U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Office Of Nuclear Energy Sensors and Instrumentation Annual Review Meeting

High Spatial Resolution Distributed Fiber-Optic Sensor Networks for Reactors and Fuel Cycle

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NEET Program

October 18-20, 2017

Project Overview

- **Goal, and Objectives: In-core and Out-of-Core Situation Awareness are key for next-gen NE in term of safety and cost reduction**
  - Develop new optical fibers for nuclear industry
  - Explore and demonstrate distributed multi-functional fiber optical sensors for nuclear industry
  - Evaluate various distributed sensing schemes and demonstrate unique capability
  - Develop manufacturing schemes for sensor-fused smart parts for nuclear industry.
  - Evaluate fiber sensors for in-pile measurements.
- **Participants: a vertically integrated team.**
  - University of Pittsburgh: Dr. Kevin P. Chen (PI), Dr. Zsolt Poole, Dr. Aidong Yan, Dr. Rongzhang Chen, and Mohamed Zaghloul
  - Westinghouse Electrical Company: Dr. Michael Heibel, Dr. Robert Flammang, and Melissa Walter
  - Corning Inc.: Dr. Ming-Jun Li and Jeffrey Stone
- **Schedule:**
  - Year 1: active fiber sensing technique developments, multi-functional fiber fabrications
  - Year 2: distributed pressure and temperature measurements in weak radiation environments
  - **Year 3: distributed and point fiber sensors in strong radiation environments (in-core)**
  - Year 4: NCE – distributed fiber sensors for chemical measurements

Project Overview

What is unique about fiber optical sensors?

- Resistant to harsh environments (but no all environments).
  - High Temperature up to 800C, high pressure up to 2500 psi, gamma radiation (MGy).
  - High neutron radiation (to be evaluated)
- Fully embeddable into concrete, metal, and existing infrastructures
- Unique capability to perform distributed measurements with high spatial resolution (1-10cm)

What is unique about nuclear applications?

- Radiation (but no all environments are extremely radioactive).
- Need perform a wide arrange of measurements beyond temperature and strains.
- **Sensor needs for in-core applications – Key to reduce design redundancy and cost of NE**

	Spent Nuclear Fuel Pool	Containment Dome	Steam Generator	Research Facilities (LHC, LMJ, ITER)
				
Normal Operation Radiation	2 mGy/hr	50 µGy/hr	<10 mGy/hr	50 Gy/day
Normal Operation 20-yr Dosage (Gy)	350 Gy	8.8 Gy	1.75 kGy	200 kGy
Post-Accident Radiation (Gy/hr)	2 Gy/hr	5Gy/hr	5 Gy/hr	N/A
Post-Accident 30-day Dosage (Gy)	1.44 kGy	3.7 kGy	3.7 kGy	N/A

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Research Approach

Fibers

- Developing new optical fibers with built-in capability to perform distribution radiation measurements (for measurements and for calibration)
- Developing new multi-functional optical fibers for multiple parameter measurements

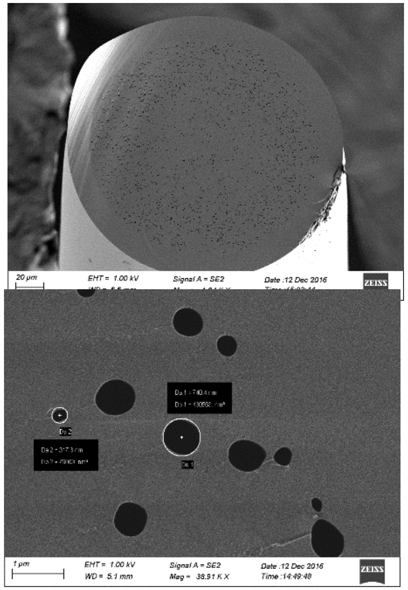
Sensing Technology

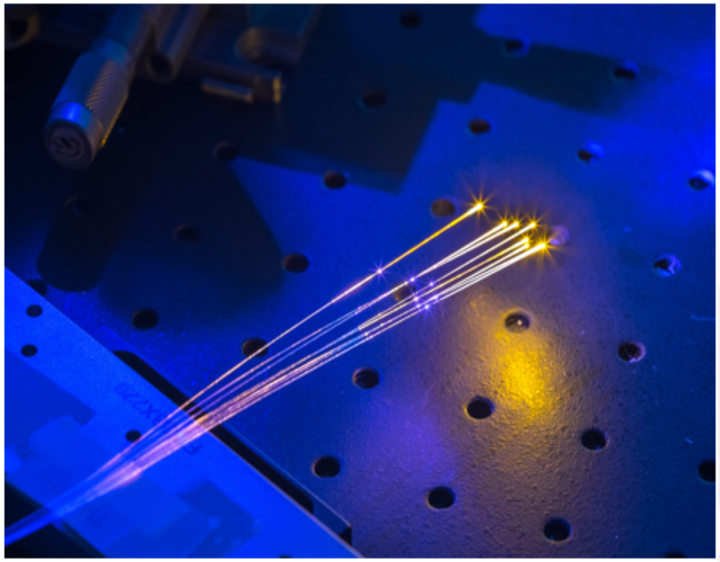
- Evaluate various distributed sensing schemes (Rayleigh, Brillouin, FBGs) under radiation for short and long terms measurements
- Develop new distributed sensing technology beyond T/strain measurements
  - Liquid levels
  - Pressure and T simultaneously + radiation
  - Chemical (hydrogen) and spatially resolved chemical reaction
  - Fiber optical vibration sensing for radiation environments

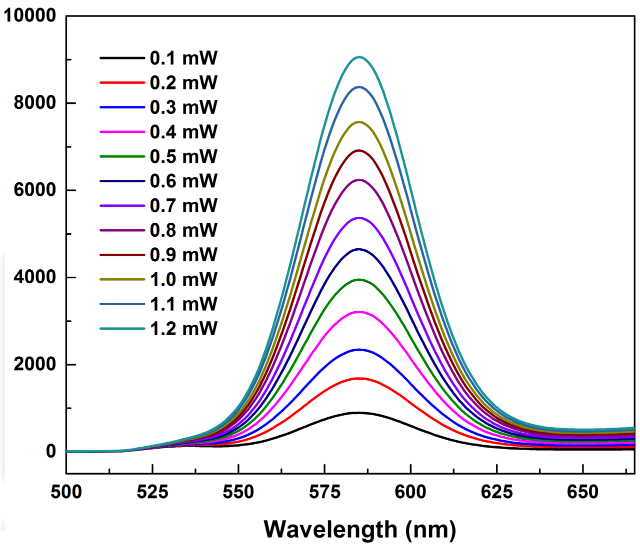
Implementations and Applications in Nuclear Engineering

- Smart parts manufacturing: Fiber embedding and testing
- New sensor platforms (smart cable, small concrete, and …?)
- Fiber sensor applications for In-Core applications.

Low-Cost Specialty Fiber for neutron/gamma radiation

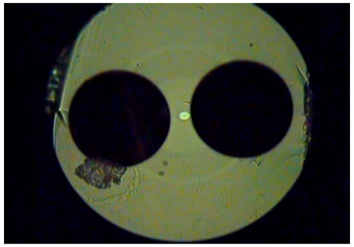




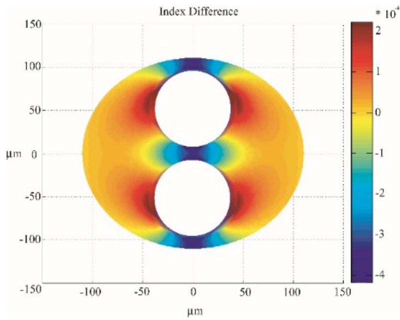


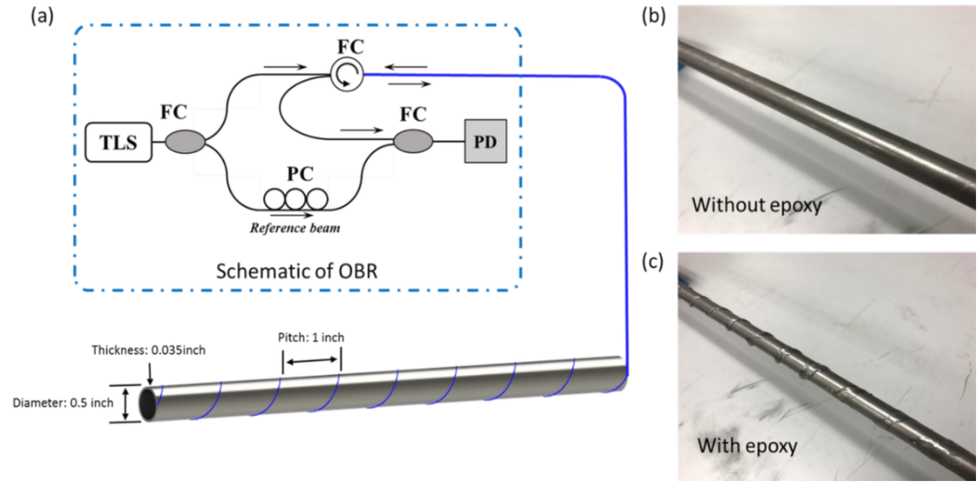
- **Random-hole fiber (both index guiding and Anderson localized guiding).**
- **Luminescent quantum dot infiltrations in random-hole (>10cm)**
- **Sensitivity and responsivity tunable by QD types, concentration**
- **Drastic enhancement of radiation-excitation efficiency**
- **Drastic enhancement of photo collection efficiency**
- **Radiation resilience (both fiber and QD)**
- **Low cost and easy insertion**

