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Strength of tantalum under high ramp compression

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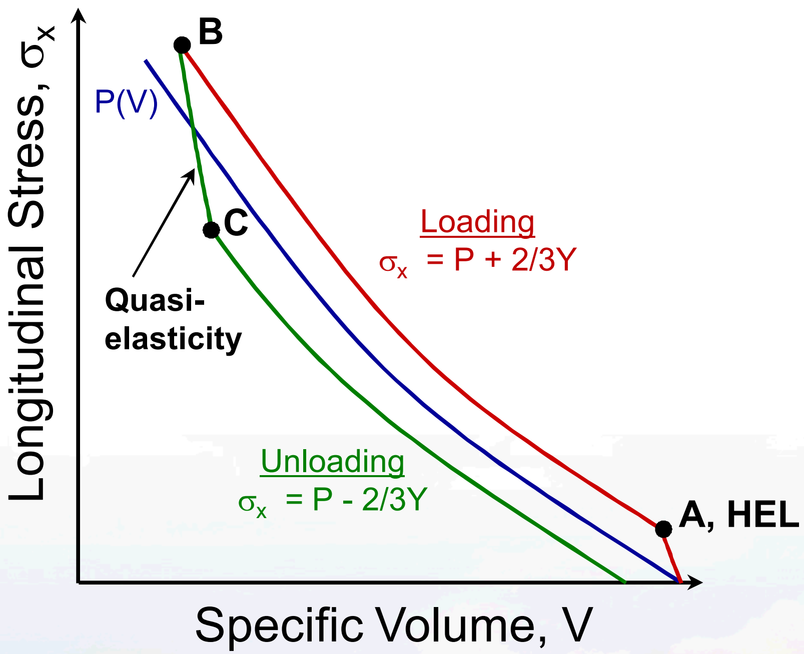
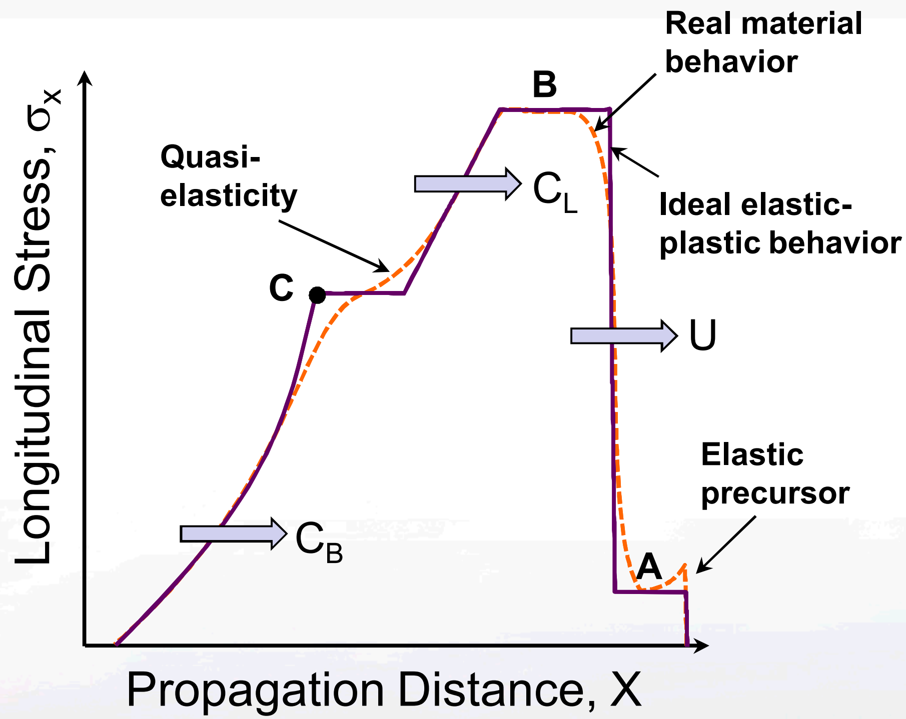
Outline

- **General introduction**
  - Extracting strength from unloading profiles
  - Problems associated with analyzing high impedance materials such as tantalum
- **Methodology for removing window effects**
  - Allow a dynamics code to the handle the complicated wave interactions
  - Map the experimental window profiles into *in situ* waveforms
- **Results from a 120 GPa Z experiment**
- **Design of future experiments**
  - Preliminary results (60 GPa)

Analysis of unloading profiles for strength is based on the elastic-plastic model





- **Measurement of the quasi-elastic unloading response provides information on yield strength at peak stress**

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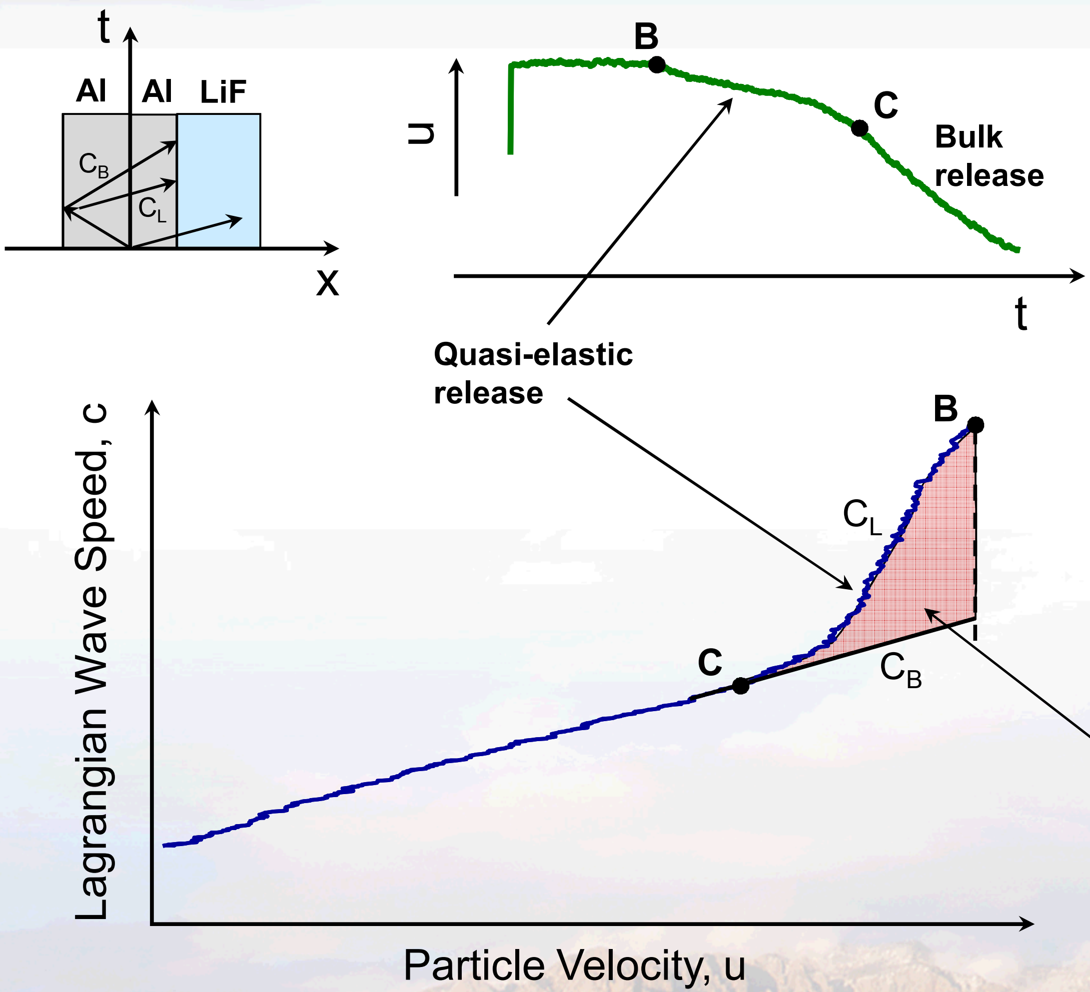
Measured unloading wave velocities may *be used to* estimate the strength



