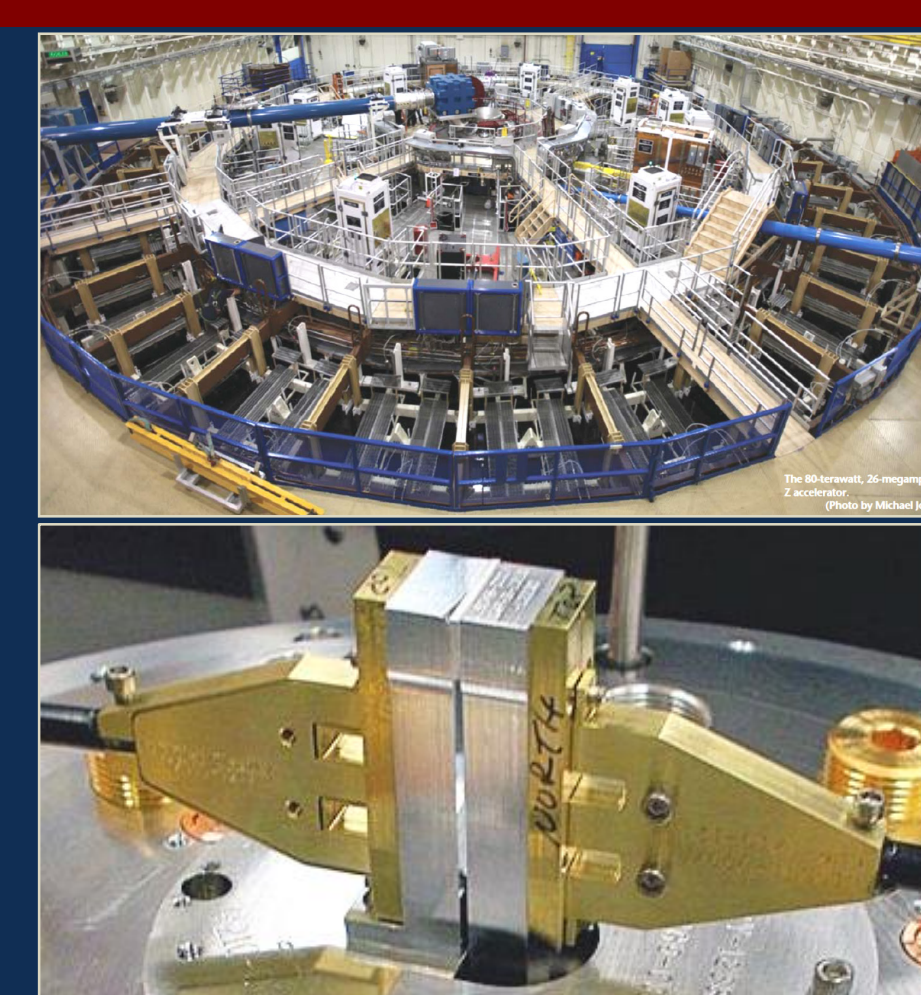


Jean-Paul Davis (jpdavis@sandia.gov)

