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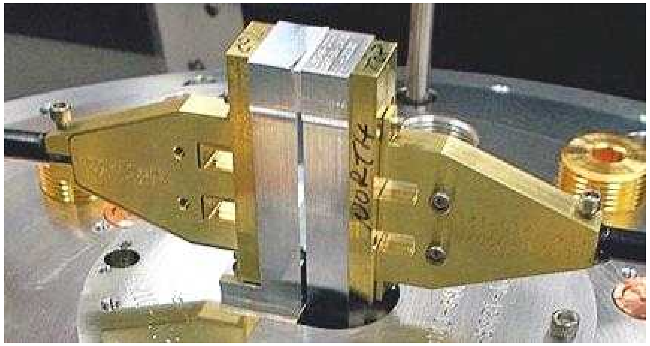

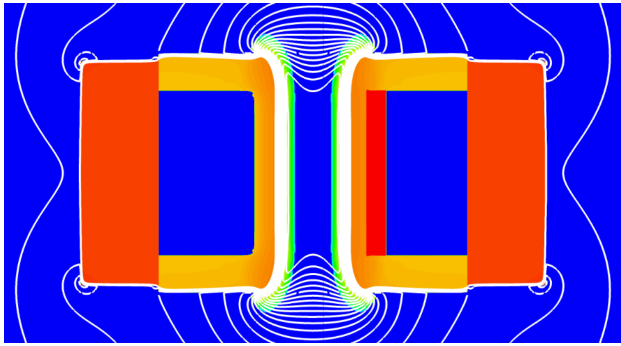

Quantitative Results from Shockless Compression Experiments on Ta, Au to Multi-Megabar Pressure

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Planar shockless compression to > 400 GPa is possible on the Z machine using stripline loads

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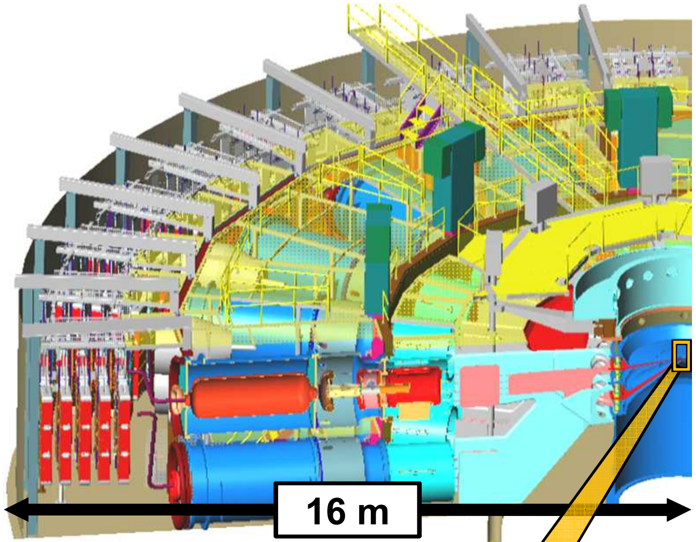
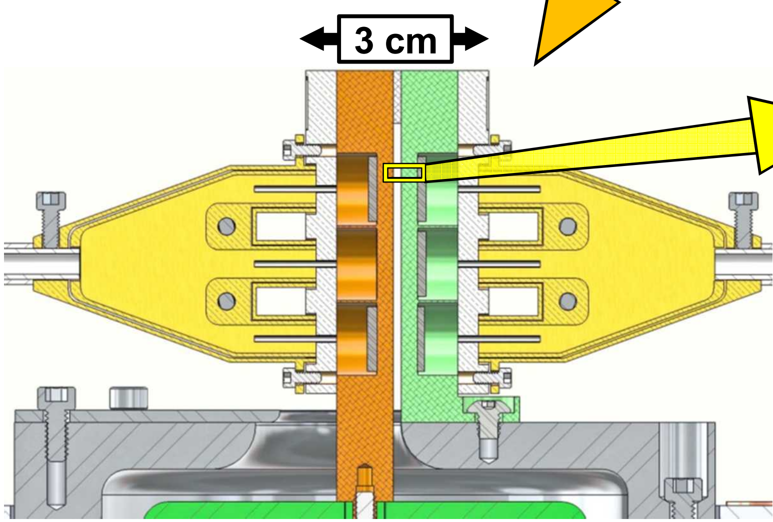
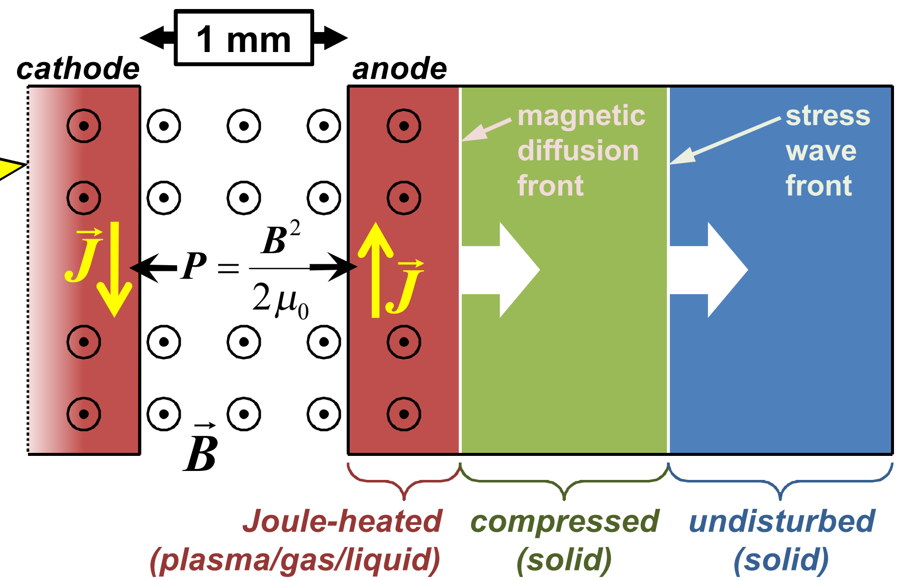
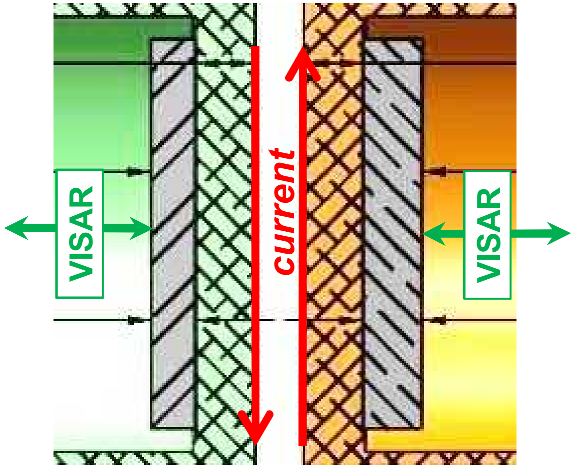
- current pulse of 7-26 MA delivered to load
- controllable pulse shape, rise time 100-1200 ns
- stripline = parallel flat-plate electrodes shorted at one end, <u>identical loading of sample pairs</u>
- magnetic ($\boldsymbol{J} \times \boldsymbol{B}$) force induces ramped stress wave in electrode material
- stress wave propagates into ambient material, de-coupled from magnetic diffusion front

