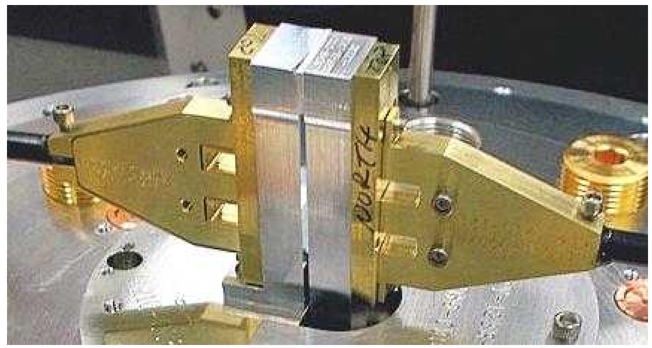
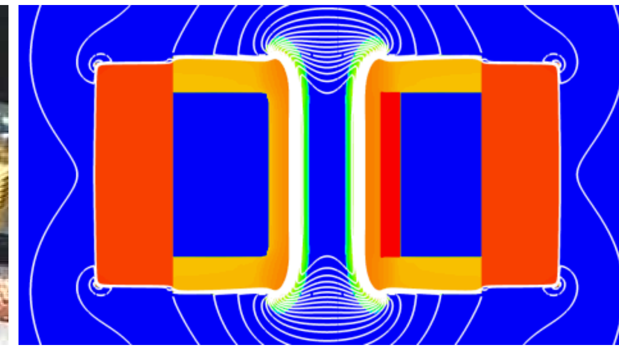
SAND2015-XXXXC

Exceptional service in the national interest

SAND2015-4697C

Sandia National Laboratories





Results from New Multi-Megabar Shockless Compression Experiments at the Z Machine

Jean-Paul Davis, Justin L. Brown, and Marcus D. Knudson

Sandia National Laboratories

Albuquerque, NM 87185

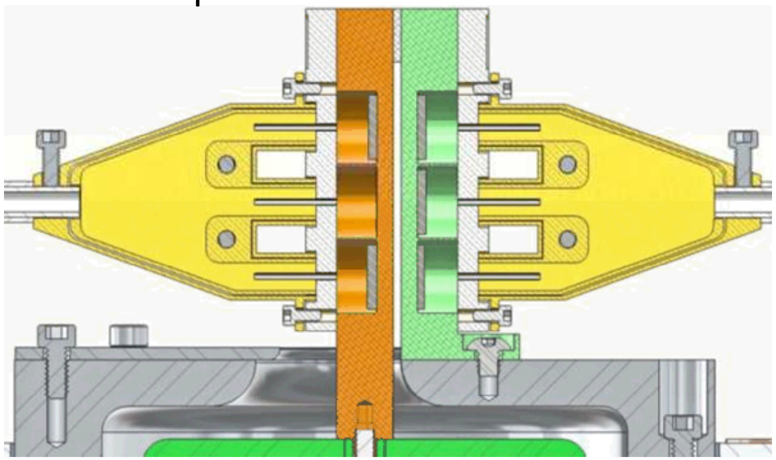
U.S. DEPARTMENT OF ENERGY

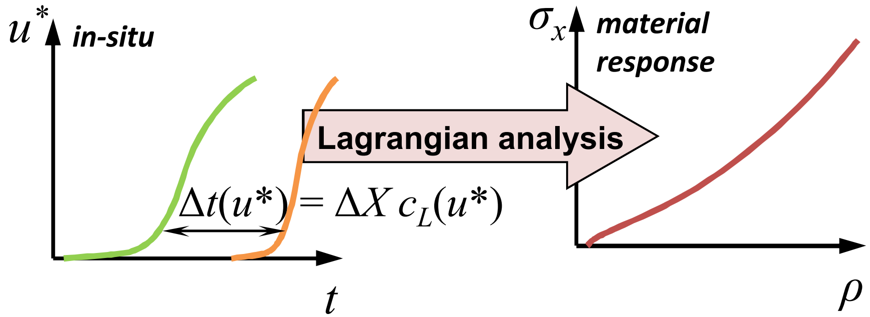
NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

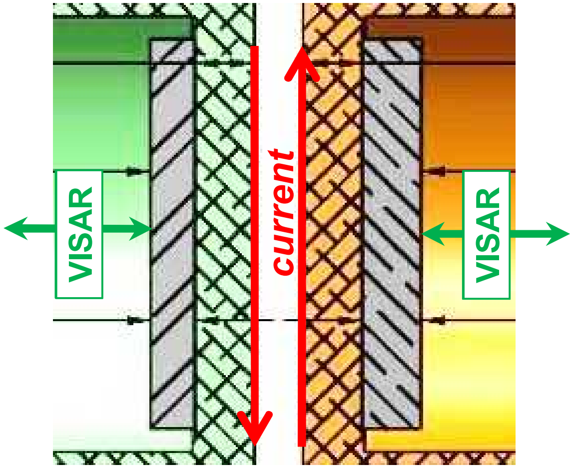
Inverse Lagrangian Analysis (ILA) extracts quasi-isentropic material response from velocimetry

Stripline load on the Z machine





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

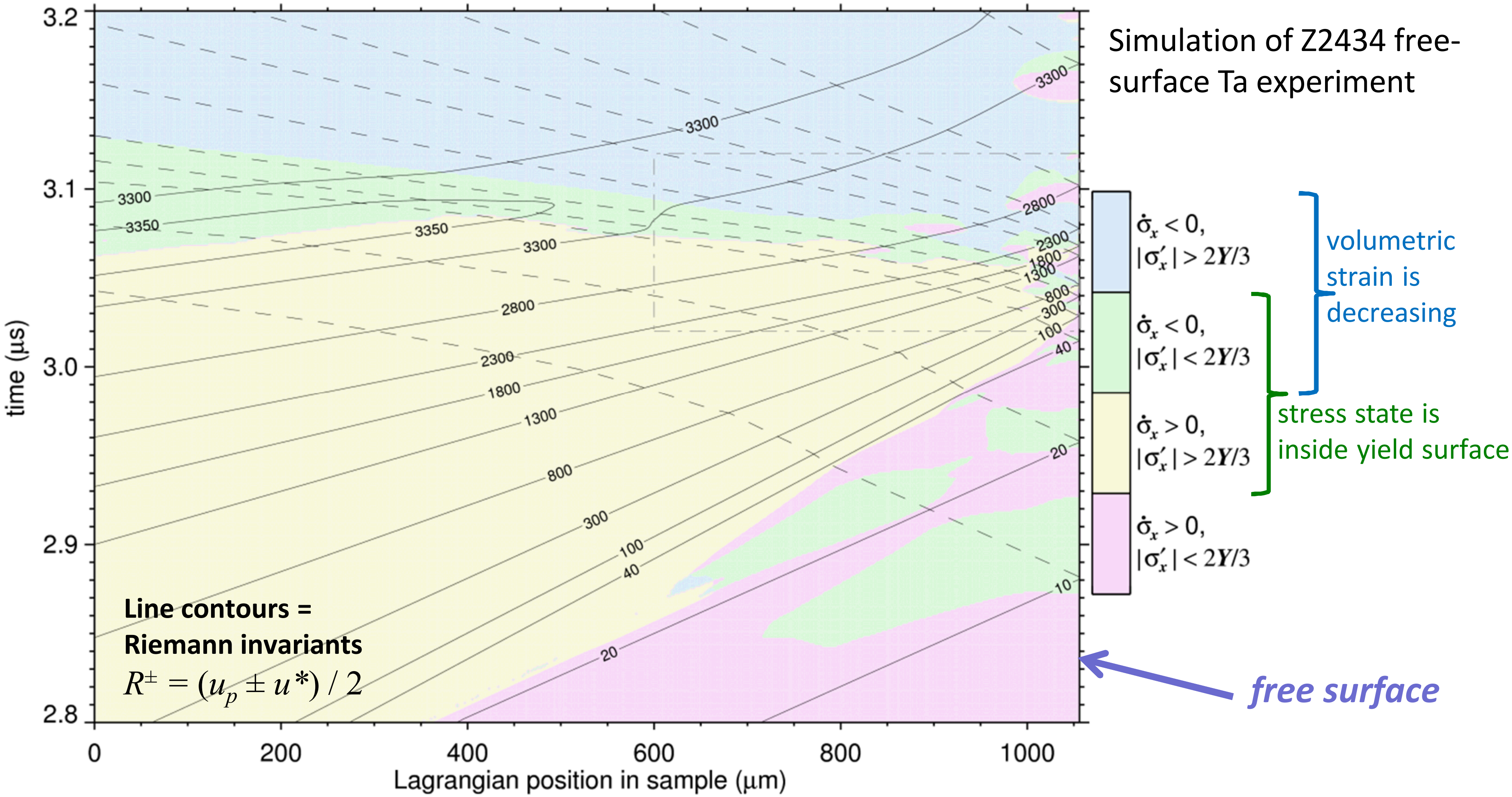


- In-situ measurements → Direct Lagrangian Analysis (DLA)
- Real measurements are free-surface or window-interface
  → Inverse Lagrangian Analysis (ILA)
  - map measured $u(t)$ into in-situ $u^*(t)$, then apply DLA
  - typically map by iterative characteristics technique[1]
  - dual-sample and single-sample approaches
  - ***assumes single-valued material response***

