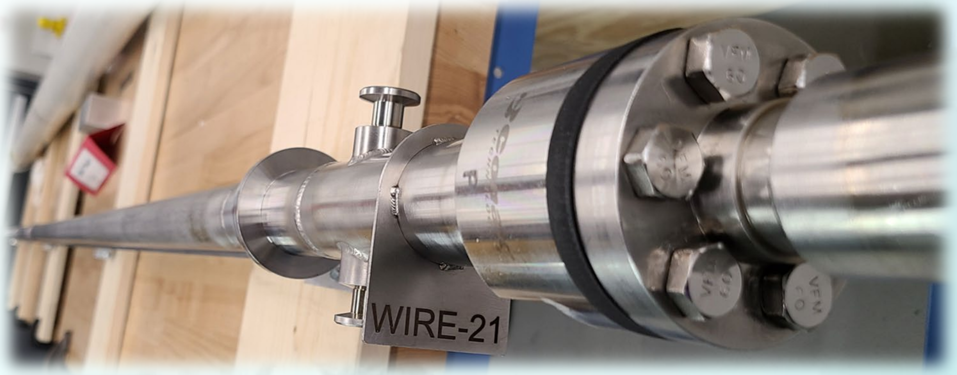
U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Advanced Sensors and Instrumentation

Analysis of Extreme Radiation Dose Effects on Fiber Optic Sensors



Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

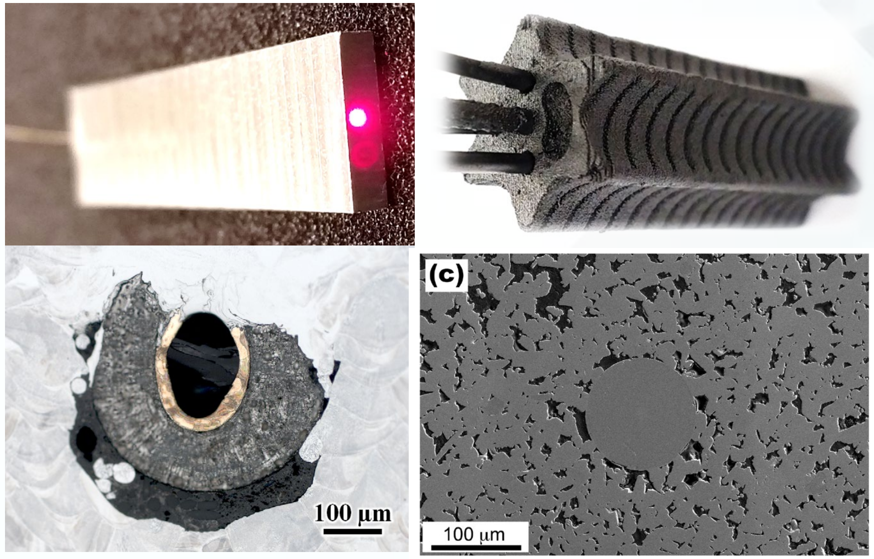
October 24 – 27, 2022

Dr. Christian Petrie, Group Leader, PI

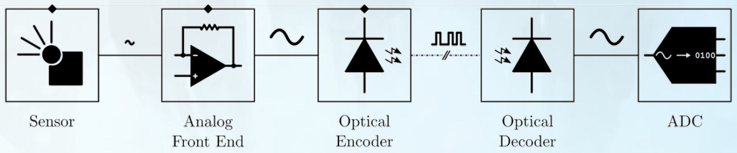
Dr. Dan Sweeney, Co-PI

Oak Ridge National Laboratory

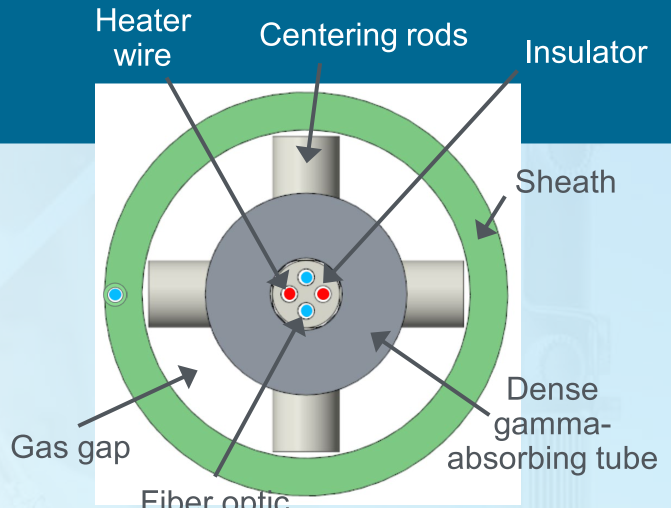
Potential Nuclear Applications of Optical Fibers



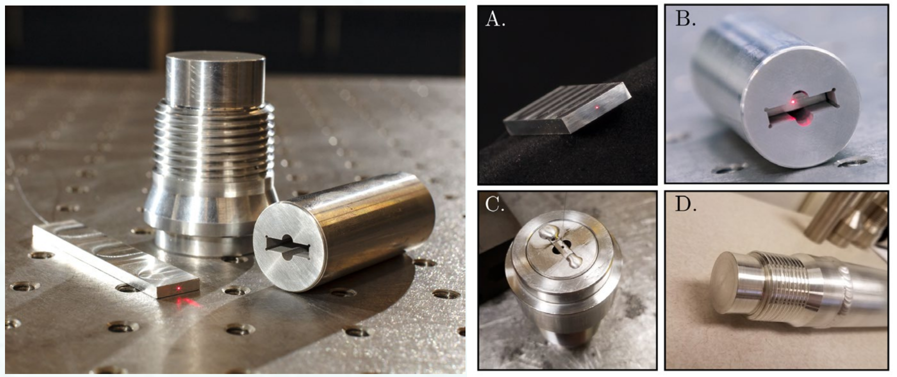
Fiber optics embedded in 3D printed stainless steel (left) or SiC (right) for local strain or vibration monitoring [1, 2]

