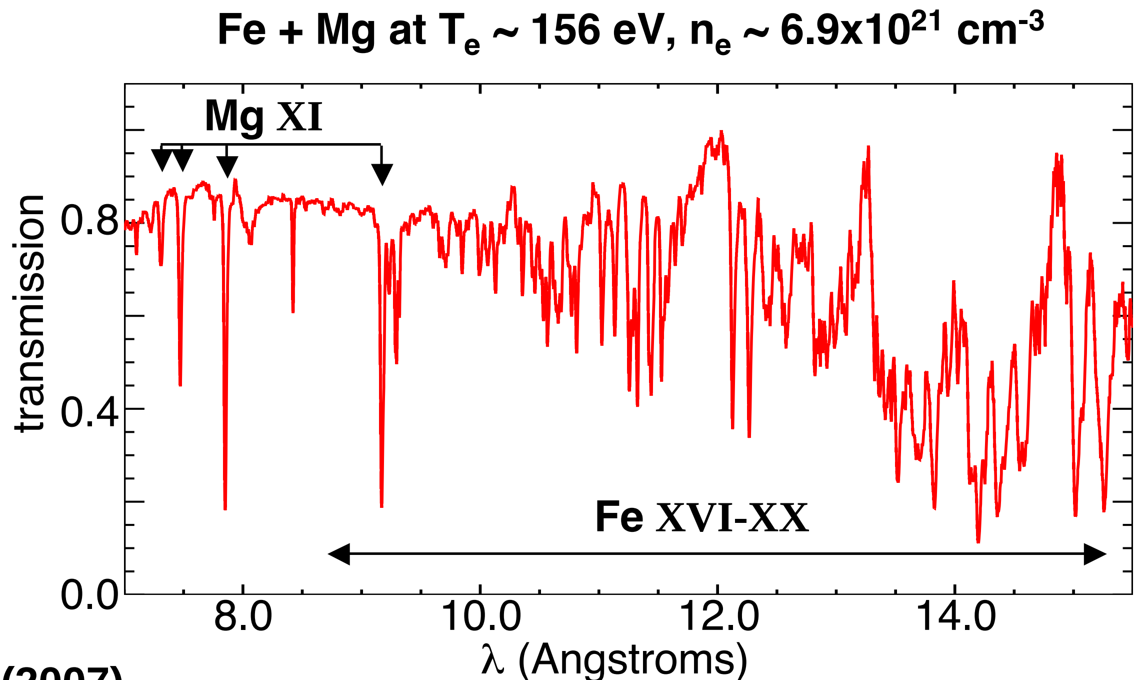
Solar structure depends on opacities that have never been measured

<u>Challenge: create and diagnose stellar interior conditions on earth</u>

High T enables first studies of transitions important in stellar interiors

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



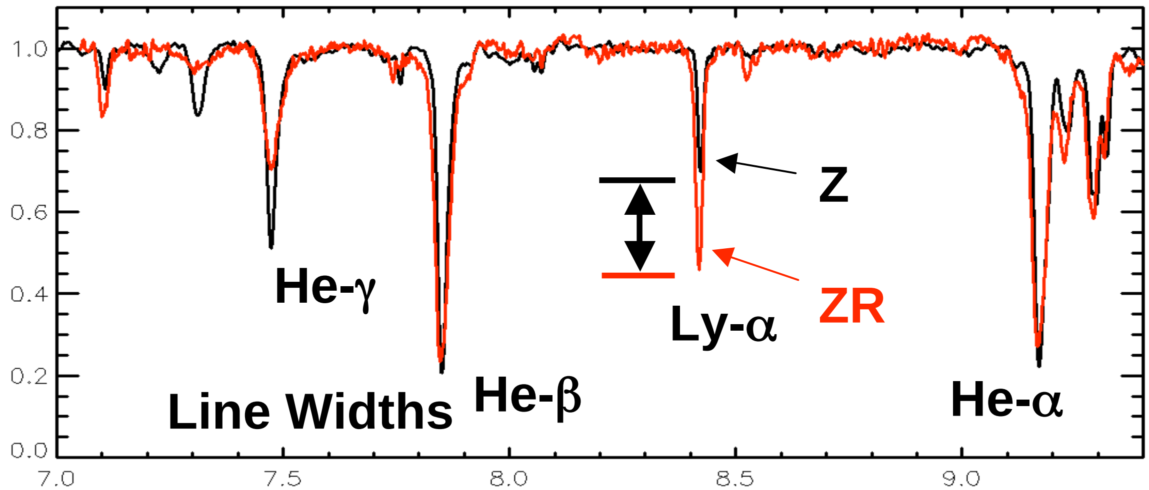


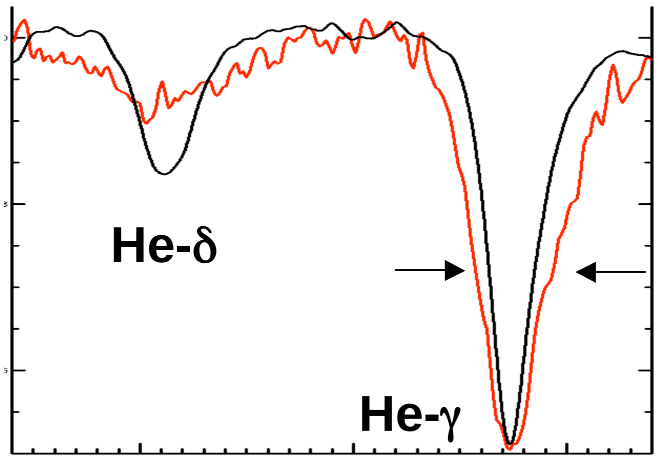
J.E. Bailey et al., PRL 99, 265002 (2007)

