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A Novel Method for Unfolding Laser Blast Wave VISAR Data

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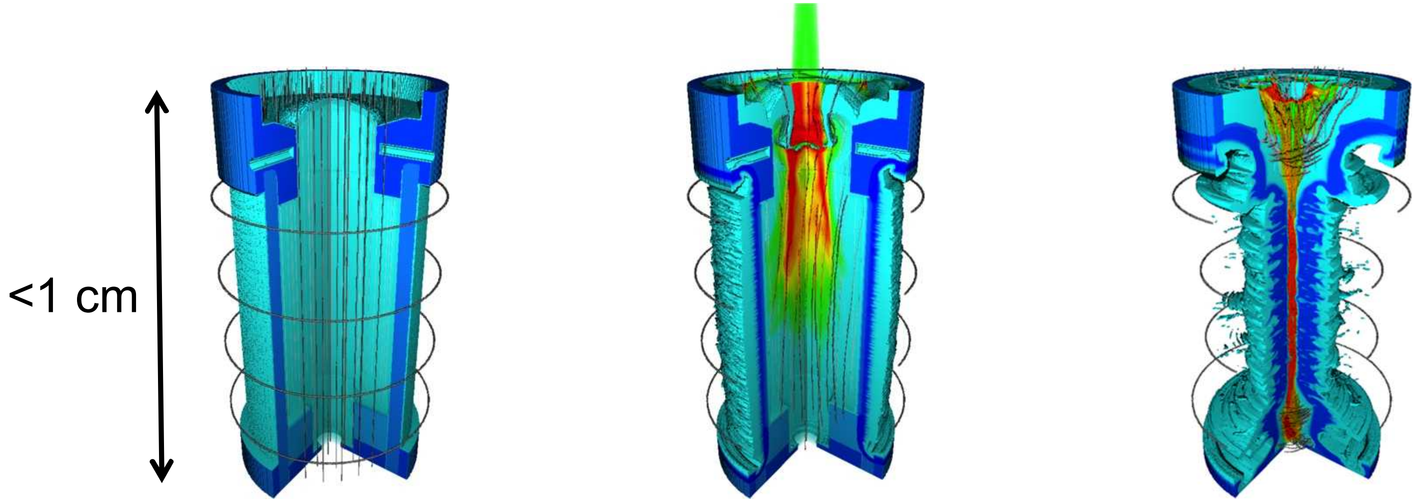
Motivation

