U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Advanced Sensors and Instrumentation

Non-contact Strain and Displacement Monitoring for Fuel Cladding Burst Detection

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Advanced Sensors and Instrumentation (ASI) Annual Program Webinar
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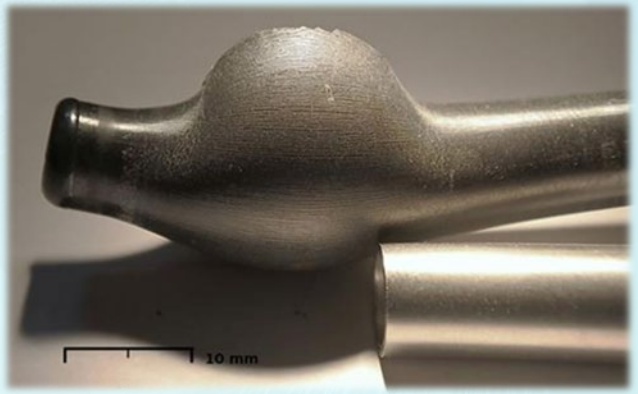
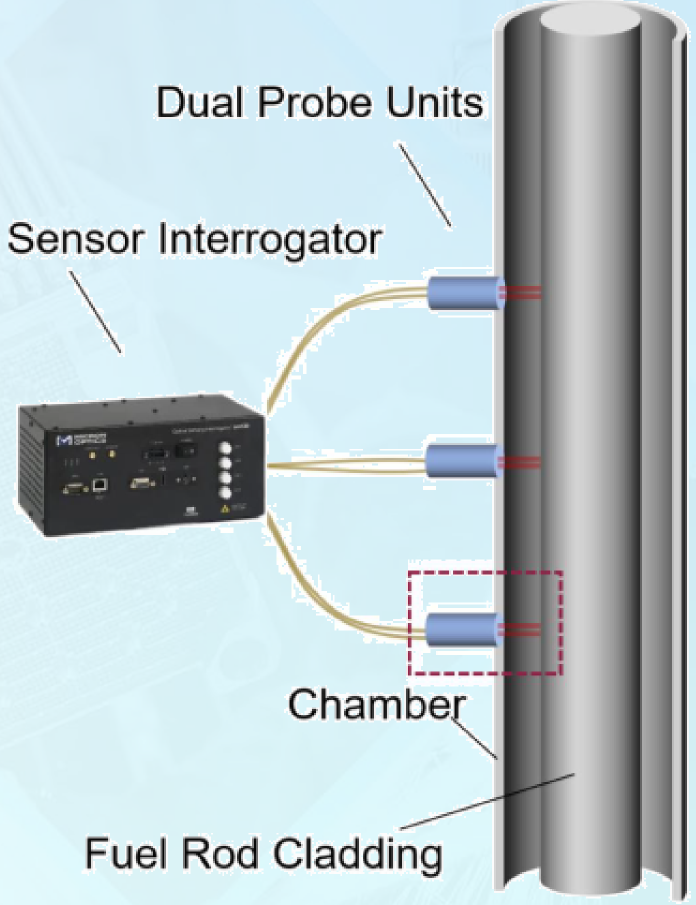
Project Overview

- **Purpose**: Develop and demonstrate a burst-onset detection system to monitor the health and condition of the nuclear fuel cladding
  - In the one-year Phase I effort, Virginia Tech (VT) engaged with INL to understand the application and develop the performance requirements for the sensing system
  - A fiber optics-based non-contact displacement and surface strain sensing system was designed and constructed to demonstrate performance via laboratory scale testing
  - In a proposed Phase II effort, a fully integrated prototype sensing system will be deployed in a reactor test at an agreed-upon National Lab test facility



Project Overview

- **Research Approach**
  - Design and construct an optical fiber based interferometric sensing system capable of measuring the displacement and radial strain of the fuel cladding in real-time
  - Demonstrate the performance of a prototype sensing system in a simulated laboratory environment
- **Research Scope**
  - Determine sensor operating requirements and specifications
  - Perform theoretical analyses and modeling of the Fabry Perot interferometric sensor response
  - Design and construct laboratory scale test setup at VT
  - Design, construct, and characterize the displacement and surface strain sensing system
  - Demonstrate performance of prototype sensing system in a laboratory setting
  - Prepare for testing of prototype sensing in selected test reactor



Technology Impact

- Fuel cladding integrity is a primary focus of safety testing and remains a significant research priority for the Advanced Fuels Campaign [1, 2]
  - Performance of accident-tolerant fuel (ATF) candidates must be evaluated under simulated loss-of coolant accident (LOCA) conditions to support licensing of these materials
  - An understanding of high-burnup fuel fragmentation, relocation, and dispersal (FFRD) in the event of cladding failure under LOCA conditions is necessary for licensing to extend the peak rod average burnup
- Fuel cladding swells (“balloons”); under some conditions it can rupture during LOCA
  - Reactor coolant pressure drops below the internal fuel rod gas pressure
  - Core behavior depends on the type of accident, the time at which swelling and rupture occurred, the magnitude of swelling, and the resulting coolant flow blockage (i.e., reduction in flow area)
- Displacement, strain, and creep measurements of standard specimens under irradiation is a prevailing interest of the nuclear community from a scientific and engineering perspective
  - Linear variable differential transformers (LVDTs) and strain gauges require mechanical contact of the specimen
  - Contact with the surface of cladding will significantly impact the thermal behavior thereby negating the value of the data
  - Recent success of fiber optic-based instruments for in-pile applications provides a basis for the contactless fiber optic-based measurement of mechanical behavior

