U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY
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Fiber-Optic Sensor for Simultaneous Measurement of Temperature and Pressure

FY2019 Progress
for
DOE SBIR Award DE-SC0017826

Advanced Sensors and Instrumentation Annual Webinar

October 30, 2019

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Luna Innovations Incorporated

LUNA

Luna Overview

We're organized into two main business segments: **Products and Licensing** and **Technology Development**, which work closely together to turn ideas into products

Products and Licensing segment

Fiber optic instruments:

Develop and commercialize breakthrough technologies for targeted industries

- Sensing products for the high growth aerospace, automotive, and energy markets
  - ODiSI™-6000 Series
  - OBR™-4600
  - Hyperion™ si155 and si255
- Test & measurement solutions, primarily for the telecommunications industry
  - OBR™-4600
  - OVA™5000

Terahertz solutions:

Develop and commercialize disruptive sensing technologies for manufacturing applications

- Leading provider of industrial systems for quality control, inspection, and process control

Technology Development segment

Applied research:

Contract research ultimately focused on commercialization

- Focused areas: **Sensing & instrumentation**, Materials, Health sciences, Optical systems, Terahertz

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Luna is a global company providing innovative products and solutions using proprietary fiber optic technologies

- Founded 1990
- Corporate headquarters in Roanoke, VA
- 260+ Employees
- IPO in 2006 - NASDAQ: LUNA
- Reporting Segments
  - Technology Development
  - Products and Licensing
- Worldwide presence and support
- Strong, consistent growth
- Recent expansion
  - **Micron Optics – 2018**
  - **General Photonics - 2019**

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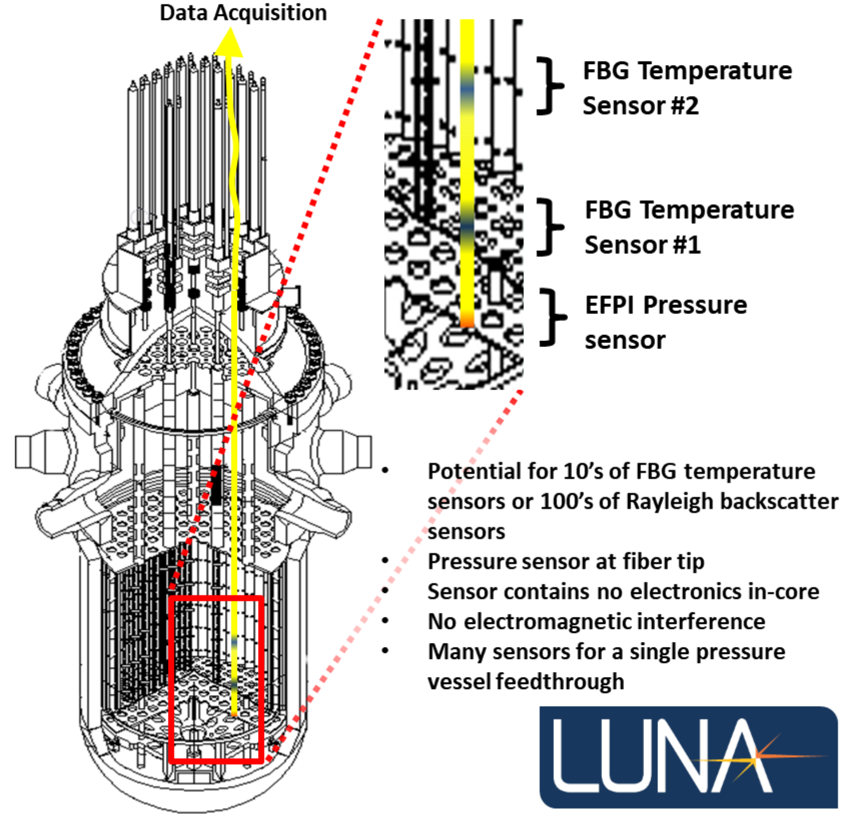
The Problem

- Desire sensors that reduce containment vessel feedthrough count
- Combine fiber optic sensors to measure multiple properties
  - No electrical power requirements in vessel
  - Serial inline sensors reduce number of signal cables
- Targeting DOE Labs, Gen III & IV Commercial nuclear power, other high temperature harsh environments

Fiber Optic Sensor for Simultaneous Measurement of Temperature and Pressure



Fiber Optic Sensor for Simultaneous Measurement of Temperature and Pressure

Technology Summary

This project is working towards the advancement of multi-point temperature and pressure sensors toward commercialization of sensors for GenIV reactor environments. During Phase I sensors were successfully evaluated to 1000˚C, combined temperature and pressure of 300˚C and 2500psi, and to neutron fluence of 9E17 n/cm^2. Phase II has produced advancements in feedthrough fabrication, material compatibility studies, and testing of sensors to 2.54E18 n/cm^2. Temperature and pressure measurements are achieved by combining Fiber Bragg Gratings (FBGs) on the same fiber as one of Luna's Extrinsic Fabry-Perot Interferometer (EFPI) sensors. This design utilizes recent advances in fiber chemistry and FBG manufacturing techniques resulting in radiation hardened sensors.

Technology Impact

Current temperature measurements utilize single point Type-K thermocouples, and to the PI's knowledge, there exist no in-core pressure sensors.

Luna's sensor under development, will provide multipoint temperature readings with single point pressure at the fiber tip. This new class of sensor will provide for advanced monitoring while decreasing cable feedthroughs.

