Benchmarking Dynamic Strain Predictions of Pulsed Mercury Spallation Target Vessels

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High-power Targetry for Future Accelerators
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Credible simulations require benchmarking

- Design of the SNS target module requires an estimate of induced stress from beam pulses.

- Historically, while simulations have predicted the response of solid targets to short pulses well, simulating liquid metal target response has significant additional difficulties:
  - Dense fluid ? structure interaction
  - Cavitation greatly changes behavior

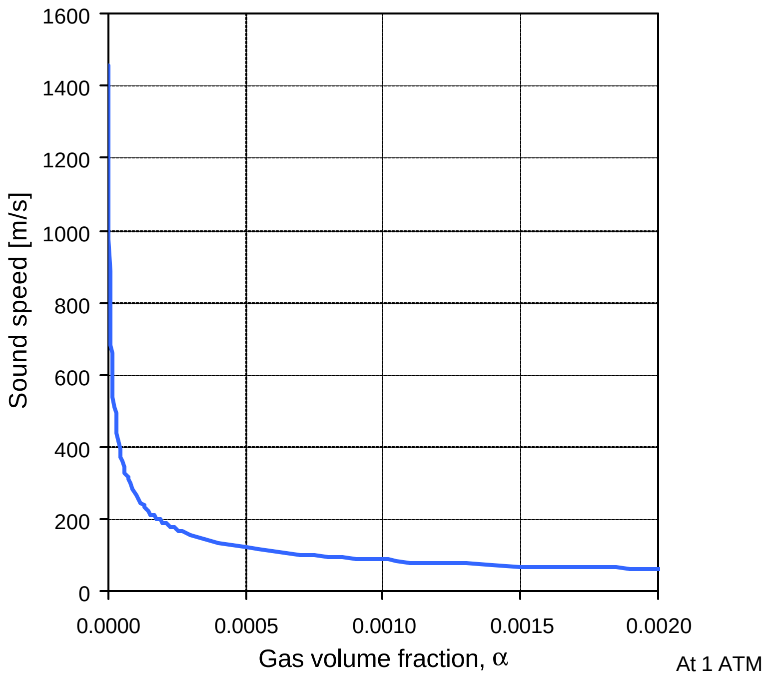
- A credible simulation technique has been developed benchmarked to experimental data obtained as part of R&D.

Bubbly mixture sound speed is very sensitive to gas volume fraction

- For sound frequencies *below* bubble resonance, a simple expression shows sensitivity of sound speed to volume fraction.

$$\frac{1}{c^2} = \frac{a}{kp}\left[r_L(1-a) + r_G a\right]$$

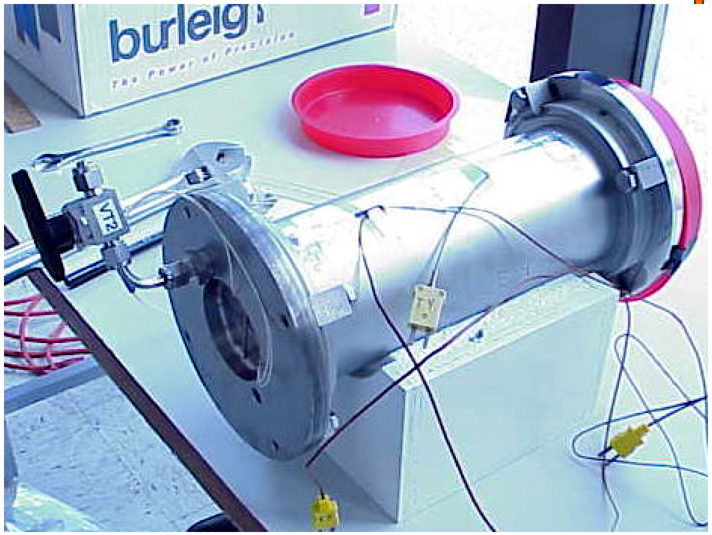
Mercury – helium mixture



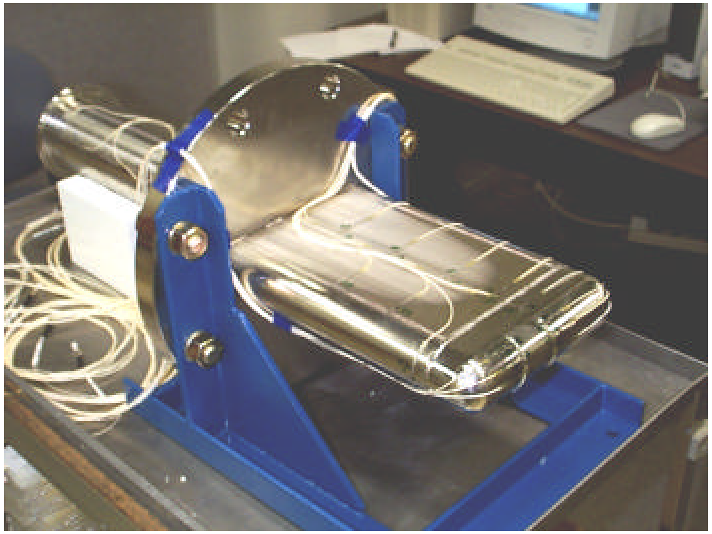
- What is the bubble population in a mercury spallation target? How does it change during a pulse interval? Who knows?

Two target types used in experiments to obtain relevant strain data

- Large Effects (LE) target.
  - Axisymmetric: modelling advantage.
  - Flange end thinned to ~ 1 mm. Strains were close to yield: easier to measure & more sensitivity to test parameters.



- Prototypic Shape (PS) target.
  - ½ scale of SNS target.
  - Thin beam window region.
  - Internal baffles.



- Induced strains are driven by fluid structure interaction … not wave propagation in steel.
- No flow. Single pulse tests.

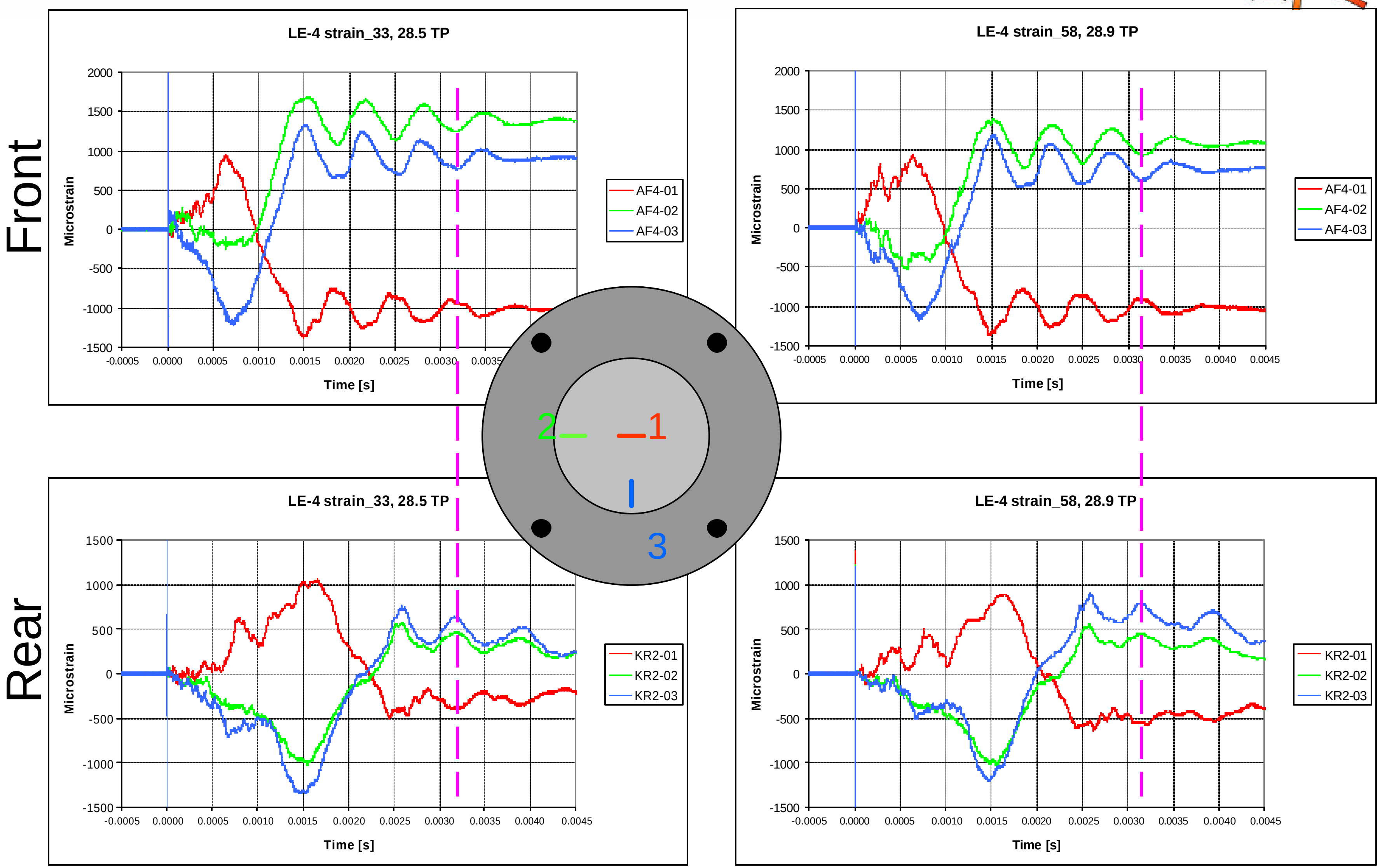
Proton irradiation performed at LANSCE-WNR

- LE type targets tested in August 2000, July 2001 and December 2001.

- PS type targets tested in August 2000.

	SNS (*@ 2 MW*)	WNR
Proton Energy [GeV]	1	0.8
Protons per pulse	2×10^{14}	2.8×10^{13}
Beam size [mm]	Elliptic ~ 70 x 200	Circular $\sigma \sim 10$
Energy deposited in mercury target [kJ]	20	2.2
Maximum deposited energy density [MJ/m^3]	13	19
Peak initial pressure [MPa]	36	51

Test data examples with 5 ms data capture. Note slow dynamic response.



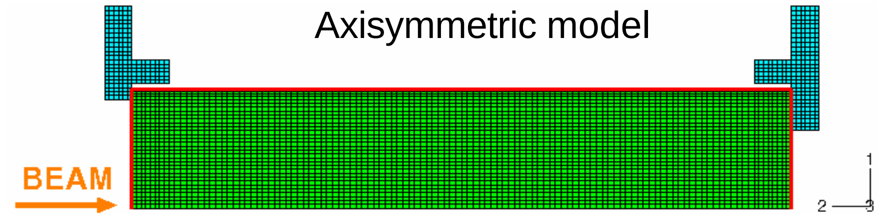
Simulations using ABAQUS/Explicit

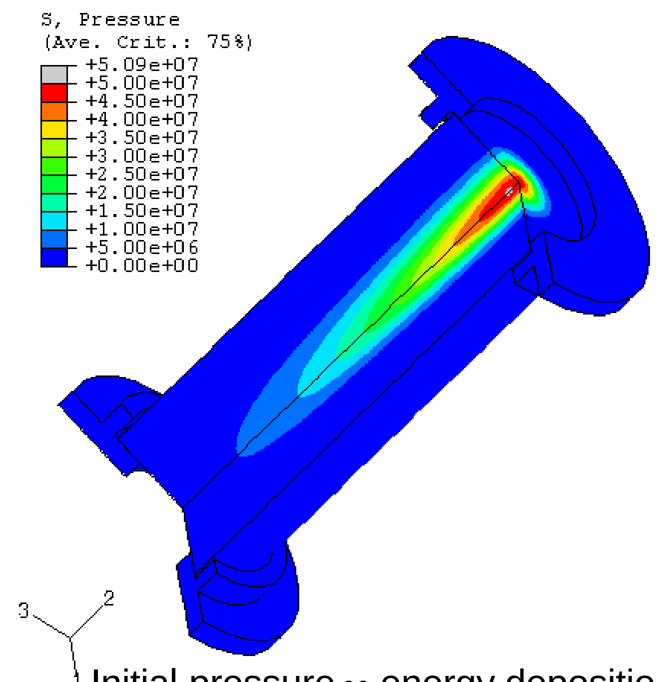
- Simple equation of state material model describes Mercury's volumetric pressure – strain behavior.

$$P = r_0 c_0^2 \left(1 - {r_0}/{r}\right)$$

- Pseudo cavitation: Material failure options can be configured to limit tensile pressure to specified threshold. Nominal behavior is restored when strain returns to threshold.