Assumptions

- Elastic-plastic model

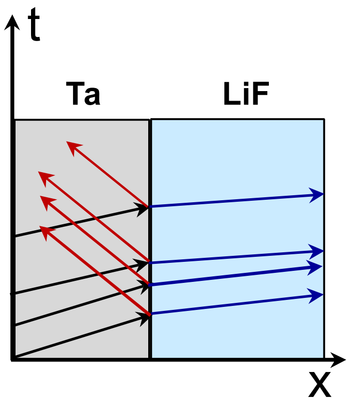
$$d\sigma(\varepsilon) = dP(\varepsilon) + \frac{4}{3} d\tau(\varepsilon)$$

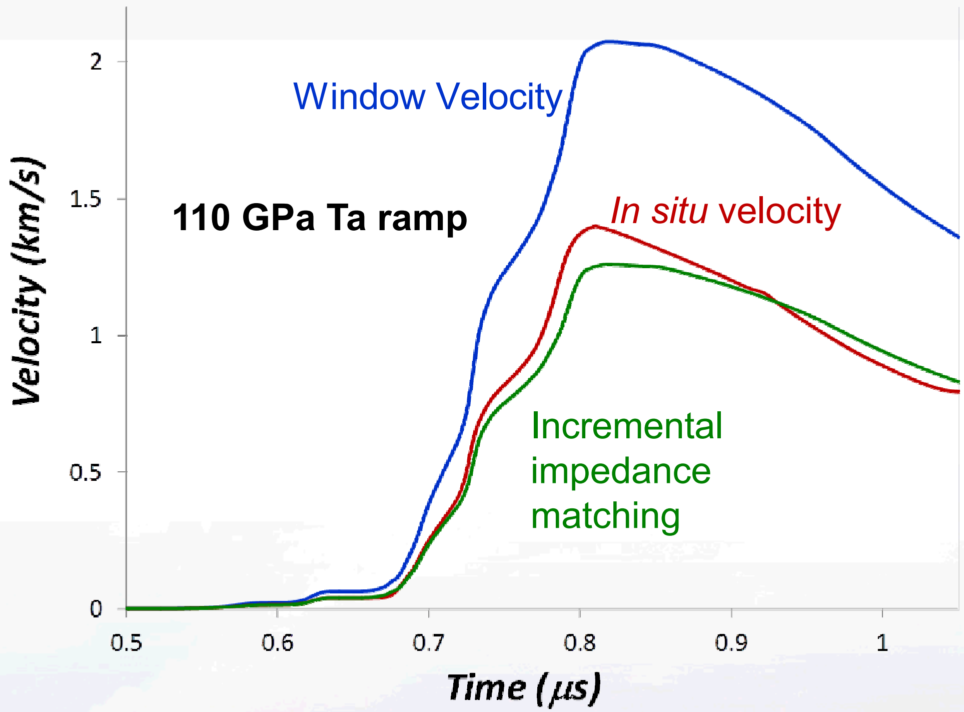
$$\frac{d\tau}{d\varepsilon} = \frac{3}{4}\rho_0\left[c_{\exp}^2 - c_B^2\right]$$

- Rate independent response
- von Mises yield surface
- Flow strength determined from quasi-elastic unloading

$$Y = \frac{3}{4}\rho_0 \int \left[c^2 - c_B^2\right]\frac{du}{c}$$

Window effects on ramp loading





- **Poor impedance match is difficult to account for**
  - Release waves are constantly generated at the window interface which interact incoming ramp
  - Produces non-uniform stress state in the sample
  - Incremental impedance matching can be a poor approximation, particularly at higher stresses

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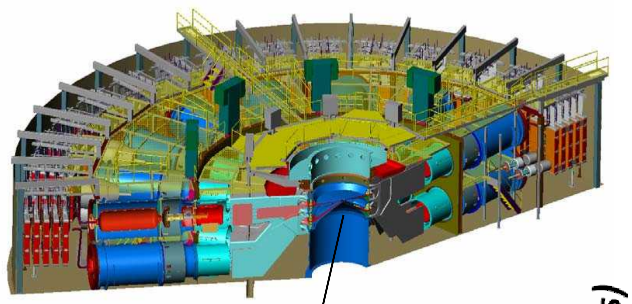
Strategy for removing window effects

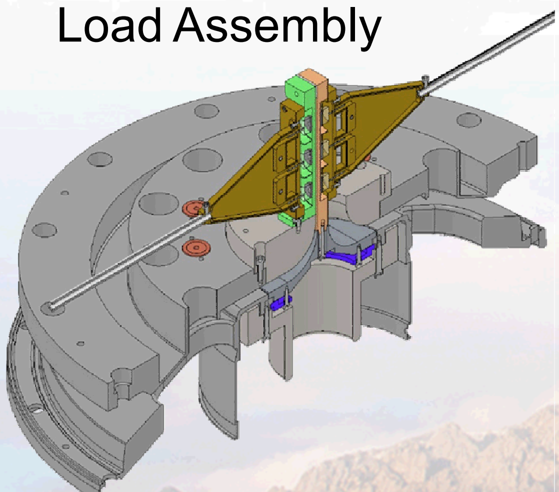
- **Use simulations to account for the wave interactions**
  - LASLO: A lightweight 1-D Lagrangian wave dynamics code with MHD
    - Standard EOS (tabular, Mie-Gruneisen, etc.)
    - Strength using a rate-independent Steinberg-Guinan formulation, modified to include quasi-elasticity
- **Use an optimization package to generate a best fit of the experimental window profiles and estimate the correction**
  - Perform forward simulations of both waveforms to determine the optimal B-Field, EOS, and strength parameters
  - Run the forward *in situ* simulations to determine the response when the LiF is replaced by Ta
  - Use the simulated window and *in situ* velocities to determine the transfer function between the two
  - Apply the transfer function to the experimental data to determine its *in situ* response