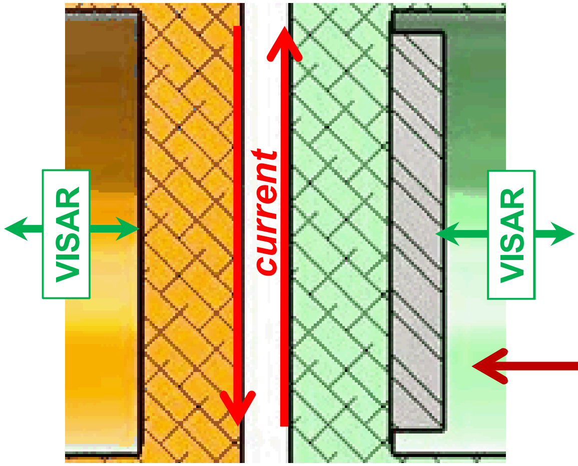


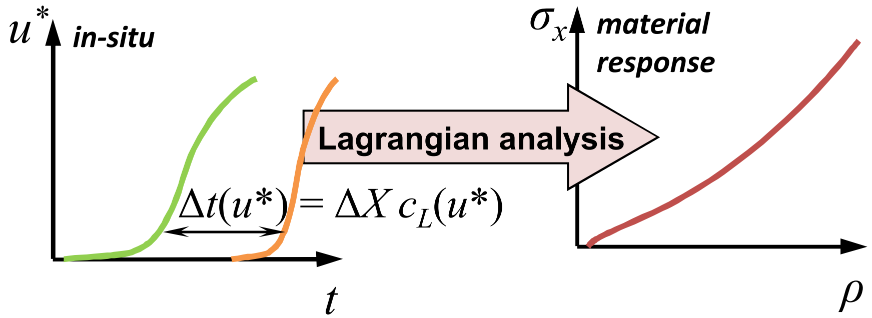




Inverse Lagrangian Analysis (ILA) extracts quasi-isentropic material response from velocimetry







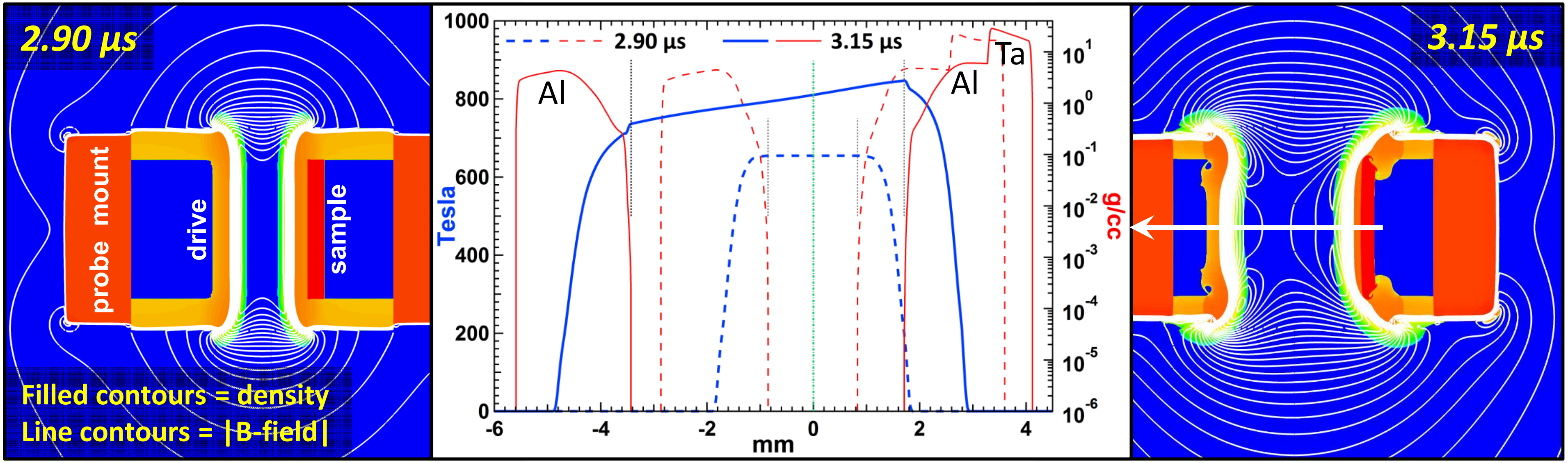
u^* = "compression velocity" (mechanical-EOS variable)