- Mercury is tied to the container wall. A contact interface is not helpful.



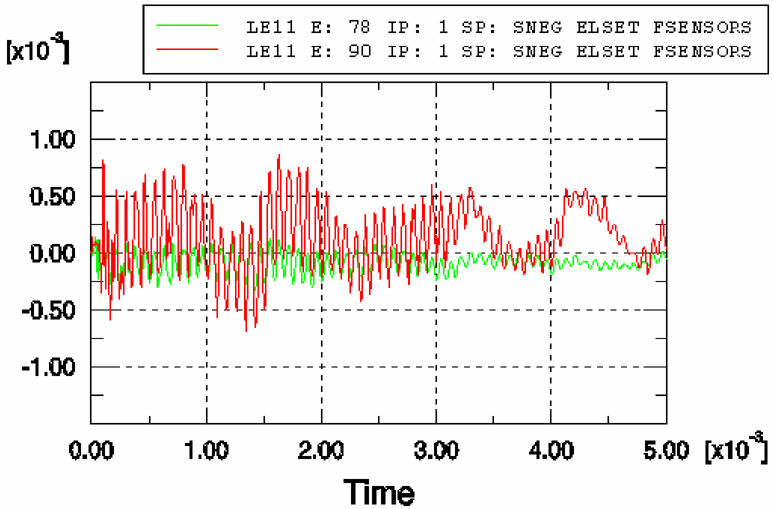


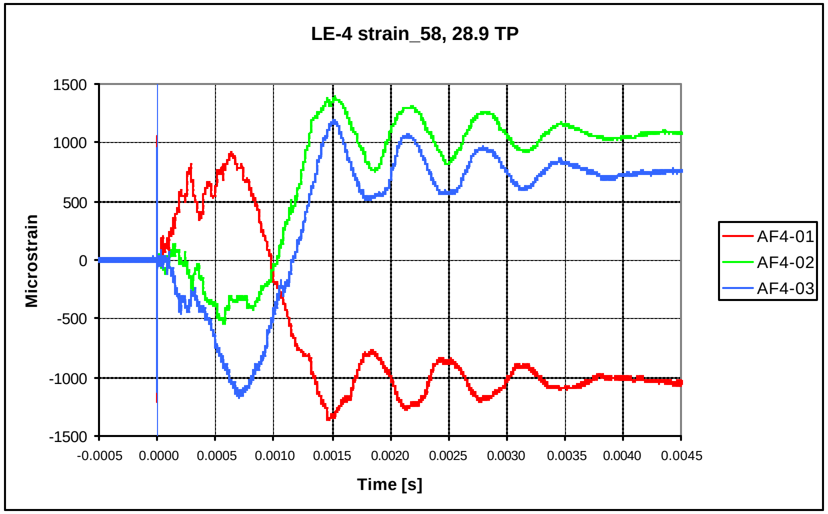
Initial pressure ∝ energy deposition

Nominal mercury (no failure / cavitation)

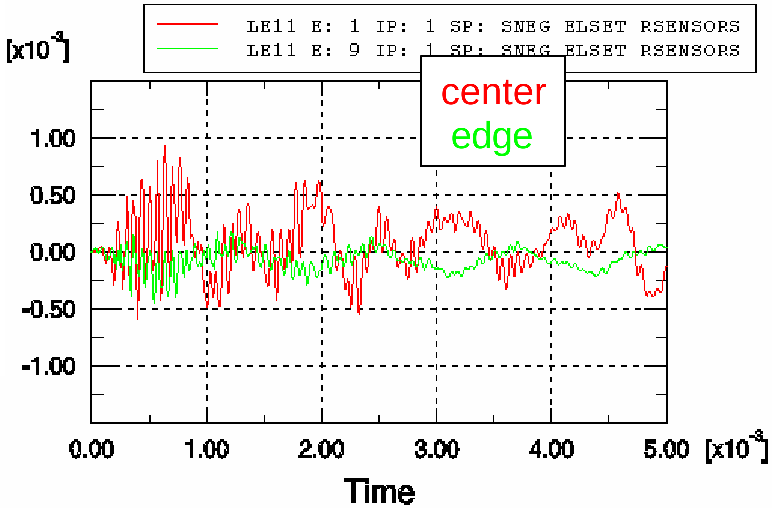
Simulation | Test data

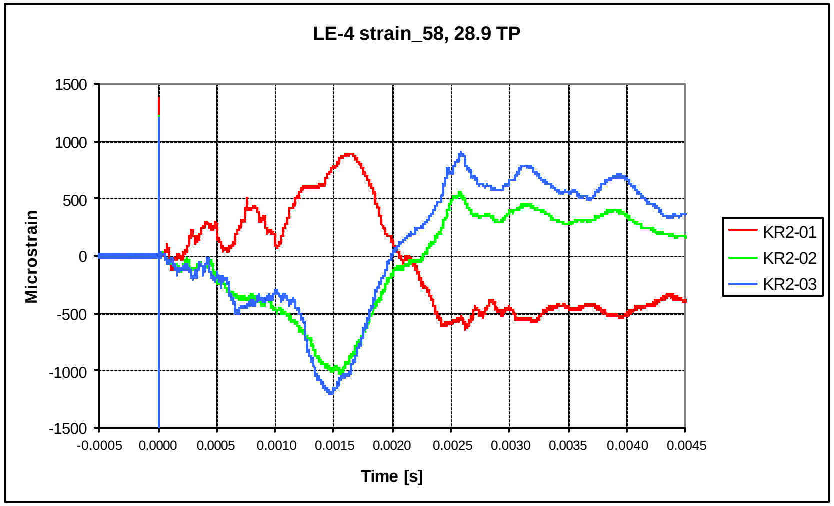
Front





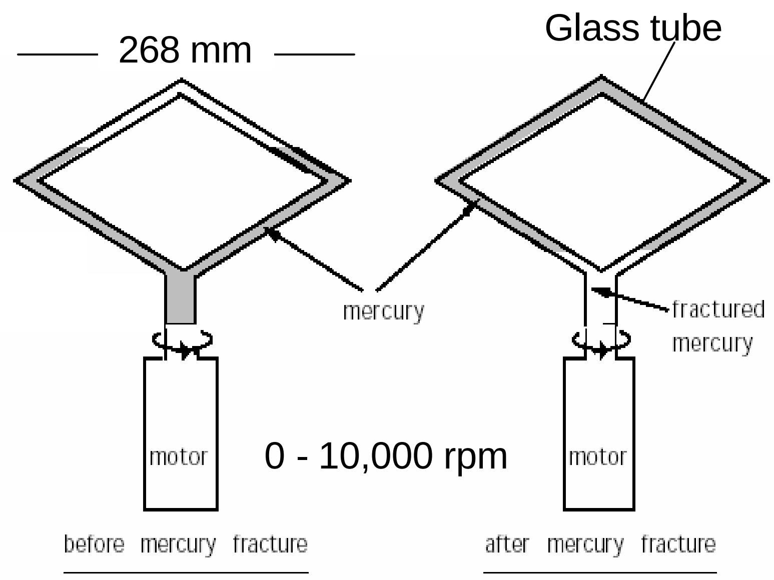
Rear

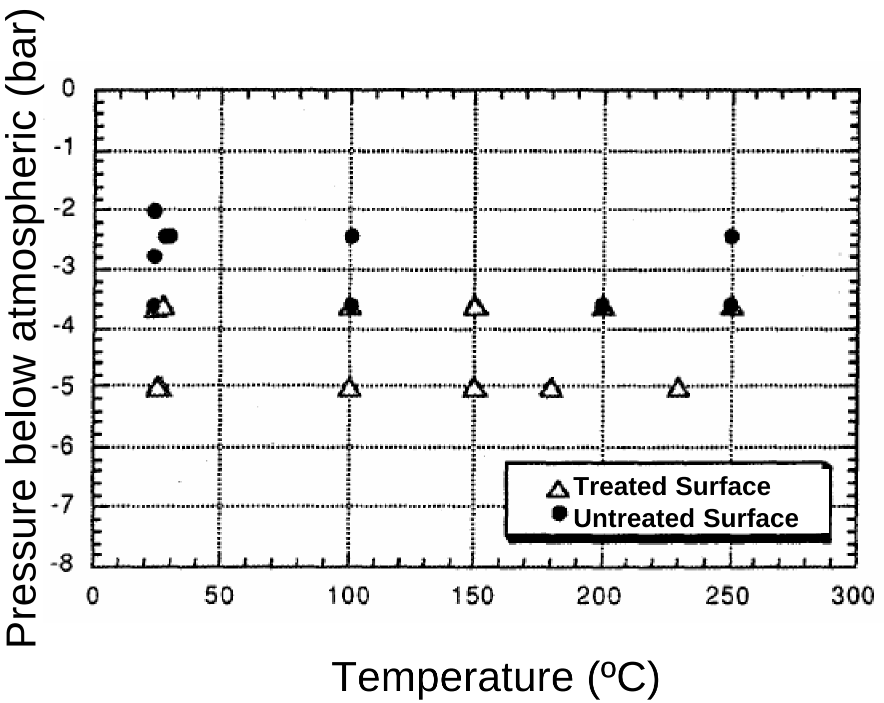




Briggs Apparatus Used to Study Mercury Cavitation Threshold Under Static Loading

- Cavitation threshold of ordinary mercury occurs at <u>only a few bar</u> tension.
- Dynamic tests using a resonant chamber & helium saturation were comparable.
- Briggs achieved a threshold of 425 bars using extreme measures on de-gassed mercury.
- Theoretical cohesion pressure for mercury is 1700 MPa.



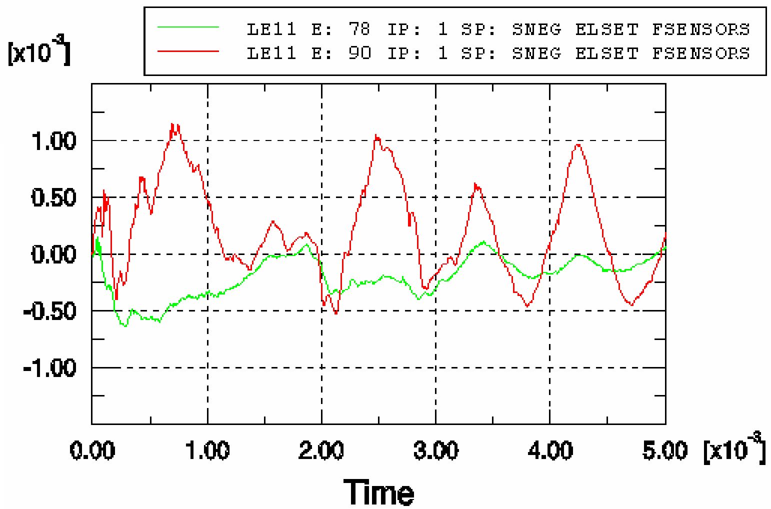


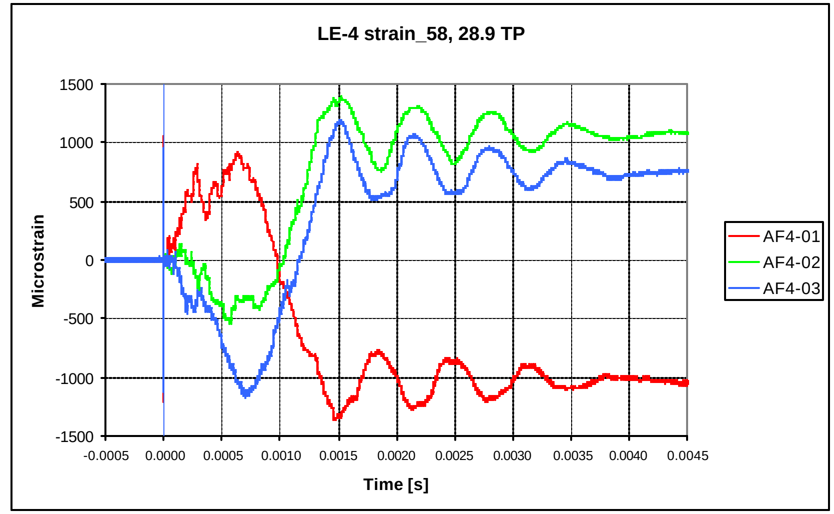
Mercury failure threshold: 3 bar tension

