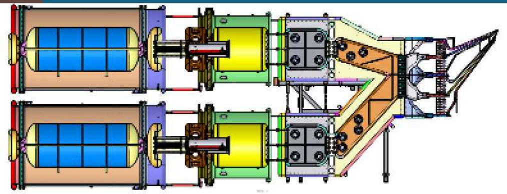
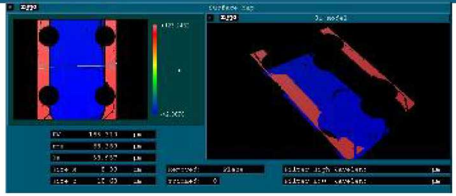
Non-Classified Research Program under the CEA-NNSA Agreement on Cooperation in Fundamental Science Supporting Stockpile Stewardship

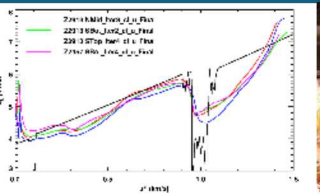
Sandia National Laboratories

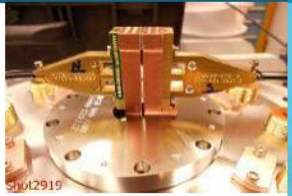
SAND2018-13416PE

Kickoff for Project P204: Kinetics of phase transformations in metals under dynamic compression









PRESENTED BY

Jean-Paul Davis

P204 Collaboration Kickoff Meeting
26-28 November 2018 in Albuquerque, NM, USA

INTRODUCTION

Overarching goal of collaboration P204

share knowledge and experience in all areas relevant to performing and analyzing experiments on phase transformation kinetics in metals, including:

- experiment design for both pulsed-power and gun drivers
- temperature, X-ray diffraction (XRD), and other diagnostics
- pre-heating (and maybe pre-cooling?) of samples
- analysis of experimental data
- materials modeling of phase transformations with kinetics

Additional goals for this kickoff meeting

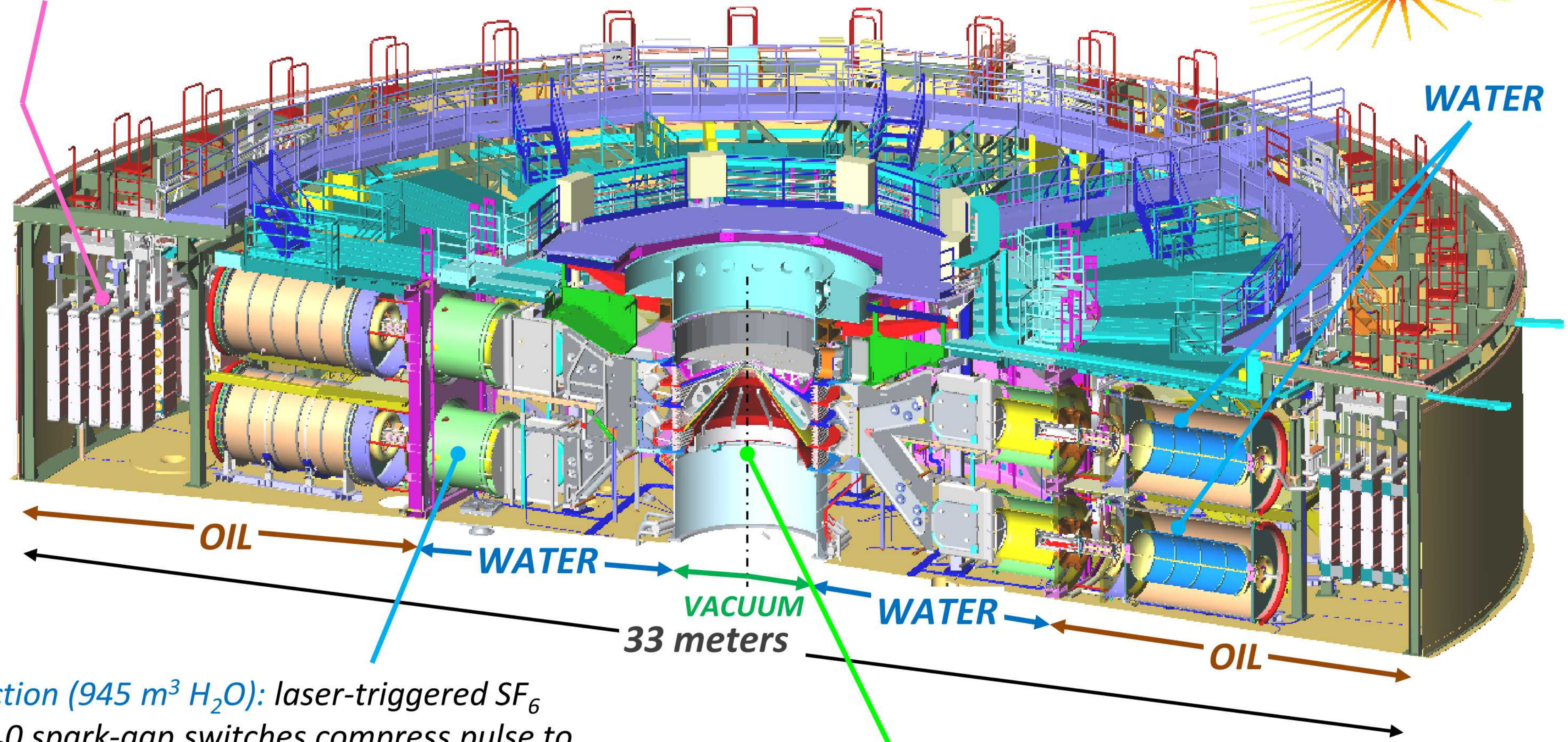
- define specific collaboration projects for continuing work
- experiments either newly proposed, or already part of lab's program
- plan future in-person and remote-video meetings to ensure continuity

NNSA:
Jean-Paul Davis
Dan Dolan, Tom Hartsfield (pyrometry)
Tom Ao, Patricia Kalita (dynamic XRD)
Justin Brown (pre-heating)

CEA:
Camille Chauvin
Thierry d'Almeida
Fréderic Zucchini
Françis Lassalle

The Z Machine, refurbished in 2007, saw subsequent upgrades of Laser-Triggered Gas Switches and Pulse-Forming Lines

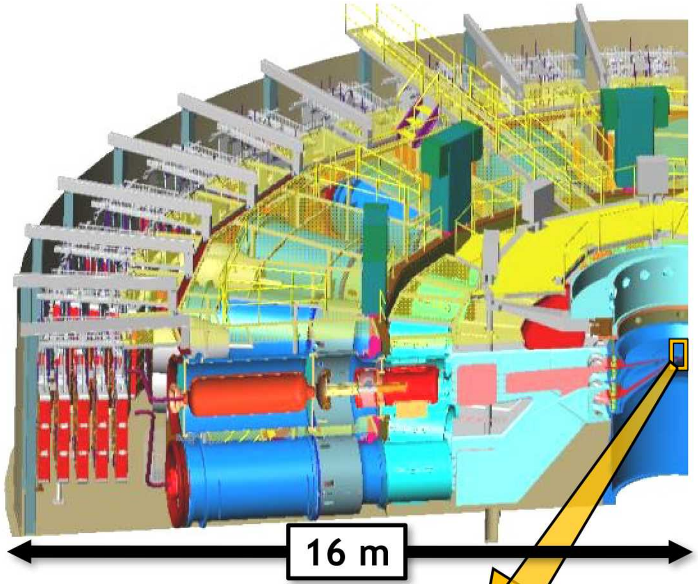
energy storage section (3215 m^3 oil): stores 23 MJ in 36 banks of 60 capacitors (each 2.3 µF), charged in parallel (90 kV), discharged in series (5.4 MV)

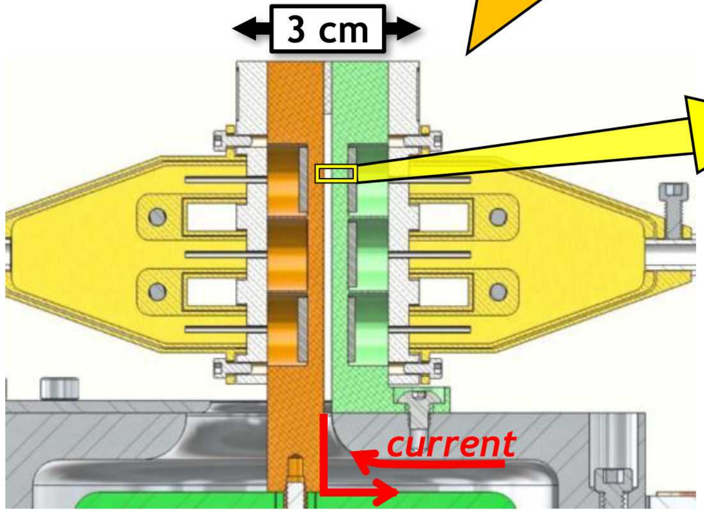


pulse-forming section (945 m^3 H_2O): laser-triggered SF_6 gas switches & H_20 spark-gap switches compress pulse to 100 ns rise time, tri-plates reduce 36 lines to 18, convolute reduces further to 4 radial feed gaps

center section (1.5 mPa vacuum): magnetically insulated transmission lines deliver up to 26 MA pulse to load, convolute reduces 4 feed gaps to 1

Planar shockless (and shock-ramp) compression to 400+ GPa is possible on the Z machine using stripline short-circuit loads



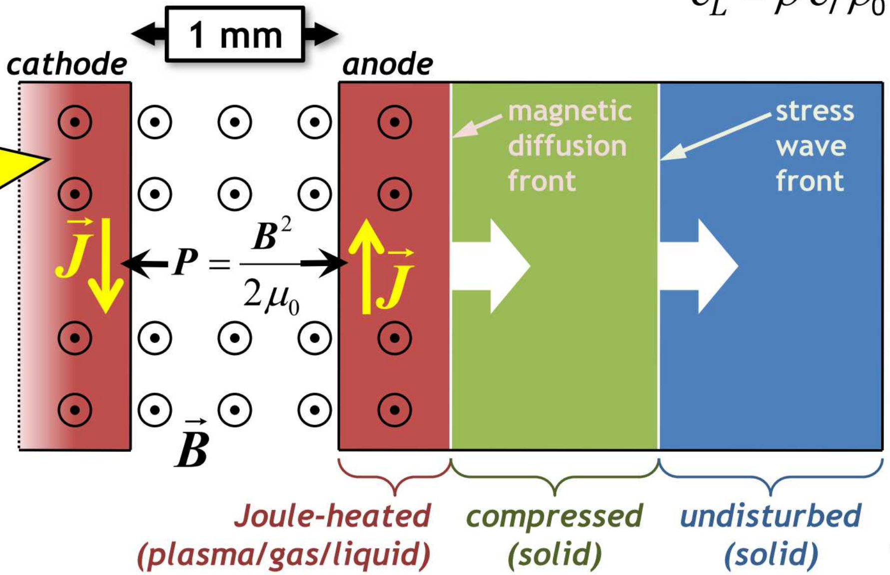


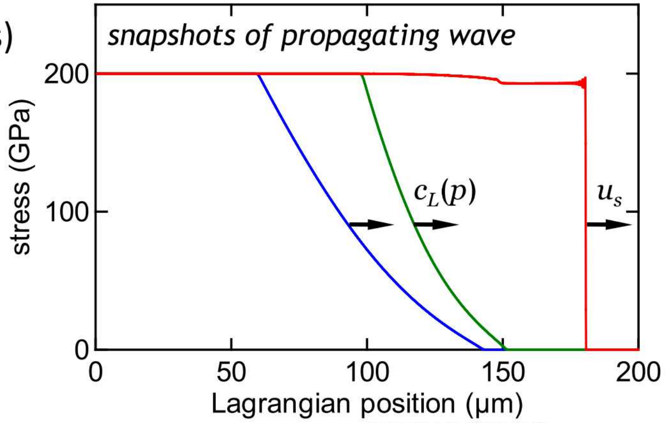
- current pulse of 7-26 MA delivered to load
- controllable pulse shape, rise time 100-1500 ns
- stripline = parallel flat-plate electrodes shorted at one end, identical loading of sample pairs
- magnetic ($J \times B$) force induces ramped stress wave in electrode material
- stress wave propagates into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

