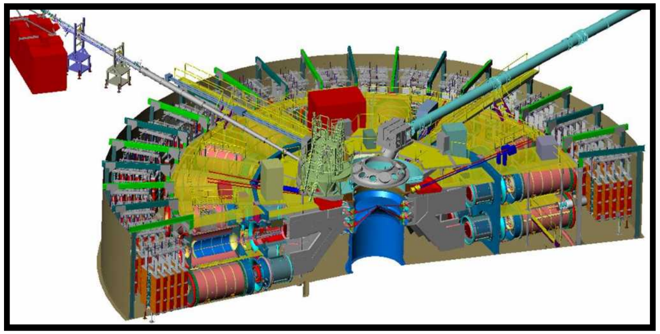
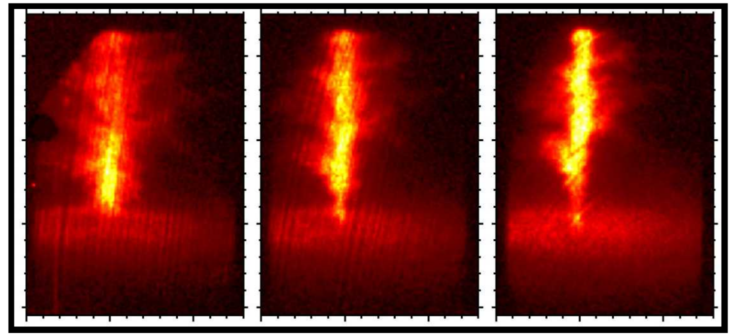
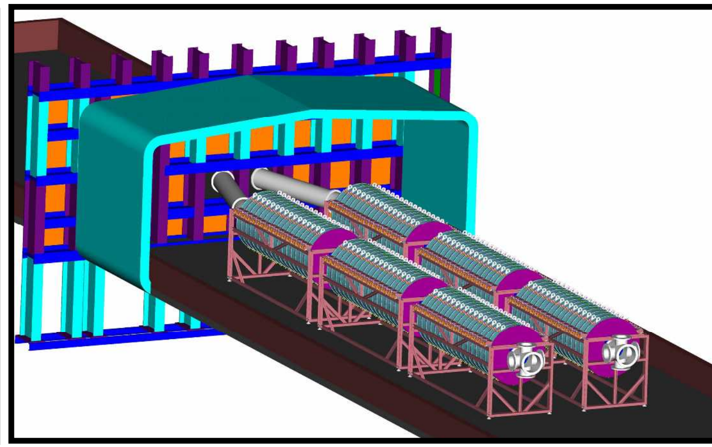
SAND2005-7865P

Pulsed Power – An Enabling Technology to Transform the Complex







Dr. Christopher Deeney

December, 2005

Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy under contract DE-AC04-94AL85000.

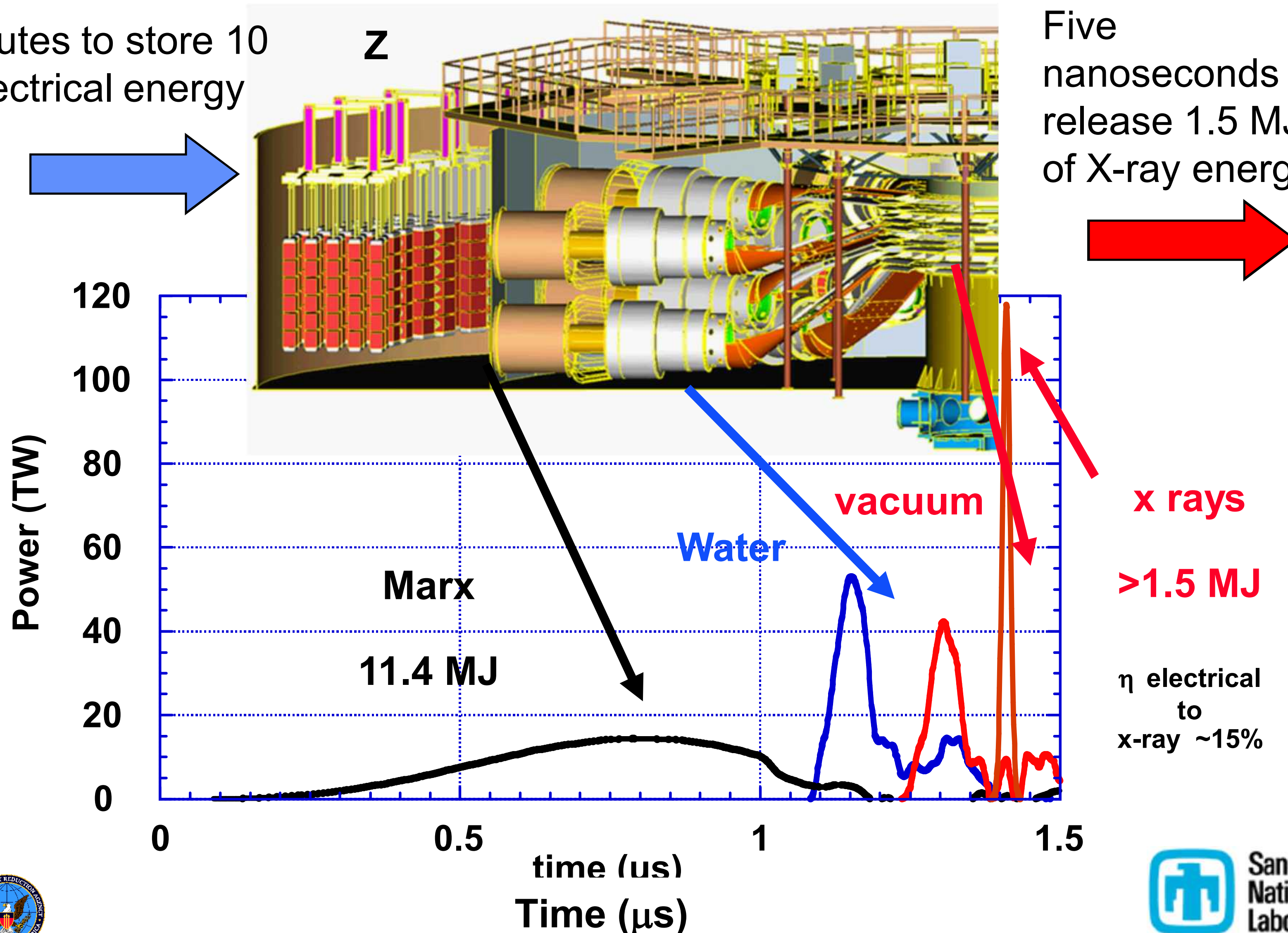
Pulsed power is inherently efficient – we continue to make it more elegant

- How can pulsed power transform the complex?
  - Technologies must provide new capabilities, and/or reduce cost/operations
- Radiography –
  - Compact systems for experiments underground and above-ground with advanced diodes
- Dynamic materials –
  - High pressure isentropic compression
  - Compact 1-Mbar class drivers at the $1k-per-sample-point
- Secondary Physics
  - Energy-rich platforms for radiation-hydrodynamic studies
- Nuclear Survivability
  - Laboratory capabilities to replace some phase space formerly limited to UGTs
- Secondary Physics and Nuclear Survivability
  - "Affordable" high yield capabilities

Pulsed Power is an efficient, hence low cost, approach to proving a high energy density (> 0.1 MJ/cc) environment for SSP

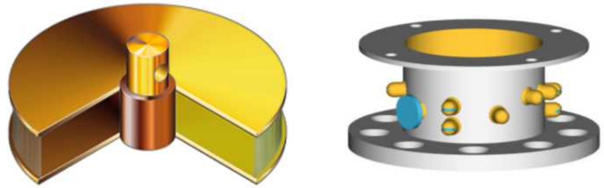
Two minutes to store 10 MJ of electrical energy

Five nanoseconds to release 1.5 MJ of X-ray energy



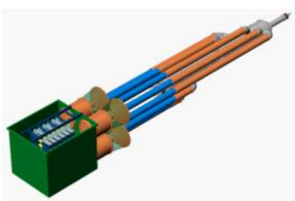
Focus is on near term applications in stockpile stewardship program

C7 - Hostile Environments
Radiation Effects

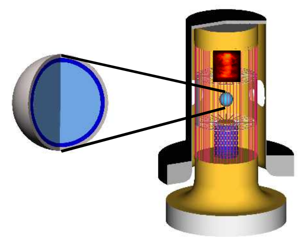


C4 - Secondary Certification
Radiation Flow

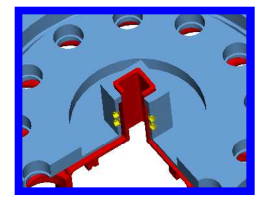
DSW, Pantex, & DoD
EM & Lighting Certification



C1 - Primary Certification
Subcritical Radiography



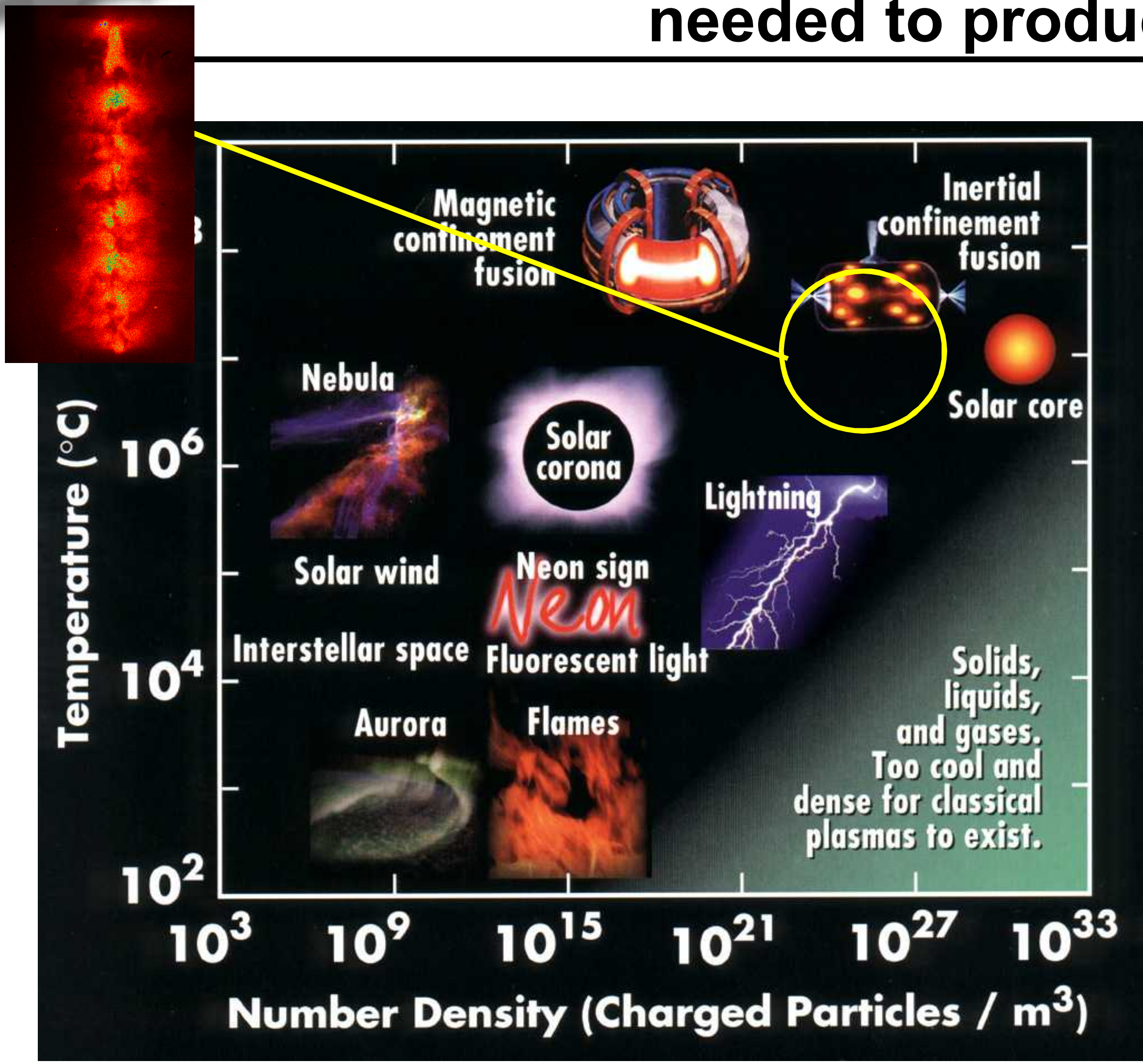
C10 – High Energy Density Physics
High Yield Assessment



C2 - Material Properties
EOS

High yield *vision* provides direction and drives - temperature, reproducibility, diagnostics, codes, pulsed power technology,...

Z-pinches produce high energy density states (10 MJ/cm^3) – these states are needed to produce 1-15 keV x-rays



Applications include:

ICF

Hydrodynamics

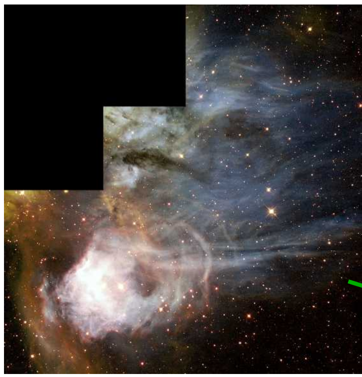
Lab Astrophysics

EOS – sort of! There is a much better way

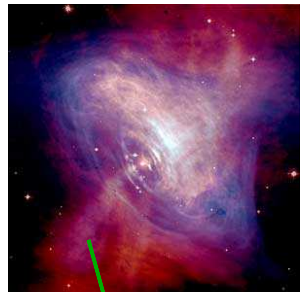
Radiation-material interactions

Most interesting astrophysics problems can be found in your neighborhood Z-pinch

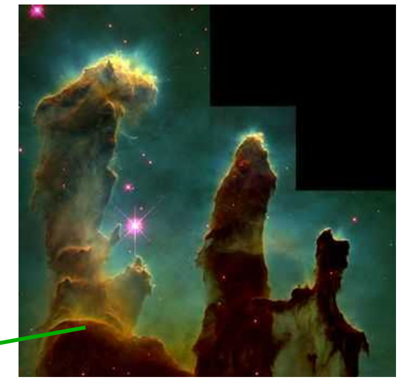
High Mach Number unstable flows

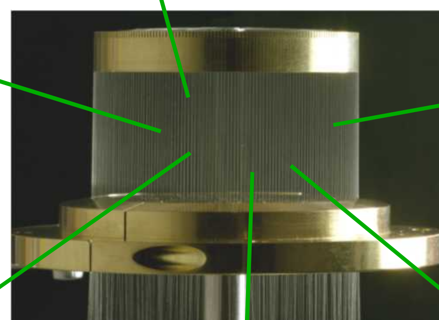


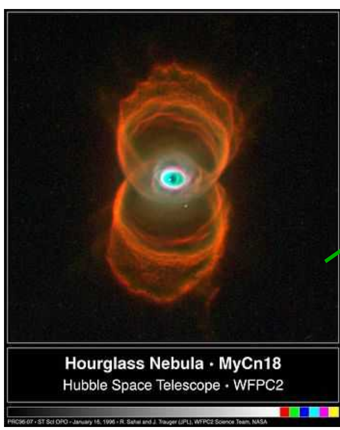
Jets



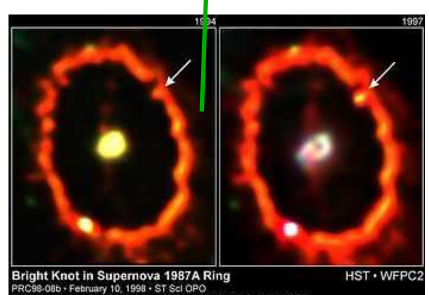
Rayleigh Taylor instabilities







Mass Outflow



Shocks and radiation transport

MHD and "anomalous" heating

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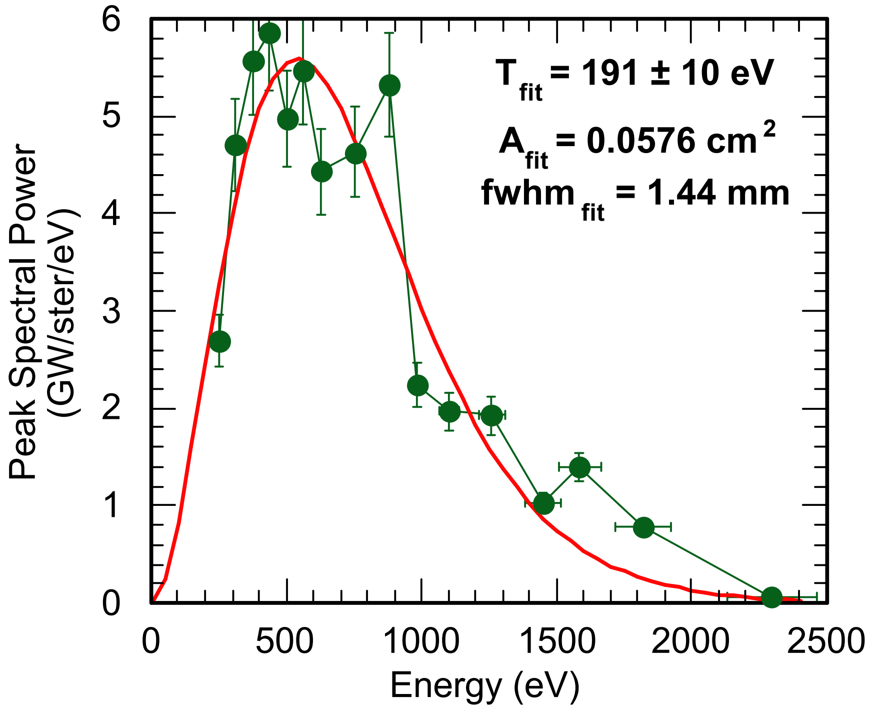
Z-pinches are excellent x-ray sources for two classes of needs: Planckian-like and non-LTE K-shell (or L-shell)

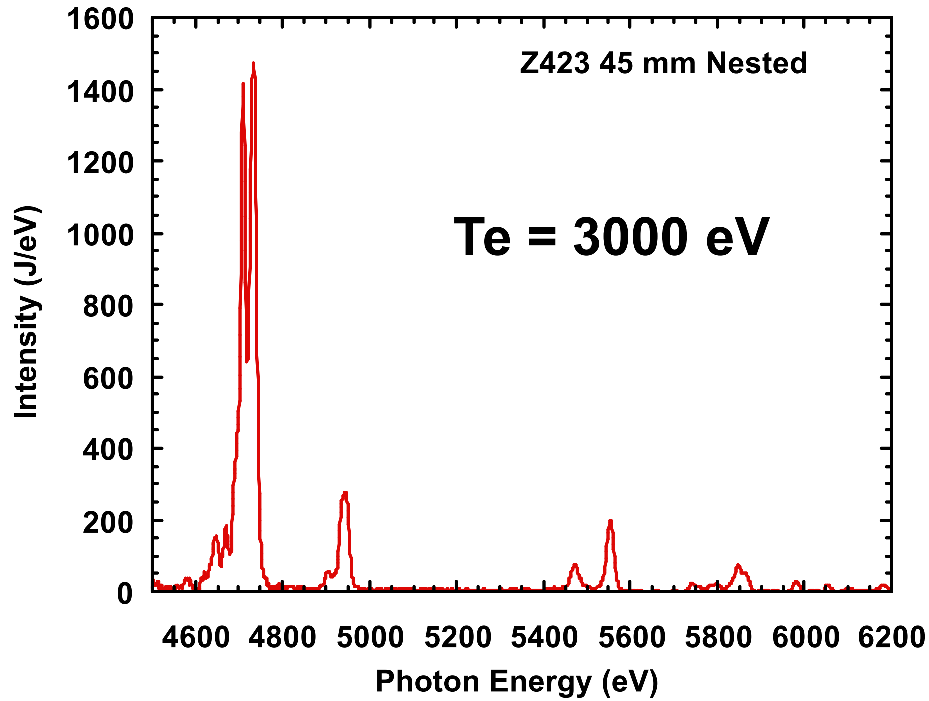
Tr = approximately equal to Te



$$\tau \approx K_R \rho r \approx 1\text{-}10$$

Cuneo, Phys. Plasmas 8, 2257, (2001)

Te much greater than Tr

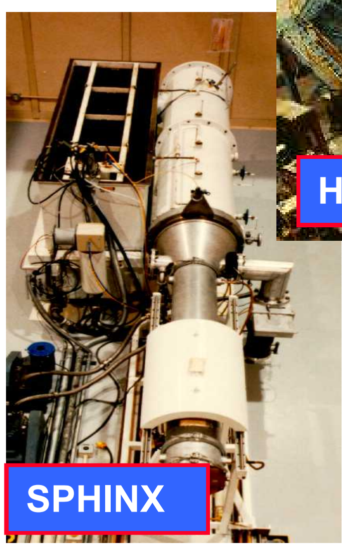


Deeney, Phys. Plasmas 5, 2081, (1999)

Nuclear Survivability Experiments on Z

SNL, AWE and ITT collaborative cavity SGEMP experiment on Z

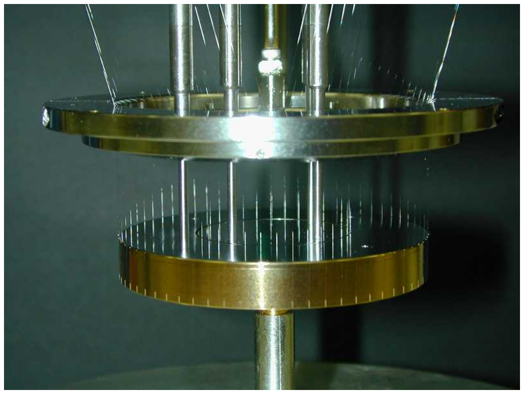
The Radiation Sciences program at Sandia have a number of unique facilities to meet mainly hard x-ray testing and code validation needs

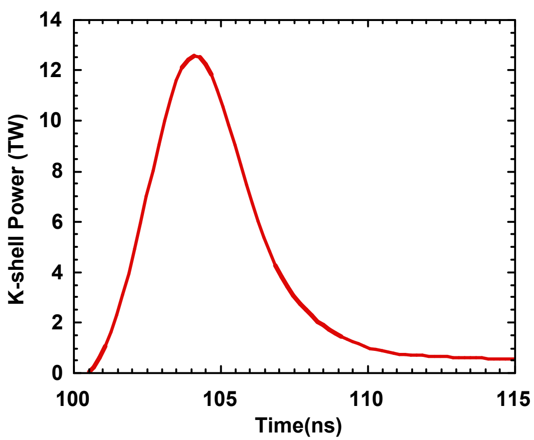


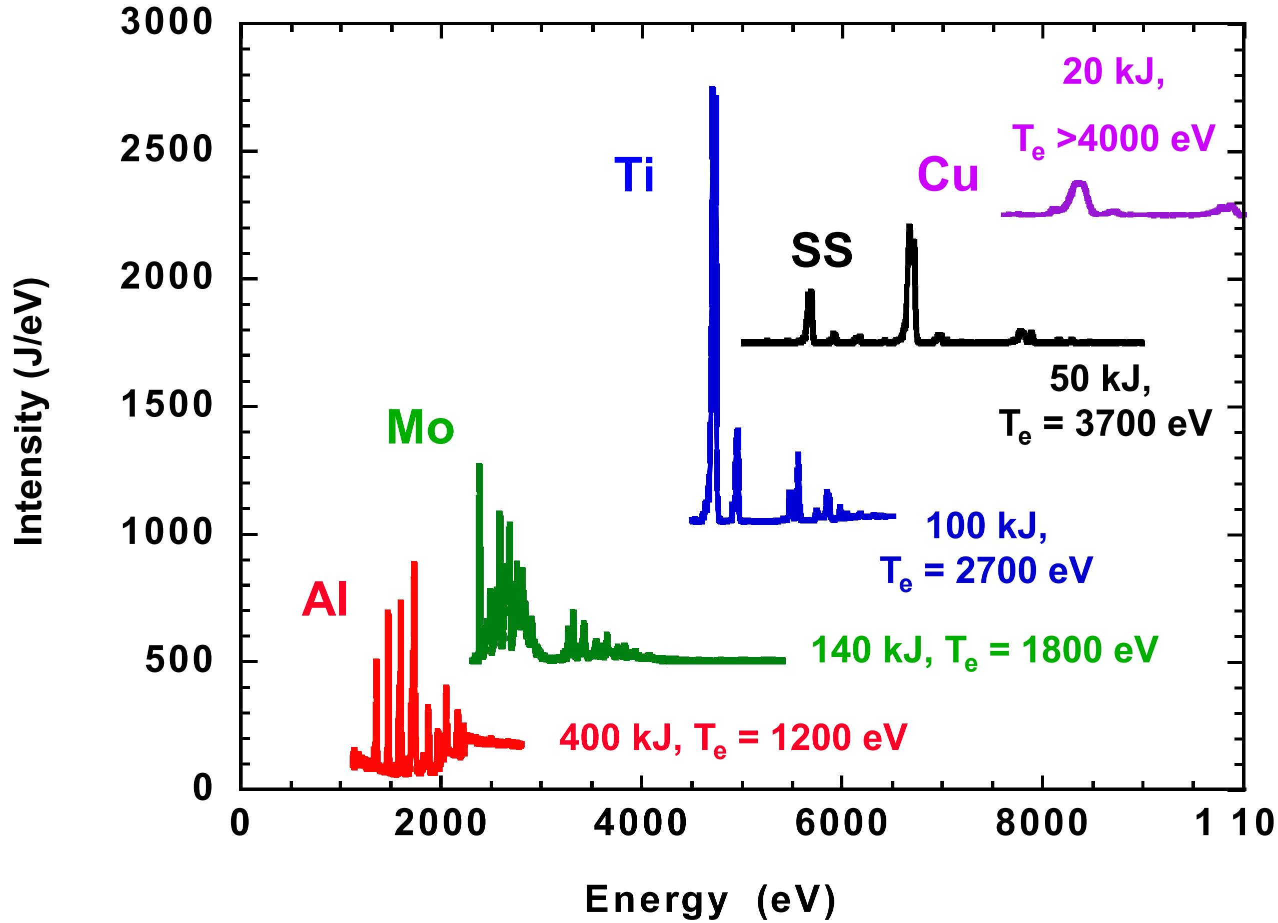
- **Hermes meets most anticipated gamma experimental environments**
- **Hermes e-beam provides a large area exposure environment to validate TSR/TMS models – LIHE provides a system capability**
- **Saturn is very useful in meeting hard x-ray requirements**
  - **Higher dose rates**
  - **Positive polarity?**
- **Saturn is the a large soft x-ray source driver (10 MA, 35 kJ @ 3 keV) and in 1992 it was the highest energy source**
  - **Small scale testing**
  - **Research and development**
- **DTRA facilities and Sphinx meet many of our small scale requirements**
  - **Reflex triode**
  - **Cable testing**

Z enabled hundreds of kilojoules of x-rays and we were able to break the 3 keV photon energy "speed limit"

Nested array







The >300kJ Ar yield by Titan/DTRA is not shown

NNSA National Nuclear Security Administration

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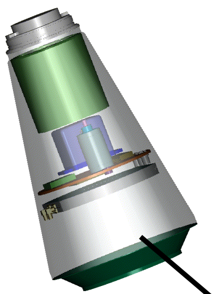
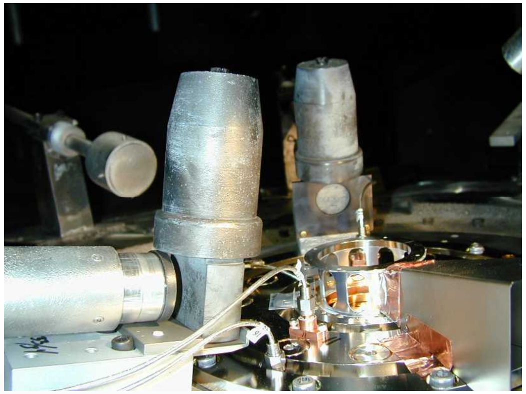
Z is being applied to SSP nuclear survivability missions and there are more to follow

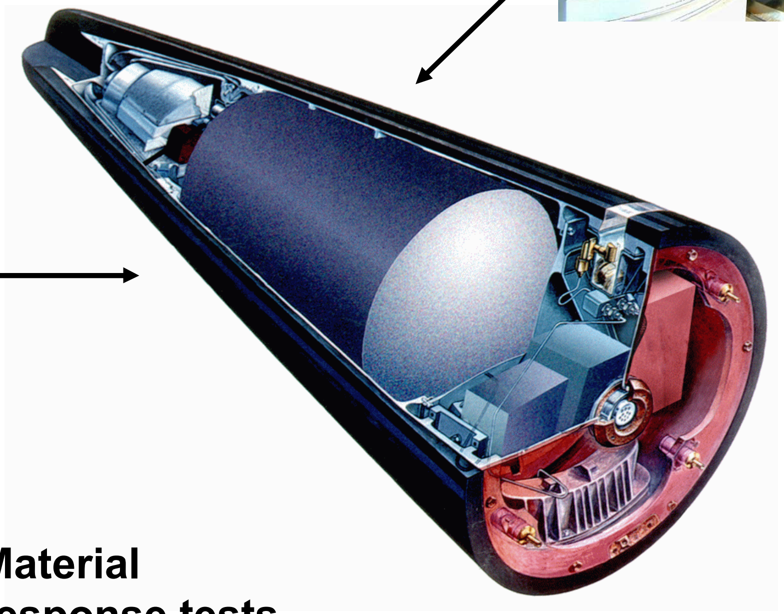
Cavity SGEMP code validation experiments

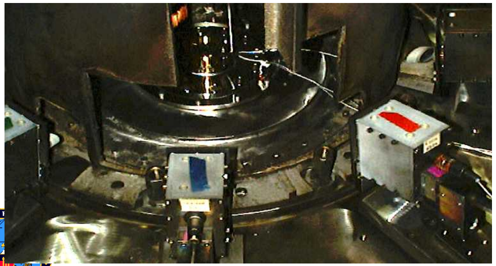


First AGEX "clean" multi-keV x-ray blow-off experiments.



