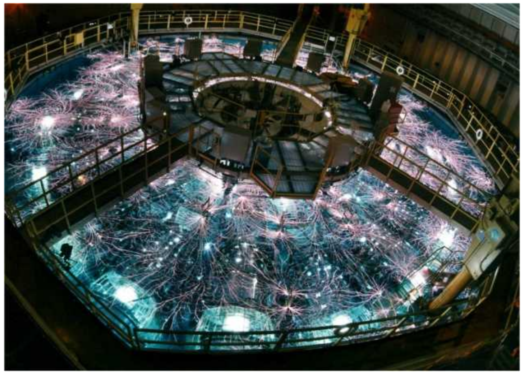
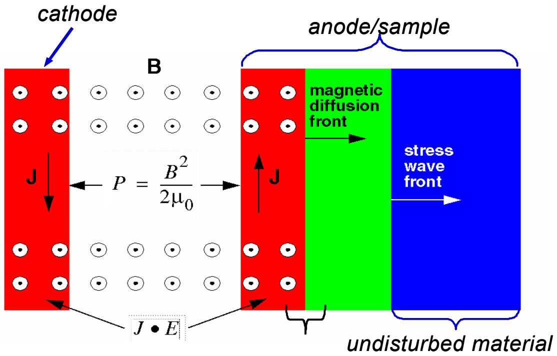
SAND2015-4705C

Mechanical Response of Metals under Dynamic Loading off the Principal Hugoniot and Isentrope

SCCM 2015
Tampa, FL

Chris Seagle
Sandia National Laboratories, Albuquerque, NM





Chris Seagle, (505) 844-0934, ctseagl@sandia.gov

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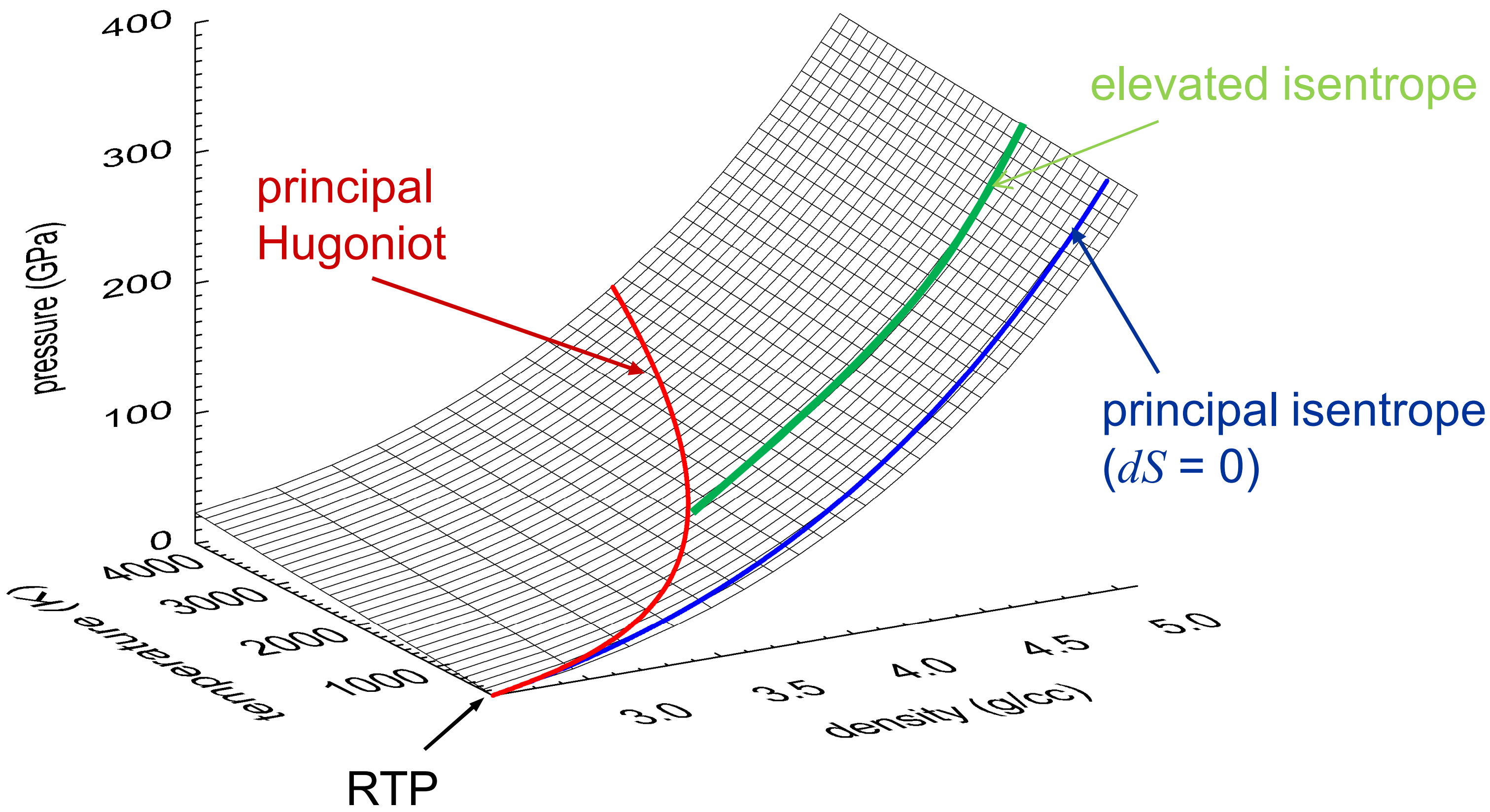
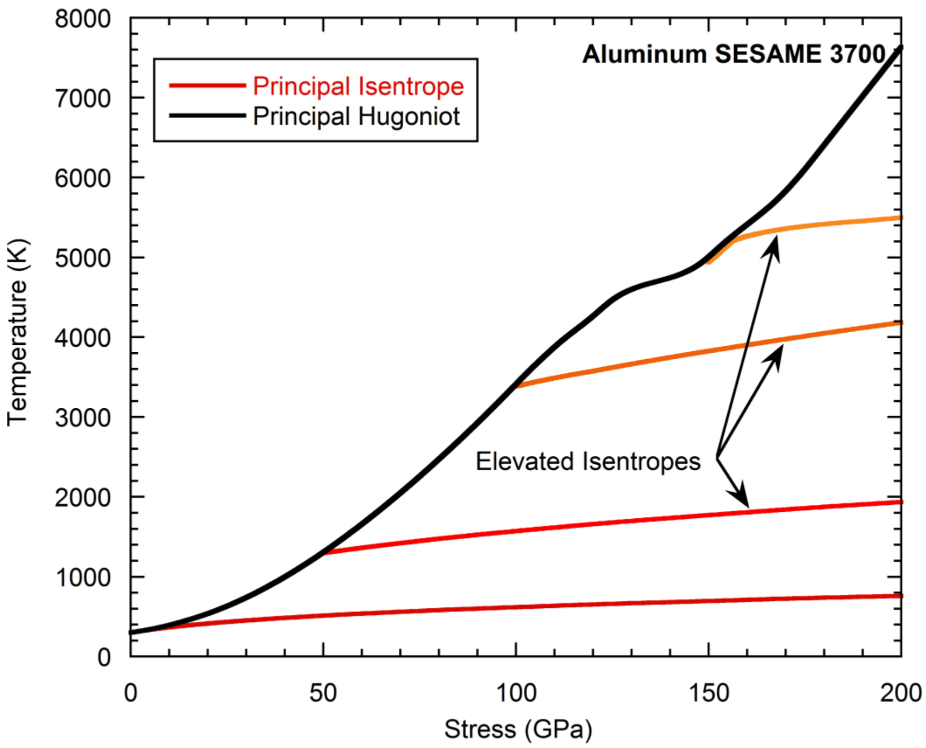
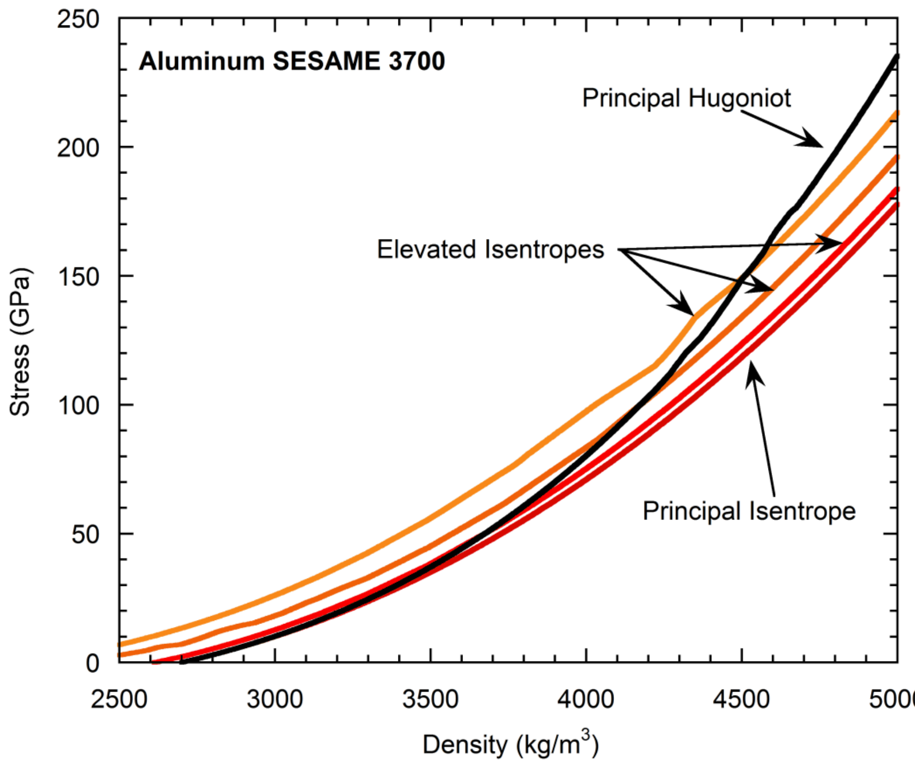
Shock-Ramp probes between the Hugoniot and Isentrope

- **Shock to a point on the Hugoniot – then shocklessly compress from this (or the release) density/stress**
- **Flyer accelerated to constant velocity – impact, then push harder**



Shock-Ramp probes between the principal Hugoniot and isentrope

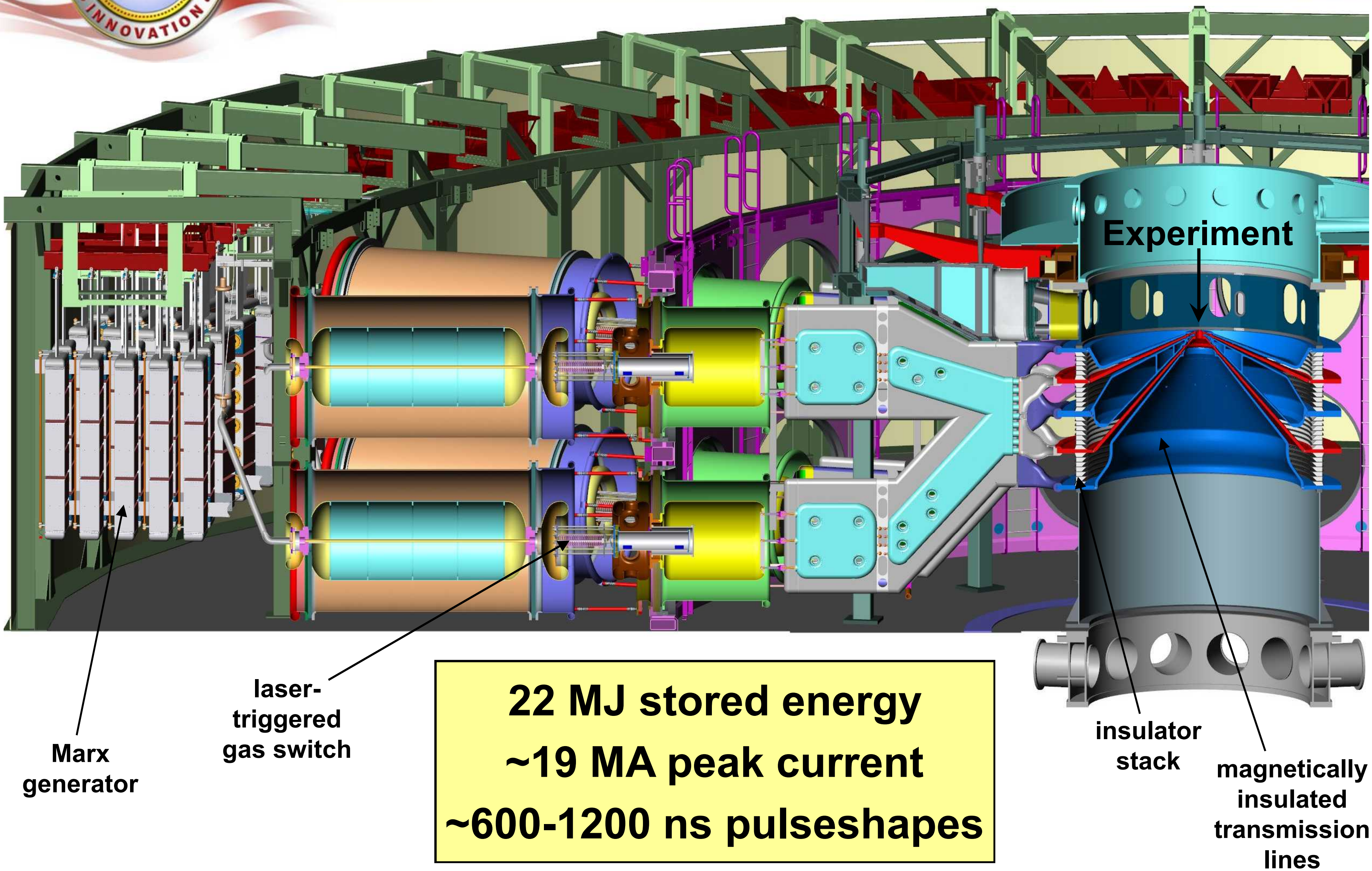




Ramp compression from a Hugoniot state results in intermediate temperatures at high compression.