Results and Accomplishments: Design Specifications

- Conducted a technical survey of the operating conditions and performance requirements
  - Leveraged expertise at INL
  - Ensure prototype is fit-for-use
- Sensor packaging and design is dictated by the specific experiment
- Identified significant technical challenges that must be addressed
  - Variable refractive index of environment
  - Vibrations
  - Minimum allowable standoff distance
- Intimate collaboration with INL to ensure sensing system will provide value to the nuclear community

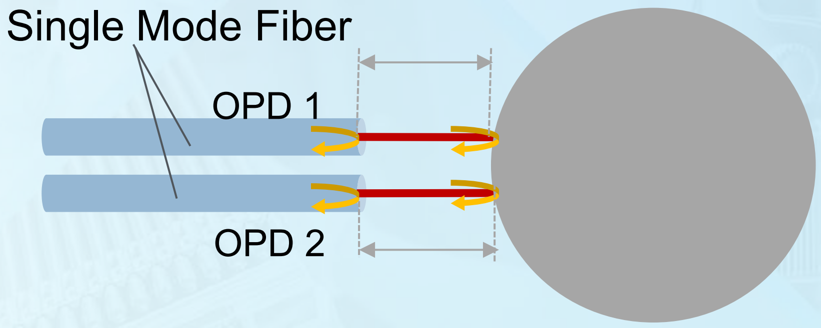
Property	SPECIFICATIONS	
	Required	**Desired**
Environmental/Operating Conditions		
Sensor: Max. Temperature	100 °C	300 °C
Viewing: Max. Temperature	200 °C	800-1200 °C ***
Viewing: Temperature Range	-----	200-1200 °C
Sensor Operating Environment	Inert (Helium/Argon) *	Inert (Helium/Argon), Water, Steam
Interrogator Operating Environment	Ambient	Ambient
Sensor Stand-Off Distance**	5-25mm	5-25 mm
Interrogator Stand-Off Distance	10 m	20 m
Sensor Performance		
Fuel Cladding Diameter	~ 10mm	~ 10mm
Fuel Cladding Material		SS-316, Zirc-2, Zirc-4, Zirlo
Fuel Cladding Length	Not a strong requirement	100 mm
Length of Interest	<50 mm; not a strong requirement	50-75 mm
Containment to Cladding Distance	15-40 mm; can be changed	15-40 mm
Maximum Change in Diameter	30% (13 mm)	100% (20mm) ****
Max. Rate of Diameter Change	1-2 seconds.	250 ms (40mm/s rate).
Min. Displacement Resolution	1 mm on the radius	$\leq$ 0.5 mm
Minimum Strain Resolution	10^{-3}	10^{-4}
Linear Coverage	Not a strong requirement	-----

** Capability of varying composition or pressure to change RI*
***In-Vessel vs. On-Vessel*
****Highly dependent on experiment*
*****Highly variable*

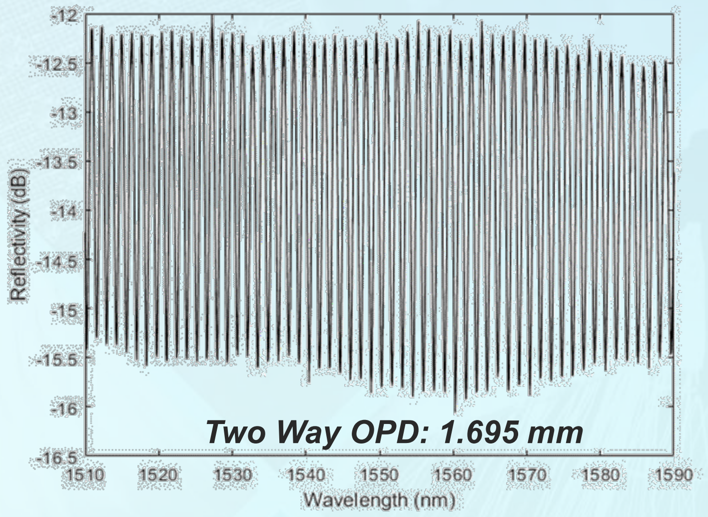
Results and Accomplishments: Sensor Design

- Proposed sensor utilizes multiple optical fiber based Fabry-Perot Interferometers (FPIs)
  - Sensing elements are 90° polished single mode fibers that are positioned parallel to the tangent surface of the test substrate
  - Interrogation system based on a tunable laser (Micron Optics SM125)
- Demodulation via white light interferometry (WLI)
  - Allows for absolute measurements
- Optical path difference (OPD) is the distance between the probe and the metal surface
  - Fit the periodicity of the interference pattern
  - Obtain the demodulated OPD via linear interpolation, zero phase filtering, linear regression, or Fourier Transform
  - Minimum detectable displacement using Type I demodulation: 2.5 μm