Project Summary

Period of Performance: Total Budget: $1,159,994

Start Date: 6/12/17 End Date:8/26/2020

Key Milestones & Deliverables	
2017 Sept.	• Phase I Project Kickoff
2018 March	• Phase I Final Report
2018 Sept.	• Phase II Project Kickoff
2019 June	• Sensor Operation in OSURR
2020 March	• Sensor Operation in OSURR
2020 Summer	• Long Sensor Operation in OSURR

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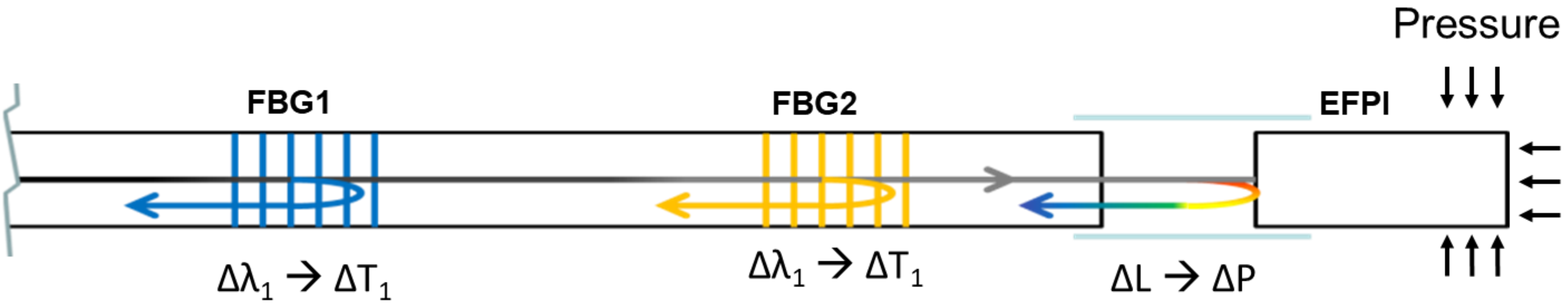
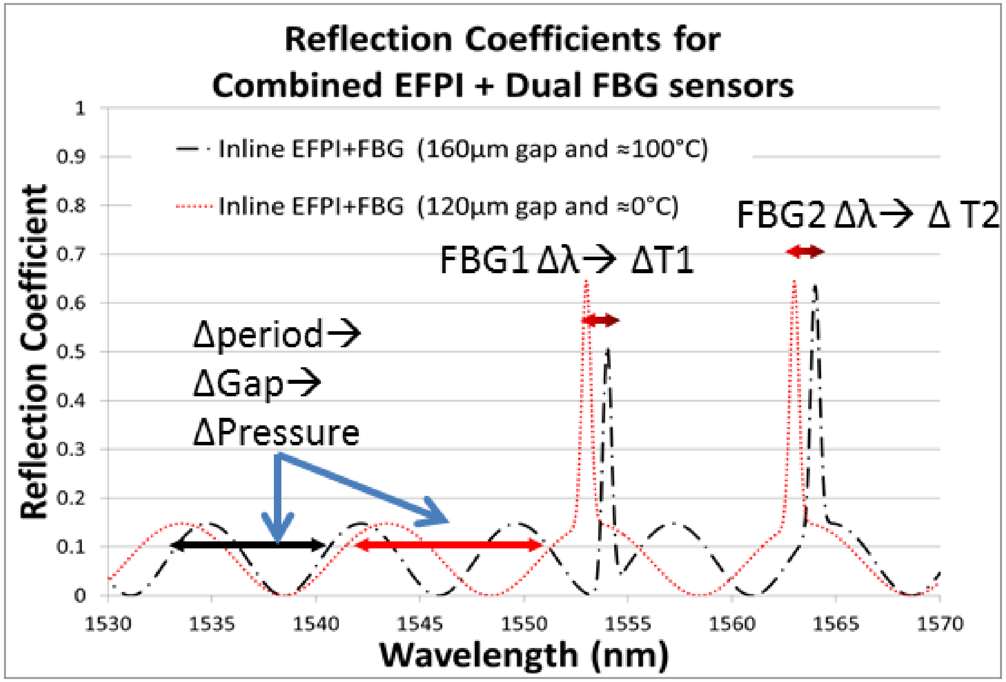
Sensor Response for EFPI with Serial FBGs





- Change in temperature at FBG yields a wavelength shift directly proportional to temperature
- Change in Pressure at the EFPI produces a change in cavity length which is measured by the change in fringe period