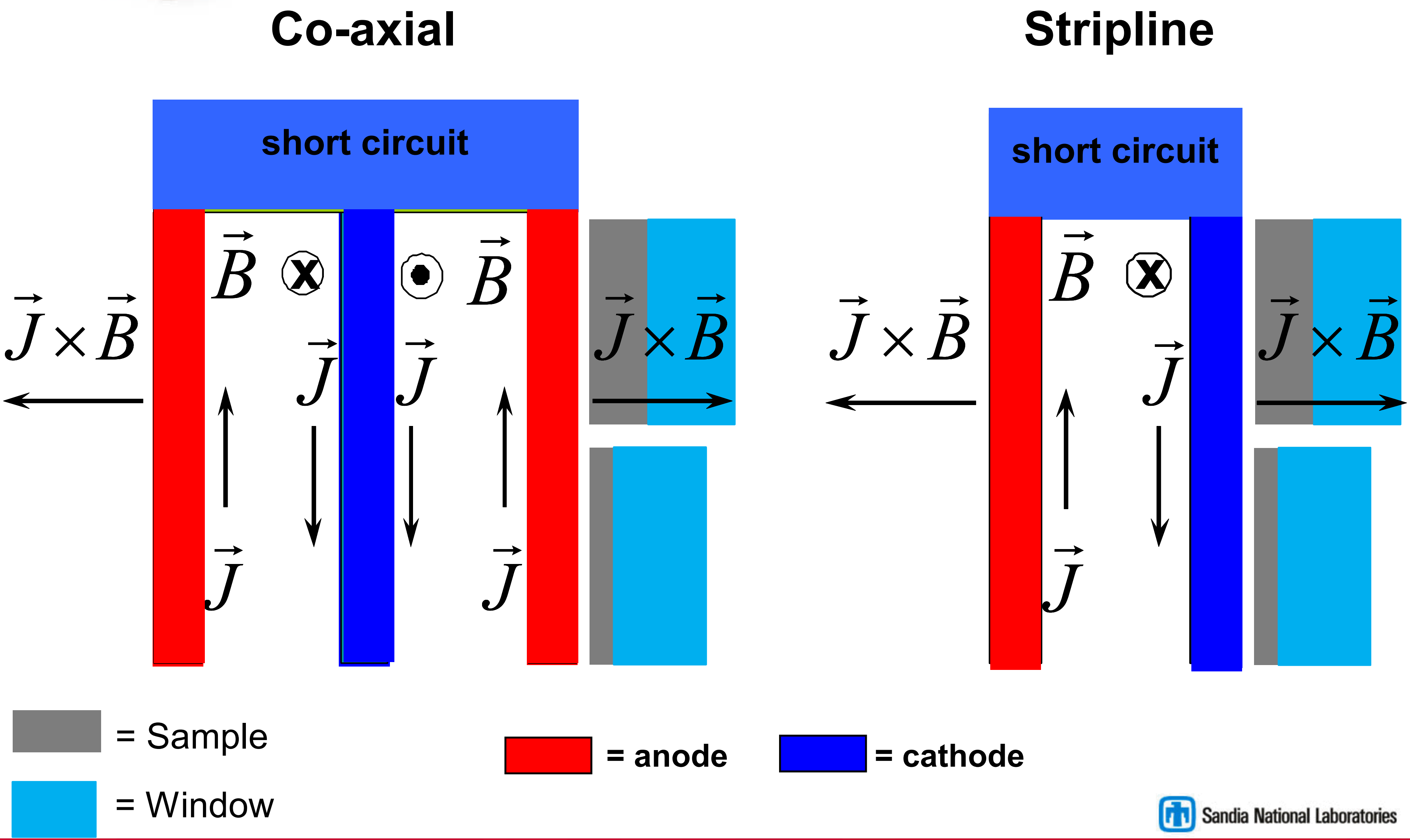
SESAME 3700: Kerley, 1987

The Sandia Z Machine



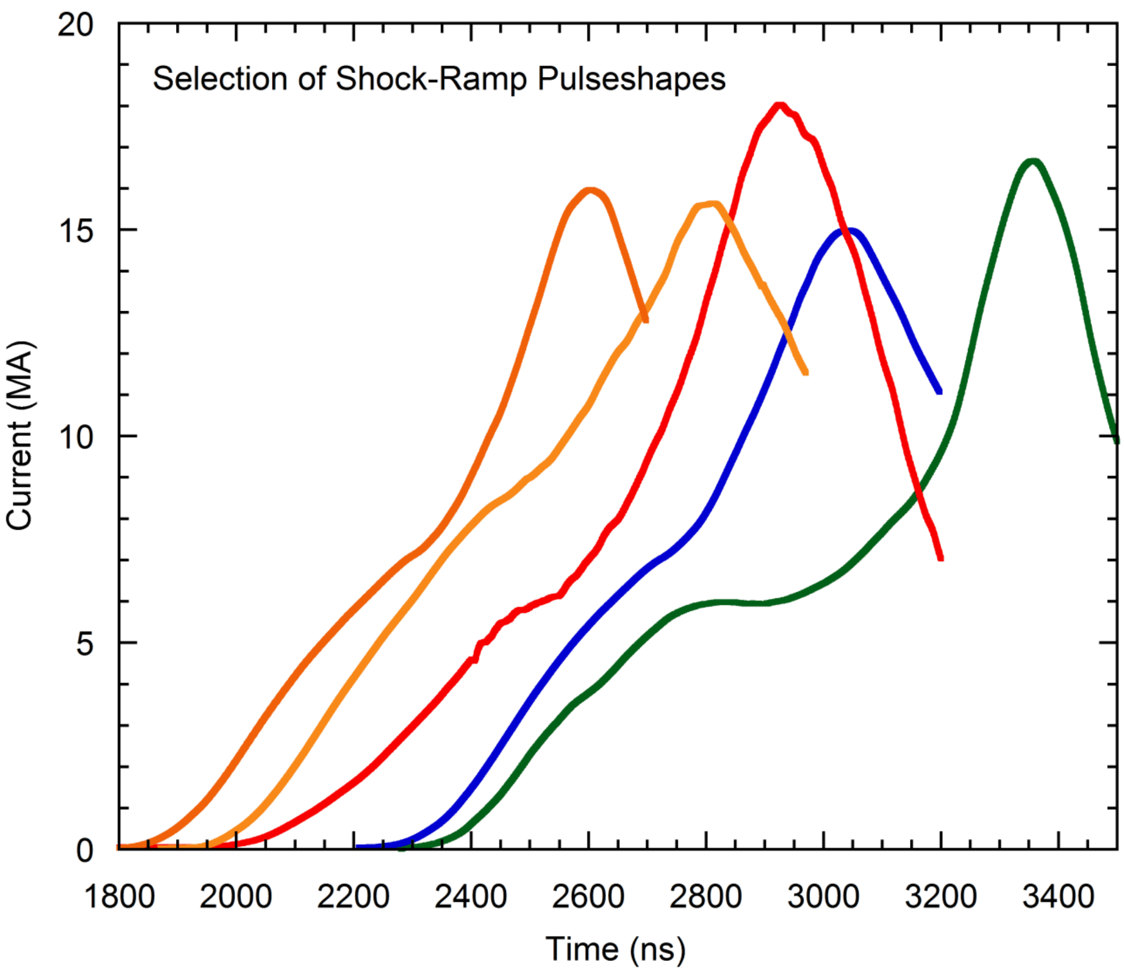
22 MJ stored energy
~19 MA peak current
~600-1200 ns pulseshapes

Typical Load Power Flow Geometries



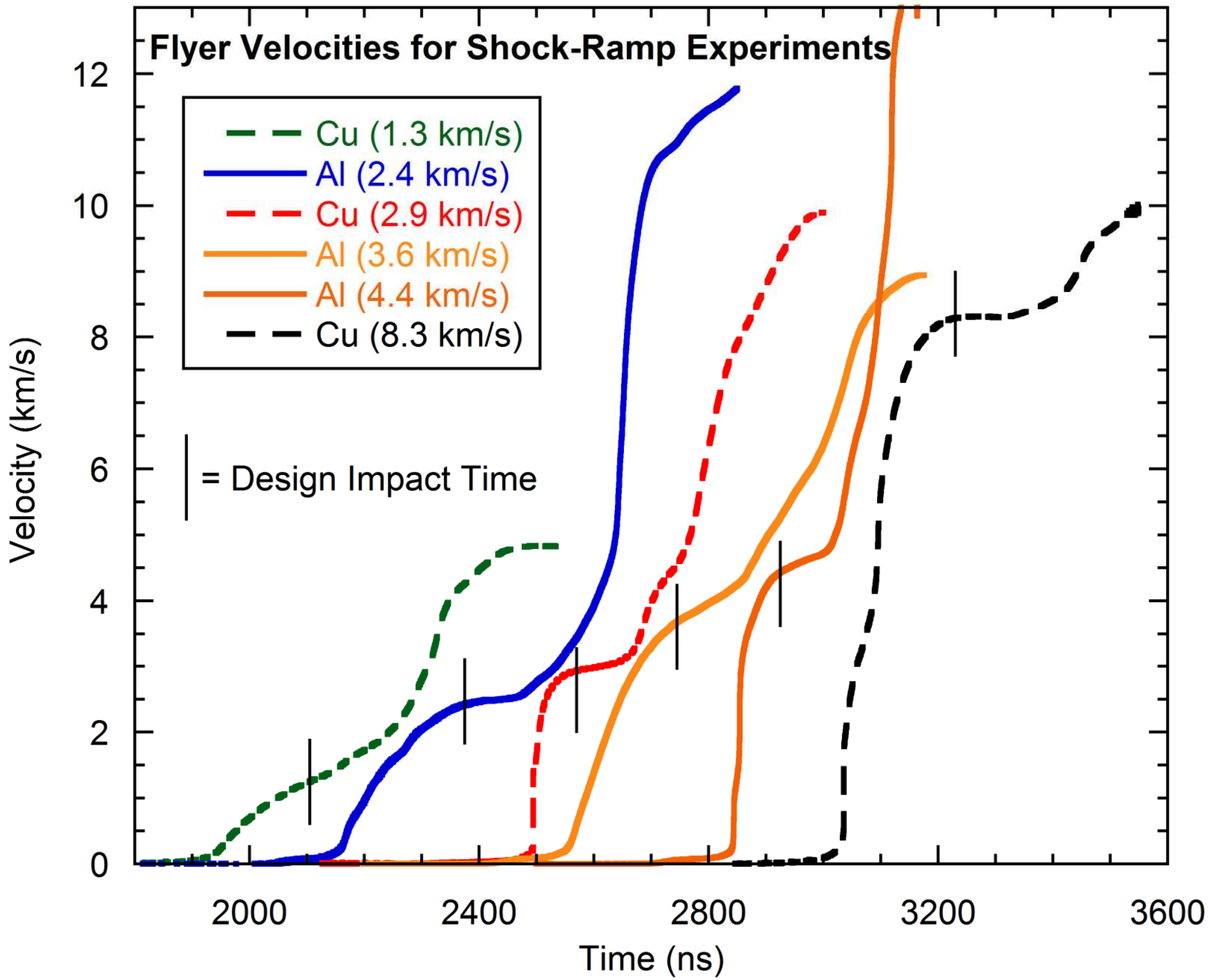
Pulseshaping capabilities

- **Double ramp type pulseshape required for shock ramp experiments**
- **Exquisite control of the shape of the current pulse and the geometry of the load allows for a wide range of experiments**

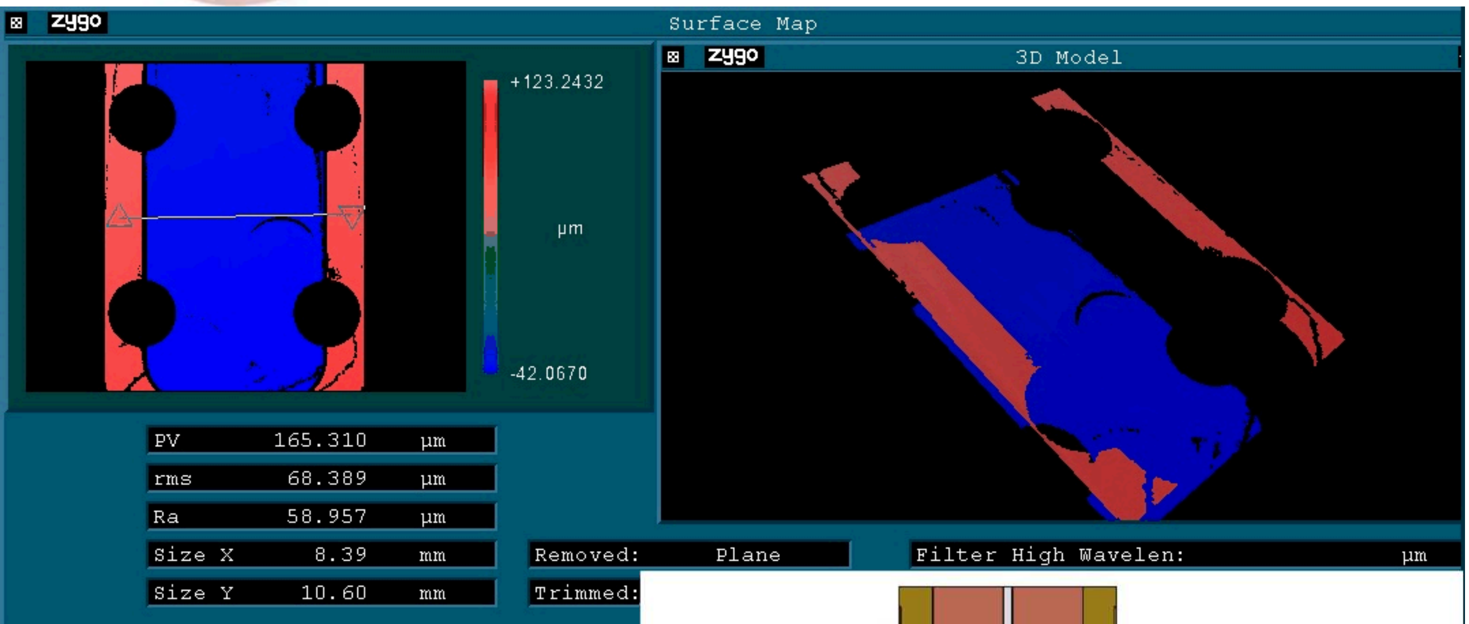


Flyer Velocities from 1.3 – 8.3 km/s have been achieved with Copper and Aluminum electrodes

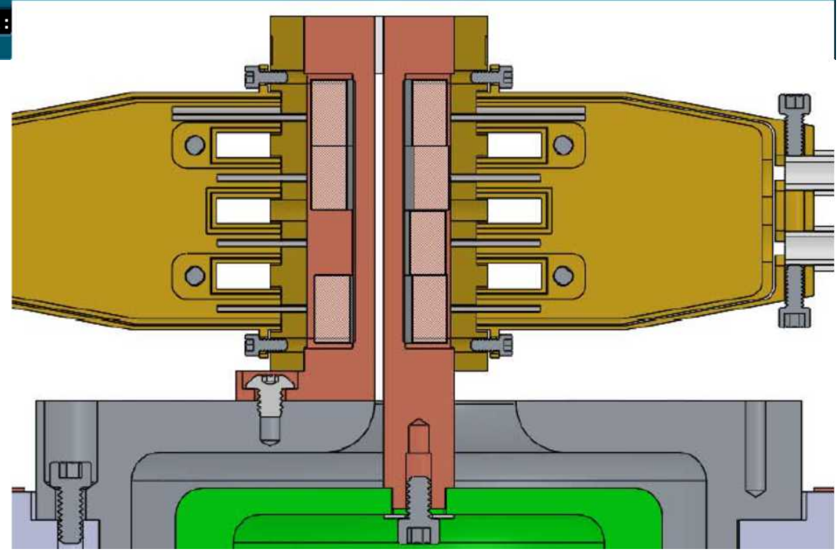
- **Observed impactor velocity (with no sample present)**
- **A wide range of EoS/Phase Transition studies are possible with these profiles**



