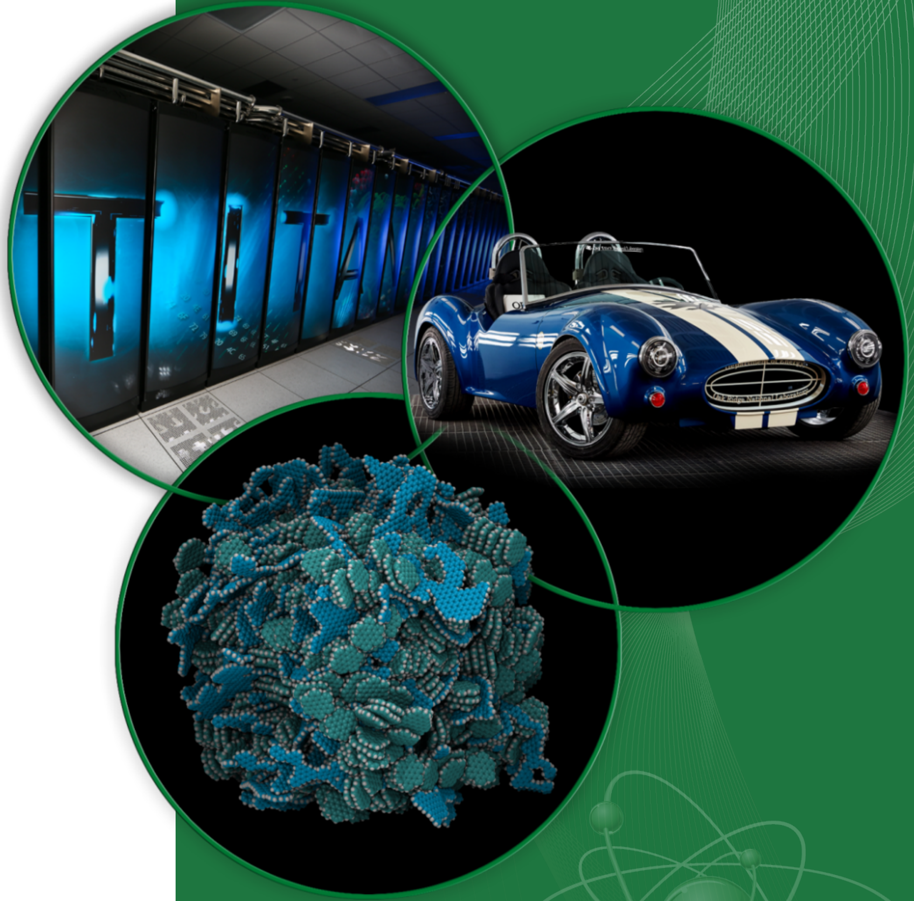
Measured SNS Mercury Target Vessel Strain Responses to Beam Pulses and Comparison to Simulations with Variations on Mercury Material Model Behavior

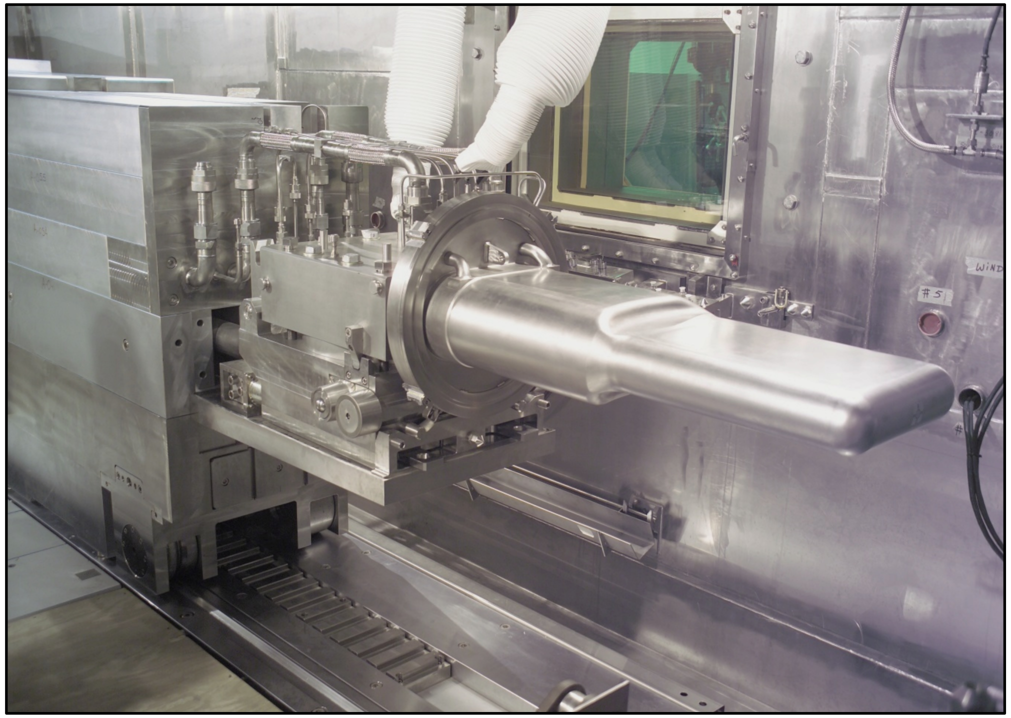
Drew Winder
Bernie Riemer
Willem Blokland
Oak Ridge National Laboratory
Spallation Neutron Source

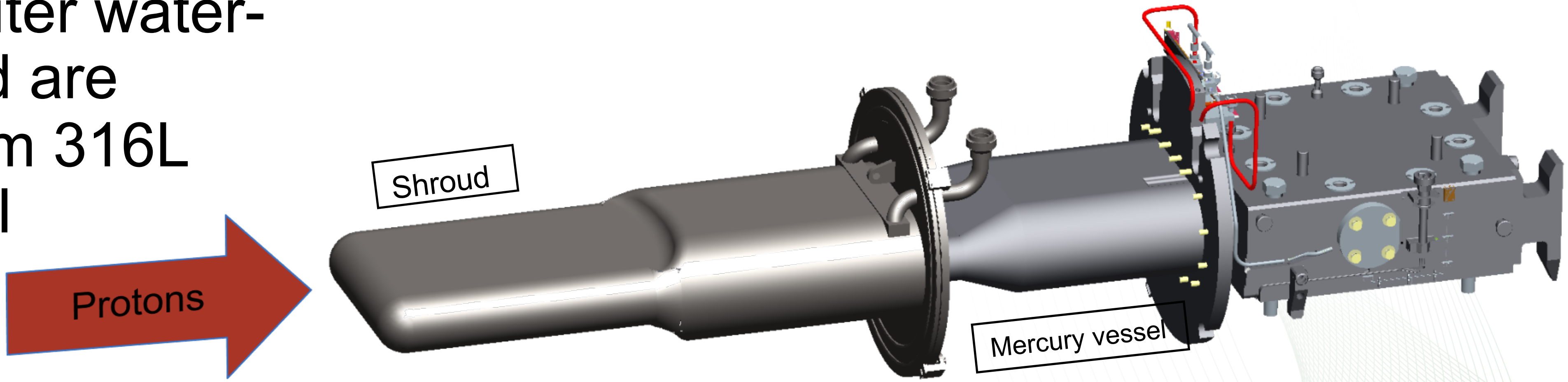


13th International Workshop on
Spallation Materials Technology

Background

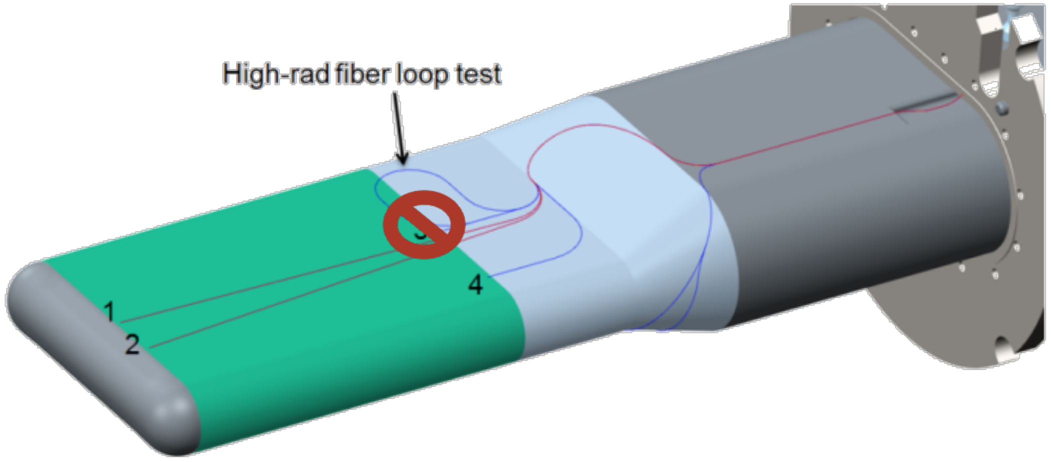
- The SNS target is a liquid metal design – uses flowing mercury as the target material.
- Target inner mercury vessel and outer water-cooled shroud are fabricated from 316L stainless steel

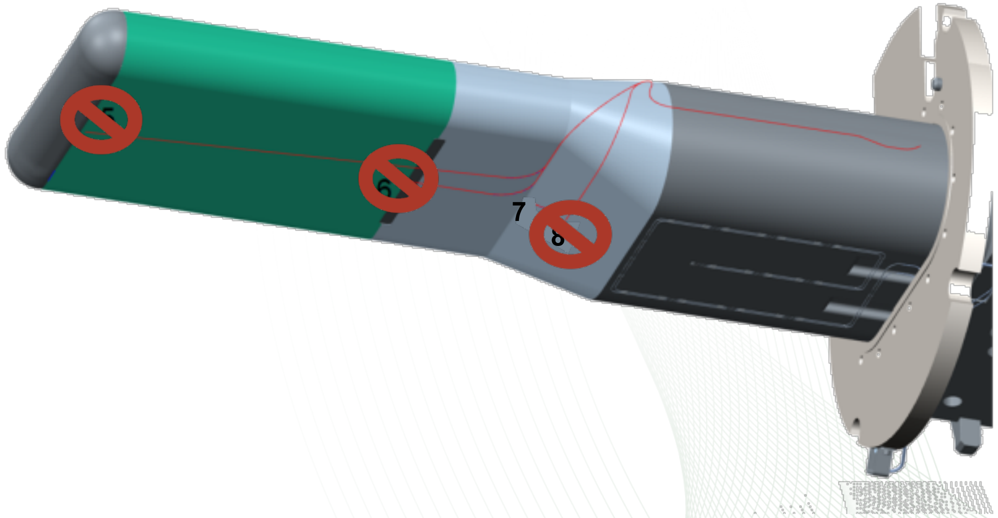




Target 13 Sensors

- Eight off-the-shelf fiber optic strain gages (FISO Technologies Inc.) were installed onto the target.
- Some sensors did not provide useable data.

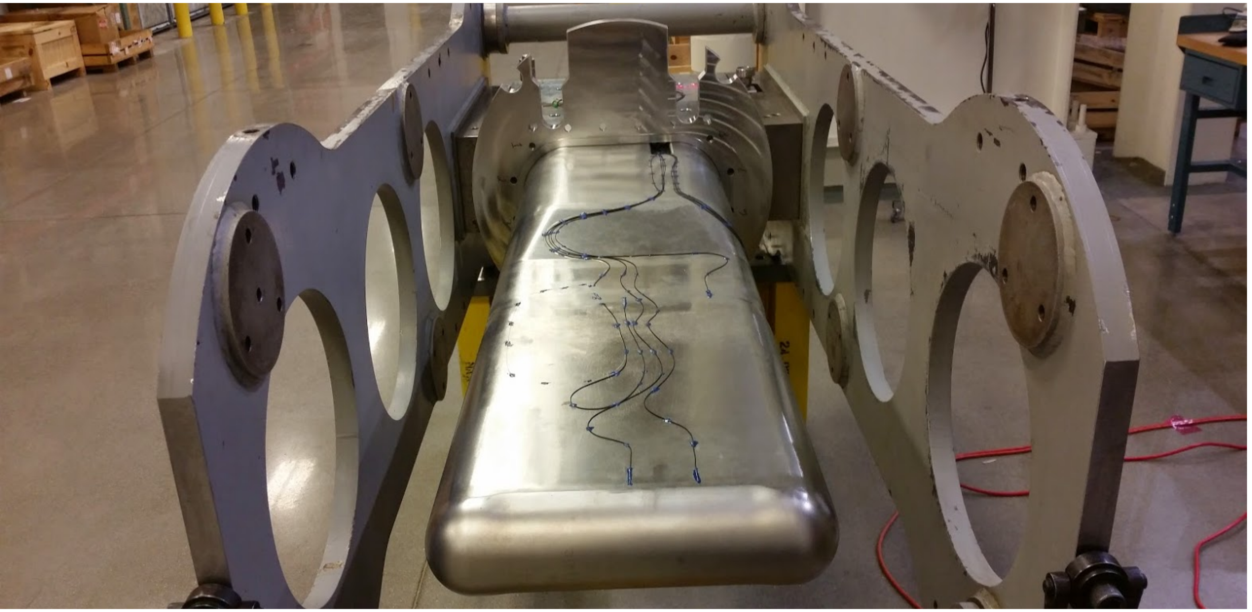


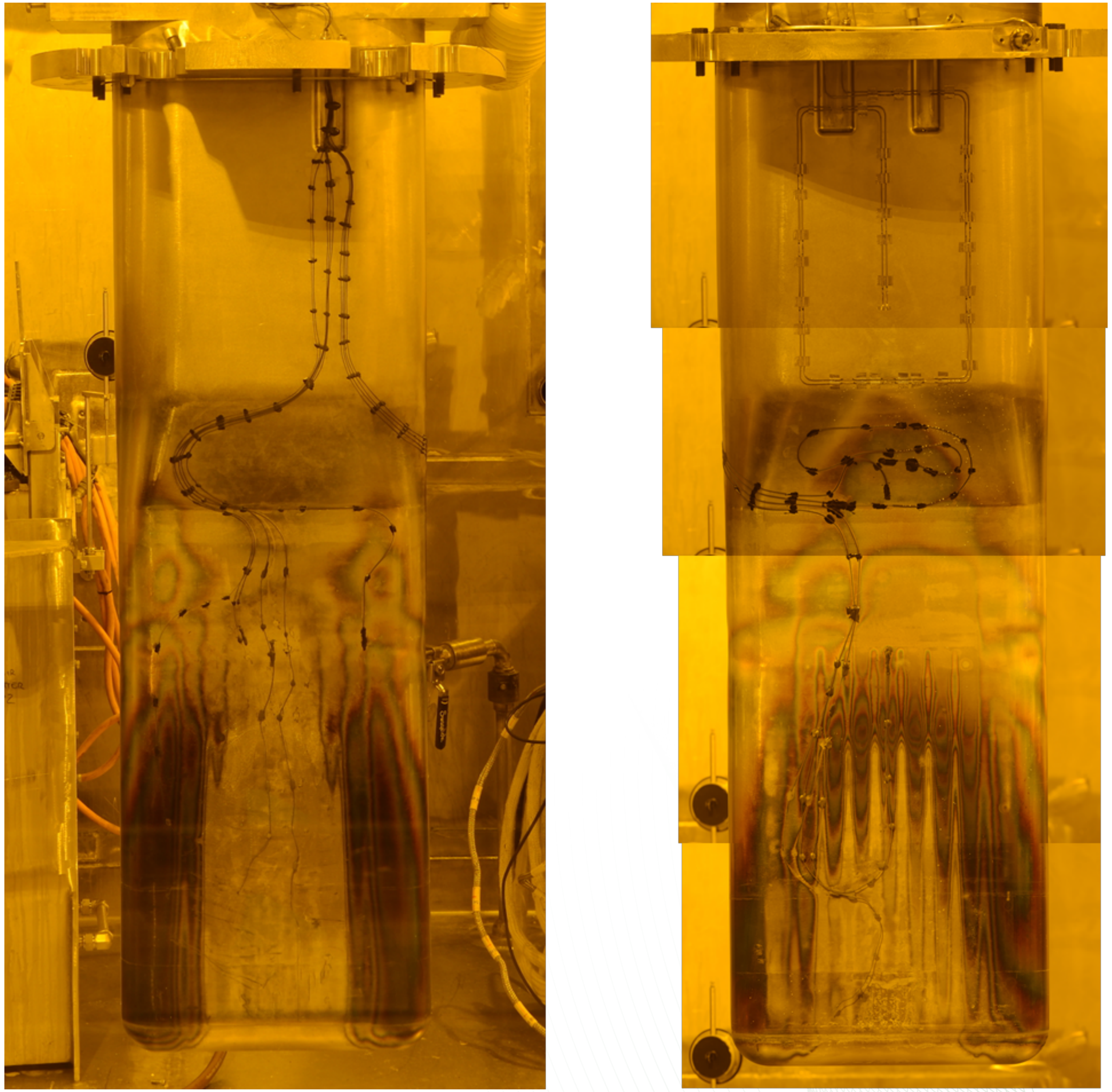


OAK RIDGE National Laboratory

Epoxy Irradiation

- Sensors attached with Stycast 2850FT with Catalyst 11.
- Target operated for 2588 MW·hr at an average power of 968 kW.