Analysis of Z1904

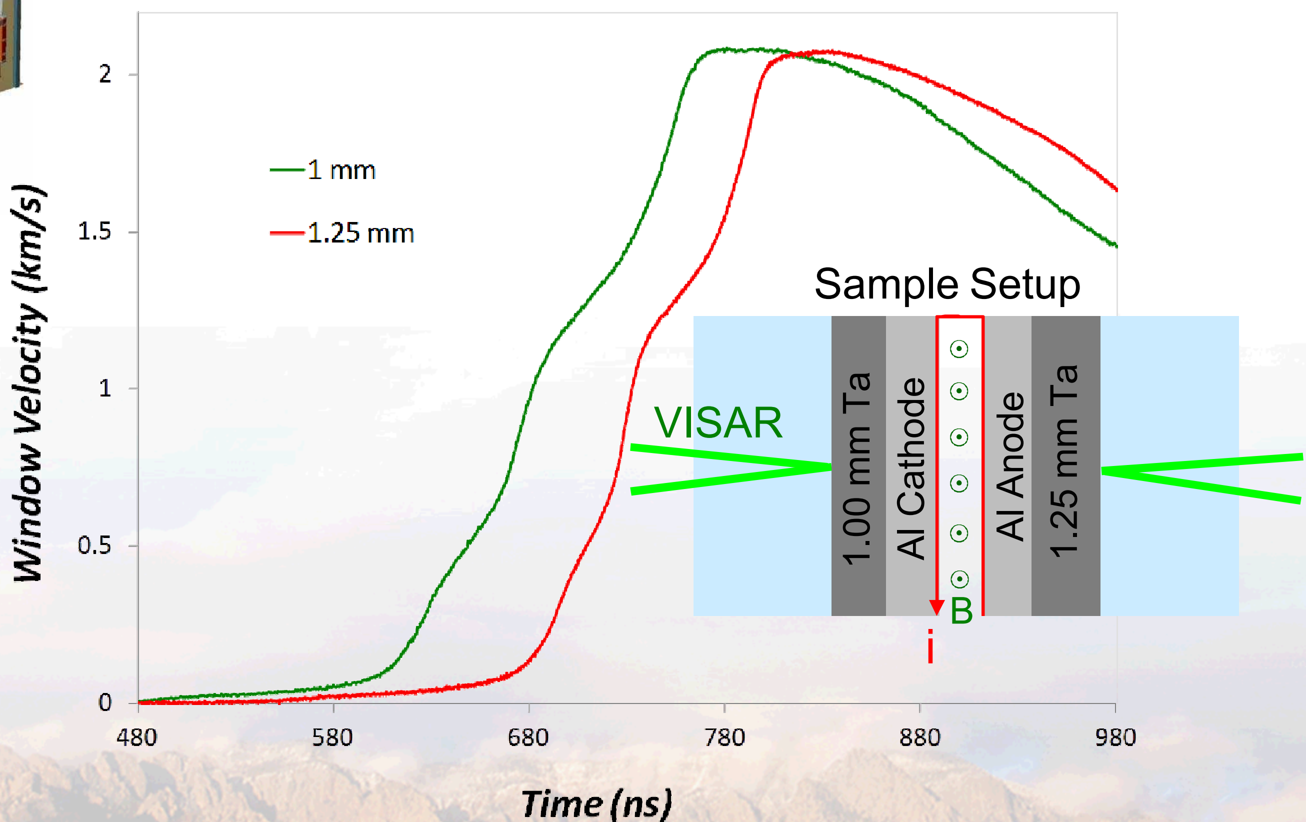
Z Accelerator



Load Assembly



- **20 mm stripline to 110 GPa**
  - Commercial Ta samples, LiF windows



Quasi-elastic strength model

- **Rate-independent Steinberg-Guinan quasi-elastic strength model**

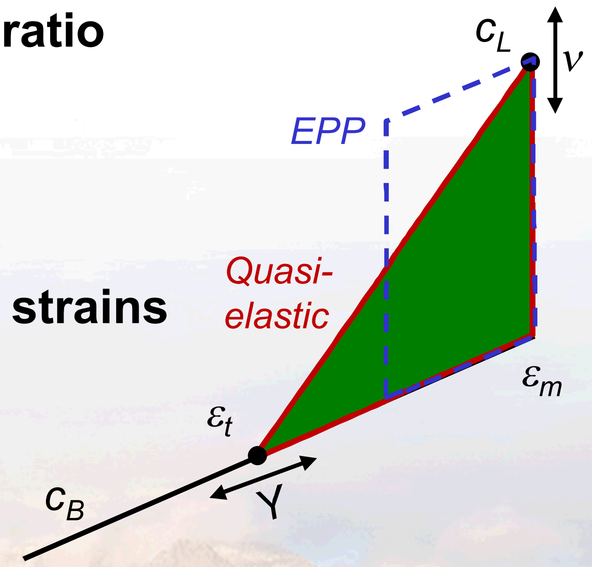
$$Y = Y_0\left[1+\beta(\varepsilon+\varepsilon_i)\right]^n\left[1 + A\frac{P}{\eta^{1/3}} + B(T-300)\right]$$

- **Determine shear modulus from EOS and Poisson's ratio**

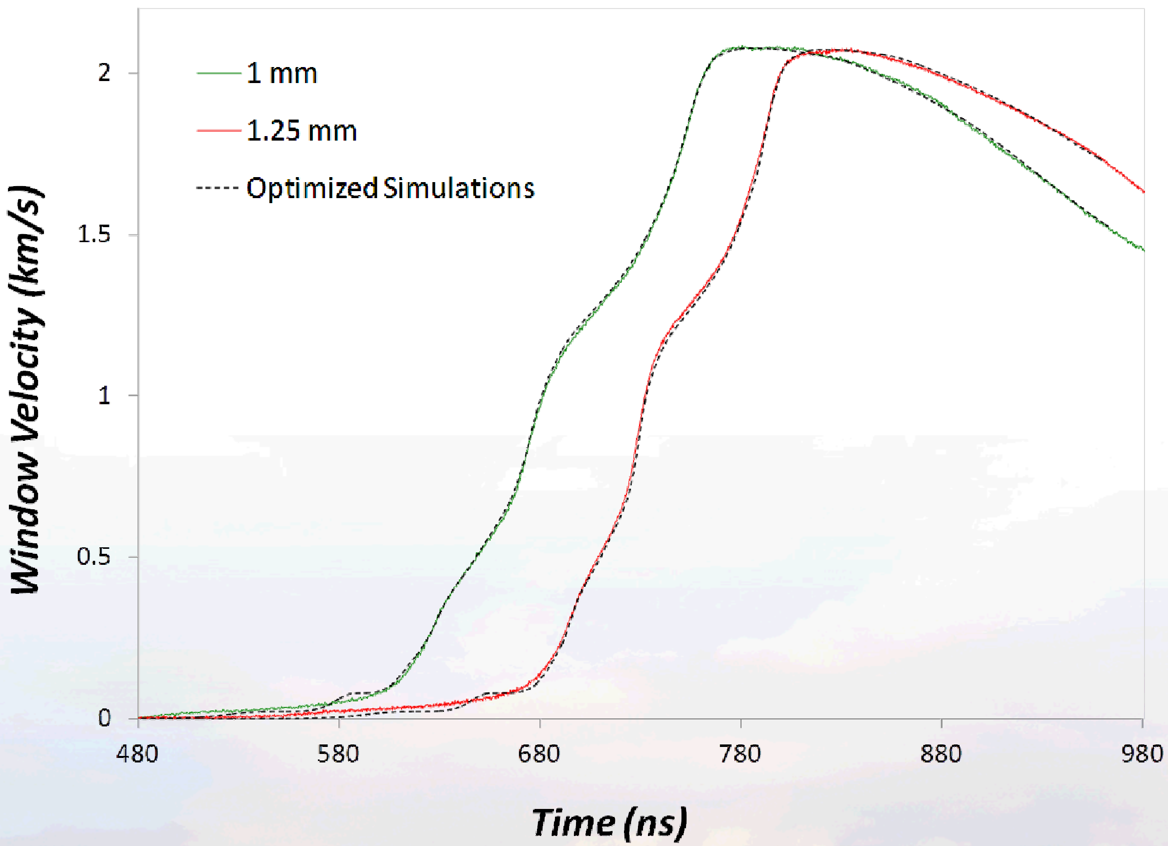
$$G = \frac{3K(1-2\nu)}{2(1+\nu)}$$

- **Vary shear modulus linearly from peak to transition strains**

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



1) Optimized simulations



- **50 control points to define the 1-D current**
  - Interpolation scheme coupled with low pass filter
- **Independent time shifts of up to 0.5 ns**
- **Mie-Gruneisen EOS**
  - Small changes to c_0 and s
- **Quasi-elastic strength model**
  - Optimize ν and strength parameters