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

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

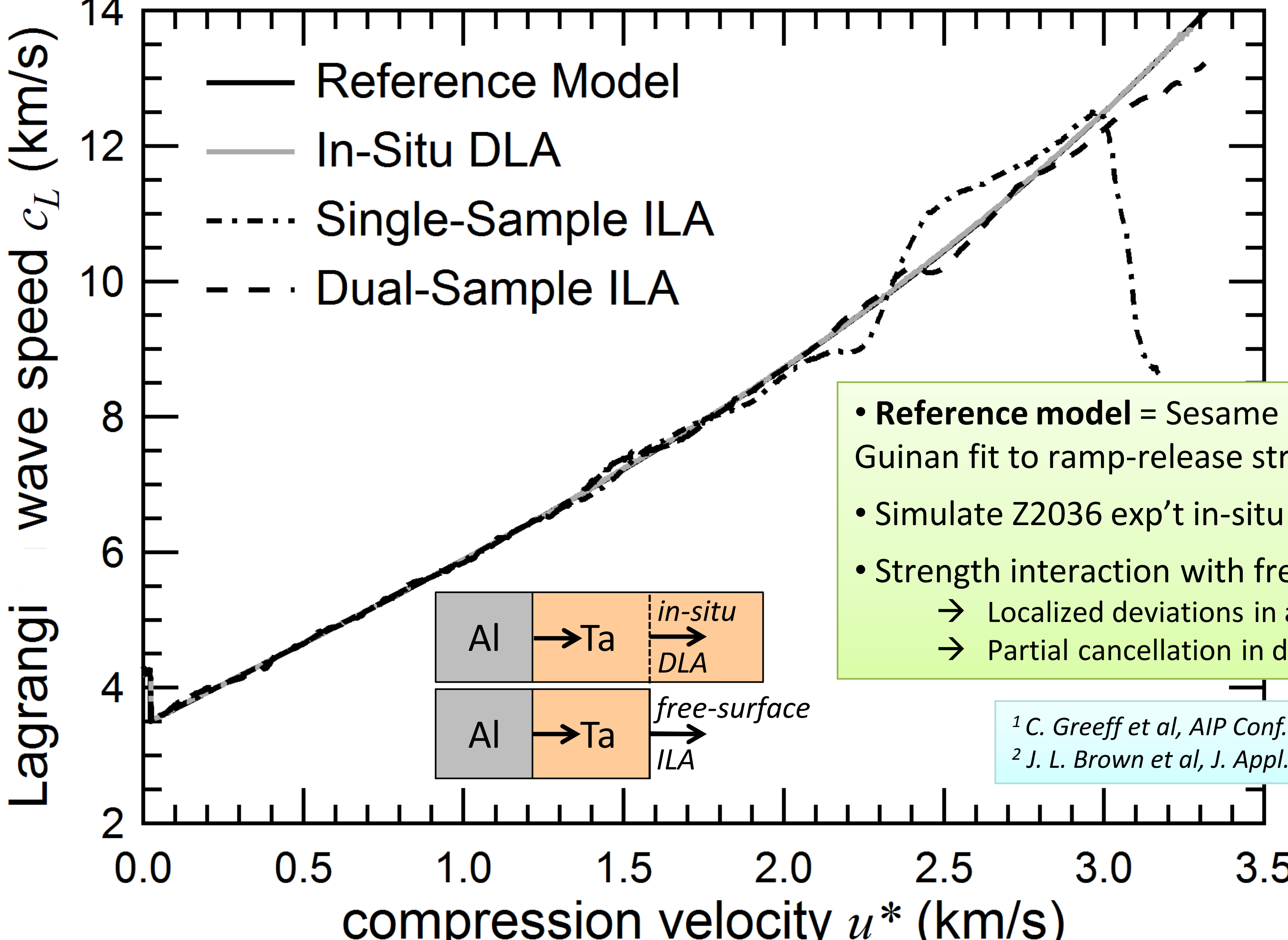
Simulation of Z2434 free-surface Ta experiment



- 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

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

Analysis of synthetic data quantifies systematic deviations due to violation of single-valued response

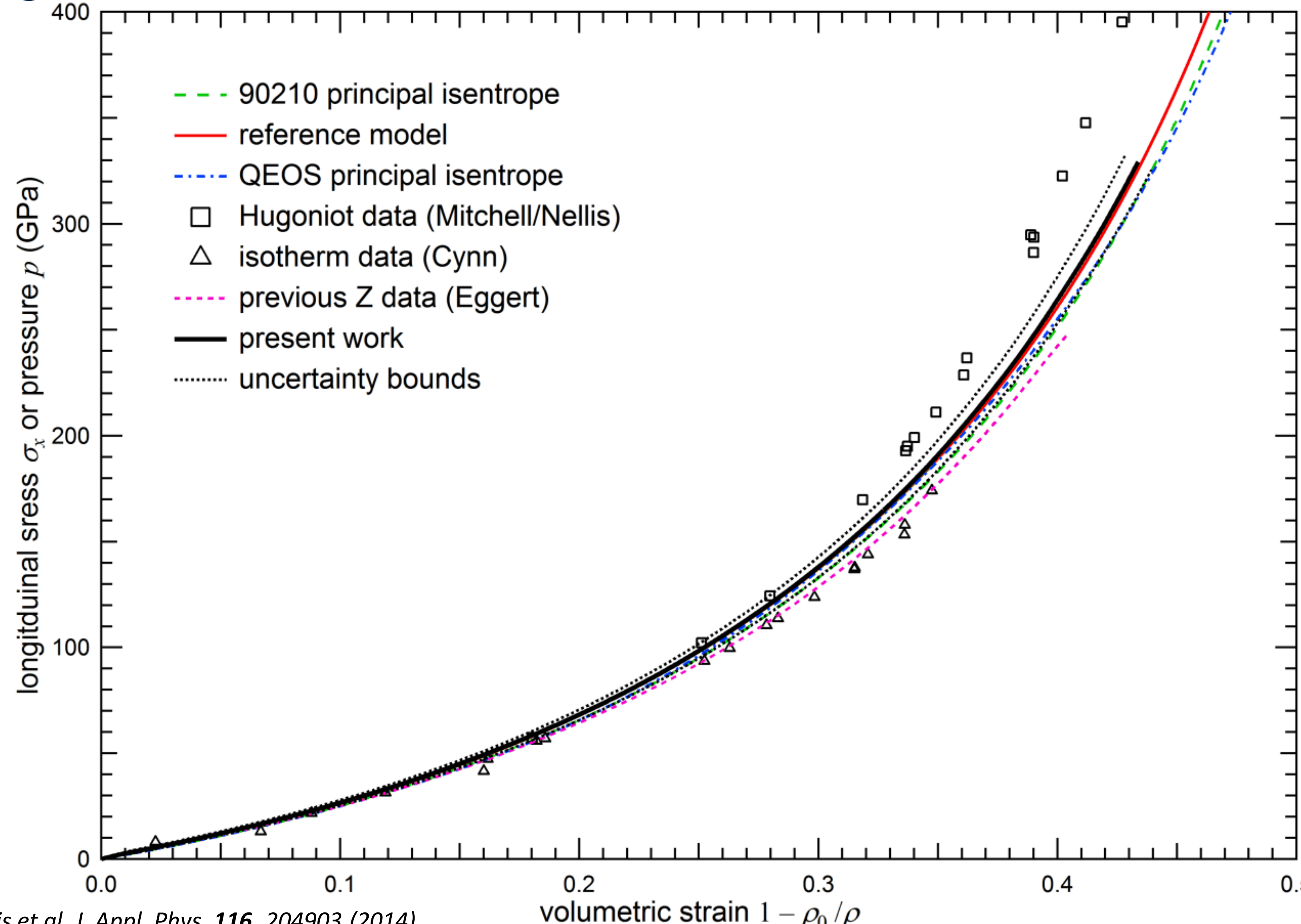


- **Reference model** = Sesame 90210[1] + Steinberg-Guinan fit to ramp-release strength data[2]
- Simulate Z2036 exp't in-situ & free-surface
- Strength interaction with free surface (ILA)
  - → Localized deviations in apparent $c_L(u^*)$
  - → Partial cancellation in dual-sample case