SPALLATION NEUTRON SOURCE

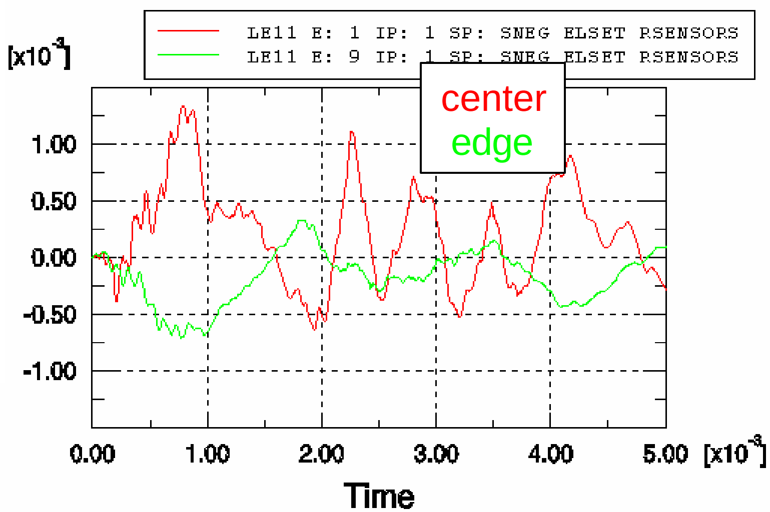
Simulation	Test data

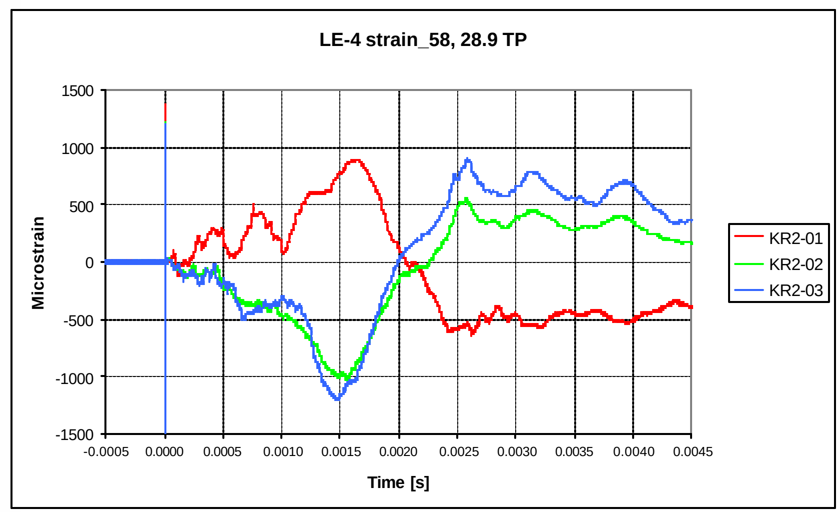
Front





Rear

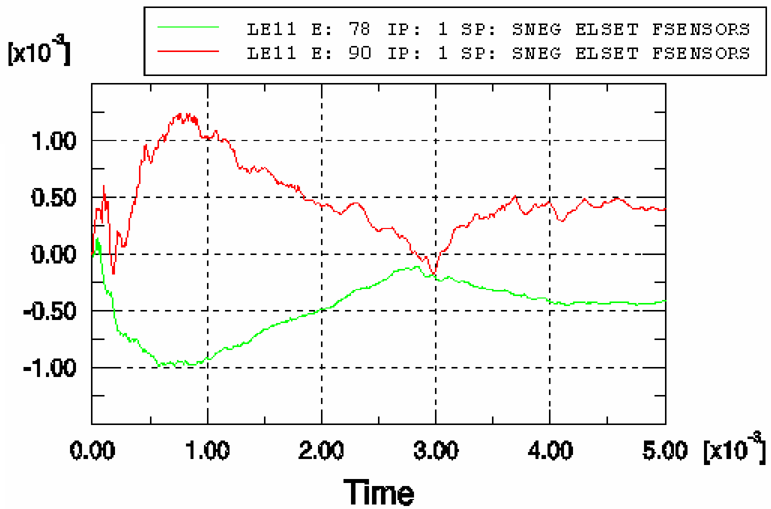


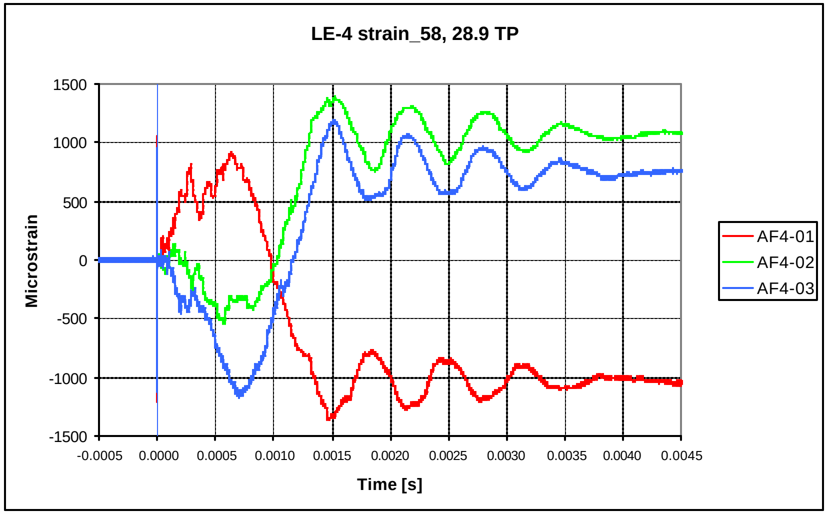


Mercury failure threshold: 0 bar

Simulation / Test data

Front





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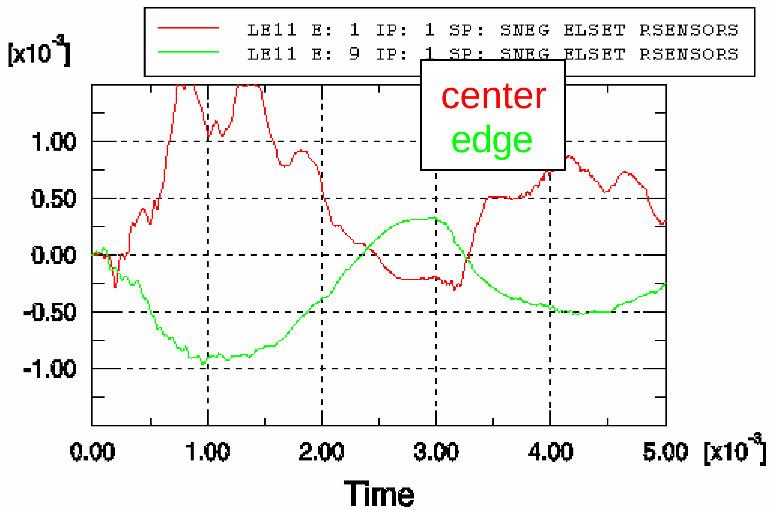
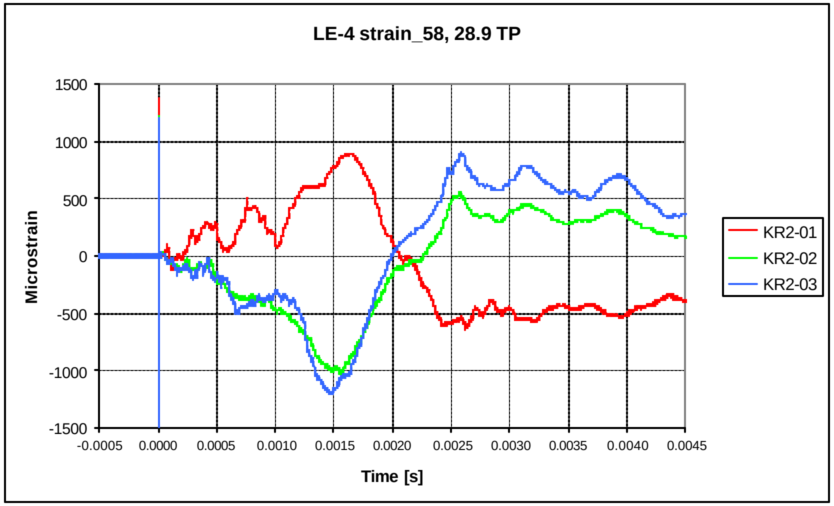
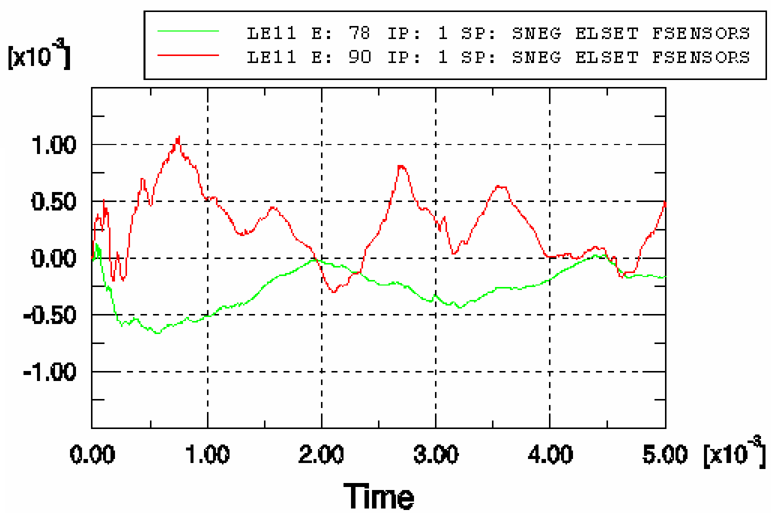


