Optical Sensors for High-Power Target Systems

Elvis Dominguez-Ontiveros

Sr. R&D Staff I Nuclear Technologies Division I SNS

Virtual Workshop on Optical Sensors for Energy Applications

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ORNL is managed by UT-Battelle, LLC for the US Department of Energy

Outline

- The SDE-SNS team
- Introduction
  - SNS facility
- High-power target applications
- Other potential applications
- Summary

The ORNL Team

- Source Development and Engineering Group (SNS)

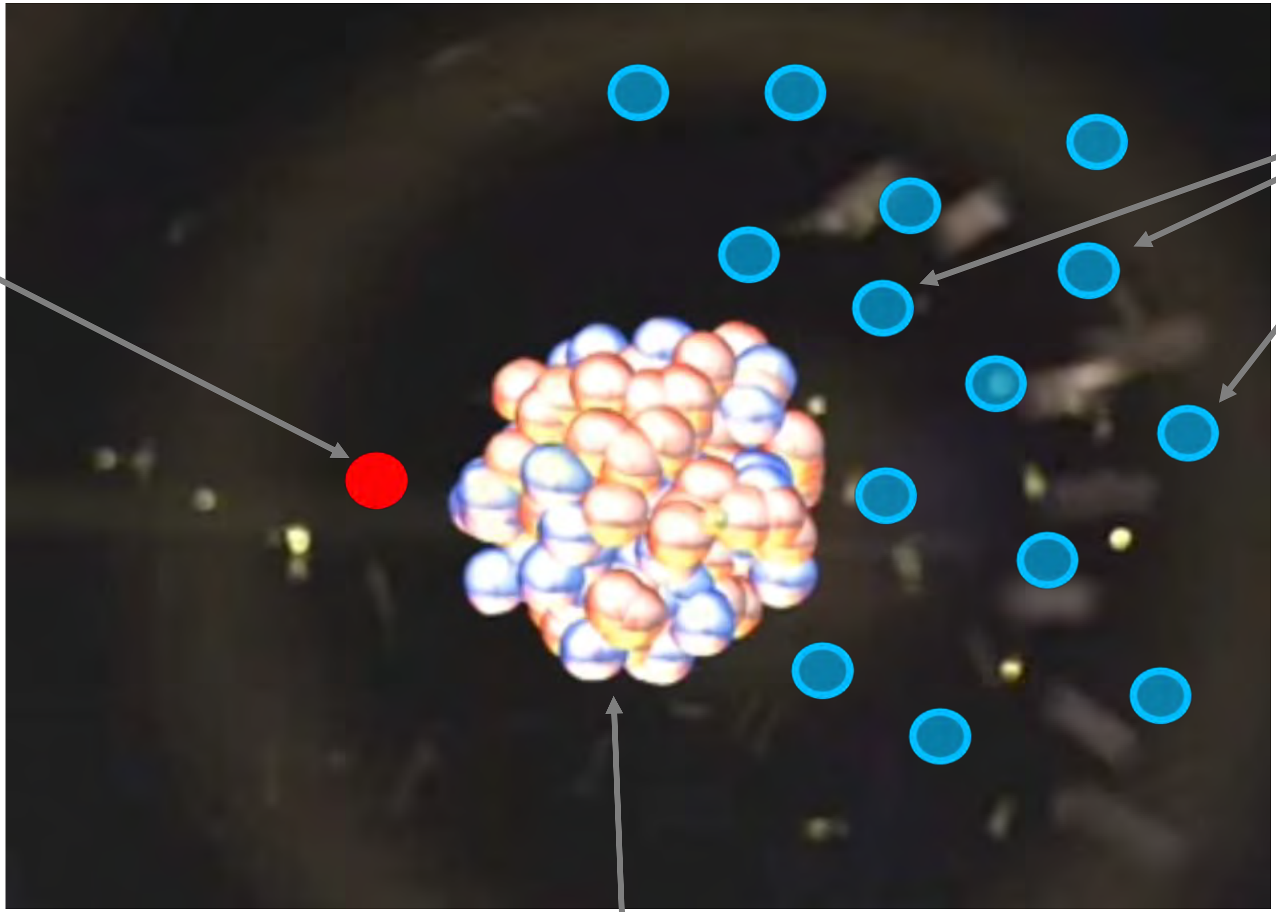
- Drew Winder
- Hao Jiang
- Kevin Johns
- David Mcclintock
- Nick Pannell
- Ryan Schultz
- Robert Sangrey
- Allie Morris

Yun Liu
Mark Wendel
Bernie Reimer
Willem Blokland
Charlotte Barbier
And many others ++++

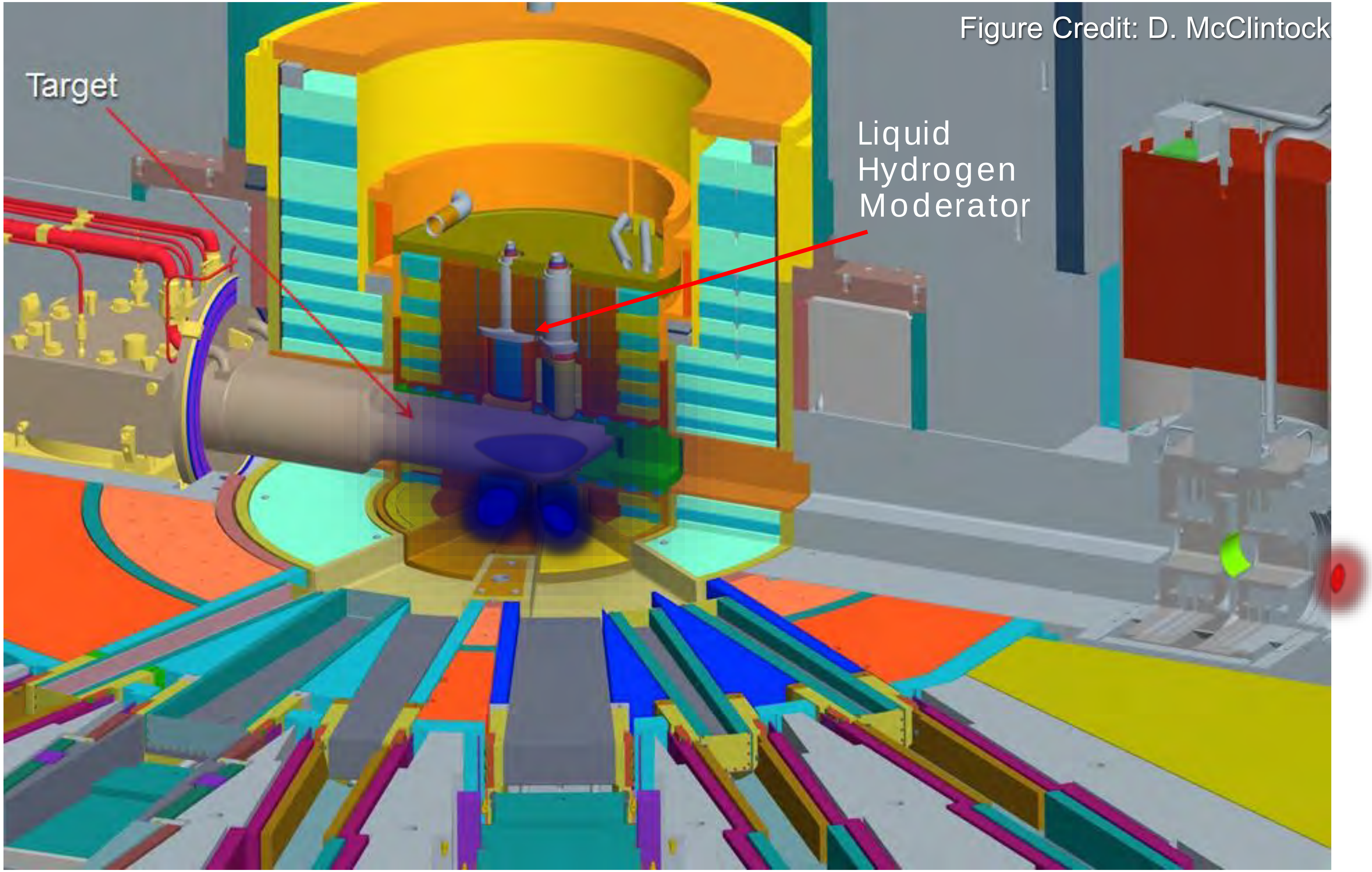
The Spallation Neutron Source is a megawatt class accelerator-based pulsed neutron source

Neutrons are produced via high-energy spallation reactions induced by injecting 1 GeV 1.55 MW protons into liquid mercury at a frequency of 60 Hz