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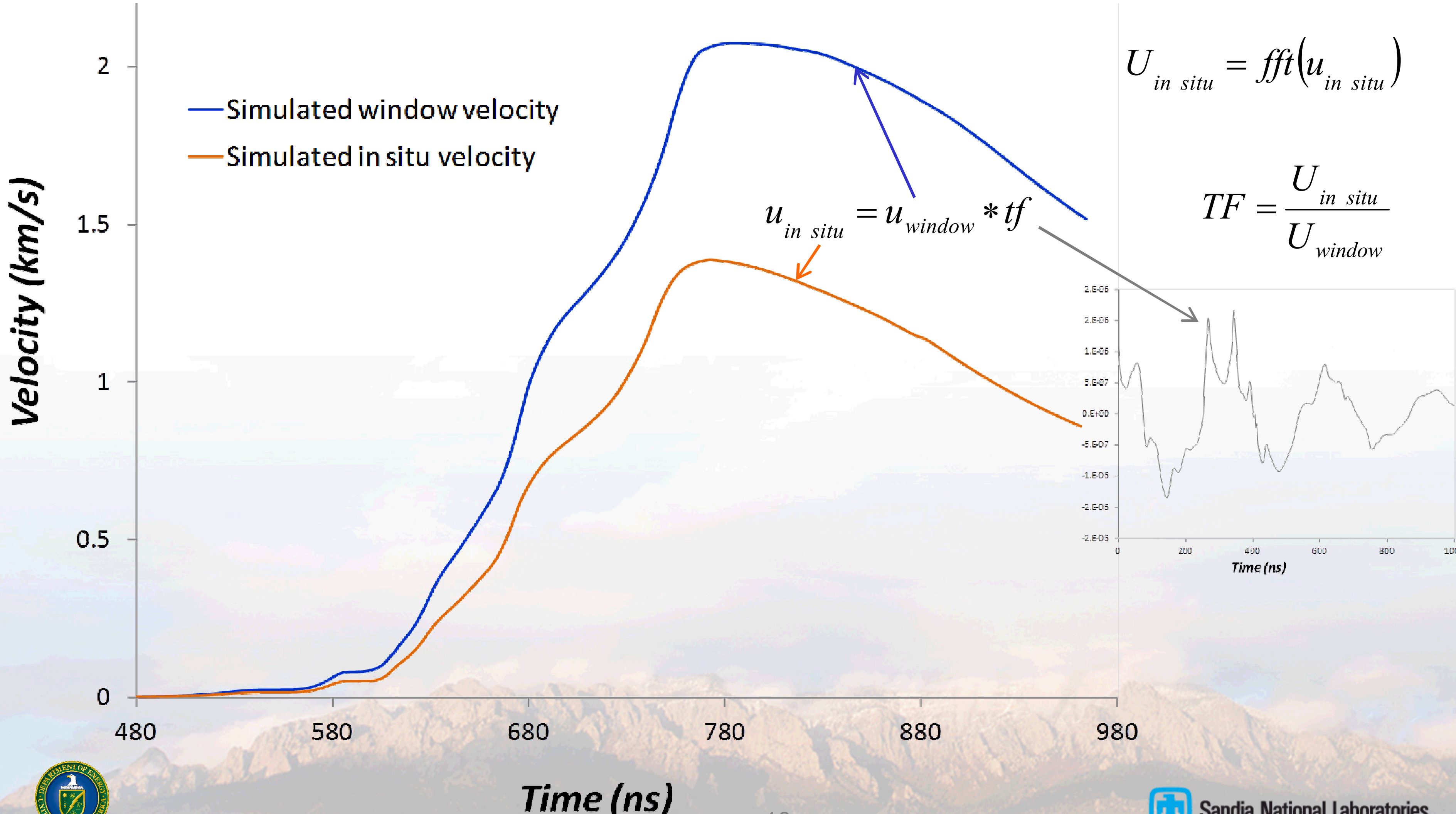
2) Run *in situ* simulation and 3) determine the transfer function



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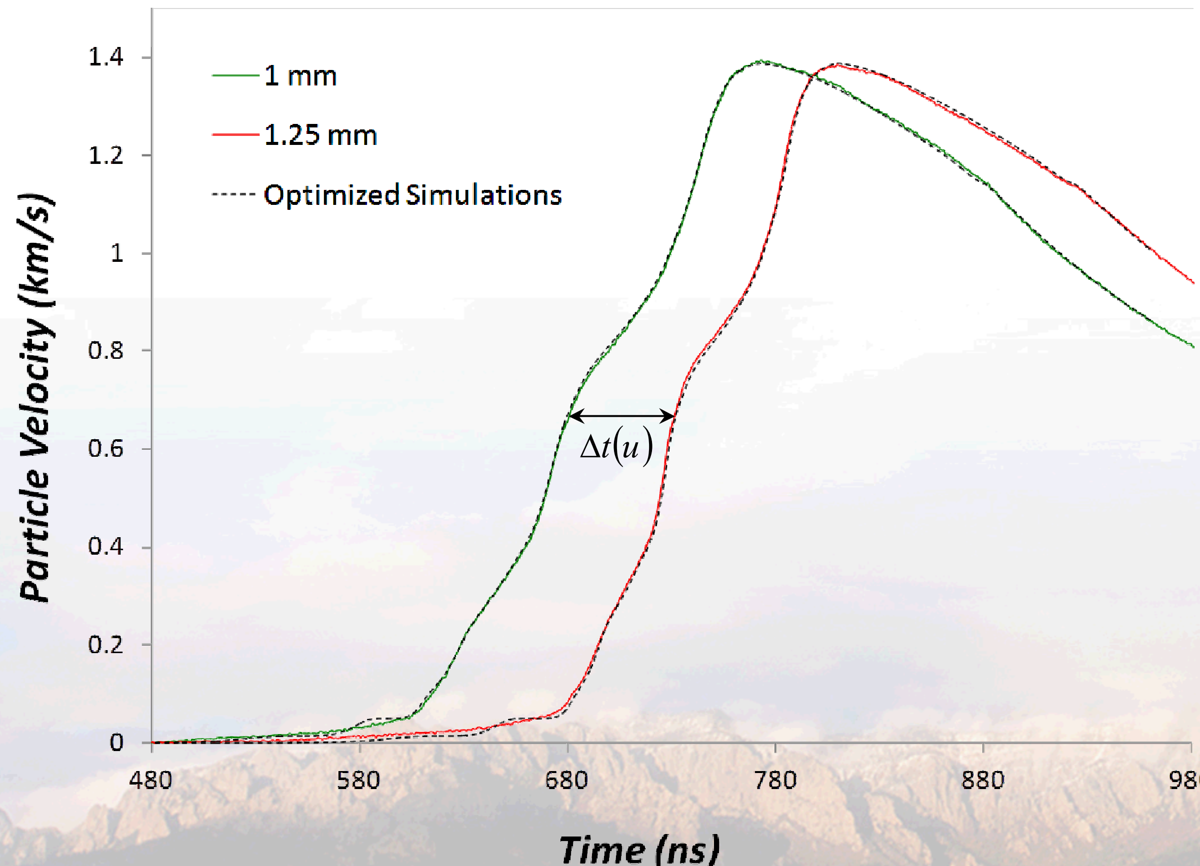
4) Use the transfer function to determine the *in situ* experimental profiles

- **Features not captured in the optimized simulations are transferred through to the *in situ* profiles**
  - Can now perform standard Lagrangian analysis



$$c(u) = \frac{\Delta x}{\Delta t(u)}$$

$$d\sigma_x = \rho_0 c du_p$$

$$d\varepsilon_x = \frac{c}{du_p}$$

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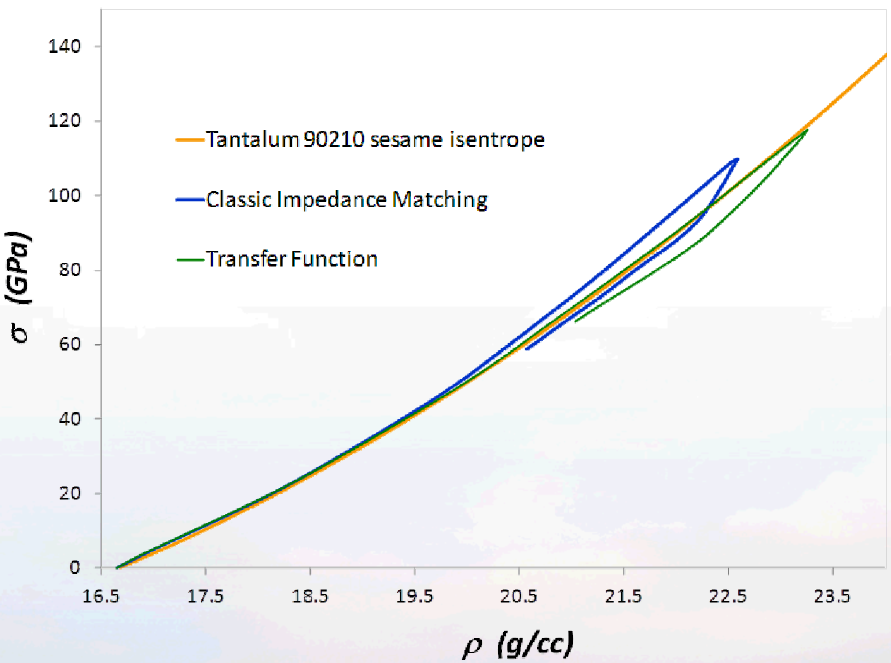
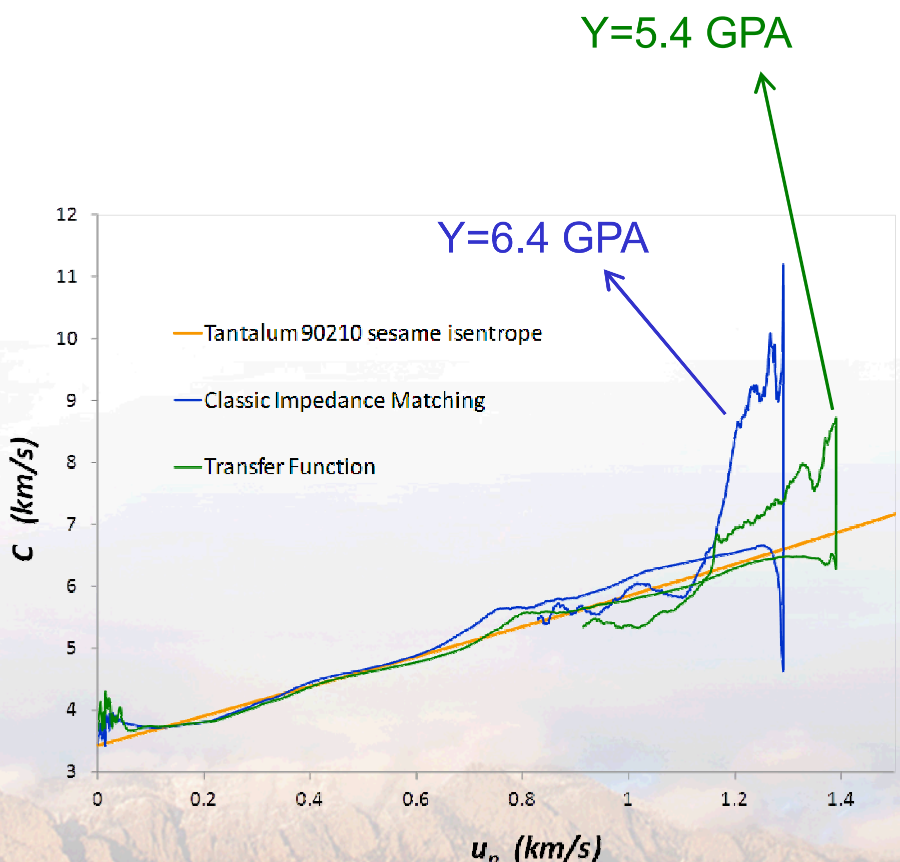
Z1904 Results

