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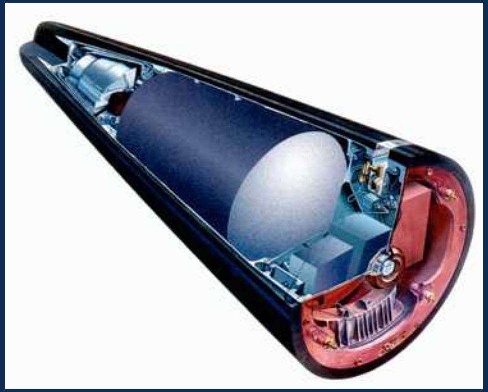

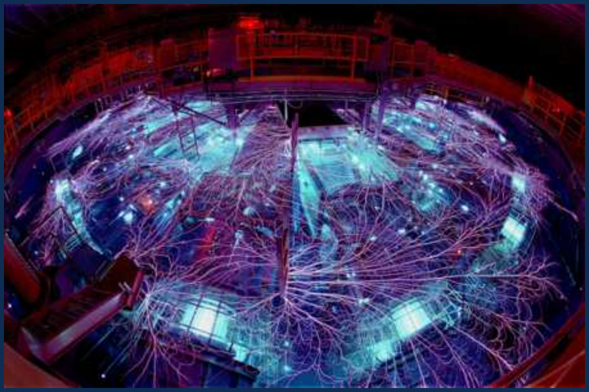

Creating, Controlling, and Diagnosing High Energy Density Matter

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U.S. DEPARTMENT OF ENERGY

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It is an exciting time to be working in High Energy Density Science

- We can use large magnetic fields and high currents to push on matter in different ways, enabling the creation of unique states of HED matter
- The Z facility is being used to explore dynamic material properties at high energy densities for many applications
- Innovative research is enabling temperature measurements and the study of material at higher pressures

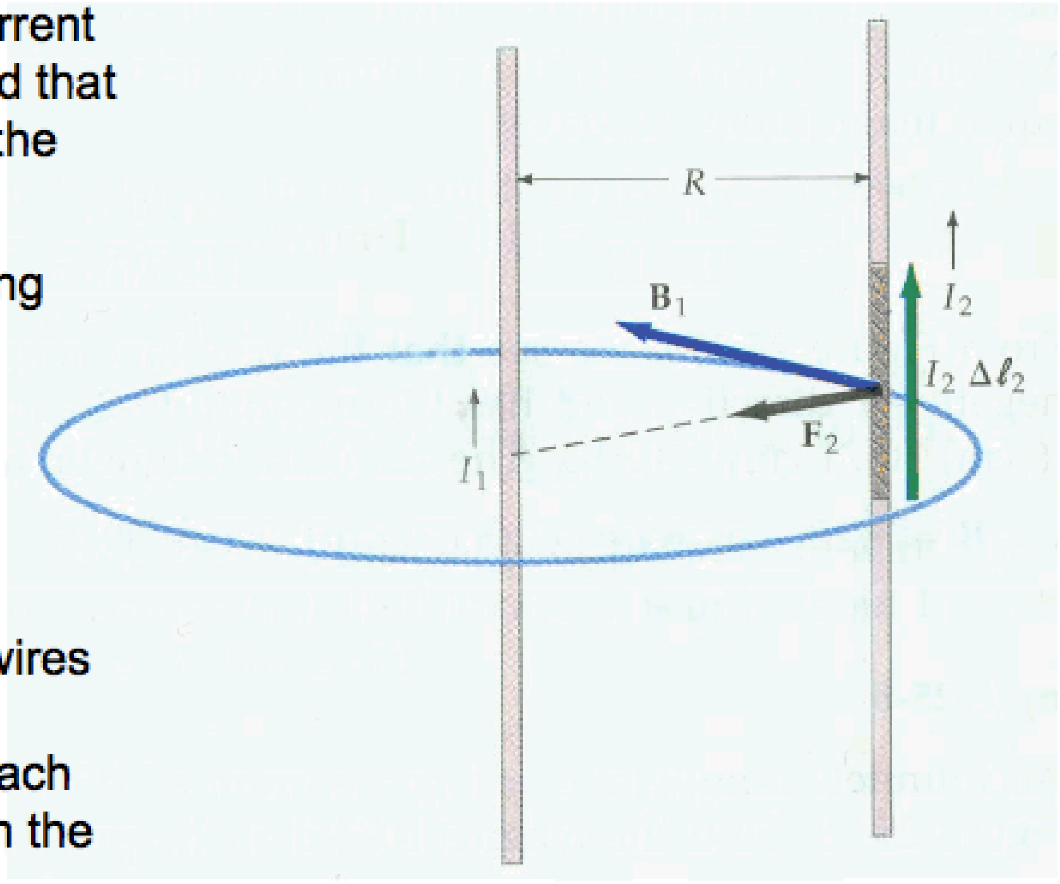
LDRD plays a key role in fostering the innovation and discovery that has enabled the rapid advance of this field

Currents create magnetic fields that in turn apply forces on other currents

A single wire carrying current produces a magnetic field that encircles it according to the right-hand rule

Two parallel wires carrying current along the same direction will attract each other (Biot-Savart Law, "JxB force")

Definition of an Ampere:
If two very long parallel wires 1 m apart carry equal currents, the current in each is defined to be 1 A when the force/length is 2e-7 N/m



Large currents and the corresponding magnetic fields can create and manipulate high energy density(HED) matter

Magnetic fields and currents can push matter around:

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

Magnetic fields have some unique advantages when creating HED plasmas:

- **Magnetic fields are very efficient at creating HED matter enabling large samples and energetic sources**
- **Magnetic fields have very interesting properties in converging geometry**

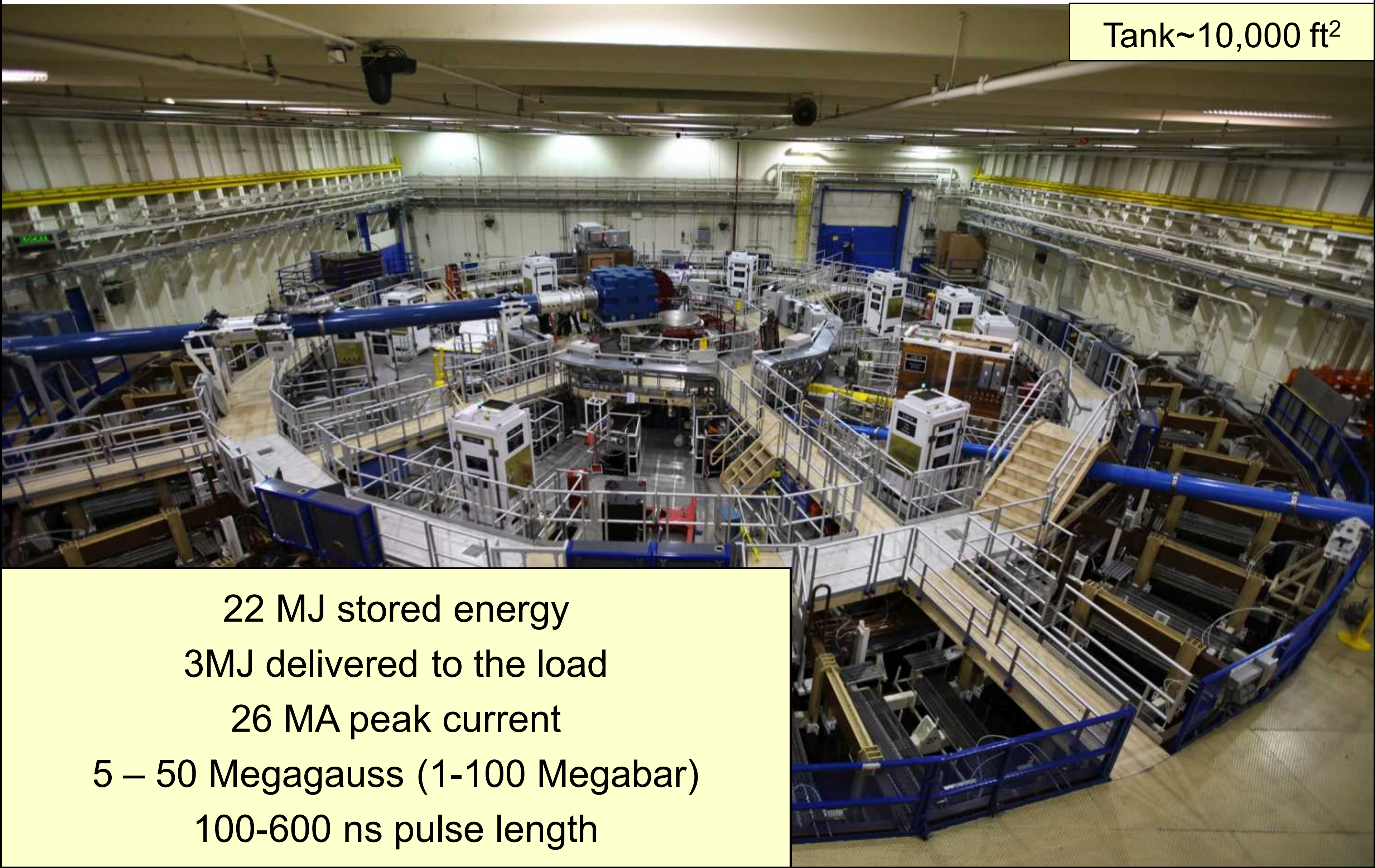
Magnetic fields have interesting contrasts with other ways of generating HED:

- **Magnetic fields can create high pressures without making material hot**
- **Magnetic fields can be generated over long time scales with significant control over the time history**

