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

Clean. Reliable. Nuclear.

Fiber Optics Sensor Enabled I&C and Artificial Intelligence Data Analytics for Nuclear Energy

Advanced Sensors and Instrumentation Annual Webinar

October 29, November 5, November 12 , 2020

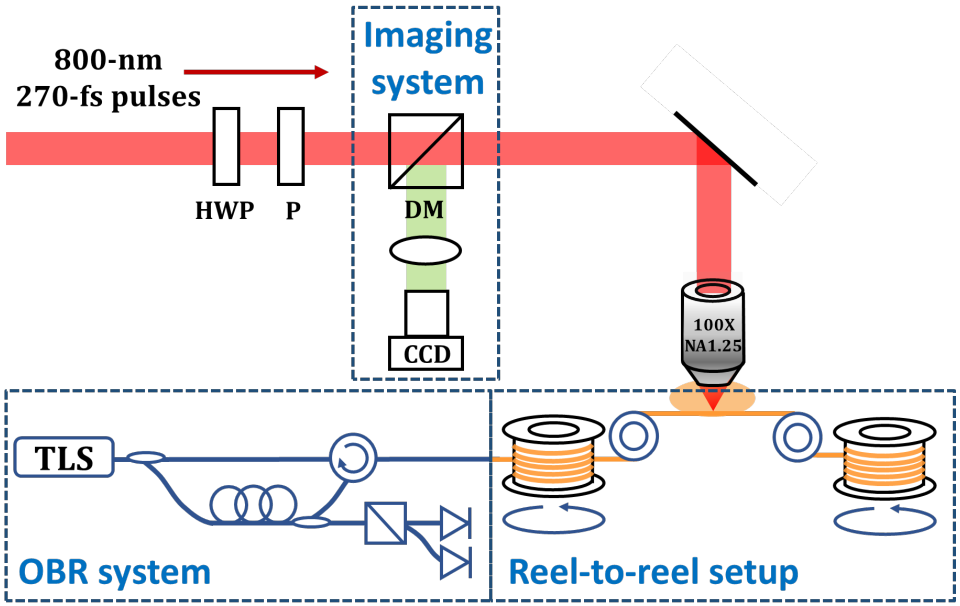
Kevin P. Chen

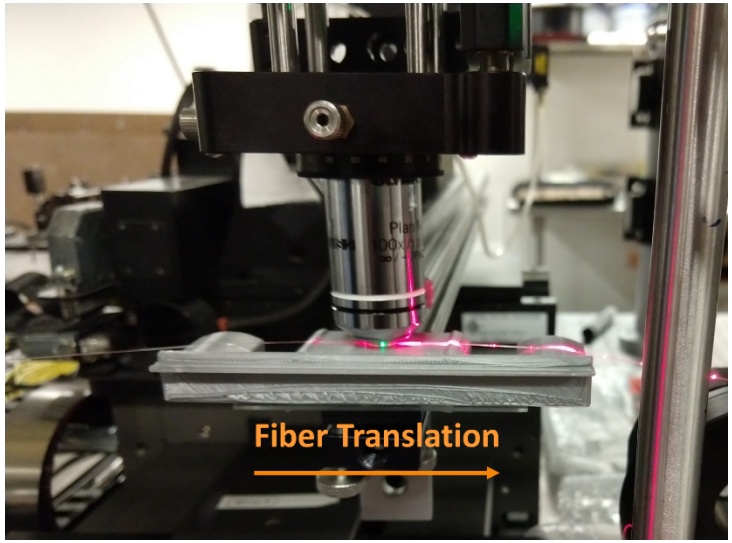
University of Pittsburgh

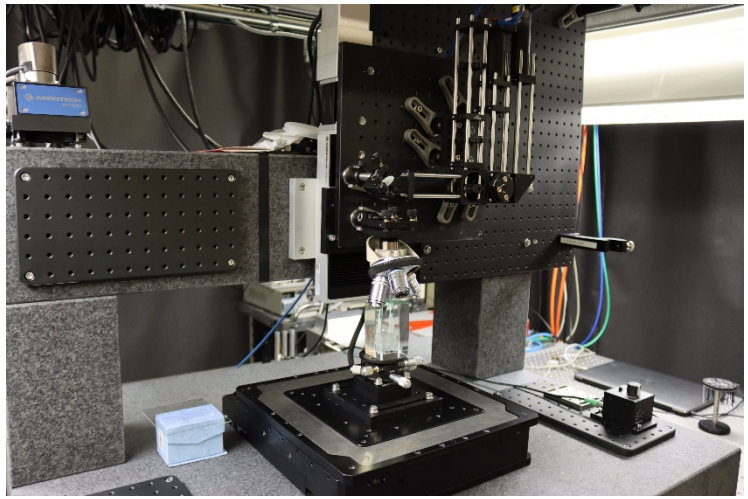
Project Overview

- **Development of radiation harden distributed fiber sensors and multiplex sensors for nuclear energy**
  - Femtosecond reel-to-reel sensor fabrications
  - Robust packaging technique to penetrate pressure boundary
  - Interrogation systems readily to be integrated with I&C
  - Computational efficiency sensor demodulation algorithm
  - High-resolution sensor data enabled artificial intelligence
  - Improve overall TRL for fiber sensor for near-future deployment
- **Participants (2020)**
  - Sheng Huang, Zachary Splain, Mohan Wang, Kehao Zhao
  - Collaborators: NETL (Michael Buric, Ping Lu, Mudabbir Bardar), Westinghouse (Thomas Tweedle, John Long)
- **Schedule**
  - 2020: Sensor development, prototyping, TRL improvements
  - 2021: Extensive Sensor testing for NE applications