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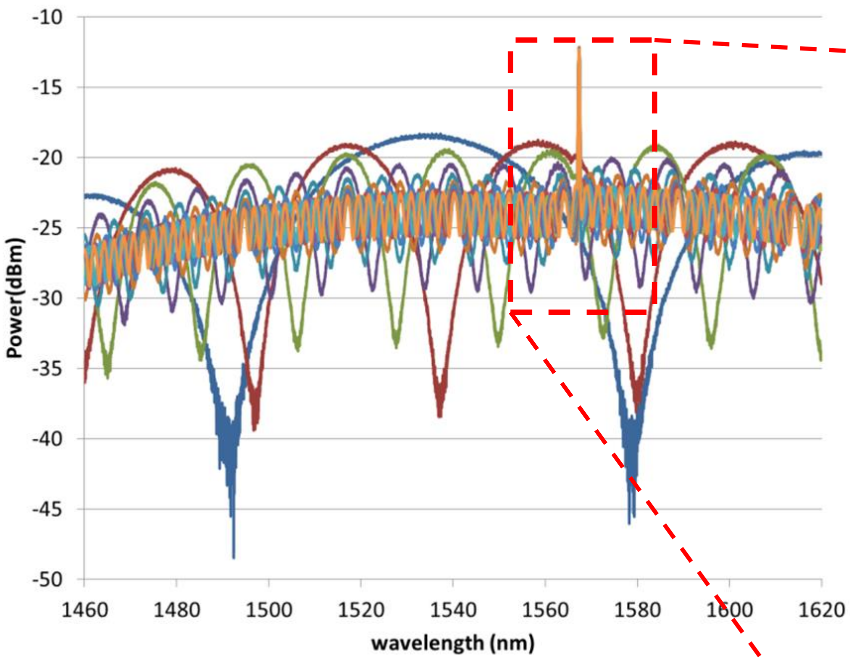
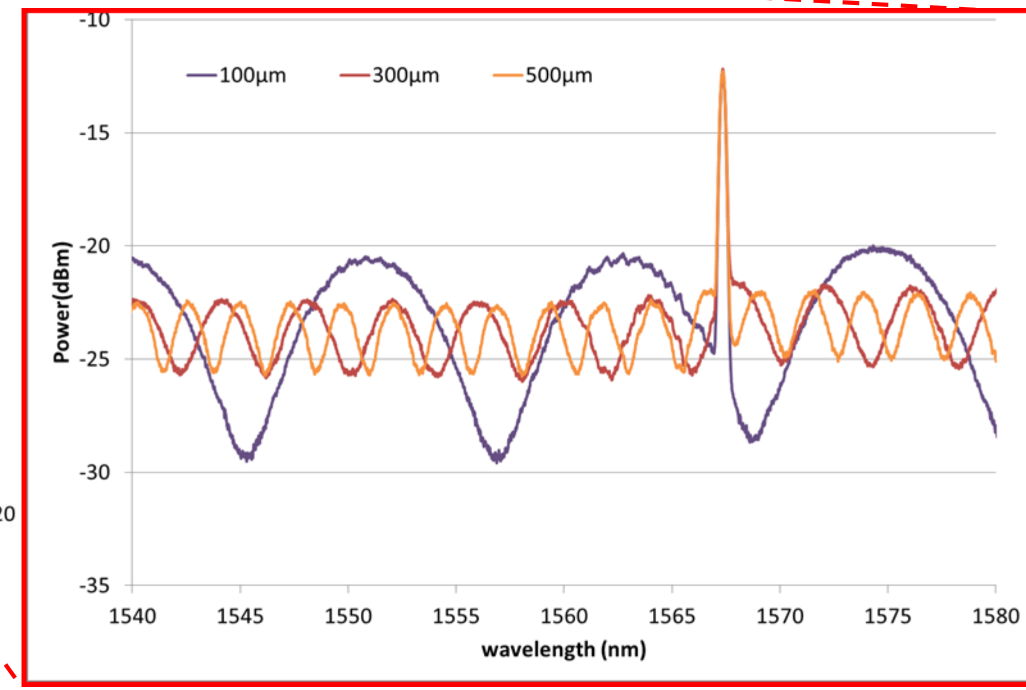
Sample Data from Combined EFPI and fsFBG Sensor Using Luna Hyperion si155