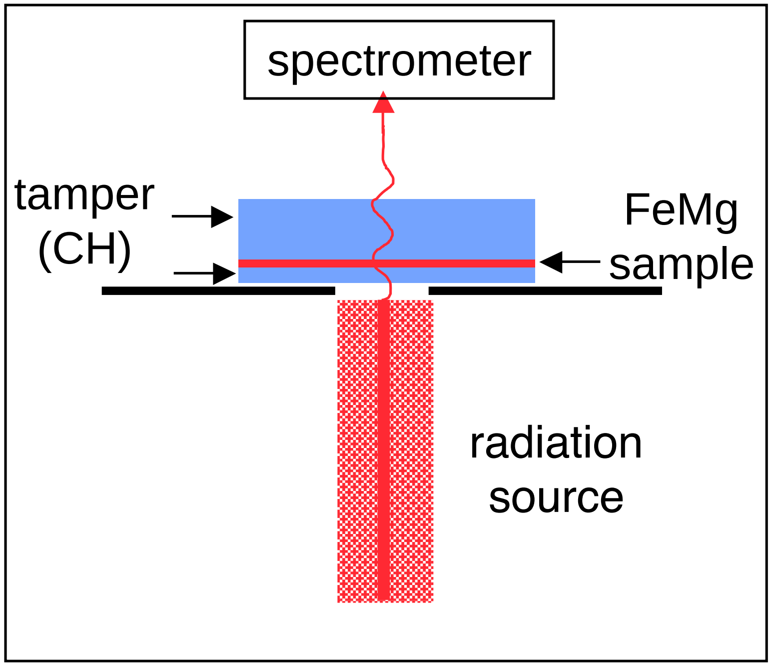
- **Mg is the "thermometer", Fe is the test element**

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

Mg K-shell absorption from a Mg/Fe foil







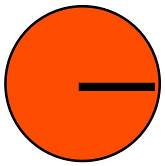
- Higher Ly/He ratios indicate ~20% increase in T_e ~190 eV
- Broader high-n lines indicate thicker tamper led to ~300% increase in n_e

This is much closer to Fe conditions in the Sun

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
- Higher currents are enabling brighter x-ray sources and hotter and denser plasmas for opacity research
- Magnetized concepts for pulsed power inertial confinement fusion look interesting
- We are working to grow a fundamental science effort on the refurbished Z

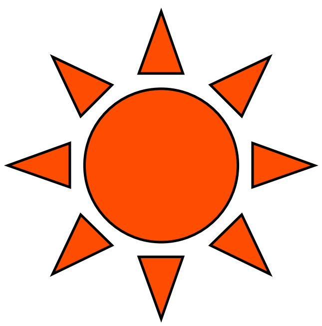
Under extreme conditions a mass of DT can undergo significant thermonuclear fusion before falling apart



ρ, R, T

- Consider a mass of DT with radius R, density ρ, and temperature T
- How does the disassembly time compare with the time for thermonuclear burn?

$${}_{disassembly} \sim \frac{R}{c_s} \sim \frac{R}{\sqrt{T}} \qquad \tau_{burn} \sim \frac{1}{n_i \langle \sigma v \rangle} \sim \frac{1}{\rho \langle \sigma v \rangle}$$



- The fractional burn up of the DT (for small burn up) is:

$$f_{burn} \approx \frac{\tau_{disassembly}}{\tau_{burn}} \sim \rho R \frac{\langle \sigma v \rangle}{\sqrt{T}}$$

- At sufficiently high ρR and T the fractional burn up becomes significant and the energy deposited by alpha particles greatly exceeds the initial energy in the fusion fuel ("ignition")

- Typical ignition conditions are:

$$\rho R \approx 0.6\,\mathrm{g/cm^2}$$

$$T \approx 5\,\mathrm{keV}$$

The fusion fuel must be brought to a pressure of several hundred billion atmospheres to achieve the goal of ignition

For ignition conditions: $\left\{ \begin{array}{l} \rho R \approx 0.6\,\mathrm{g/cm^2} \\ T \approx 5\,\mathrm{keV} \end{array} \right\}$ $\rho R T \approx 3.0 \left(\frac{\mathrm{g\,keV}}{\mathrm{cm^2}} \right)$

$$P(\mathrm{Bar}) = 8 \bullet 10^8 \rho(\mathrm{g/cm^3}) T_i(\mathrm{keV}) \qquad PR \sim 2.4 \bullet 10^9\,\mathrm{Bar-cm}$$

$$\mathrm{E} \sim \frac{3}{2} PV \sim \frac{3}{2} P\left(\frac{4\pi}{3} R^3 \right) \sim 1.5 \bullet 10^9 R^2(cm)(\mathrm{J})$$

