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Dynamic Compression Science at Sandia's Z Machine

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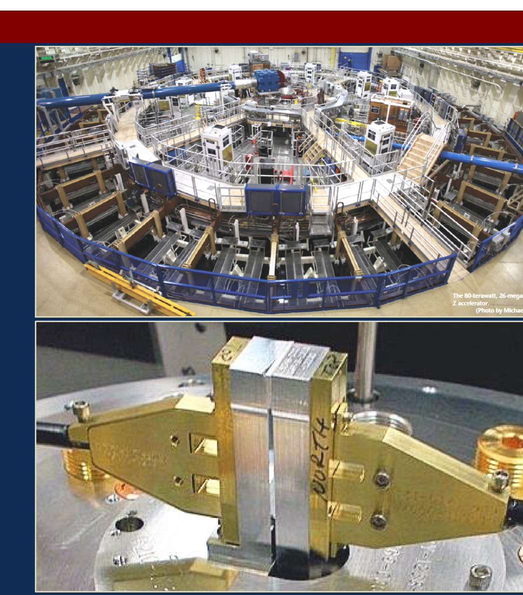
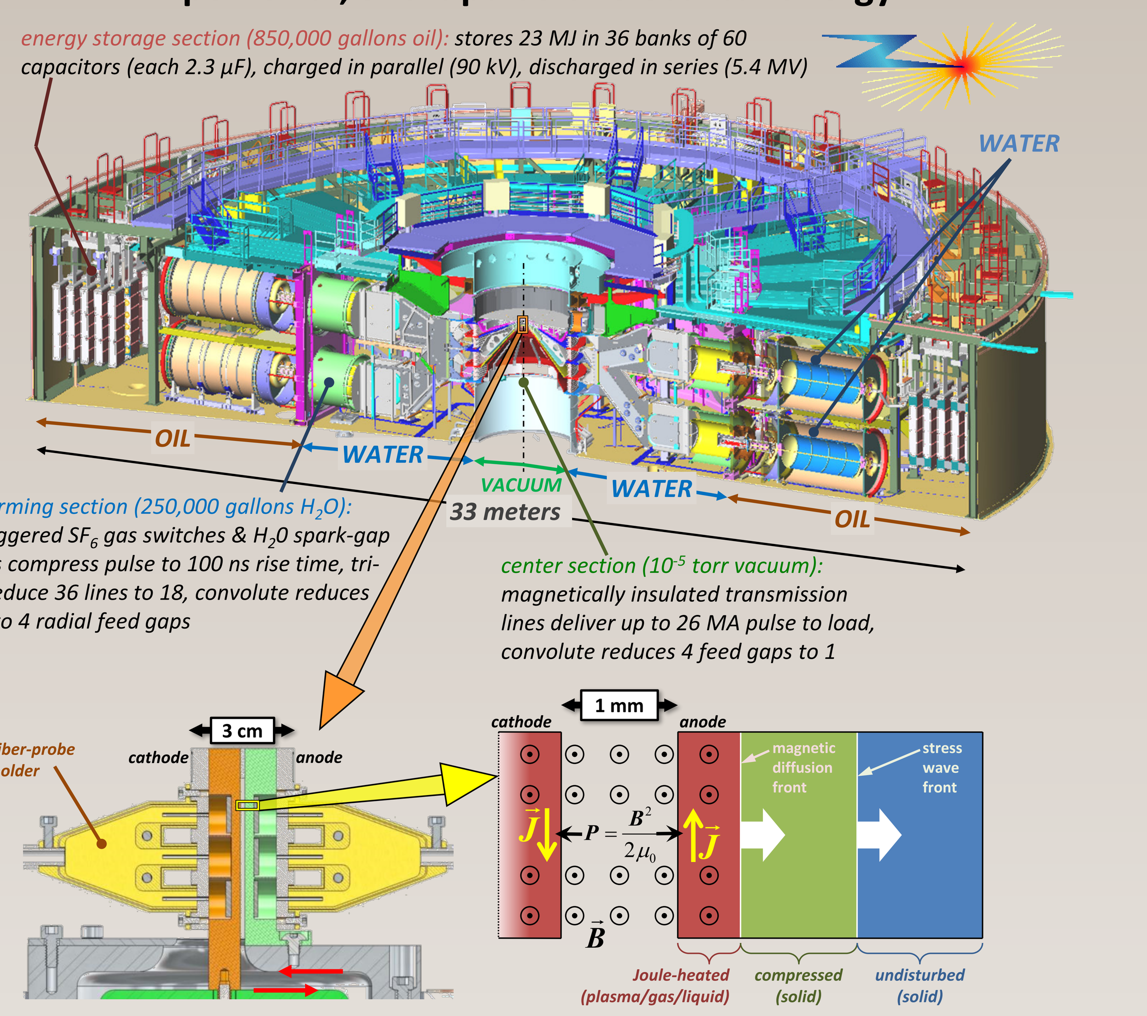