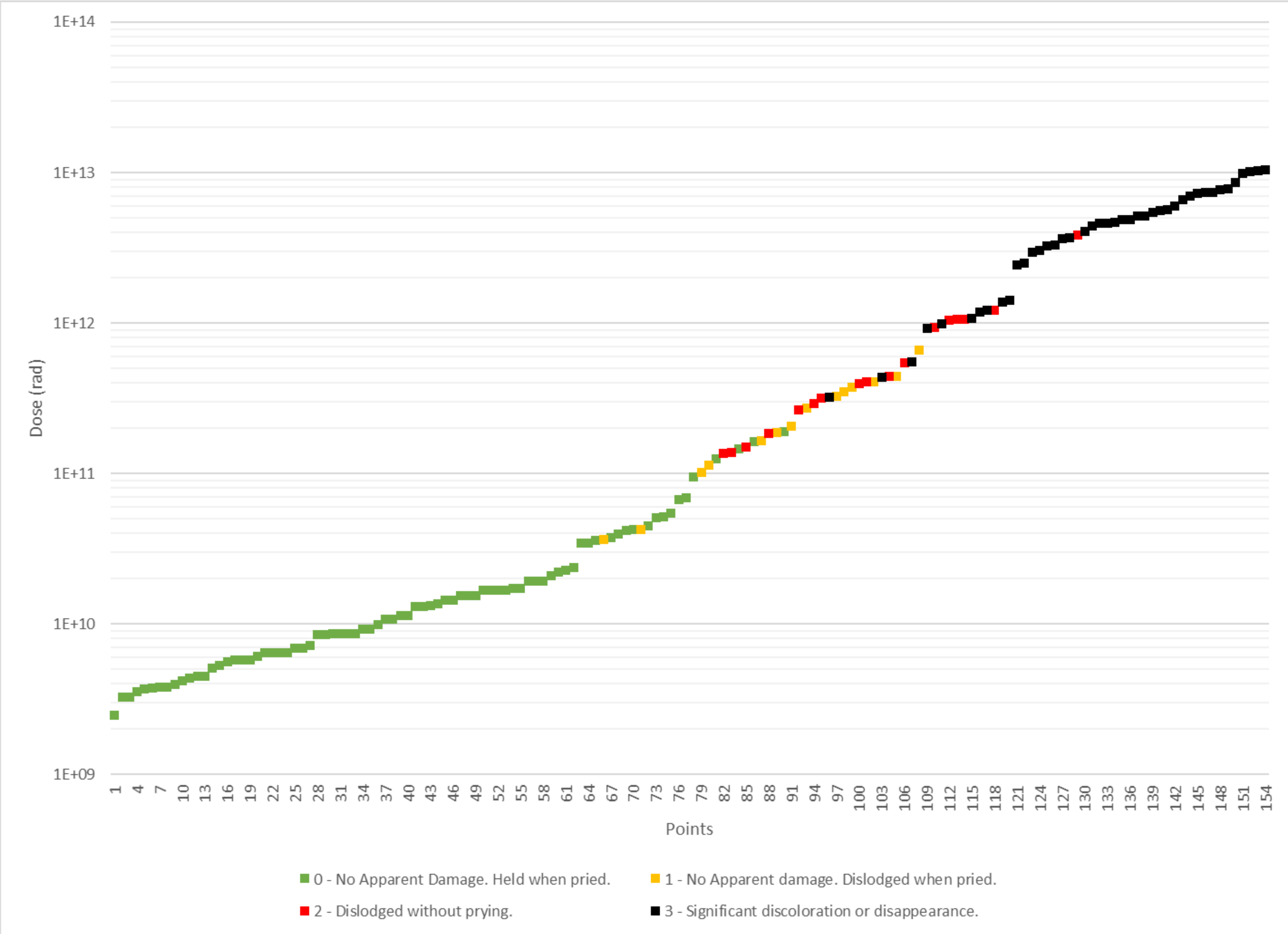




Images by David McClintock

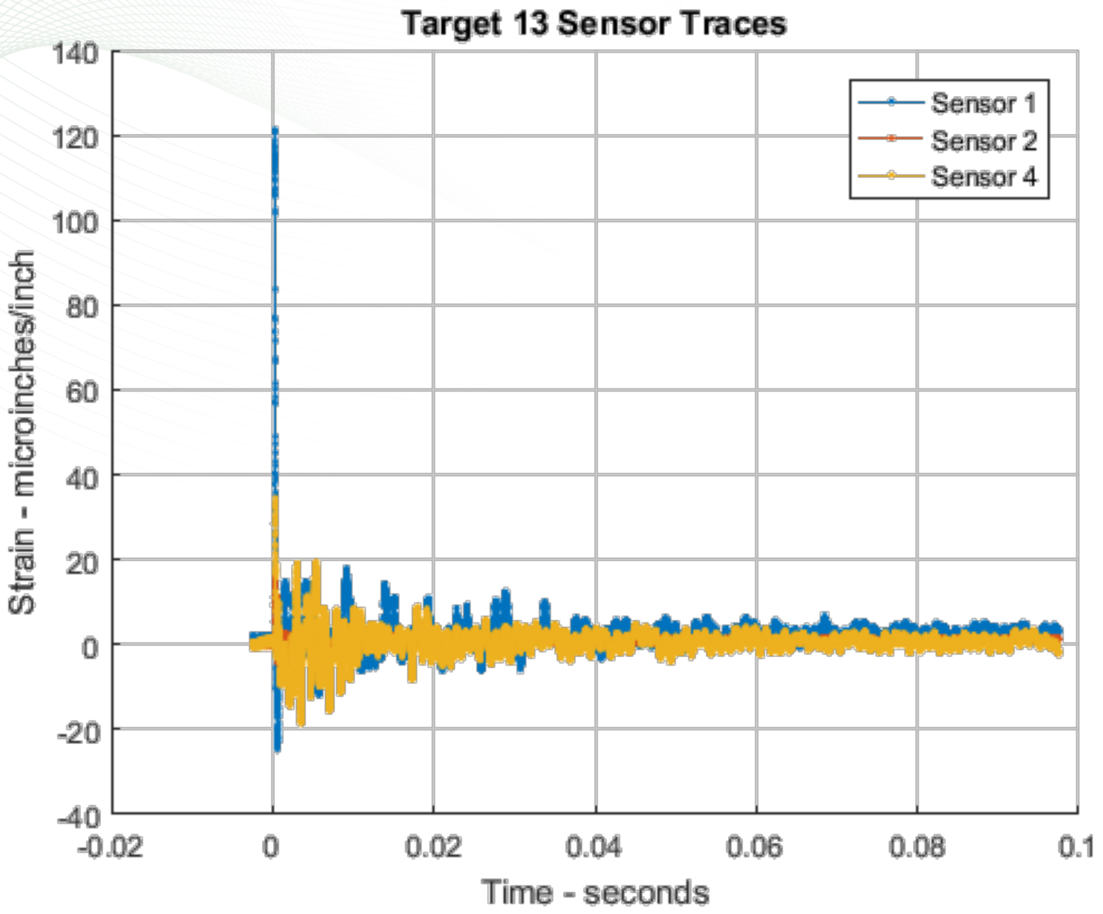
Epoxy Irradiation

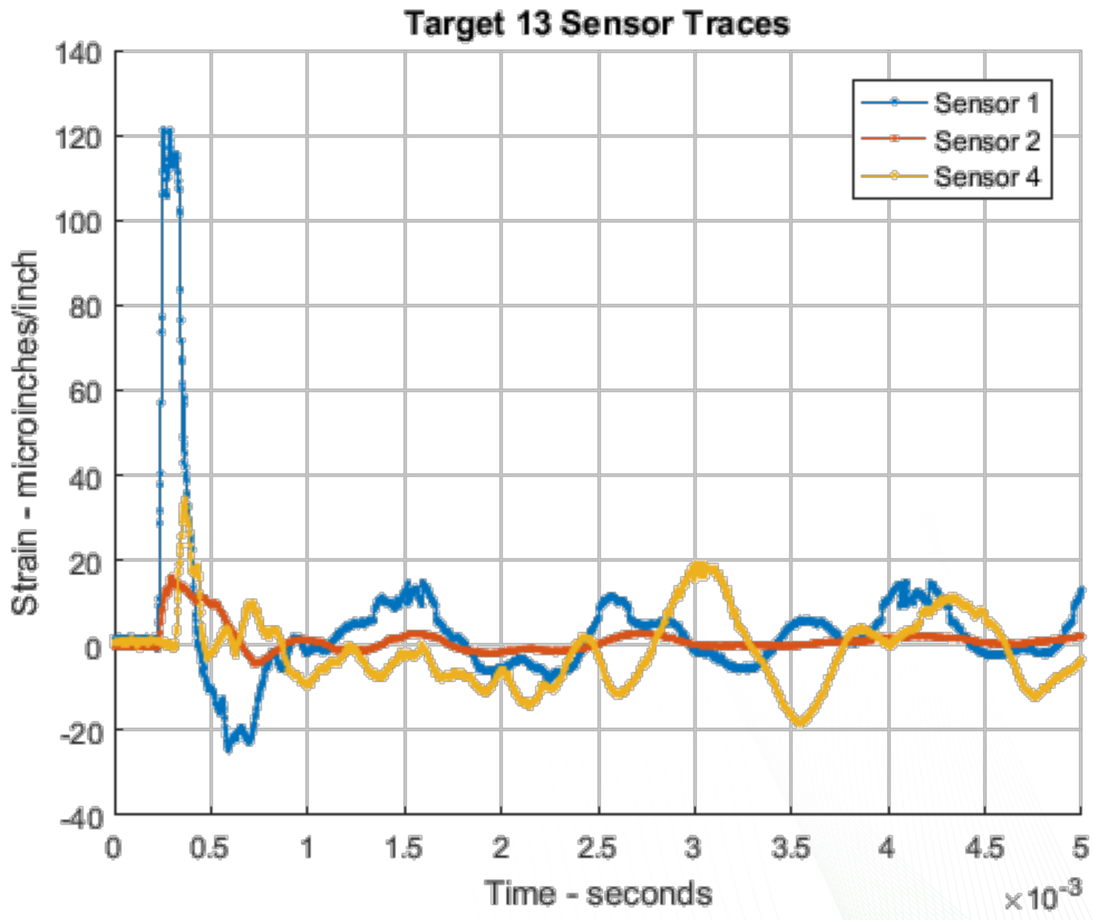
- Vendor data supported use for up to 10^9 rad (10 MGy) gamma.
- Temperatures for all sensors less than 150°C.
- Epoxy held up to 10^{10} rad (100 MGy), stayed until pried at up to 10^{11} rad (1000 MGy).