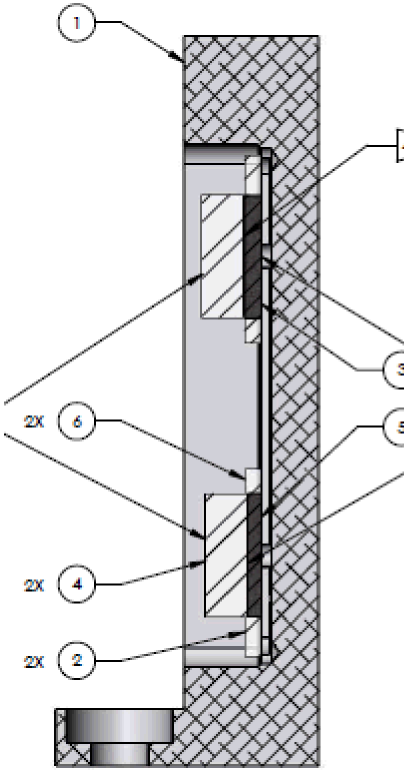
Flight Gaps Machined into Electrodes (panels)

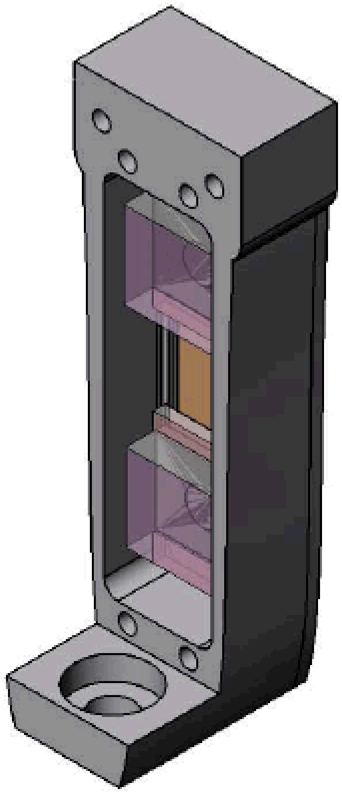


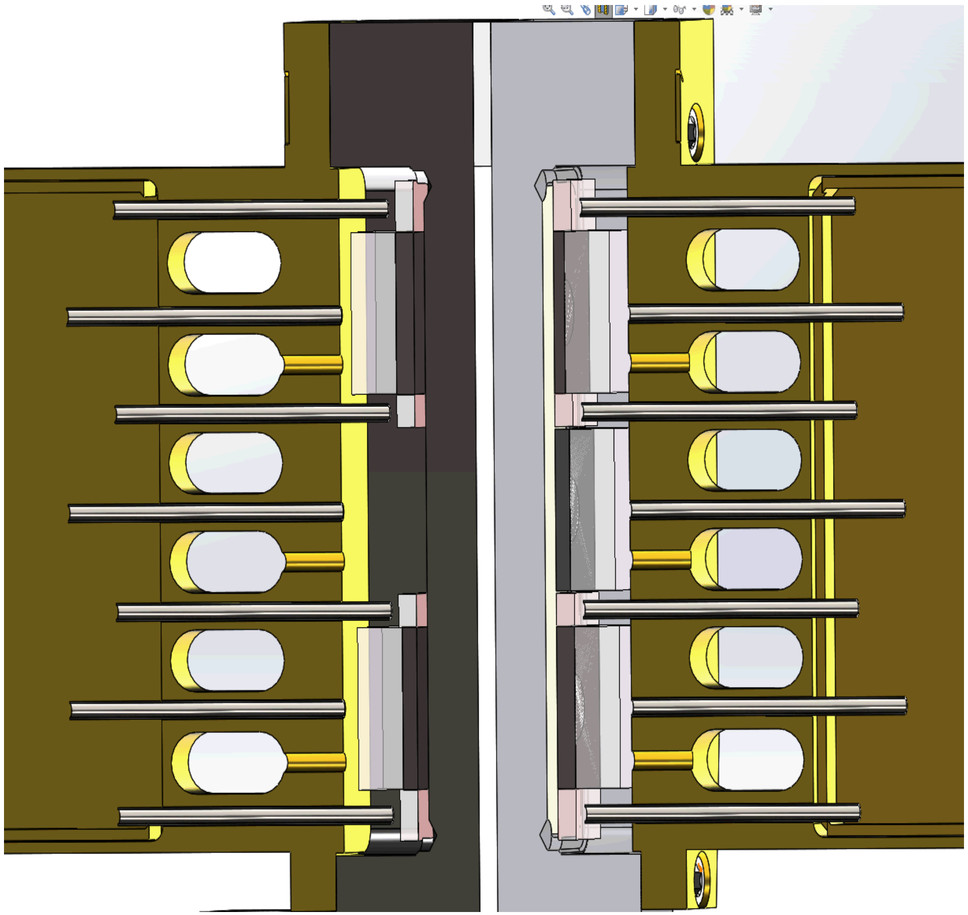
Diamond milling of single “pocket” and “step” ensures uniformity of electrode thickness and flight gap for multiple samples



Future Designs to include "impact timing" windows to reduce error

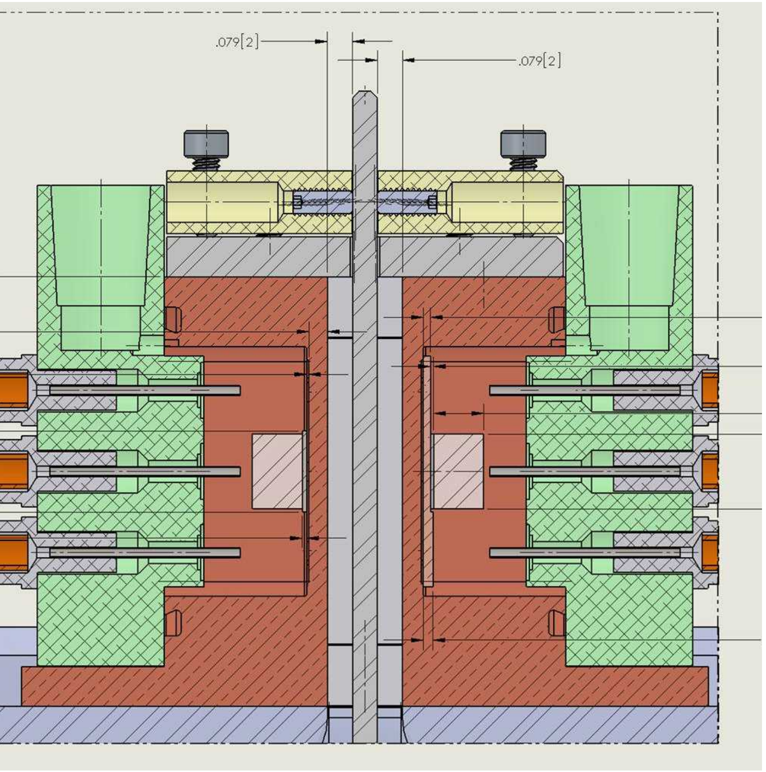


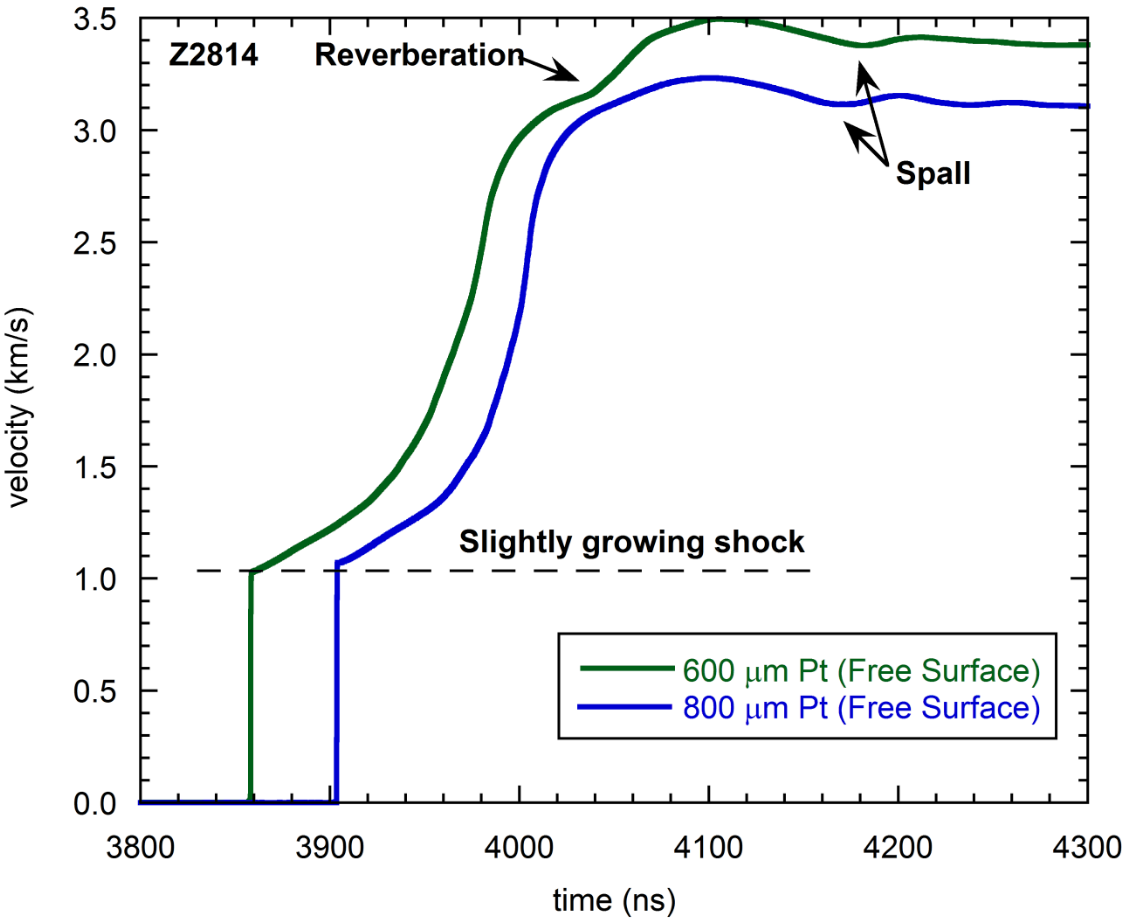




Measurement of impact timing to reduce error associated with (typically assumed) initial Hugoniot state

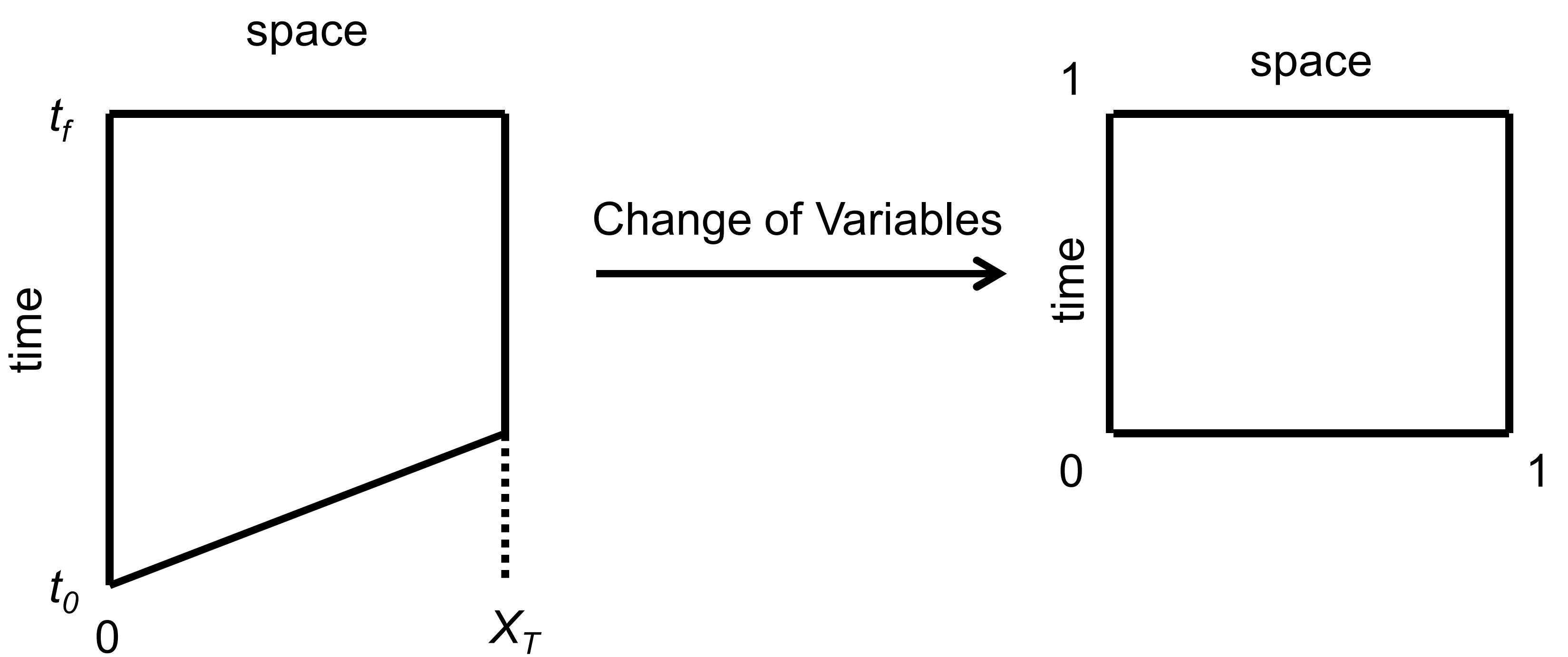
Z2814 Platinum “Stepped Bar”





- The Pt stepped bar is used as a “standard”: the mechanical response is measured during the experiment and this response then used in forward simulations/iterations of another test sample glued to the bar
- This procedure has the advantage of uncoupling the MHD/EoS properties of the electrode from the forward analysis of the test sample

Backward Integration Routines Apply (force) the Hugoniot State on the Shock-Wave Characteristic



This change of variables allows one to easily apply a boundary condition on the shock wave characteristic – not so simple without this change because cells must be prepended as the integration proceeds backward in space

This *may* also allow growing shocks to be treated directly (with assumptions)

The geometrical interpretation is very simple…

$$\left(\frac{\partial \boldsymbol{P}[\boldsymbol{\rho}(x,t)]}{\partial x}\right) = -\rho_0\left(\frac{\partial \boldsymbol{u}(x,t)}{\partial t}\right)$$

$$\frac{1}{\rho_0}\left(\frac{\partial \boldsymbol{u}(x,t)}{\partial x}\right) = -\frac{\partial\left({}^{1}/_{\boldsymbol{\rho}(x,t)}\right)}{\partial t}$$