Combined EFPI and fsFBG Sensor
For Multiple EFPI gap distances

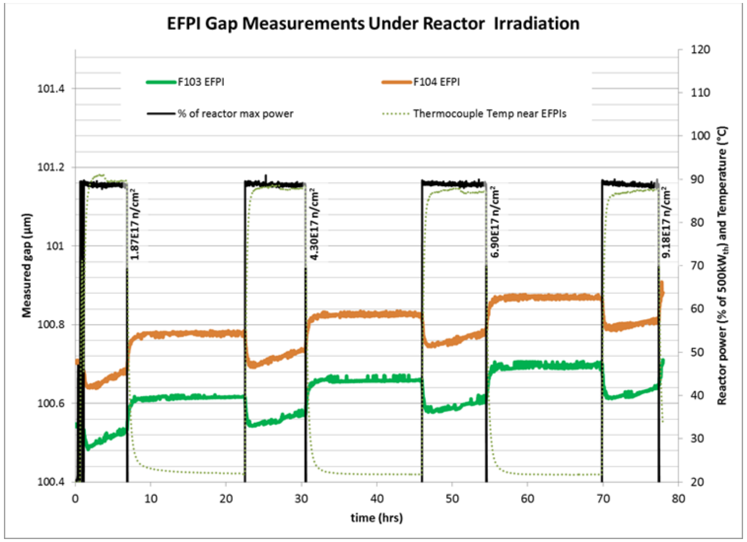


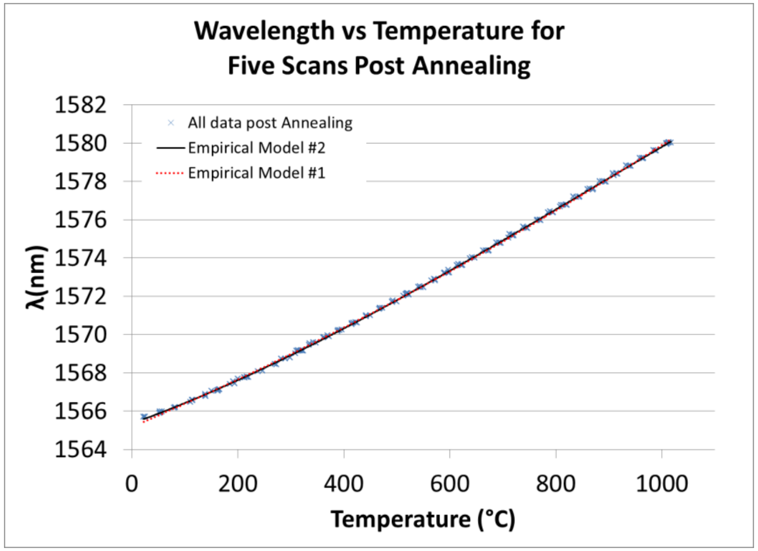


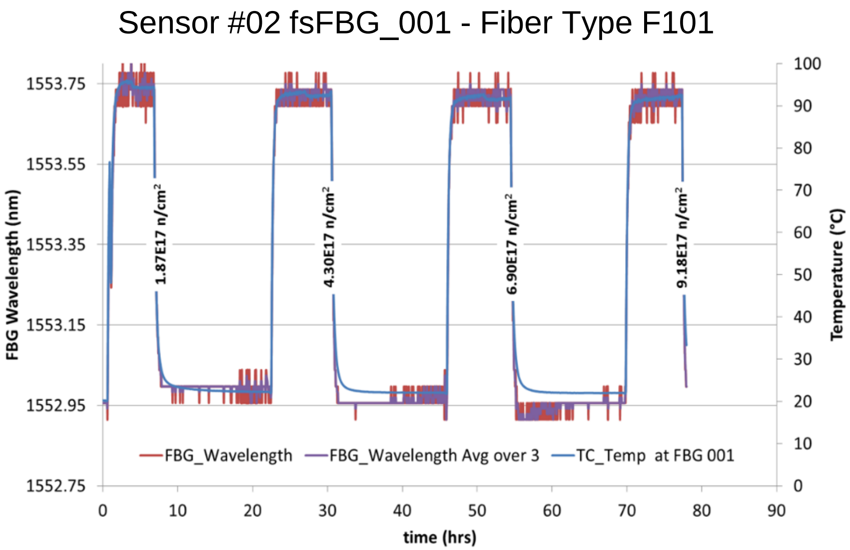
Data collected at room temperature using a translational stage to vary EFPI gap

Year 1 (Phase I) Accomplishments

Temperature sensing to 1000˚C
FBG Temperature and EFPI gap sensing
in radiation environment of:
9.18E17 n/cm2
2.6E7 rad-Si neutron dose
1.3E9 rad-Si gamma dose
Temperature and pressure sensing to
300˚C and 2500 psi







Year 2 (Phase II year 1)

The focus of Year 2 has been on:

1. Continuing analysis of phase I data
2. Developing moderate temperature high pressure feedthrough
3. Developing high temperature moderate pressure feedthrough
4. Advancing sensor development
5. Performing high irradiation tests
6. Publishing Phase I and Phase II results

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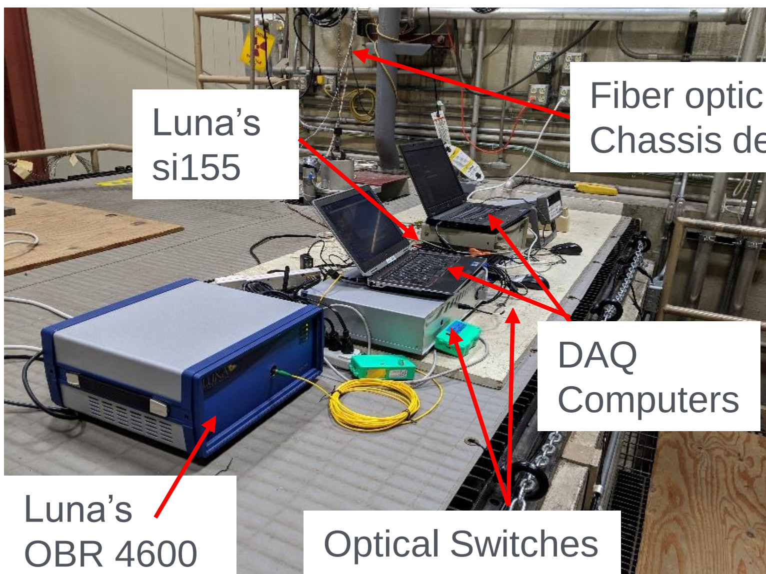
VIRGINIA TECH