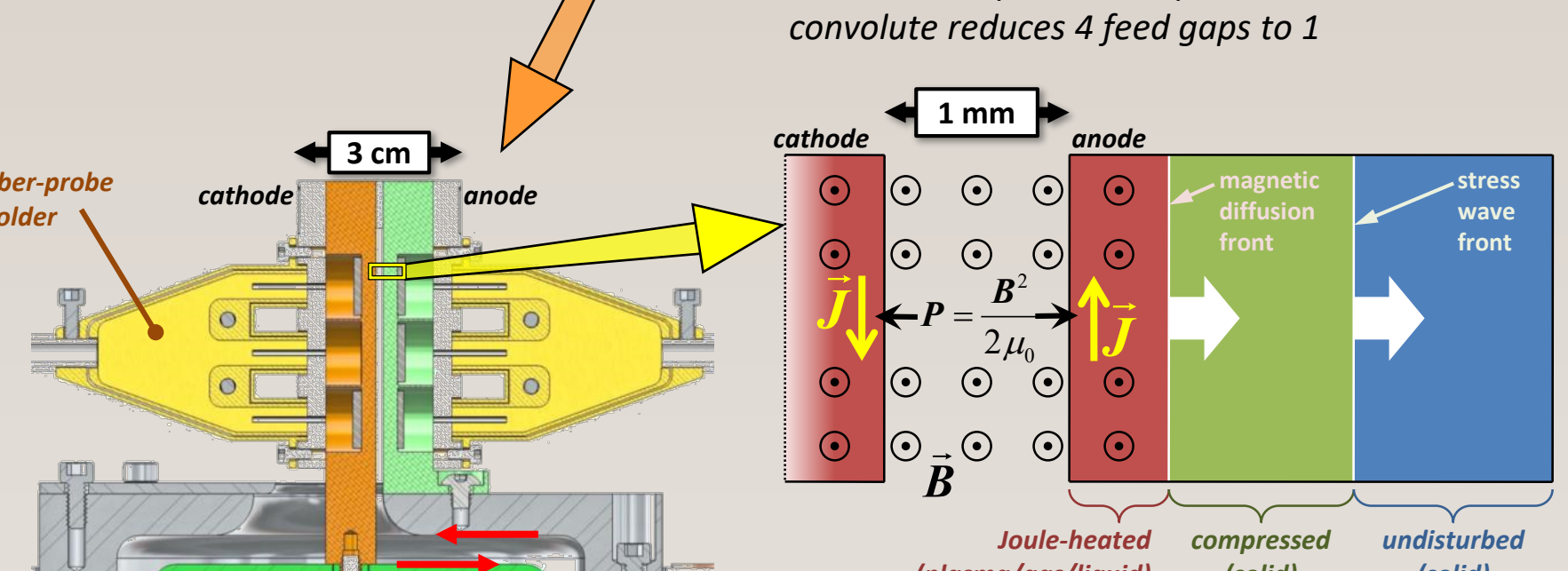


**Sandia
National
Laboratories**

energy storage section (850,000 gallons oil): stores 23 MJ in 36 banks of 60 capacitors (each 2.3 μF), charged in parallel (90 kV), discharged in series (5.4 MV)

central solenoid section (250,000 gallons H_2O): triggered SF_6 gas switches & H_2O spark-gap compress pulse to 100 ns rise time, triode 36 lines to 18, convolute reduces to 4 radial feed gaps

center section (10^{-5} torr vacuum): magnetically insulated transmission lines deliver up to 26 MA pulse to load,



- 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

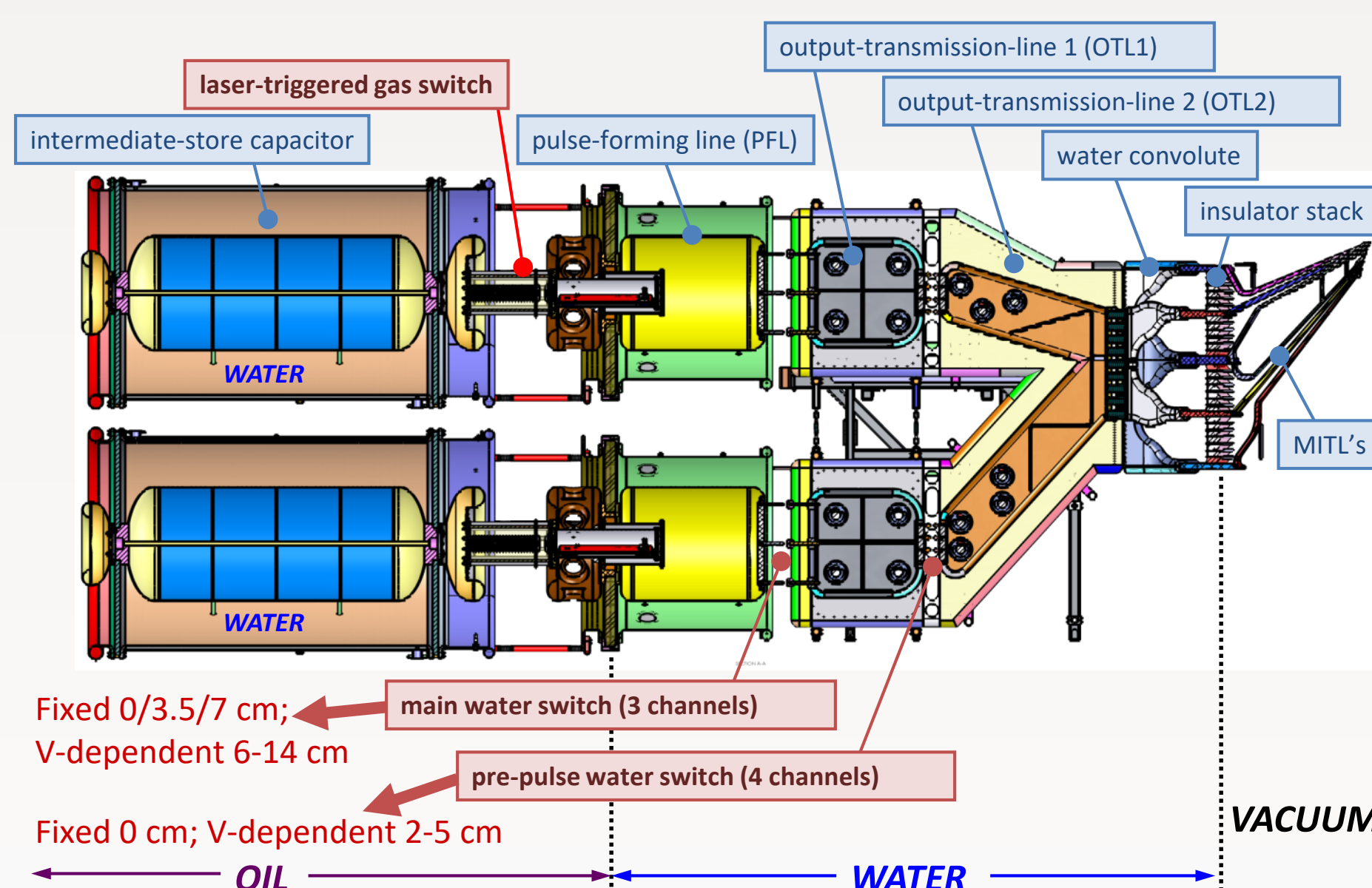
Figure 1 consists of three subplots illustrating the effective loading histories and snapshots from hydrodynamic simulations for two different shots, Z864 and Z1190.