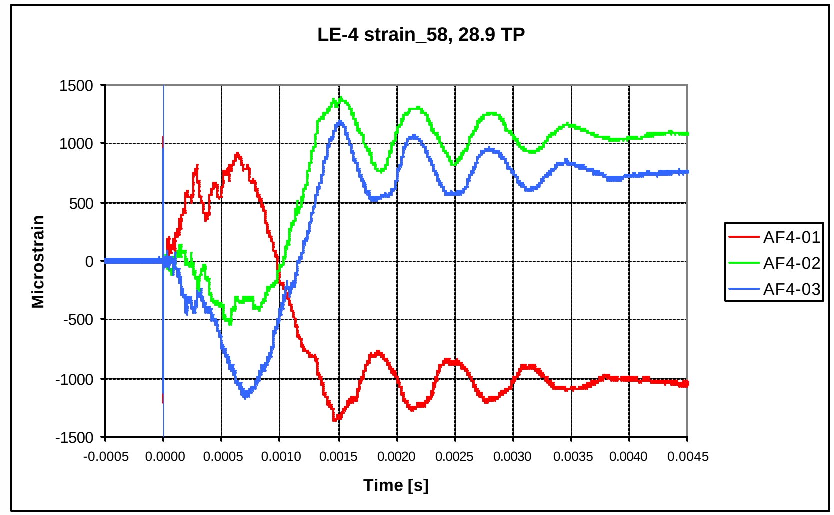


Mercury failure threshold: 1.5 bar tension

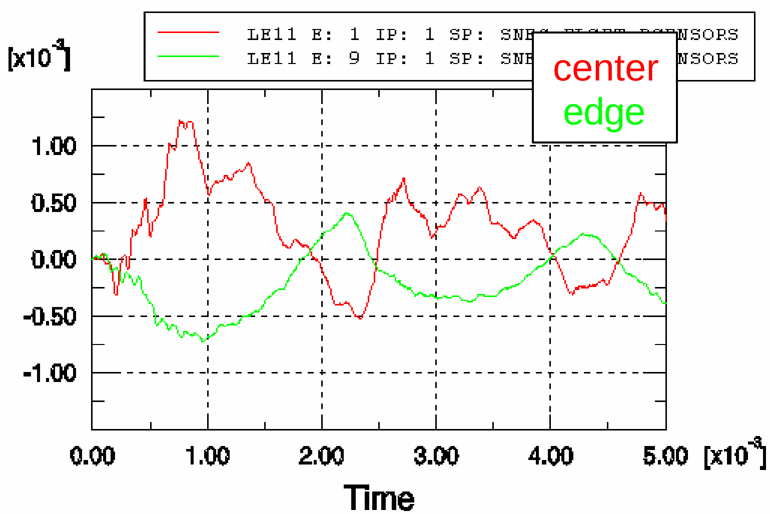
Simulation | Test data

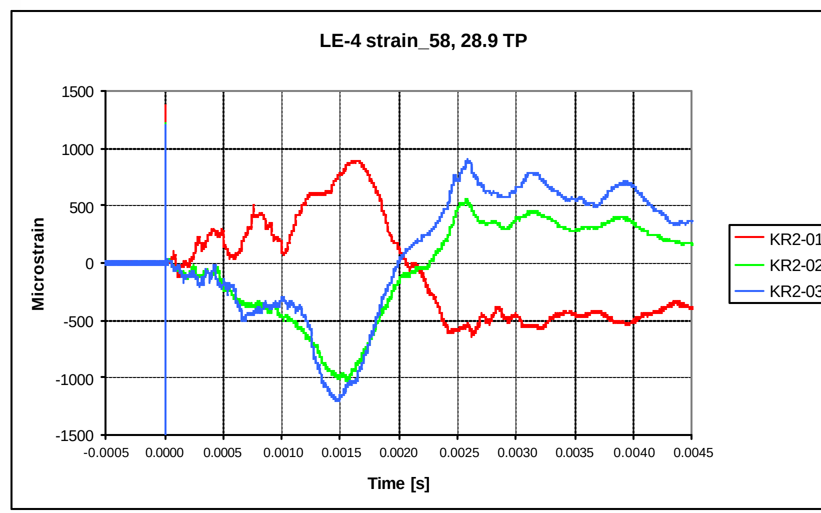
Front



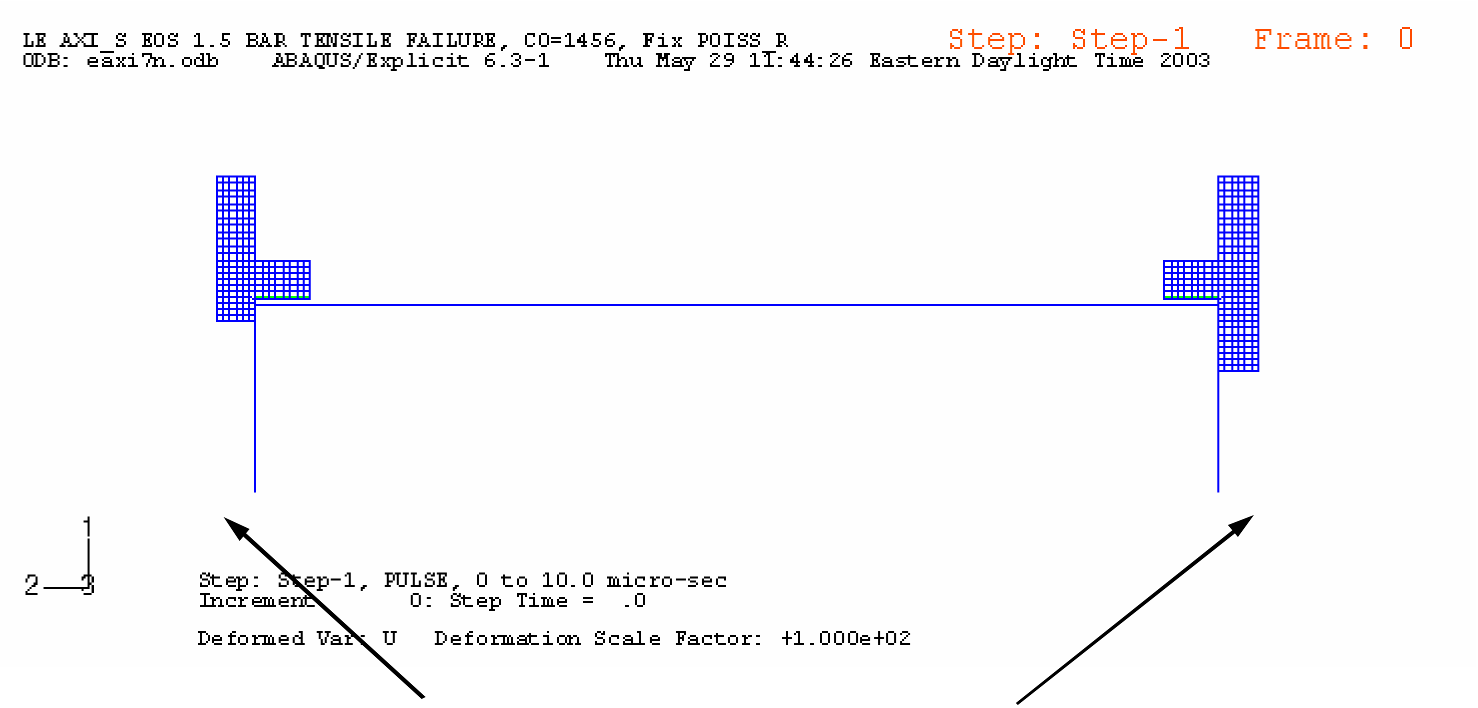


Rear





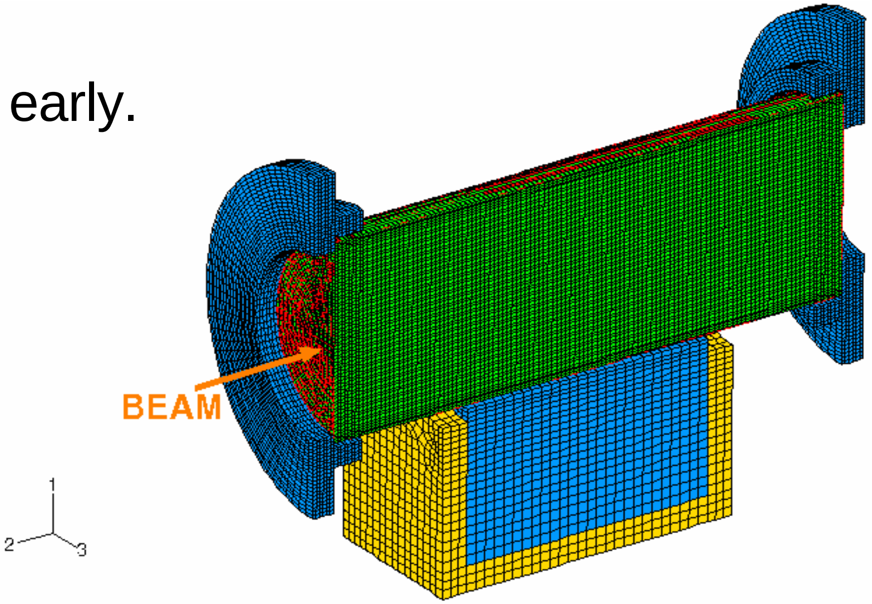
Target vessel deformation (100x)



Maximum axial movement ~0.5 mm

Significant improvement in simulation, but …

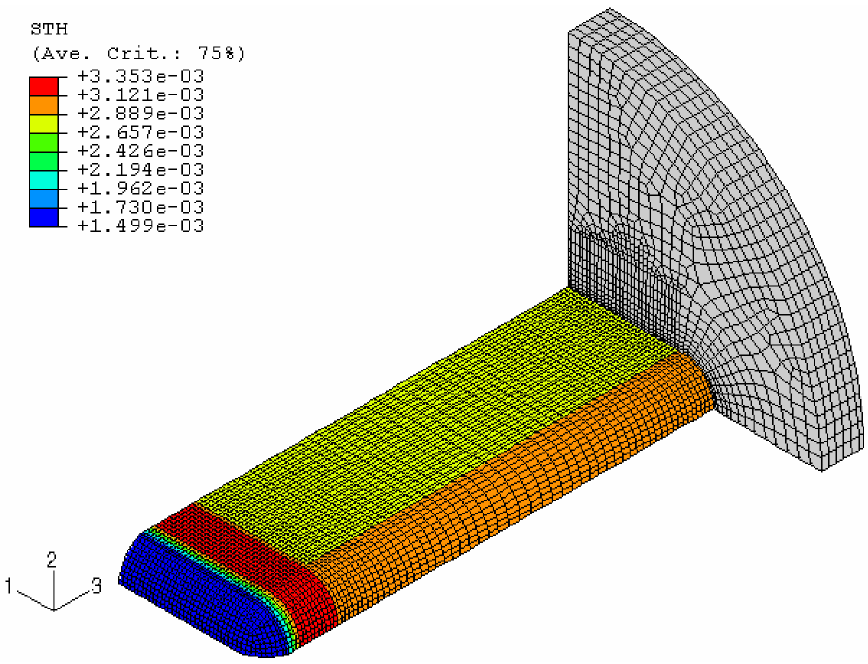
- Major swing in strains is not predicted.
- Rear initial strain peaks occur too early.
- Possible causes?
  - 3D effects
  - Gravity
  - Vent tube
  - Damping



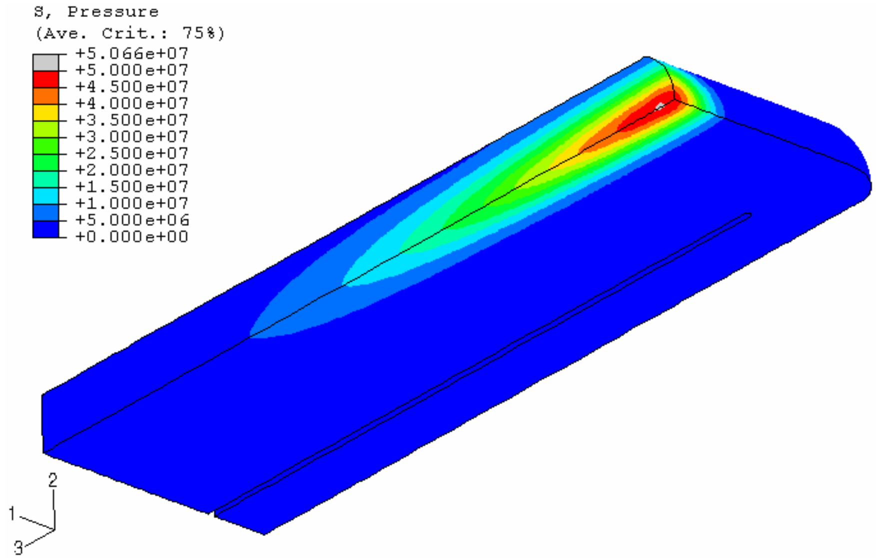
- May be at limits of this simple approach to modeling cavitation.
- Time to move on with PS target simulations.

PS model with ¼ symmetry

- Use simulation parameters determined with LE benchmark.
- 3D model. Neglects stand & gravity.