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

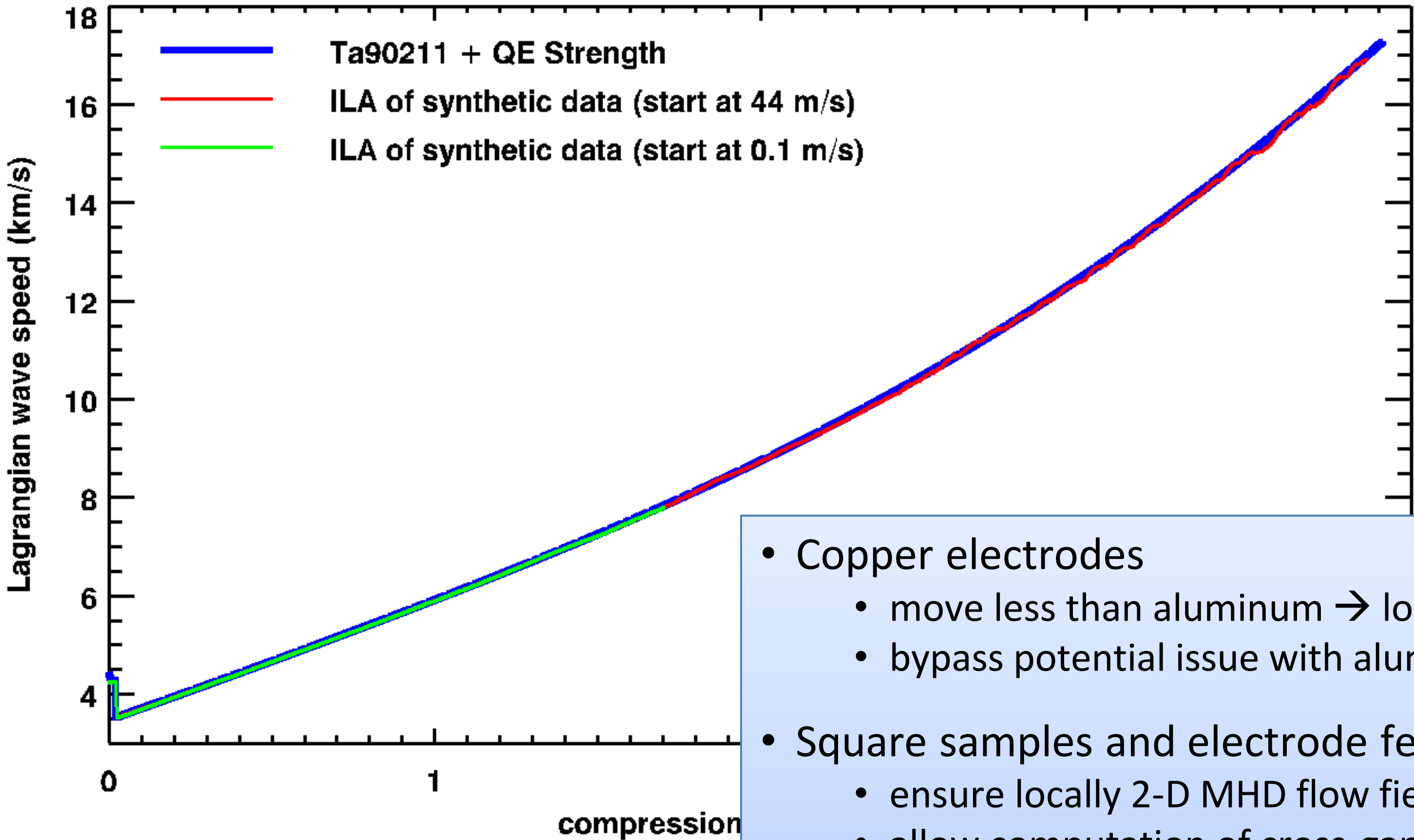
J.-P. Davis et al, J. Appl. Phys. ***116****, 204903 (2014)*

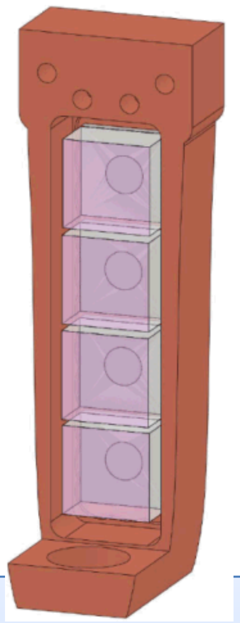
Averaged stress-strain of 15 Ta experiments agrees well with the reference model



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

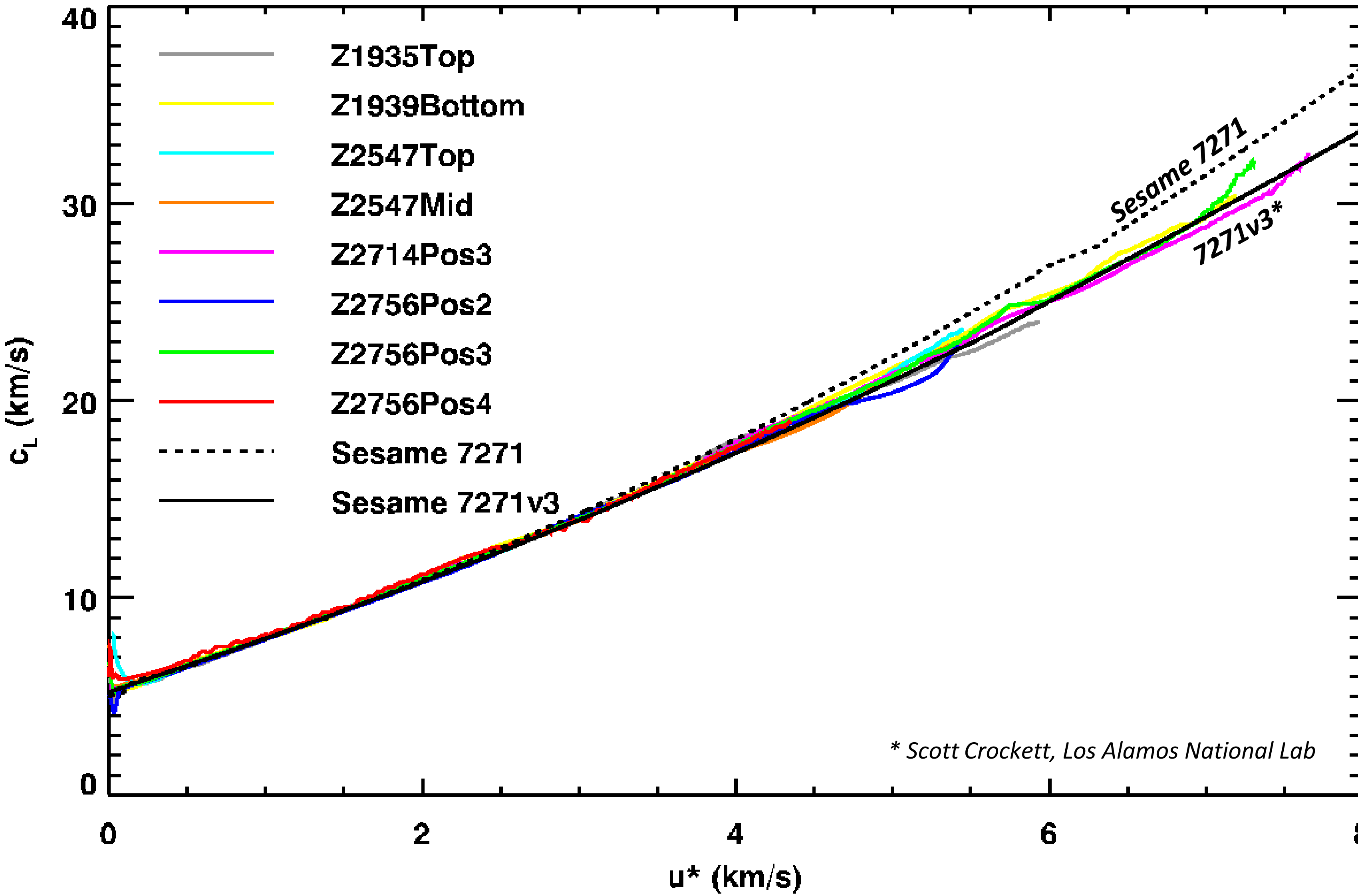
Improvements to experiment design are enabling quasi-isentrope measurements to higher stress





