Development of High-Radiation-Tolerant Fiber-Optic Sensors for SNS Mercury Target Strain Measurement

Yun Liu on behalf of SNS target strain sensor team

7th High Power Targetry Workshop
June 4-8, 2018

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

OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

Outline

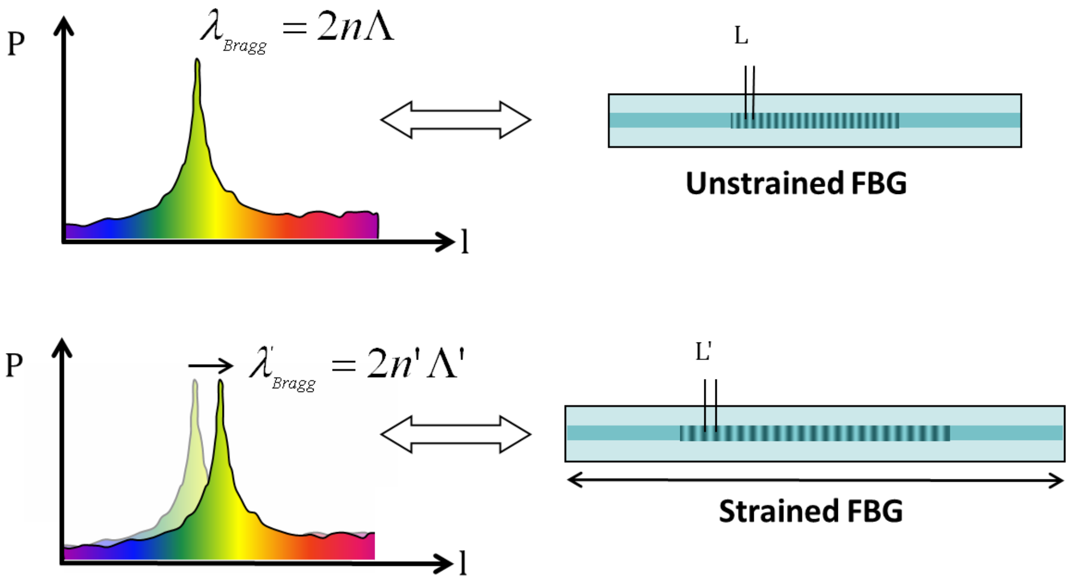
- Background and motivation
- Sensor Instrumentation
  - Sensor type
  - Fiber type
  - Phase interrogation setup
  - Data acquisition
- Strain Measurement Performance
  - Laboratory test of static and dynamic strains
  - Strain measurement in the SNS target module
  - Issues and mitigation methods
- Conclusion and future work

Challenges of strain measurement in pulsed targets: *Findings from the SNS mercury target vessel*

- Fiber-optic strain sensors have been used to measure the dynamic strain waveforms on the mercury target vessel
  - Commercial sensors only lasted a few tens of pulses
  - Even high-OH fiber sensors have limited lifetime
- Challenges
  - High radiation - > 10^9 Gy radiation level due to protons, neutrons, and high energy photons
  - High bandwidth – high intensity particle beam induces fast dynamic strain pulses which require mega-hertz measurement bandwidth

Goal - Development of high-radiation-tolerance, high-bandwidth, high-reliability fiber-optic sensors through optimization of sensor configuration, fiber, and processor.

Fiber-Optic Strain Sensor

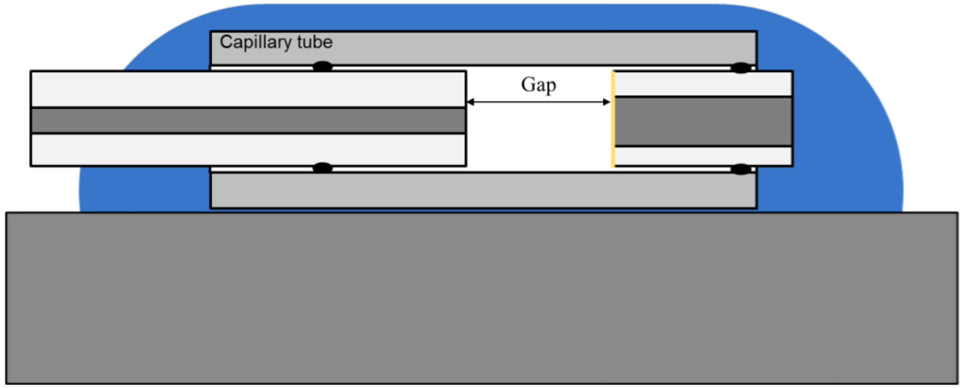


Fiber Bragg grating (FBG) based sensors

- Well developed fabrication technology
- Fiber sensitive
- Radiation induced attenuation/grating bleach
- Measurement bandwidth

Interferometer based sensors

- High flexibility (any type of fiber)
- Interrogation setup easy to customize
- Radiation induced attenuation
- Measurement bandwidth



Optical Fiber Selection

Fiber Type
Pure silica fiber
Ge-doped fiber
High OH fiber
Hollow-core fiber
Fluorine-doped fiber