Braze joint evaluation





Material response tests

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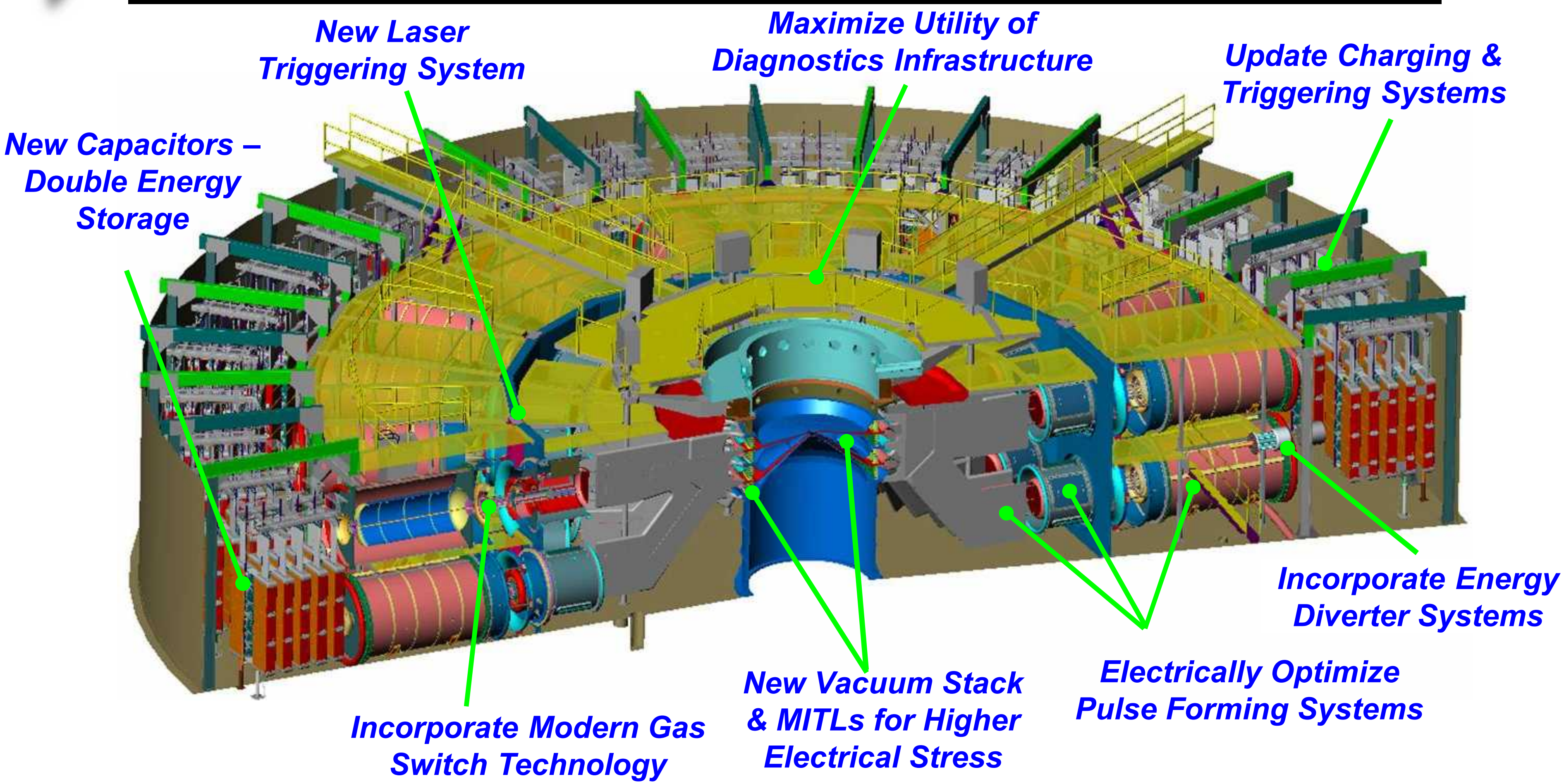
Future requirements for increased PRS capabilities

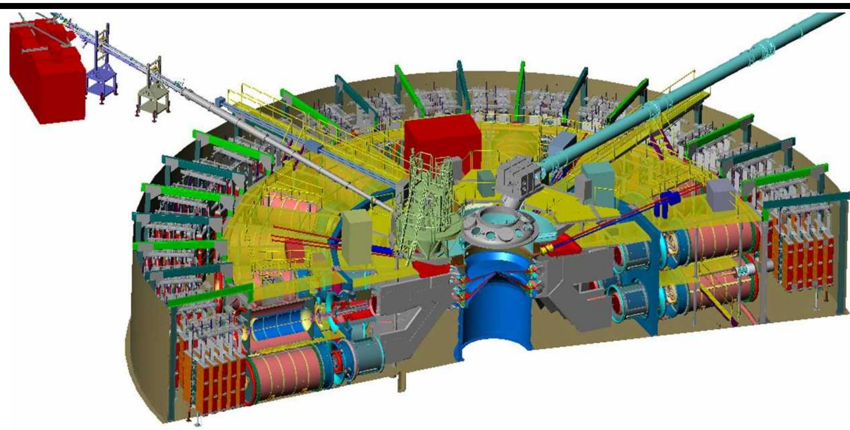
- SGEMP
  - More complex cavities to test 3D effects
  - Higher photon energies to test emission models (present Z experiments are at 7 to 8 keV with different materials)
- Material Properties
  - Radiation driven experiments with more penetrating x-rays
  - New RB/RV materials
  - Accurate (few %) materials data
  - Data to support LIHE tests
- TSR/TMS
  - Scaled tests with soft x-rays to complement work with e-beams
- Warm x-rays
  - Higher fluence capabilities
- Improved yield measurements
  - New thermo-elastic calorimeters using particle displacement interferometer has given accurate yield measurements
  - The AWE calorimeters are giving good data

What is ZR?

Refurbishment of the Z Pulsed Power Accelerator



ZR will extend the yields and useful photon range for effects tests



Generator	>1 keV (kJ)	3 keV (kJ)	5 keV (kJ)	7 keV (kJ)	8 keV (kJ)	10-13 keV (kJ)
10 MA Saturn	75	35	10	2	2	0
20 MA Z	450	300	100	50	18	*10*
26 MA ZR	900	500	300	200	72	*40*

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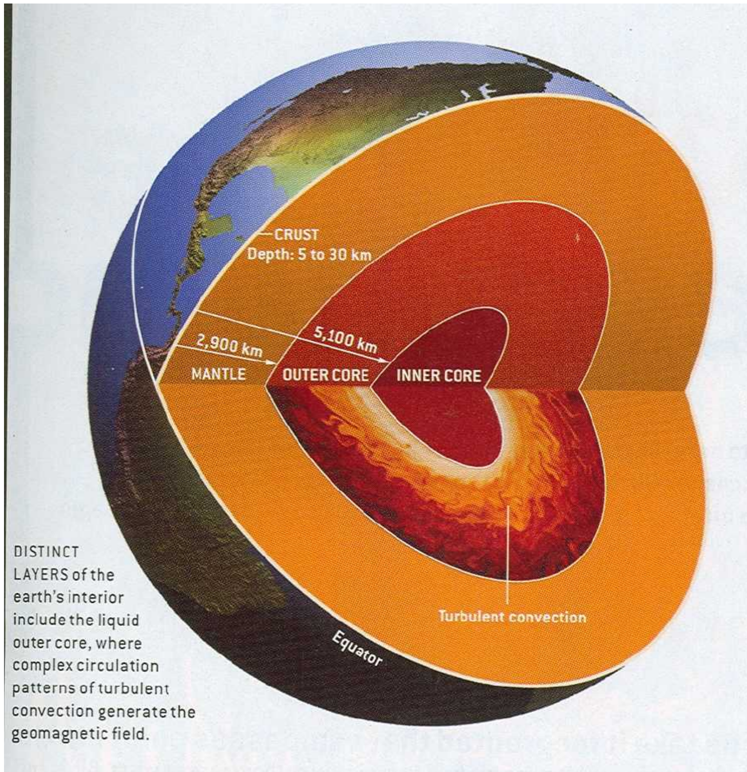
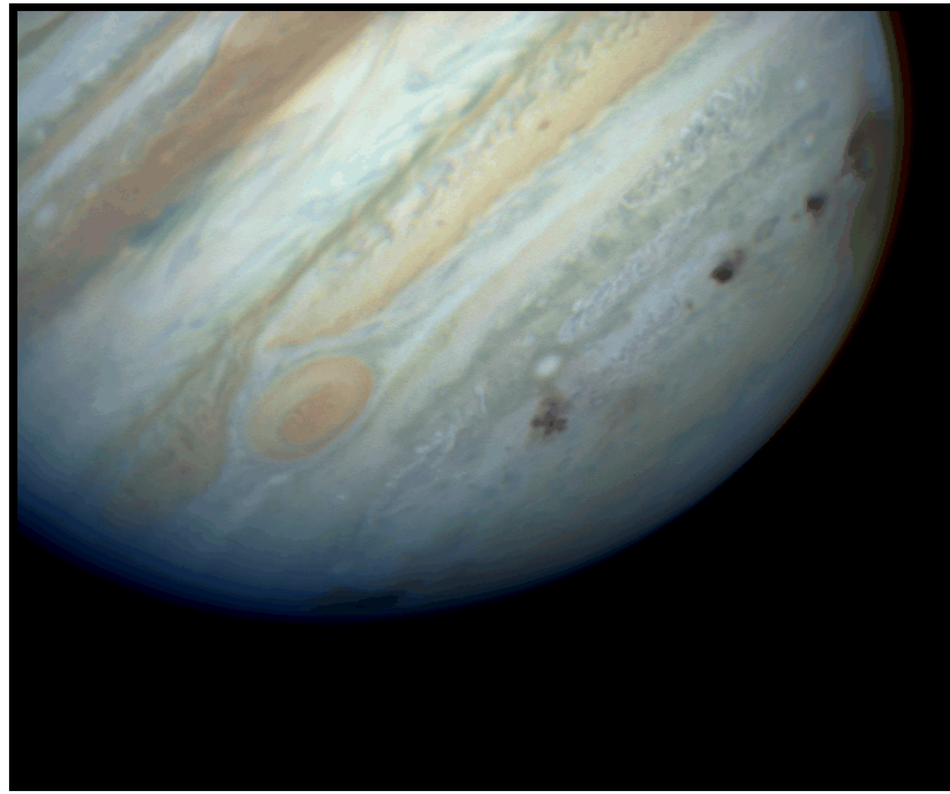
Dynamic Material Research using Pulsed Power





Magnetically driven dynamic material experiments reach conditions similar to those in the interior of planets

National Nuclear Security Administration

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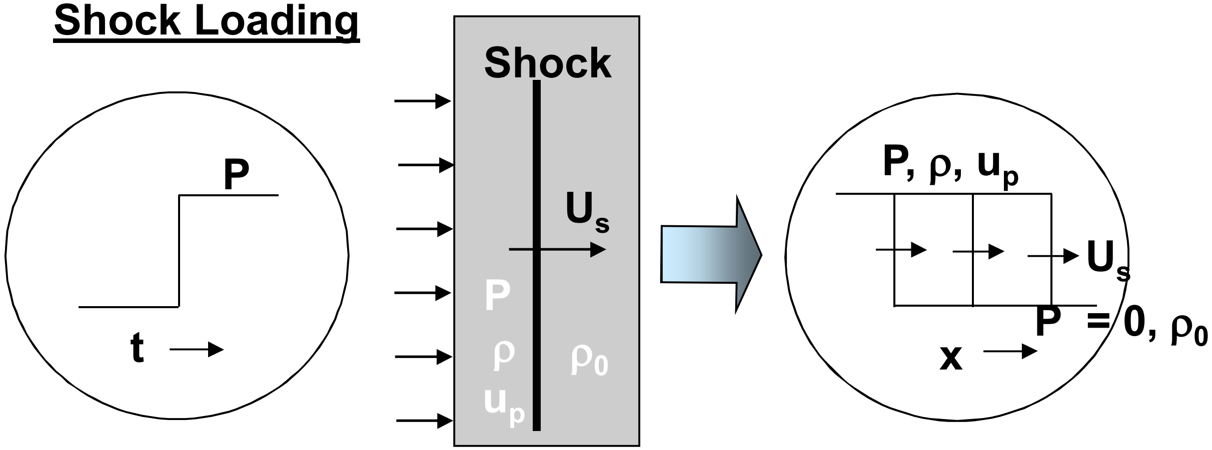
Planar conservation equations are used to obtain P(V) data for shock and isentropic loading

Shock Loading



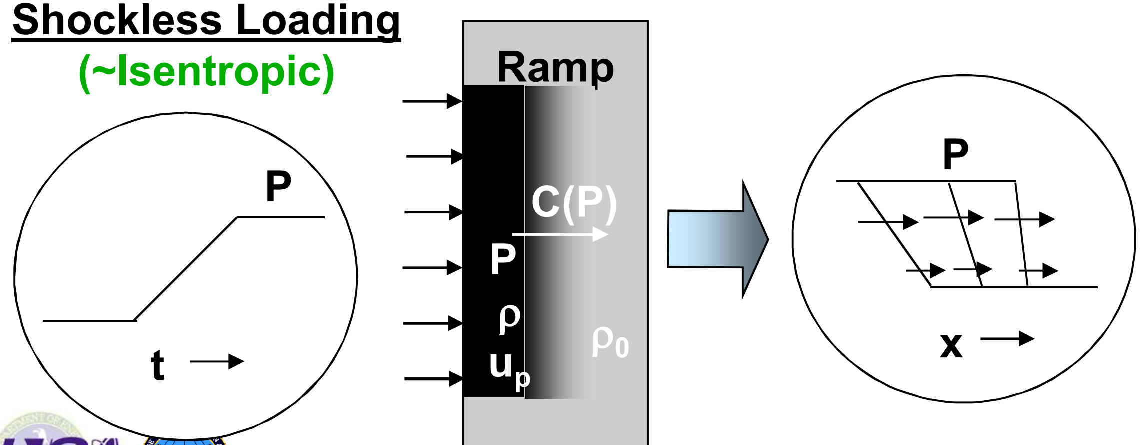
$$P = \rho_0 \, U_s \, u_p$$

$$\rho_0/\rho = 1 - u_p/U_s$$

} $P_H(V)$

Shockless Loading

(~Isentropic)