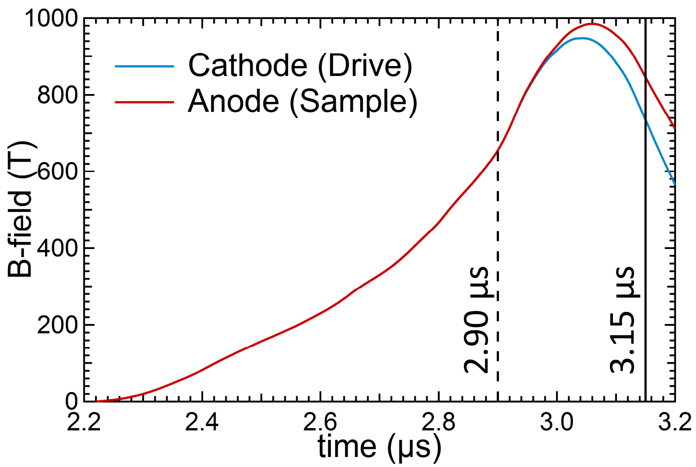
- In-situ measurements → Direct Lagrangian Analysis (DLA)
- Real measurements are free-surface or window-interface
  → Inverse Lagrangian Analysis (ILA)
  - map measured $\boldsymbol{u(t)}$ into in-situ $\boldsymbol{u^*(t)}$, then apply DLA
  - typically map by iterative characteristics technique[1]
  - assumes single-valued material response
  - assumes identical state at both electrode-sample interfaces
- Single-sample approach uses full sample thickness
  - measure driving $\boldsymbol{B(t)}$ from sample-less electrode
  - simulate in-situ velocity at electrode-sample interface
  - iterate the ILA procedure, recomputing input velocity
  - assumes identical state at both electrode driven surfaces

[1] *S. D. Rothman & J. Maw, J. Physique IV* ***134****, p745 (2006)*

2-D MHD calculations elucidate late-time cross-gap non-uniformity of driving B-field

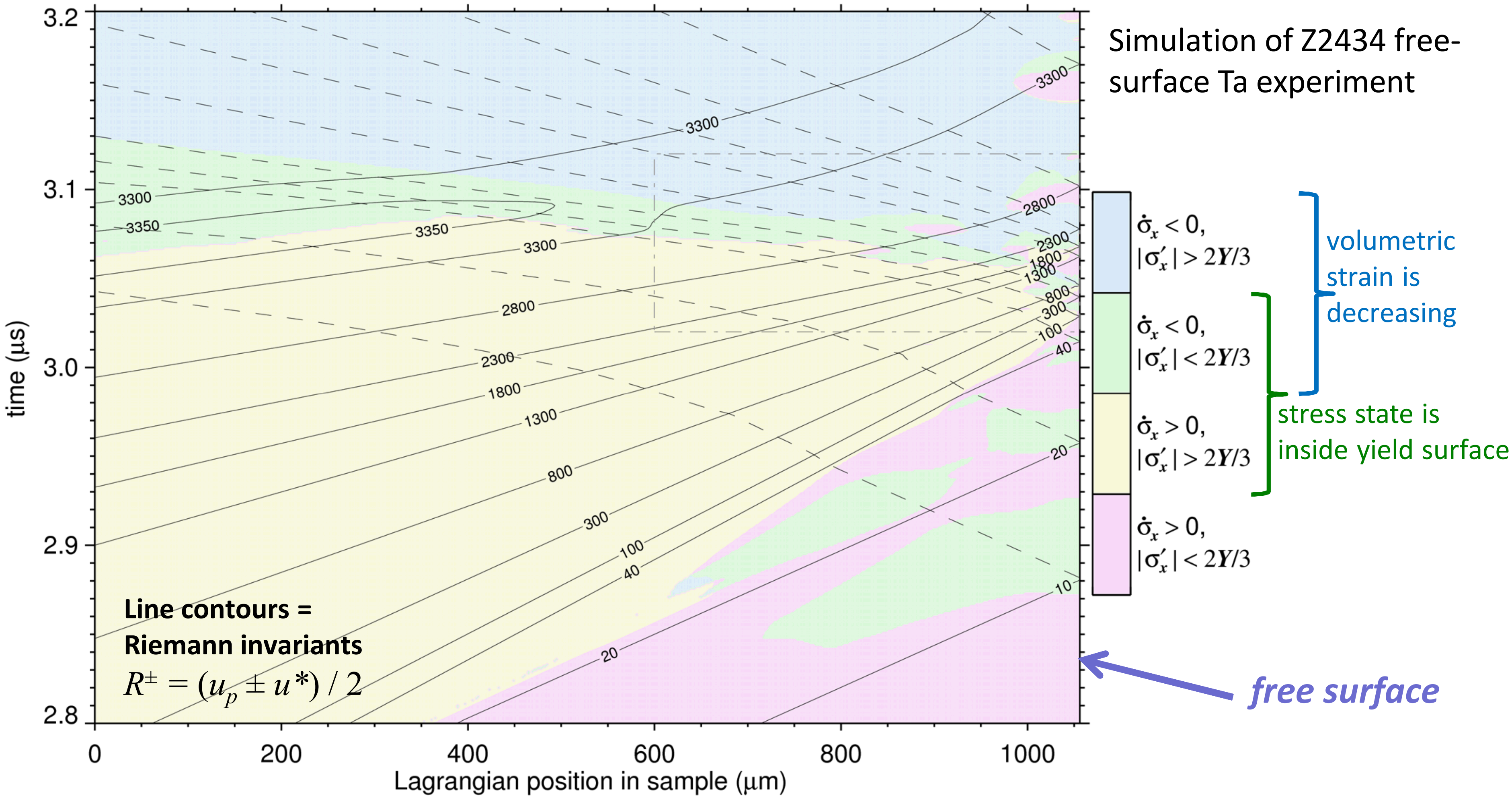
Snapshots with line-outs from Alegra simulation of Z2434 mid-height position