The top-left plot shows the longitudinal stress (GPa) versus time (ns). The red curve represents the loading history for shot Z864, labeled "shot Z864 standard pulse". The blue curve represents the loading history for shot Z1190, labeled "shot Z1190 shaped pulse".

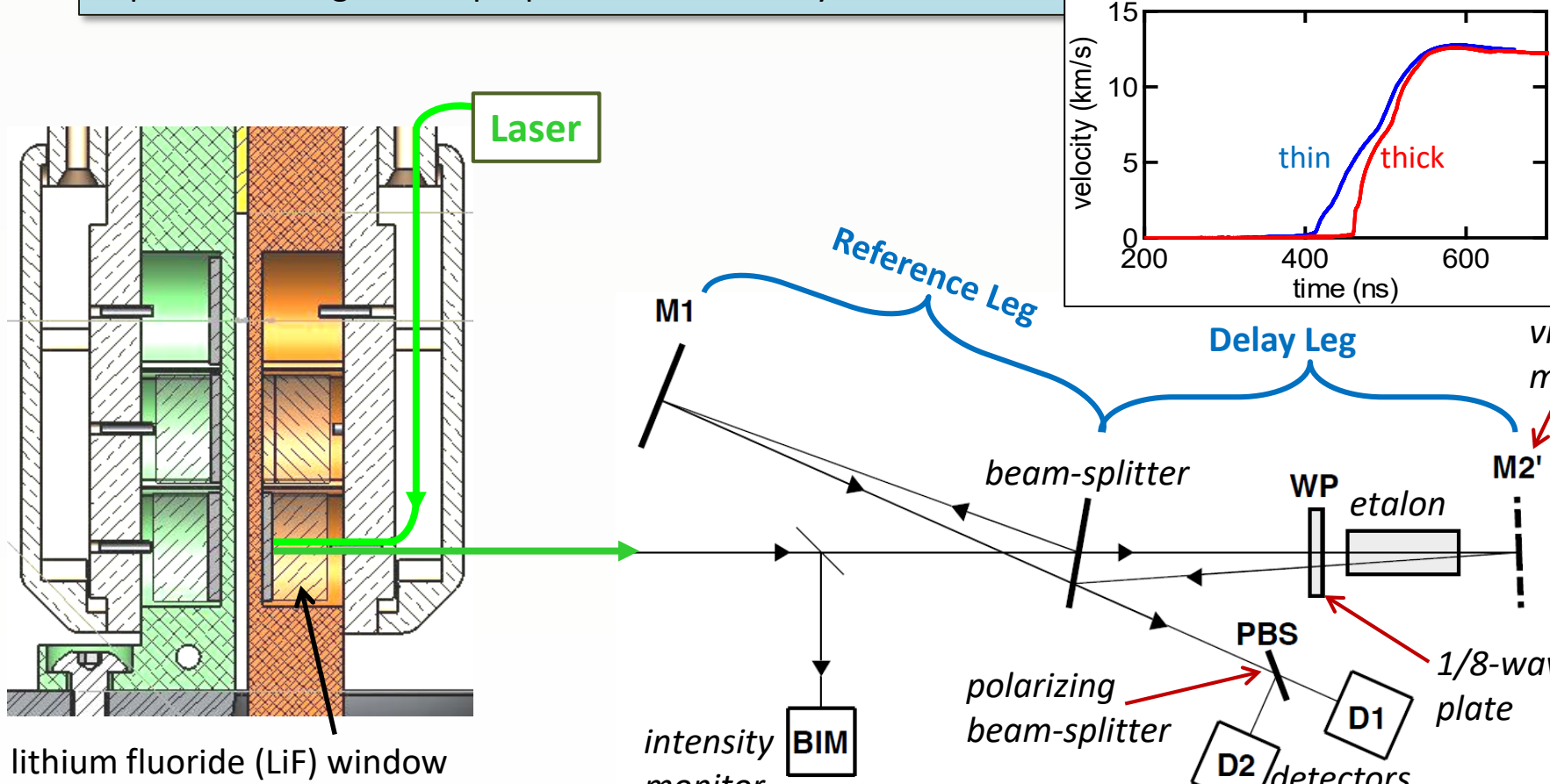
The top-right plot shows the longitudinal stress (GPa) versus Lagrangian position (mm) for shot Z864 (red) and shot Z1190 (blue) at two different times, t and t' . The red curve is labeled "0.8 mm" and the blue curve is labeled "1.8 mm".