The Spallation Process

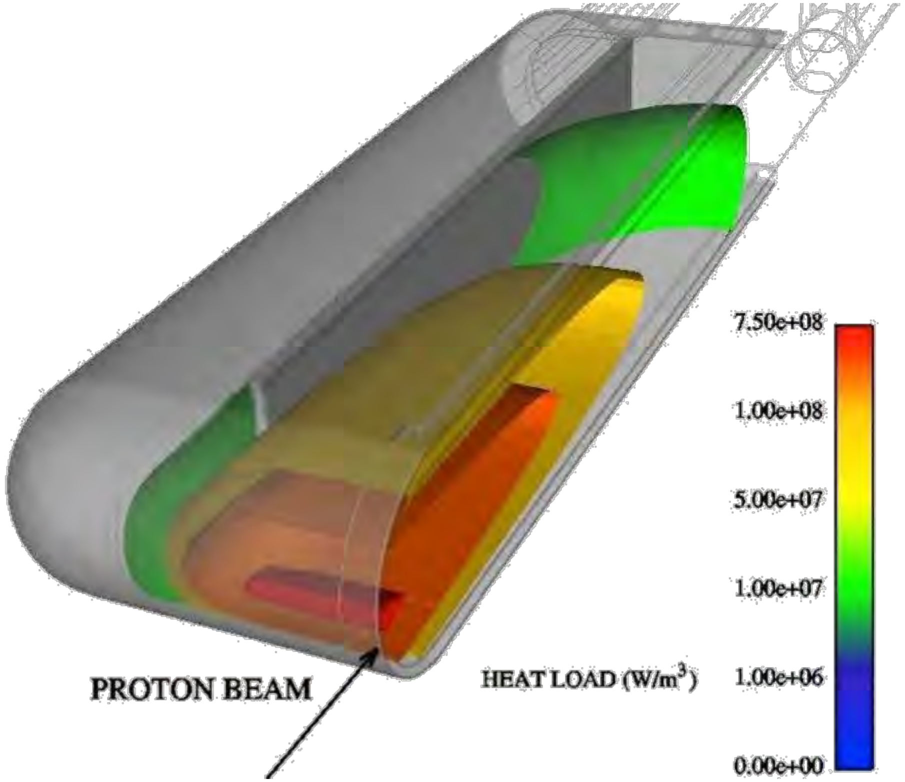


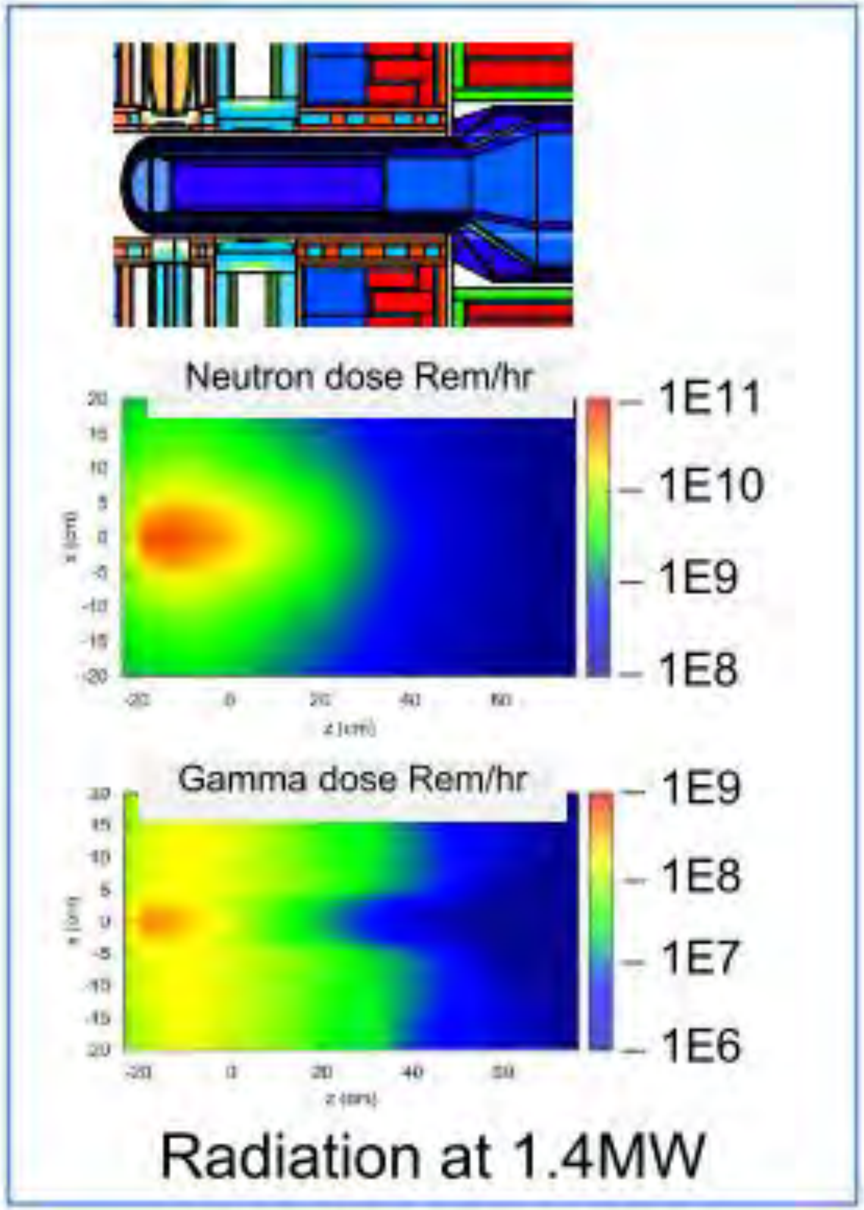
The target provides neutrons to 18 beam lines - instrument



The Harsh Sensor's Environment

- High Radiation during production
  - 1E8 up to 1E11 Rem/hr at 1.4 MW (2 MW upgrade)
  - typical rad level of 10E9 Gy over its lifetime





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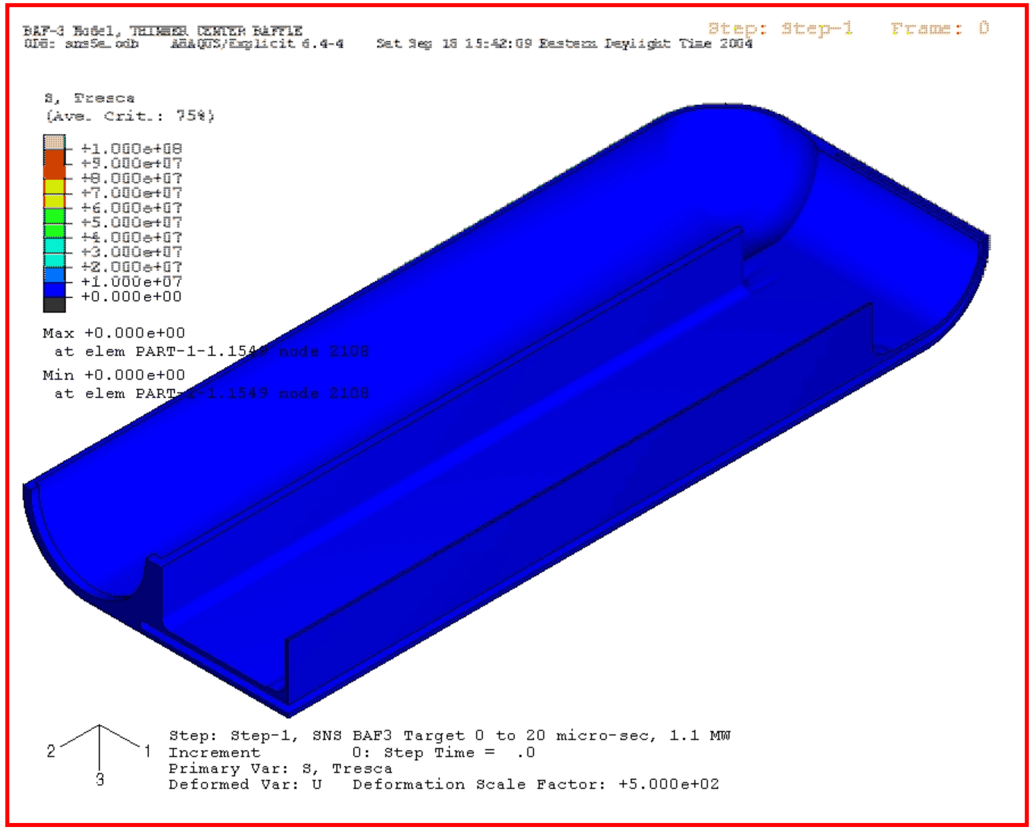
The Harsh Sensor’s Environment

- Intense electro-magnetic interference and ionizing radiation
- High dynamic range due to pulsed phenomena
- Mechanical
  - Pressure wave
  - ~60% of beam energy deposited in target
  - The isochoric (constant volume) energy deposition leads to formation of tensile pressure waves in the mercury

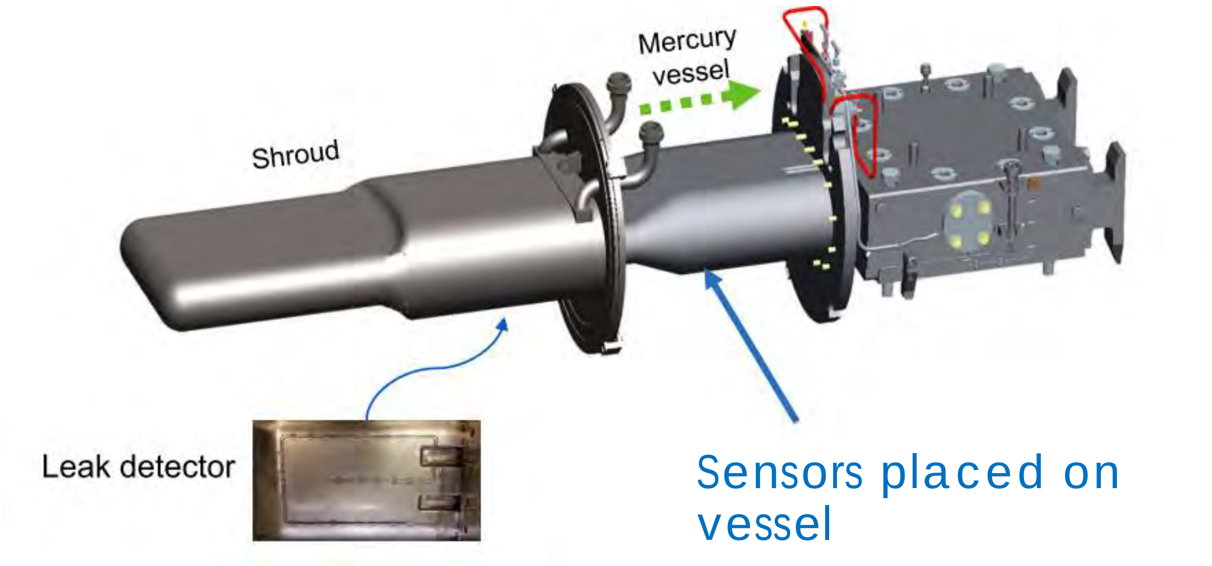


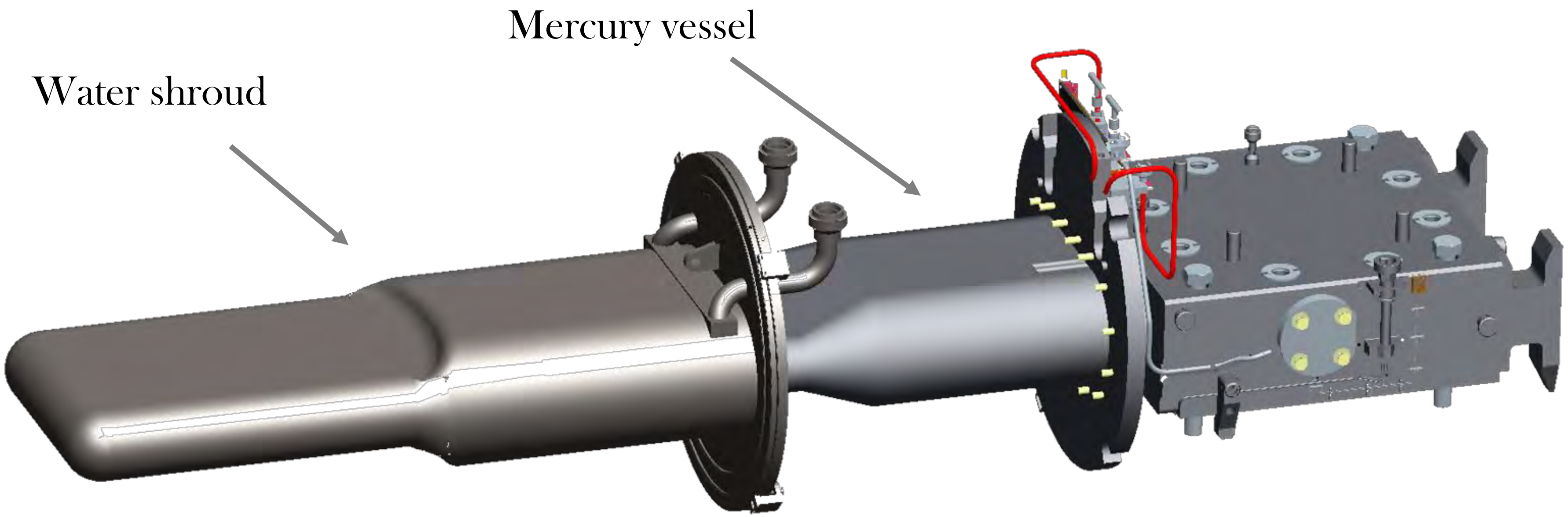
Front body & beam windows, ¼ section
Stress intensity [Pa]

