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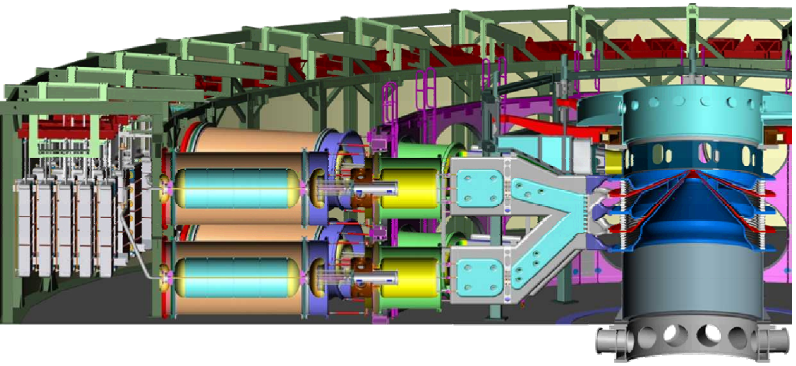

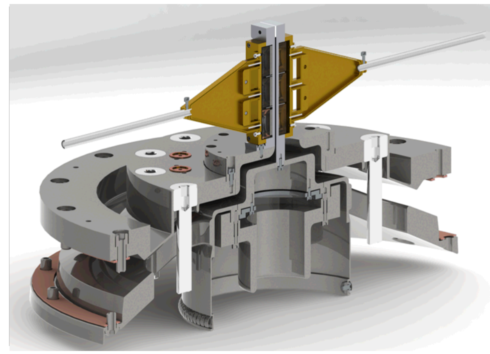

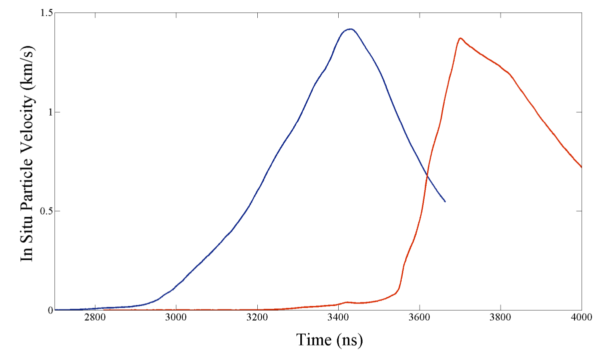

Extracting Strength from Ramp-Release Experiments on Z

Justin Brown

SCCM July 8, 2013

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Acknowledgments

Scott Alexander
Jim Asay
Tracy Vogler

Rate-Dependent Simulations

Jon Belof (LLNL)
Jow Ding (WSU)

MHD Discussions

Ray Lemke
Jean-Paul Davis

Beryllium Experiments

Marcus Knudson

Monte Carlo Methodology

Dan Dolan

Target Design

Dustin Romero
Devon Dalton

Diagnostics

Charlie Meyer

What is strength?

$$\bar{\sigma} = \begin{bmatrix} \sigma_x & \sigma_{xy} & \sigma_{xz} \\ \sigma_{xy} & \sigma_y & \sigma_{yz} \\ \sigma_{xz} & \sigma_{yz} & \sigma_z \end{bmatrix}$$

$$P = \sigma_{kk}/3$$

Pressure (EOS)

$$\bar{S} = \bar{\sigma} - P\bar{I}$$

stress deviator (strength)

- Can find an equivalent deviatoric stress using J2 / von Mises flow theory:

$$\sigma_Y = \sqrt{3/2\, S_{ij} S_{ij}}$$

$$\sigma_Y \le Y\left(\bar{\sigma}, \bar{\varepsilon}, \dot{\bar{\varepsilon}}, T, \xi\right) \longrightarrow \text{Elastic}$$

$$\sigma_Y > Y\left(\bar{\sigma}, \bar{\varepsilon}, \dot{\bar{\varepsilon}}, T, \xi\right) \longrightarrow \text{Plastic, } \sigma_y = Y$$

Uniaxial strain mechanics

$$\bar{\varepsilon} = \begin{bmatrix} \varepsilon_x & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \Rightarrow \bar{\sigma} = \begin{bmatrix} \sigma_x & 0 & 0 \\ 0 & \sigma_y & 0 \\ 0 & 0 & \sigma_y \end{bmatrix}$$

$$P = \frac{\sigma_x + 2\sigma_y}{3}$$

$$\bar{S} = \begin{bmatrix} \frac{2}{3}(\sigma_x - \sigma_y) & 0 & 0 \\ 0 & \frac{1}{3}(\sigma_y - \sigma_x) & 0 \\ 0 & 0 & \frac{1}{3}(\sigma_y - \sigma_x) \end{bmatrix}$$

- Uniaxial strain results in a simplified yield criteria:

$$\sigma_Y = \sqrt{\frac{3}{2} S_{ij} S_{ij}} = \sigma_x - \sigma_y$$

If deformation is plastic (on the yield surface):

$$Y = \sigma_x - \sigma_y = 2\tau$$

$$\sigma_x = P + \frac{2}{3} Y$$

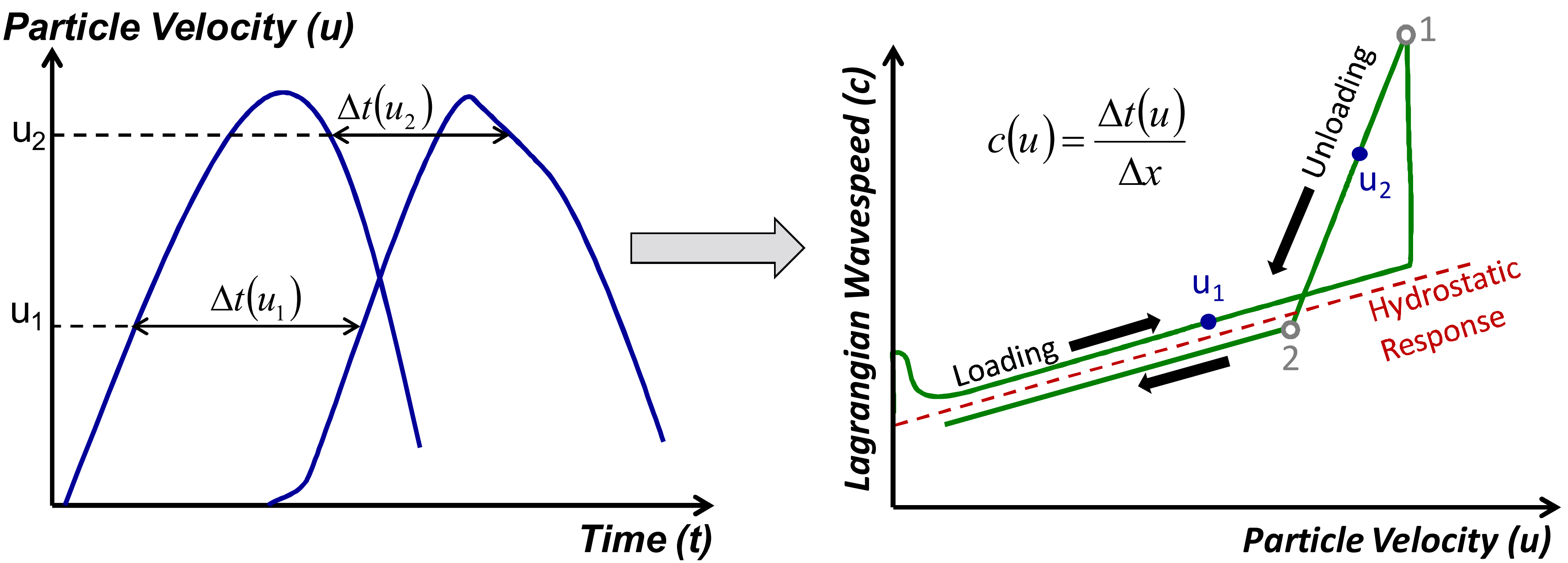
Fowles, JAP, 1961

Outline

- Background/Theory
  - Self-consistent method
  - Corrections
    - Mean pressure
    - Attenuation
    - Rate effects
    - Window : transfer function
- Experiments
  - Analysis of a typical Z strength experiment
    - Extracting a point on the yield surface
  - Results for Ta

Experimental observables and Lagrangian analysis

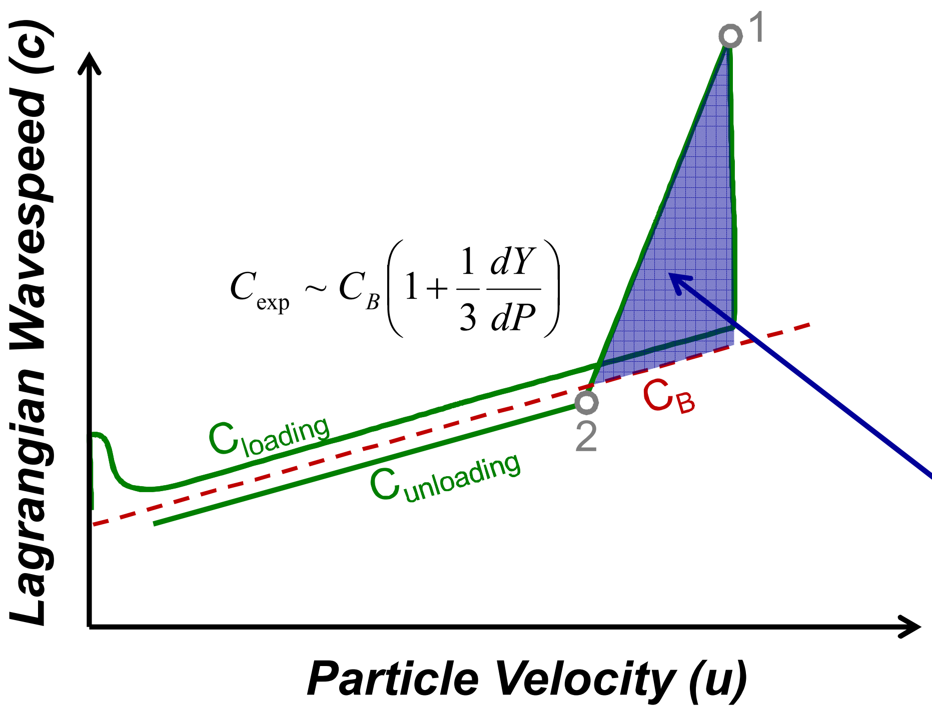
- Line outs of ***in situ*** particle velocities at 2 thicknesses give corresponding wavespeeds.
  - Assumption of simple wave propagation



Aidun and Gupta, JAP, 1991

How we are measuring strength: self-consistent method

- Advantages
  - Requires only 1D loading and velocimetry
  - No pressure restrictions



- Assumptions
  - Rate-independent response
  - J2 plasticity (Von-Mises yield)
- Uniaxial strain results in simplified coupling:

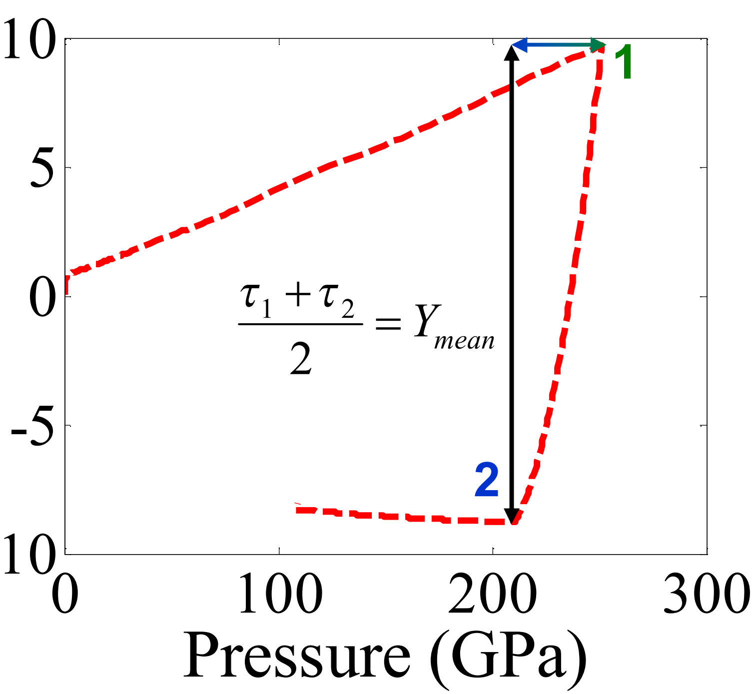
$$\sigma_x(\varepsilon) = P(\varepsilon) + \frac{4}{3}\tau(\varepsilon)$$

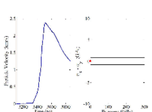
$$\frac{d\tau}{d\varepsilon} = \frac{3}{4}\rho_0\left[c_{exp}^2 - c_B^2\right]$$

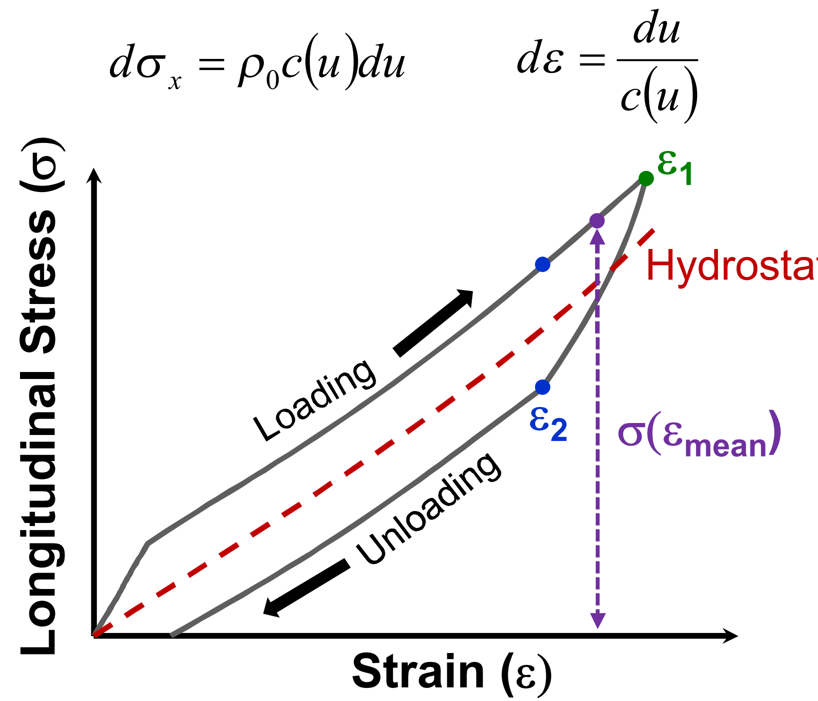
$$\tau_2 - \tau_1 = \frac{3}{4}\rho_0\int_{u_1}^{u_2}\left[c_{exp}{}^2 - c_B^2\right]\frac{du}{c}$$

A closer look at the interpretation: mean yield strength and pressure

- Material unloads from the upper to lower yield surface over a finite pressure range