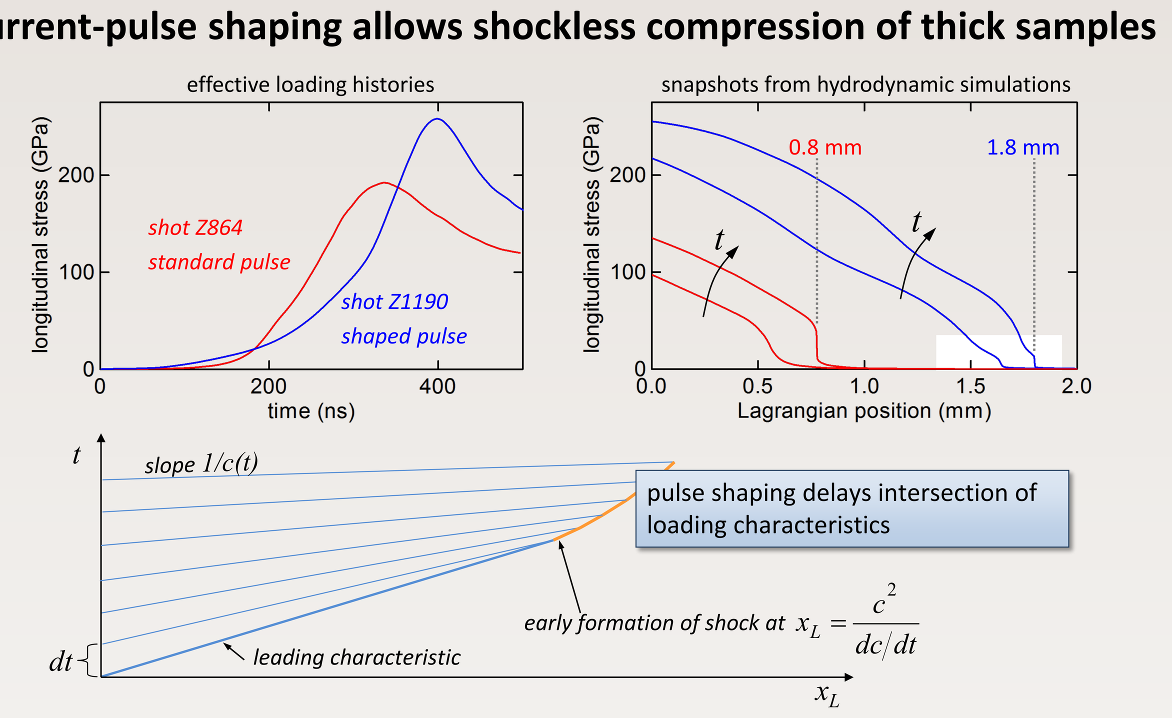
Sandia National Laboratories

Z is a pulsed-power machine that delivers a powerful, short pulse of electrical energy

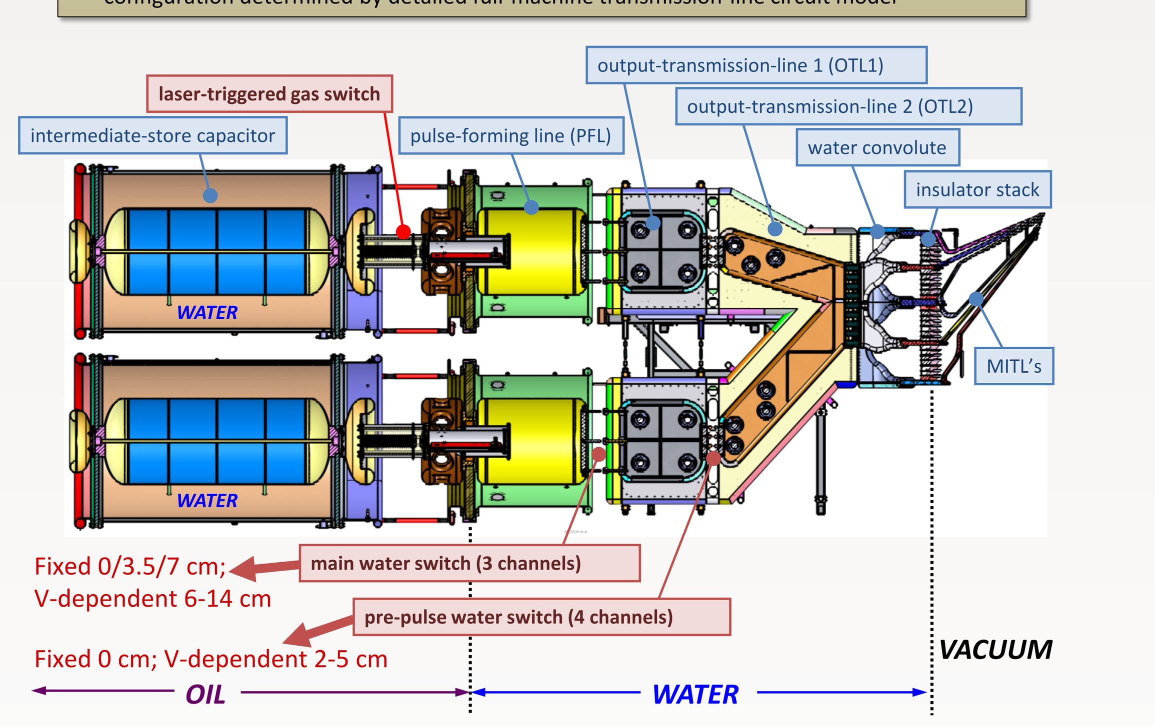


- current pulse of 7-26 MA delivered to load; controllable pulse shape, rise time 100-1500 ns
- shorted, planar electrodes convert current pulse to ramped magnetic loading
- stripline = parallel flat-plate electrodes (unconfined B-field), identical loading of sample pairs
- magnetic ($J\times B$) force induces ramped stress wave in electrode material
- stress wave propagates into ambient material, de-coupled from magnetic diffusion front