Solution method: B.W. Riemer, Jnl. Nucl. Mat. 343 (2005) 81-91

Target module: A stainless steel vessel containing mercury

Beam power	1.4 MW
Beam frequency	60 Hz
Beam pulse length	700 ns
Module material	AISI 316L
Mass (empty)	~1,100kg
Mass (filled)	~1,900kg
Length	~2.1 m





Cavitation Erodes Inner Surfaces

Outer Wall

Inner Wall

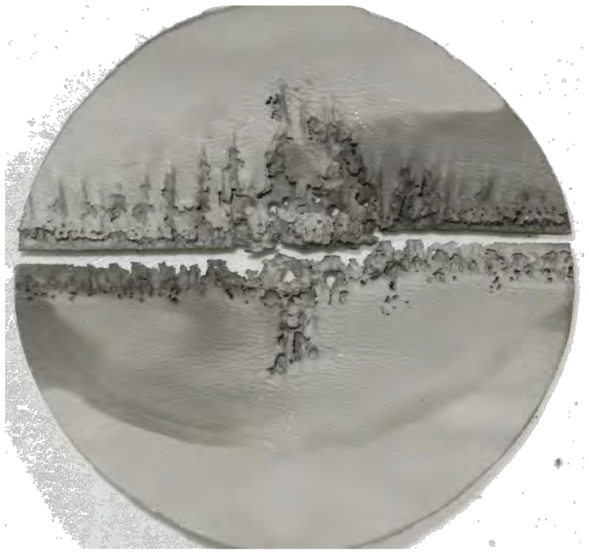
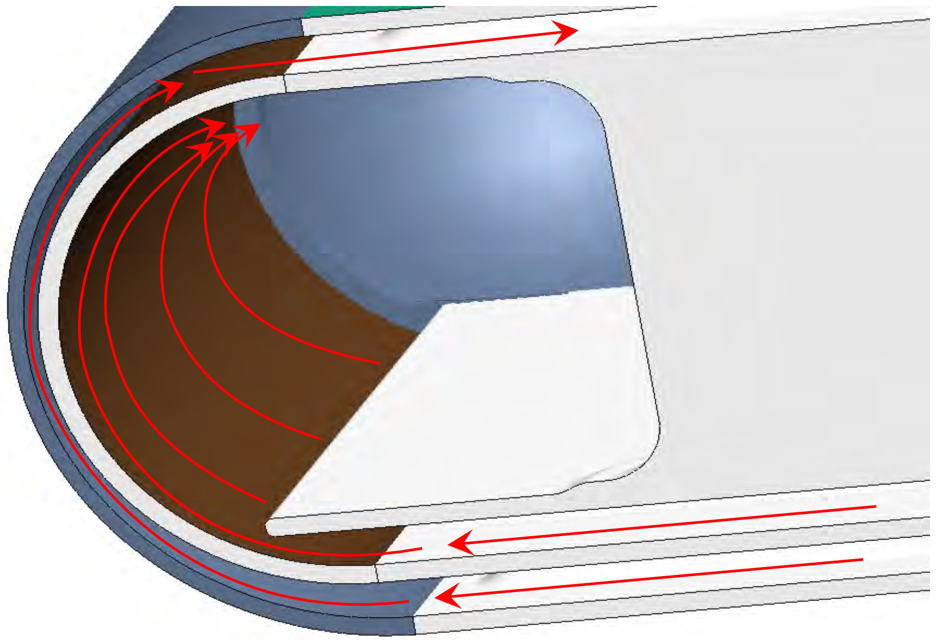


Figure Credit: P. Rosenblad



Jet Flow Target Cross Section

- The pressure waves cause regions of negative pressure
  - The mercury change phase to gas
  - When the gas collapses back to liquid, shock and liquid jets are created
- The shock and jets erode the stainless-steel vessel

Sensor Installation

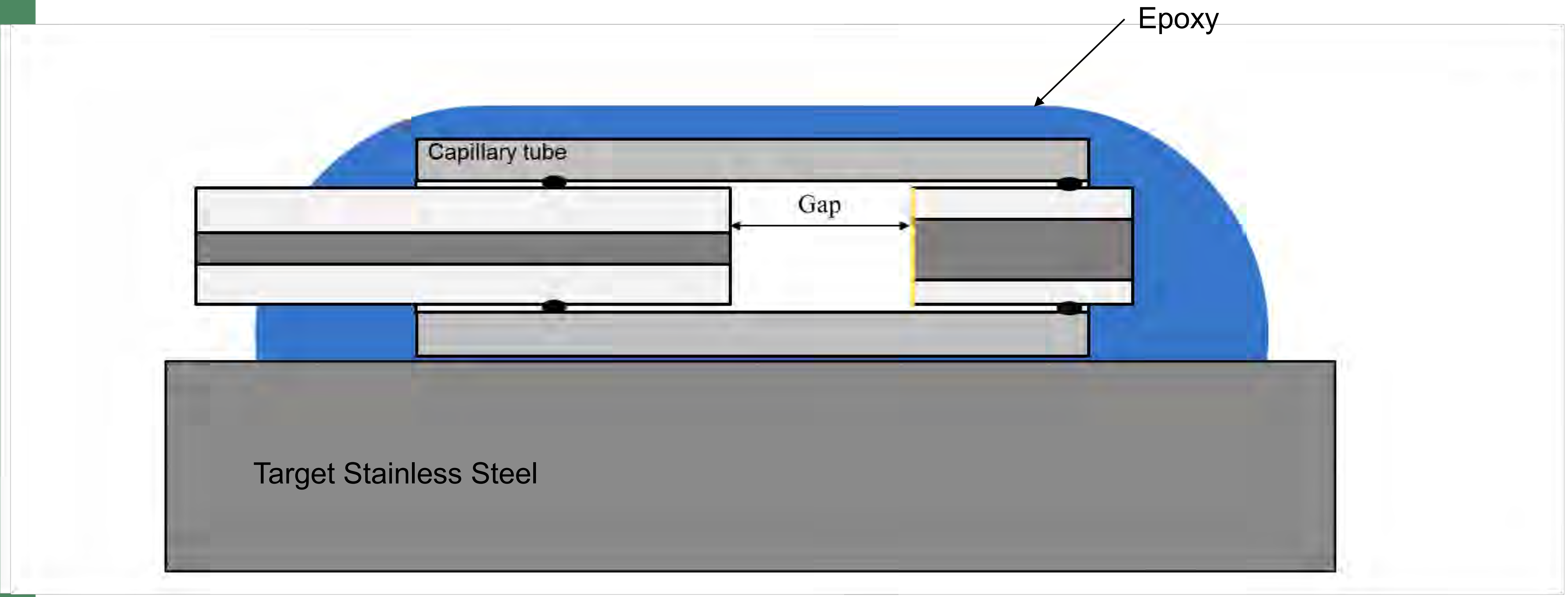
- Different types of fiber compositions tested over the years
  - Fluorine-doped single mode- Fujikura RRSMFB
- Installation
  - Mounting sensors on SS vessel using Stycast 2850FT epoxy cured with catalyst 11
  - Installed in a ~3mm gap interstitial space