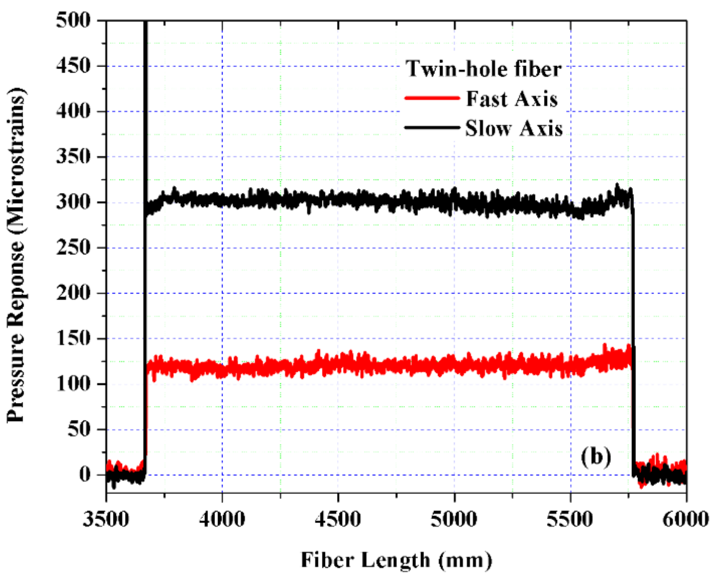
Distributed Pressure Sensor

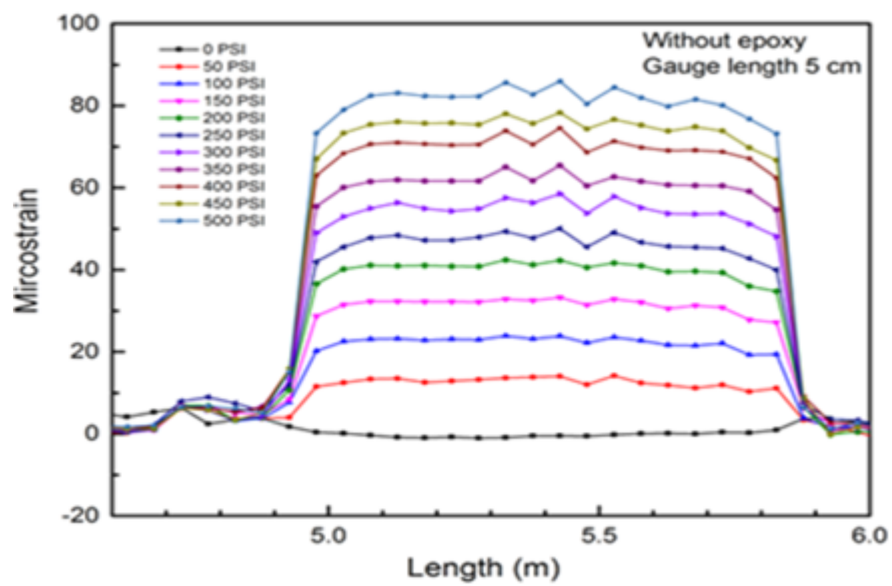


Large Diameter Elliptical-Core-Off-Centre Twin-Hole Fiber

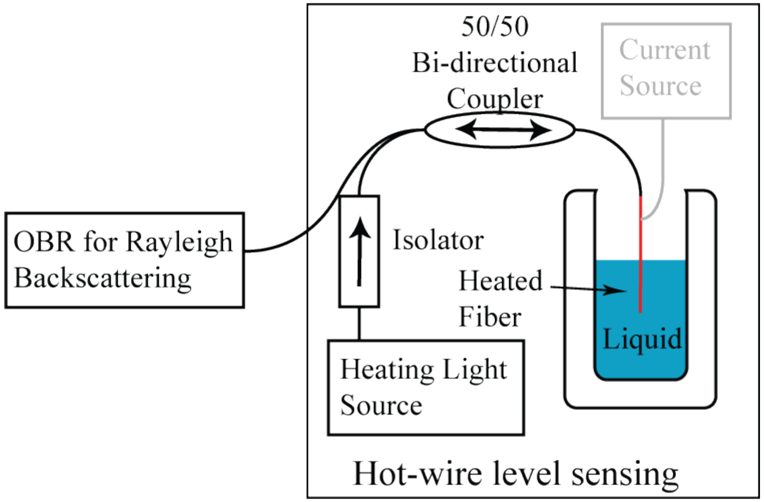








Active Fiber Sensor Power by In-Fiber Light



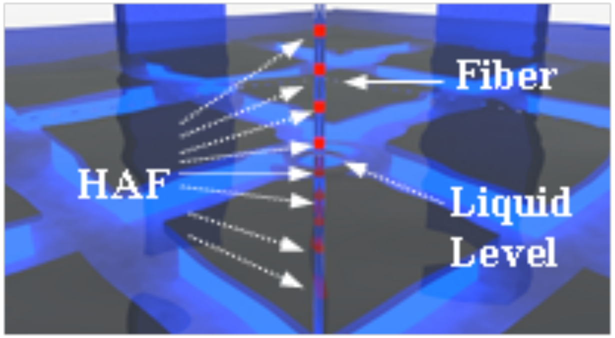
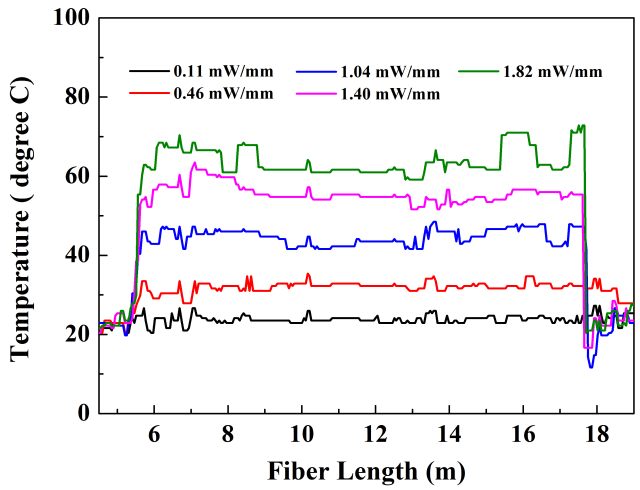
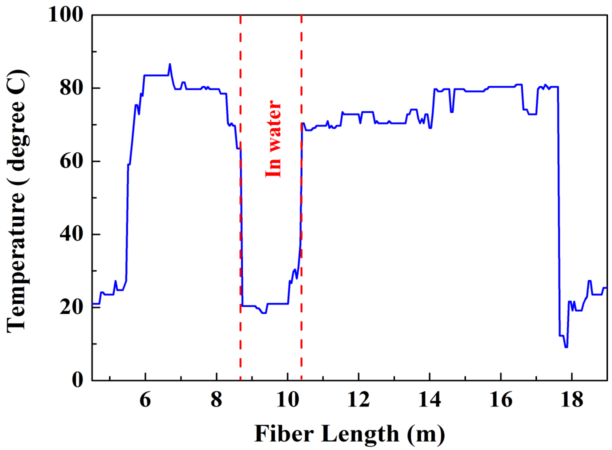


Fig. 10: schematic of active fiber level sensor in spent fuel rod pools.

Uniform Heating Cross 10-m Span



Level Sensing in Waters



Fiber-Fused Additive Manufacturing

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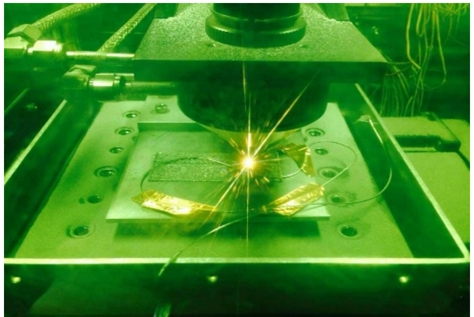
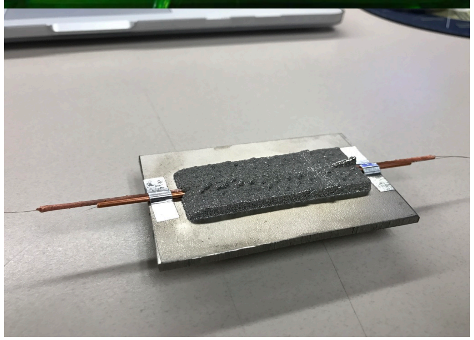
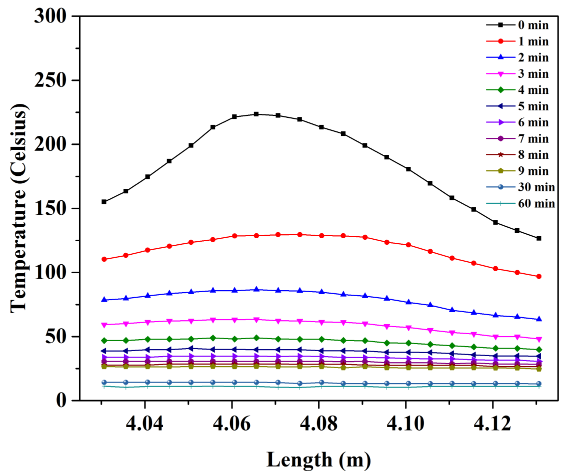
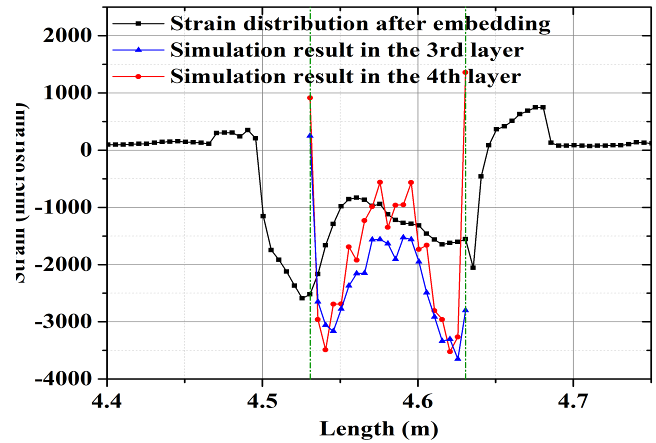