$$\frac{\partial \sigma_x}{\partial x} = -\rho_o \frac{\partial u}{\partial t}$$

$$\frac{\partial u}{\partial x} = \rho_o \frac{\partial V}{\partial t}$$

} ~ $P_S(V)$

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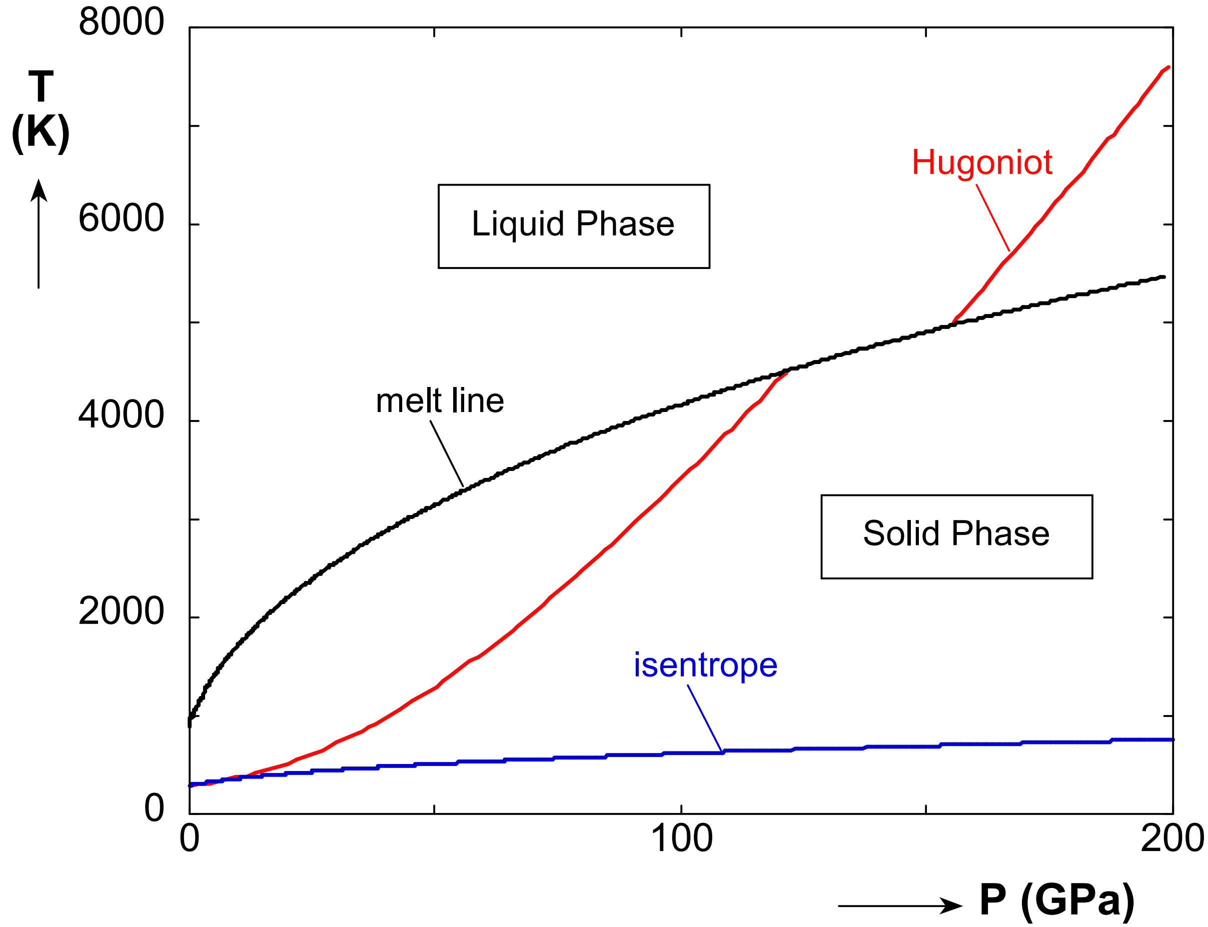
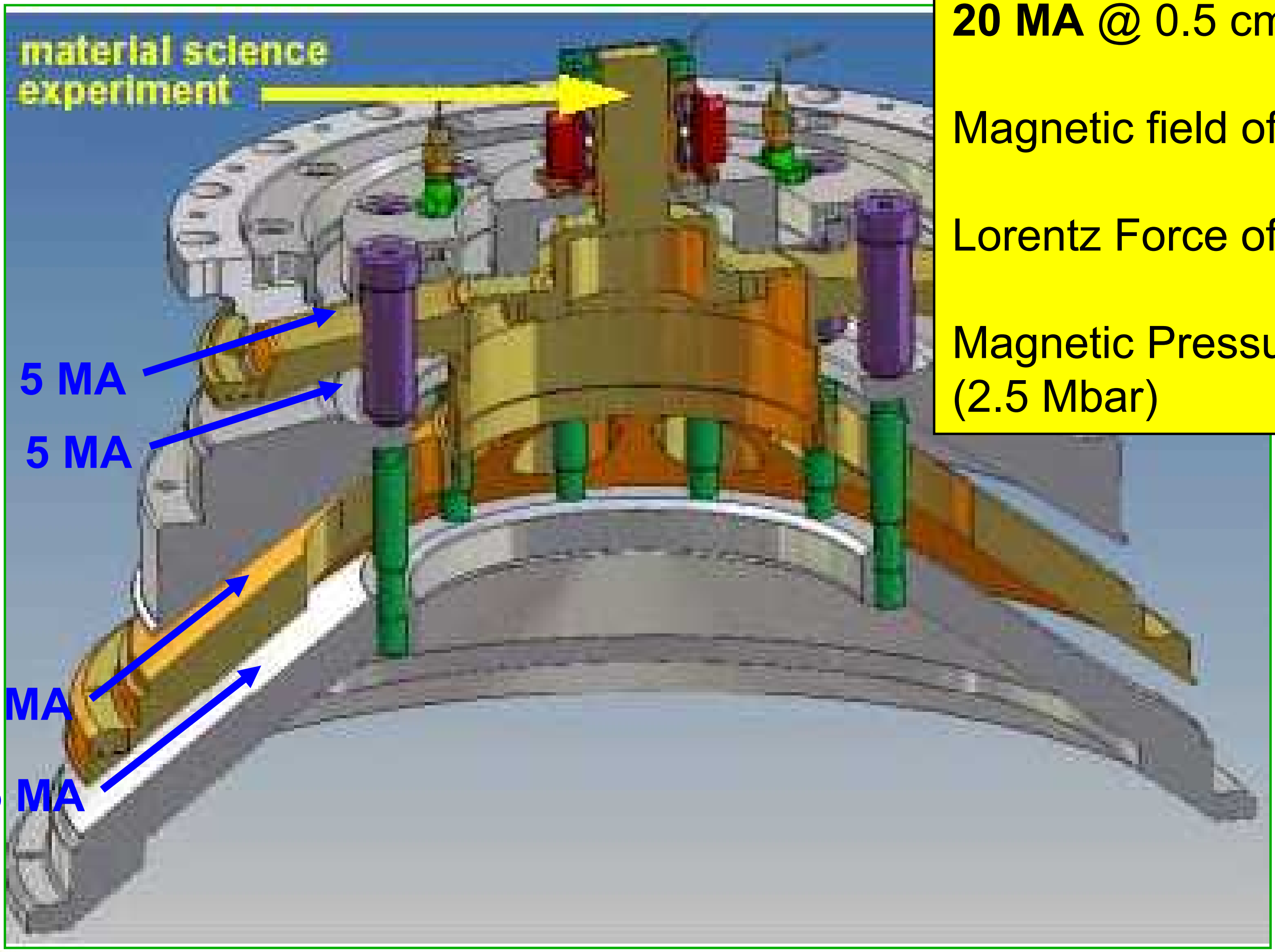
Phase Diagram for Aluminum



- **Hugoniot passes into Liquid phase at ~120 GPa**
- **Isentrope remains in solid phase**

Converging current into a small circumference produces large forces and extreme pressures



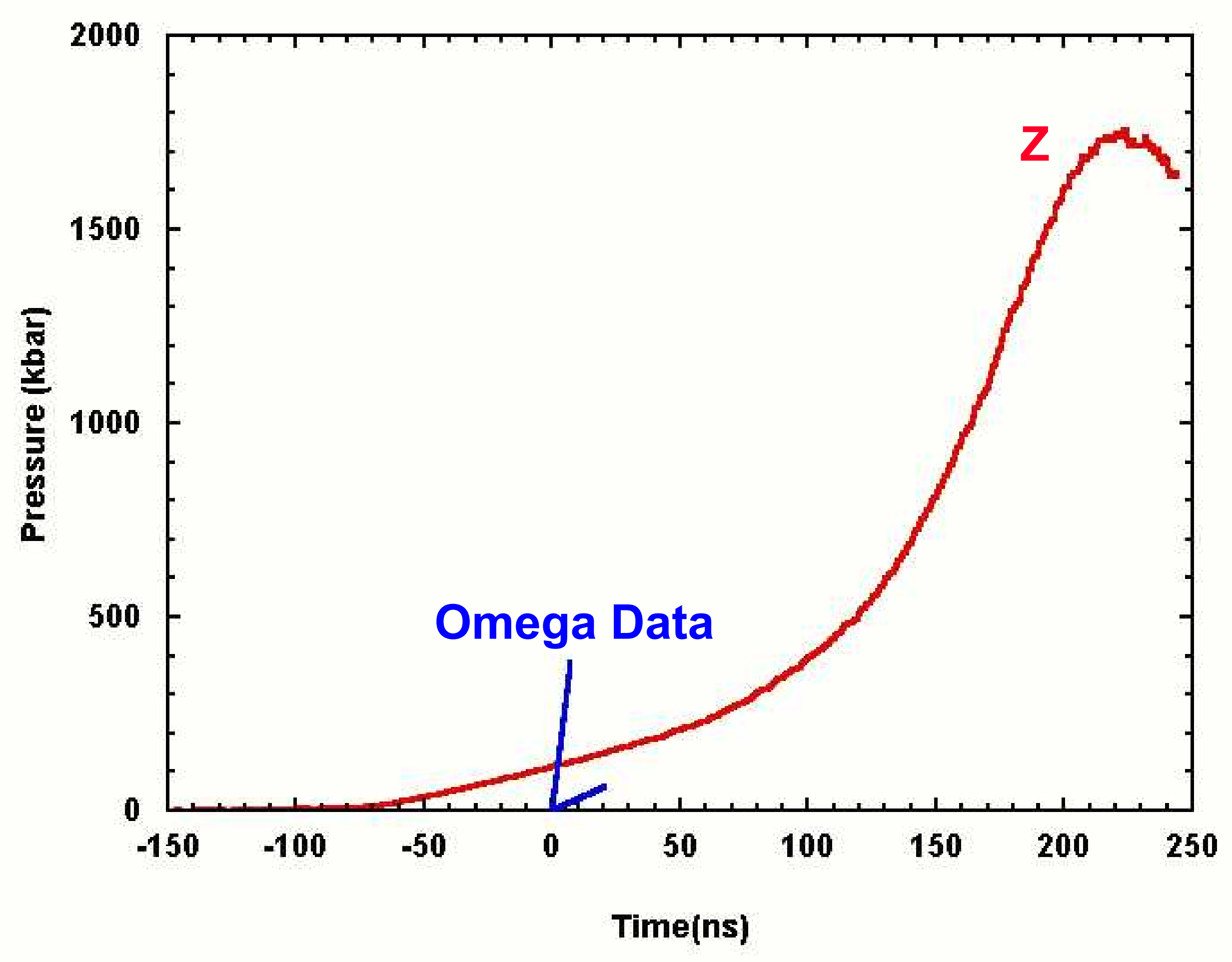
20 MA @ 0.5 cm

Magnetic field of **800T** (8 MG)

Lorentz Force of approx. 1×10^9 **N**

Magnetic Pressure of **250 GPa** (2.5 Mbar)

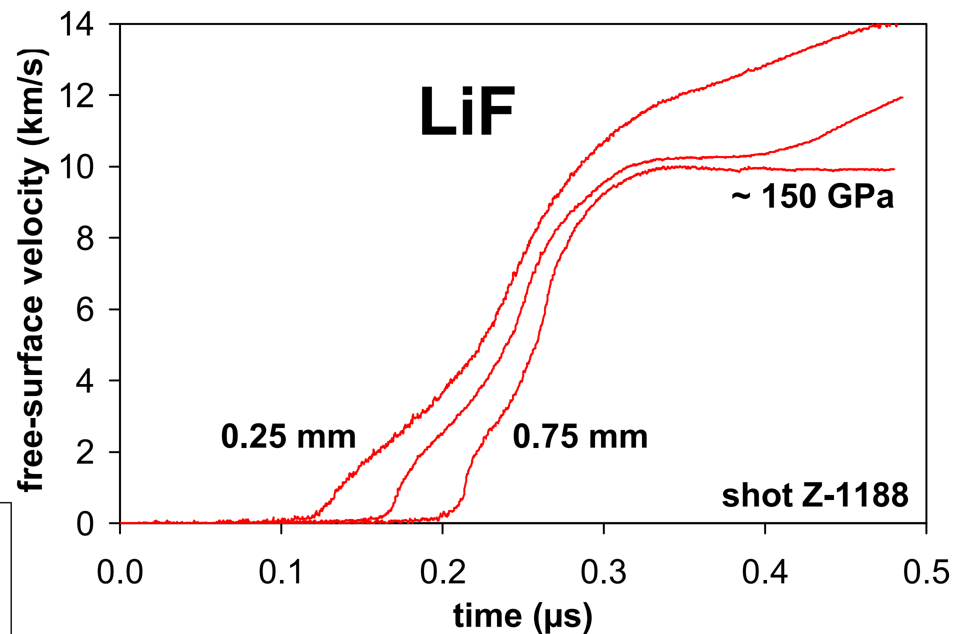
Our competitors -Laser vapor drive techniques have a long way to go!

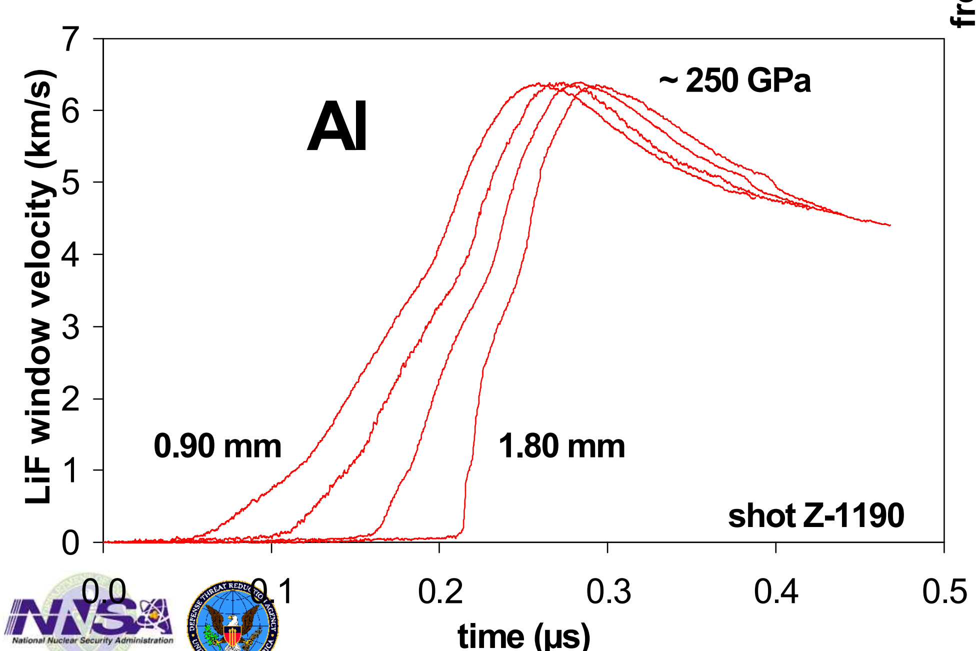


Graded density impactors on gas guns are also being looked at by LLNL – not scalable to high pressures though

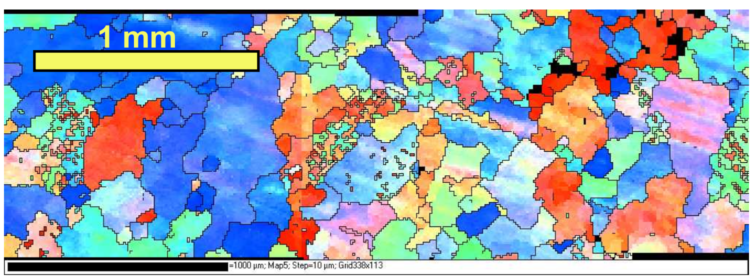
Recent experiments have shown an improvement in the ability to obtain desired shape