- 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

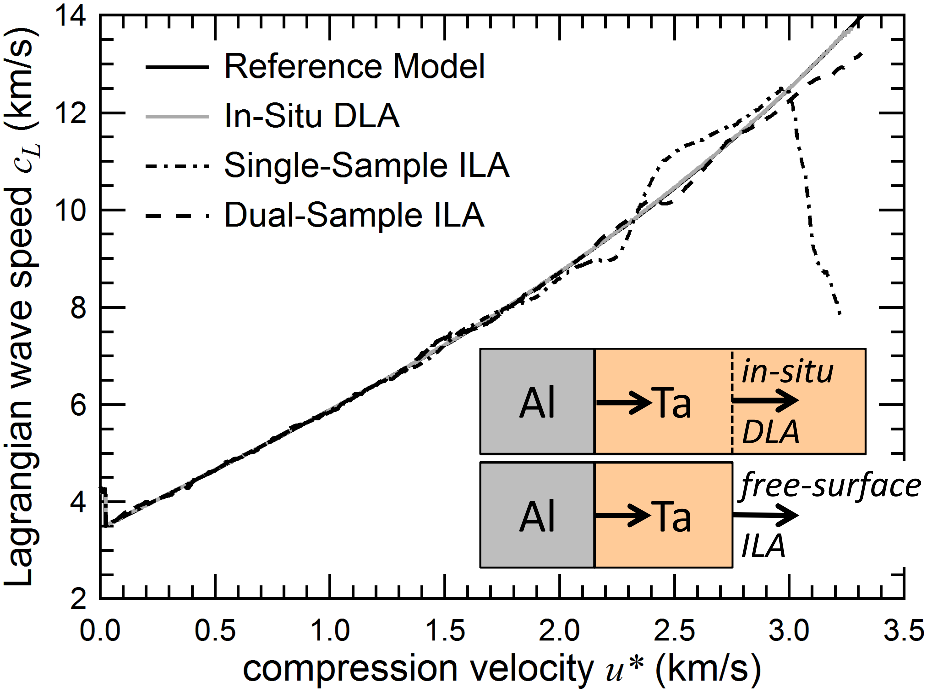
Localized unloading in high-strength materials violates ILA assumption of single-valued response

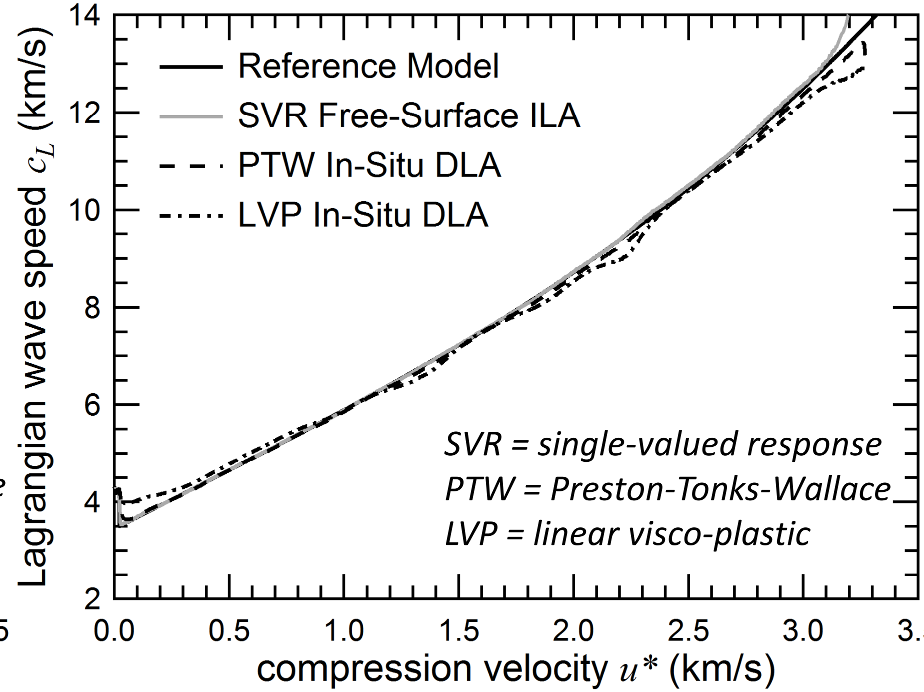


Simulation of Z2434 free-surface Ta experiment

- High-pressure pseudo-characteristics traverse regions in t-x that are inside the yield surface
- Elastic propagation speed in these regions increases apparent wave speed measured across sample

Analysis of synthetic data quantifies expected deviations due to strength and time dependence