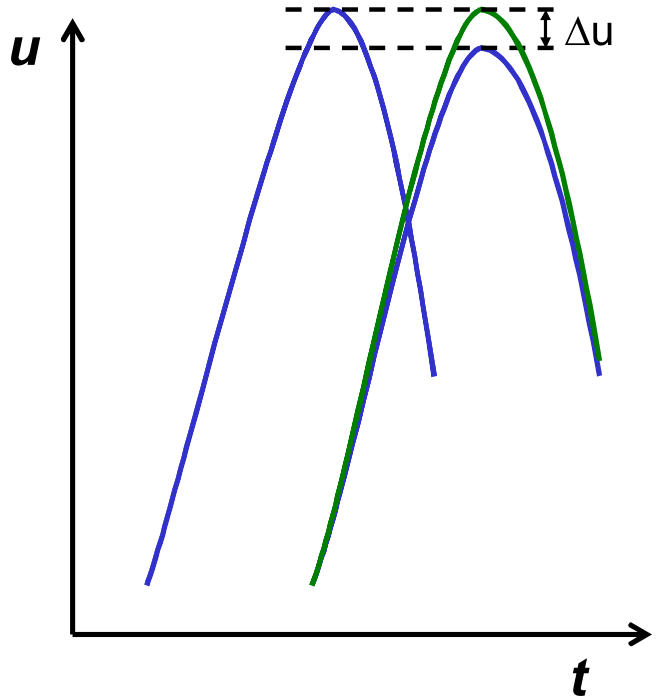


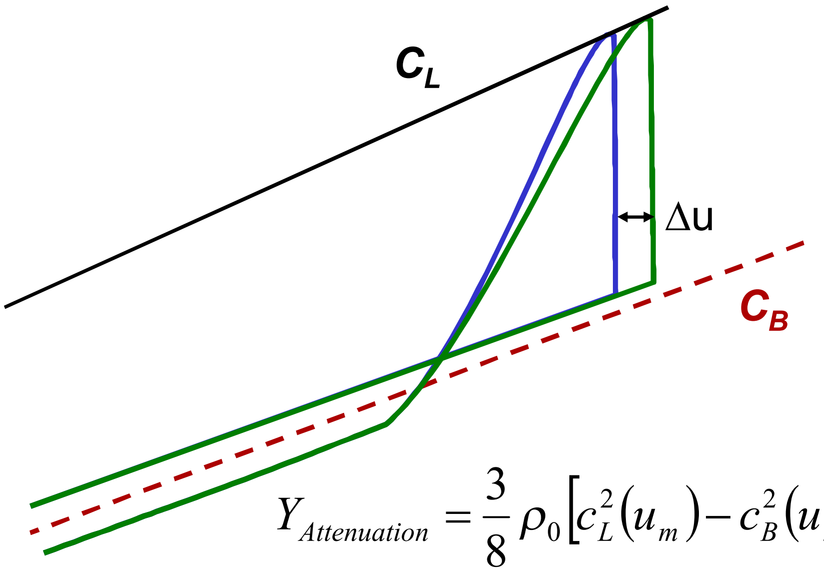
Assuming linearity of the yield surface over the unloading pressure regime:

$$\tau_{mean} = \frac{\tau(\varepsilon_1)+\tau(\varepsilon_2)}{2} = \tau\left(\frac{\varepsilon_1+\varepsilon_2}{2}\right) = \tau(\varepsilon_{mean})$$

Correction for attenuation

- Attenuation can have a dramatic effect on the strength measurement
  - A correction can be formulated assuming quasi-elasticity is linear near peak
  - Validity of the assumption can be addressed with synthetic data

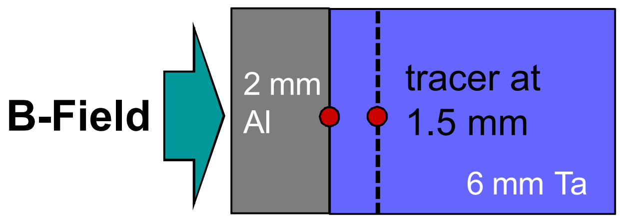




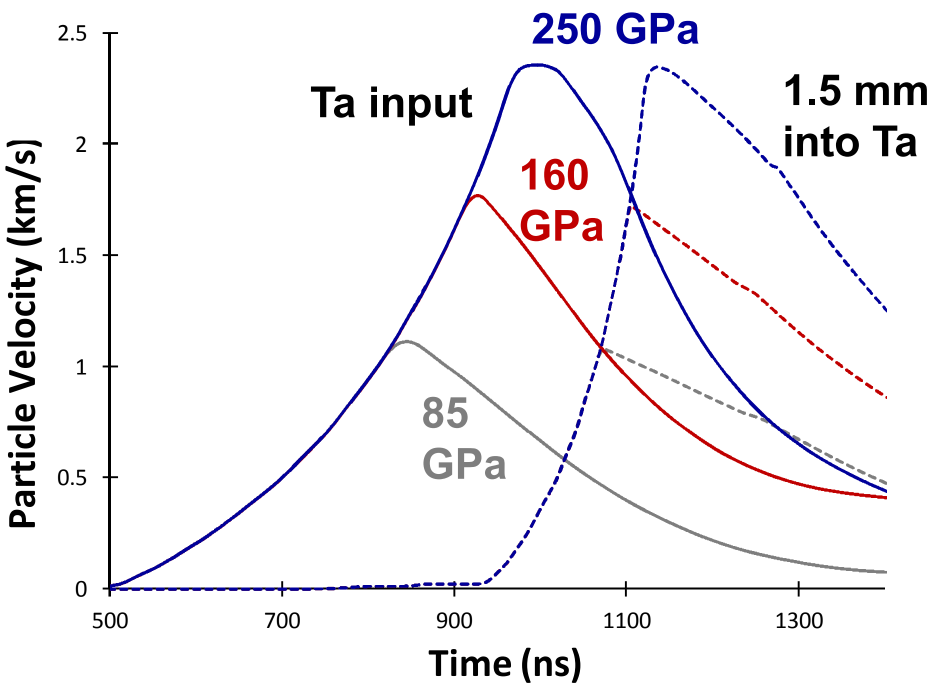
$$Y_{Attenuation} = \frac{3}{8}\rho_0\left[c_L^2(u_m) - c_B^2(u_m)\right]\frac{\Delta u}{\bar{c}}$$

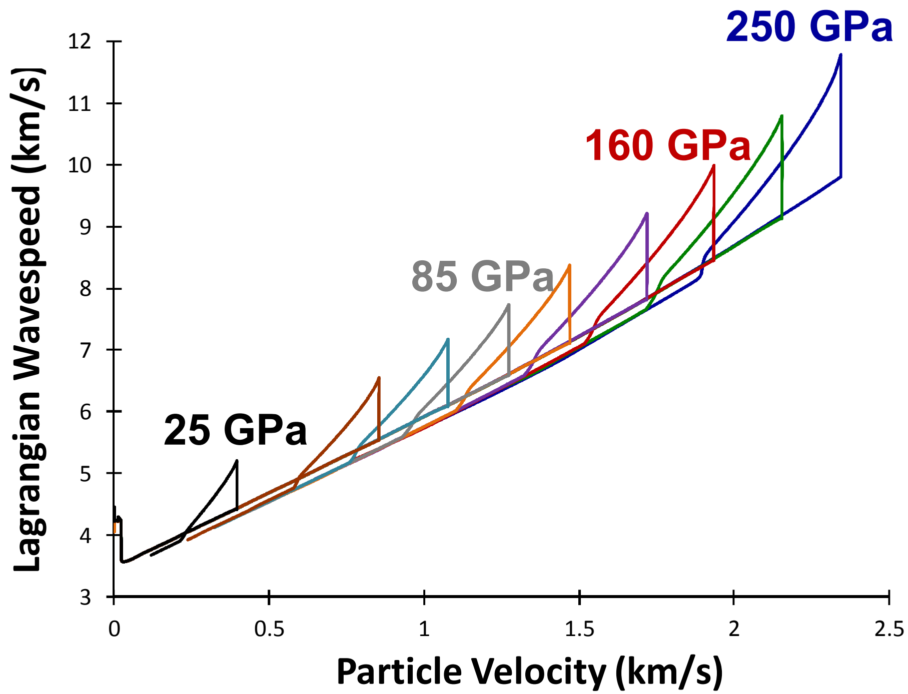
Asay et al., JAP, 2009

Numerical simulations of tantalum to 2.5 MBar

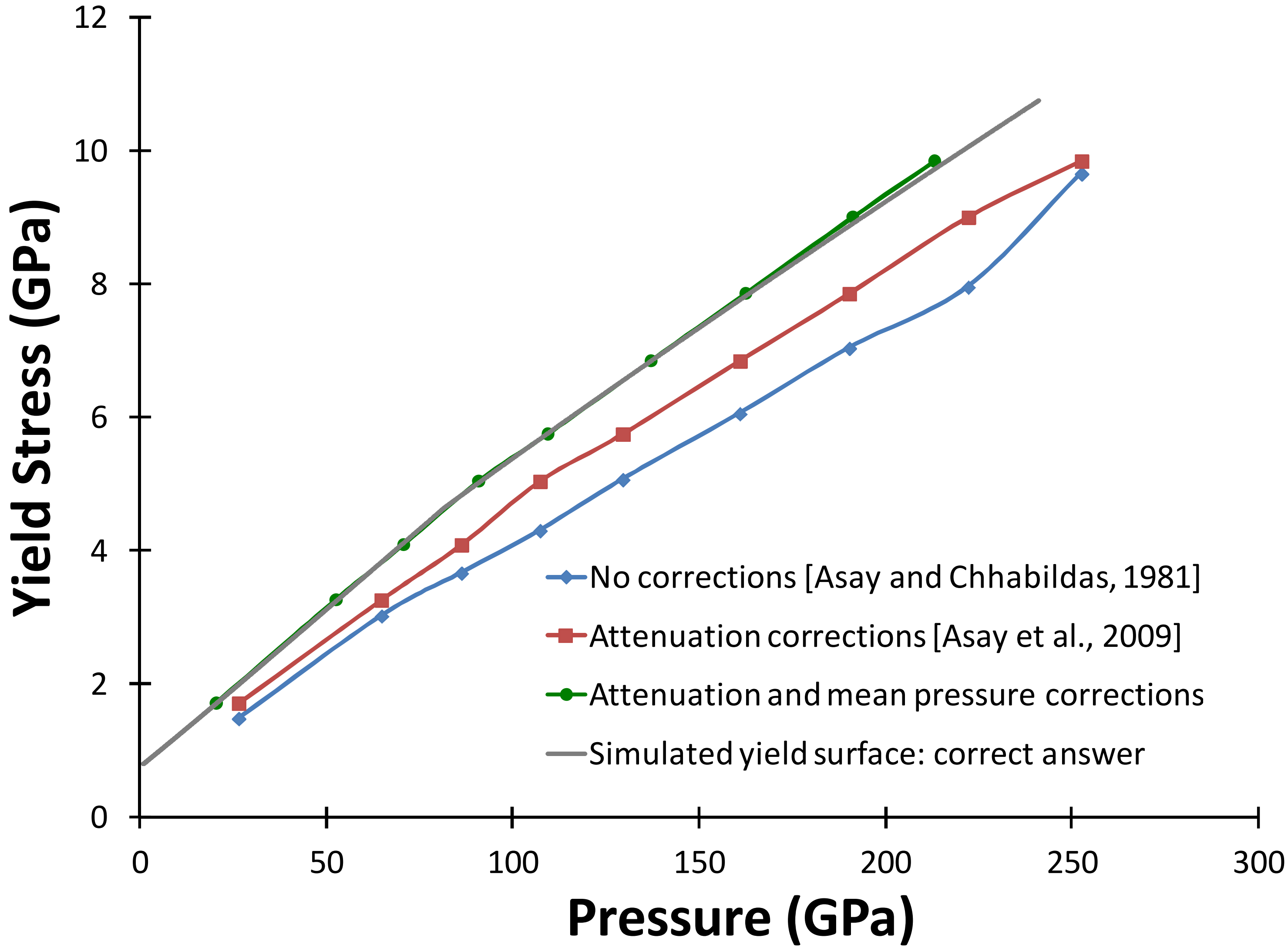


- EOS: sesame 90210
- Strength: standard SG Ta parameters, except A (pressure hardening) is 3x higher



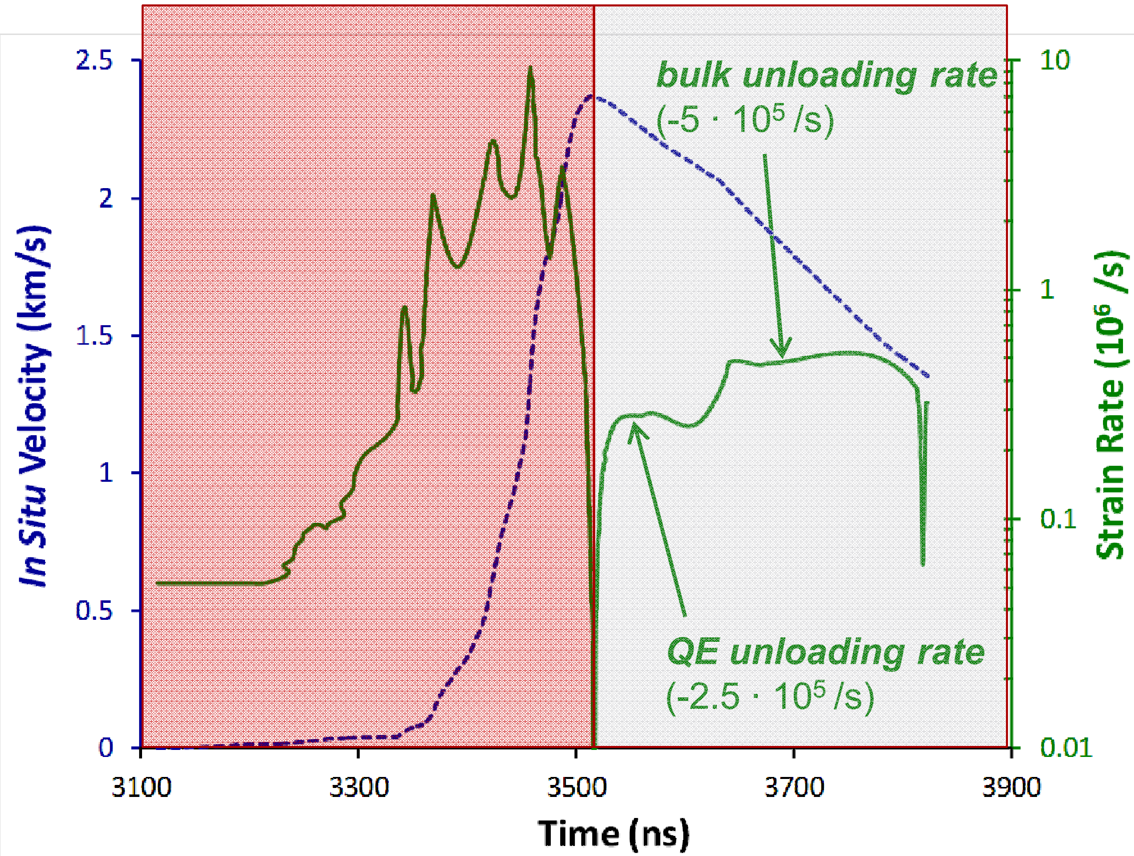


Self-consistent analysis reproduces yield surface with corrections



Strain-rate is relatively constant where the strength is extracted

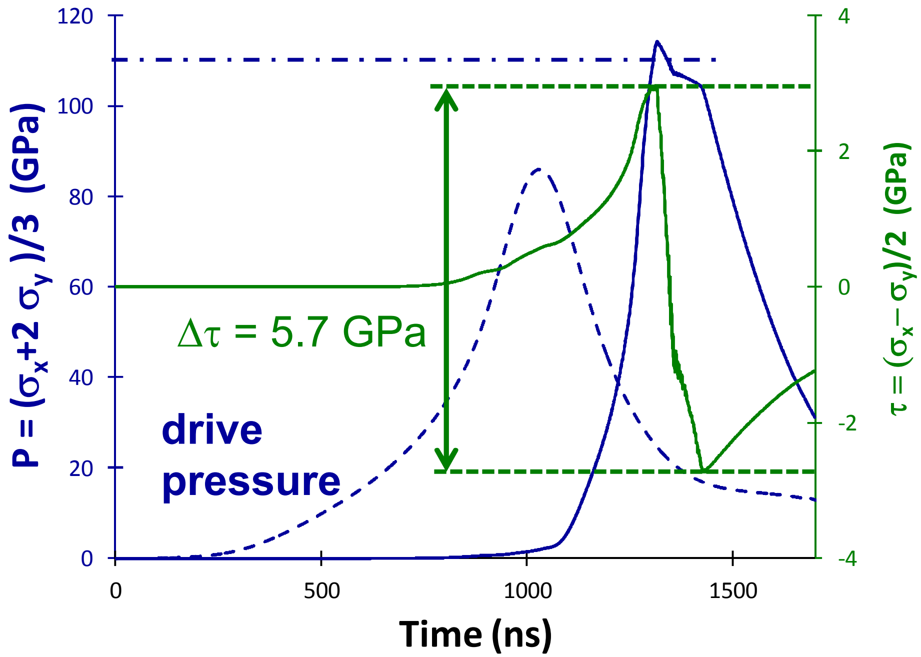
- A typical Z ramp experiment
  - Loading rates: $10^5 - 10^7$ 1/s
  - Unloading rates: $2.5 - 5\ 10^6$ 1/s