Magnetic fields change the way particles and energy are transported in a plasma

A 5 Megagauss (500 T) magnetic field applies a pressure of 1 Megabar (MB) to a conductor.
A current of 25 MA at 1cm radius is 5 10^6 G= 1 Mbar of pressure
A current of 25 MA at 1mm radius is 5 10^7 G= 100 Mbar of pressure

We use the Z pulsed power facility to generate large magnetic fields



Tank~10,000 ft^2

22 MJ stored energy

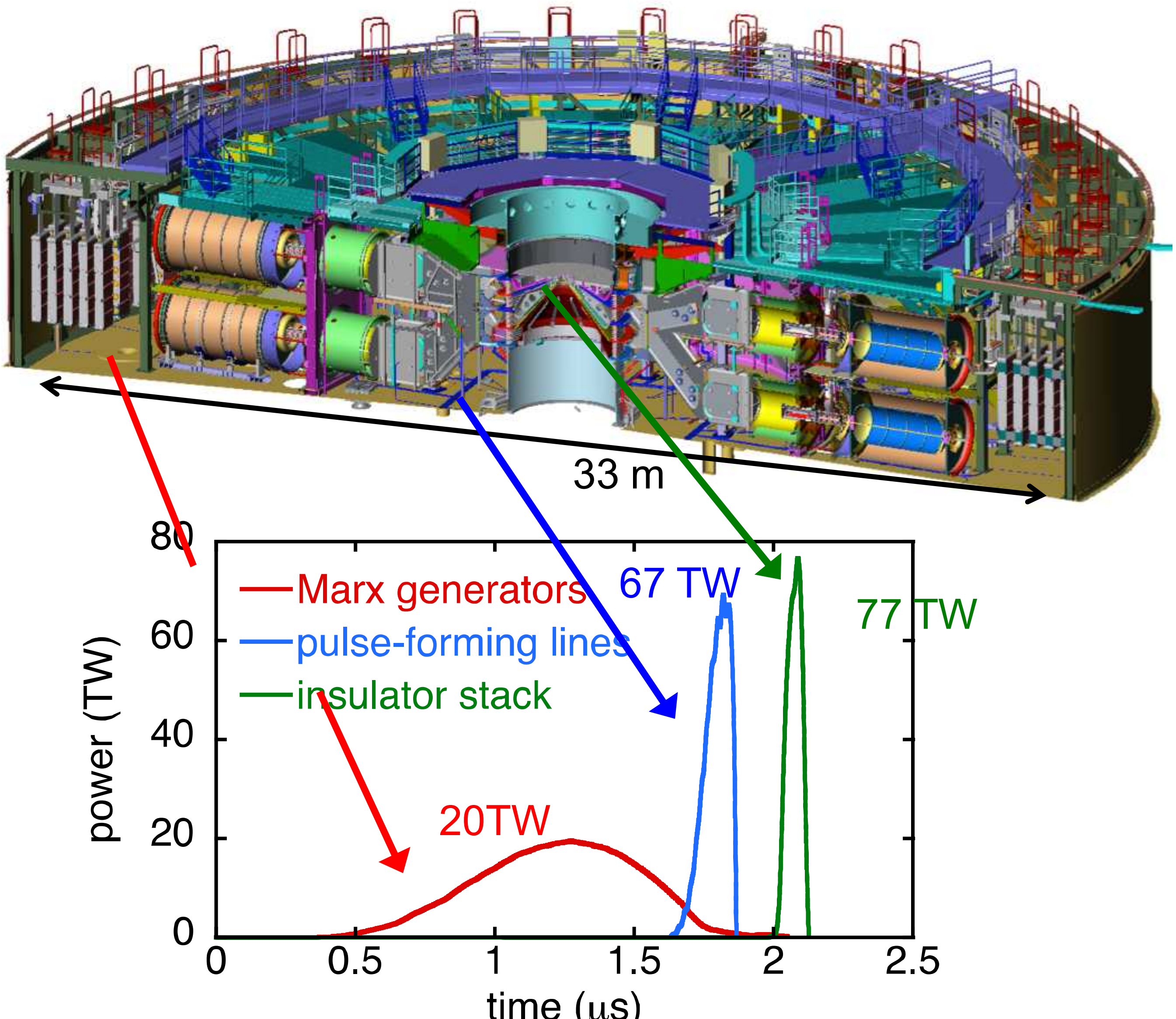
3MJ delivered to the load

26 MA peak current

5 – 50 Megagauss (1-100 Megabar)

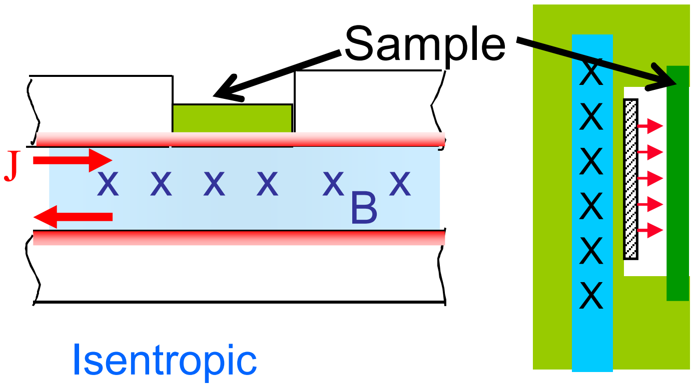
100-600 ns pulse length

Z works by compressing electromagnetic energy in time and space



We use magnetic fields to create HED matter in different ways for different applications

Materials Properties

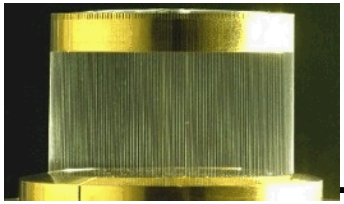


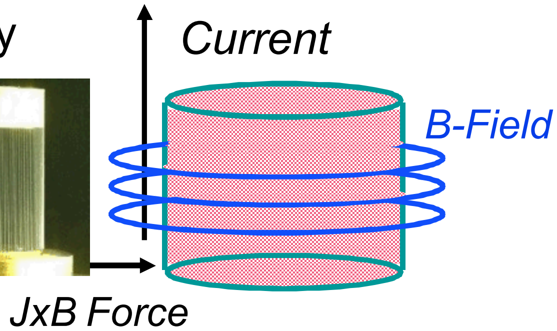
Isentropic Compression

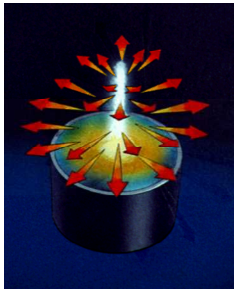
Flyer Plate

Z-Pinch X-ray Sources

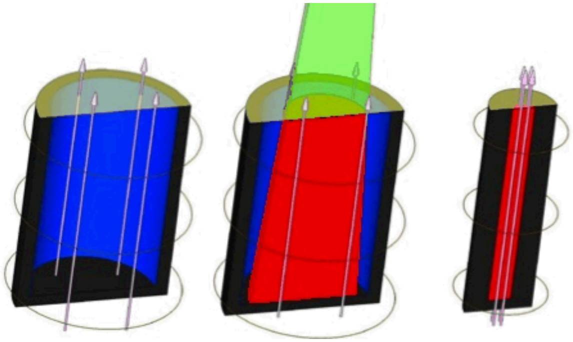
wire array





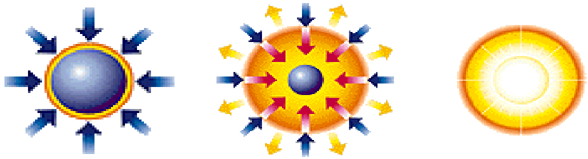


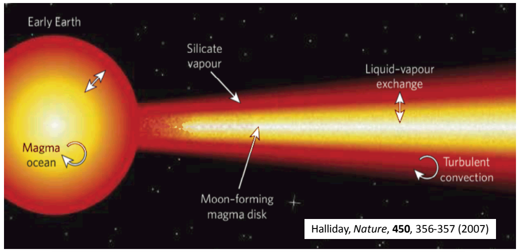
Inertial Confinement Fusion



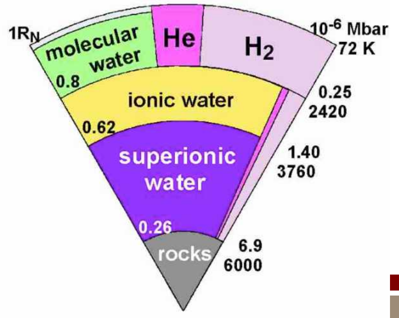
Understanding material properties at high pressure is important for Stockpile Stewardship, ICF, and understanding planets

- Nuclear Weapons materials
  - In the absence of underground testing we need a predictive capability
  - Material properties are a key input to nuclear weapons simulations
- Inertial confinement fusion (ICF) materials
  - Behavior of hydrogen, plastics, beryllium, diamond
- Planetary science
  - Giant impacts (e.g. Moon Forming Event)
  - Earths and super-earths
    - Equation of state of Mg, Fe, Si, C, O and related compounds
  - Giant Planets (e.g. Uranus & Neptune and exo ice-giants)
    - High-pressure mixtures of H, He, C, O, N