Accomplishments # 1: Reel-to-Reel Sensor Fabrications





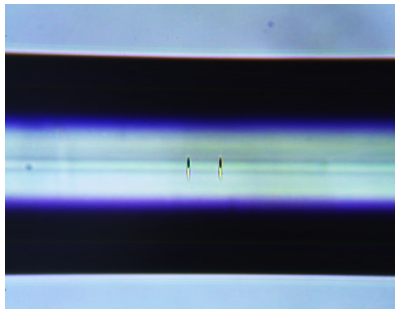


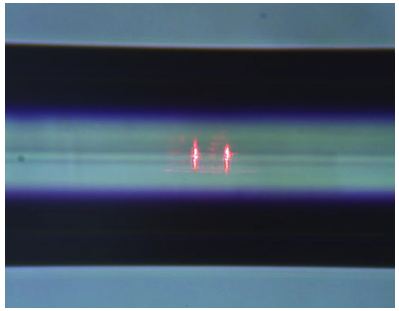
Reel-to-reel oil-immersion fiber writing setup

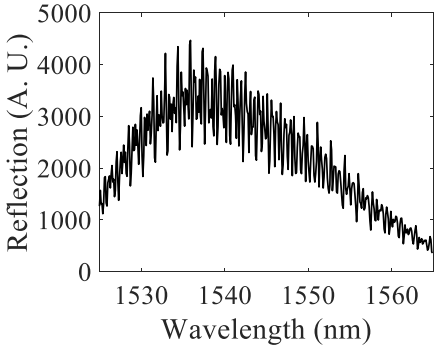
- Fast and continuous fabrication over >tens meters
- -fs (190fs – 5 ps), 800-nm, 532-nm, 355 nm outputs
- Sensors fabrication over 20 m continuously
- Applied to wide array of rad-hard fibers
- Real-time monitoring using an Optical Backscattering Reflectometer (OBR) and OSA
- New laser system comes online

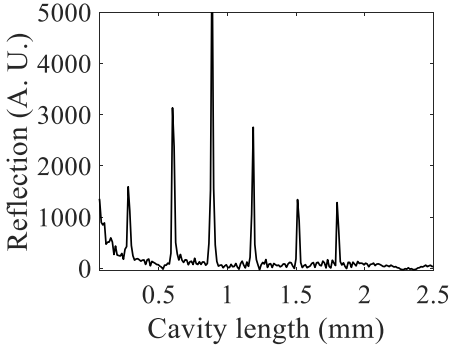
Accomplishments # 1: Reel-to-Reel Sensor Fabrications

Fs-laser inscription of Type-II IFPI Sensor Array

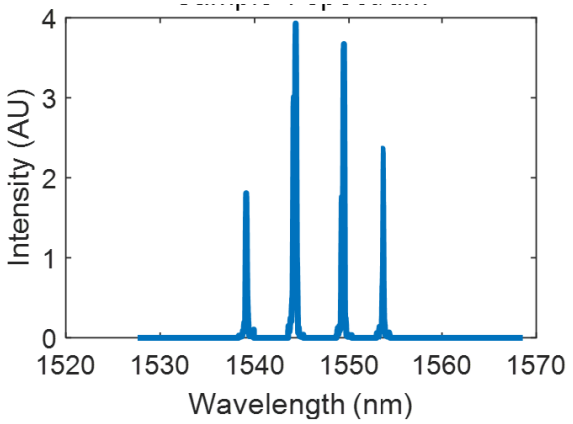




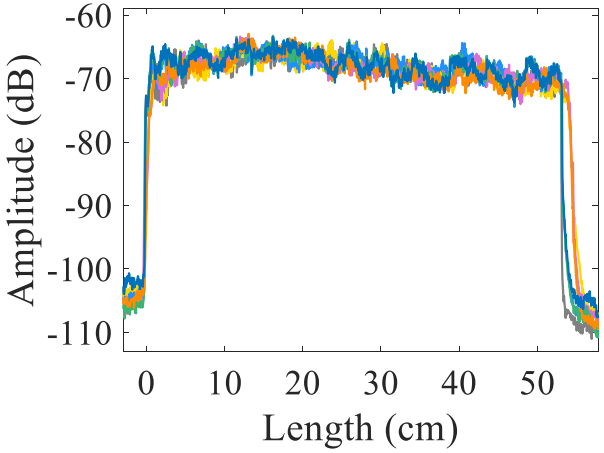




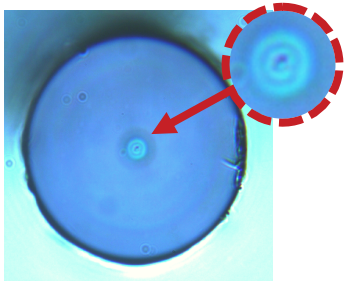
FBG Sensor String

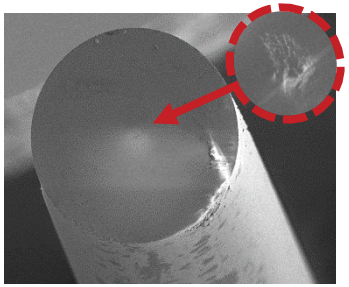


Laser Enhanced Rayleigh Scattering Profile



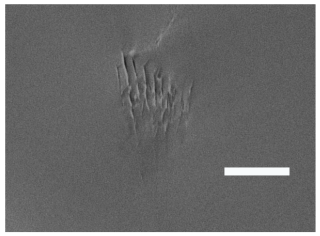
Precision Control of Formation of Nanograting