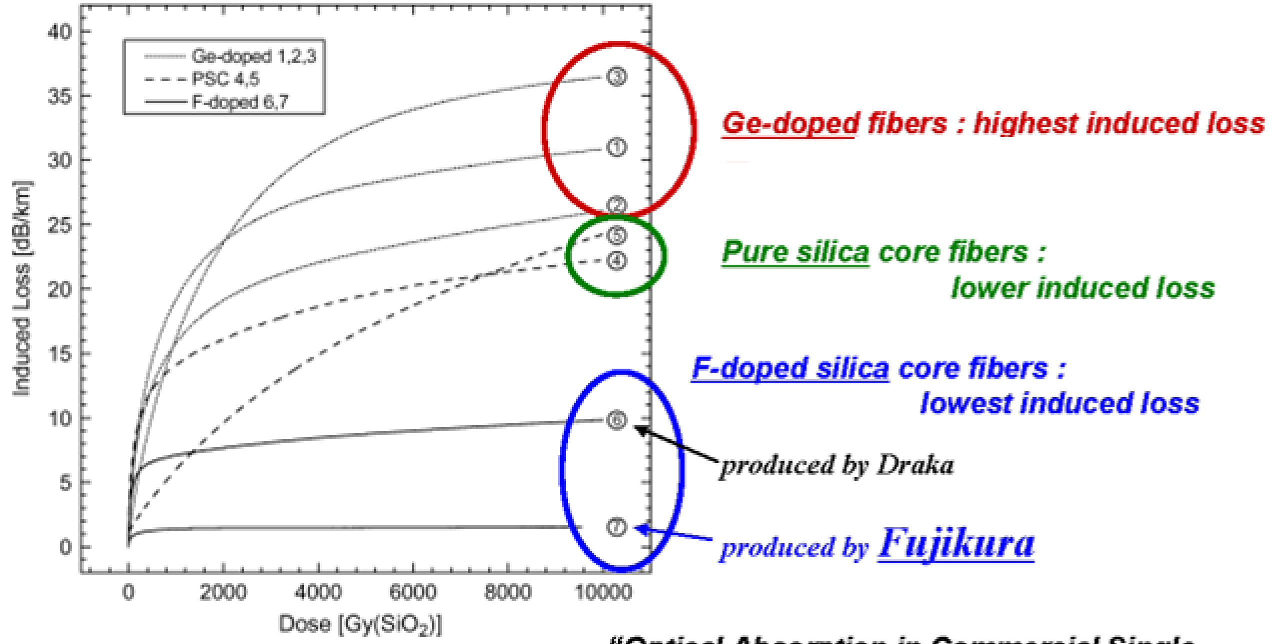


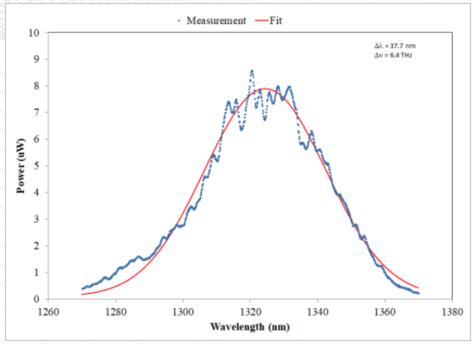
Fig. 5. RIA in the initial sample screening test (^{60}Co source).

Tests performed by Frunhofer Institute.

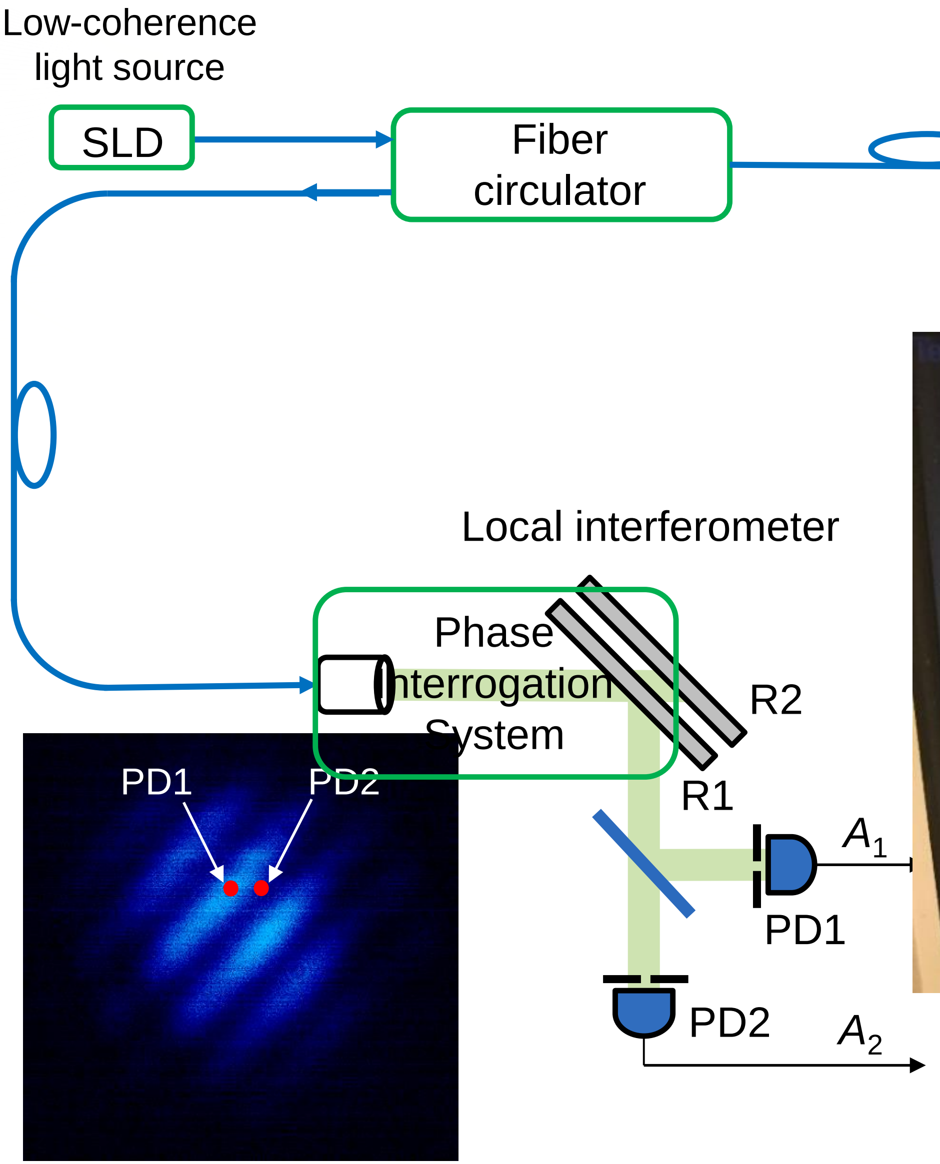
"Optical Absorption in Commercial Single Mode Optical Fibers in a High Energy Physics Radiation Field", Thijs Wijnands,et al., NUCLEAR SCIENCE, VOL. 55, NO. 4, AUGUST 2008

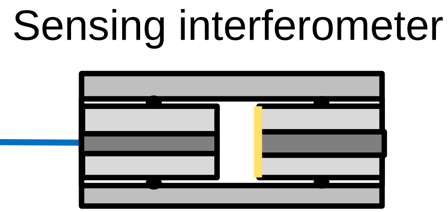
Our experiment verified that Fujikura (RRSMFB) fluorine-doped single-mode fiber shows extraordinary radiation resistance at 1300 nm.

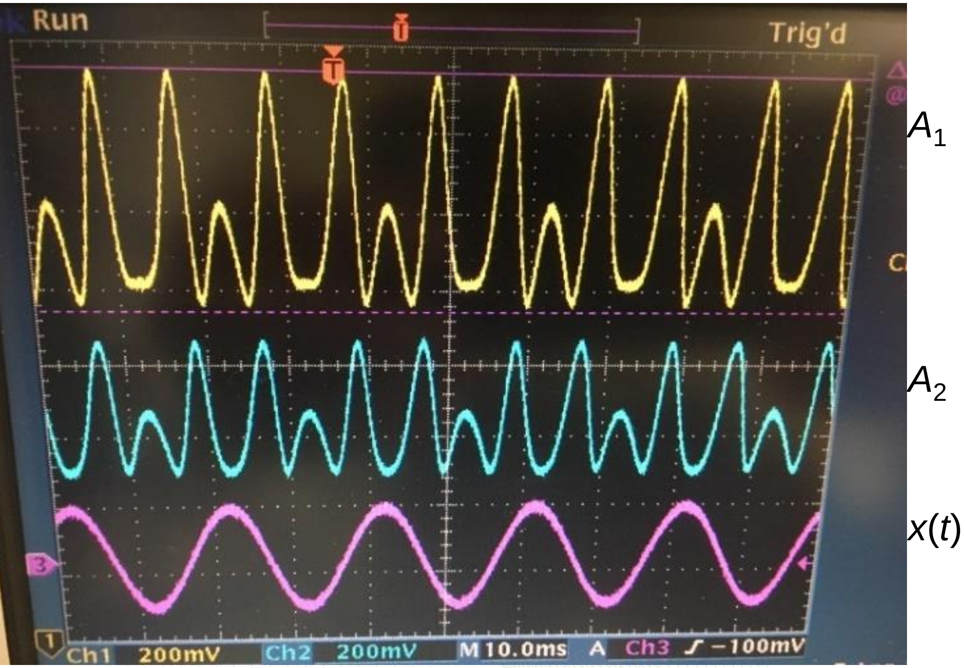
Phase Interrogation – Low-Coherence Interferometry