Al	250 GPa	1.8 mm
LiF	150 GPa	0.8 mm
Ta	300 GPa	0.7 mm

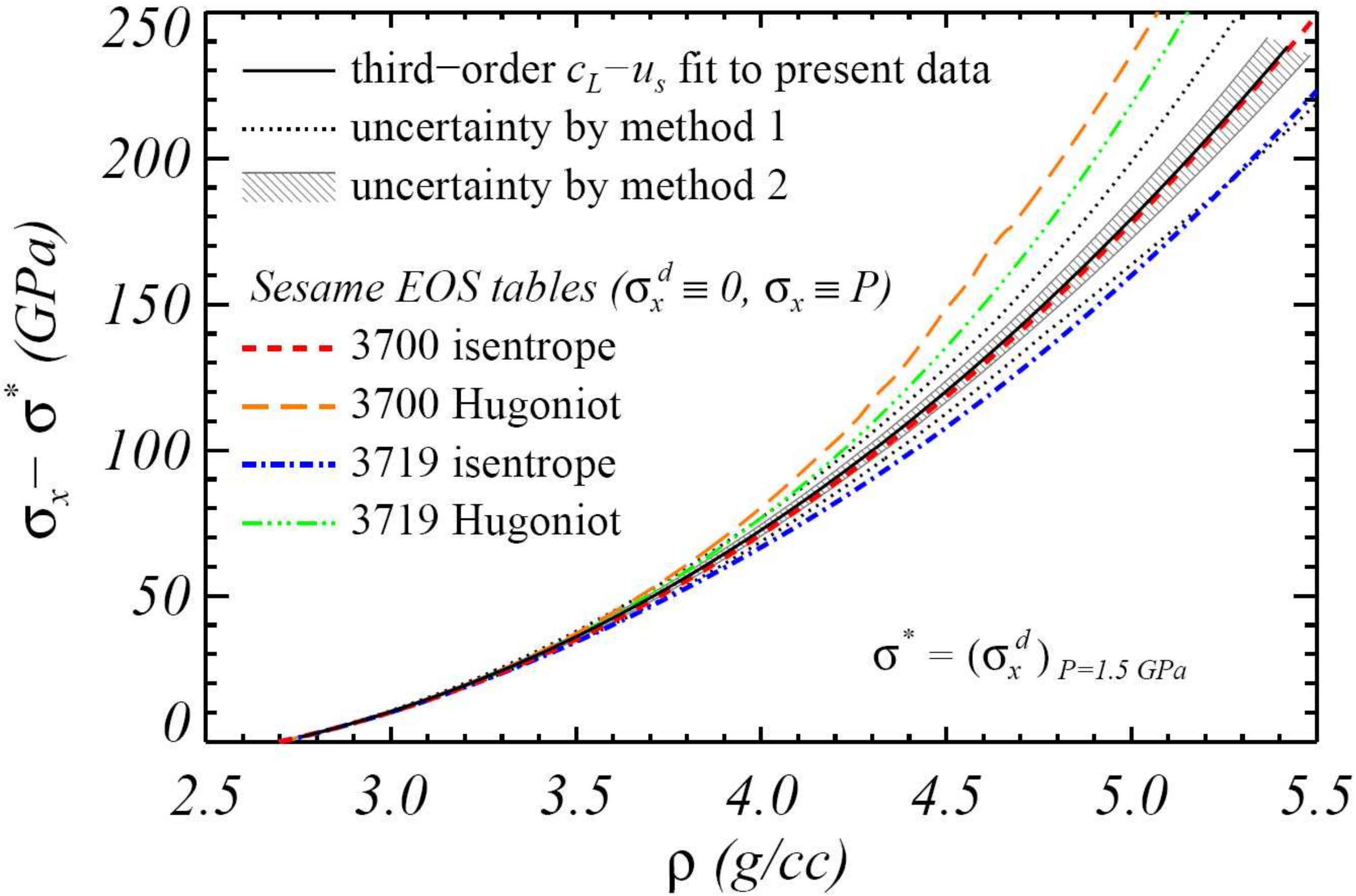




Iron Grains



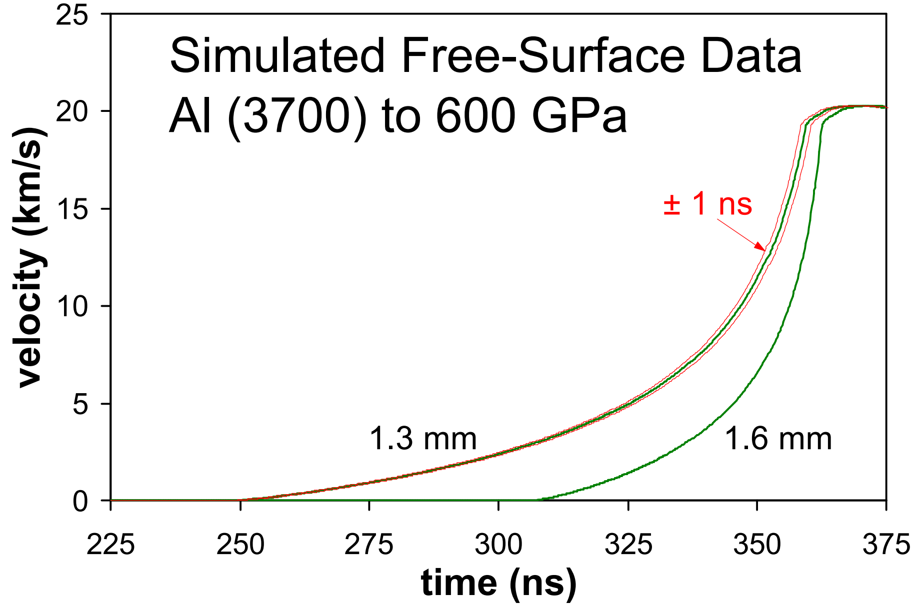
Aluminum isentrope measured to 2.5 Mbar

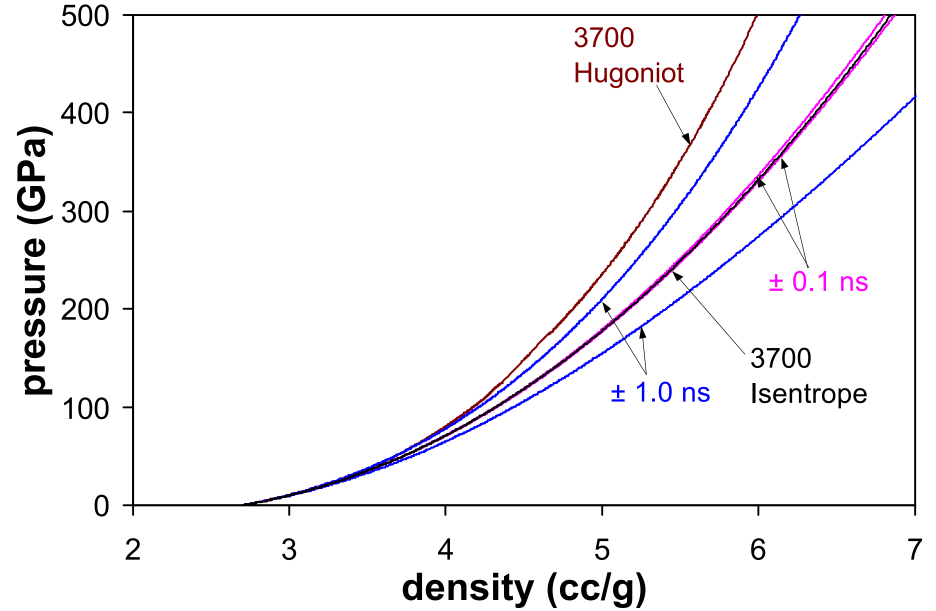


Presented as an Invited talk at the 2005 SCCM meeting in and published in Phys. Plasmas. May 2005

Timing accuracy of order +/- 100 ps needed for better than 1% accuracy in multi-Mbar P(ρ)

Δx = 300 μm

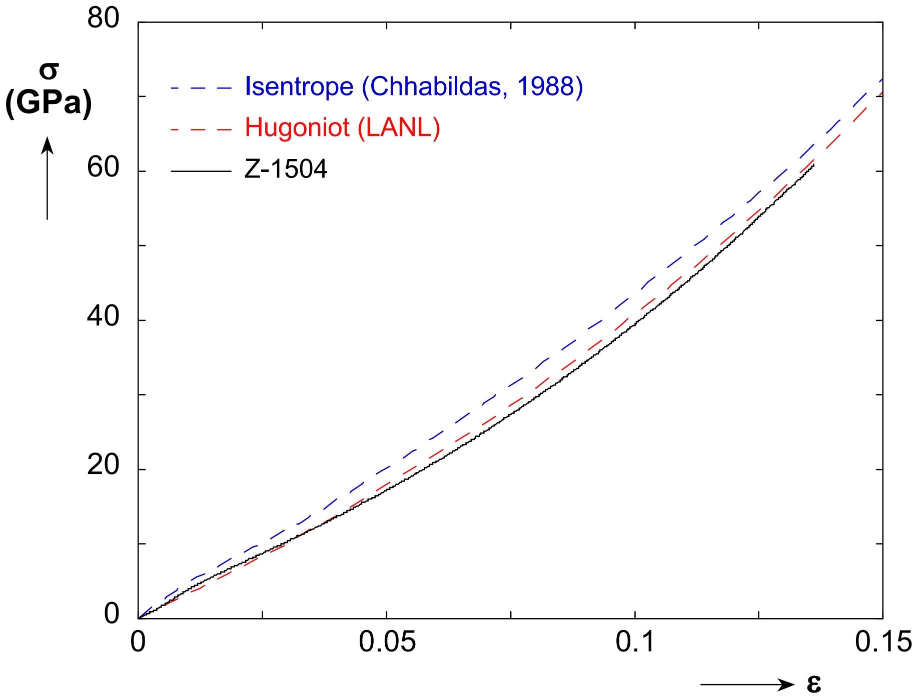


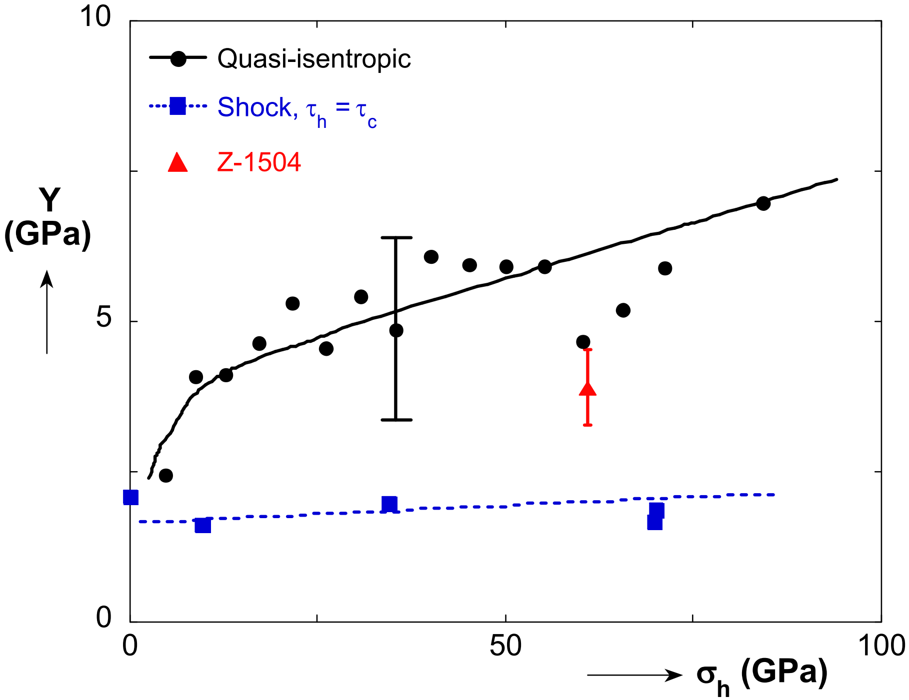


Strategy to approach "1%":

- Pulse shaping to get big step sizes and multiple profiles
- Better timing accuracy on VISAR
- Streak Cameras with line VISAR

Tungsten isentrope measured to 61 GPa, but we have been having issues with current symmetry on high pressure shots – a new load design will be tested at the end of Q1 FY06

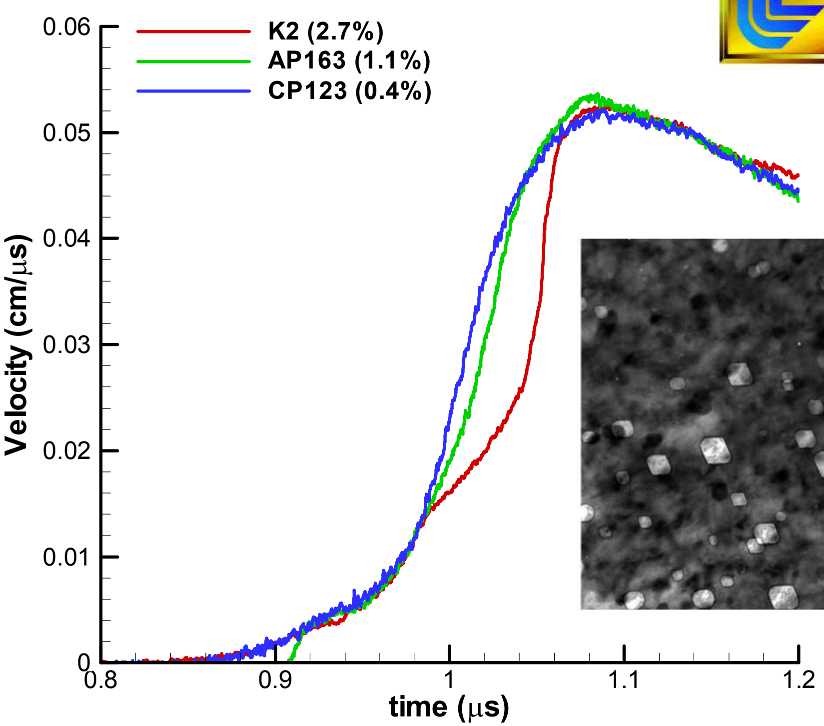


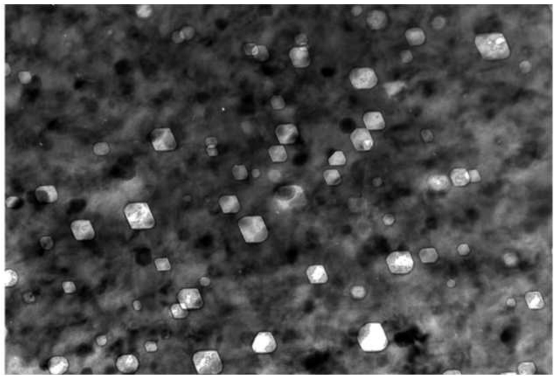


Effects of radiation induced damage (aging) in stainless steel is clearly seen using ICE techniques

Four days to clean-up without containment

800 μm Irradiated Stainless Steel





Isentropic compression of irradiated stainless steel on the *Z* accelerator

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(Received 13 January 2003; accepted 13 March 2003)

We have performed quasi-isentropic compression experiments on radiation-damaged stainless steel. The samples were dynamically loaded by Sandia National Laboratory's *Z* accelerator with a ramp compression wave. Sample/window interface velocities were recorded with VISAR. The velocity histories suggest a sudden volume reduction of the material above 40 kbar caused by the collapse of nanosized voids. This is predicted by a theoretical model of void collapse based on the emission of vacancy-type dislocations loops. We compare the results of these experiments to hydrodynamic calculations performed using a constitutive model which is derived from the atomistic void collapse mechanism. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1571969]

I. INTRODUCTION

Quasi-isentropic compression experiments (ICE) are a technique for producing near-adiabatic loading of materials using the pressure from the strong magnetic pulse generated from the *Z* accelerator.[1,2] This technique allows the isentrope of a material from an initial state to be measured in one experiment over a range of zero to the peak pressure in the ramp wave. Using this method the isentropes of many materials ranging from metals such as copper and aluminum[1,2] to organic materials such as high explosives[3] have been determined to high accuracy.

ICE wave profiles develop features that mirror the material response of phase transitions, elastic-plastic transitions, or changes in compressibility. In the following sections we will describe experiments which exhibit volume collapse in a material due to the squeezing-out of nanosized voids. We introduce an atomistic model for this process, and we construct with it a macroscopic constitutive model. Using this model in a hydrodynamic code we compare calculated and experimental velocity histories, and demonstrate that a void collapse process by dislocation loop emission explains well the observations.