Laying out the sensors

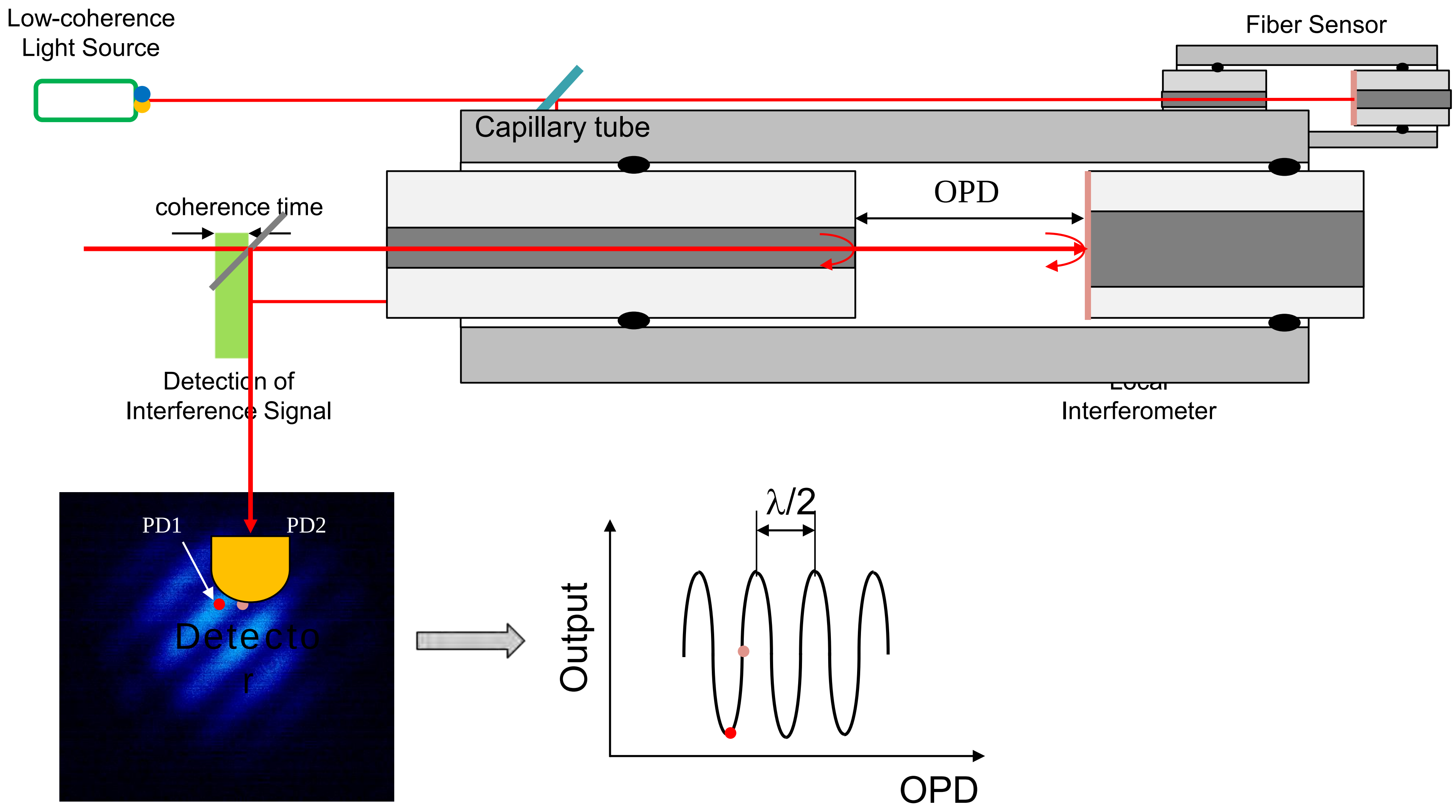
Installed sensors

Curing of epoxy glue

Fiber Optic Strain Gauges

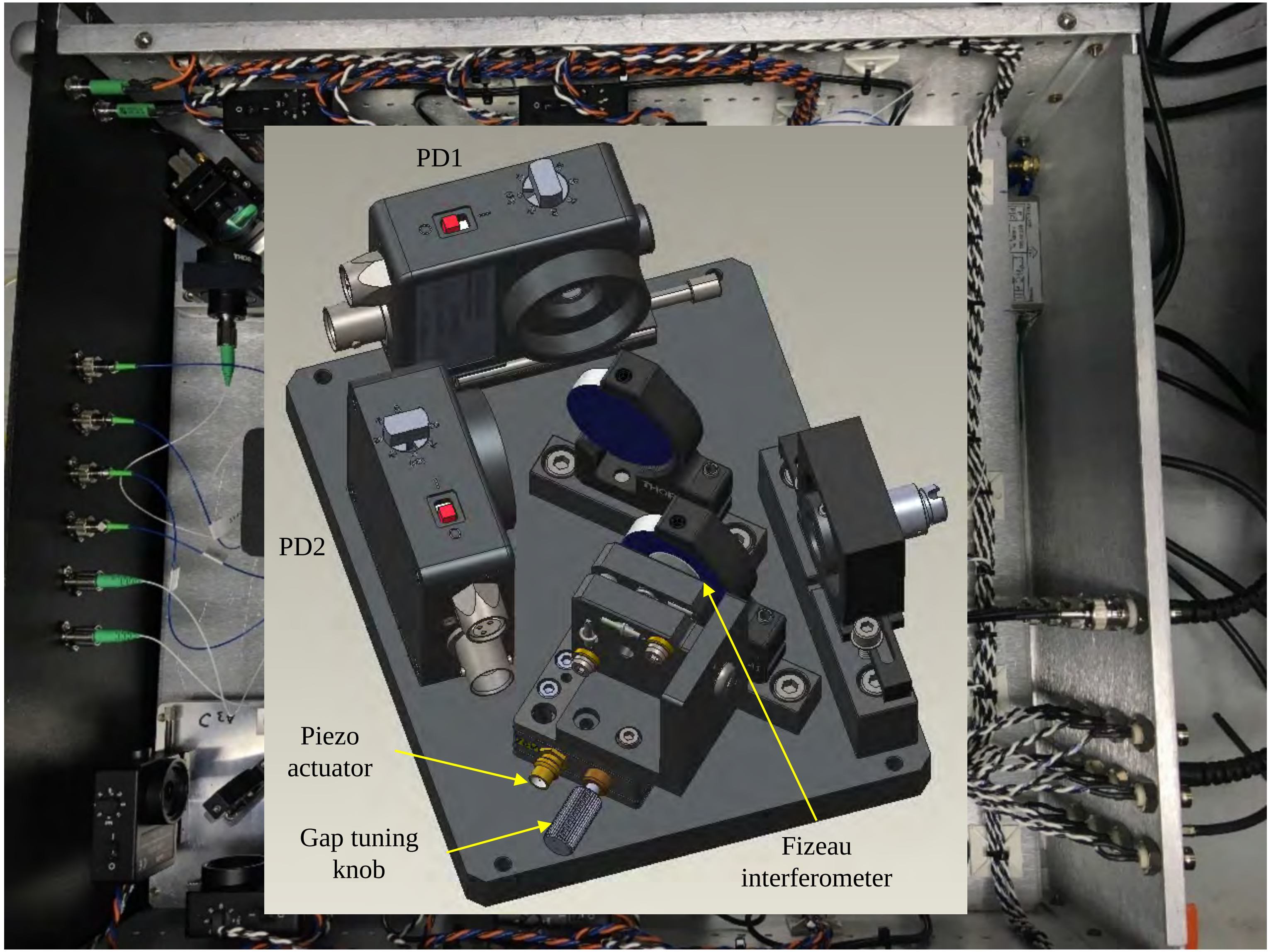


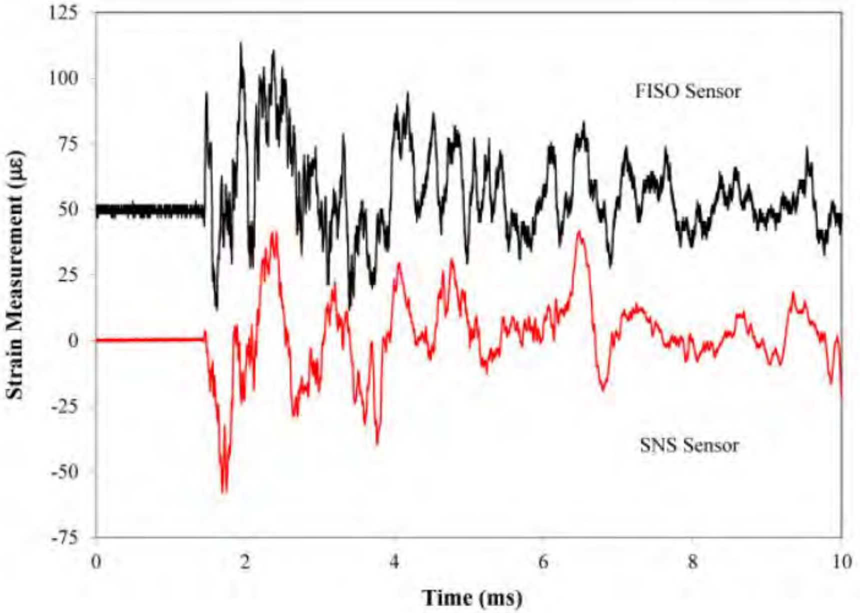
Signal interrogation – low-coherence interferometry



Y. Liu et al. "Radiation-Resistant Fiber Optic Strain Sensors for SNS Target Instrumentation", Proceedings of IPAC2016, Vol. 21, NO 23, 2021

Signal interrogation – optical setup





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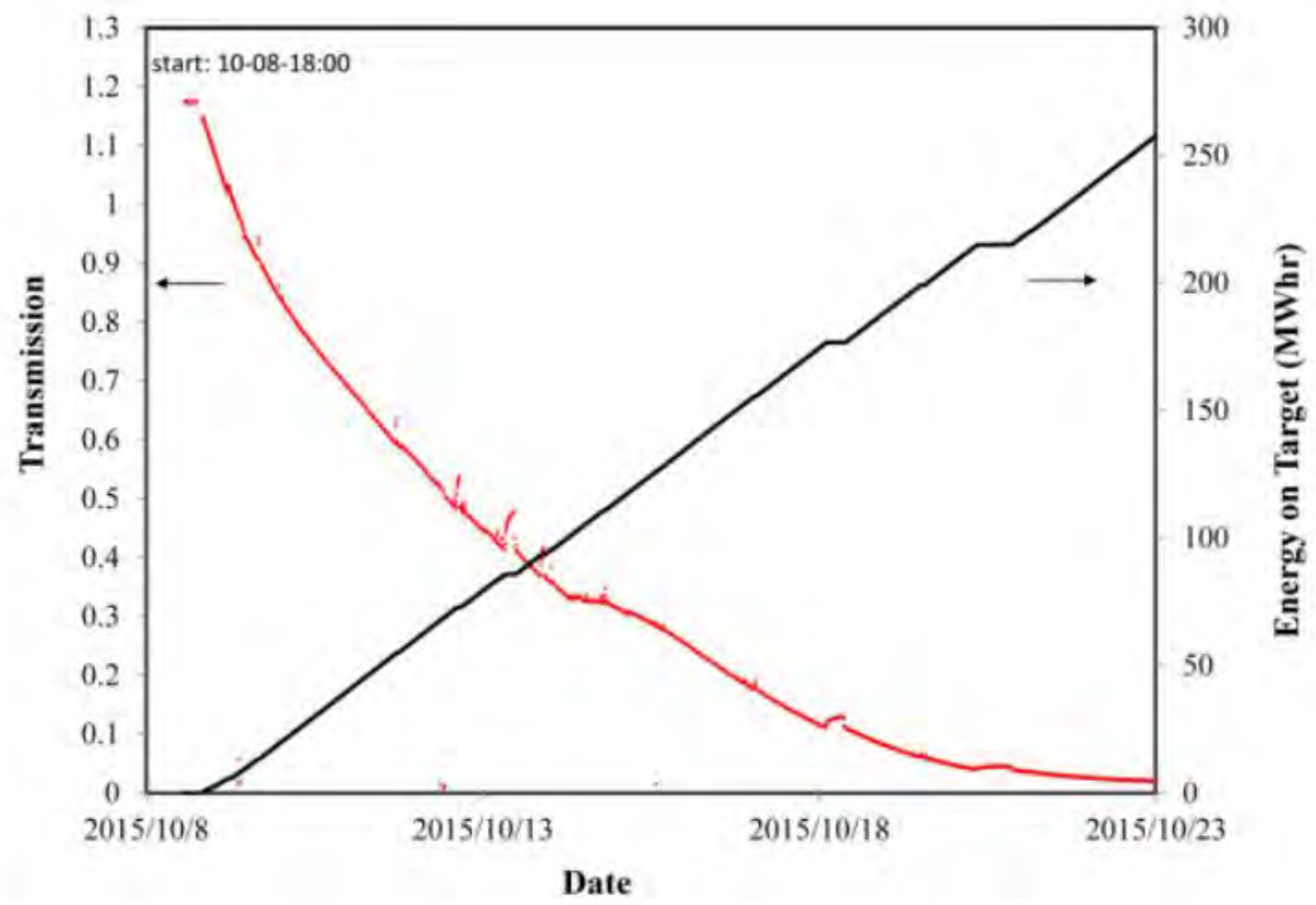
Y. Liu et al. "Radiation-Resistant Fiber Optic Strain Sensors for SNS Target Instrumentation", Proceedings of IPAC2016, Vol. 21, NO 23, 2021

Transmission behavior vs radiation



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Upgraded Fiber-Optic Sensor System

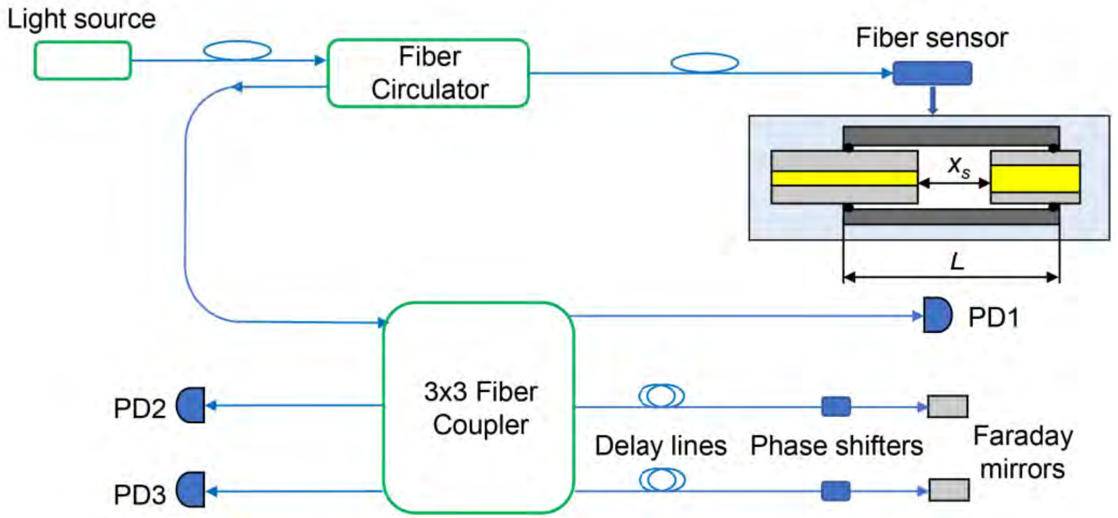

Fig. 1. Schematic of the fiber-optic sensor head and interrogator setup. PD: photodetector. Each sensor had a 2.5-m-long lead fiber with a polyimide coating, and the outer diameter of the coating was 250 μm. Inset box shows the sensing FP interferometer. x_S: sensor gap, L: sensor length.