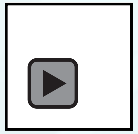


Rad-hard Front End Digitizer (FREND) to transmit conventional sensor data through reactor containment over fiber optic cables to reduce noise in cabling [3]

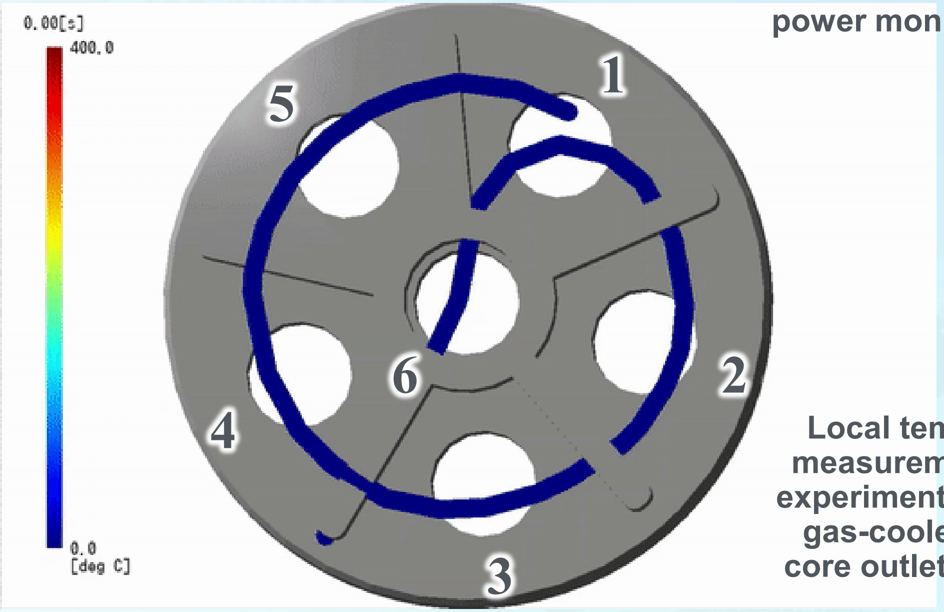


Distributed gamma thermometer (local power monitoring) [4]





Embedded fiber optic sensor for measuring pressure, corrosion, or acoustic emissions [5, 6]



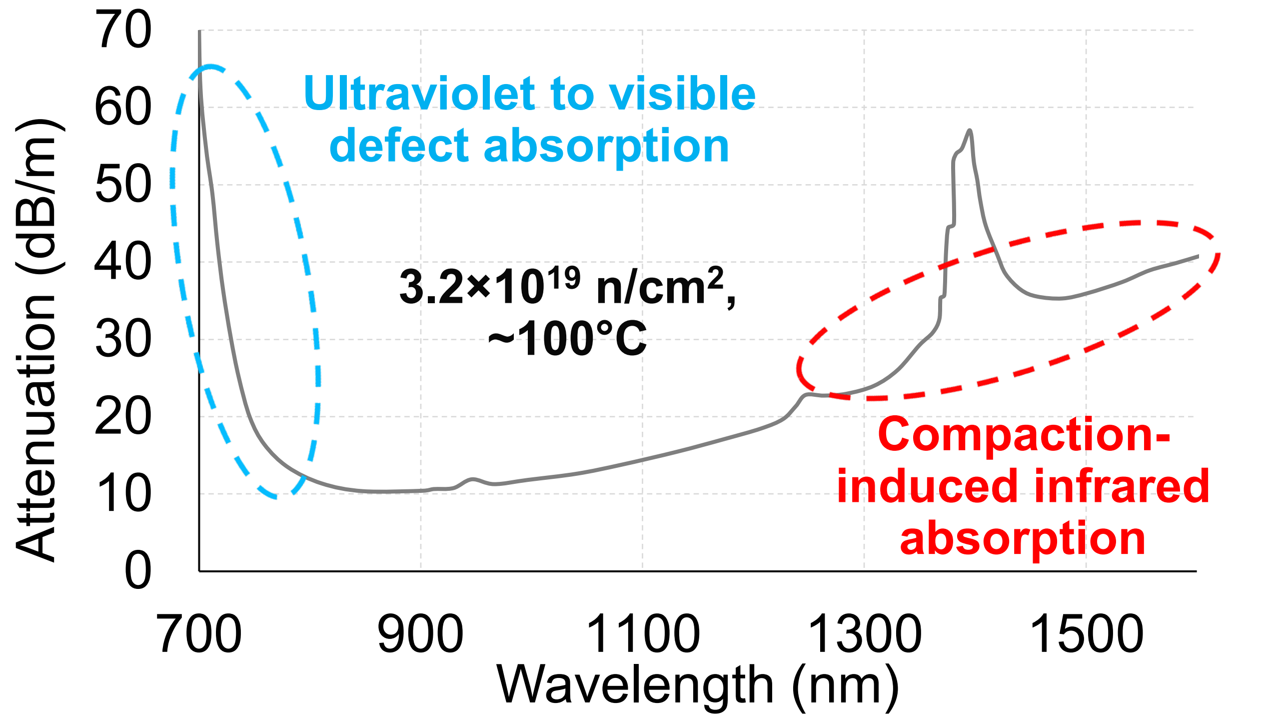
Local temperature measurements in an experiment simulating gas-cooled reactor core outlet mixing [7]