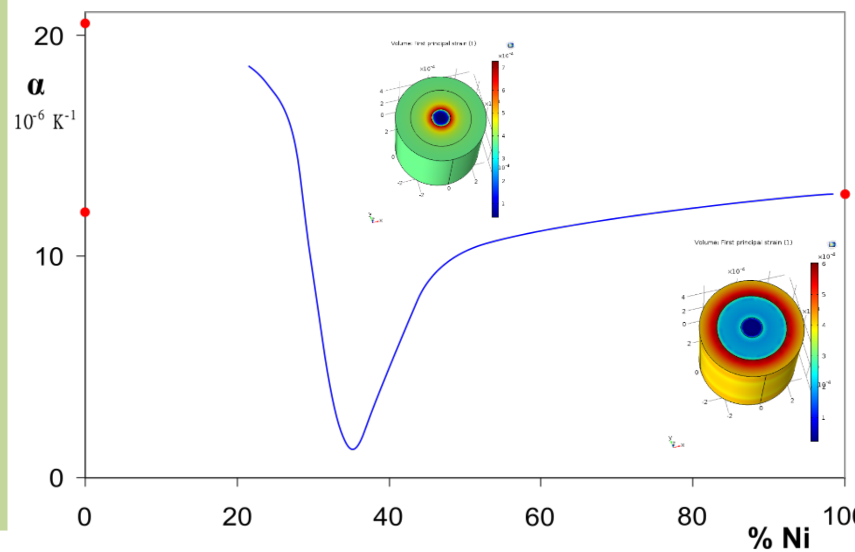
Temperature Profile



Exp. Vs. Simulation



TEC of Fe-Ni Alloy

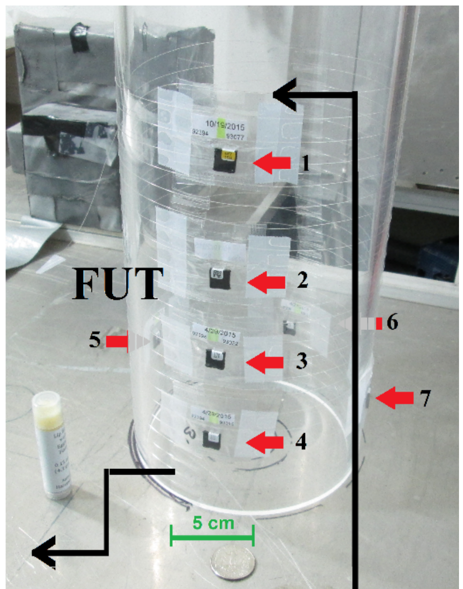


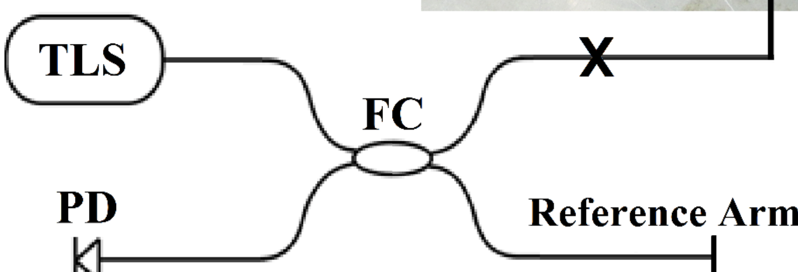
- **Establish a reliable way to implement fibers in harsh environments**
  - Standard optical fibers
  - Electroless/sputtering coating of glue layers
  - Electroplating of Ni/Fe protective layer
  - Embedding process using a 3D printing scheme (LENS) into mixed alloy
  - Repeated thermal cycling and annealing at 900C appears to yield consistent results
  - 3D printing provide GREAT protection to fiber sensors

Distributed Fiber Sensors for weak radiation environments for nuclear energy

Distributed Fiber Sensors for Weak Radiation Environments

Establish Sensor and Platform to perform distributed measurements for Radiation (& others) from 0.1 to 100 km with 1-cm to 50-cm spatial resolution

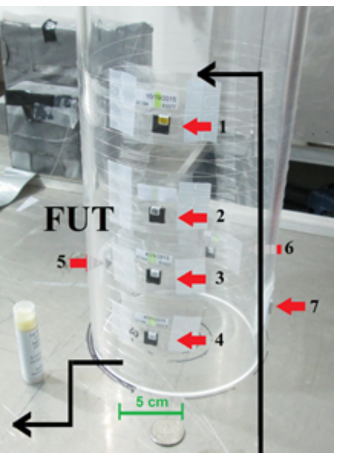


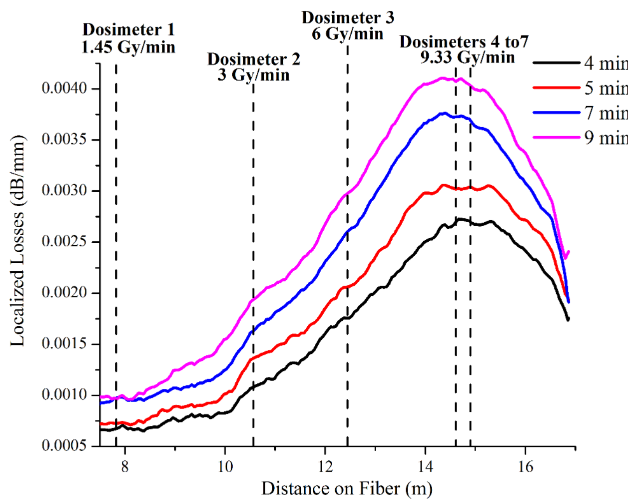


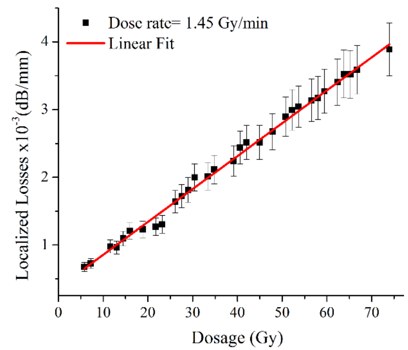
- Aluminum-doped optical fiber (radiation sensitive)
- Radiation sensitive specie: Al (4.8 wt%)
- Radiation sensitivity controlled by Al concentration (balanced by Ge dopant)
- Utilize existing distributed fiber sensing schemes
  - OFDR
  - OTDR
- No more point sensors
- Continuous measurement across large distance using one fiber
- Sensor sensitivity tunable
- Also simultaneous measurement of T/strains

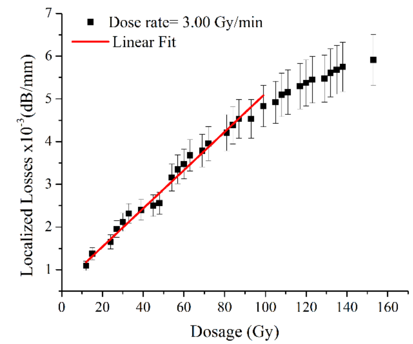
Distributed Fiber Sensors for Weak Radiation Environments