Oak Ridge National Laboratory

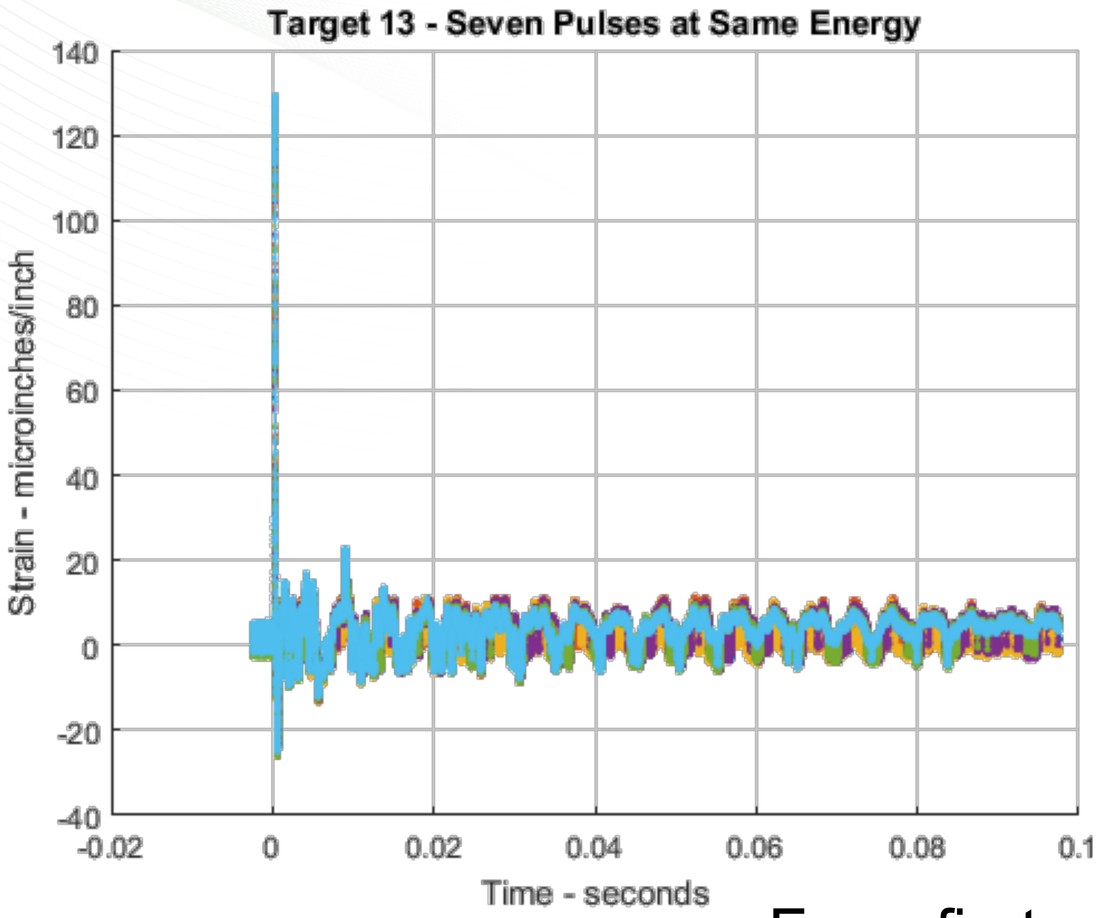
Target 13 Measured Data Example

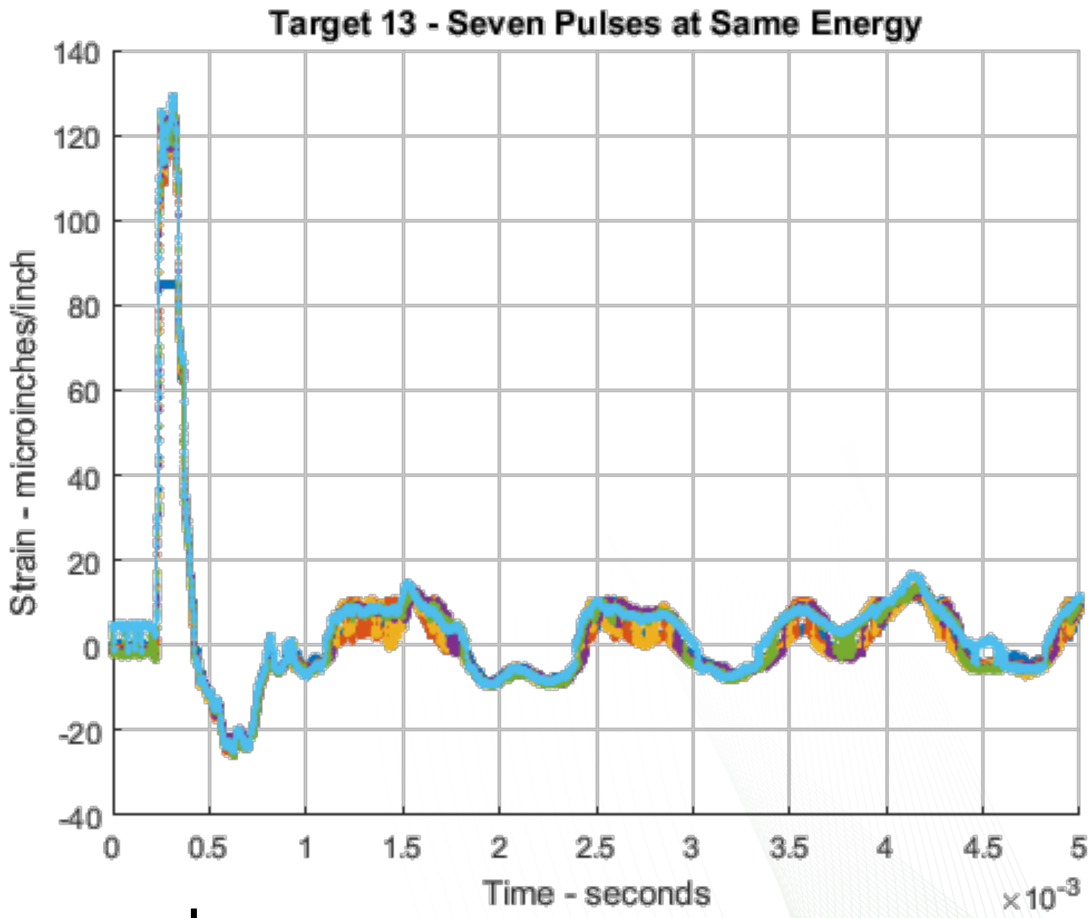




From first beam pulse,
600 kW equivalent

Target 13 Measured Data Example



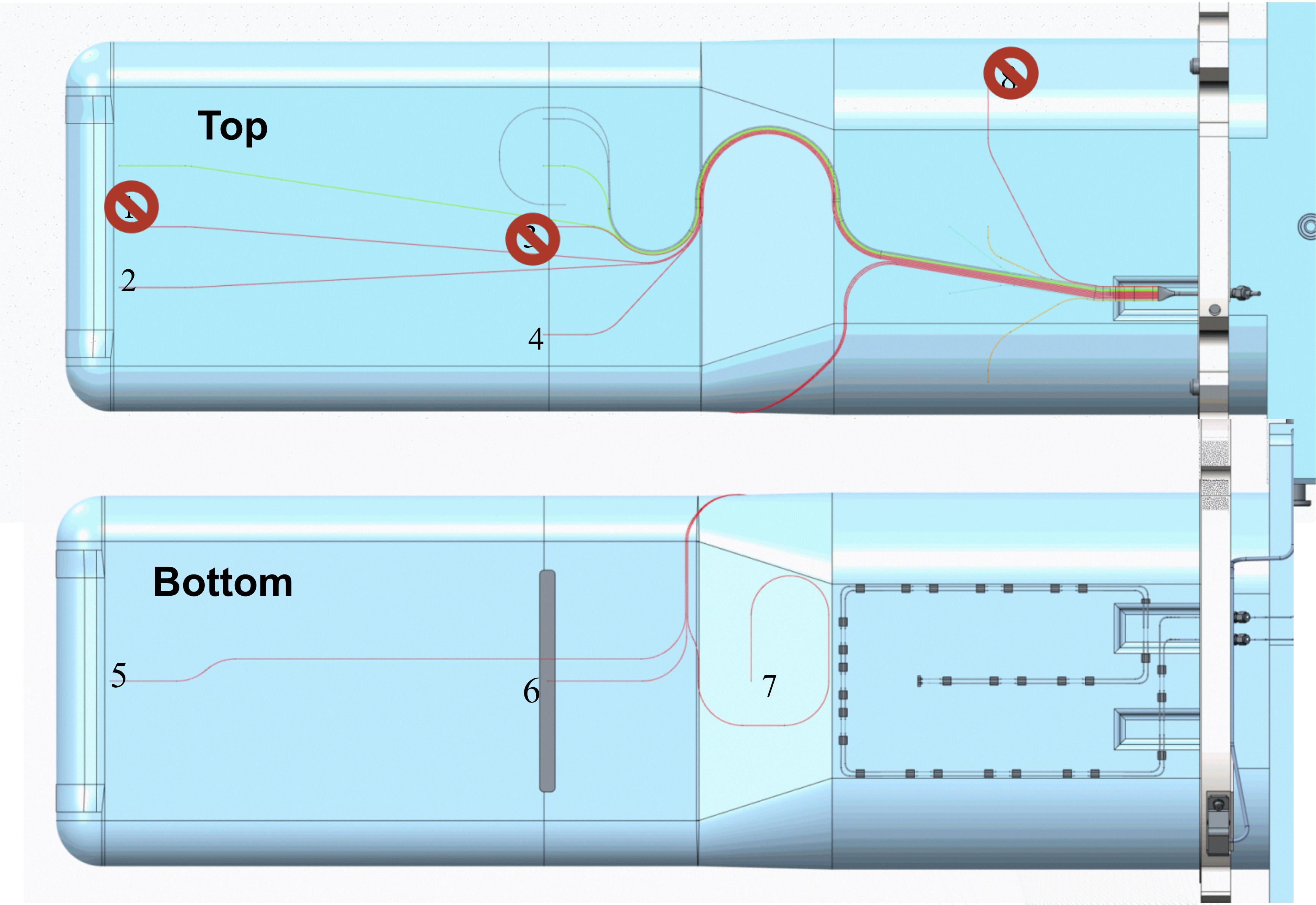


From first seven beam pulses,
all 600 kW equivalent

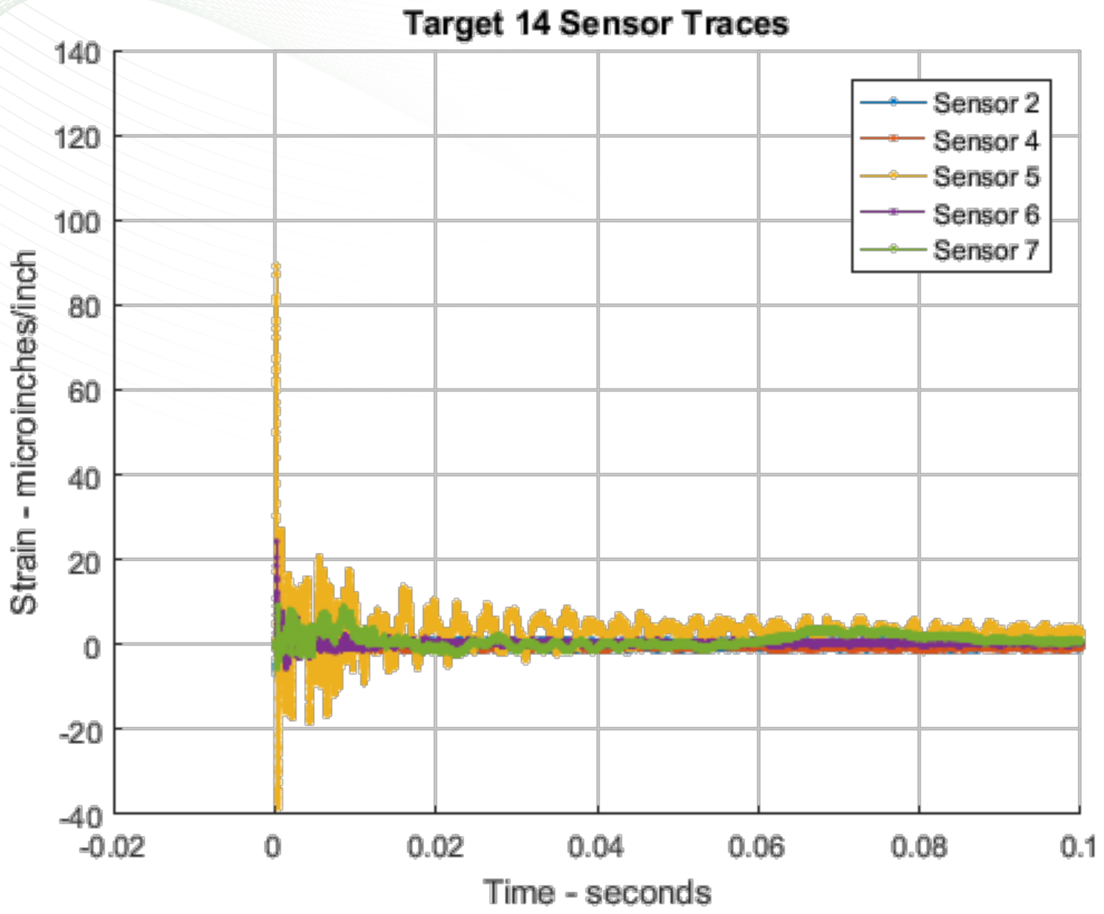
OAK RIDGE National Laboratory

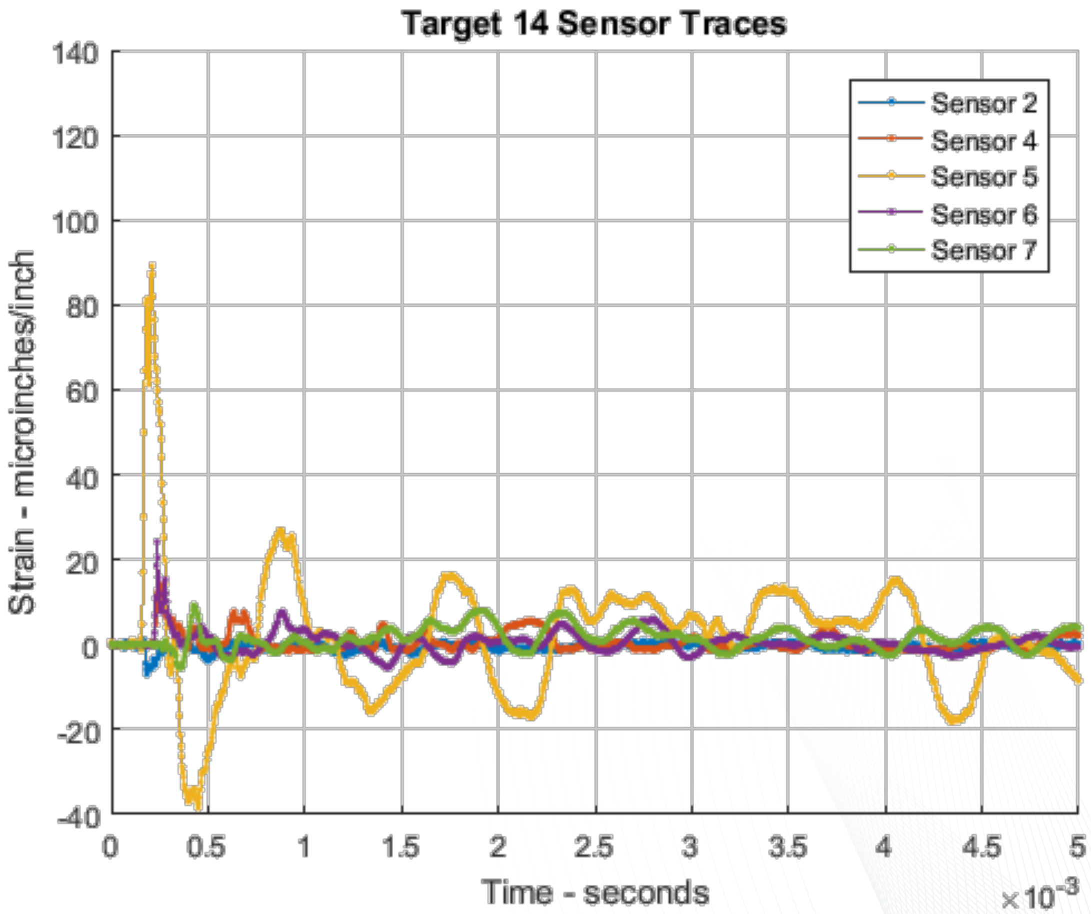
Target 14 Sensors

- Eight rad-hard fiber optic strain gages were installed on the target.
- Again, some sensors did not provide useable data.



Target 14 Measured Data Example

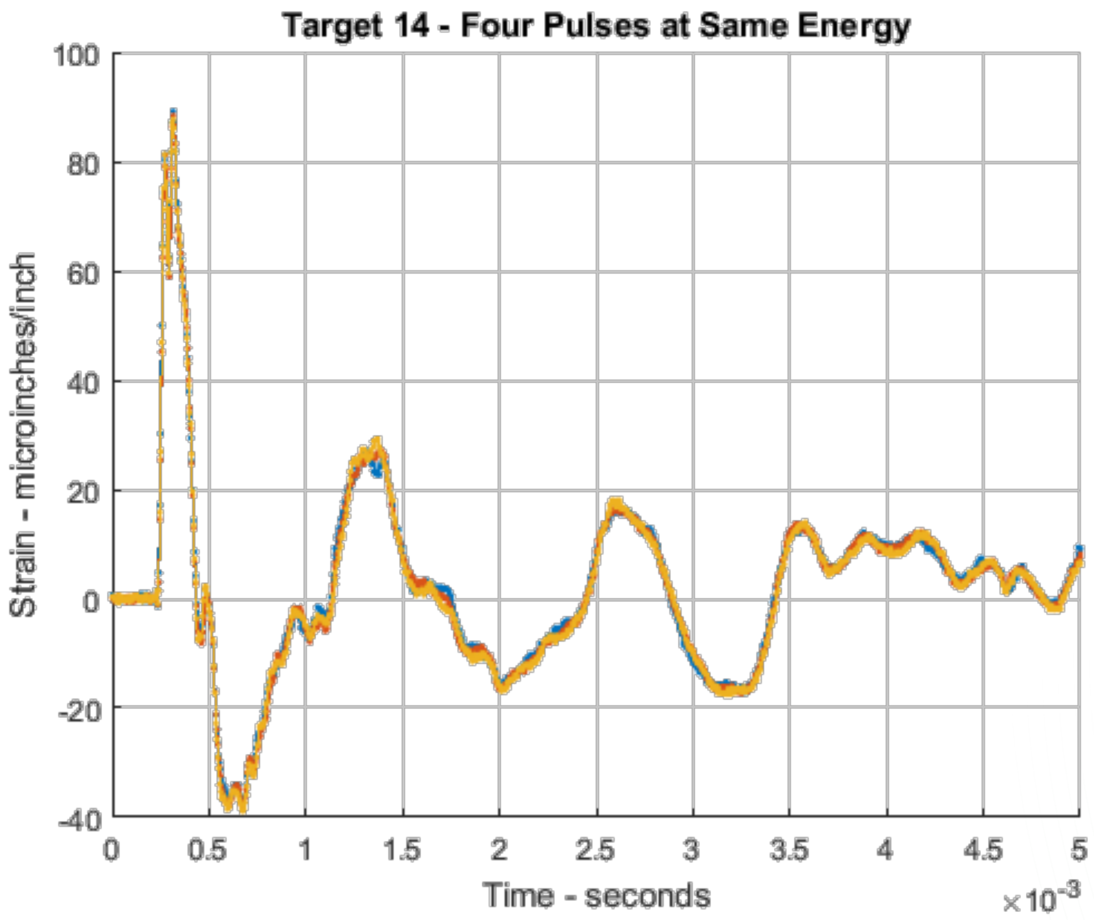




From first beam pulse,
600 kW equivalent

OAK RIDGE National Laboratory

Target 14 Measured Data Example

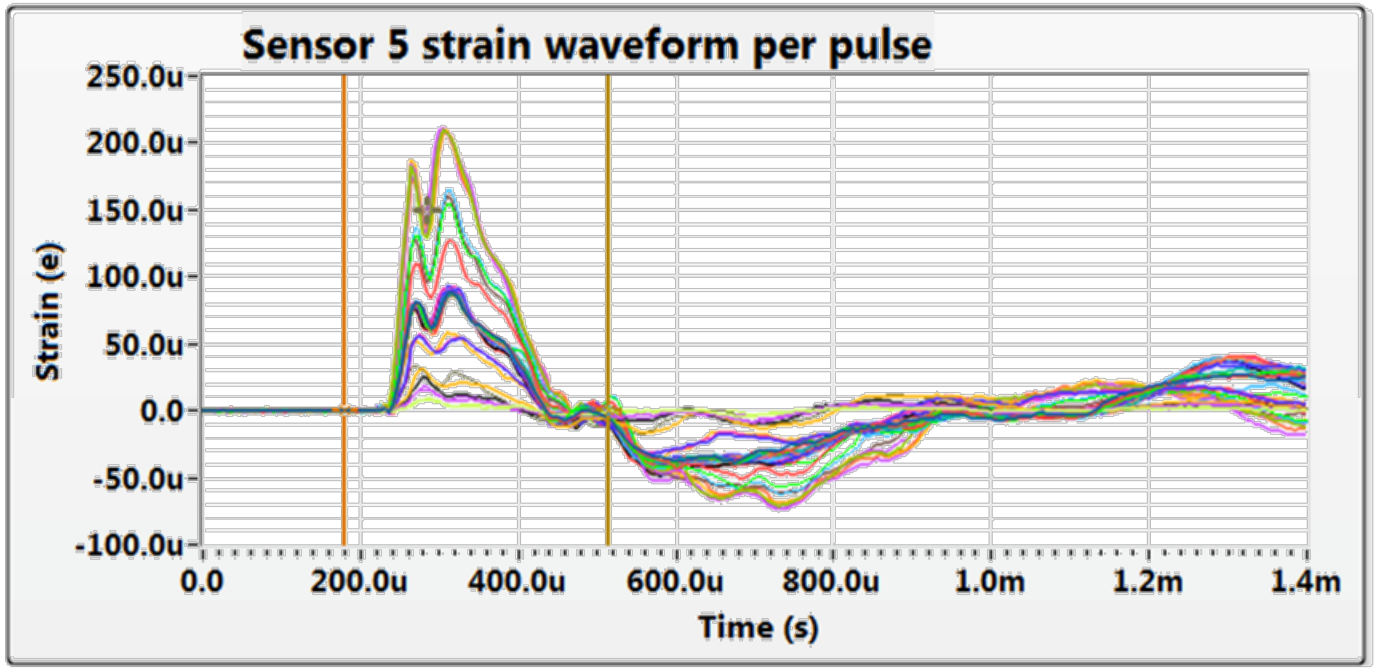


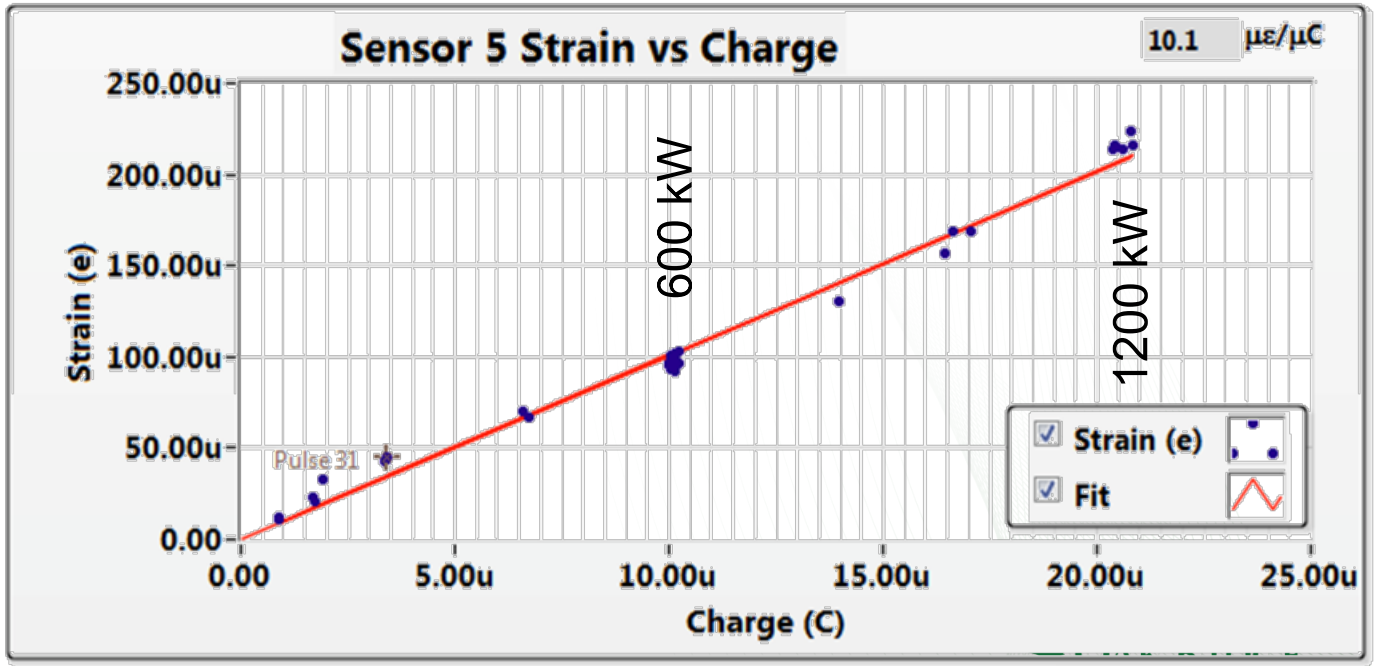
From four beam pulses,
600 kW equivalent

OAK RIDGE National Laboratory

Linearity with Power

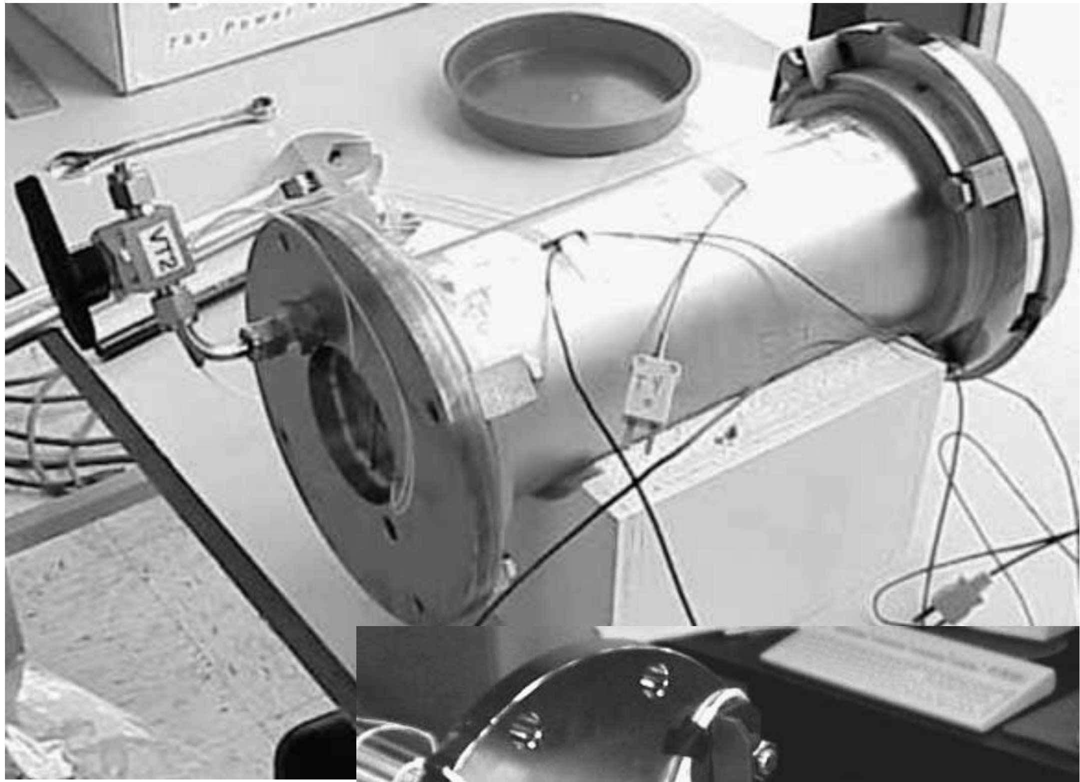
- Strain response was linear with power, despite non-linear material behavior.