The bottom plot shows the slope $1/c(t)$ versus time (ns). The red curve represents the slope for shot Z864 and the blue curve represents the slope for shot Z1190. A box indicates "pulse shaping delays intersection of loading characteristics". The plot also shows the "leading characteristic" and the "early formation of shock at $x_L = \frac{c^2}{dc/dt}$ ".

- 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 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 ($\Delta t = 0.02\text{--}1.5\text{ ns}$) 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 Radiometer in near-infrared (under construction)
- X-Ray Thomson Scattering (X-Ray Diffraction is under development) using Z Beamlet

Figure 1 is a 3D plot showing the Hugoniot locus and various isentropes in the pressure-density-temperature space for diamond. The vertical axis is pressure (GPa) from 0 to 400. The horizontal axis is density (g/cc) from 2.7 to 5.0. The depth axis is temperature (K) from 0 to 4000. The Hugoniot locus is a red curve. The principal Hugoniot is a red curve. The shock-release isentrope is a green curve. The shock-ramp isentrope is a blue curve. The principal isentrope is a blue curve. The room-temperature isotherm (static diamond-anvil cell compression) is a black curve.

- Unsteady ramped compression waves probe low-temperature EOS (until steepening into shock)
- High-acceleration 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

Direct Lagrangian Analysis (DLA)

$l^0 \leftarrow$ "compression velocity"
(mechanical-EOS variable)

l^* In-situ

Lagrangian analysis

$\Delta l(u^*) = \Delta X \cdot c_l(u^*)$

σ_x stress-density response

$\frac{d\sigma_x}{d\rho} = \frac{du}{\rho_0 c_L}$

conservation of mass and momentum

- 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**

— N02-2594 μm
— S02-2709 μm

22791
Cu free-surface
(bare electrode)

— Deviatoric Stress
— Plastic Work Thermal Pressure
 $P = P_{298}$

• this work–298 K isotherm
• Dewaele et al. 2004, isotherm
• Mitchell and Nellis, 1981, Hugoniot
• Alshuler et al. 1960, Hugoniot
• Nellis et al. 1988, Hugoniot

With accurate models for pressure-dependent strength and Grüneisen

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)

Tantalum

- Sputtered 0.25- μm grains
- Annealed 40- μm grains

Plastic ramp compression

- Peak $\sigma = 1.2$ MBar
- Peak $\epsilon = 30\%$
- $\dot{\epsilon} = 10^5$ to 10^7 s^{-1}
- $T < 2000$ K

Plastic release

$\dot{\epsilon} = -3 \cdot 10^5$ s^{-1}

$\dot{\epsilon} = -5 \cdot 10^3$ s^{-1}

"Quasi-elastic" Release

Dynamic Yielding

Window Velocity (km/s)

Time (ns)

