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

Advanced Sensors and Instrumentation

Optical Fibers

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

October 30 – November 2, 2023

Instrumentation Engineer: Austin Fleming, PhD

Idaho National Laboratory

Project Overview

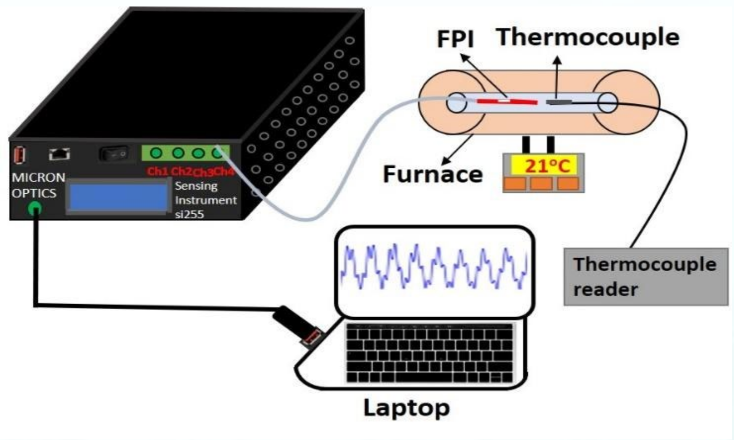
- Fiber optic technology has many sensing advantages, but few applications in nuclear environments.
- Fiber optic sensors have unique challenges associated with in-pile applications
  - Radiation Induced Attenuation
  - Radiation Induced Emission
  - Radiation Induced Compaction
  - These can result in a loss of signal or significant drift in many conventional fiber optic sensor designs
- The direct funded fiber optic activities under NEET-ASI focused on relatively high TRL items with the potential for high impact to the nuclear industry. These include the development and qualification of:
  - Fiber optic based pressure sensor
  - Distributed in-pile temperature sensing
  - In-pile imaging
  - Active Compensation/Drift correction for intrinsic temperature sensing
- An overview of these 4 activities will be given here

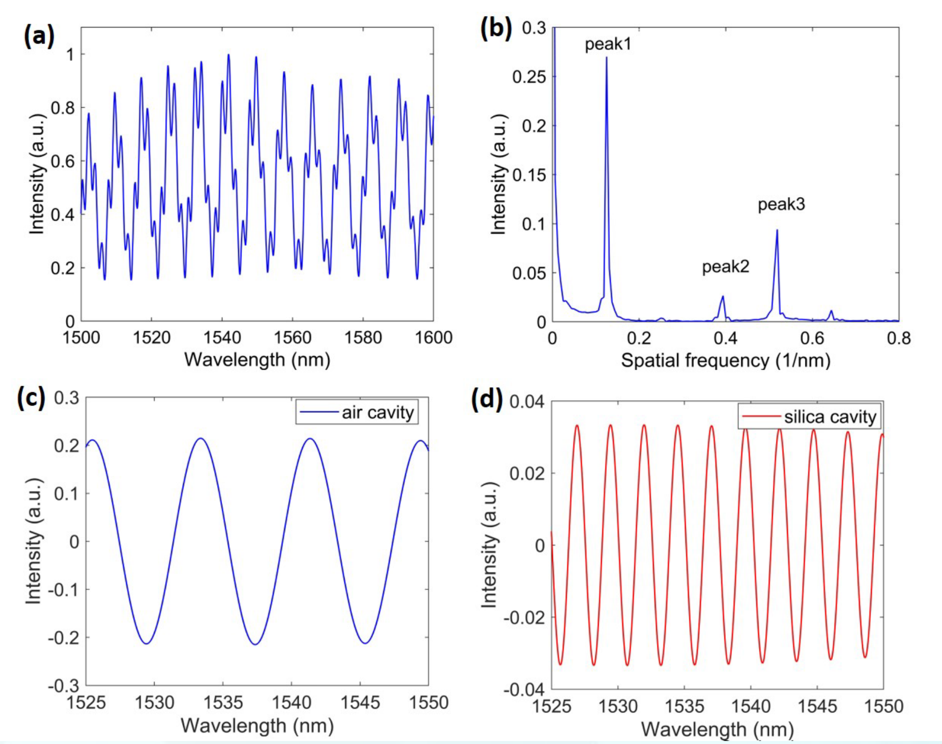
Project Overview (Intrinsic Temperature Sensor)