[1] H.C. Hyer et al., *Additive Manufacturing*, **52** (2022), 102681.
[2] C.M. Petrie et al., *Journal of Nuclear Materials* **552** (2021) 153012.
[3] D.C. Sweeney et al., "Analog Front End Digitizer using Optical Pulse-Width Modulation for Nuclear Applications," *IEEE Trans. Instrum. Meas.* (under review)
[4] A. Birri and T.E. Blue, *Progress in Nuclear Energy* **130** (2020) 103552.
[5] D.C. Sweeney, A.M. Schrell, and C.M. Petrie, *IEEE Trans. Instrum. Meas.* **70** (2021) 1-10.
[6] C.M. Petrie, D.C. Sweeney, and Y. Liu, US Non-Provisional Patent No. US 2021/0033479 A1, Application No. 16/865,475, published February 4, 2021.
[7] H.C. Heyer, D.R. Giuliano, and C.M. Petrie, *Appl. Therm. Eng.* **230** (2023) 120847.

Challenge: Signal Attenuation and Drift

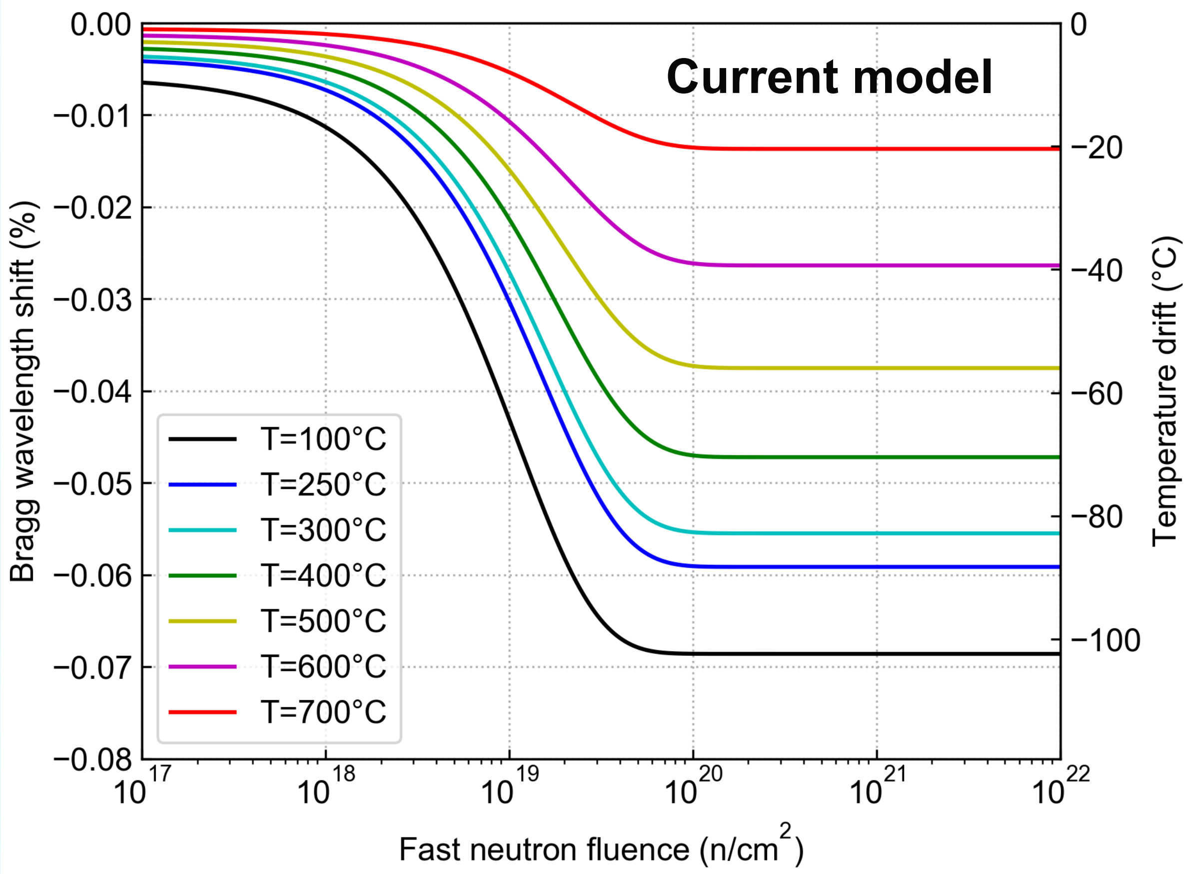
Signal attenuation could be a show-stopper

- Existing data at moderate neutron fluence and low temperature (<100°C) [1]
- Need to improve understanding for different fiber compositions and gratings at higher temperatures and neutron fluences



