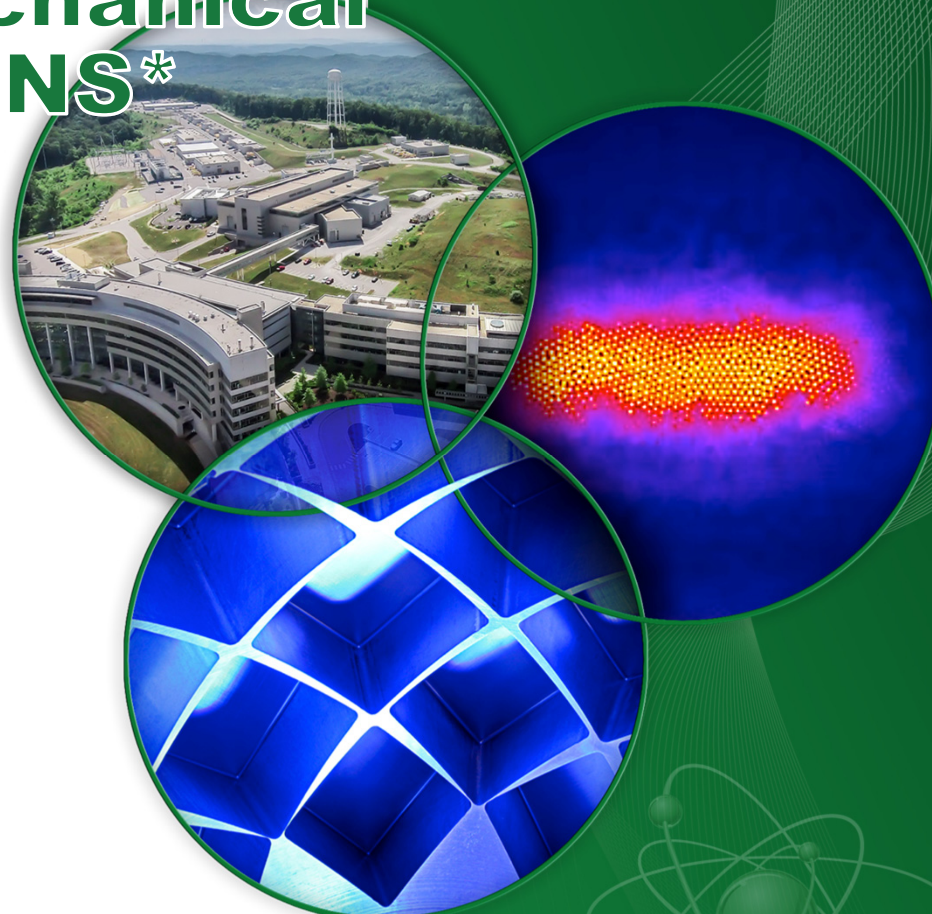
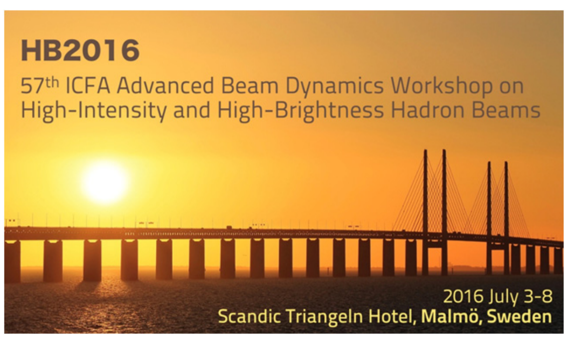
Measurements of beam pulse induced mechanical strain inside the SNS* target module



W. Blokland, M. Dayton, Y. Liu, B. Riemer, M. Wendel, D. Winder

Oak Ridge National Laboratory*



* ORNL is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. Department of Energy. This research was supported by the DOE Office of Science, Basic Energy Science, Scientific User Facilities.

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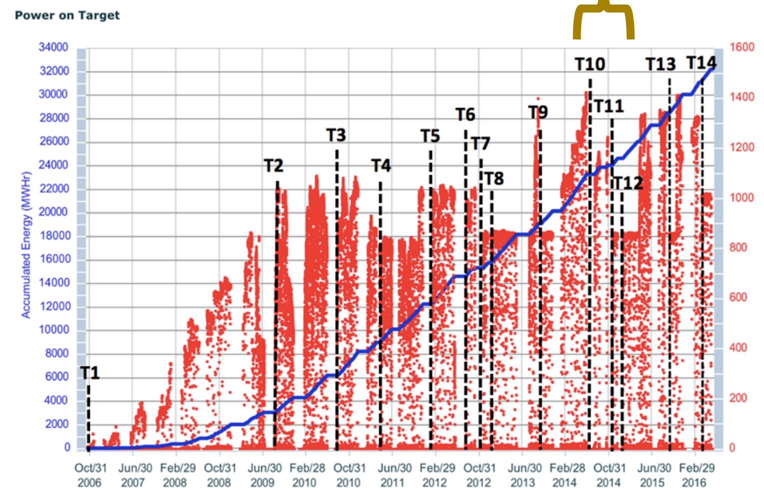
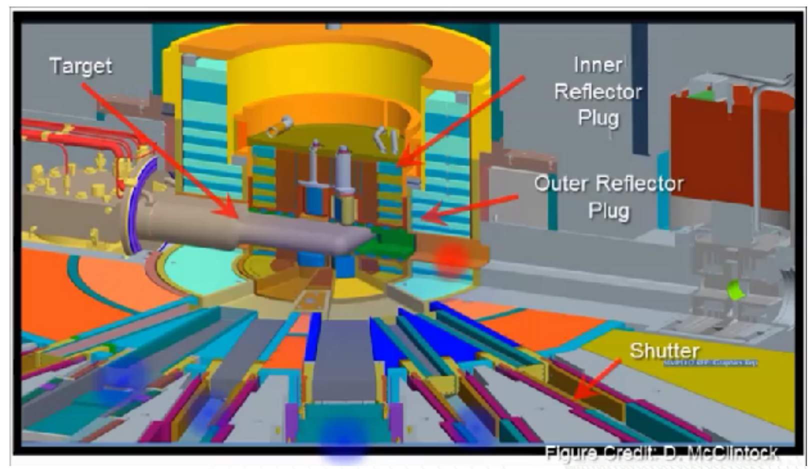
Introduction

- SNS: neutron scattering to study the structure and properties of materials and macromolecular and biological systems
- Direct ~1 GeV proton pulses at a stainless steel target vessel filled with mercury to produce neutrons
- Target has limited lifetime at 1.4MW
- To understand the target lifetimes better, we need to know the strain induced on an installed target:
  - Is the strain on the target higher than we expected?
  - Are we hitting a resonance frequency?
  - How will we know if future mitigation methods are working?

→ Add strain sensors

Target failures in quick succession





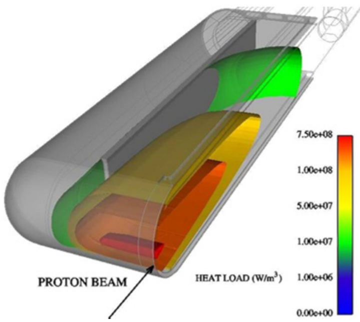
Sensor Environment

- Shockwave
  - ~60% of beam energy is deposited as heat in the target
  - The isochoric (constant volume) energy deposition (10 K over ~1 µsec) leads to formation of tensile pressure waves that cavitate the mercury

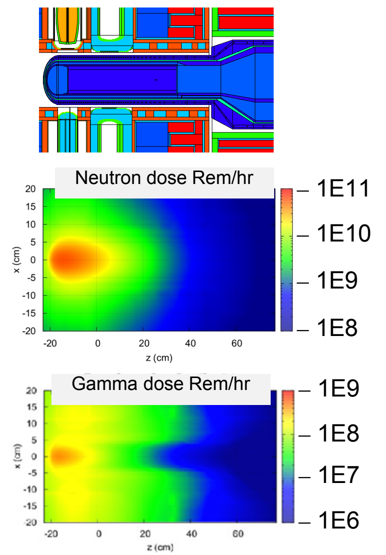
→ < 200 µε on mercury wall

→ Up to 100 kHz bandwidth

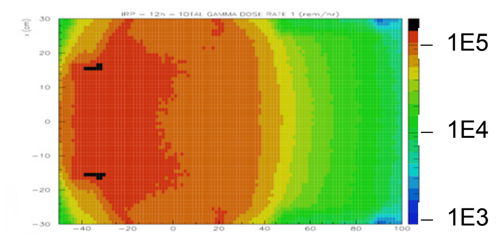
→ 25-100 Celsius



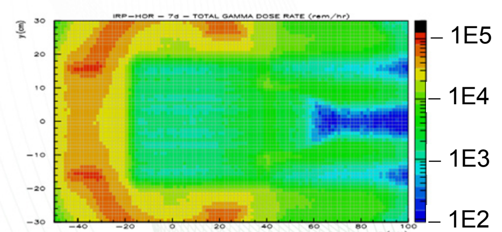
Mercury vessel



Radiation at 1.4MW



Residual radiation at 12 hours



Residual radiation at 7 days

- Radiation
  - Radiation during production: 1E8 up to 1E11 Rem/hr at 1.4MW → 5E6 to 500 Rem per pulse (~24µC)
  - Residual radiation: →100 to 100,000 Rem/hr