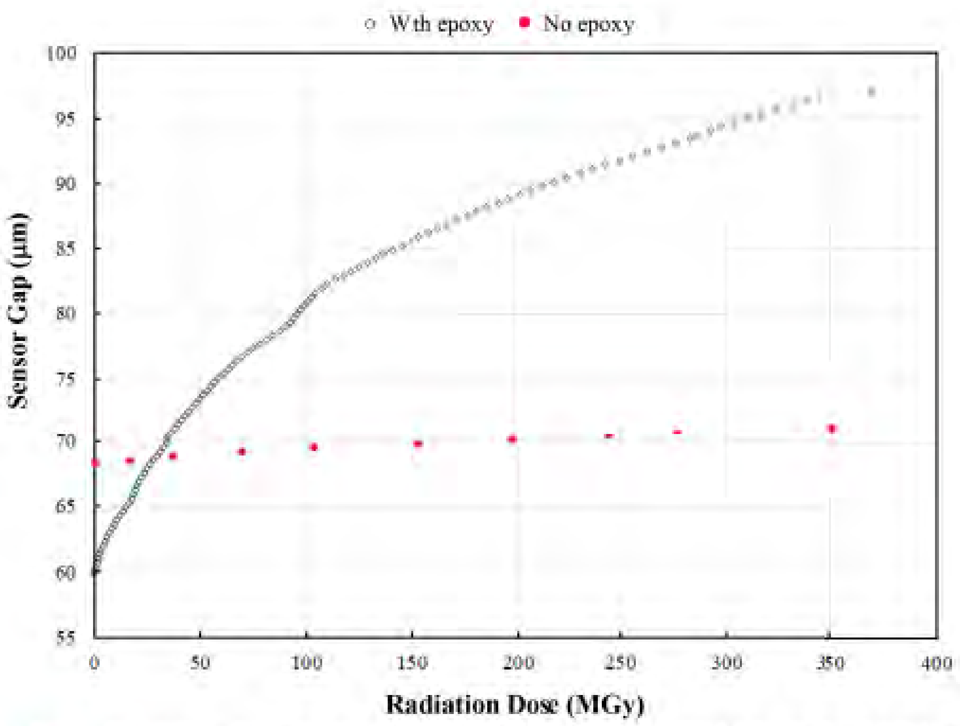

Fig. 16. Measured sensor gap variation as a function of the radiation dose on the sensor head. The increased gap growth is due to the radiation-induced volume expansion of the epoxy.

Y. Liu et al. "Upgraded Fiber-Optic Sensor System for Dynamic Strain Measurement in Spallation Neutron Source", IEEE Sensors Journal, Vol. 21, NO 23, 2021

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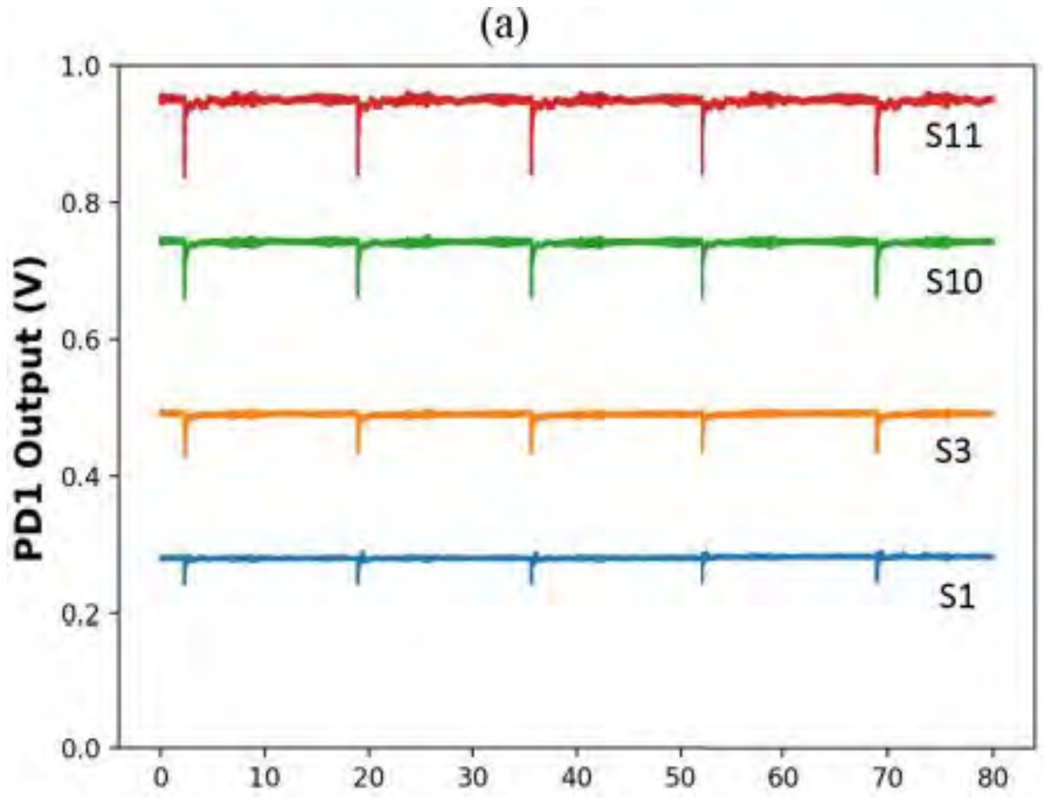
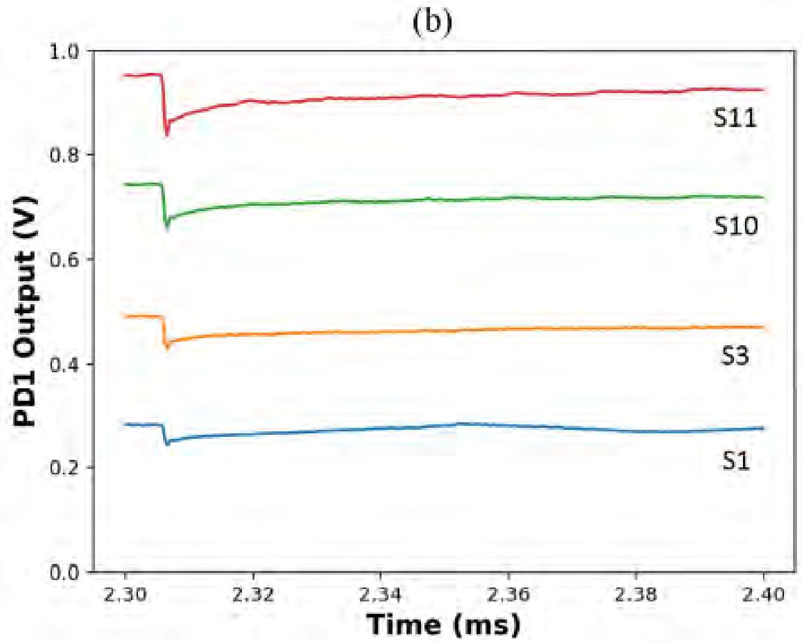
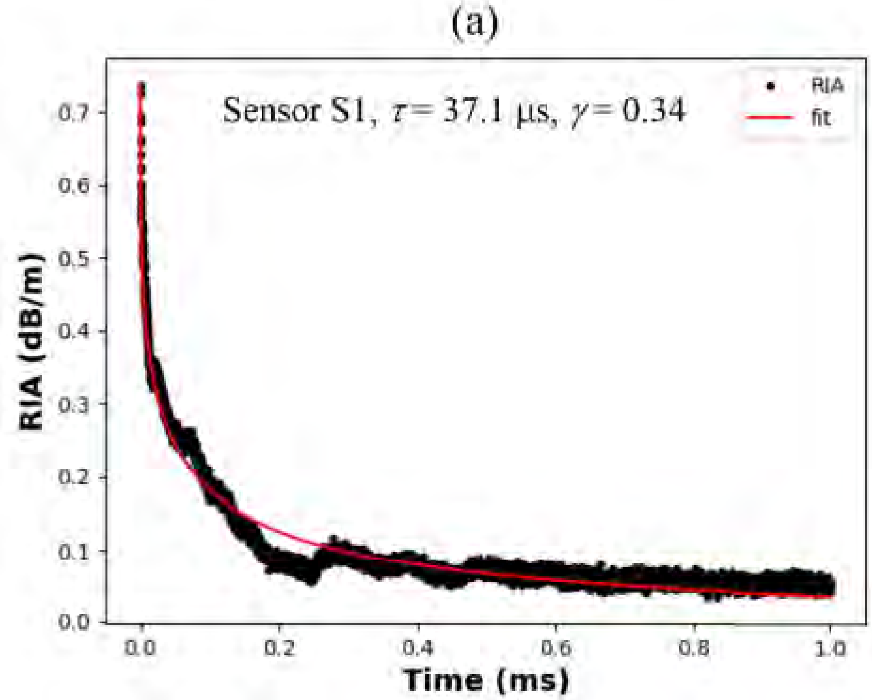
Initial PD Raw Signal