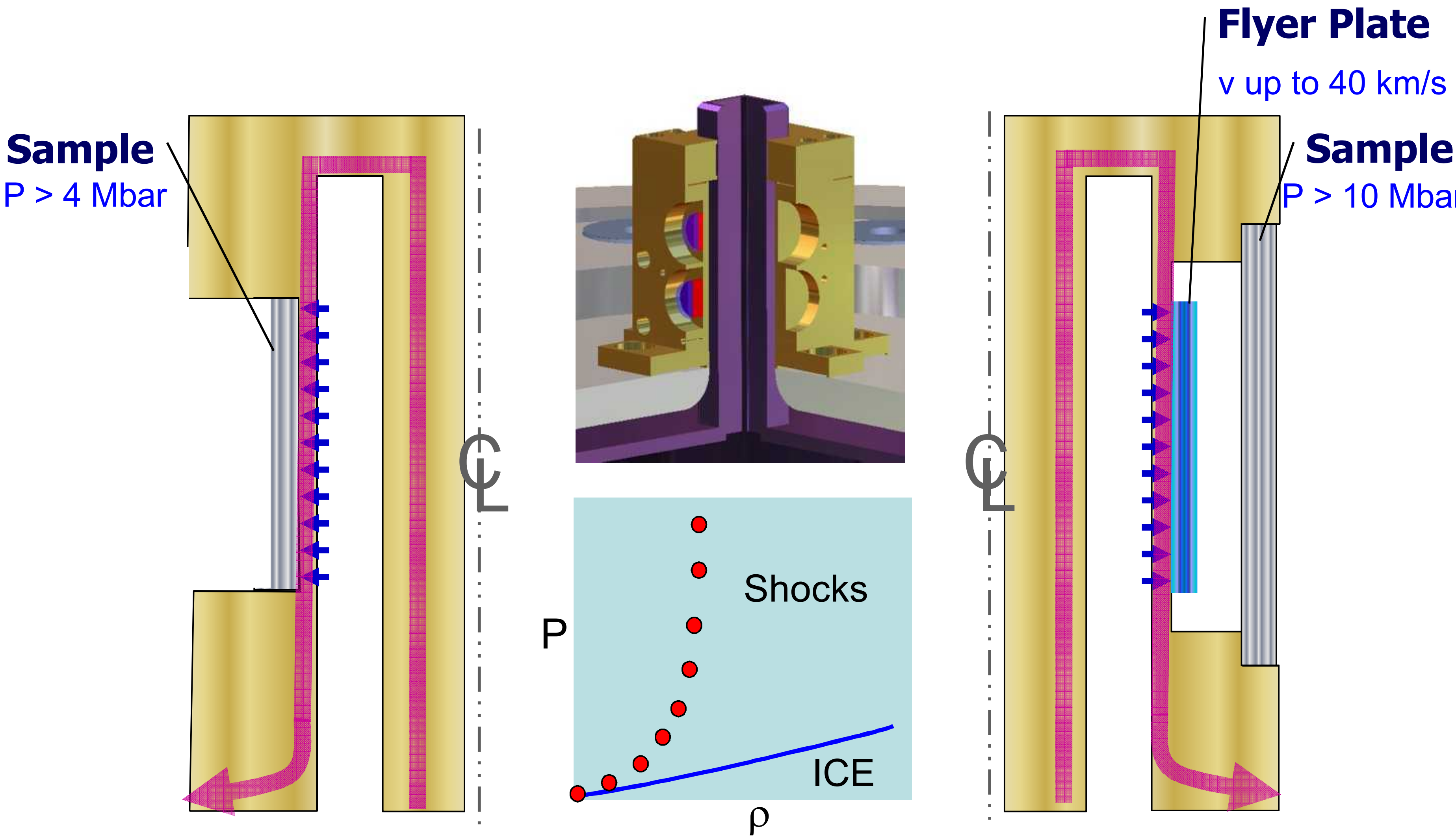




Neptune



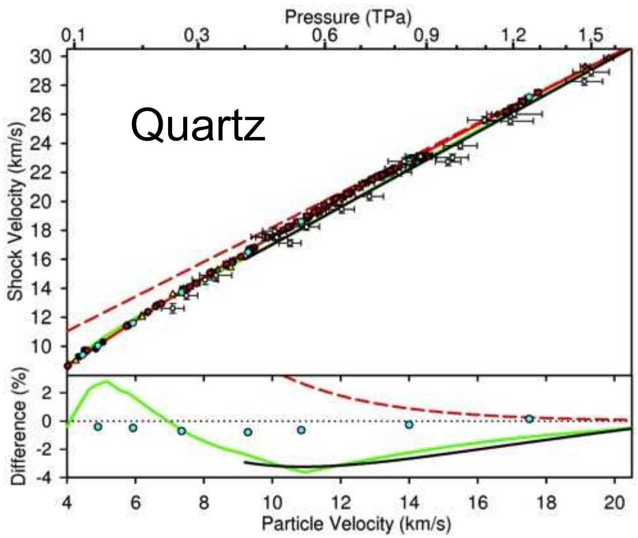
Z can perform both shockless compression and shock wave experiments

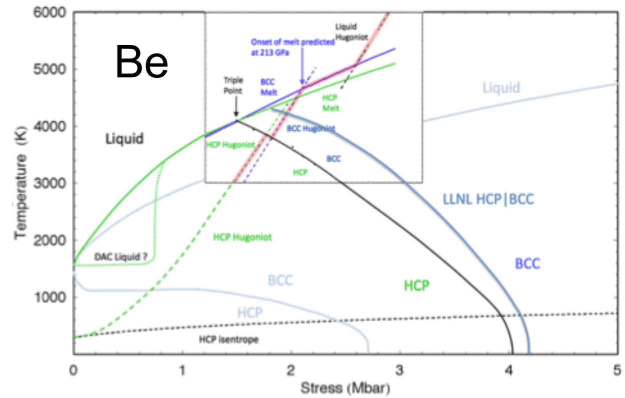


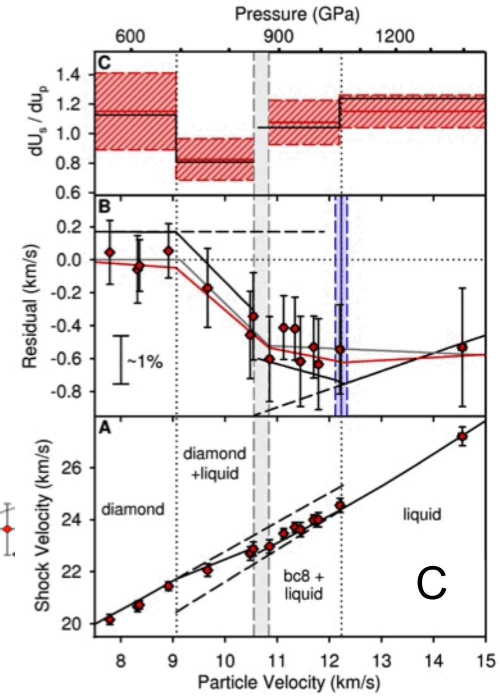
Isentropic Compression Experiments:
gradual pressure rise in sample

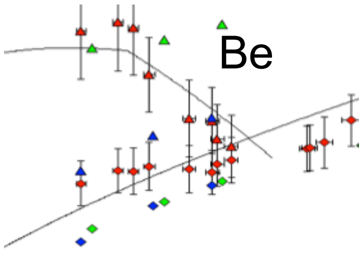
Shock Hugoniot Experiments:
shock wave in sample on impact

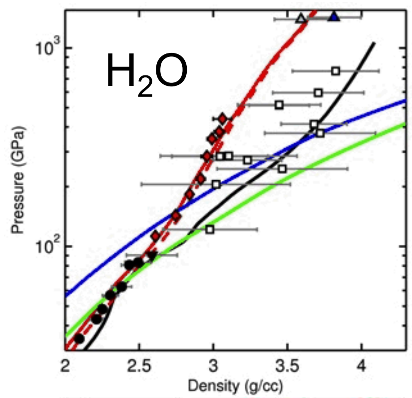
Z has been used to study material properties in the multi-Mbar regime for many materials