Hydrodynamic Equations

$$q \leftrightarrow \frac{x}{X_T}$$

$$\tau \leftrightarrow \frac{U_s(t_i - t) + qX_T}{U_s(t_i - t_f) + qX_T}$$

Change of Variables

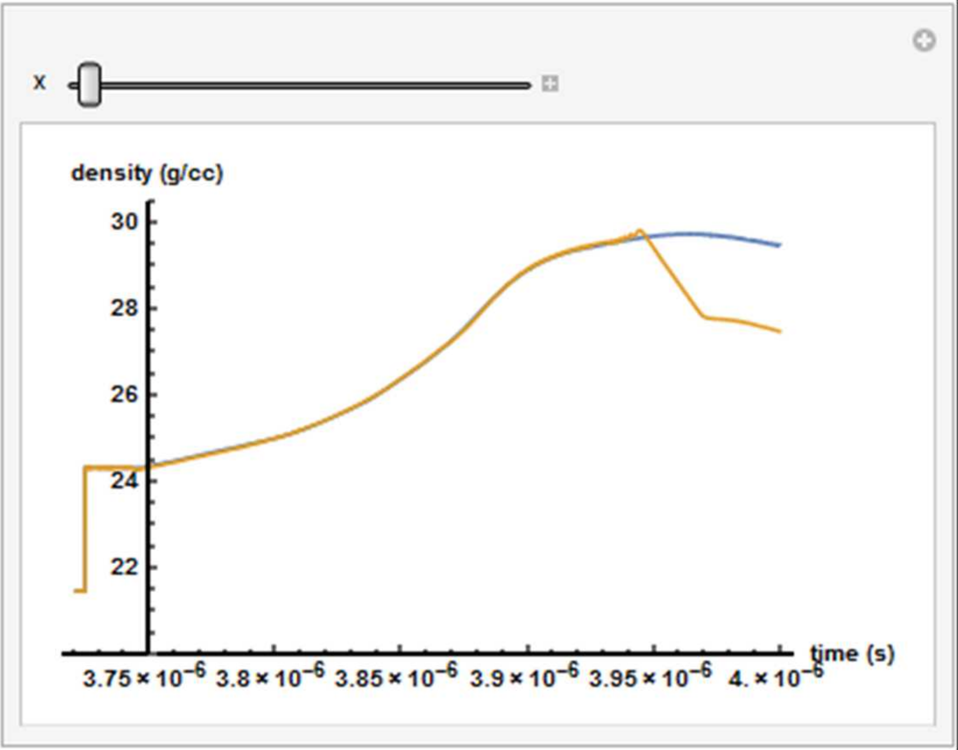
P = stress
u = velocity
ρ = density
X_T = sample thickness
t_f = final time
t_i = impact time
U_s = shock velocity

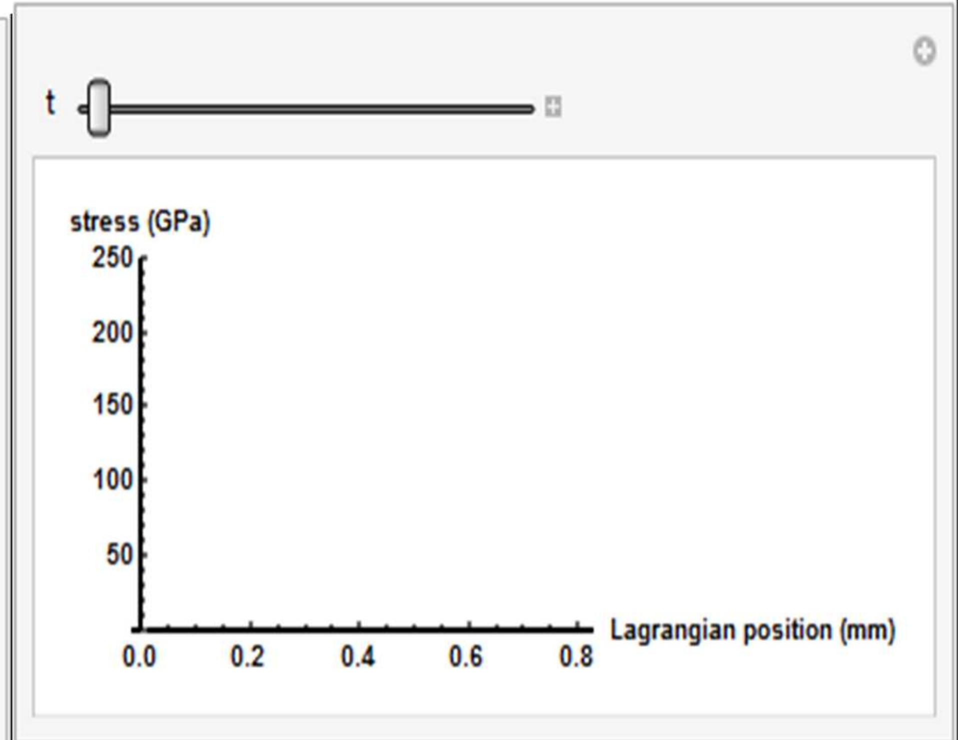
$$\left(\frac{\partial \boldsymbol{P}[\boldsymbol{\rho}(q,\tau)]}{\partial q}\right)\left(\frac{1}{X_T} + \frac{\frac{\partial \boldsymbol{\rho}(q,\tau)}{\partial \tau}}{\frac{\partial \boldsymbol{\rho}(q,\tau)}{\partial q}}\right)\left(\frac{\tau - 1}{U_s(t_f - t_i) - qX_T}\right) = \rho_0\left(\frac{\partial \boldsymbol{u}(q,\tau)}{\partial \tau}\right)\left(\frac{U_s}{U_s(t_i - t_f) + qX_T}\right)$$

$$\frac{1}{\rho_0}\left(\frac{\partial \boldsymbol{u}(q,\tau)}{\partial \tau}\right)\left\{\frac{1}{X_T}\left(\frac{\partial \boldsymbol{u}(q,\tau)}{\partial q}\right) + \left(\frac{\tau - 1}{U_s(t_f - t_i) - qX_T}\right)\right\} = -\frac{\partial\left({}^{1}/_{\boldsymbol{\rho}(q,\tau)}\right)}{\partial \tau}\left(\frac{U_s}{U_s(t_i - t_f) + qX_T}\right)$$

New Equations

Solution Visualization confirms expected behavior





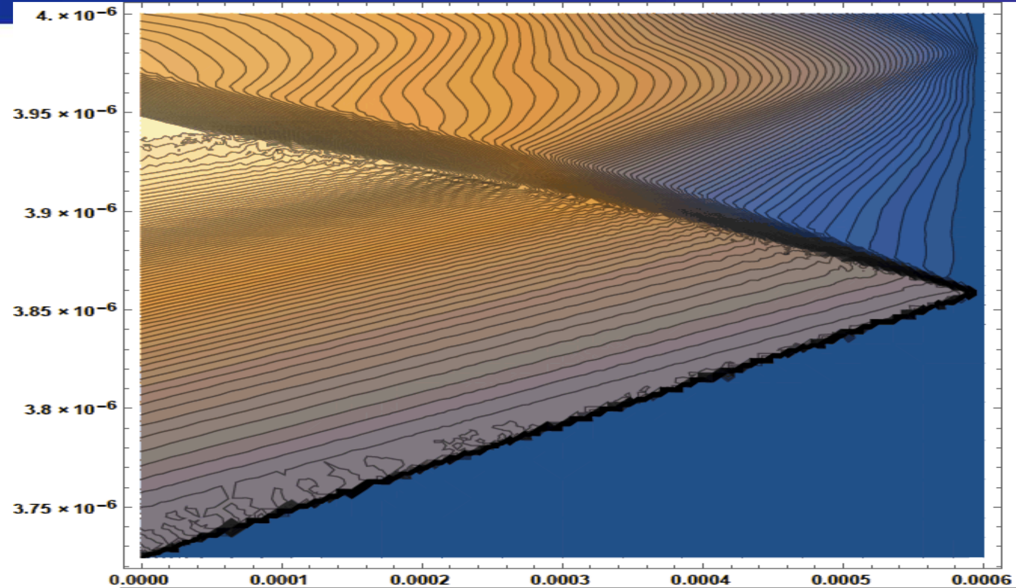
At Lagrangian position zero (the impact surface), the stress, density, and velocity should be identical up to the time of reverberation

Initial spatial boundary condition along the shock wave characteristic contains a discontinuity at the free surface

Contours of Stress in Space-Time coordinates can be used to gain insight into wave dynamics of the experiment

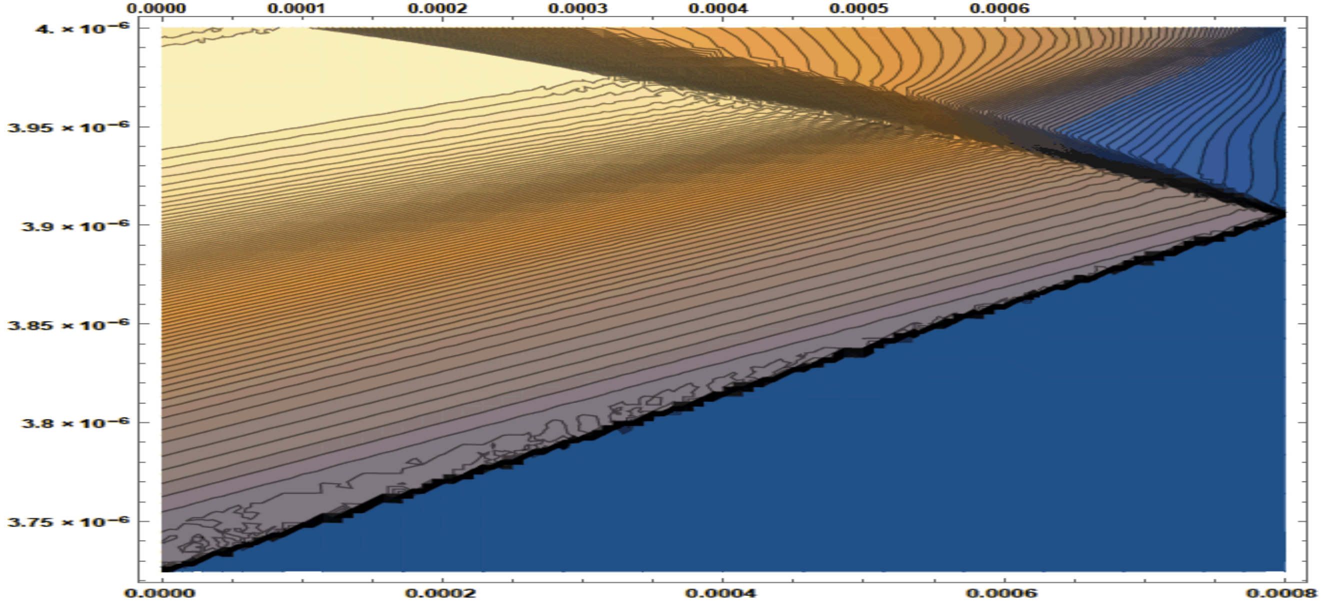
- **Visualization of the release fan as it disperses in time while traveling away from free surface**

- **This release interacts with the oncoming ramp at different (x, t) coordinates for differing thickness: correctly capturing this interaction (for strong shocks) is critical for correct analysis**

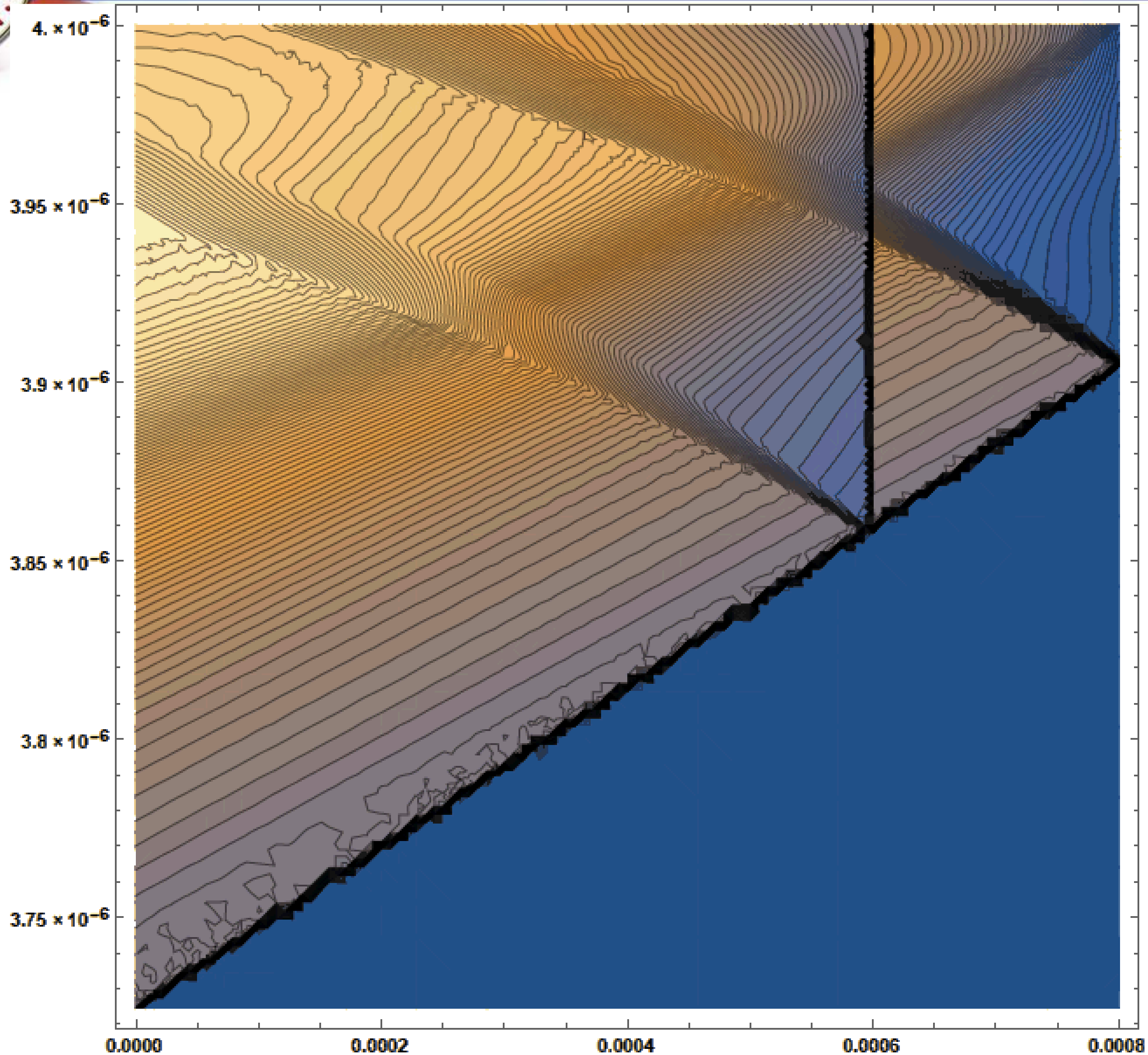


Blue = 0 GPa (free surface)