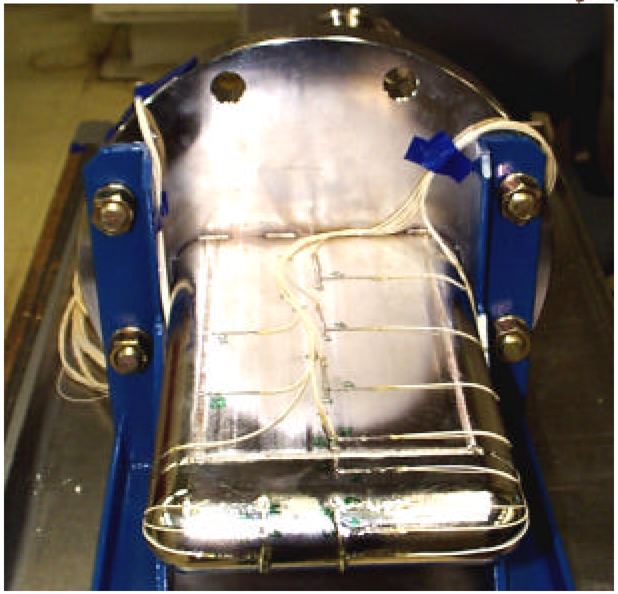
As built vessel thicknesses

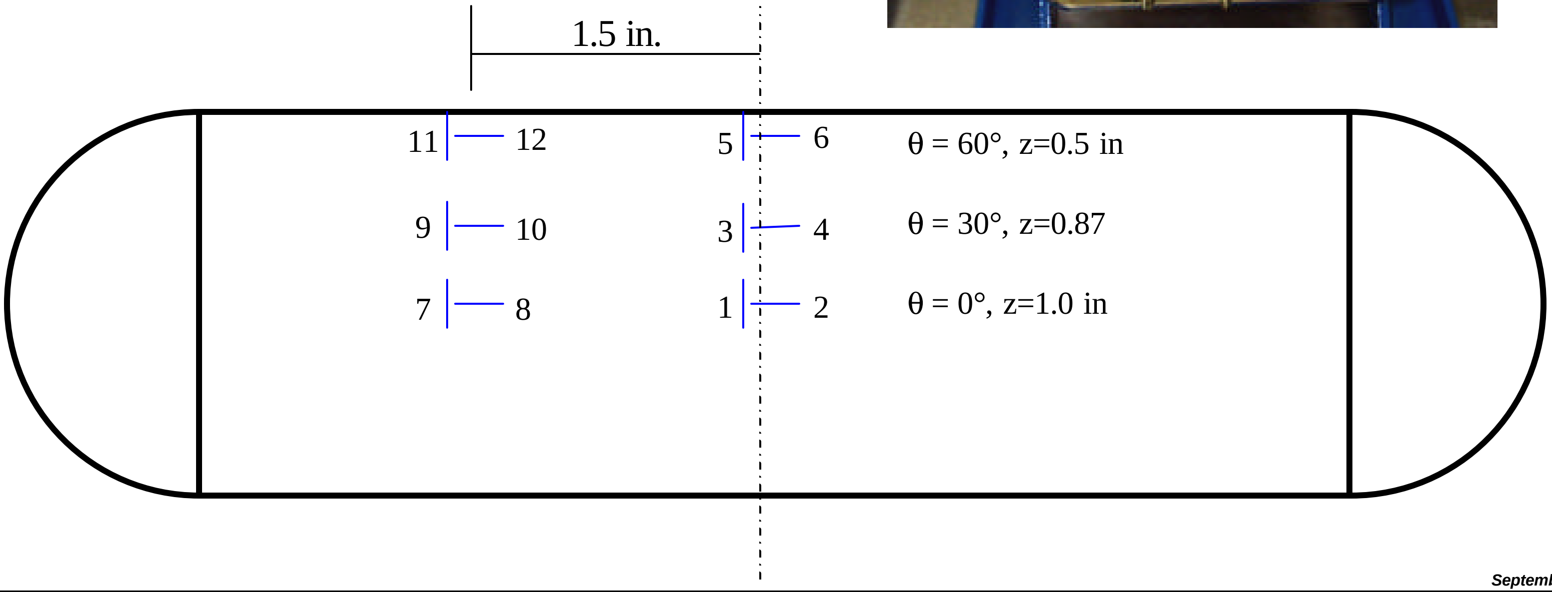


Initial mercury pressure ∝ energy deposition

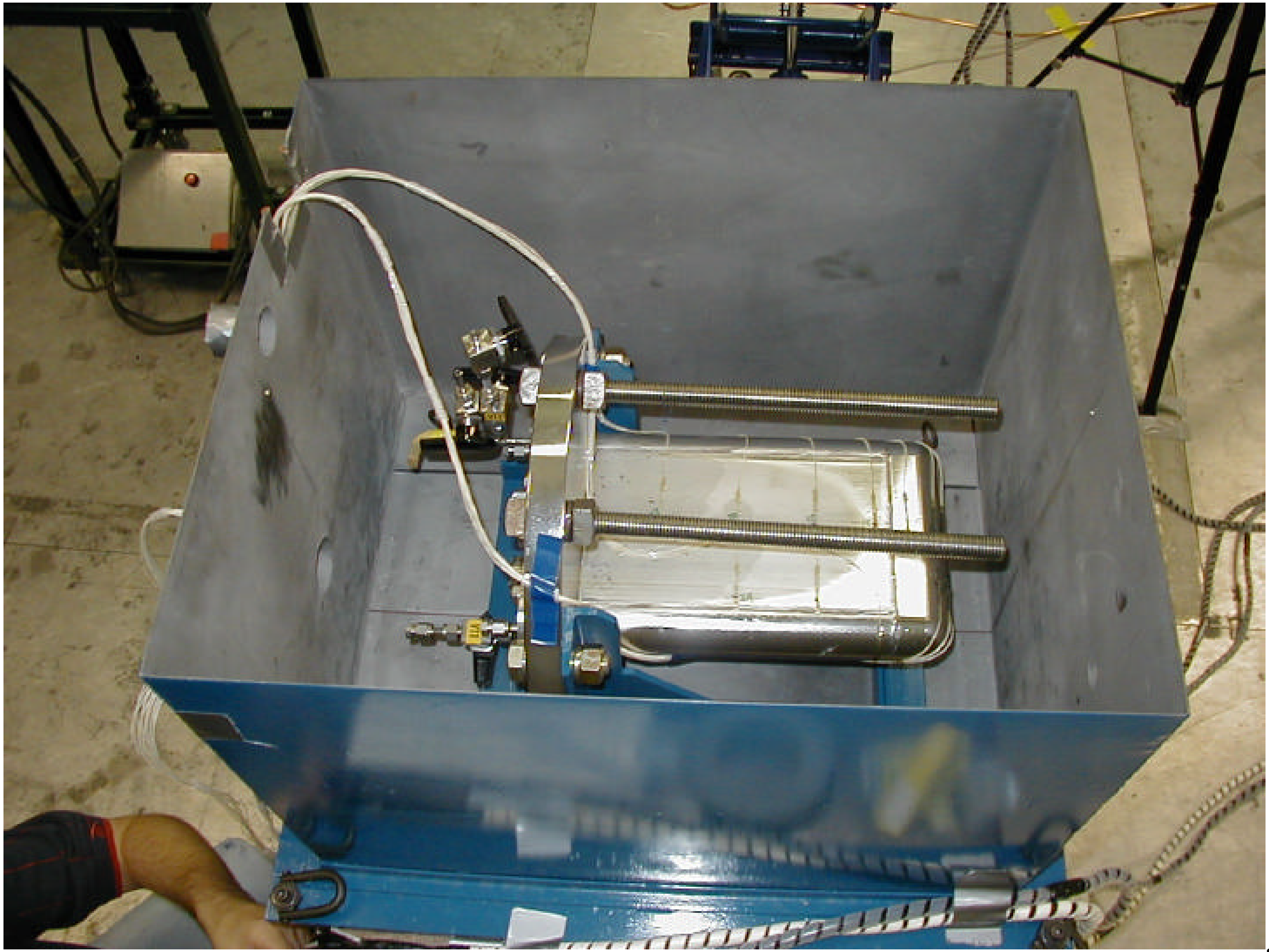
PS Target nose sensor locations

- Odd numbered sensors oriented in hoop direction around target nose.
- Even numbered sensors oriented across the target nose.



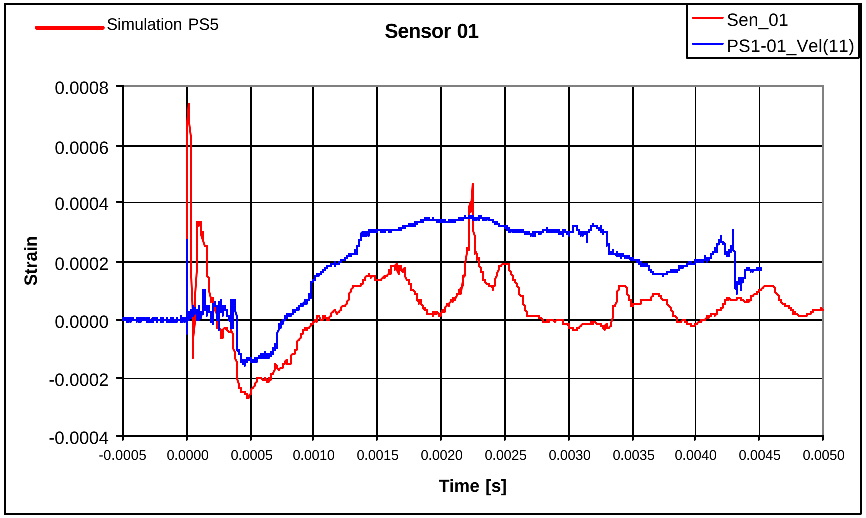


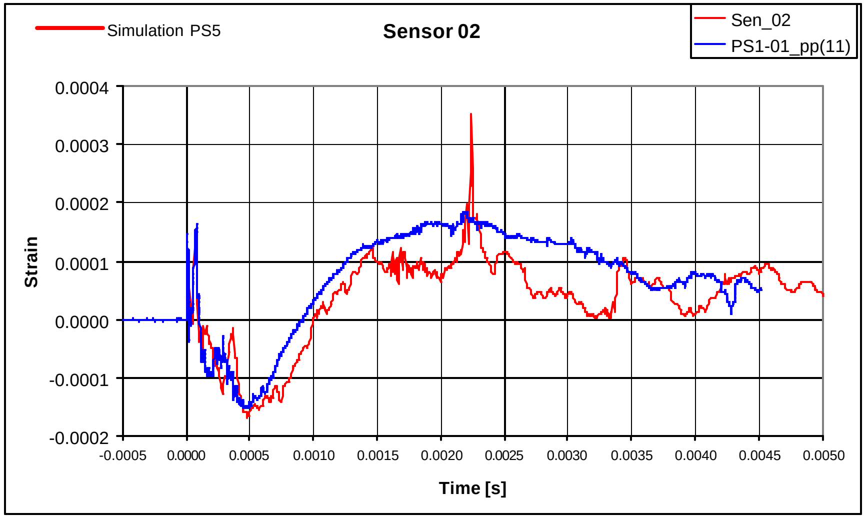
PS target ready for test.