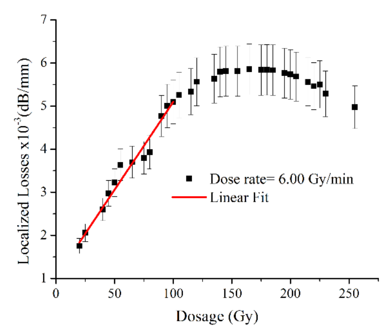
Localized Loss
1-cm Spatial resolution

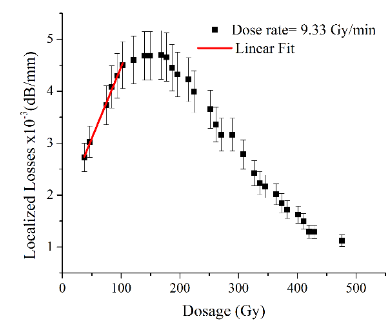




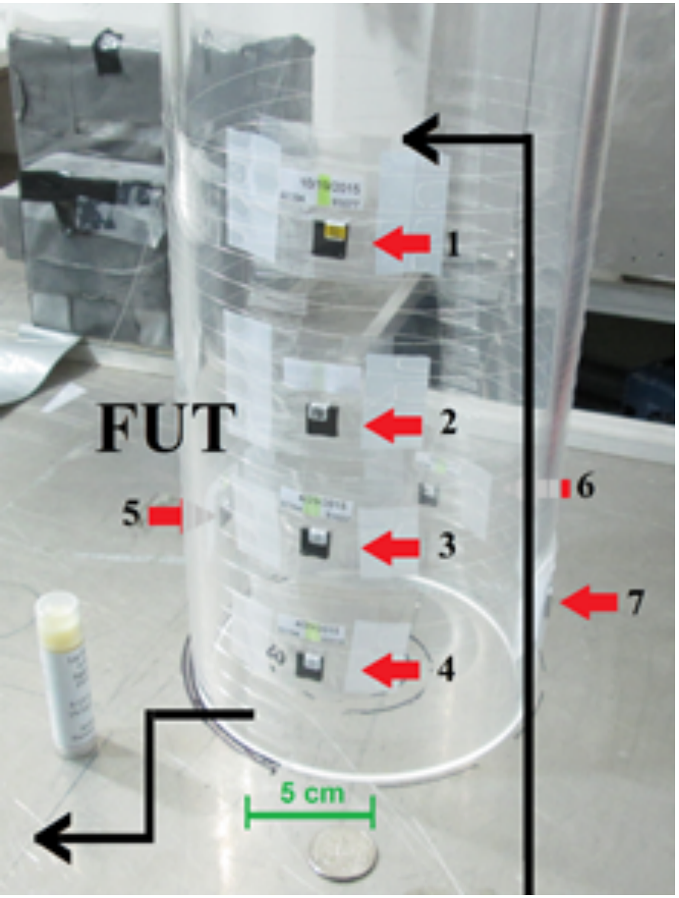


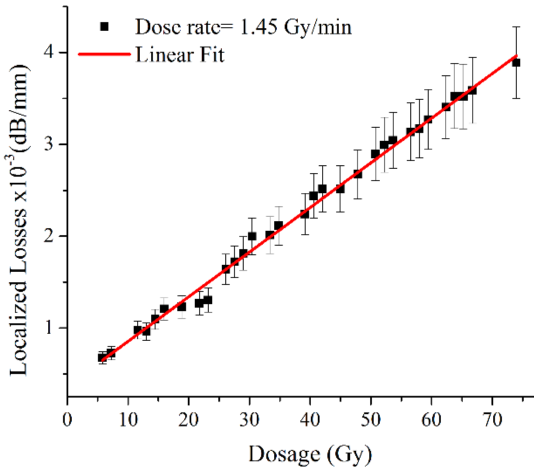


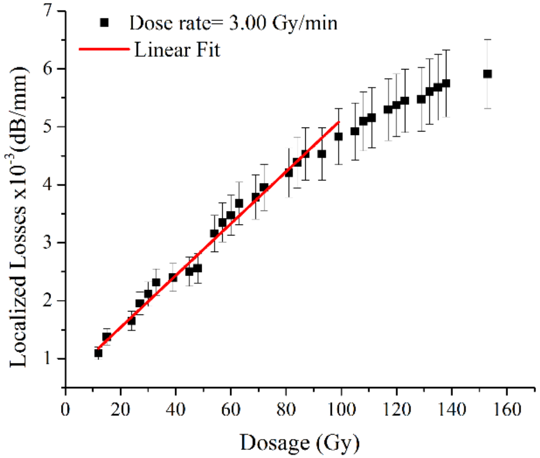


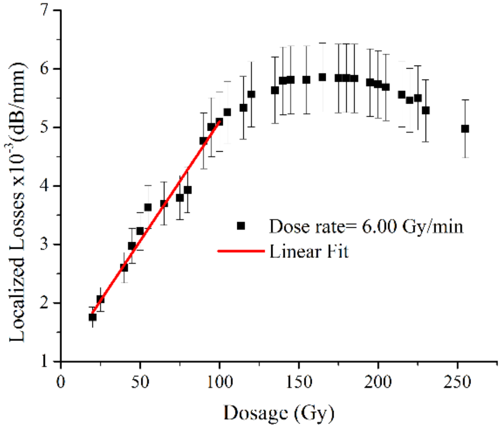


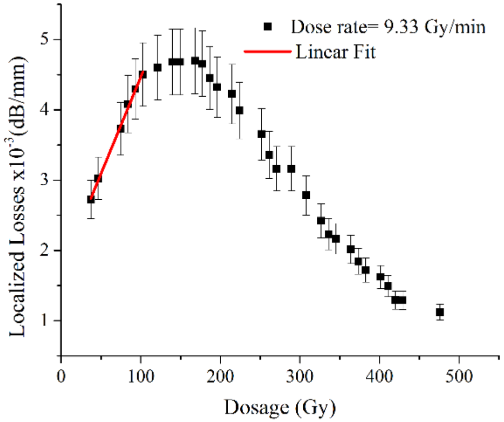
Distributed Fiber Sensors for Weak Radiation Environments





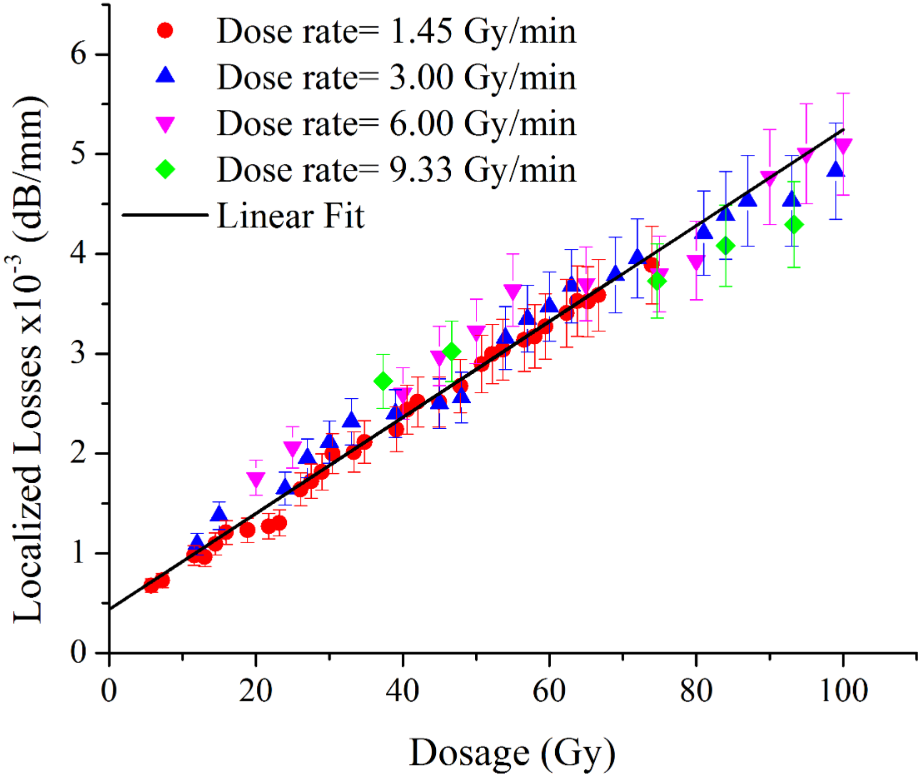




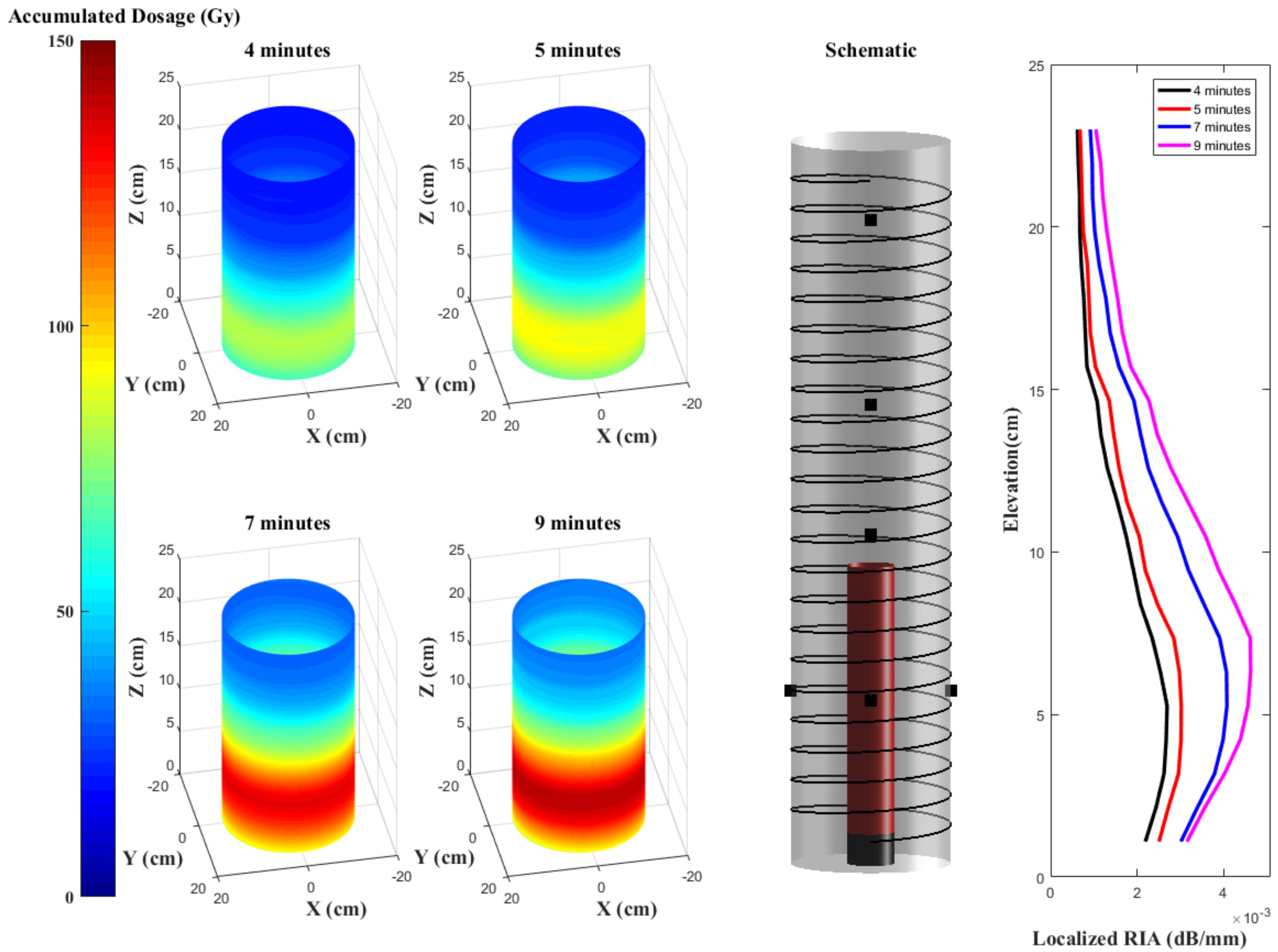


Distributed Fiber Sensors for Weak Radiation Environments

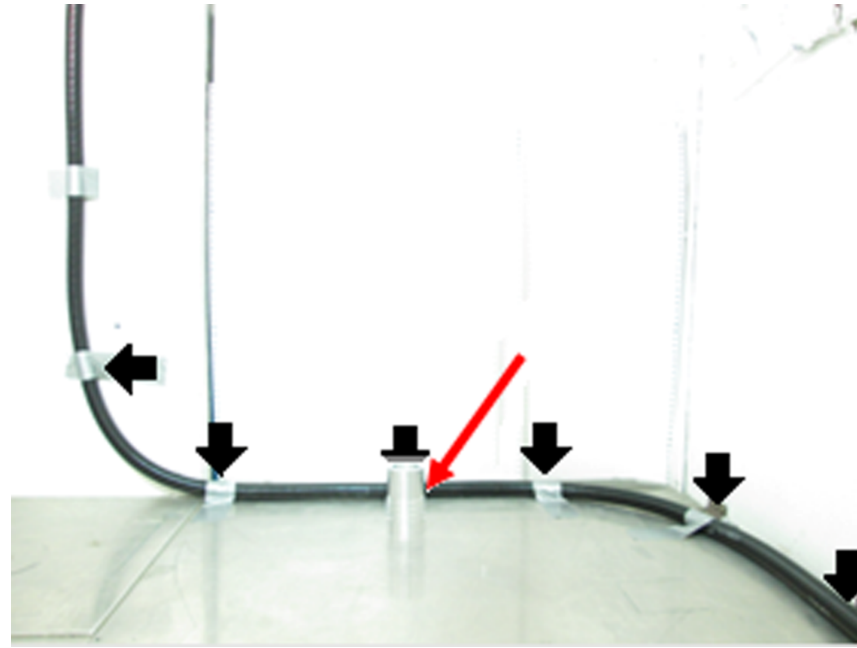
- **Within 100 Gy and 9 Gy/min: 8.3% error**
  - Radiation dosage can be linearly correlated by localized loss
  - Linear relationship: RIA (db/mm)= 4.81×10^{-5} Dose (Gy) + 4.33×10^{-4} (dB/mm)
  - Average error: 8.3% (less than 7 Gy/min, 5%, 7-10 Gy/min, 12%)