Comparison to Model

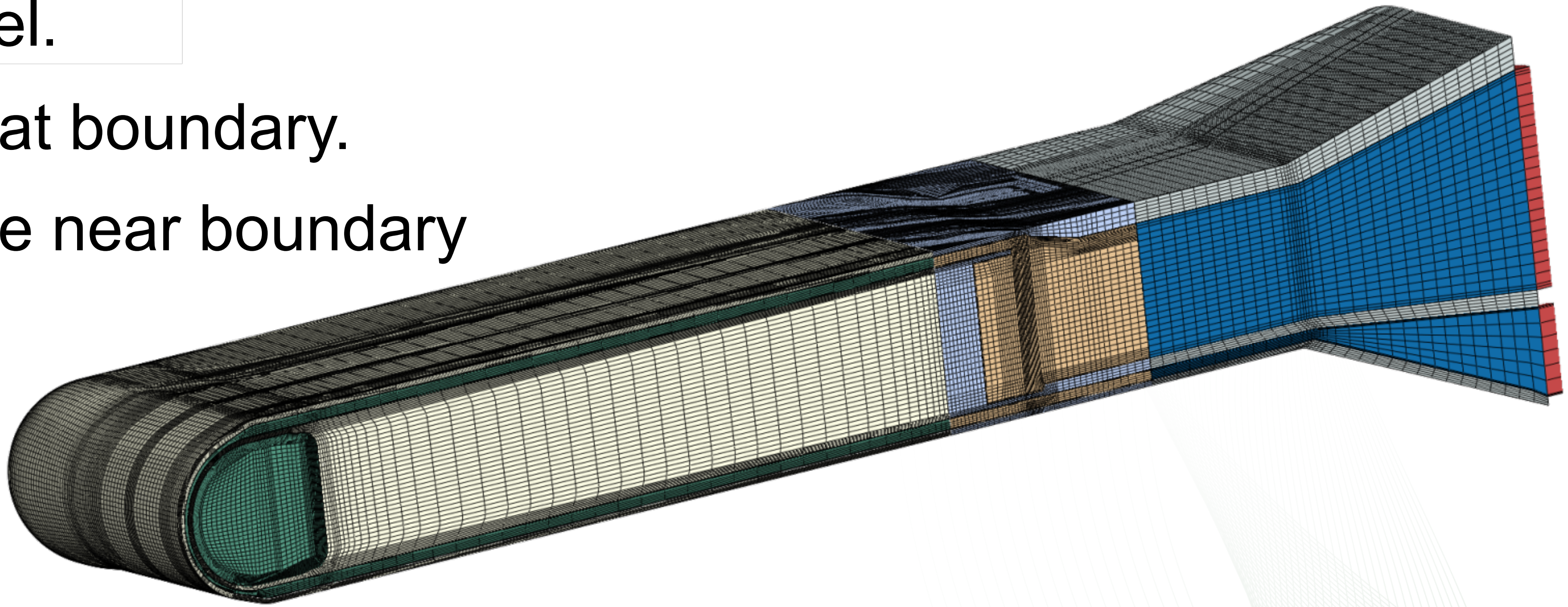
- SNS has used ABAQUS/Explicit for simulations of the pulse loading.
- Material model is based on work done by Bernie Riemer*
  - Mercury model is Mie-Gruneisen Equation-of-State model, with 1456 m/s as the bulk speed of sound and Gruneisen constant Γ and particle speed coefficient S are set to zero.
  - Includes a tensile failure criterion of 1.5 bar.
  - Developed as best fit from experimental data of mercury filled targets struck with beam.



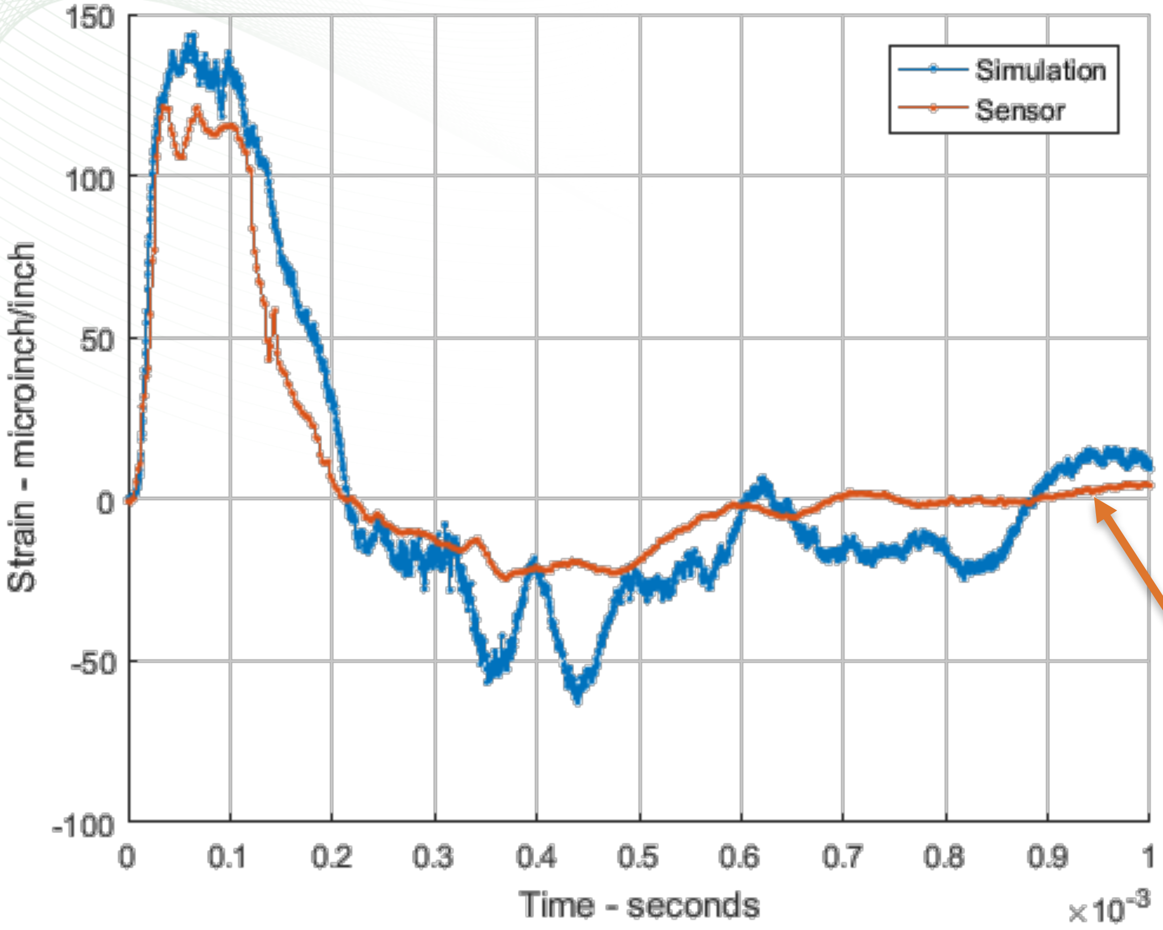
* - *Benchmarking dynamic strain predictions of pulsed mercury spallation target vessels*, B. W. Riemer, Journal of Nuclear Materials 343 (2005) 81-91.

Comparison to Model

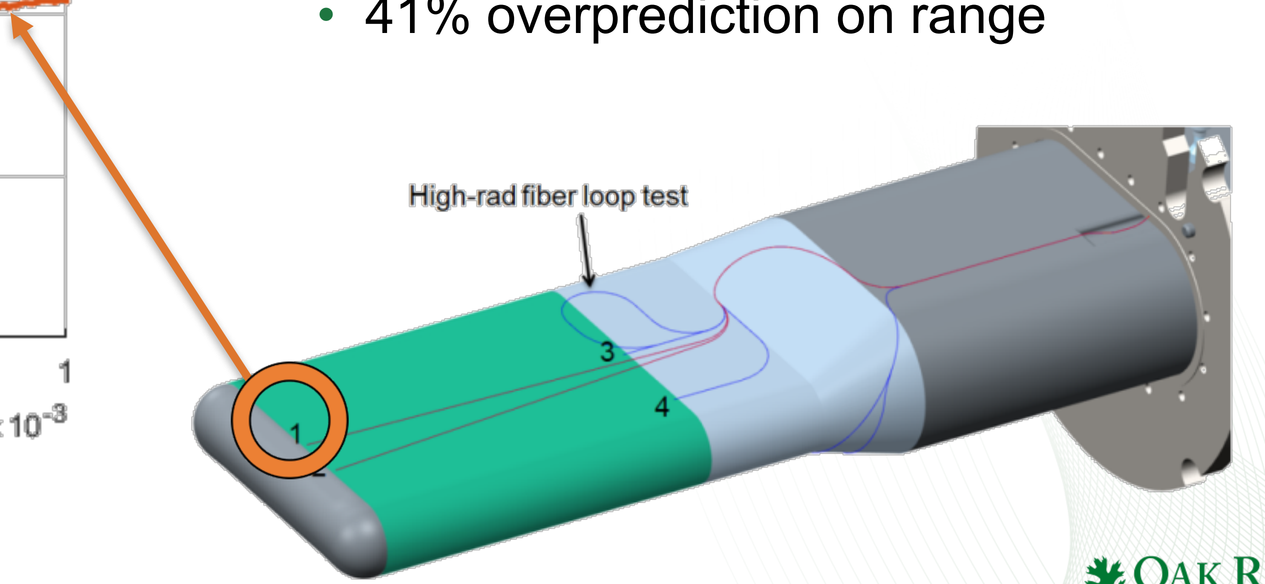
- Model built using C3D8R reduced integration elements for mercury and stainless steel.
- Infinite elements at boundary.
- Some sensors are near boundary conditions.



Comparison to Model

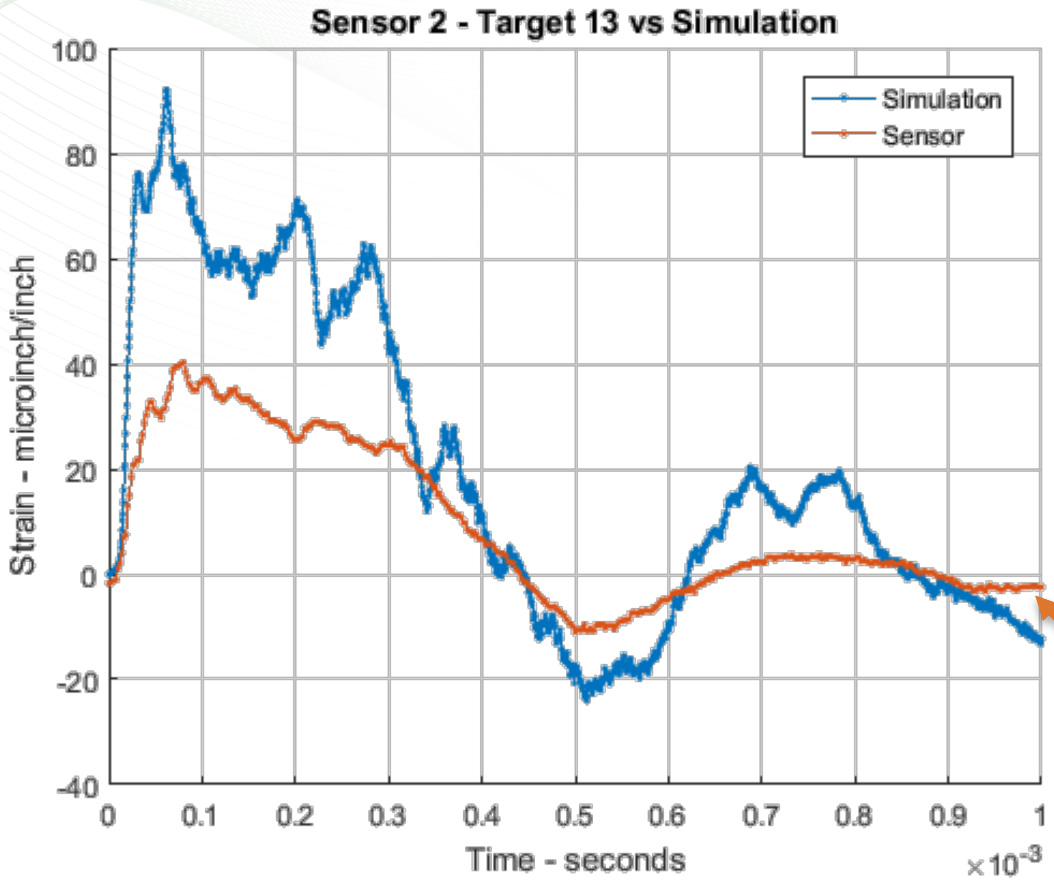


- Simulation agrees relatively well at beam location, though simulation overpredicts strain.
  - Sensor response range 146µe
  - Simulation response range 207µe
    - 41% overprediction on range

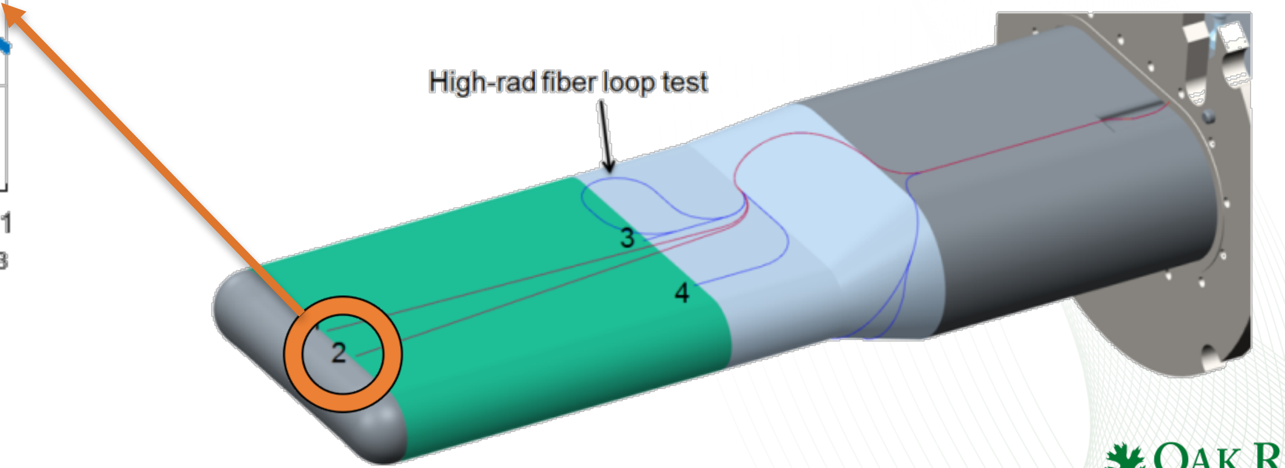


OAK RIDGE National Laboratory

Comparison to Model

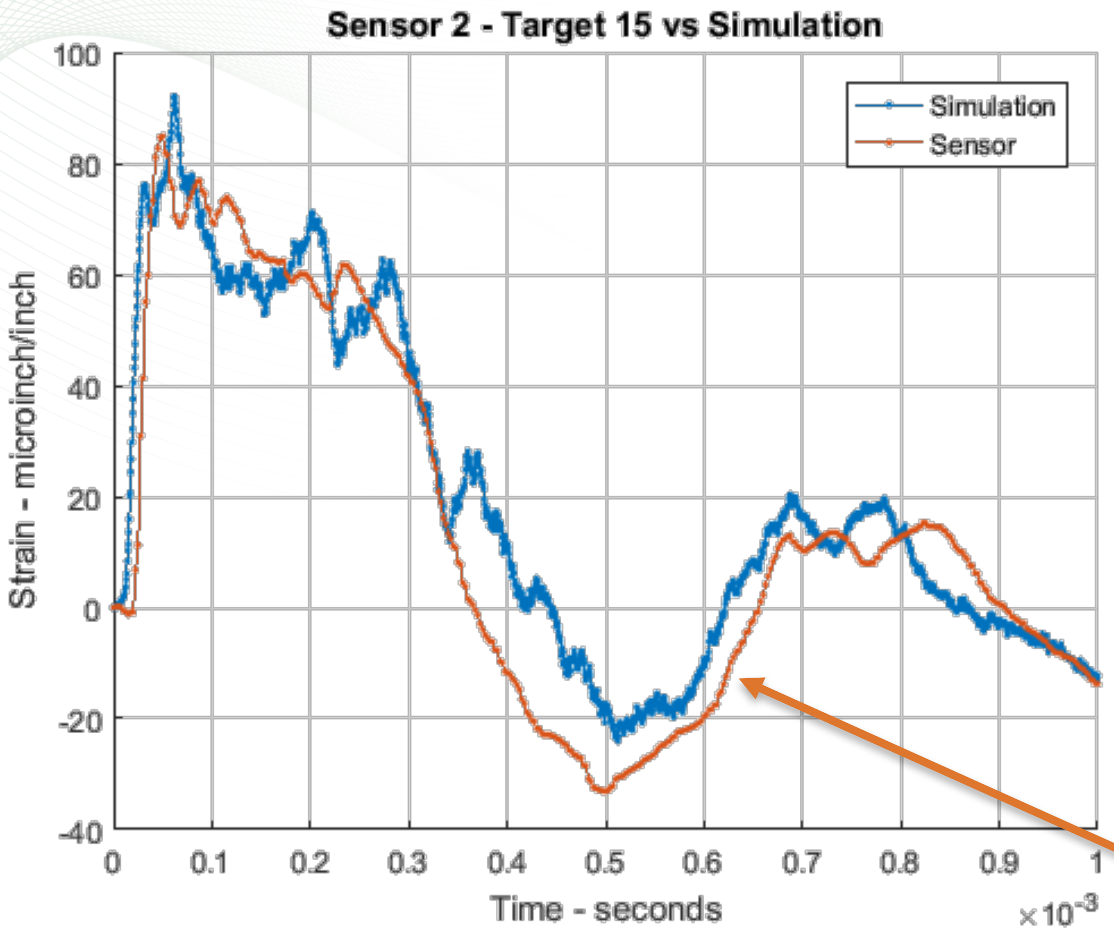


- Overprediction appeared to get worse farther away from the center of the beam.
  - Sensor response range 50με
  - Simulation response range 116με
    - ~2.3X overprediction

