Instrumentation and Sensors – Acoustics

Paul Geimer, Andrew Delorey
Los Alamos National Laboratory

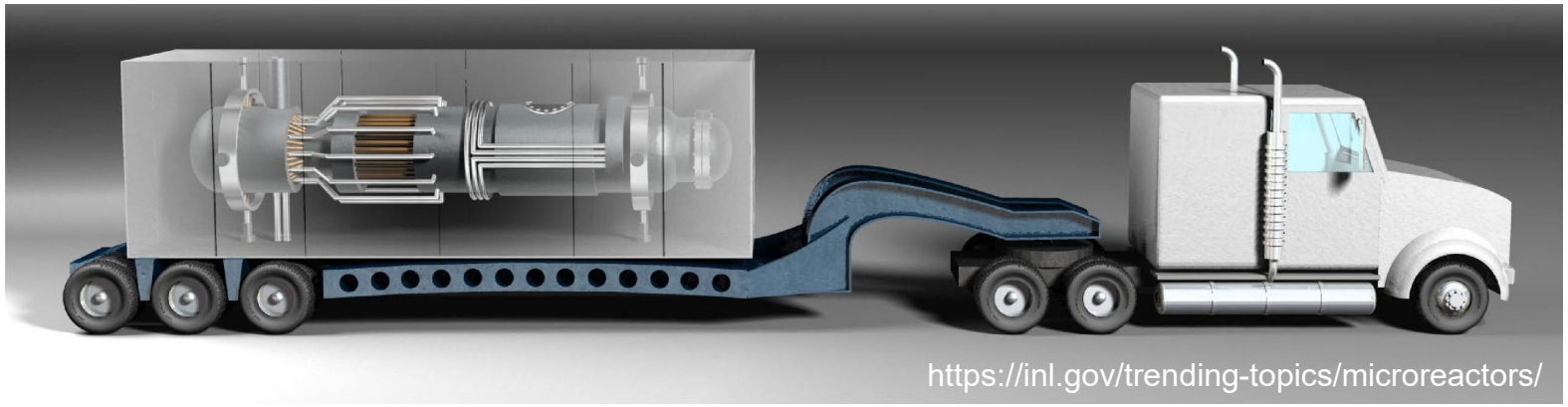
March 4, 2026

Microreactor Program Annual Winter Review

Motivation: Advancing structural health monitoring readiness for microreactor applications

Goal: Enable condition-based monitoring to reduce technical and operational risks

- Improve operational autonomy in remote environments
- Reduce inspection burden
- Support qualification for long-duration deployments