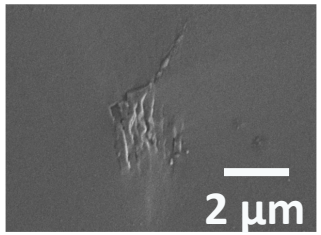




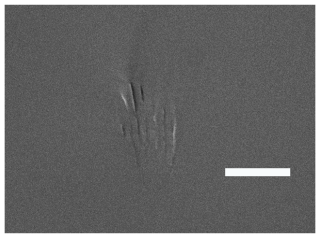
Accomplishments # 1: Reel-to-Reel Sensor Fabrications

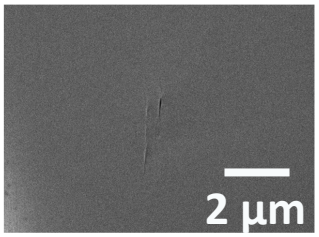
Optimization of Laser Processing to Ensure High-T Stability and Low-Loss


160-nJ

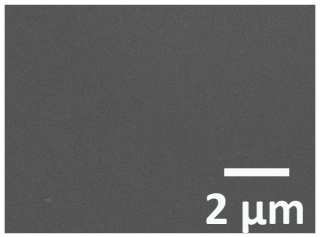


140-nJ

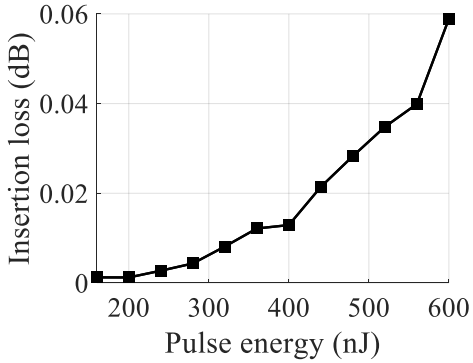

120-nJ

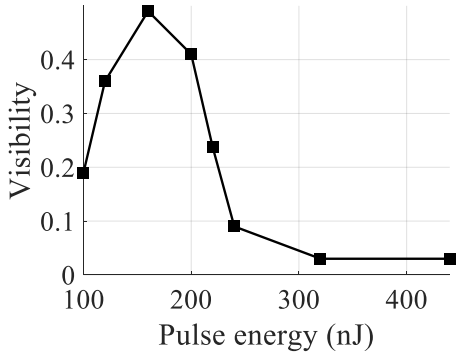


100-nJ



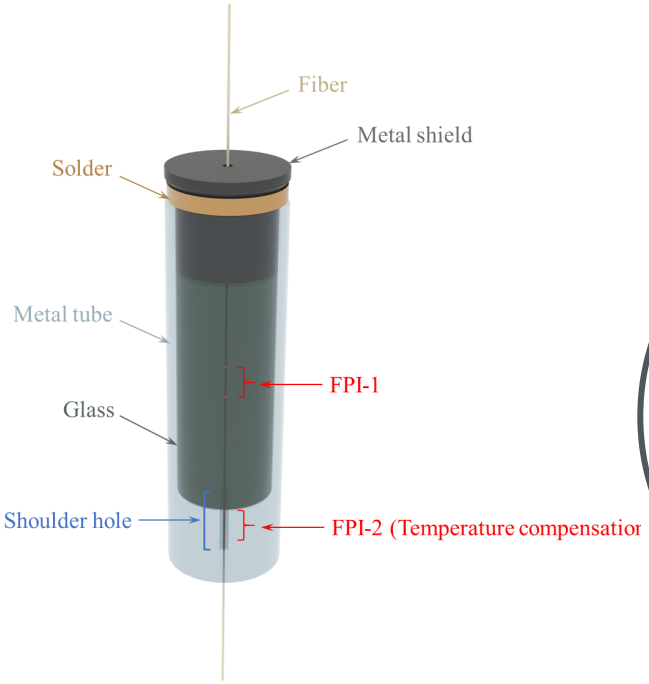
80-nJ

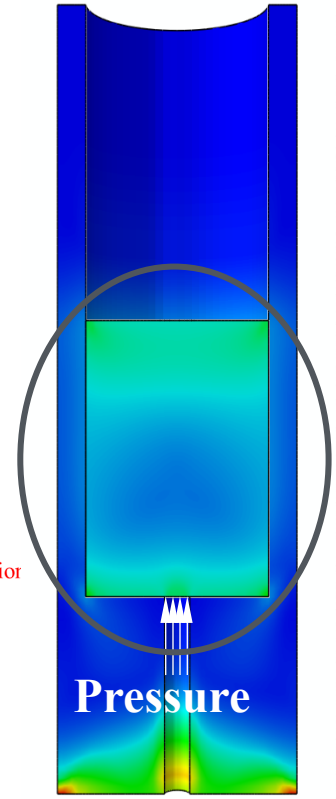


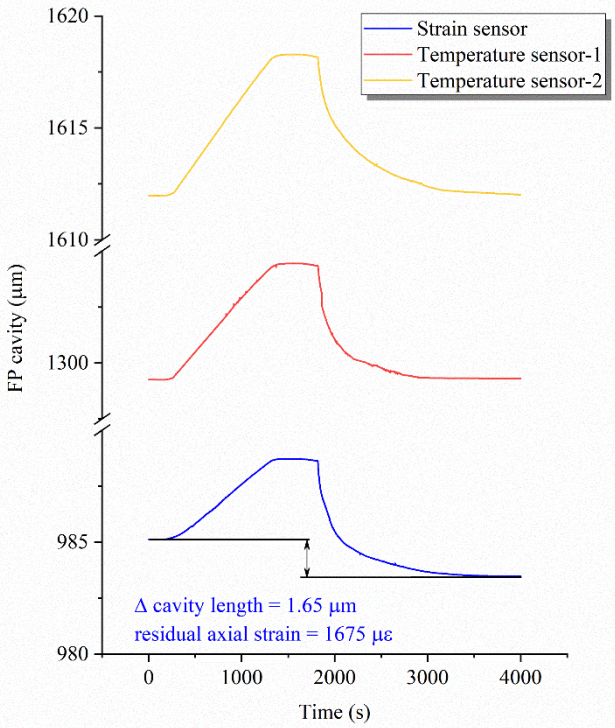


- Nanograting formation threshold at 100 nJ pulse energy
- With the increase of pulse energy, size of nanograting increases
- High visibility of 0.49 at optimized pulse energy of 160 nJ