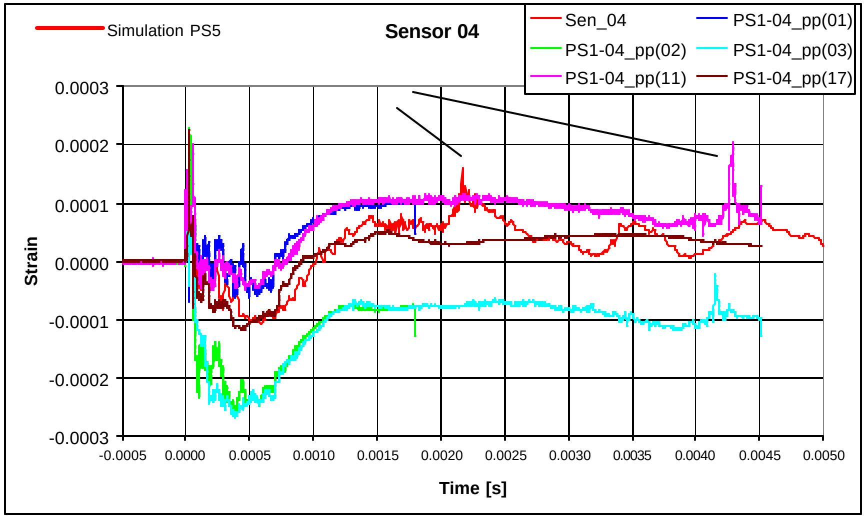


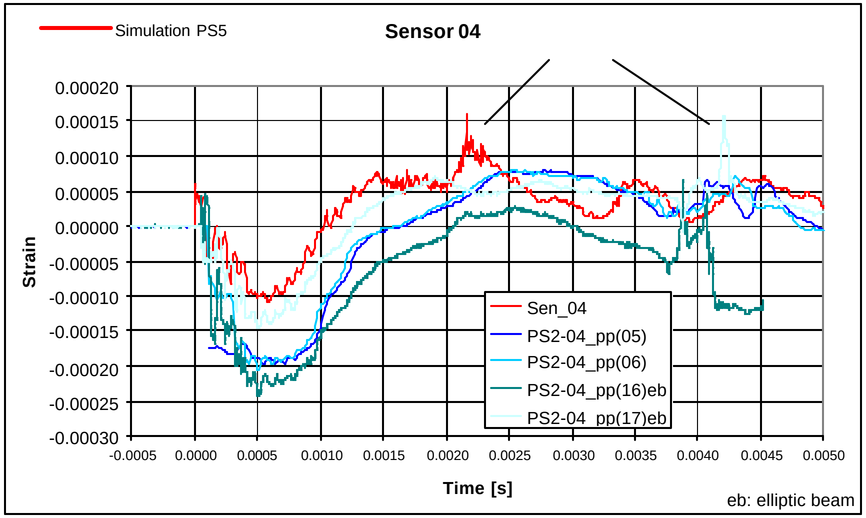
Simulation vs. test data: nose - center

RED = SIMULATION

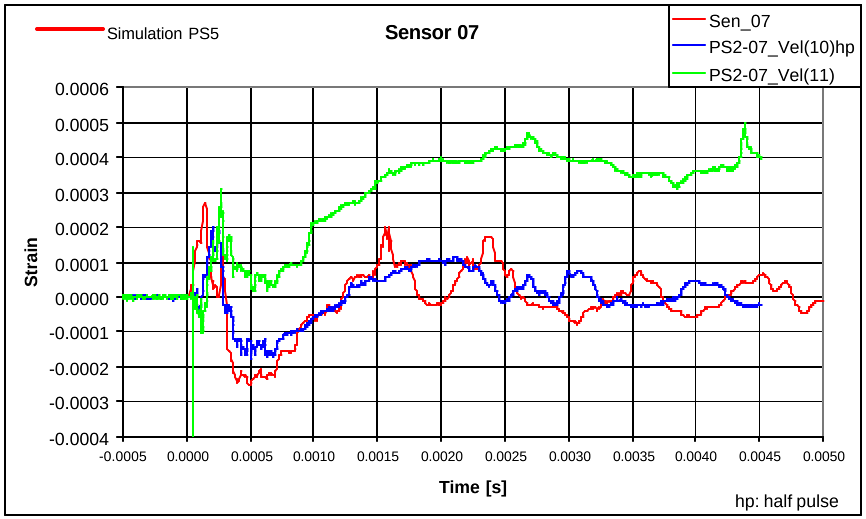


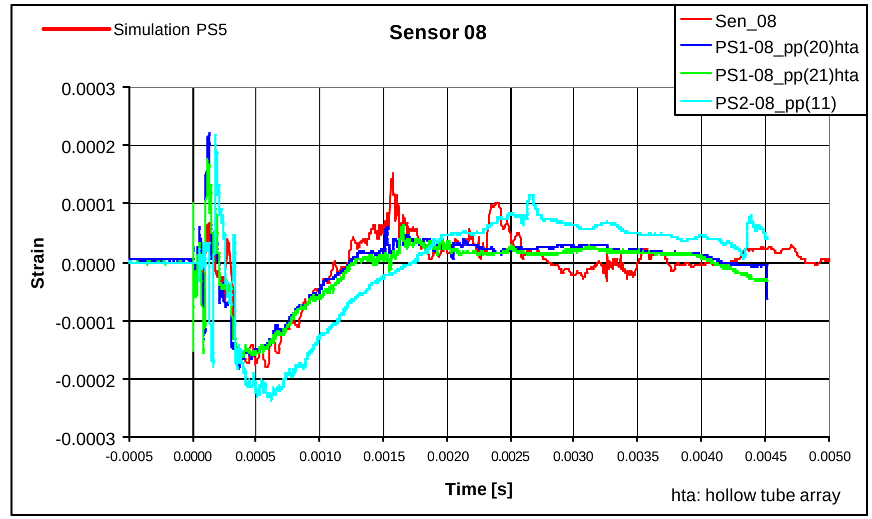


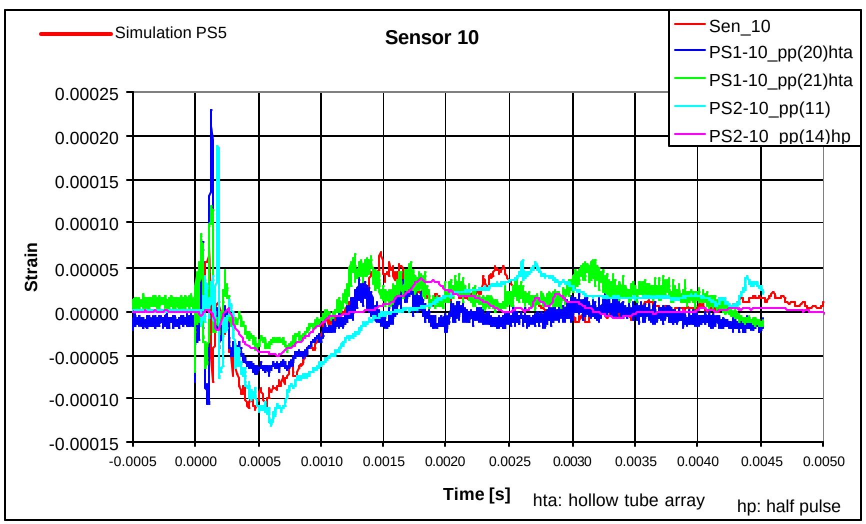


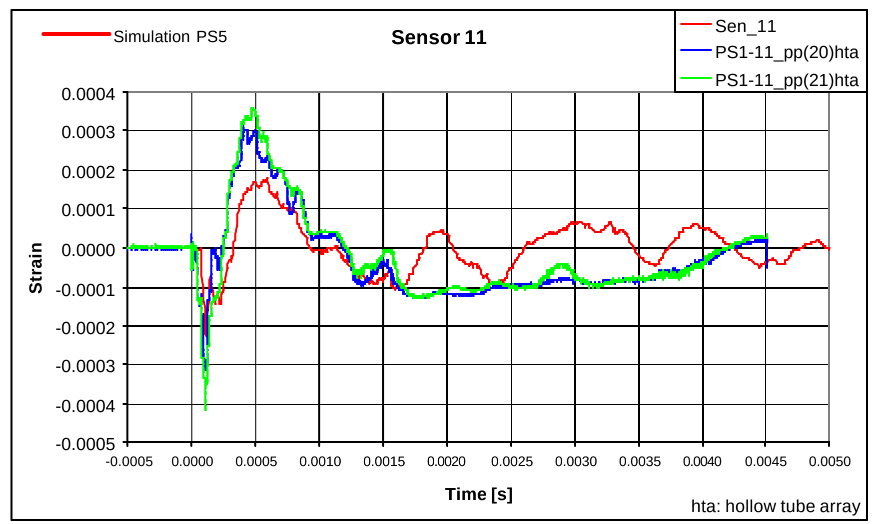


Simulation vs. test data: nose - side



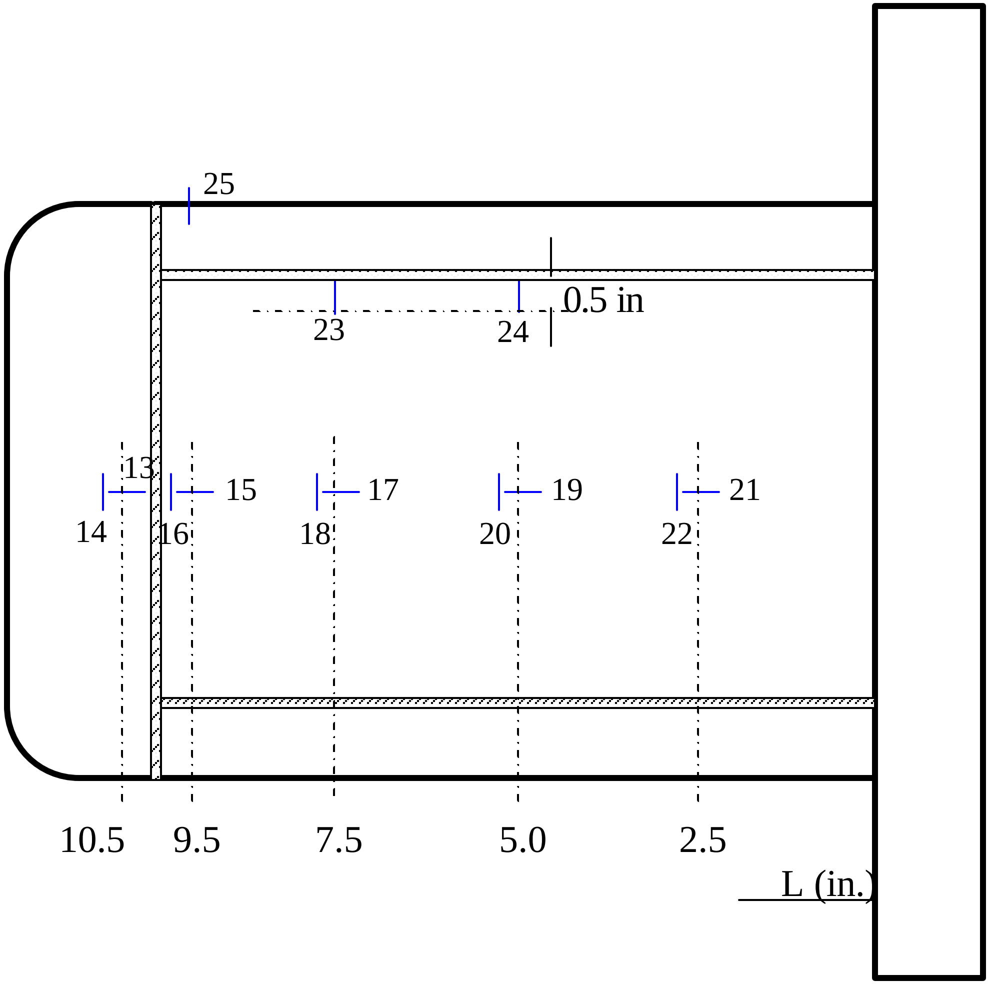




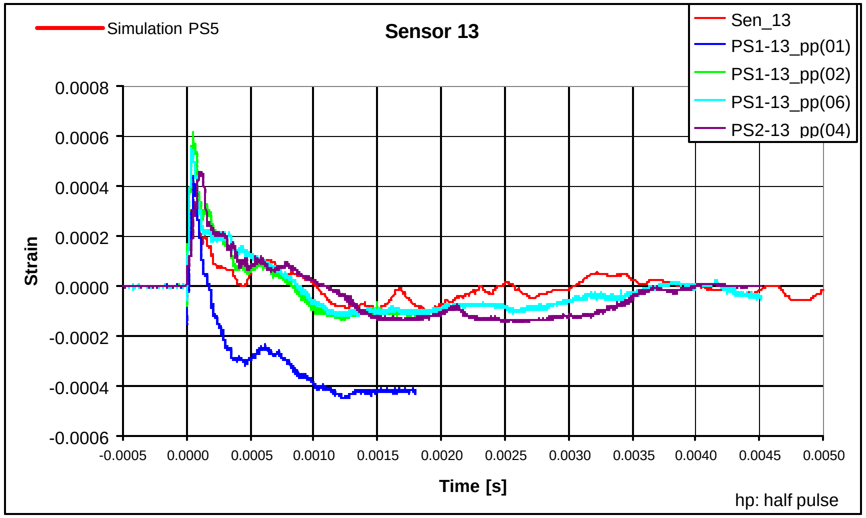


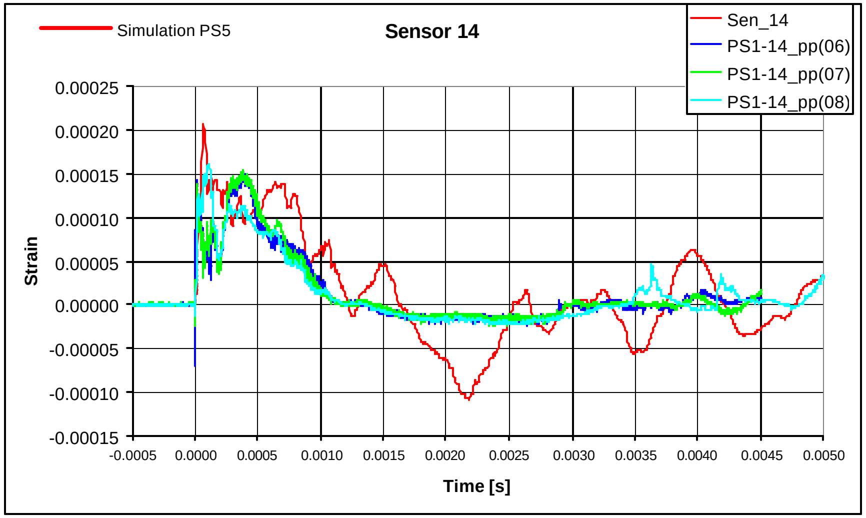
PS Target body sensor locations

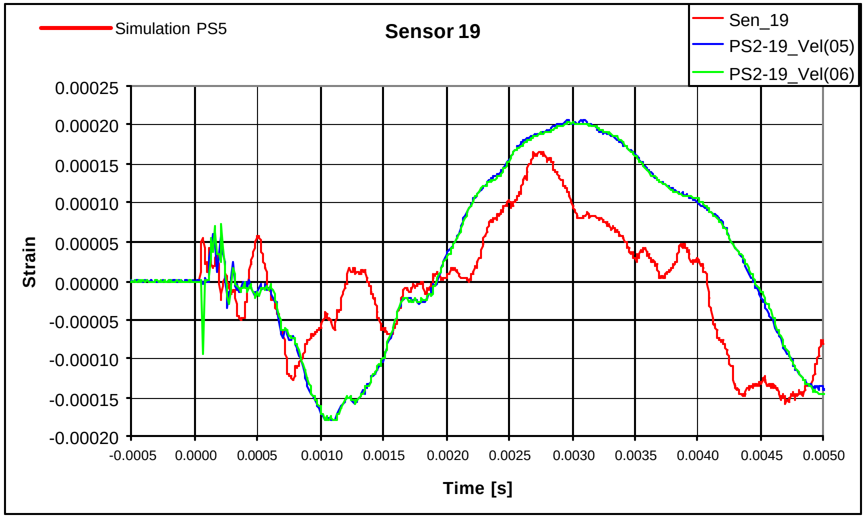
- Odd numbered sensors are oriented parallel to beam axis, *except* for #23 and #25.
- Even numbered sensors are oriented across the target.