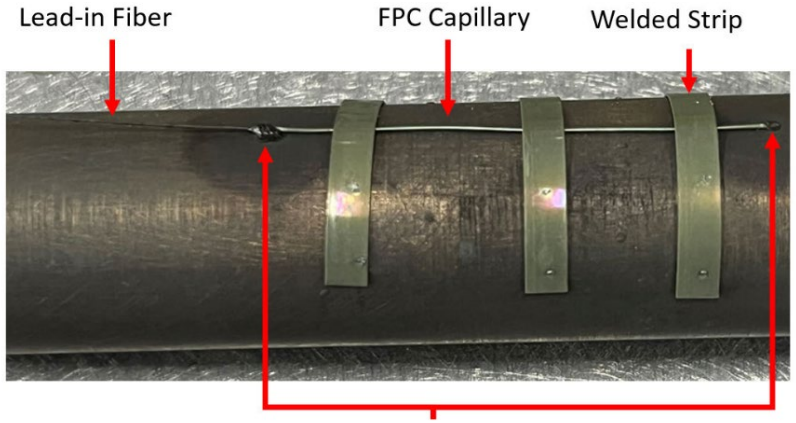


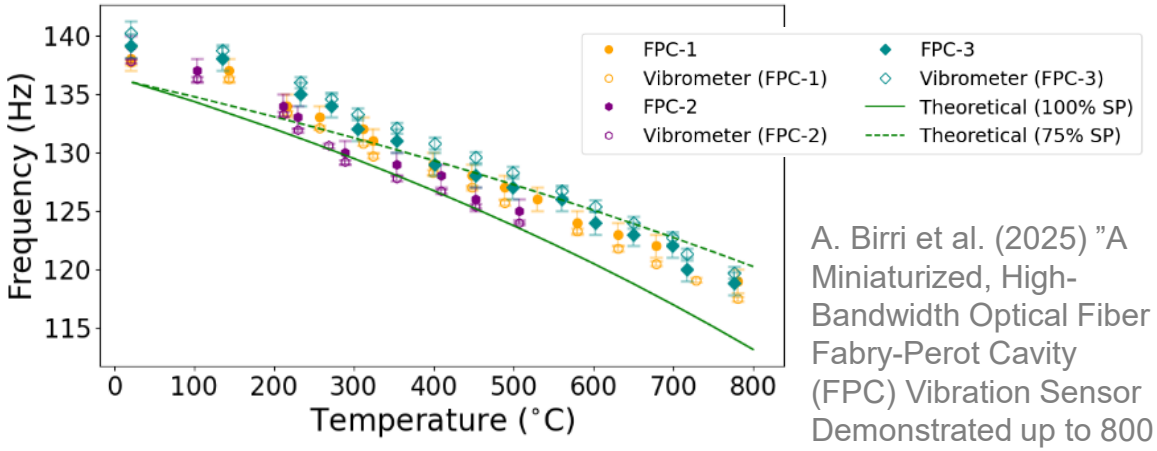
https://inl.gov/trending-topics/microreactors/

MRP Microreactor Program

Structural anomaly characterization using in-situ vibration / acoustic measurements

- If fiber-based sensors can measure high-bandwidth vibrations in high-temperature environments, how to best utilize similar signals for in-situ structural health monitoring?
- How well can localized anomaly detection be achieved in both one and two dimensions?

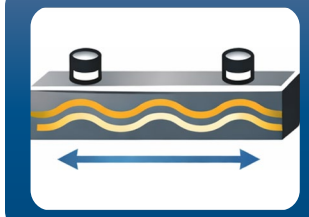




A. Birri et al. (2025) "A Miniaturized, High-Bandwidth Optical Fiber Fabry-Perot Cavity (FPC) Vibration Sensor Demonstrated up to 800 °C" *IEEE Sens. J.*