Schematic of Dual Probe Interrogation

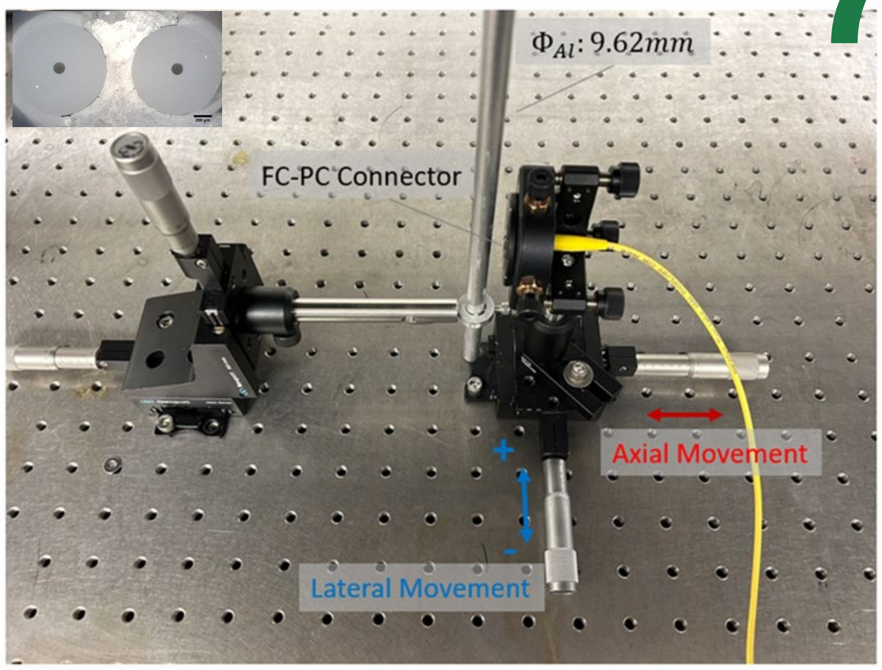


Example of Fringe Pattern

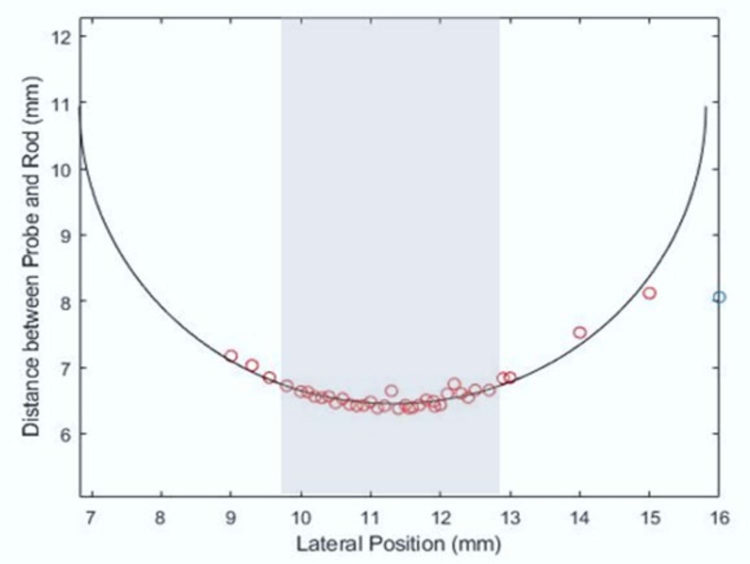


Results and Accomplishments: Demonstration of Feasibility

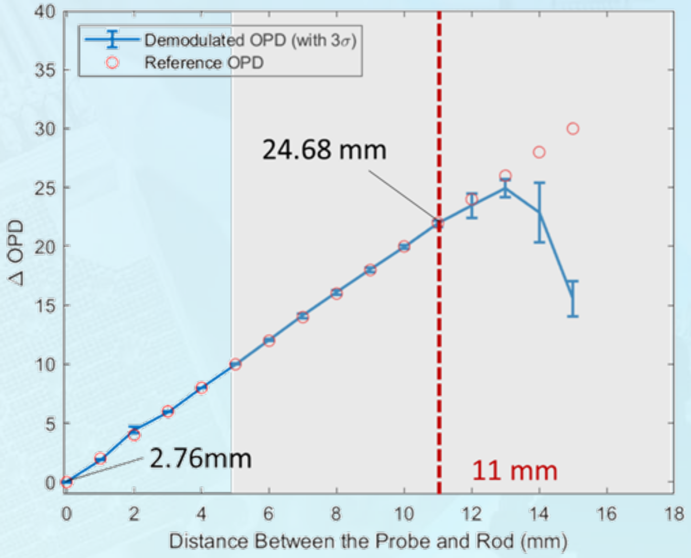
Demonstration of Sensing Approach



Lateral Movement



Radial Movement



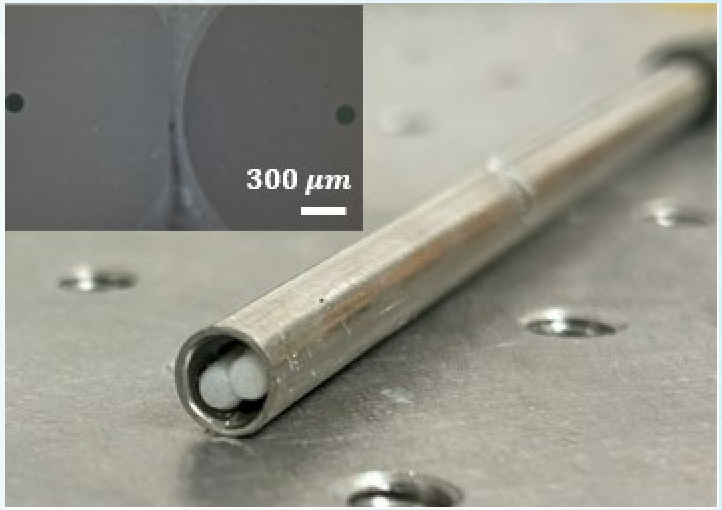
Max Standoff Distance: 11 mm (center probe)