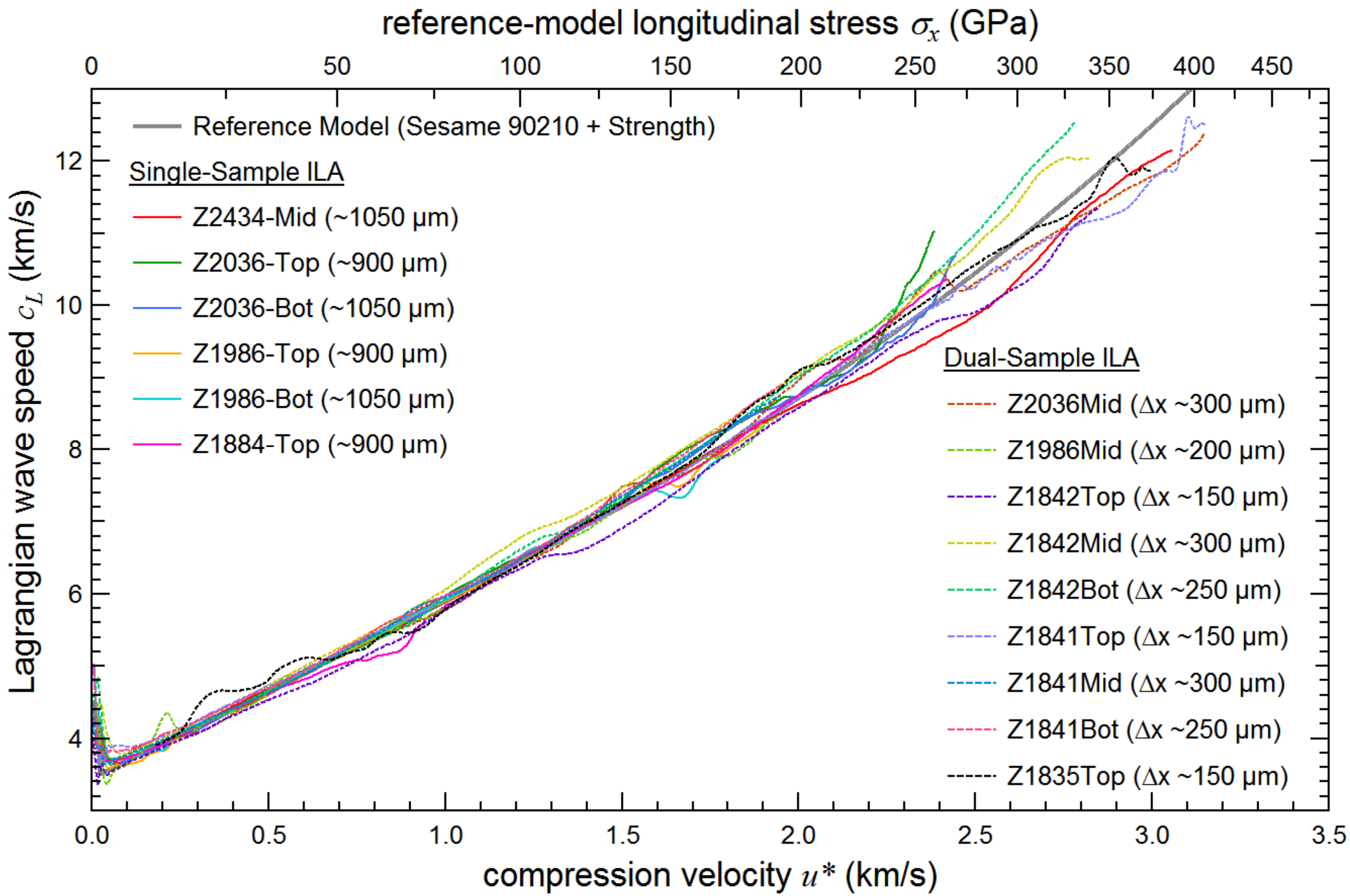


- **Reference model** = Sesame 90210[1] + Steinberg-Guinan fit to ramp-release strength data[2]
- Simulate Z2036 exp't in-situ & free-surface
- Strength interaction with free surface (ILA)
  - → Localized deviations in apparent $c_L(u^*)$
  - → Partial cancellation in dual-sample case

- Single-valued tabular $\sigma_x(\rho,T)$ without strength
  - → deviations due only to reverberation
- Time-dependent strength models
  - Explicitly rate-dependent yield stress (PTW)
  - Time-dependent plasticity algorithm (LVP)
  - → Localized deviations even for in-situ DLA

[1] *C. Greeff et al, AIP Conf. Proc.* ***1195****, 681 (2009)*
[2] *J. L. Brown et al, J. Appl. Phys.* ***115****, 043530 (2014)*

15 experiments on free-surface Ta allowed meaningful averaging of measured quasi-isentrope