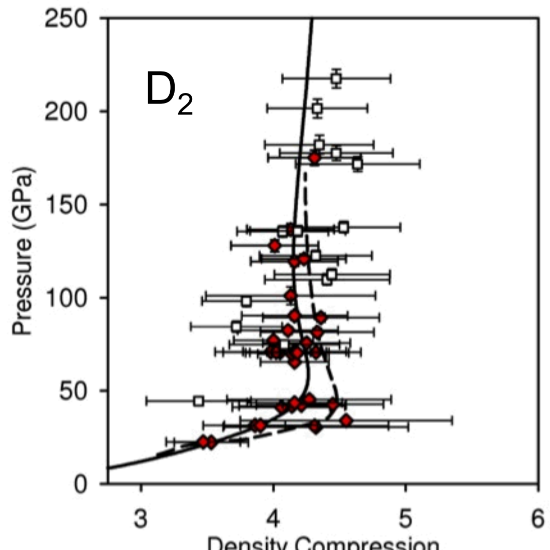


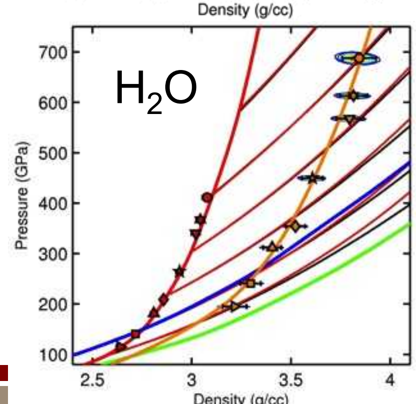


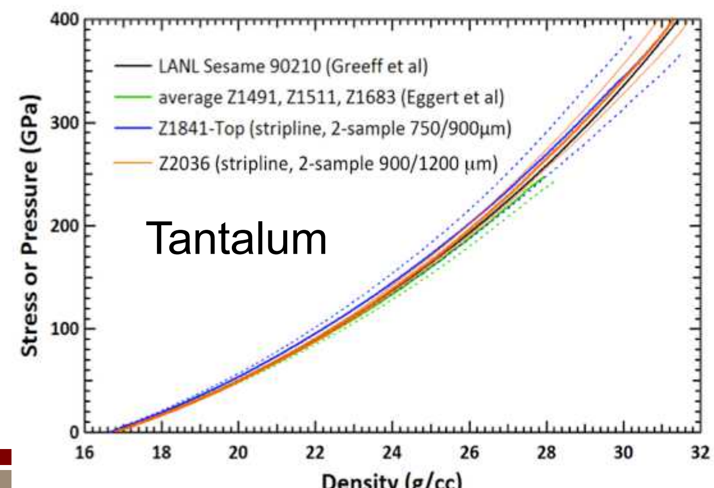




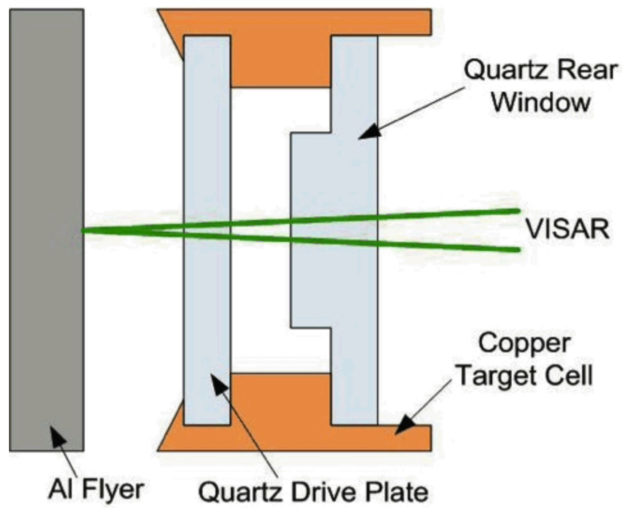


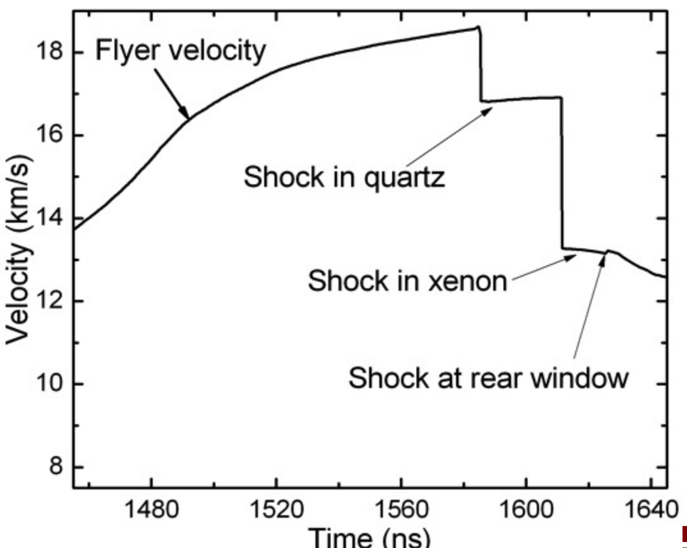


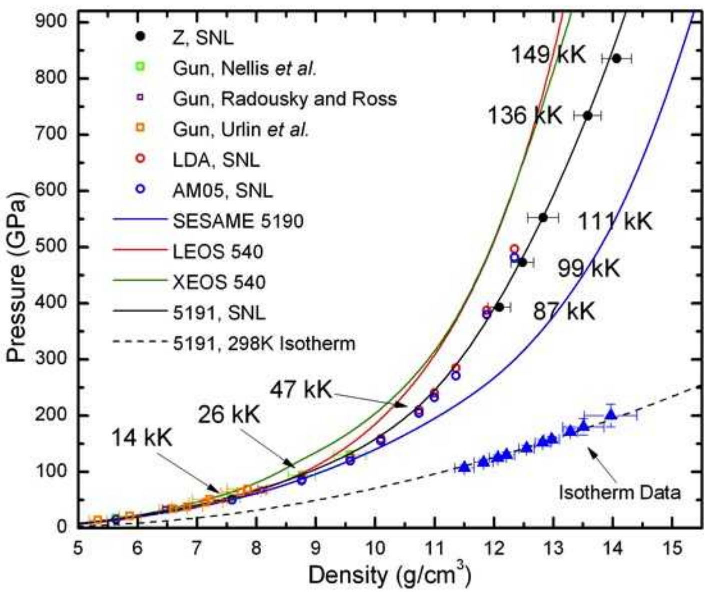




Large sample sizes and “long” time scales enable sub-percent accuracy at record pressures



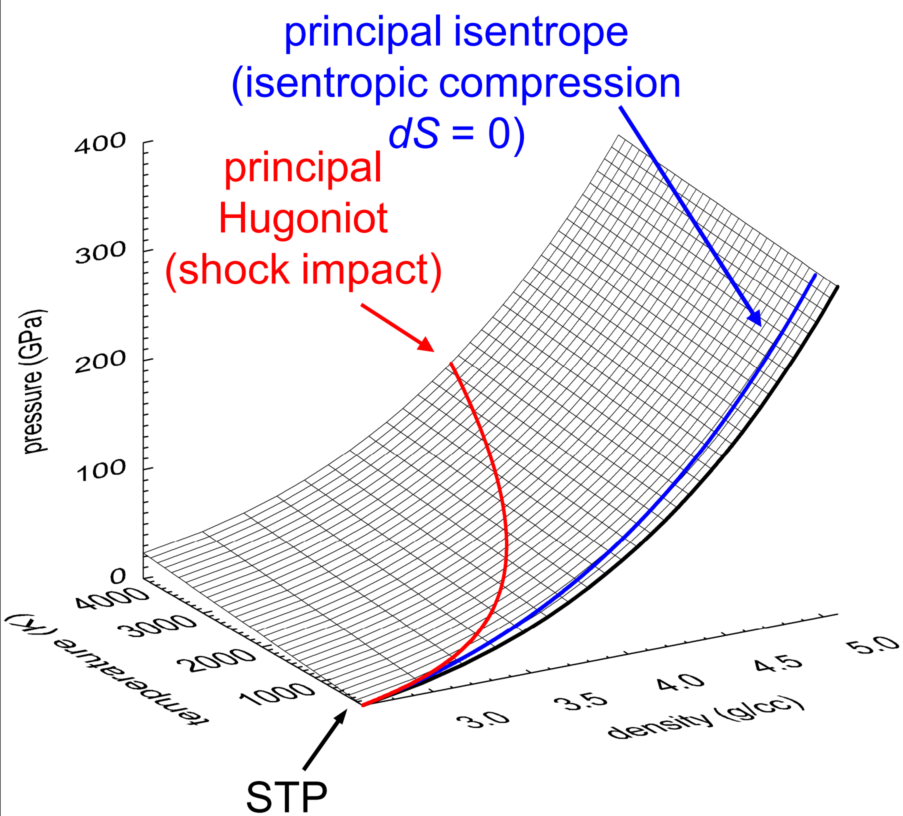




S. Root *et al.*, Phys. Rev. Lett. 105, 085501 (2010).

VISAR trace from a xenon experiment with 18.5 km/s impact velocity

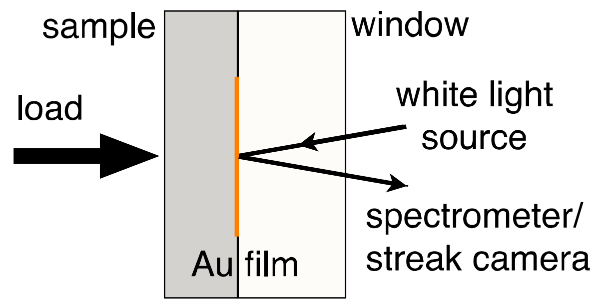
Measuring the very low change in temperature in dynamic isentropic compression experiments is very challenging



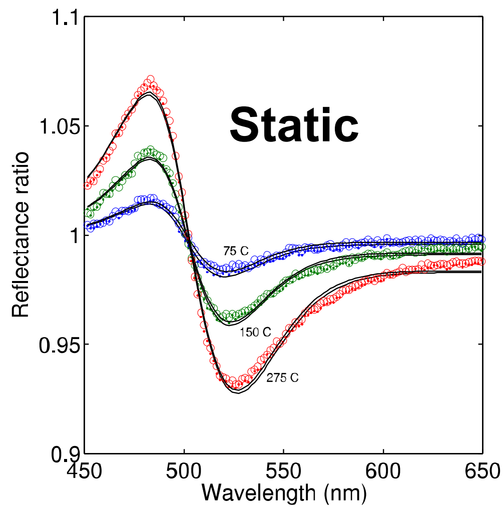
An LDRD led by Dan Dolan of SNL is exploring a new way of dynamically measuring low temperatures