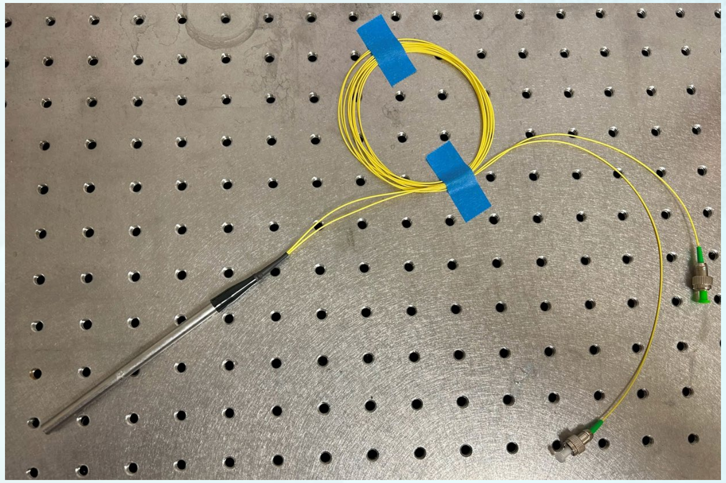
Max Sensor Spacing: 1.5 ~ 2.0 mm

Results and Accomplishments: Laboratory Standard Probe and Testing

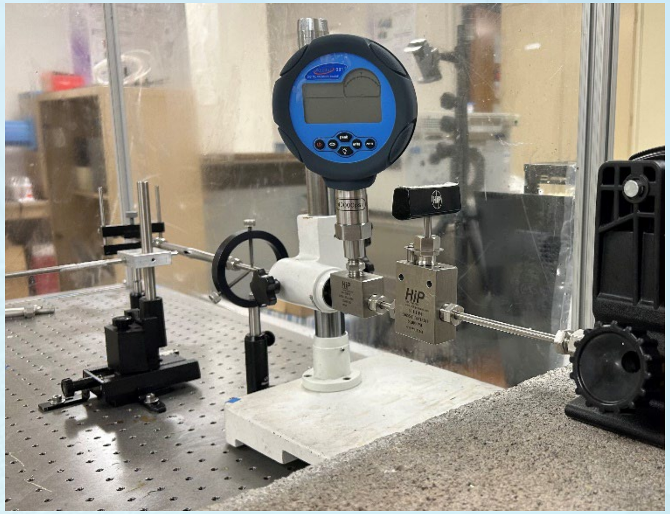
- "Laboratory Standard" dual probe sensor
  - Attached two 1.25 mm ceramic ferrules with cyanoacrylate.
  - Inserted bare SMF 28 fibers into the ceramic ferrules (separated by 2.16 mm)
  - Housed in stainless steel ¼" tubing with fiber strain relief
  - Polished sensor end faces
- Bench-top pressurized tube "burst test" setup
  - Enerpac P2282 Ultra-High Pressure Hydraulic Hand Pump
  - High pressure hydraulic stainless-steel tubing (1/4")
  - Thin wall "burst tubing" (3/8")
  - Full plexiglass enclosure