Current-pulse shaping allows shockless compression of thick samples

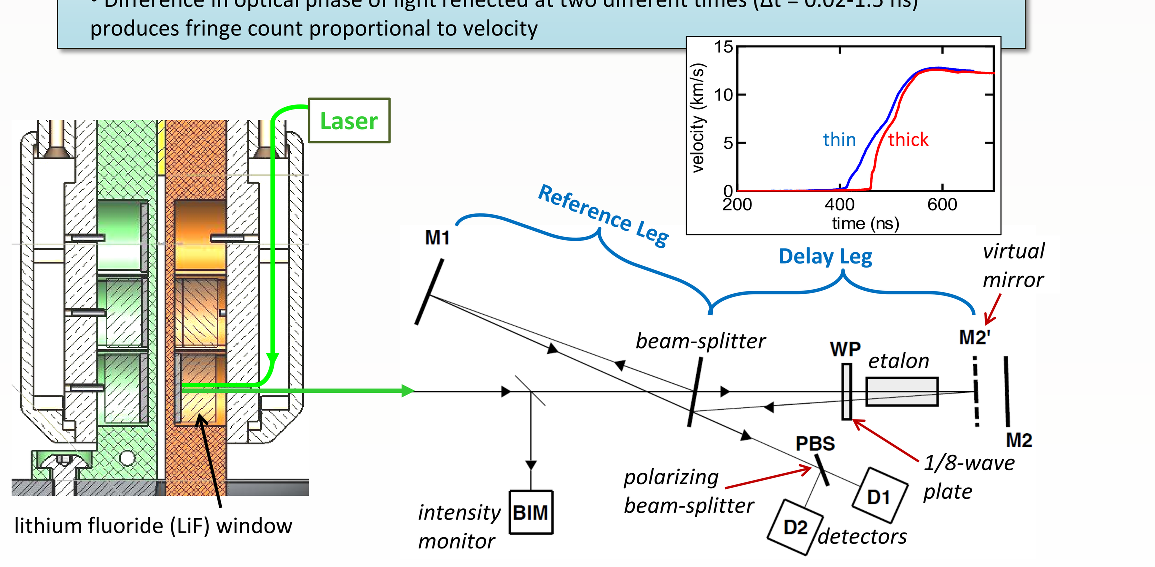


- staggered timings of 36 laser-triggered gas switches; gas pressure limits time advance
- two separate Marx trigger times available to increase total spread of gas-switch timings
- gap settings for 72 water spark-gap switches (36 main & 36 pre-pulse)
- configuration determined by detailed full-machine transmission-line circuit model



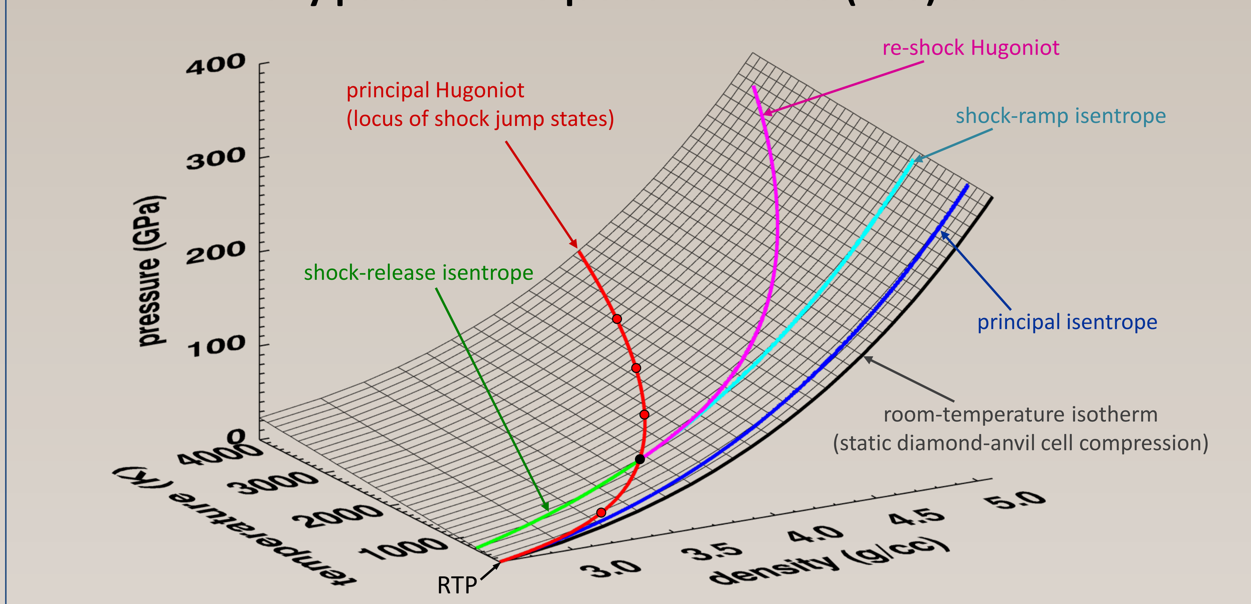
Velocity interferometry is the primary of several available diagnostics

- Velocity Interferometry System for Any Reflector (VISAR)
- Laser fiber-coupled to reflector on sample (free surface or sample/window interface)
- Difference in optical phase of light reflected at two different times (Δt = 0.02-1.5 ns) produces fringe count proportional to velocity



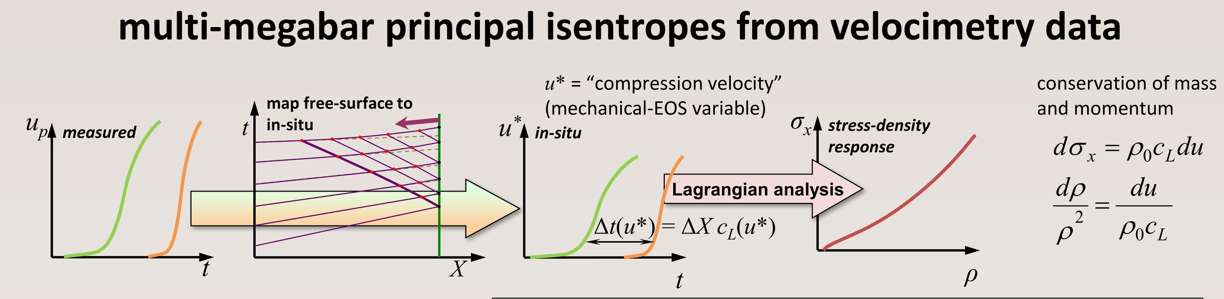
- Photonic Doppler Velocimetry (PDV): velocity from beat frequency with reference
    - System has other uses (plasma detection, Faraday rotation, radiation sensing, etc.)
- Streaked Visible Spectroscopy (SVS): fiber-coupled
    - visible pyrometry (measure temperature > 2500 K from sample emission)
    - phase change/identification from simple reflectance measurements
    - thermo-reflectance (infer temperature from reflectance of embedded gauge)
- Low-temperature pyrometry (under development)
    - 6-channel visible (450 nm) to near-infrared (1400 nm) system (Los Alamos Nat'l Lab)
    - Bracketed Infrared Radiometry in near-infrared (under construction)
- X-Ray Thompson Scattering (X-Ray Diffraction is under development) using Z Beamlet

