SAND2023-08068C

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RAMP AND SHOCK-RAMP CAPABILITIES AT Z

Z Fundamental Science Workshop, 9-11 August, 2023

Jean-Paul Davis

Dynamic Material Properties (Org. 1646)

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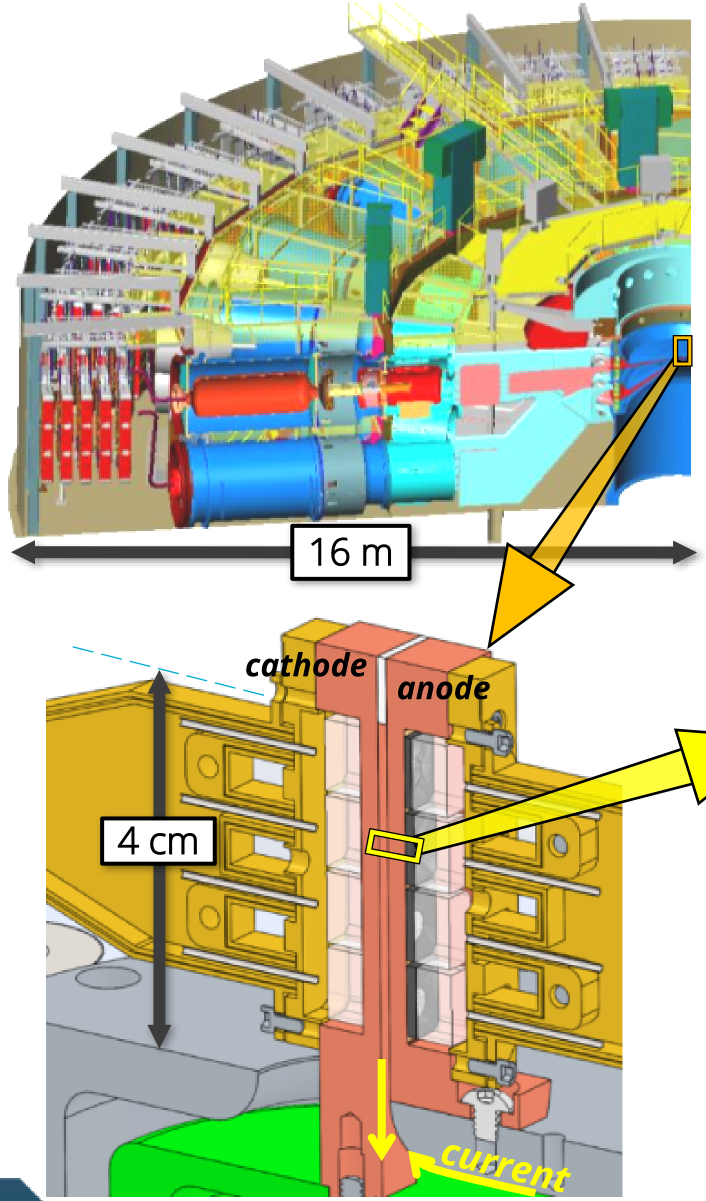
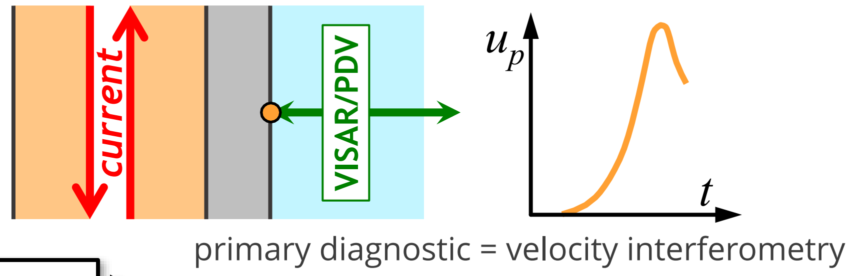
Stripline short-circuit loads on the Z pulsed-power machine can produce planar shockless compression of solids to 400+ GPa

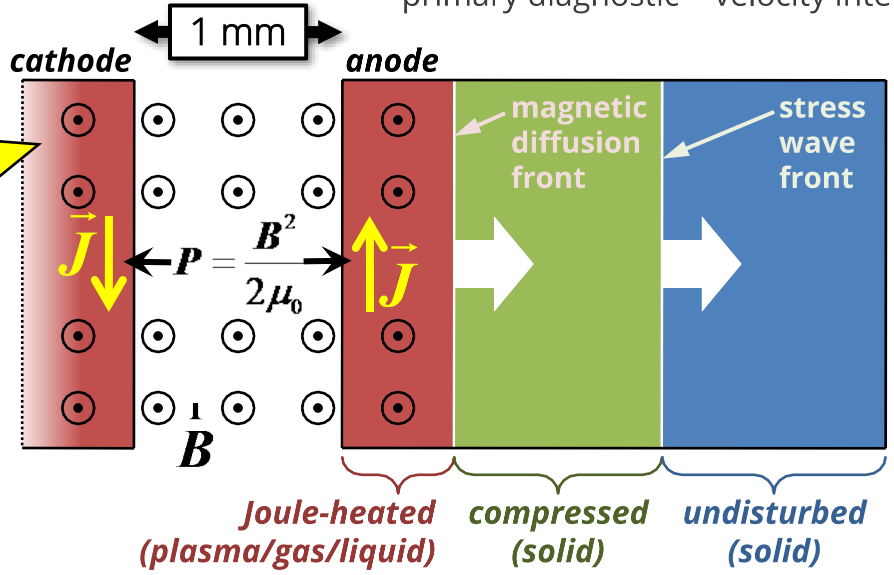
Stripline = parallel flat-plate electrodes shorted at one end

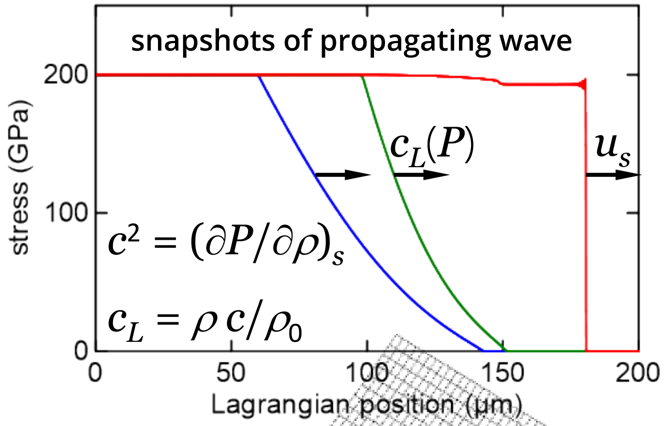
Magnetic ($\boldsymbol{J}\times\boldsymbol{B}$) force induces ramped stress wave in electrode material

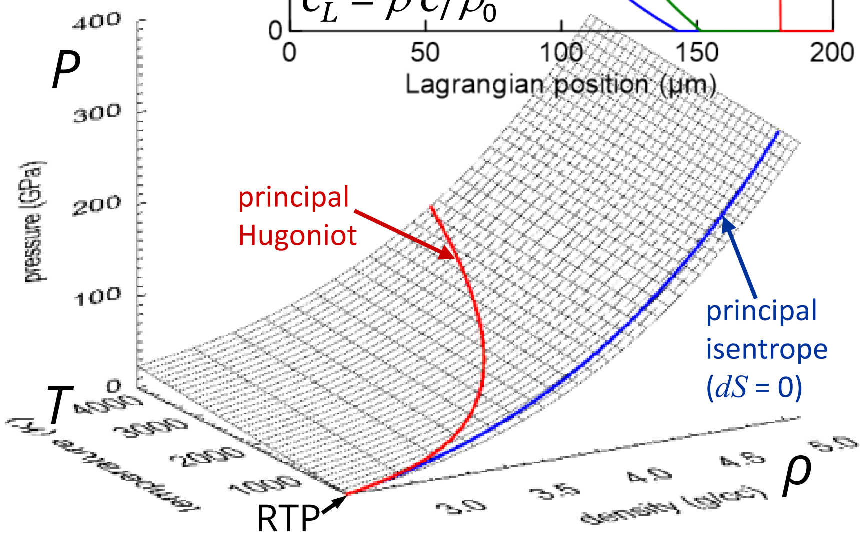
- stress wave propagates into ambient sample material, decoupled from magnetic diffusion front



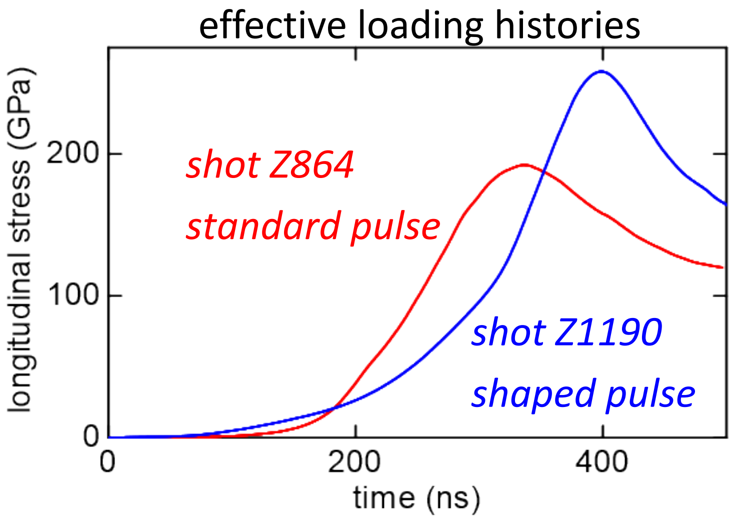


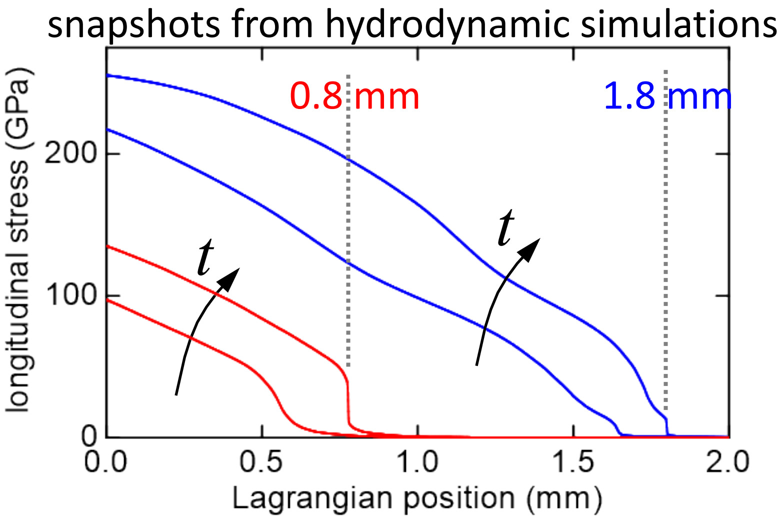






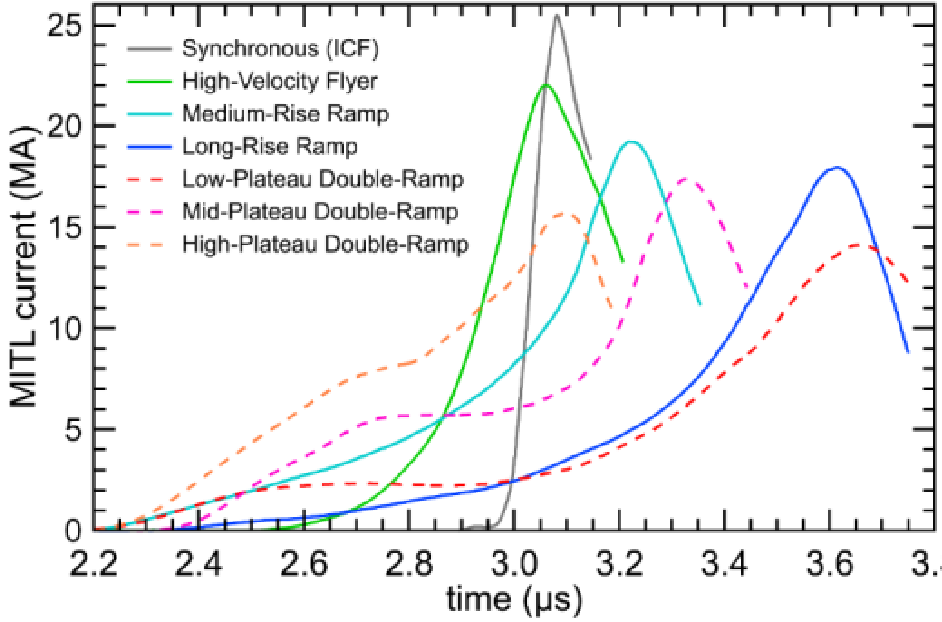
Z offers fine control of driving pulse shape over a wide range to avoid shock formation or to generate complex loading paths