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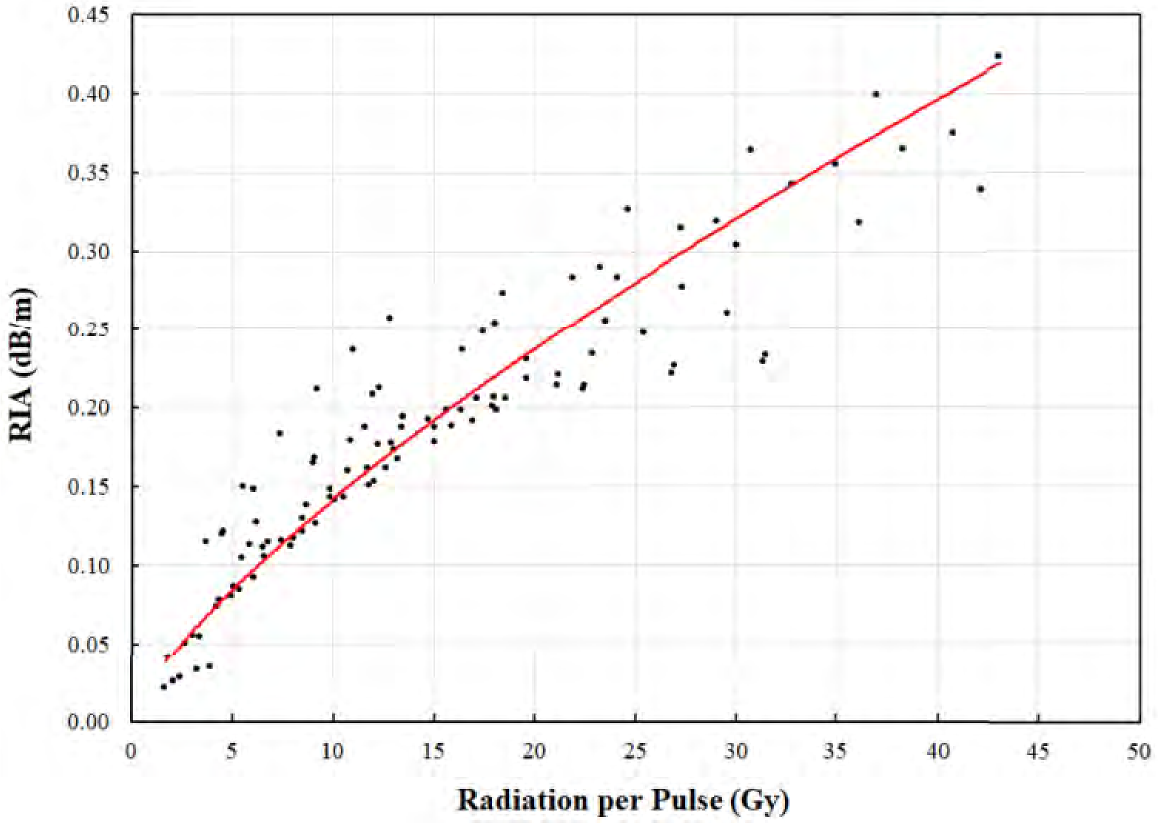
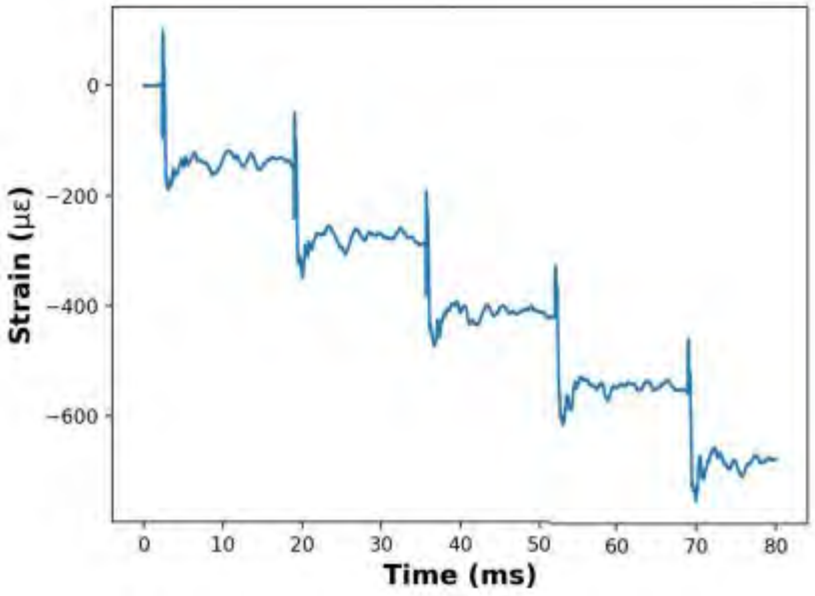
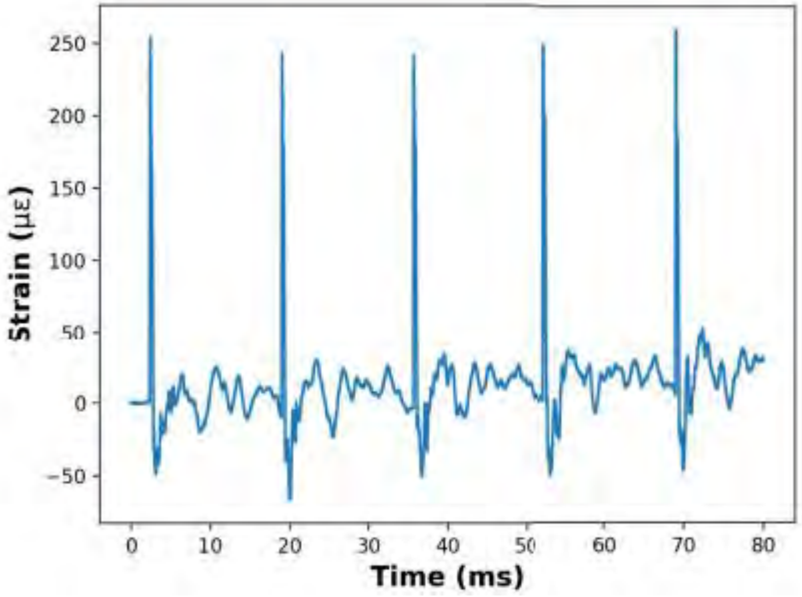
Measurements Corrections

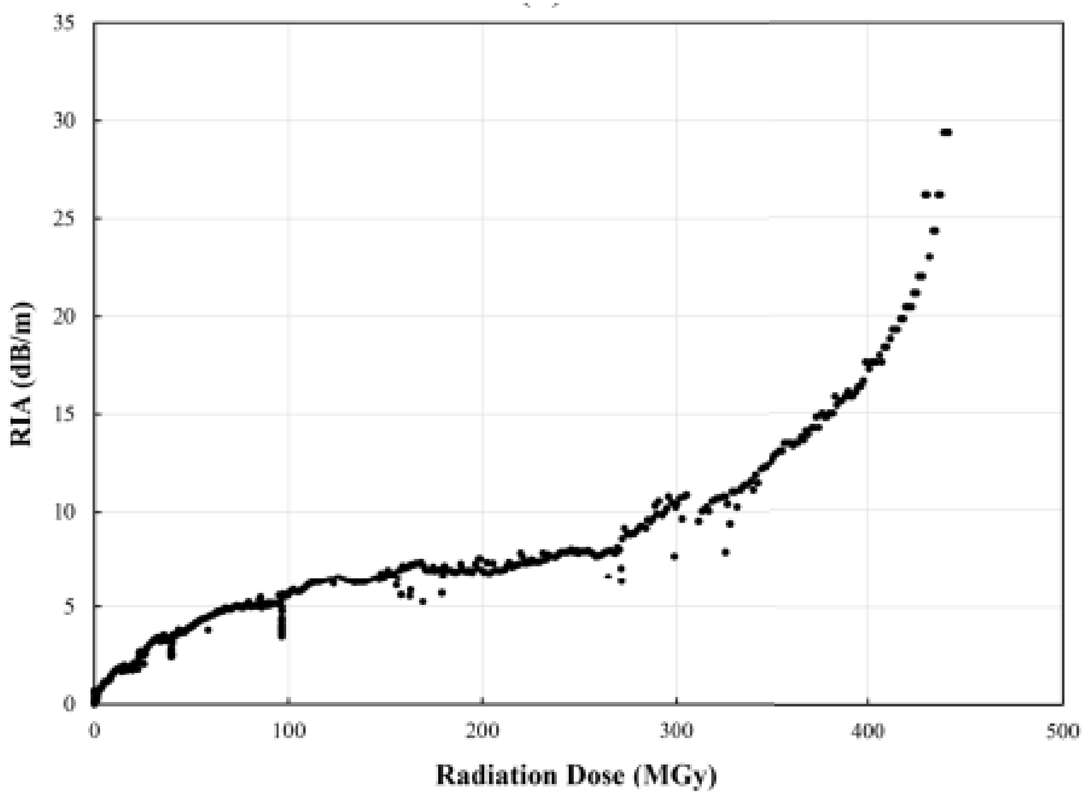




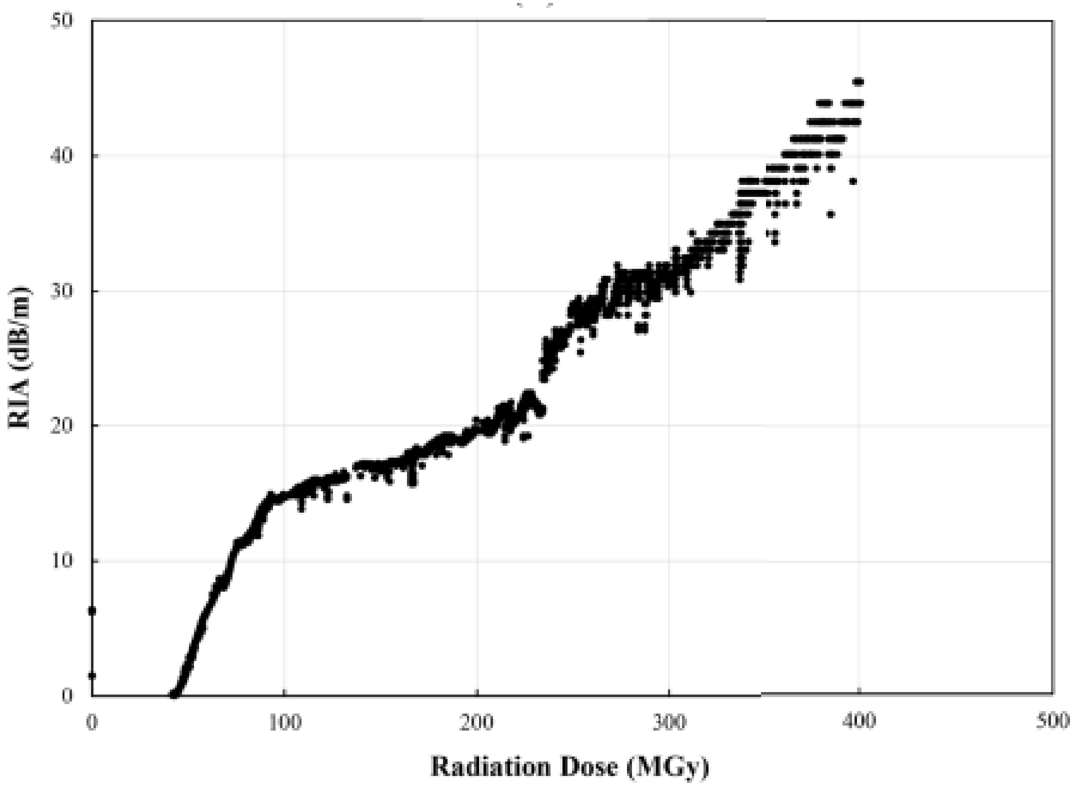


Y. Liu et al. "Upgraded Fiber-Optic Sensor System for Dynamic Strain Measurement in Spallation Neutron Source", IEEE Sensors Journal, Vol. 21, NO 23, 2021

Radiation-Induced-Attenuation vs Radiation



Sensor located in high radiation zone (front of target)