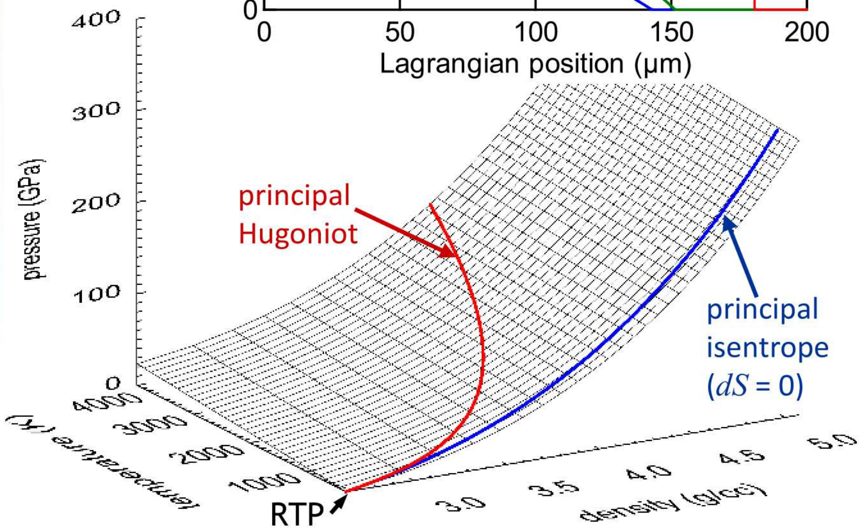
- sound speed c increases with pressure (normal materials)
- ramp steepens into a shock

$$c^2 = (\partial P / \partial \rho)_s$$

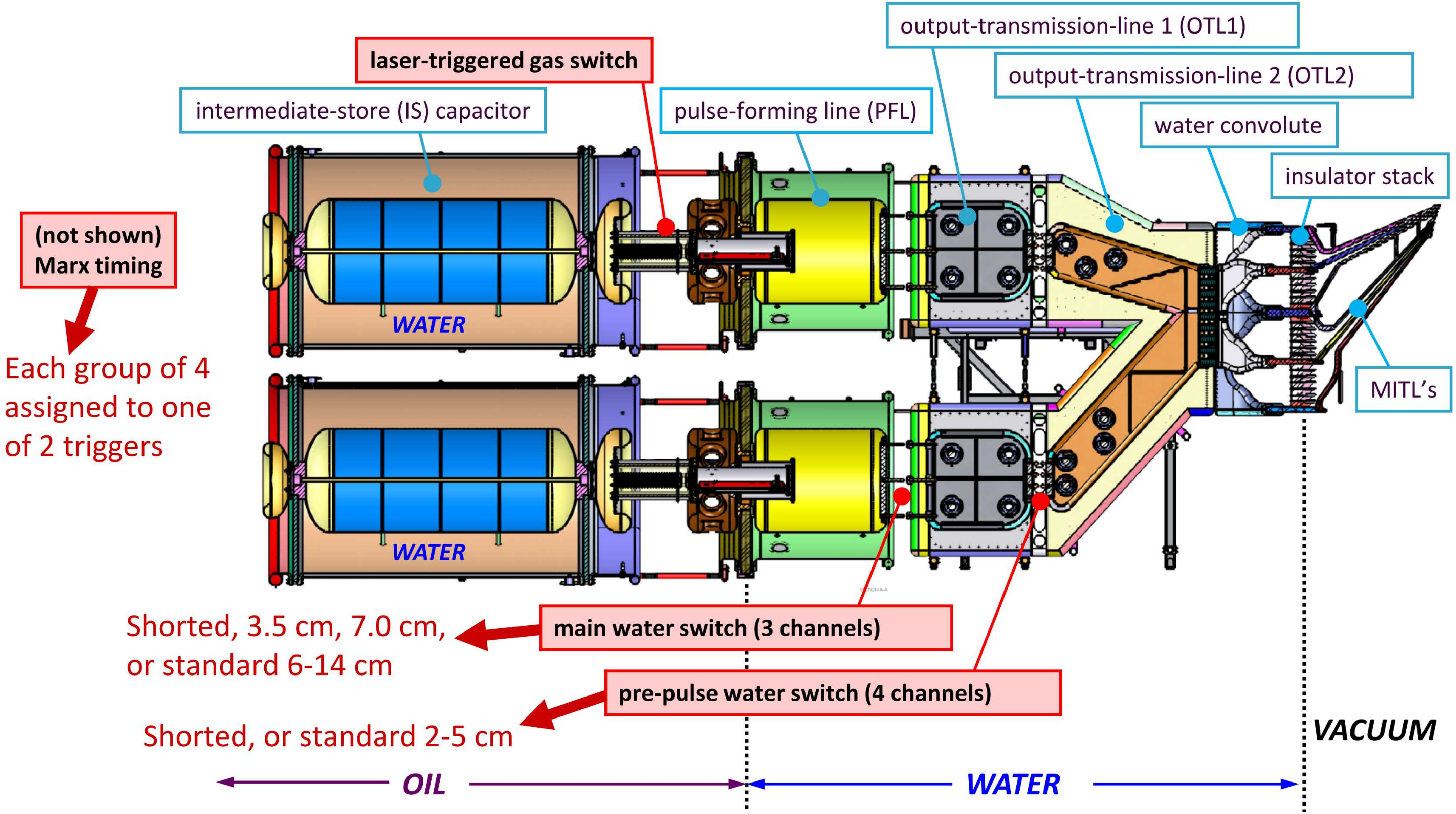
$$c_L = \rho c / \rho_0$$







Switch settings on 36 pulse lines control the pulse shape

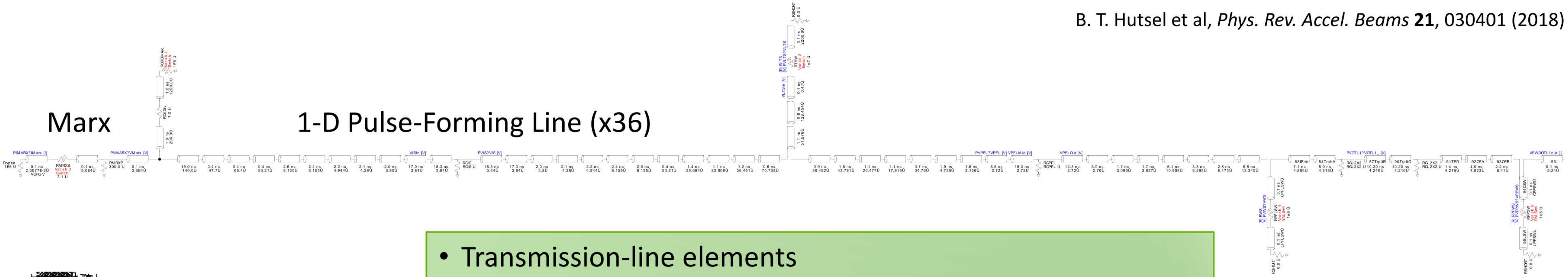


Transmission-line circuit model of Z used to determine desired machine settings

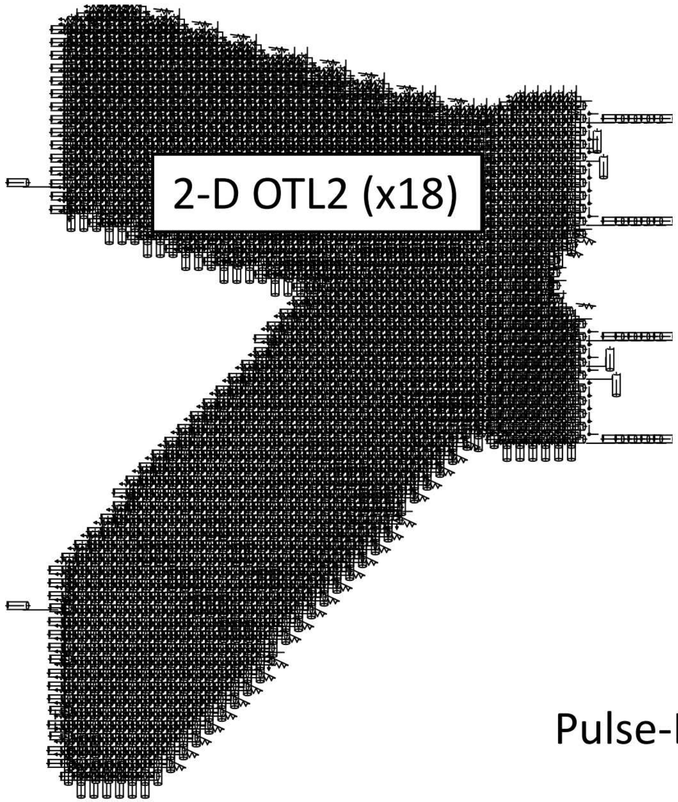
B. T. Hutsel et al, *Phys. Rev. Accel. Beams* **21**, 030401 (2018)

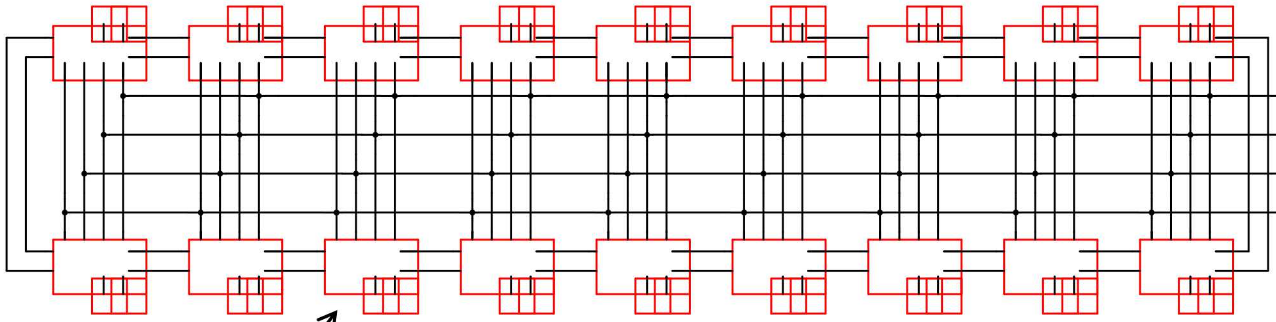
Marx

1-D Pulse-Forming Line (x36)



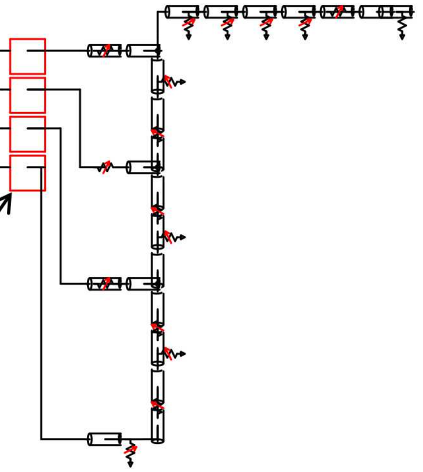
- Transmission-line elements
  - Defined by impedance Z, length (time) τ
  - Have capacitance $C = \tau / Z$, inductance $L = \tau Z$
- Specialized routines for switches, losses, time-dependent L





Pulse-Line Pair (x18)

Load

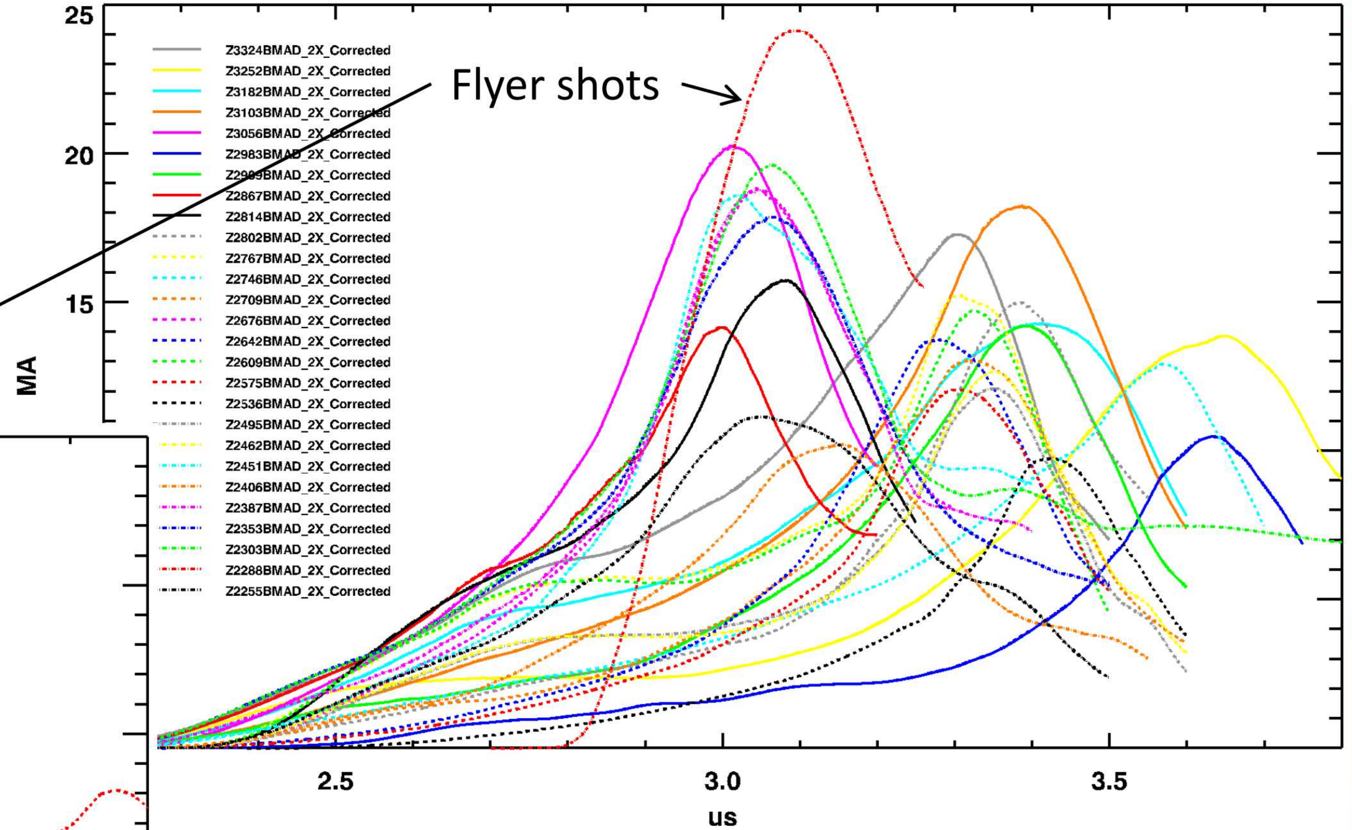


1-D MITL (x4)