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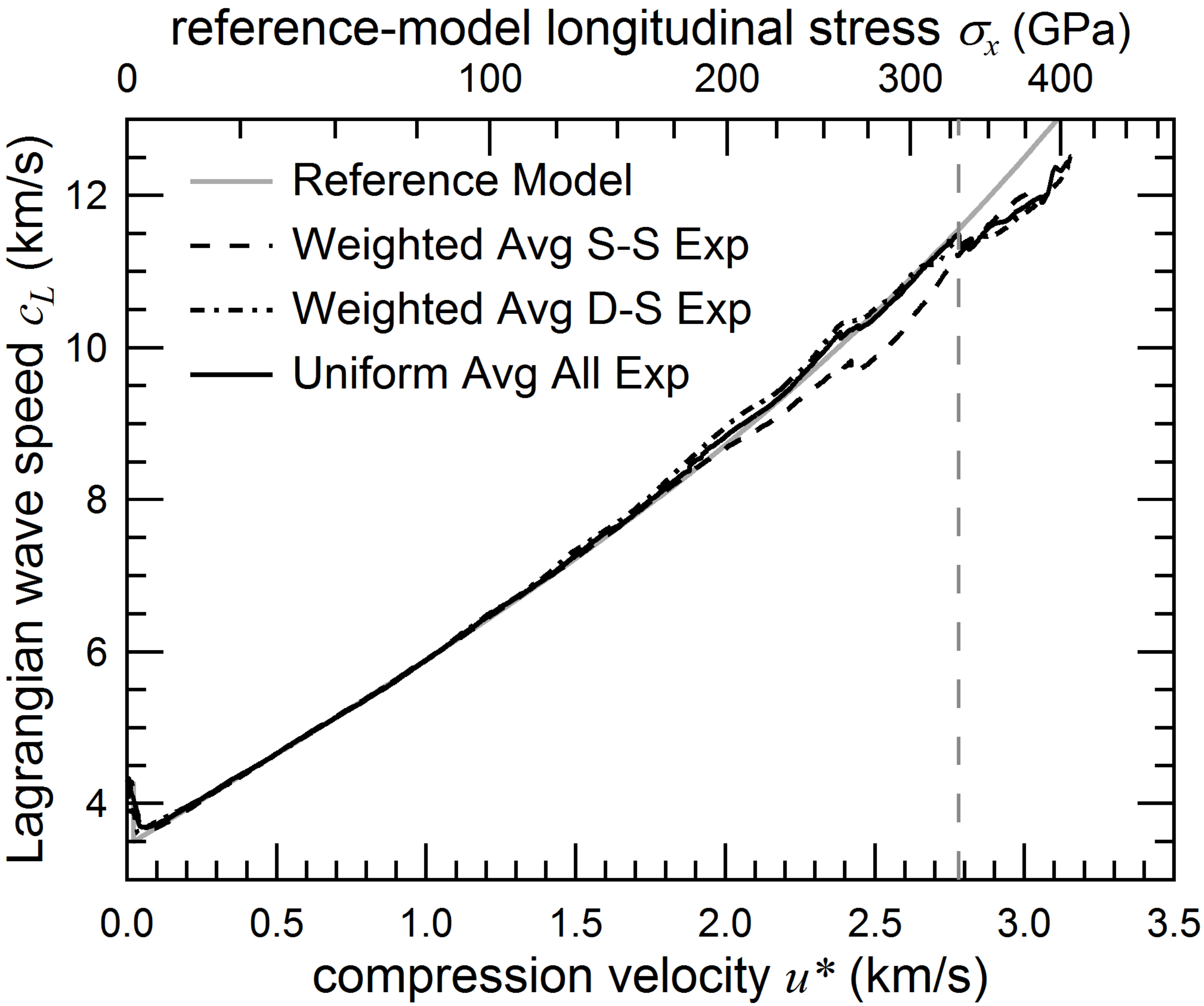
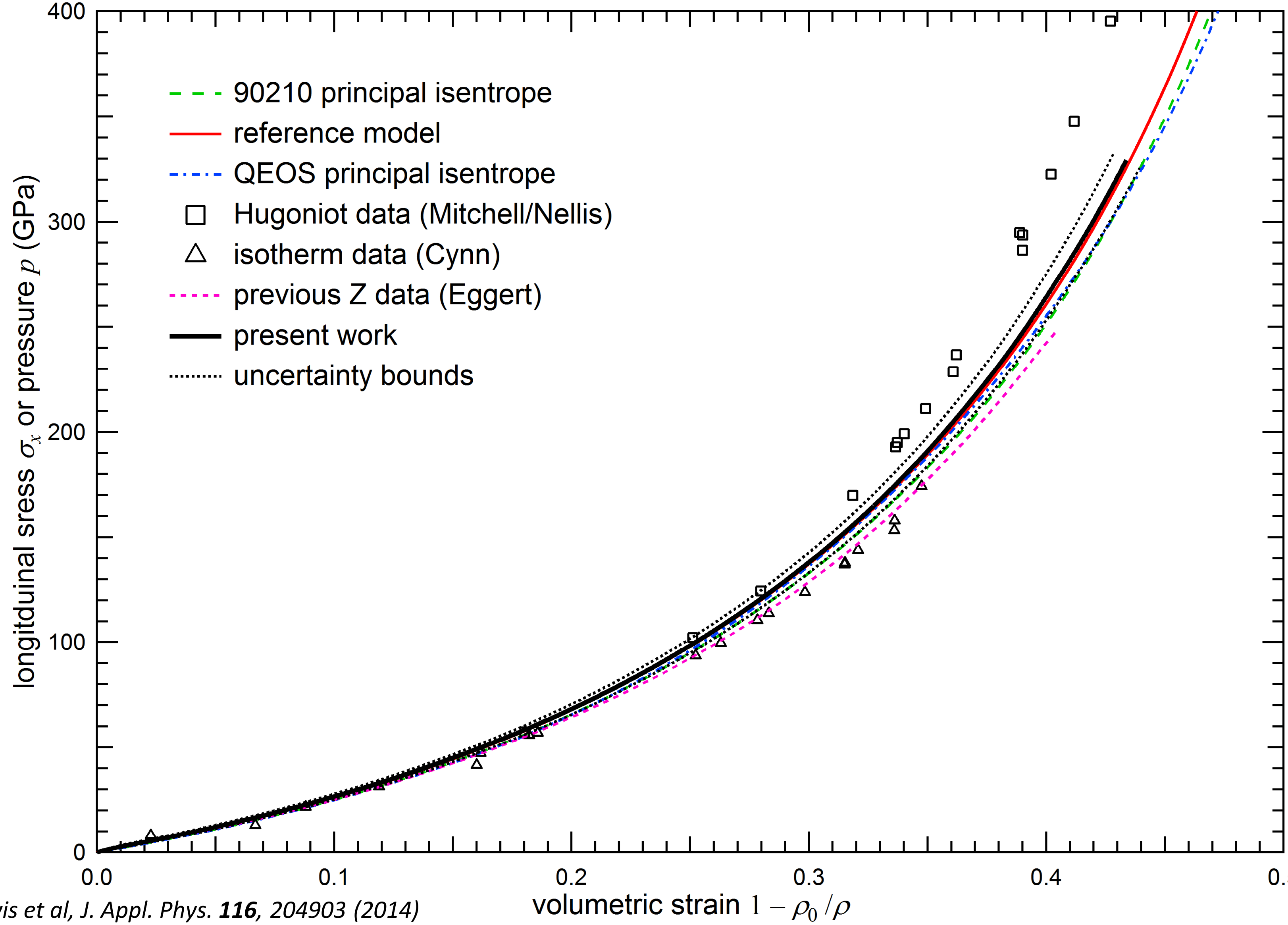


Averaged stress-strain of Ta experiments agrees well with the reference model



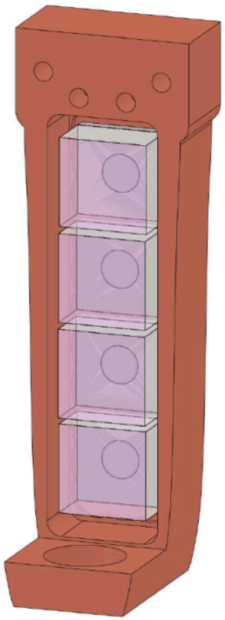
J.-P. Davis et al, J. Appl. Phys. ***116****, 204903 (2014)*

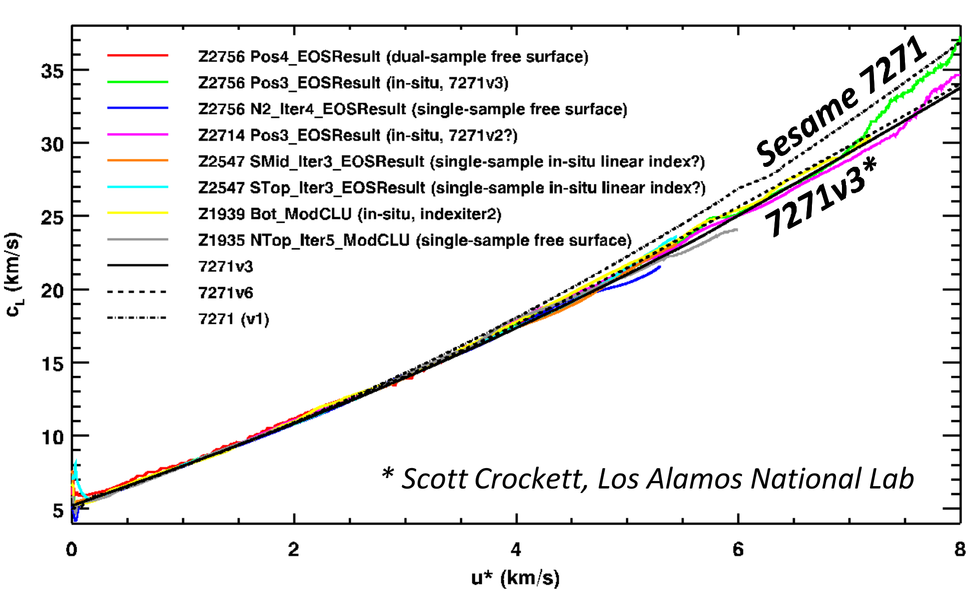
Improvements to experiment design are enabling quasi-isentrope measurements to higher stress