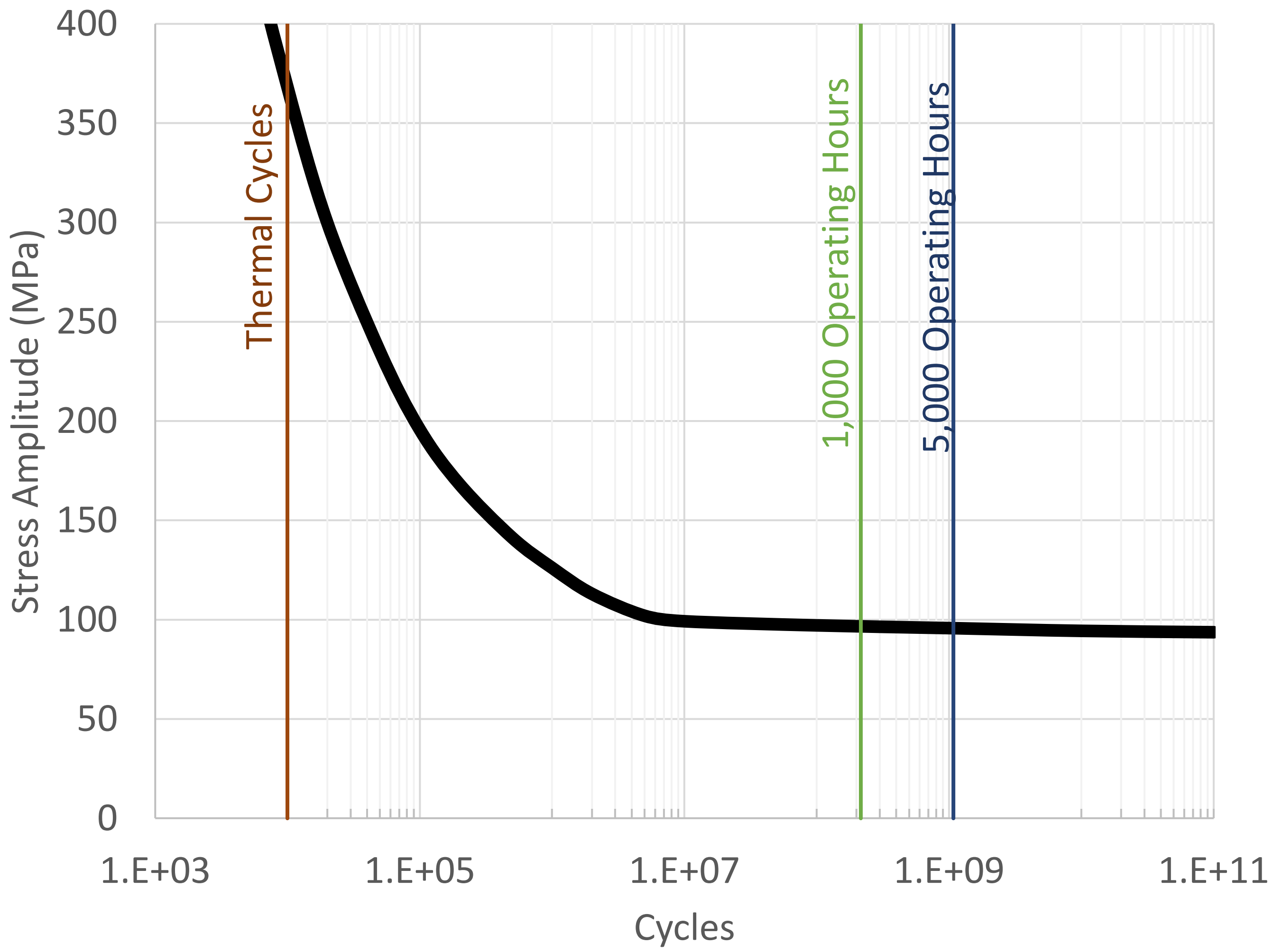


Sensor located in moderated radiation zone (back of target)

Y. Liu et al. “Upgraded Fiber-Optic Sensor System for Dynamic Strain Measurement in Spallation Neutron Source”, IEEE Sensors Journal, Vol. 21, NO 23, 2021

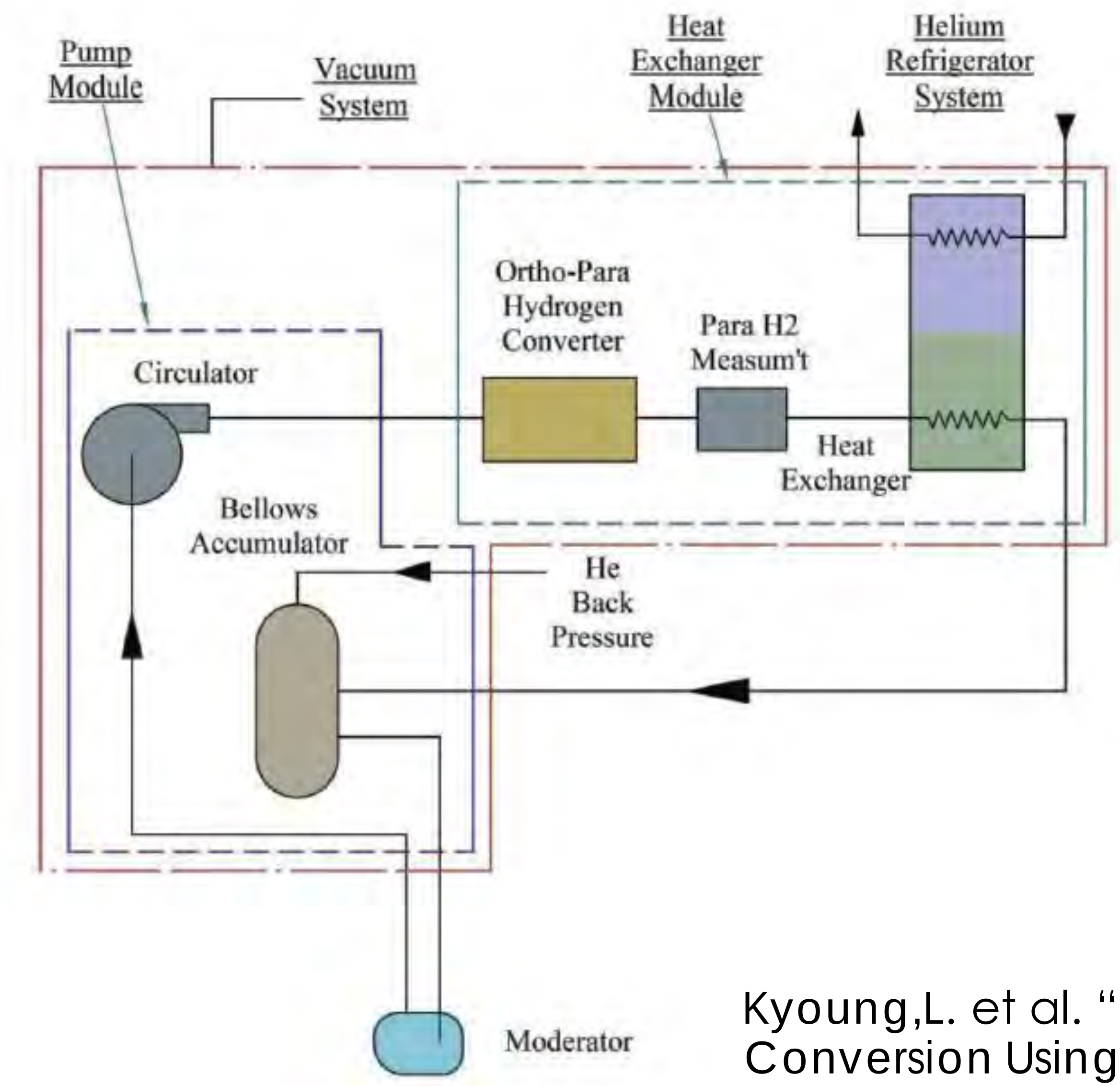
What does the strain reduction mean to target longevity?

- Reduced stress means longer fatigue life
- Complicated by
  - Cavitation damage
  - Cracks and wear in target
  - Combined pulse and thermal stress cycles