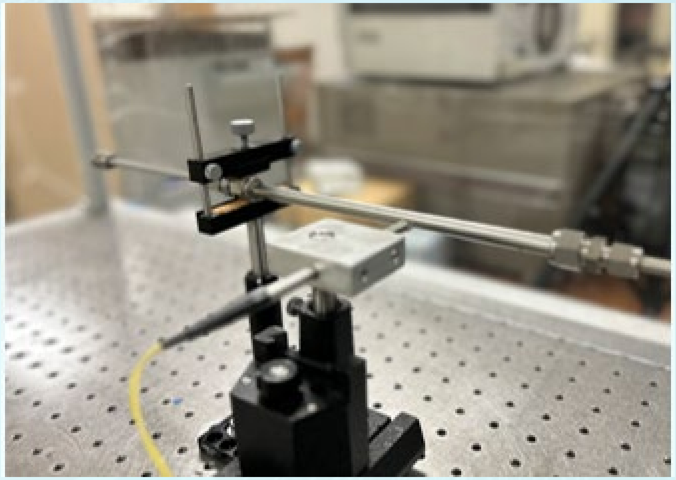
"Laboratory Standard" Sensor



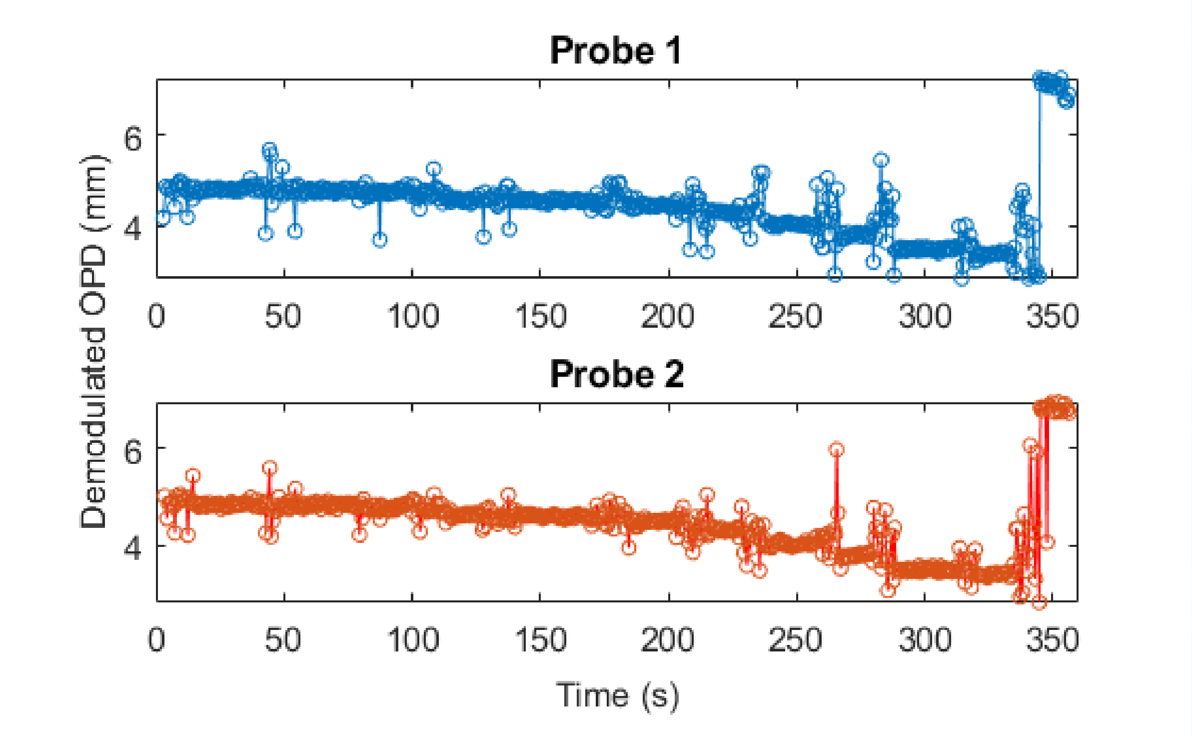


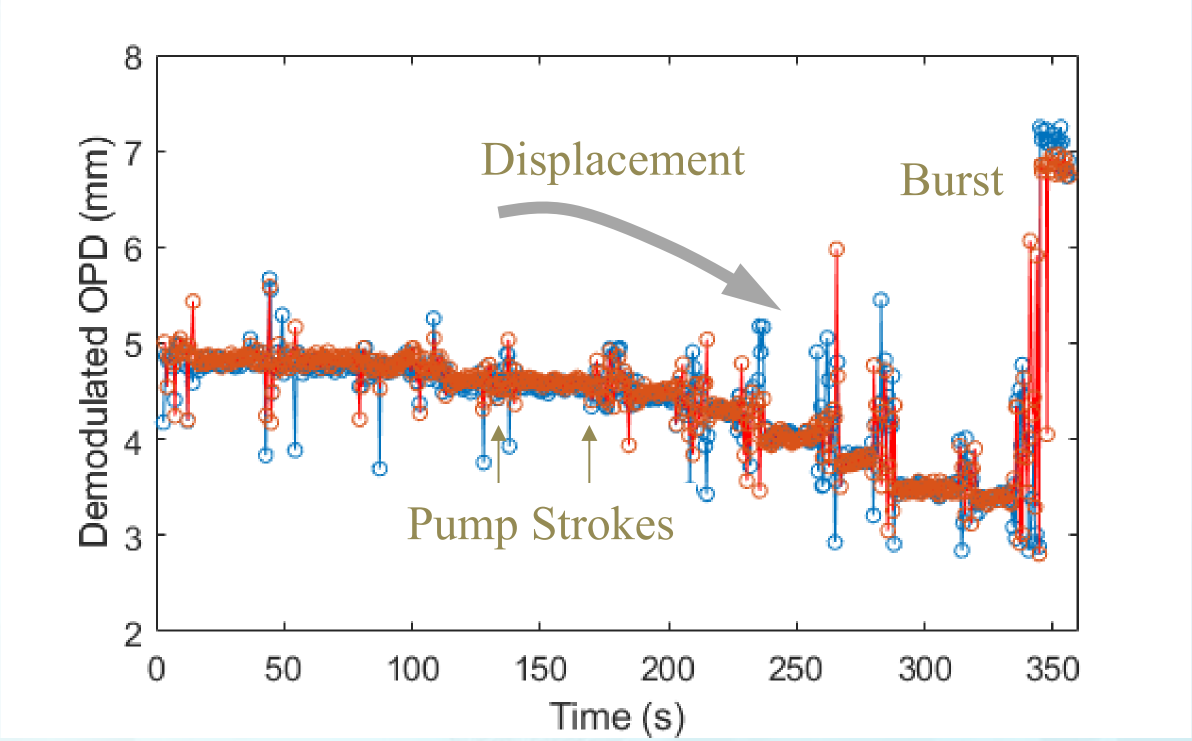
"Burst Test" Setup





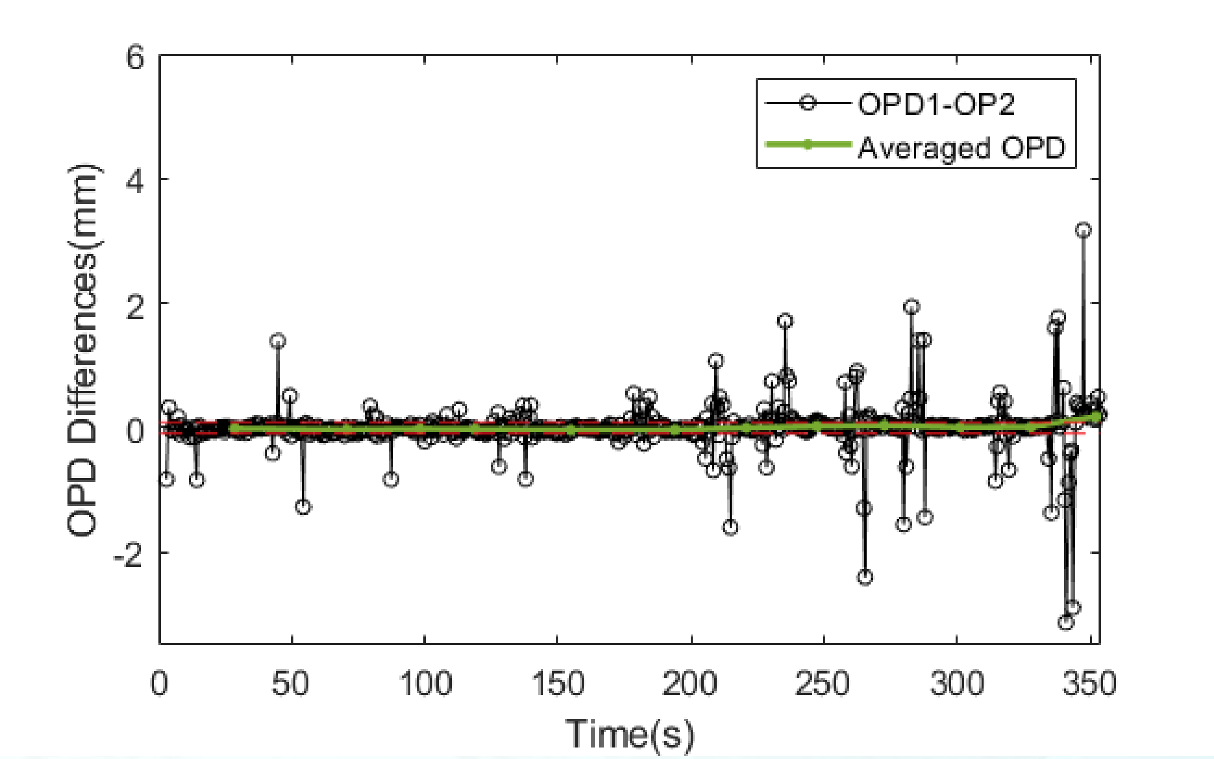
Results and Accomplishments: Testing of Dual-Probe Sensor Design

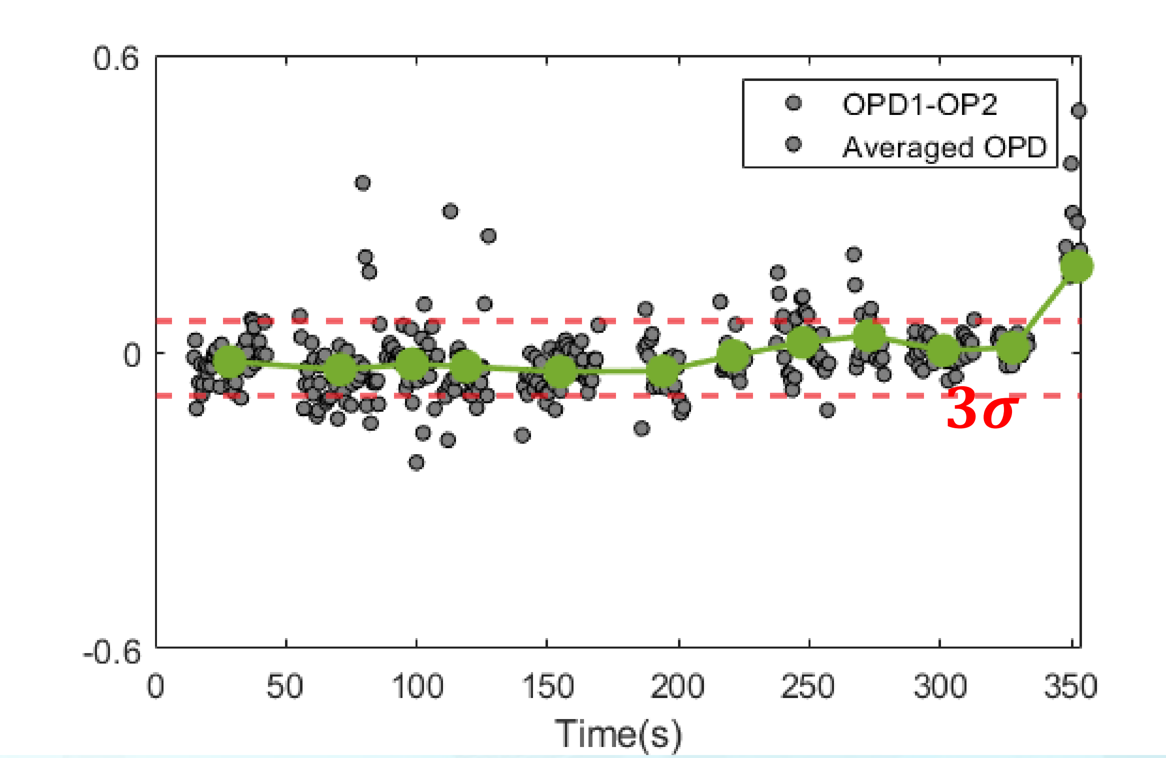




- The hydraulic pump incrementally raises the internal pressure of the tube in a stepwise manner, involving a few strokes, followed by intermittent waiting periods.
- Demodulated OPDs: stepwise pattern with intermittent large variations; overall decreasing value
- Abrupt change in the OPD was observed upon tube bursting (at the end of test)