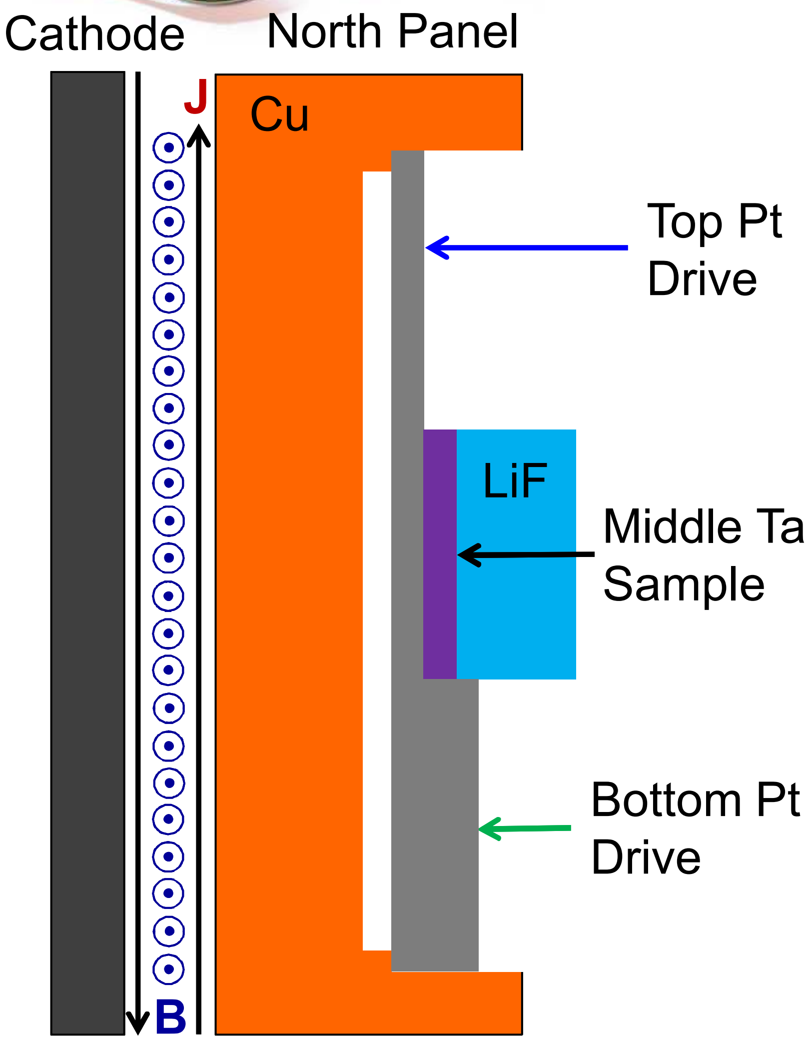
Yellow ≈ 206 GPa (peak)

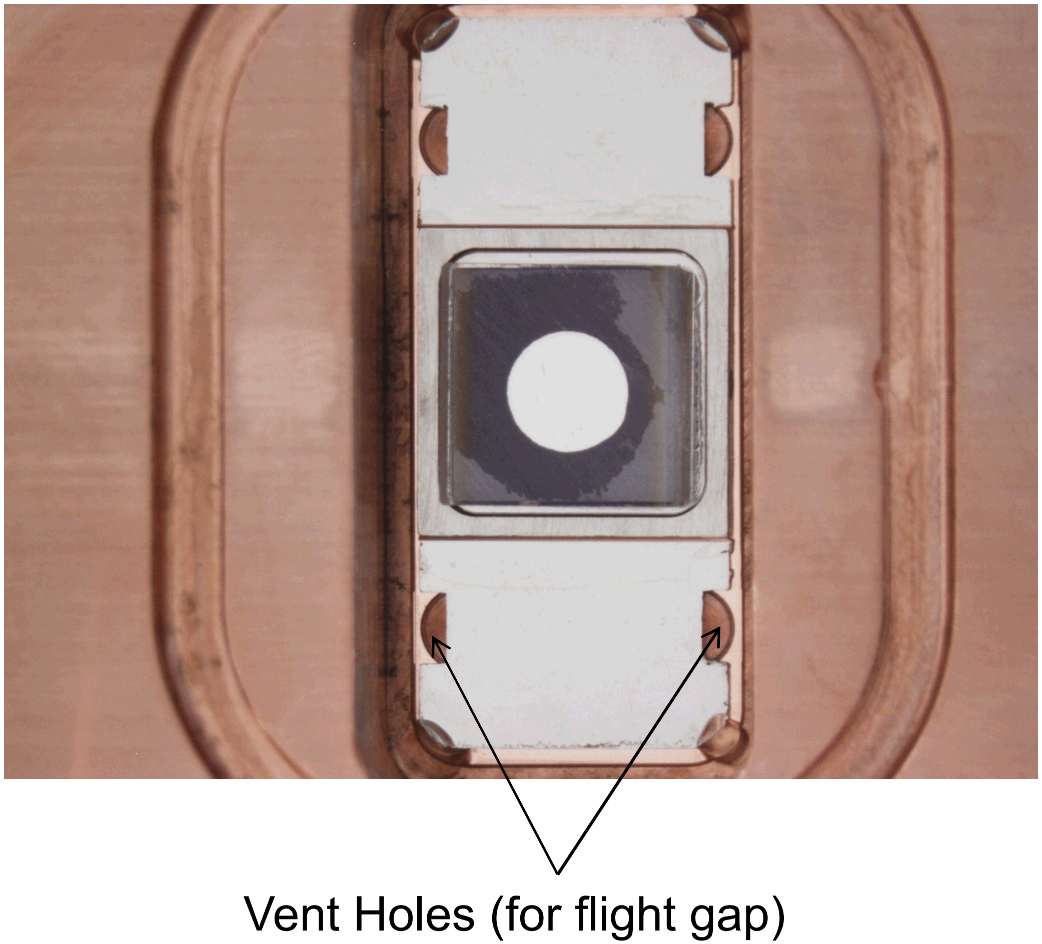


An average of the two stress contour plots illustrates the importance of treatment of the release fan



Ta shock ramp experimental configuration and VISAR data (Previous Talk)





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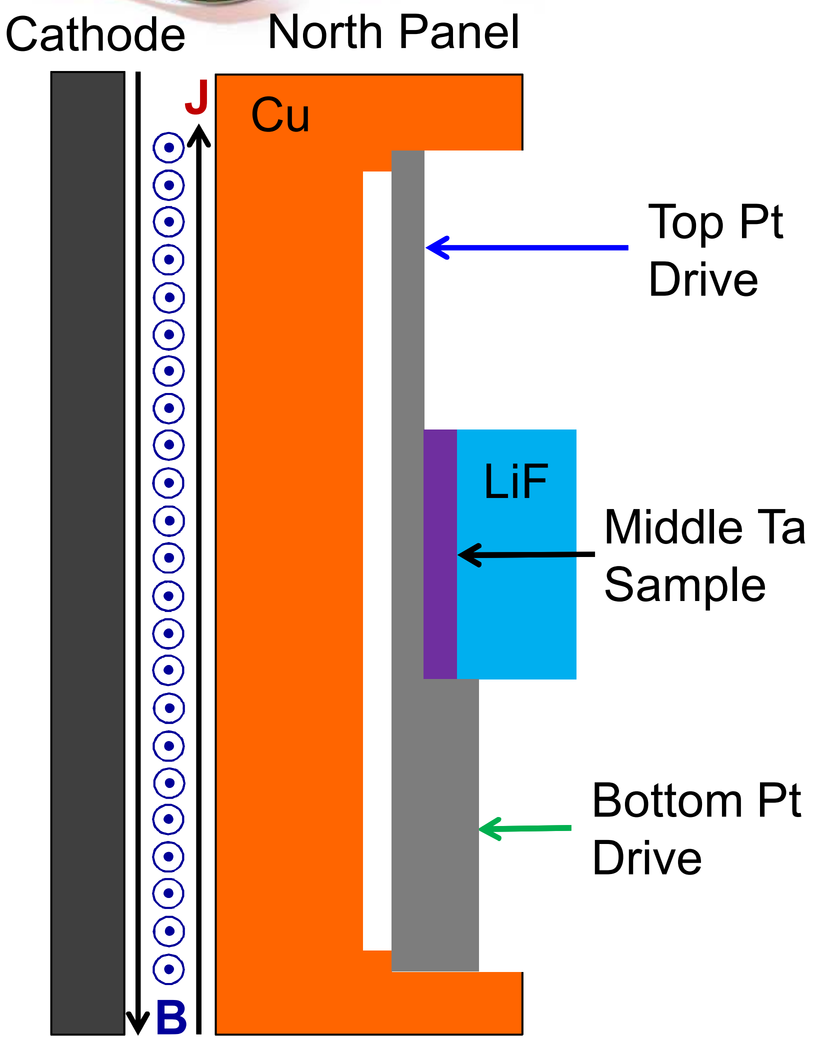
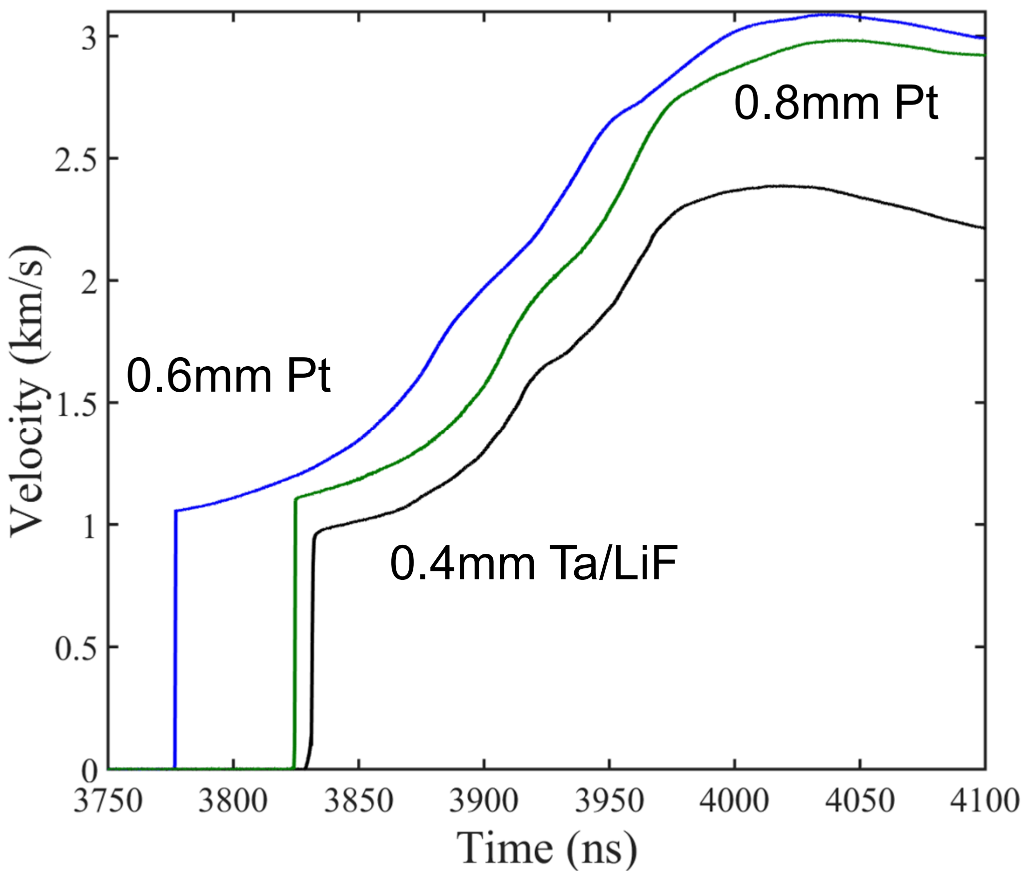
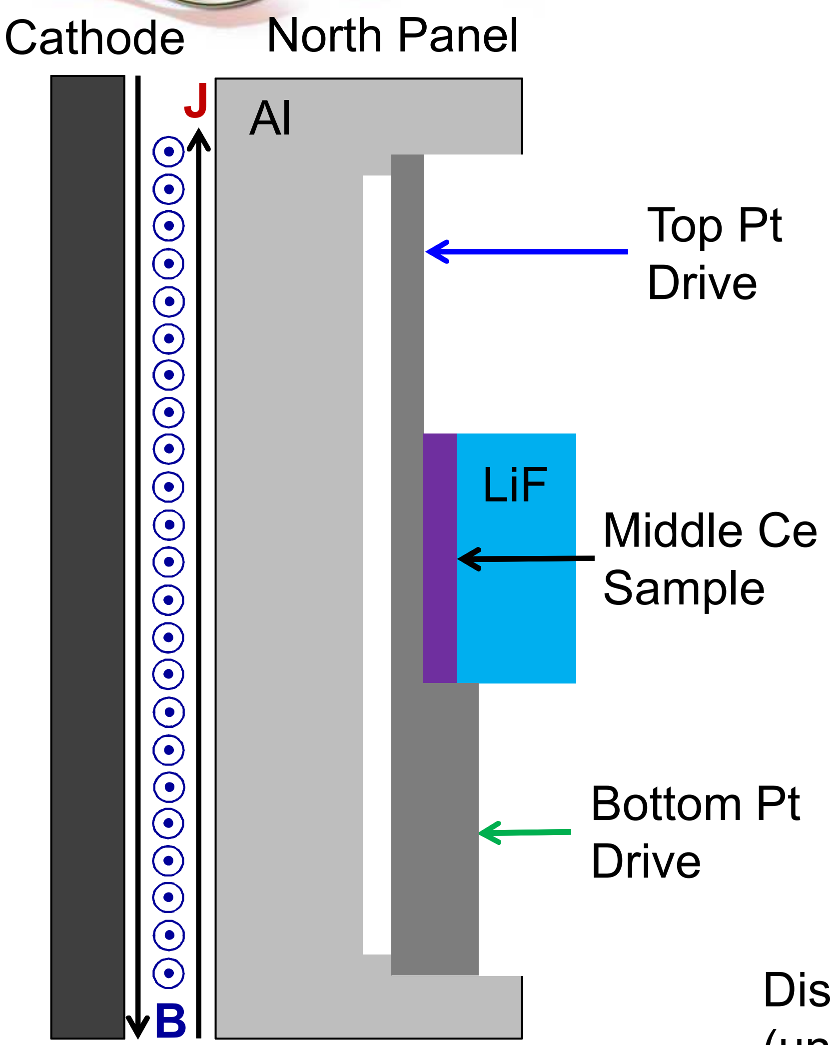
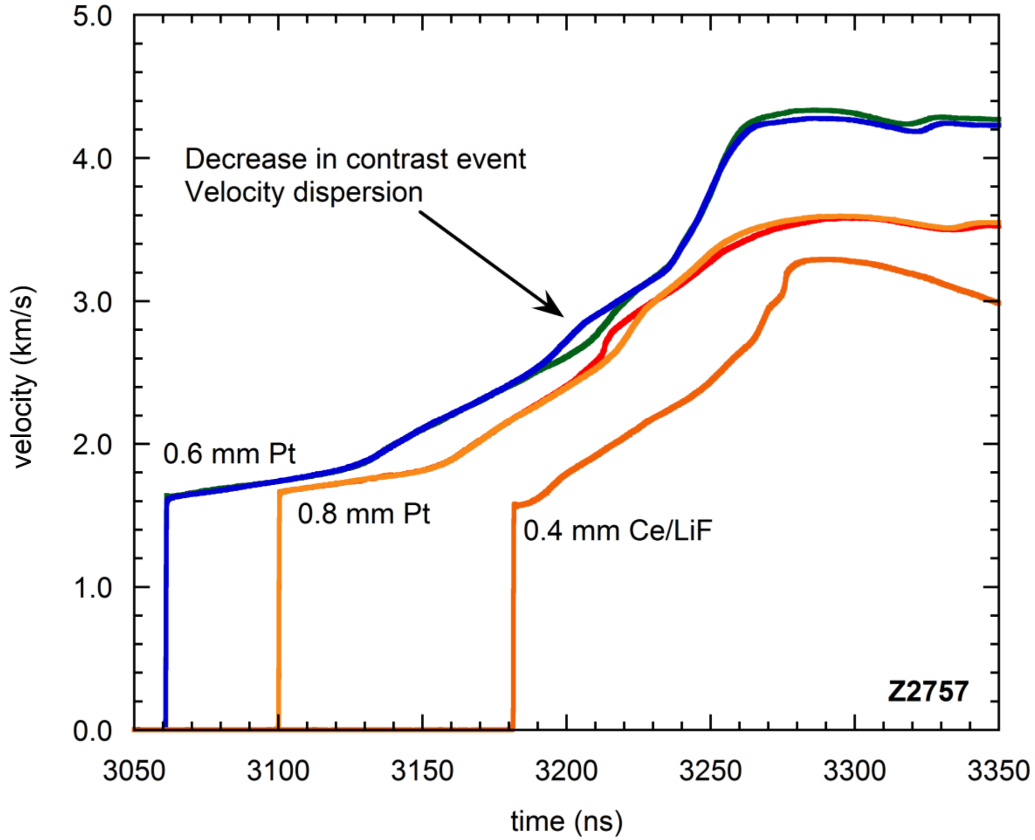