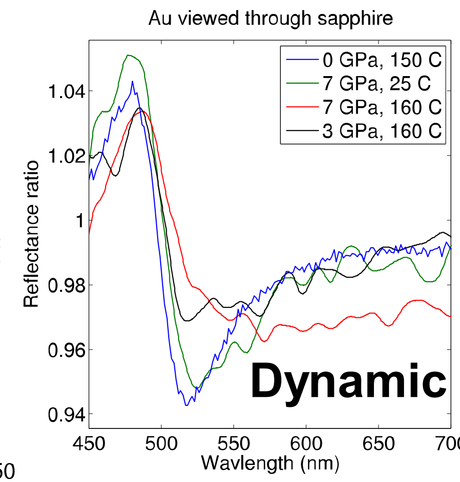
See poster by Dolan

Place an embedded standard on the sample being studied

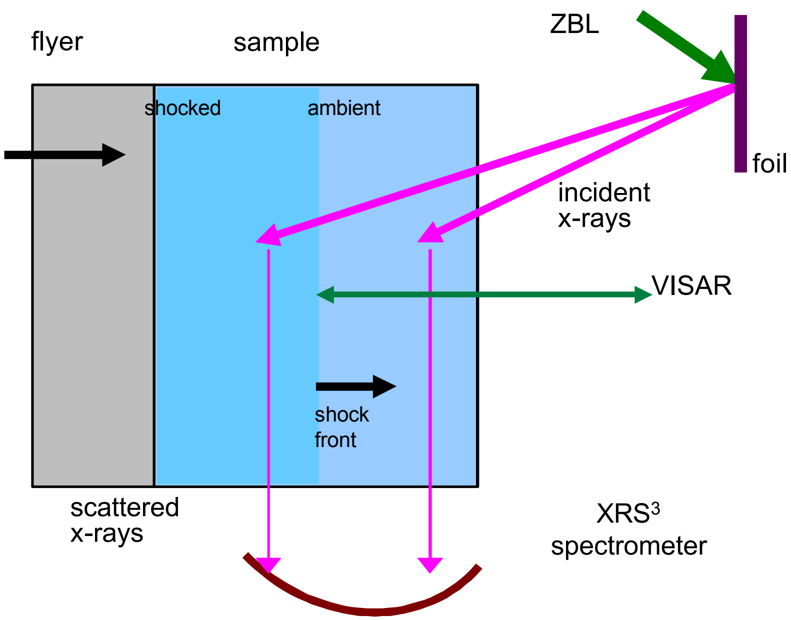


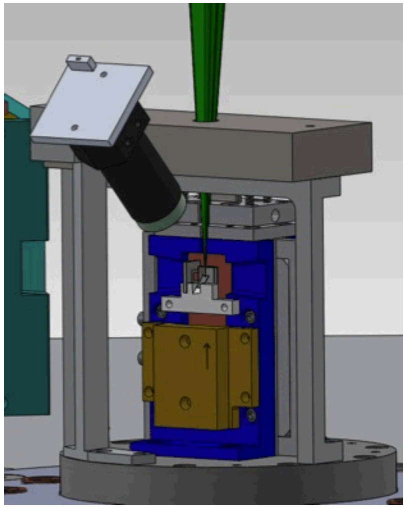
Exploit the spectrally dependent variation in the reflectivity of Gold as a function of temperature



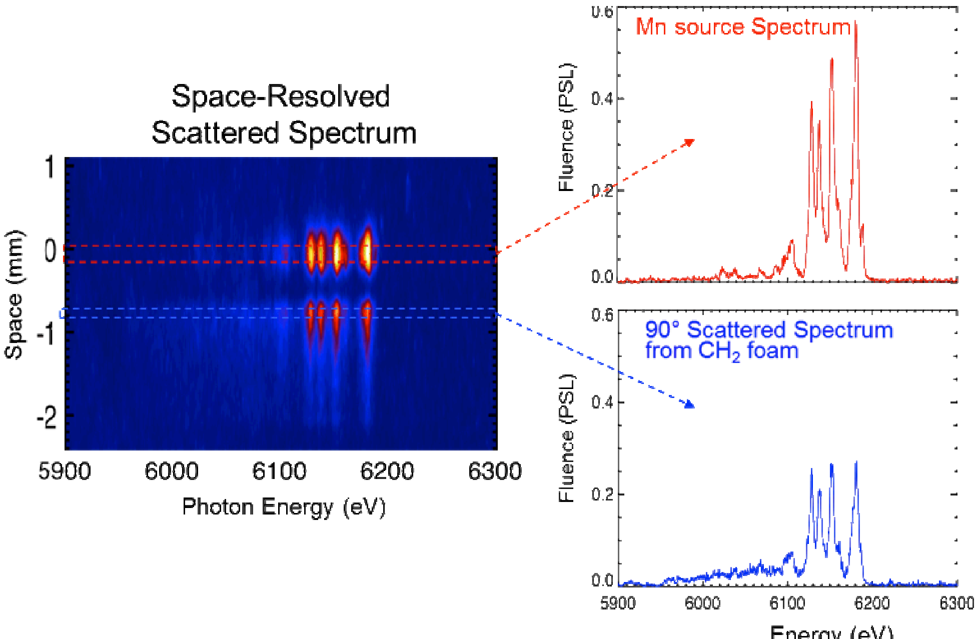


X-ray Thomson scattering enables a new approach to probing the behavior of Warm Dense Matter

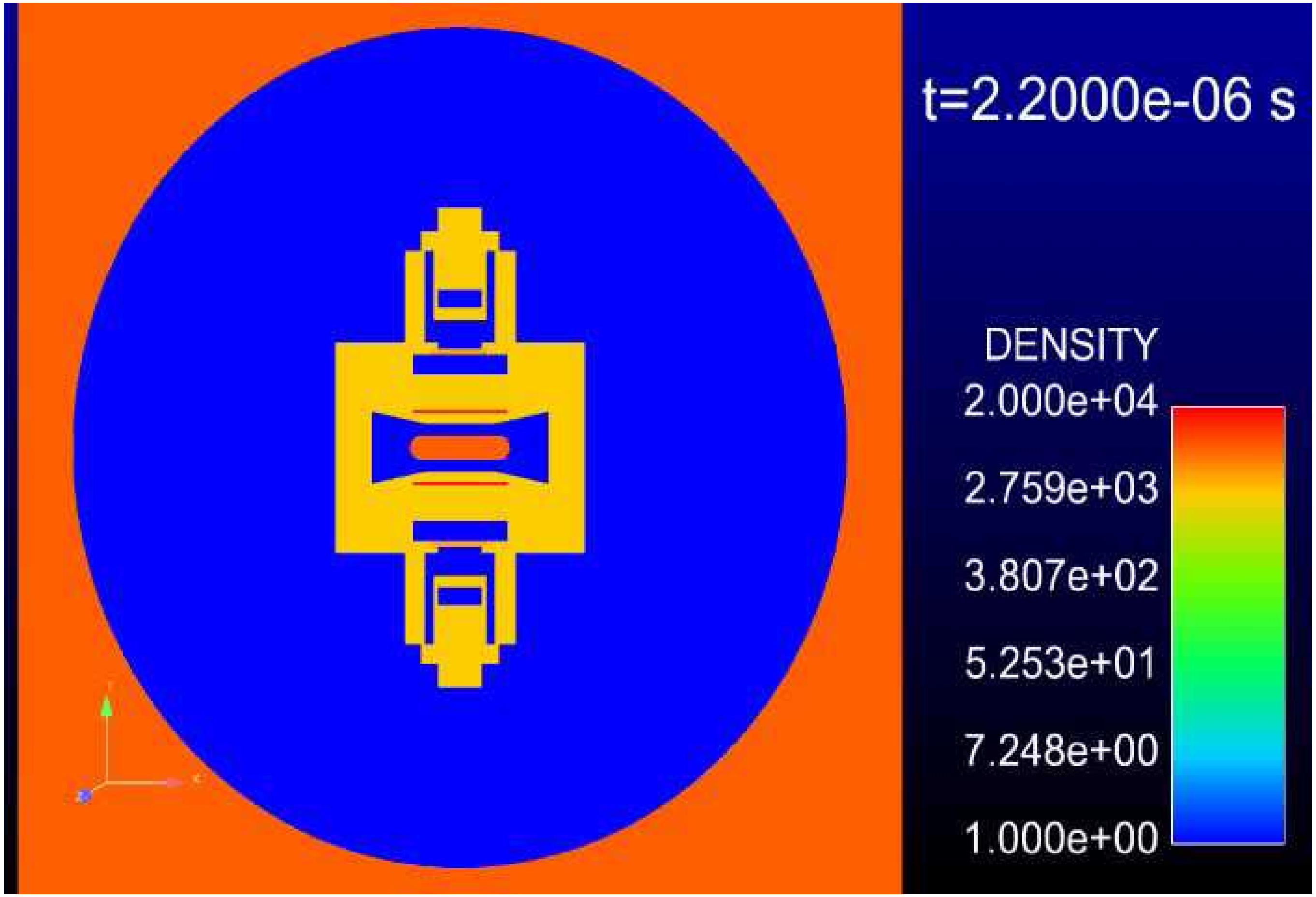




An LDRD led by Jim Bailey of SNL researched and developed X-ray Thomson Scattering as an approach to probing Warm Dense Matter



Planar loads explode during a shot, divergent geometry limits maximum magnetic pressure



Simulation by R.W. Lemke, SNL

Higher pressures are produced in convergent liner z-pinch experiments on Z, but controlling and diagnosing the implosion is a challenge!