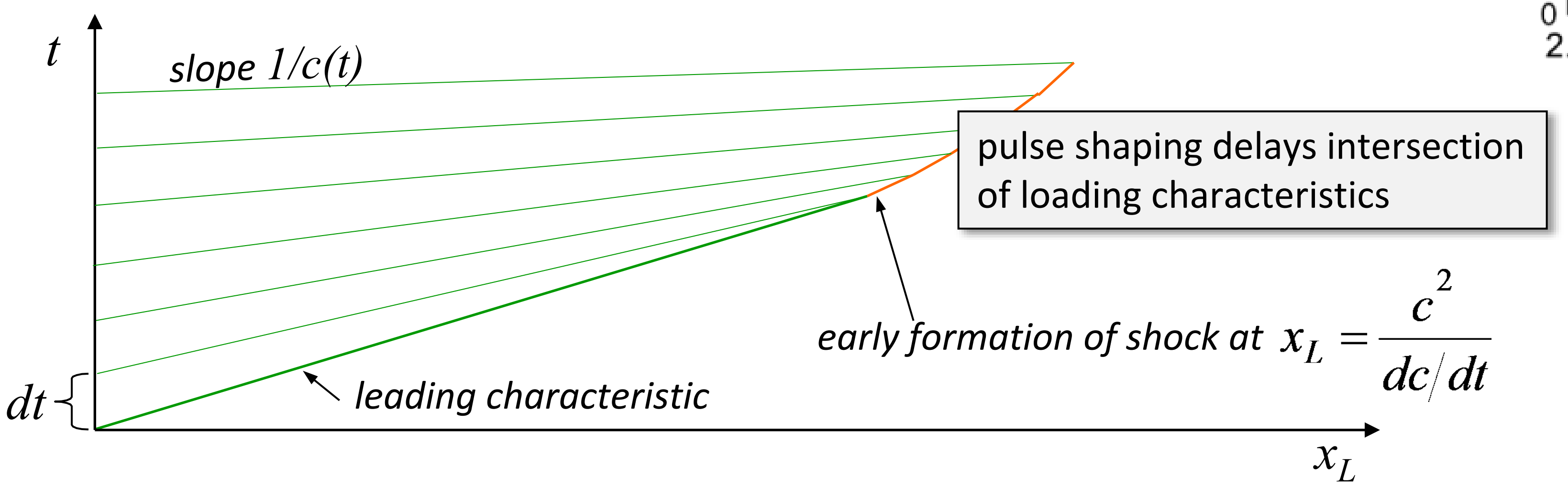


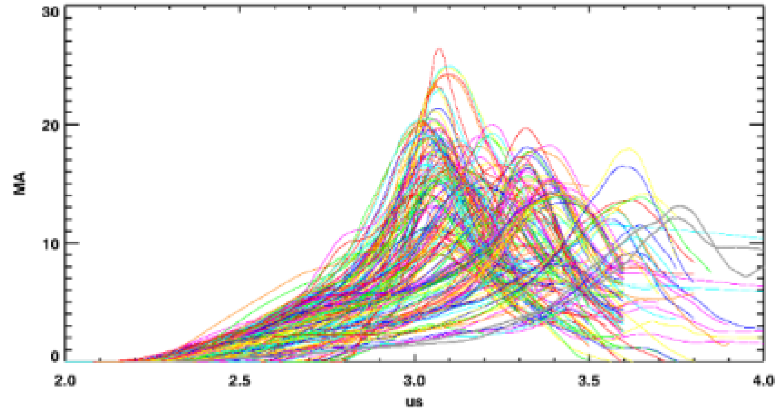


Davis et al, Phys. Plasmas ***12****, 056310 (2005)*

Sinars et al, Phys. Plasmas ***27****, 070501 (2020)*







Velocimetry optically measures time-resolved rear-surface motion of samples and electrode "drive"

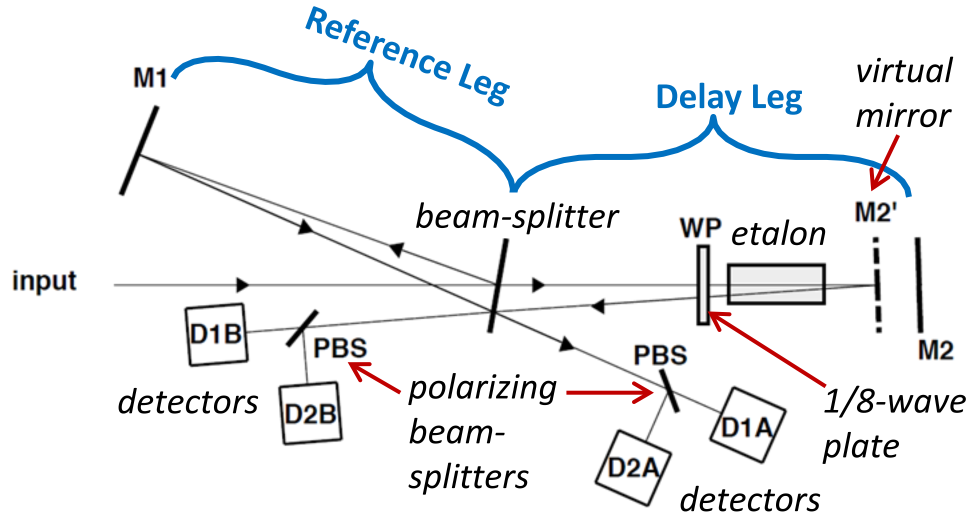
Laser fiber-coupled to reflector on sample (free surface or sample-window interface)

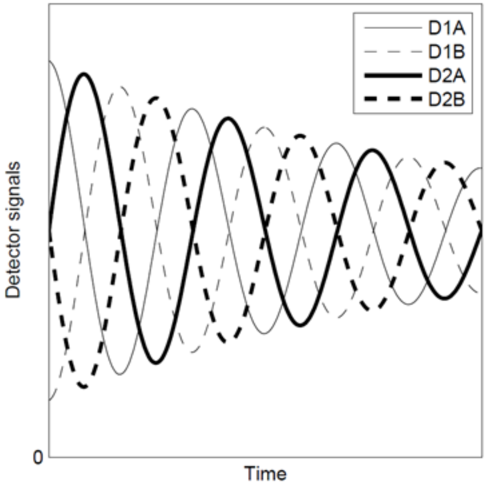
VISAR = Velocity Interferometry System for Any Reflector at 532 nm (green)

- Velocity ∝ difference in optical phase of doppler-shifted light reflected at two different times (Δt = 0.02-1.5 ns)

PDV = Photonic Doppler Velocimetry at 1550 nm (infrared)

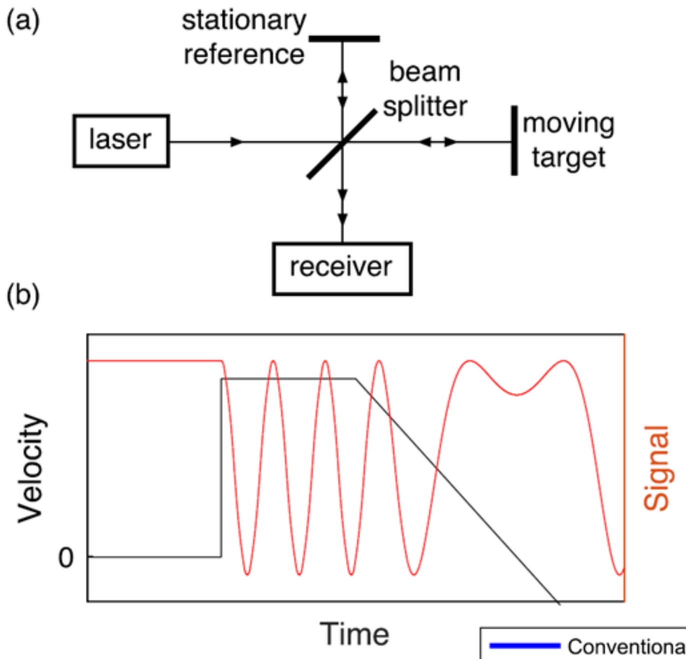
- Velocity ∝ beat frequency between reference and doppler-shifted light



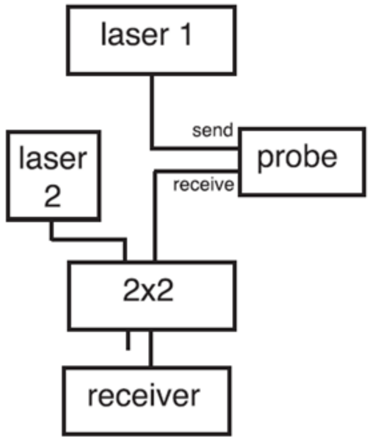


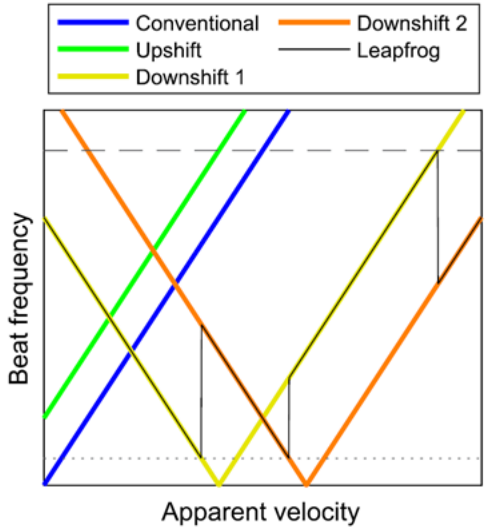
Dolan, "Foundations of VISAR analysis," SAND2006-1950

push-pull VISAR



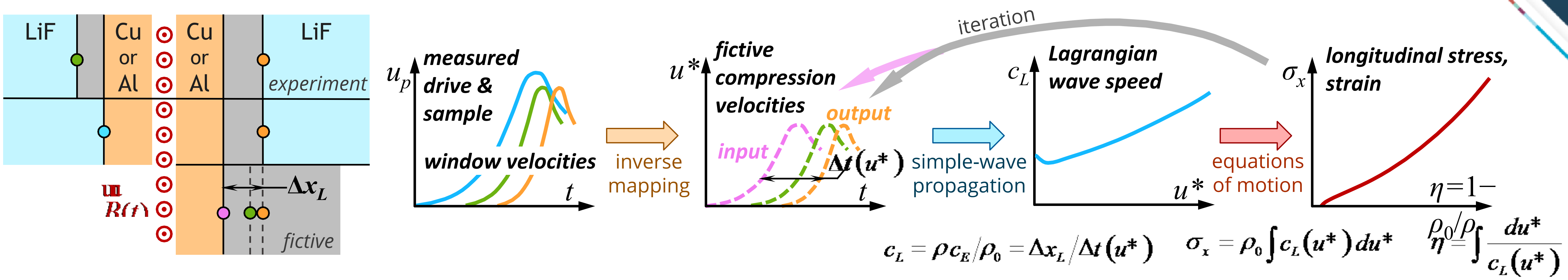
PDV





Dolan, Rev. Sci. Instrum. ***91****, 051501 (2020)*

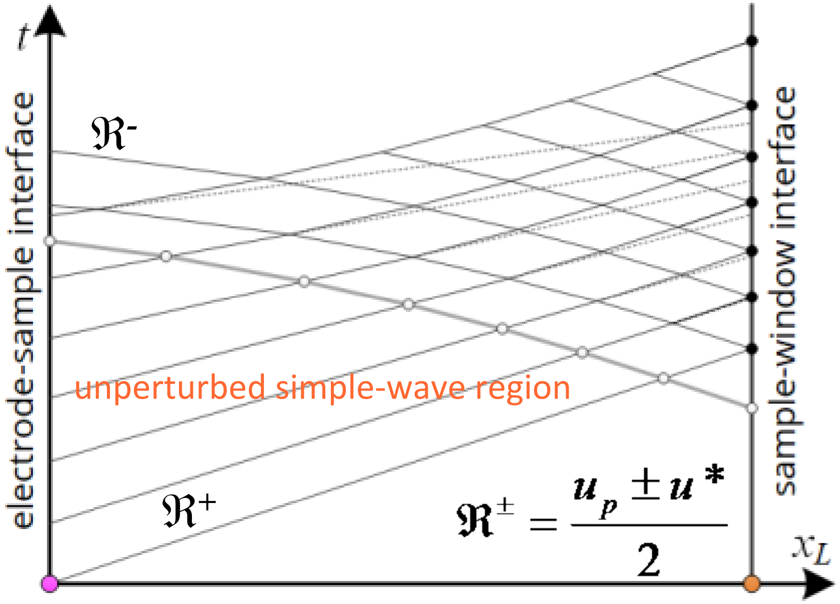
Velocity waveform measurements essentially probe Lagrangian wave speed, i.e., compressibility under uniaxial strain