- Distributed temperature sensing using Rayleigh scattering (Optical Frequency Domain Reflectometry)
  - Commercially available systems
  - Unique considerations are required for in-pile work
- Much longer lead in lengths compared to other applications (often ~20-30m of fiber length with the *only* the last 1-2m providing data of interest.
- Multiple feed throughs, often multiple connections required.
- Unique considerations for fiber selection (minimize radiation effects)
- High temperature operations
  - Often bare fibers (coating is removed) are used for high temperature, but this makes fiber fragile
  - Sensor incorporation often requires robust sensors for experiment assembly (preferably with coating)

Project Overview (Active Compensation)

- Like radiation, temperature also alters the refractive index (RI) and length of fiber optic
- As a proof-of-concept, we experimentally demonstrate real-time monitoring of temperature effects on the RI and length and measure thermal expansion coefficient (TOE) and thermo-optic coefficient (TOC) using the cascaded Fabry-Perot.
- Temperature is increased from 21 to 486° C and data is monitored by optical interrogator





Linear compaction in air cavity,

$$C_a = \frac{L_{a,i} - L_{a,f}}{L_{a,i}}$$

Linear compaction in silica cavity,

$$C_s = \frac{L_{s,i} - L_{s,f}}{L_{s,i}} = C_a$$

Final length of silica cavity,

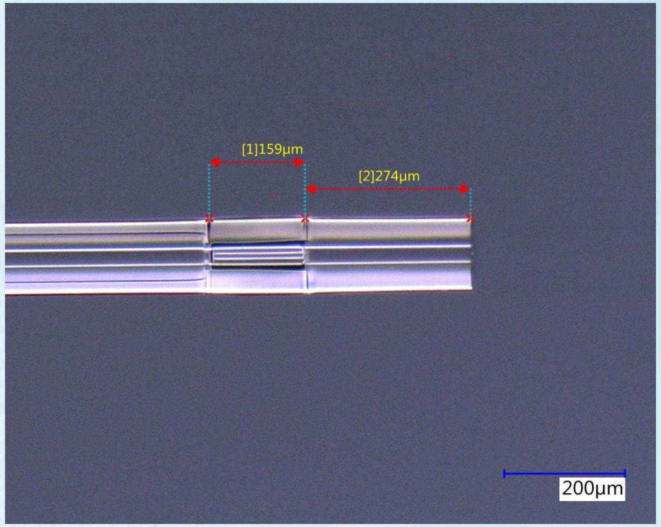
$$L_{s,f} = L_{s,i} - L_{s,i} \times C_s$$