$\Delta\lambda \approx 38$ nm
$l_c \approx 31$ μm
$\tau_c \approx 0.11$ ps



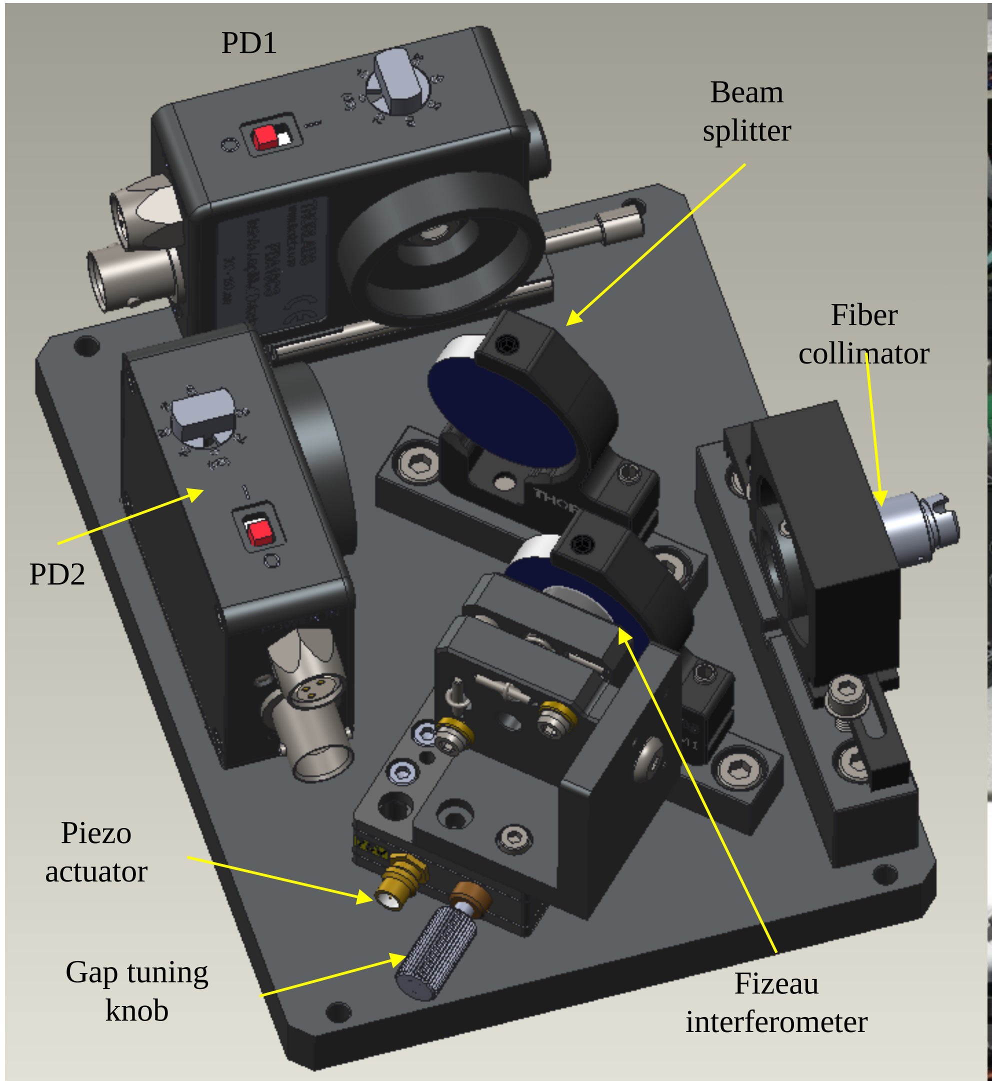


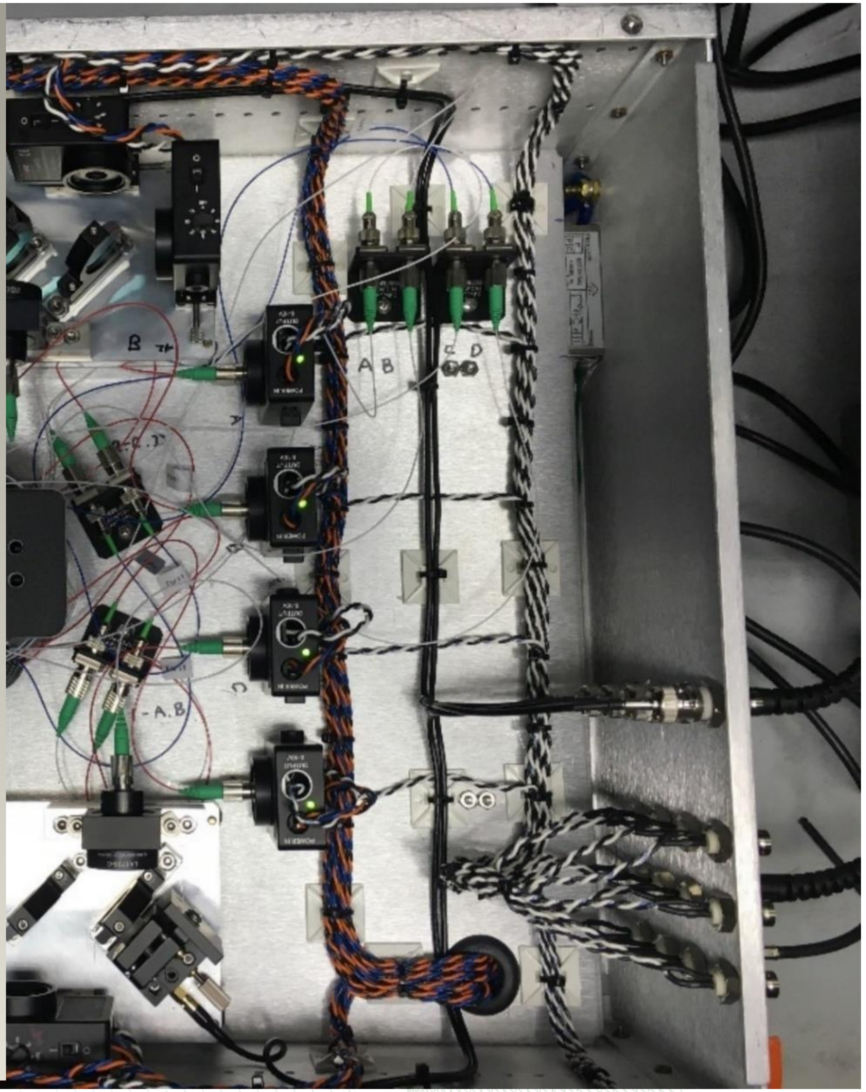


Y. Liu et al., *Opt. Commun*. **411** (2018) 27.

OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

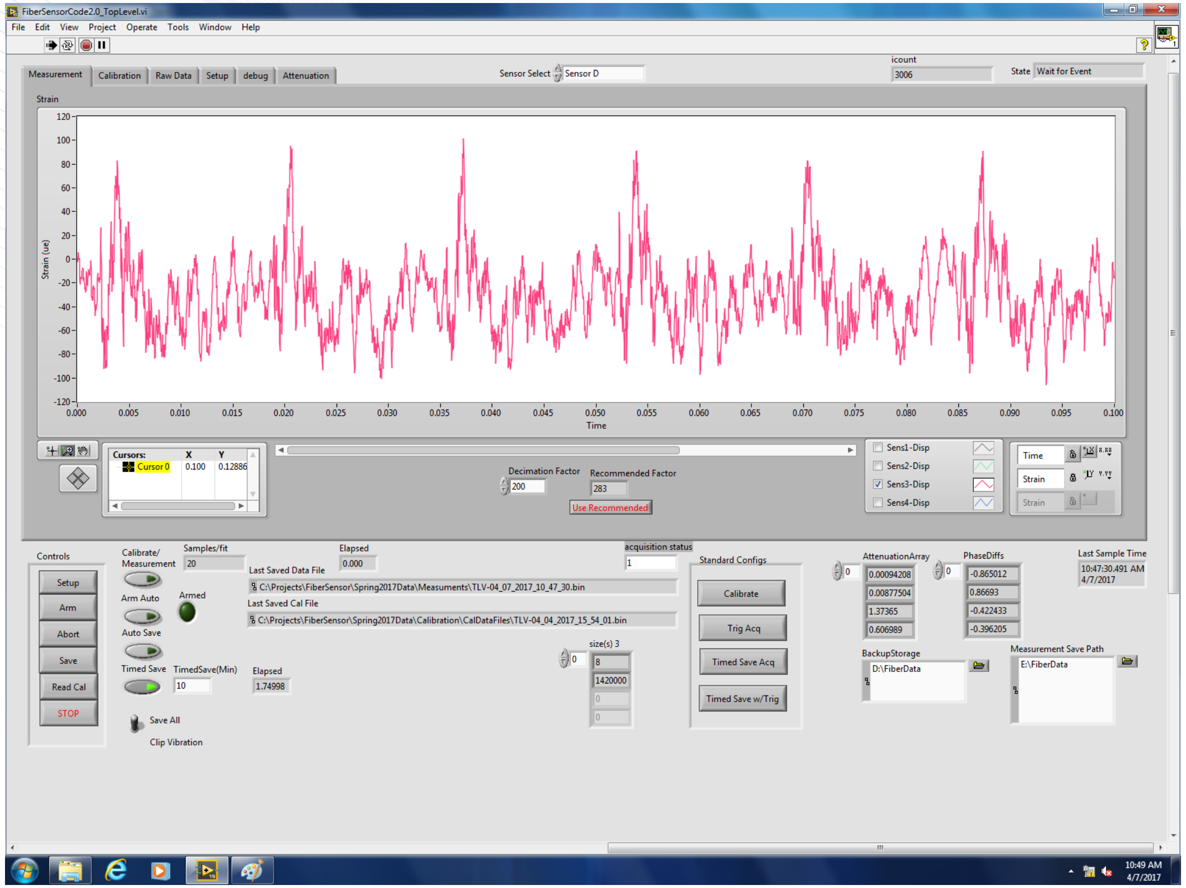
Optical Setup



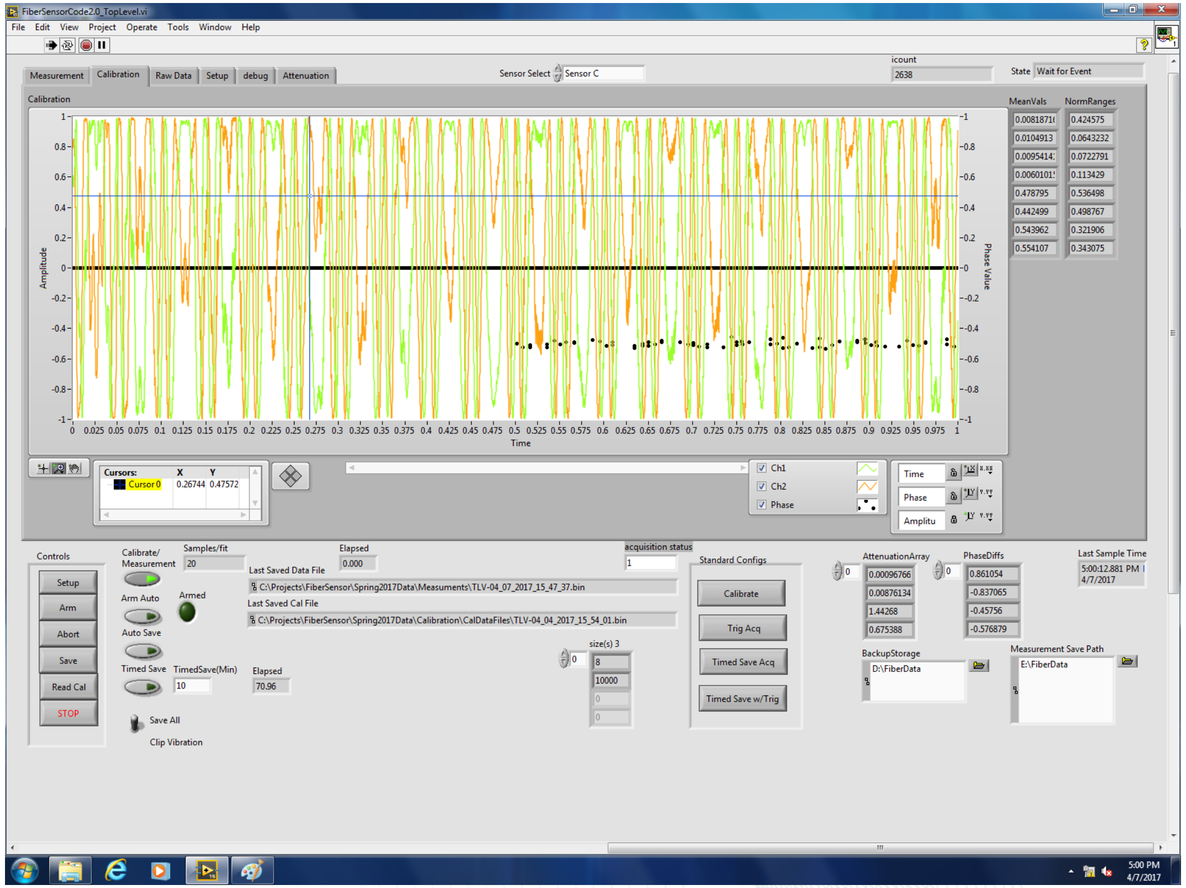


Data Acquisition and Software Platform

Strain Measurement



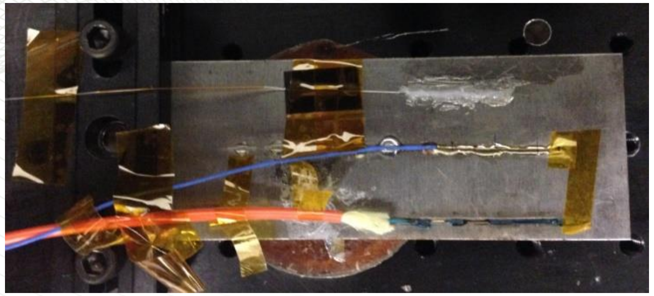