Fictive "in-material" measurements → Direct Lagrangian analysis (DLA) of wave propagation

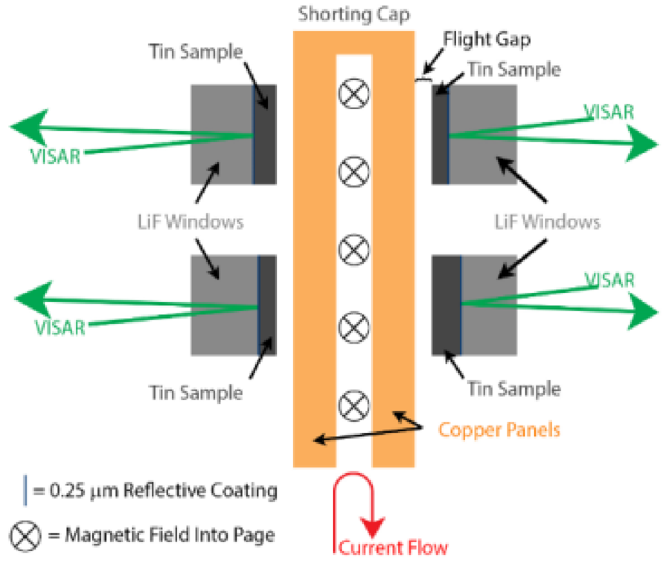
Real measurements at window interface → **Inverse Lagrangian analysis (ILA)**

- solution maps $u_p(t)$ to $u^*(t)$ by backward integration, self-consistent with DLA of $u^*(t)$
- most developed approach uses characteristics net in t-x_L for mapping, iteratively or non-iteratively
- requires assumption of single-valued material response $c_L(u^*)$



Davis et al, J. Appl. Phys. ***116****, 204903 (2014)*

Z experiments can also probe shock-release-ramp isentropes

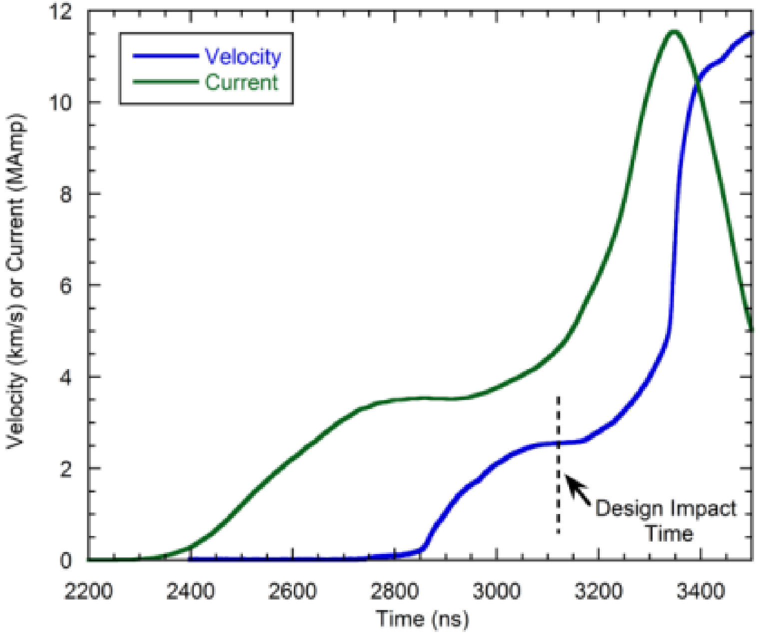


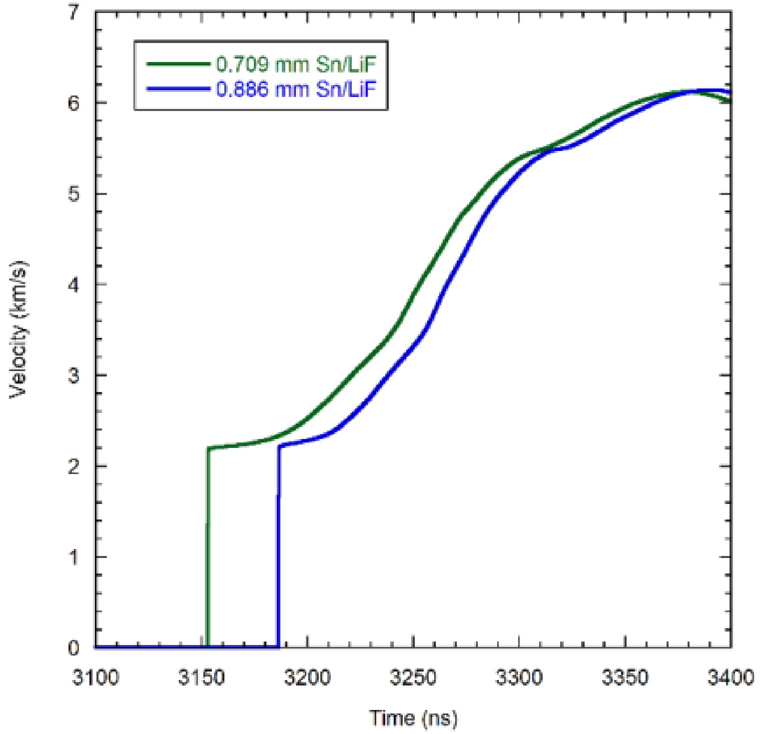
Double-ramp pulse shape with flight gap

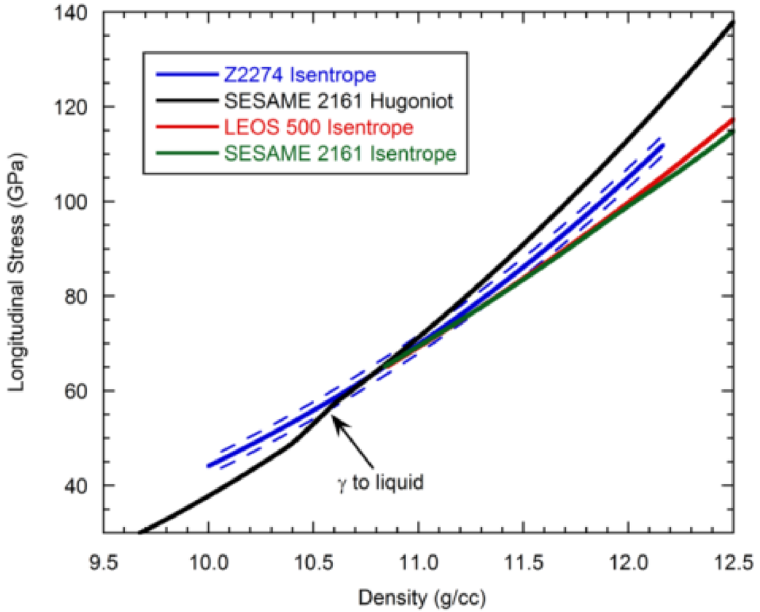
- shock (impact) followed by dwell then ramp
- at lower-impedance window interface: shock-release-ramp
- determine compressibility along isentrope if sample's Hugoniot known

Now moving toward "gapless" shock-ramp

- pulse shaping to get shock-dwell-ramp inside electrode material





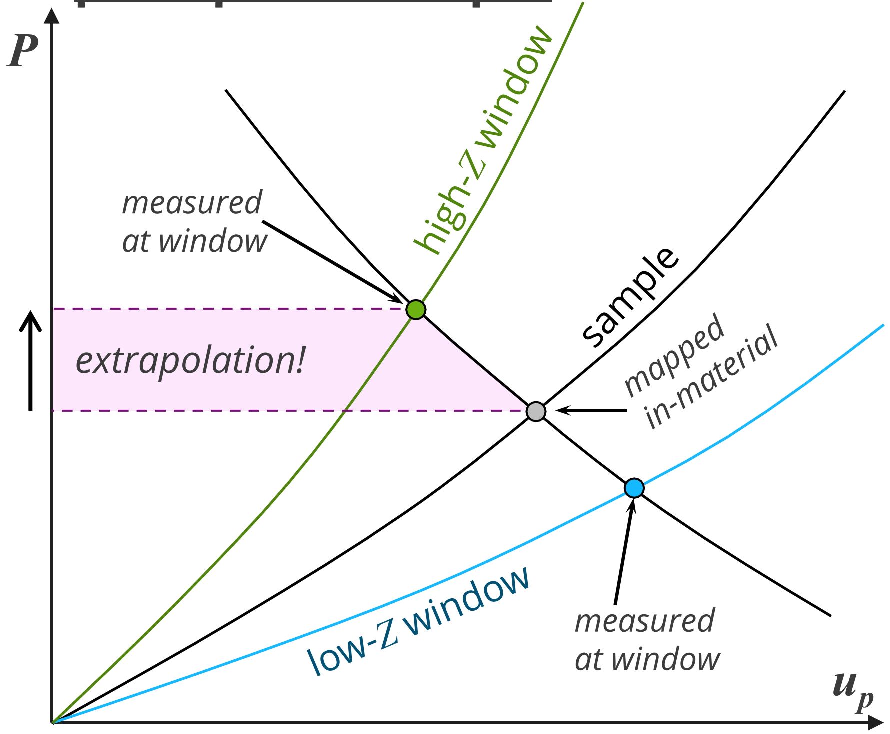


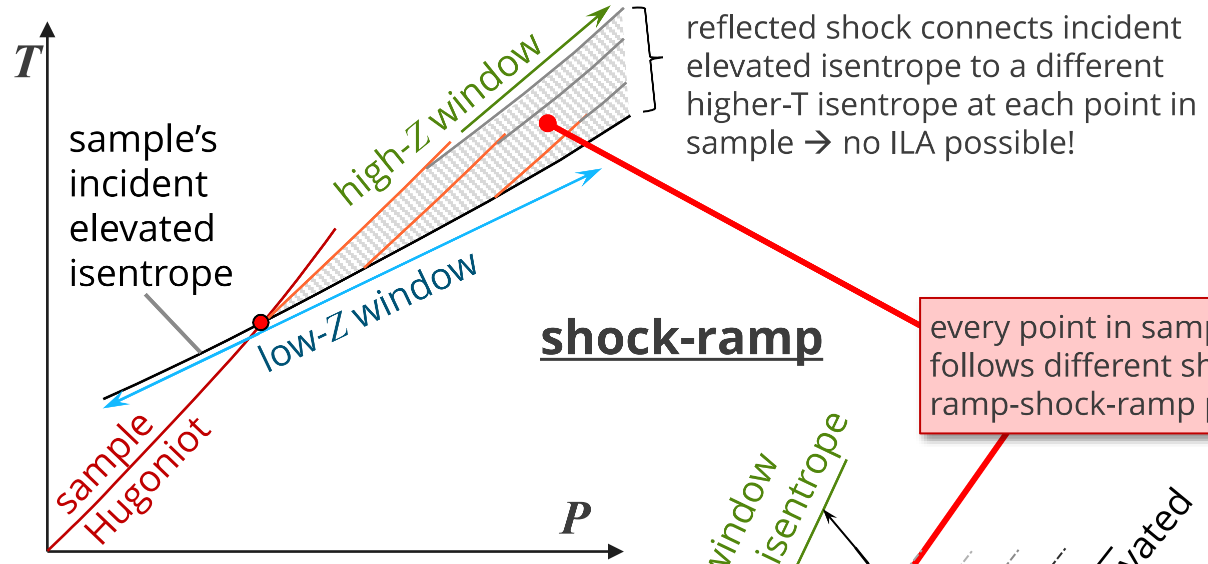
Seagle et al, Appl. Phys. Let. ***102****, 244104 (2013)*