Results and Accomplishments: Testing of Dual-Probe Sensor Design

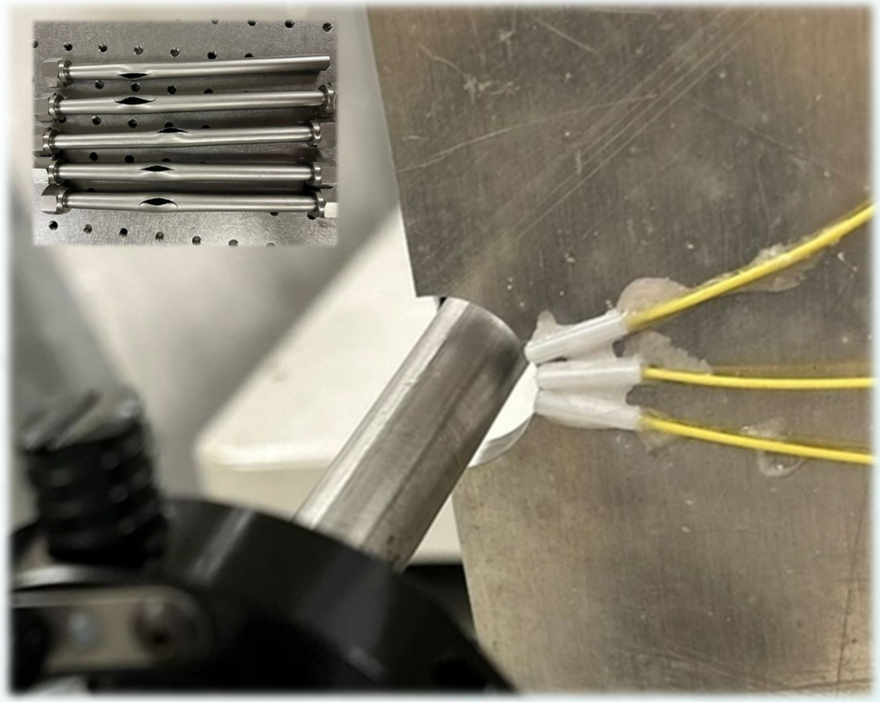


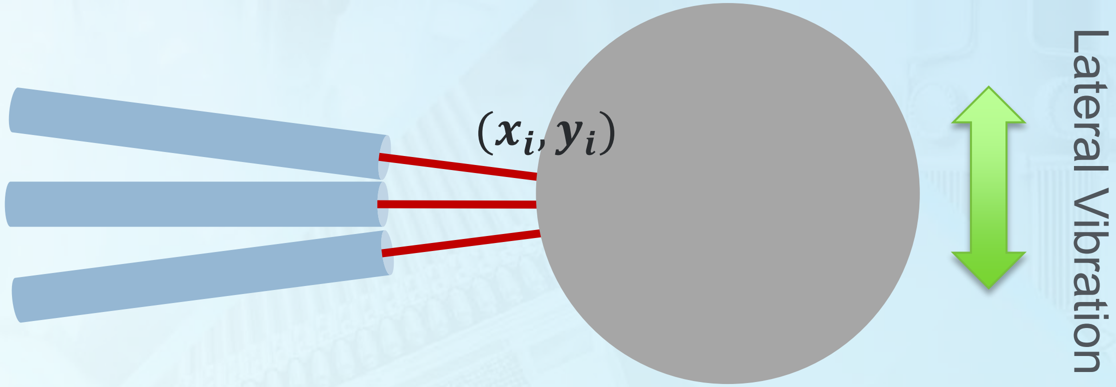


- Small variations in the relative OPD changes between probes were observed
- “Bursting event” was characterized by an abrupt change that exceeded 3σ
- Tube bursting events can be detected via monitoring changes in the relative sensor OPDs

Results and Accomplishments: Triple Probe Design

- "Triple Probe" sensor design
  - Probe aligned to the center of the tube
  - Real-time measurement of "lateral vibrations"
  - Fit a unique circular shape of unknown radius





- Given n probes, and the reflected points are $(x_i, y_i), 1 \leq i \leq n$, the object function should be fitted to have the minimum value