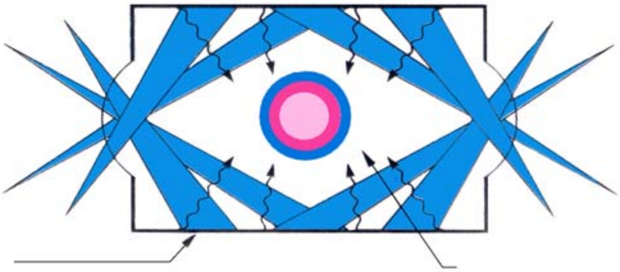
$$\mathrm{E_{NIF}} \sim 15\mathrm{kJ} \Rightarrow R \sim 30\mu\mathrm{m} \Rightarrow \quad P \sim 800\mathrm{GBar} \quad \text{and} \quad \rho \sim 200\, g/cm^3$$

$$\tau_{conf} \sim \frac{R}{c_s} \sim 30\,ps \qquad \mathrm{Power} \sim \frac{E}{\tau_{conf}} \sim 0.5 \bullet 10^{15} W$$

Calculations of NIF ignition capsules without burn reach similar (~500GB) pressures

High velocity, low adiabat thin shells are needed to reach these pressures

Indirect Drive (X-ray)



Direct Drive (Laser)

In either direct or indirect drive, peak drive pressures are of order ~ 50-150 MBars

We need to get pressures to >1000X that for ignition!

Spherical implosions enable us to store energy in the fusion fuel in the form of kinetic energy, which is converted to pressure at stagnation

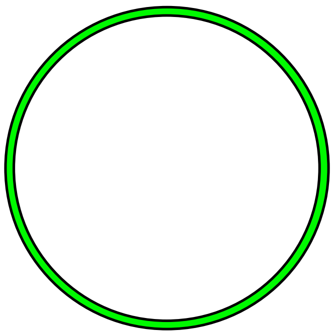
$$P_{stag} \sim \alpha \rho_{stag}^{5/3} \quad \alpha \rho_{stag}^{2/3} \sim v^2 \Rightarrow P_{stag} \sim v^5 / \alpha^{3/2}$$

$$\alpha \equiv P / P_{Fermi}$$

Thin shell implosions can reach the 200-400 km/sec needed for ICF

$$\int P_{drive} dV = \frac{1}{2} m v^2 \quad m \sim 4\pi R^2 \rho \delta R$$

$$P_{drive} R^3 \sim R^2 \rho \delta R \, v^2 \Rightarrow v^2 \sim \frac{P_{drive}}{\rho} \frac{R}{\delta R}$$

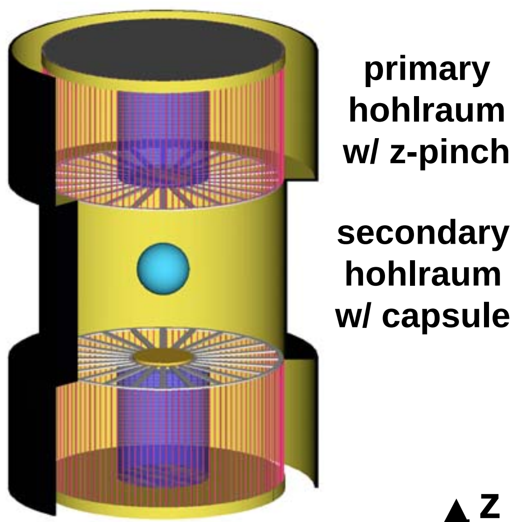


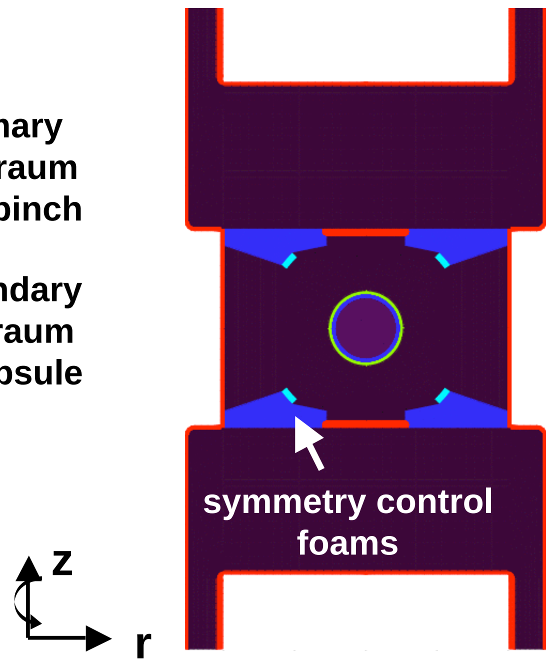
Sandia National Laboratories

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

Double z-pinch hohlraum fusion concept

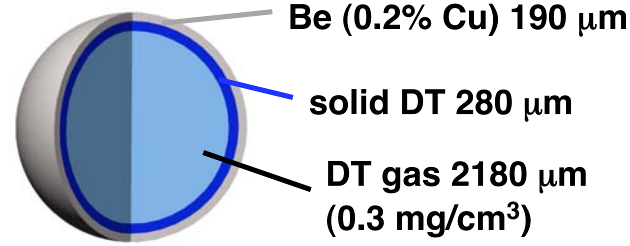
R. A. Vesey, M. C. Herrmann, R. W. Lemke *et al.*,
Phys. Plasmas (2007)