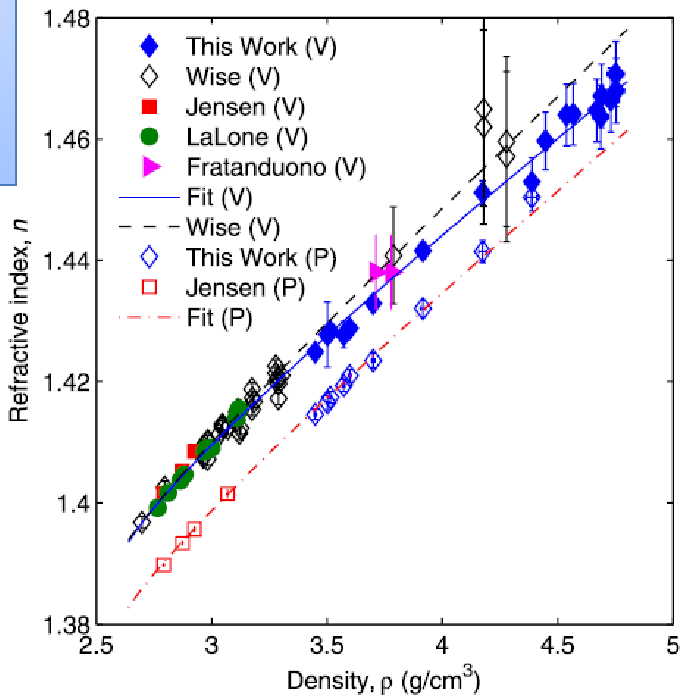
- Copper electrodes move less than aluminum → higher B/I
- Square samples and electrode features ensure 2-D MHD
- LiF windows
  - significantly reduce errors due to local unloading
  - uncertainty in stress-strain response at multi-megabar
  - uncertainty in index of refraction (nonlinear in density)
  - given $n(\rho,T)$, determine actual velocity waveform by iterating simulation of window to match measured apparent velocity

$$\frac{n-1}{n_0-1} = \frac{1-\gamma\eta^{\kappa}}{1-\eta} + c\Delta T$$

$$\eta = 1 - \rho_0/\rho$$







P. A. Rigg et al, J. Appl. Phys. **116**, 033515 (2014)

Preliminary analysis of Au experiments to 500 GPa suggests lower compressibility than leading model

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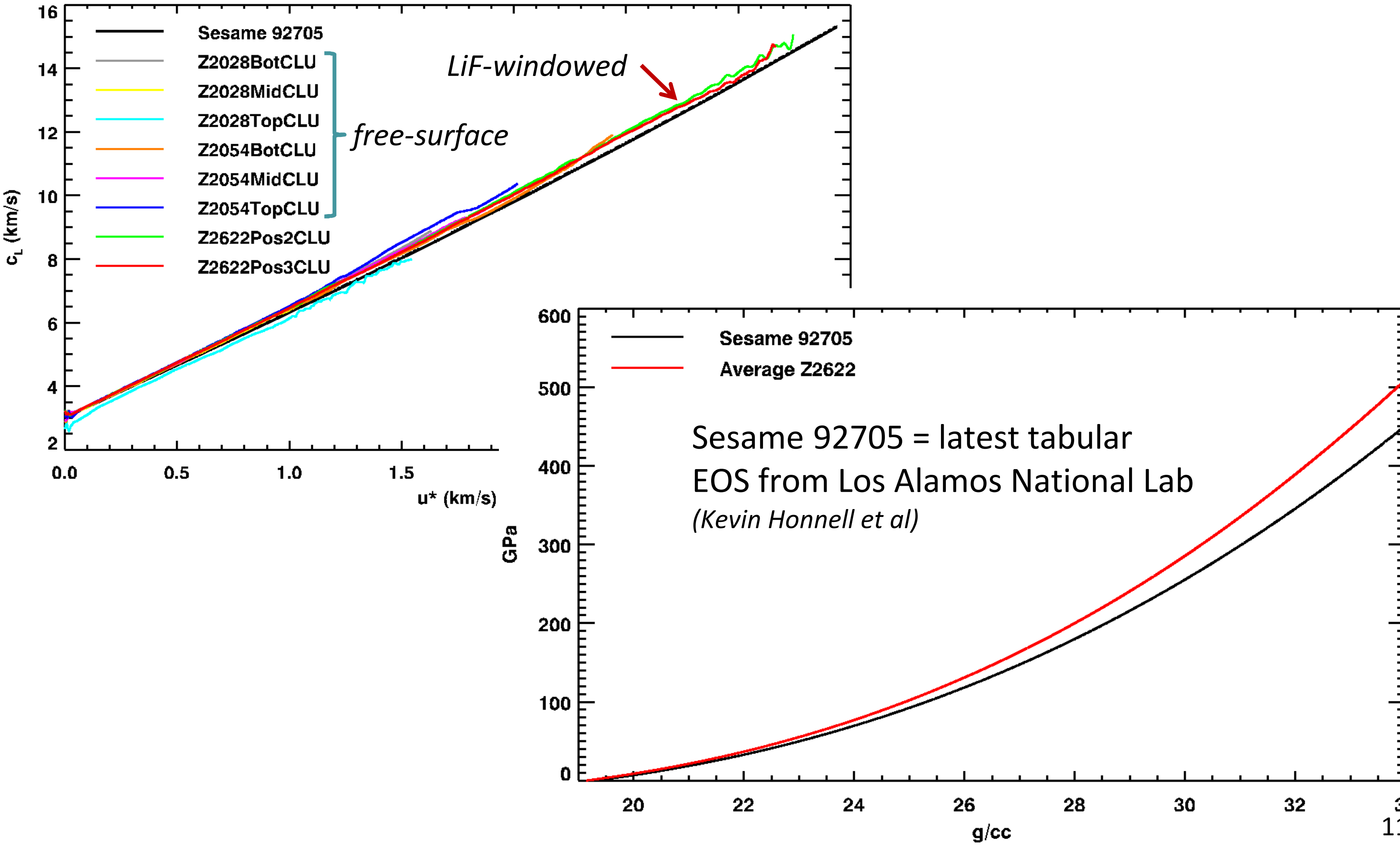