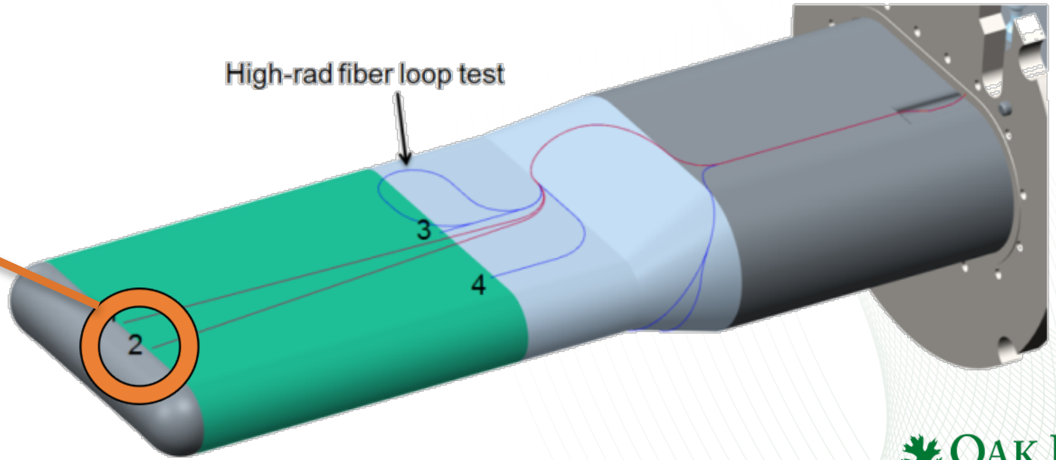


OAK RIDGE National Laboratory

Comparison to Model

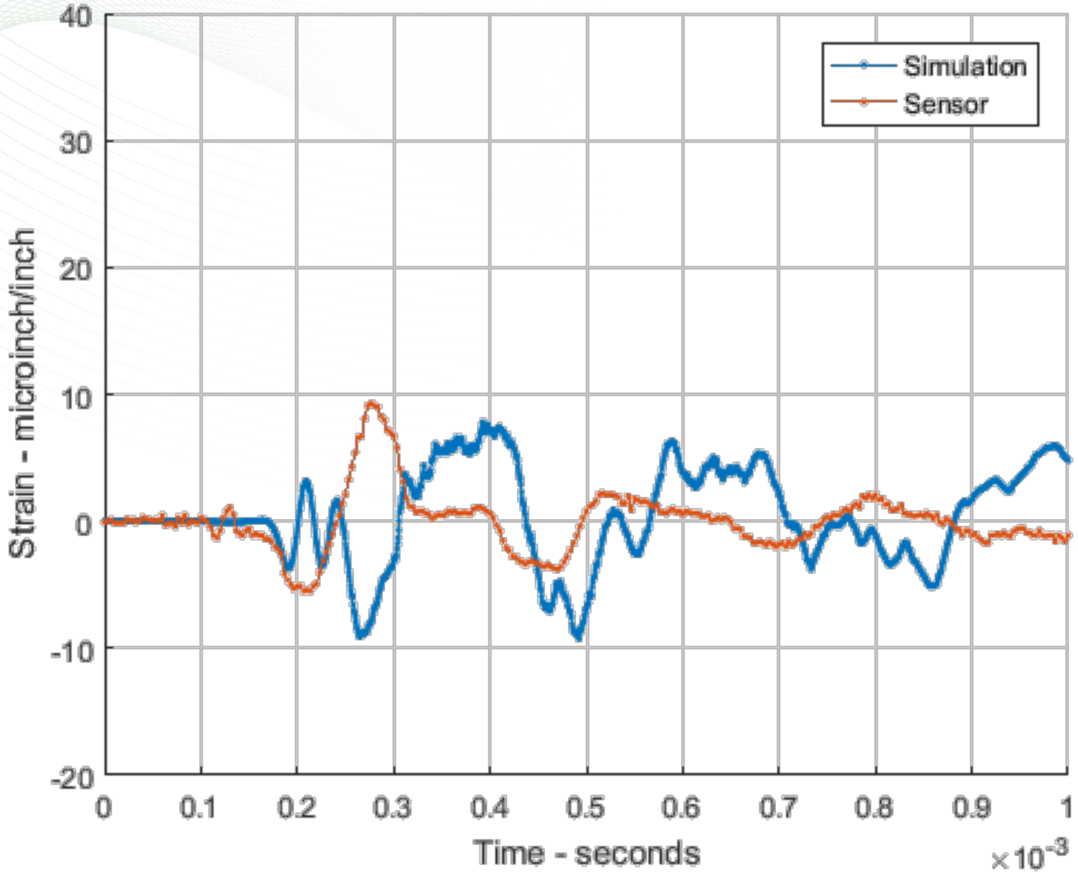


- Measurements on latest target show a better fit.
  - Sensor response range 118µe
  - Simulation response range 116µe
- Difference due to sensors or actual target variation?

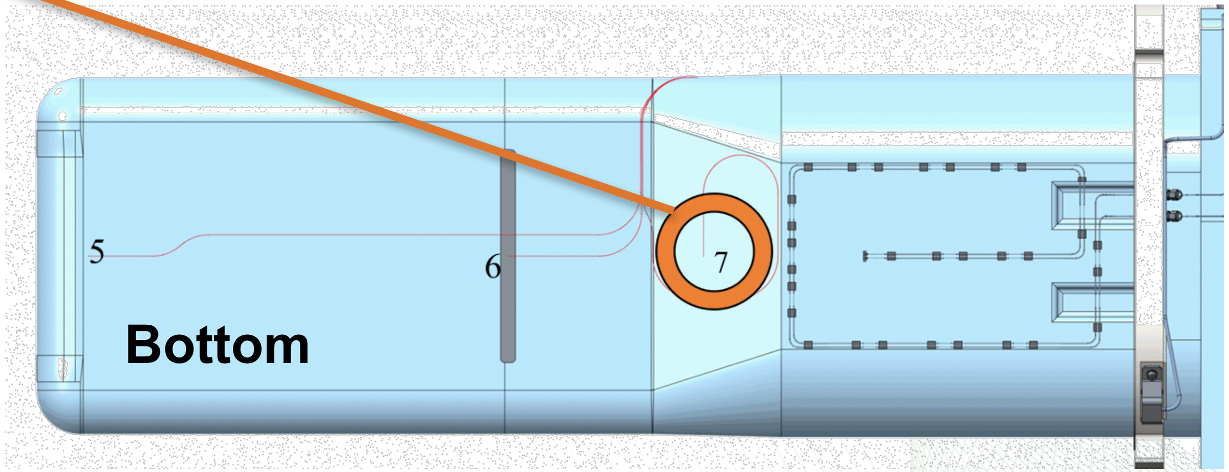


OAK RIDGE National Laboratory

Comparison to Model

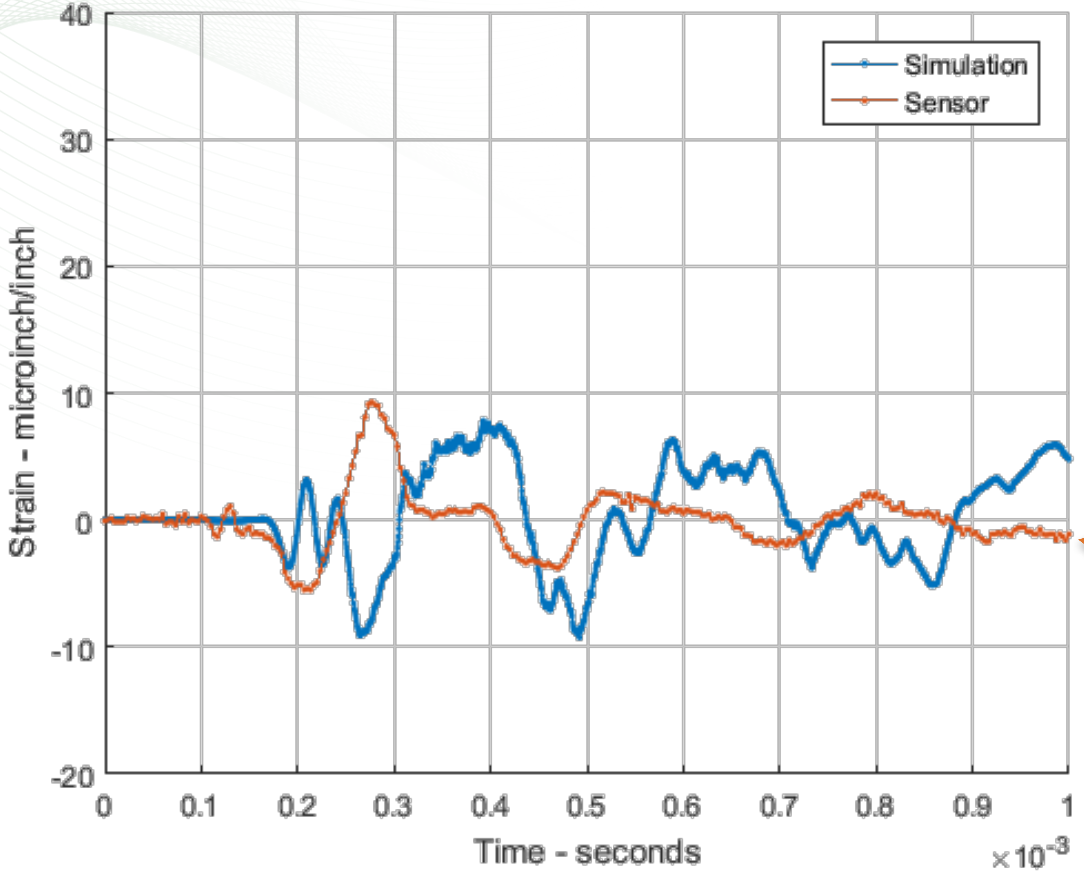


- In area far from beam, magnitude is similar, but response pattern is not.
  - Sensor response range 18με
  - Simulation response range 15με

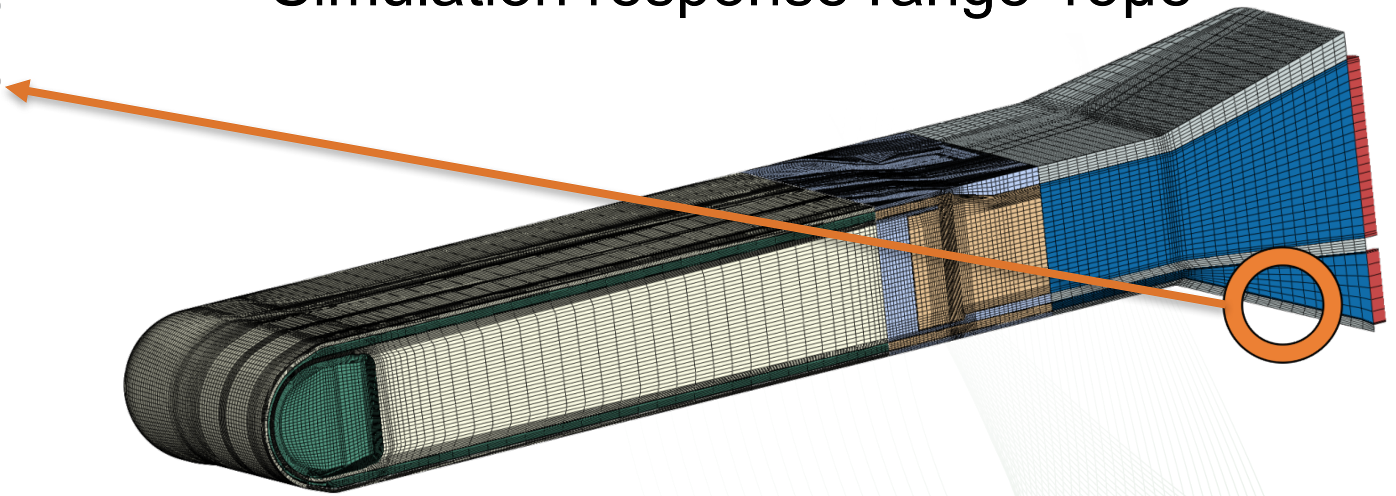


OAK RIDGE National Laboratory

Comparison to Model



- In area far from beam, magnitude is similar, but response pattern is not.
  - Sensor response range 18με
  - Simulation response range 15με

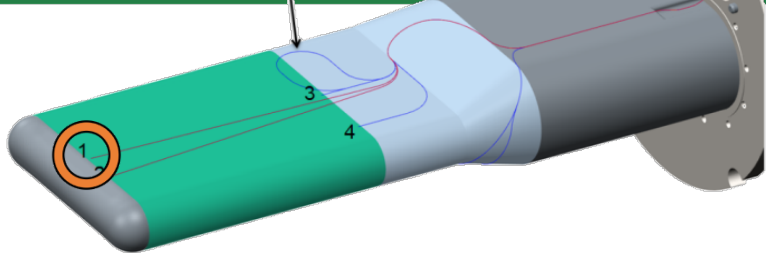


OAK RIDGE National Laboratory

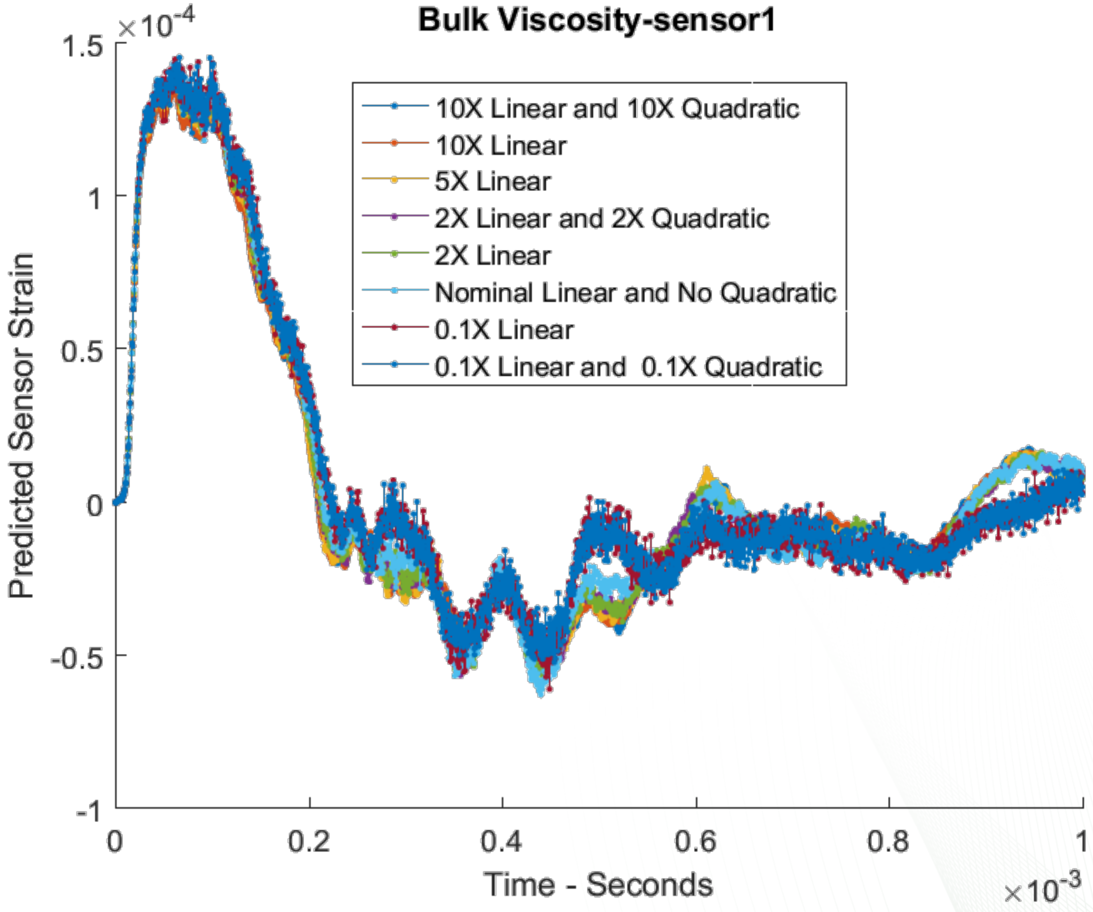
Simulation Parameter Study

- Varied parameters of model to determine if any would result in a better fit to the measured data.
- Added damping
  - Bulk viscosity term of simulation
  - Rayleigh damping in steel
- Material property changes
  - Mercury bulk modulus
  - Mercury tensile cutoff pressure

Effect of Bulk Viscosity on Simulation

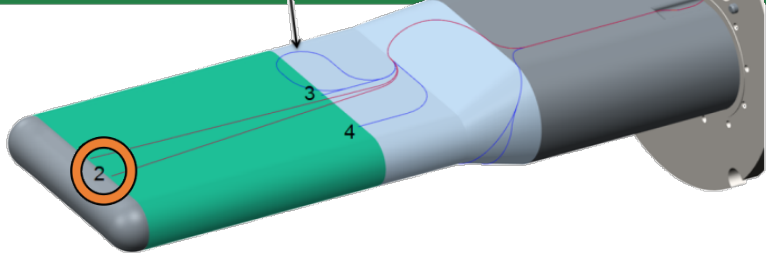


- ABAQUS/Explicit introduces a small amount of damping to control high frequency oscillations.
- Allows for a linear and quadratic parameter.