- Low insertion loss of 0.0024 dB per sensor

Accomplishments # 2: Robust Sensor Packaging Scheme



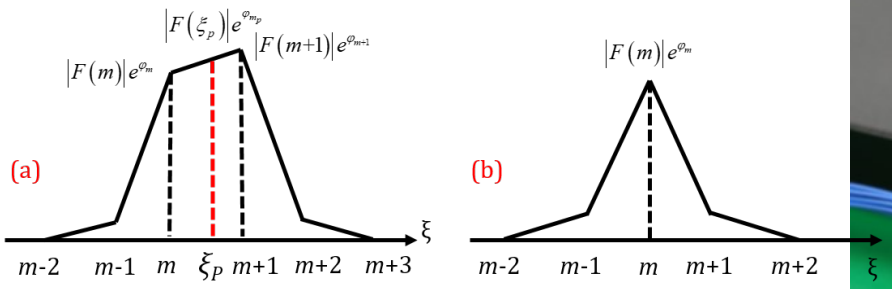




- **Glass sealant packaging to ensure high-T operation**
- **Provide strain and temperature sensors through pressure boundary**
- **Flexible packaging schemes enable multi-parameter measurements**

Accomplishments # 3: Rapid Demodulation Algorithm and Interrogation Systems for NE I&C

Bunman Frequency Estimation

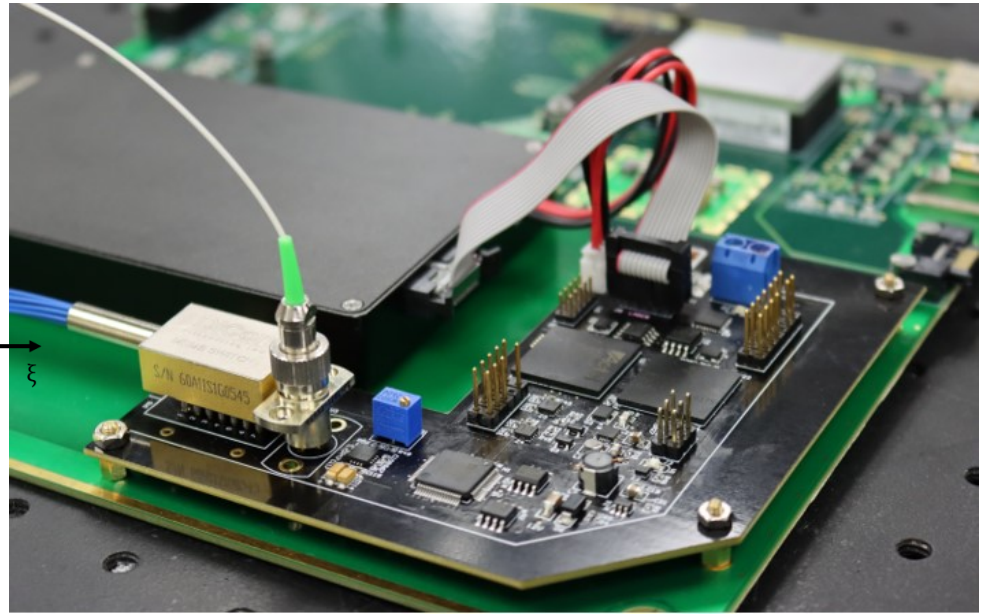


$$F(\xi)=\sum_{n=0}^{N-1}\gamma e^{i(\frac{l\Delta kn}{N}+lk_0+\varphi_0)}e^{-2\pi in\xi/N}$$

$$=\gamma e^{i[lk_0+\varphi_0+\pi(\frac{l\Delta k}{2\pi}-\xi)(\frac{N-1}{N})]}\frac{\sin[\pi(\frac{l\Delta k}{2\pi}-\xi)]}{\sin[\pi(\frac{l\Delta k}{2\pi}-\xi)/N]}$$