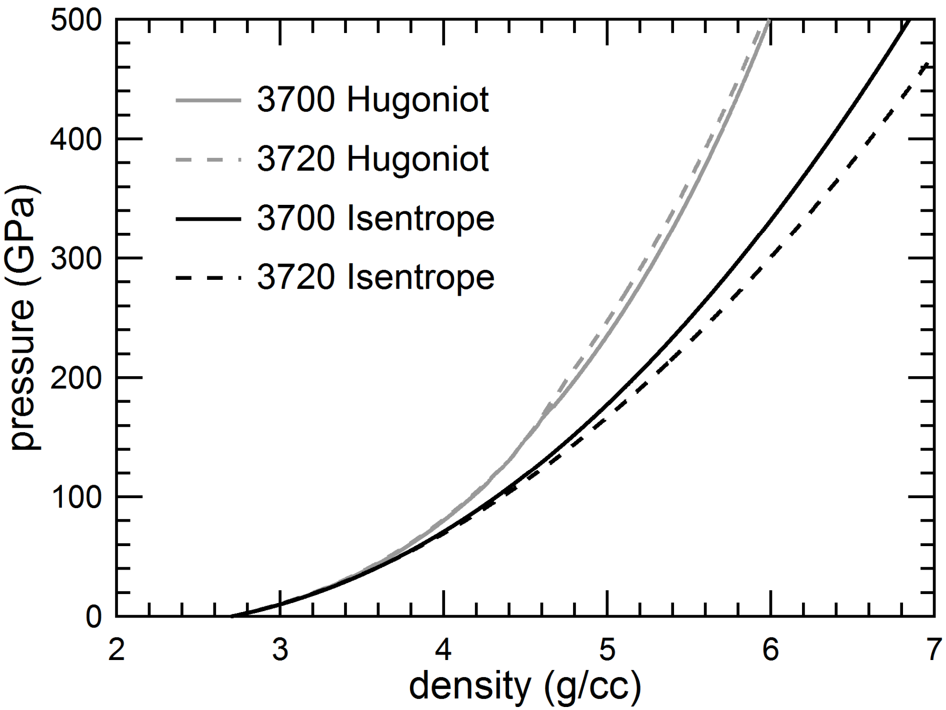
Conclusions

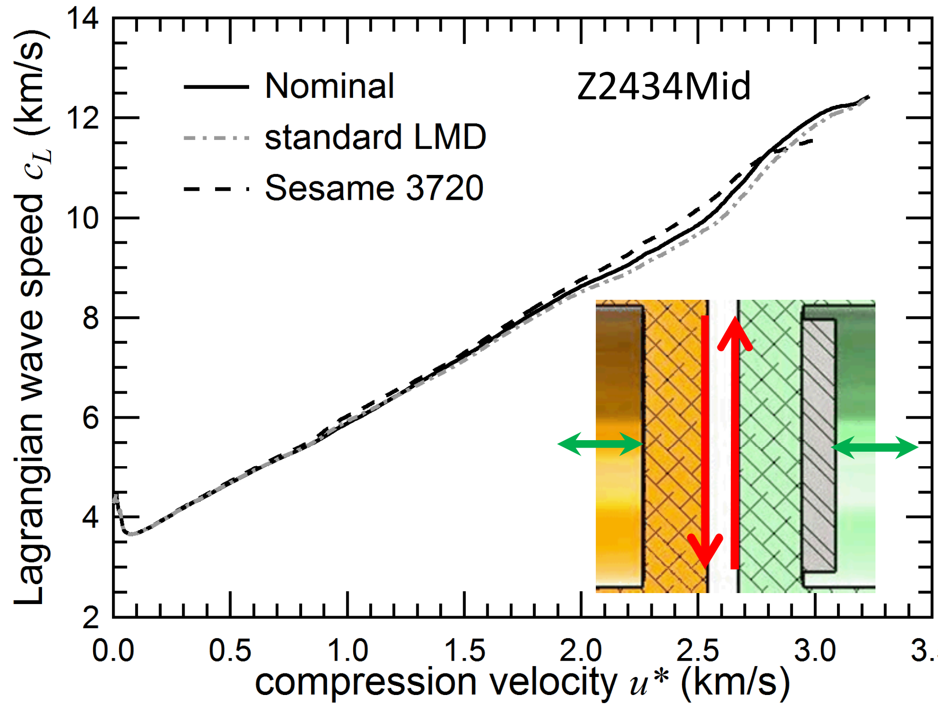
- Systematic deviations in ILA apparent wave speed for free-surface experiments with high-strength materials are due to non-single-valued propagation speed
  1. locally unloading material → regions of elastic propagation
  2. time dependence of yield stress and plasticity
- Averaged free-surface Ta data agree well with Sesame 90210 to 330 Gpa
- Recent/future experiments use:
  1. copper panels to reach higher pressure
  2. square samples to allow accounting for asymmetric drive by 2-D simulation
  3. LiF windows to alleviate errors due to strength effects
- Preliminary result for quasi-isentrope of Au to 500 GPa

<u>Future Work:</u>

- Further experiments on LiF to accurately measure mechanical and optical response to 300+ GPa
- Optimization of EOS/strength models using forward simulations

EXTRA SLIDE: Single-sample ILA has sensitivity to models used for electrode standard material





- Aluminum electrode sees different states in drive-side and sample-side electrodes
- Reanalyzed Z2434Mid changing only Al conductivity model, and again changing only Al EOS model
- Off-nominal models known to be inaccurate (nominal models largely validated)
- True uncertainty expected to be smaller than deviations shown here