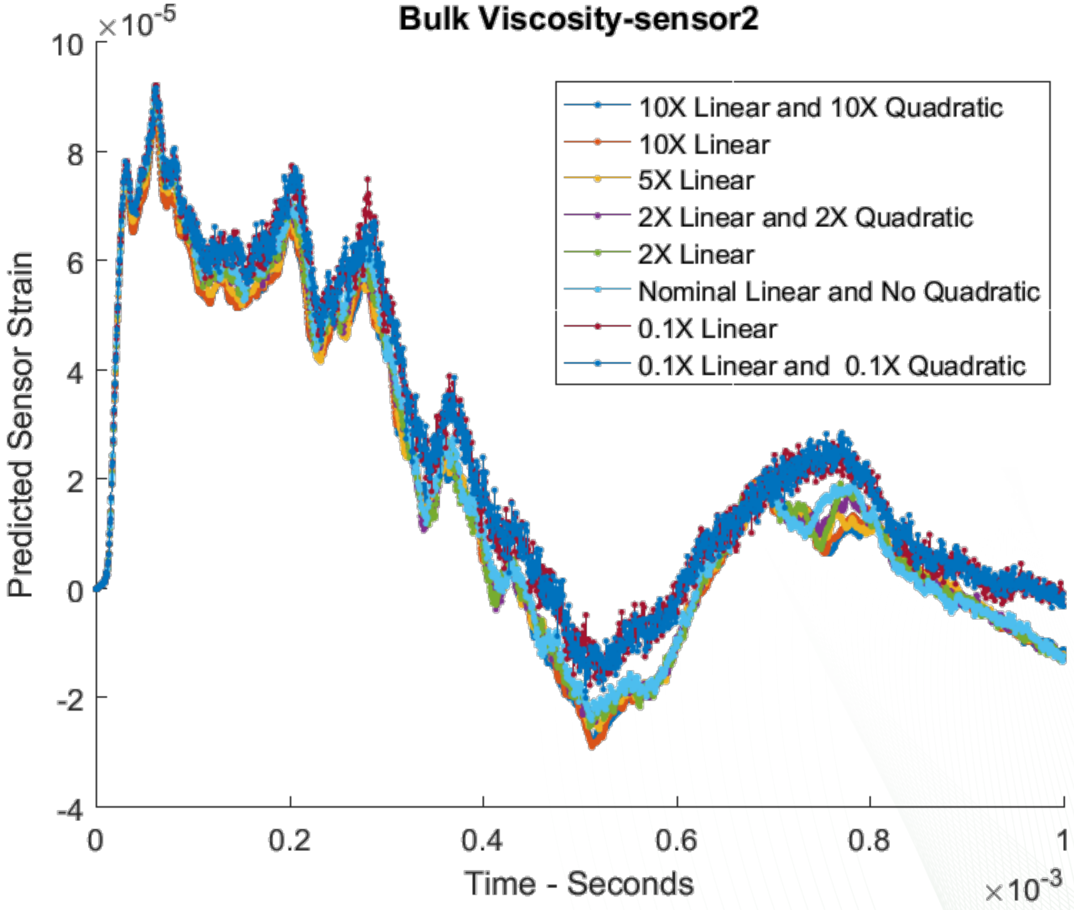


OAK RIDGE National Laboratory

Effect of Bulk Viscosity on Simulation

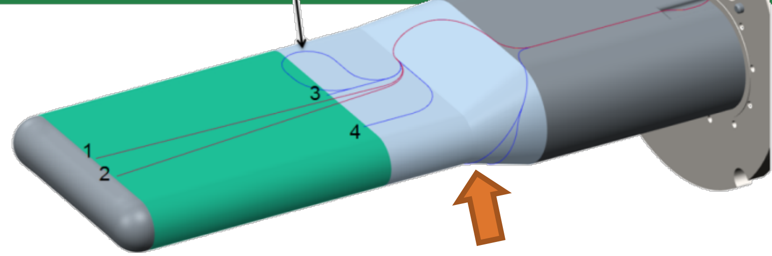


- ABAQUS/Explicit introduces a small amount of damping to control high frequency oscillations.
- Allows for a linear and quadratic parameter.

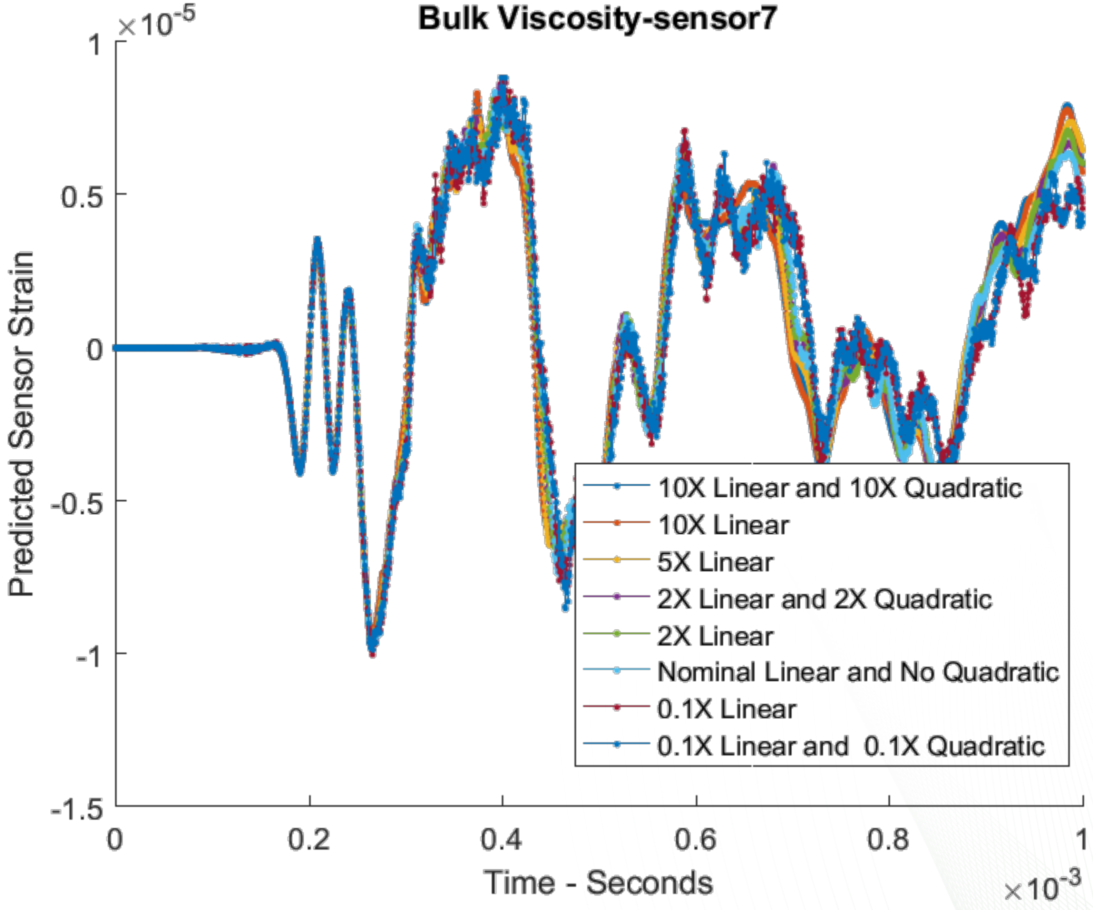


OAK RIDGE National Laboratory

Effect of Bulk Viscosity on Simulation



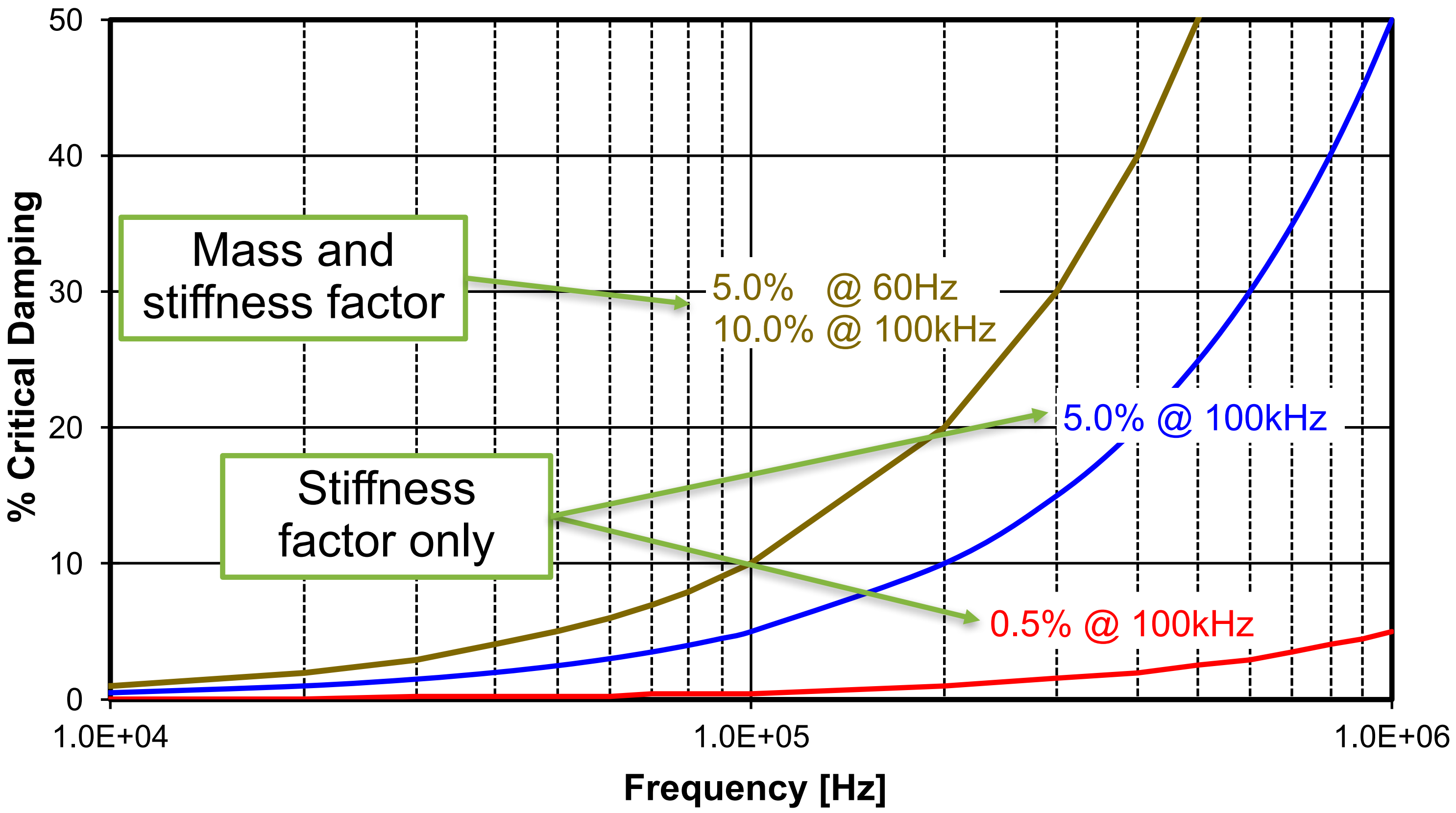
- ABAQUS/Explicit introduces a small amount of damping to control high frequency oscillations.
- Allows for a linear and quadratic parameter.
- Neither has much influence on predicted strain response.



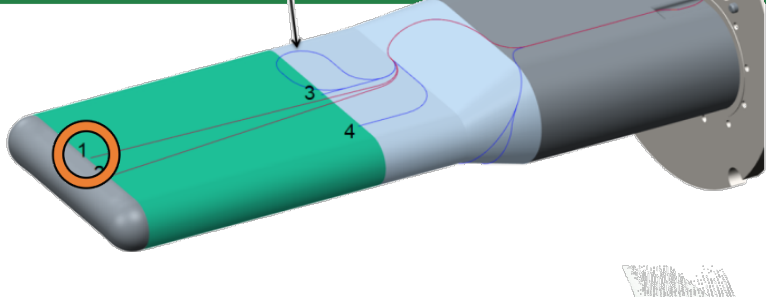
OAK RIDGE National Laboratory

Effect of Rayleigh Damping in Stainless Steel on Simulation

- This damping can include both a mass factor and a stiffness factor.
- Provides a frequency dependent damping.
- Normally not included in model.
- Added only for the stainless steel.