Phase Calibration



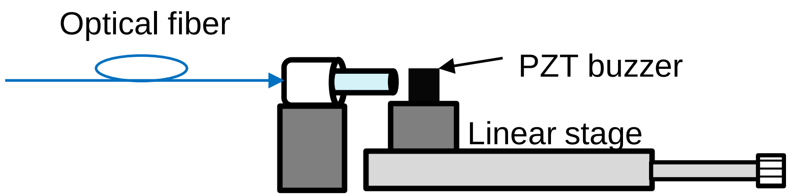
Sampling rate: 10 ~ 250 MHz
Measurement bandwidth: > 300 kHz

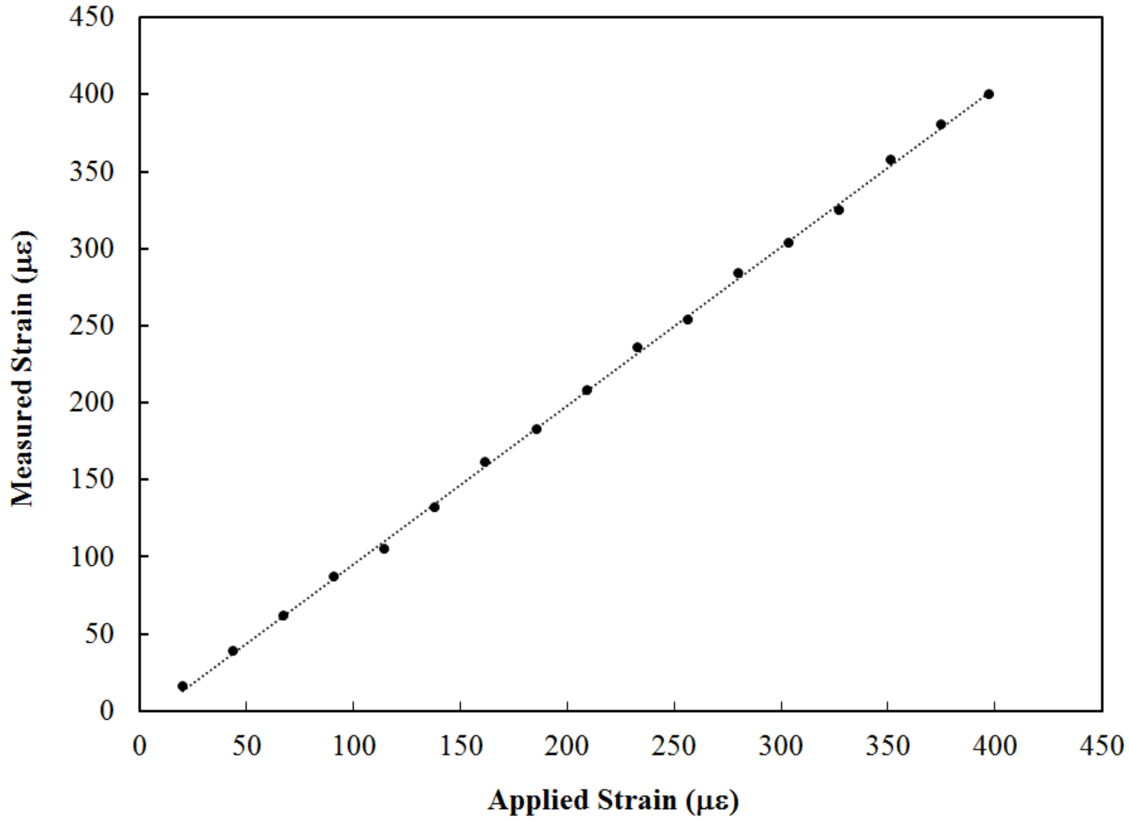
Measurement Performance – Laboratory Test