MRP Microreactor Program

Acoustic techniques for structural health monitoring



Guided waves

Impulse / ringdown

Active

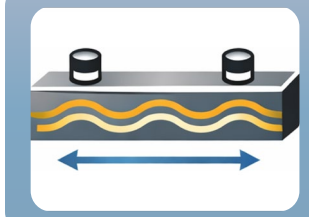
Acoustic emissions

Modal analysis

Passive

MRP Microreactor Program

Acoustic techniques for structural health monitoring

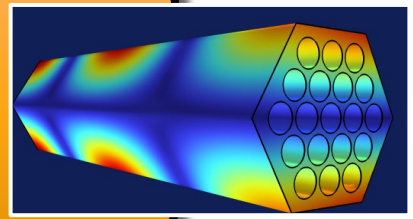


Guided waves

Impulse / ringdown

Acoustic emissions

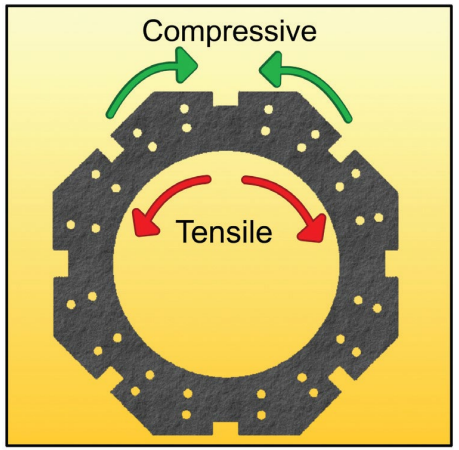
Modal analysis



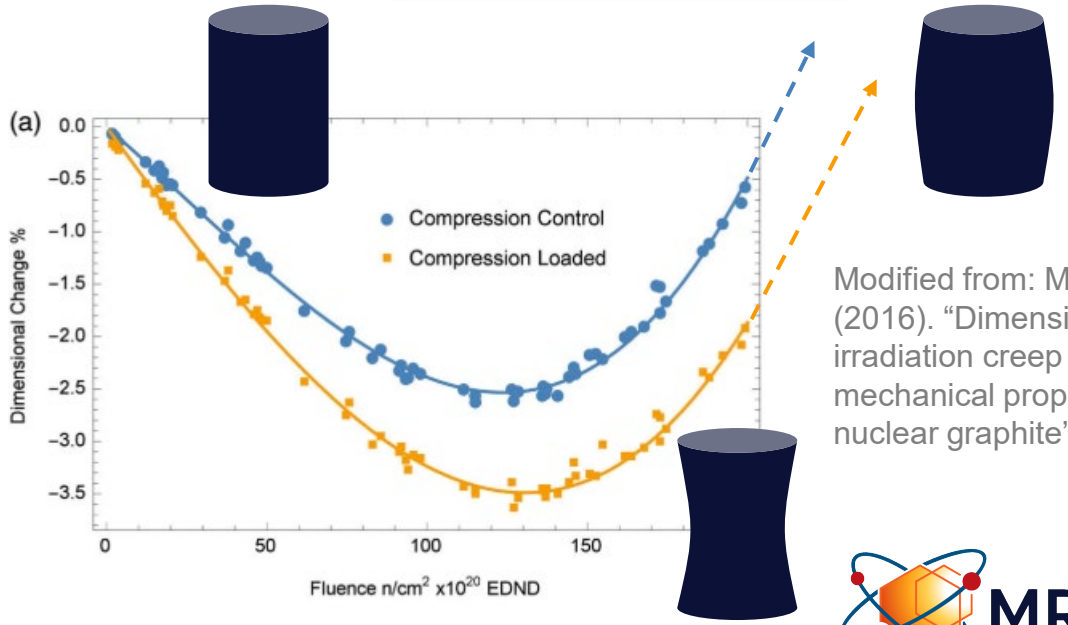
MRP Microreactor Program

FY25/26 efforts have focused on graphite components

- Graphite fracture toughness is ~50-100x less than stainless steel
- Creep, dimensional change, thermal expansion are all affected by fluence
  - Transition from shrinkage to swelling (“turnaround”) shifts to lower fluence as irradiation temperatures increase
- Hunterston B shutdown moved up by 2+ years after inspection discovered 100s of cracks in graphite core bricks



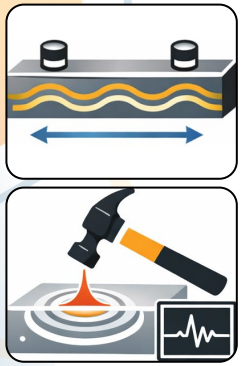
Maul et al. (2017). “Cracking in Nuclear Graphite” *Math. Today.*

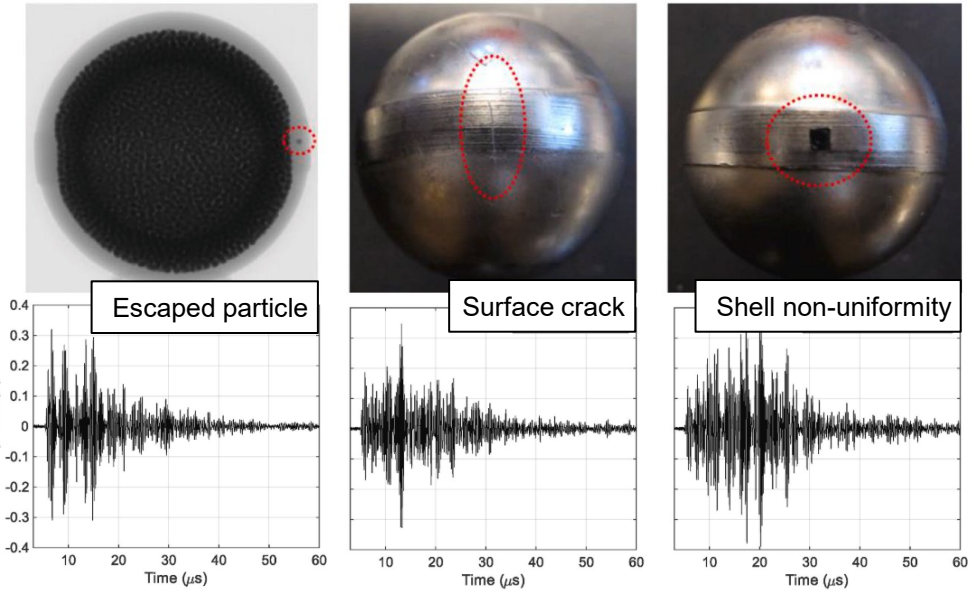


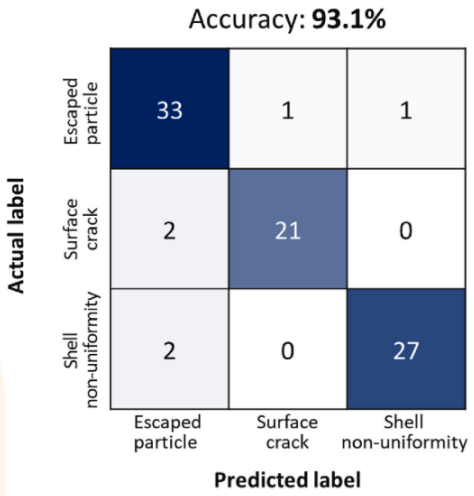
Modified from: Marsden et al. (2016). “Dimensional change, irradiation creep and thermal / mechanical property changes in nuclear graphite” *Int. Mat. Rev.*