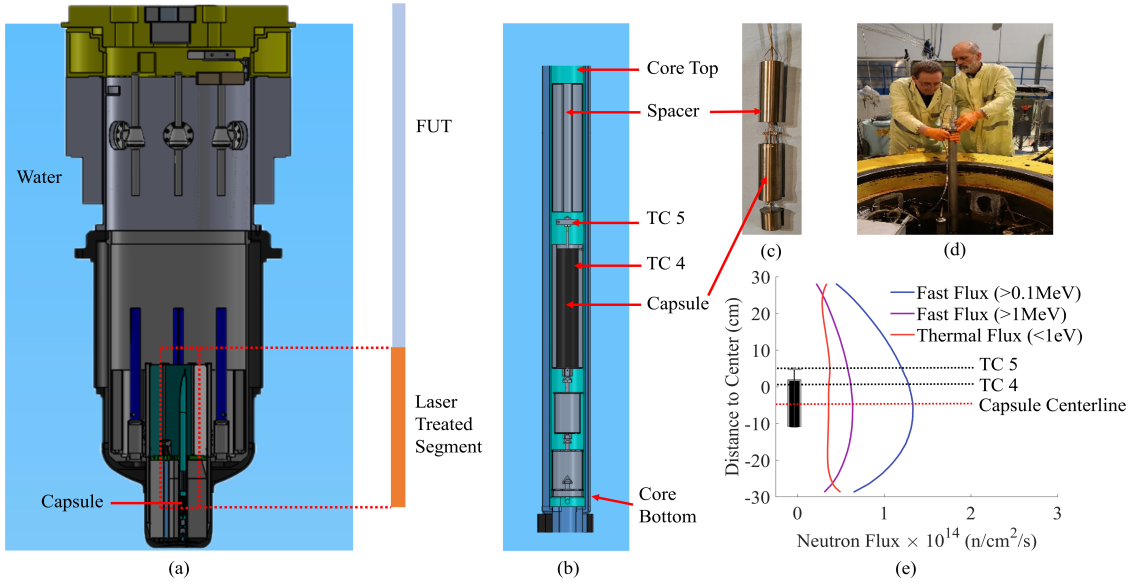
$$\varphi\left(\frac{l\Delta k}{2\pi}\right)=\varphi_{\xi p}+2\pi a=\varphi_m+2\pi a$$

$$\xi_p=\frac{k_1-k_0}{k_0}\left(\varphi_m-\varphi_0+2\pi[a]\right)$$



- Phase based demodulation
- Robust algorithm avoid “phase jump”
- Computationally efficient
- Easy implementation into DSP chips
- Dedicate sensor demodulation electronics developed
- Support 2 kHz sampling rates
- 40-nε or 0.01C temperature accuracy.
- Eight channels

Accomplishments # 3: Distributed Fiber Sensor In-Pile Testing



- Extensive in-Pile Testing
- MIT Reactor at 650C
- Two type of rad-hard fiber
- Low-cost Telecom fiber
- Fs-enhanced Rayleigh Profile
- Two month testing (due to COVID)
- Collaboration with LUNA Innovation, MIT, and INL

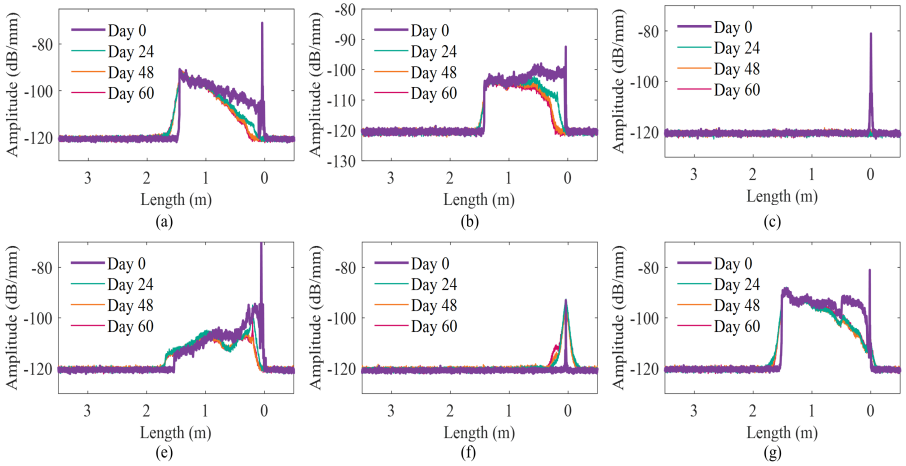


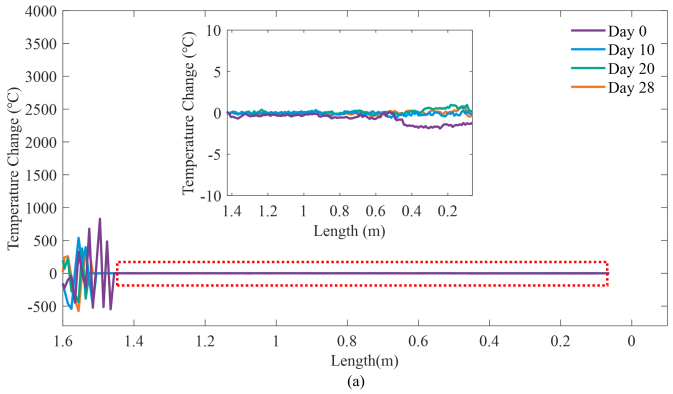
TABLE I
THE MAIN CHARACTERISTICS OF OPTICAL FIBERS FOR IN-CORE RADIATION TEST.

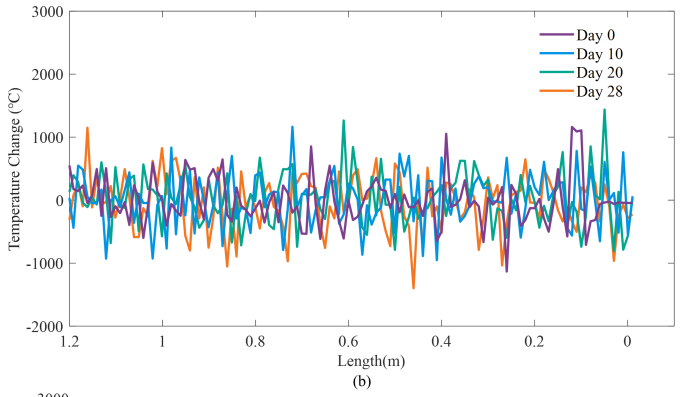
SAMPLE#	Fiber type & Vendor	Single-mode specifications	Laser enhance-ment
1, 2	SMF28e+ from Corning	NA=0.14, Ge-doped core	✓
3			×
4,5	Super RadHard from Draka	≥ 0.41 wt% and 1.2 wt% fluorine doped in core and cladding	✓
6			×
7	RRSMFB from Fujikura	Fluorine-doped silica core and cladding, chlorine concentration of core ≥ 1ppm	✓