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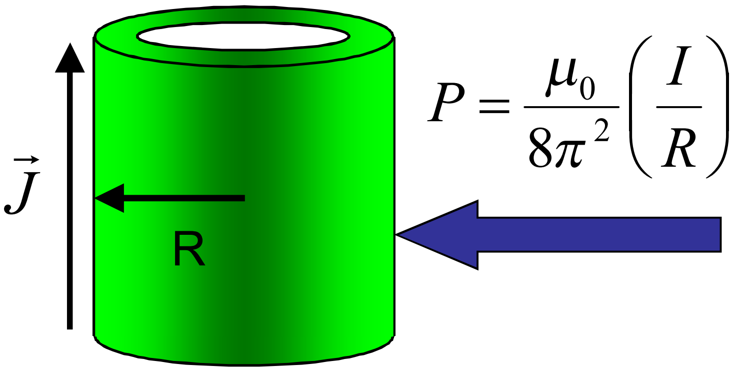
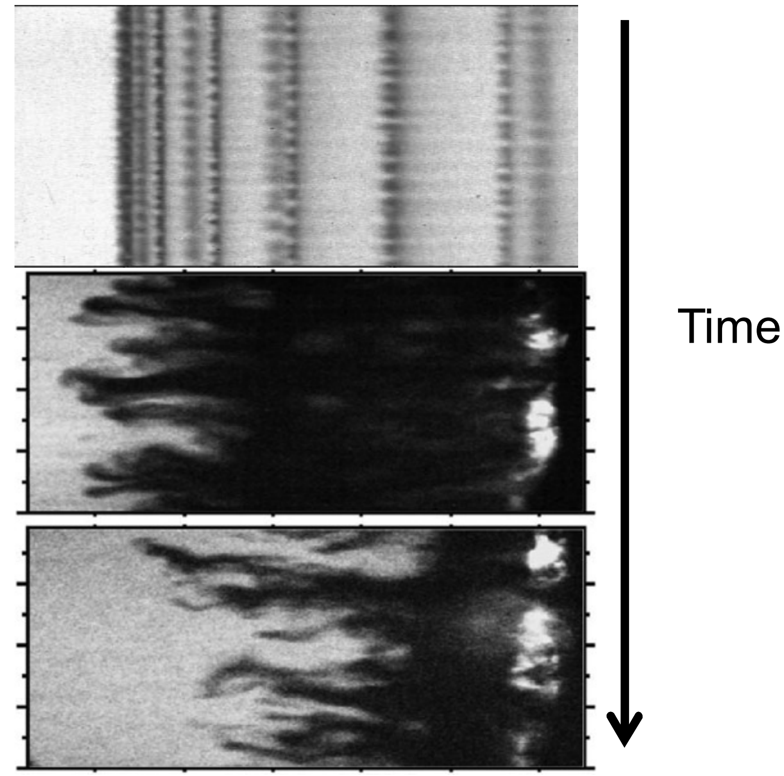
Liner Z-Pinch Implosion

$$P = \frac{\mu_0}{8\pi^2}\left(\frac{I}{R}\right)^2$$



I= 20 MA; R= 0.2 cm;
$P_B \approx$ 16 Mbar.

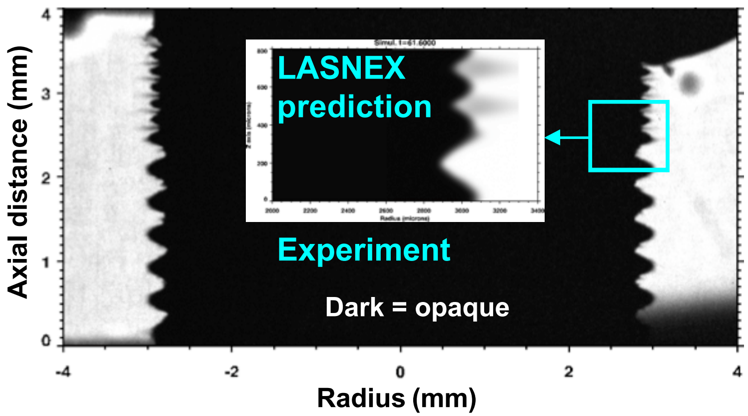
Wire-Array Implosion

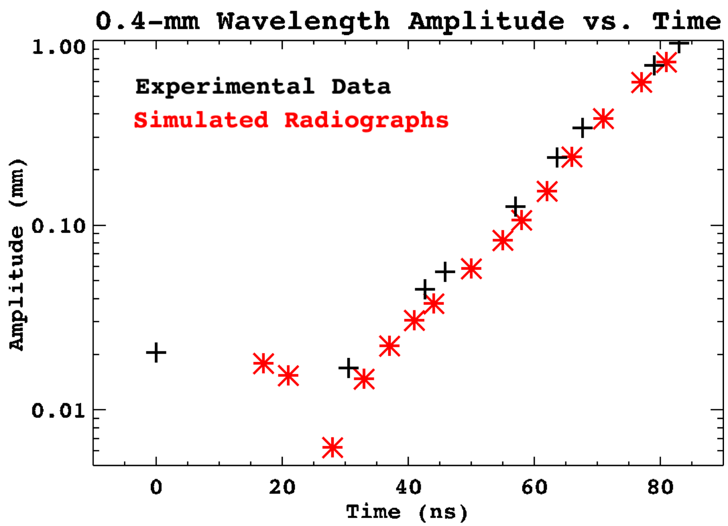


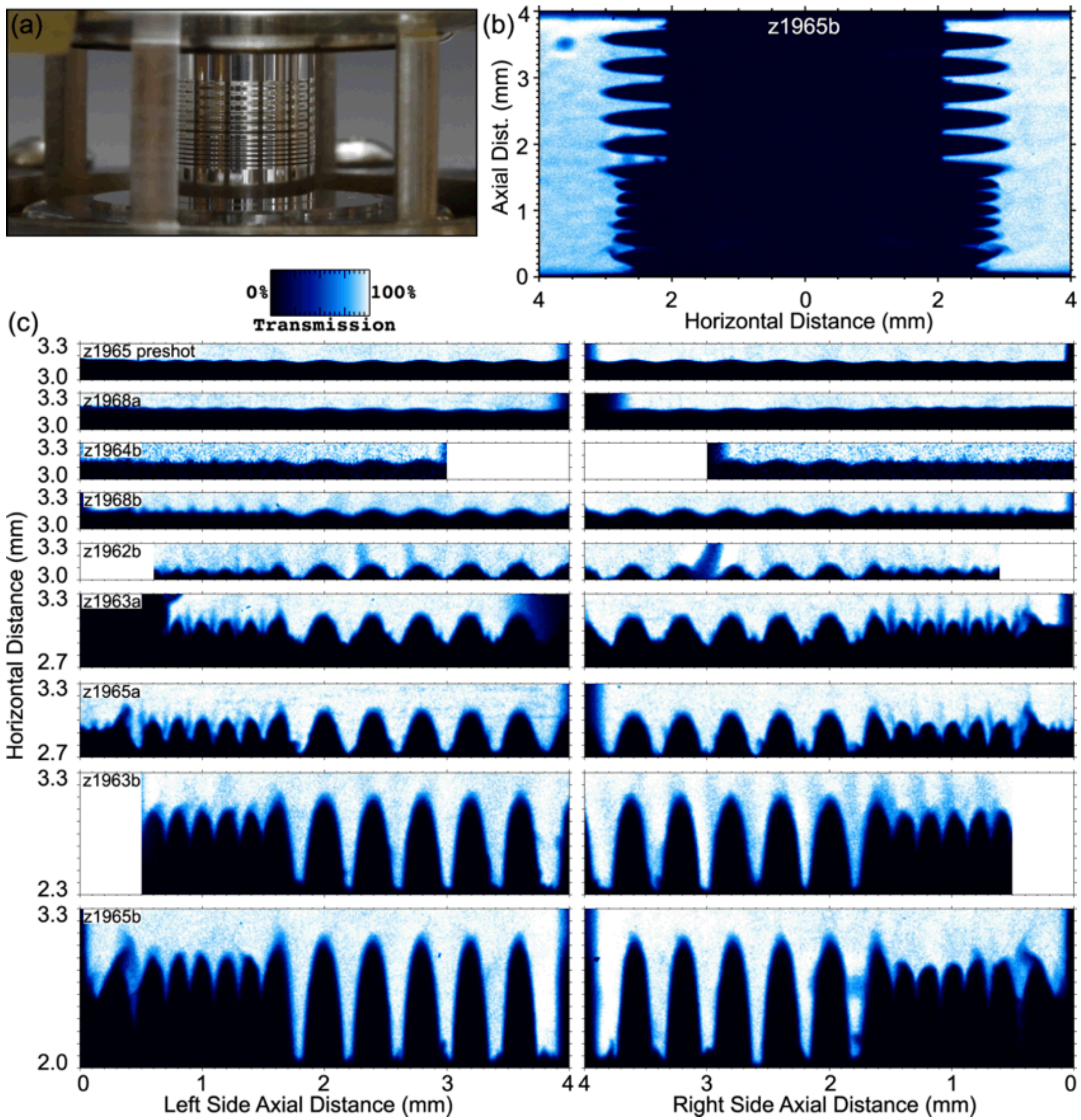
An LDRD studying the stability of liner implosions posed the question: Can we understand and control a liner implosion?

Our initial experiments served as the first critical test of our understanding of the Magneto-Rayleigh Taylor instability

*D.B. Sinars *et al.*, Phys. Rev. Lett. (2010).
*D.B. Sinars *et al.*, Phys. Plasmas (2011).