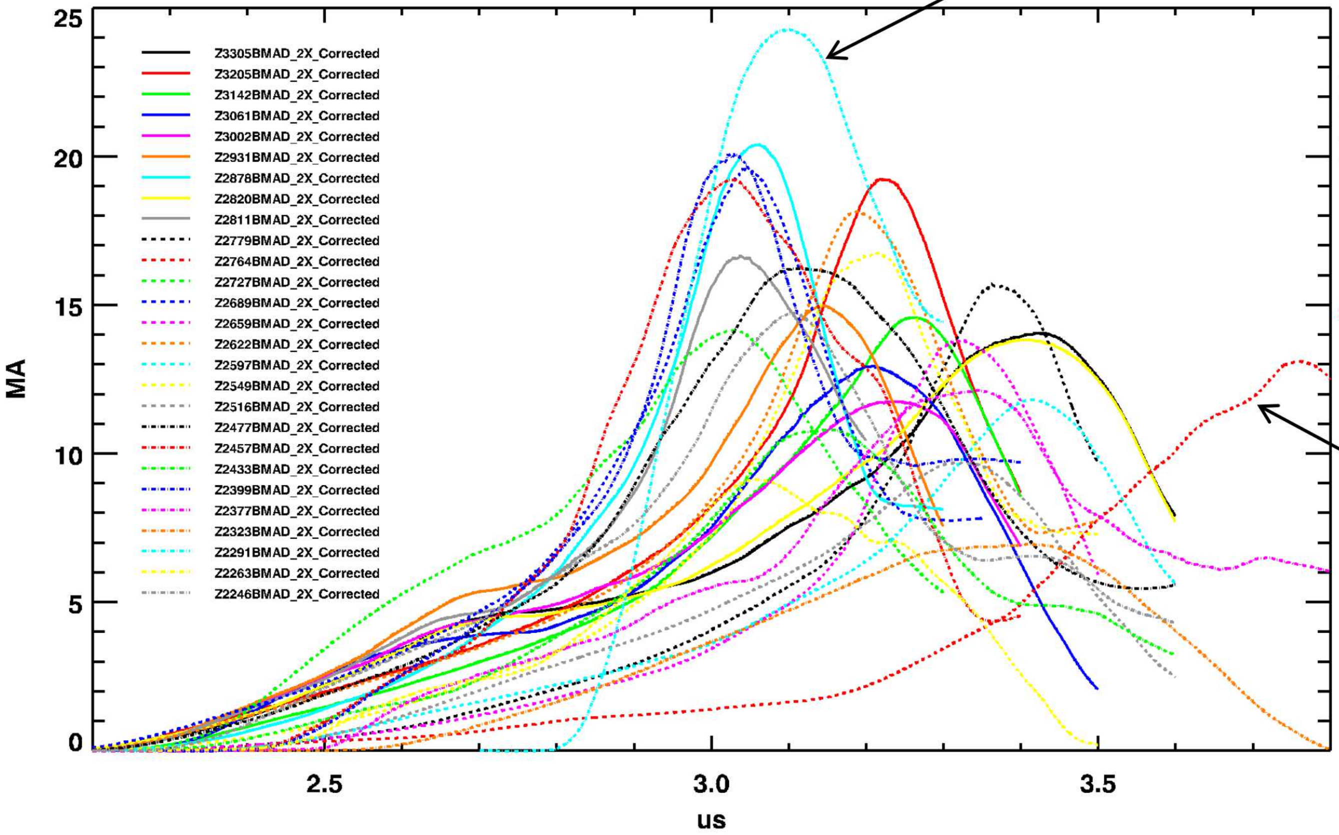
Z can produce a wide range of pulse shapes

Showing 54 of 190 measured MITL-current waveforms found on my computer

“Corrected” = reconstructed to account for missing monitors



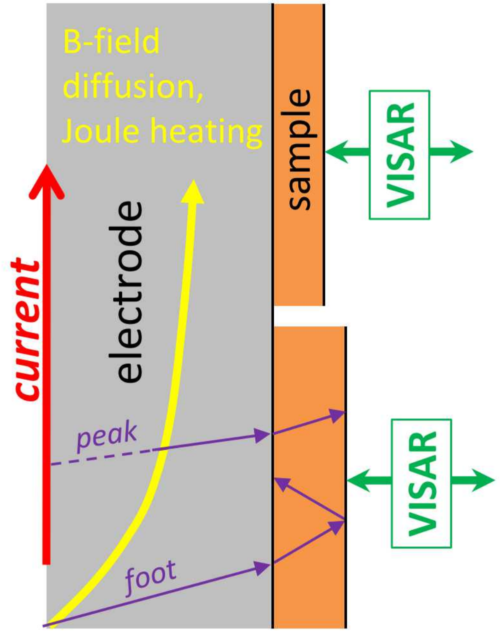
Flyer shots



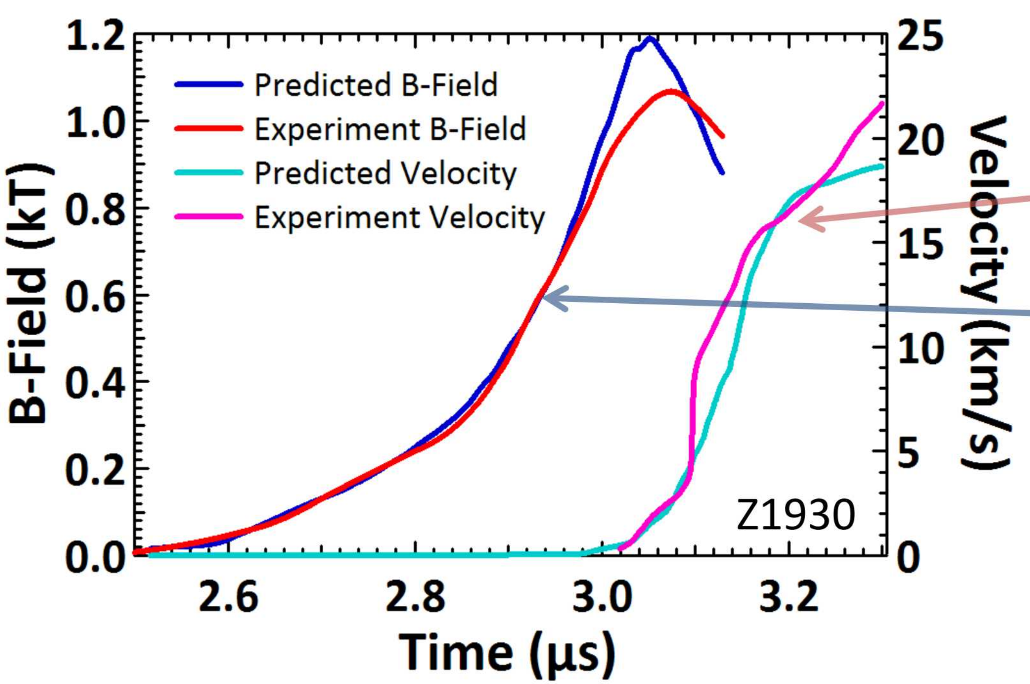
Rise time ***too*** long, failed

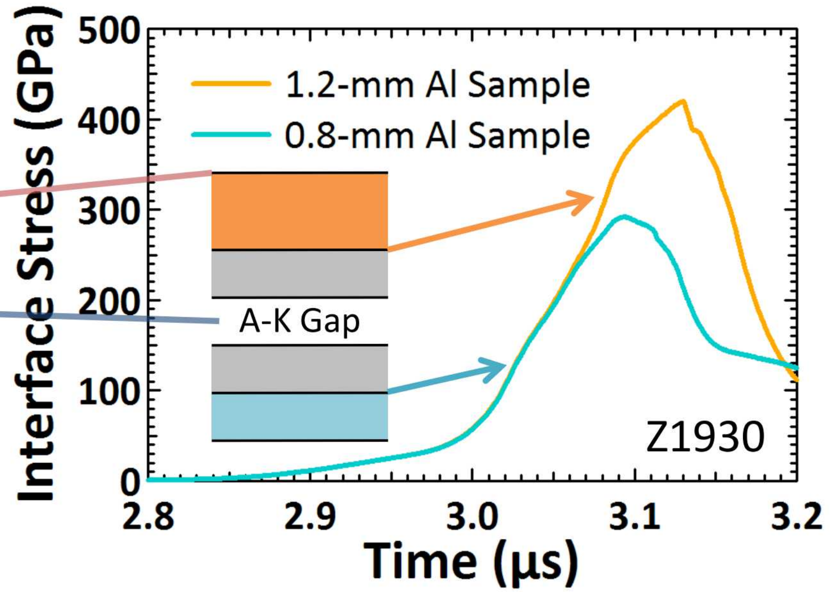
Sample thickness constrained by reverberation and pulse shaping

- uncertainty in $c_L = \Delta X / \Delta t$ 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

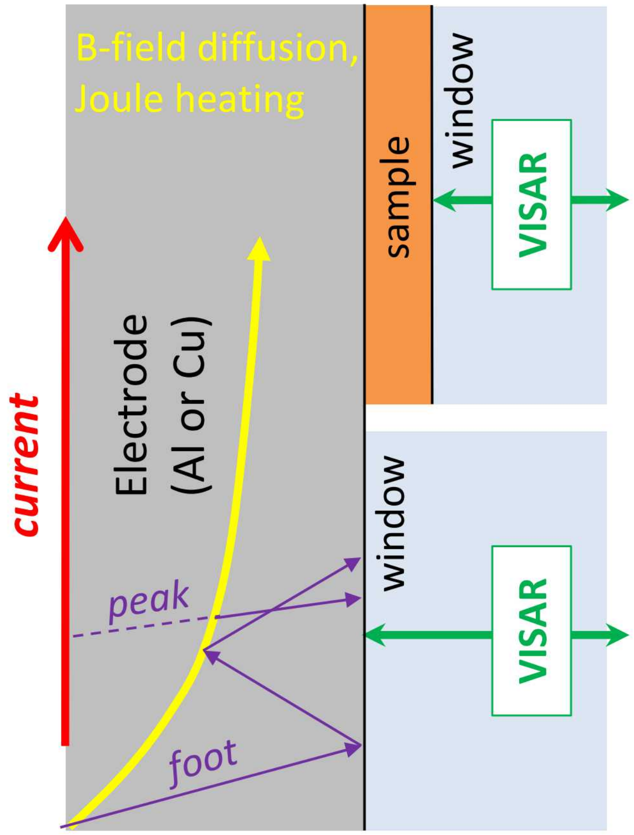


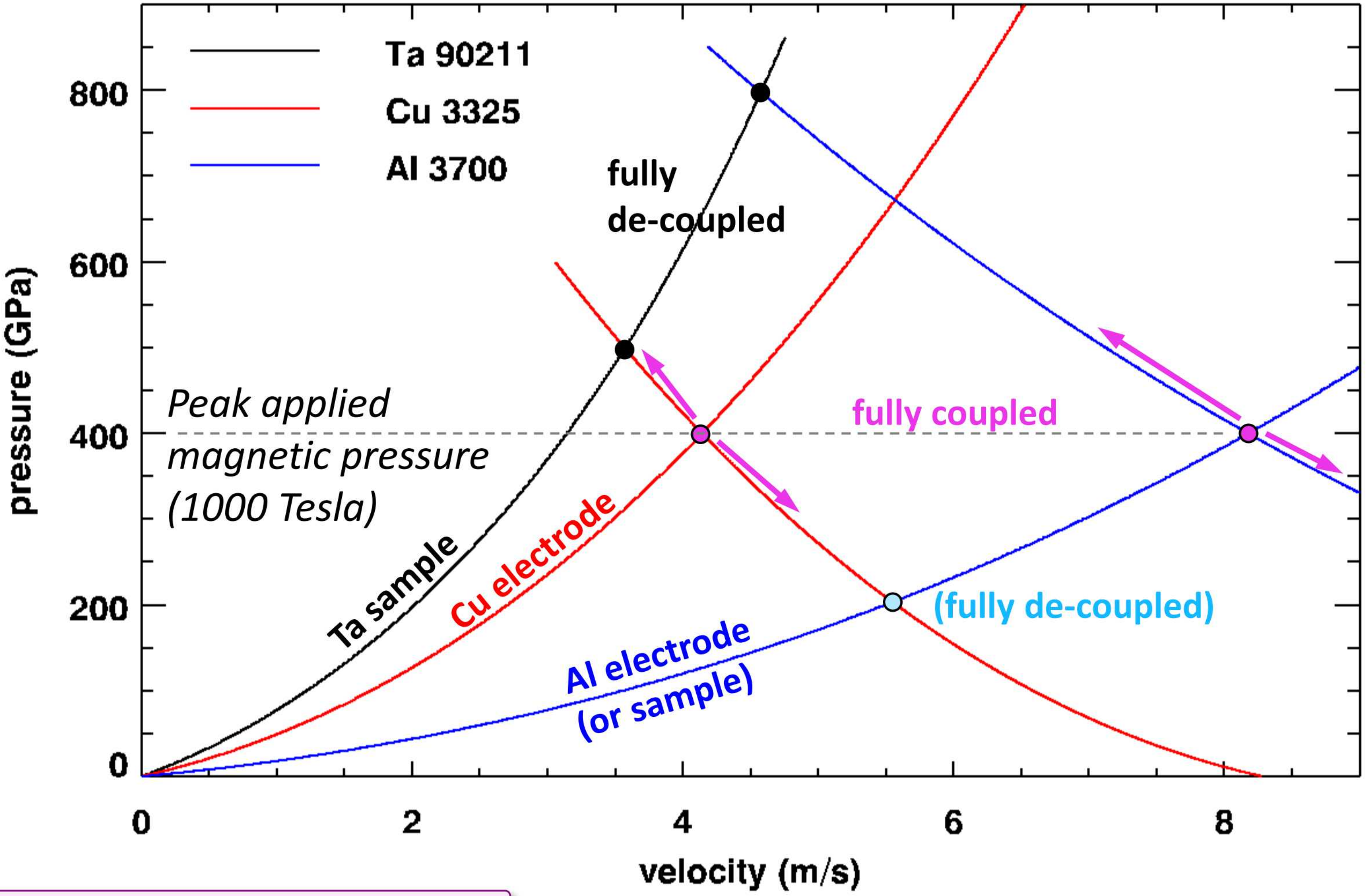
Narrow (highest pressure) stripline is ~11 mm wide, samples 6-8 mm wide: edge waves & pulse shape constrain maximum thickness