- **Results are in good agreement with the tabular isentrope (and previous experimental data)**





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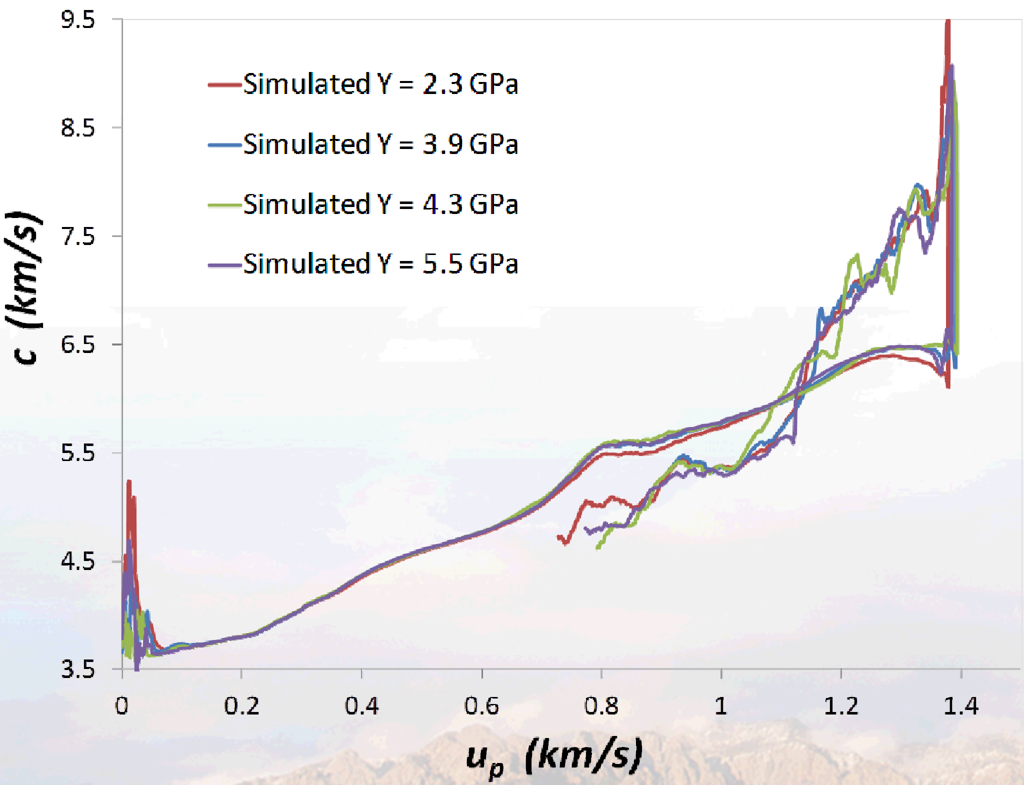
Analysis appears to be model independent

- **As long as the optimized simulations are "close", the experimental data seems to dictate the response**



Mean Y:
5.3 GPa

Standard Deviation:
0.2 GPa (4%)