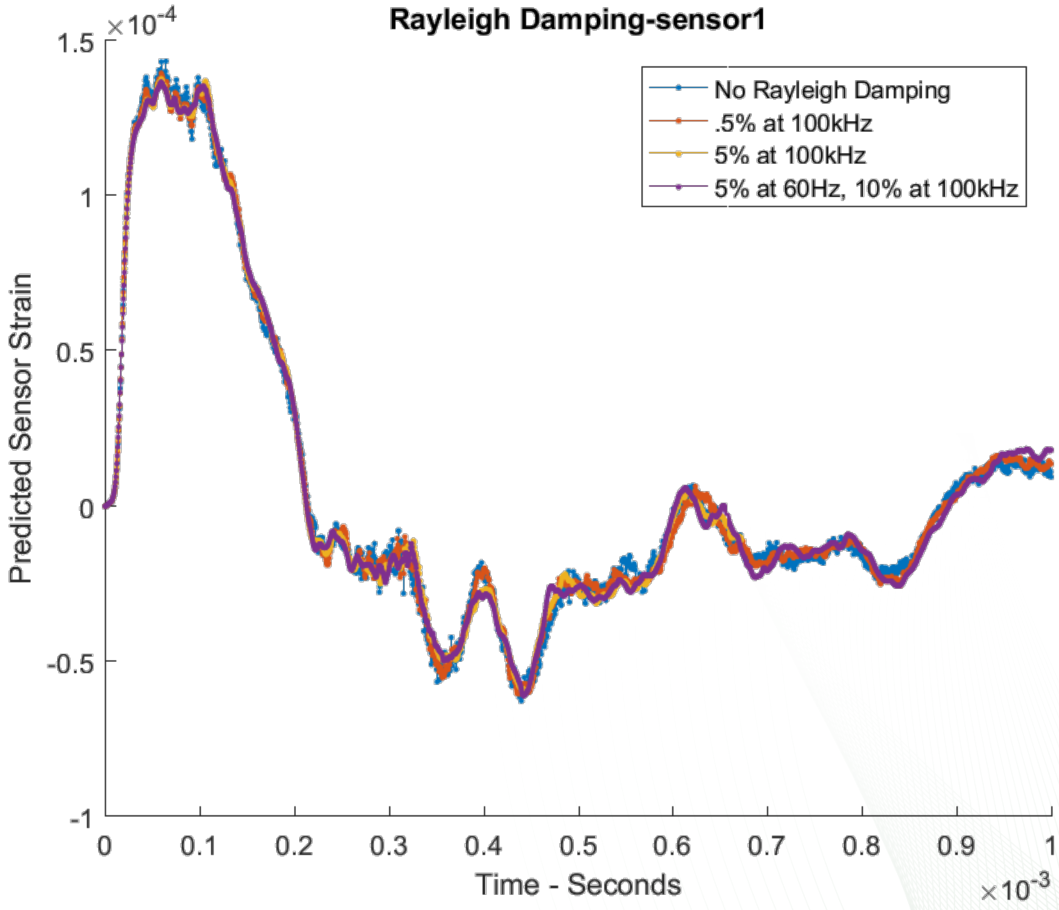


OAK RIDGE National Laboratory

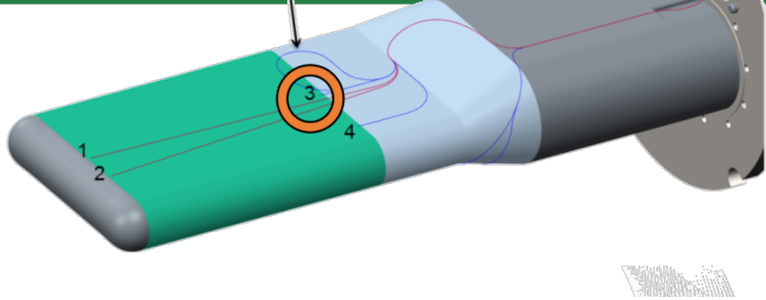


Effect of Rayleigh Damping in Stainless Steel on Simulation

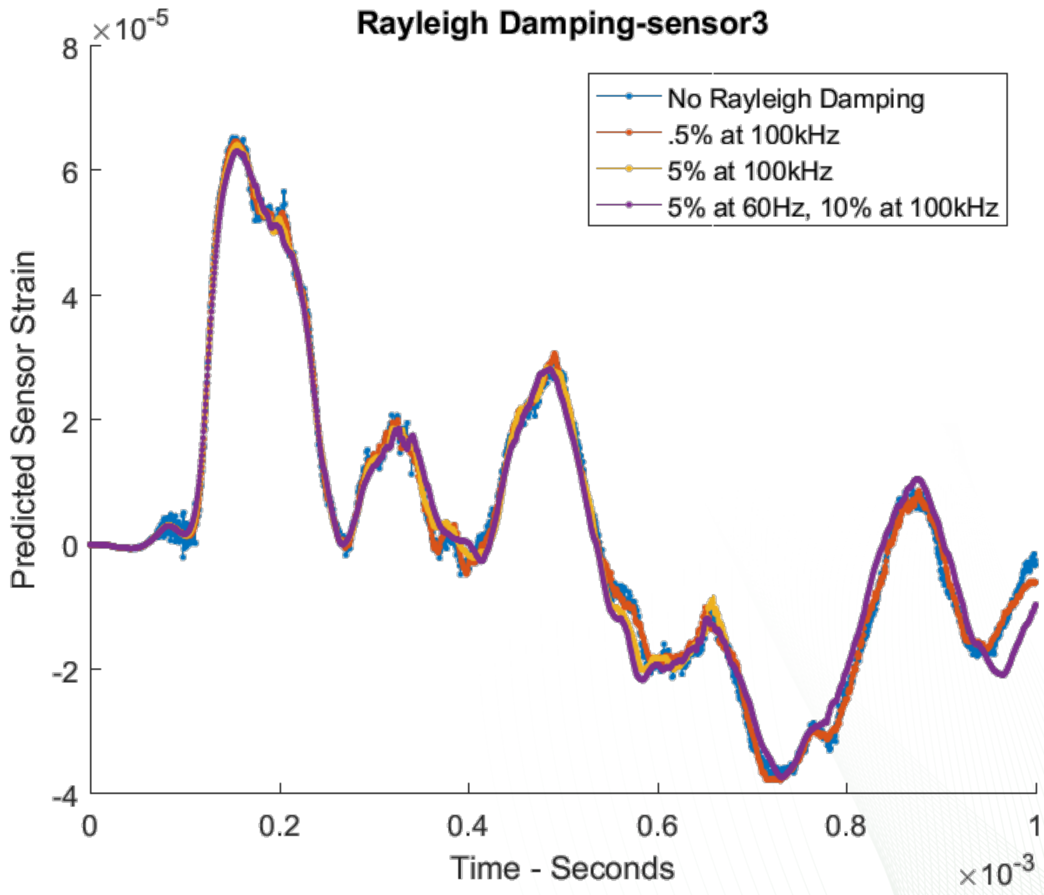
- Rayleigh damping does dampen noise in response.
- However, no significant change in sensor response.
- Simulation with mass damping required ~50X the computing run time.



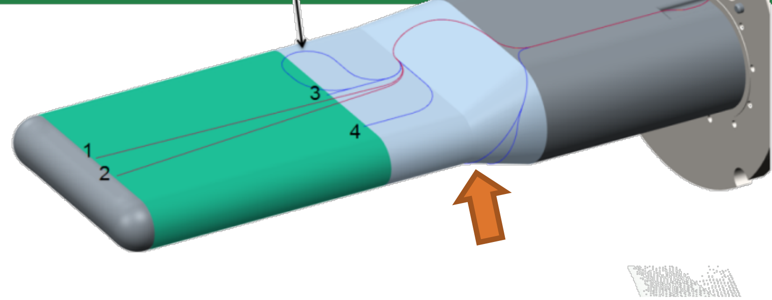
Effect of Rayleigh Damping in Stainless Steel on Simulation



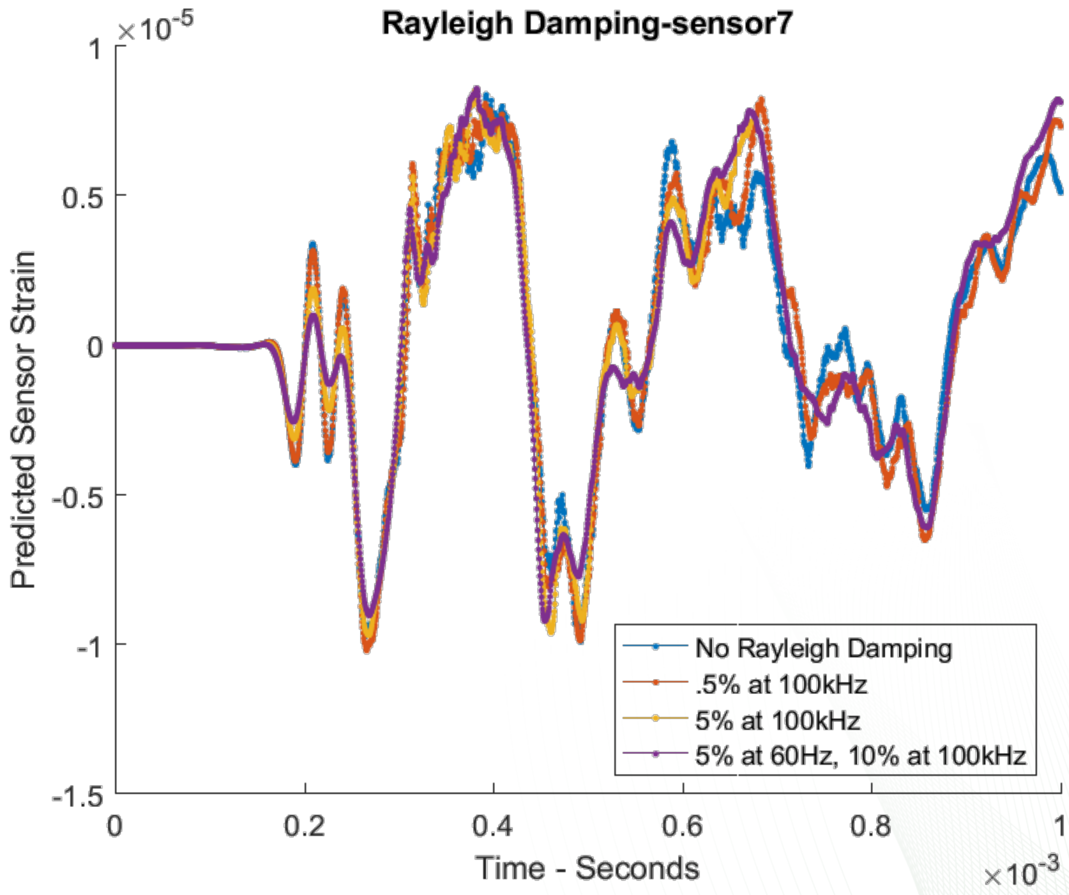
- Rayleigh damping does dampen noise in response.
- However, no significant change in sensor response.
- Simulation with mass damping required ~50X the computing run time.



Effect of Rayleigh Damping in Stainless Steel on Simulation

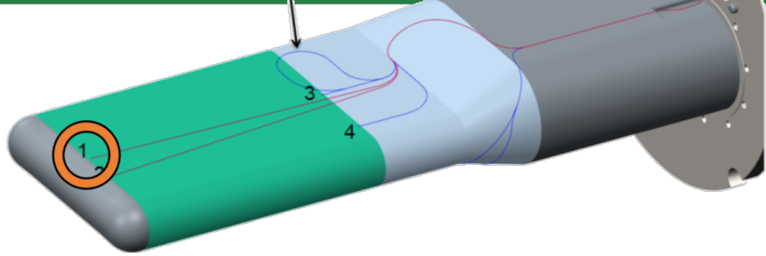


- Rayleigh damping does dampen noise in response.
- However, no significant change in sensor response.
- Simulation with mass damping required ~50X the computing run time.

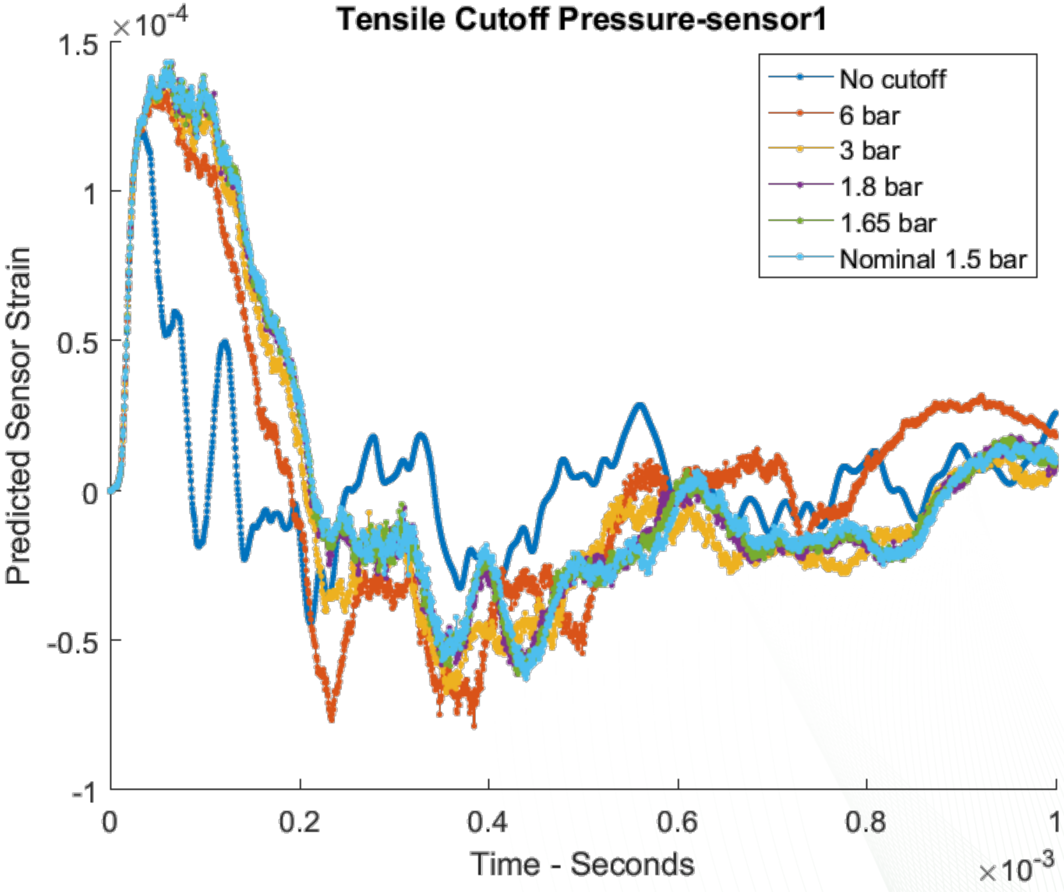


OAK RIDGE National Laboratory

Effect of Mercury Tensile Cutoff Pressure on Simulation

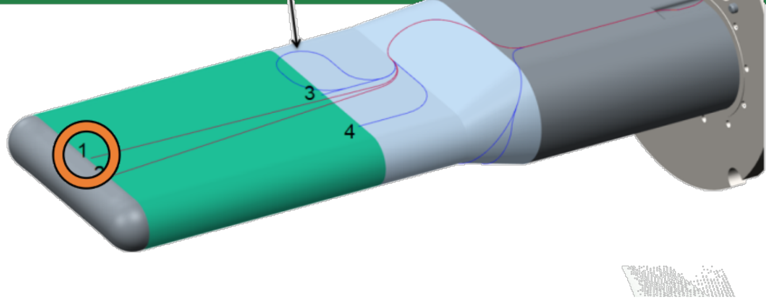


- The mercury material model tensile cutoff pressure is used to simulate the cavitation behavior.
- At the beam entrance, adding and then lowering the tensile cutoff adds a holding time to the first peak, and influences the later troughs.

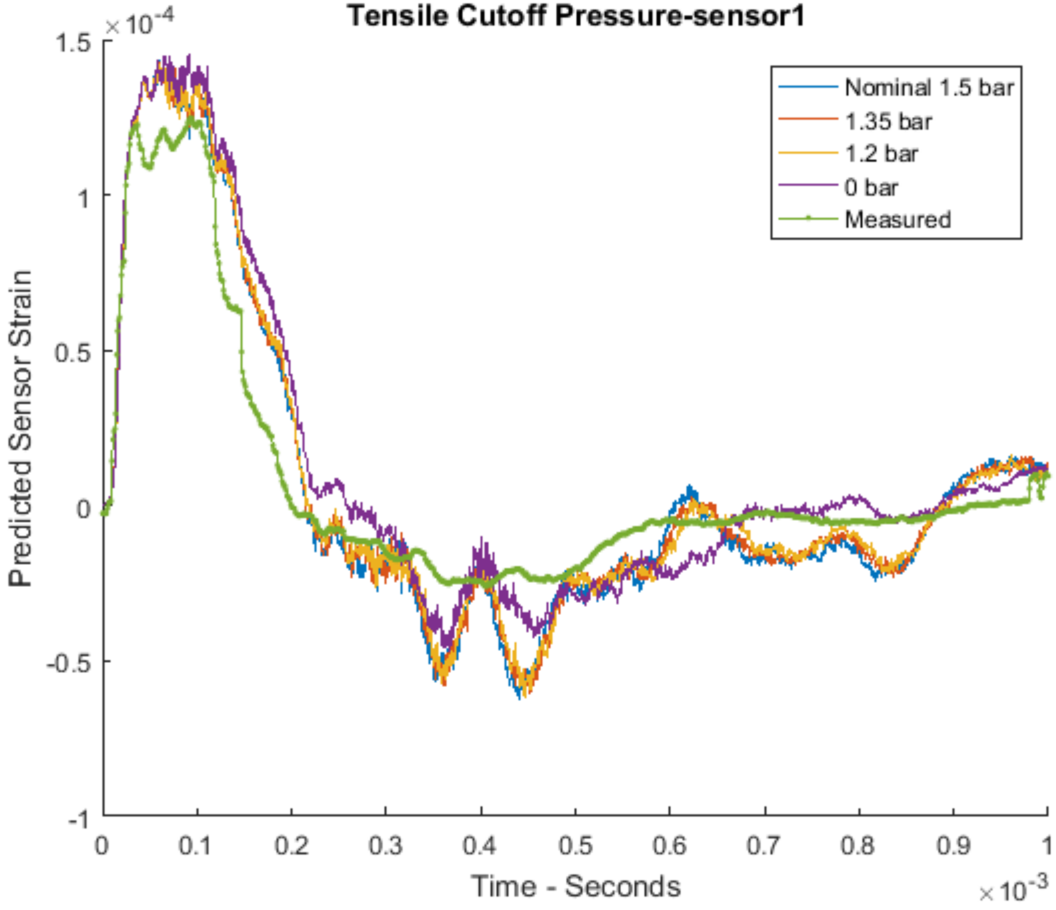


OAK RIDGE National Laboratory

Effect of Mercury Tensile Cutoff Pressure on Simulation

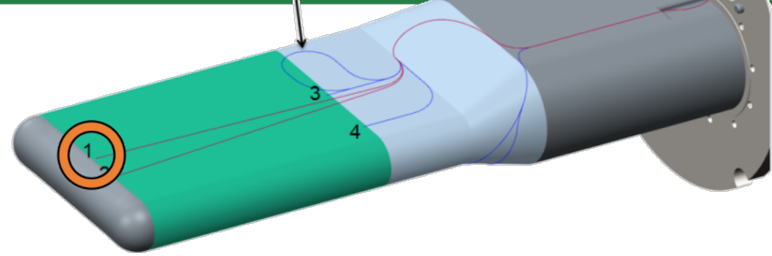


- The mercury material model tensile cutoff pressure is used to simulate the cavitation behavior.
- At the beam entrance, adding and then lowering the tensile cutoff adds a holding time to the first peak, and influences the later troughs.
- Reducing the cutoff below 1.5 bar has less of an effect.