Accomplishments # 3: Distributed Fiber Sensor In-Pile Testing

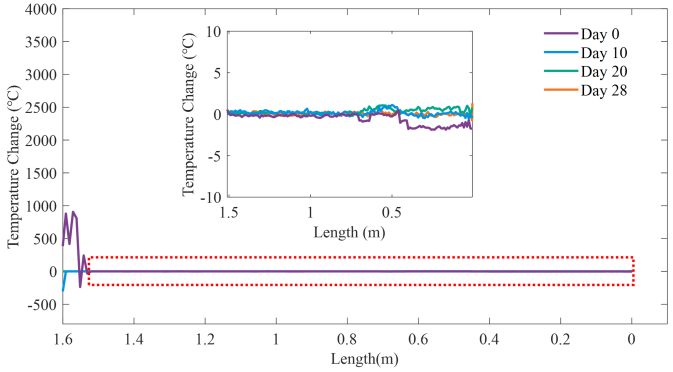
Laser Enhanced | **Pristine Fibers**

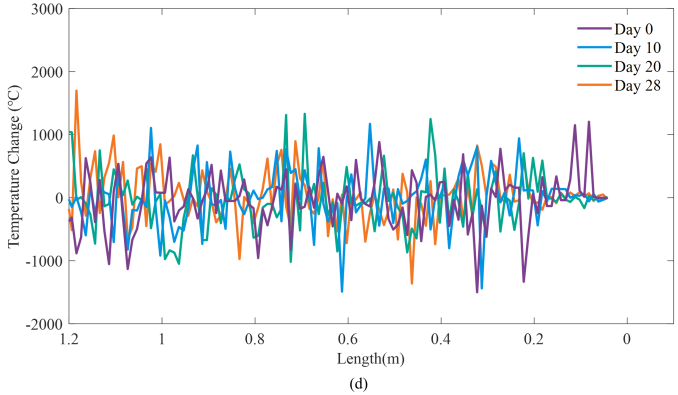
SMF-28





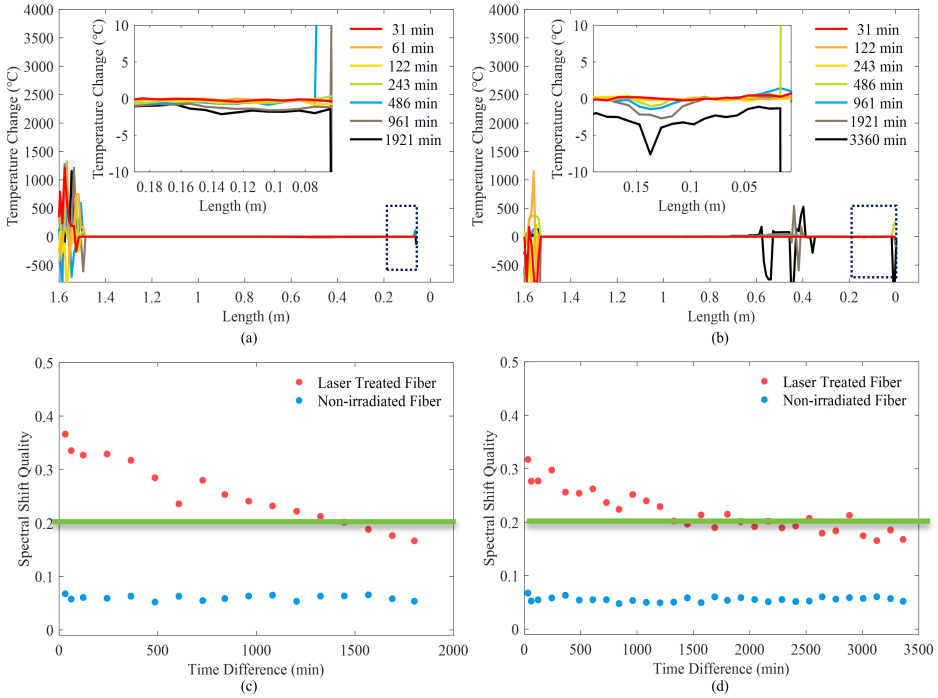
RadHard





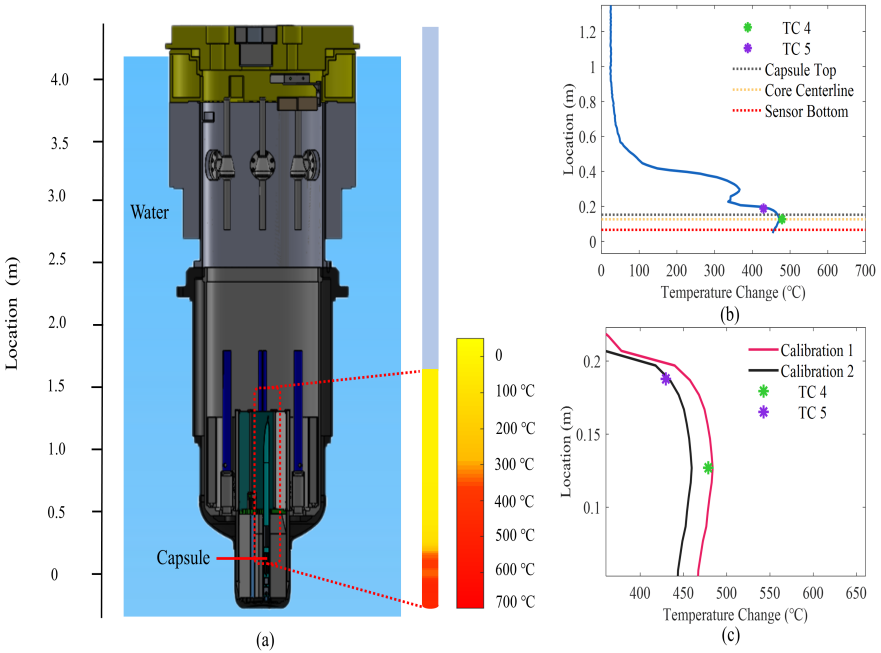