University of Pittsburgh



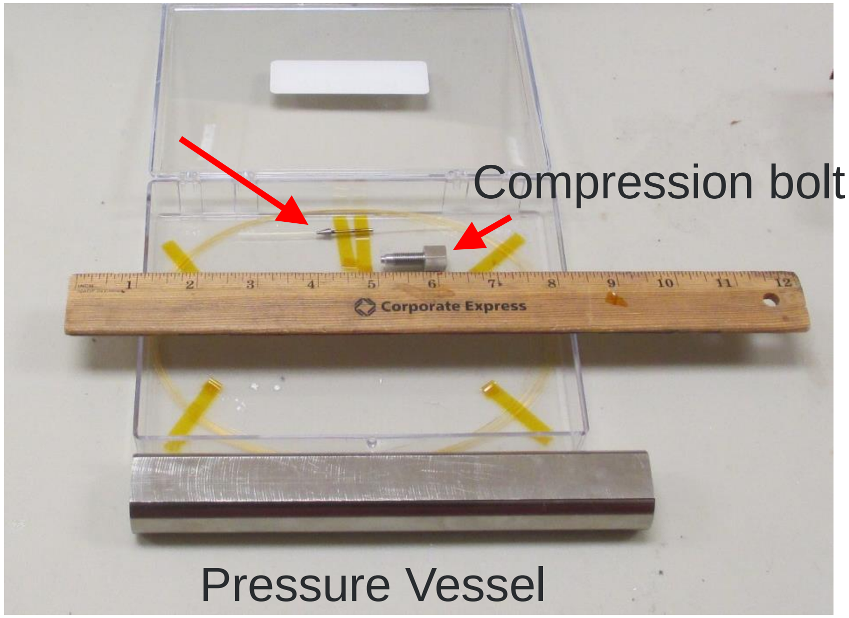
Pressure Feedthrough Development

Phase I lower temperature feedthroughs acquired from external source.

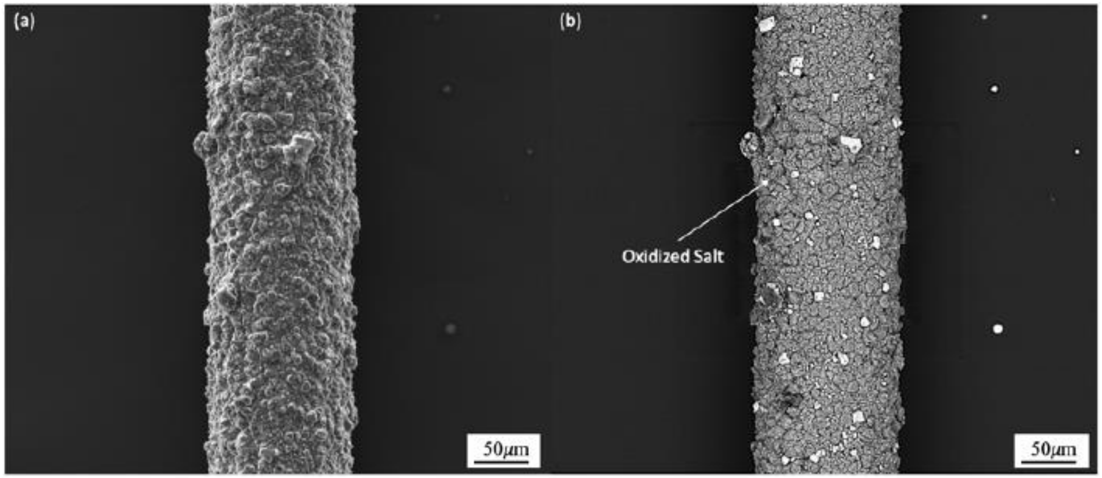
Acquisition of Micron Optics (Luna-Lightwave, Atlanta) provided additional manufacturing capabilities

1. Feedthroughs are being developed at Luna-Lightwave, Atlanta.
    1. Glass to metal transition mechanical design complete
    2. Initial feedthroughs developed
    3. Thermal cycling from room temperature to 350˚C
    4. Assembly cross-sections show no degradation
    5. Pressure and combined pressure and temperature sensor construction expected in early 2020.
    6. High-temperature moderate pressure feedthrough expected in mid-2020.

Phase I pressure penetrator:
Fiber optic pressure vessel feedthrough
Rated for 300°C and 5000psi



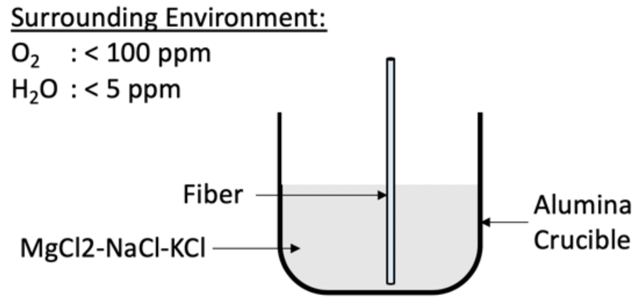
Sensor compatibility studies

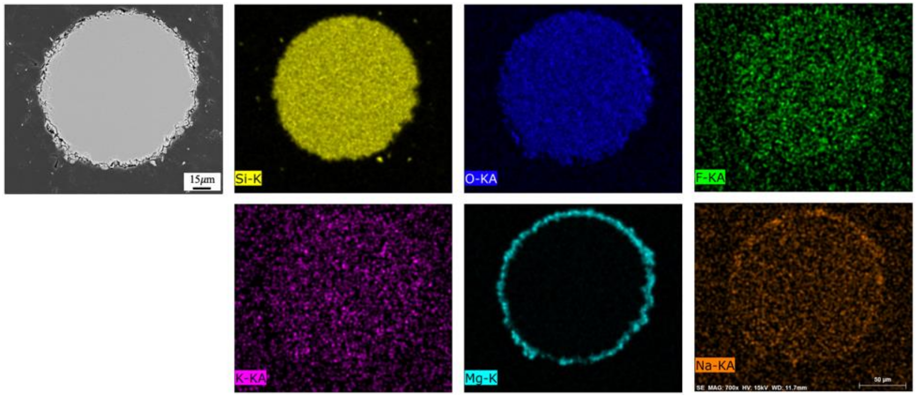


(a) SE and (b) BSE images showing oxidized salt fully cover fiber optic F103 immersed in MgCl2-KCl-NaCl after 24 hours