OAK RIDGE National Laboratory

Effect of Mercury Bulk Modulus on Simulation



- Bulk modulus is the ratio of pressure increase to decrease in volume.
- Initial stress must be adjusted:

$$dP = P \cdot \frac{\beta K}{f \rho \, C_V} \cdot F$$

P = volumetric power deposition [W/m^3]

β = Hg volumetric expansion coefficient

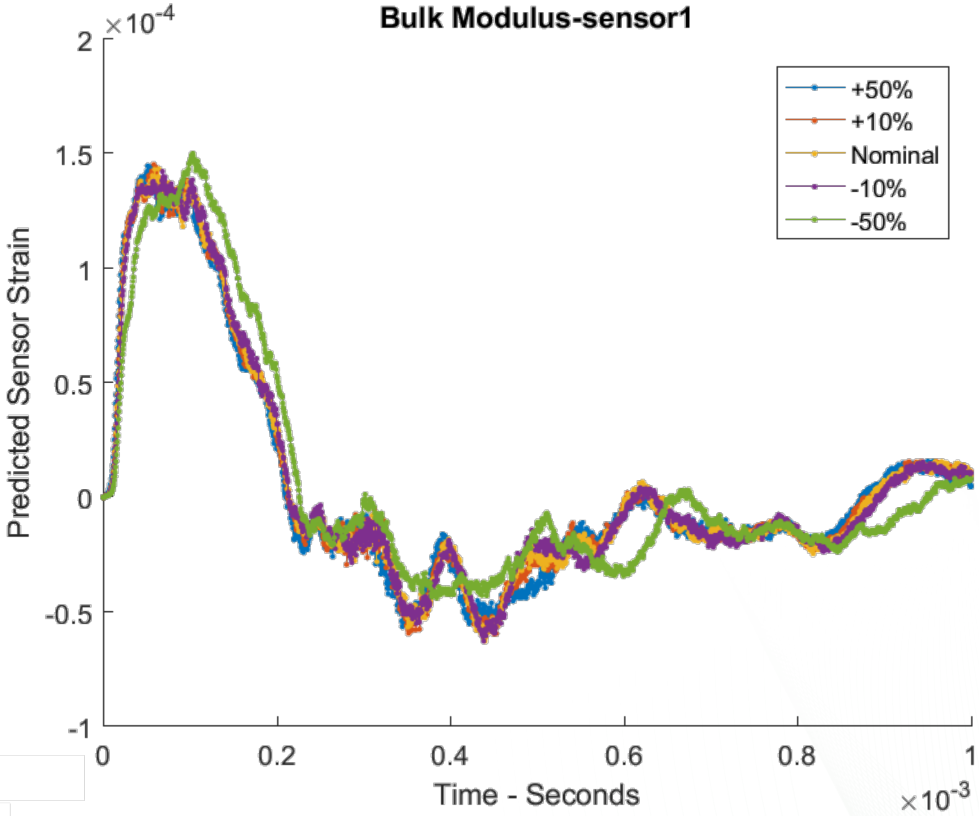
K = Hg bulk modulus of elasticity

f = beam pulse frequency

ρ = Hg density

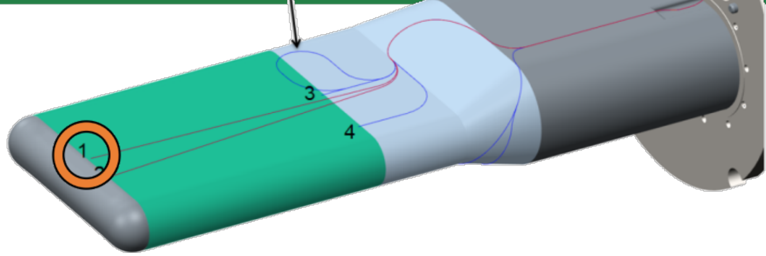
C_V = Hg constant volume specific heat

F = Beam power scale factor

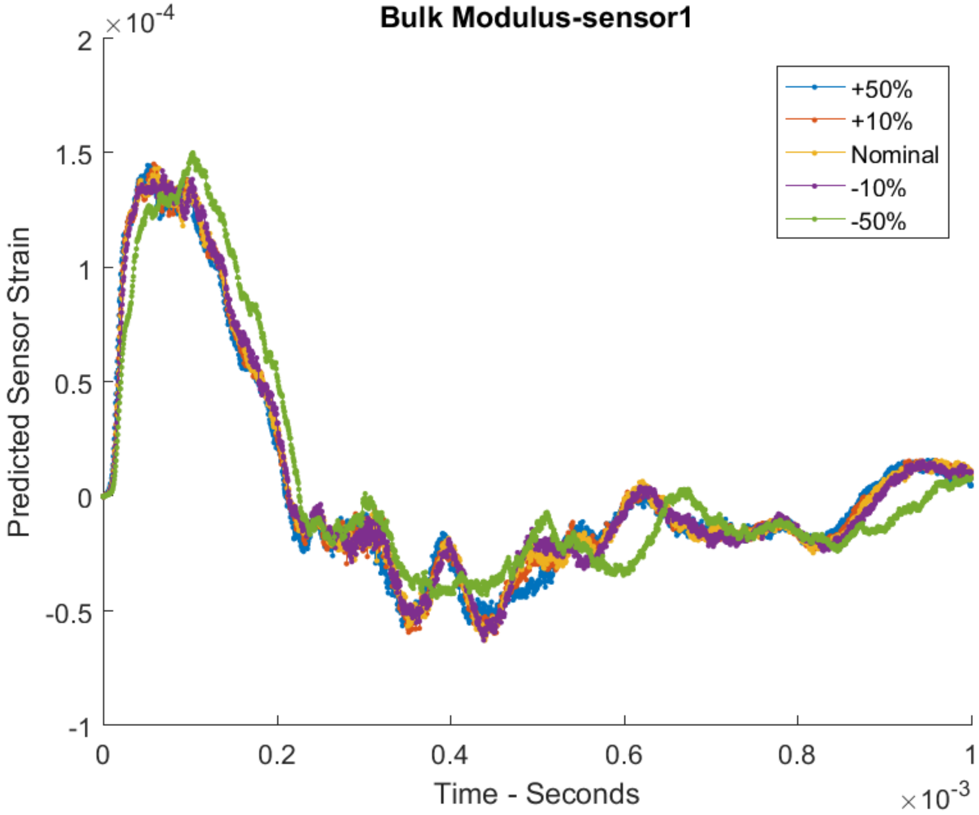


OAK RIDGE National Laboratory

Effect of Mercury Bulk Modulus on Simulation

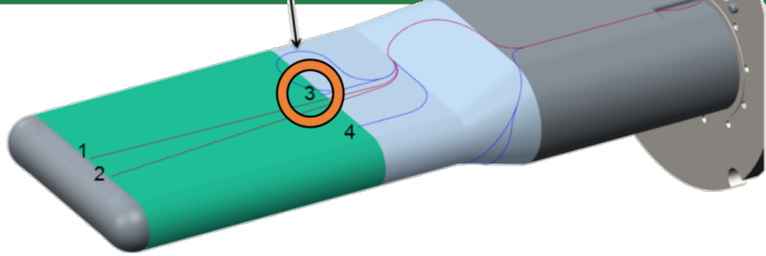


- Peak strain relatively insensitive to mercury bulk modulus. Lower values delay the timing of the peak.
- Less than 6% change in strain response maximum and range at this location from nominal.

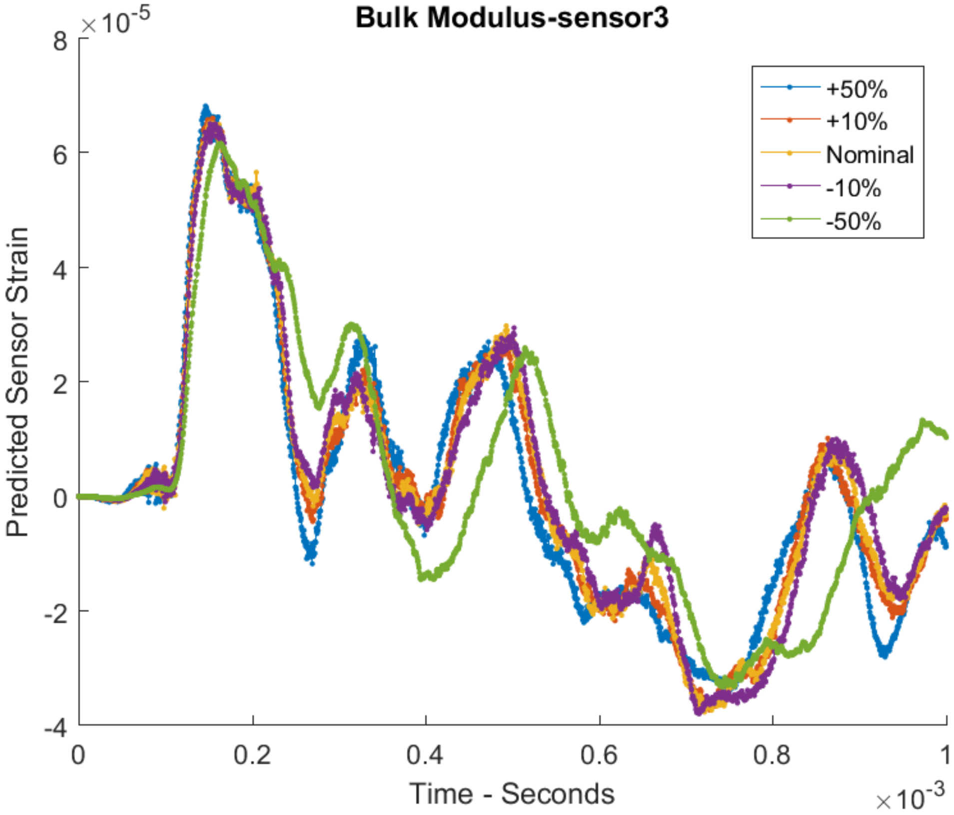


Oak Ridge National Laboratory

Effect of Mercury Bulk Modulus on Simulation

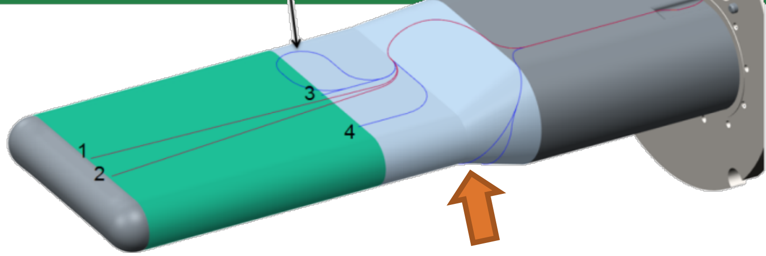


- Similar change seen farther from the beam.
- Less than 8% change in strain response maximum and range at this location.

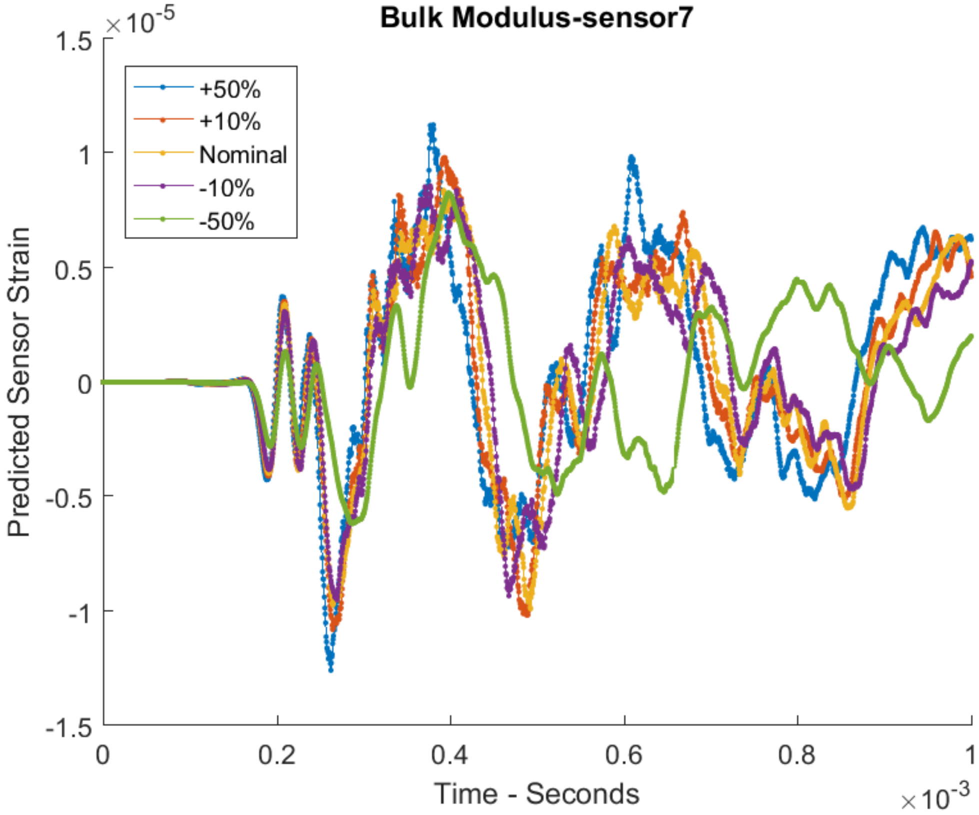


OAK RIDGE National Laboratory

Effect of Mercury Bulk Modulus on Simulation



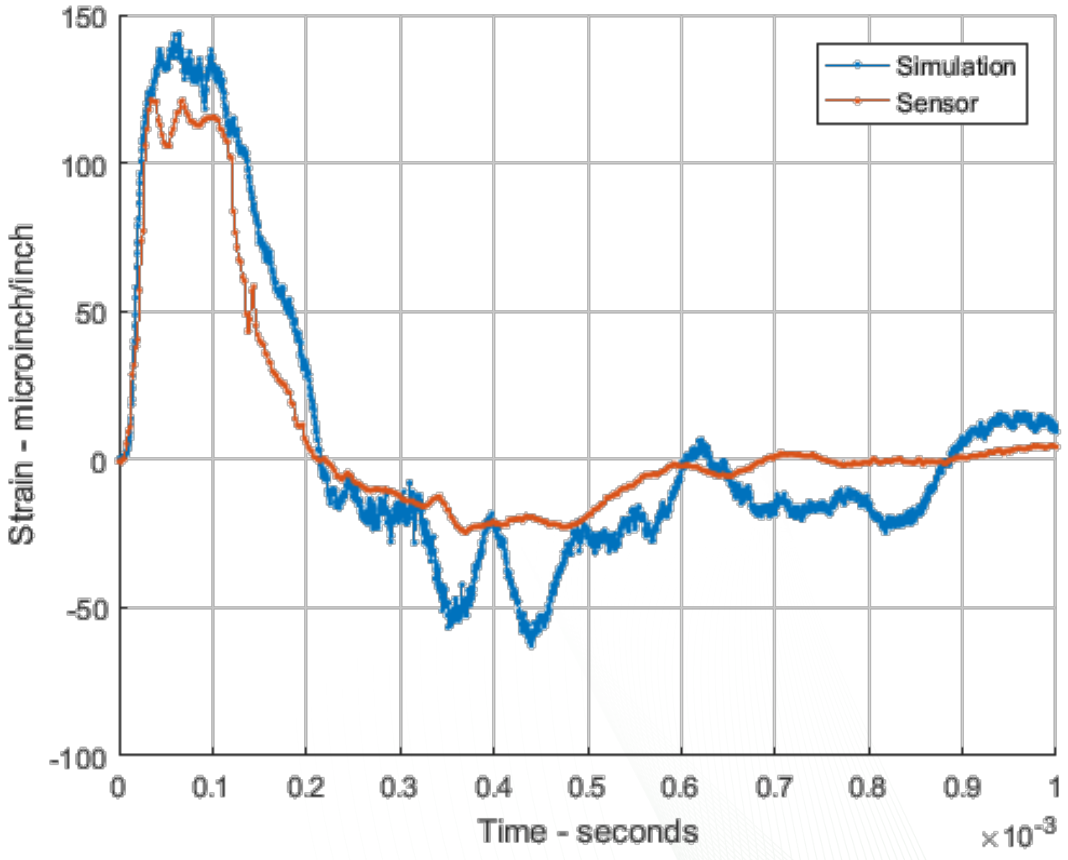
- Largest relative change far from the peak.
- Range changed up to 30% from nominal, peak changed up to 35% with high bulk modulus.
- Predicted strains remain low, 11 microstrain maximum.



OAK RIDGE National Laboratory

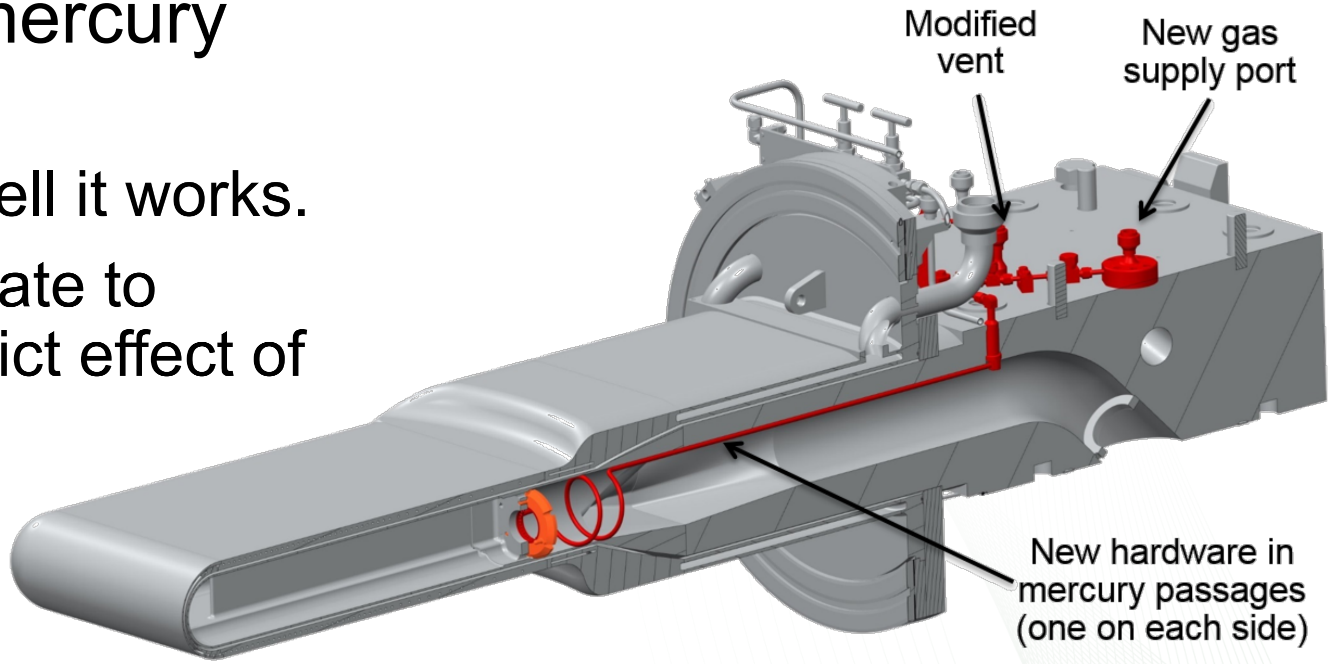
Summary and Future Work

- Measurements show that our predictive model is getting us in the right range of expected pulse stresses, but there is still room for improvement.
  - None of the modifications studied here make significant improvements to fit of data.
- Measurements are repeatable on the same target, but still working to understand target to target variations.



Summary and Future Work

- Measurements of strains on the target are critical for upcoming rollout of helium gas injection into the mercury target
  - Will provide feedback on how well it works.
  - Will provide data needed to update to material models needed to predict effect of design changes.



OAK RIDGE National Laboratory