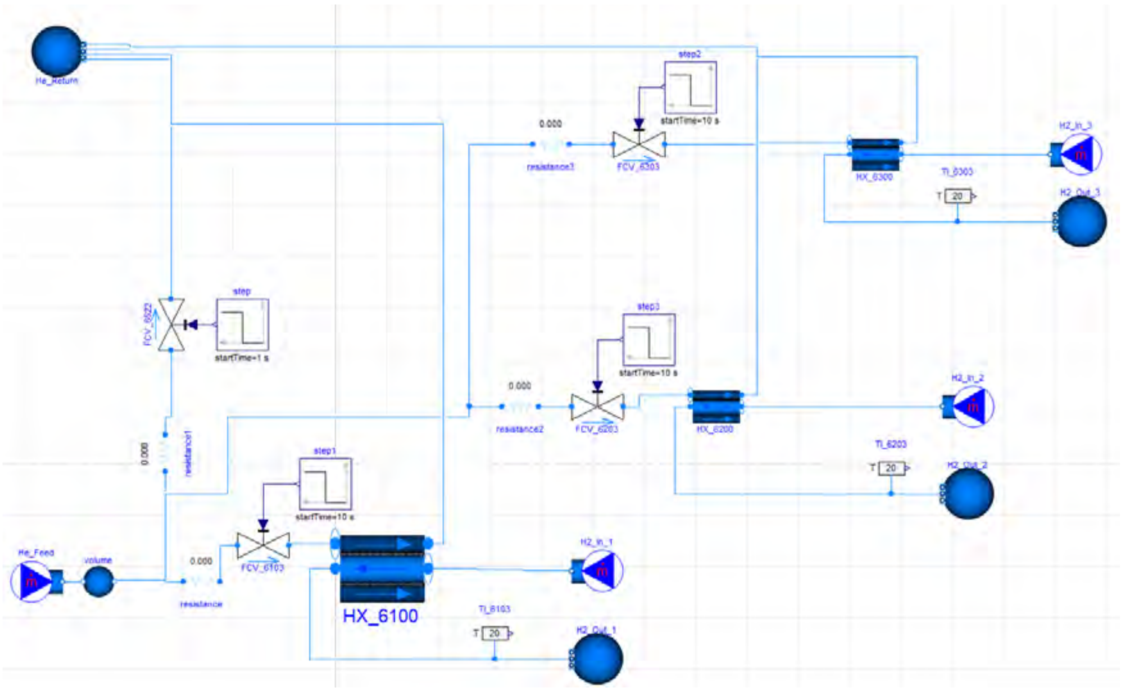


Stainless Steel Fatigue Curve

Potential Application to Cryogenic Systems: CMS Conceptual simplified system

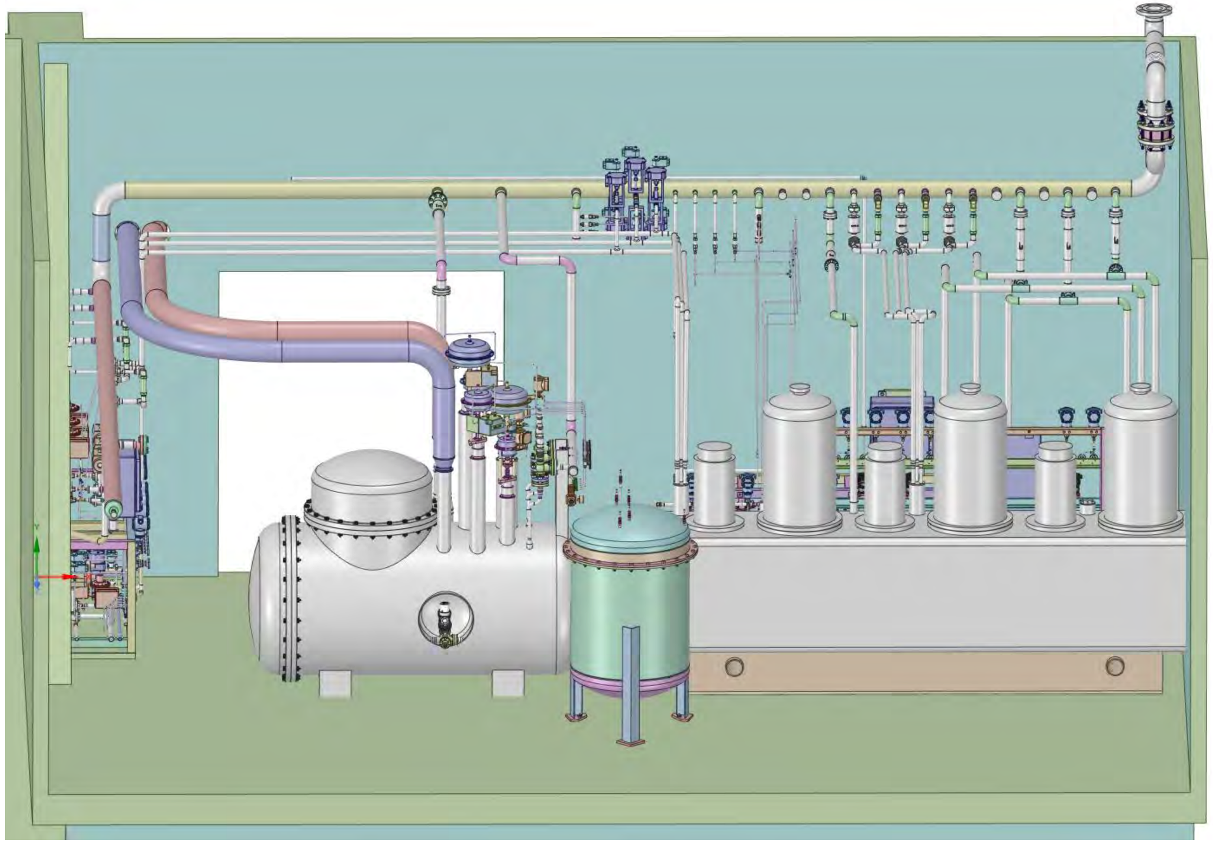


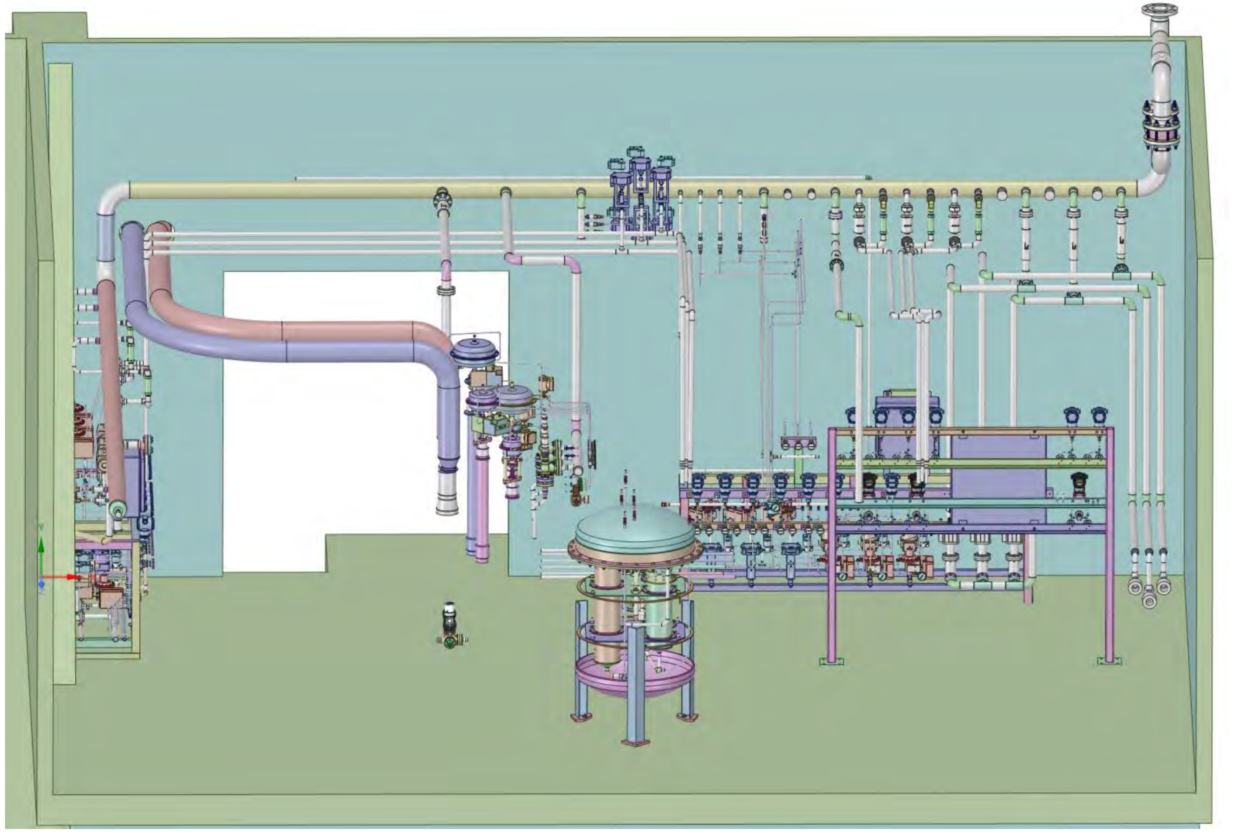
Digital Twin of CMS Helium Heat Exchanger System



Kyoung,L. et al. "Engineering Scale Simulation of Ortho-Para Hydrogen Conversion Using Hydrogen Analysis Runtime Environment (HARE) in the Moose Fraamework", Proceedings of ICAPP, paper:2023333, April 2023

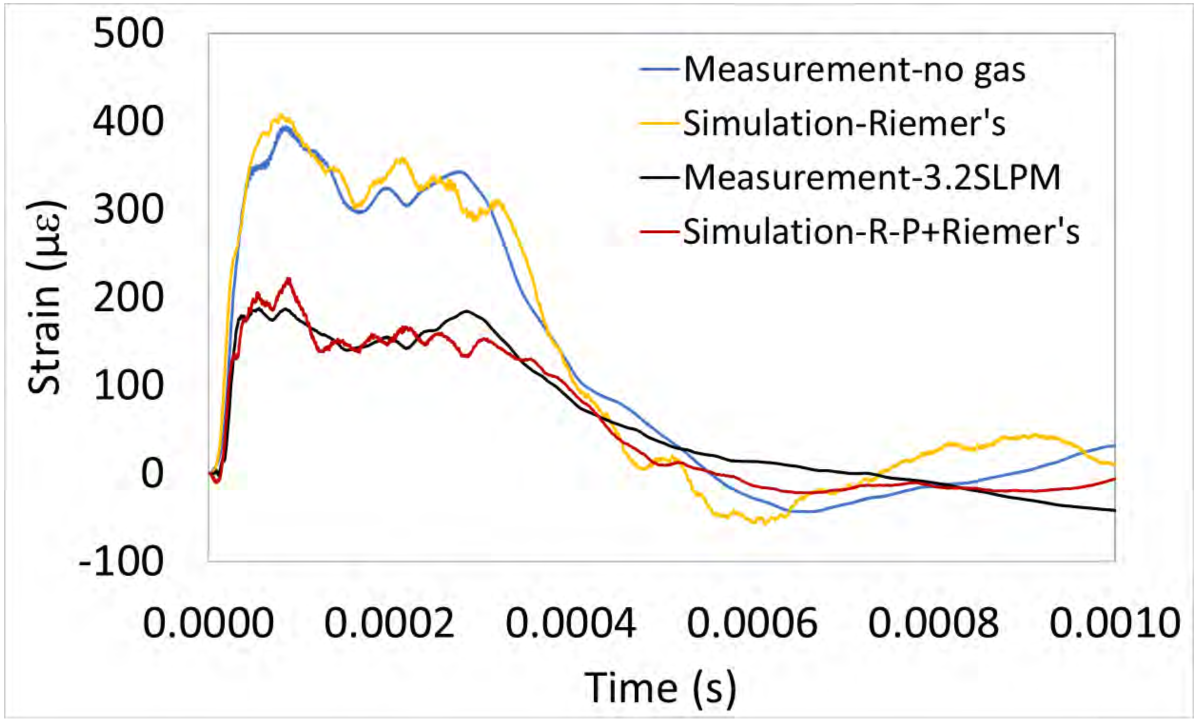
H2 Room

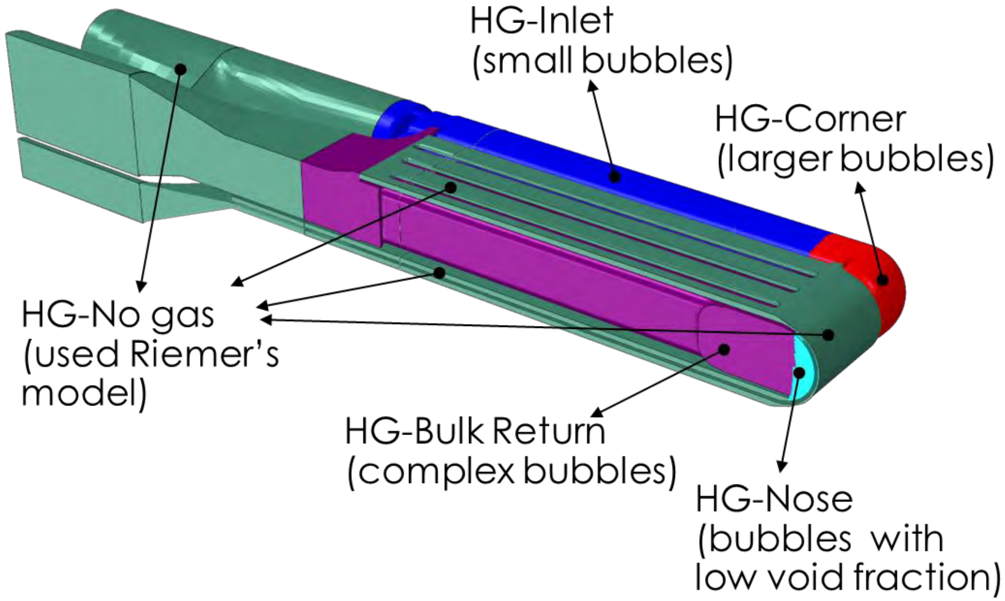




V&V of strain prediction with gas injection

A new simulation technique was developed to predict strain response of target with gas injection





FEA Lagrangian approach using RP equations to account for gas phase

Oak Ridge National Laboratory

Hao Jiang *, Drew E. Winder, Charlotte Barbier, Bernard W. Riemer, **Implementing mercury bubble material model in the pulse simulation to predict strain on the Spallation Neutron Source target vessel with gas injection,** Submitted

Summary

- The ORNL's SNS has tested various optical sensors for the last 7+ years
  - Commercial
  - In-house development
- Fiber materials have proven to be a limitation for long term harsh environments, such as high-power targets
- The single point strain measurement sensor systems developed at the SNS provide a customized high sampling rate and radiation resistance solution for target strain measurements
- SNS's data on RIA is available in the literature for pulsed sources with radiation levels as high as 10E9 Gy

Acknowledgement

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Questions?

Thank you !

dominguezoee@ornl.gov

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