0.1 μm

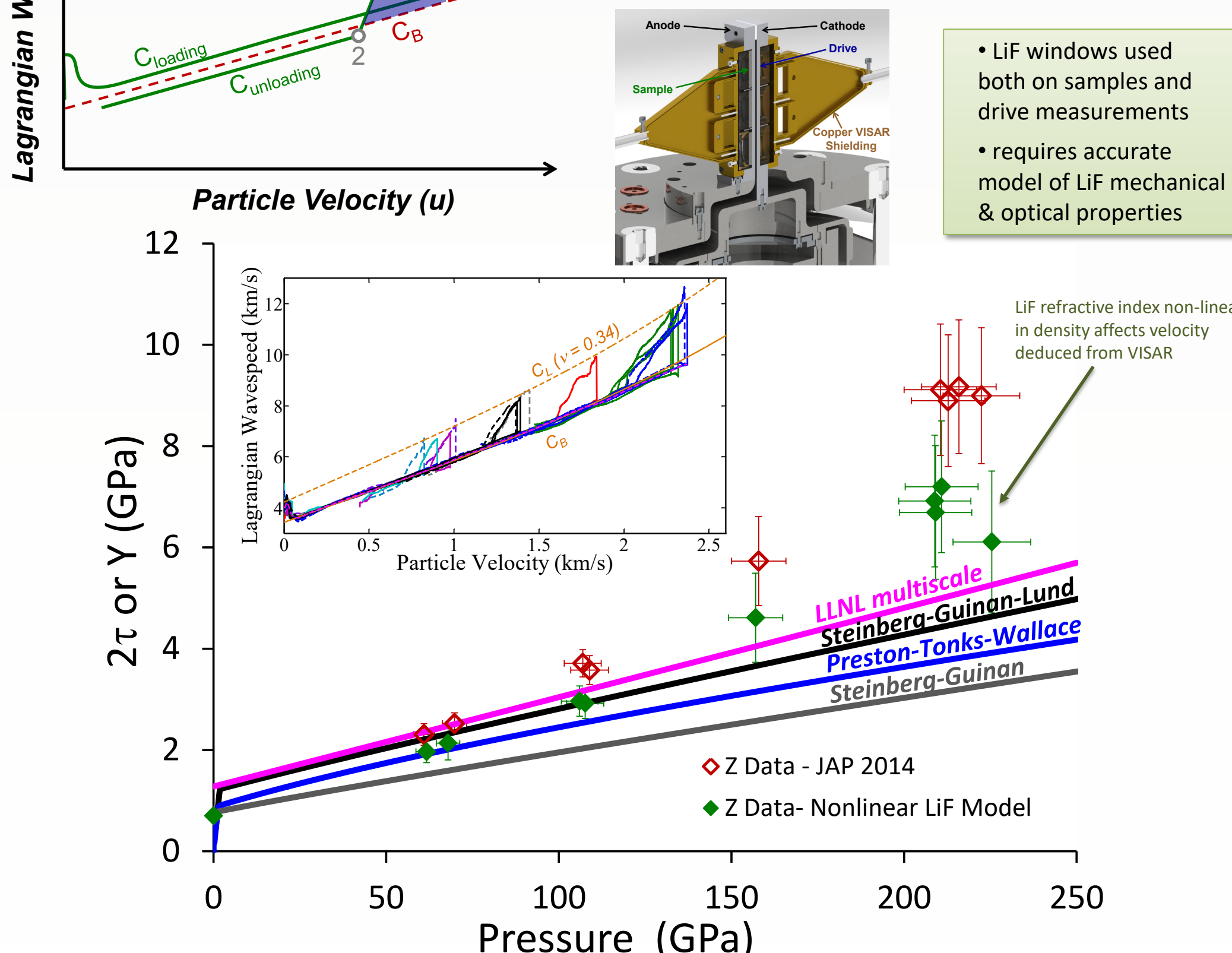
100 μm

- “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

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

$$C_{\text{exp}} \sim C_B \left(1 + \frac{1}{3} \frac{dY}{dP} \right) \quad \tau_2 - \tau_1 = \frac{3}{4} \rho_0 \int_{u_1}^{u_2} [c_{\text{exp}}^2 - c_B^2] \frac{du}{c}$$