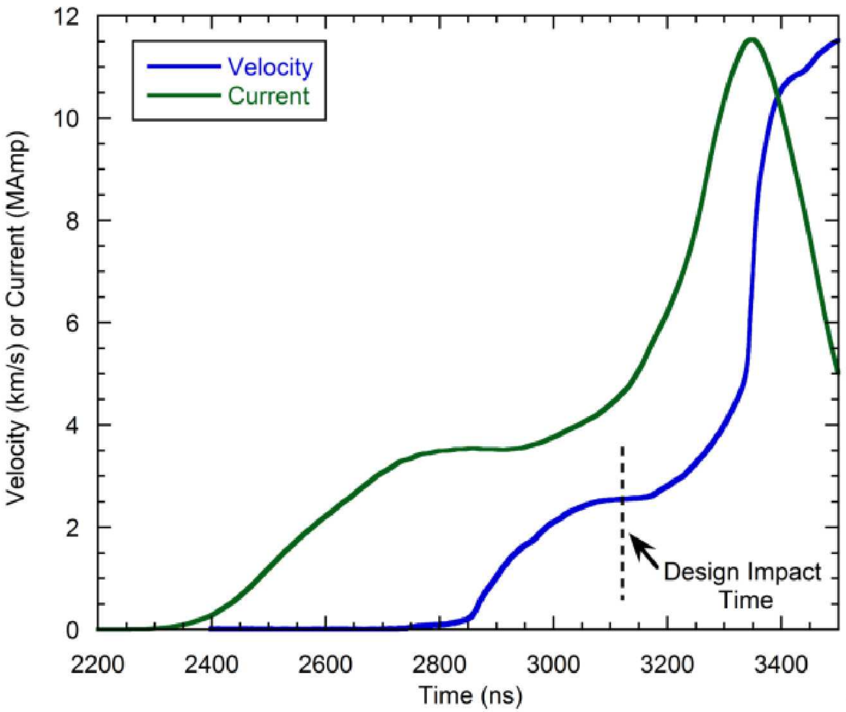
Electrode thickness constrained by desired MHD coupling (reverberation inside the electrode)

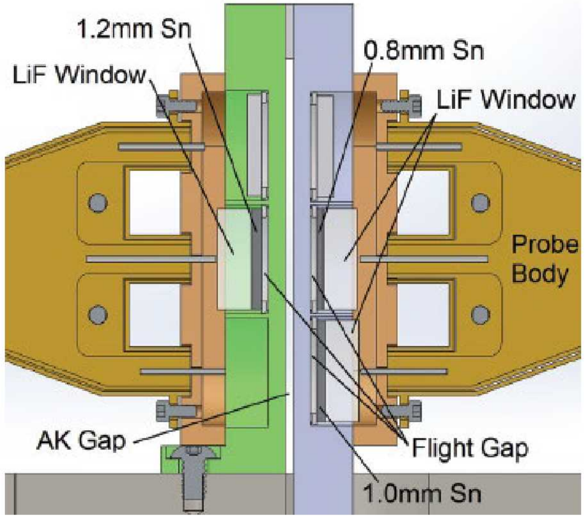


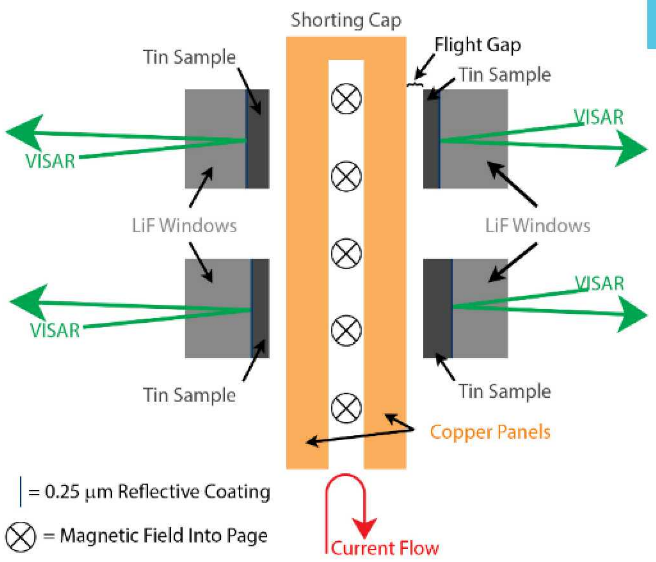


- **minimum thickness** to avoid “burn-through” of B-field to sample
- **maximum thickness** to decouple MHD, ramp-load sample

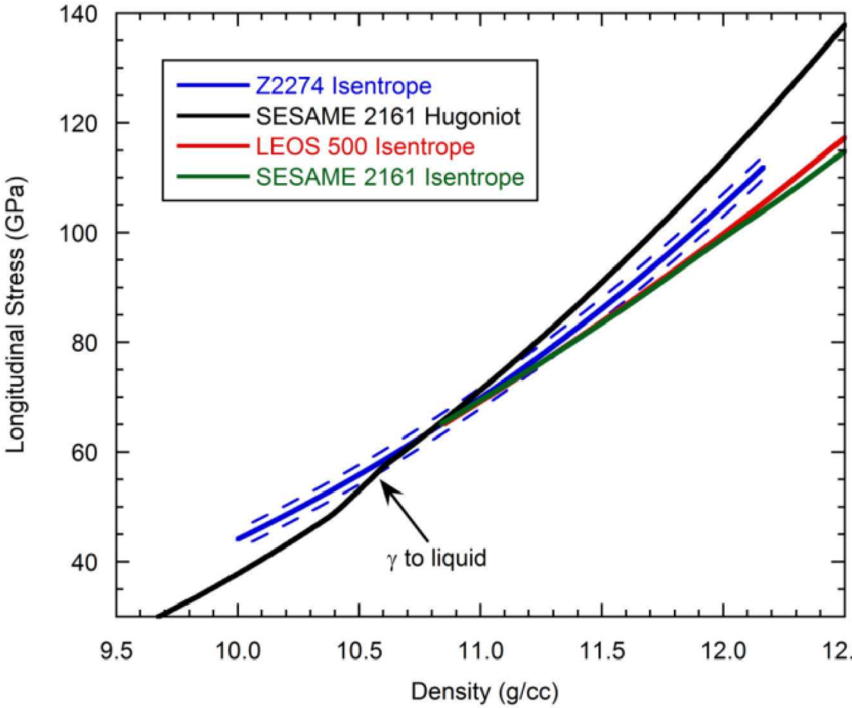
Shock-ramp loading: double-ramp pulse shape "holds" a Hugoniot state in the sample before ramping

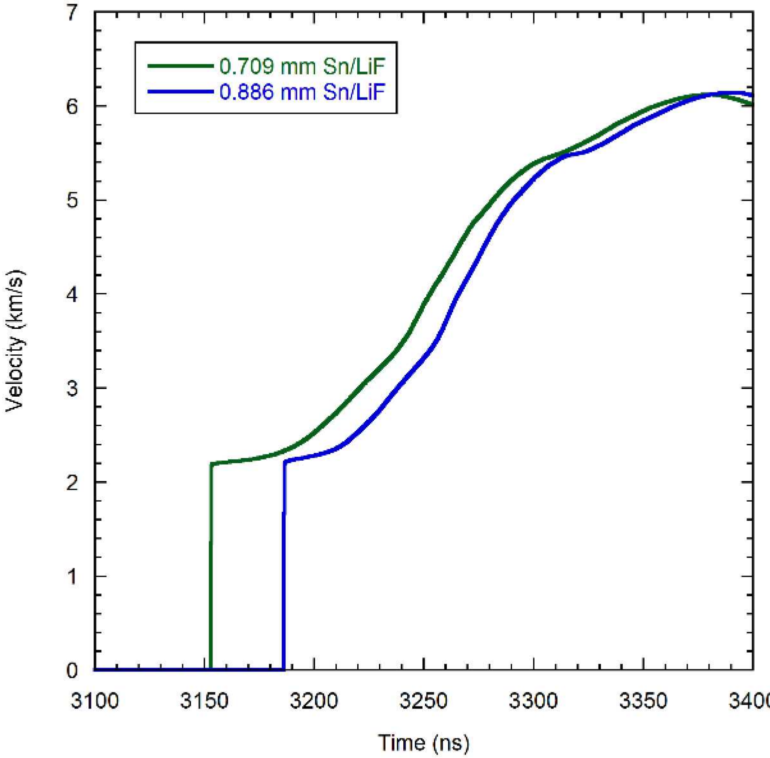






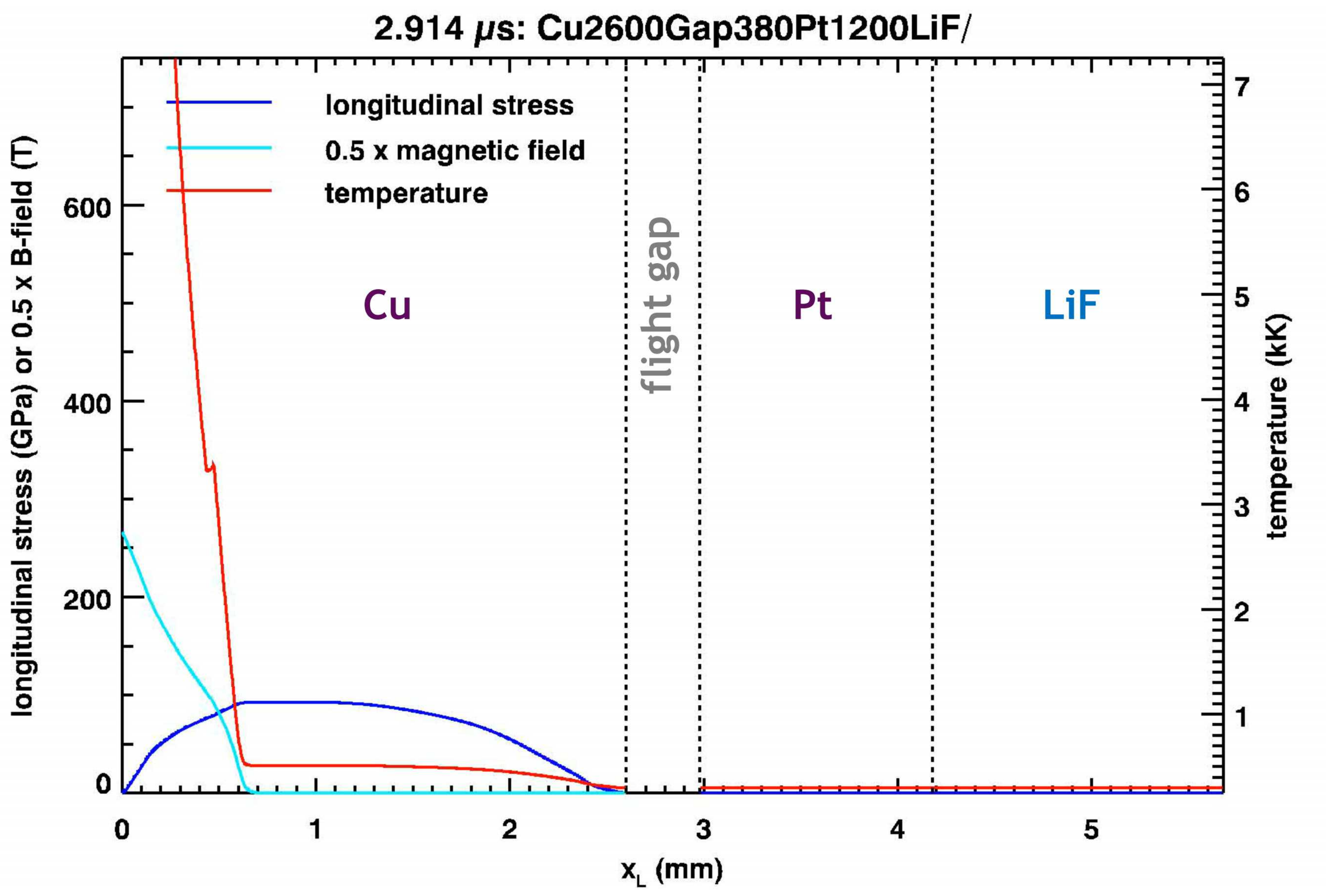
- Small flight gap causes shock, then ramp in sample
- Analysis assumes shock state is known
- Tin shocked to liquid phase (?), then isentropically compressed



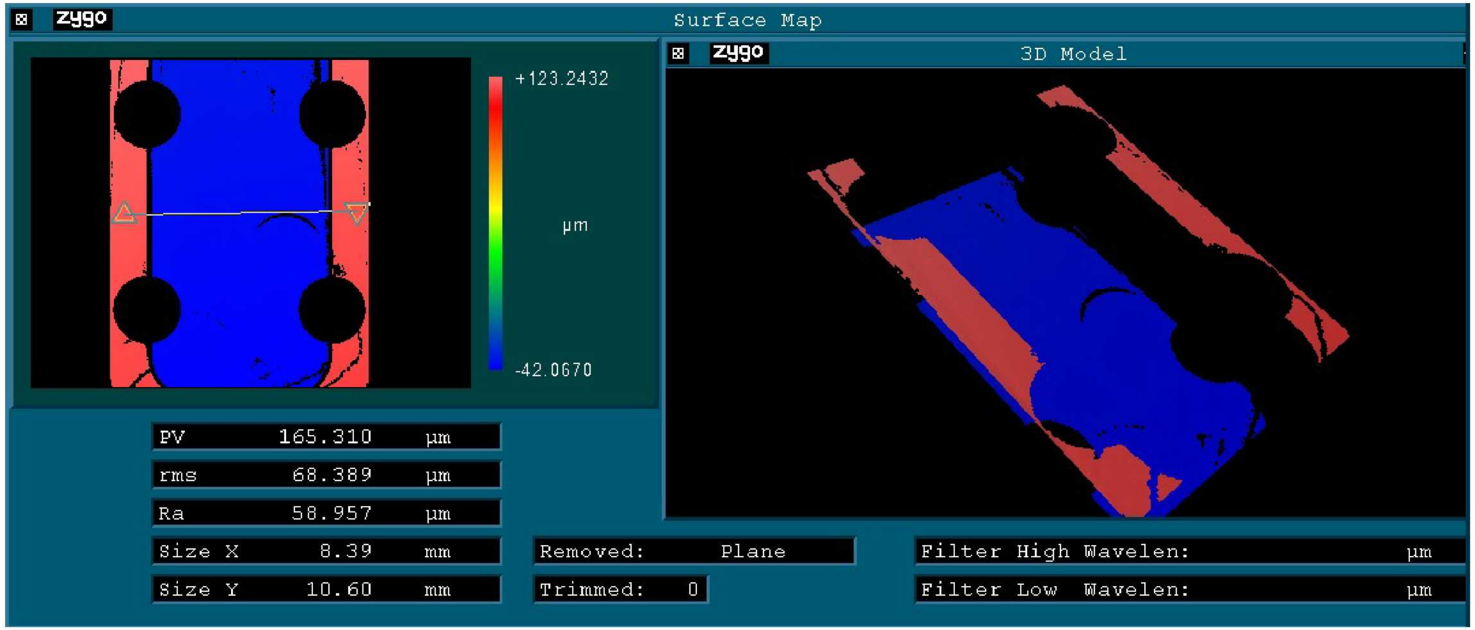


C. T. Seagle et al, *Appl. Phys. Let.* **102**, 244104 (2013)

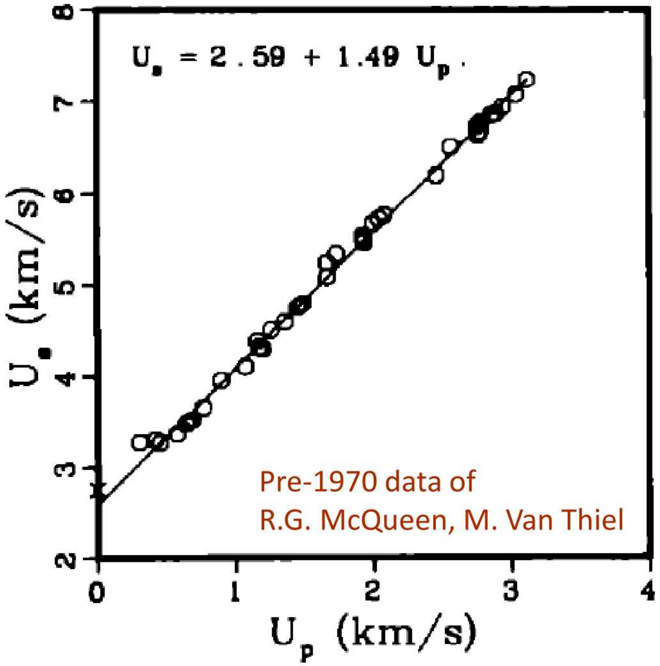
Reverberation across sample and MHD coupling across electrode can be even more important in shock-ramp design