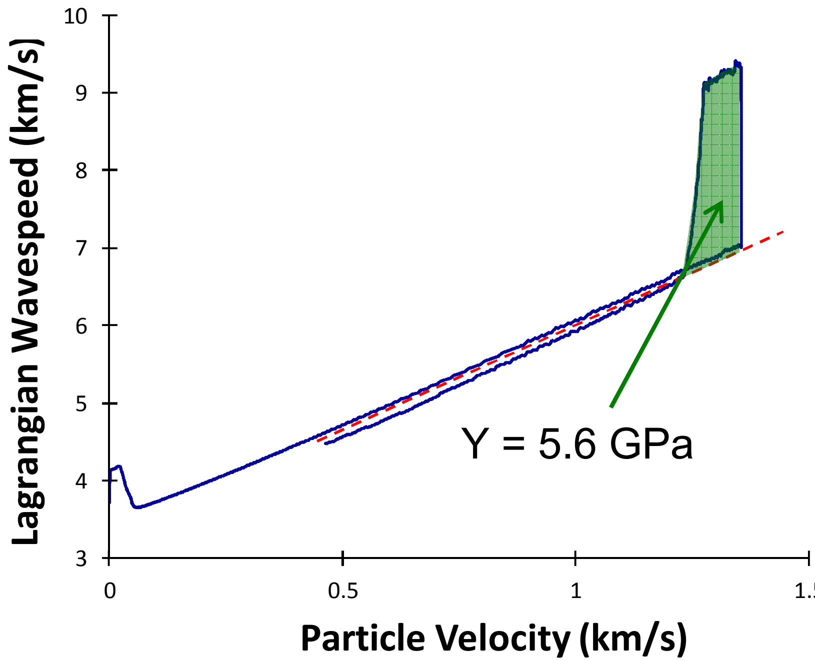
Self-consistent analysis of a rate-dependent simulation still works

- Synthetic analysis of a dislocation based model courtesy J. Ding

Stress tensor analysis



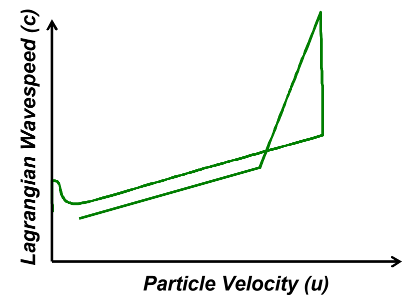
Self-consistent analysis

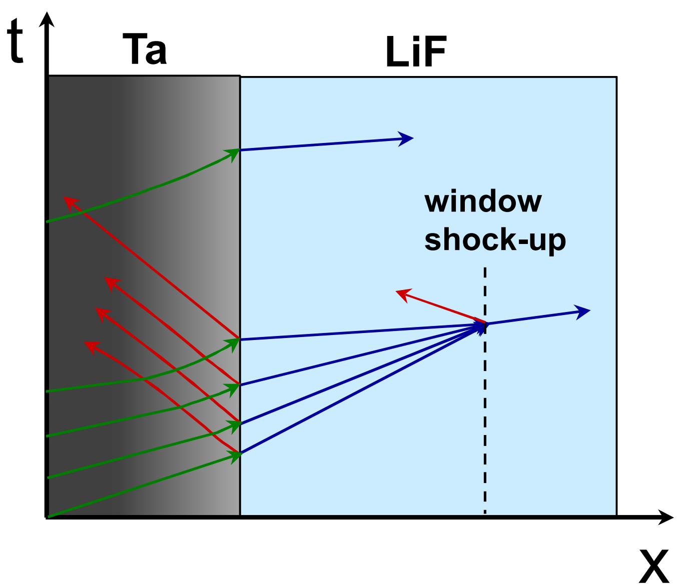


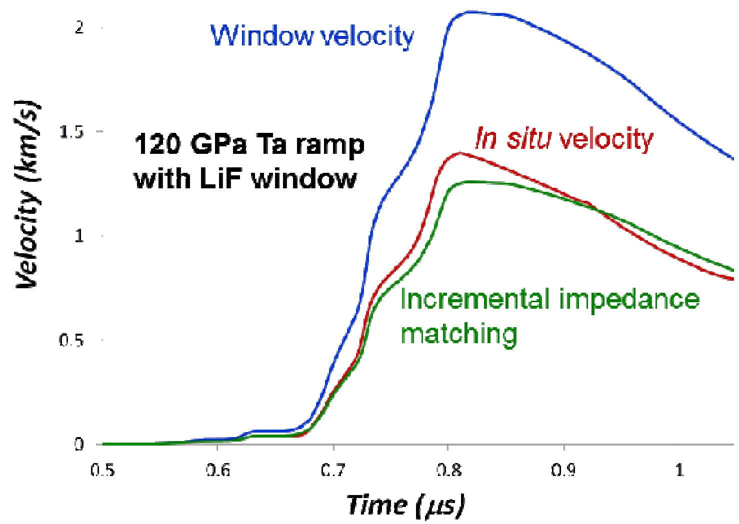
Ding et al., JAP, 2010

It is critical to properly account for window effects

- A window is necessary to measure a full release into bulk unloading
  - Wave reflection: creates highly non-uniform state in the sample
  - Characteristic bending : changes timing of the measured waveform
- Traditional analysis methods do not work
  - Impedance matching only accounts for impedance mismatch
  - Backwards characteristics requires a 1-1 wavespeed response

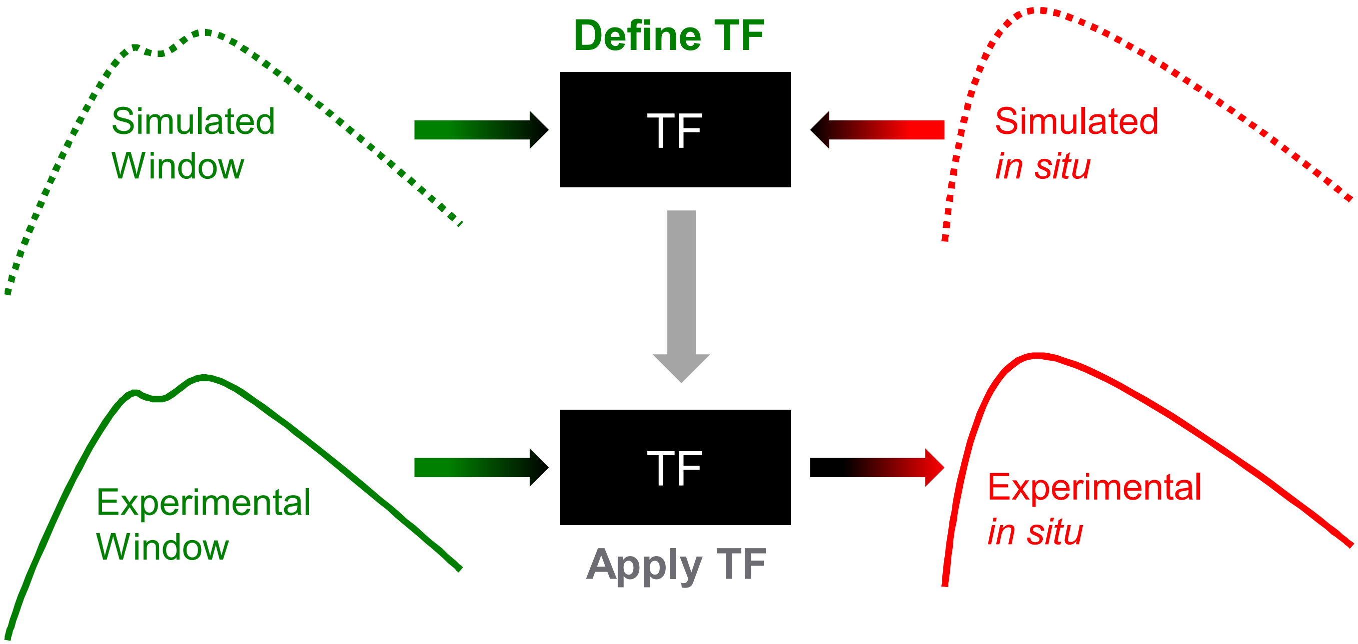






Transfer function methodology

- Use the hydrocode (EOS + Strength) to approximate the wave interactions
  - Determine mapping from *in-situ* to window velocities
- Map these interactions to the actual experiment
  - Map from experimental window to experimental *in situ*



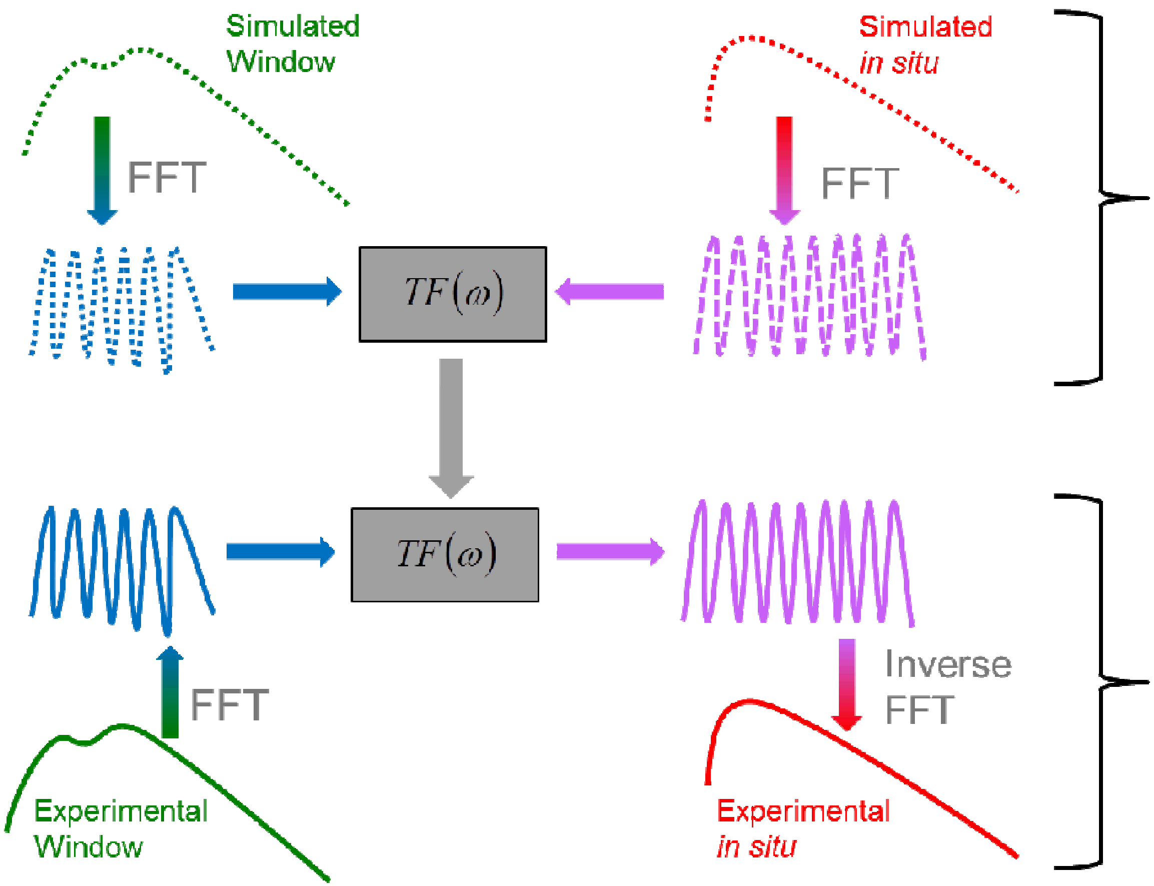
Numerical simulations determine the transfer function

The transfer function is then applied to the experimental measurement

Transfer function defined

- **A linear time invariant (LTI) system can be defined by the convolution integral:**

$$u_{in\ situ}^{simulated}(\bar{t}) = u_{window}^{simulated}(\bar{t}) * tf(\bar{t}) = \int_{-\infty}^{\infty} u_{window}^{simulated}(\bar{t}-\tau) \cdot tf(\tau) d\tau$$



The transfer function is defined in the frequency domain by the numerical simulations

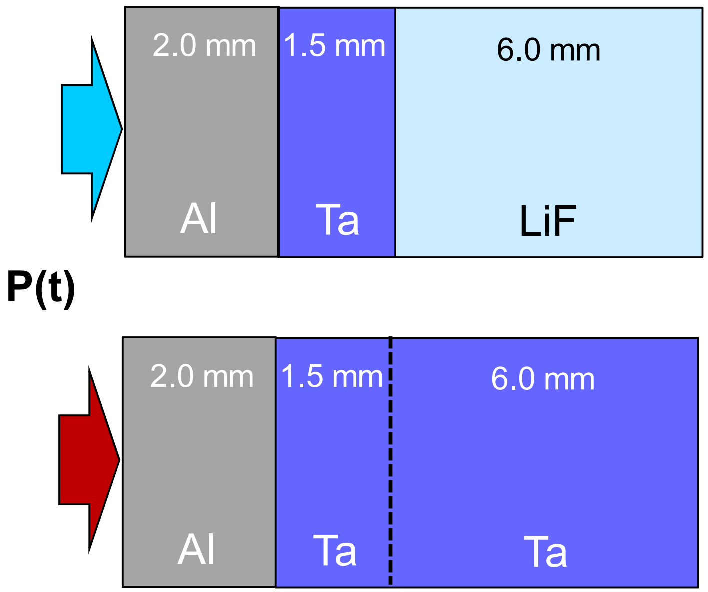
$$U_{in\ situ}^{simulated}(\omega) = U_{window}^{simulated}(\omega) \cdot TF(\omega)$$

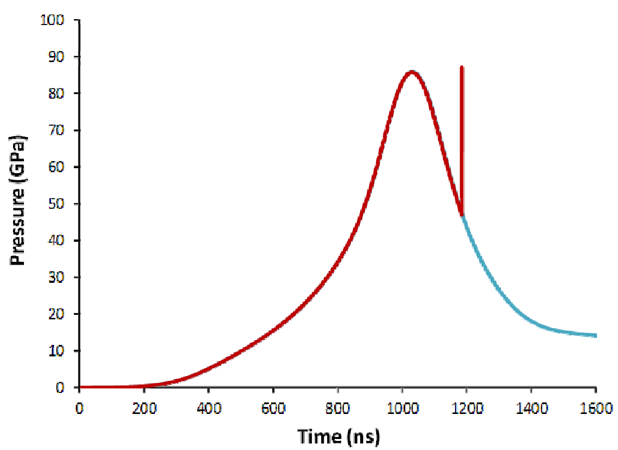
$$TF(\omega) = \frac{U_{in\ situ}^{simulated}(\omega)}{U_{window}^{simulated}(\omega)}$$

The transfer function is applied to the experimental data

$$U_{in\ situ}^{experimental}(\omega) = U_{window}^{experimental}(\omega) \cdot TF(\omega)$$