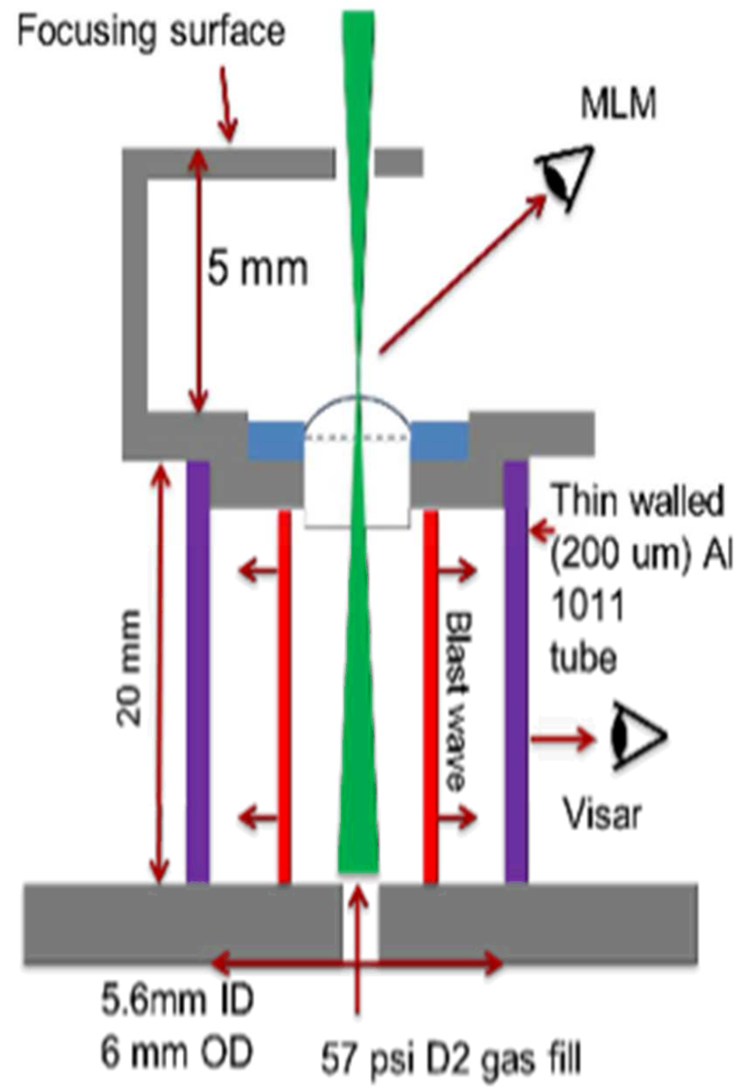
- A novel fusion concept called MagLIF (Magnetized Liner Inertial Fusion) is currently under development at Sandia.
  - A cylindrical metal liner, e.g. Al or Be, that contains a fuel is initially axially magnetized.
  - The fuel is preheated with a laser.
  - The liner, fuel, and magnetic field are all compressed with high-current magnetic drive, e.g. Z machine, which can lead to fusion relevant conditions in the fuel.
  - The compressed axial magnetic field gives reduced electron thermal heat conduction losses and increased ion confinement.