Windows of higher acoustic impedance than the sample complicate analysis of ramp and shock-ramp experiments

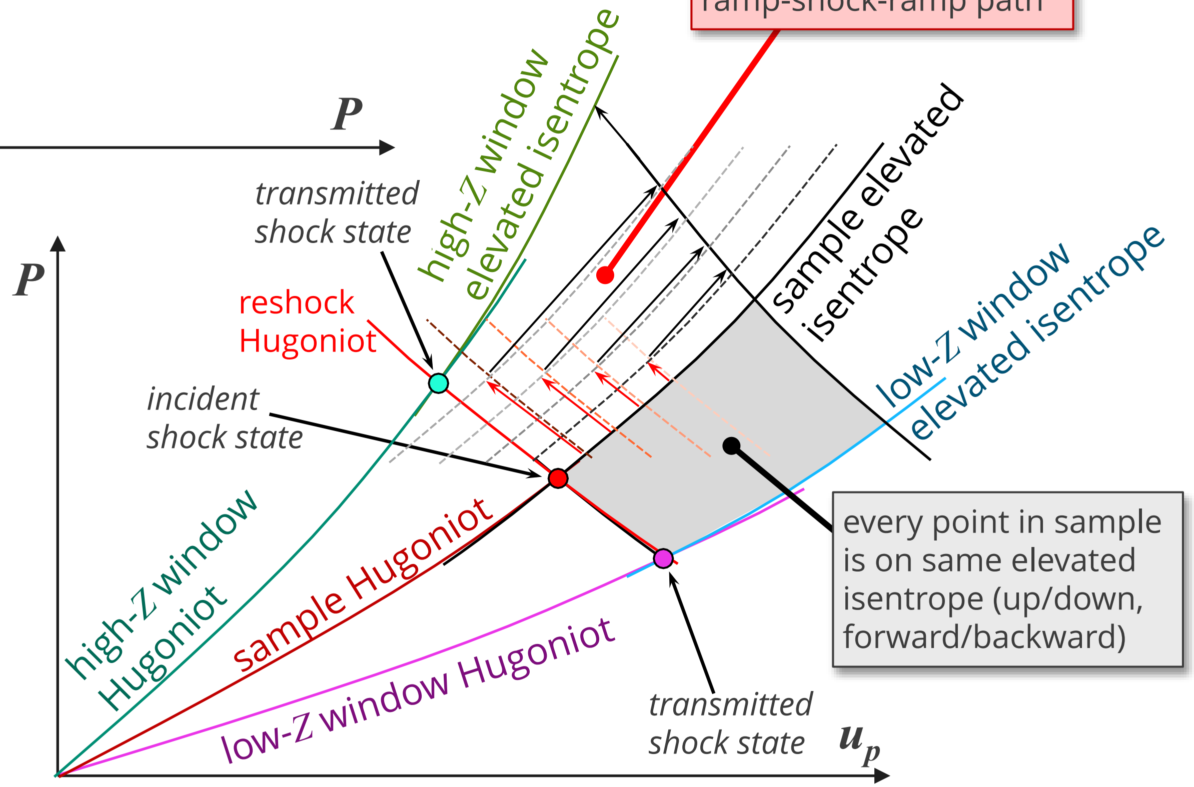
$$\text{impedance} \;\; Z = \rho c \propto \frac{dP}{du_p}$$

P-u_p diagrams relate hydrodynamics & wave interactions to EOS





shock-ramp



When/where ILA is not valid, compressibility can be determined using forward analysis — Bayesian model calibration (BMC)

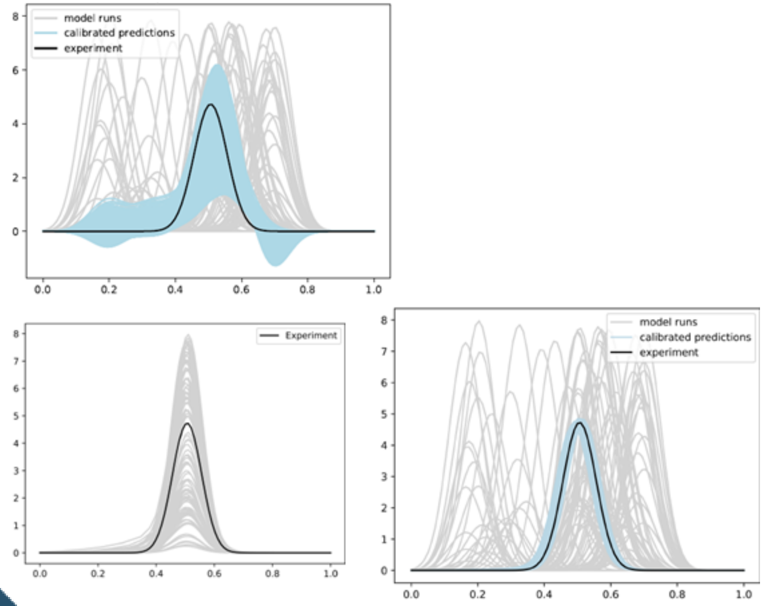
Bayesian model calibration (BMC)

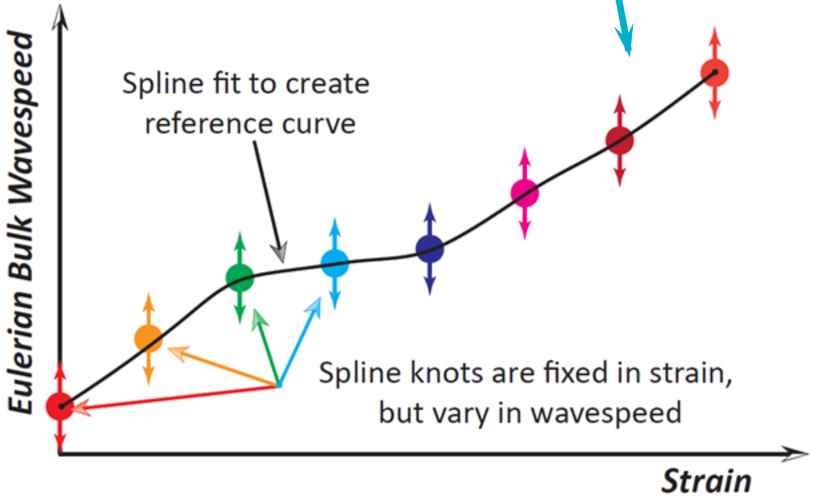
- requires known input (drive measurement)
- >10k runs of 1-D MHD computational model to train emulator
- “elastic functional analysis” aligns training data to experiment

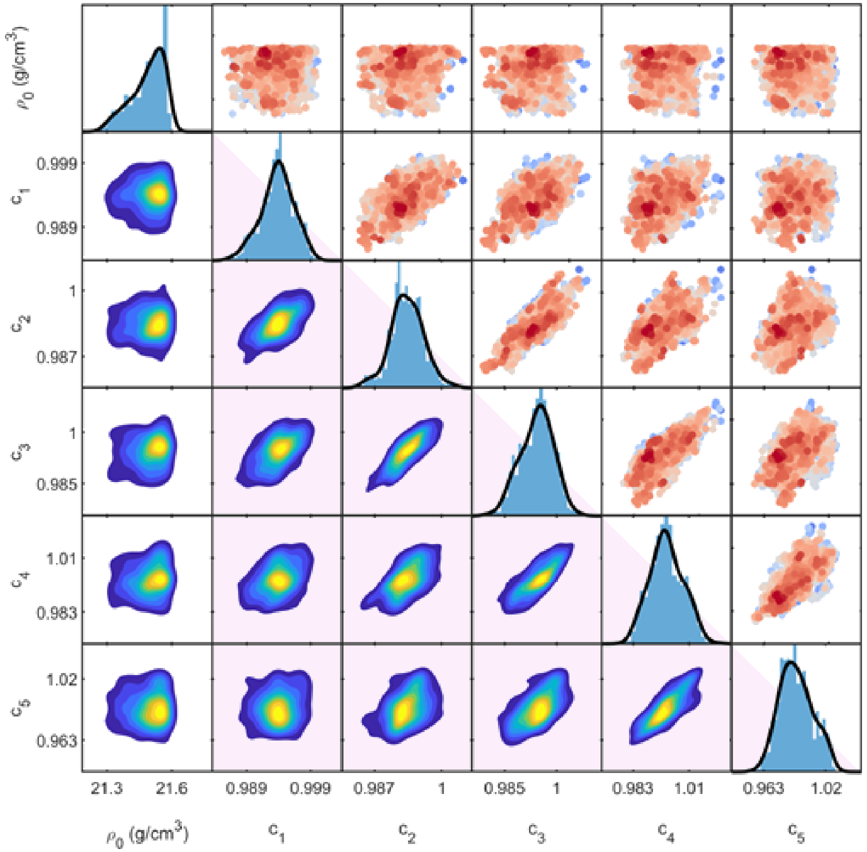
Francom et al, “Elastic Bayesian model calibration,” arXiv:2305.08834 [stat.ME] (2023)

- non-parametric model for bulk $c_E(\eta)$ on principal isentrope
- models may include strength, kinetics, etc.
- calibrate simultaneously to disparate data sets

Brown et al, “Quantifying uncertainty in analysis of shockless dynamic compression experiments on platinum, Part 2: Bayesian model calibration,” in preparation for submission to J. Appl. Phys. (2023)



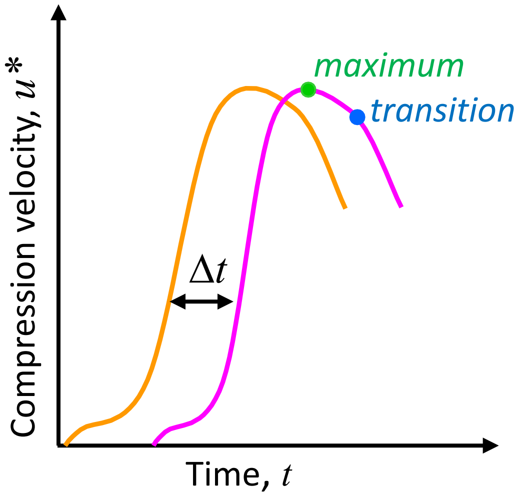


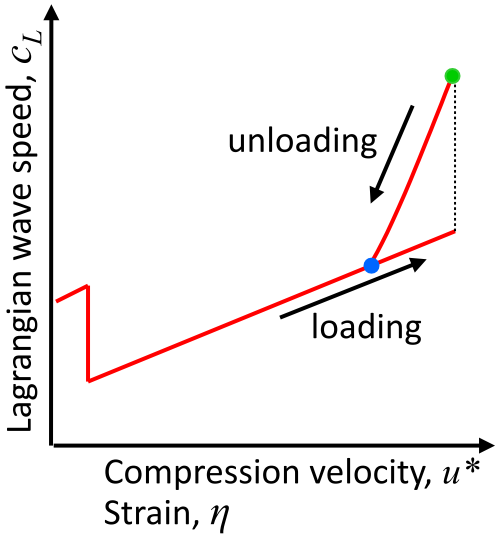


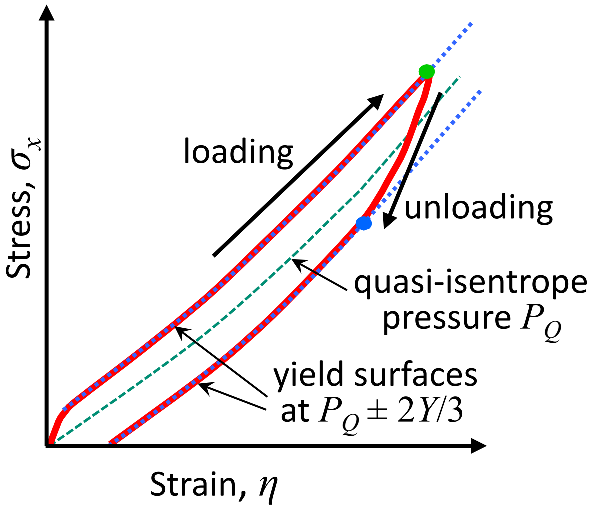
Important distinctions: uniaxial compression is not hydrostatic, and shockless compression is not (usually) isentropic