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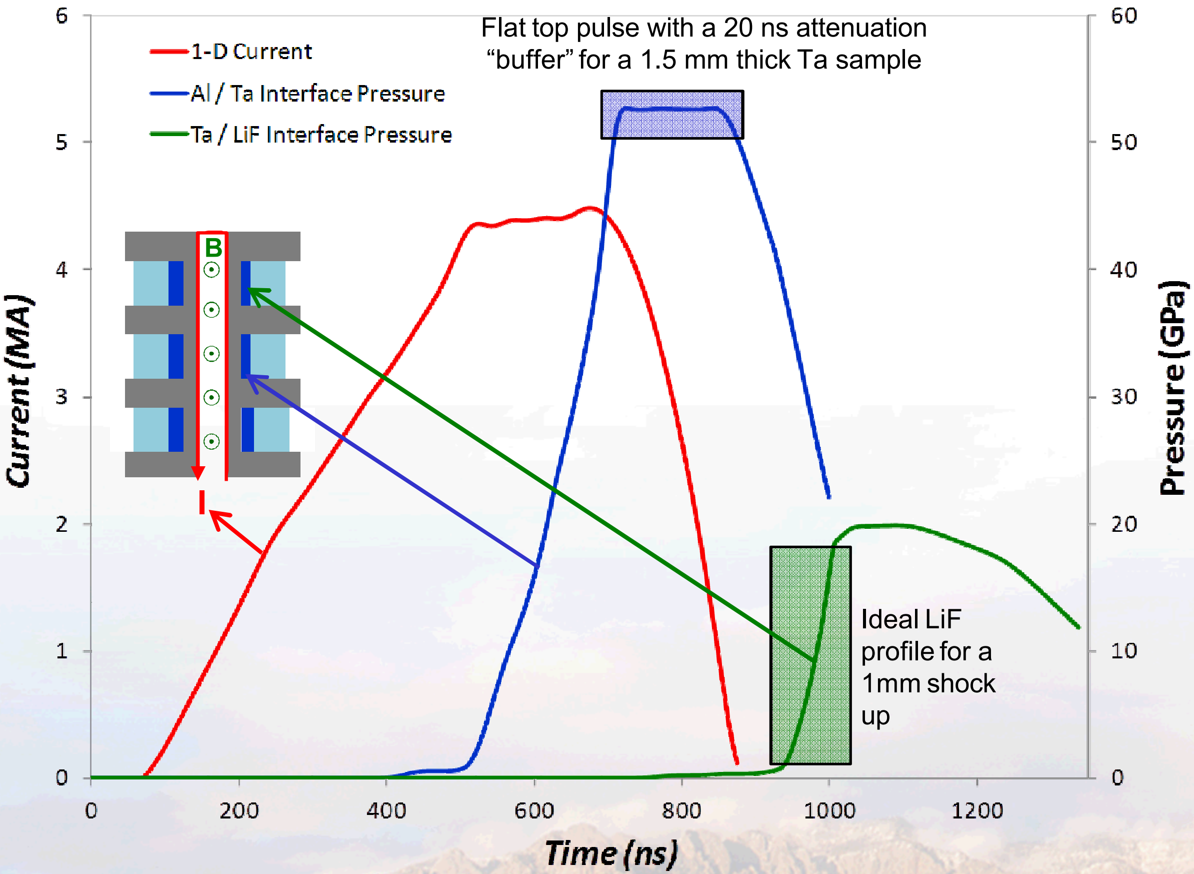
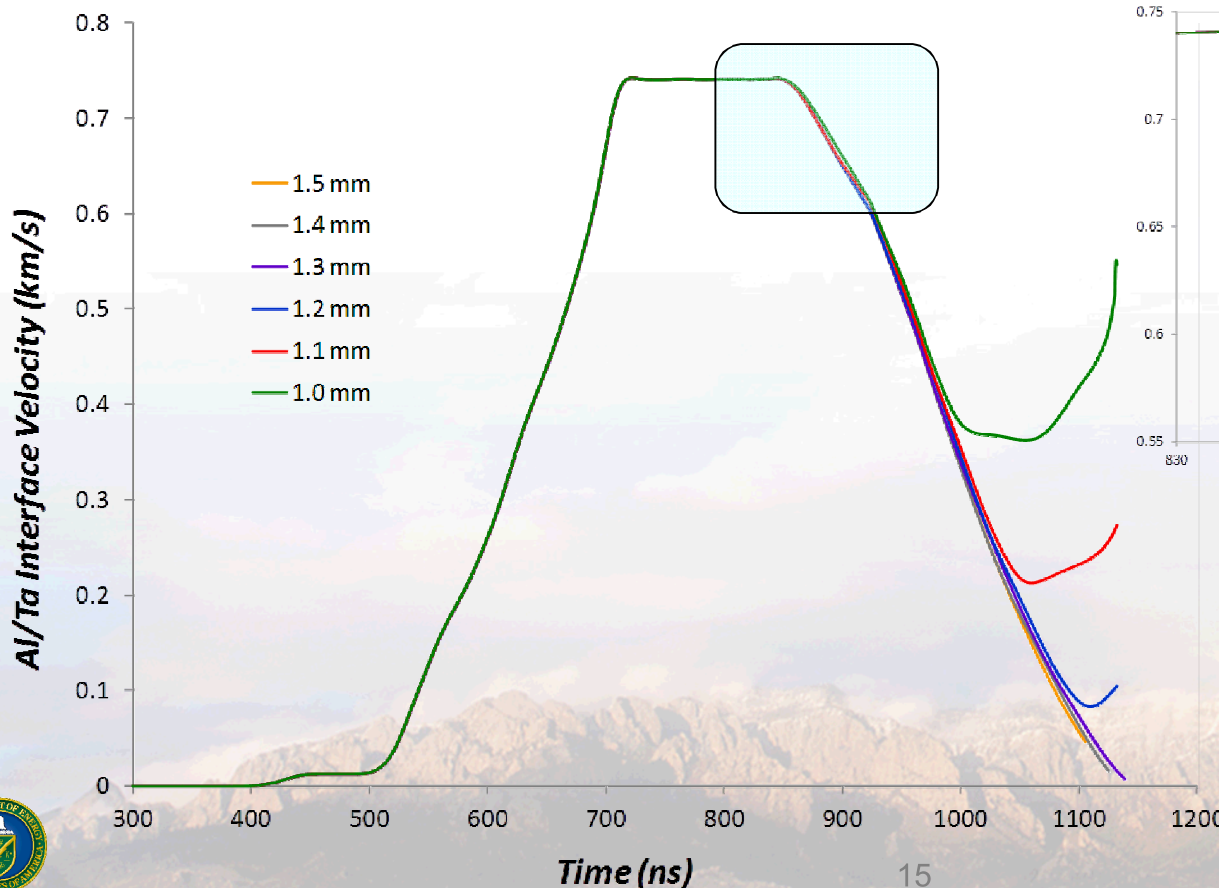
Design of new experiments

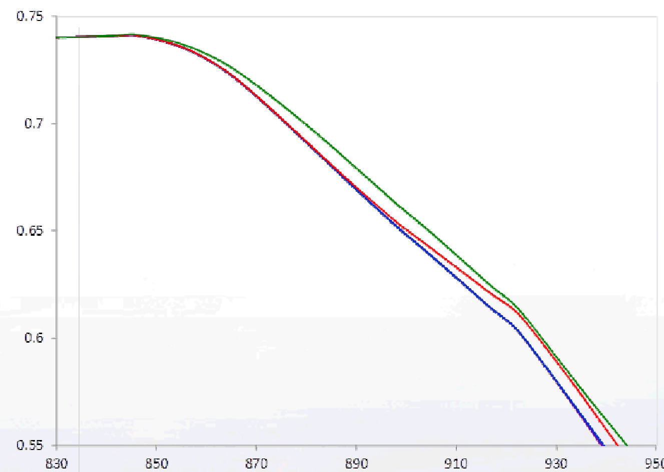


- **50 GPa peak stress in 1.5 mm thick Ta**
- **Used optimized simulations to generate a drive current such that:**
  - Flat top pulse such that there is 0 attenuation in the in-situ case
  - 1 mm shock up distance in the window
  - Tried to pick a realistic tail current fall off

Reverberation is taken into account

- **Sample thicknesses can then be chosen to avoid corruption of the unloading wave (reverberation)**
  - 1.2 mm is the minimum thickness to maintain consistency through the quasi-elastic unload