S. A. Slutz, *et al.*, Phys. Plasmas (2010); M.R. Gomez *et al.*, Phys. Rev. Lett. (2014).

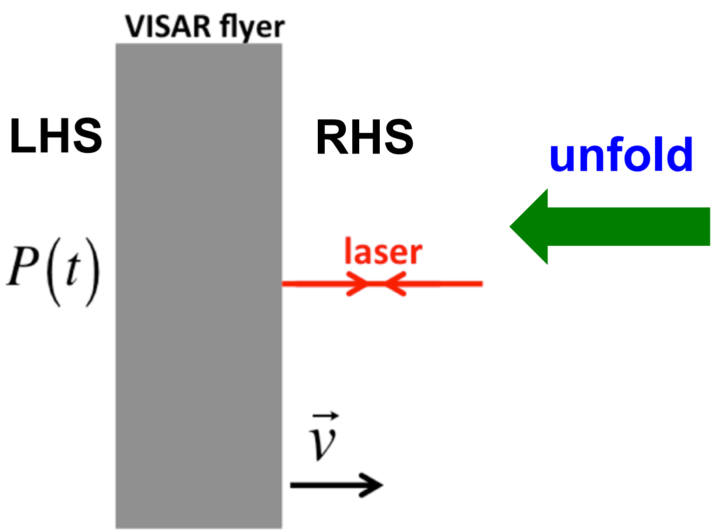
Laser Blast Wave Experiment

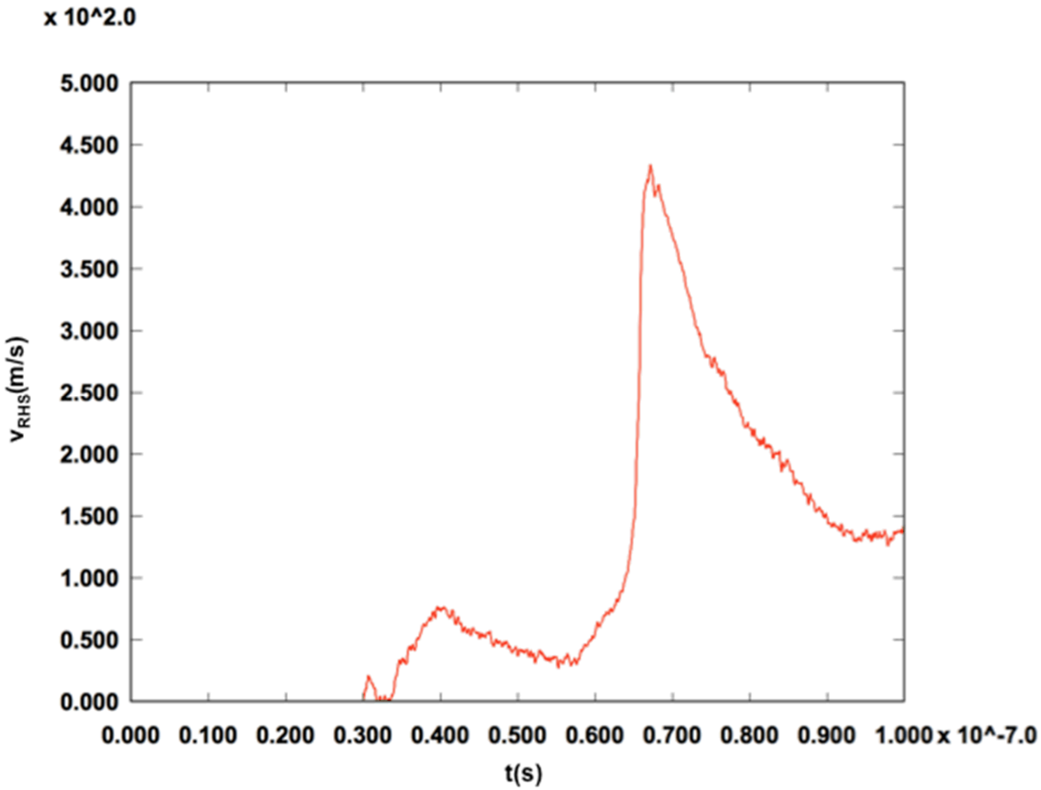
- A laser blast wave experiment using the Z Beamlet Laser (not firing Z) to test the preheat component of MagLIF was performed.
- VISAR was fielded at 15 locations: 3 LOS (30 ,150, 280) and 5 axial locations: 3.59 mm, 5.71 mm, 7.84 mm, 9.96 mm, and 12.09 mm from the LEH.



VISAR Unfolds

- The laser blast wave produces a pressure, P(t), as a function of time on the inner liner surface.
- This translates into motion of the outer liner surface that is tracked by the VISAR diagnostic as a v(t) (velocity vs. time) trace.
- We developed an efficient method for unfolding P(t) using:
  - each unfold takes about 30 seconds
  - runs on Python script





New Unfold Method

- The method is decomposed into two parts: low-pressure regime component and a high-pressure regime component