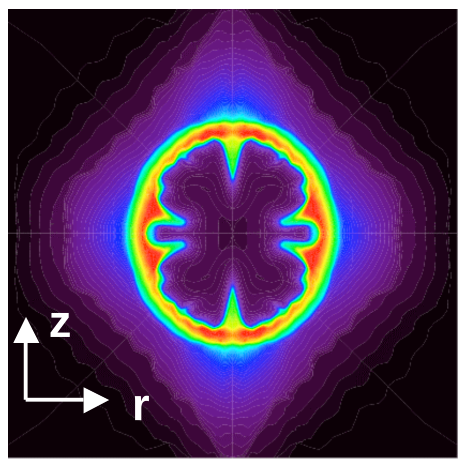


- **Two z-pinches, each with 9 MJ x-ray output**
- **Symmetry control to 1% via geometry, shields**
- **Capsule absorbs 1.2 MJ, yields 400-500 MJ**

High yield capsule design

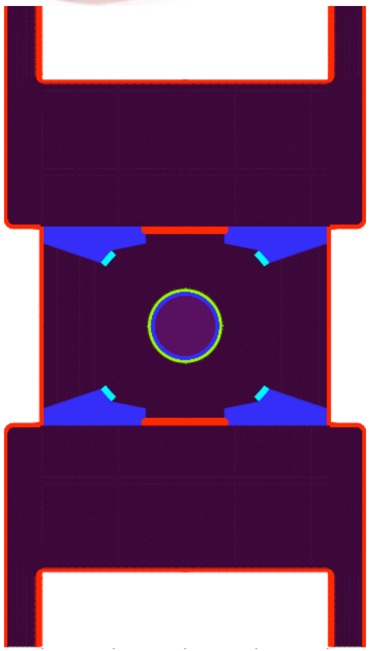


Fuel density at ignition

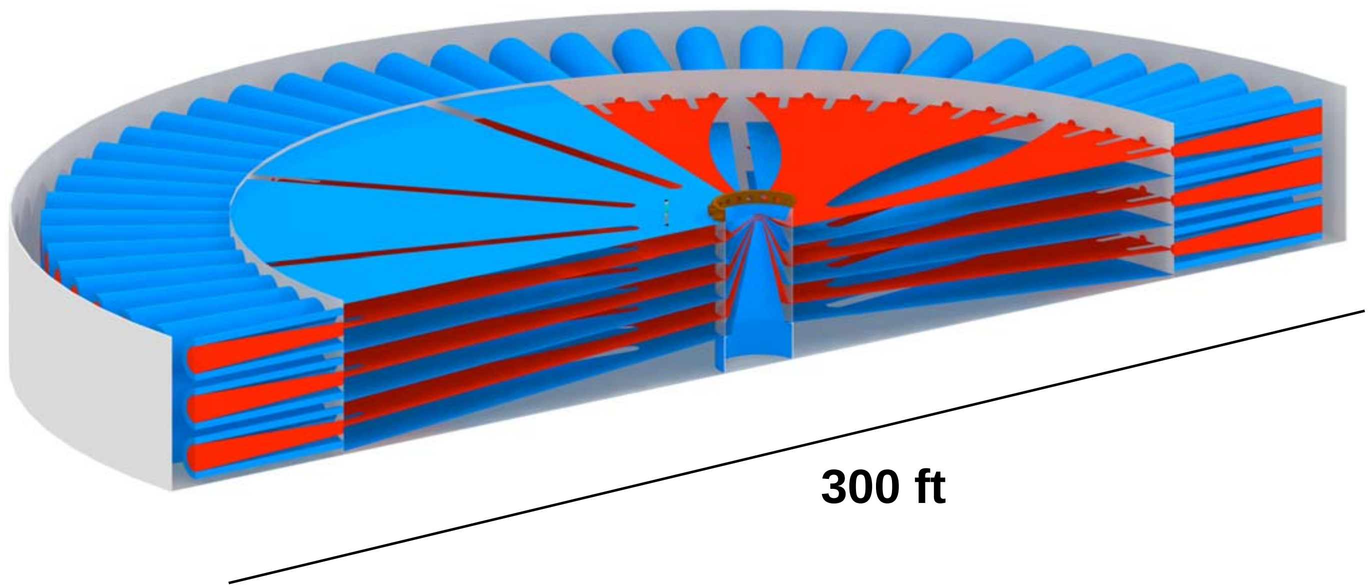


1D capsule yield 520 MJ
2D integrated yield 470 MJ

A large driver (beyond ZR) is needed is needed to drive the high yield double ended hohlraum



- Power required (1 PW/pinch @ 20-mm-diam.)
- Energy required (8-9 MJ/pinch)



Because of the inefficiencies in this concept only 0.04% of the driver energy gets to the fusion fuel

Are there more efficient concepts? Is there any way to lower the required pressure?