Distributed Fiber Sensors for Weak Radiation Environments

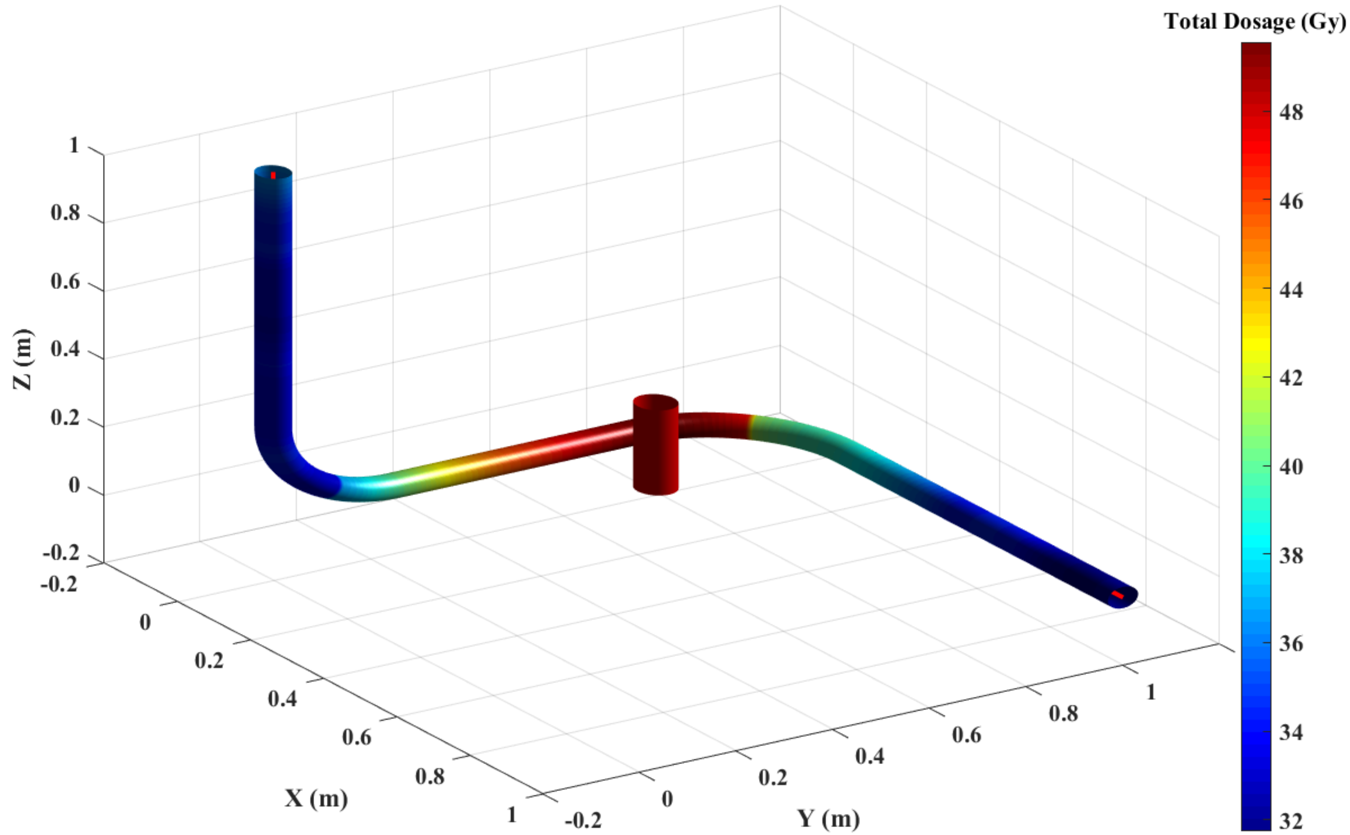


Smart Electrical Cable for Nuclear Energy Using Electrical Cable as Sensor Platform



Electrical Cable with embedded fiber sensors for radiation and temperature measurements
1-cm Spatial resolution

Distributed Fiber Sensors for Weak Radiation Environments



More Data, Less Installation, High Spatial Resolution!

Fiber Sensors for in-core environments and real-time in-core anomaly monitoring

Fiber Sensors for In-Core Applications

- Fiber Bragg grating (FBG) multiplexible sensors
- Rayleigh Scattering distributed Sensor (1-cm spatial resolution)
- FBG fabricated by ultrafast laser via phase mask
- Distributed sensors fabricated by ultrafast laser (point-by-point writing) to enhance Rayleigh Profile and temperature stability
- Four types of fibers:
  - Random hole pure silica fibers: NEW
  - Standard telecom fibers (Corning SMF-28): Reference
  - F-doped glass fibers: Known to be radiation resistant
  - D-shaped fiber: In-core chemical measurements

Distributed Sensors for In-Core Applications

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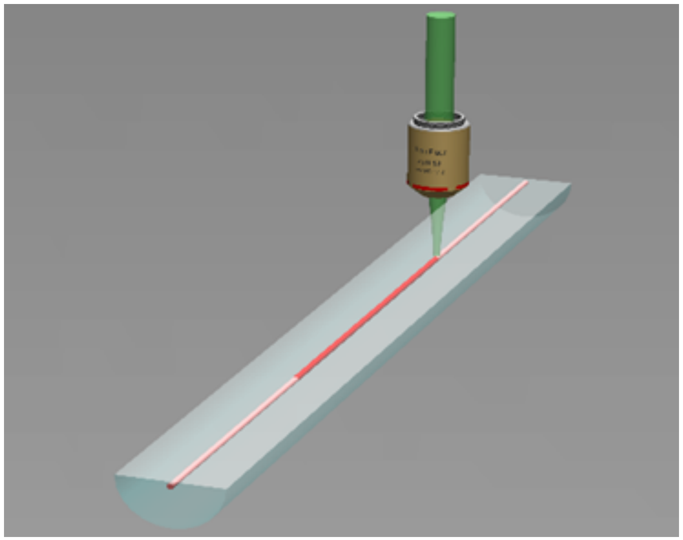
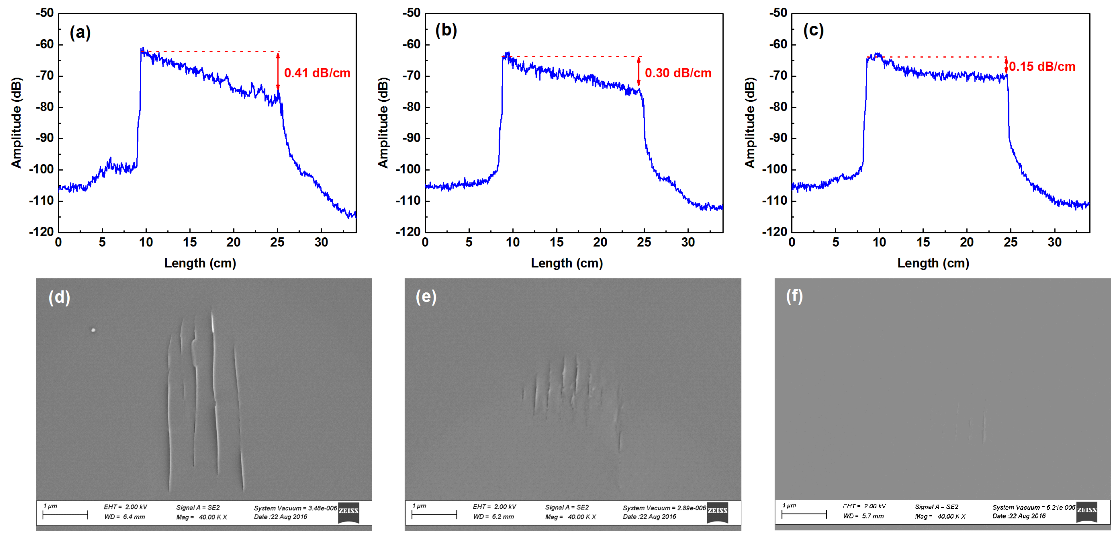
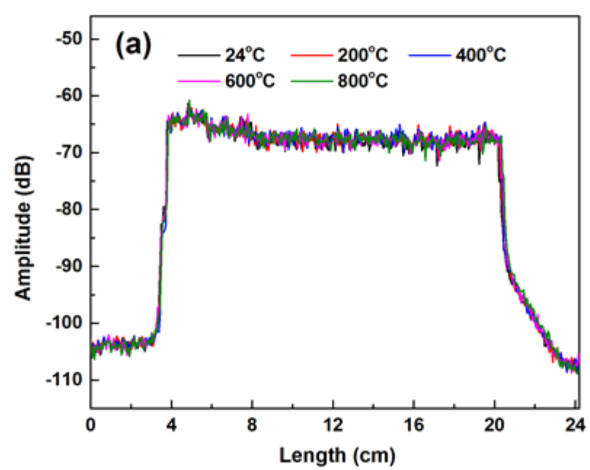
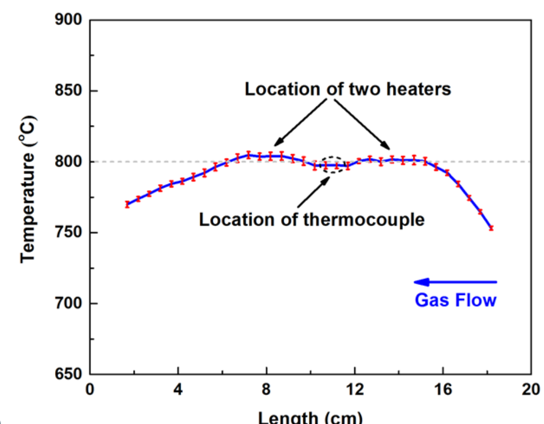
Ultrafast laser irradiation to enhance T resilience and measurement accuracy





- Temperature can now be measured at 800C with H2 atmosphere
- Stability verified for ~72 hours at 800C
- 4C accuracy with heat/reheat cycles (10 cycles tested).