Dynamic compression experiments on Z can probe many parts of an equation-of-state (EOS) surface



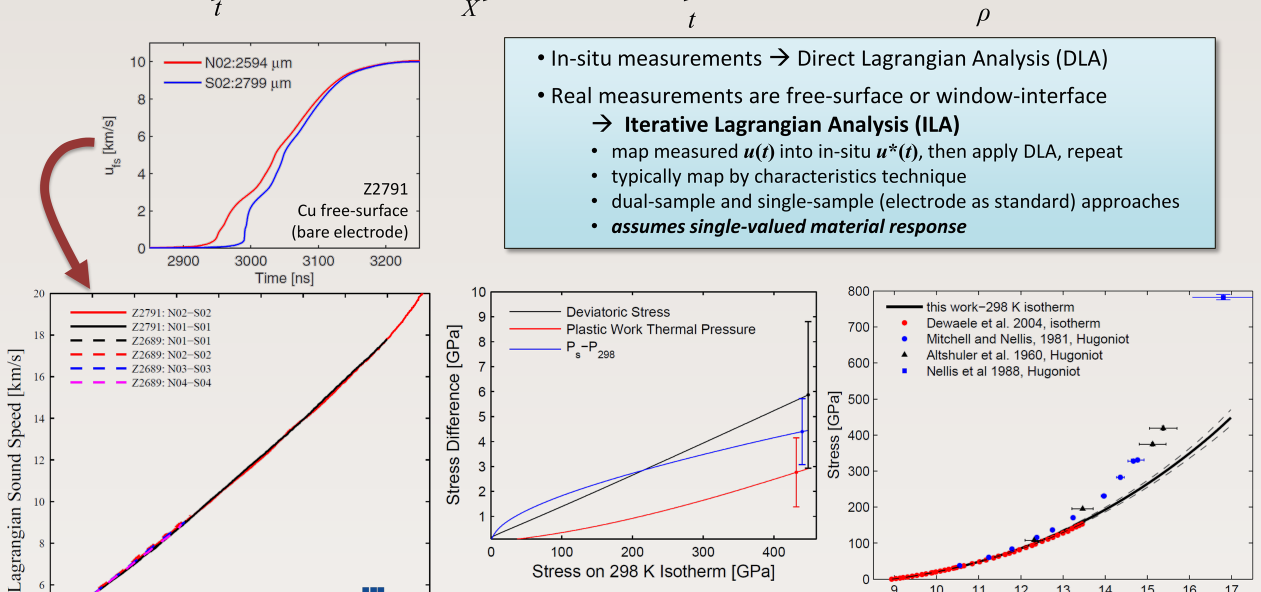
- Unsteady ramped compression waves probe low-temperature EOS (until steepening into shock)
- High-accuracy stress-density along quasi-isentrope to 100's of GPa, where DAC accuracy limited
    - Entropy generated primarily from dissipative inelastic deformation (e.g., plastic work)
- Technique is sensitive to variation of sound speed across structural phase transformations
- Can also ramp-accelerate flyers to > 30 km/s for impact experiments (shock, shock-release, etc.)
    - Traditional two-stage gas guns can only attain about 8 km/s impact velocity
- Shock-ramp loading produced by using special pulse shapes with smaller flyer flight gaps

Analysis techniques have been developed to extract multi-megabar principal isentropes from velocimetry data



$$d\sigma_x = \rho_0 c_L du \qquad \frac{d\rho}{\rho^2} = \frac{du}{\rho_0 c_L} \qquad \Delta t(u^*) = \Delta X\, c_L(u^*)$$