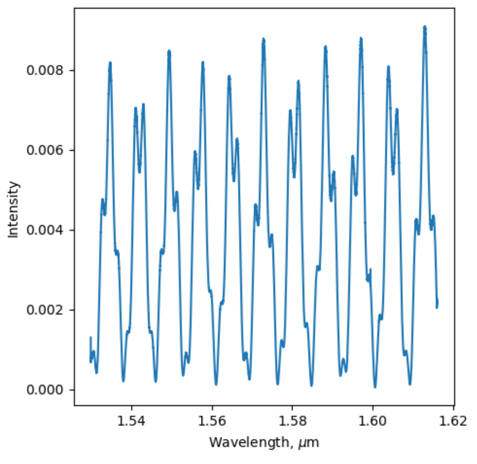
Optical length of silica cavity

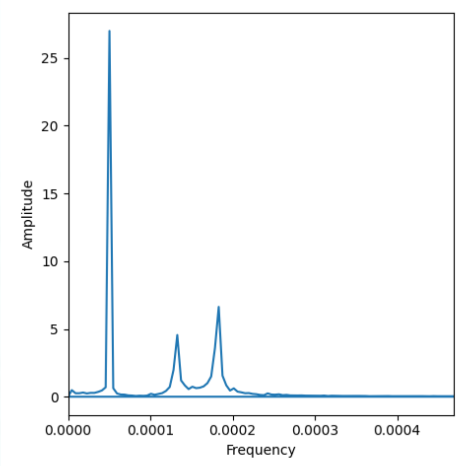
$$L_{s,opt} = n_{2f} L_{s,f}$$

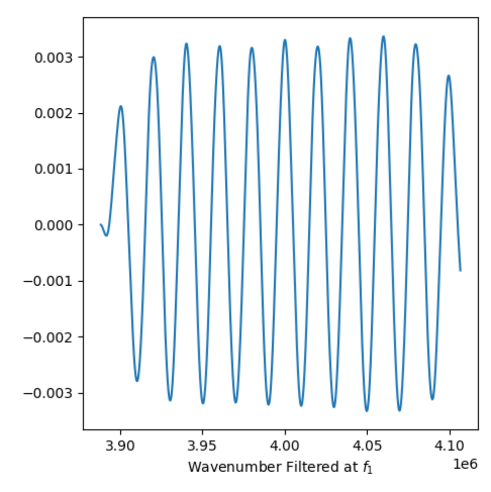
Project Overview (Active Compensation)

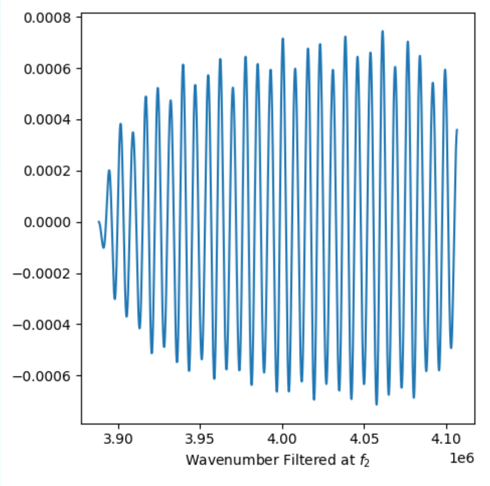
- The active compensation “sensor” has been deployed in MITR
  - Sensor shown at right and initial data from irradiation
- Scheduled to be irradiated in BR2 in collaboration with our French counterparts with CEA
  - CEA has been working on a similar setup with free space optics which is being tested as part of the experiment
- Data analysis from irradiation is ongoing, report to come out shortly.





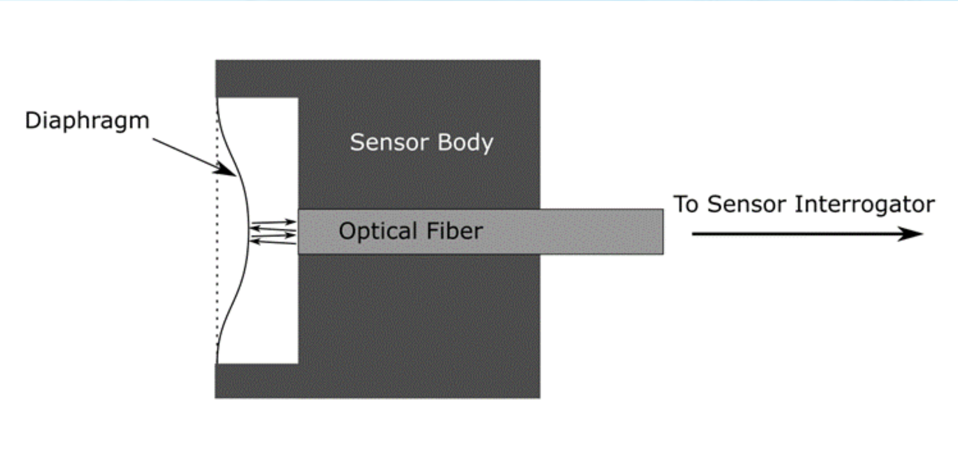


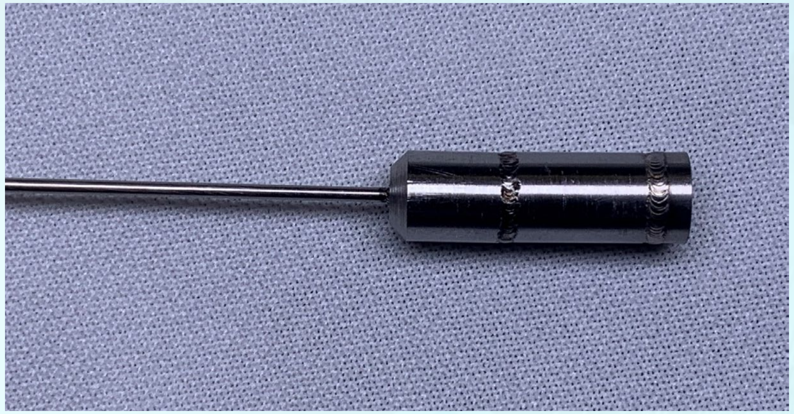




Project Overview (Pressure Sensor)