II. EXPERIMENT

Isentropic compression experiments were performed on irradiated 304 stainless steel samples using the "square short" assembly.[1,2] In this configuration pairs of samples consisting of 6 mm diameter disks of thickness 400 and 800 μm were placed on copper driver panels of base thickness 400 μm (Fig. 1). Windows of LiF were bonded to the back of the stainless steel samples to minimize wave interactions and to aid in the analysis. Each sample pair had a different amount of void swelling, or porosity. The values chosen were 0.0%, 0.4%, 1.1%, and 2.7%. The material originated from components of the EBR-II nuclear reactor, except for the material with no voids which came from archive samples not exposed to neutron irradiation. The void swelling in the irradiated samples had been measured earlier by immersion density. Furthermore, other samples from the same components had been examined by transmission electron microscopy which provided visible evidence of the size and density of the voids. A example of the numerous pictures obtained is shown in Fig. 1.

A pressure ramp of approximately 200 ns duration and peak pressure of approximately 160 kbar was applied to the copper surface (Fig. 2). The resulting stainless/window interface velocities were recorded using single-point VISAR.[4]

The inflection seen in the velocity versus time curve for the porous samples suggests that the material has undergone a volume collapse (Fig. 3). This is commonly referred to as a two-wave structure and is typical of samples undergoing a phase transition where a volume change is involved.[5] Due to the structure of the pressure–volume ($P-V$) diagram, the isentropic compression wave will split into two waves moving at different speeds. The first wave, in this case in porous material, will travel faster through the material than the second wave in the collapsed material. This means that the dis-

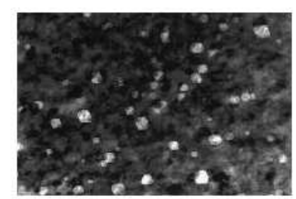
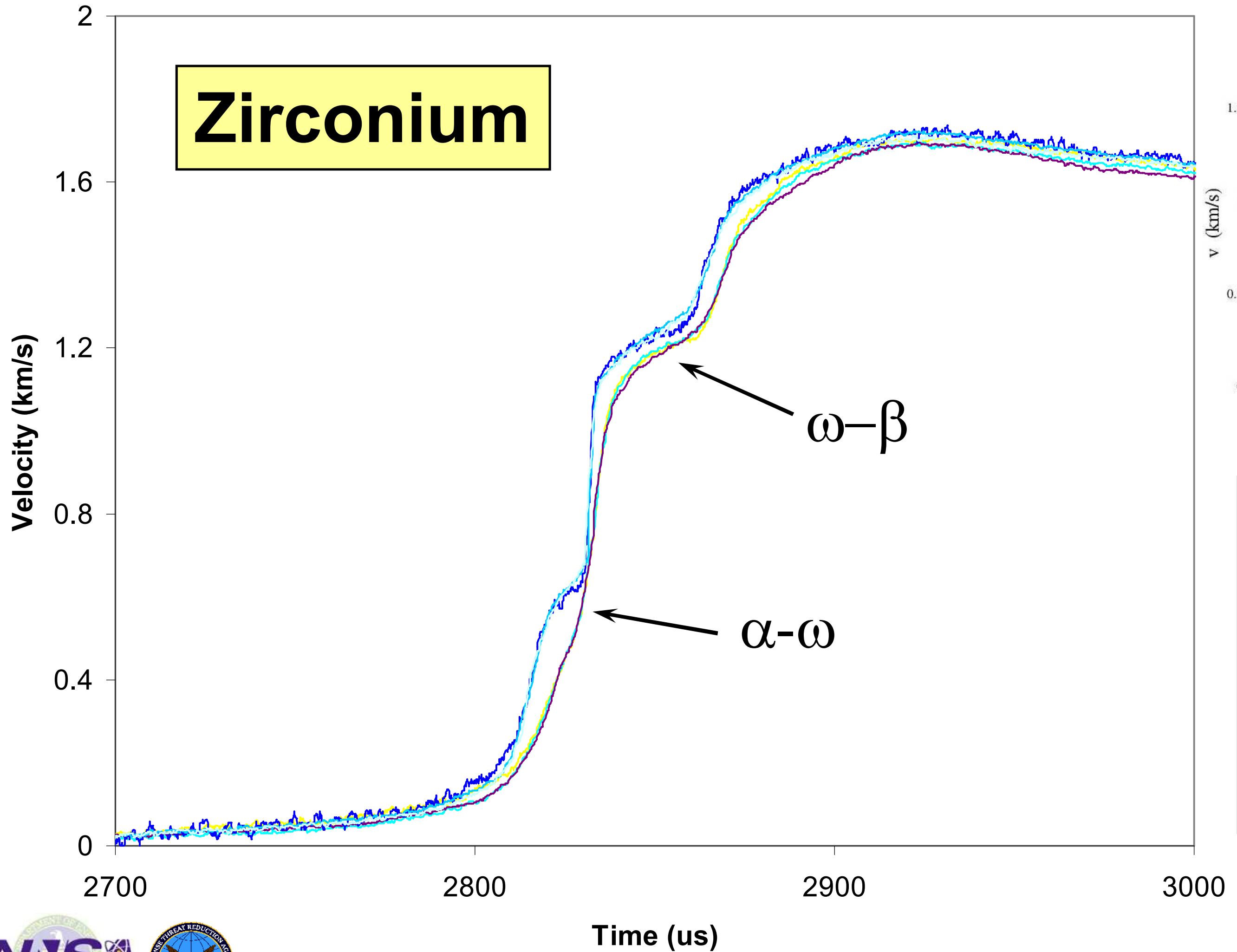
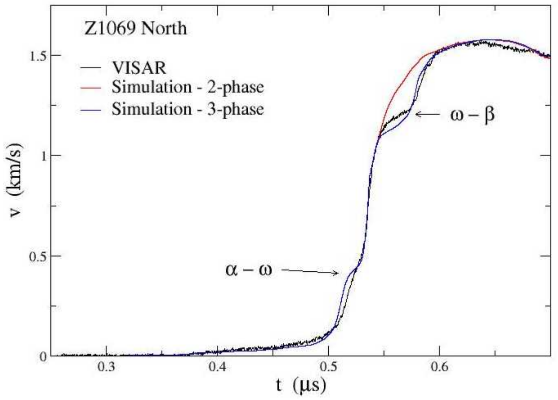


FIG. 1. Voids observed in annealed 304 AISI irradiated in EBR-II at 380 °C, 8.4×10^{-8} dpa/s to 21.7 dpa with 1% swelling (courtesy of G. H. Bond and F. A. Garner, Pacific Northwest National Laboratory).

[a]Electronic mail: reisman1@llnl.gov

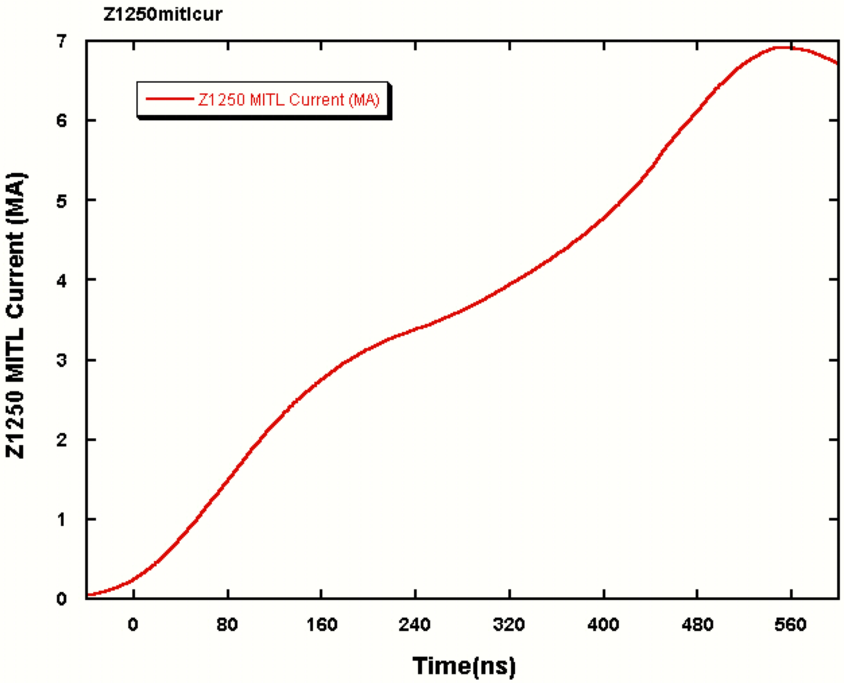
Phase transition data has been obtained on various impure samples of Zr

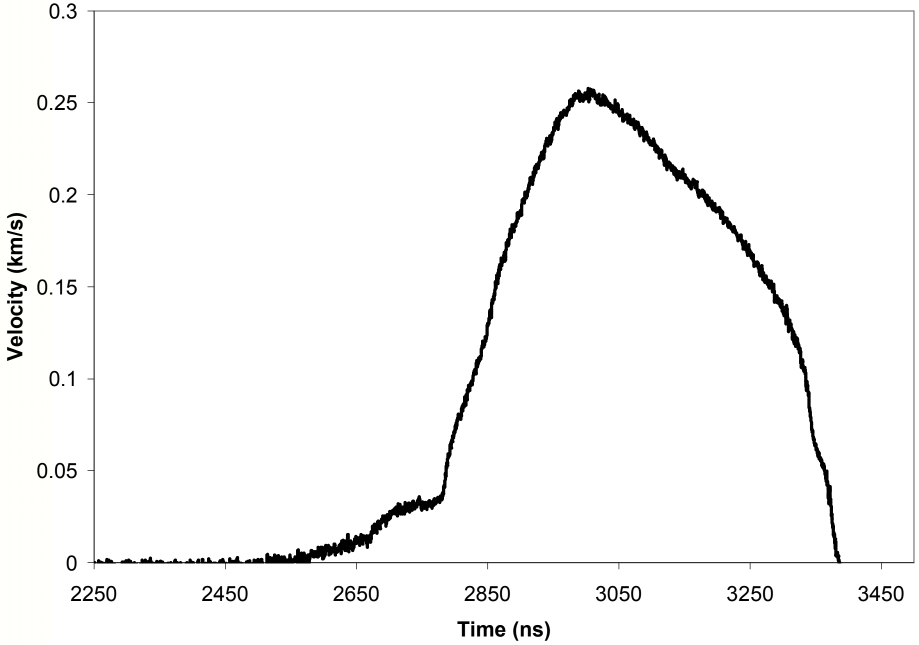




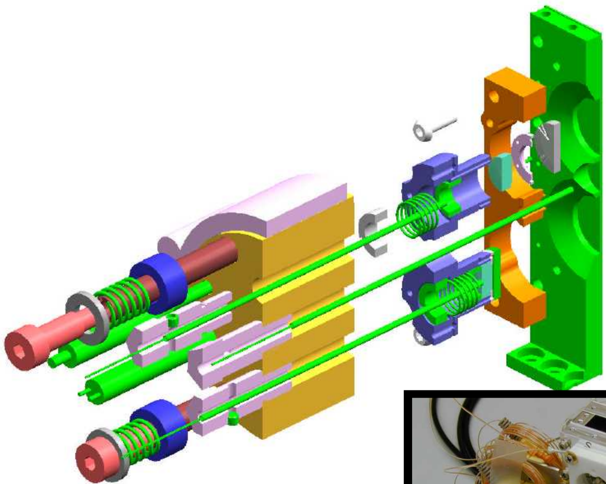
Significant differences in the α-ω phase transition observed for different oxygen impurity levels

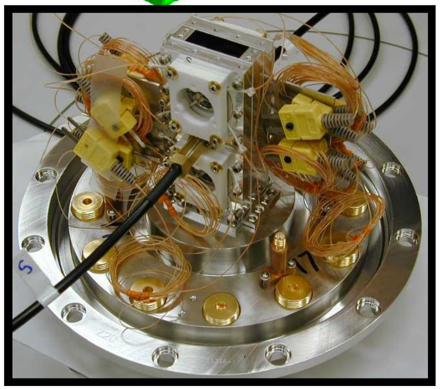
Extreme Pulse Shaping for phase transition work

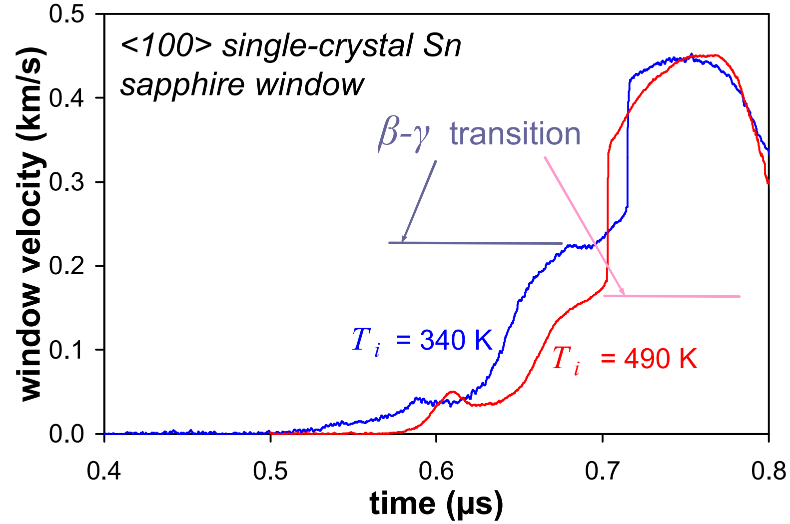


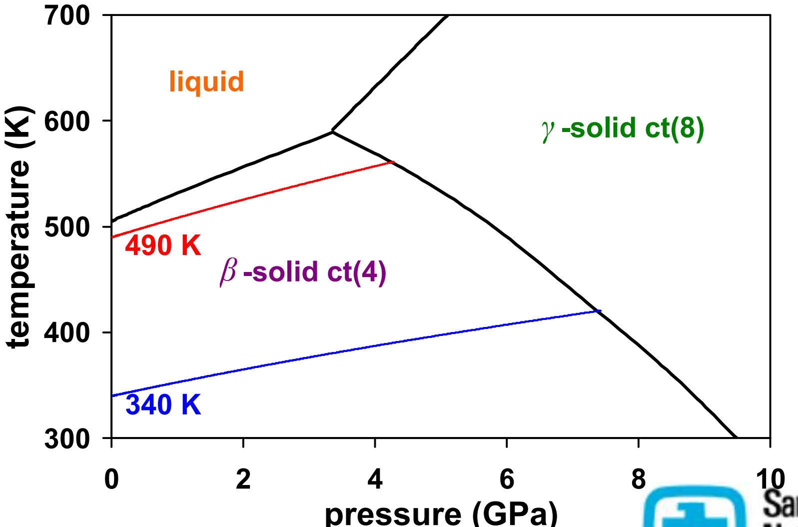


Resistive Pre-Heat: Many SSP issues require understanding of phase transitions. BN's preheat system is essential studying phase transitions









- heat up to 8 samples per shot using 4 heaters
- all samples same temperature, or ΔT up to 150°C
- max. T > 500°C pending bond & window issues
- up to 20 thermocouples
- In FY05, we will complete the technology transfer to SNL