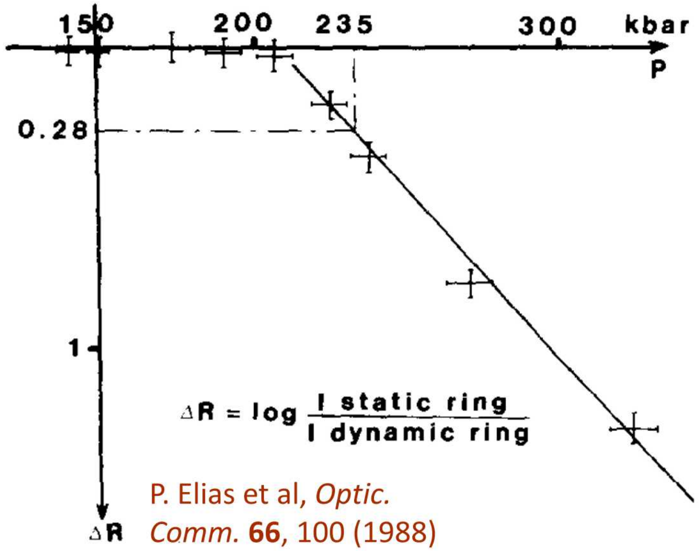
Precise, uniform, repeatable shock-ramp flight gap obtained by diamond-tool milling the electrode panel itself



Existing data on Sn: shock

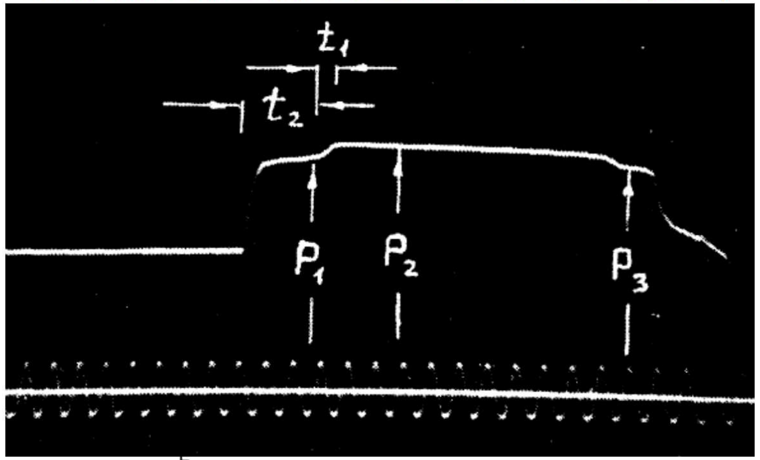


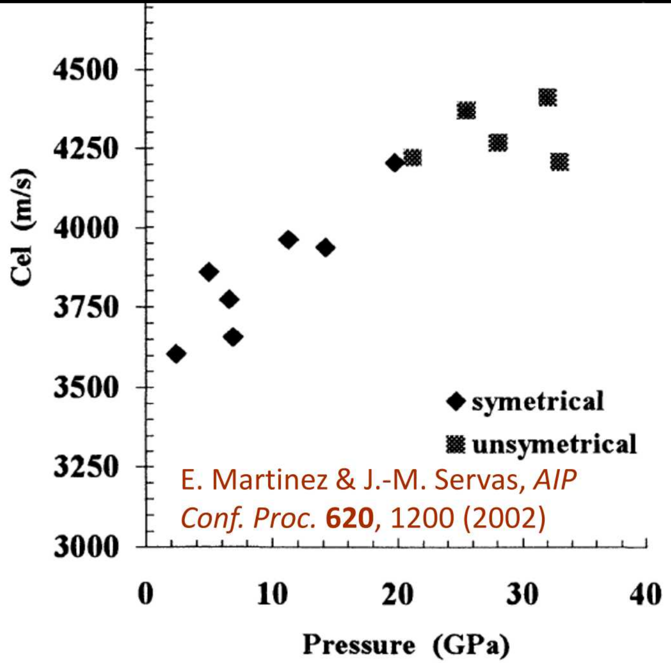
Pre-1970 data of
R.G. McQueen, M. Van Thiel



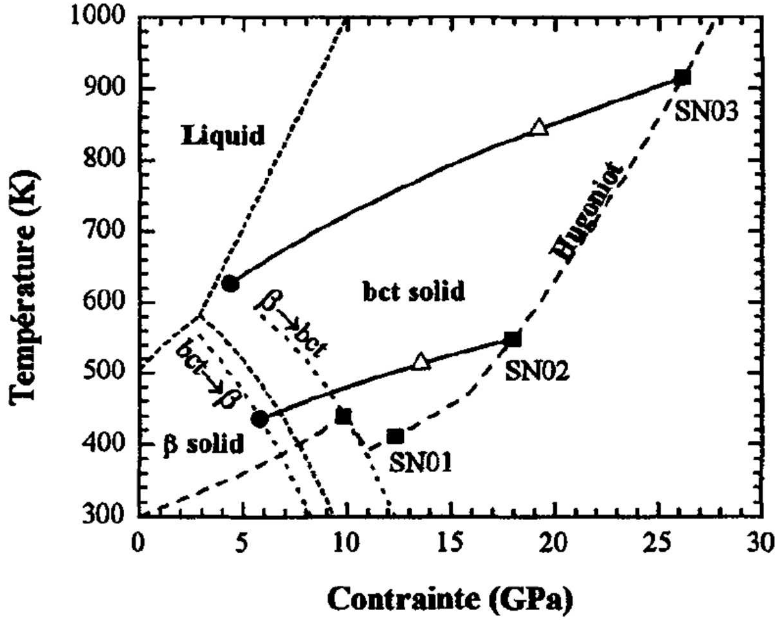
P. Elias et al, *Optic. Comm.* **66**, 100 (1988)

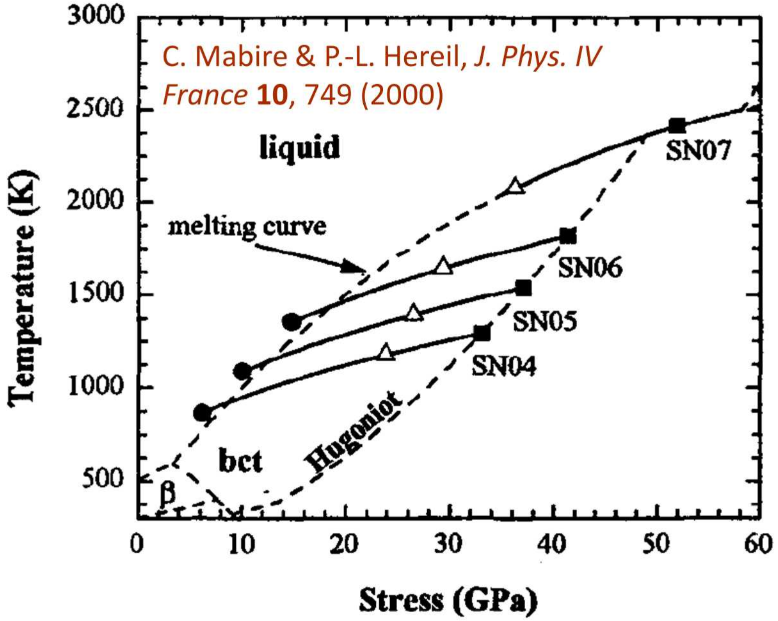
M.N. Pavlovskii & V.V. Komissarov, *JETP* **71**, 981 (1990)





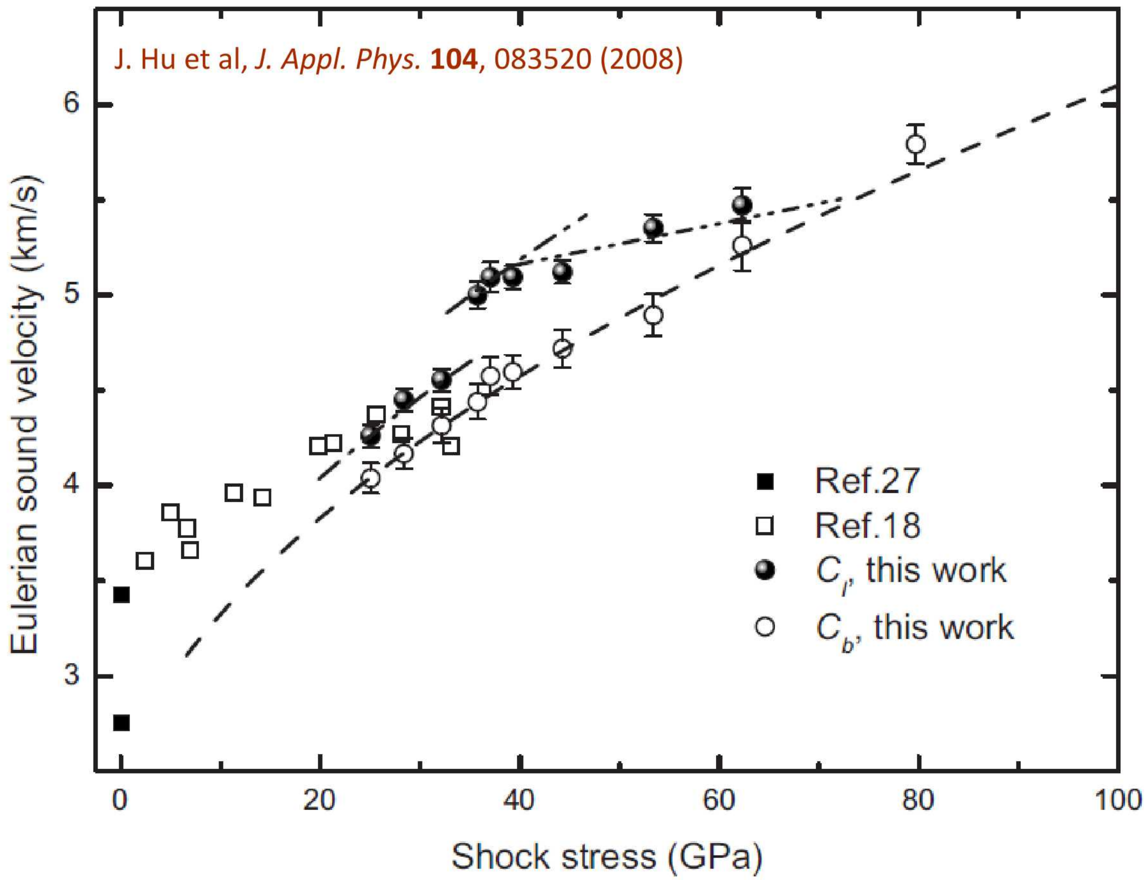
E. Martinez & J.-M. Servas, *AIP Conf. Proc.* **620**, 1200 (2002)