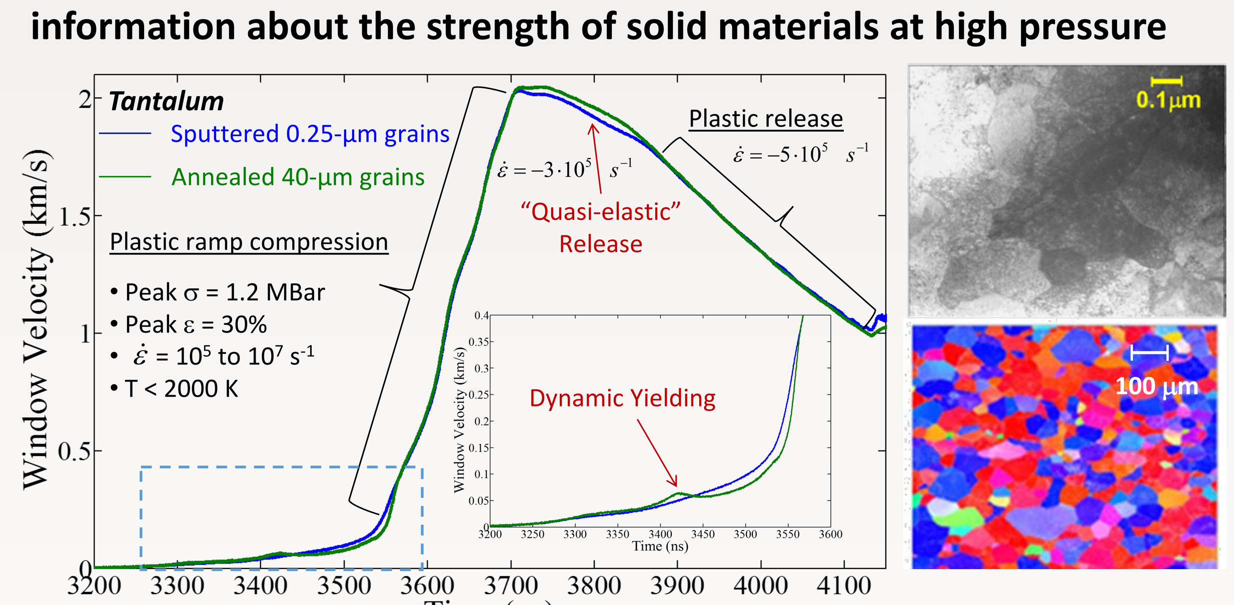
- In-situ measurements → Direct Lagrangian Analysis (DLA)
- Real measurements are free-surface or window-interface
    → **Iterative Lagrangian Analysis (ILA)**
    - map measured $u(t)$ into in-situ $u^*(t)$, then apply DLA, repeat
    - typically map by characteristics technique
    - dual-sample and single-sample (electrode as standard) approaches
    - ***assumes single-valued material response***



With accurate models for pressure-dependent strength and Grüneisen parameter, the measured quasi-isentrope can be reduced to an isotherm

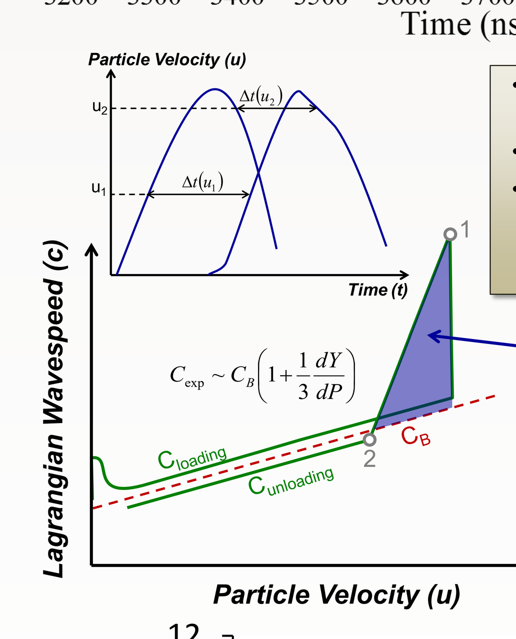
R. G. Kraus, J.-P. Davis et al, "Dynamic compression of copper to over 450 GPa: A new high–pressure standard," Phys. Rev. B 93, 134105 (2016)

Velocimetry of release from peak ramp compression can contain information about the strength of solid materials at high pressure

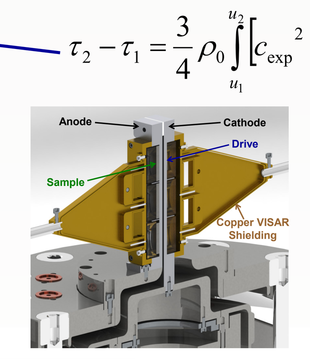


- "Self-Consistent Method" provides measure of change in shear stress during elastic unloading from peak
- assume simple wave propagation, J2 plasticity (Von-Mises yield)
- then uniaxial strain results in simplified coupling

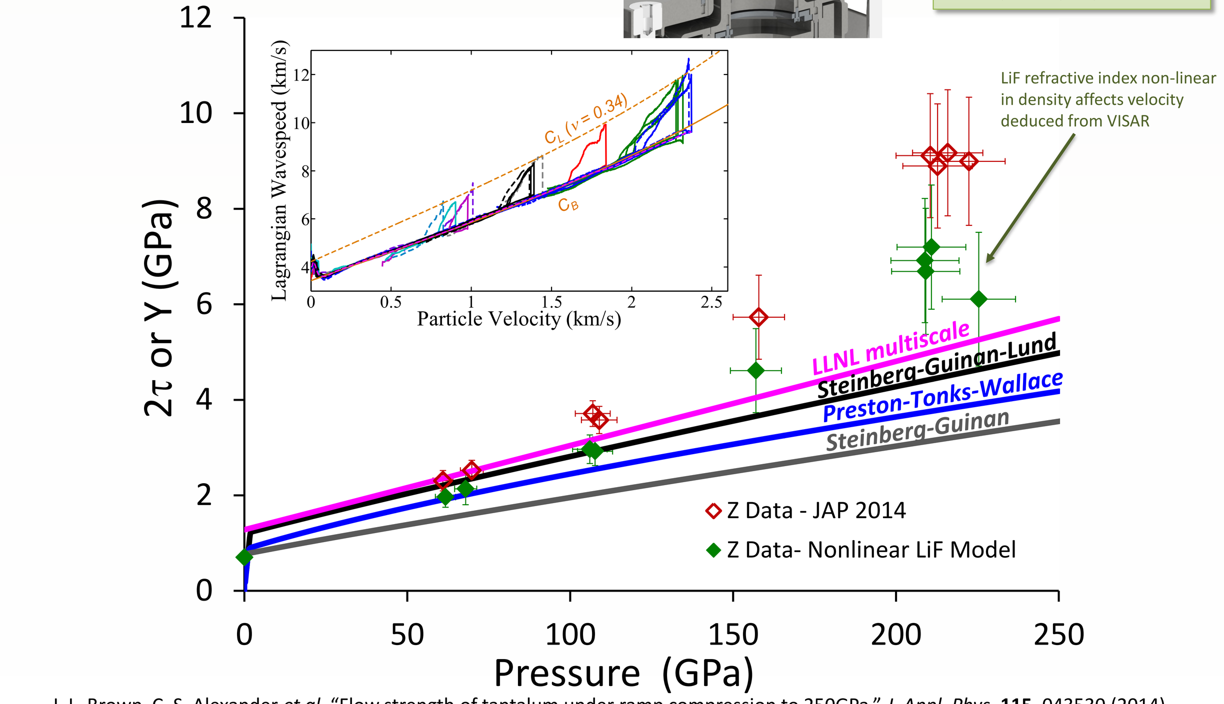
$$\sigma_x(\varepsilon) = P(\varepsilon) + \frac{4}{3}\tau(\varepsilon) \qquad \frac{d\tau}{d\varepsilon} = \frac{3}{4}\rho_0\left[c_{exp}^2 - c_B^2\right]$$