NNSA National Nuclear Security Administration

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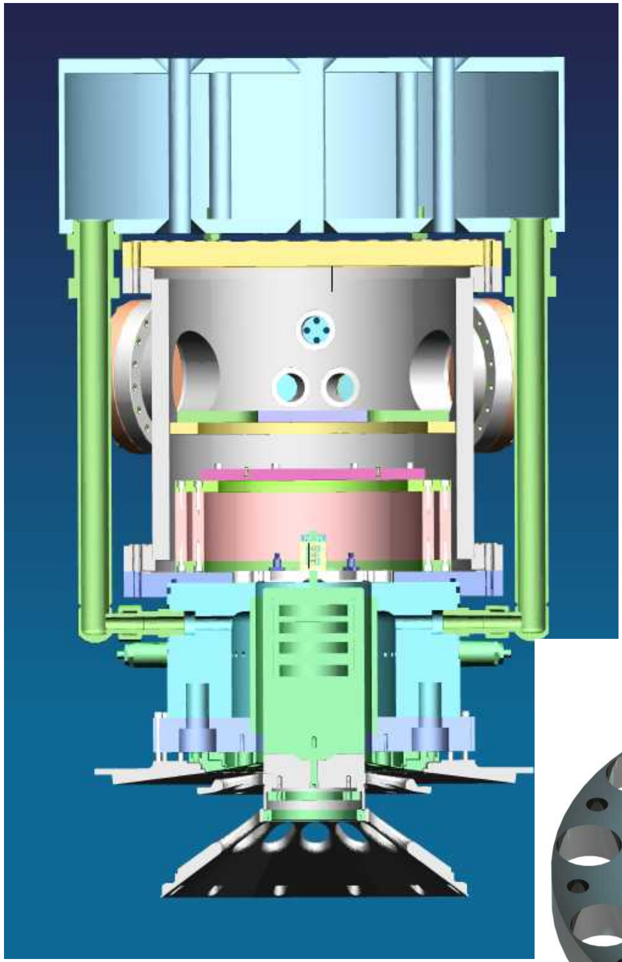
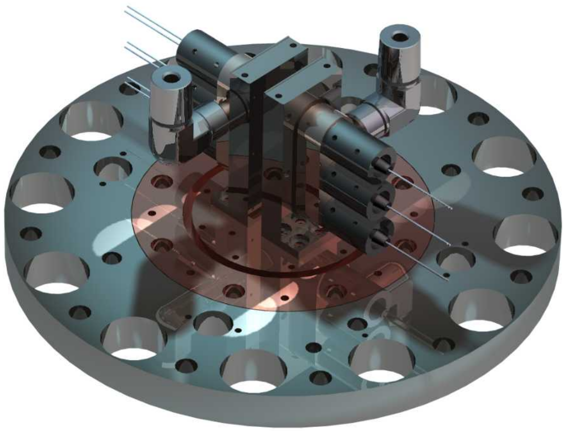
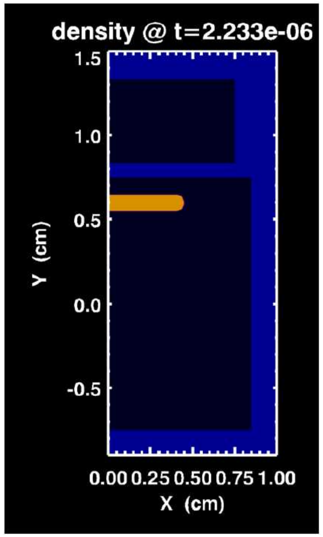
Pu on Z is moving into the final stretch

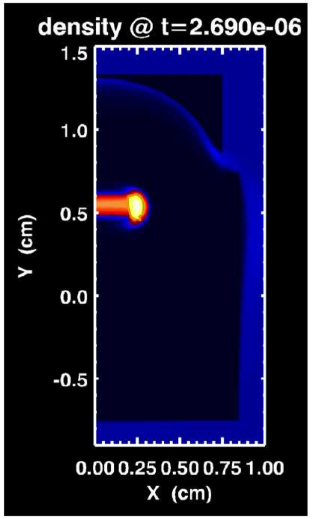


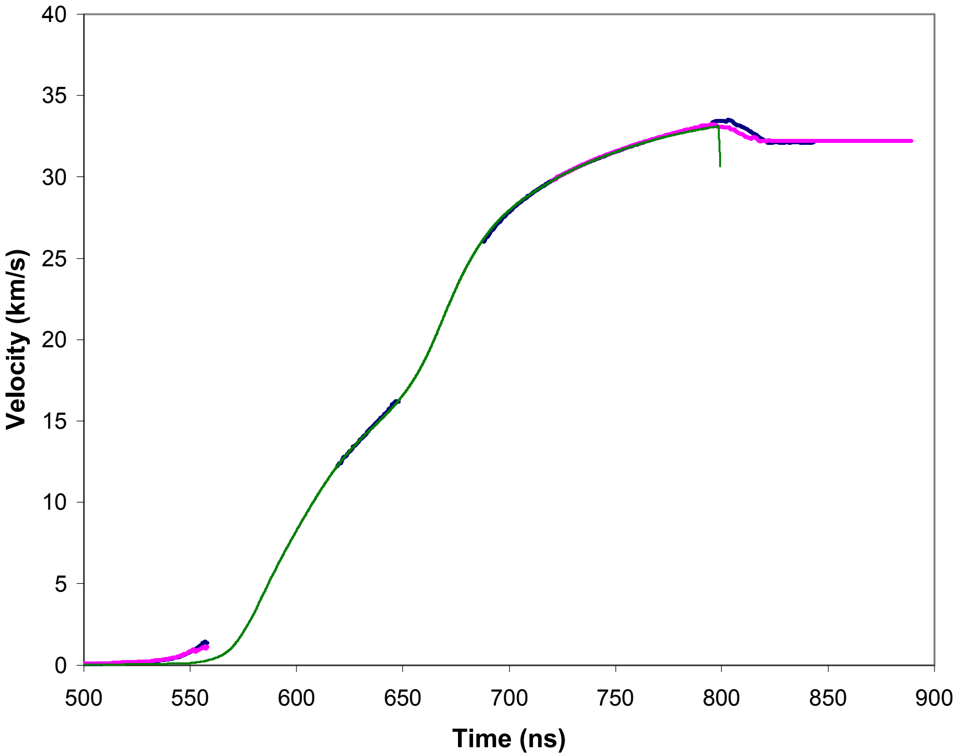
- LANL are preparing the samples.
- The Management Self-assessment began on Nov 21st
- The Corporate assessment is due to start in December.
- SSO has reviewed the Standalone HA.

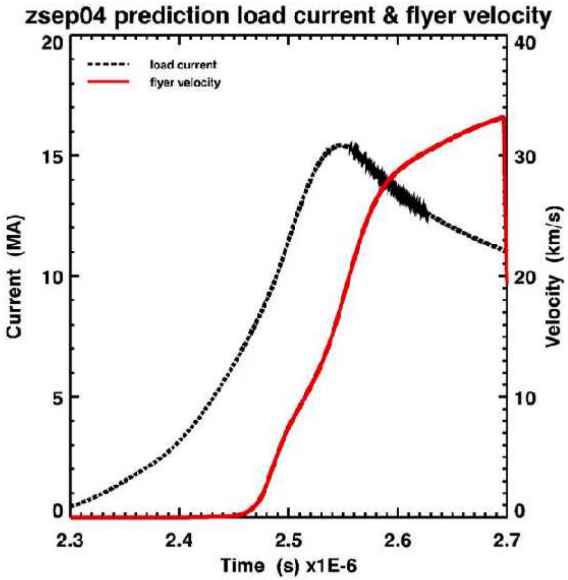


Z shot confirmed Alegra simulations (Ray Lemke) that predicted we should achieve 33 km/s









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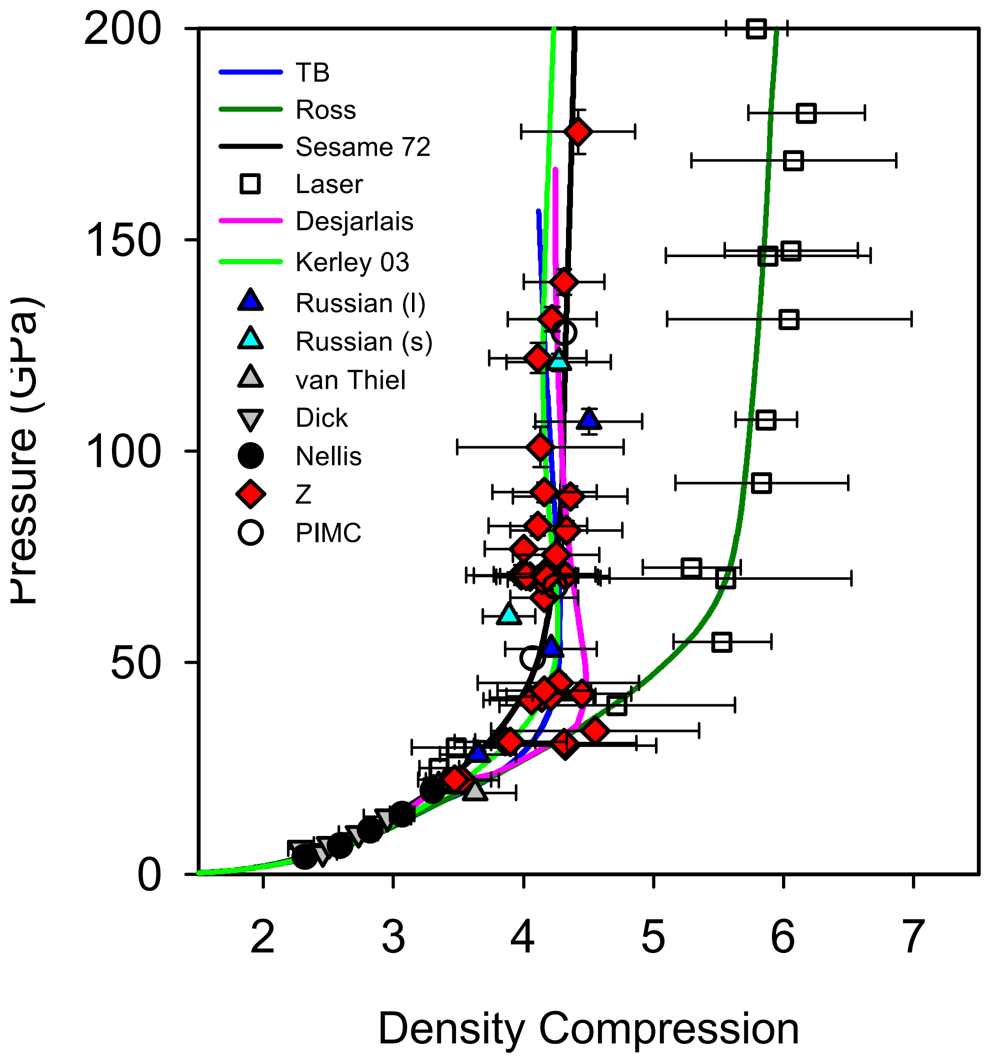
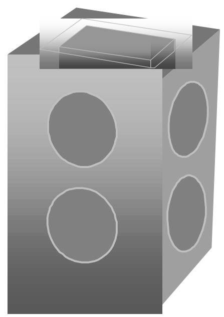
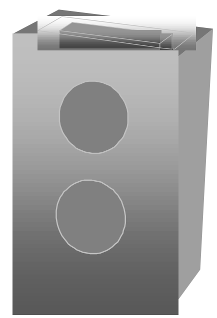
Data has been obtained to 1.75 Mbar in deuterium and 11 Mbar in aluminum



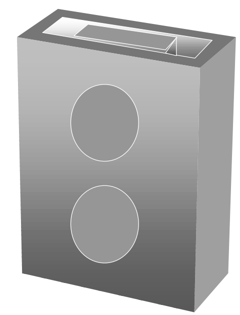
We are continuing to investigate higher pressure ICE and flyer plate configurations



Square



Rectangular

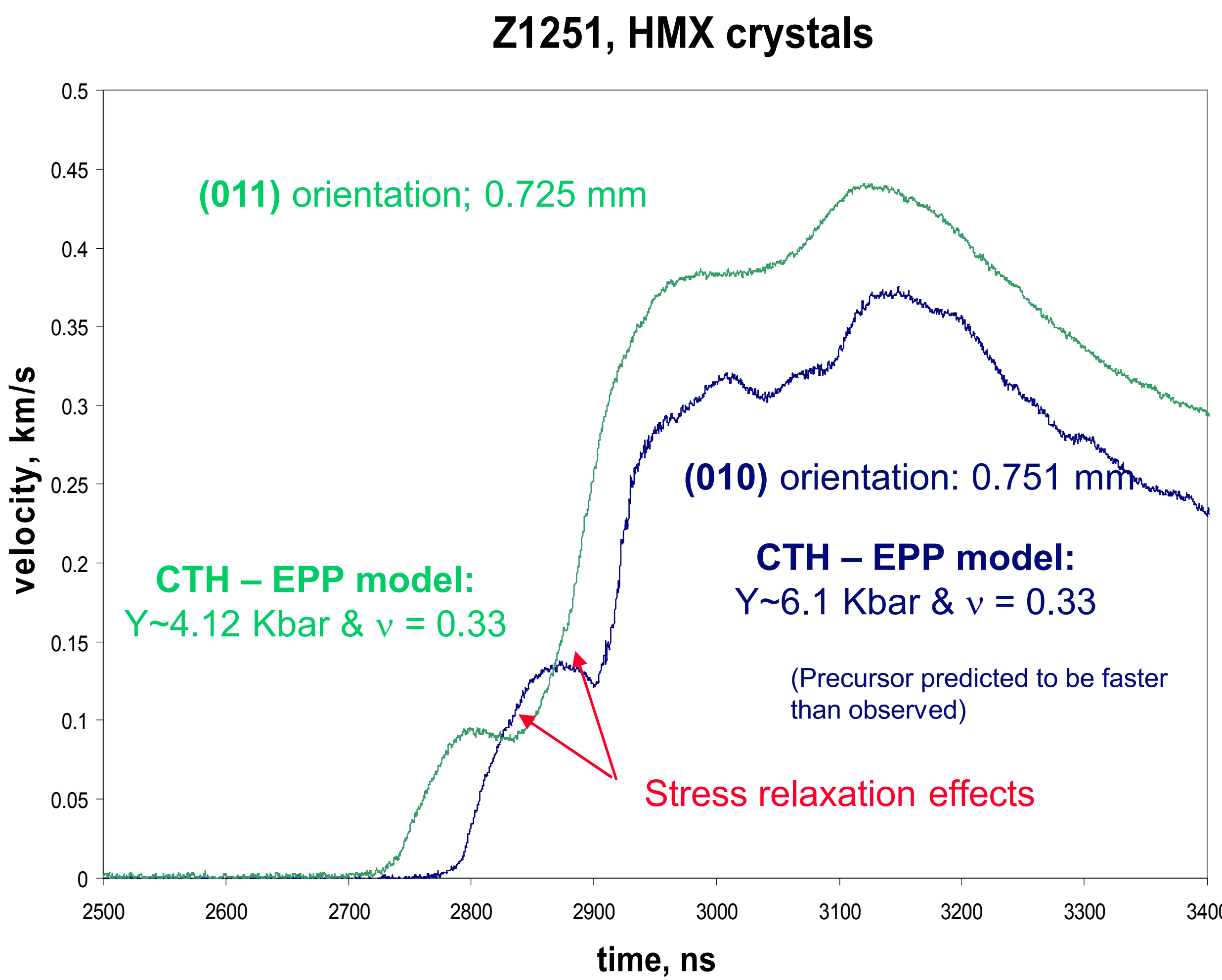


Rectangular Variant

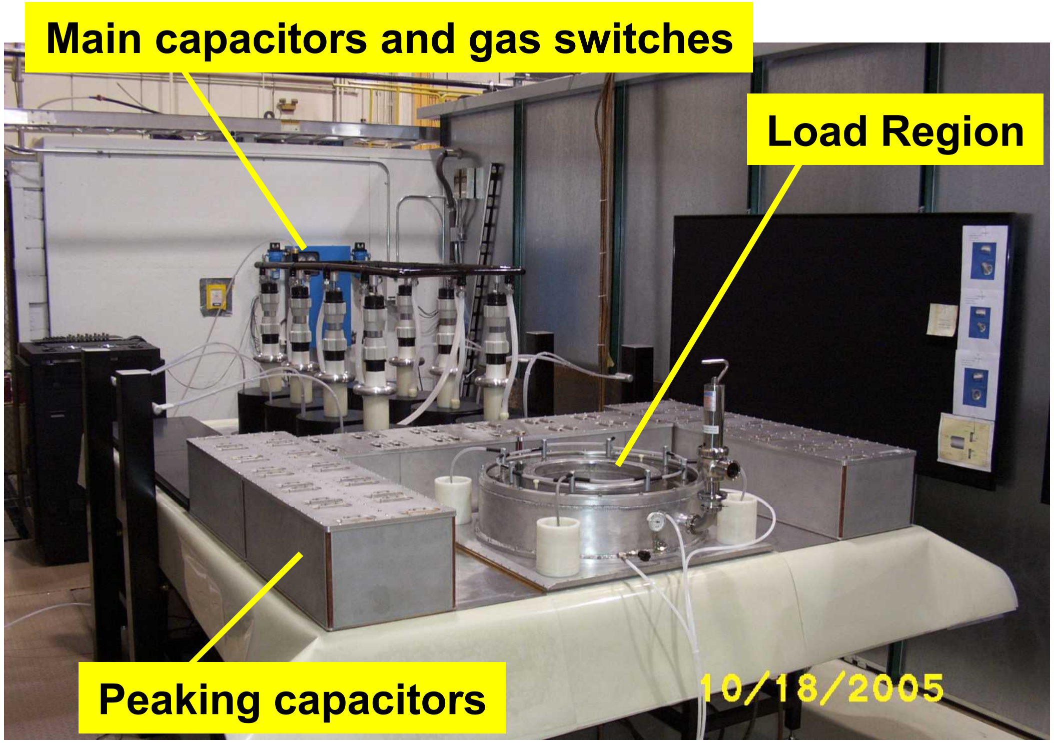
	Square	Rectangular	Rectangular Variant
Z Flyer	**16 km/s (3/6)**	**21 km/s (5/10*)**	**34 km/s (12/22)**
Z-R Flyer	**21 km/s (5/10)**	**28 km/s (10/18)**	**>40 km/s (15/30)**