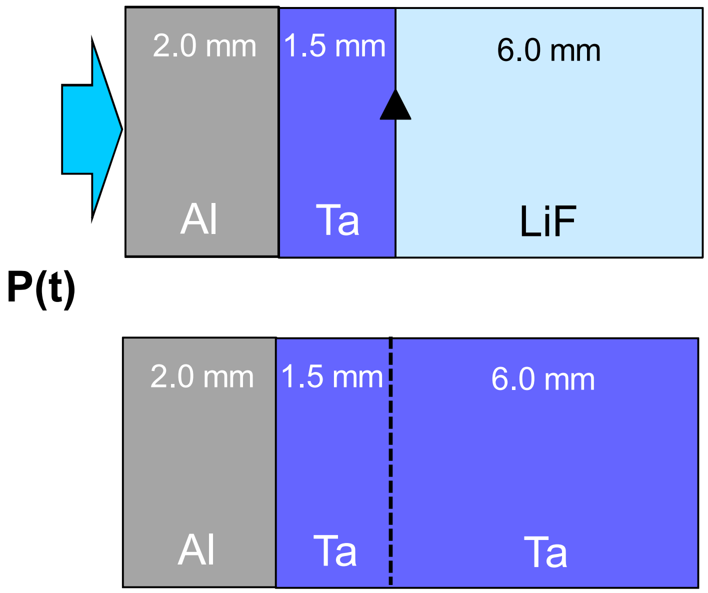
Application to the rate-dependent simulation



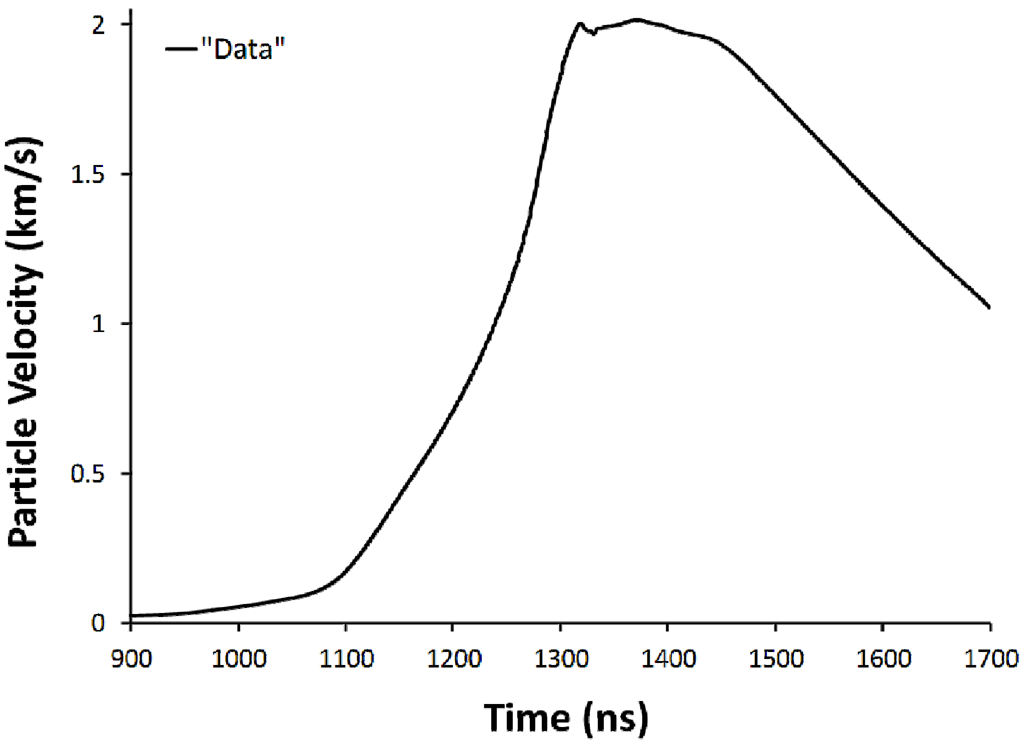


- "Experimental Data" models
  - Mie-Grüneisen EOS
  - Strength:
    - Al : hydrodynamic
    - Ta: dislocation mechanics
    - LiF: elastic perfectly plastic
- Simulation models
  - SESAME tabular EOS
    - Al3700, Ta90210, LiF7271
  - SG QE strength

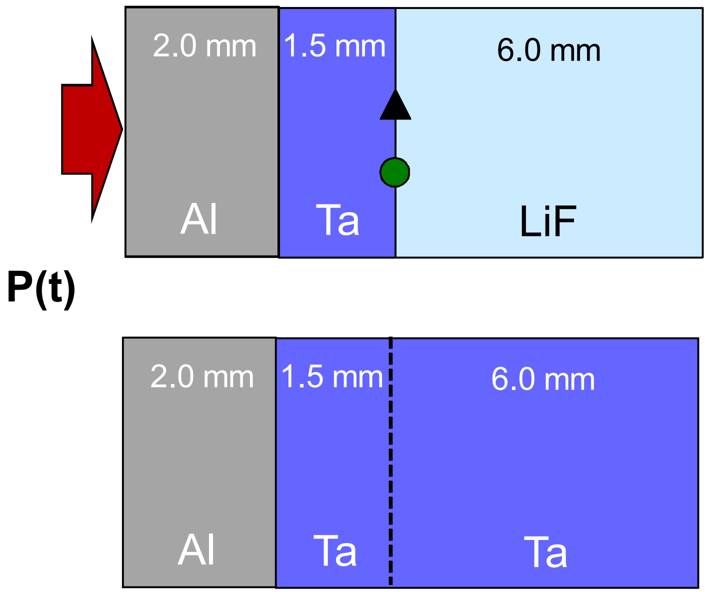
Application to the rate-dependent simulation



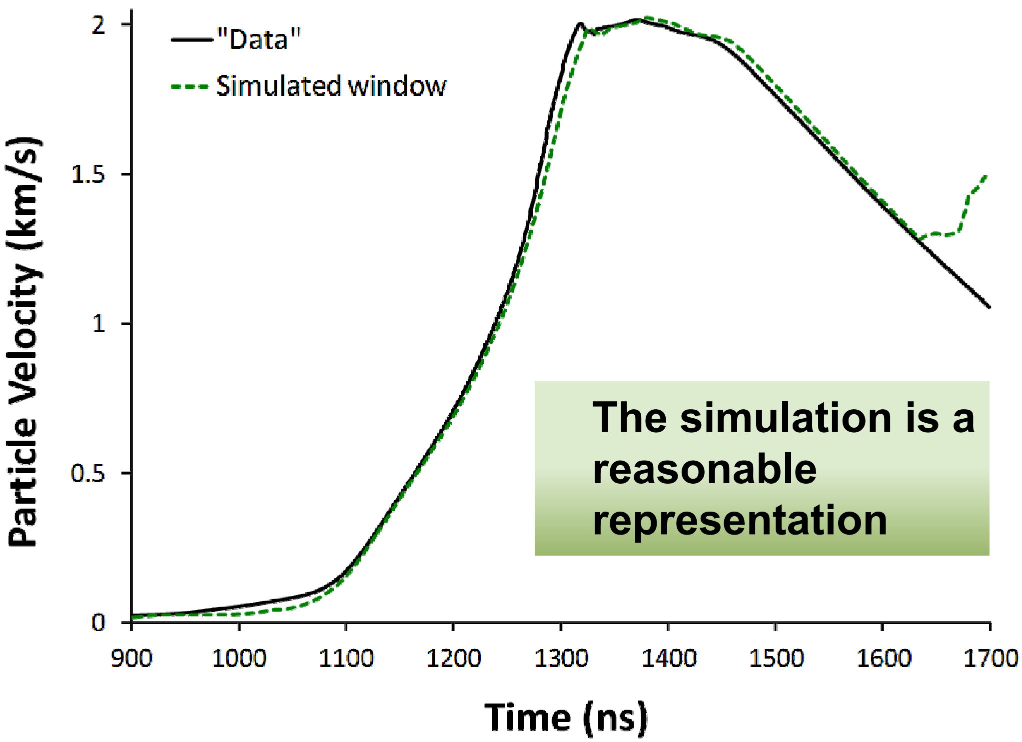
"Experimental" window velocity



Application to the rate-dependent simulation

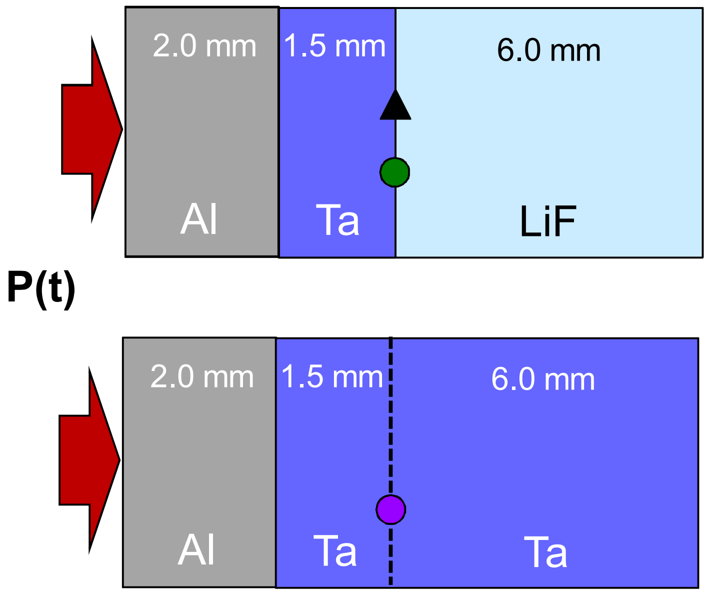


A forward simulation of the experiment is performed

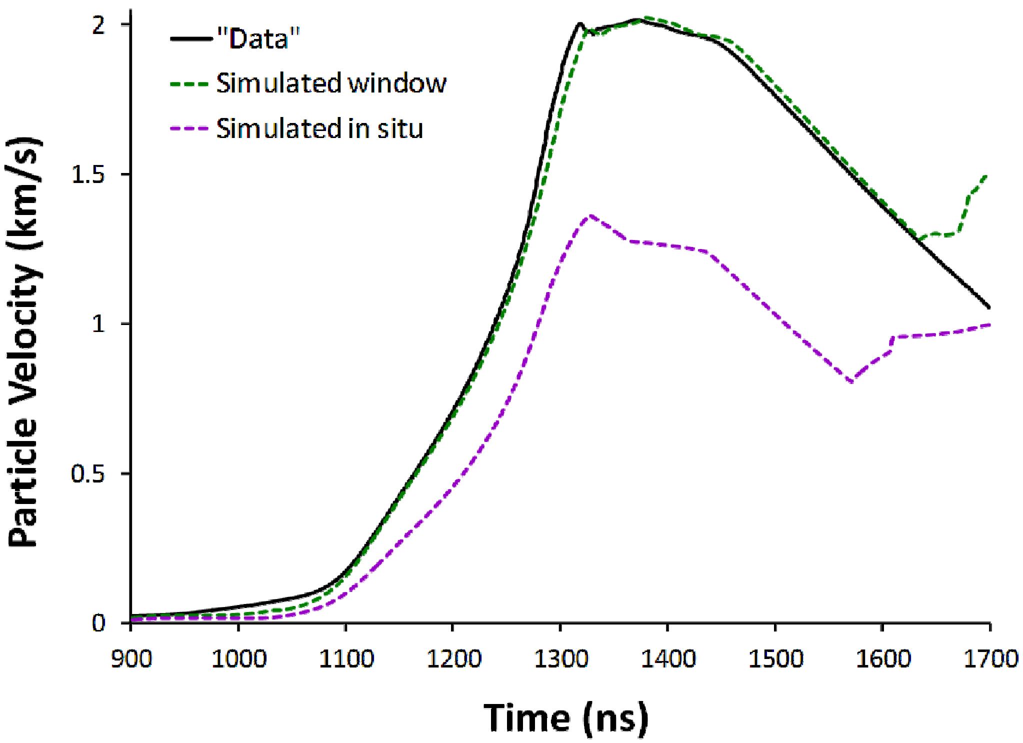


The simulation is a reasonable representation

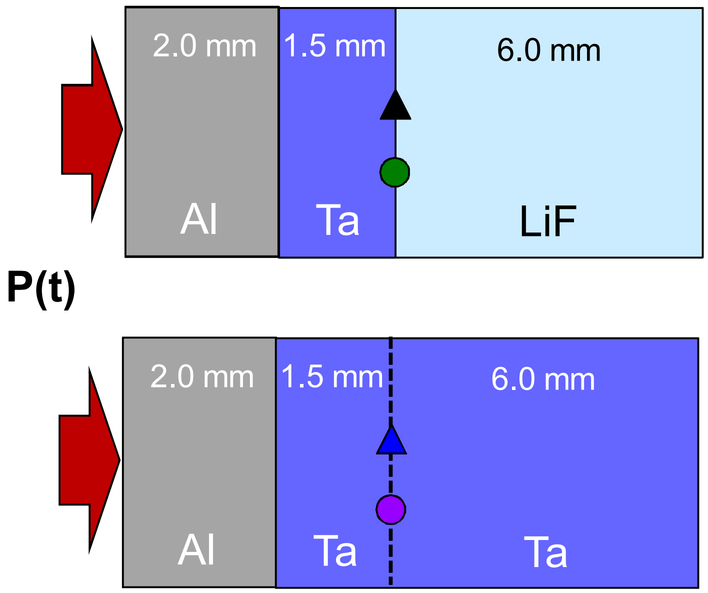
Application to the rate-dependent simulation



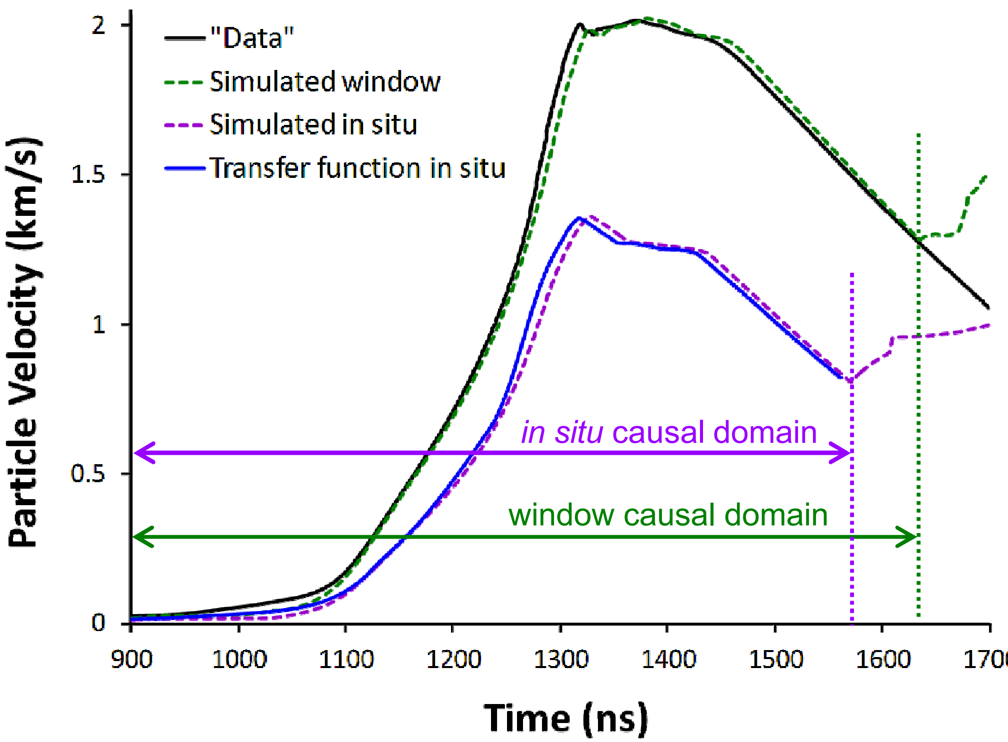
The corresponding *in situ* forward simulation