$$\tau_2 - \tau_1 = \frac{3}{4}\rho_0 \int_{u_1}^{u_2} \left[{c_{exp}}^2 - c_B^2\right]\frac{du}{c}$$

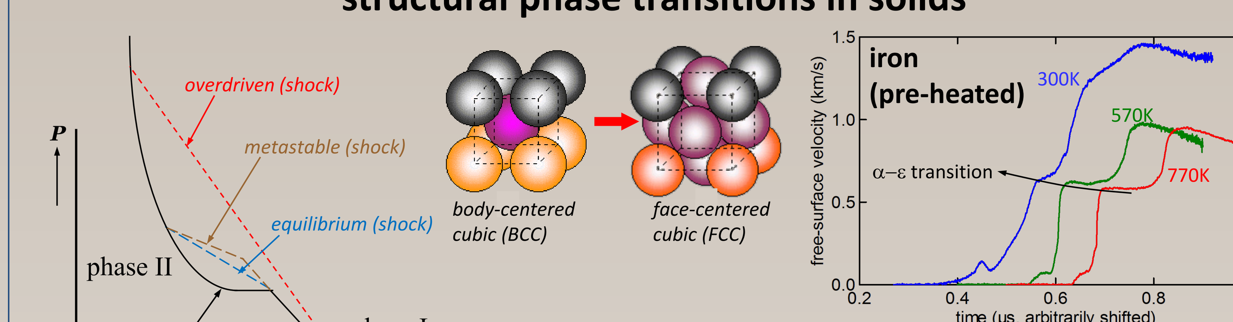


- LiF windows used both on samples and drive measurements
- requires accurate model of LiF mechanical & optical properties

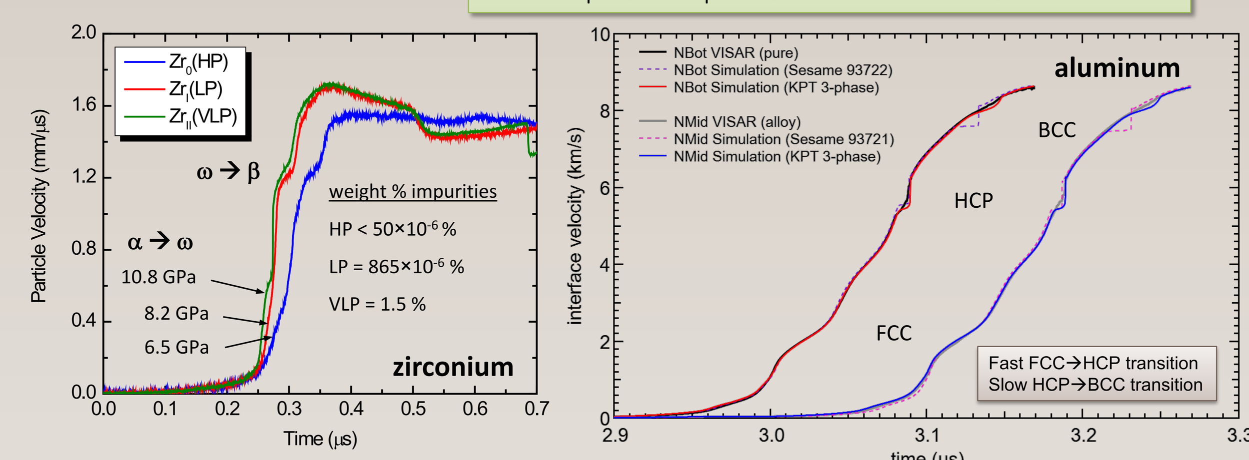


J. L. Brown, C. S. Alexander et al, "Flow strength of tantalum under ramp compression to 250GPa," J. Appl. Phys. 115, 043530 (2014)

Ramp compression has been used to investigate structural phase transitions in solids