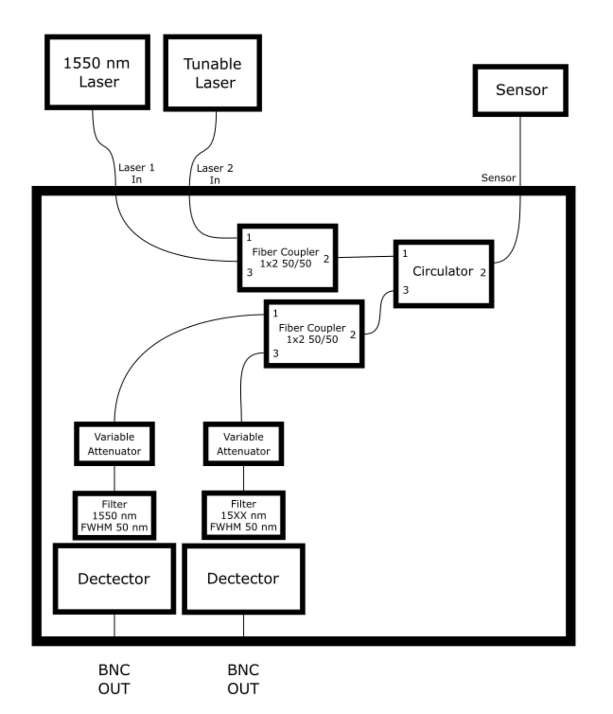
- **Motivation:** Pressure is an extremely important parameter for thermodynamic and structural considerations
    - Heat Transfer
    - Phase Change
    - Structural Integrity (cladding/primary containment)
    - Coolant Flow (measurement/control)
- **Background:** Fiber Optic Fabry Perot Pressure Sensors
    - Widely documented in literature
    - Limited commercial availability
    - Based on light interference spectrum
    - Small Footprint
    - Relatively High Temperature
    - Customizable Pressure Range

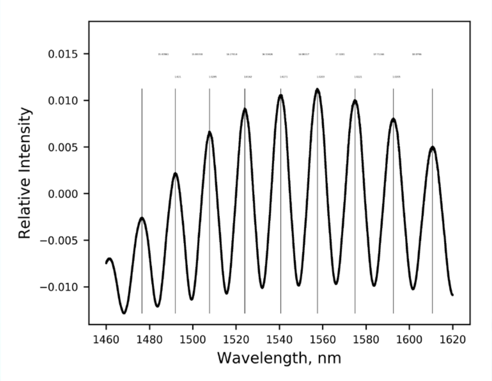


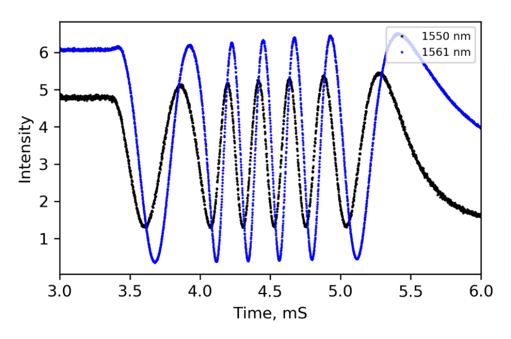


Project Overview (Pressure Sensor)

- Several design improvements have been made to increase reliability and sensor fabrication yield
- Designed, assembled, and integrated a “high-speed” data acquisition system for