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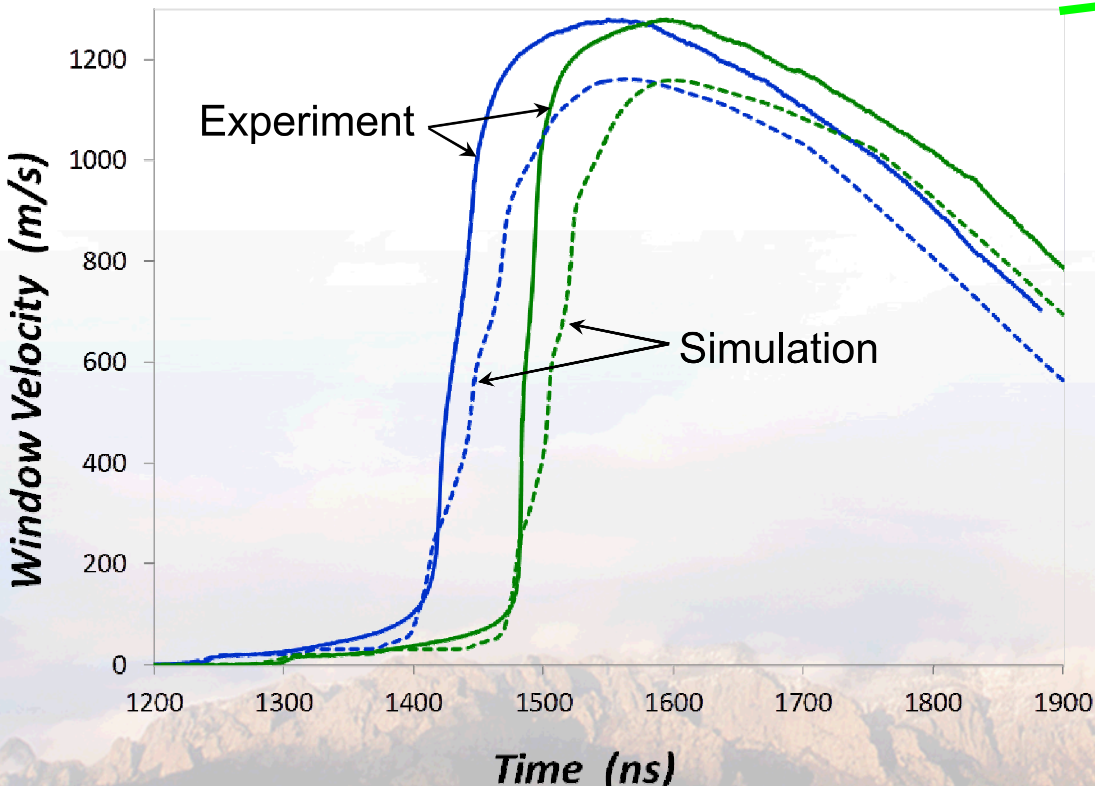
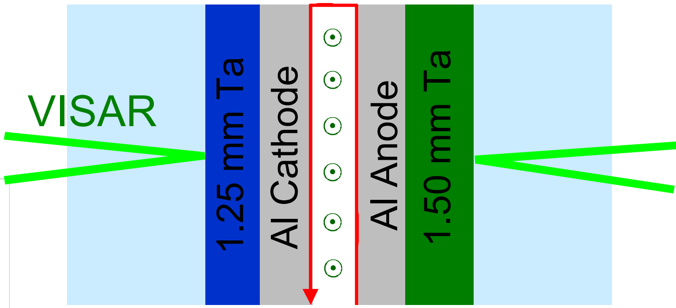
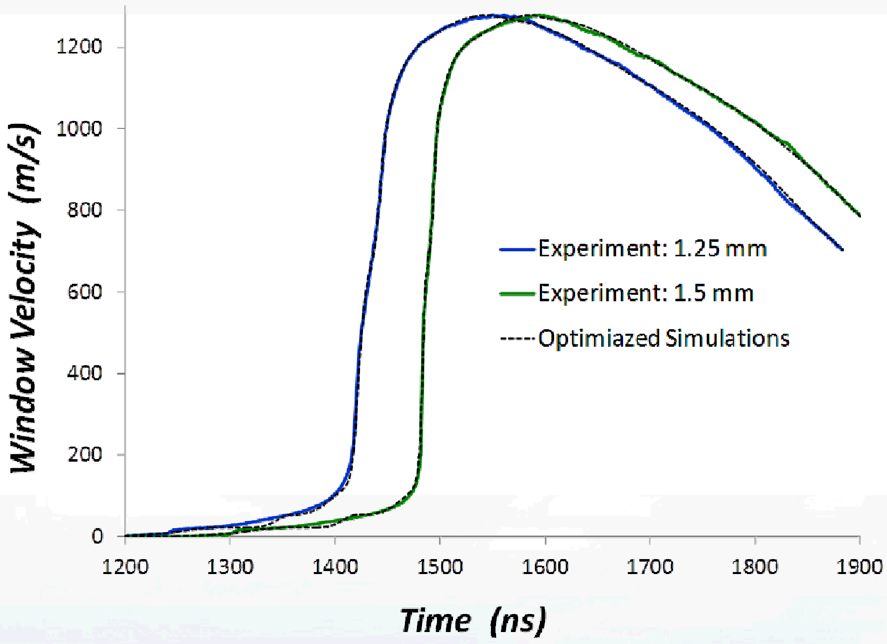
Preliminary Z2296 shot results

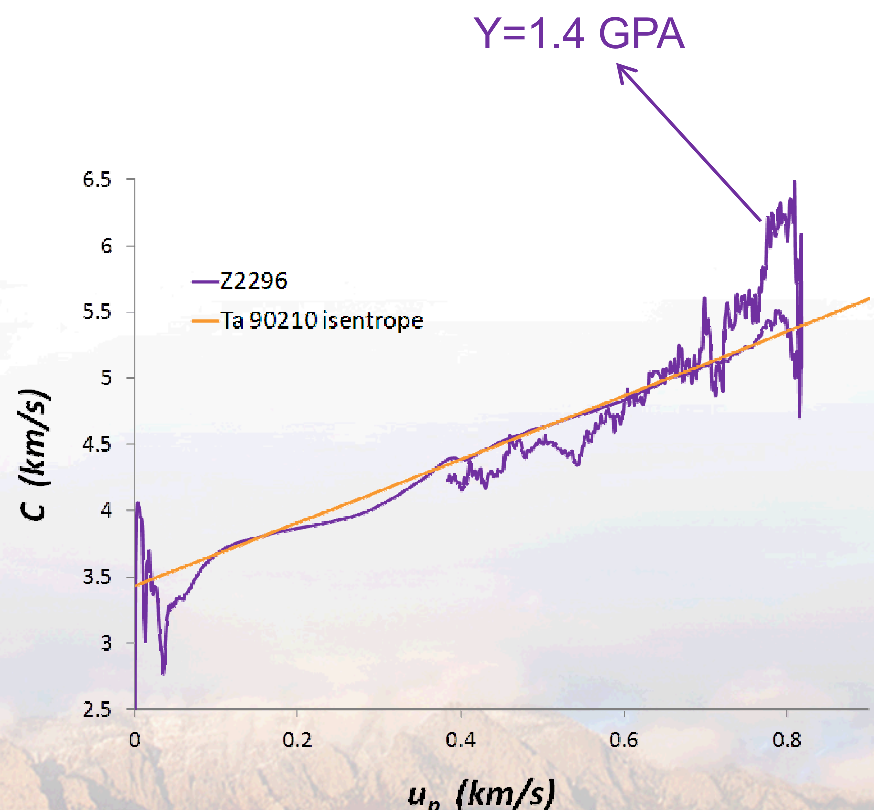
- **Current was higher than predicted**
  - Steeper waveforms
  - Attenuation is negligible





Optimization and Lagrangian analysis





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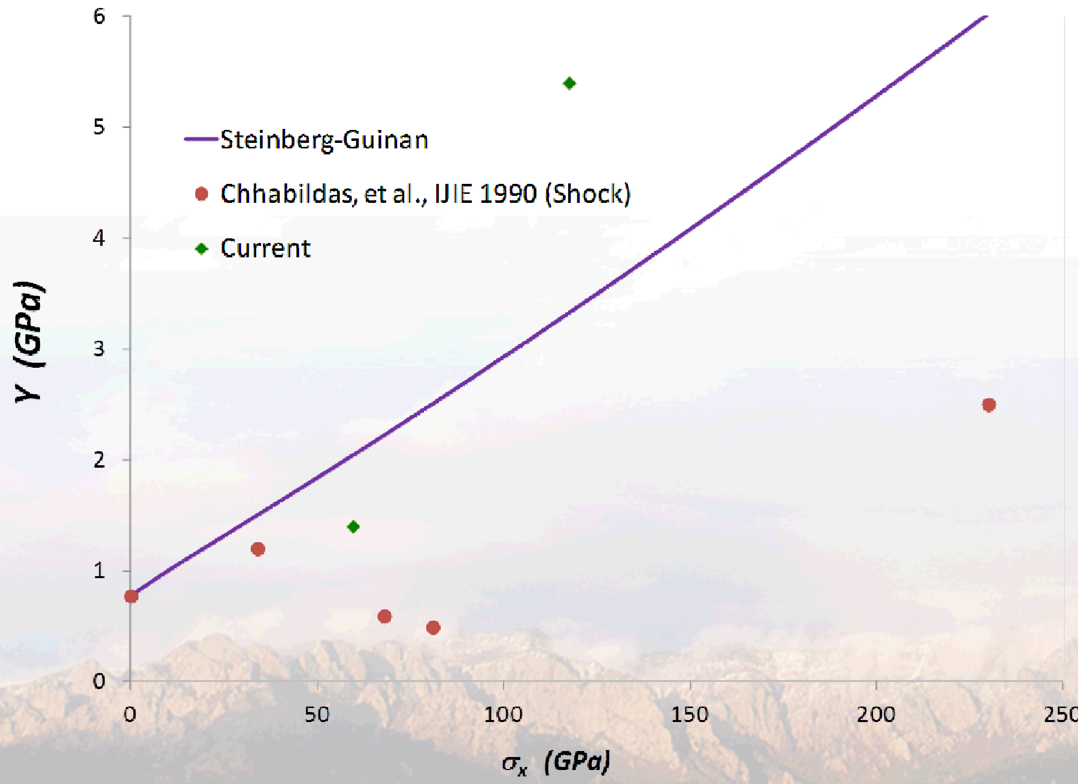
Measured strength

- Lower pressure point (60 GPa) is in reasonable agreement with shock data
- Higher pressure point (120 GPa) suggests tantalum is significantly stronger under ramp compression