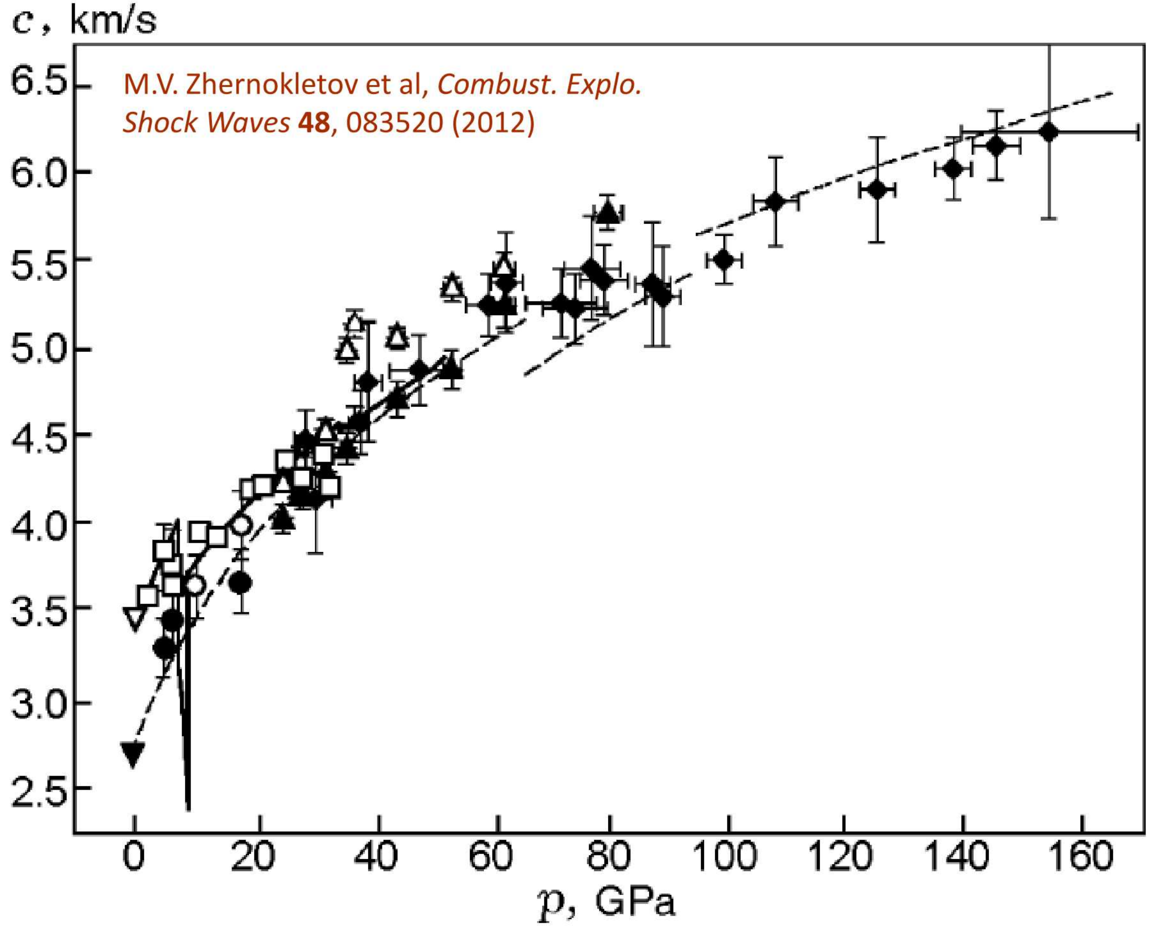




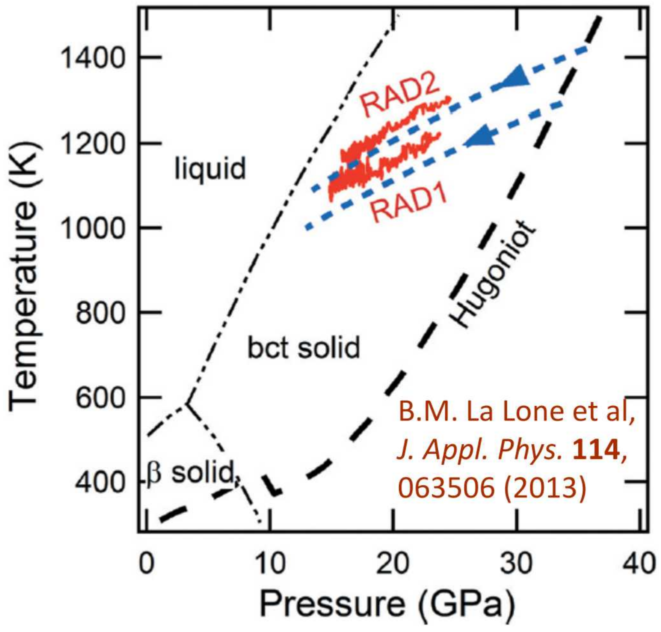
C. Mabire & P.-L. Hereil, *J. Phys. IV France* **10**, 749 (2000)

Existing data on Sn: more shock

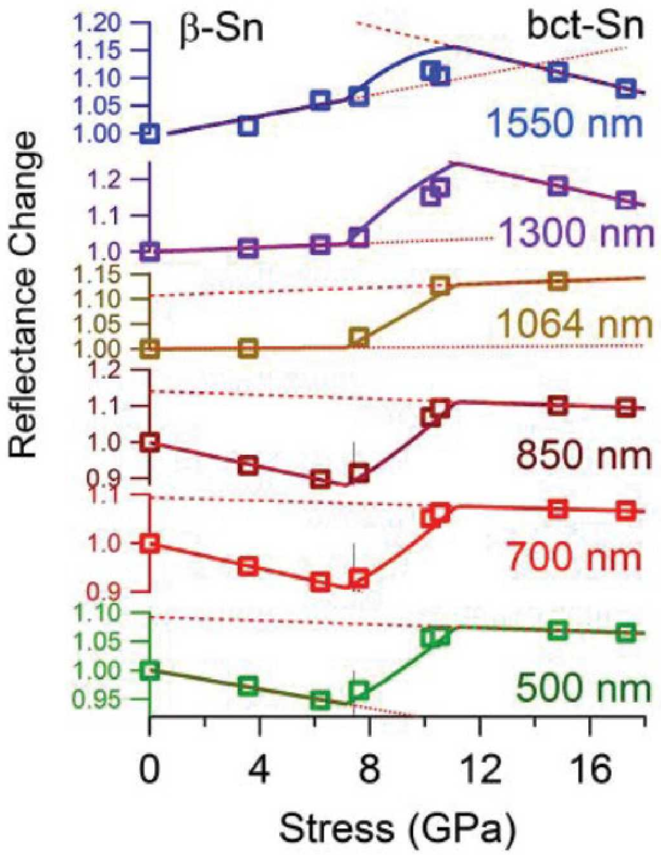




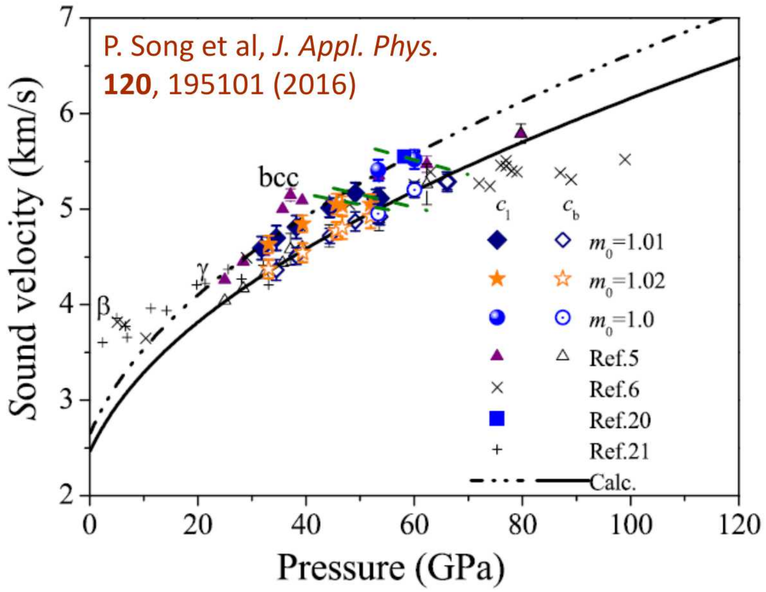
Existing data on Sn: even more shock



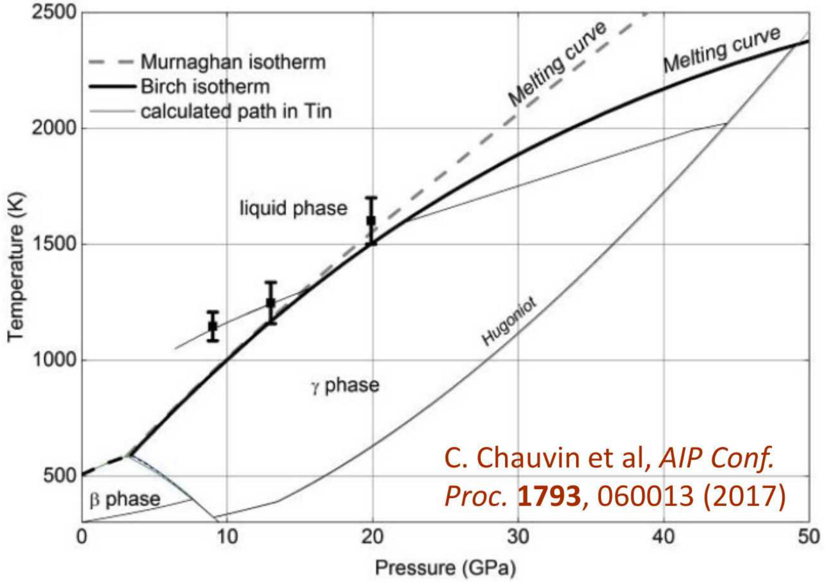
B.M. La Lone et al, *J. Appl. Phys.* **114**, 063506 (2013)



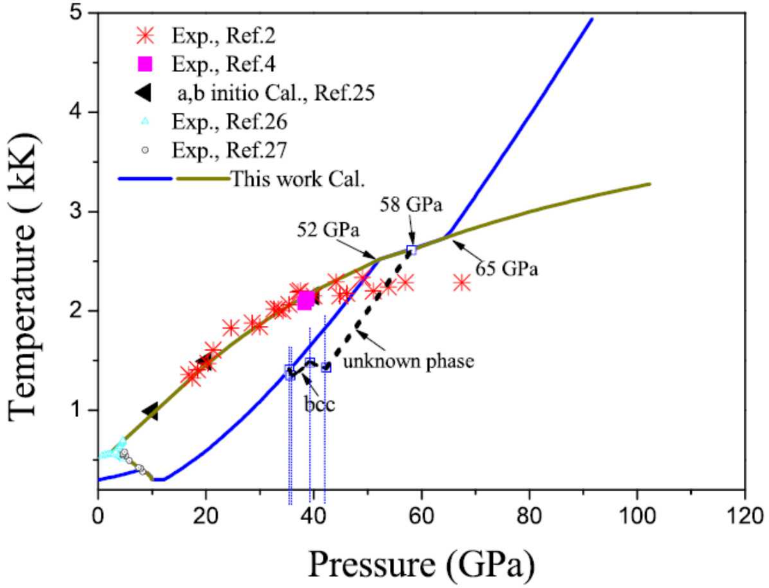
G.D. Stevens et al, *AIP Conf. Proc.* **1793**, 130002 (2017)



P. Song et al, *J. Appl. Phys.* **120**, 195101 (2016)

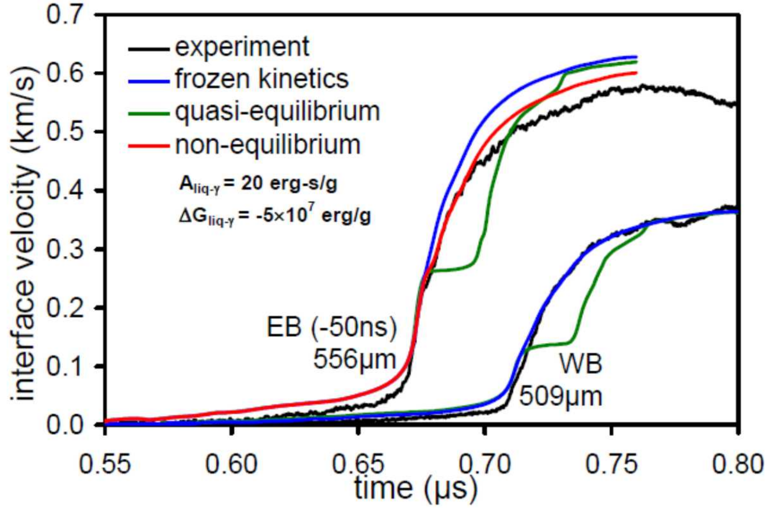


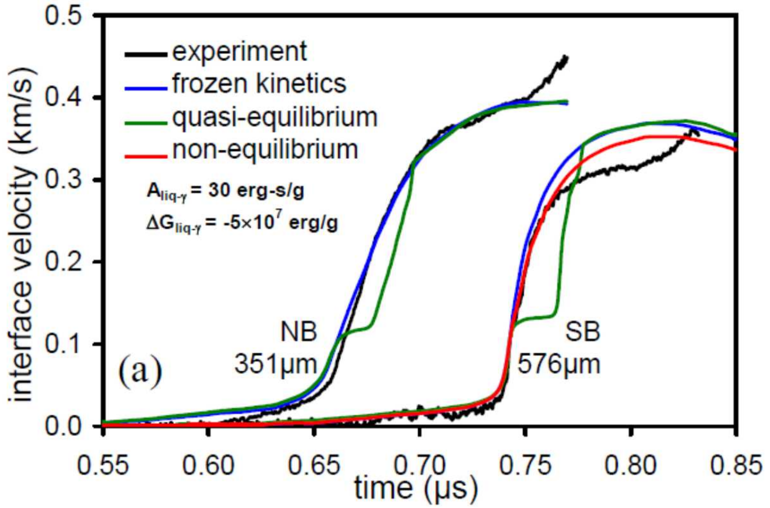
C. Chauvin et al, *AIP Conf. Proc.* **1793**, 060013 (2017)