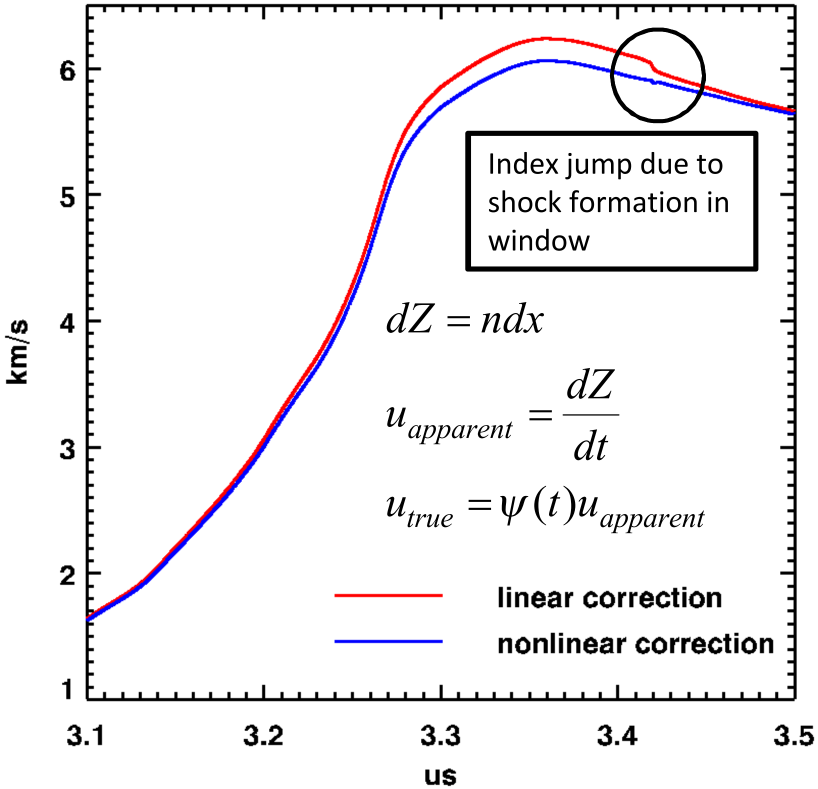
- Copper electrodes
  - move less than aluminum → lower dI/dt, higher B/I
  - bypass potential issue with aluminum phase transitions
- Square samples and electrode features
  - ensure locally 2-D MHD flow field
  - allow computation of cross-gap non-uniformity
- LiF windows
  - significantly reduce errors due to local unloading
  - uncertainty in stress-strain response at multi-megabars
  - uncertainty in index of refraction (nonlinear in density)

Collection of preliminary results on LiF mechanical response indicate LANL 7271 EOS is too stiff



True velocity deduced from non-linear index of refraction with temperature correction

Sandia National Laboratories

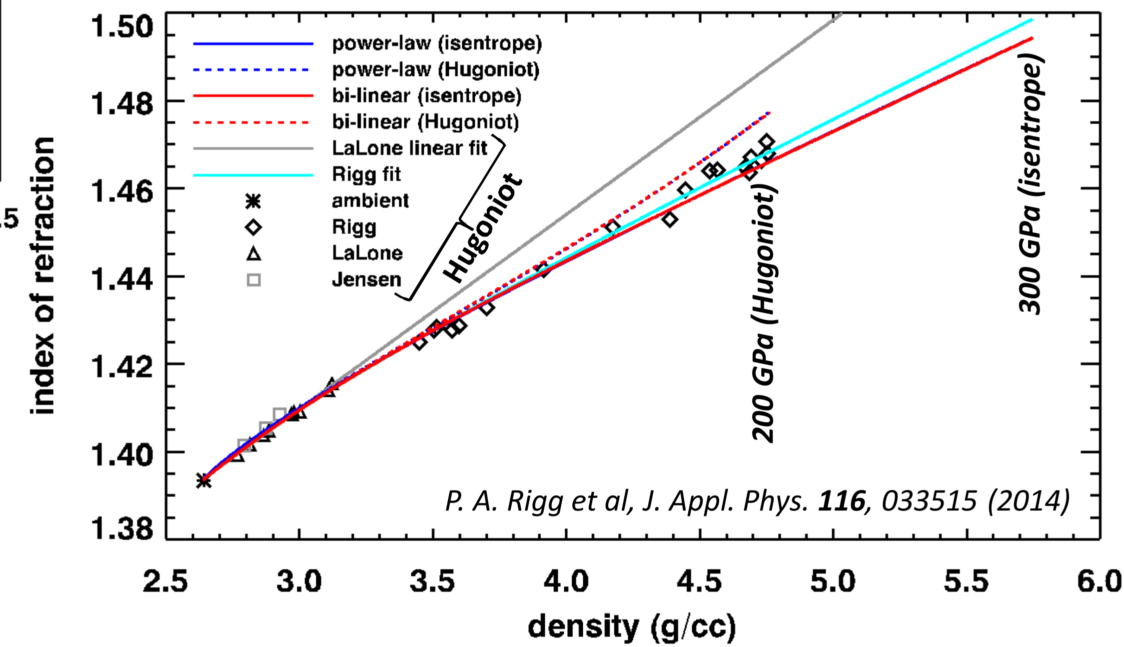


$$\text{power-law: } \frac{n-1}{n_0-1} = \frac{1-\gamma\varepsilon^{\kappa}}{1-\varepsilon}, \text{ where } \varepsilon = 1-\rho_0/\rho$$

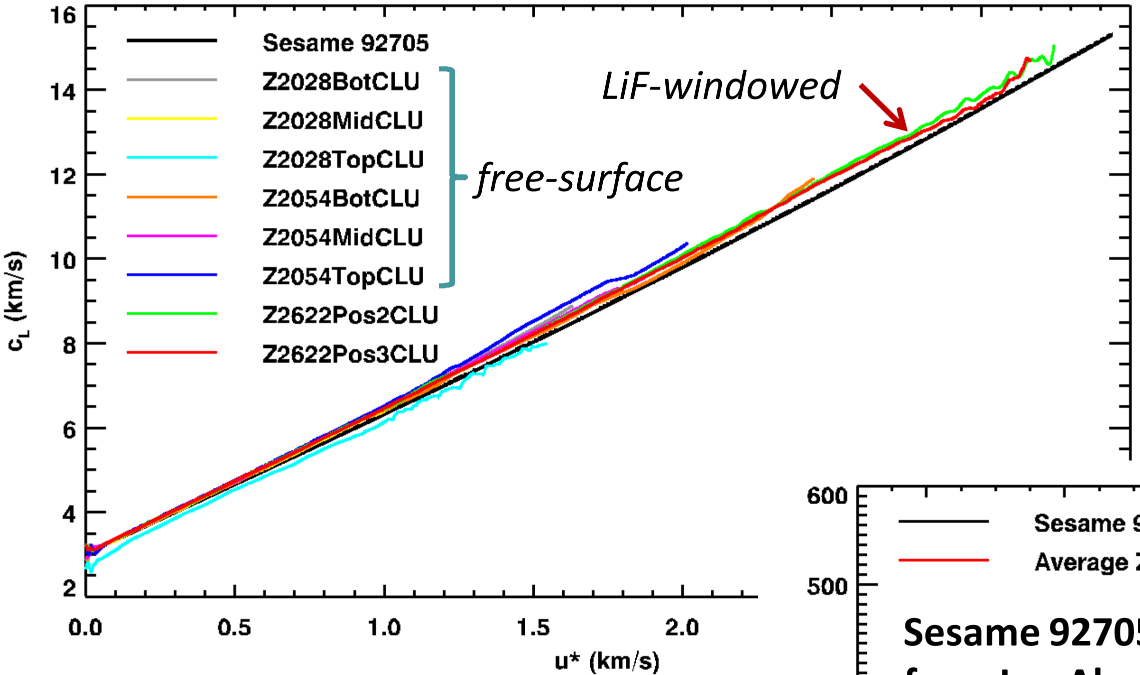
$$\text{bi-linear: } n = \frac{a_1 + a_2\rho}{1+e^{a_3(\rho-a_4)}} + \left(a_5 + a_6\rho\right)\left(1 - \frac{1}{1+e^{a_3(\rho-a_4)}}\right)$$

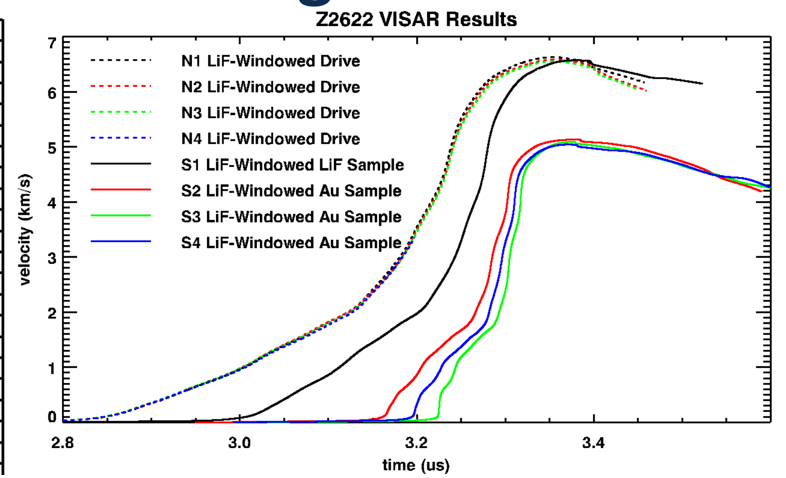
$$n = n_{isentrope} + c\left(T - T_{isentrope}\right)$$