Fused silica compacts ~2% under neutron irradiation

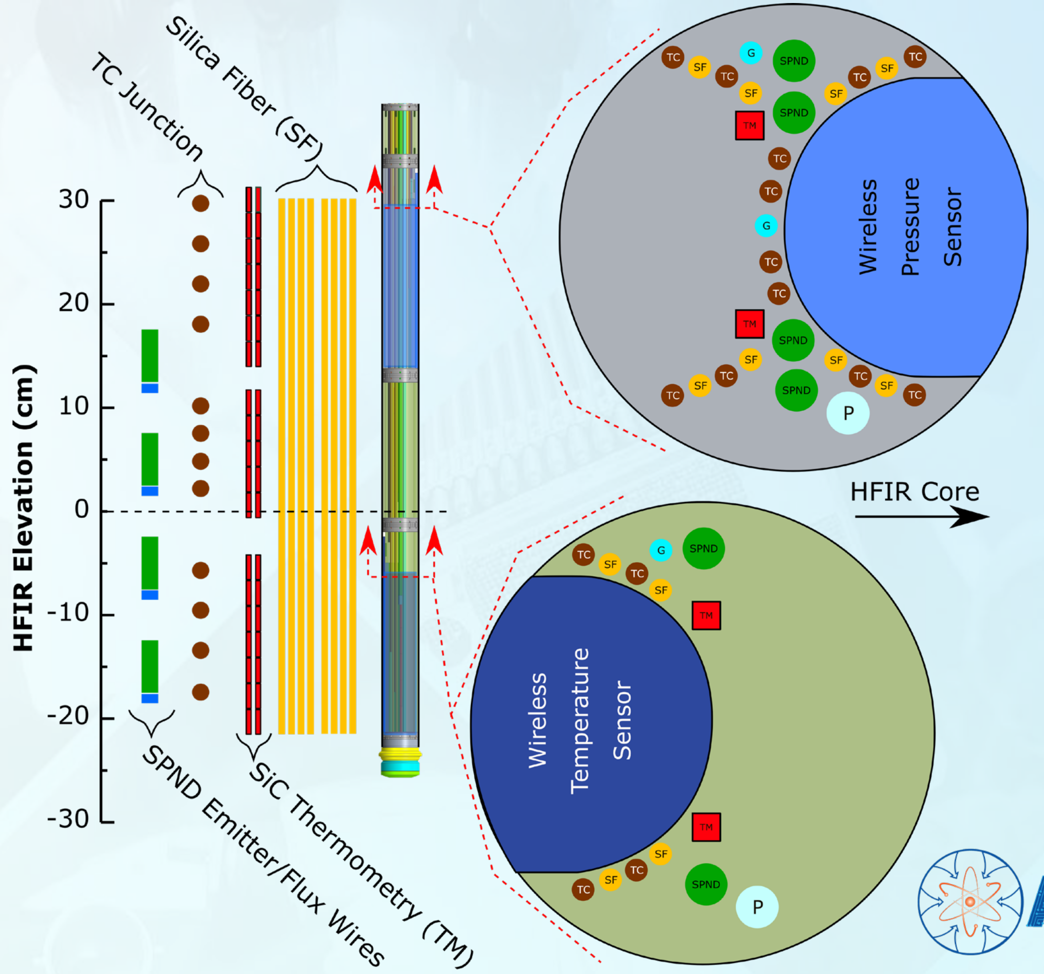
- Temperature-dependent, saturates at ~10^{20} n/cm^2 [2]
- Results in significant sensor drift



[1] G. Cheymol et al., IEEE Trans. Nucl. Sci. **55** (2008) 2252-2258
[2] C.M. Petrie et al., *J. Non-Cryst. Solids* **525** (2019) 119668.

WIRE-21: HFIR's Most Highly Instrumented Experiment

- Primary goal: Irradiate WEC's wireless temperature & pressure sensors at LWR temperatures (~300° C)
- Broader goal: Develop a platform for economical, accelerated testing of advanced sensors
  - Thermocouples (14)
  - Distributed fiber optic temperature sensors (8)
  - Self-powered neutron detectors (4)
  - Passive SiC temperature monitors (31) and flux wires (4)
- Completed 3 HFIR cycles
  - $\sim 3 \times 10^{21}\ n_{fast}/cm^2$
  - $\sim 8 \times 10^{21}\ n_{thermal}/cm^2$



FY20				FY21				FY22				FY23			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
WIRE-21 experiment design					Fabrication		Assembly		Irradiation			Data analysis			

ASI Supported the Analysis of All Fiber Optic Data

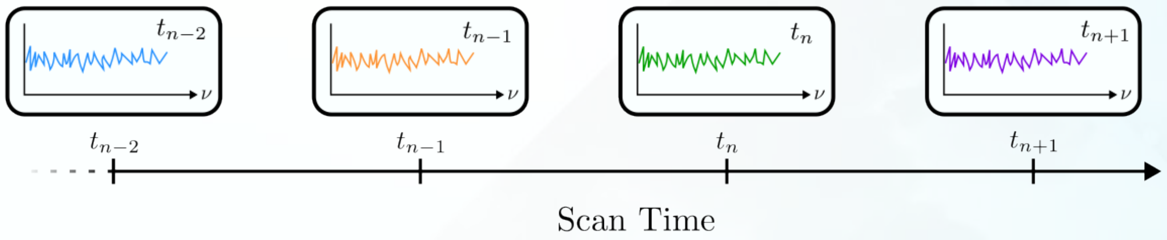
Goal is to understand differences in signal attenuation and drift at high neutron fluence

- Fibers with and without gratings
- Singlemode and hollow core fibers
- Varying fiber dopants (F, Ge)
- Varying grating types (Type I and II)