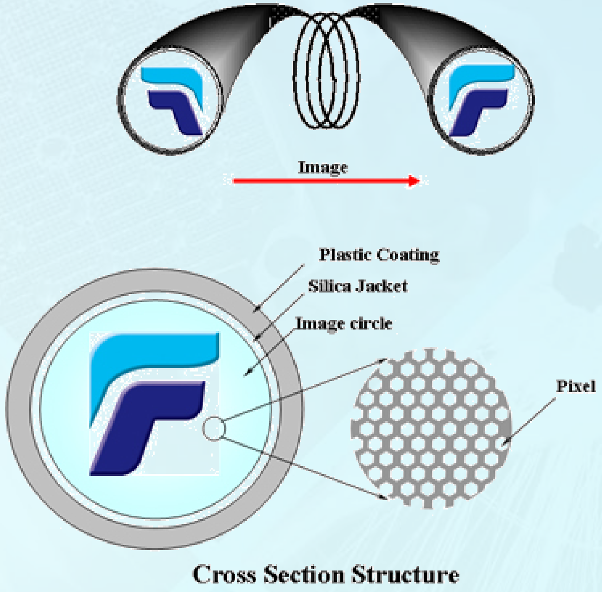






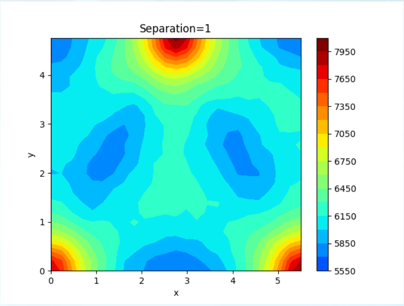
Project Overview (In-pile imaging)

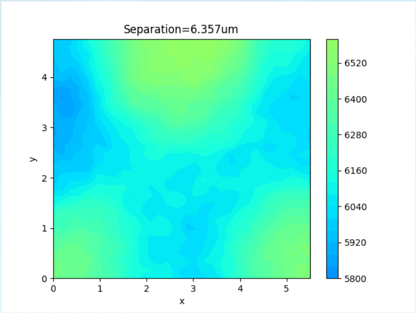
- Motivation:
  - Quantitative and qualitative information about in-pile conditions, properties or state
  - Diagnostics or control of systems
- Image bundles are commercially available “off-the-shelf” with up to100,000 fibers, the fiber bundle used in this demonstration had 10,000 fibers
- Fiber bundles have the potential to be compatible with various experiments, as their feedthroughs and footprints are similar to those of other sensor types
  - Diameter 0.5 mm - 2 mm
  - Would not require facility modifications

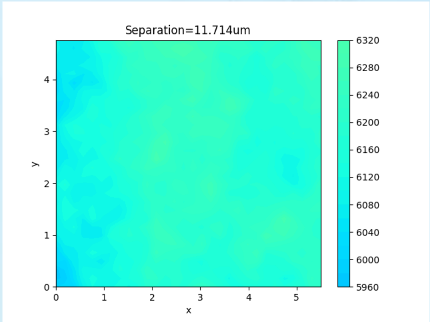


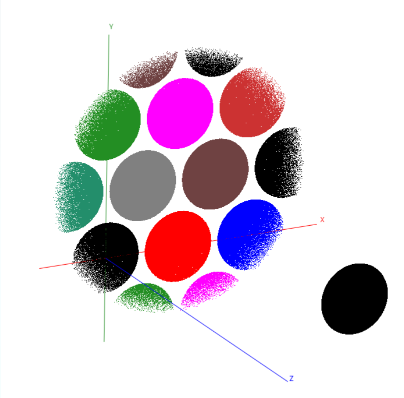
Project Overview (In-pile imaging)

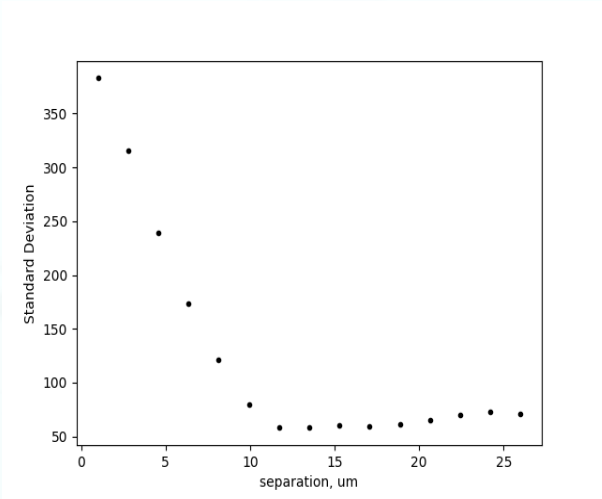
- Unique challenges for nuclear environments:
  - RIA
  - RIE (Cherenkov and Radioluminescence)
  - Long lead lengths (connections)
  - Index of refraction changes (lenses and fibers)
  - Fiber acceptance angle (NA) and challenges with designing lens systems with high magnification