MgCl2-KCl-NaCl test

- **Salt covered surface**
- **No salt penetrated the fiber**





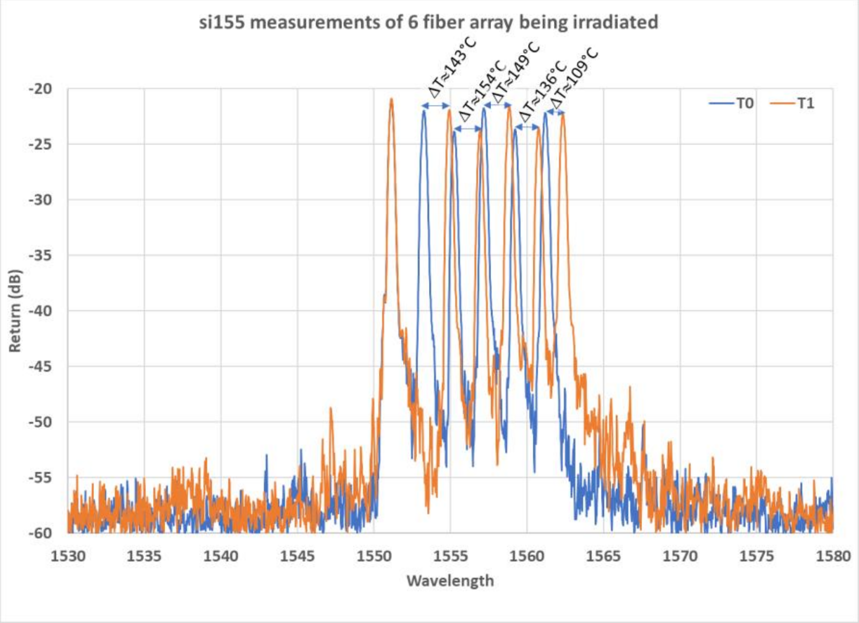
	Material	Environment				
		Steam	FLiNaK	Pb-Bi	PWR	MgCl2-KCl-NaCl
Fiber Packaging	SS 316	✗	✗	◦	•	n/a
	Hast. N	◦	◦	✗	•	n/a
	Hast. X	◦	✗	✗	•	n/a
Raw Fibers	F 101	•	✗	✗	n/a	TBD
	F 102	•	✗	✗	n/a	TBD
	F 103	✗	✗	◦	✗	✓
	F 105-1	✗	✗	◦	n/a	TBD
	F 105-2	✗	✗	•	n/a	TBD
	F 106	✗	✗	✗	n/a	TBD

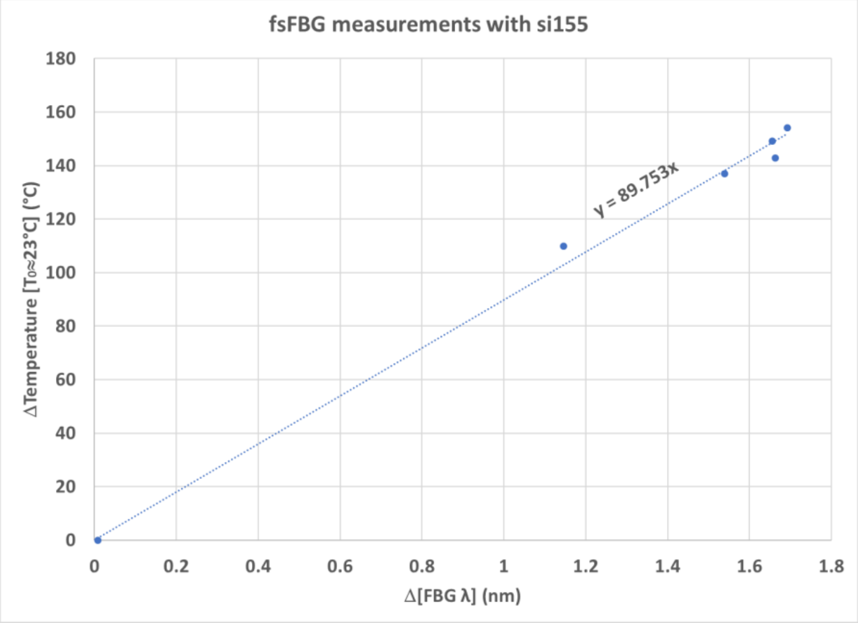
Legend

✓ Excellent • Good ◦ Moderate ✗ Incompatible n/a Not Applicable

Type-II FBG’s Tested in Rad-Hard Optical Fiber

- fsFBG λ shifts near linearly with respect to temperature
- The measurements shown are at room temperature and 100˚ C+ with the first fsFBG always at room temperature
- Proportionality constants vary depending on fiber with ranges of 8-16 pm/˚C (62-125˚C/nm)