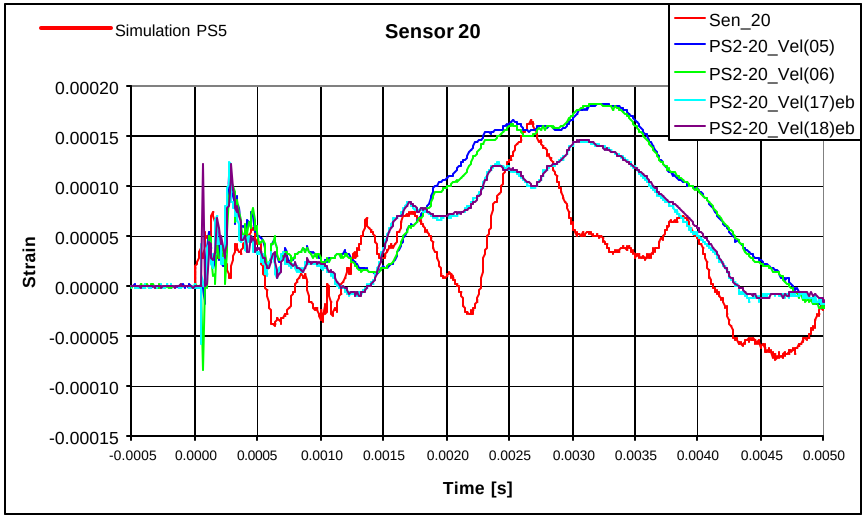


Simulation vs. test data: body - center

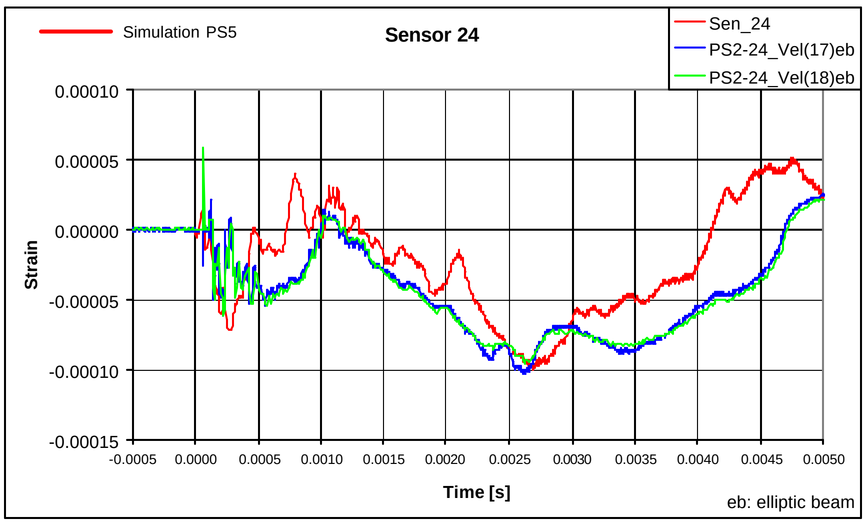


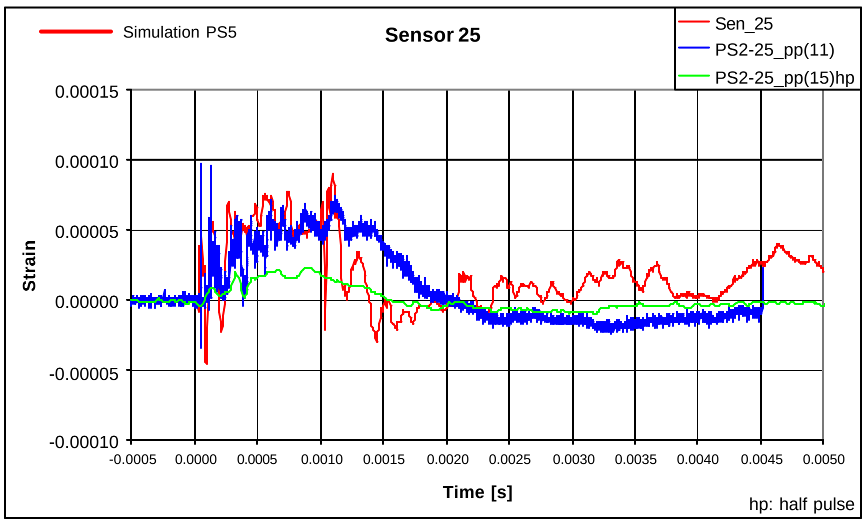




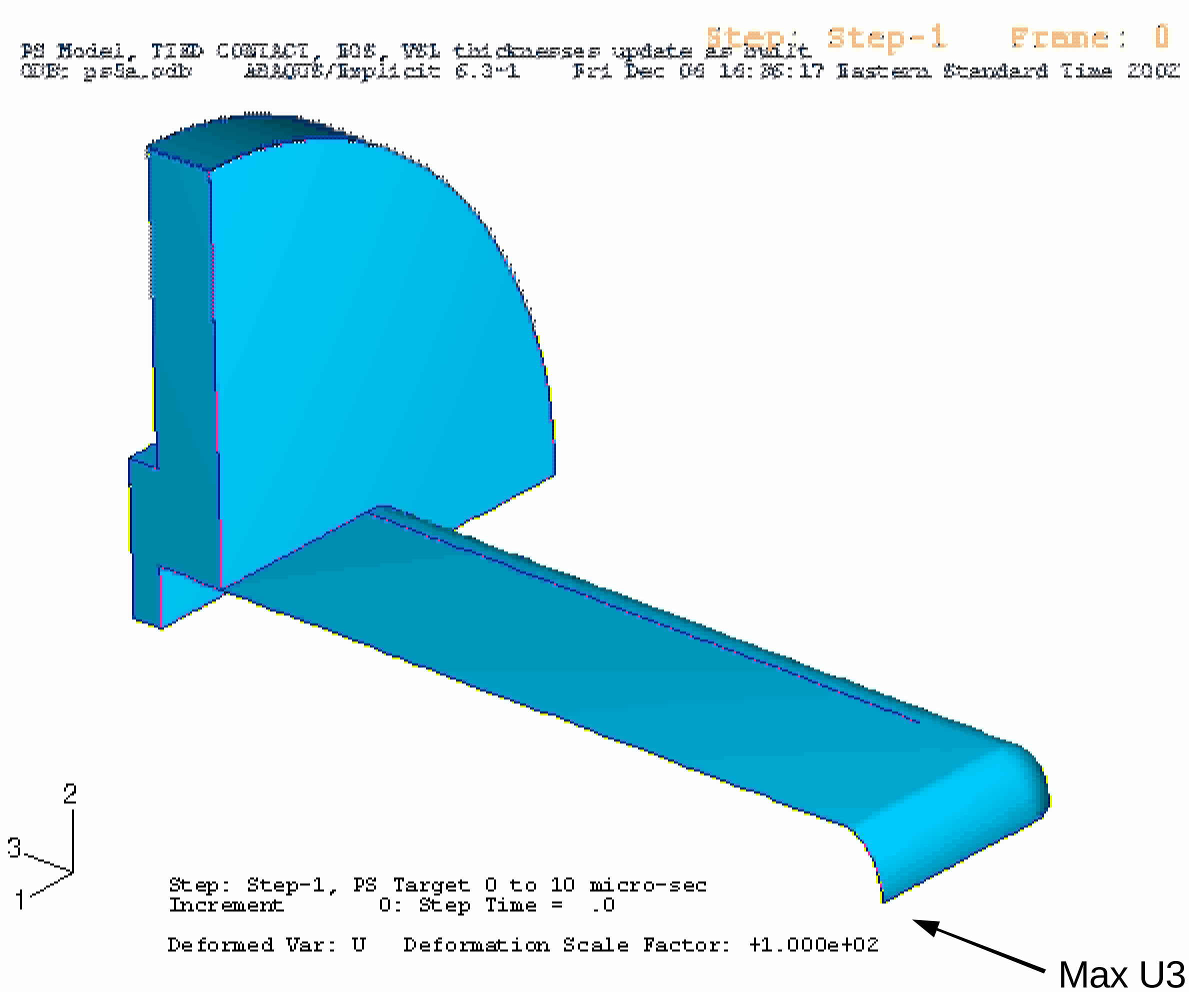


Simulation vs. test data: body - side





PS target deformation (100x)



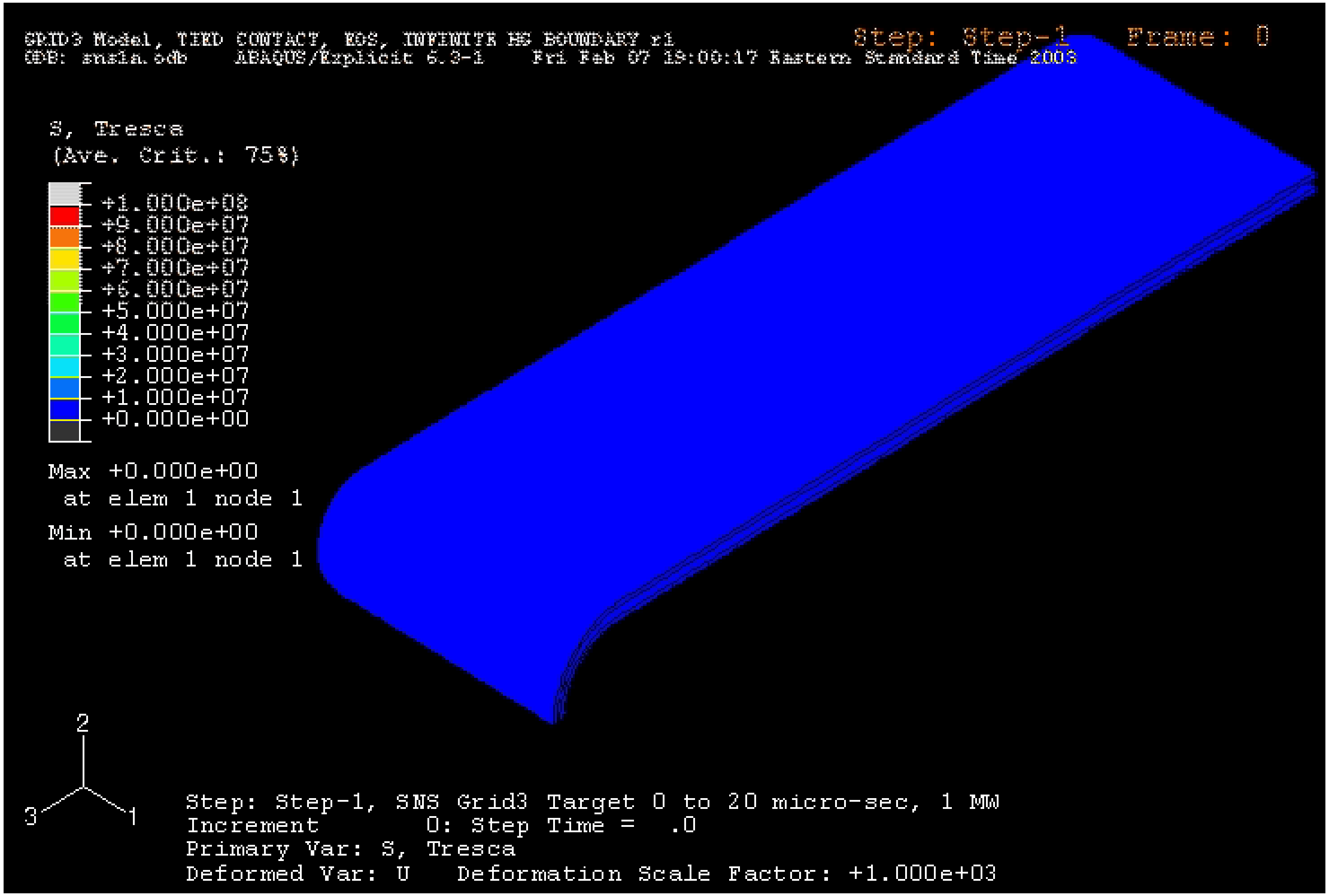
Max U3 < 0.1 mm

PS simulations compare well to data.