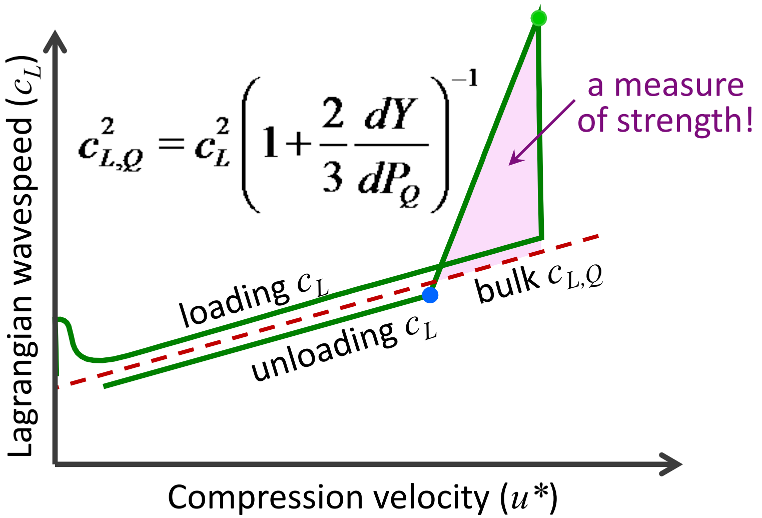
strength (resistance to deformation) → deviatoric (non-hydrostatic) component of stress

- wave speed depends strongly on whether material locally deforming elastically or inelastically
- for P-dependent strength, even pure inelastic deformation gives wave speed ≠ bulk quasi-isentrope



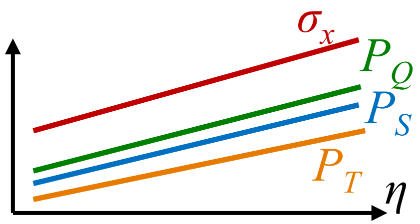






any irreversible process (e.g., plastic deformation) adds entropy → quasi-isentropic loading

- path/history dependent thermal pressure offset from isentrope (with different wave speed)

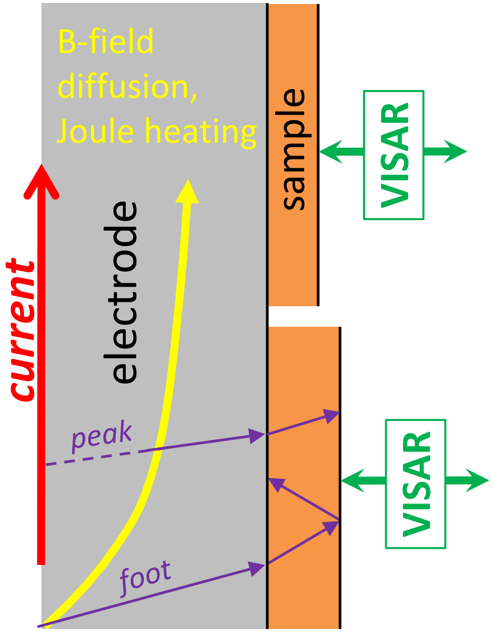


longitudinal stress
quasi-isentrope
isentrope
isotherm

$$c_L = \sqrt{\frac{1}{\rho_0}\frac{d\sigma_x}{d\eta}}, \quad c_{L,Q} = \sqrt{\frac{1}{\rho_0}\frac{dP_Q}{d\eta}}, \quad c_{L,S} = \sqrt{\frac{1}{\rho_0}\frac{dP_S}{d\eta}} = \frac{\rho}{\rho_0}\sqrt{\left(\frac{\partial P}{\partial \rho}\right)_S}$$

Davis and Brown, "Quantifying uncertainty in analysis of shockless dynamic compression experiments on platinum, Part 1: Inverse Lagrangian analysis," in preparation for submission to J. Appl. Phys. (2023)

Sample thickness constrained by reverberation and pulse shaping



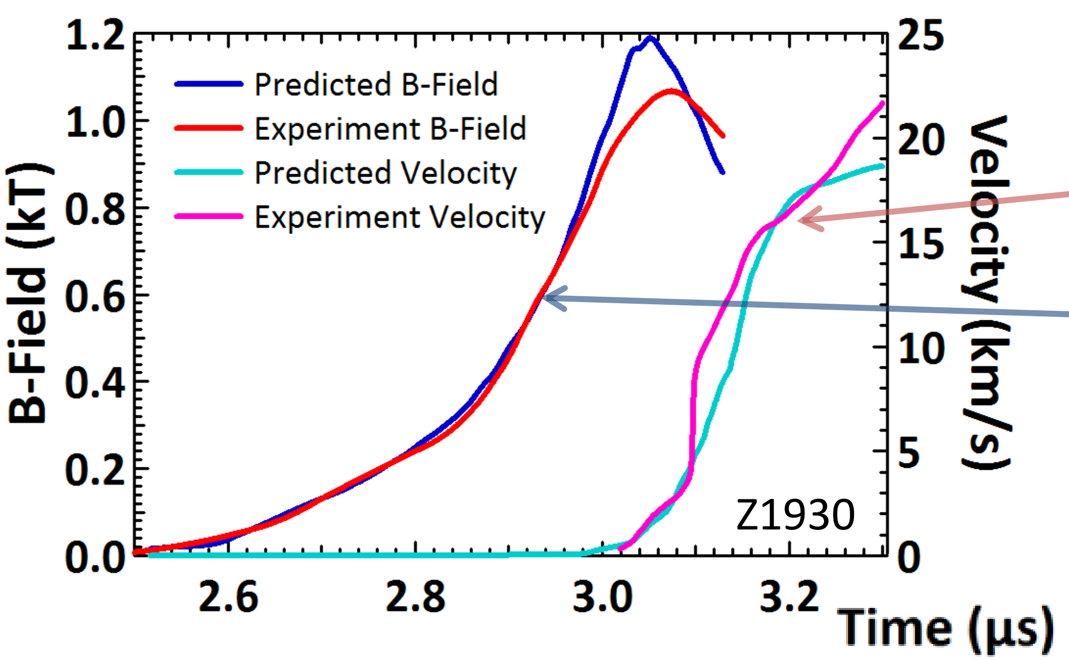
Narrow (highest pressure) stripline is ~11 mm wide, samples 6-8 mm wide: **edge waves** & pulse shape constrain maximum thickness

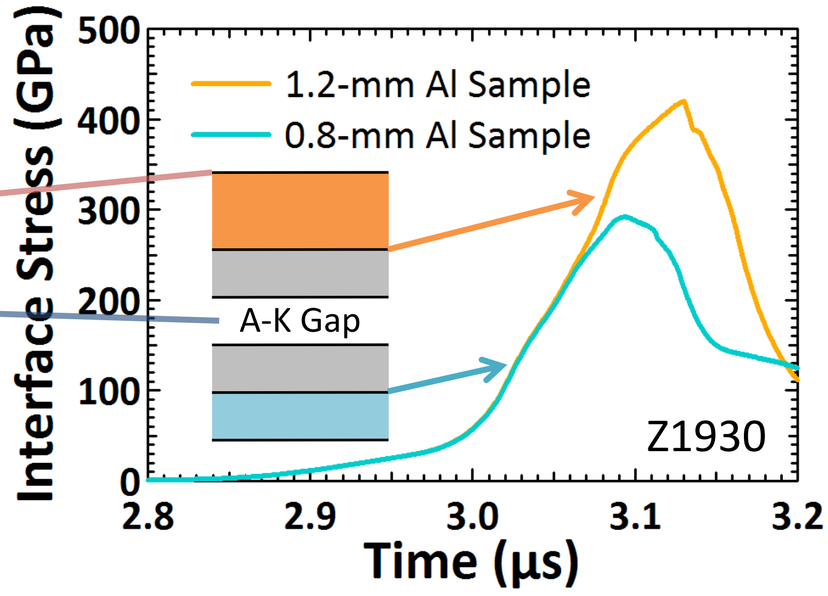
uncertainty in $c_L = \Delta x_L / \Delta t$ depends on relative uncertainty in thickness difference
- must maximize difference in thickness between samples

requirement for 1-D shock-free loading limits maximum thickness
- imprecision in pulse shaping makes ideal shock-up distance difficult to attain

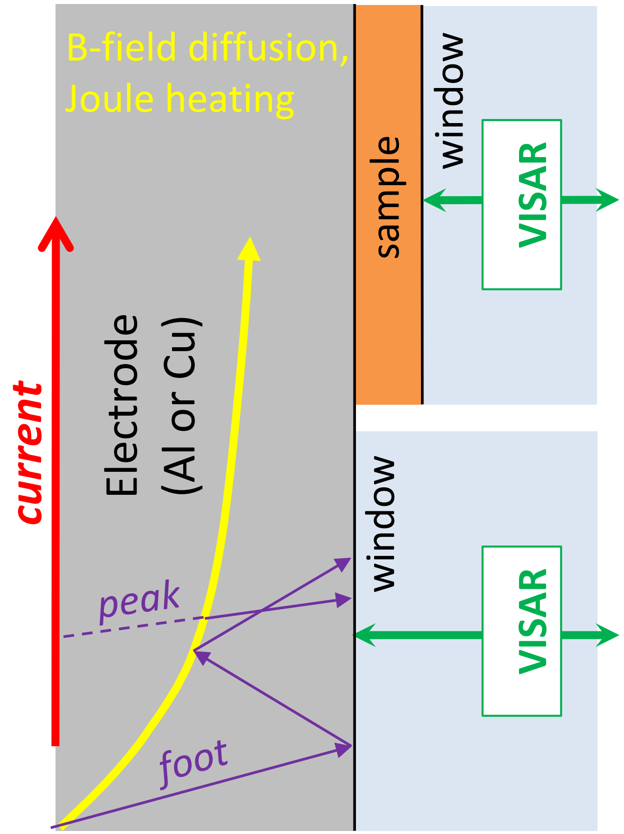
arrival of back-surface reflection at sample's front surface (reverberation) limits minimum thickness to achieve desired stress state

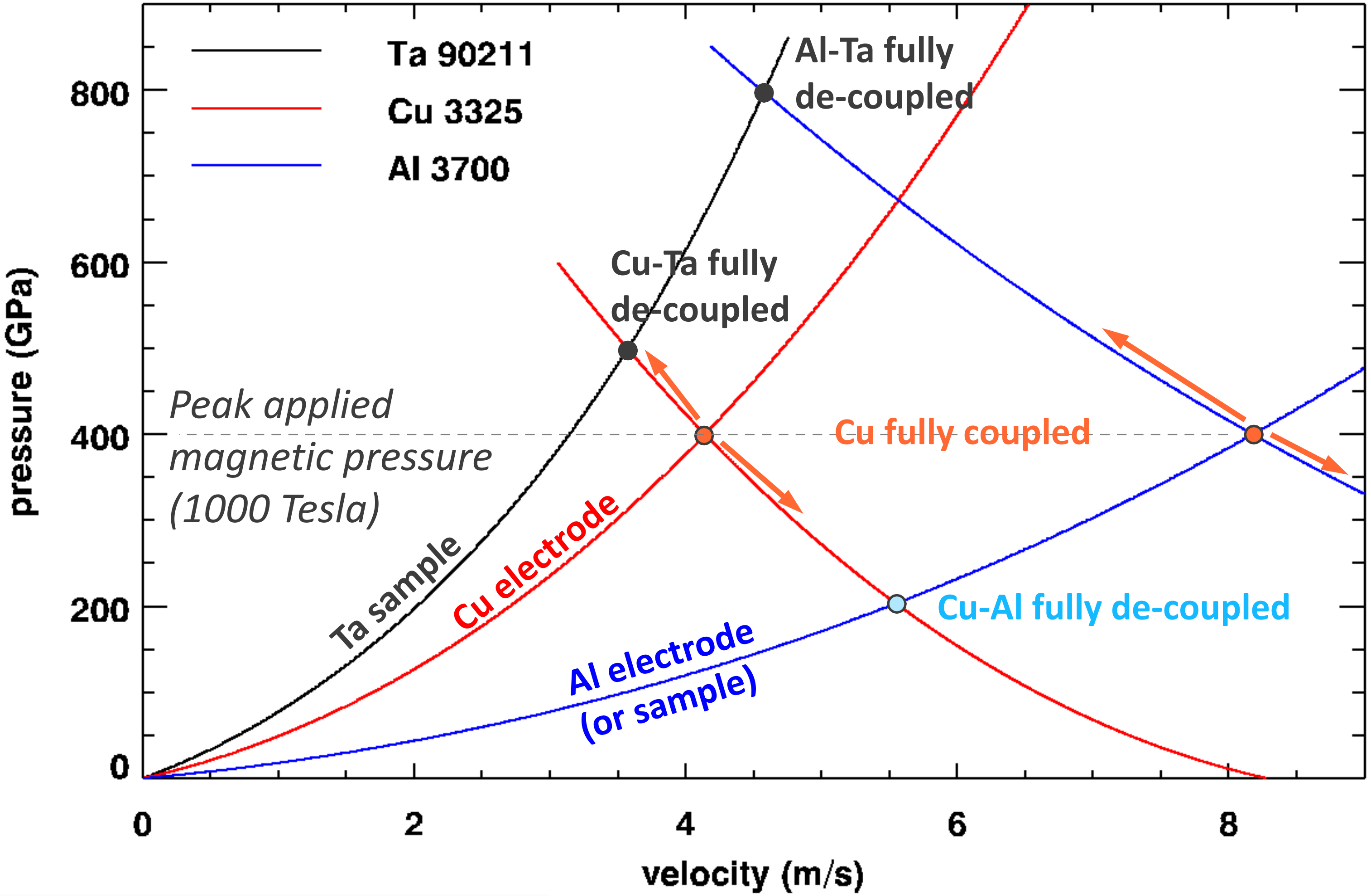
increasing rise time to delay shock formation in thick sample reduces peak stress at front surface of thin sample