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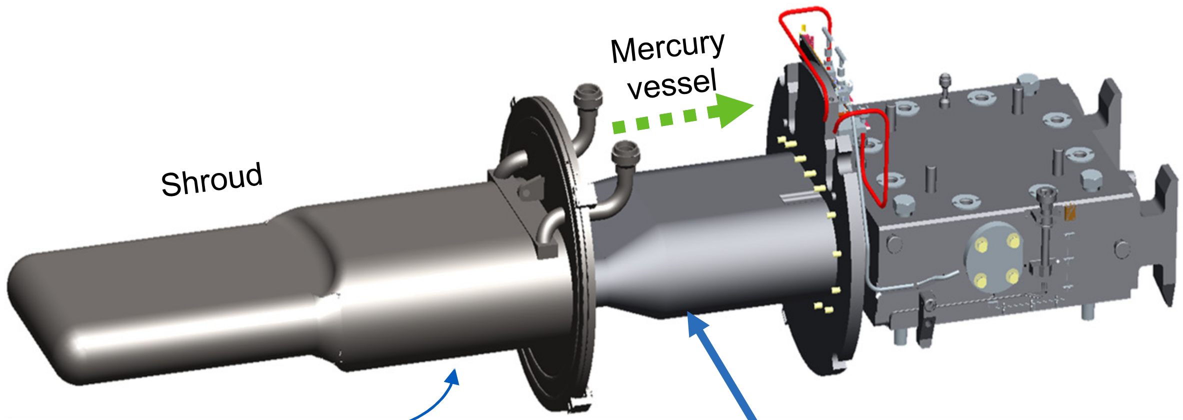
Sensor Environment



Leak detector

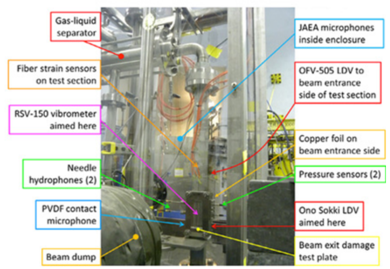
This is where we will place the sensors

- Interstitial space:
  - <3 mm height
- Electrical noise:
  - Beam pulse (~24μC in 600ns, peak current normally around 50 Amps)
  - Pumps and other equipment
- Leak Detector:
  - Cannot affect detector → limit new materials and keep interstitial space gas separated from outside air.

Design

Selection of sensor

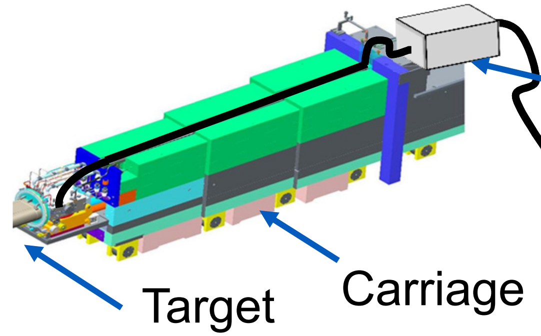
- Experience with different sensors from previous studies at LANSCE:
  - Fiber optic strain sensor is:
    - Fast enough
    - Small enough
    - Not sensitive to EMP
    - Is proven to work
    - Doesn't affect leak detector

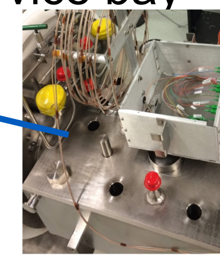


B. Riemer

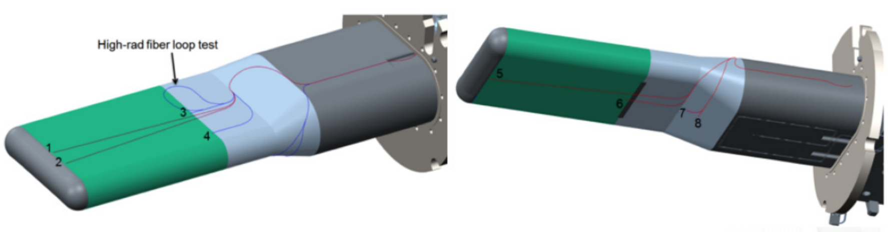
Signal cable routing

- Flexible cable for use with manipulators
- Route via box to outside service bay





Locations of sensors



Additional Diagnostics

- Accelerometers on target mount and mercury return line to try and correlate with internal sensors
- Rad-hard single-mode fiber loops to test attenuation vs radiation exposure

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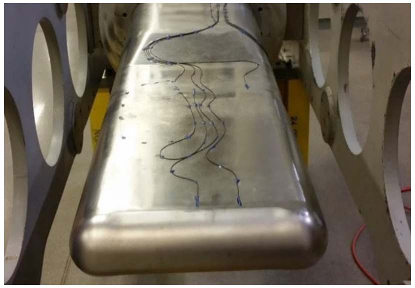
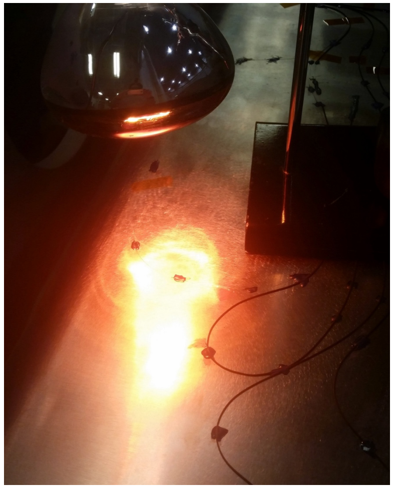
Sensor installation

- At location in Cincinnati
- Few sensors broke during installation, most were replaced or repaired

Laying out the sensors



Installed sensors



Curing of epoxy glue

Vessel being inserted into the water-cooled shroud.

Setting up data-acquisition

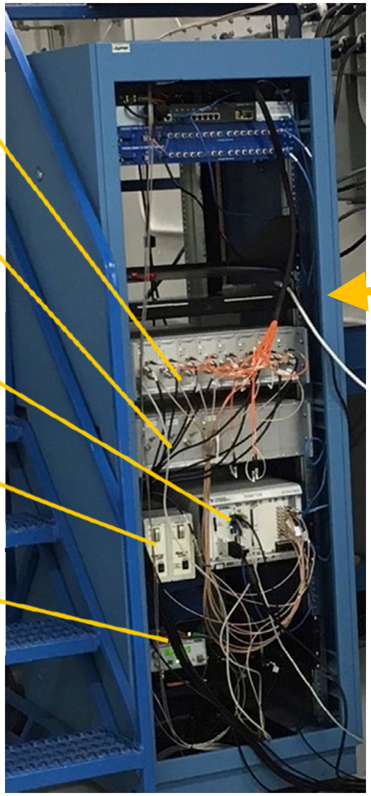
Optical Signal Processors (OSP) from FISO

Spare OSP

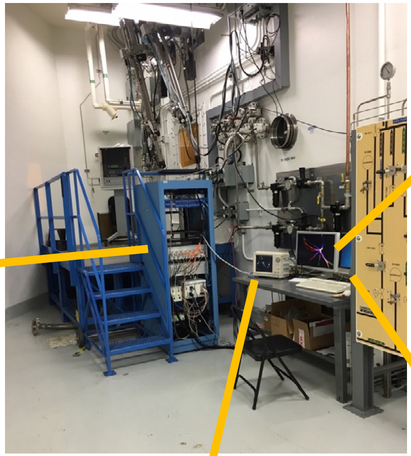
PXI Data-acquisition and Timing

Accelerometer PS and Amps (PCB)