Beryllium liner implosion data was collected and is actively being used to benchmark our modeling tools

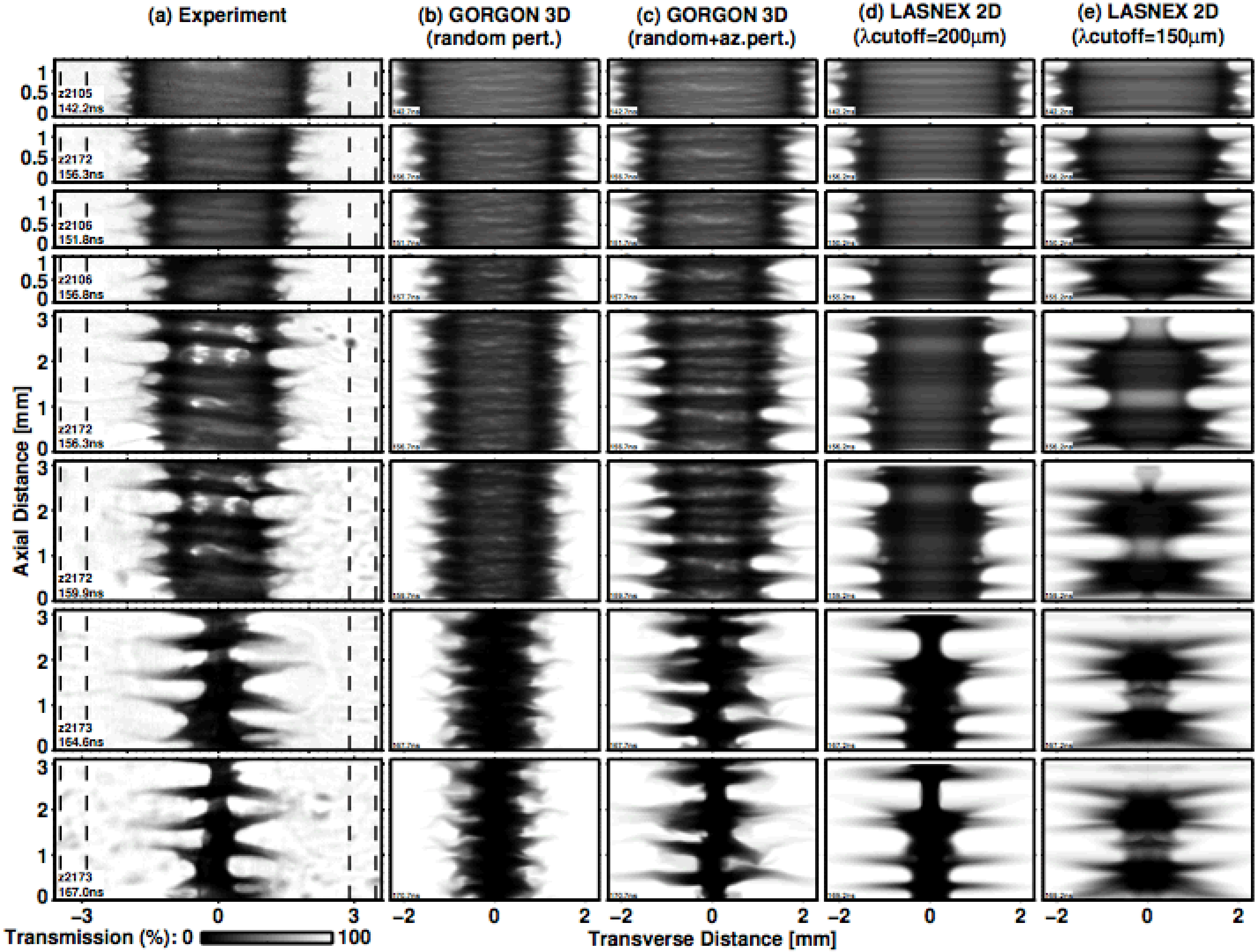
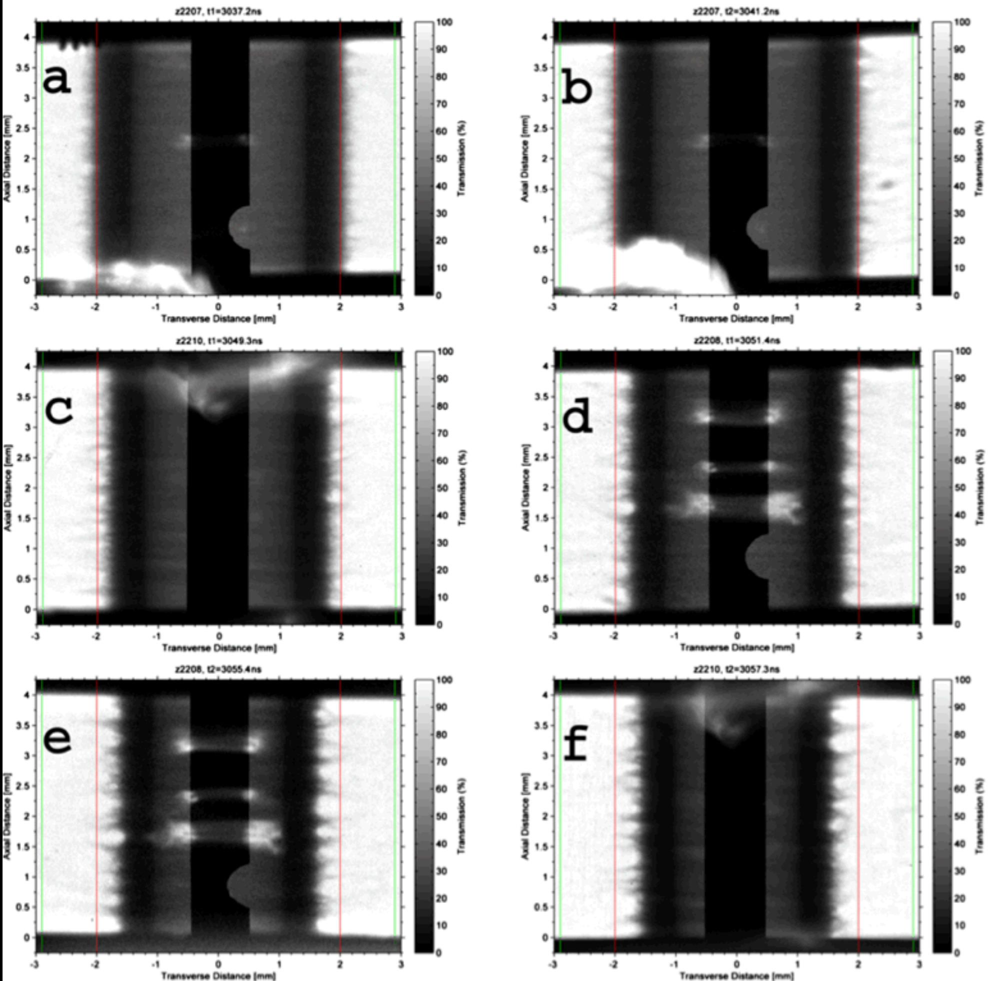


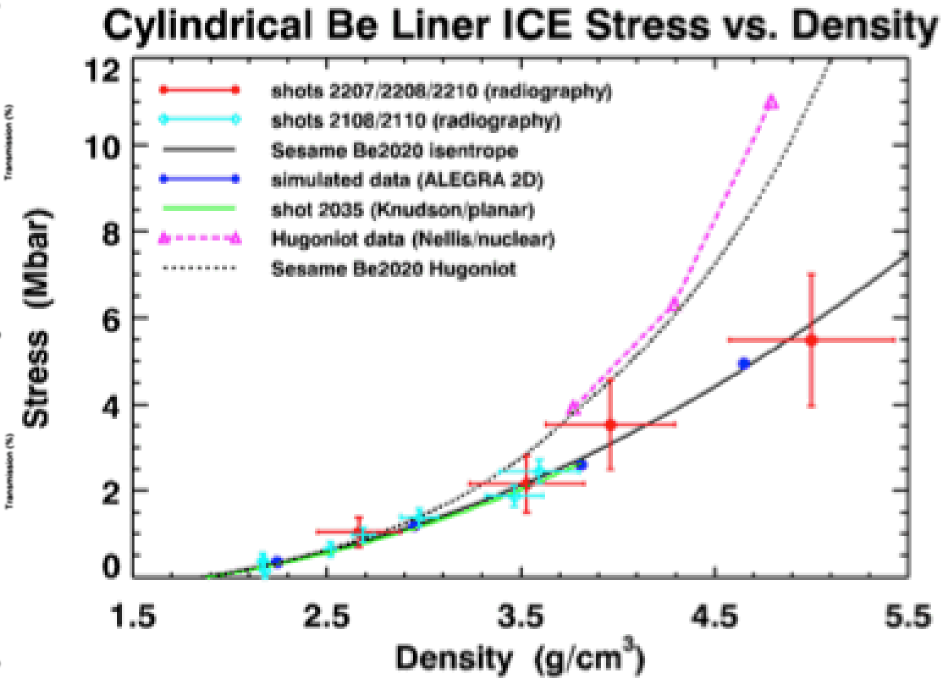
FIG. 2. (a) Radiographs from Z experiments. The vertical dashed lines indicate the initial positions of the inner and outer liner surfaces (inner and outer radii of 2.89 and 3.47 mm, respectively). (b–e) Synthetic radiographs from radiation magneto-hydrodynamic simulations using the 3D GORGON code [16] (b–c) and the 2D LASNEX code [2] (d–e).