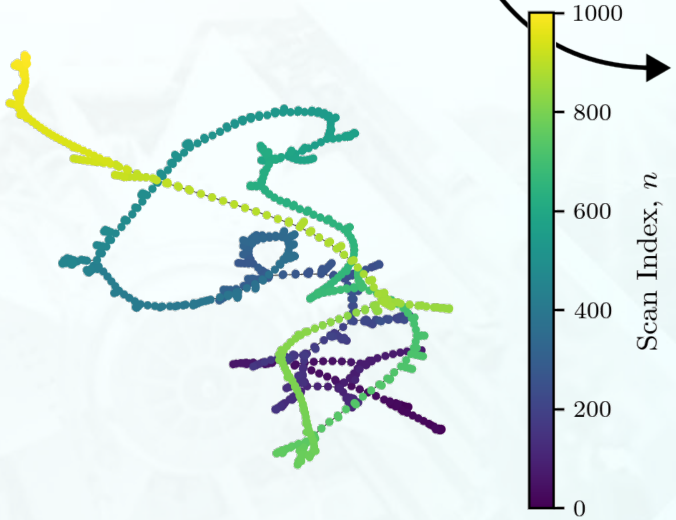
Fiber	Description	Gratings
1	Pure SiO_2 core, F-doped SiO_2 cladding	N/A
2	Ge-doped SiO_2 core, pure SiO_2 cladding	
3	F-doped SiO_2 core and cladding with Type II gratings	Type II, ~1% reflectivity, ~65 mm spacing
4		
5	Pure SiO_2 core, F-doped SiO_2 cladding with Type II gratings	Type II, ~0.5% reflectivity, ~10 mm spacing
6	Ge-doped SiO_2 core, pure SiO_2 cladding with Type I gratings	Type I, <0.1% reflectivity, ~10 mm spacing
7	Hollow core photonic crystal fiber	N/A
8		

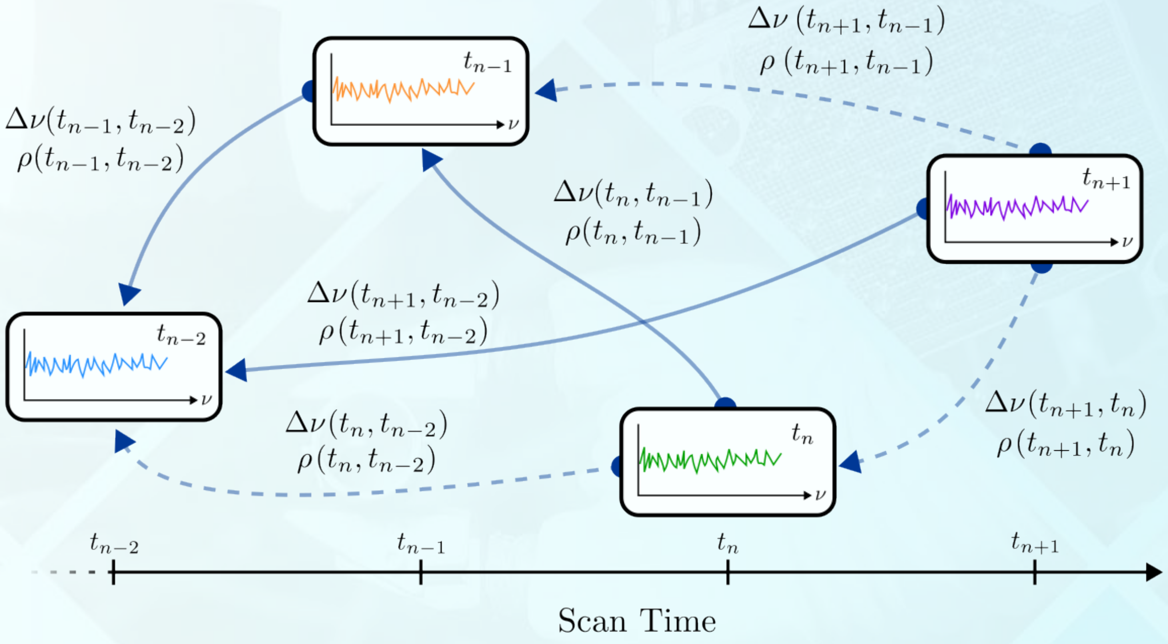
Some Data Can Only be Analyzed Using ORNL's Adaptive Reference Techniques