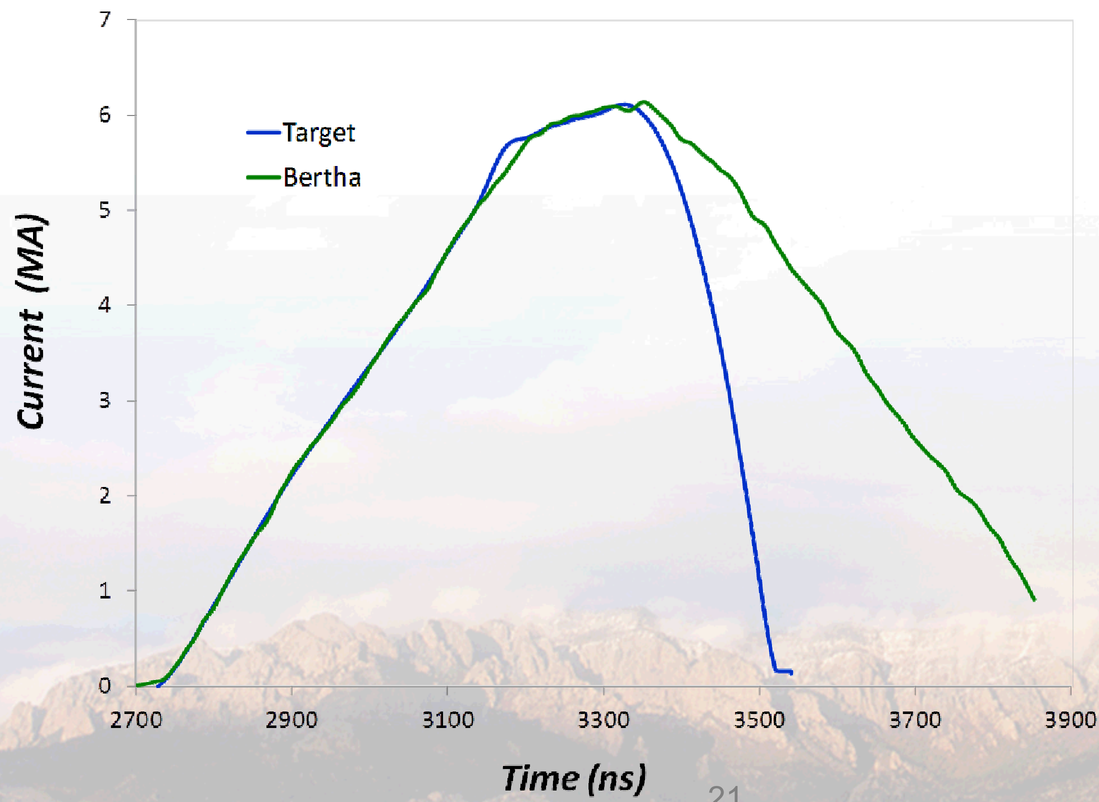
Future work and challenges

- **Go to higher pressures**
  - Becomes extremely difficult to avoid reverberation issues at pressures above 2 Mbar
    - In theory the transfer function methodology should still provide accurate results, but it is not clear if this will prove to be true in practice
- **Explore the possibility of using an input/output configuration**
  - Make a drive measurement on one panel and perform a forward calculation to estimate the input to the sample
    - The increased thickness difference compared to the uncertainty in the forward calculation could result in smaller overall errors
    - Simulations will require a different MHD boundary condition which allows the conservation of current while allowing the magnetic fields to vary
  - For sample materials with high wavespeeds (eg. Diamond), the current configuration will result in very large uncertainties.
- **Quantify uncertainties**
  - Monte Carlo simulations

Additional Slides

Pulse shaping

- **Problem simultaneously maintaining the steep rise along with the "flat top" portion of the pulse.**
  - Loose ~ 30 ns off of the flat top
  - An attempted correction is made by extending time at which peak current occurs



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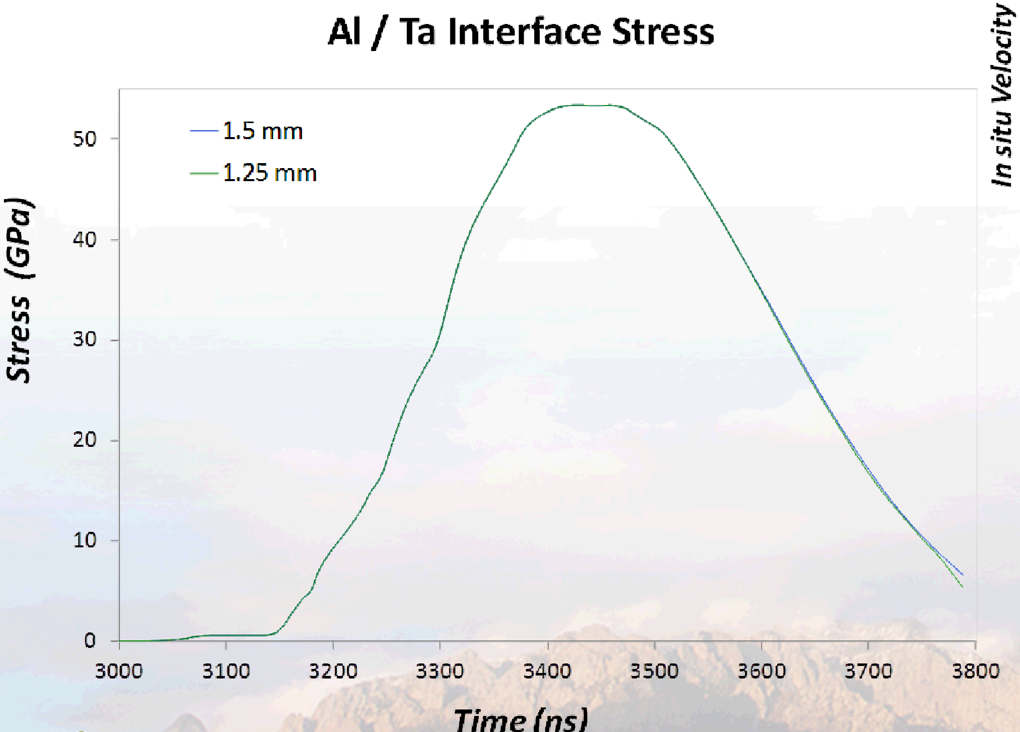
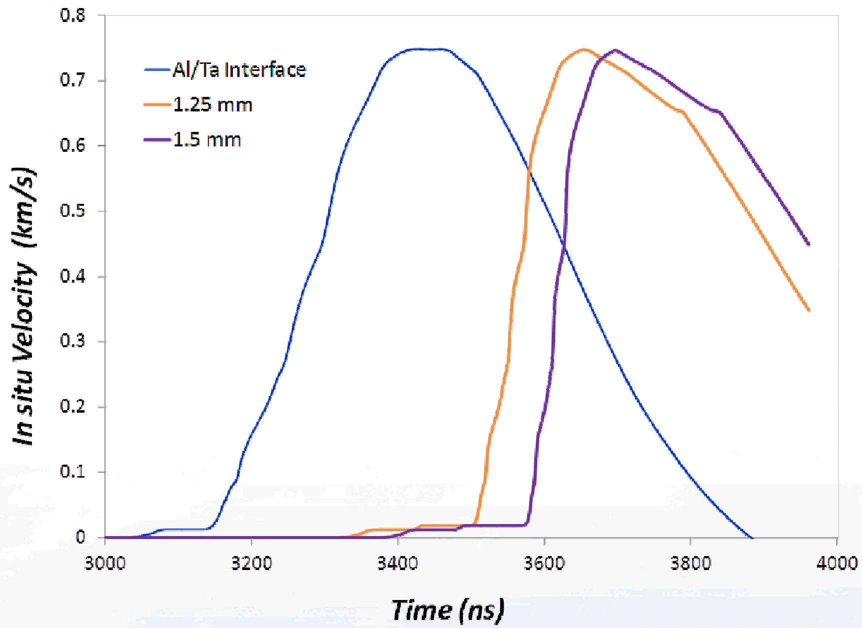
- **Reverberation is still avoided in the 1.25 mm thick sample**





- **Negligible attenuation over 1.5 mm thickness**

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