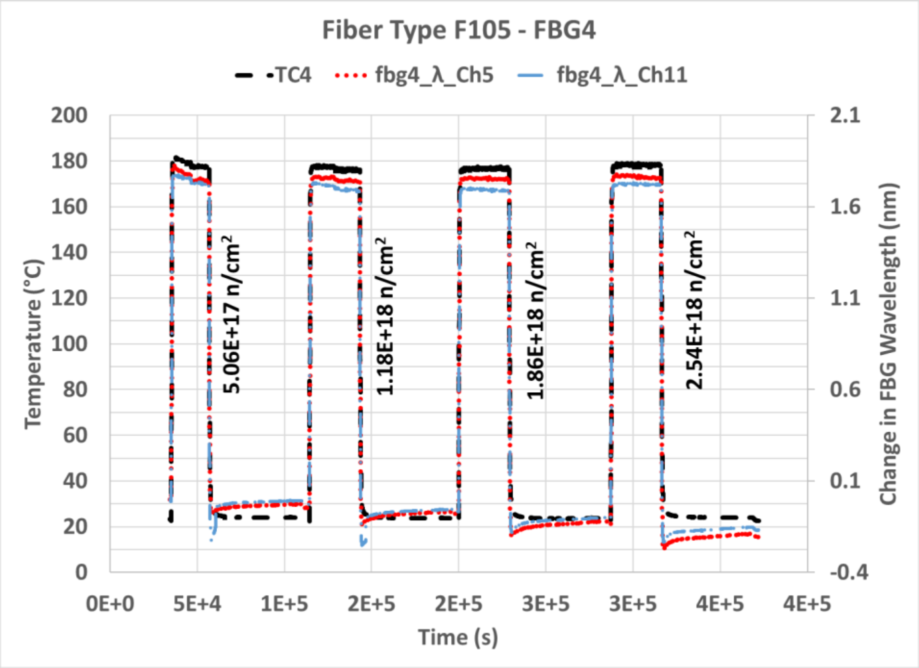


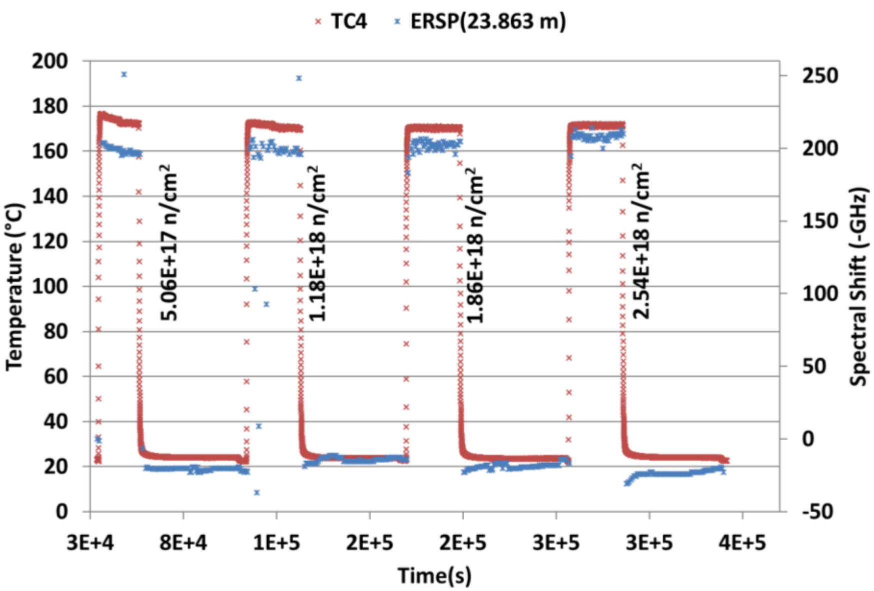


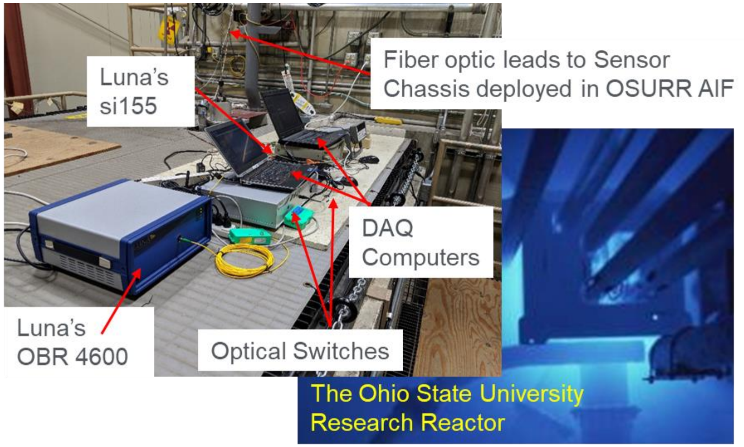
Type-II Enhanced Rayleigh Scatter Tested in Rad-Hard Optical Fiber

- Similar to fsFBG's the spectral data from Rayleigh scatter for a given region of fiber shifts as temperature changes.
- By writing scattering points we are able to raise the Rayleigh scatter level increasing the signal to noise ratio for such measurements
- The graphs below show the FFT from the delay domain to the frequency domain for in regions with and without Enhanced Rayleigh Scatter Points.