1.) Acquire OFDR scans over time

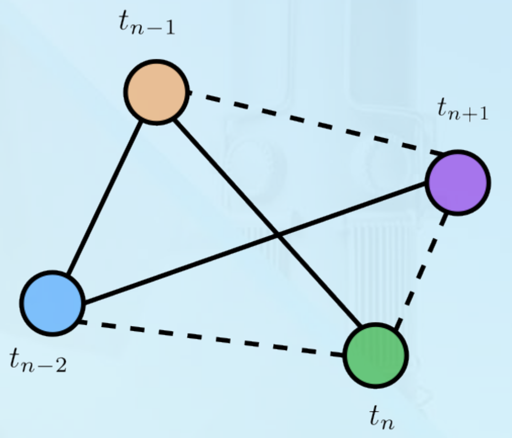


2.) Cross-correlate scans with all previous scans



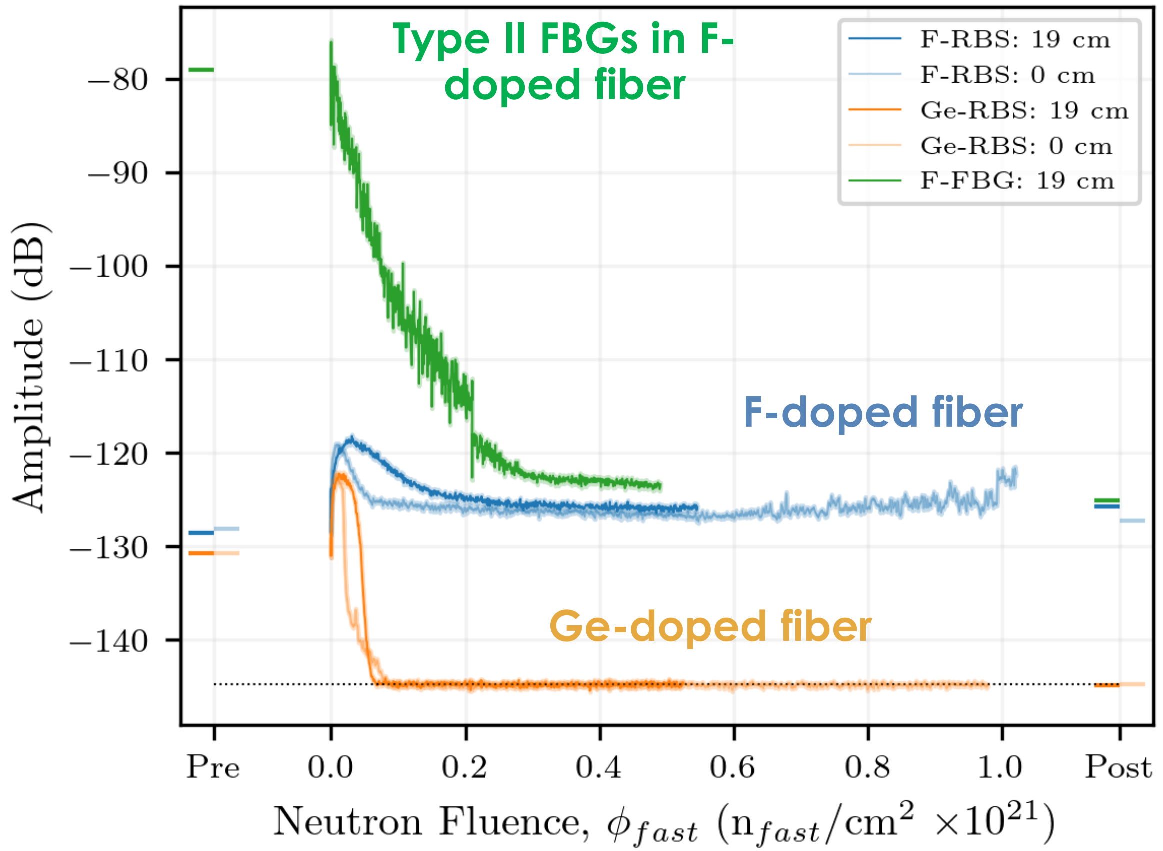


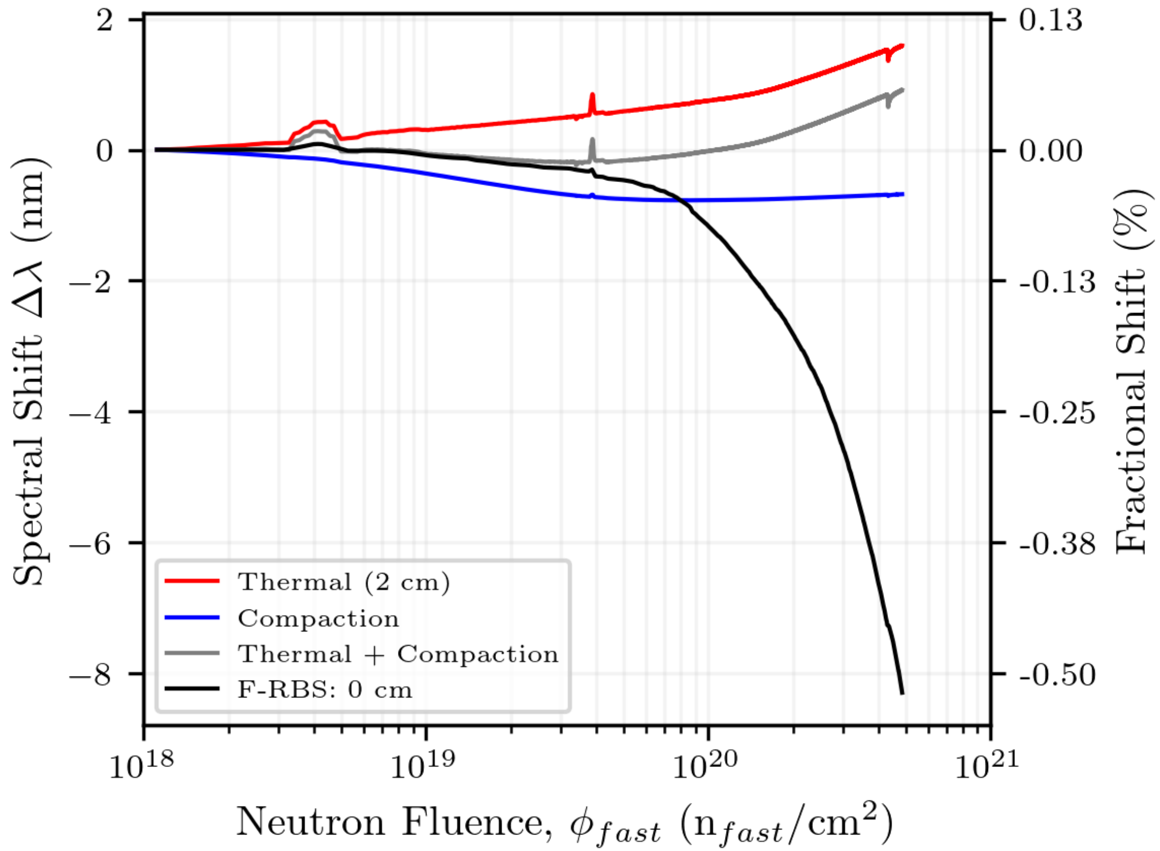
3.) Generate Pearson correlation coefficient (PCC)-weighted, directed graph to find cumulative shift



D.C. Sweeney and C.M. Petrie, "Methods for Continuously Resolving Spectral Shifts in Distributed Optical Fiber Sensors Irradiated to Extreme Neutron Fluence," *Nuclear Plant Instrumentation, Control & Human-Machine Interface Technologies* (2023) 1431–1440.