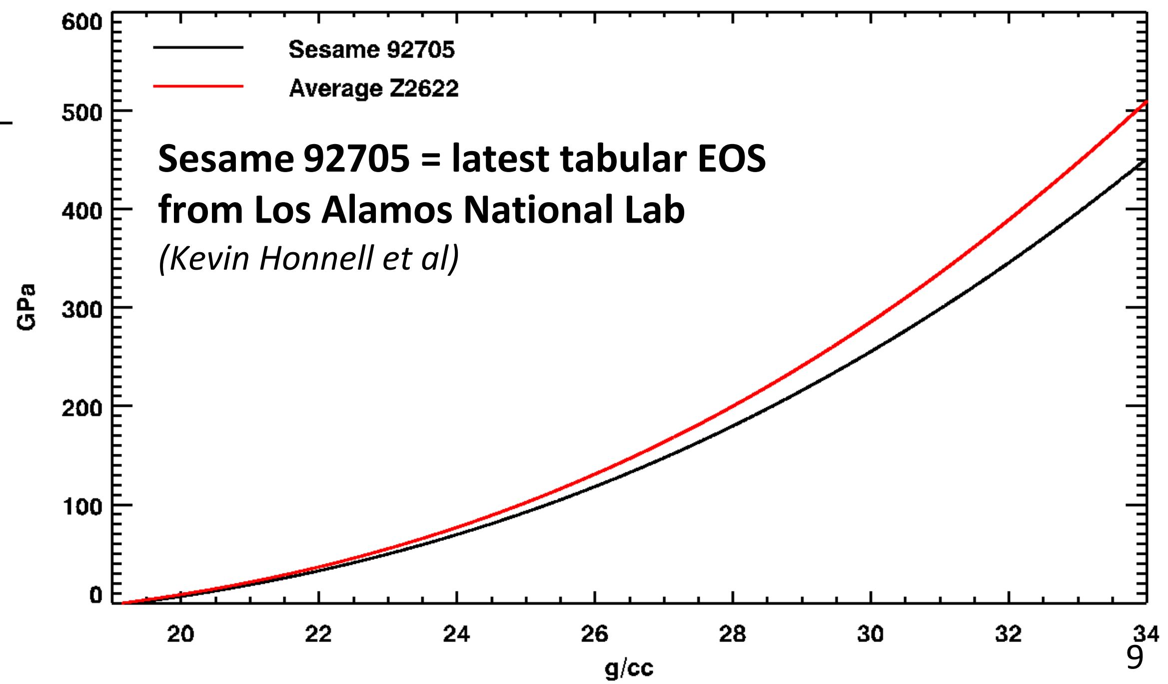
- 1-D hydrocode computes $u_{apparent}$ from given u_{true}
- update u_{true} from measured $u_{apparent}$
- iterate until simulation matches measured $u_{apparent}$



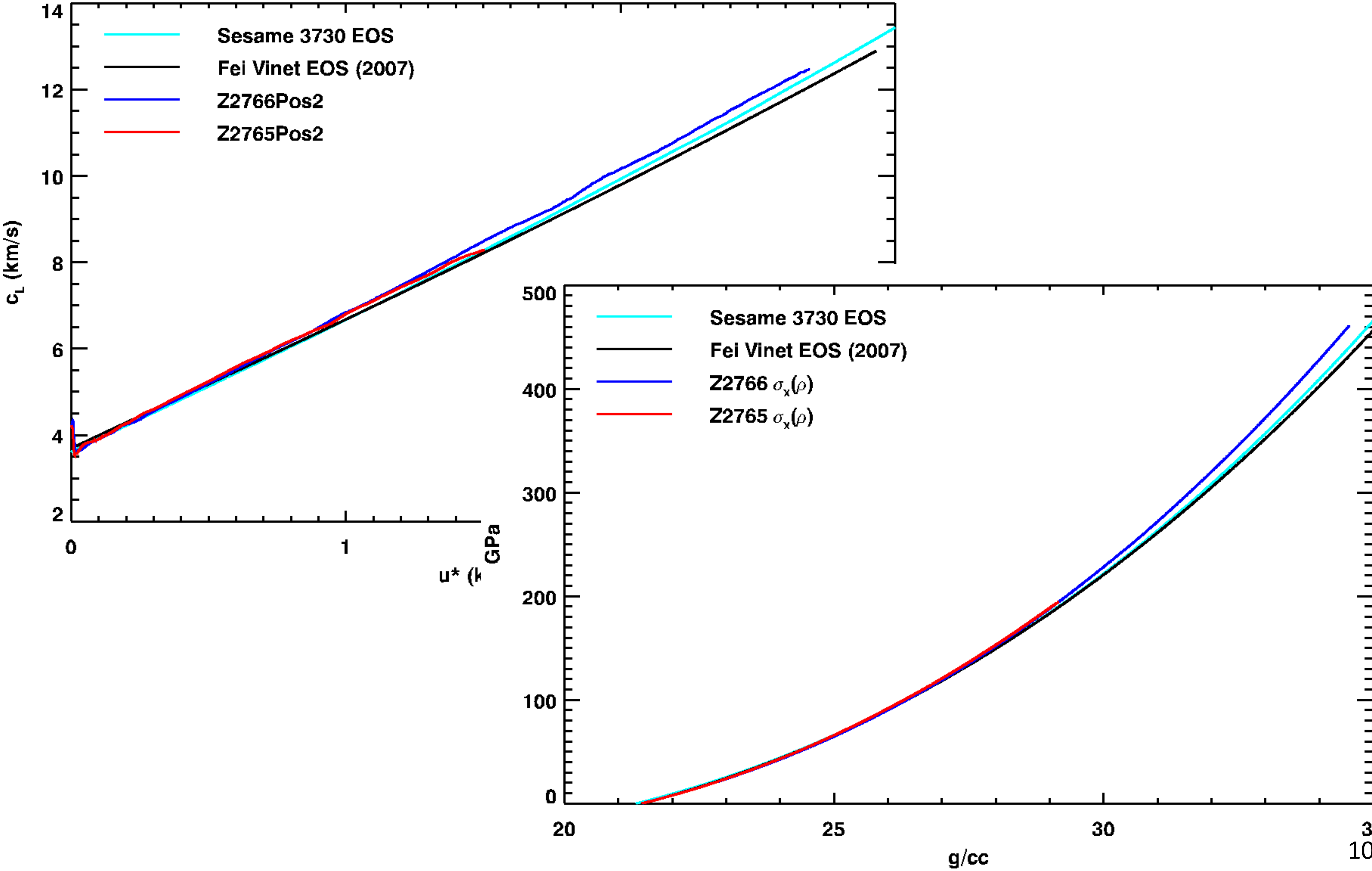
Preliminary analysis of Au data to 500 GPa suggests lower compressibility than leading model