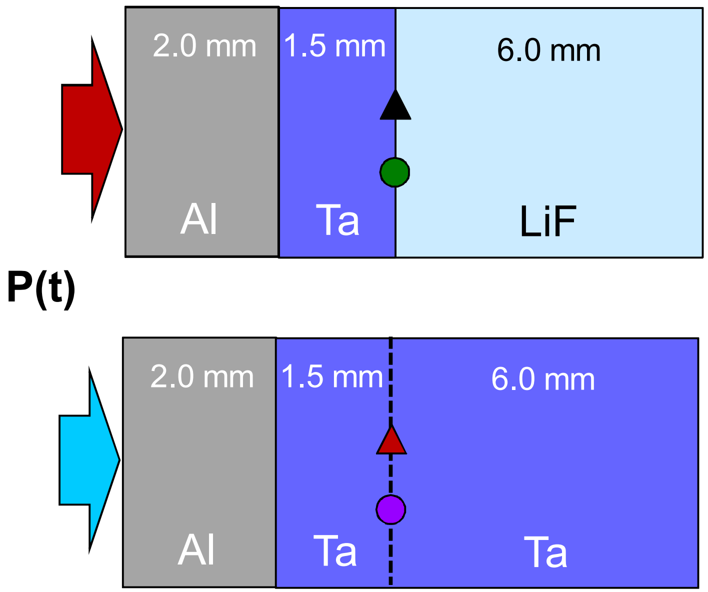
Application to the rate-dependent simulation



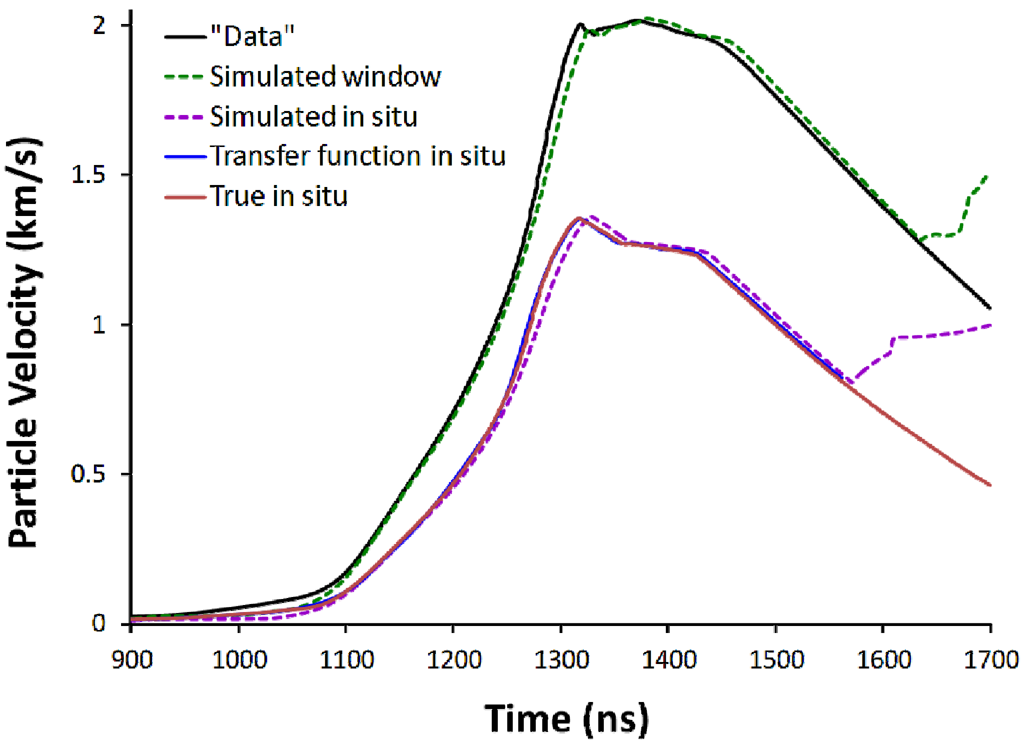
Apply the transfer function to the "data" to determine the experimental *in situ* response



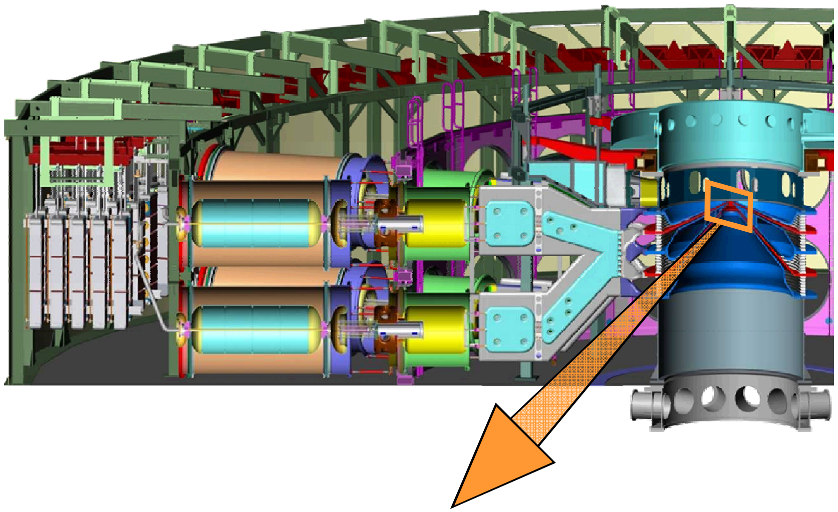
Application to the rate-dependent simulation



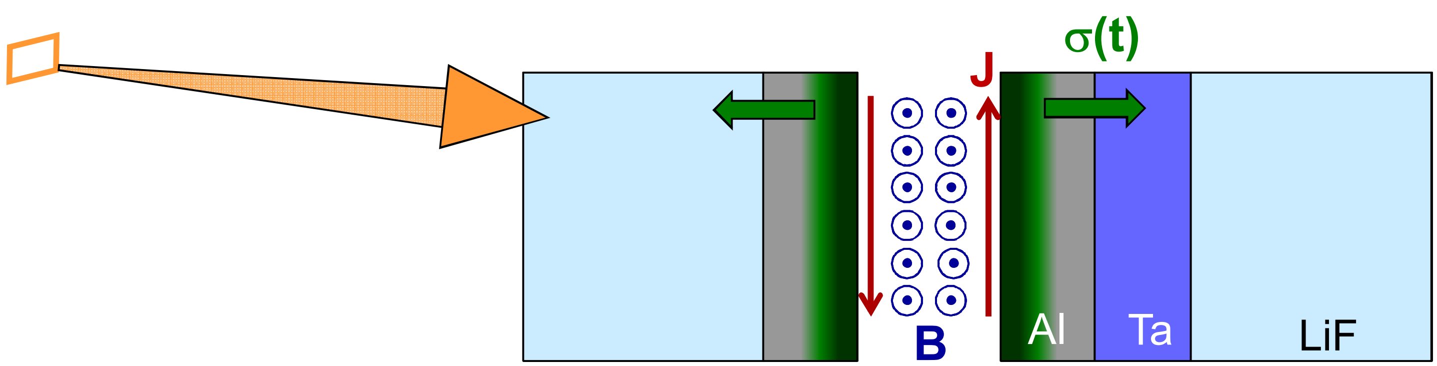
Despite significant differences in the models, the TF reproduces the correct *in situ* response!



The Sandia Z machine

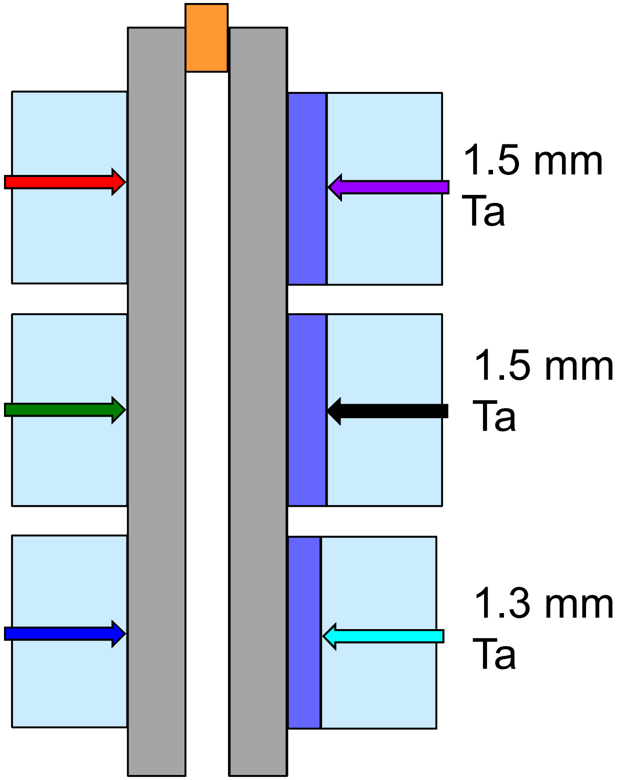


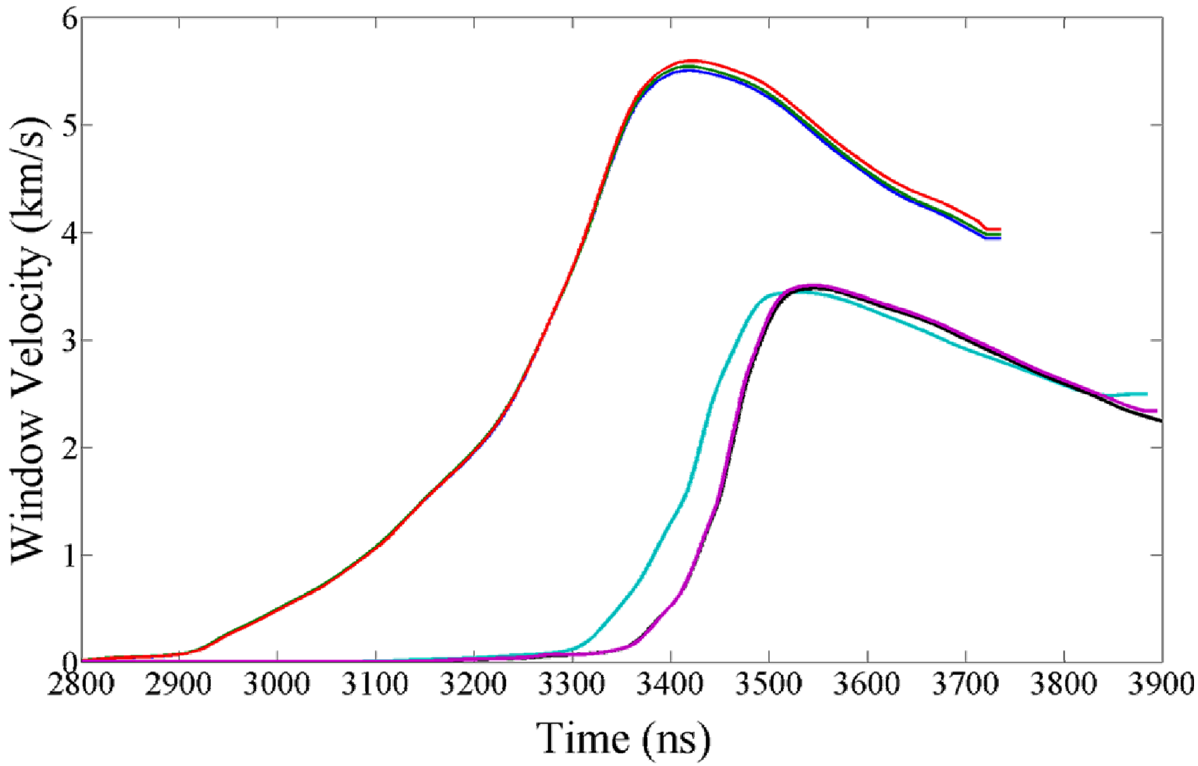
- Current pulse of up to 26 MA delivered to parallel flat-plate electrodes shorted at one end
- Magnetic (J x B) force induces ramped stress wave in electrode material
- Stress wave propagates into ambient material, de-coupled from magnetic drive
- Controllable pulse shape, rise time 100 – 1200 ns
- Identical magnetic loading of sample pairs



A typical experiment: Ta to 2.5 MBar

- 15 mm tapered stripline, 1mm AK gap
  - 12 mm diameter samples/windows
  - 2 mm aluminum electrode floor thickness