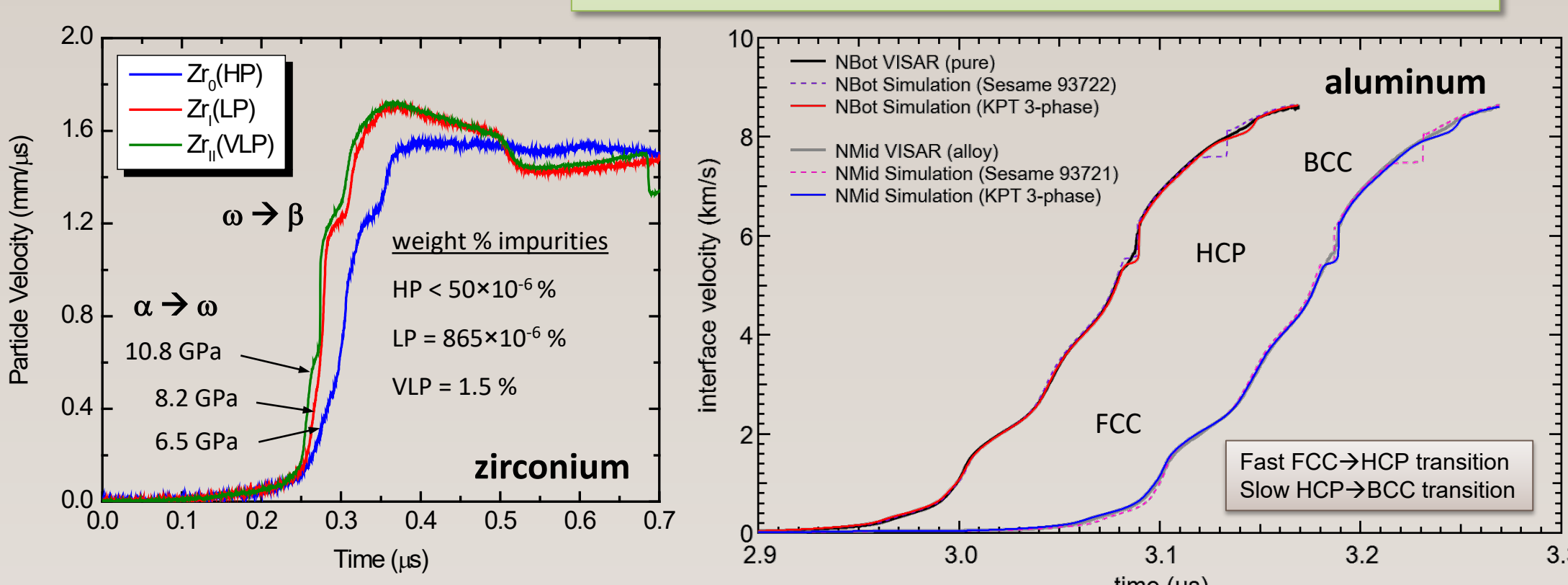
- LiF windows used both on samples and drive measurements
- requires accurate model of LiF mechanical & optical properties



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

Figure 10 consists of three parts. On the left is a phase diagram with pressure P on the vertical axis and velocity v on the horizontal axis. It shows phase I and phase II regions. Three paths are indicated: 'overdriven (shock)' in red, 'metastable (shock)' in blue, and 'equilibrium (shock)' in green. A 'static' equilibrium path is also shown. In the center is a diagram showing the structural transition from body-centered cubic (BCC) to face-centered cubic (FCC) iron, represented by spheres. On the right is a plot of free-surface velocity (m/s) versus time (μ s, arbitrarily shifted) for iron (pre-heated). Three curves are shown for different temperatures: 300K (blue), 570K (green), and 770K (red). The 300K curve shows a sharp transition labeled ' α - γ transition'.

- 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)

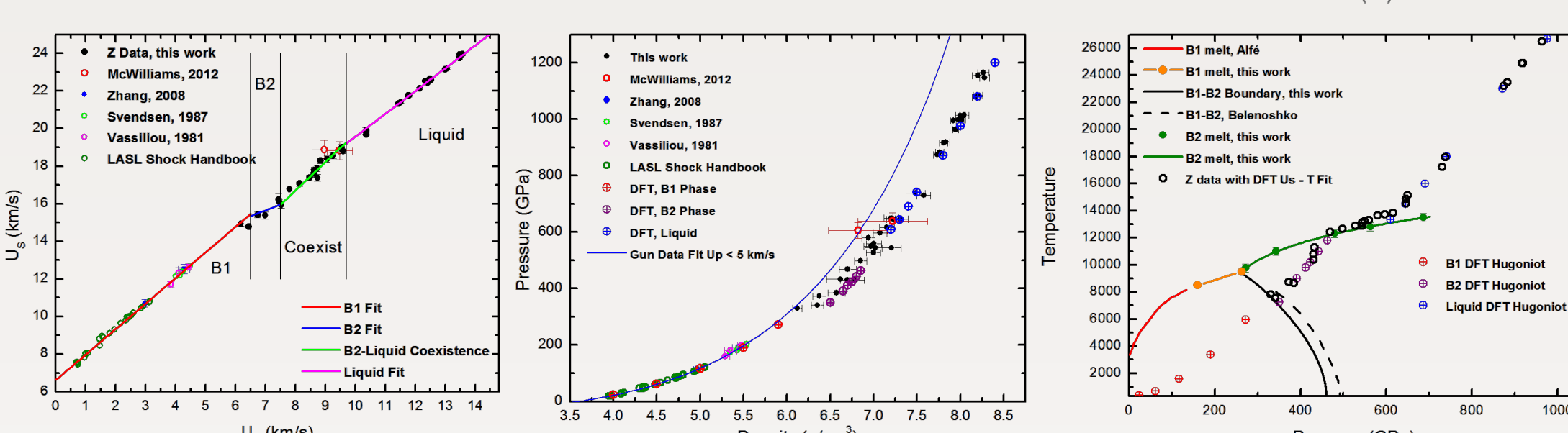
The diagram illustrates a laser-driven flyer experiment setup and the resulting data. The top part shows a schematic of the experimental setup: a rectangular co-axial load with two anode "panels" acting as flyers, an asymmetric AK gap, and a cathode. A shorting cap is placed over the top. The current flow (J) is indicated by red arrows. The setup includes an Al 6061 Flyer Plate, MgO Samples, and Opaque samples. The voltage (V) is measured across the samples. The bottom part shows two plots: the top plot is a graph of Flyer Velocity (km/s) versus Time (ns), showing a shock transient into quartz and an impact with MgO. The bottom plot is a graph of Voltage versus Time (ns), showing a transient time ΔT .