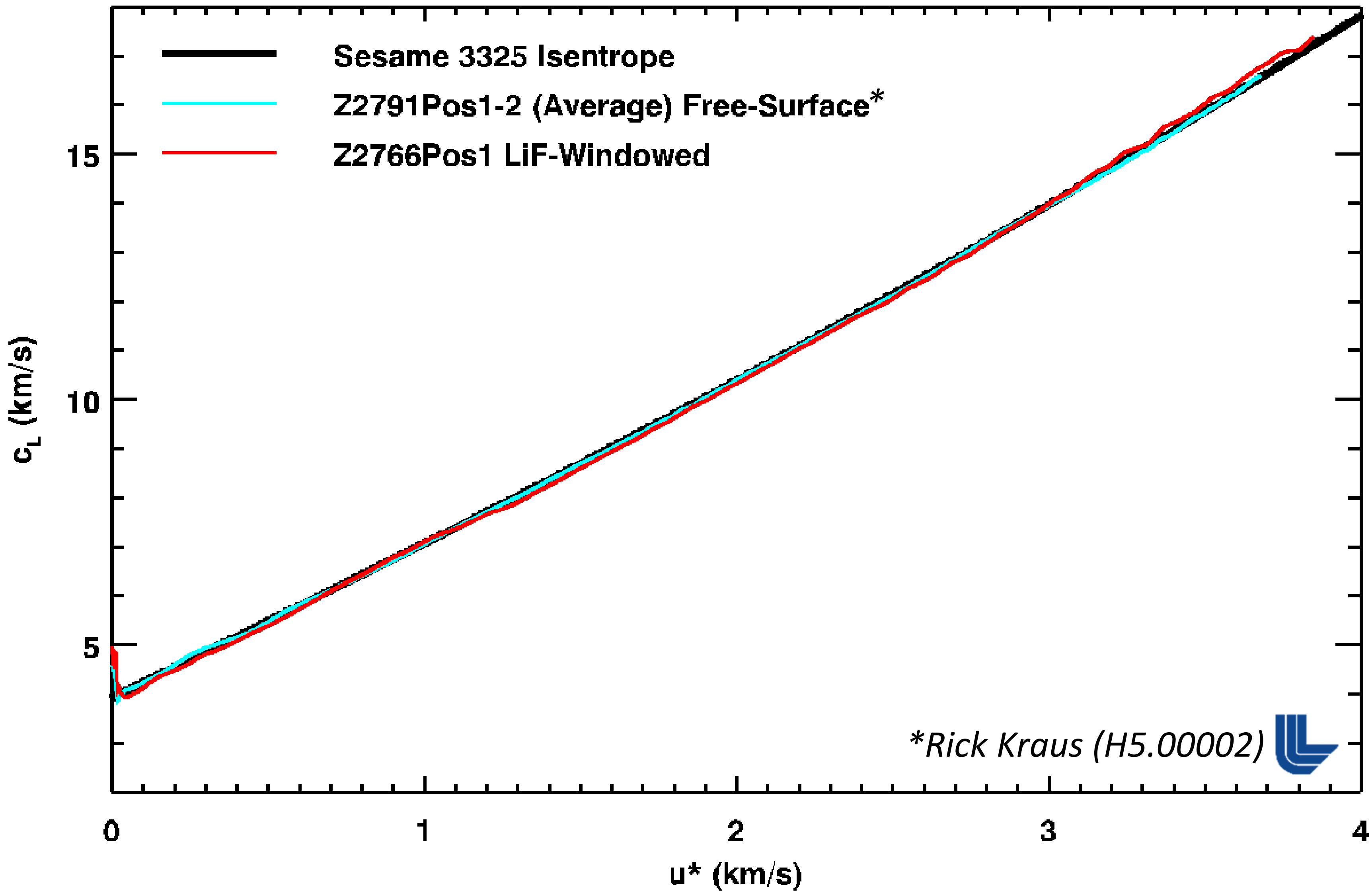




LiF-windowed Pt data also show stiffer response

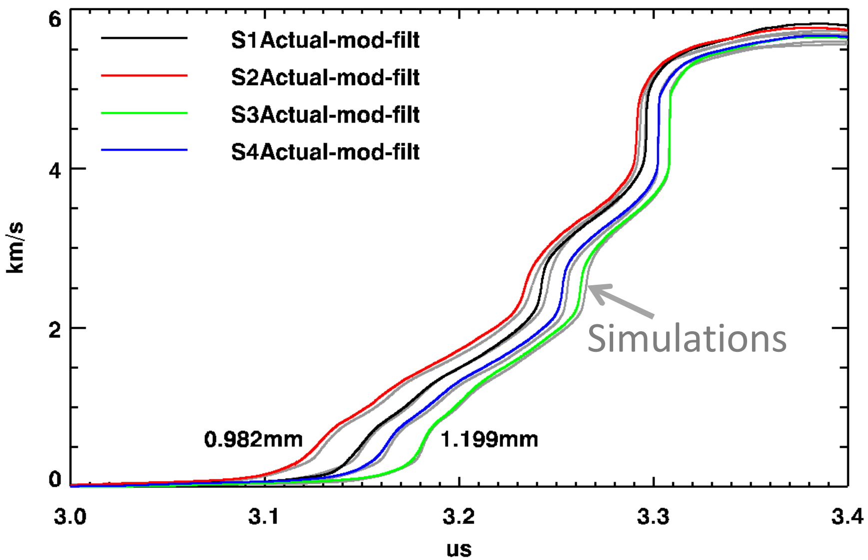


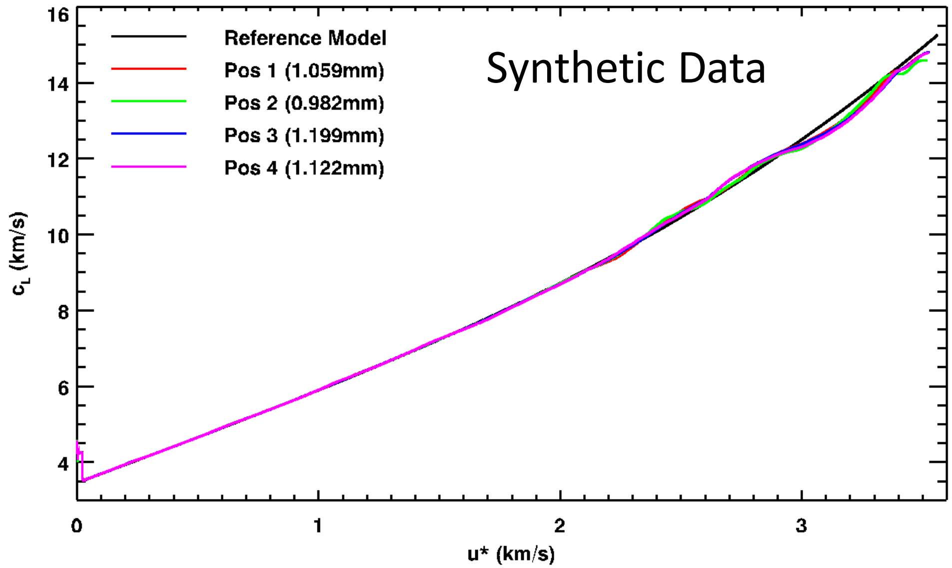
LiF-windowed Cu data agree with results from free-surface experiments

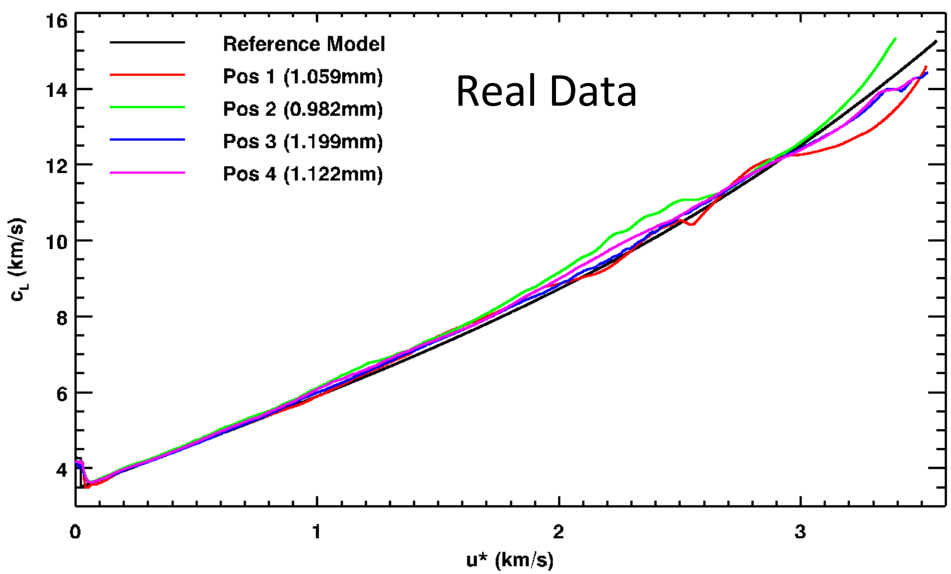


*Rick Kraus (H5.00002)

500-GPa experiment on Ta was compromised by formation/growth of shocks in LiF near sample







Concluding Remarks

- Systematic deviations in ILA apparent wave speed for free-surface experiments with high-strength materials
- Averaged free-surface Ta data agree well with Sesame 90210 to 330 GPa
- Recent experiments use LiF windows to alleviate errors due to strength effects
- LiF quasi-isentrope softer than existing models
- Must account for nonlinear density dependence of LiF index of refraction
- Preliminary results for quasi-isentrope of Au to 500 GPa, Pt and Cu to 450 GPa

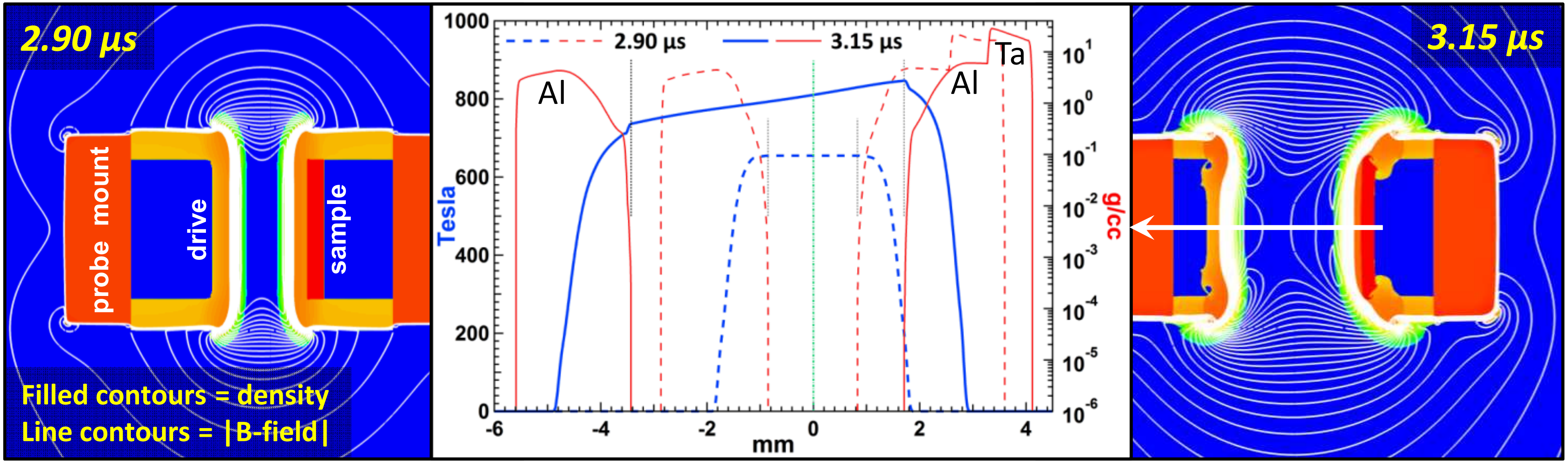
Future Work:

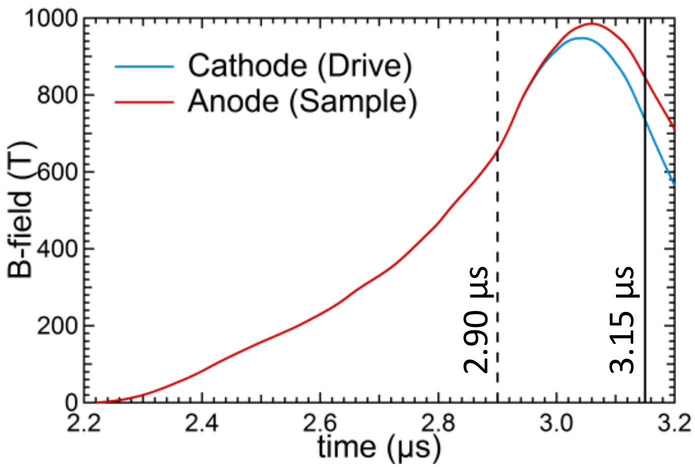
- Further experiments on LiF to accurately measure mechanical and optical response to 300+ GPa
- Revisit 500-GPa Ta experiment (pulse shaping), other materials
- Independent measurements of strength at shocklessly-compressed states
- Optimization of EOS/strength models using forward simulations
    - *Ray Lemke (D1.00001), Justin Brown (E5.00004), Rick Kraus (H5.00002)*

Extra Slides

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

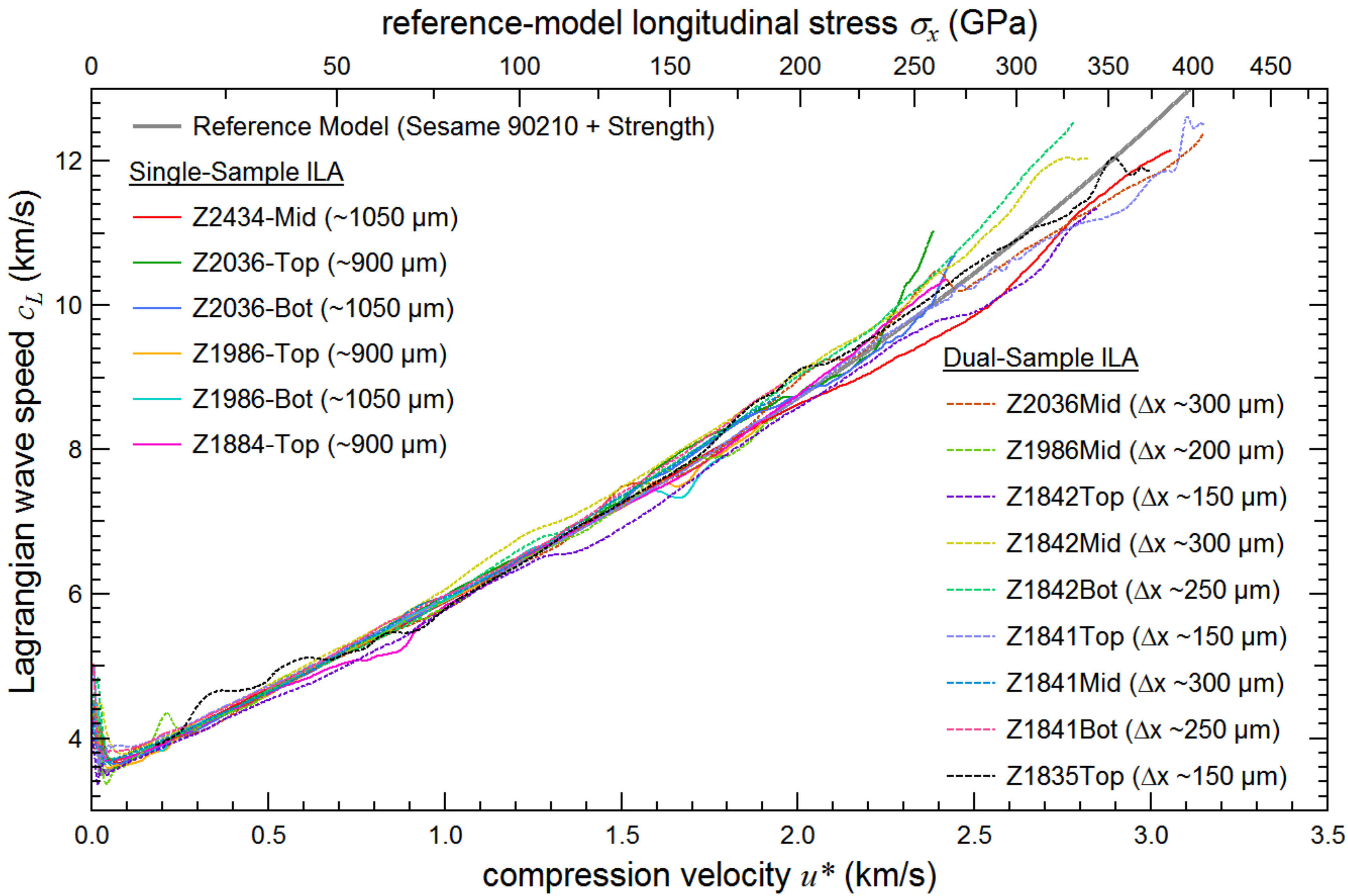




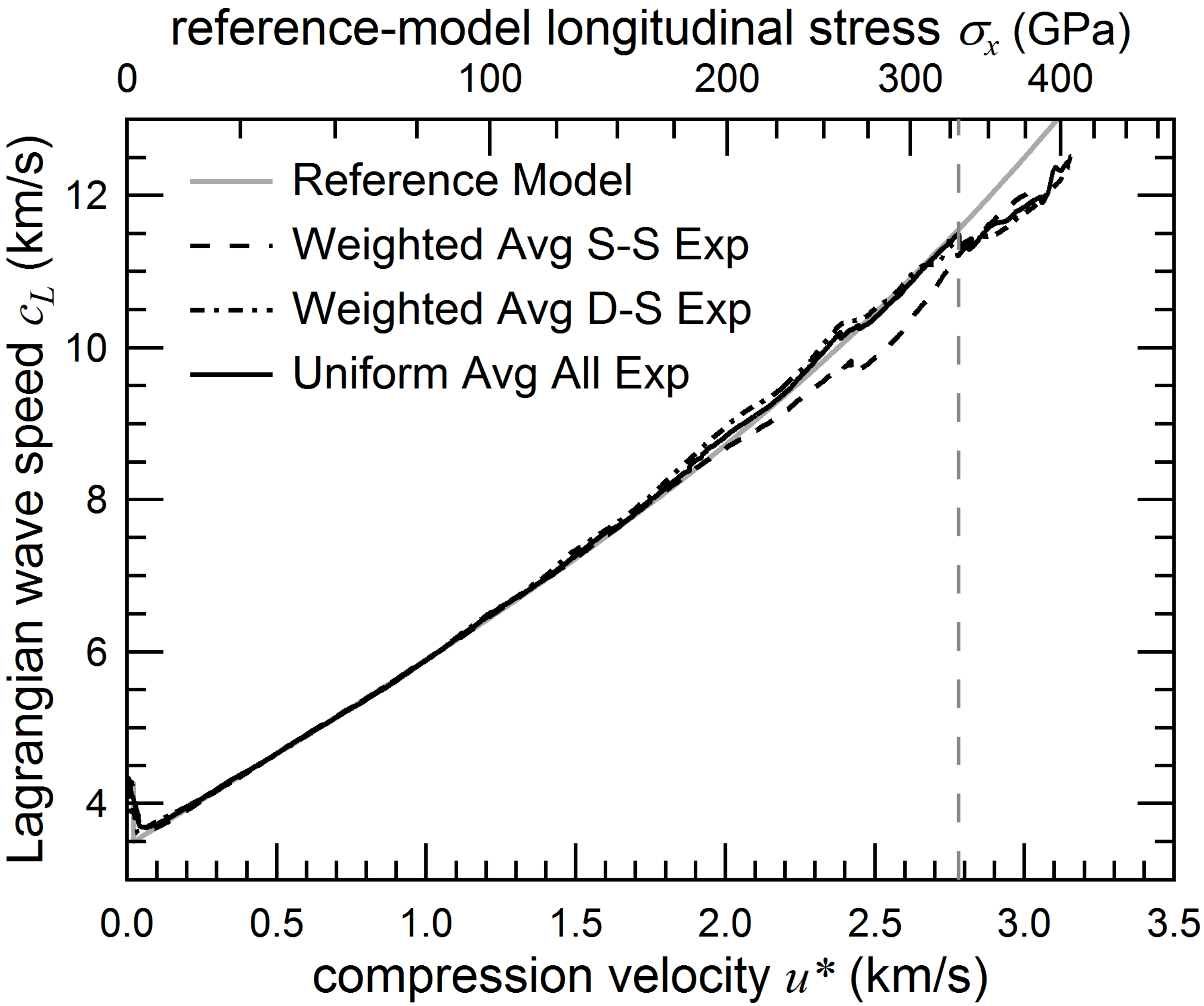
- Asymmetric wave reverberations in electrodes
  - Left (drive): reflection from free surface
  - Right (sample): reflection from high-impedance material
- Resulting 2-D effects cause asymmetric B-field topology
- Can occur prior to time of peak current
- Use 2-D B-field Sample/Drive ratio to correct 1-D B-field
  - Only if experiment is really 2-D!
  - For cylindrical samples, discard beyond divergence