Low-Pressure Component

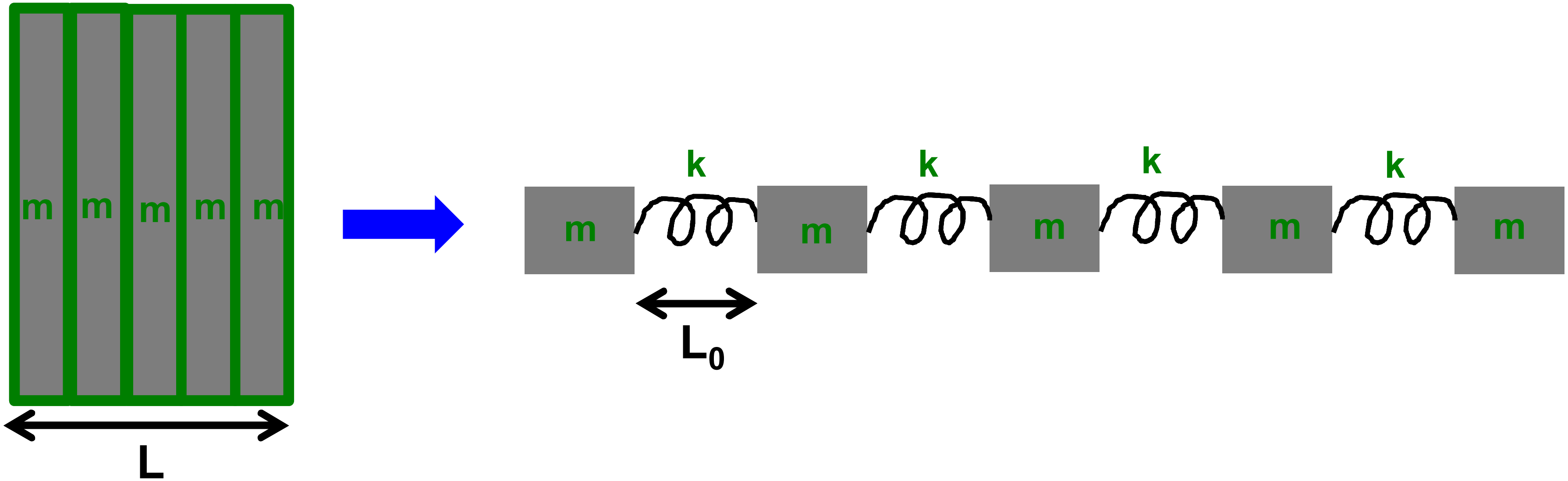
- Model flyer as infinite series of mass and springs
- Applicable when $P \ll \rho c^2$
- Ideal for modeling the low pressure "foot" of the blast wave
- Assume speed of sound, *c*, and flyer thickness is constant (pressure is not continuously differentiable at P = 0)

High-Pressure Component

- Utilizes EOS tables, e.g. SESAME, to model $P(\rho)$ and $c(\rho)$ in flyer
- Utilizes pressure/momentum continuity at both boundaries
- Accounts for time-dependent thickness change of flyer and appropriate time-delay response between LHS and RHS

M. Hess et al., High Power Laser Science and Engineering, 3, (2015).

Low-Pressure Component



Mass-Spring Equations:

$$ma_1 = m\frac{d^2x_1}{dt^2} = -k\left(x_1 - x_2 - L_0\right) + F\left(t\right)$$

$$ma_j = m\frac{d^2x_j}{dt^2} = -k\left(x_j - x_{j+1} - L_0\right) + k\left(x_{j-1} - x_j + L_0\right)$$

$$ma_N = m\frac{d^2x_N}{dt^2} = k\left(x_{N-1} - x_N + L_0\right)$$

Velocity Response:

$$M = \rho AL \qquad P = F/A \qquad k = NMc^2/L^2$$

$$v_N \to v_{RHS}\left(t\right) = \sum_{l=0}^{\infty}\frac{2P\left(t - \left(2l+1\right)L/c\right)}{\rho c}$$

Analysis of Low-Pressure Component

- By substituting the Nth mass-spring equation into the (N-1)th, the (N-1)th into the (N-2)th, and so on, one arrives at a differential equation for a_N. In the limit of large N, a_N approaches a_{RHS}, and one arrives at:

Equation for the RHS (VISAR) acceleration:

$$\frac{F}{M} = a_{RHS} + \frac{1}{3!\tilde{\omega}^2}\frac{d^2 a_{RHS}}{dt^2} + \frac{1}{5!\tilde{\omega}^4}\frac{d^4 a_{RHS}}{dt^4} + \frac{1}{7!\tilde{\omega}^2}\frac{d^6 a_{RHS}}{dt^6} + \ldots$$

$$= \sum_{n=0}^{\infty} \frac{1}{(2n+1)!\tilde{\omega}^{2n}} \frac{d^{2n} a_{RHS}}{dt^{2n}} = \sum_{n=0}^{\infty} \frac{1}{(2n+1)!\tilde{\omega}^{2n}} \frac{d^{2n+1} v_{RHS}}{dt^{2n+1}}$$

$$= \frac{\tilde{\omega}}{2}\left[v_{RHS}\left(t + 1/\tilde{\omega}\right) - v_{RHS}\left(t - 1/\tilde{\omega}\right)\right]$$

where $\tilde{\omega} = \omega/N = c/L$

is a renormalized frequency.