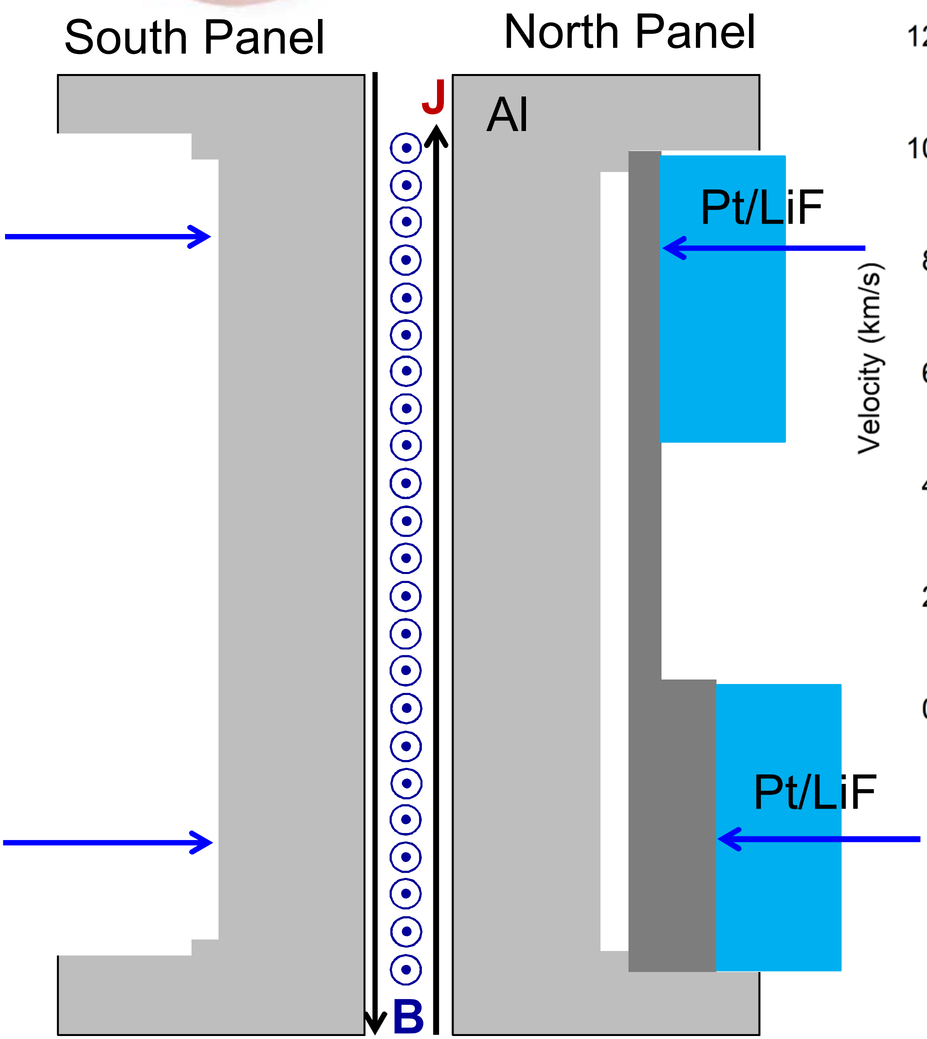
Ce shock ramp experimental configuration and VISAR data

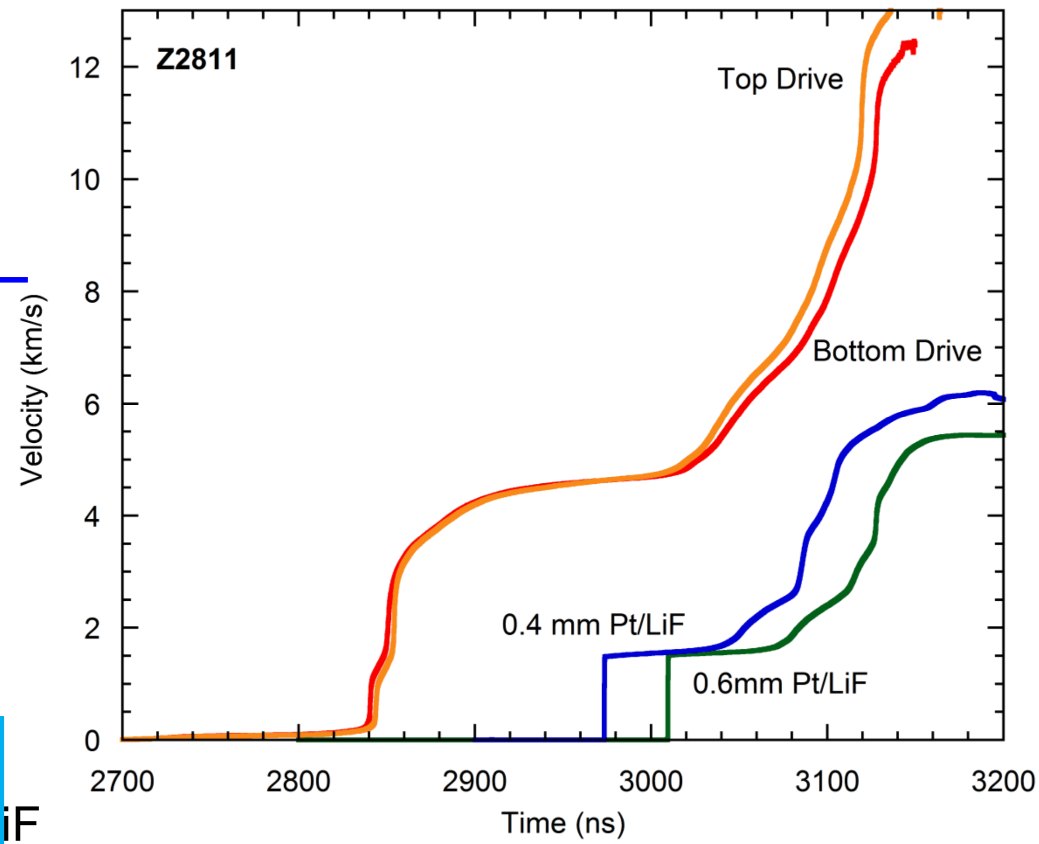




Dispersion observed in free surface Pt data (unknown cause). Pt shock stress ~ 86 GPa

Similar loading path to previous shot was repeated w/LiF windows (no dispersion observed)

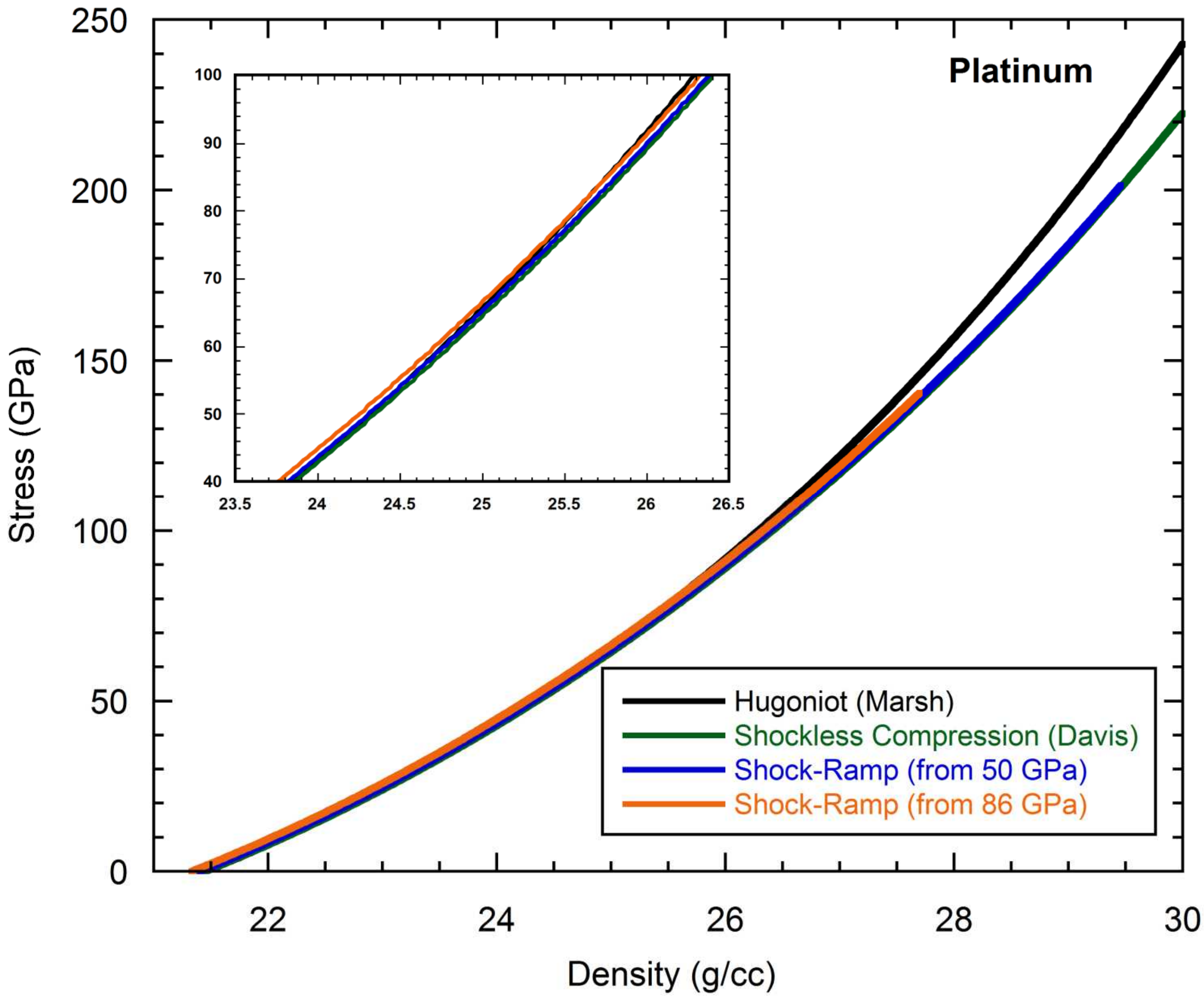




Pt shock stress ~92 GPa

Single sample analysis intended

Pt Response



- **Pt is a good standard for these experiments because it is very incompressible**
- **Pt also has a low sound speed which delays reverberation relative to other possible standards**
- **Pt has no known phase transitions**

See Jean-Paul Davis Tue. H5, 9:15 AM for Principal Isentrope Data

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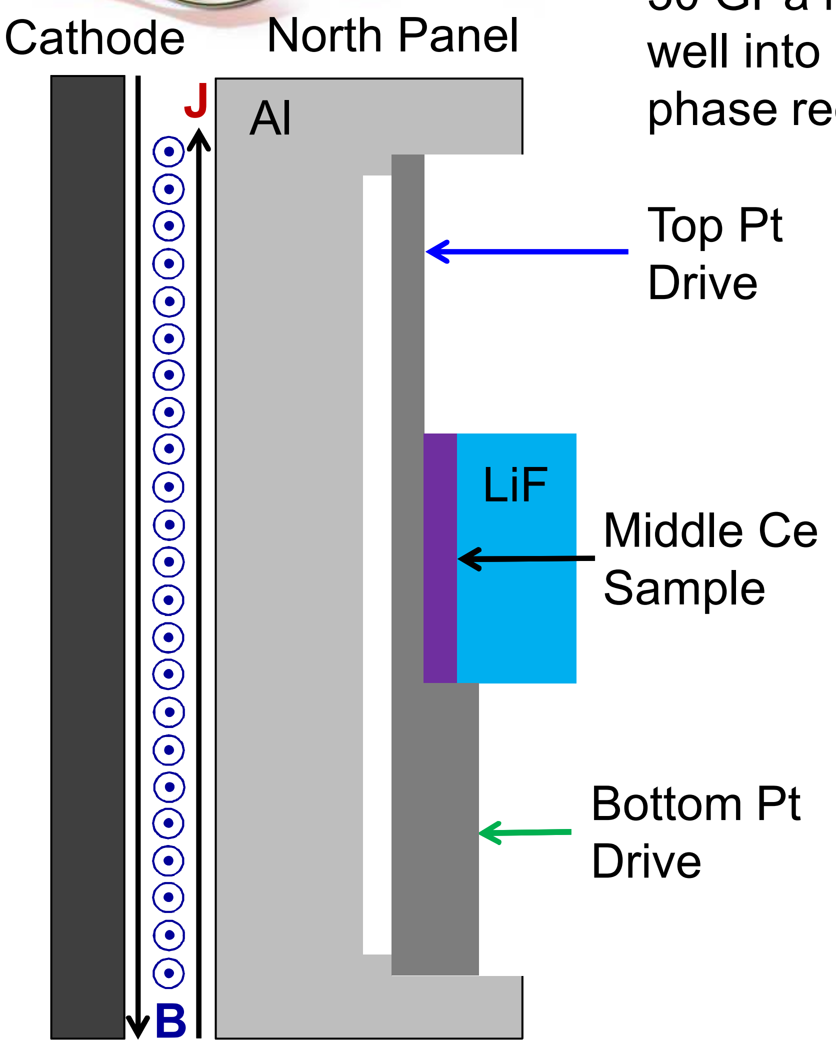
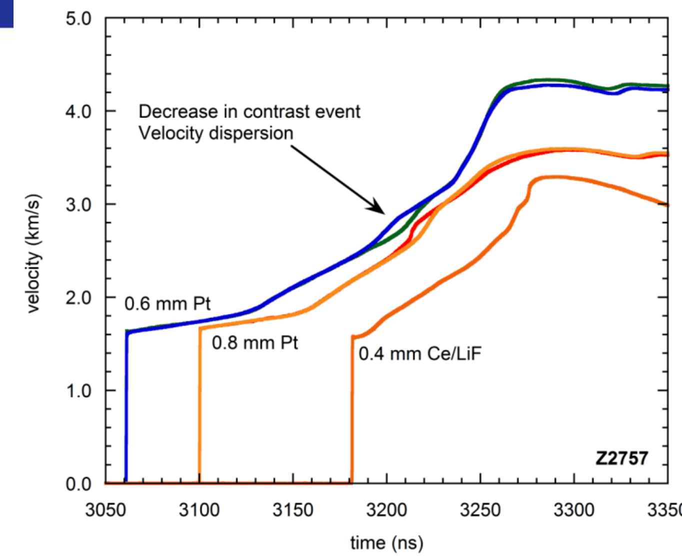
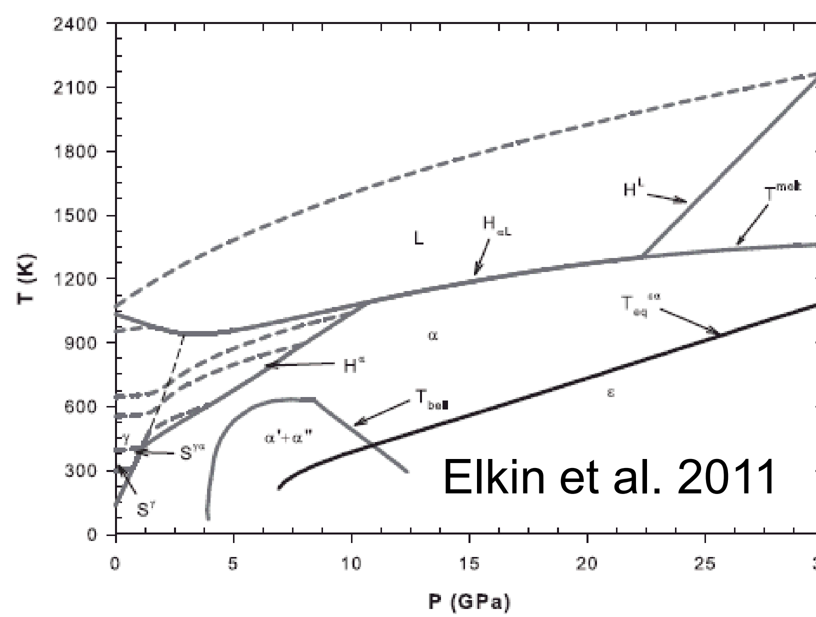
Experiments to probe the liquid isentrope of cerium