Experimental Setup:

- Induced B-field
- Shorting Cap
- Current flow (J)
- Al 6061 Flyer Plate
- MgO Samples
- Opaque samples
- AK Gap (asymmetric)
- Cathode
- Anode (Flyers)
- Voltage (V)

Results:

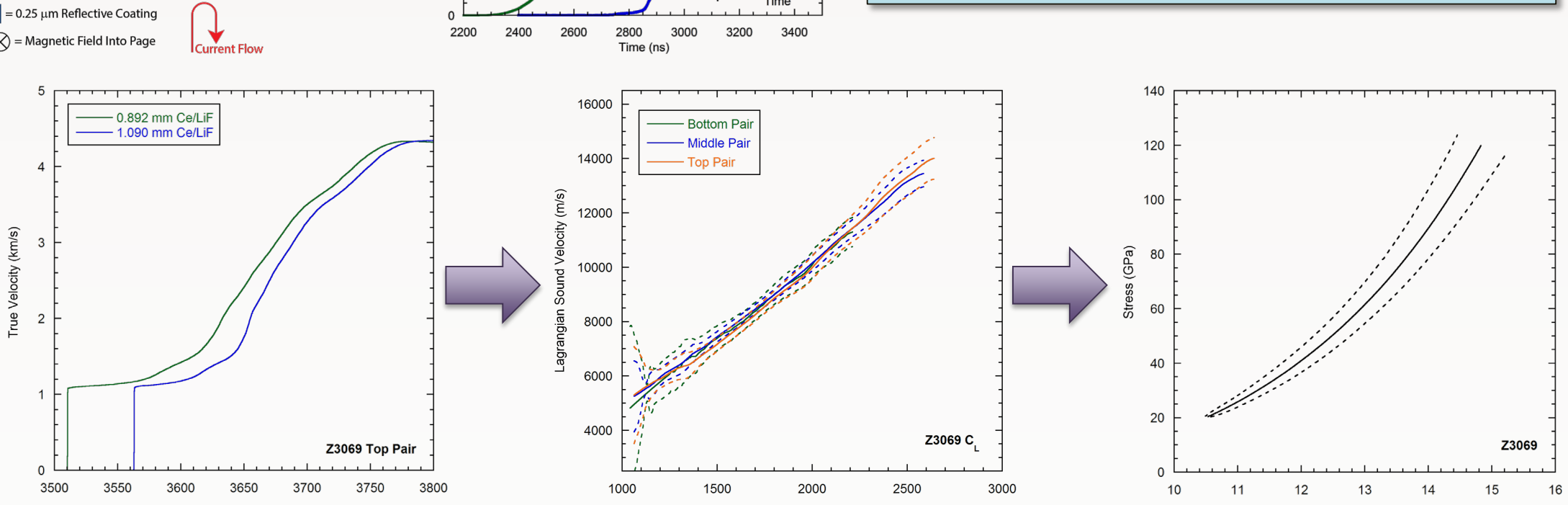
- rectangular co-axial load with 2 anode "panels" acting as flyers
 - asymmetric AK gap provides 2 different flyer velocities
- transparent samples allow in-line flyer velocity measurement
- raw signals show clear impact & transit-time fiducials
 - shock-speed in sample measured directly when shock front 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)