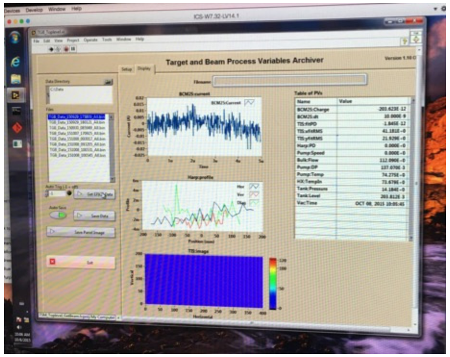
Lights source and power meters



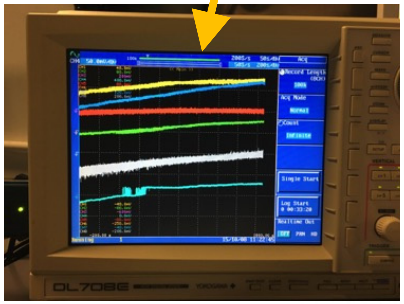
Instrument rack



TSM Control Room



Data from accelerator



Backup scope

Strain data

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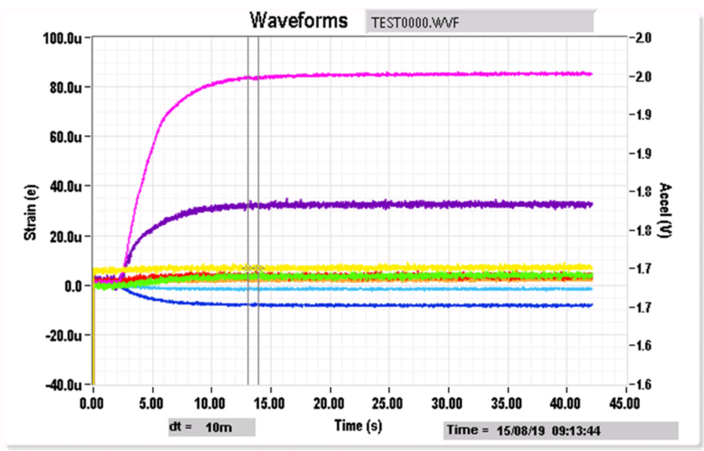
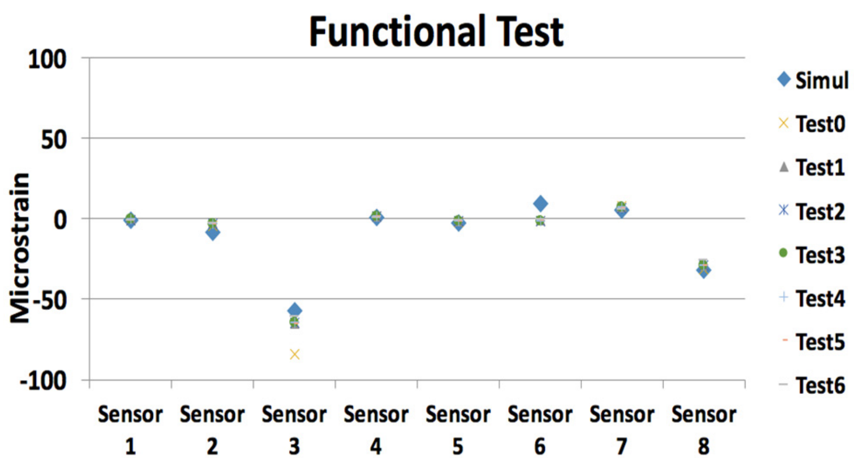
Functional tests

- Test the strain while pulling a vacuum and venting and compare to simulation
  - Do the sensors work?
  - Do the measurements agree with the simulation?



Measured strain during testing (venting).



Measured strain versus simulated results (pumping)

→ Measurements do agree in general, we did discover a scale factor between the old and new optical processor!

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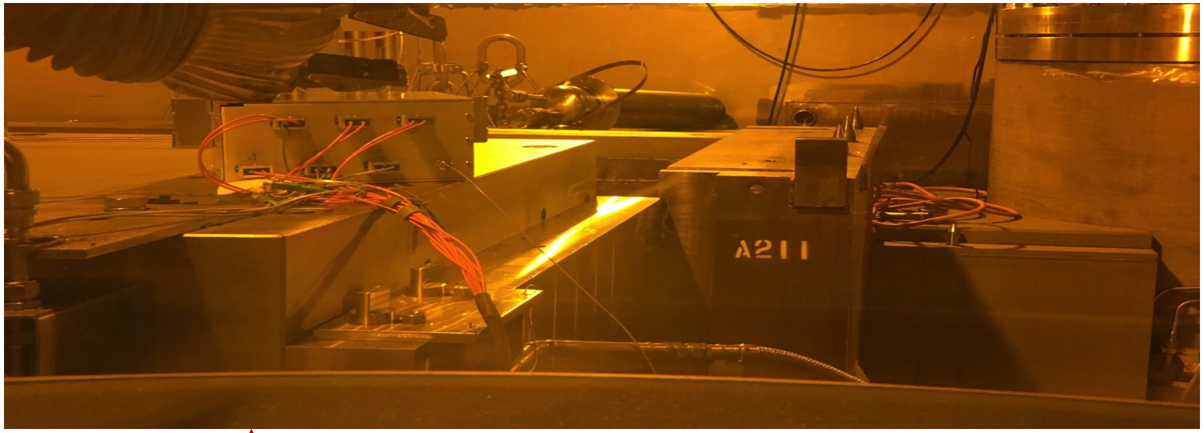
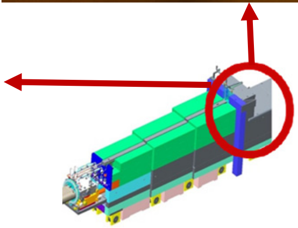
Installation