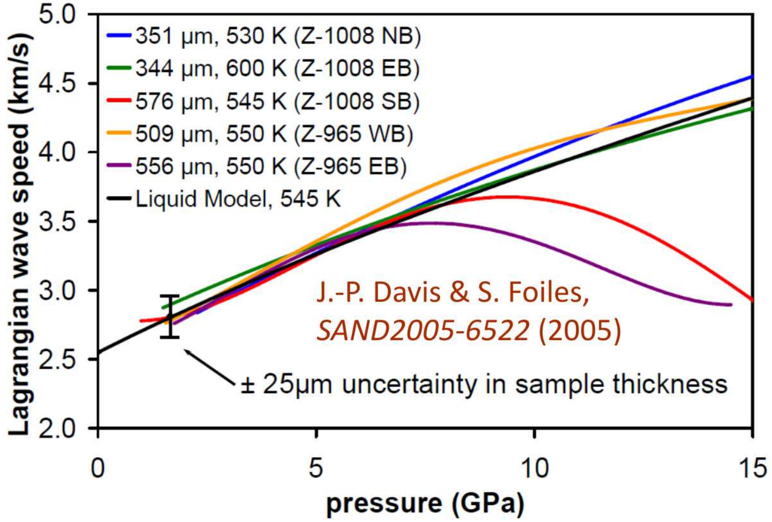


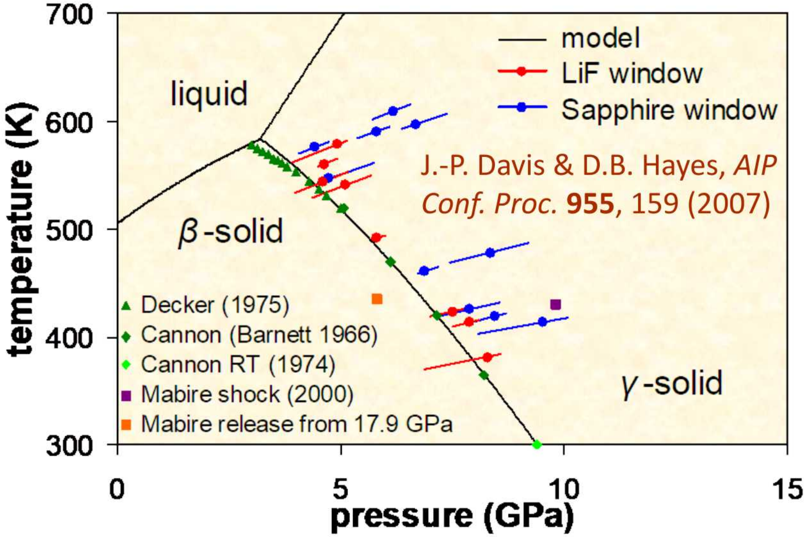
Existing data on Sn: ramp (including pre-heat) and shock-ramp

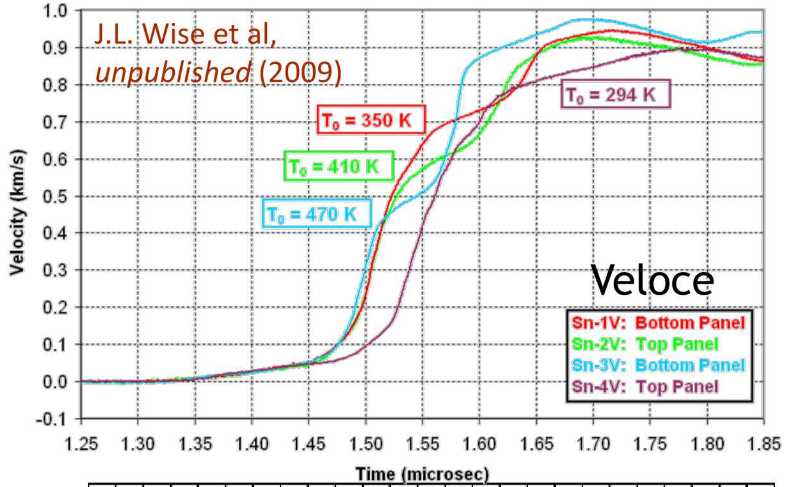
J.-P. Davis & D.B. Hayes, *AIP Conf. Proc.* **706**, 163 (2004)

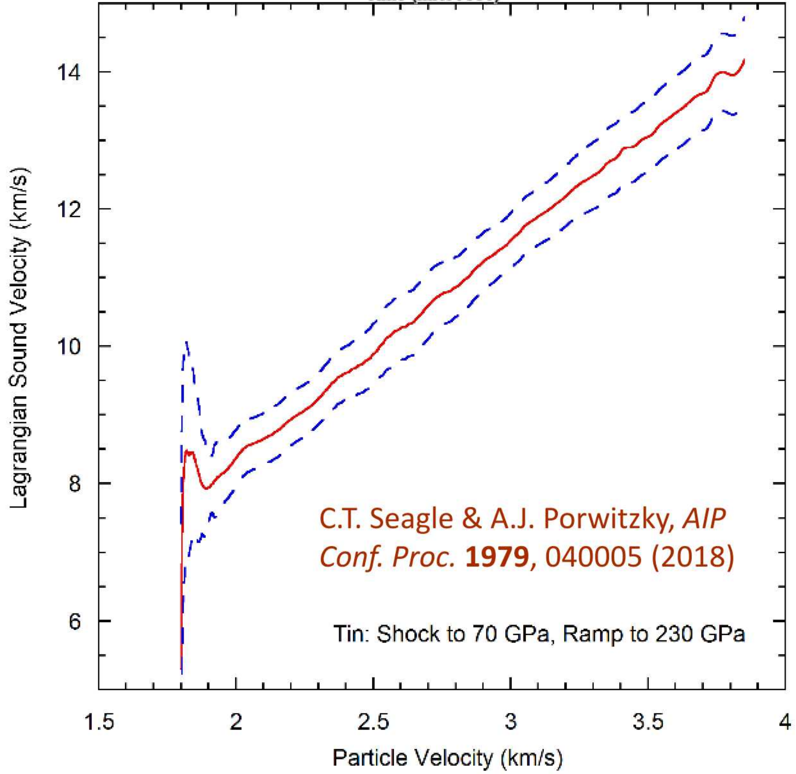






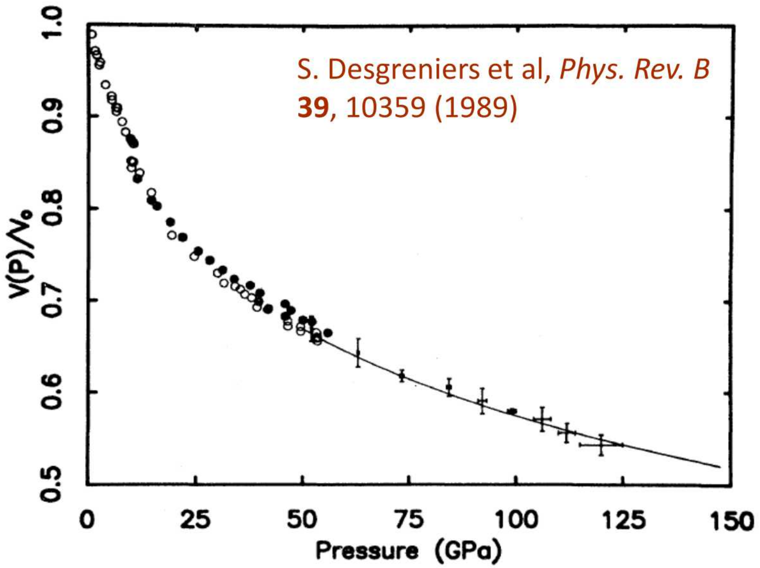




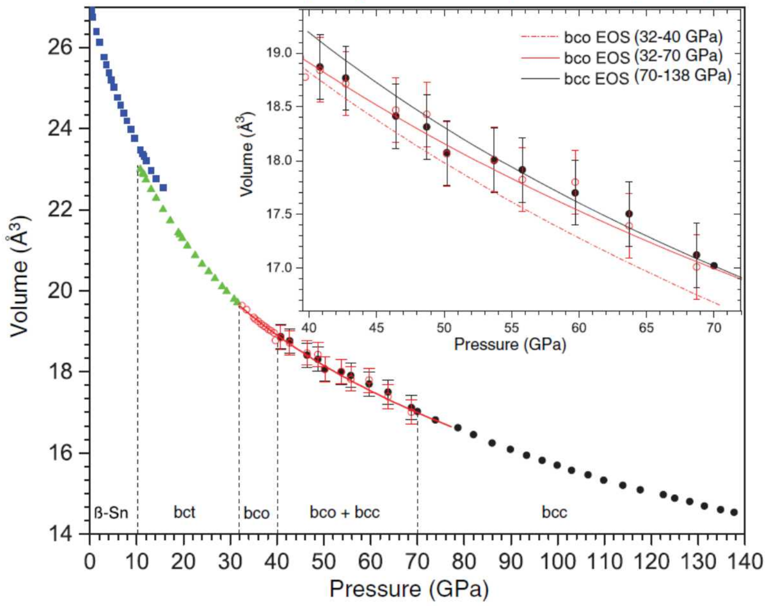


Existing data on Sn: static and dynamic XRD

S. Desgreniers et al, *Phys. Rev. B* **39**, 10359 (1989)

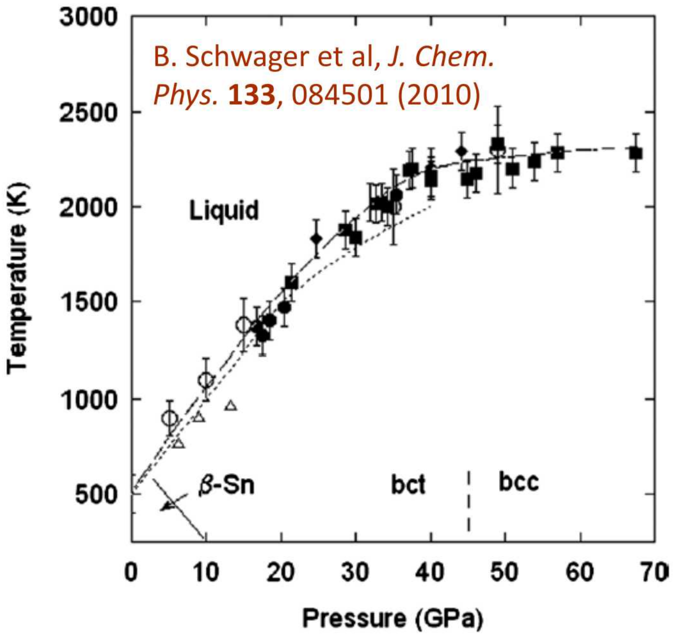


A. Salamat et al, *Phys. Rev B* **88**, 104104 (2013)

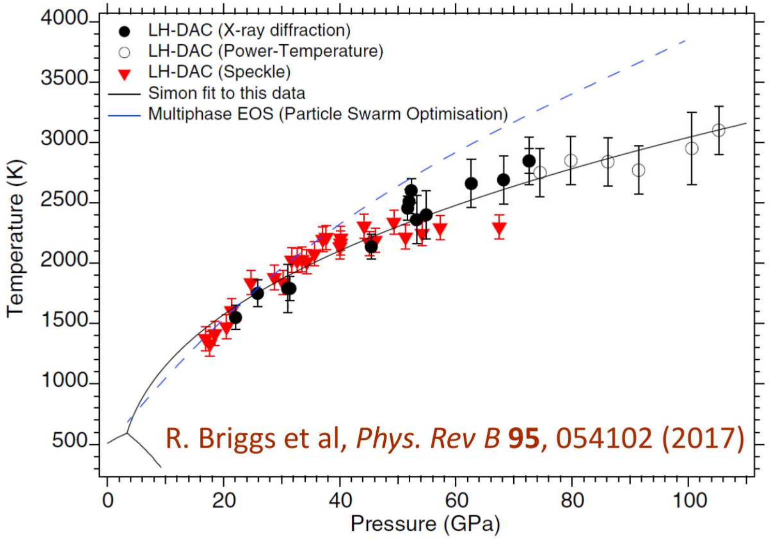


Older data not shown: Liu (1986), Kingon (1980), Barnett (1966)

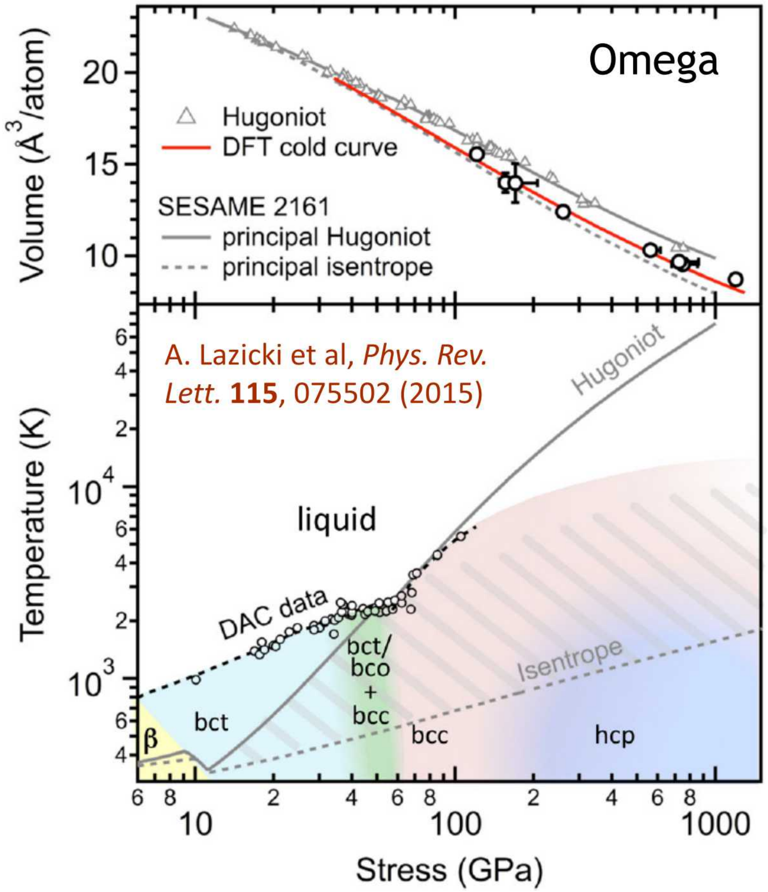
B. Schwager et al, *J. Chem. Phys.* **133**, 084501 (2010)



R. Briggs et al, *Phys Rev B* **95**, 054102 (2017)



A. Lazicki et al, *Phys. Rev. Lett.* **115**, 075502 (2015)



LASLO (Lagrangian Analysis and Simulation of Loading in One dimension) is a 1-D research hydro-code for experiment design/analysis

Originally developed c2010 in C++ by Josh Robbins, now maintained by John Carpenter

Replaces venerable WONDY code that was written in pre-77 Fortran (!)

Major goal is ease of development/implementation of material models, physics, etc.