R.D. McBride *et al.*, Phys. Rev. Lett. (2012);

Based on our understanding of liner stability we developed a platform to measure the isentrope of Beryllium at 5.5 Mbar

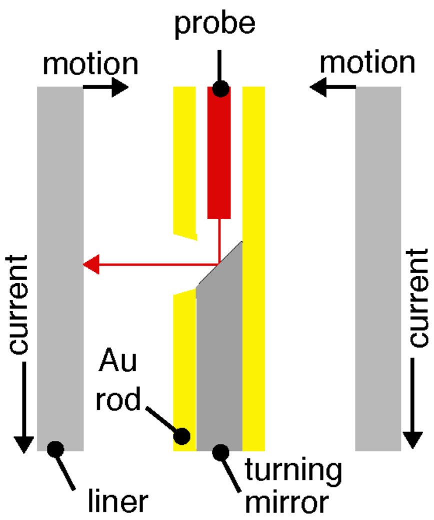
Radiographs of Be liner implosions at different times

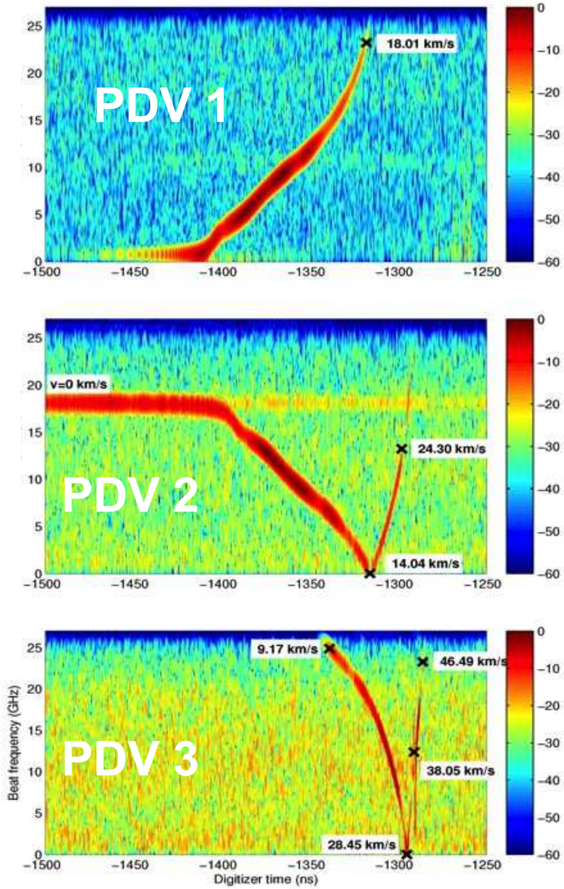


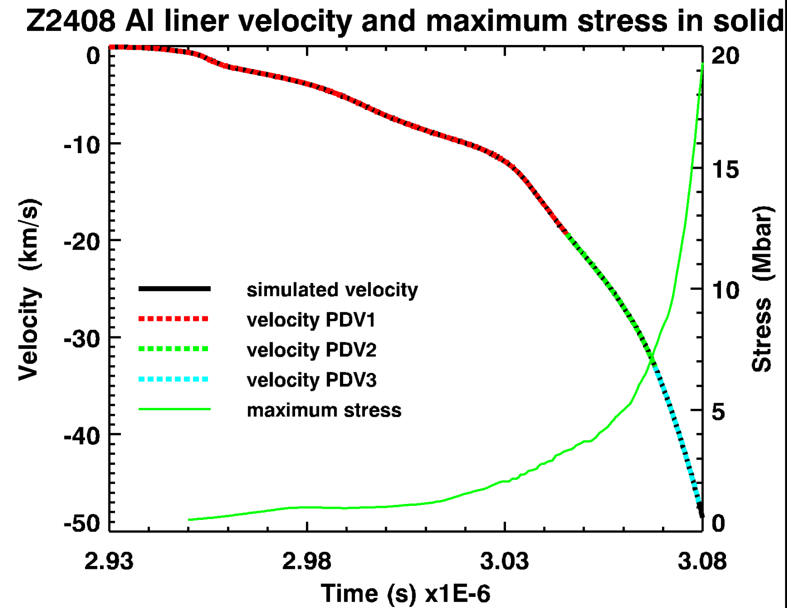


Peak stress is 2x higher than previously studied in planar geometry

Coupling an internal velocity probe to the cylindrical EOS platform enables shockless compression measurements to 20 Mbar in Al (4 x planar)







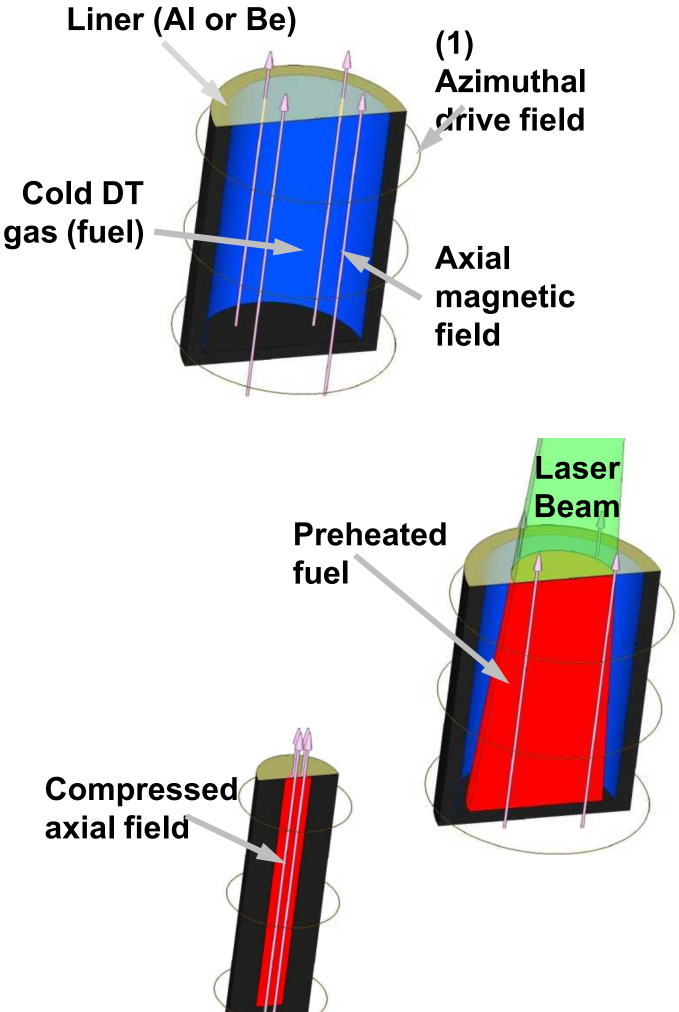
PDV technique developed at SNL with data acquisition/ analysis system by NSTec/NNSS

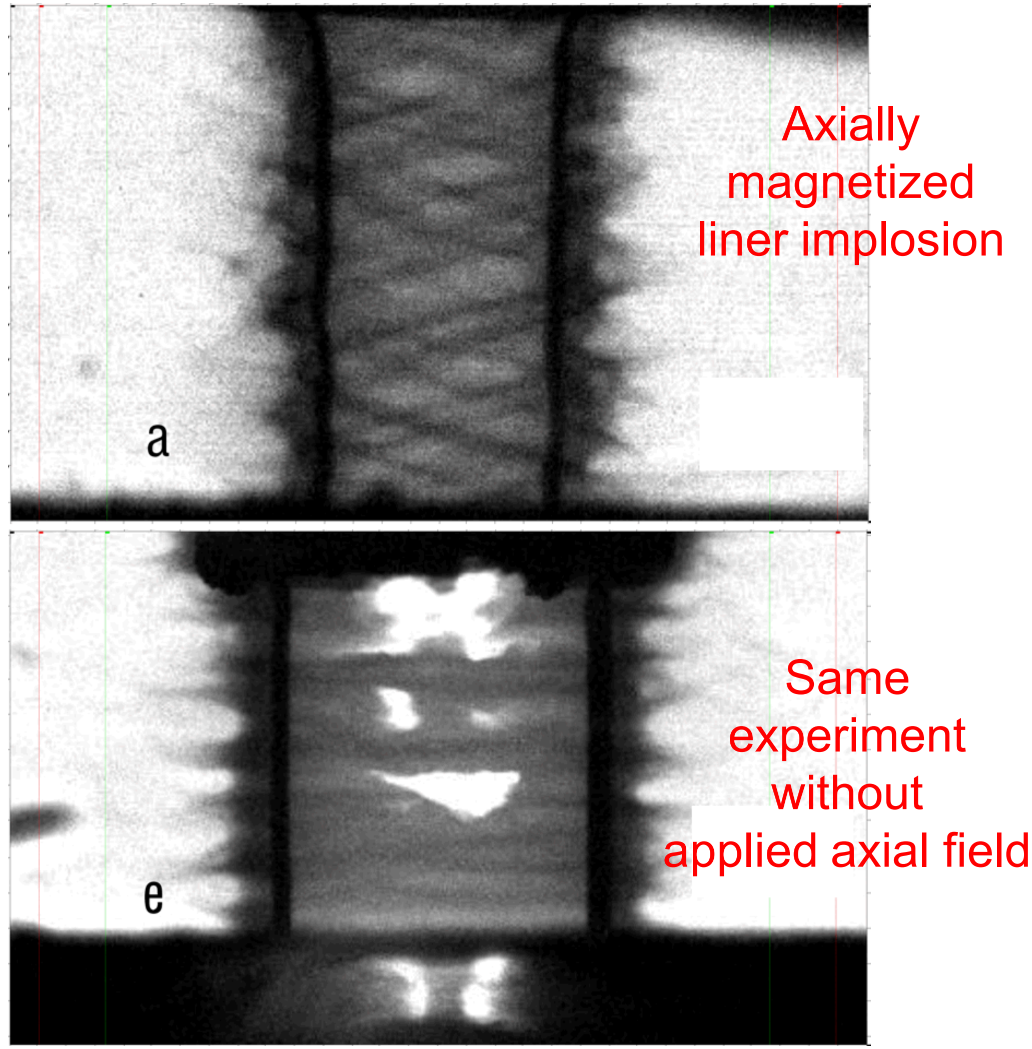
Simulated velocity (black) and approximate ranges for the three PDV frequencies (colors)

Pressure in solid Al (green)

This innovation could significantly broaden Z's ability to obtain data needed for Stockpile Stewardship

We are now studying how we can use liner implosions with a preimposed magnetic field to relax the conditions needed for inertial confinement fusion





See poster by McBride

* New data from T.J. Awe *et al.*, manuscript in preparation. R.D. McBride *et al.*, Phys. Plasmas 20, 056309 (2013).

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- **The Z facility is being used to explore dynamic material properties at high energy densities for many applications**
- **Innovative research is enabling new measurements of temperature and the study of material properties at higher pressures**

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