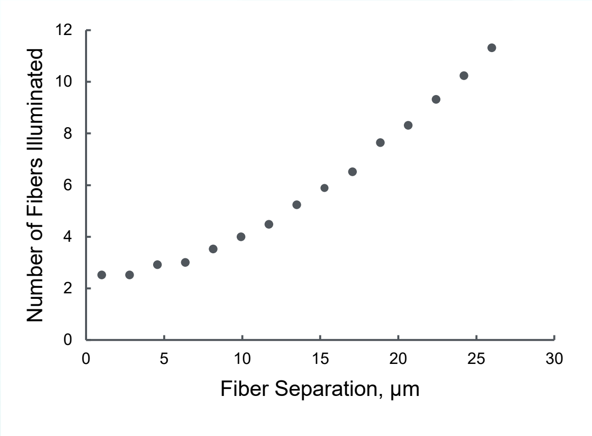


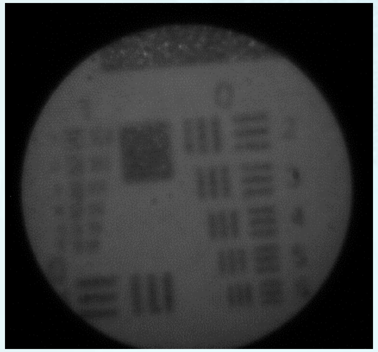




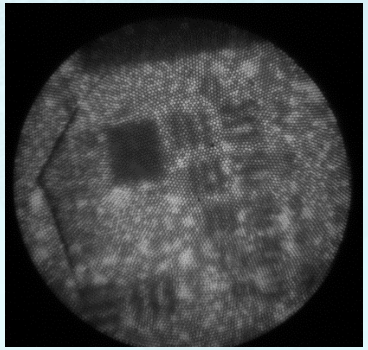




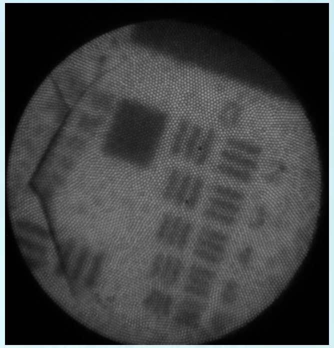




Single Bundle



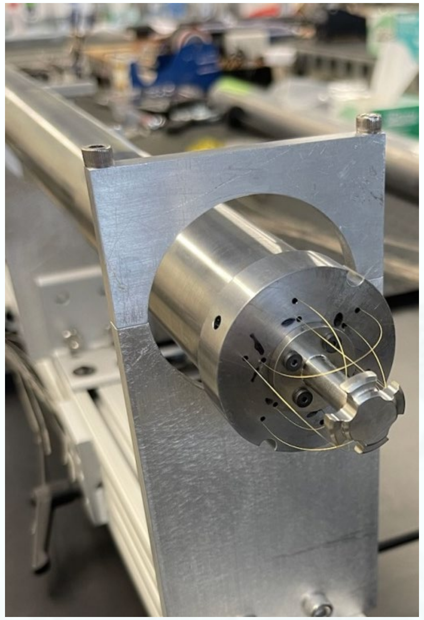
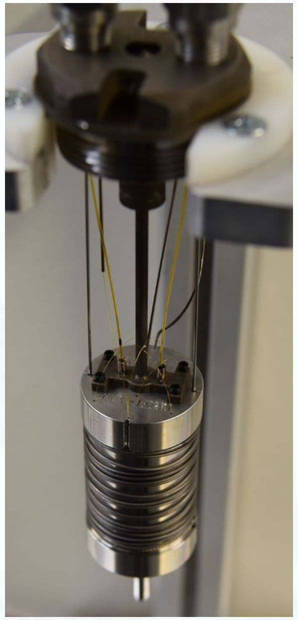
Two Bundles in Contact