Generalized 1-D: velocity, stress, etc. are 3-D but vary only in one direction

Includes 1-D MHD physics for simulation of magnetic loading, electromechanics for PZT

Features:

- Central-differencing time integration, will soon have more accurate predictor multi-corrector
- Many options for non-uniform element spacing
- Non-uniform initial conditions, graded-property materials
- Initial gaps between Lagrangian mesh blocks close naturally (e.g., for shock-ramp)
- Choice of tracking isotropic or anisotropic stress state (two versions of many strength models)
- New material models or derived variables can be written in Python, used without re-compiling Laslo
- Relatively simple to integrate new and existing models written in Fortran or C++

Does **NOT** (yet) include thermal conduction, spall/fracture, non-cartesian coordinates

The list of material models available in Laslo is extensive and growing

Equations of State
- Ideal Gas
- Mie-Gruneisen (U_s-U_p, power-law, arbitrary)
- Extended Vinet
- Tabular (Sesame, UTri)
- piezo- & ferro-ceramics
- Hayes' Wondy STAT5 multi-phase w/ kinetics

Plasticity
- Radial return
- Linear elastic
- Arbitrary (anisotropic) plastic
- Quasi-elastic (Johnson's pinned-loop model)

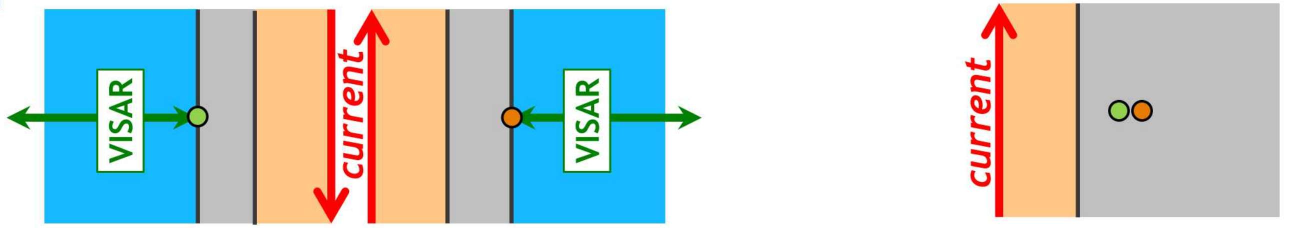
Electrical Conductivity
- Linear conductor
- Lee-More-Desjarlais
- Tabular (Sesame)

Strength (yield stress)
- Linear plastic, elastic-plastic
- Johnson-Cook
- Steinberg-Guinan-Lund
- Mechanical Threshold Stress
- Preston-Tonks-Wallace

Meta-models
- Kinetics Phase Transition (Greeff kinetics)
- Reuss/Voigt mixtures
- P-lambda porosity

Python derived variable
- Apparent velocity through window

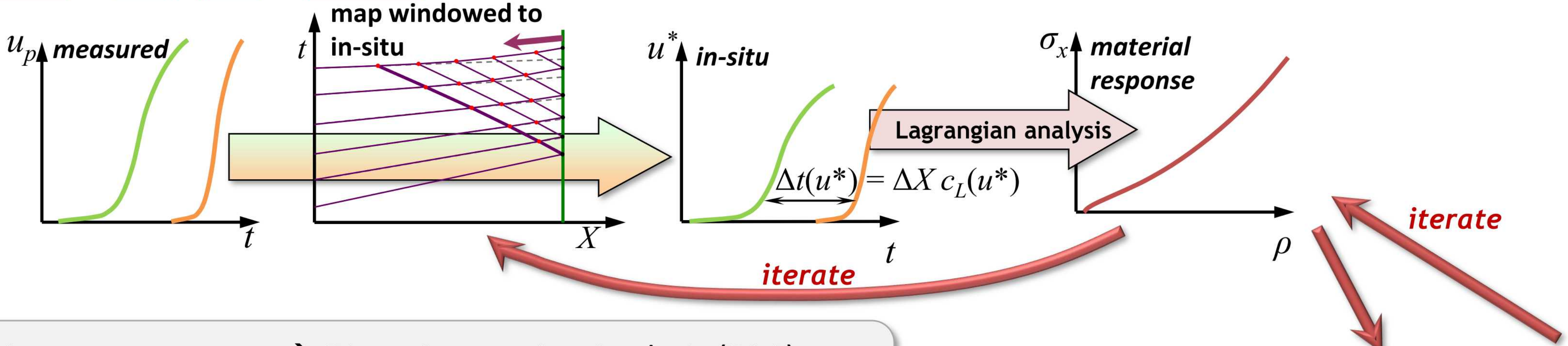
Lagrangian analysis can extract compressibility from velocimetry



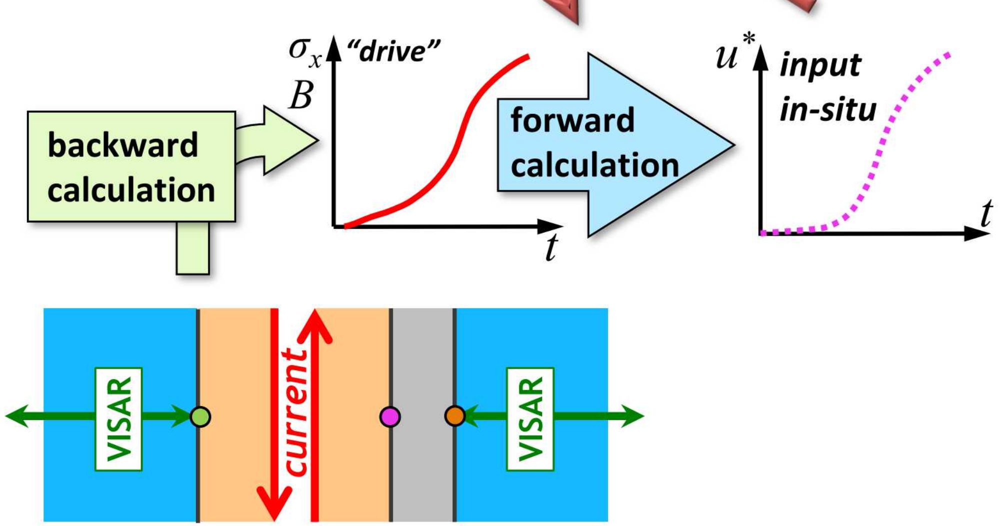
$$d\sigma_x = \rho_0 c_L du^*$$

$$\frac{d\rho}{\rho^2} = \frac{du^*}{\rho_0 c_L}$$

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



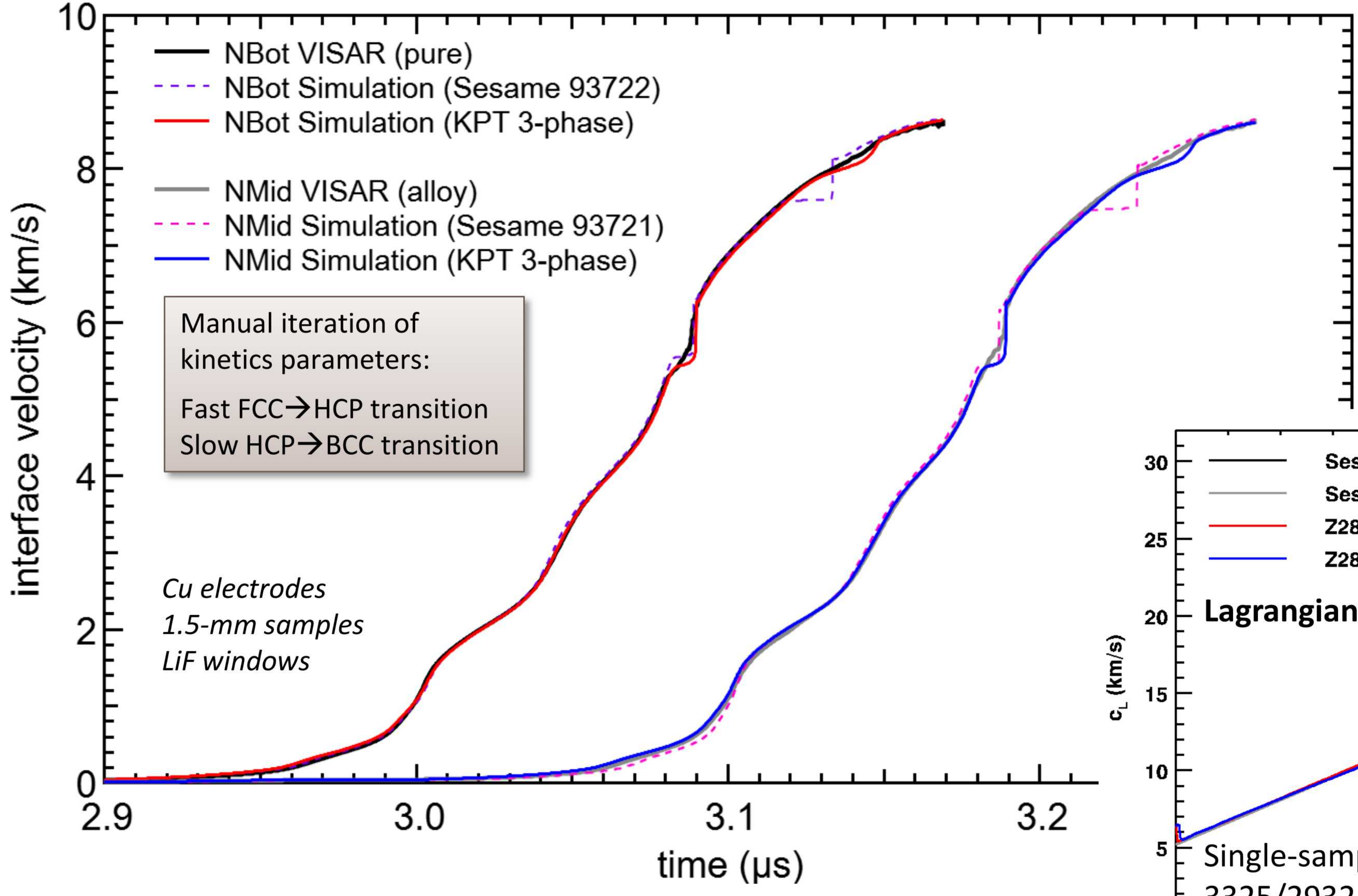
- in-situ measurements → Direct Lagrangian Analysis (DLA)
- real measurements are free-surface or window-interface
  - <u>**map measured *u*(*t*) into in-situ *u**(*t*)**</u>, then apply DLA
  - **shockless compression:** map by iterative characteristics technique[1]
    - referred to as Iterative Lagrangian Analysis (ILA)
  - **shock-ramp:** map by backward integration with minimization
    - *both of these assume single-valued material response*
    - *both encompass dual-sample and single-sample approaches*
  - **strength in release:** map by simulation-based transfer function[2]

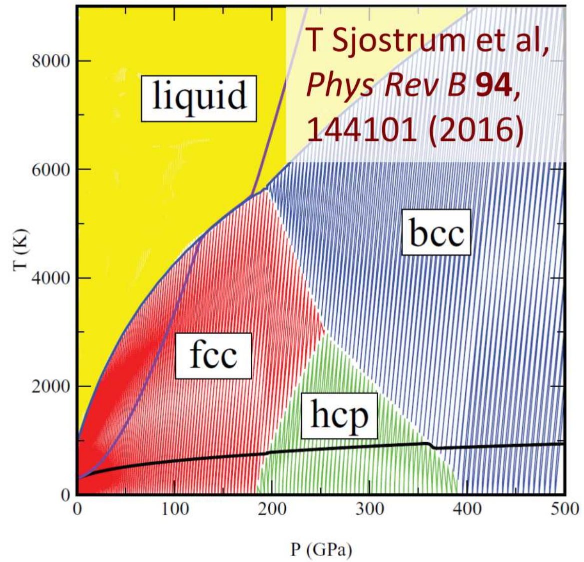


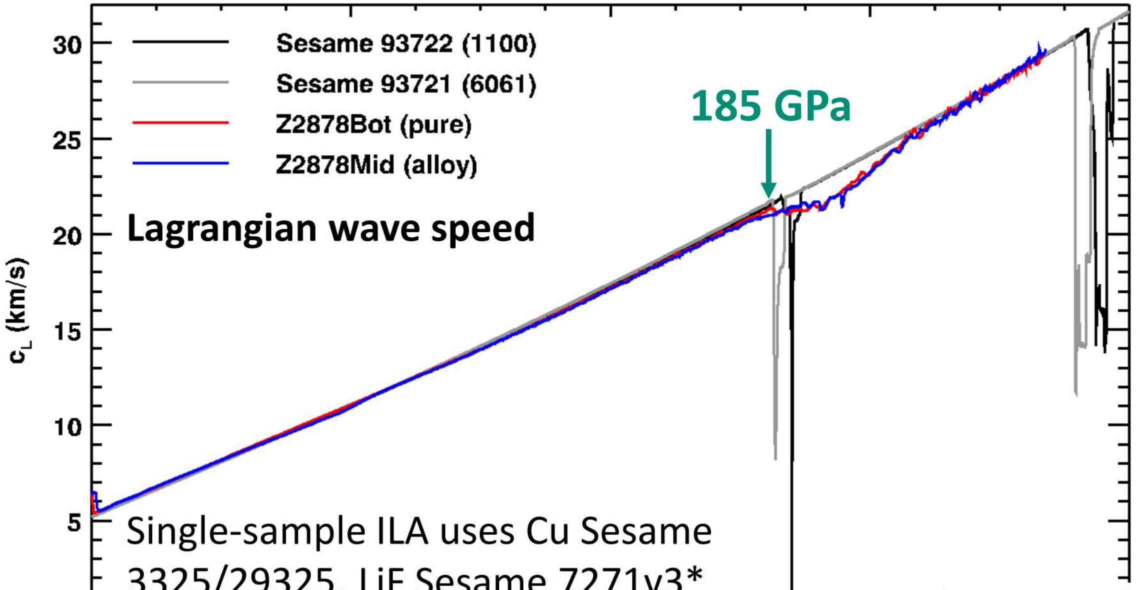
Single-sample approach

[1] *S. D. Rothman & J. Maw, J. Physique IV **134**, p745 (2006)*
[2] *J. L. Brown et al, J. Appl. Phys. **114**, 223518 (2013)*

Iterative Lagrangian analysis (ILA) can recover second-phase wave speed above fast transition of small volume change







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

More generally, when ILA converges post-transition, the apparent wave speed is not related to material sound speed