Results: Good and Bad News for F-doped Fibers





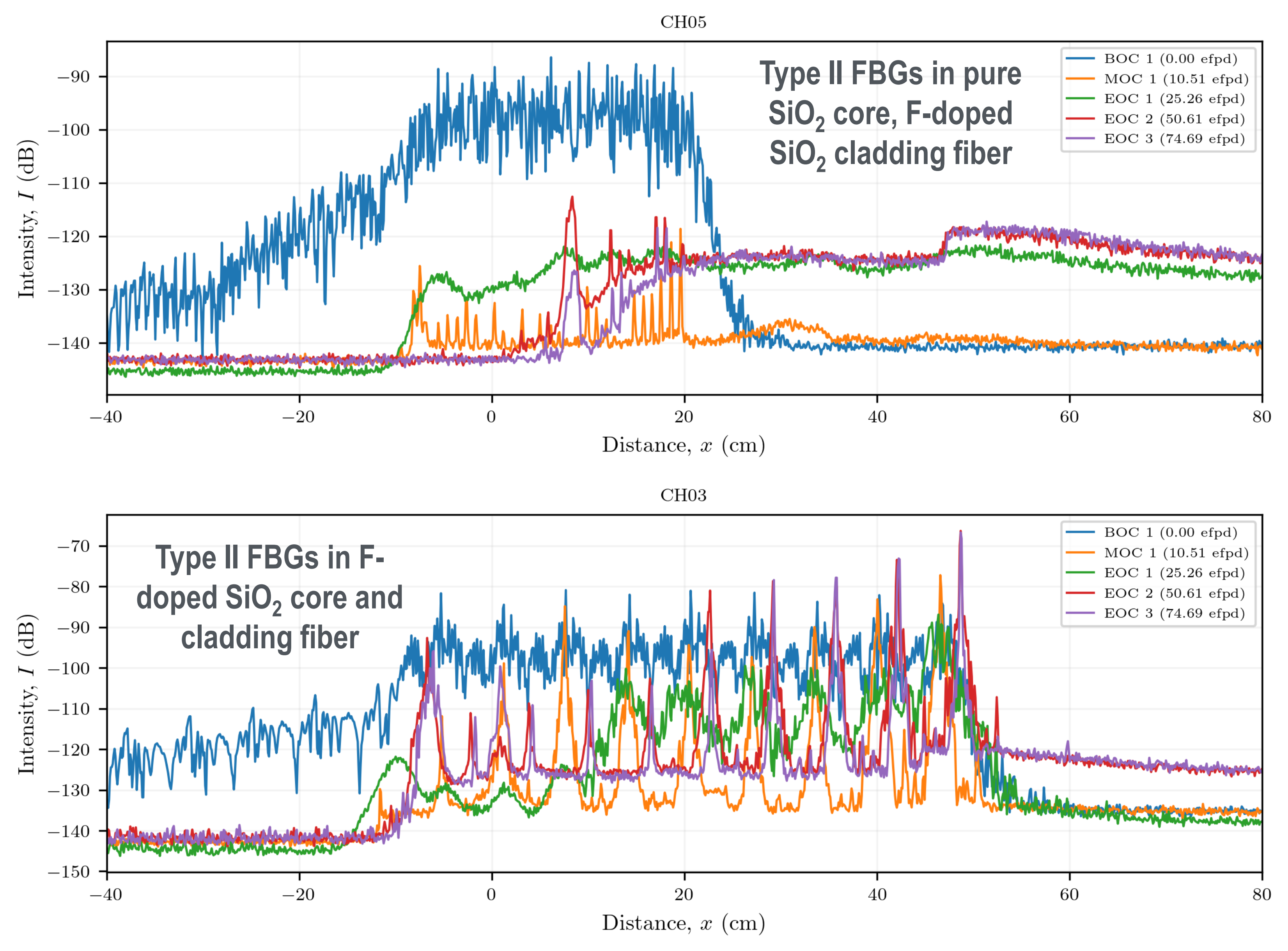
Drastic differences in reflected signal amplitudes at high neutron fluence

Measured spectral shifts (temperatures) deviate from thermal + compaction models at high neutron fluence

C.M. Petrie and D.C. Sweeney, "Enhanced backscatter and unsaturated blue wavelength shifts in F-doped fused silica optical fibers exposed to extreme neutron radiation damage", *J. Non-Cryst. Solids* **615** (2023) 122441 doi.org/10.1016/j.jnoncrysol.2023.122441