Equation for the RHS (VISAR) velocity:

$$v_{RHS}(t) = v_{RHS}(t - 2L/c) + \frac{2P(t - L/c)}{\rho c}$$

$$= \sum_{l=0}^{\infty} \frac{2P\left(t - (2l+1)L/c\right)}{\rho c}$$

High-Pressure Component

We assume that the temperature remains small and constant. The pressure and sound speed are functions of density given by the EOS table, e.g. Al 3700/3719.

$$P(\rho)$$

$$c(\rho) = \sqrt{dP/d\rho}$$

The density and velocity of the LHS can be found from pressure continuity and momentum conservation at the LHS boundary.

$$P(\rho_{LHS}) = P_{ext}(t) \quad \Rightarrow \quad \rho_{LHS}(t) = P^{-1}(P_{ext}(t))$$

$$v_{LHS}(t) = \int_0^{P_{ext}(t)} \frac{dP}{\rho_{LHS}\, c(\rho_{LHS})}$$

Ignoring density variations due to reflections, momentum conservation yields the VISAR (RHS) velocity in terms of the LHS velocity (term in brackets accounts for time-dependent time delay of signal).

$$v_{RHS}(t) = 2v_{LHS}\left(t - \frac{L\rho_0}{c(\rho_{LHS}(t))\,\rho_{LHS}(t)}\right)$$

Analysis of High-Pressure Component

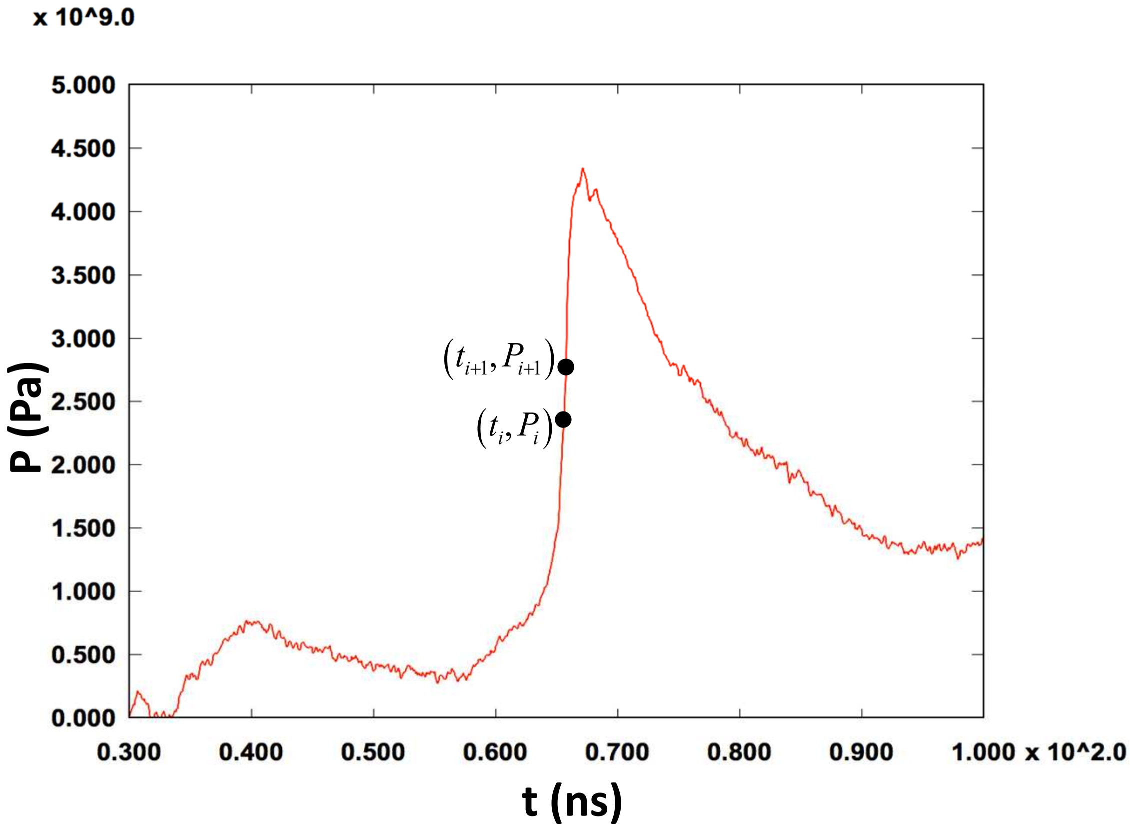
- We assume that any pressure drive $P(t)$ can be divided into a series of infinitesimally small pressure shocks P_i at times t_i:

The velocity increase behind each shock, e.g. at LHS, can be computed using conservation of momentum across the shock front.

$$v_{i+1} = v_i + \frac{P_{i+1} - P_i}{\rho_i c(\rho_i)}$$

Each new shock travels with a speed $c(\rho_{LHS})$, and since the flyer is compressed, the time-delay to reach the RHS is:

$$\frac{L\rho_0}{c(\rho_{LHS}(t))\rho_{LHS}(t)}$$



High-Pressure Component

- Given a VISAR velocity data, we want to unfold the time-dependent pressure.

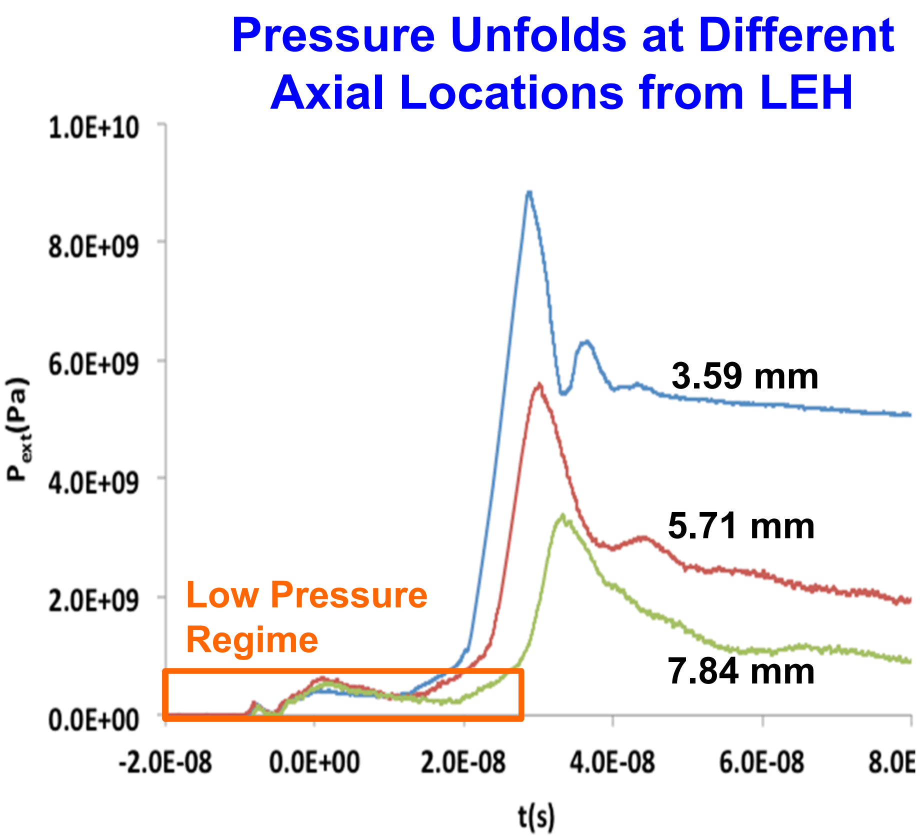
$$v_{RHS}(t) = \int_{\rho_0}^{\rho_{LHS}\left(t - \frac{L\rho_0}{c(\rho_{LHS}(t))\rho_{LHS}(t)}\right)} \frac{2c(\rho)\,d\rho}{\rho}$$