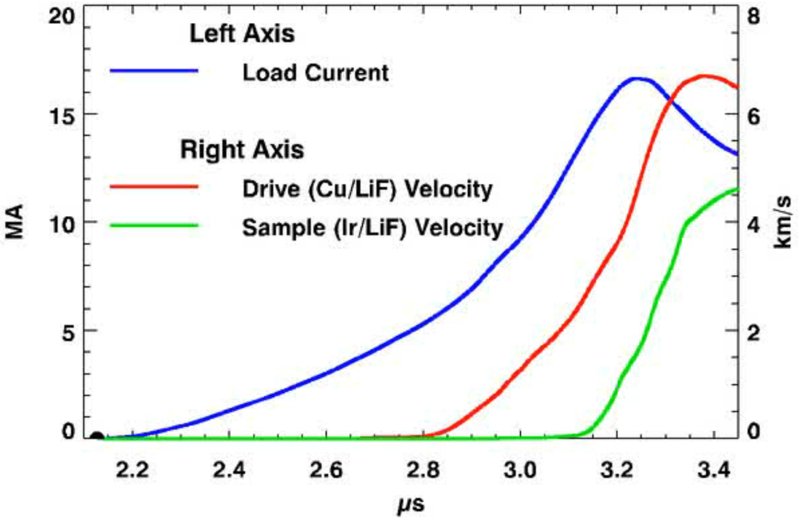
Electrode thickness constrained by desired MHD coupling (reverberation inside the electrode)

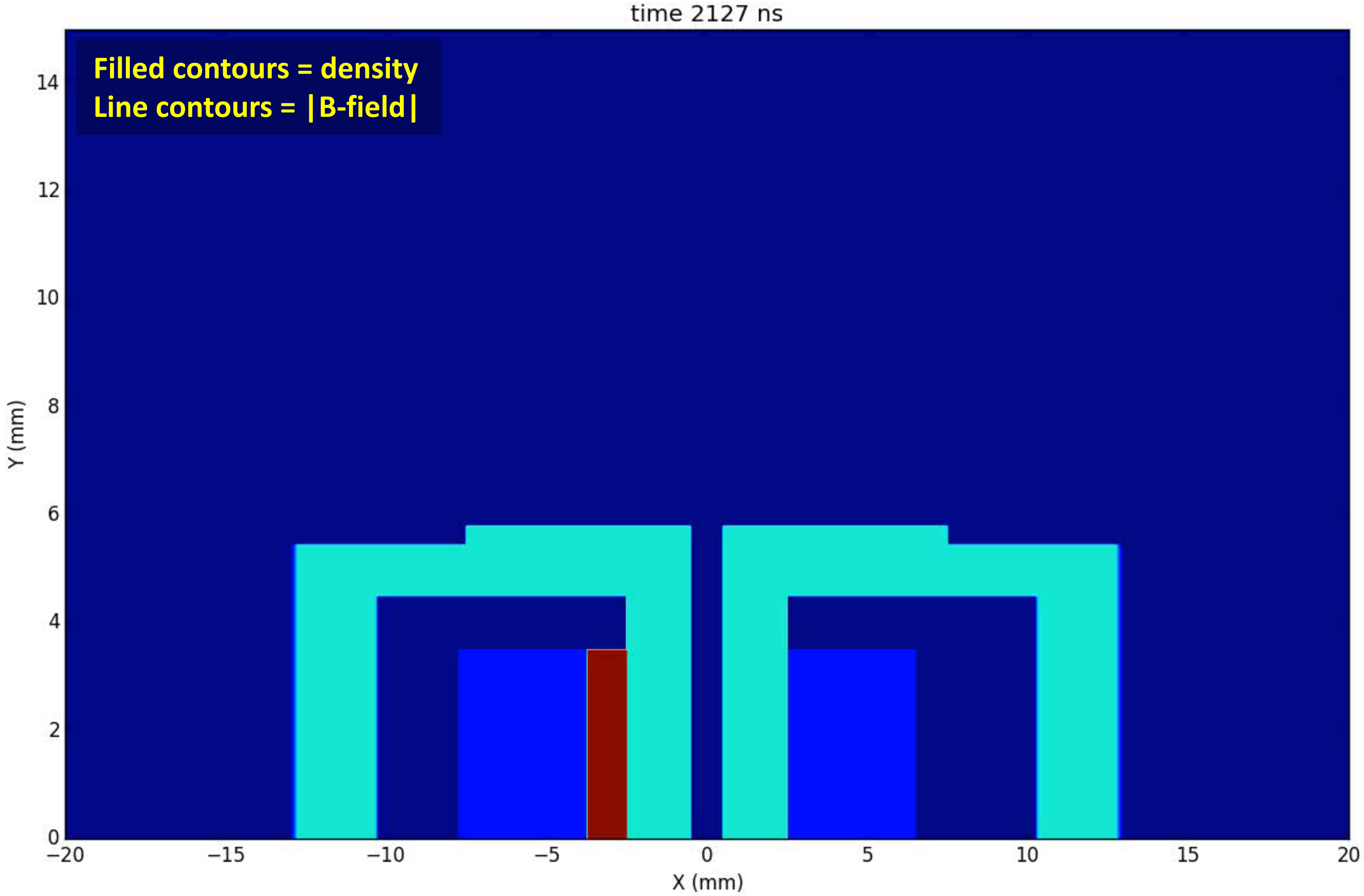




- **minimum thickness** to avoid "burn-through" of B-field to sample
- **maximum thickness** to decouple MHD, ramp-load sample

Design & analysis aided by 2-D magneto-hydrodynamic (MHD) simulations in horizontal plane through sample center



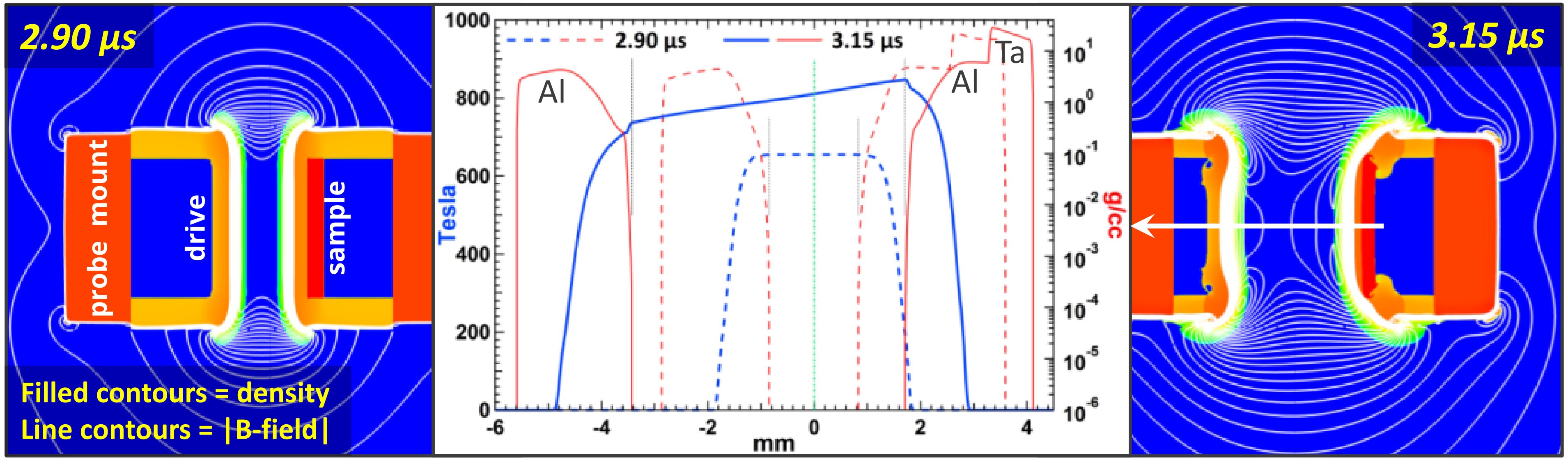


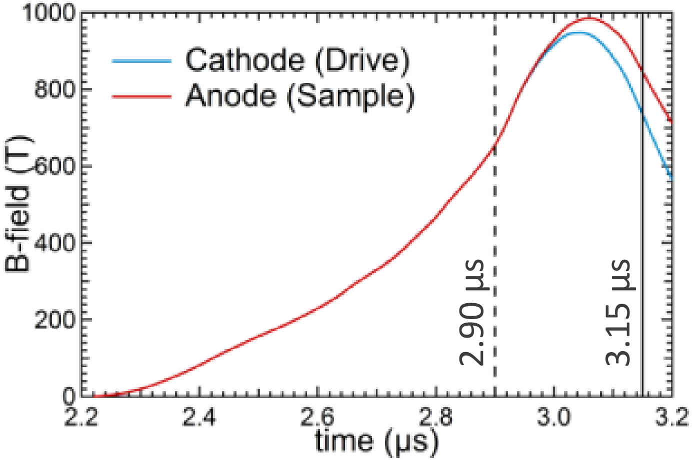
2-D MHD needed to…

- compute dynamic inductance for use in Z circuit model
- compute dynamic scale length to relate current & B-field
- quantify and correct for cross-gap asymmetry (next slide)

2-D MHD can correct for asymmetry in magnetic drive

Snapshots with line-outs from Alegra simulation of Z2434 mid-height position





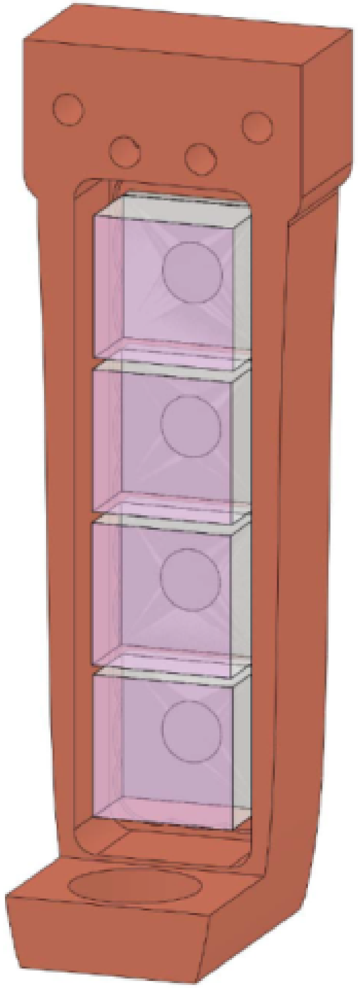
Asymmetric wave reverberations in electrodes

- Left (drive): reflection from free surface
- Right (sample): reflection from high-impedance material