An approach to reduce the requirements would be to drop the ρr needed

For ignition conditions: $\left\{ \begin{array}{l} \rho R \approx 0.6\,\mathrm{g/cm^2} \\ T \approx 5\,\mathrm{keV} \end{array} \right\}$ $\rho R T \approx 3.0\left(\frac{\mathrm{g\,keV}}{\mathrm{cm^2}}\right)$

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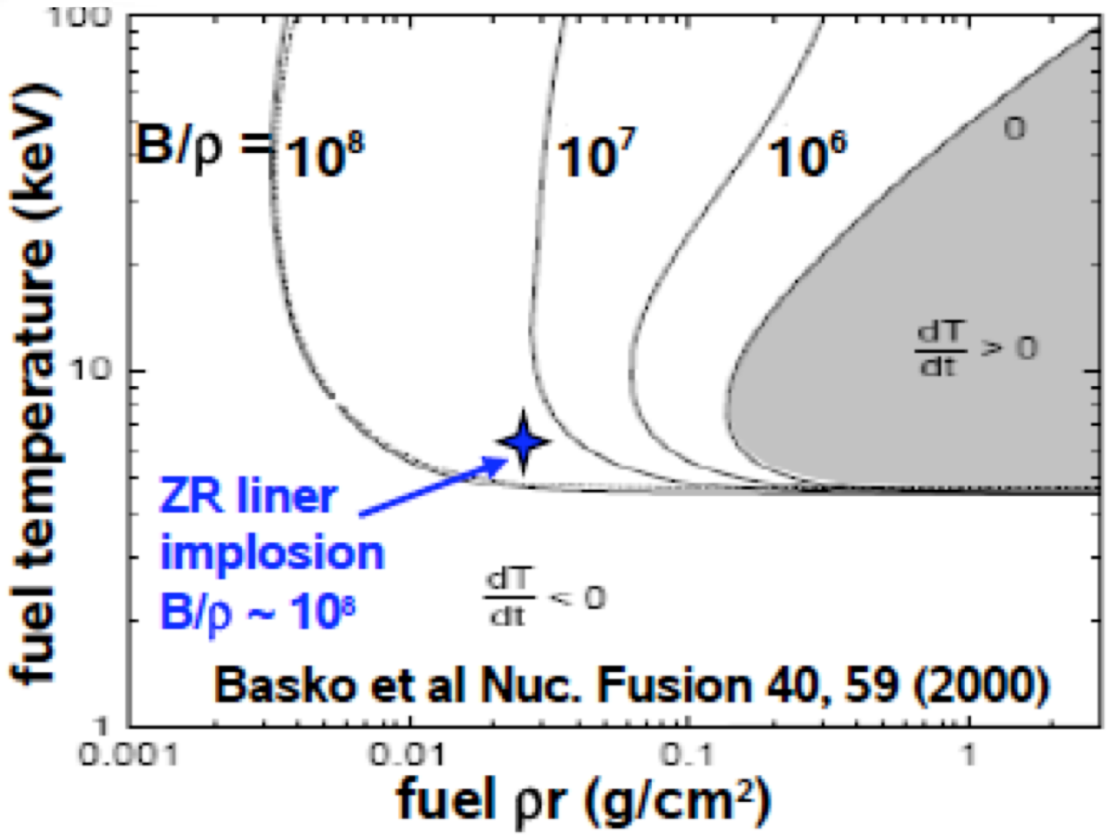
$$\mathrm{E} \sim m\,T \sim \rho R^3 T$$

$$\mathrm{E_{NIF}} \sim 15\mathrm{kJ} \Rightarrow R \sim 30\mu\mathrm{m} \Rightarrow \quad P \sim 800\mathrm{GBar} \quad \text{and} \quad \rho \sim 200\, g/cm^3$$

$$\rho\mathrm{R} = 0.01 \frac{\mathrm{gm}}{\mathrm{cm^2}} \quad \Rightarrow P \downarrow 60$$

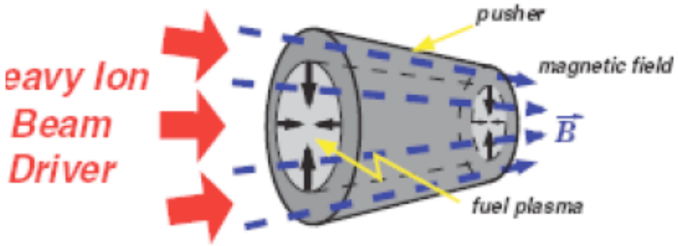
Imposing an axial magnetic field on a cylindrical implosion may allow self heating without high ρr