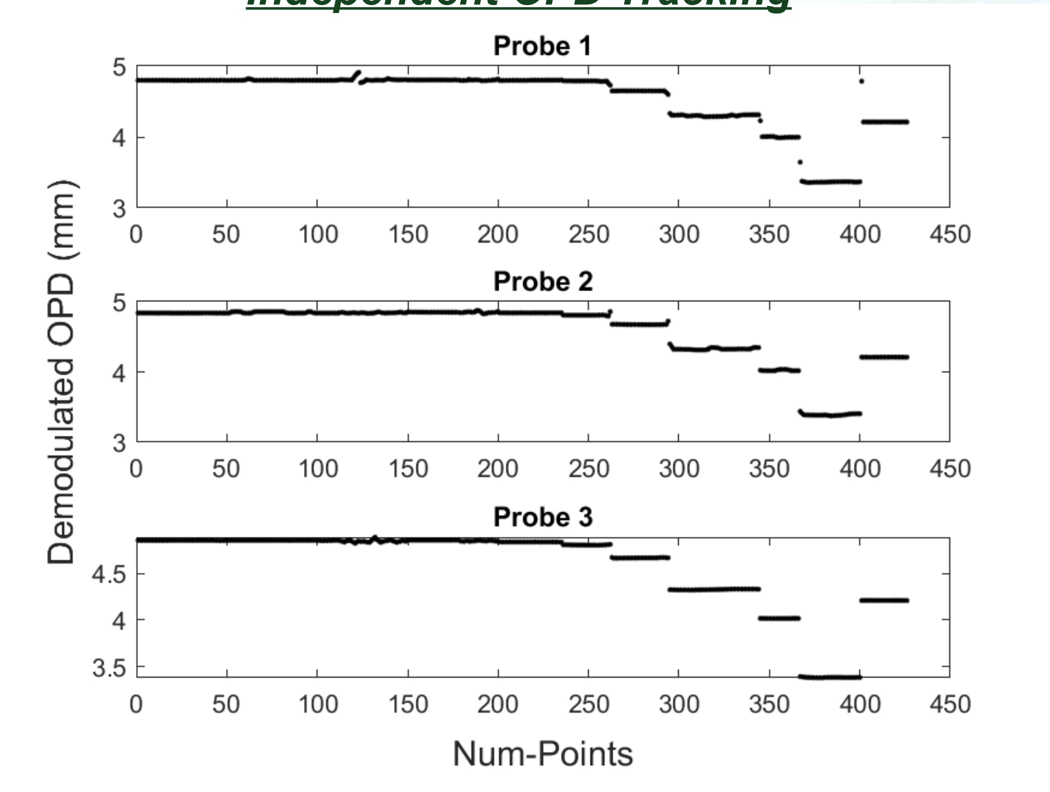
$$\mathcal{F} = \sum_{i=1}^{n} d_i^2$$

$$d_i = \sqrt{(x_i - a)^2 + (y_i - b)^2} - R$$

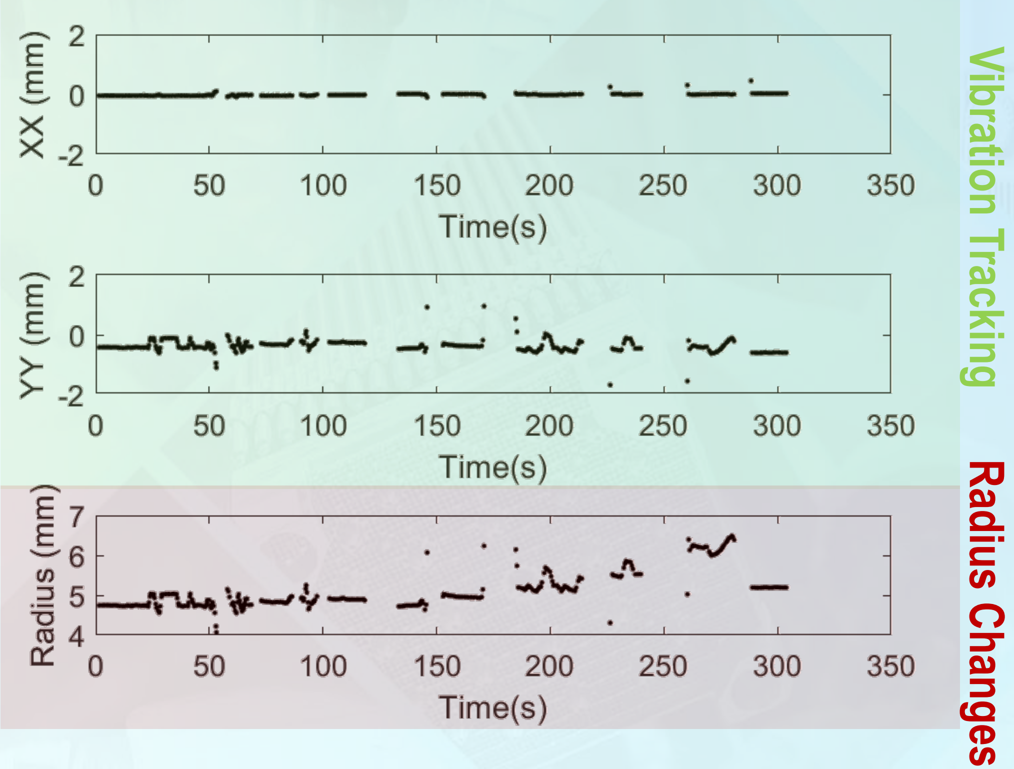
- Surface strain can be calculated after the radius is fitted

Results and Accomplishments: Triple Probe Design

Independent OPD Tracking



Vibration and Radius Change Tracking



- The hydraulic pump incrementally raises the internal pressure of the tube in a stepwise manner, involving a few strokes, followed by intermittent waiting periods.
- Circular curve fitting shows both the motion of the vibration and tube expansions.

Concluding Remarks

- Project Status and Accomplishments
  - Met deliverables and milestones per schedule
  - Submitted IP disclosures with VTIP
  - Presented at CLEO (conference)
  - Present results at TREAT Program Meeting
    - August 27, 2024
  - Phase I project ended 5/31/24

- Near-Term Work Plan
  - Phase II – Field Testing
    - Collaborate with INL team for “field test”
    - Identify test reactor/application
    - Develop sensor packaging for “permanent” install
  - Currently “On-Pause”

M	D	Description	D	M
M1	D1	Sensor Specifications and Requirements	7/23	9/23
	D2	Simulated Laboratory Test Facilities	9/23	
	D3	Theoretical Analyses of Sensor Response/Algorithms	9/23	
M2	D4	Prototype Non-Contact Displacement Sensing System	2/24	5/24
	D5	Prototype Non-Contact Strain Sensing System	3/24	
	D6	Performance Testing in Laboratory Environment	5/24	

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Thank You