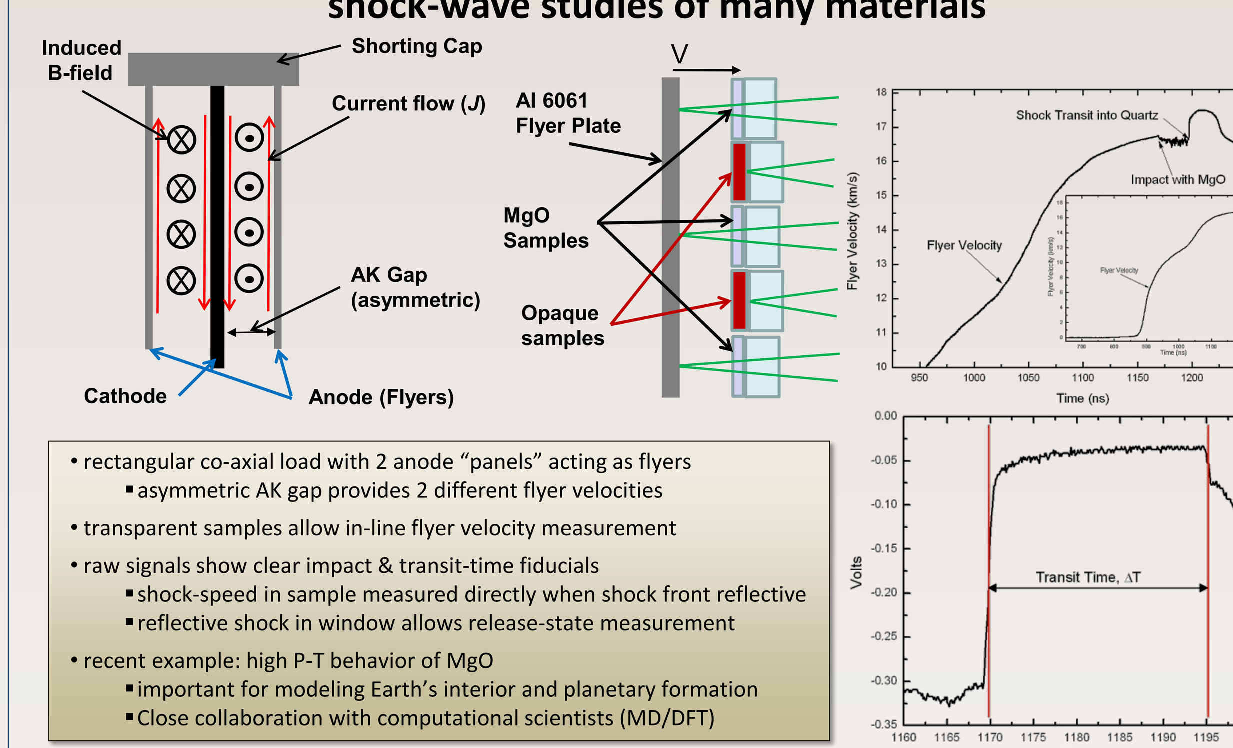


- volume collapse at constant P, T causes wave splitting
    - ramp loading does not overdrive transition (shock loading can)
- possibility of short-lived meta-stable structural phases
- complex time dependence (kinetics)
    - impurities can promote or retard transformation

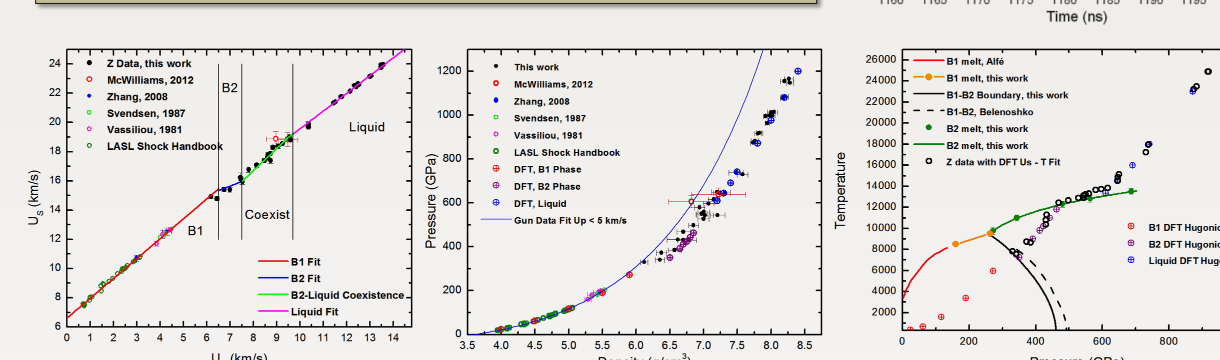


P. A. Rigg, C. W. Greef et al, "Influence of impurities on the α to ω phase transition in zirconium under dynamic loading conditions," J. Appl. Phys. 106, 123532 (2009)

Z launches hyper-velocity planar metal flyers for shock-wave studies of many materials

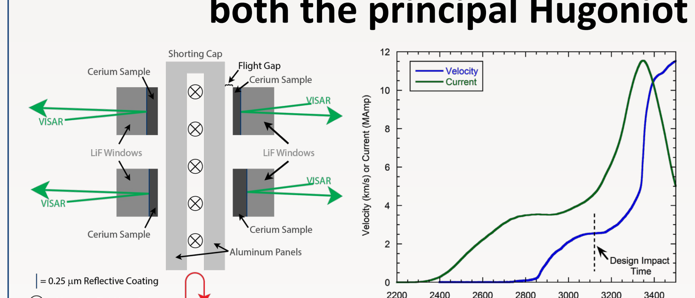


- rectangular co-axial load with 2 anode "panels" acting as flyers
    - asymmetric AK gap provides 2 different flyer velocities
- transparent samples allow in-line flyer velocity measurement
- raw signals show clear impact & transit-time fiducials
    - shock-speed in sample measured directly when shock front reflective
    - reflective shock in window allows release-state measurement
- recent example: high P-T behavior of MgO
    - important for modeling Earth's interior and planetary formation
    - Close collaboration with computational scientists (MD/DFT)