OSURR Irradiation







Publications and Conferences

- S. Derek Rountree, “Fiber Optic Sensor for Simultaneous Measurement of Temperature and Pressure,” Advanced Sensors and Instrumentation Newsletter, Issue 9, Sept. 2018,
- Brian Risch, et. al, “Characterization of Fiber Optics with Femtosecond-Infrared Fiber Bragg Gratings for Extreme Applications,” SPIE OPTO 2019
- Steven Derek Rountree, et. al, “Fiber Optic Pressure and Temperature Sensors for Gen IV Reactor Environments,” 2019 ANS Winter Meeting & Expo, Washington D.C. November 17-21, 2019 **(Accepted)**
- Steven Derek Rountree, et. al, “Multi-parameter fiber optic sensing for harsh nuclear environments,” SPIE Defense and Commercial Sensing, 26 - 30 April 2020 **(Submitted)**

Year 3 (Phase II Year 2)

1. Continue analysis of phase I data
   - 0-1000 ˚C at ambient pressure
   - 300˚C @ 2500psi
   - 0 - 9.18E17 n/cm^2 with varying temperature 0-90˚C
2. Publish Phase I results
3. Advance sensor development for 350˚C @ 3500psi
   - Test sensors to 350˚C @ 3500psi in noble gas
   - Test sensors to 350˚C @ 3500psi water loop
4. Advance sensor development for 525˚C+ @ 100psi
   - Test sensors to 537˚C @ 100psi in noble gas
   - Test sensors to 537˚C @ 100psi in molten salt loop
5. Advance sensor development for 750˚C+ @ 100psi
6. Develop advanced analysis algorithms
7. Determine standard operating procedure for sensor calibration
8. Perform high temperature and pressure tests in irradiation environment
9. Perform high irradiation tests

Technology Impact

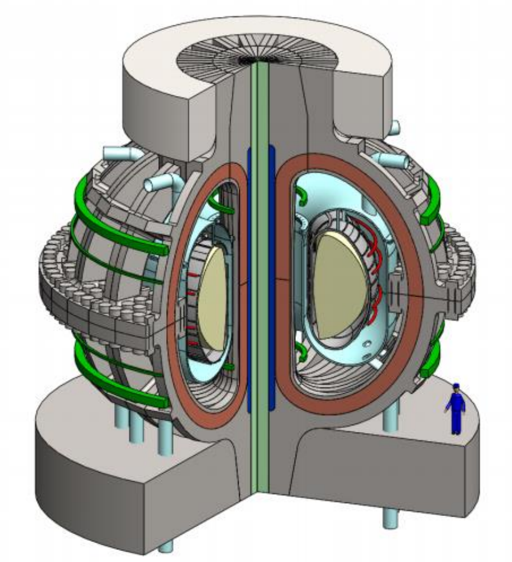
The sensor development of the "Fiber-Optic Sensor for Simultaneous Measurement of Temperature and Pressure" project will:

- *Provide never before available:*
  - *In-core single feedthrough multipoint temperature sensing*
  - *In-core pressure sensing*
  - *Multipoint temperature with endpoint pressure sensing*
- *Provide enhanced sensing capabilities for:*
  - *Reactor monitoring*
  - *GenIV fuel and fuel assembly studies*
  - *Solar salt loop monitoring*
- *Enable advanced instrumentation and controls*
- *Be Commercialized via Luna's extensive network of commercial partners in the nuclear industry.*

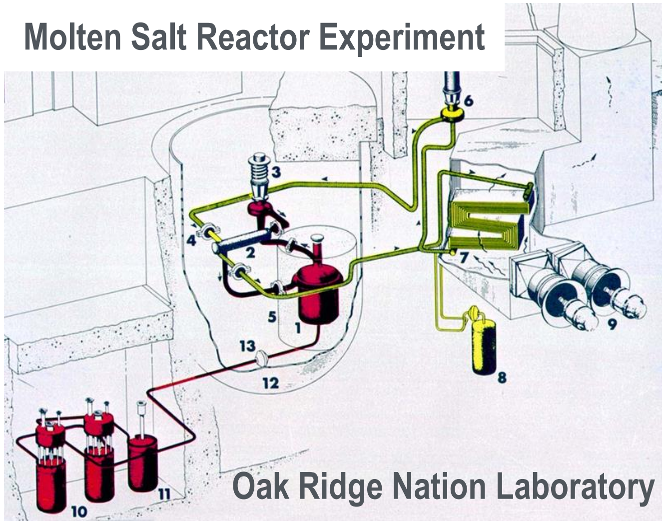
Energy Markets

- **Gen IV Reactors**
- **Fusion Reactors**
- **Solar Concentrator Power Plants**
- **And More**

ARC fusion reactor



B.N. Sorbom et. al, “ARC: A compact, high-field, fusion nuclear science facility and demonstration power plant with demountable magnets,” Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, MA 02139, USA, https://arxiv.org/pdf/1409.3540.pdf



Conclusion

Phase I Accomplishments:

- Temperature sensing to 1000˚C
- Temperature and EFPI gap sensing in radiation environment of:
  - 9.18E17 n/cm2
  - 2.6E7 rad-Si neutron dose
  - 1.3E9 rad-Si gamma dose
- Temperature and pressure sensing to 300˚C and 2500 psi

Phase II Goals:

- Sensor packaging for existing PWR fleet
- Sensor packaging for GenIV molten salt reactor environment
- Sensor packaging for GenIV molten metal reactor environment
- Sensor testing in combined temperature, radiation, and pressure environment

Team

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Pitt – Kevin Chen, Mohan Wang

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This material is based upon work supported by the Department of Energy, Office of Science, Office of Basic Energy Sciences under Award Number DE-SC0017826."

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