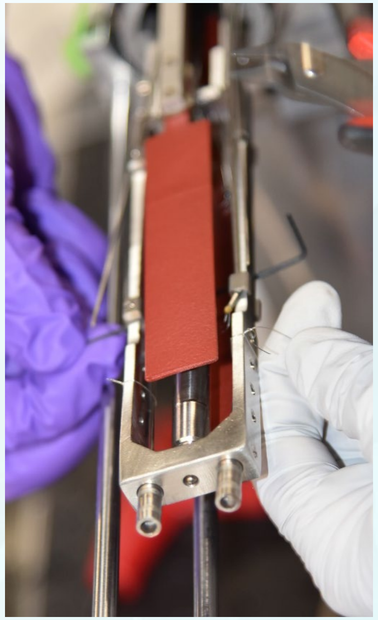
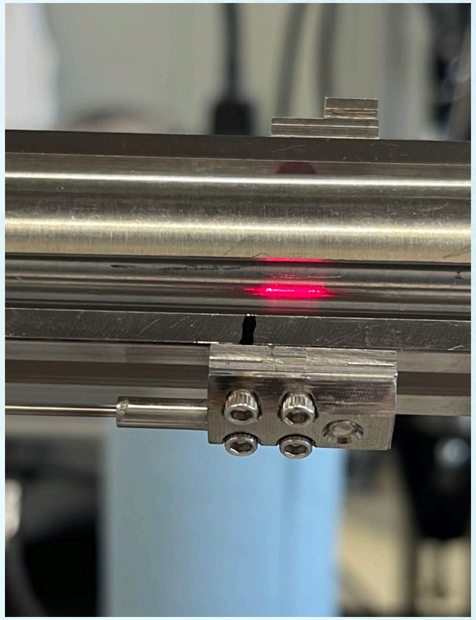
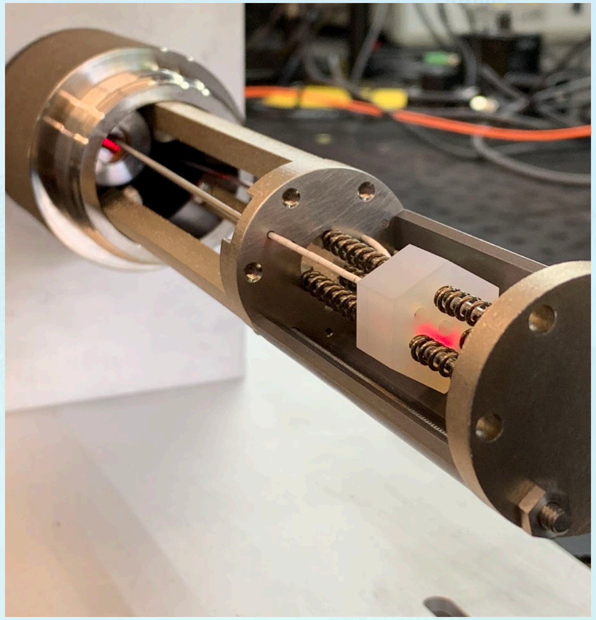


Two bundles separated slightly

Technology Impact

- Fiber optic sensors presented here are now routinely used in irradiation experiments to meet data objectives
- Some advanced reactor companies are planning to use fiber optic sensors as part of reactor monitoring & control

Fiber optic sensors in all these irradiation experiments were included to meet experiment data objectives

This was made possible by the ASI program

Concluding Remarks

- Broad set of fiber optic technologies for nuclear applications is being matured through the ASI program
- Significant progress has been made in the development and deployment of fiber optic sensor in irradiation environments (significant experience on fabrication, packaging, and installation that is unique to nuclear applications)
- Fiber optic sensors have a very exciting future for nuclear applications
  - Scratched the surface of their potential
- FY23 Significant work scope and limited personnel bandwidth
  - Recently hired Charles Payne (Start date December 4)

Austin Fleming
austin.fleming@inl.gov

Thank You