- Cables pulled, hooking up duplex connectors

Hooking up duplex connectors





Hookup completed

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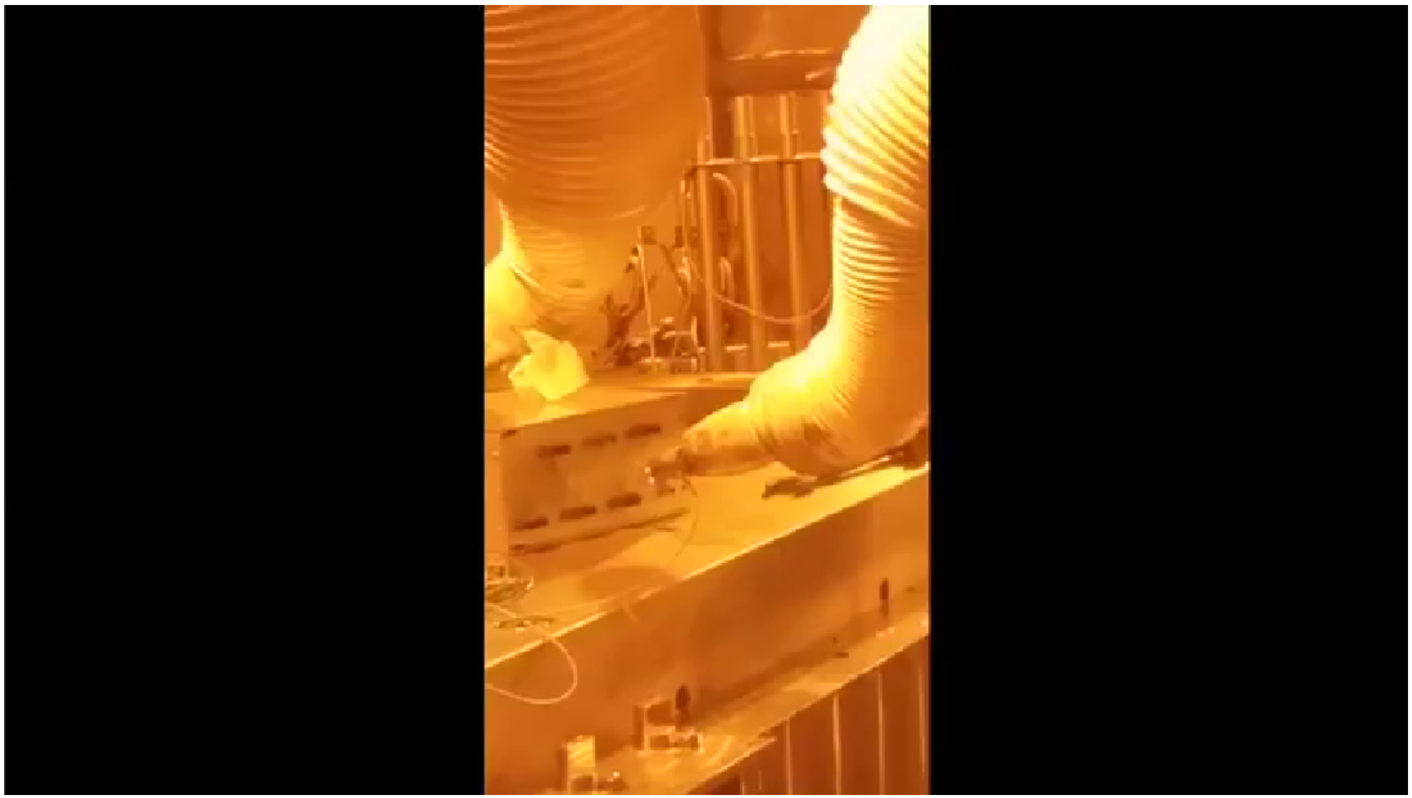
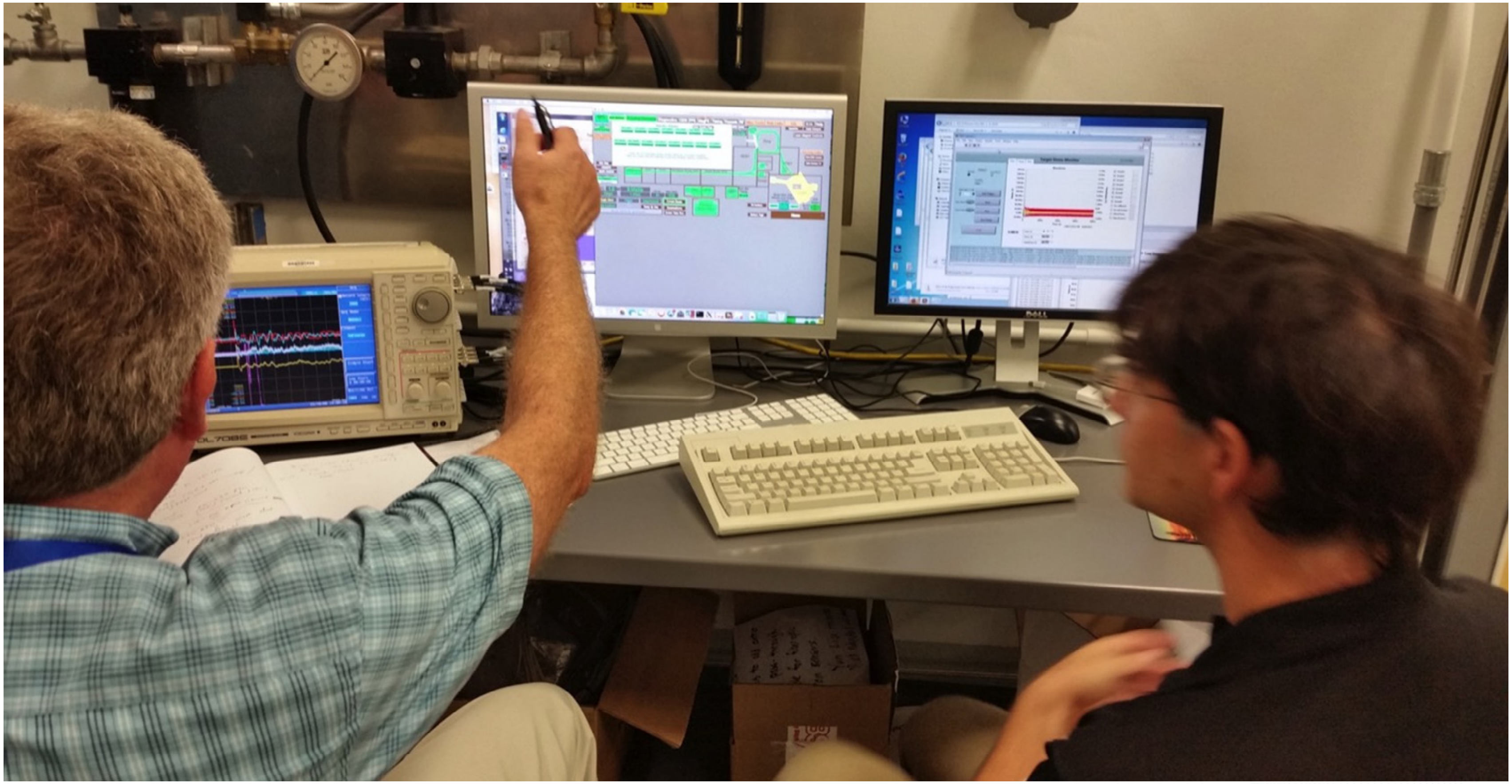
Installation

- Cables pulled, hooking up duplex connectors

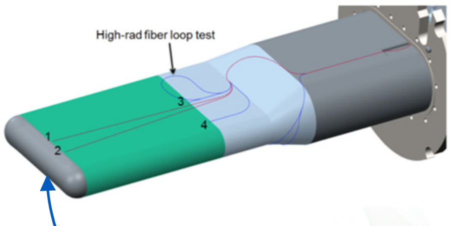


Waiting for beam

First strain data!