Accomplishments # 3: Distributed Fiber Sensor In-Pile Testing

Spectral Shift Quality VS. Time



Radhard **SMF-28**

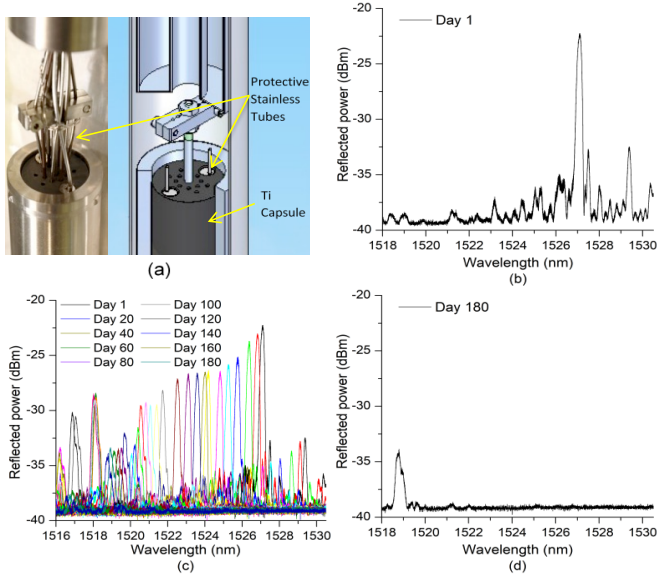
First Ever Temperature Profile of a Running Reactor (1-cm Resolution)

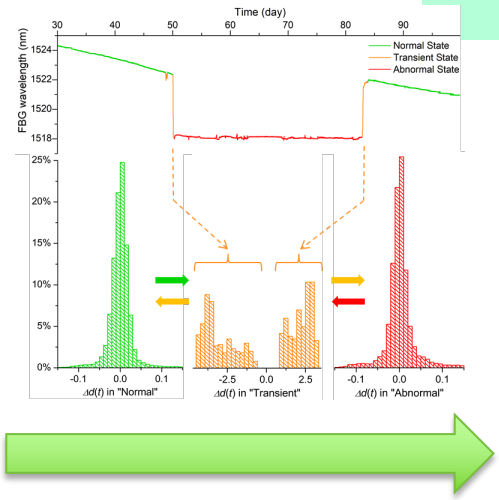


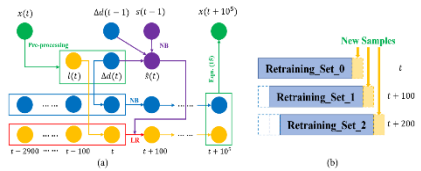
Sensor Data Enabled VR and AI !