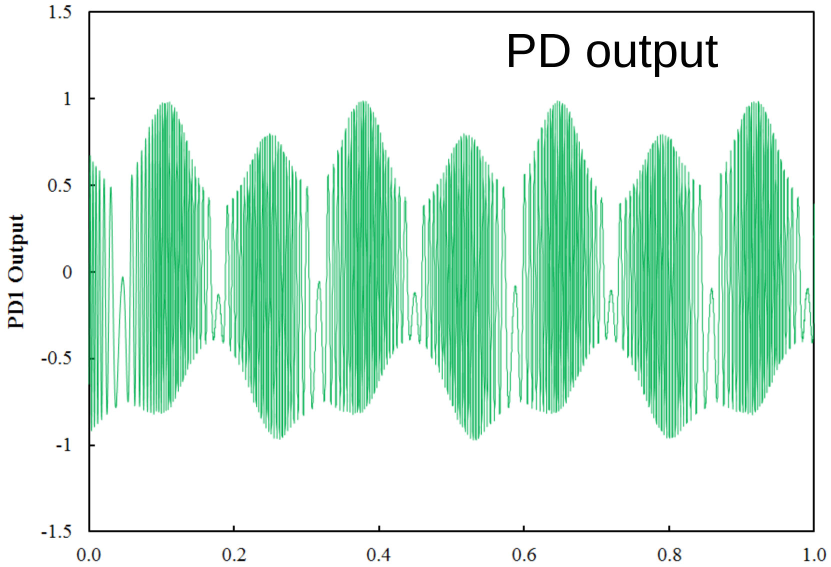
Strain test plate

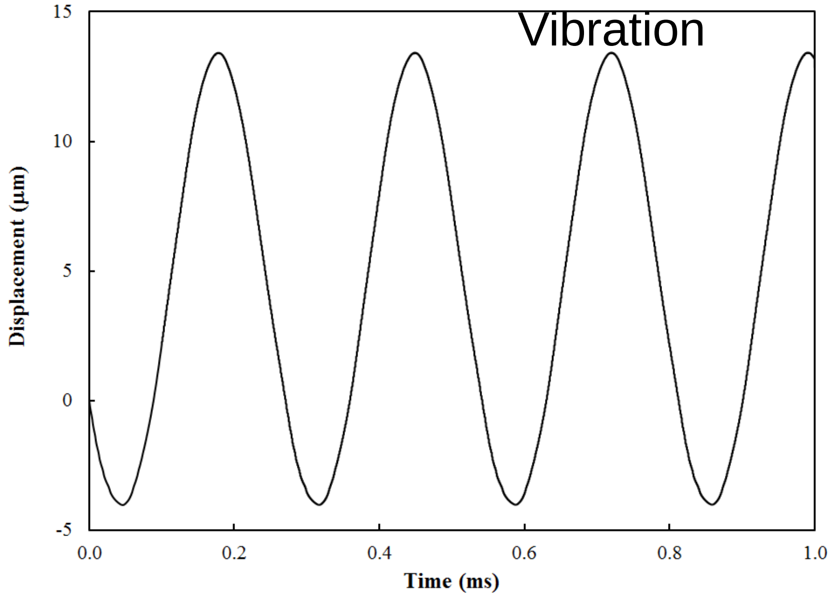


Vibration test setup

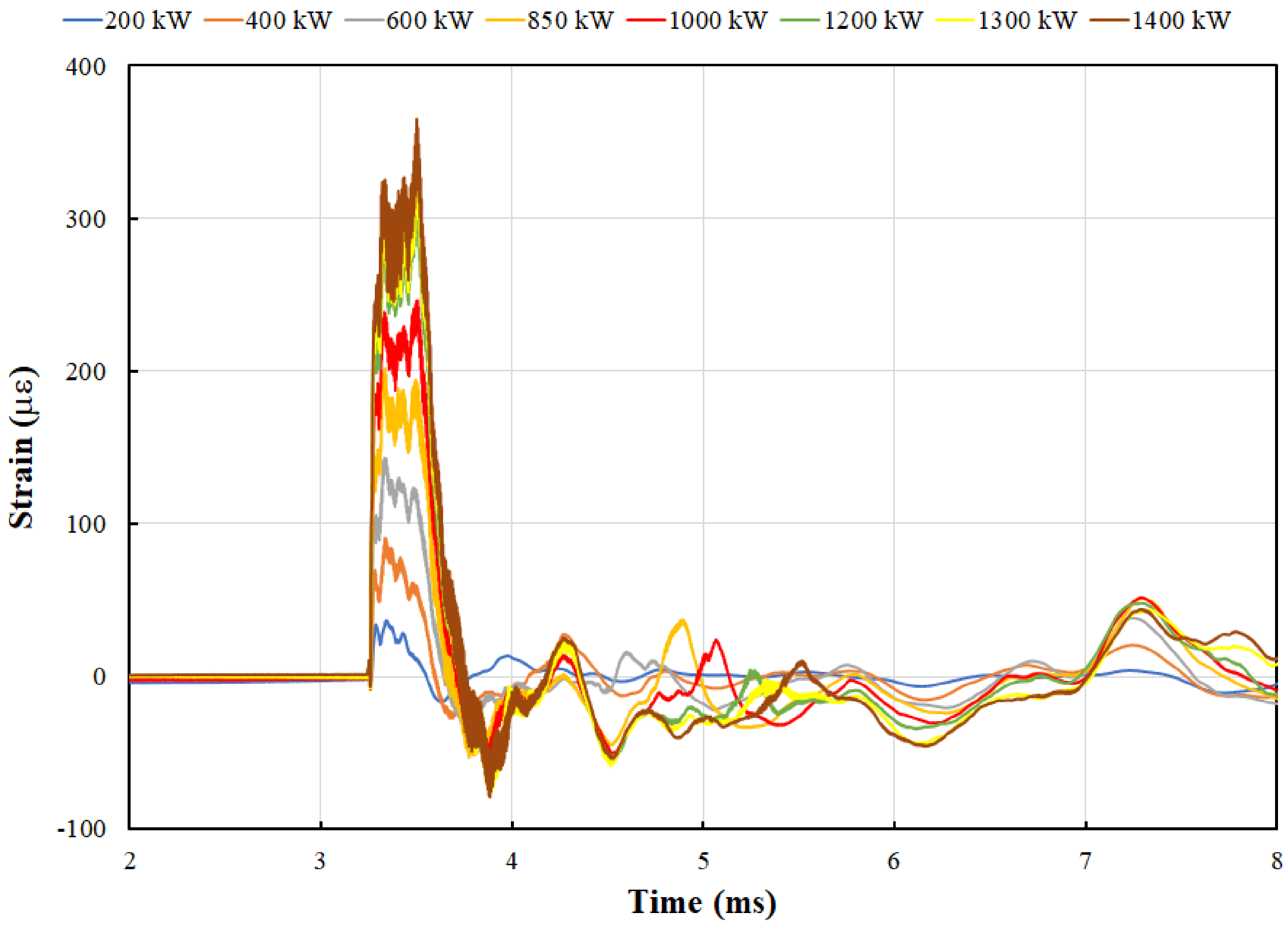


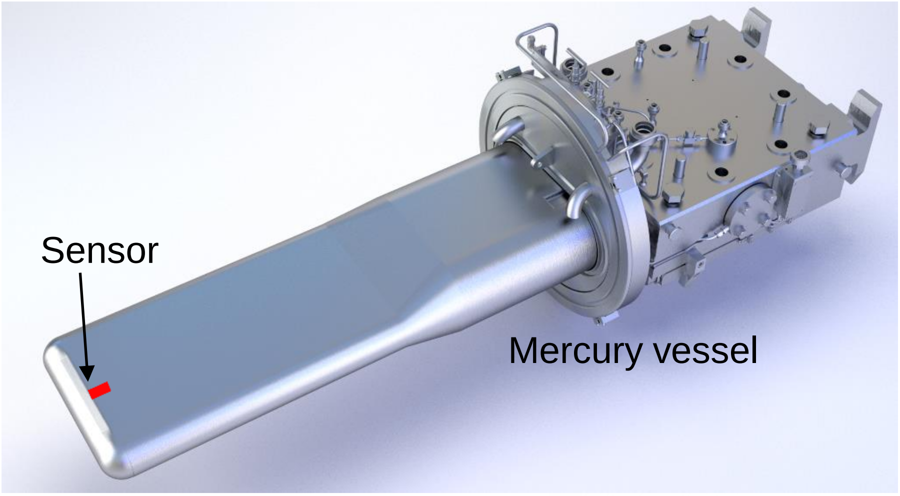


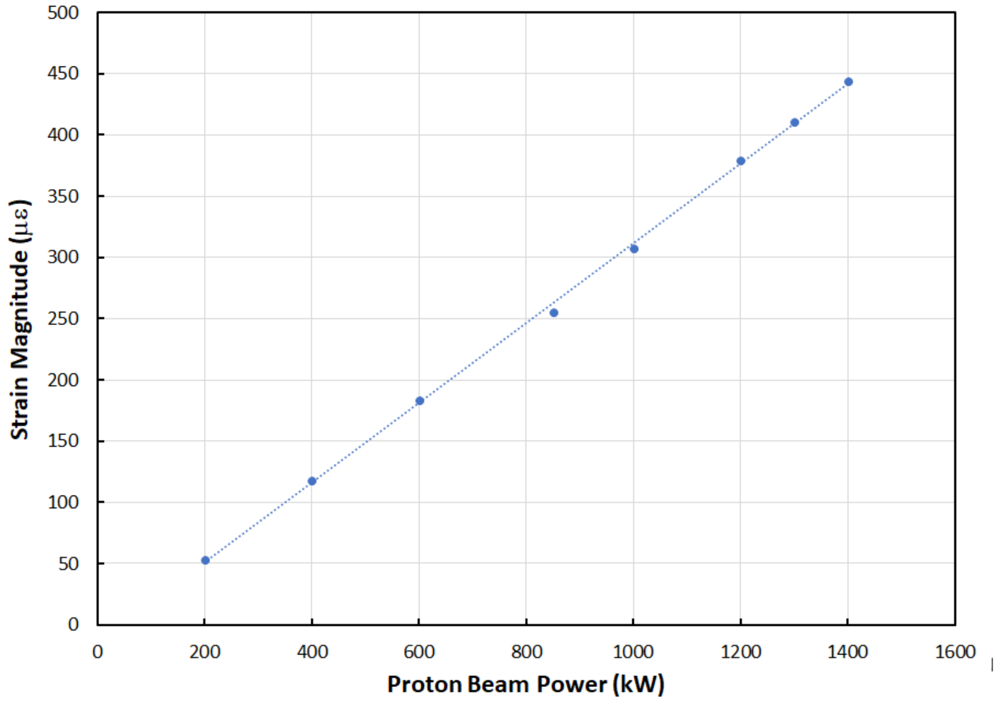




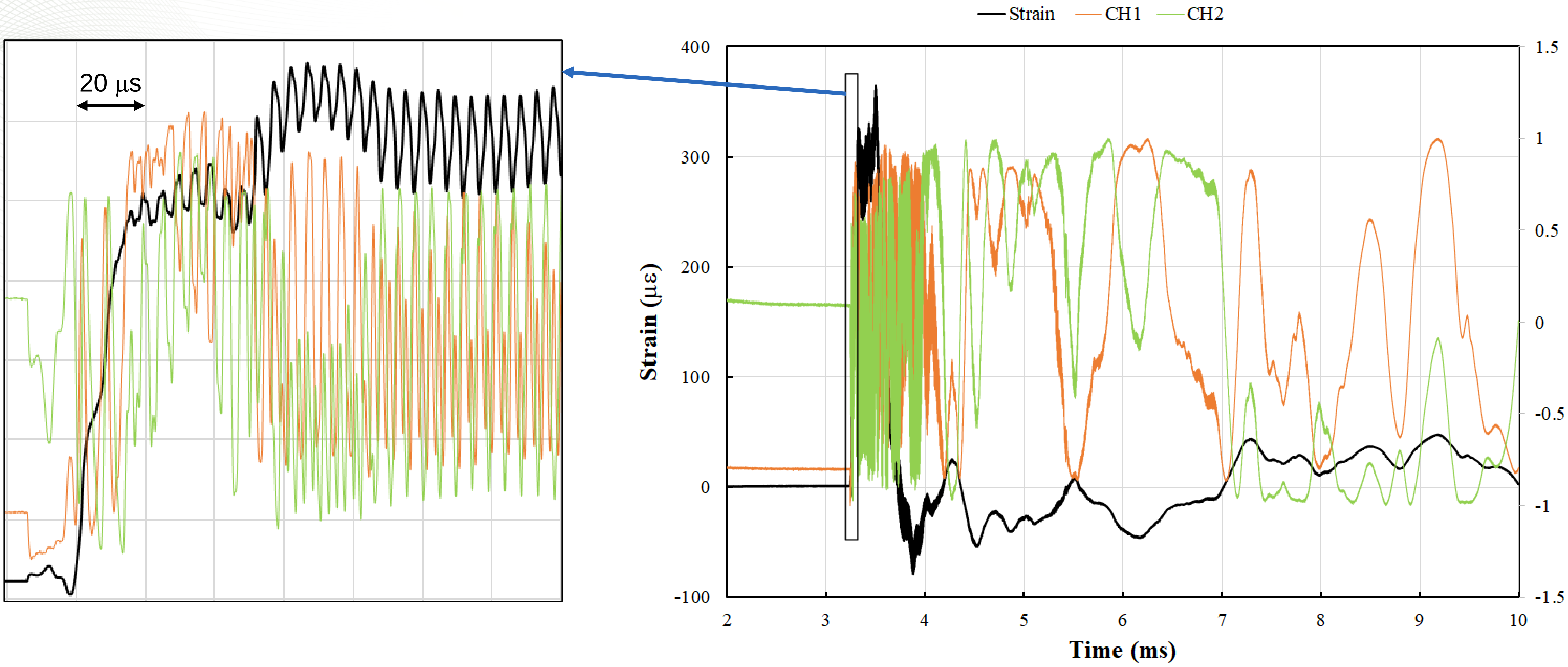
Measured Strain Waveforms







Strain Measurement Results



Radiation Induced Attenuation (RIA) and Sensor Lifetime

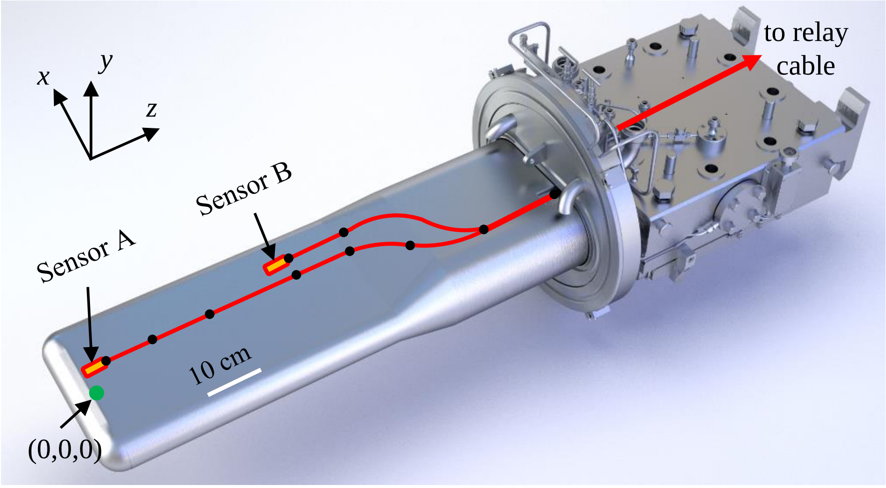
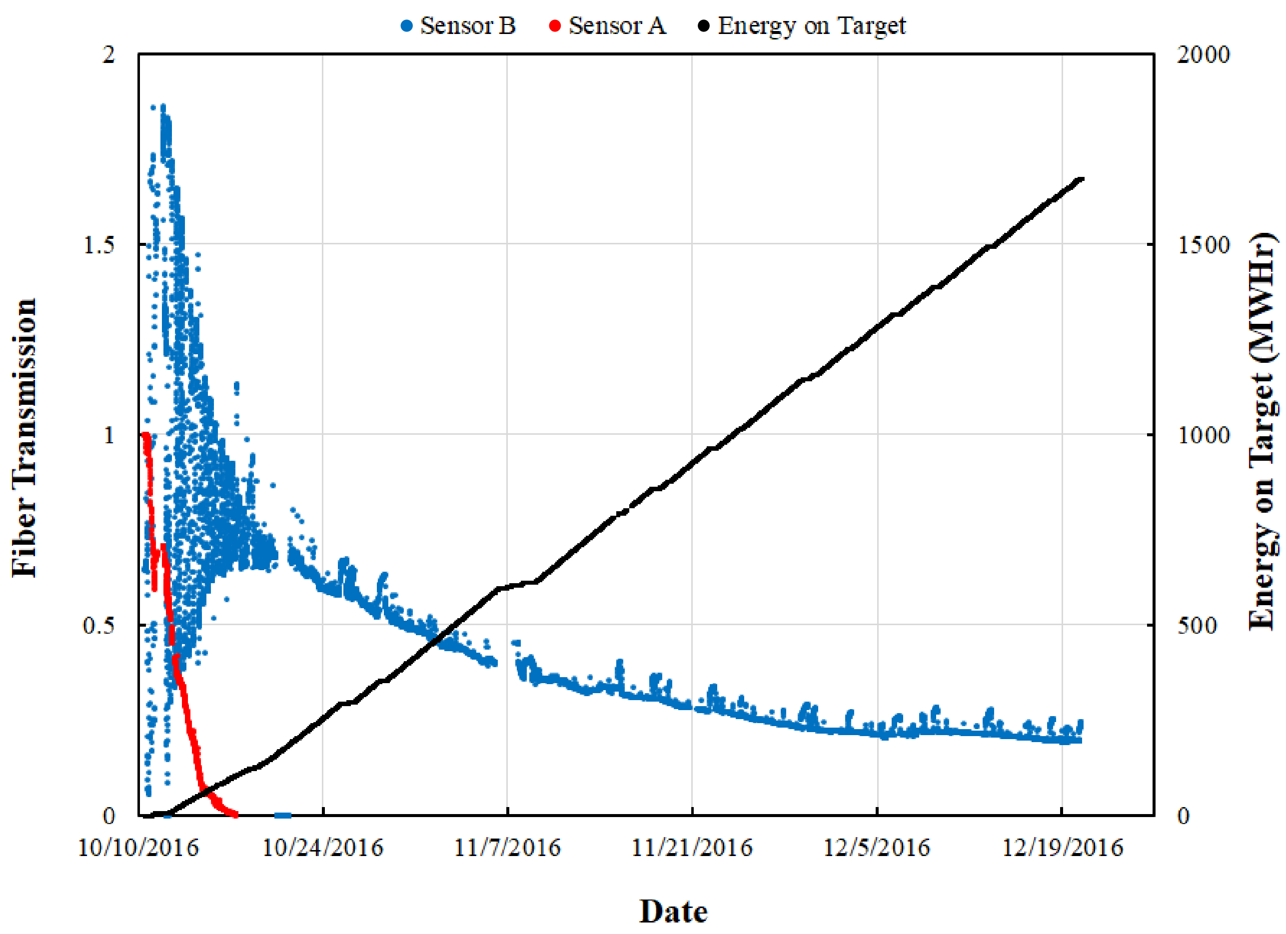
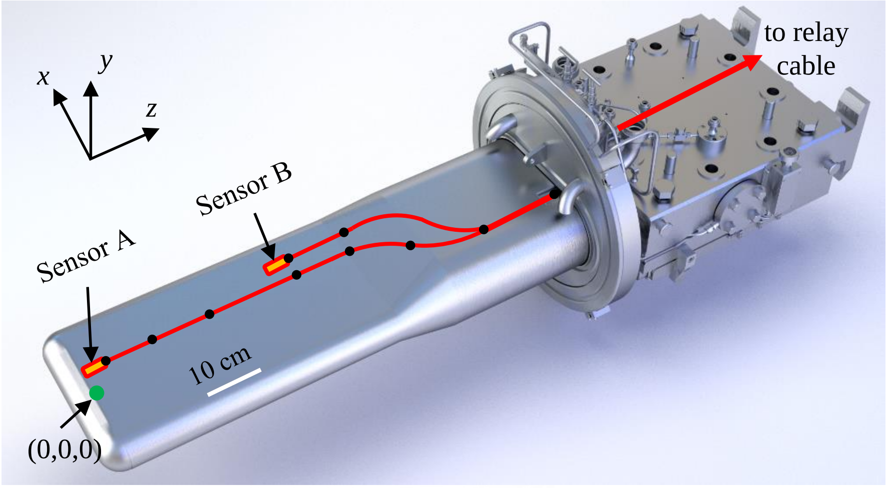


TABLE I
COORDINATES AND RADIATION DOSE OF SENSORS AND THEIR LEAD FIBER CABLES

Sensor A		Sensor B	
Position (cm)	Radiation Dose (MGy/MWHr)	Position (cm)	Radiation Dose (MGy/MWHr)
6.6, 5.2, 1.0	16.161	12.7, 5.2, 50.5	0.419
6.5, 5.2, 6.0	16.644	12.6, 5.2, 54.8	0.280
7.4, 5.2, 19.6	9.071	11.5, 5.2, 57.4	0.251
7.9, 5.2, 30.0	5.333	3.9, 5.2, 60.0	0.305
7.6, 5.2, 39.3	1.895	0.2, 5.2, 63.0	0.260