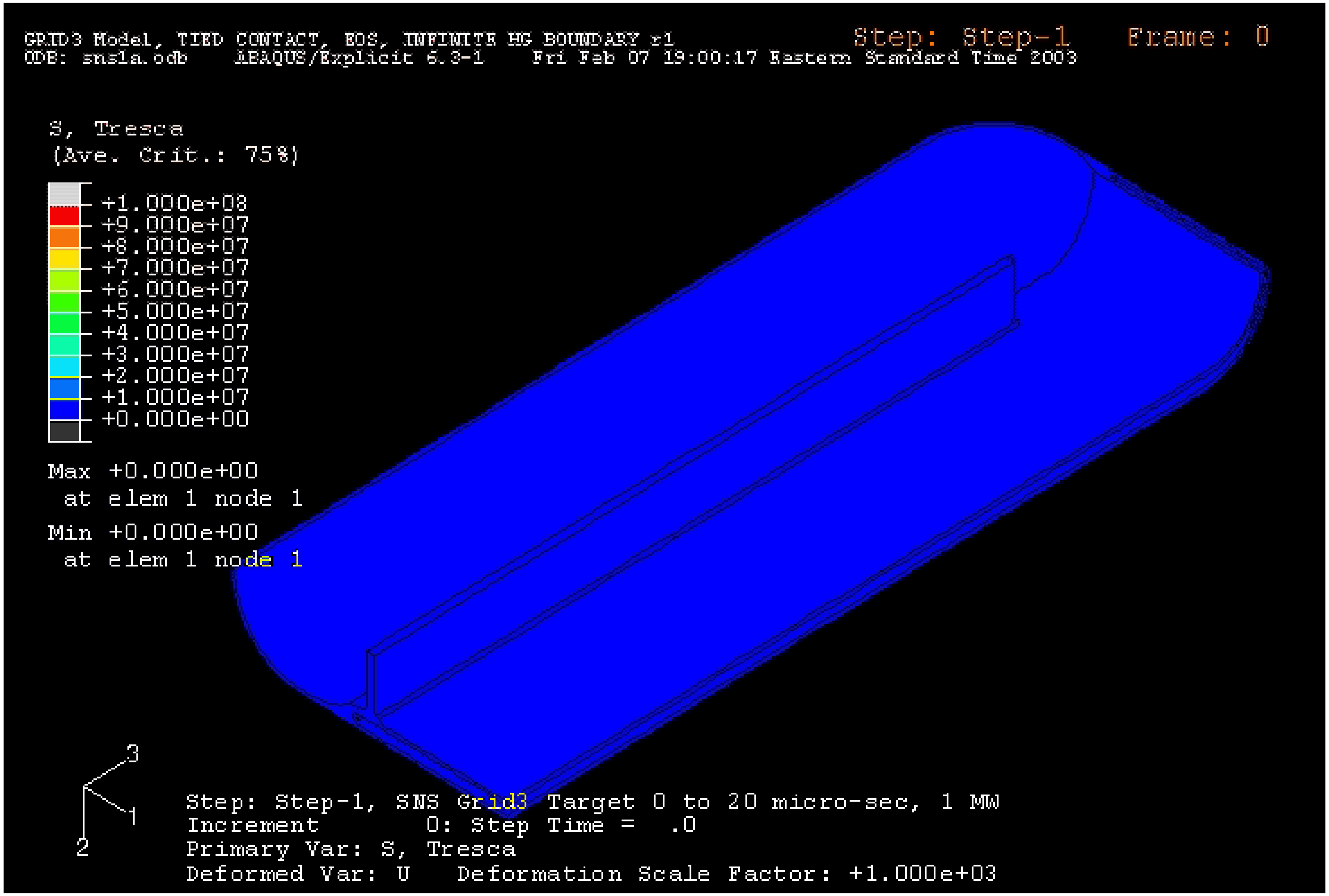
- Generally good prediction of dynamic response.
- Predicted strain magnitudes are good match to data, although fatigue analysis could use better.
- A few locations matched poorly; it’s hard to tell what could be wrong.
  - Experiment data setup; gravity / stand effects?
- It will have to do for now for application to SNS. There is no better benchmark available.

SNS target vessel stress from 1 MW beam pulse

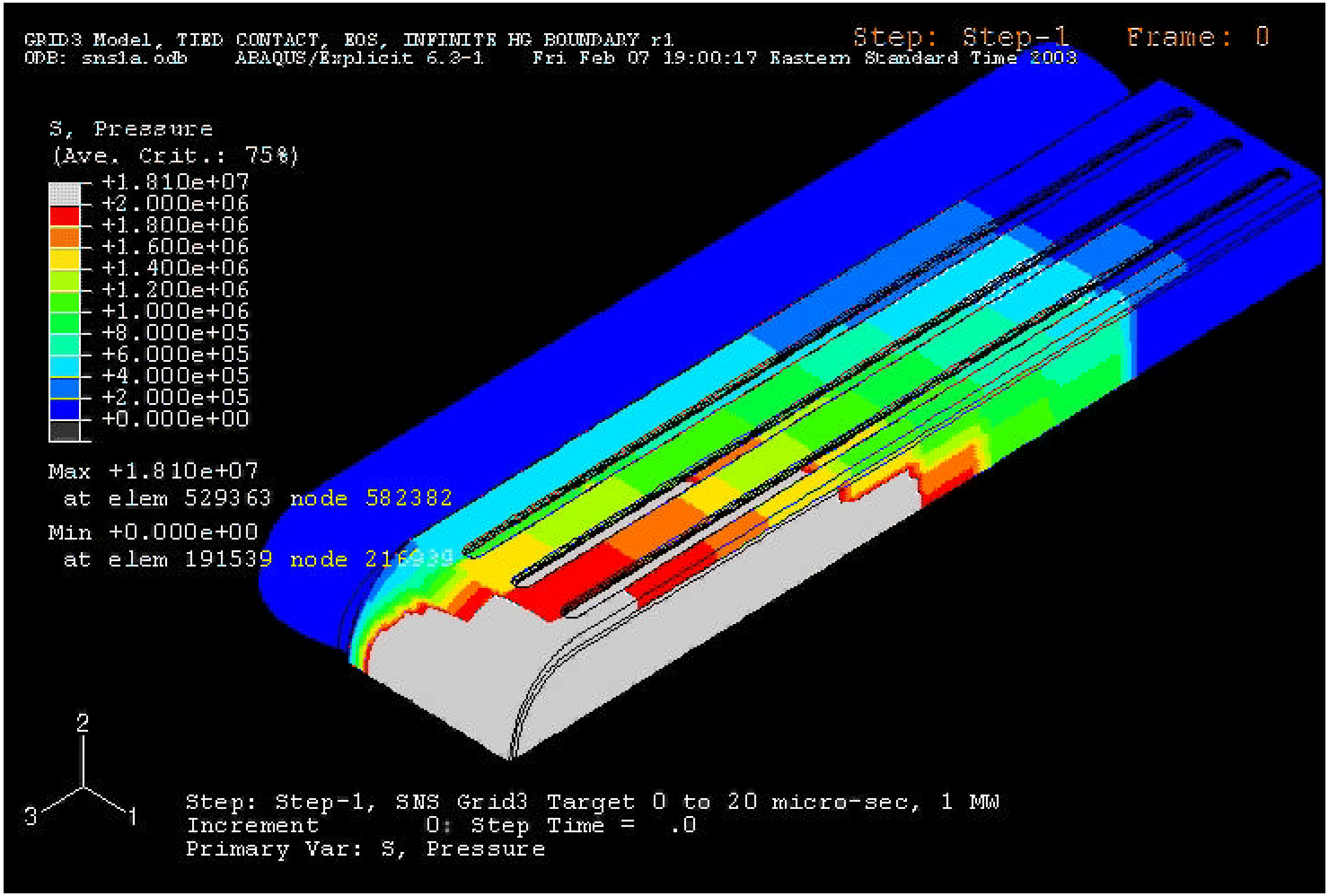
- Simulation using benchmark parameters; ¼ symmetry model.



SNS target vessel stress from 1 MW beam pulse



SNS target mercury pressure evolution



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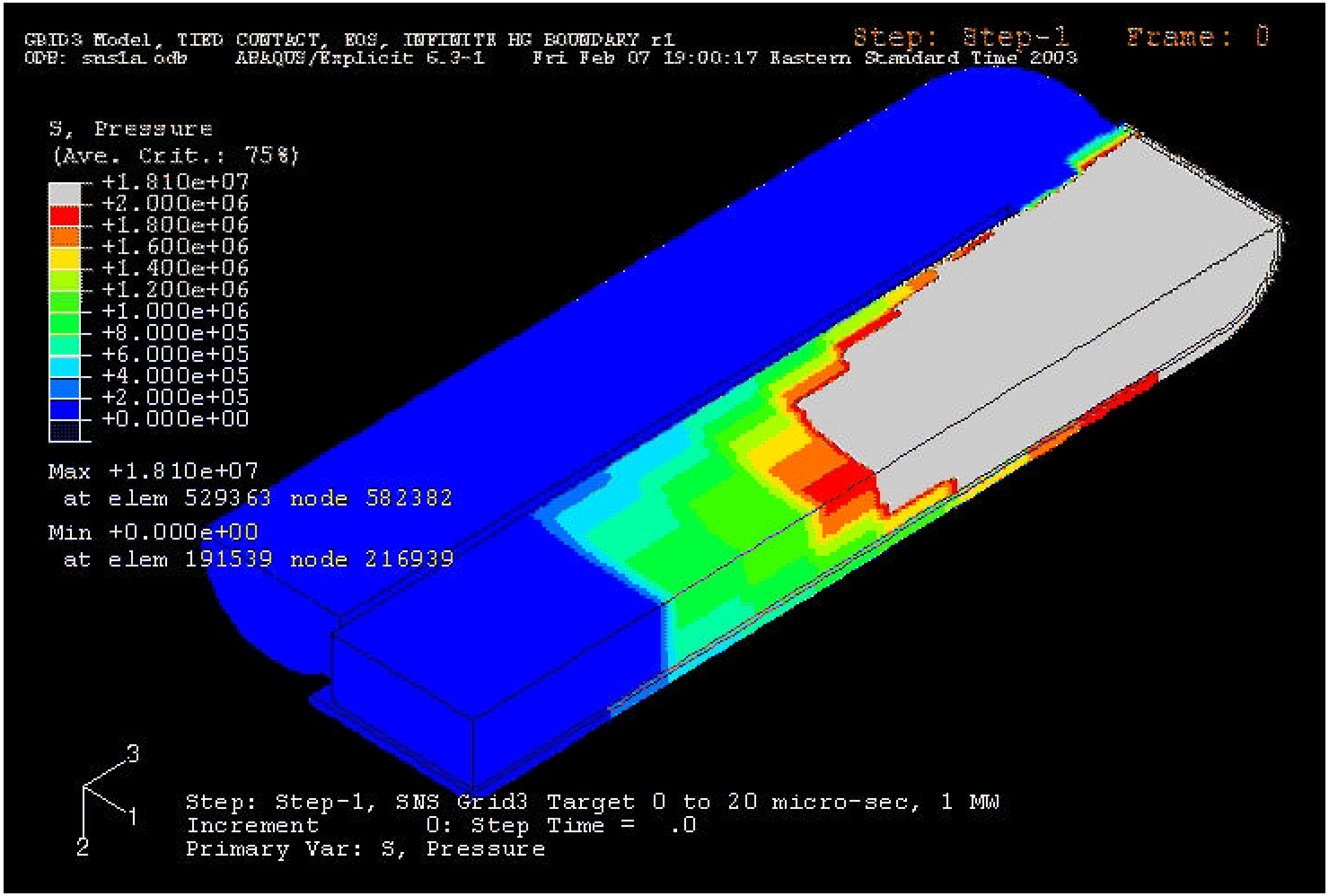

Final thoughts …

- **<u>IF</u>** bubble population were known as f(x,y,z,t), it might be possible to develop a material model that does a better job for wave speed and damping. This is a tough problem.

- Effects of pre-existing bubbles, such as those that may remain when operating at 60 Hz *or* by bubble injection techniques, have not been benchmarked. Plans are being made to test bubble injection in TTF and in a beam experiment at the WNR in the coming year.