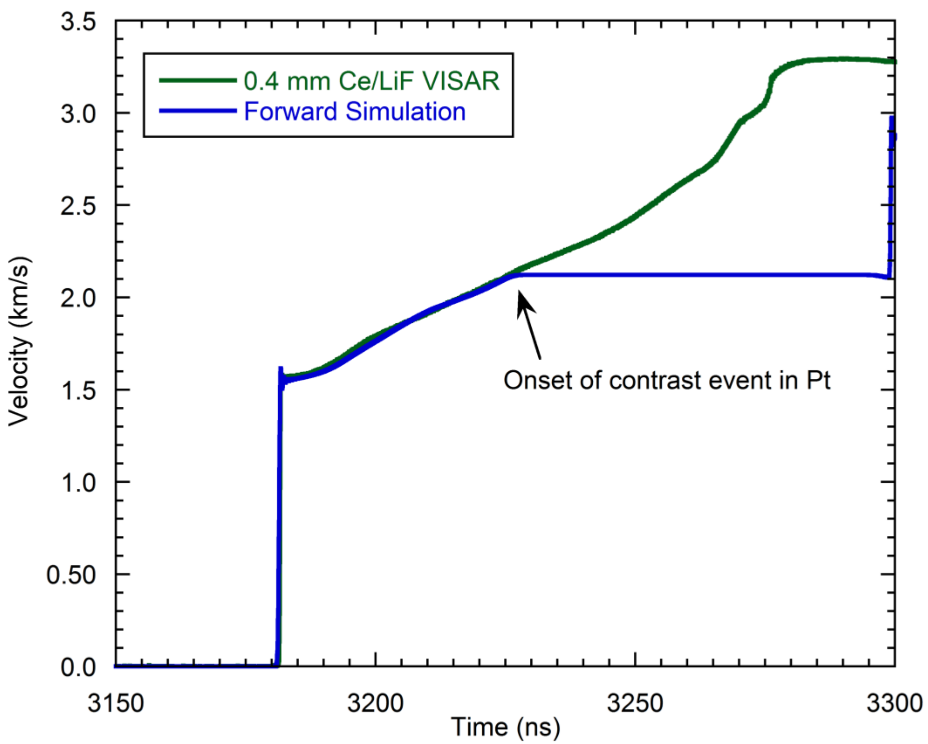
30 GPa initial shock well into liquid phase region

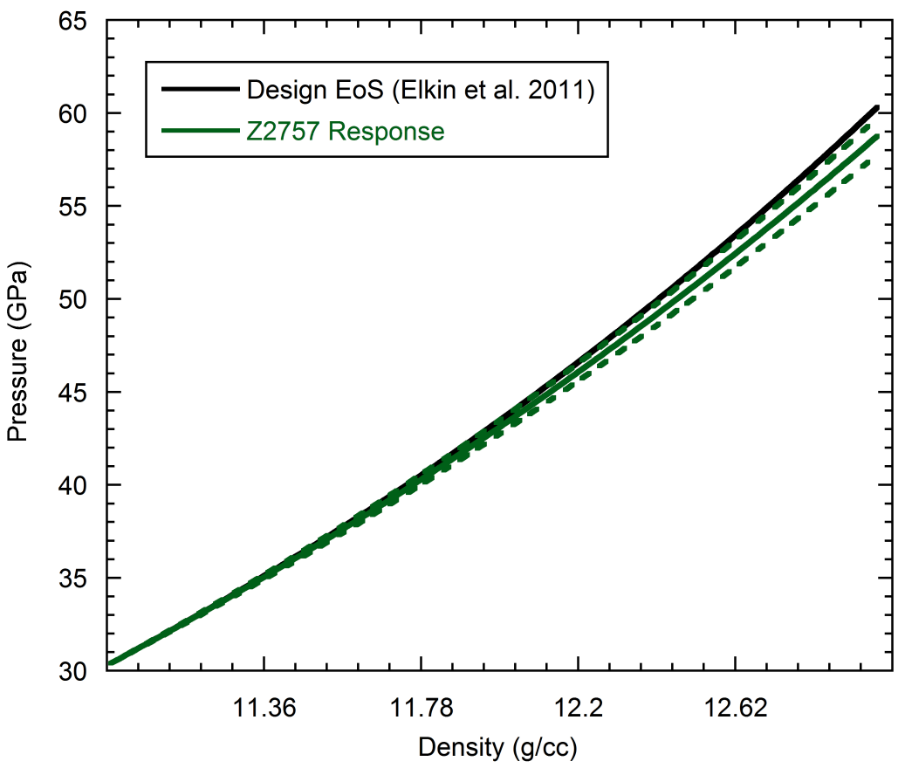






Cerium Response

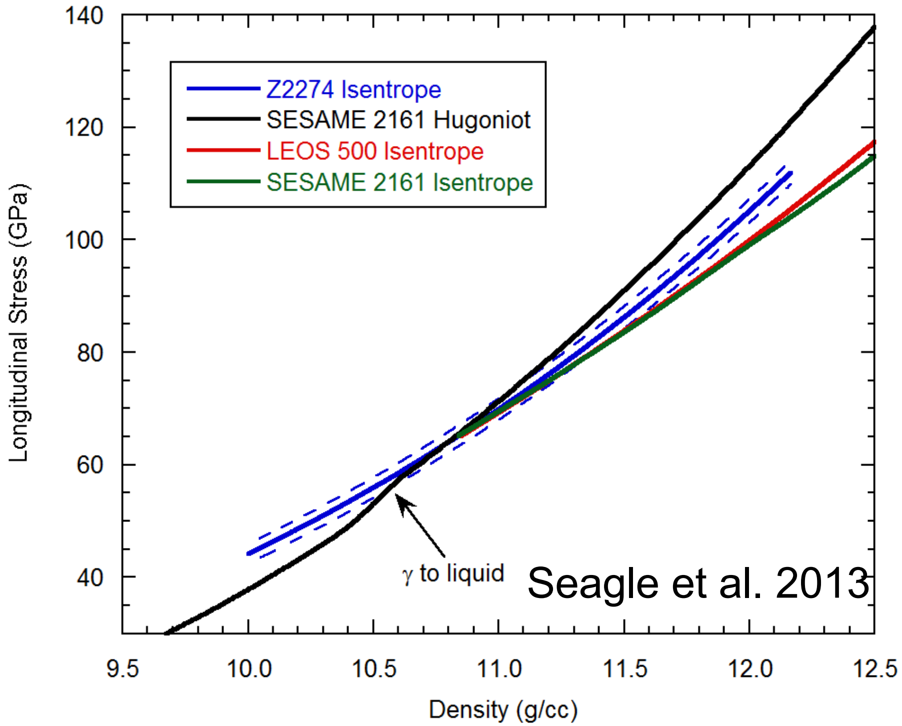


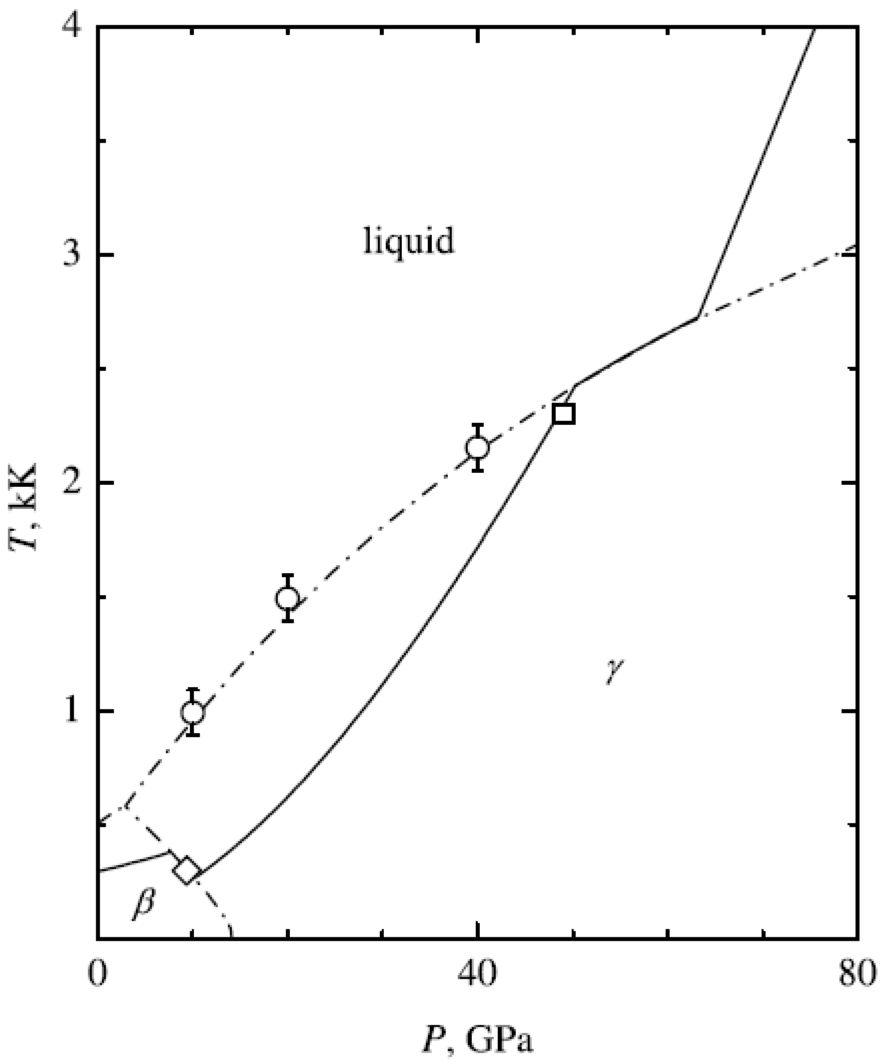


The design EoS (Elkin et al. 2011) was extrapolated above the range reported. Only the melt curve and 1 bar liquid data was used to build the liquid EoS.

Liquid Tin Isentrope

One of the first shock ramp experiments attempted shock melt – re-solidify on isentropic compression



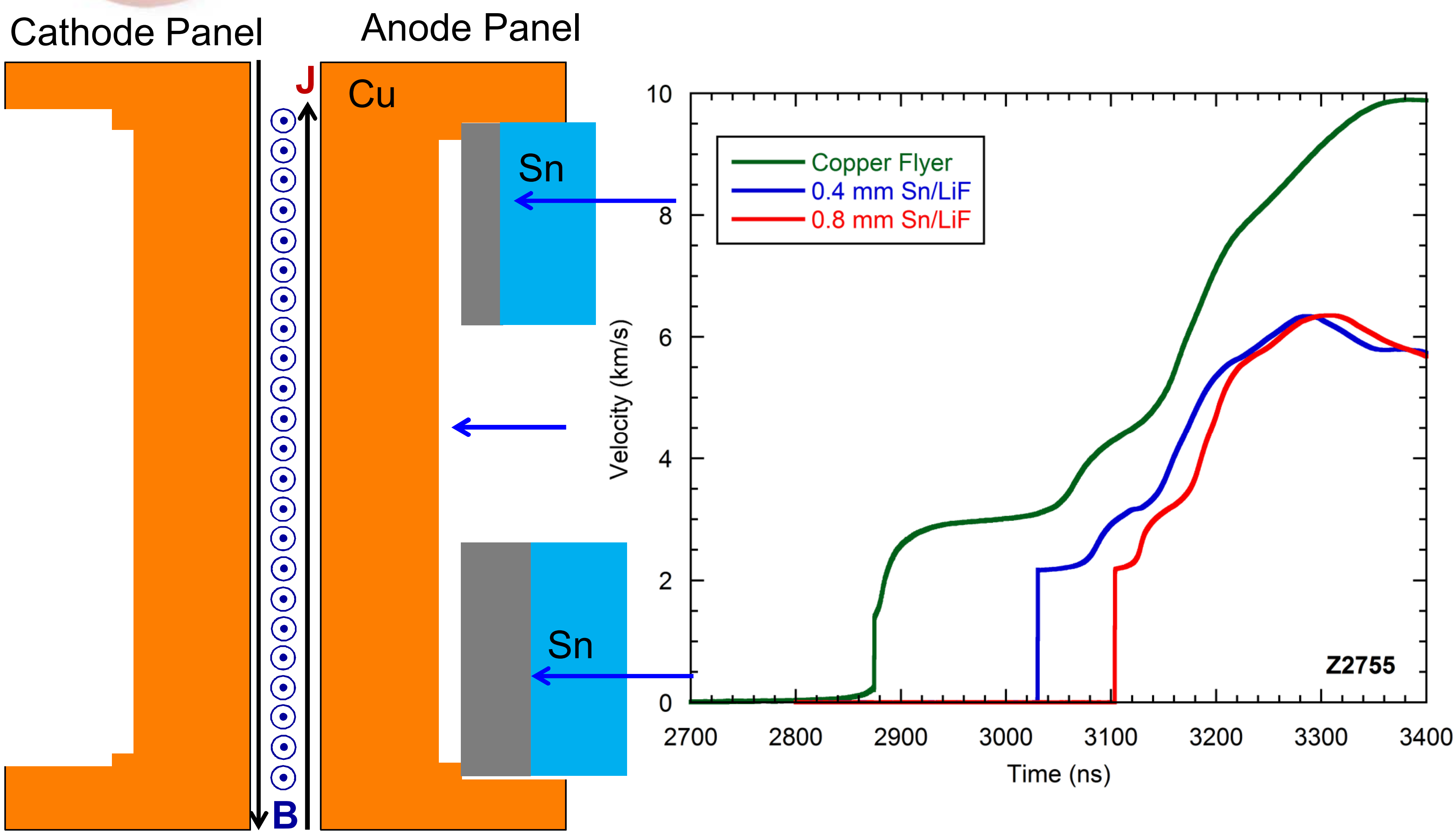


No evidence of solidification was observed up to ~1.1 Mbar

Khishchenko, 2008

Higher peak stress attempt was made in collaboration with LLNL based on their x-ray diffraction results*