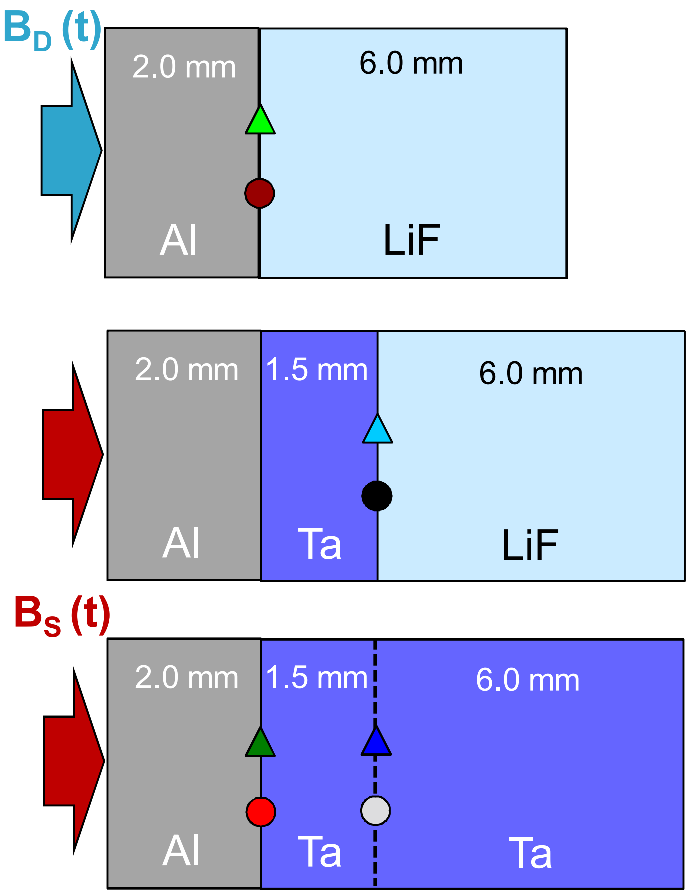


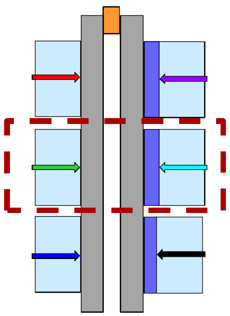


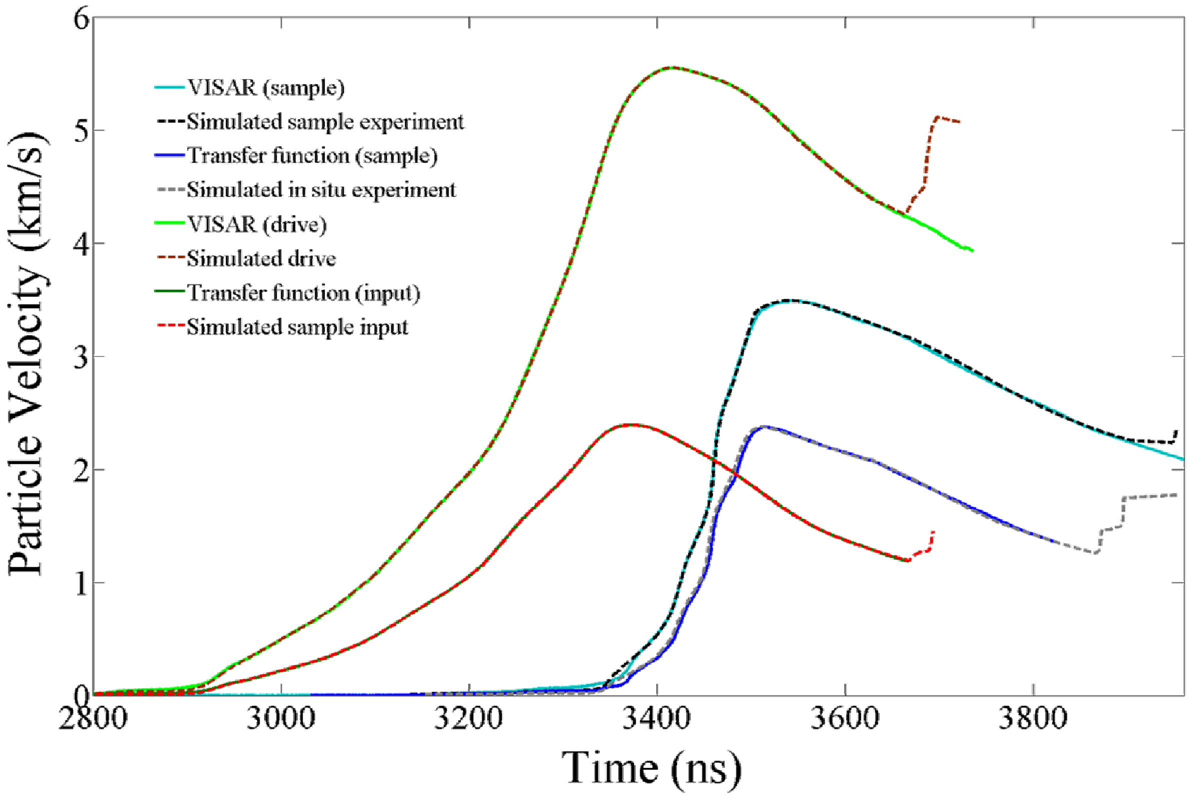
Lemke et al., IJIE, 2011

J.P. Davis' talk Thursday: V5.2

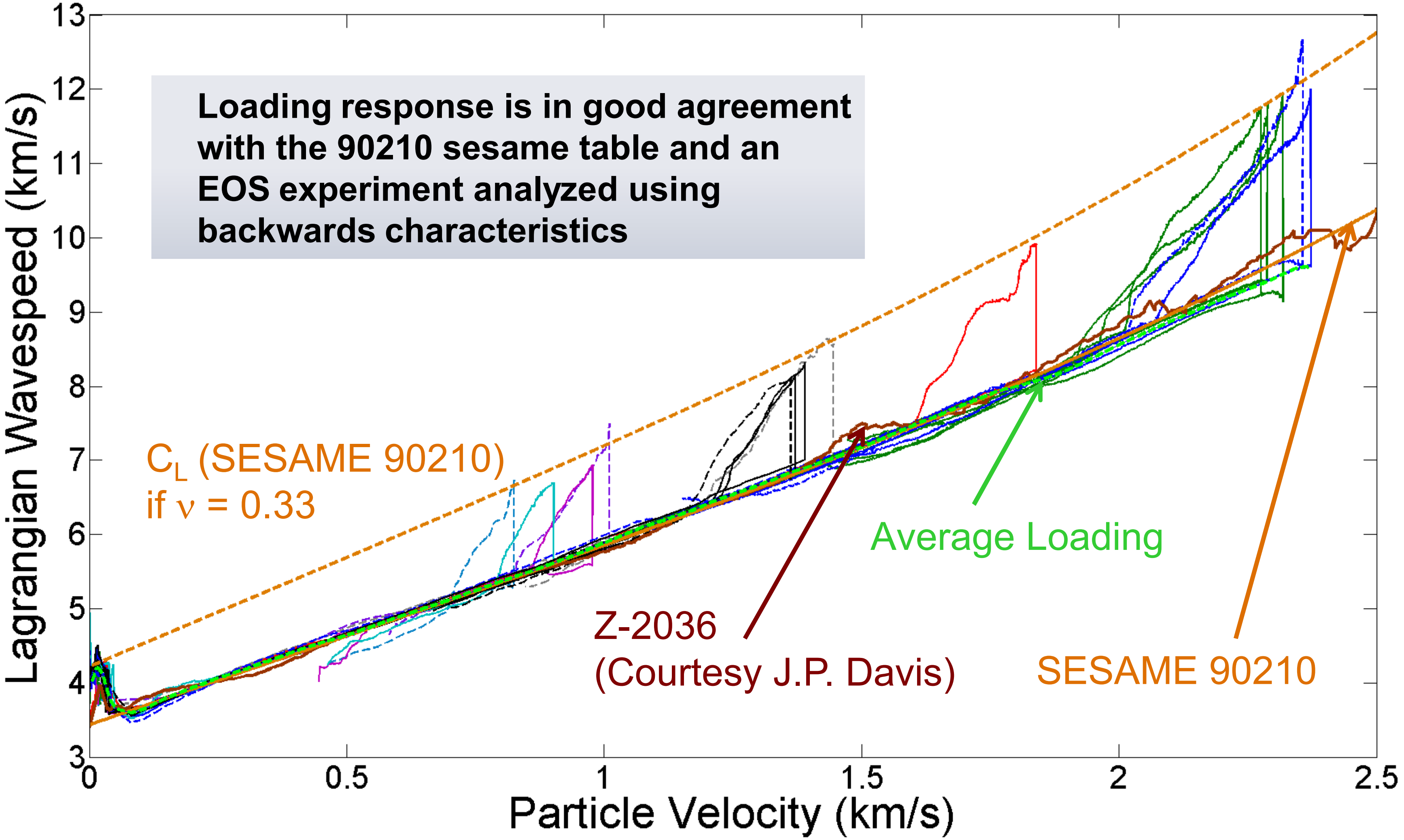
In situ profiles are determined from the transfer function





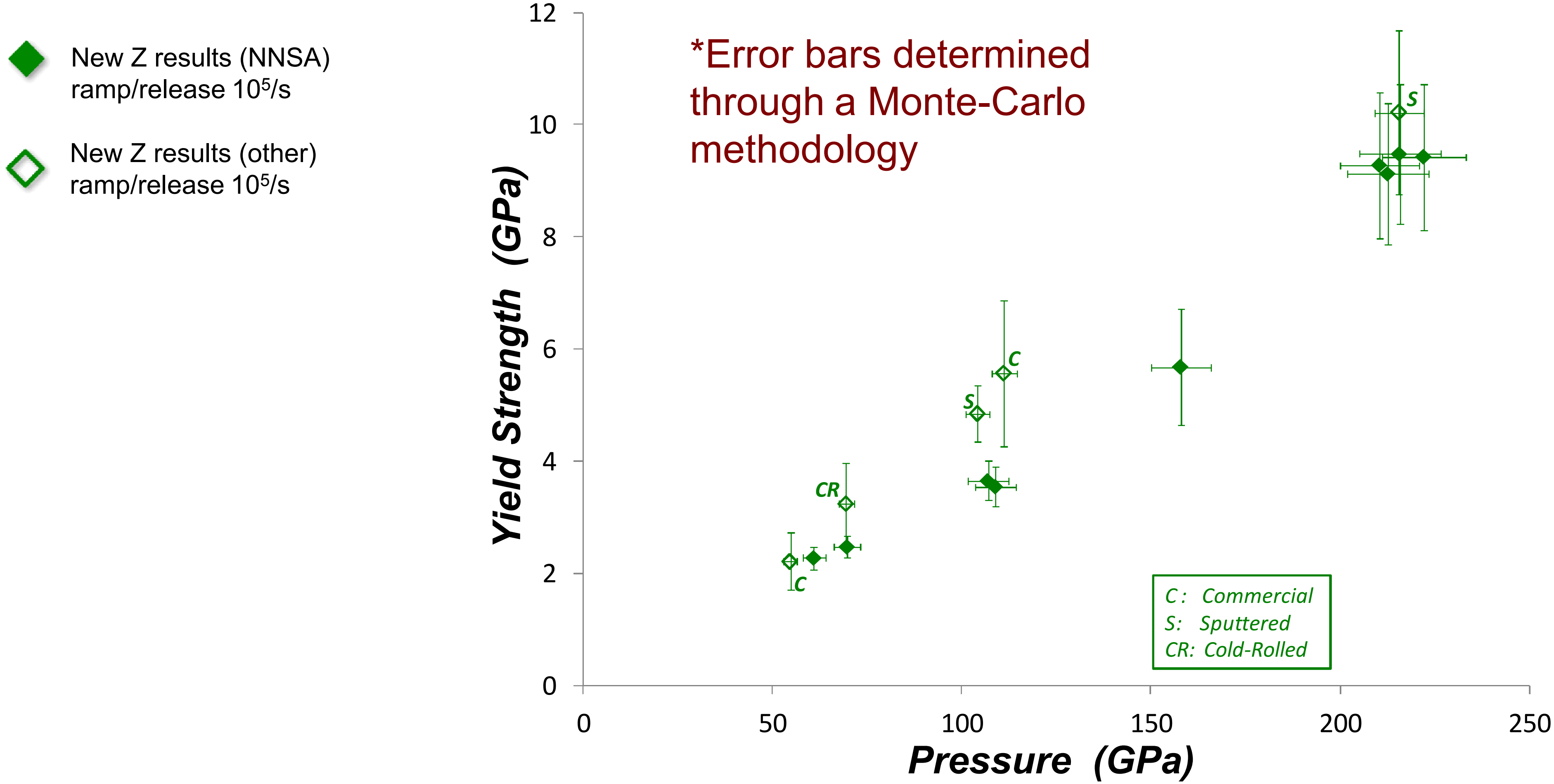


Wavespeed profiles for all of the Ta experiments



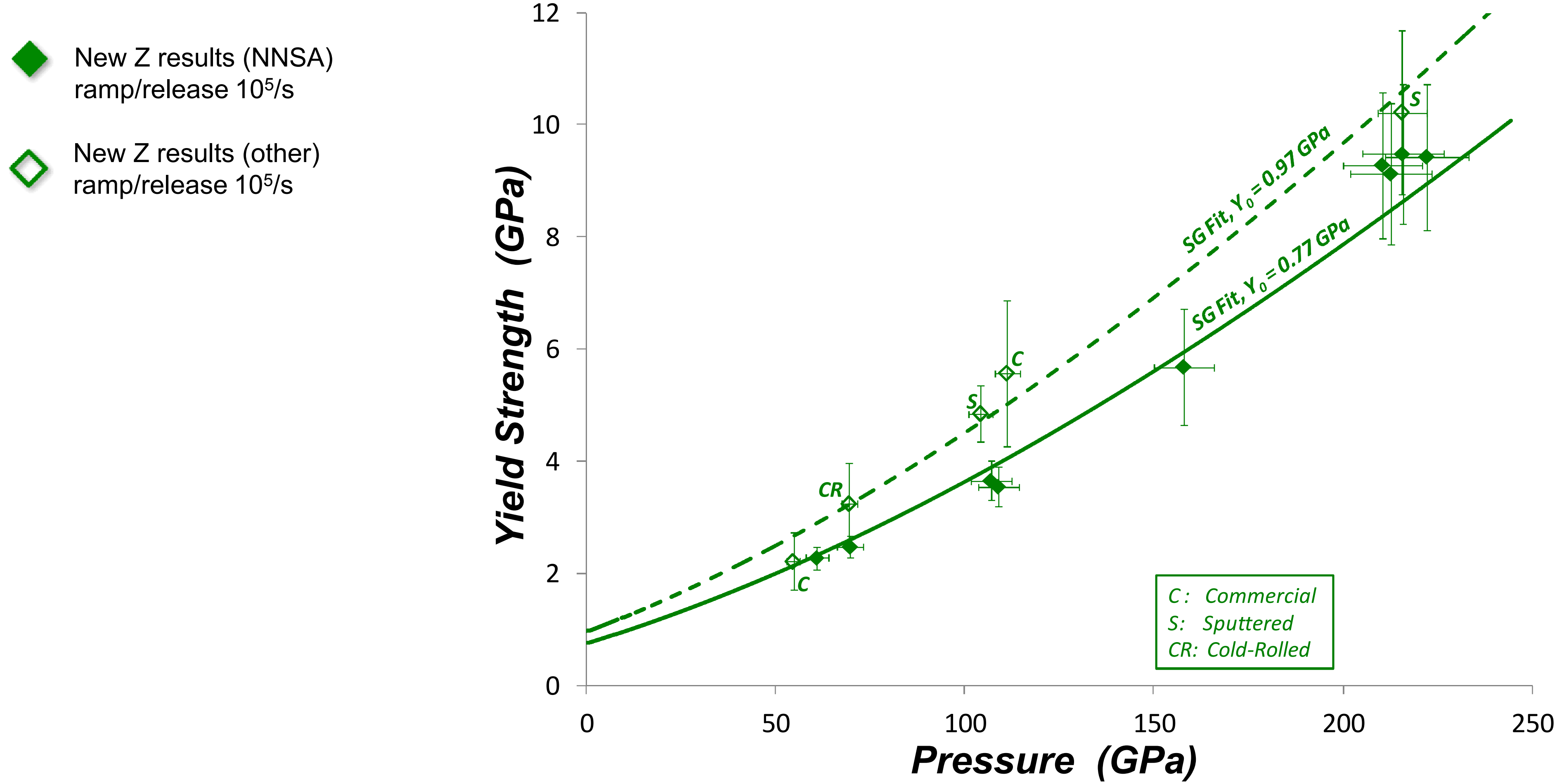
Ta strength data obtained on Z

- See an effect of material processing



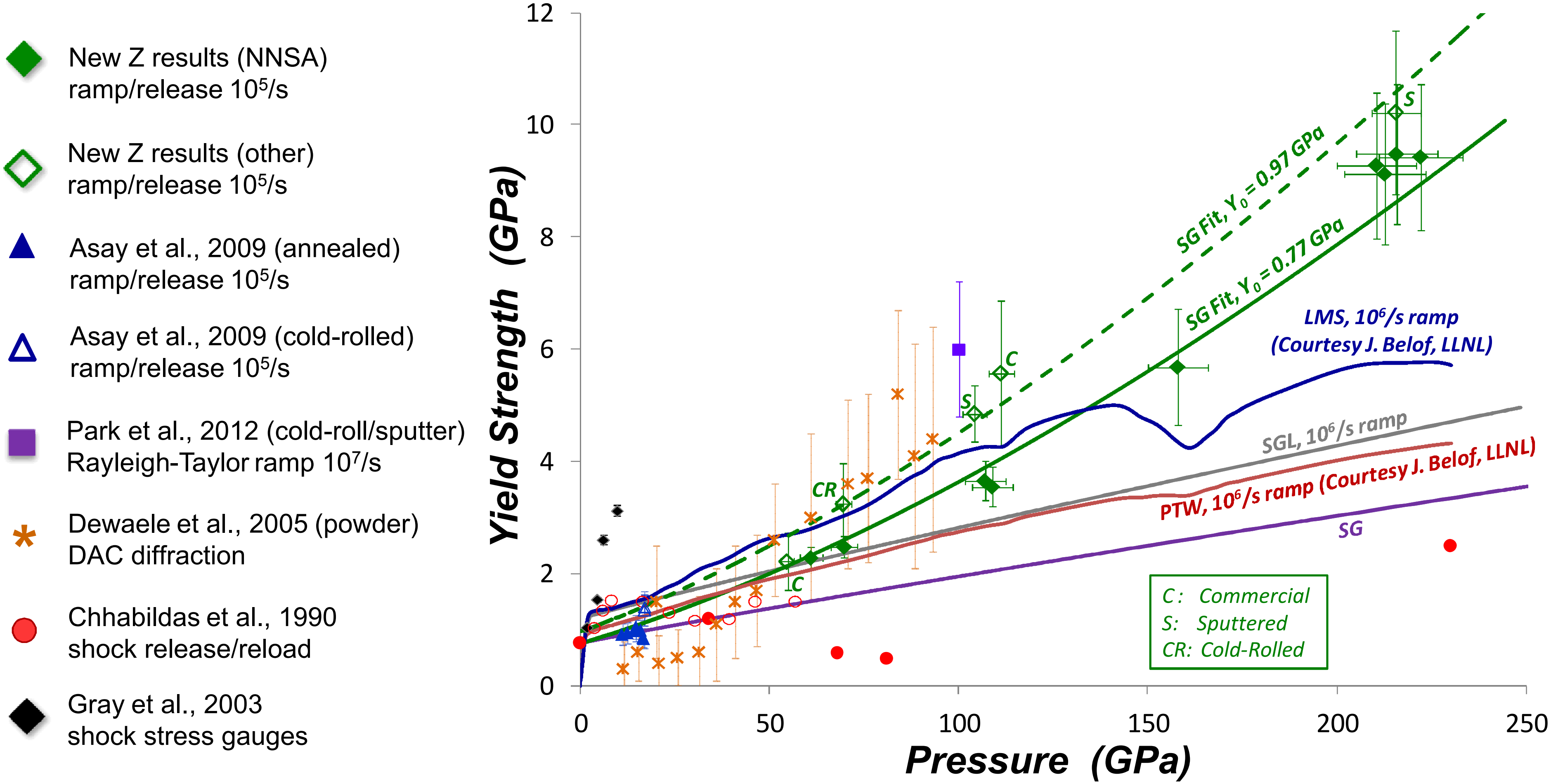
Ta strength data obtained on Z

- See an effect of material processing



Ta strength : a compilation of data

- In good agreement with RT data / LLNL multiscale model
- Ta is significantly stronger than previously believed: factor of 2 at P > 2 MBar