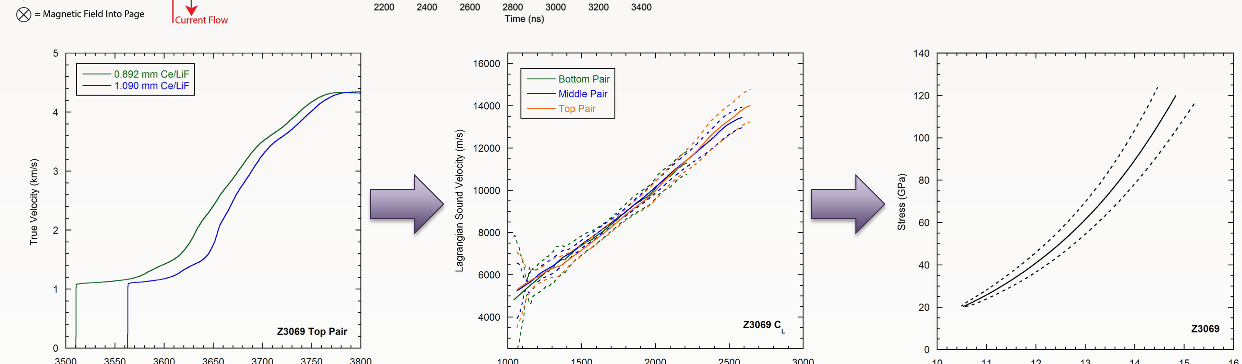


S. Root, L. Shulenburger et al, "Shock Response and Phase Transitions of MgO at Planetary Impact Conditions," Phys. Rev. Let. 115, 198501 (2015)

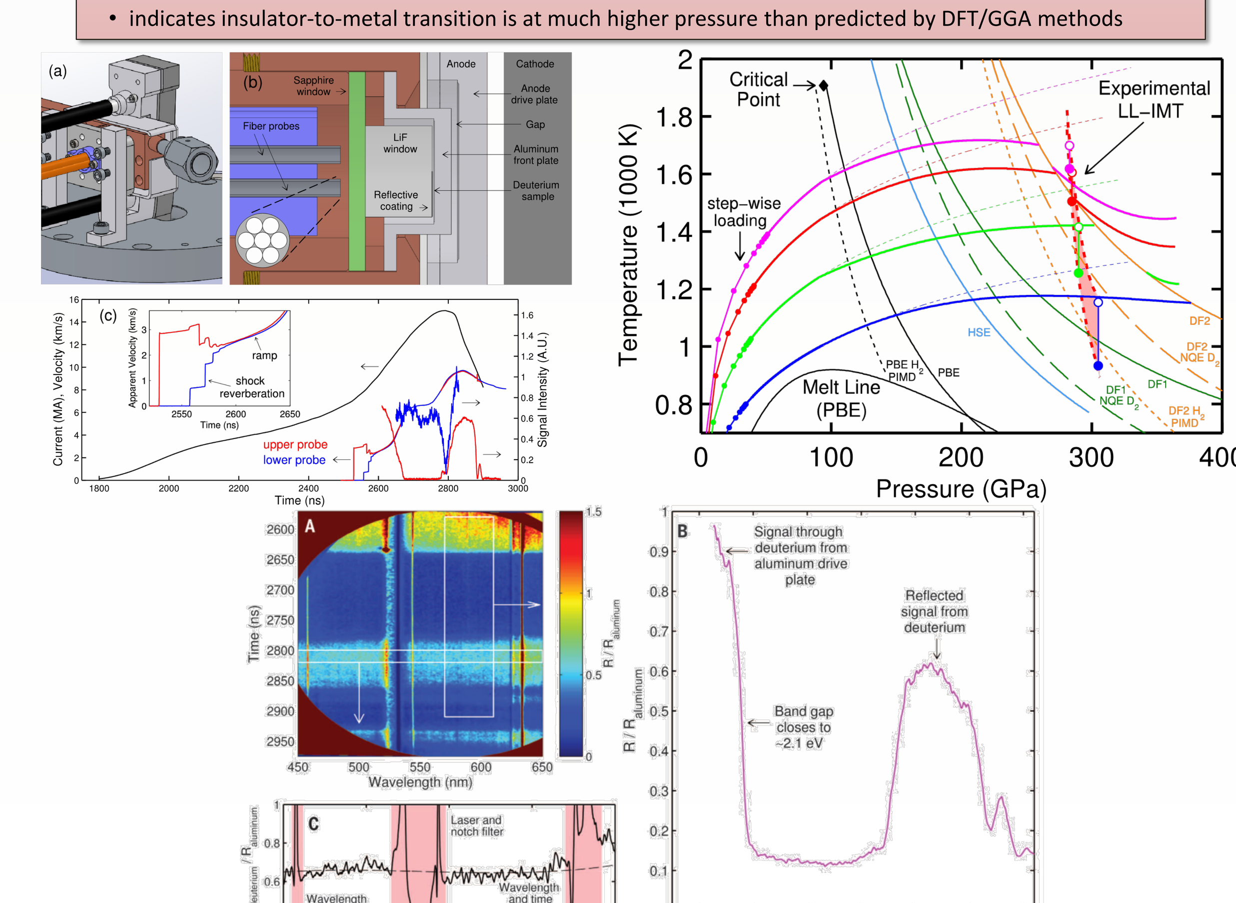
The shock-ramp technique probes material behavior far from both the principal Hugoniot and principal isentrope



- small flight gap machined into electrode panel
- double-ramp pulse accelerates flyer to ballistic
    - plateau holds shock state, then ramps
- analysis assumes shock state is known
- recent example: shock-melt of cerium
    - melt curve unknown above 30 GPa



- shock-ramp dynamic compression of liquid deuterium to over 300 GPa while remaining below 2000 K
    - thin liquid sample "rings up" through multiple shock reverberations to the pre-ramp state
- a dramatic and abrupt increase in reflectivity was observed near 300 GPa
    - Reflectivity changes in both VISAR and SVS data (latter allows absolute measurement)
- indicates insulator-to-metal transition is at much higher pressure than predicted by DFT/GGA methods



M. D. Knudson, M. P. Desjarlais et al, "Direct observation of an abrupt insulator-to-metal transition in dense liquid deuterium," Science 348, 1455 (2015)

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