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

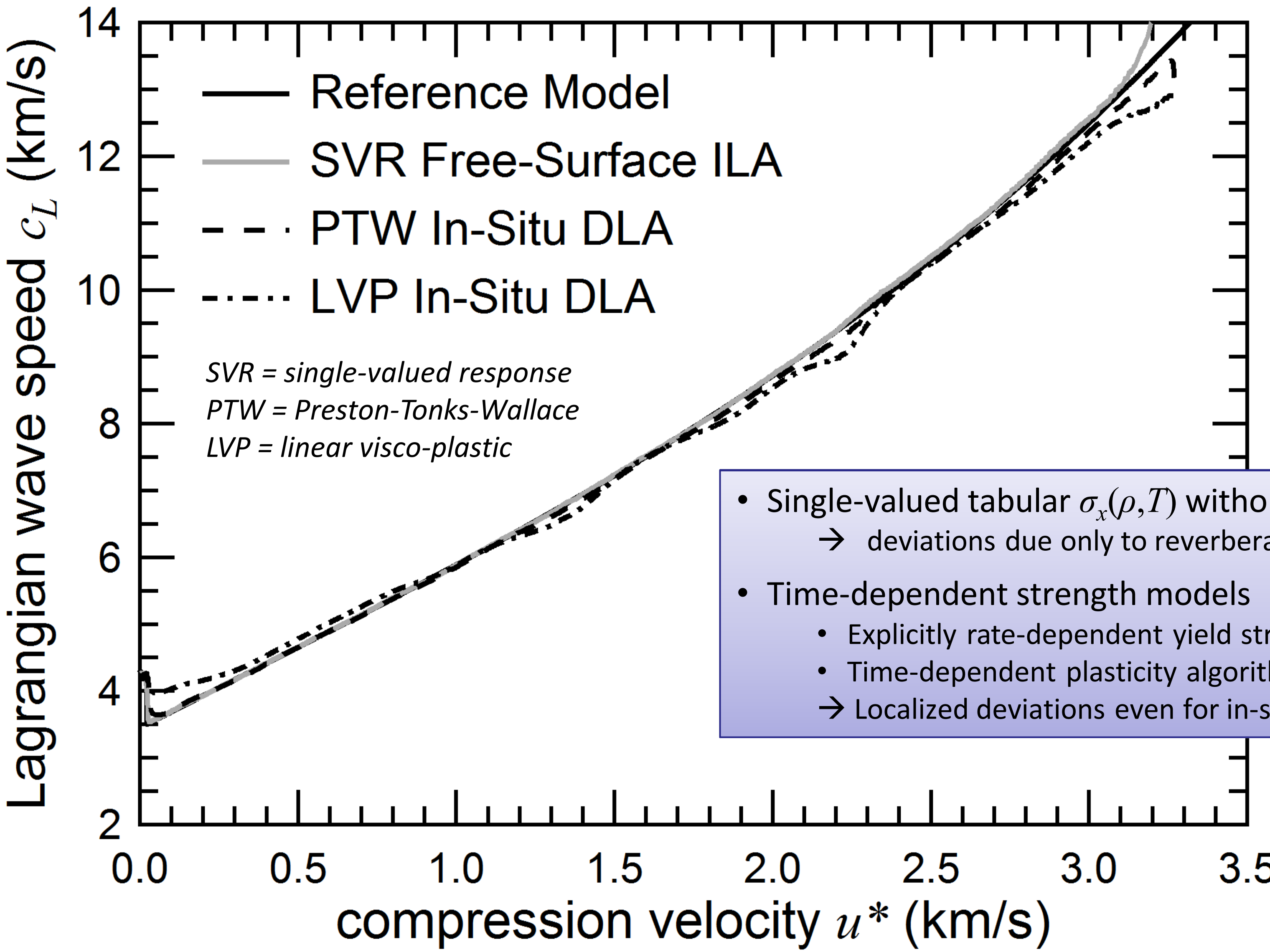
Sandia National Laboratories



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

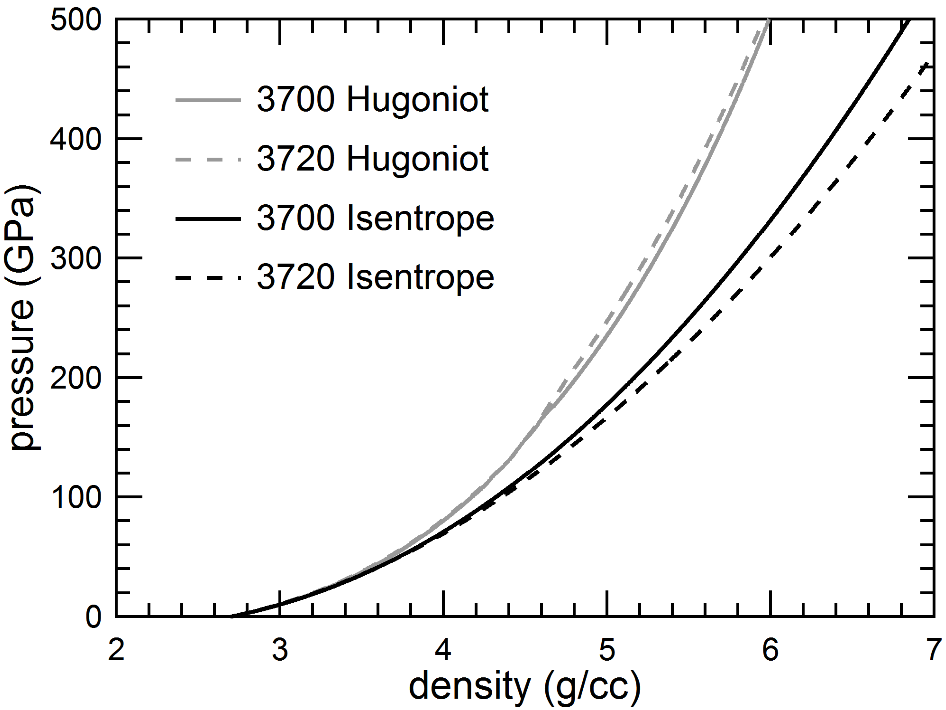


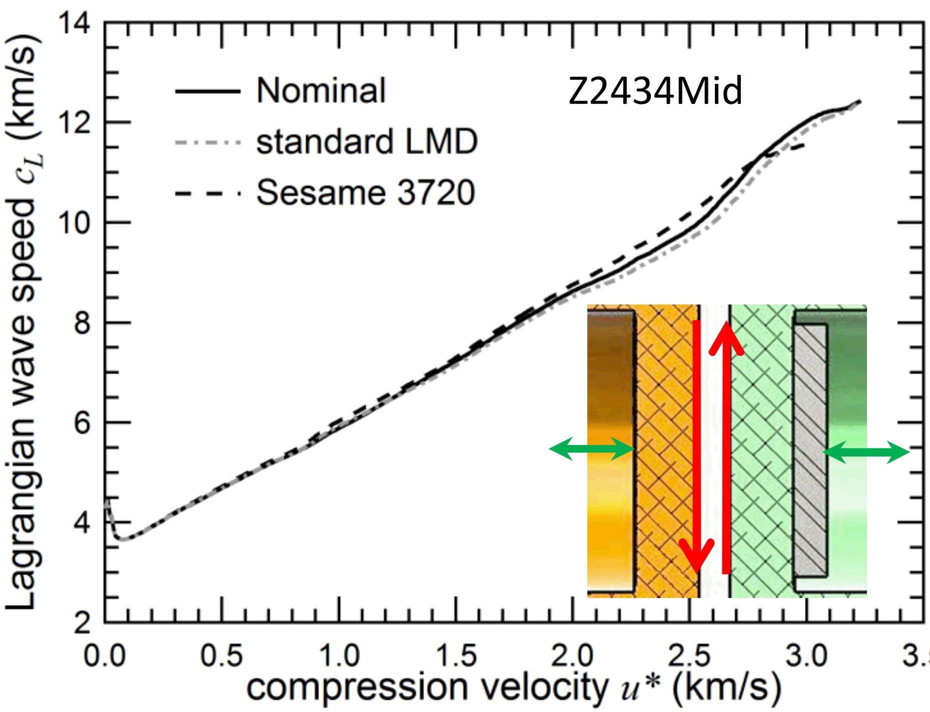
Time dependence in strength can cause small systematic deviations in apparent wave speed



- 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

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