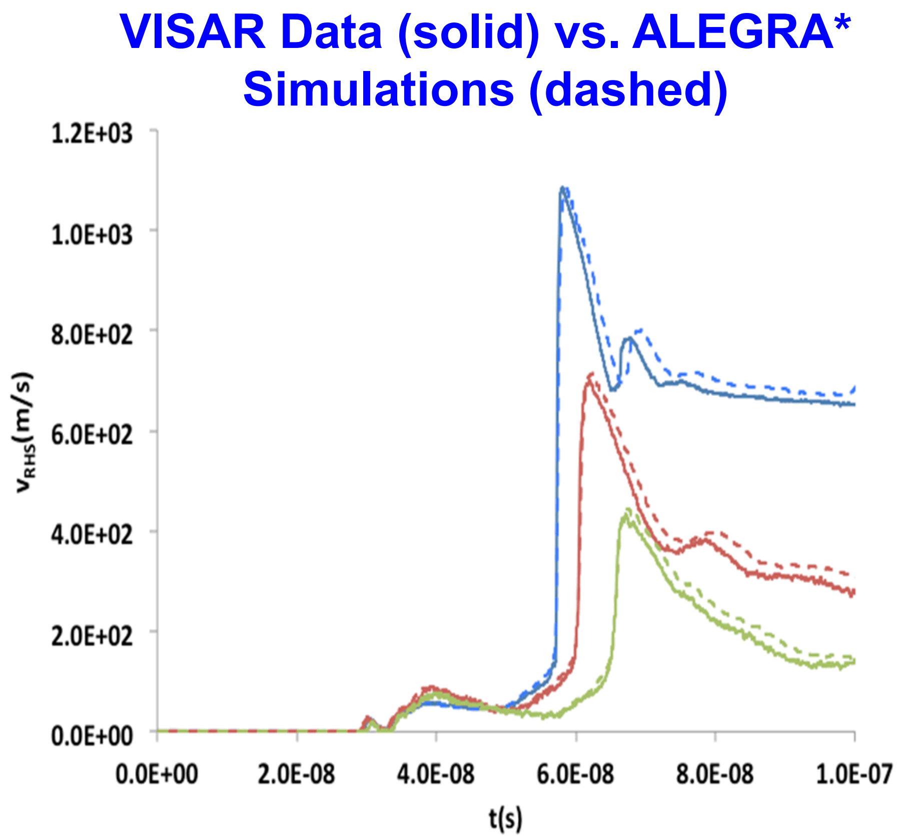
- For each time t, we numerically integrate the above expression to find ρ_{LHS}. Then we time shift the LHS density to produce $\rho_{LHS}(t)$. The LHS density immediately yields the time-dependent external pressure.

$$P(\rho_{LHS}) = P_{ext}(t)$$

Laser Blast Wave Unfolds

- The simulated VISAR velocities using the Sandia code ALEGRA* with the unfolded pressure from our method gives excellent agreement with VISAR data.





*A. C. Robinson, et. al., AIAA Aerospace Sciences Meeting, January 2008, AIAA2008-1235.

Current Limitations

- At present, we have not yet included any thermal effects, as well as, material strength models (under development).
- Although the low-pressure component includes the effect of reflections, this has not yet been included in the high-pressure component of the unfold (under development).
- For the laser blast wave experiments, there is the possibility that some material of the inner liner surface could be ablated. This effect is not included in our model.

Conclusions

- We have a method for efficiently unfolding pressure driven VISAR data, which has been successfully implemented in Python.
- The method incorporates EOS tables, as well as an appropriate time-delay response, to correctly unfold the pressure.
- The model has been utilized to predict the time-dependent pressure of laser blast waves in MagLIF.
  - We are currently working to infer the energy deposition into the MagLIF fuel from the pressure.