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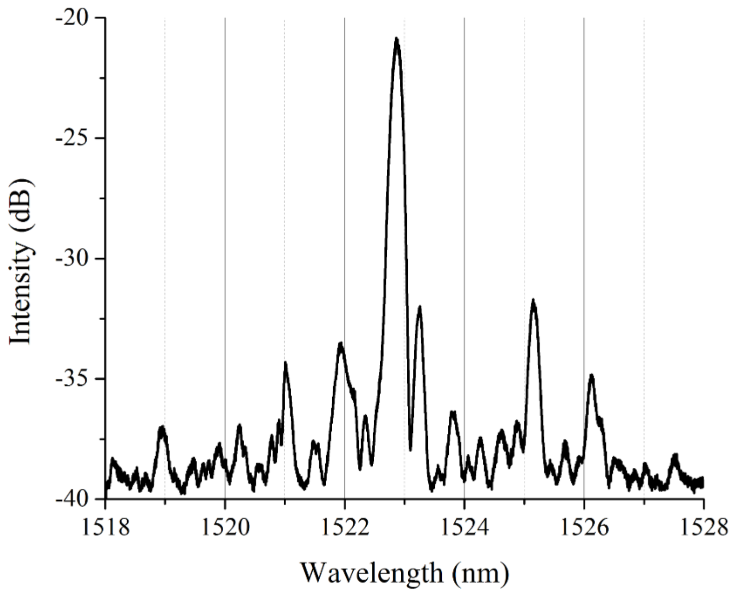
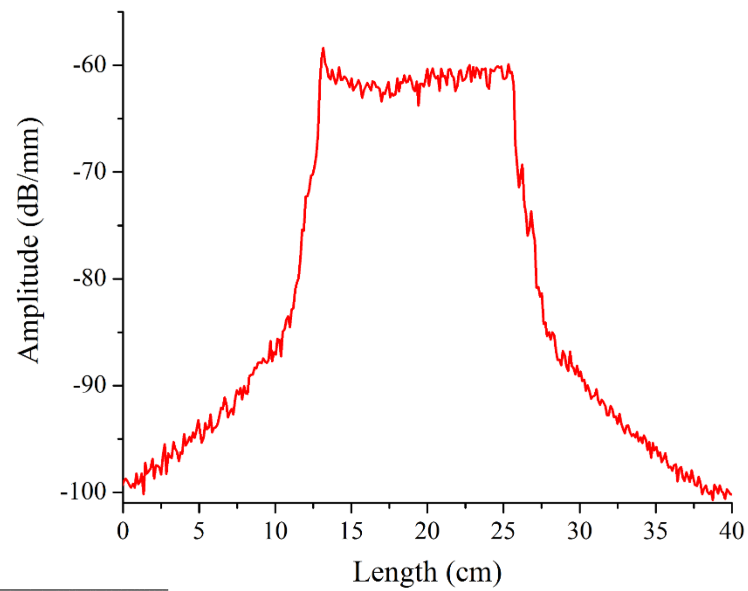
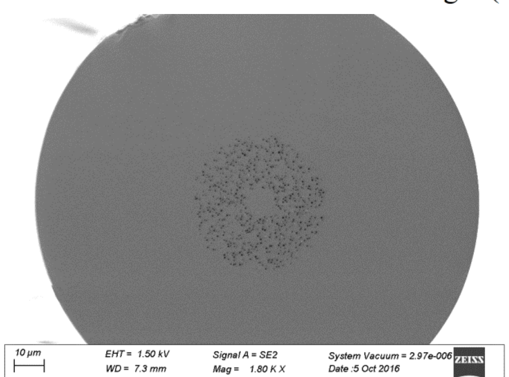
In-Core Reactor Testing

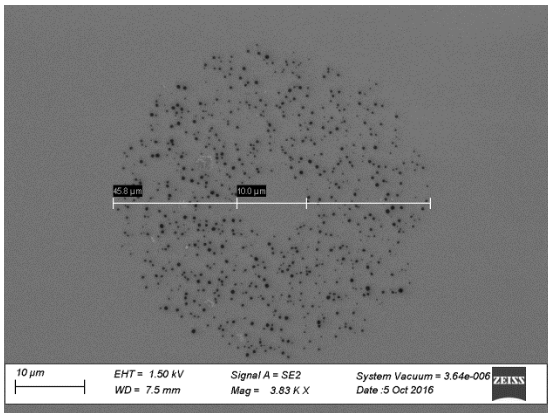
FBG Sensor via. Ultrafast laser



Rayleigh Distributed Sensor via. Ultrafast laser (F-doped fiber)







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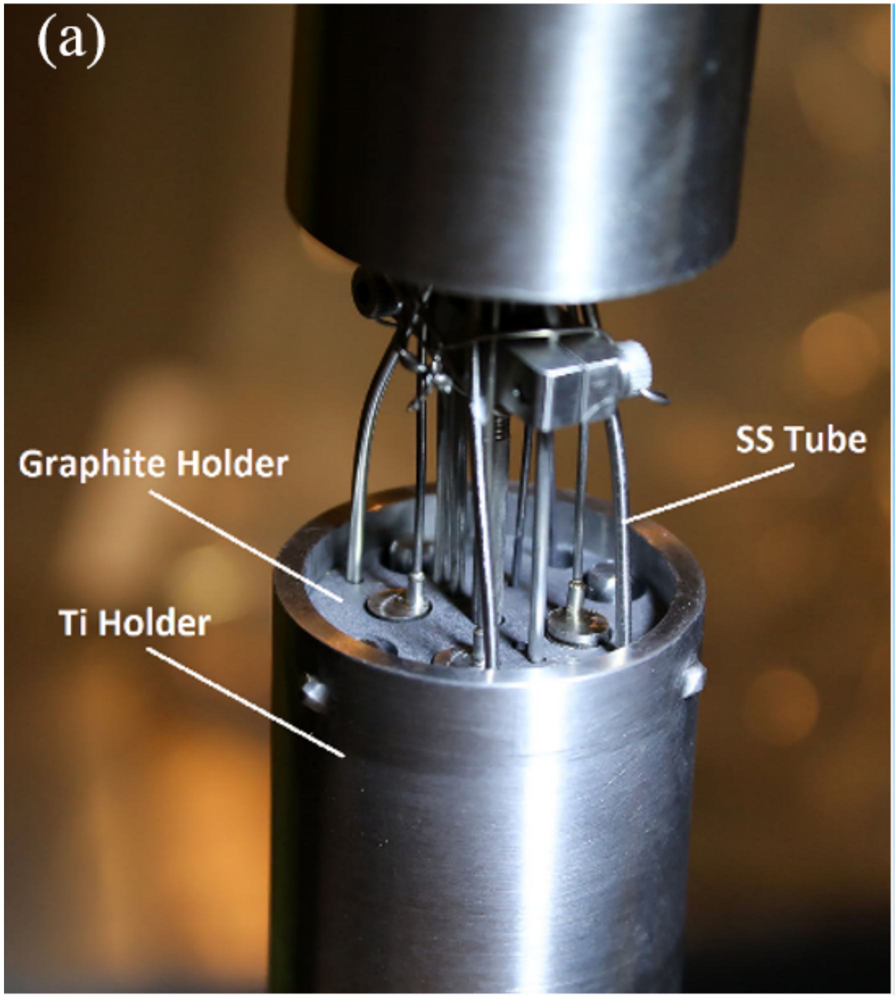
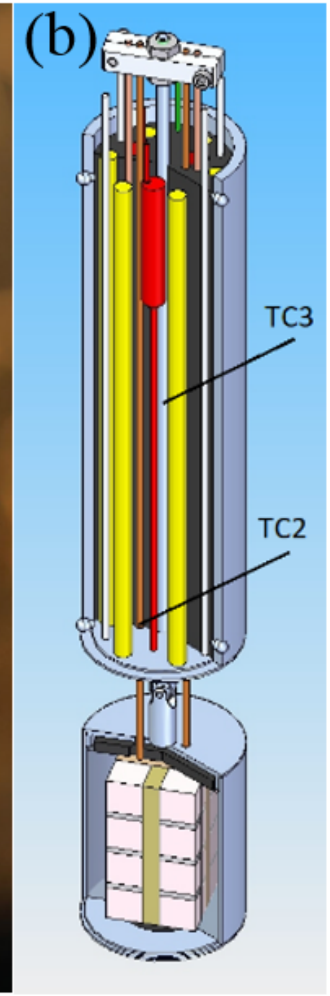
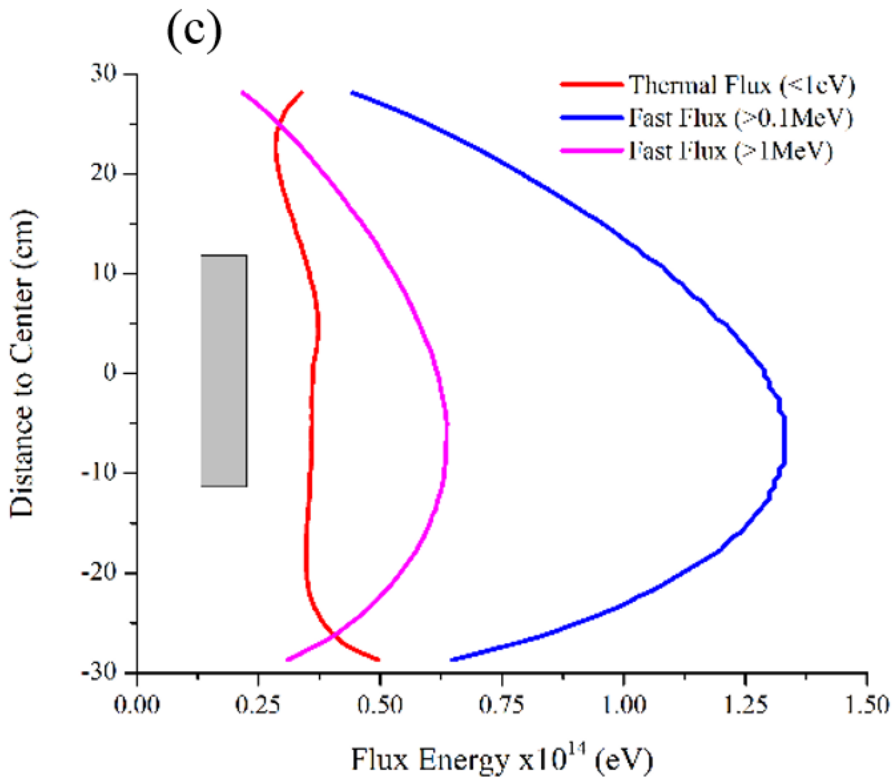
Fiber Sensors for In-Core Applications