Is the strain as predicted? T13 Data: Sensor 2

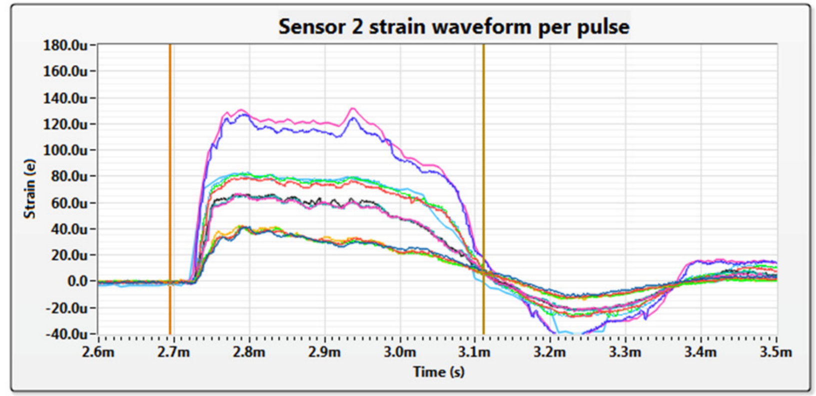


Sensor 2

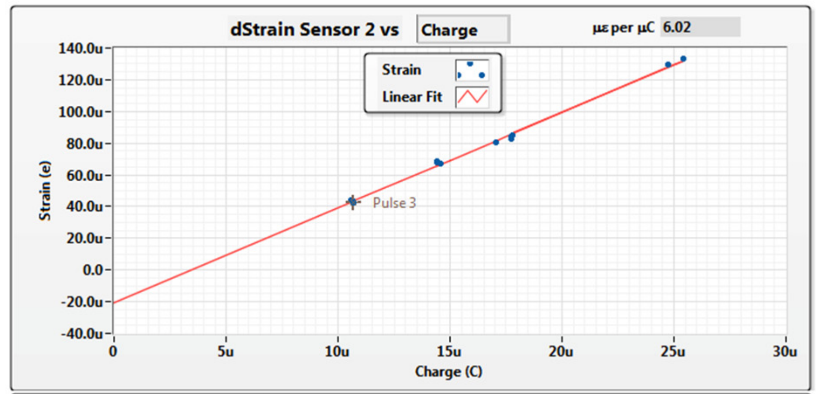
Pulse 1 at 10μC

Pulse 19 at 25μC

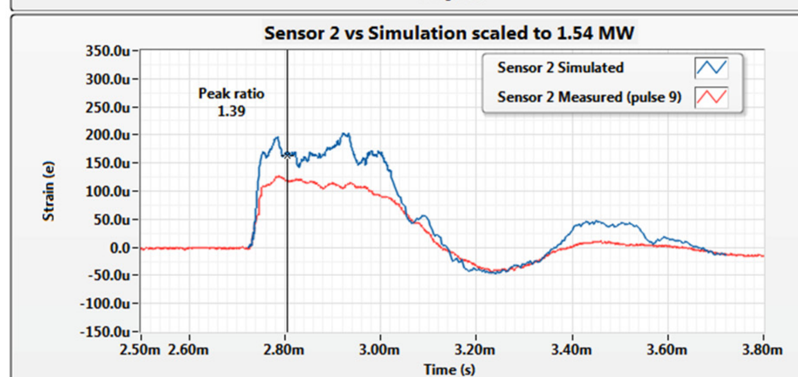
Consistent looking strain waveforms



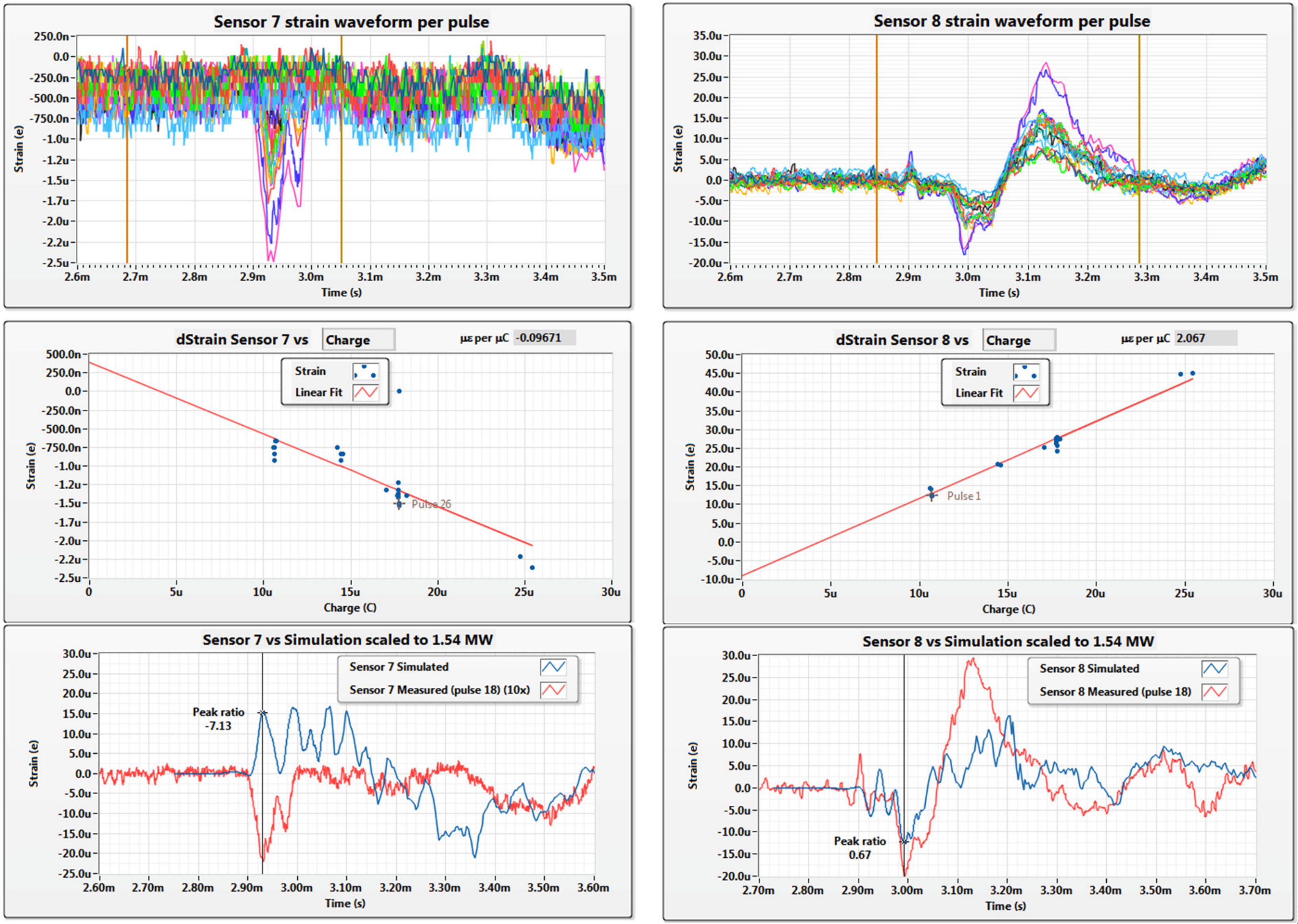
Linear relationship between Strain and beam Charge but not through intersect



Measured strain waveform shape matches simulation



T13 Example signals: Sensor 7 and 8

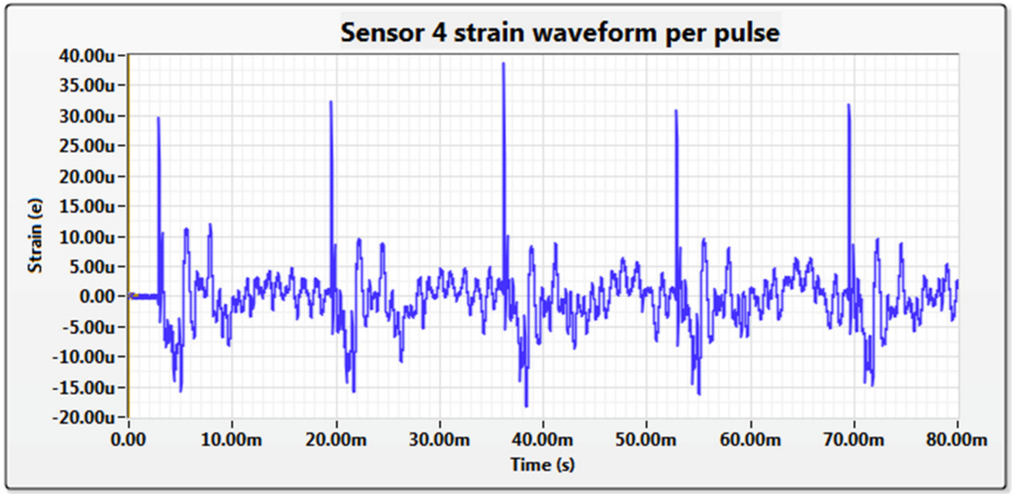


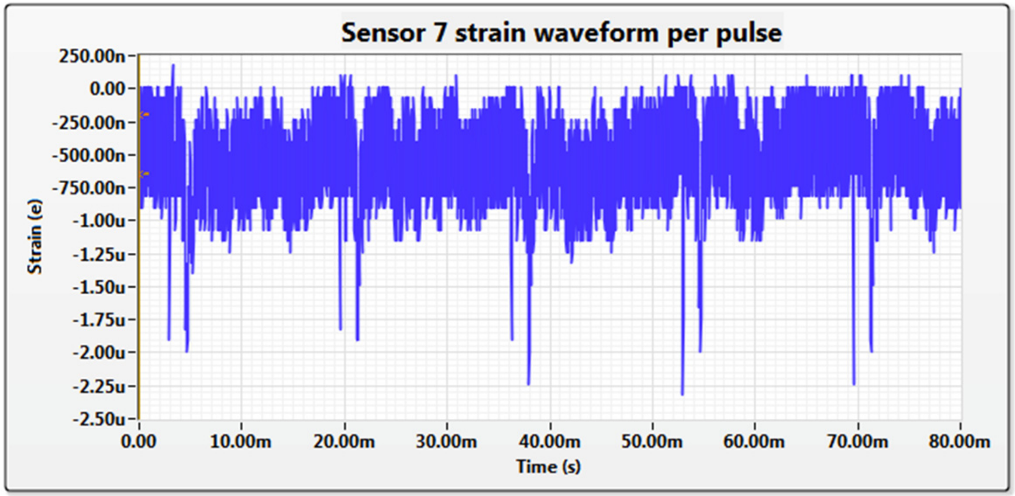
Is there a resonance?