*See Rick Kraus Wed. O4 9:45AM



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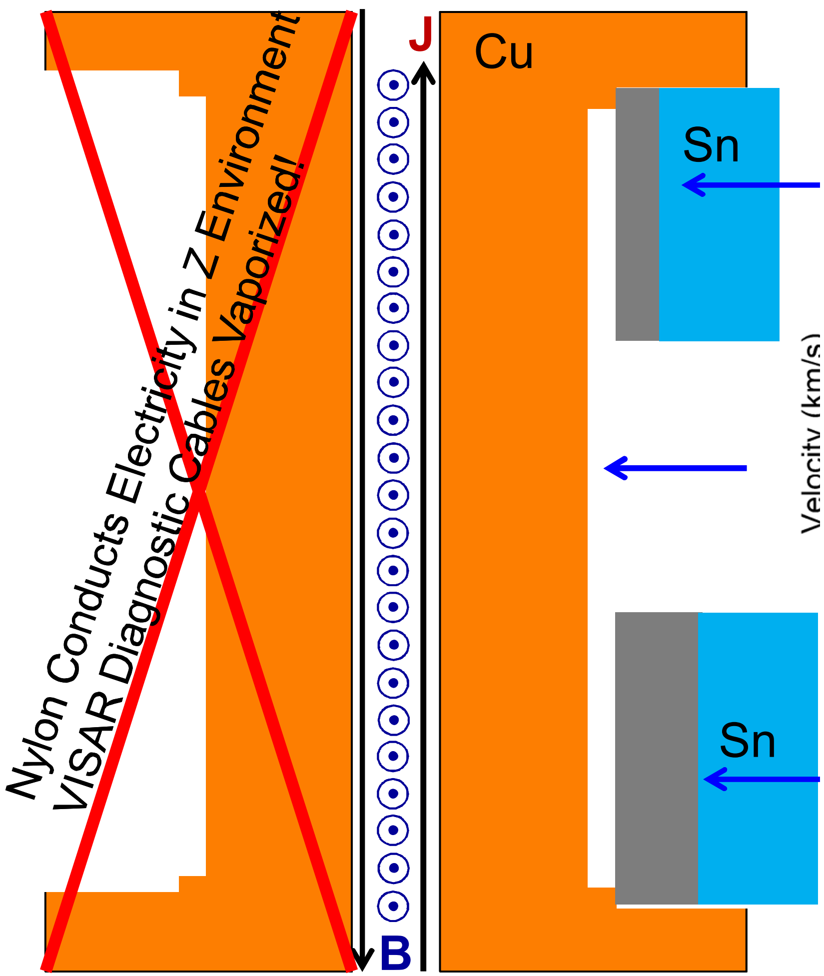
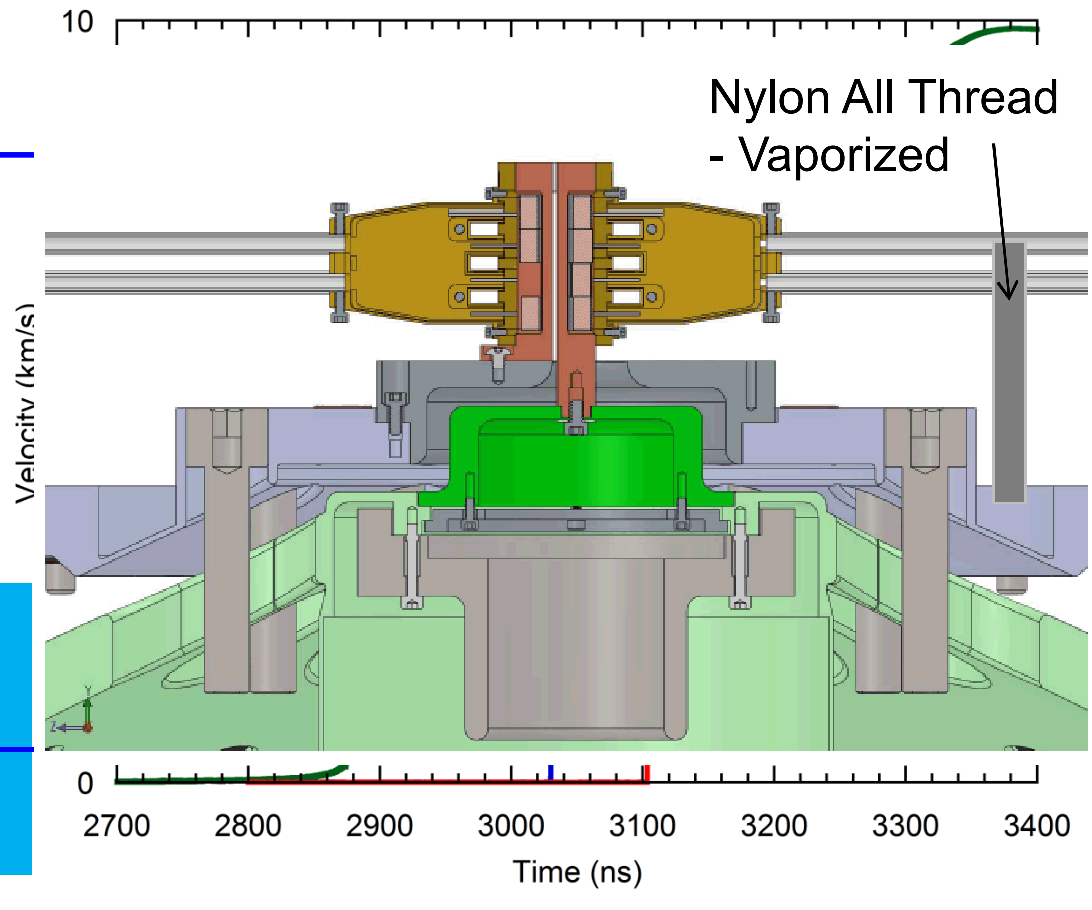
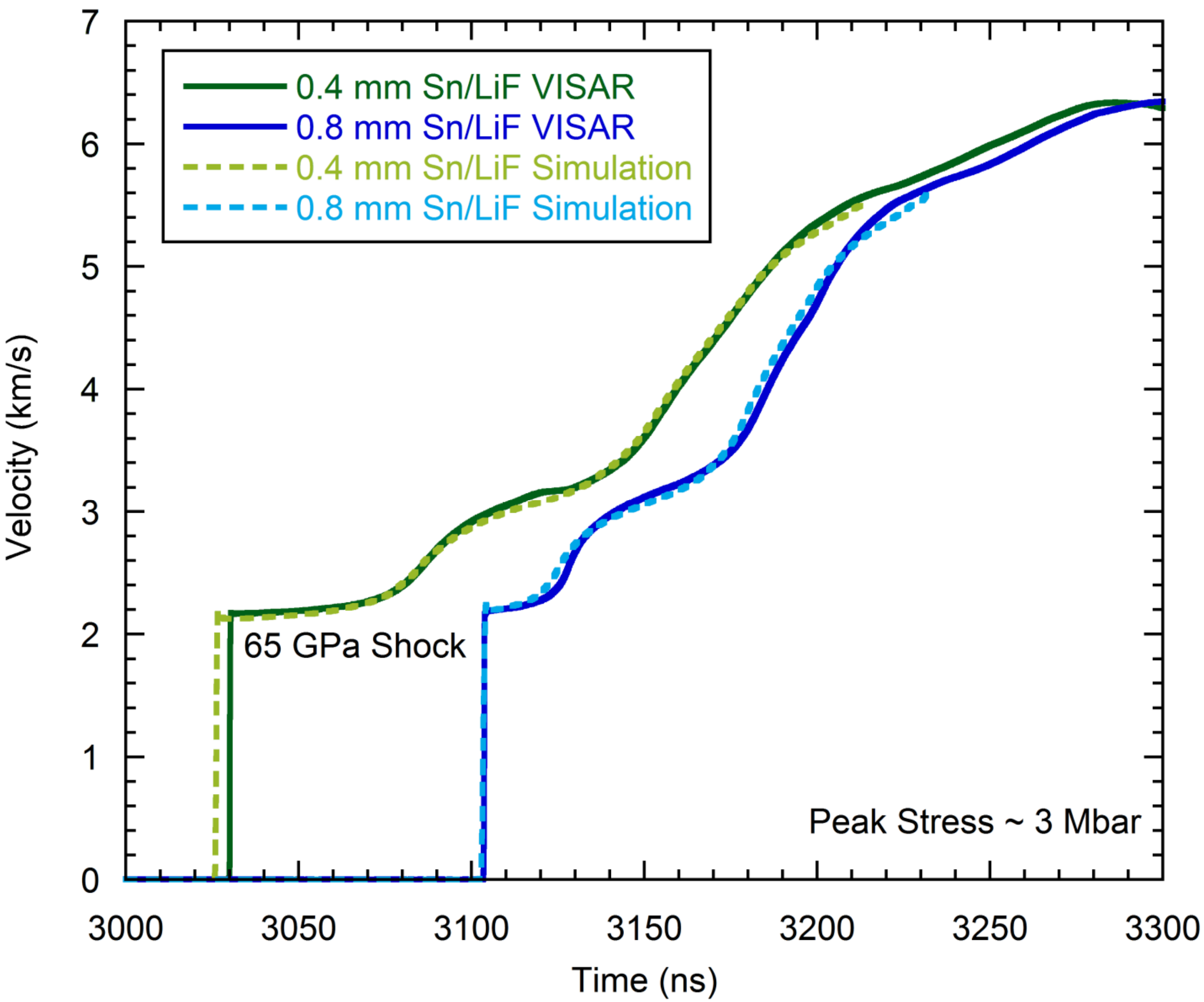




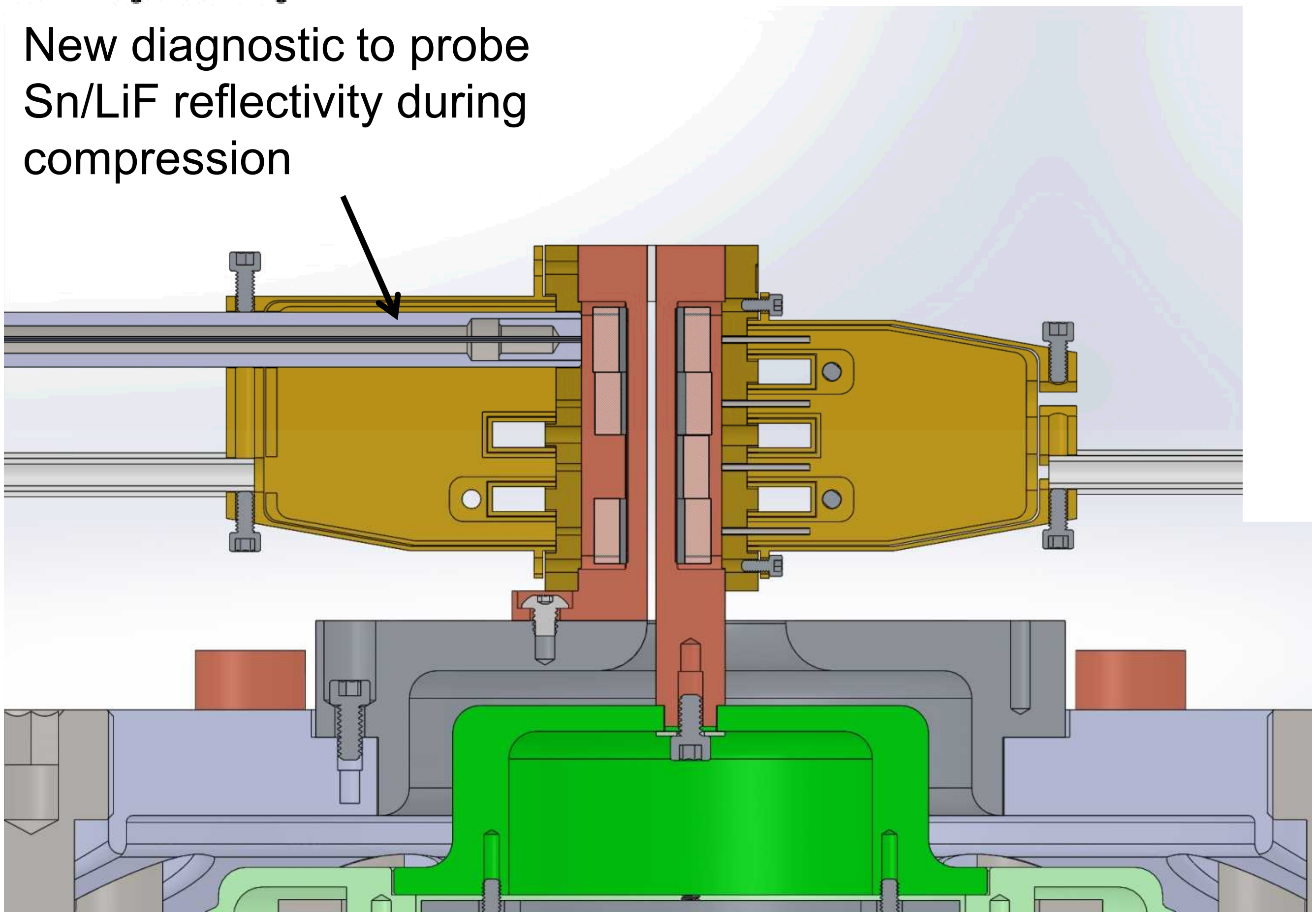
New data suggests stiffer response (relative to tables) is correct

- **Forward simulations with the Sn EoS from Seagle et al. 2013**
- **No clear evidence of resolidification in this non-ideal geometry**
- **Repeat (w/o nylon) planned for July 2015**



Additional diagnostics may be needed to detect subtle or broad changes in sound speed

New diagnostic to probe Sn/LiF reflectivity during compression



Camera flash lamp light source: see Jerry Stevens, Wed O4 10AM

Shock-Ramp technique at Sandia's Z Machine has matured to the point of "routine" experiments

- A combination of pulseshaping control, hardware development, and analysis routines have enabled a wide range of "off-principal" experiments to probe mechanical response at otherwise difficult to reach regions of phase space

- Sandia is currently exploiting the maturation of the technique to validate/improve equation of state models for a number of metals in solid and liquid regions of phase space (eg. Sn, Ce, Ta, Pt).

- We are also developing Platinum as a "standard" to be utilized with forward analysis on materials with complex/time-dependent response

Acknowledgements

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