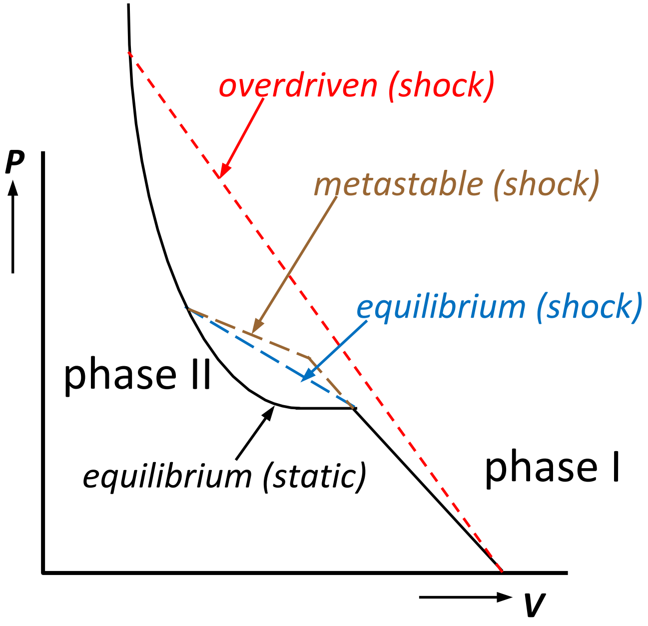
Resulting 2-D effects cause asymmetric B-field topology, can occur prior to time of peak current

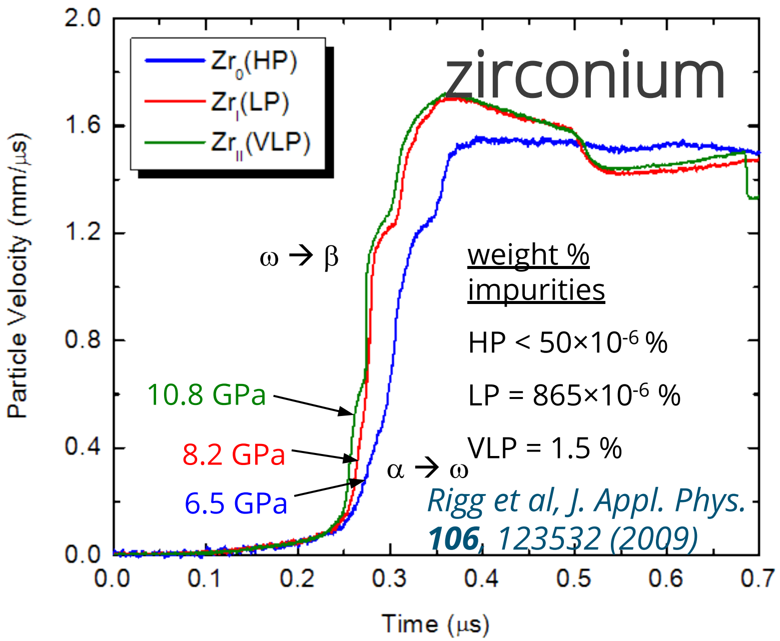
Use 2-D B-field Sample/Drive ratio to correct 1-D B-field

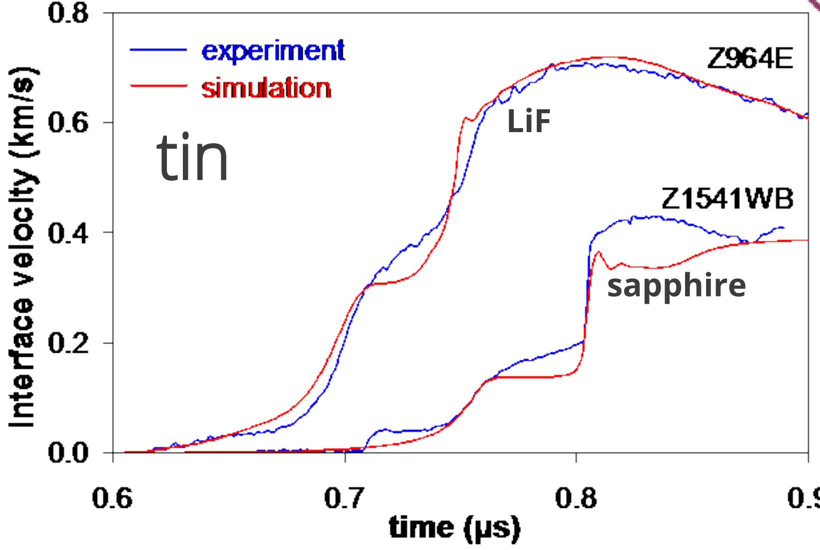
- Only if experiment is really 2-D!
- For cylindrical samples, discard beyond divergence

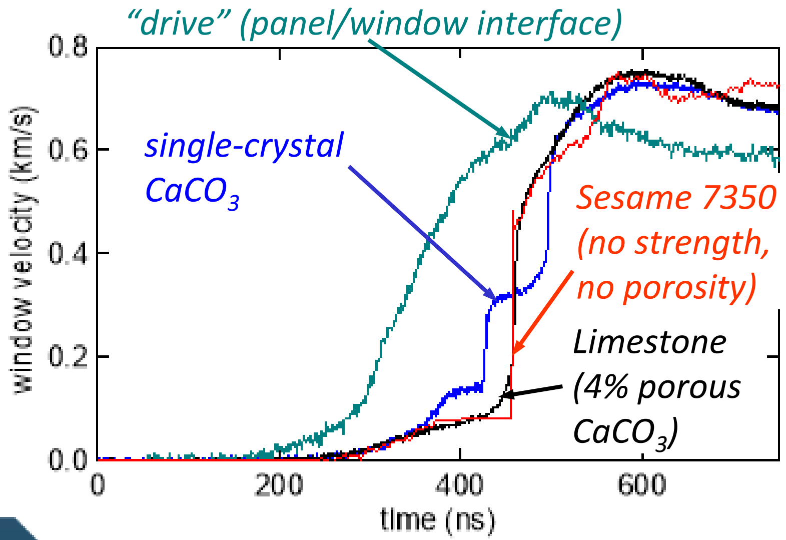


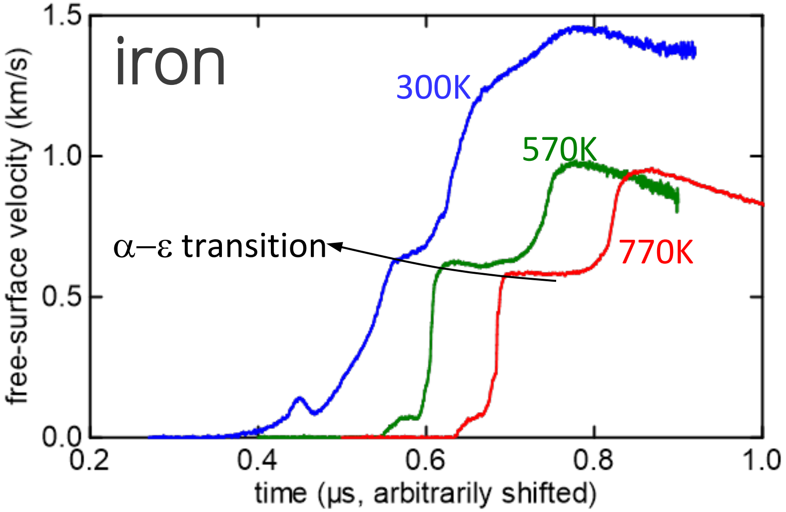
Evolution of ramped compression wave can be sensitive to structural phase transitions due to changes in sound speed