6.4, 5.2, 43.7	1.151	0.2, 5.2, 65.5	0.205
4.7, 5.2, 47.6	0.988	2.2, 5.2, 67.4	0.190
1.5, 5.2, 53.1	0.591	14.4, 5.5, 69.4	0.094
-3.5, 5.2, 60.5	0.284	17.8, 6.5, 80.6	0.044
-4.0, 5.2, 62.7	0.234	12.9, 9.1, 92.1	0.027

Radiation Induced Attenuation (RIA) and Sensor Lifetime





Location	Beam Energy (MWHr)	Peak Radiation Dose (Gy)
Front	77	1.3×10^9
	7.1	10^8
Middle	>1,670	$> 7 \times 10^8$
	80	5×10^7

RIA measurement results: ~ 5.5×10^{-8} dB/Gy/m

SNS customized sensors
Commercial sensors

Y. Liu et al., *IEEE Sensors Journal* **18** (2018) 3645.

OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

Possible Mitigation Approaches

Sensor Failure Scenarios

- Sensor gap extension induced by radiation
- Epoxy failure/effects of epoxy hardening
- Sensing interferometer broken
- Lost of light reflection

Mitigations

- Gap compensation in optical interrogation setup
- Improvement of sensor mounting methods (ultrasonic welding)
- Modification of sensor design (shorten sensor length), sensor mounting method
- Fiber material optimization?

Conclusion and Future Work

- We have developed fiber-optic strain sensors using Fluorine doped single-mode fiber, low-coherence optical interferometry technique, and digital signal processing scheme.
- The sensors have been applied to a number recent SNS mercury targets and the measurement performance demonstrated higher radiation tolerance and bandwidth than commercial products.
- Future work
  - Improvement of sensor performance using all-fiber interrogation scheme
  - Investigation of radiation effects
  - Looking into ultrasonic soldering technology
  - Collaboration

Colleagues involved in this work

- W. Blokland, C. Long (RAD/Beam Science and Technology group)
- D. Winder, B. Riemer, M. Wendal (NTD/Source Development and Engineering group)
- B. Qi (CSED/Quantum Optics group)
- R. Strum (MSU), D. Stiles (ERAU)