Results and Conclusions

- Self-consistent method produces low systematic errors
  - Strain rates are approximately constant over unloading
  - Corrections: window (transfer function), mean pressure, attenuation
- Strength experiments to MBar stress levels on Z have been performed on Ta
  - See an effect of material processing
  - Tantalum is much stronger than previously believed

Backups

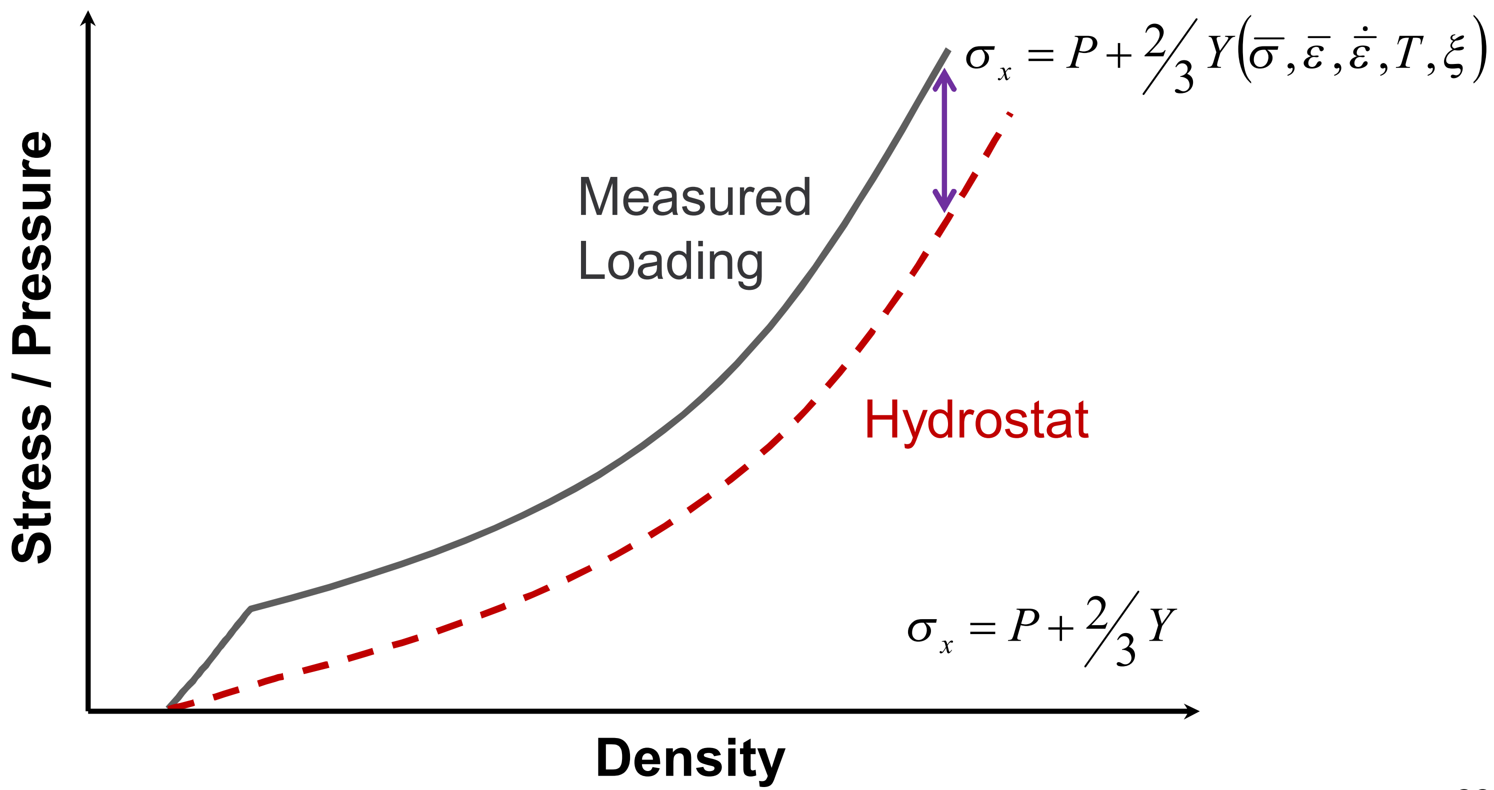
Why is strength important?

- Deviatoric stresses are important
  - Lots of interesting physics: dislocations
  - EOS: We measure σ_x not P!

Tantalum Example

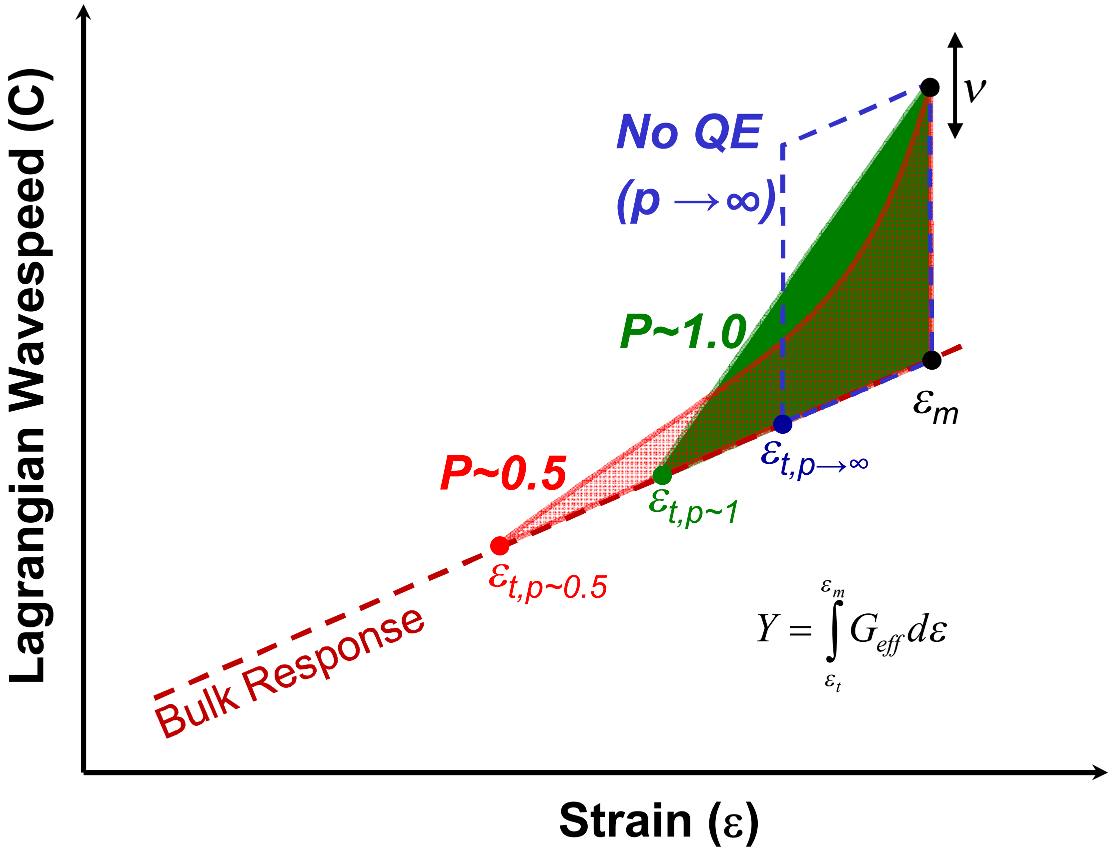
Y = 5 GPa at P = 100 GPa

3% effect



A quasi-elastic strength model

- Steinberg-Guinan yield surface: $Y = Y_0[1+\beta(\varepsilon+\varepsilon_i)]^n \left[1 + A\frac{P}{\eta^{1/3}} + B(T-300)\right]$



$$Y = \int_{\varepsilon_t}^{\varepsilon_m} G_{eff}\, d\varepsilon$$

Calculate a shear modulus:

$$G = G_0\left[1 + A\frac{P}{\eta^{1/3}} + B(T-300)\right]$$

OR

$$G = \frac{3K(1-2\nu)}{2(1+\nu)}$$

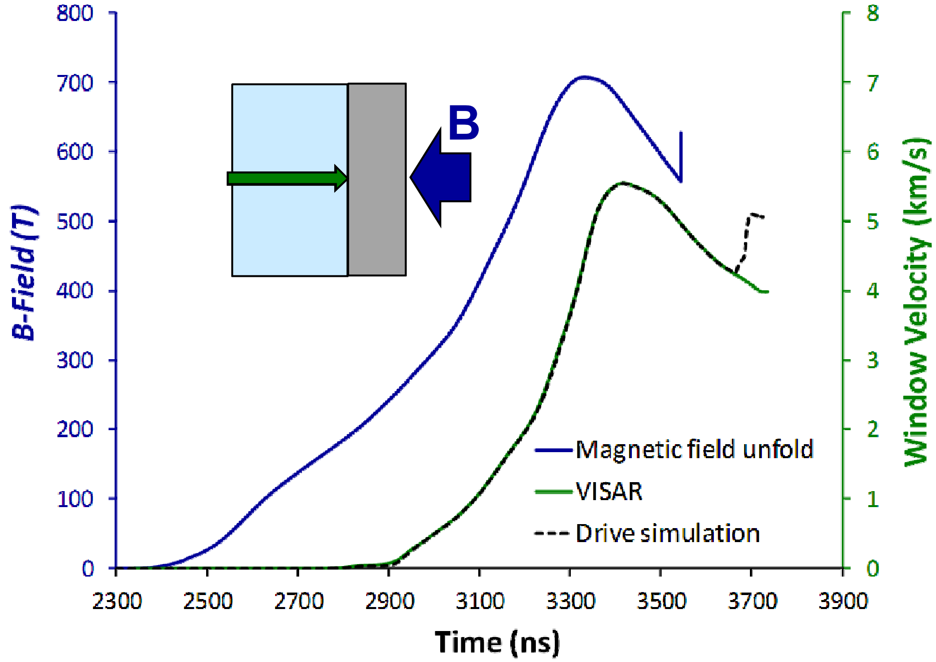
Determine an effective G over unloading and a transition strain consistent with Y:

$$G_{eff} = G\left(1 - \frac{\varepsilon_m - \varepsilon}{\varepsilon_m - \varepsilon_t}\right)^p$$

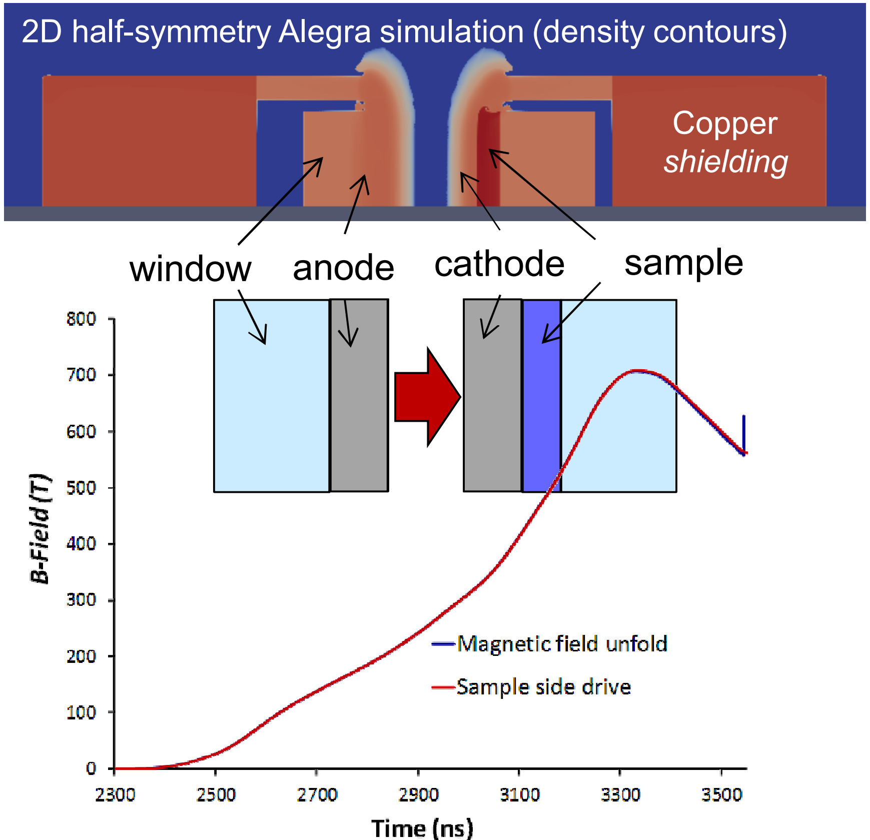
$$\varepsilon_t = \varepsilon_m - \frac{Y}{G}\left(\frac{p+1}{p}\right)$$

Determination of sample side B-Field

- 1-D "unfold" of drive B-Field
  - MHD hydrocode coupled with Dakota optimization package
    - Sesame 3700 + LMD

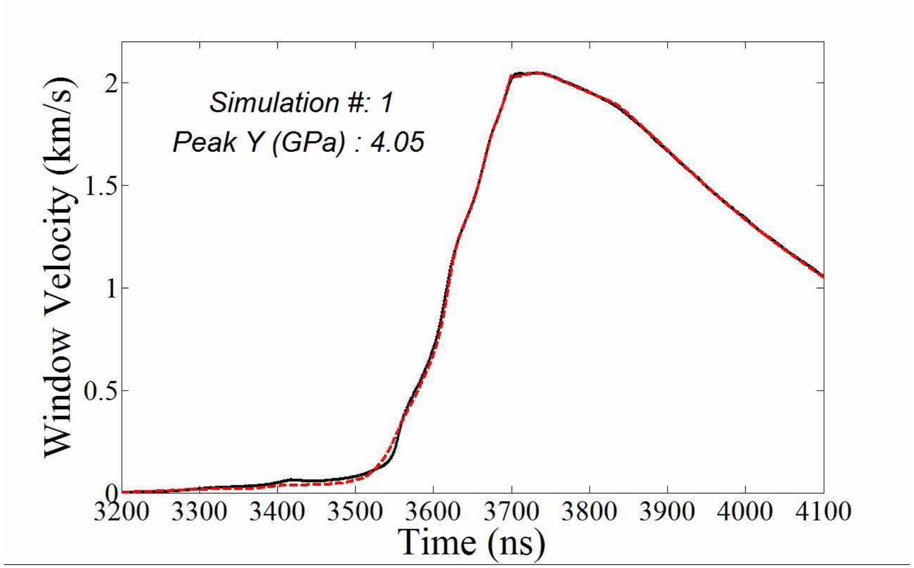


- 2D current driven simulations determine sample side B-Field



Monte-Carlo UQ methodology

- Allow experimental uncertainties and model parameters to vary by Monte-Carlo statistics
  - Automate the analysis for each statistical variation
    - Run window and *in situ* simulations
    - Apply the transfer function
    - Perform Lagrangian analysis
    - Calculate strength including attenuation and pressure corrections