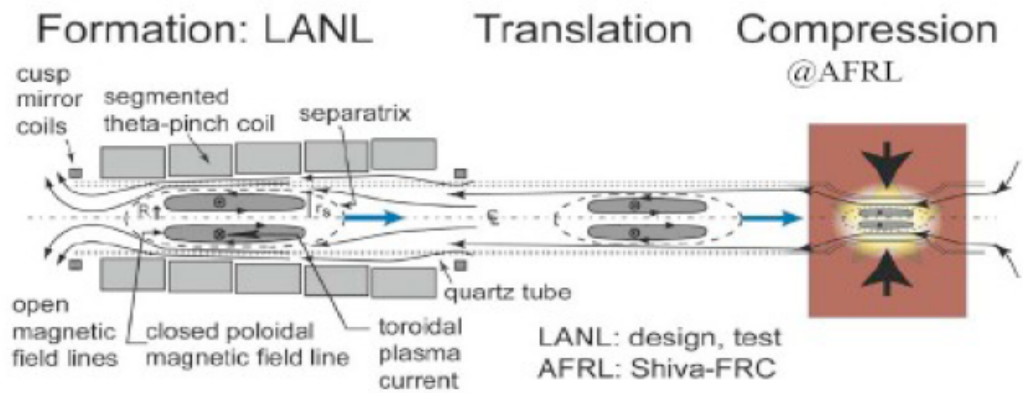


A magnetic field inhibits electron thermal conduction and enhances alpha particle deposition within the fuel lowering the ρr needed for self heating