- Ten pulses in a row

Sensor 4 pulse 24

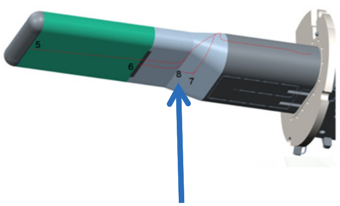
Sensor 7 pulse 24



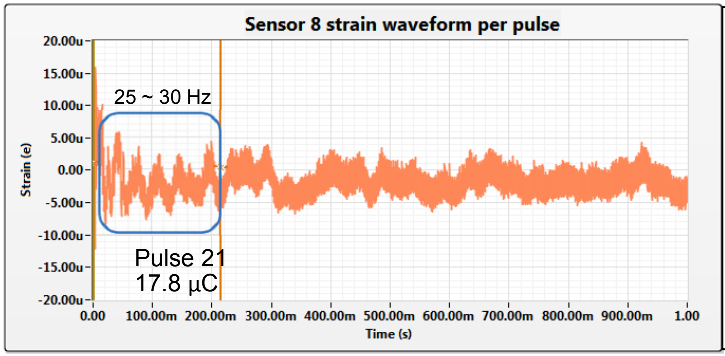


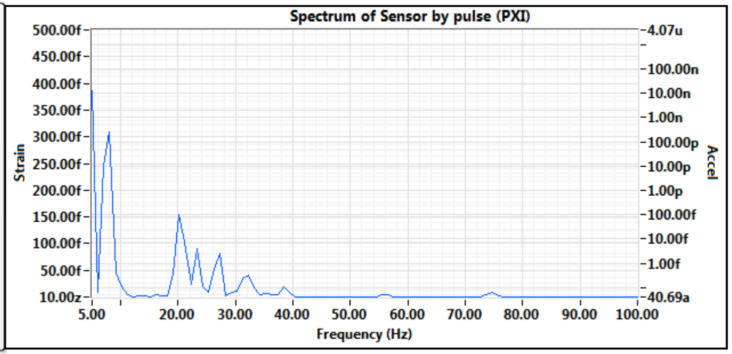
→ No proof of buildup of dynamic stress

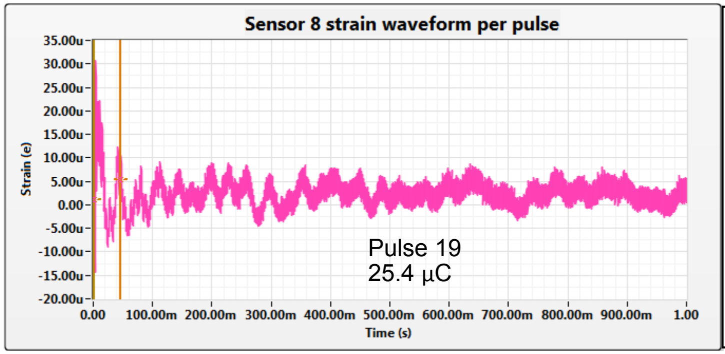
Some ringing is seen

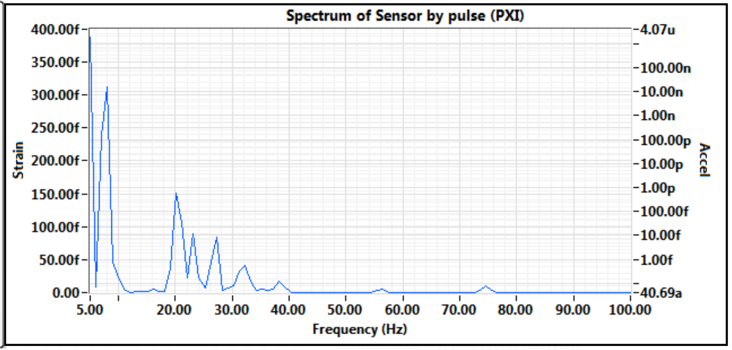


Sensor 8





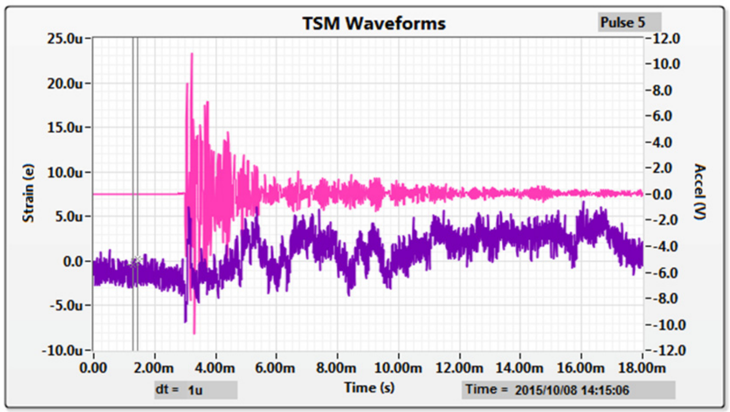


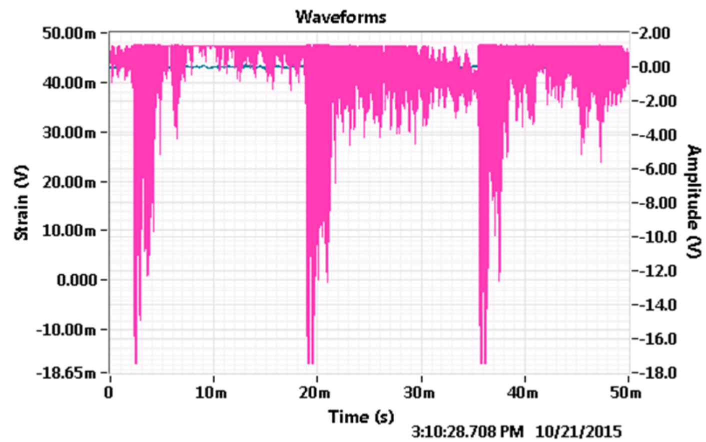


→ Possible ringing response

What can we learn from accelerometer data?

- Signal saturates at > 10 μC on target mounted accelerometer





Target Mount

10μC

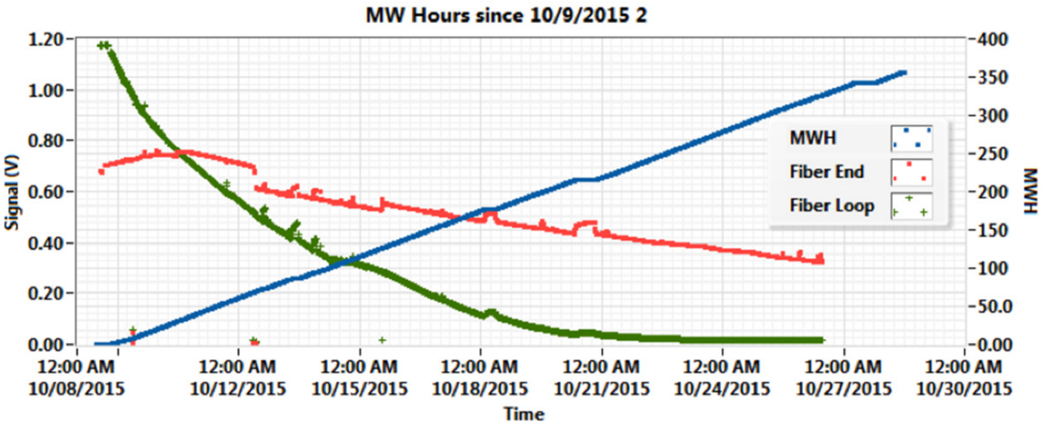
Mercury return

15μC@60Hz

→ T13 accelerometer data inconclusive thus far: One saturated sensor, other far away. Analysis continues.

What is the radiation response of the single mode fiber?

- Radiation Induced Attenuation is equivalent to 0.4 dB/km/MRad and peaks at 0.9 dB/km/MRad.
- The peak dose amount is 83.6 GRad and the peak dose rate is 329 kRad/s at 800 kW beam power.



Optical signal attenuation over time

→ At least a two-week lifetime for the single-mode sensors

- If the sensors can last for several weeks we might be able to see when an internal baffle cracks.

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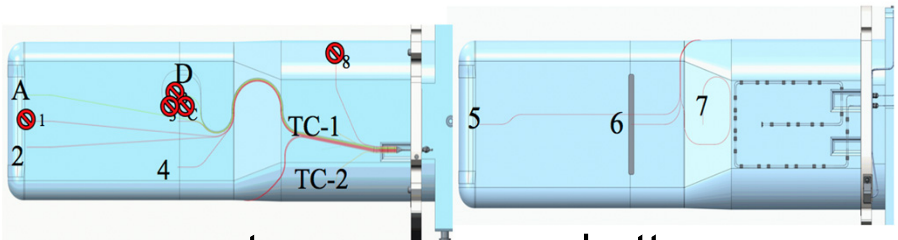
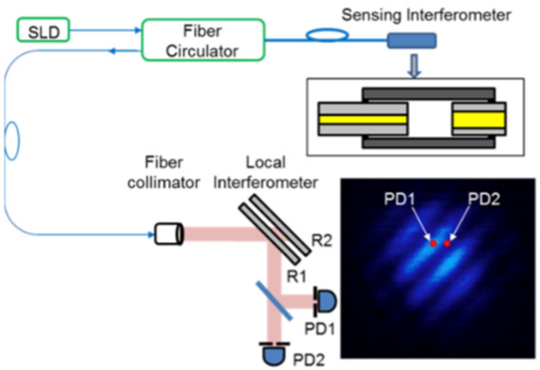
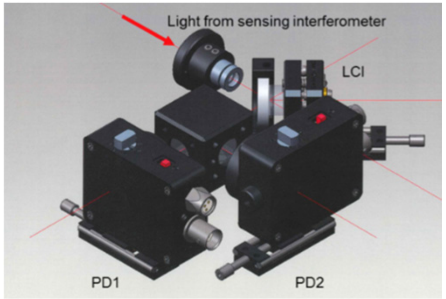
T14 Instrumentation