Accomplishments # 4: Sensor Data Enabled Artificial Intelligence

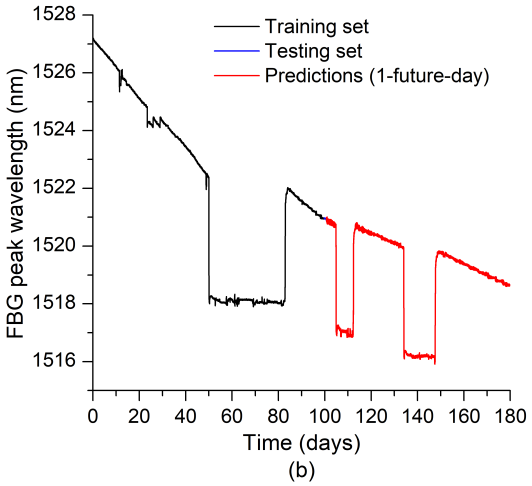
FBG Sensor In-Pile Testing

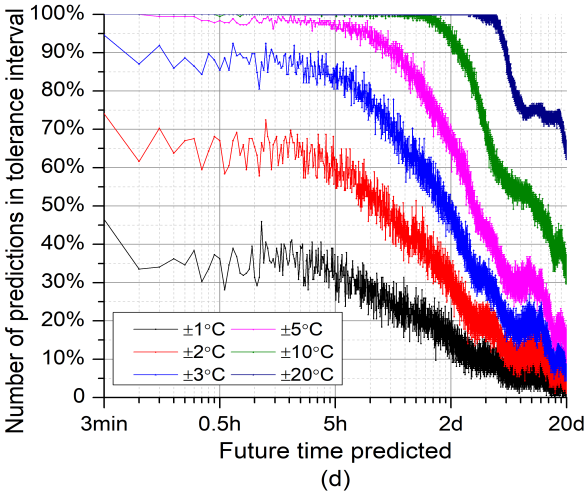






Bayesian Learner Prediction

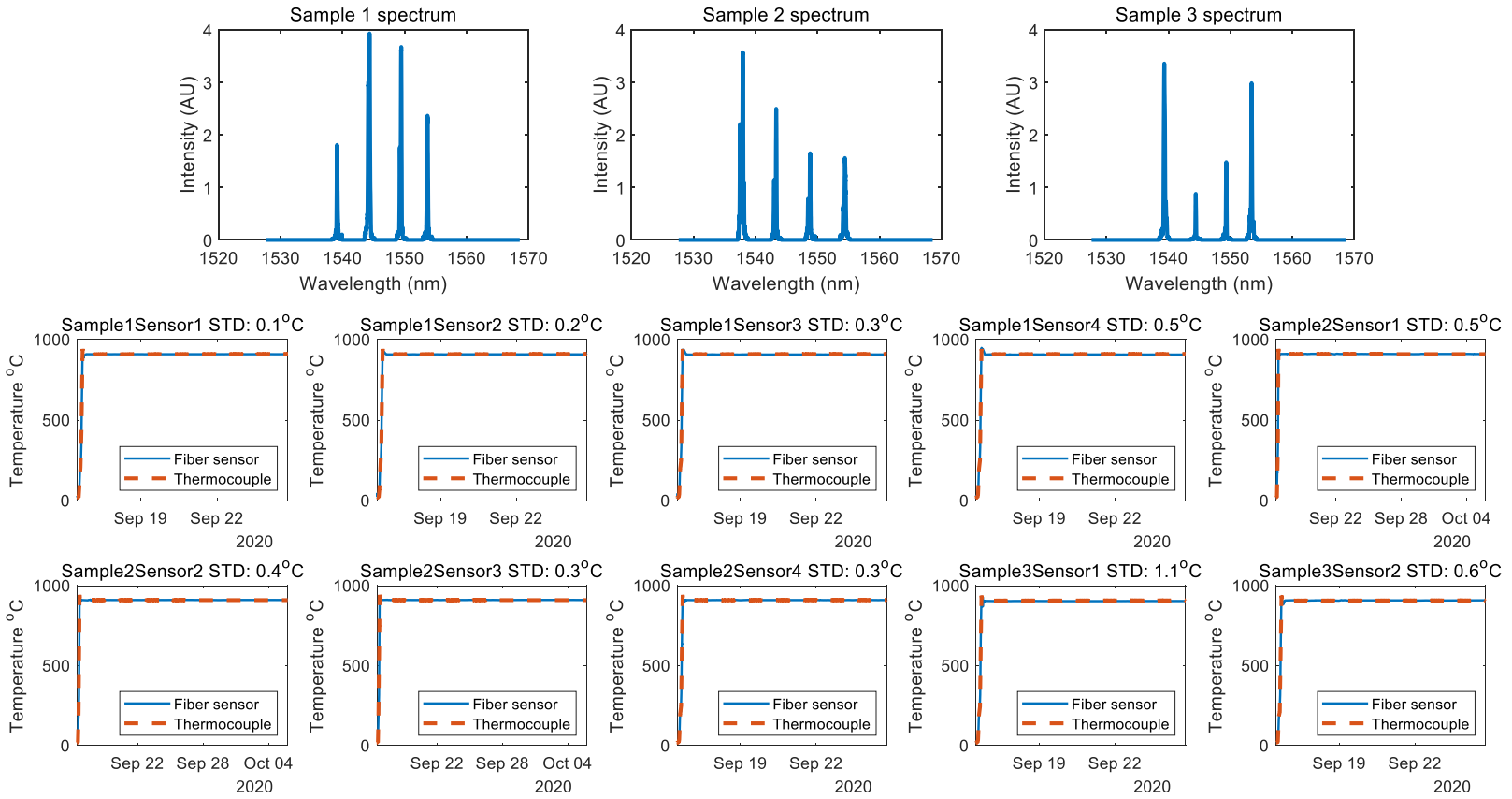




- Machine learning mitigation of sensor drift
- Bayesian learner for reactor anomaly event detection
- 98.3% of sensor drift can be eliminated through ML
- Anomaly event trigged 3C temperature variation can be detected.
- **"Bad Sensor" is better than No Sensor!**

Accomplishment #5: Improving TRL for Reactor Deployments

- **Comprehensive FBG sensor array high-T testing (900C-1000C)**
- **Average STD <0.6C over 10 days spans (comparing with TC)**
- **Further increase sensor counts and testing duration in 2021.**



Technology Impact

- *Innovation from reel-to-reel laser fabrication of fiber sensor for high spatial resolution data harness for NE*
- *Comprehensive R&D efforts aiming to serve cross-cutting I&C technical needs*
- *Sensors can be deployed for*
  - *Neutron flux <10^{13} n/cm^2/s*
  - *Temperature < 900C*
- *I&C electronics, demodulation schemes, and AI algorithms are being developed for NE deployments and potential commercialization.*

Summary of accomplishments

- Developed reel-to-reel sensor fabrication system with high fabrication yield.
- Computational efficient sensor demodulation algorithm directly implemented in DSP chips
- Comprehensive high-T testing of fiber sensor array at 900C
- Customized sensor interrogation board for NE I&C system.
- New fiber sensor package method for multi-parameter sensing.
- First ever temperature mapping of nuclear reactor core.
- Machine learning algorithm to mitigate sensor drift and reactor anomaly identification using Bayesian Learner.
- Two US patents and 13 technical publications

Conclusion

Comprehensive R&D efforts from Sensor Devices to AI algorithm.

Aiming Field Deployment in a Near Future

Questions?

Kevin P. Chen: Email: pec9@pitt.edu