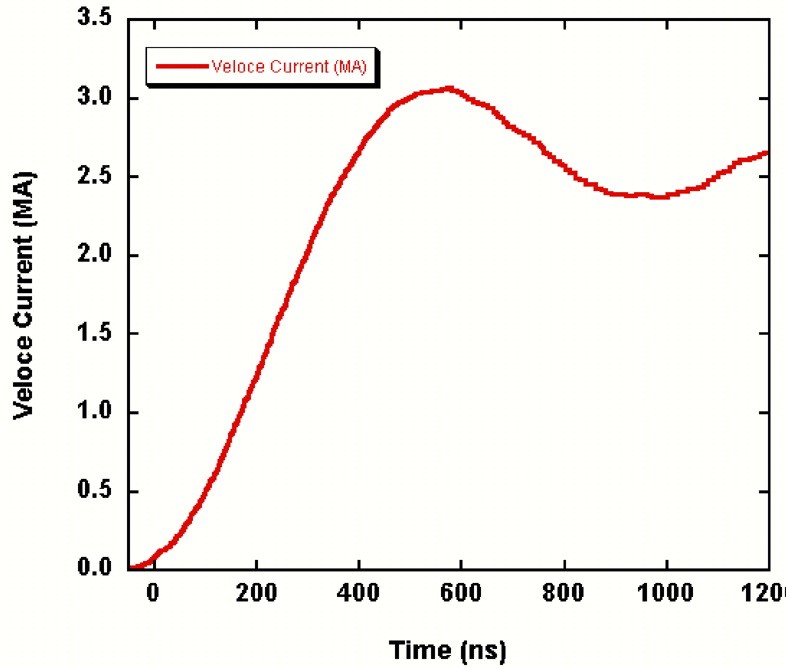
*** Mbar in Al / Mbar in Ta**

Acceleration waves in pure HMX crystals experimental observations in Z1251 test



Small pulser is operational – we will be taking VISAR data in the next month



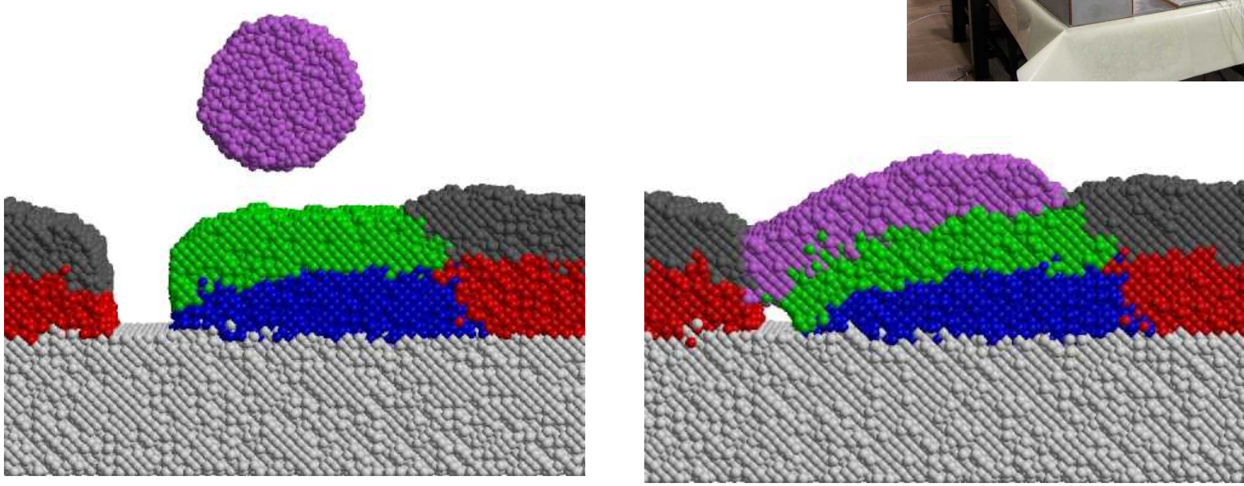


Visar system has been brought up on the gas gun
We had a capacitor failure (infant mortality) during initial pulsed power shakedown

We are demonstrating a science based engineering approach with flame sprays

Process

Dynamic experiments



Modeling

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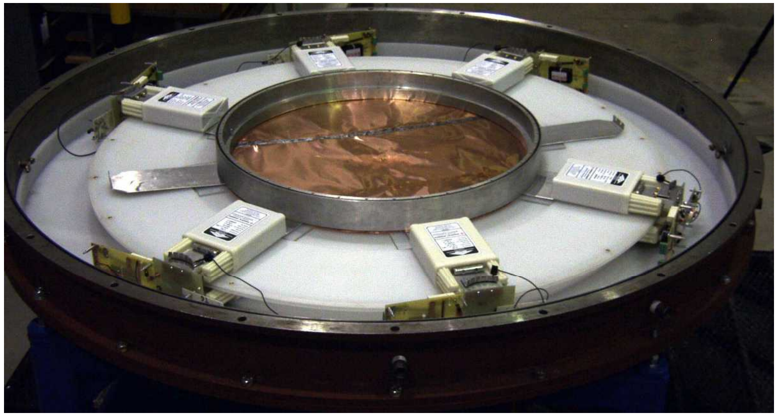
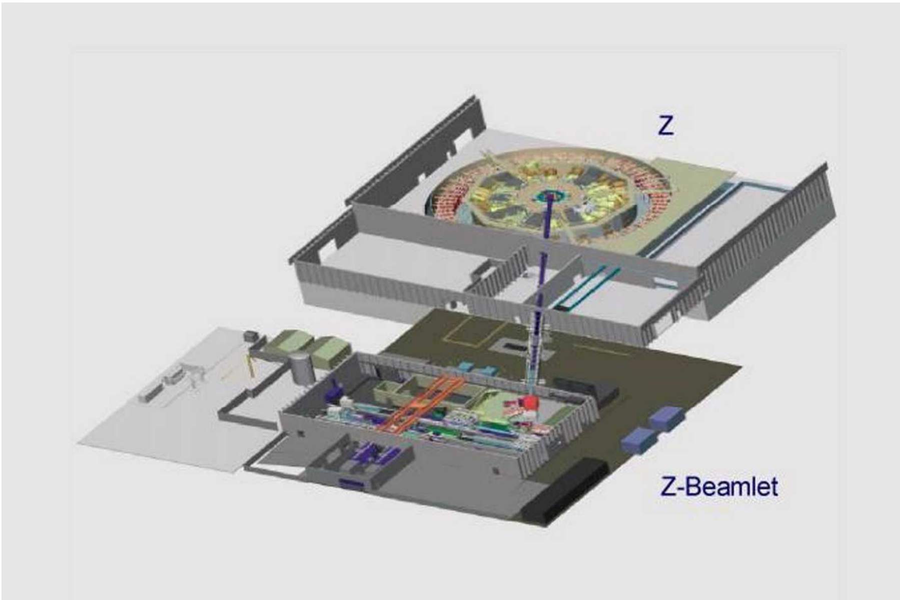
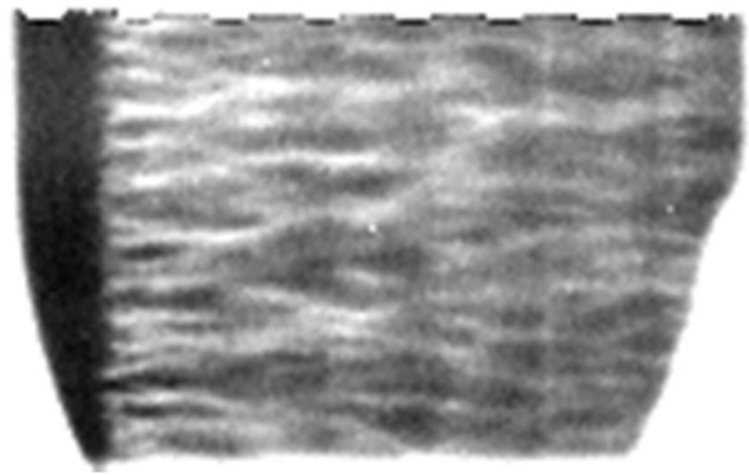
Linear transformer drivers are being considered for many applications

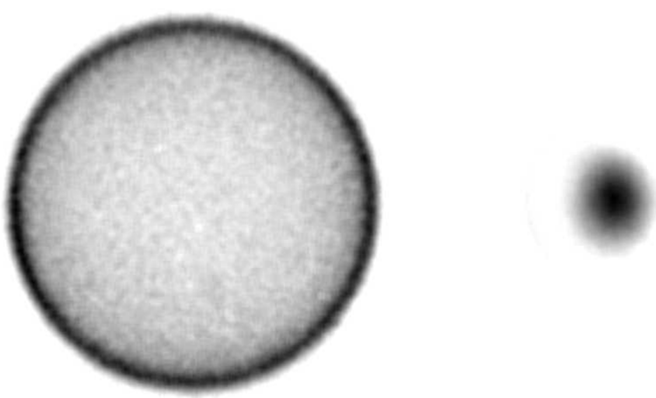


- Internal cavity pulse-shaping for ICE
- LTDs for radiography
- High current (0.5 and 1 MA) cavities for high current and IFE applications

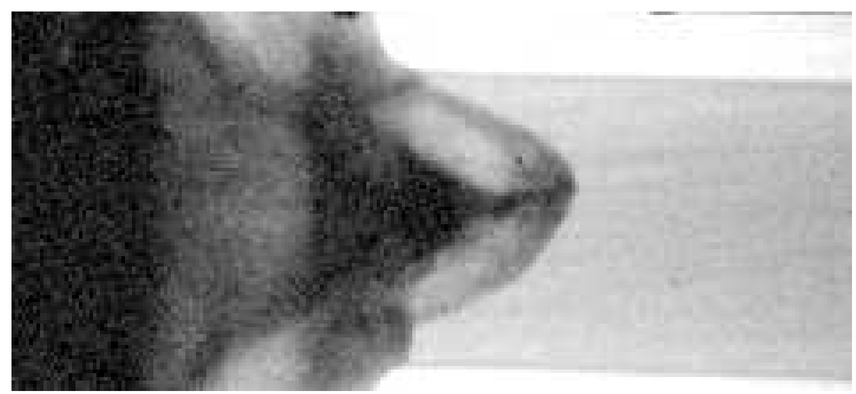
The marriage of the Z Beamlet backlighting capability to Z is a major advance





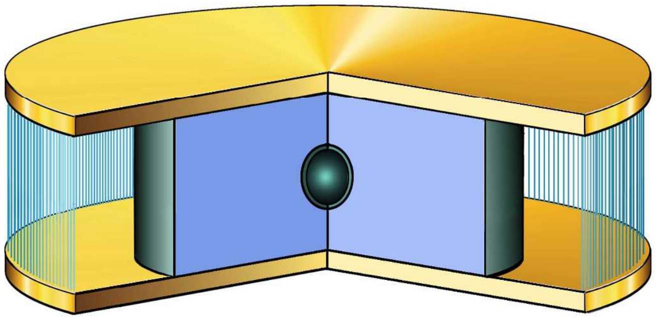


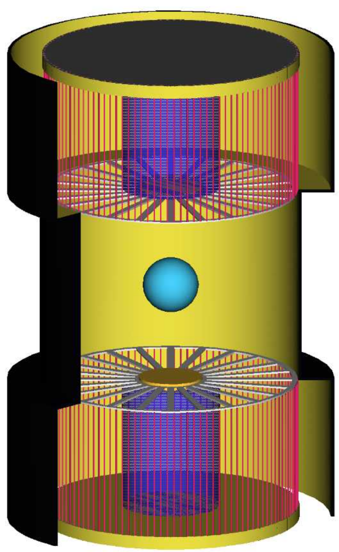
Capsule implosion imaging



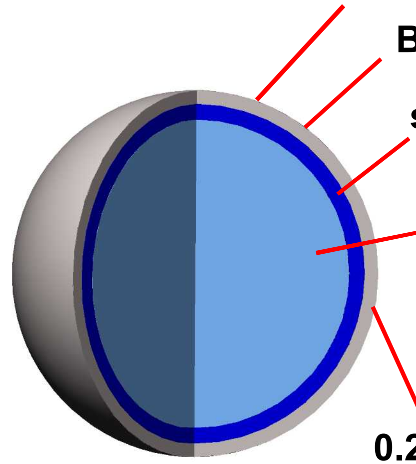
High yield fusion is one of the major motivators for the Z-pinch research at Sandia

Dynamic Hohlraum





Z-pinch Driven Hohlraum



Peak drive temperature	350 eV
In-flight aspect ratio	48
Implosion velocity	3.3×10^7 cm/s
Convergence ratio	27
DT KE @ ignition	50%
Peak density	444 g/cm^3
Total ρr	2.14 g/cm^2
Driver energy	12 MJ
Absorbed energy	2.3 MJ
Yield	527 MJ
Burnup fraction	34%

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Conclusions

- Pulsed power facilities can provide efficient, capable and flexible technologies to meet SSP needs
  - In the early 90s, pulsed power was efficient: now it is efficient and elegant!
- The Z accelerator is supporting nuclear survivability and dynamic material missions today: ZR will greatly enhance our ability to support the weapons program through the rest of this decade and the next
- The revolution that was "ICE" is driving the development of smaller facilities to enable more agile support
- Progress on high yield fusion could be a revolution in the nuclear survivability arena
- Pulsed power has become an enabling technology for transformation and responsiveness