- Use high OH multi-mode fiber → more rad-hard → longer lasting
- Two prototype single-mode fiber sensors → very rad-hard → much longer lasting
- Two thermo-couples



top bottom





Prototype rad-hard single-mode fiber optical strain measurement setup

From: Y. Liu, et al.,"Radiation-Resistant Fiber Optic Strain Sensors for SNS Target Instrumentation", in Proc. 7th International Particle Accelerator Conference (IPAC'16), Busan, Korea, May 2016, paper MOPMR055, pp. 371-373

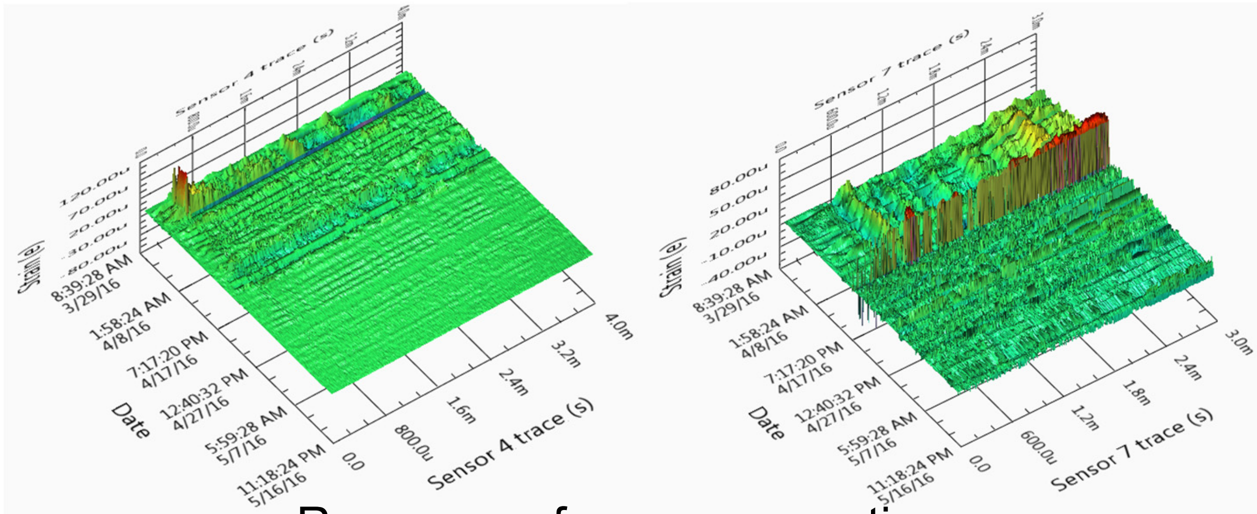
Initial Results:

→ See up to two weeks with multi-mode fiber or ~5th order improvement (1.5 secs at 850 kW vs 2 weeks at 850 kW)

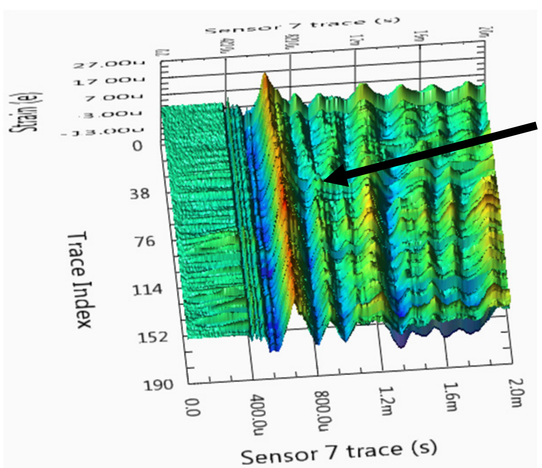
→ 5 weeks for rad-hard single-mode

Longer life-time on multi-mode sensors

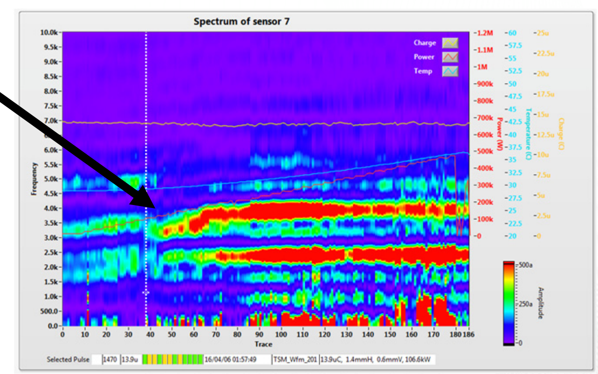
- Longer life-time allows us to look for target structural changes: 1.5 s versus 2 weeks at 850 kW



Response of sensors over time



Change



Sudden change in response

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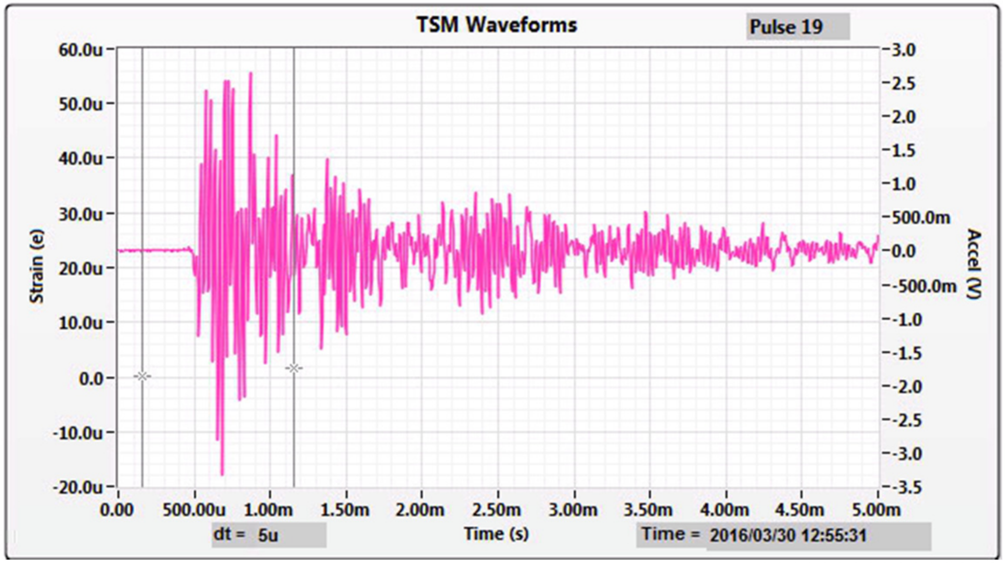
T14 Accelerometer

- Replaced target mounted accelerometer with a less sensitive version to prevent saturation → now see up to maximum intensity