A number of groups around the world are looking in to this

Max Planck/ITEP

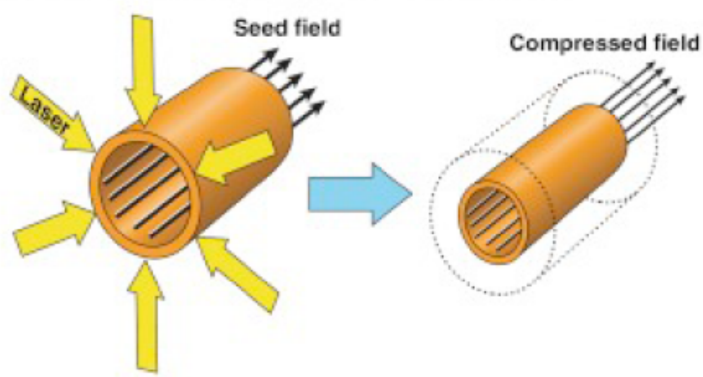


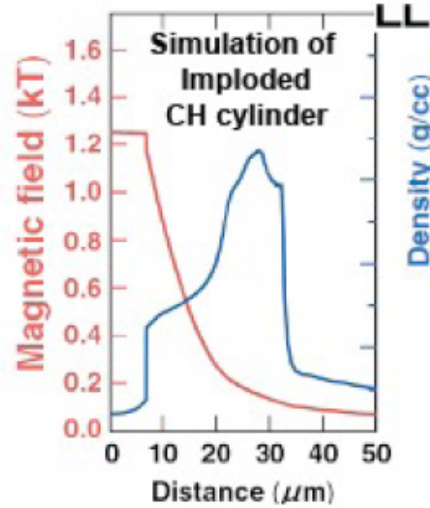


FSC — UR LLE

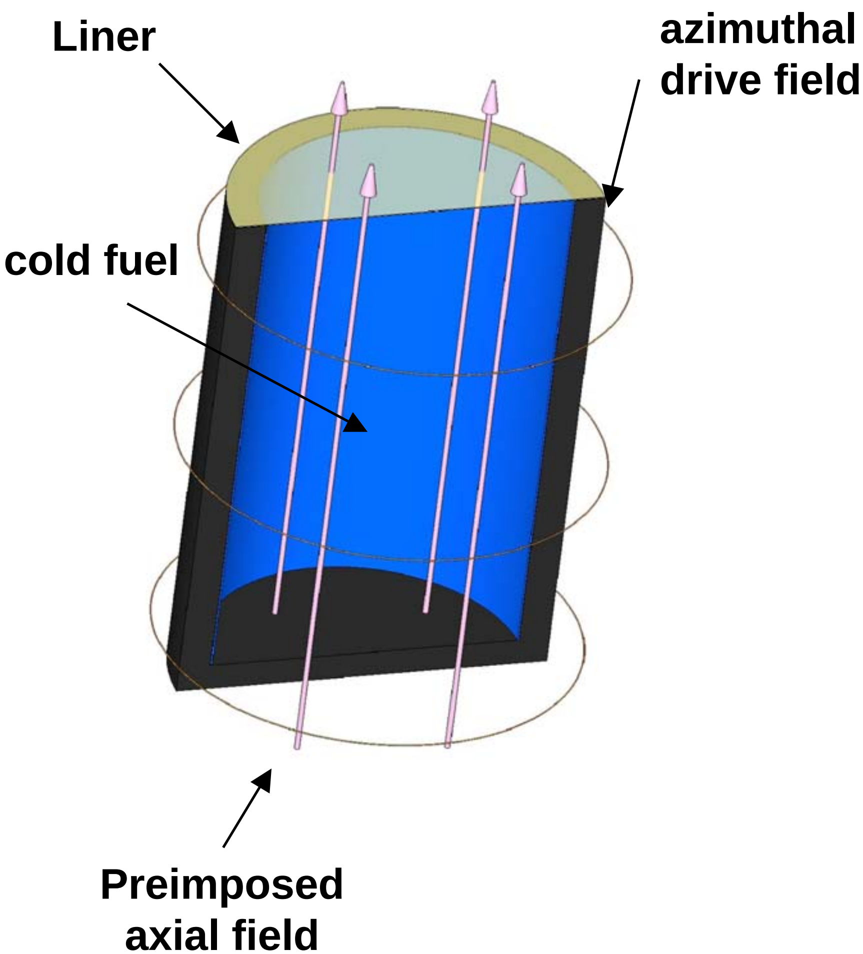
Initial seed field of 3-5T

A magnetized ICF implosion yields higher hot-spot temperatures





Magnetized Liner Experiments on ZR look interesting



A ~ 10Tesla axial field is preimposed on a thick liner containing D2 or DT gas

Liner must be low aspect ratio (R/ΔR ~ few) so it is not ripped up during implosion

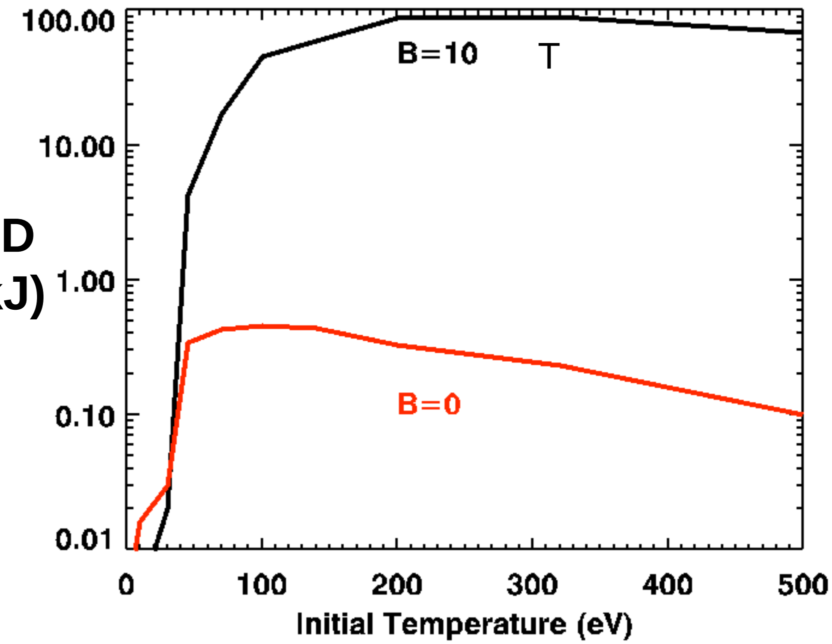
How low the aspect ratio must be for an implosion to be stable enough is an open question

Low aspect ratio shells implode slowly (50-100 km/sec) so we need another way to get the plasma heated to ~ 10keV

Simulations show that both a magnetic field and a preheated plasma are needed to obtain interesting fusion yields on ZR

Aspect Ratio 6, I=20 MA, 1cm tall Be liner,DT Gas

Clean 1D Yield (kJ)



These are 1D simulations so many caveats apply

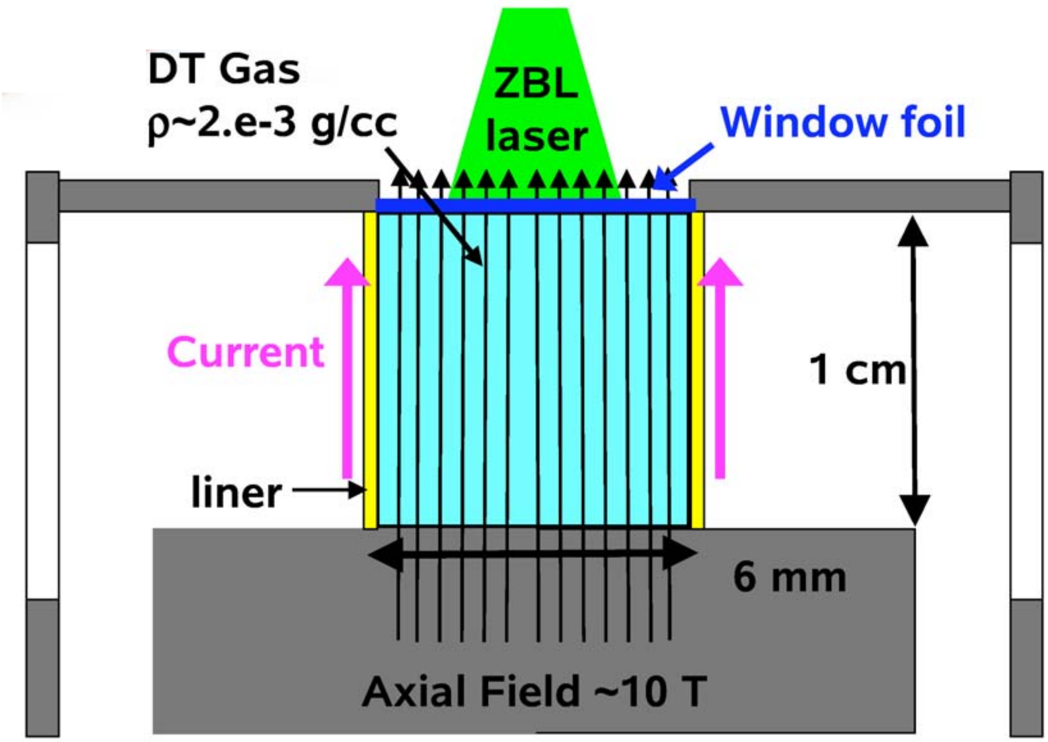
At stagnation field is ~ 100 MG
Fuel ρr is ~ 0.01 gm/cm^2
liner ρr is high ~ 1gm/cm^2
Electron conduction losses are strongly reduced