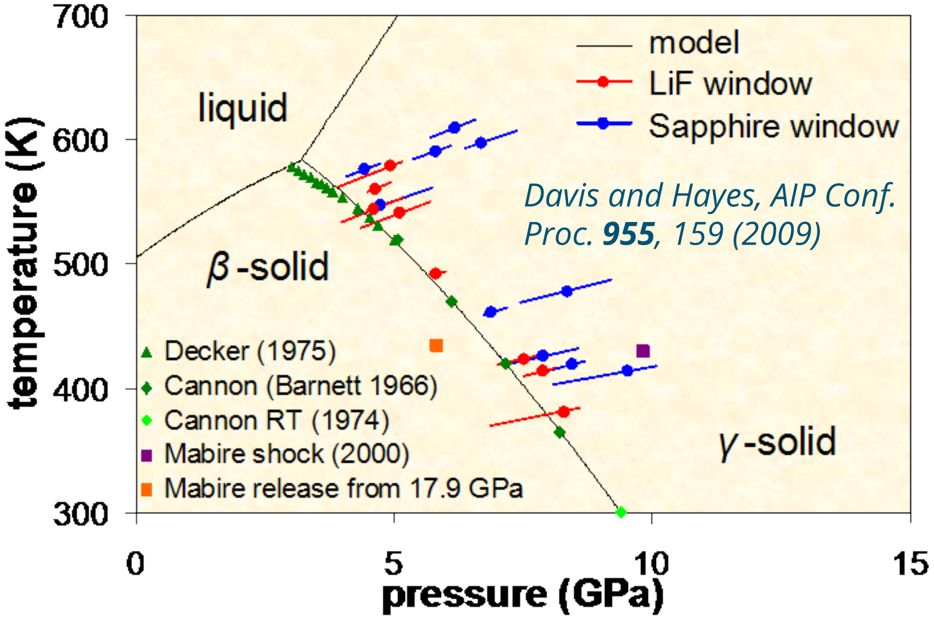




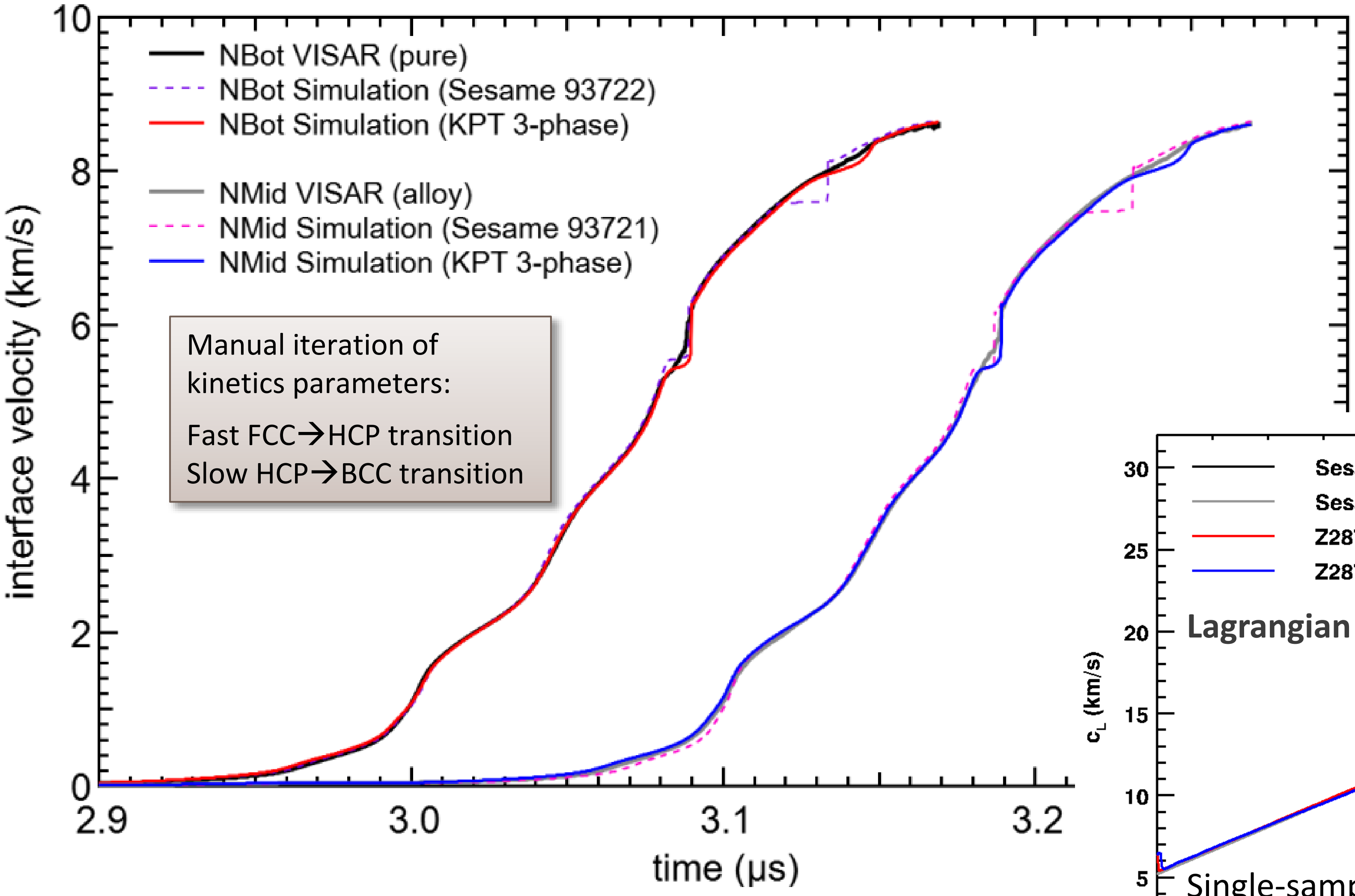


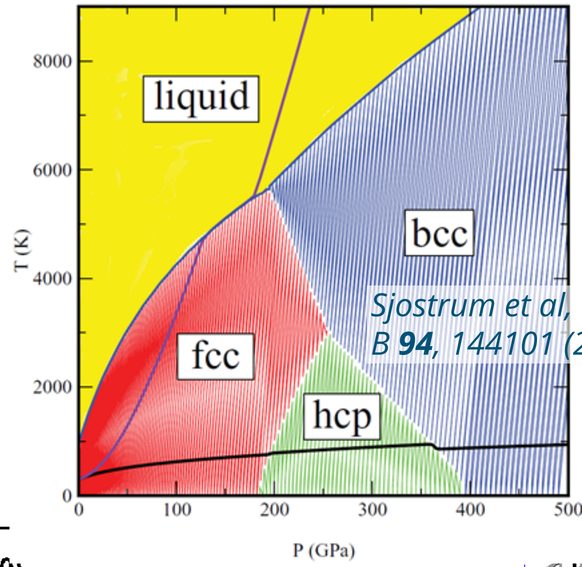




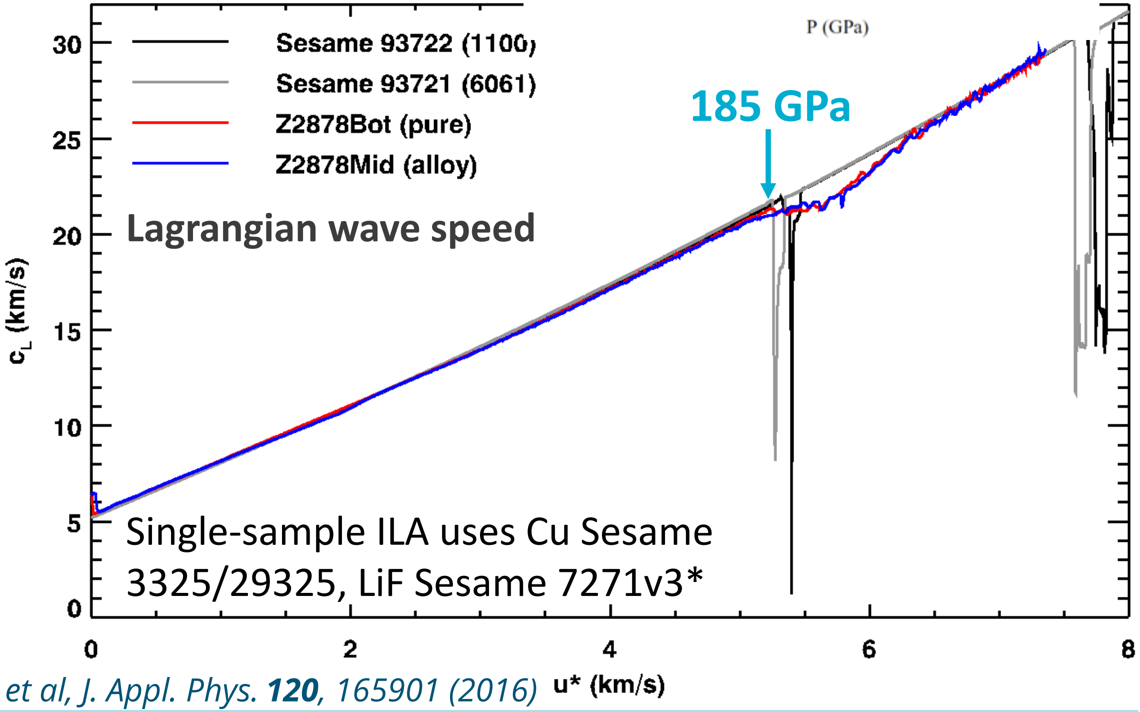


Velocimetry of aluminum ramp-compressed to ~400 GPa precisely constrains stress at solid-solid phase boundaries





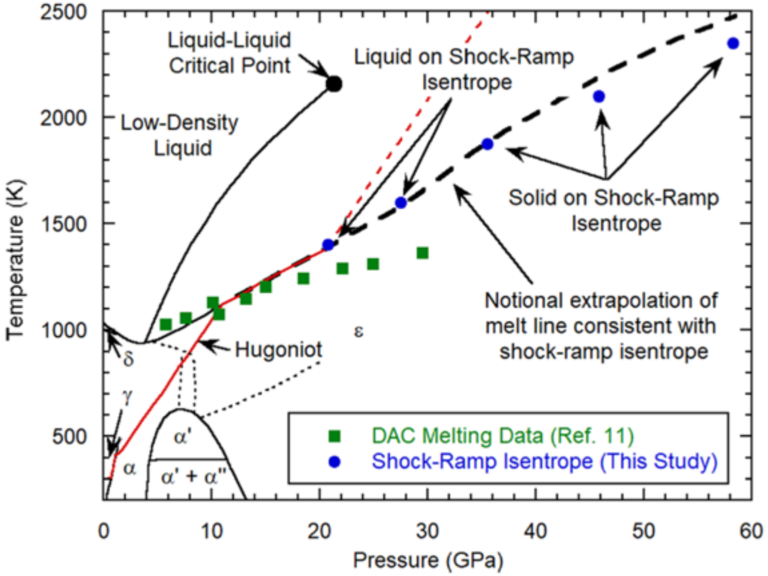
*Sjostrum et al, Phys. Rev. B **94**, 144101 (2016)*



** Davis et al, J. Appl. Phys. **120**, 165901 (2016)*

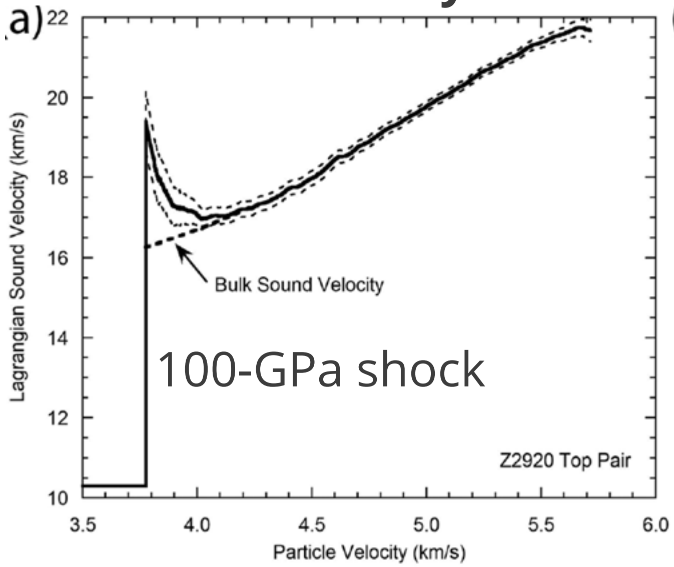
Shock-ramp loading can probe phase boundaries in P-T, skip problematic transitions at lower pressure, and more

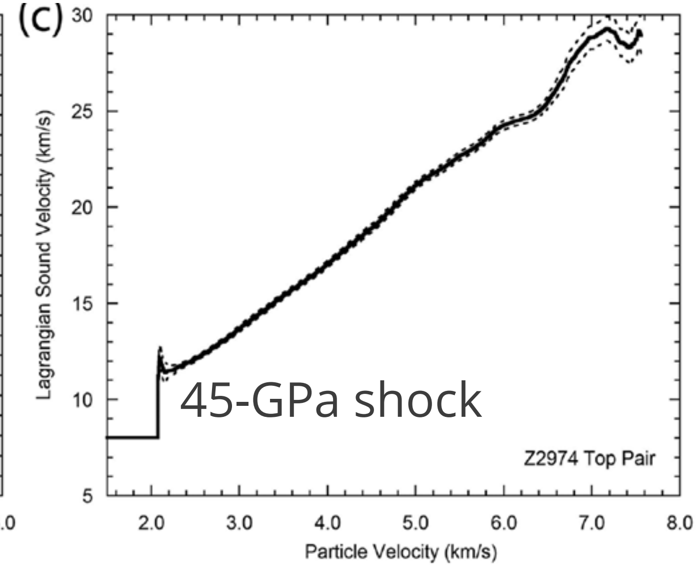
overdriven shock to known Hugoniot state in higher-pressure phase, then ramp

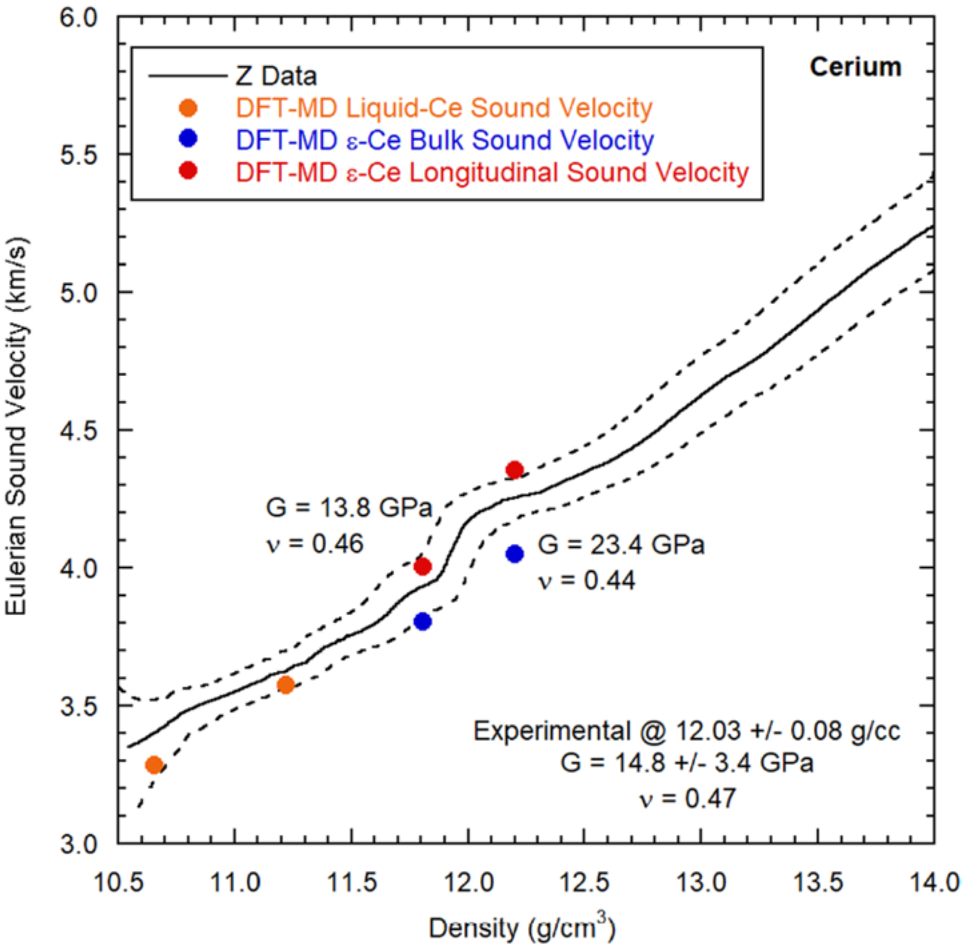


<u>LiF-windowed Ce:</u> resolidification from shock-melted state

<u>LiF-windowed LiF:</u> shock state is not on yield surface







*Seagle et al, Appl. Phys. Let. **120**, 165902 (2016)*

*Seagle et al, Phys. Rev. B **102**, 054102 (2020)*