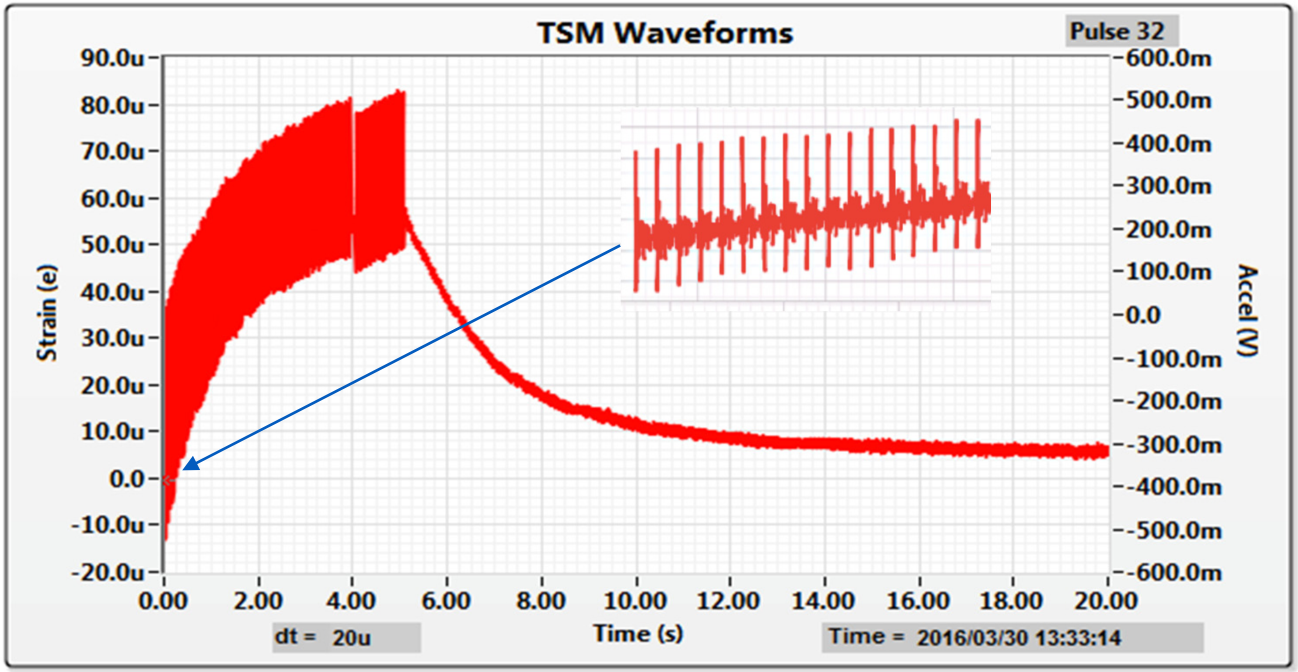


T14 data from less sensitive accelerometer 24µC

→ T14 accelerometer data is useable at high intensities

T14 Long pulse train

- Both sensor types can now see production beam aka very long pulse trains

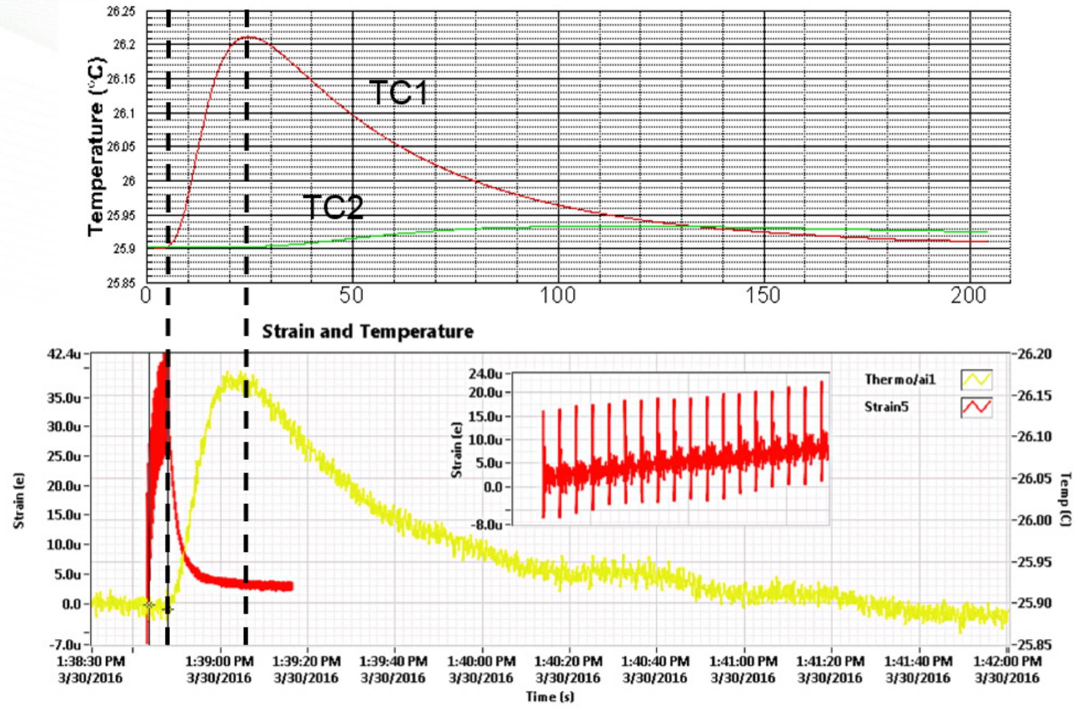


300 pulses of 3.5 μC on sensor 5

→ T14 strain data shows a slow strain buildup

T14 Temperature data

- Compare measured temperature with simulated



600 pulses of 3.5 μC on sensor 5

→ We assume that static strain buildup is due to temperature increase

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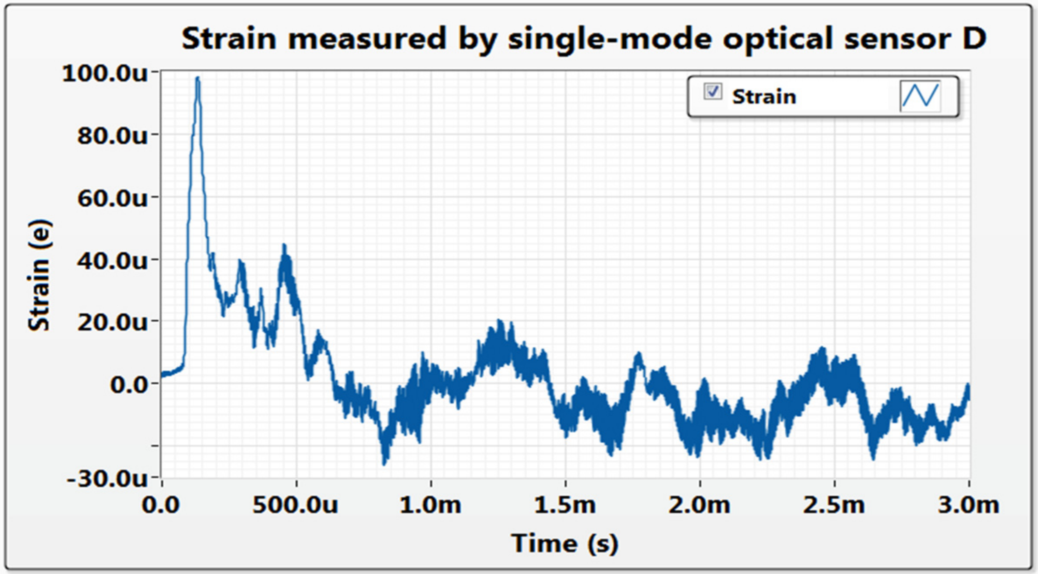
T14 Prototype Single-mode fiber

- The sensor (A) located in the front edge of the target vessel survived for about 3 days while the sensor (D) located in the middle of the vessel was able to provide strain measurements over 5 weeks.



Example of sensor (D) waveform

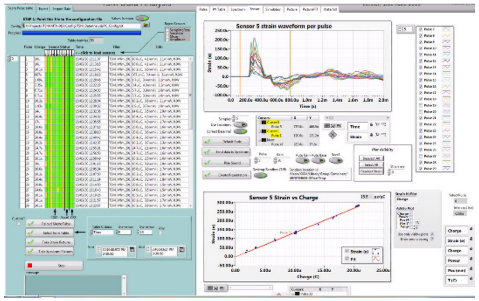
→ Single mode sensors do last longer, we are in the process of validating the data.

Summary and conclusions

- After a year-long effort (T13) by many people, we have results!
  - While a year seems like a long time, given all the preparations and deadlines associated with target manufacturing, the time constraint in developing the measurements was actually fairly tight.
- The T13 instrumentation lived just long enough to give us data.
  - No dynamic buildups of strain (no resonance)
  - Mostly linear behavior between beam intensity and strain response (mercury behaves non-linear)
  - Some ringing seen
  - Simulation typically predicts waveform shape and over predicts amplitude
- T14 Instrumentation
  - We now have strain data well into production runs (2-5 weeks)
  - The temperature response is as expected.
  - We haven’t fully analyzed the data from T14 yet. We are in the process of validating the single-mode fiber sensor data.

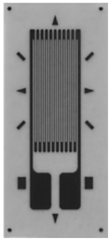
→ No additional cause for target failures found, no additional mitigation besides those already planned

Future



Off-line analysis program

- Analysis of optical strain data
  - Compare large data-sets from single-mode, multi-mode sensors, and accelerometers to validate signals and find changes in target response



Strain gauge

- Metal strain gauges in next target
  - Test to see if noise can be overcome
- Integrate data-acquisition for all sensors into one program (easier for off-line analysis)
- Take measurements of target damage mitigation methods: jet-flow, gas bubble injection and other modifications to the target to determine effectiveness