Results: Gratings

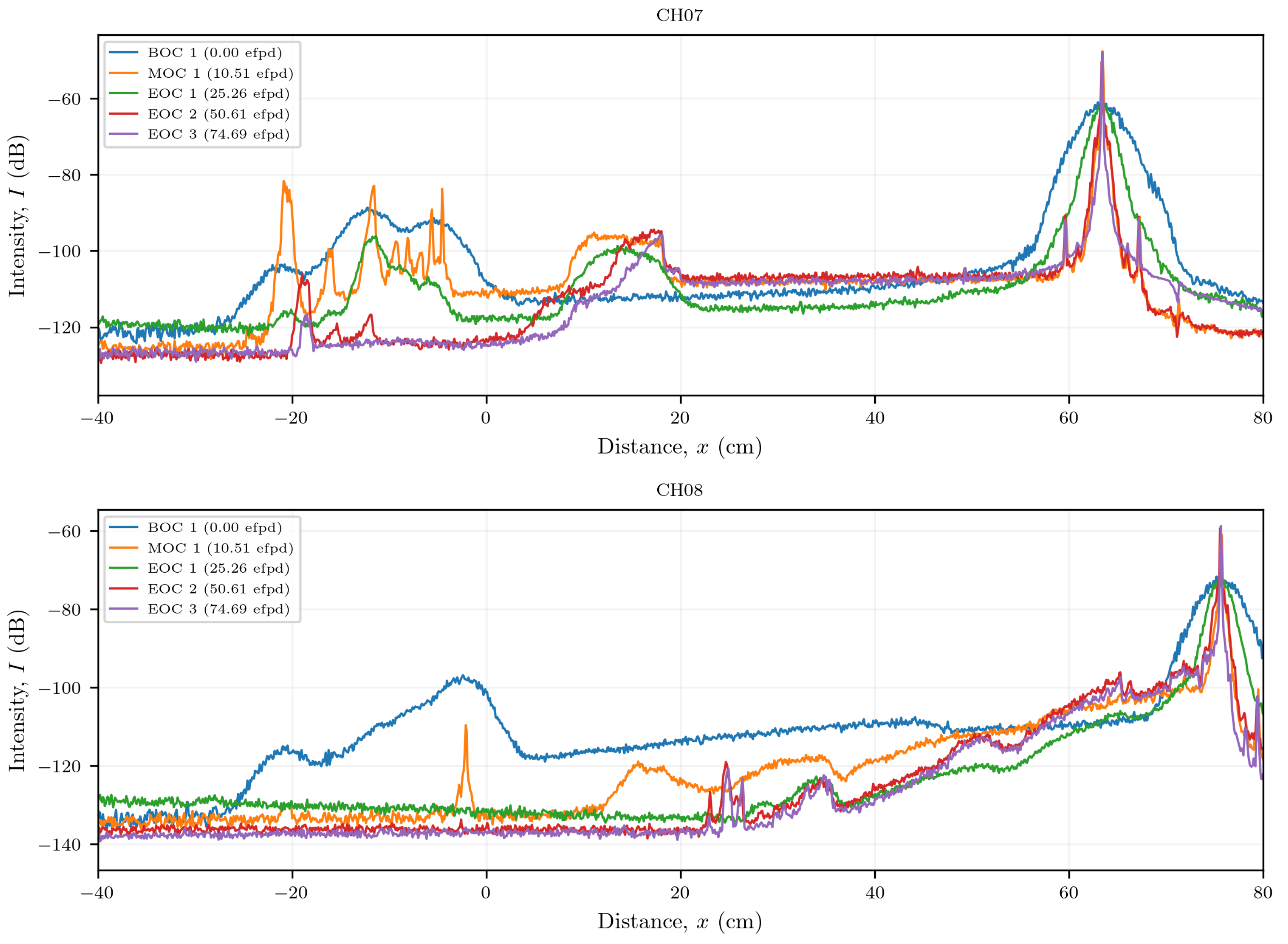
- Type II FBGs are clearly more radiation-tolerant than Type I FBGs
  - Type I FBGs erased within 2 days of irradiation
  - Type II FBGs in pure SiO_2 core, F-doped SiO_2 cladding fiber started to degrade significantly in 2nd HFIR cycle
  - Type II FBGs in F-doped *core and cladding* fiber survived entire experiment (~3×10^{21} n_{fast}/cm^2)
- **Core dopants have strong effect on FBG stability**



D.C. Sweeney et al., "Analysis of WIRE-21 SPND and Optical Fiber Sensor Measurements", ORNL/TM-2023/2024(2023) doi.org/10.2172/1997703

Results: Hollow Core Fibers May Not Be a Silver Bullet

- Hollow core fibers thought to be more rad-hard because light is transmitted in a gas that is immune to radiation damage
- Clear degradation in CH08
- CH07 maintains measurable reflected intensities >10 cm above the core
- Difficult to draw conclusions regarding transmission from reflected intensities in this fiber



D.C. Sweeney et al., "Analysis of WIRE-21 SPND and Optical Fiber Sensor Measurements", ORNL/TM-2023/2024(2023) doi.org/10.2172/1997703

Concluding Remarks

Analysis of the WIRE-21 optical fiber data reveals several interesting phenomena under extreme neutron flux/fluence

- Ge-doped fibers, with or without Type I FBGs, are not suitable for in-core applications (>10^{19} n_{fast}/cm^2)
- Pure SiO_2 core, F-doped SiO_2 cladding fibers showed *higher* reflected intensities after ~10^{21} n_{fast}/cm^2 than before irradiation
- Type II FBGs in the same fiber were essentially erased after ~10^{21} n_{fast}/cm^2
- Type II FBGs are much more radiation tolerant when inscribed in fibers with F-doped SiO_2 core and cladding
- All fibers showed significant drift that cannot be explained by radiation effects in SiO_2 (suspected coating effect to be studied in FY24)
- Hollow core fibers showed significantly reduced backscattered intensities during irradiation (may not be a silver bullet) but it is difficult to draw conclusions on their transmission properties

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Questions?

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