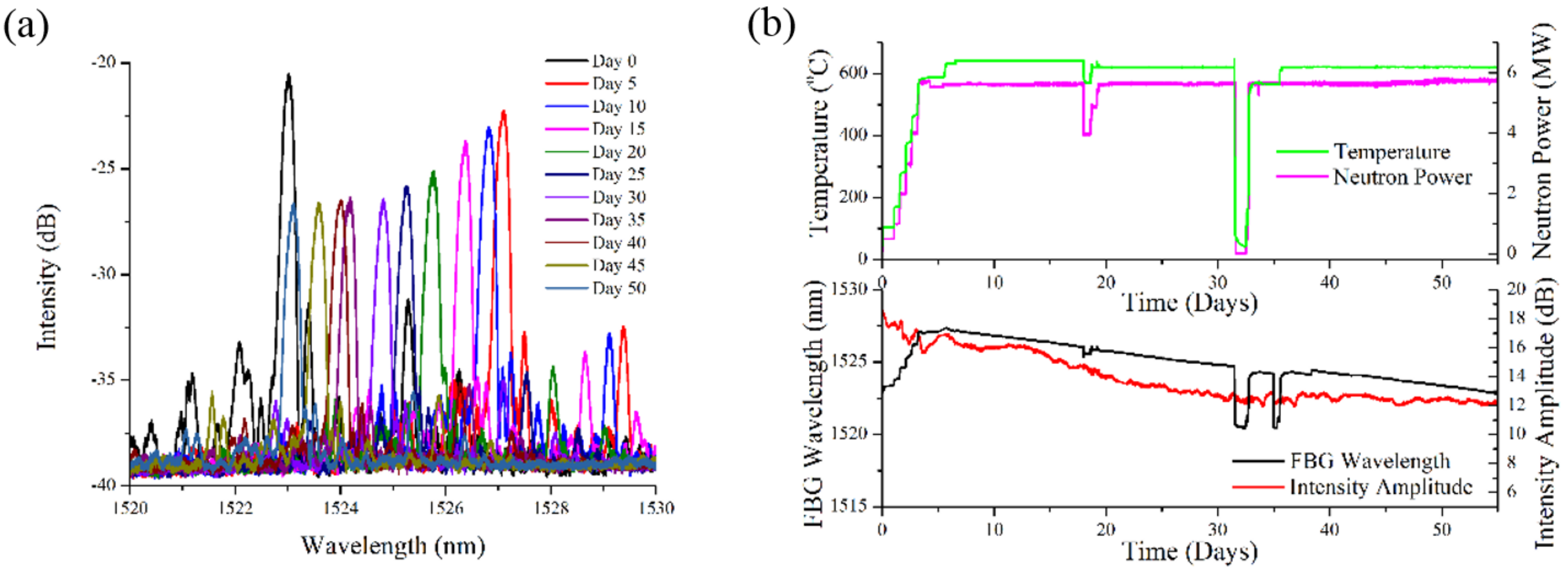
Fiber Sensors for In-Core Applications



- Radiation started on May 5, 2017, scheduled for 50 days, so far 40 days
- Target temperature 800C
- Fast neutron flux 10^{14} n/s*cm^2
- Real-time monitoring (remote access)
- Through Joshua Dow’s NSUF project

Fiber Sensors for In-Core Applications

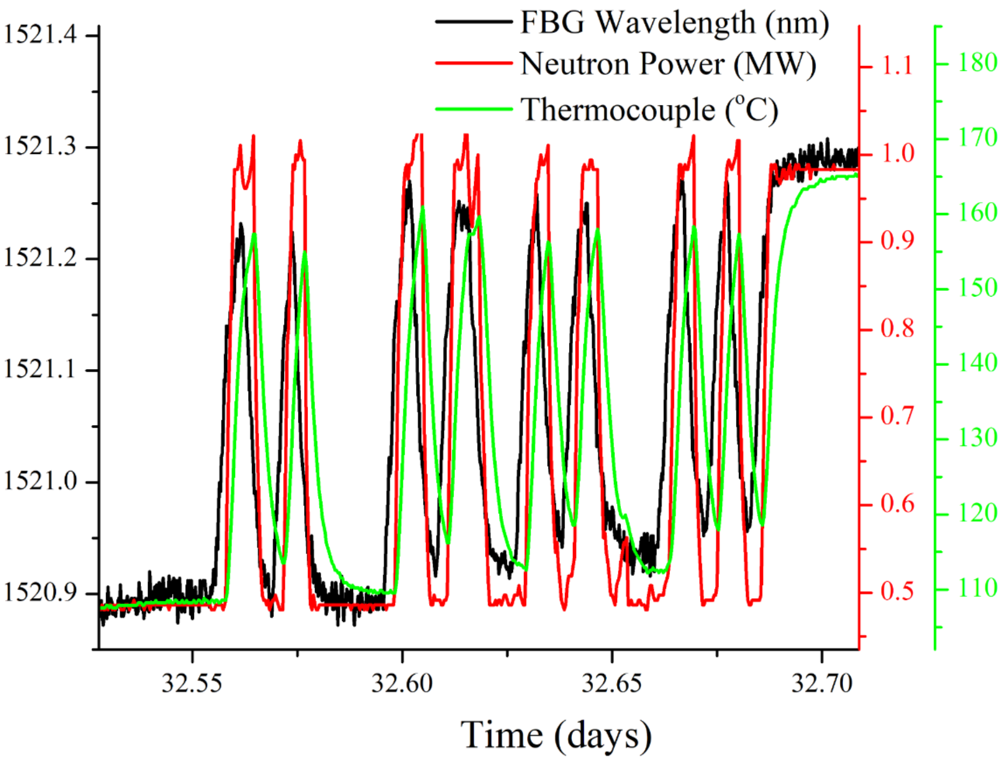
Fiber Bragg Grating

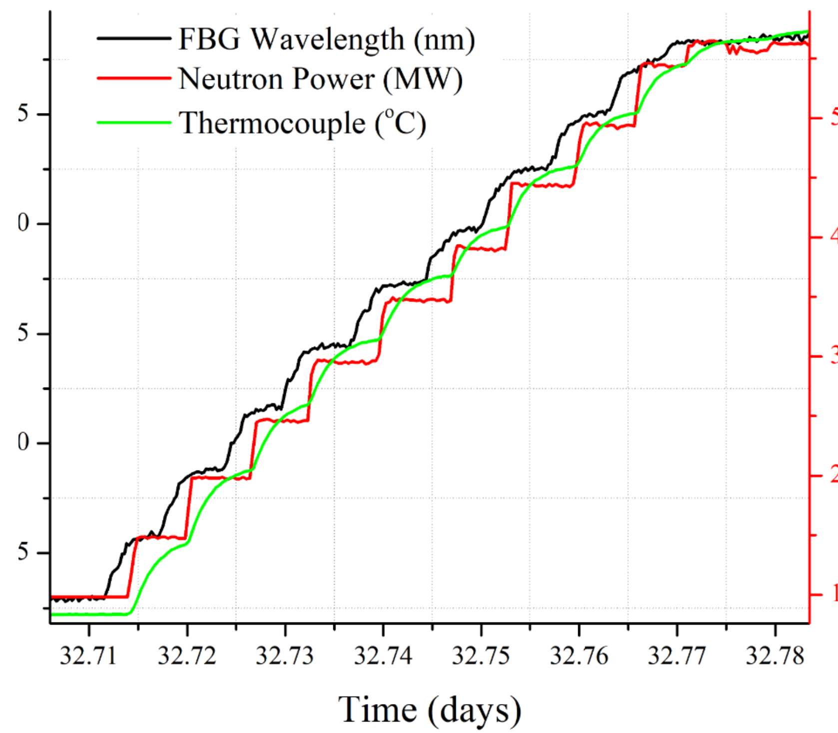


- FBG peak shifts toward to shorter wavelength: linear vs. dosage (0.1 nm/day)
- FBG peak reduce by ~ 3.3dB – saturated (stabilized) after 30 days.
- Could be due to RIA increase or FBG degradation (RIA less than 1 dB).
- FBG peak drift highly linear, suggest a single underlying mechanism (can be compensated)

Fiber Sensors for In-Core Applications

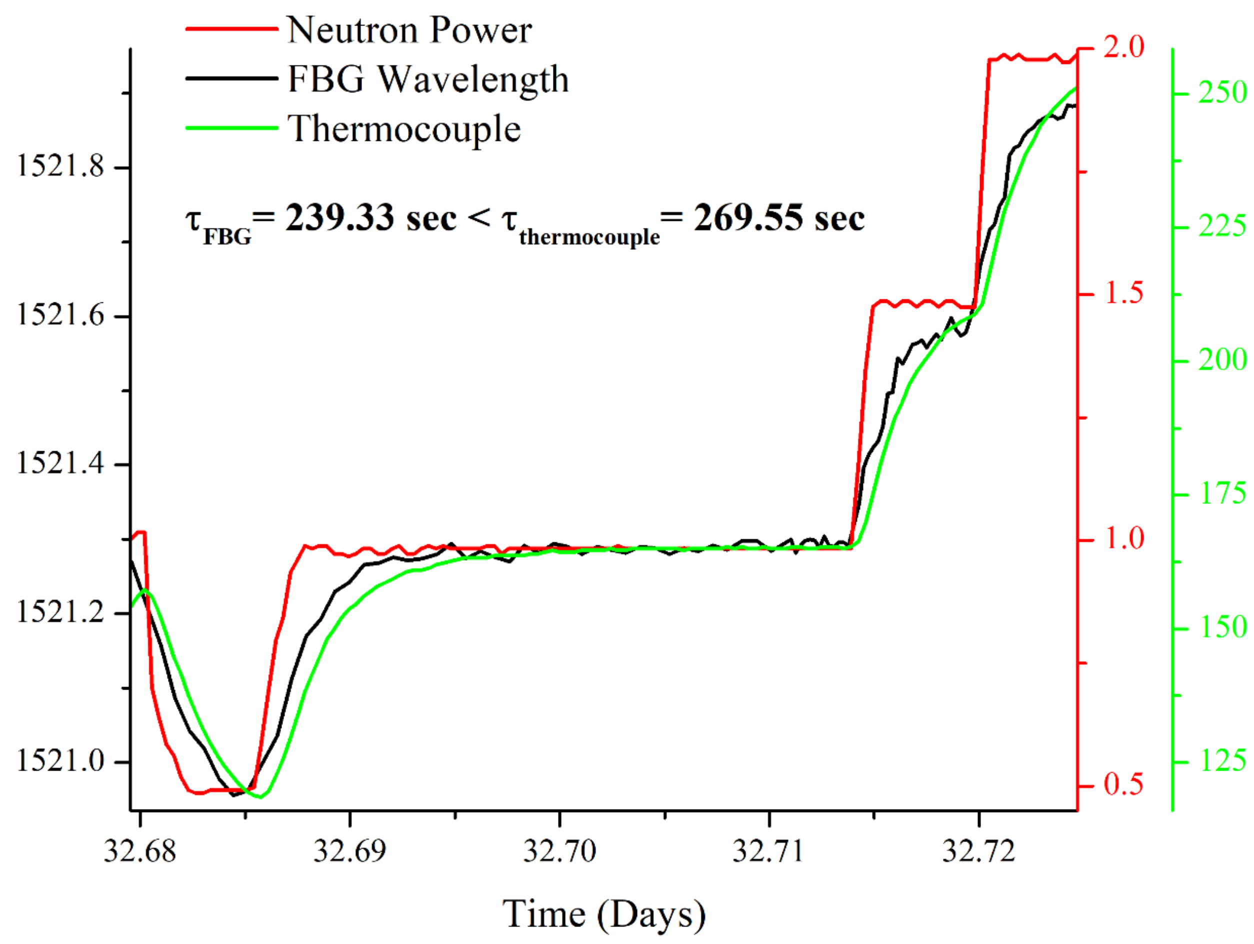
Can we monitor this reactor "anomaly"? --- YES