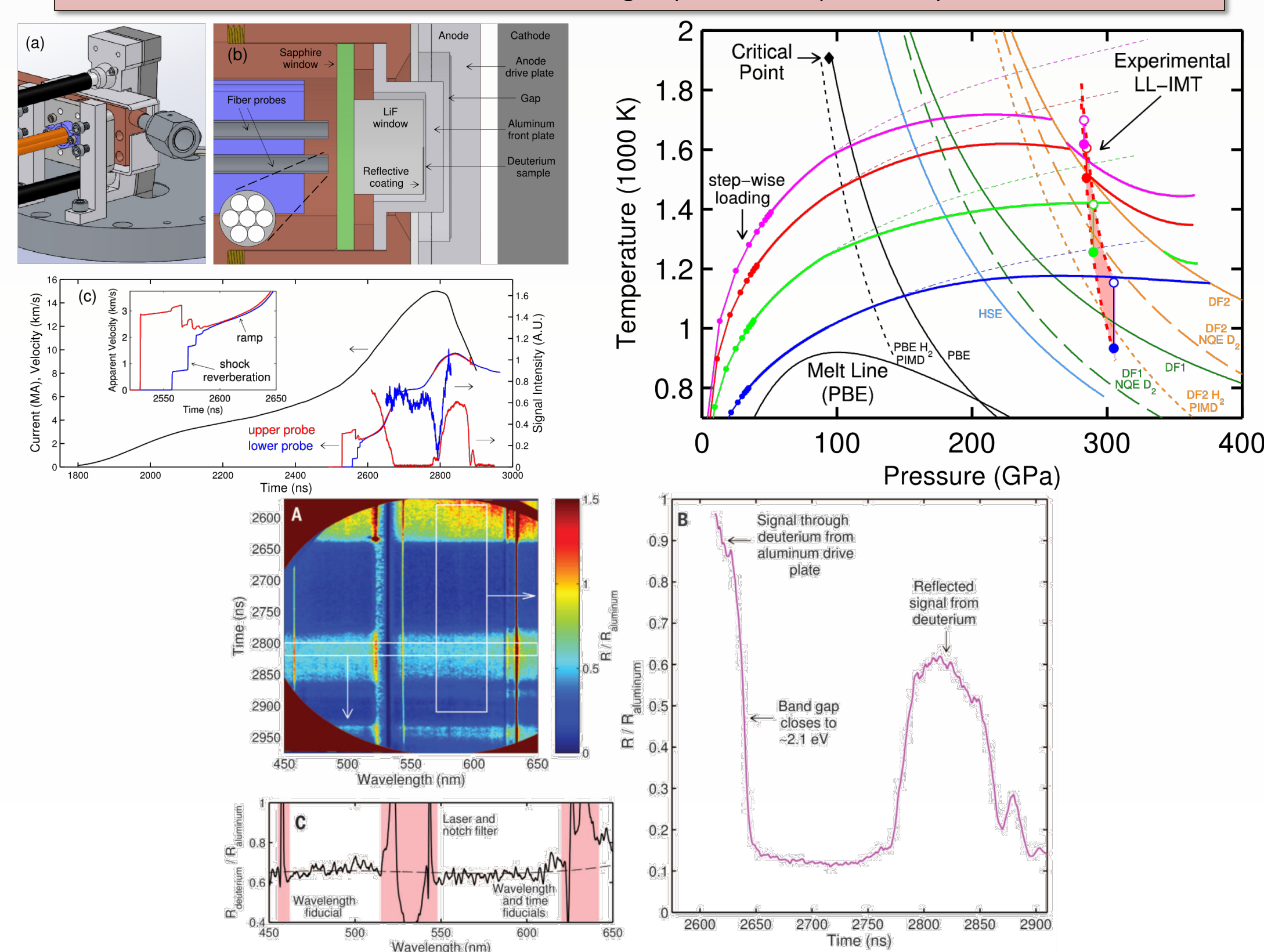
S. Root, L. Shulenburger *et al.*, "Shock Response and Phase Transitions of MgO at Planetary Impact Conditions." *Phys. Rev. Lett.* **115**, 198501 (2015)

Figure 1 consists of a schematic diagram on the left and a graph on the right. The schematic shows a cross-section of the experimental setup: a 'Flyer Cap' (Aluminum) is positioned above a 'Cerium Sample' (Aluminum). A 'Light Gap' is indicated between them. A 'Shock Ramp' is shown as a dashed line. The 'Cerium Sample' is supported by 'Aluminum Porch' and 'Cerium Sample' layers. A 'Cerium Sensor' is located below the sample. The graph on the right plots 'Shock Velocity (km/s)' on the y-axis (0 to 10) against 'Time (ns)' on the x-axis (0 to 10). Two curves are shown: a blue line for 'Indefinite' and a green line for 'Cerium'. The 'Indefinite' curve shows a sharp increase in velocity starting around 4 ns, reaching a plateau of approximately 8 km/s. The 'Cerium' curve shows a similar trend but with a more gradual increase, reaching the same plateau around 6 ns. A 'Shock Ramp' is labeled on the 'Cerium' curve.

- 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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