Due to presence of magnetic field and low fuel density (low radiation losses), fuel is compressed nearly adiabatically

$$T \sim T_0 \left(\frac{\rho}{\rho_0} \right)^{2/3} \sim T_0 \left(\frac{R_o}{R} \right)^{4/3}$$

How do we preheat the fuel?

The Z beamlet laser could efficiently preheat the fuel



The Z Beamlet laser provides ~ 3kJ of green light to the Z target chamber for backlighting

Optimal densities for these targets from 1D calculations at ZR currents are 1-2 mg/cc ~ 5 to 10% of critical density for green light

Lasnex calculations suggest that the plasma can be heated to ~ a few 100 eV

Issues like uniformity of heating, window foil interaction, and end losses have been briefly looked at.
No show stoppers identified.

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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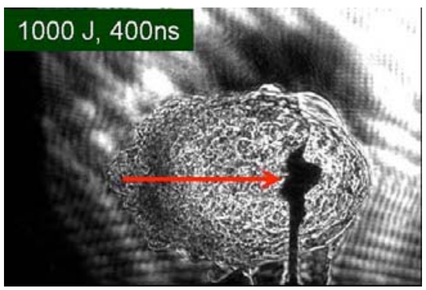
- **Higher currents are enabling brighter x-ray sources and hotter and denser plasmas for opacity research**
- **Magnetized concepts for pulsed power inertial confinement fusion look interesting**
- **We are working to grow a fundamental science effort on the refurbished Z**

The Z and Z Backlighter Facilities have an active collaboration with University students and faculty

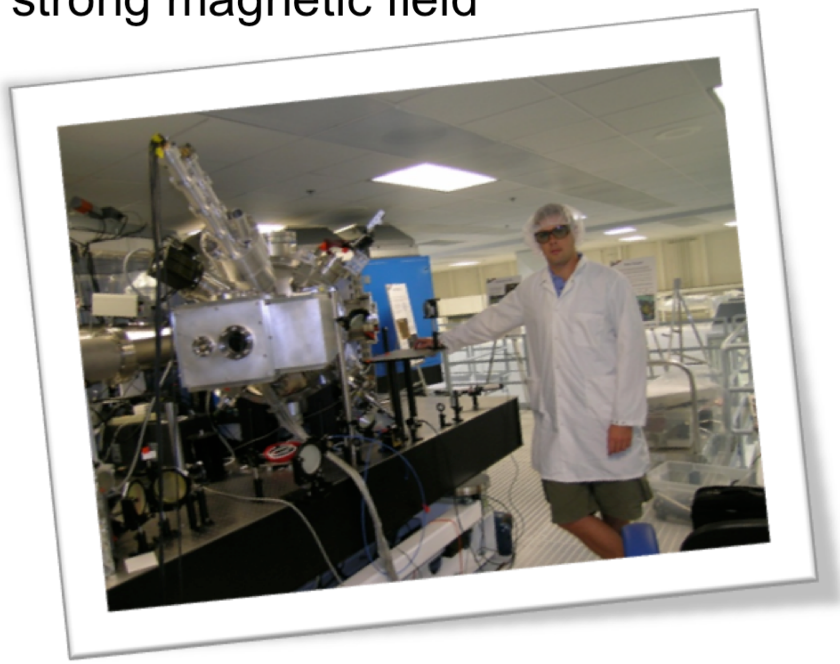
Have explored the physics of high Mach number radiative shocks, such as those found in supernova remnants

Edens et. al., Physical Review Letters, 95, 244503 (2005)



To propose experiments contact:	
Z Facility	Mike Lopez mrlope@sandia.gov
Z Backlighter	Briggs Atherton bwather@sandia.gov

Future experiments are planned to study the equation-of-state of warm dense matter and the confinement of a high energy density plasma by a strong magnetic field



Z Facility Basic Science Call for Proposals due out in September 2009.

We will be holding a workshop on Science with High-Power Lasers and Pulsed Power in late July

Meeting will be held in Santa Fe
Organized by Alan Wootton, director of the Institute for High Energy Density Science

Goal is to identify the most interesting,exciting fundamental science experiments that can be performed using the high-power lasers and pulsed power facilities at Sandia National Laboratories(SNL) and the University of Texas(UTX).

The workshop is being held under the auspices of the Institute for High Energy Density Science, joint between UTX and SNL.

Please see http://www.ph.utexas.edu/~iheds/index.html or email Alan at wootton1@comcast.net if you are interested.

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