Fiber Sensors for In-Core Applications

Time Response



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Fiber Sensors for In-Core Applications

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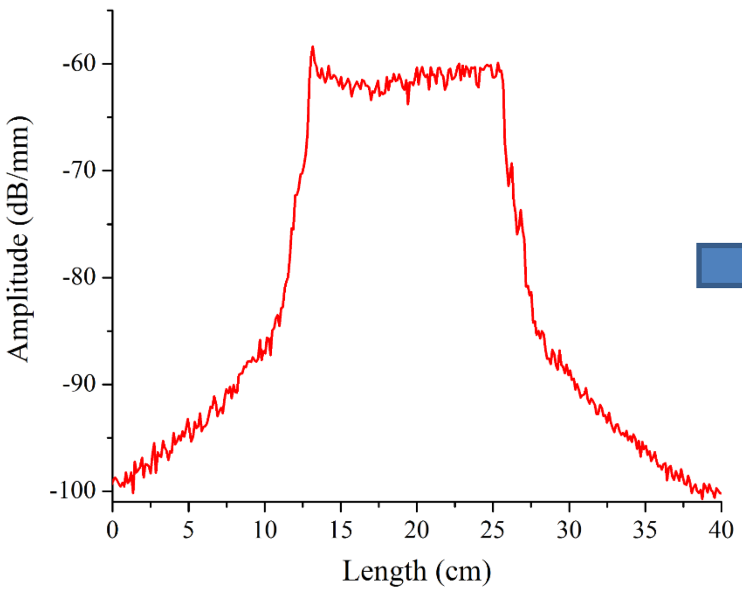
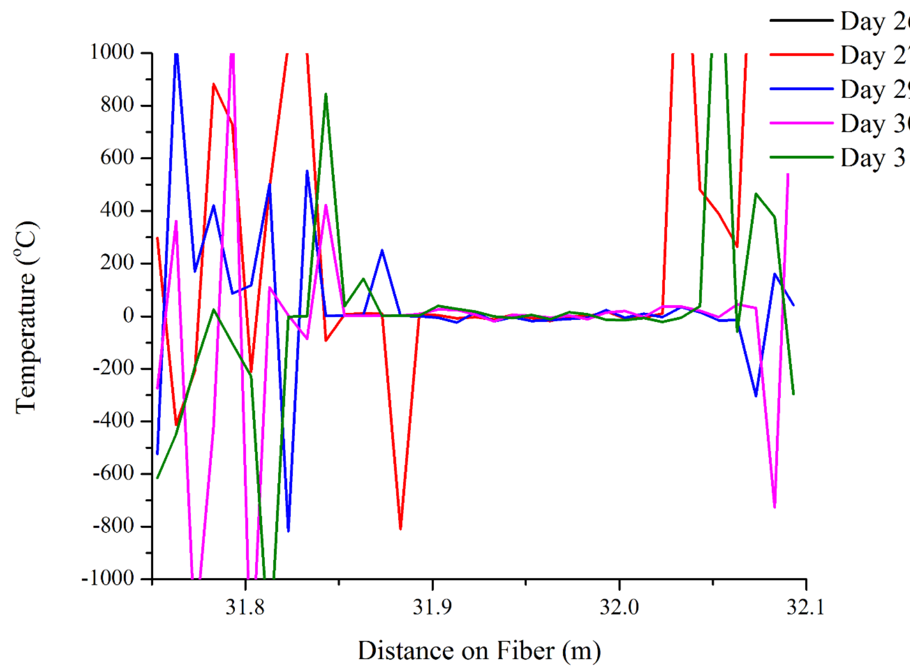
Distributed Fiber Sensors



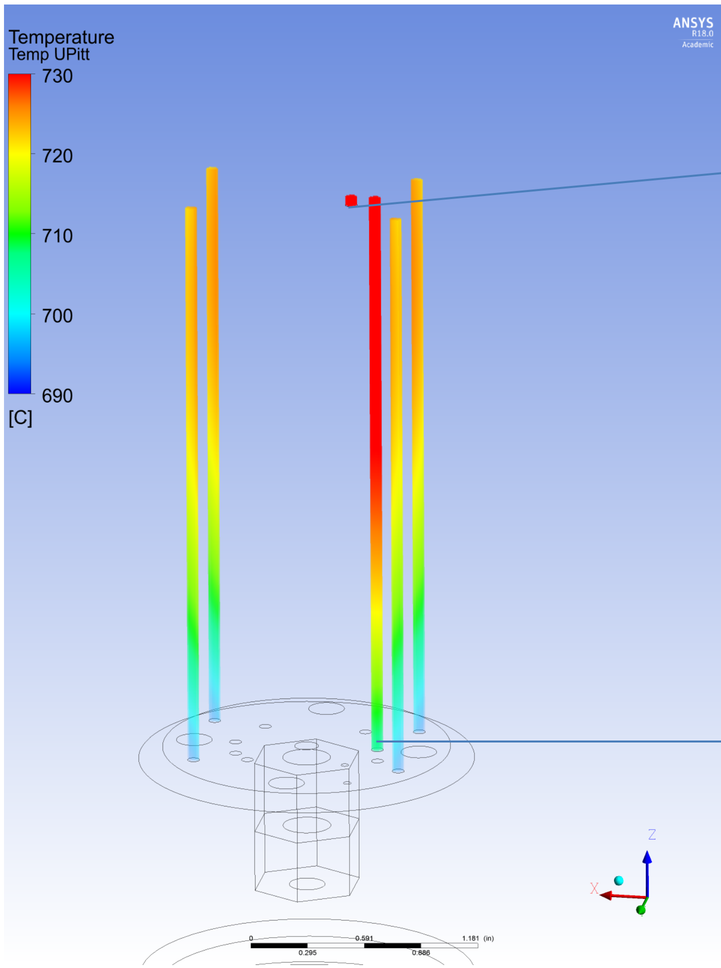


- **12-cm section of fiber enhanced by ultrafast laser**
- **Temperature stability confirmed at 800C**
- **Rayleigh enhancement up to 40-dB (critical)**
- **F-doped glass (SURVIVED) and standard fiber (NOT VIABLE)**

Fiber Sensors for In-Core Applications

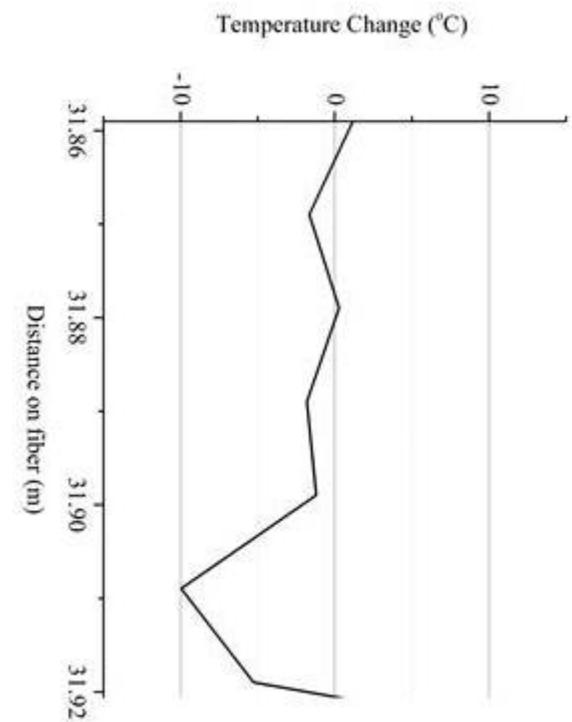
Temperature Profile Measurement!
(1-cm resolution)

Lower-half Sensor Capsule



TC 3: 733°C

TC 2: 707°C



Summary and Outlooks

- Optical fibers CAN survive in-core conditions (Fiber material matter!!).
- Both FBG point sensors and distributed sensors Functional.
- Through fiber materials, fiber design, and laser processing innovation, we can improve sensor calibration, improve measurement functionalities.
- In-core real-time calibration is need for static measurements.
- However, fiber sensors (in this present form) can be used to measure quasi-static (~ days) and transient response.

- Next Step for in-core monitoring: acoustic, pressure, maybe chemical.
- Self-calibration structures included in fibers.
- High-spatial measurements with one-fiber and one feedthrough solution possible.
- Interdisciplinary collaboration essential.

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Technology Impacts and Conclusion

- ***Advances the state of the art and support NE and nuclear industry***
  - *In-core and out-of-core sensors for high spatial resolution measurement is key for the future of nuclear power --- potentially cost reduction!!!*
  - *Develop new optical fibers with an integrated function for distributed radiation measurements.*
  - *Provide unique sensing capability unattainable by other measurement schemes*
- ***Explain how this technology impacts nuclear stakeholders***
  - *Improve safety of nuclear power systems: distributed fiber chemical sensors for gas measurements (e.g. Hydrogen), distributed fiber sensors to monitor spent nuclear fuel pools, and etc.*
  - *Provide new tools to monitor radiation effects to critical components, systems, and infrastructures.*
  - *Mature TRL levels of fiber sensors by developing new sensor packaging scheme and sensor-fused smart components*