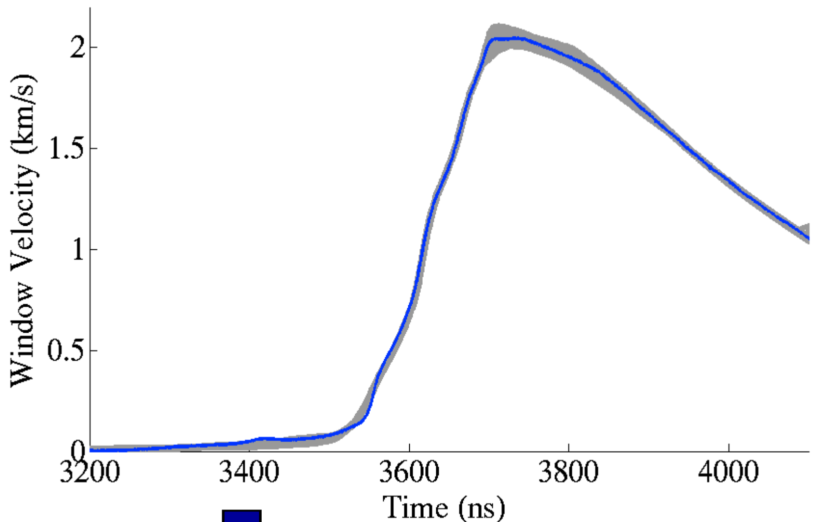
- Experimental variance
  - Thickness : ± 3 μm
  - Relative timing: ± 1 ns
  - VISAR uncertainty: 0.2 %

- Model variance
  - Y_0 : 5%
  - β, n, A : 20%
  - ρ_0, B: 2%
  - ν: 0.3 ± 0.1
  - p: 1.0 ± 0.5

$$Y = Y_0\left[1+\beta\left(\varepsilon+\varepsilon_i\right)\right]^n\left[1+A\frac{P}{\eta^{1/3}}+B\left(T-300\right)\right]$$

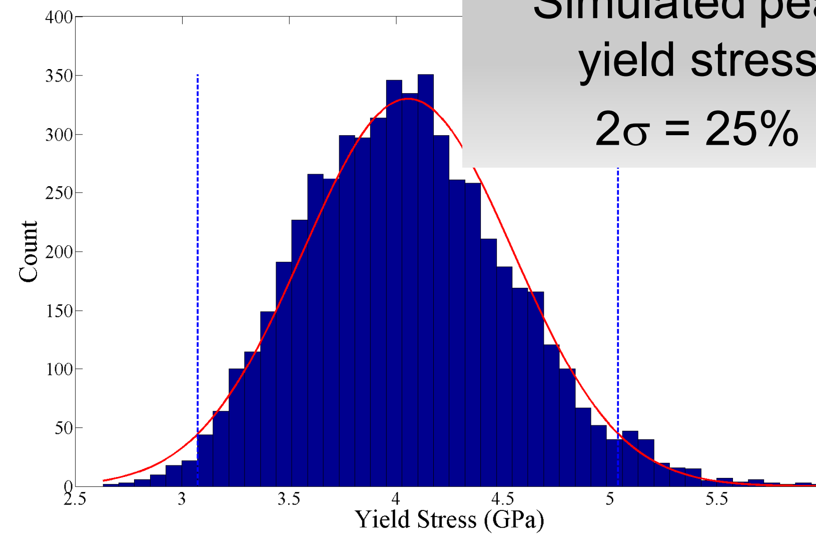
10,000 Runs later, distributions are obtained for Y and P

Variation from Monte-Carlo

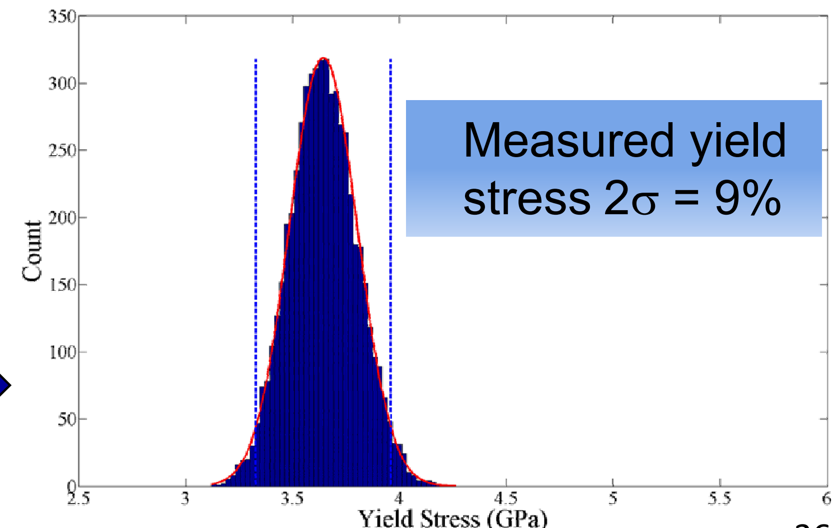


Transfer function/strength analysis applied to each simulation

Simulated peak yield stress $2\sigma = 25\%$

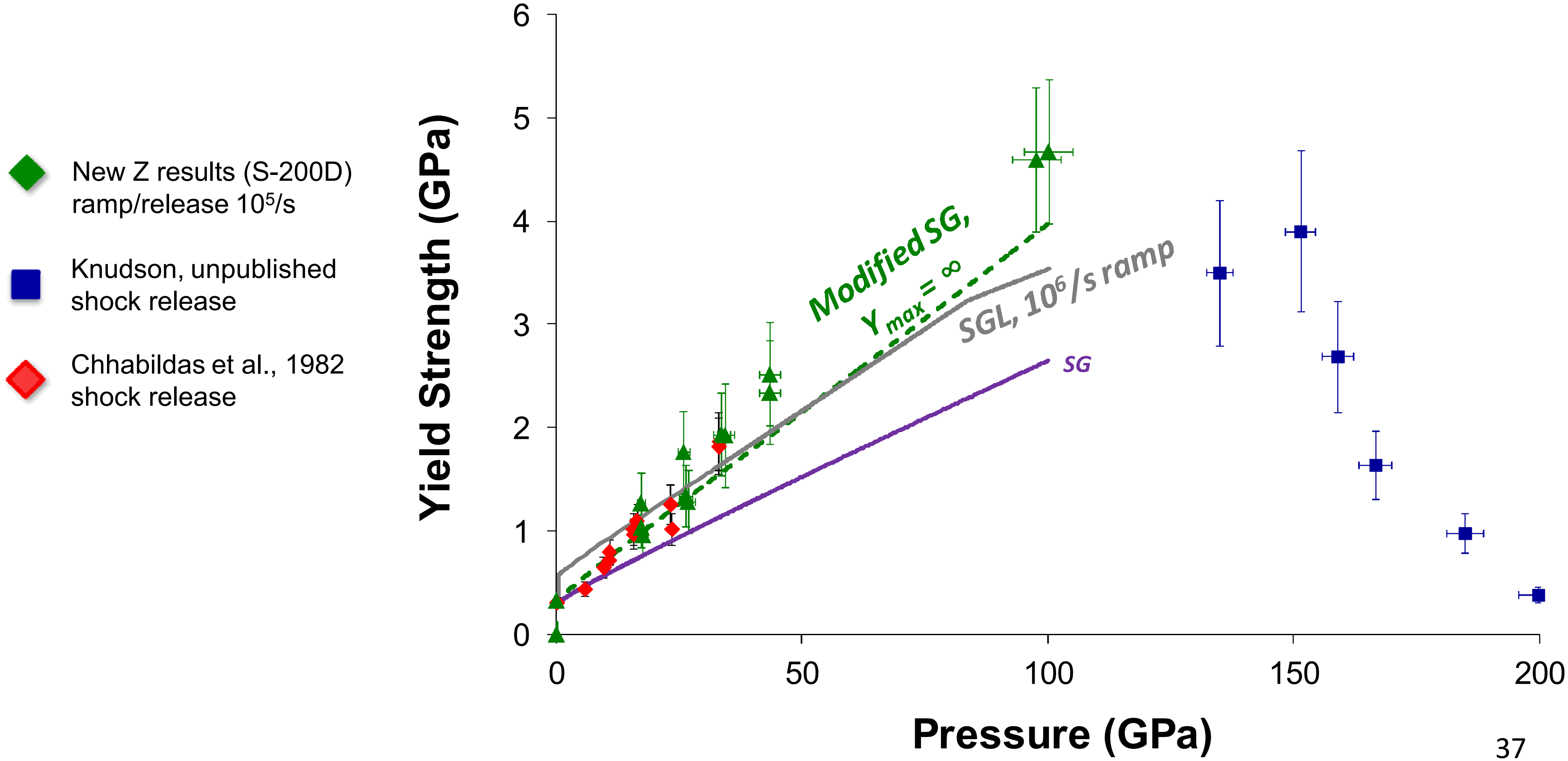


Measured yield stress $2\sigma = 9\%$



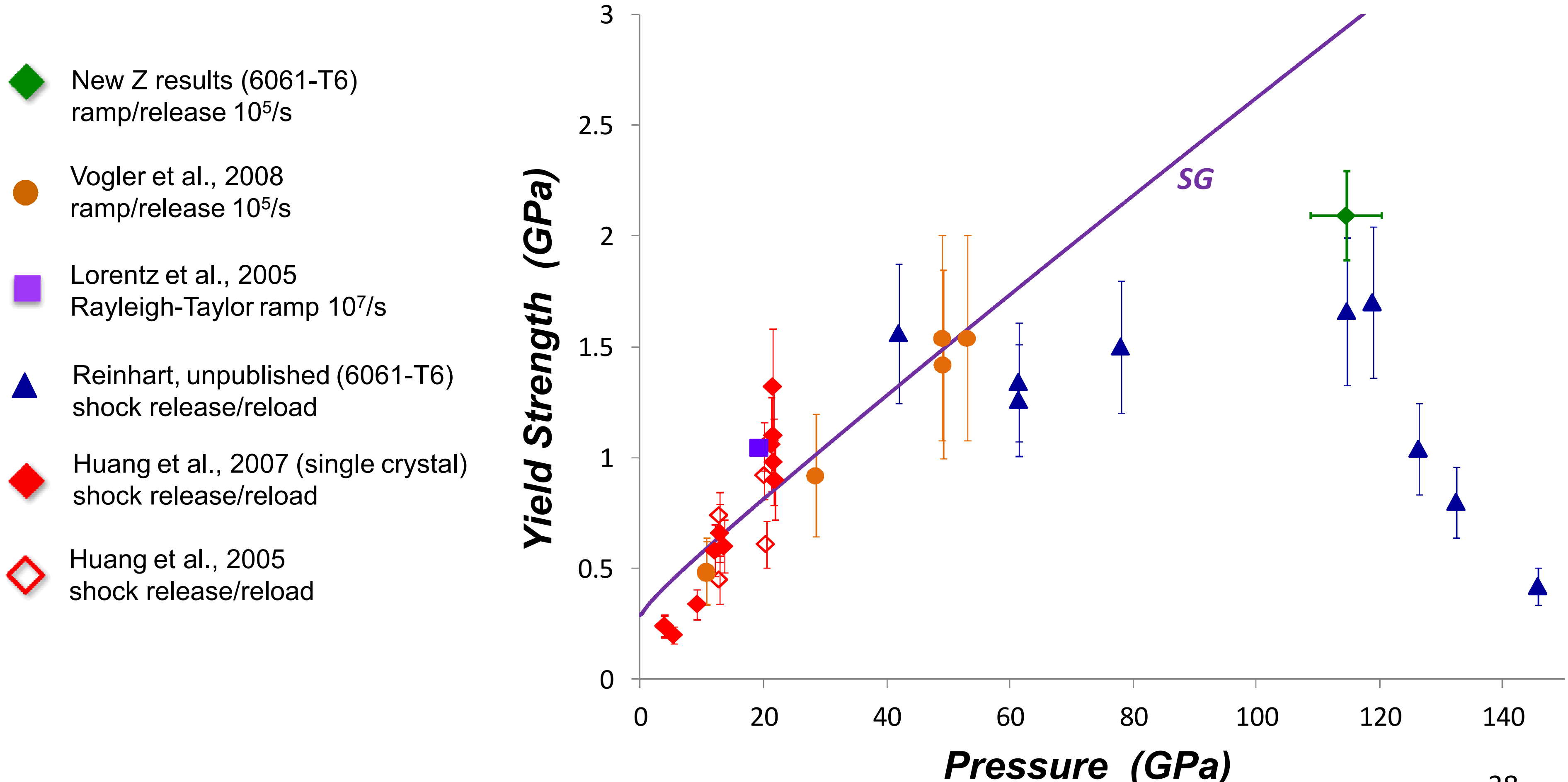
Beryllium strength

- Shock data in good agreement with ramp until thermal softening decreases the strength approaching shock melt.



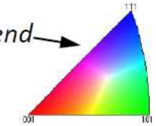
Aluminum strength

- Shock, ramp, RT data all in good agreement



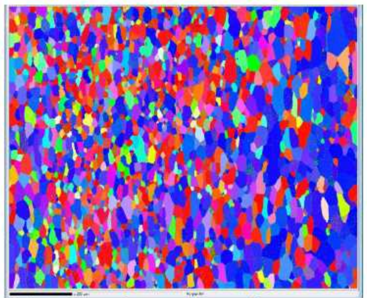
NNSA Ta characterization

Orientations colorized by IPF legend

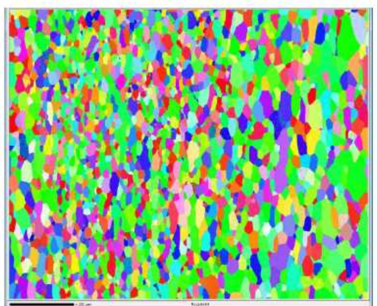


EBSD result

2. Center 'y-normal' middle of plate

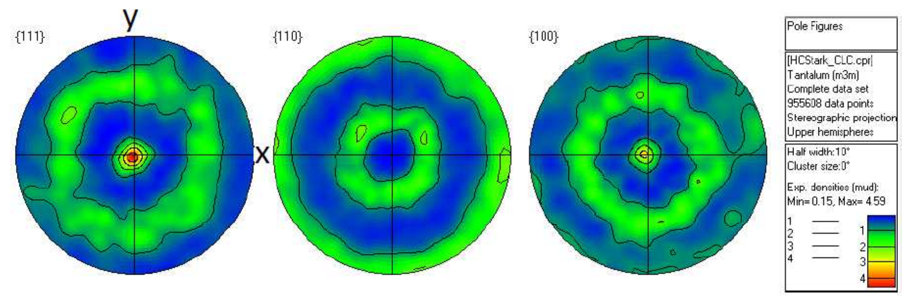


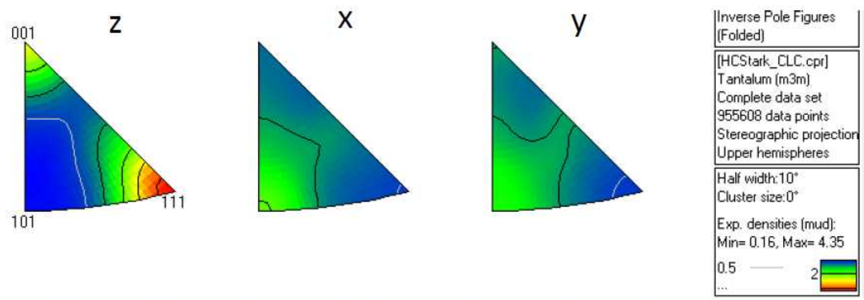
Z- normal to rolling direction



X- 'rolling' direction

Y- transverse direction





- <110> '*α-fiber*' rolling direction texture (typical for BCC metals [Kocks, 1998]) spread across x-y plane, presumably due to clock rolling
- Tendency toward <111> '*γ-fiber*' normal texture , although texture component spreads along <001>-<111> axis in IPF's with intensities found at the poles