MRP Microreactor Program

Incorporating deep learning into graphite inspection

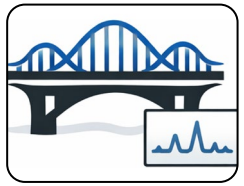


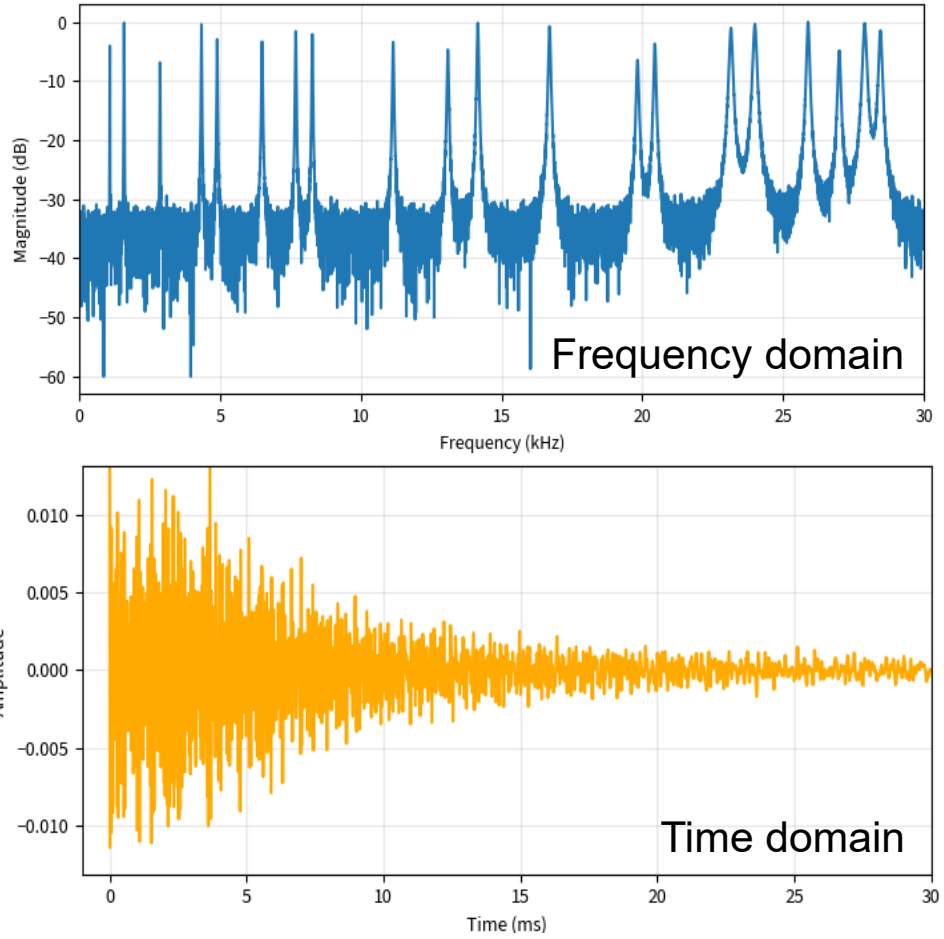




vs. accuracy of only ~80% when using traditional ultrasonic parameters

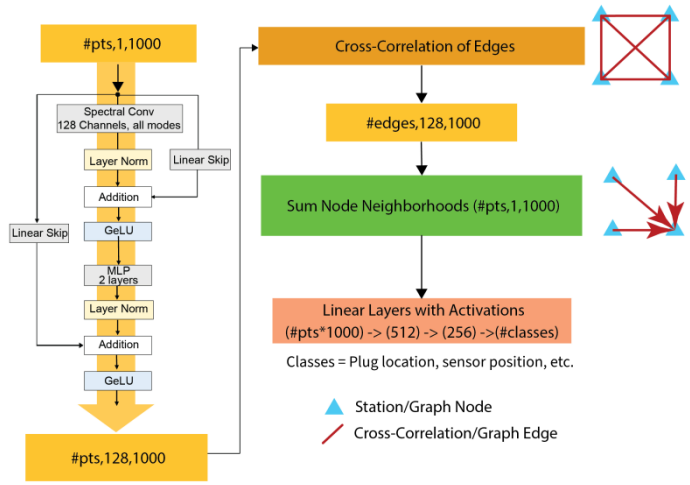
Pyun et al. (2025). Comprehensive defect evaluation of advanced nuclear fuels using high-resolution acoustic signals and optimized sensor separation *Nondestruct. Test. & Eval. Int.*

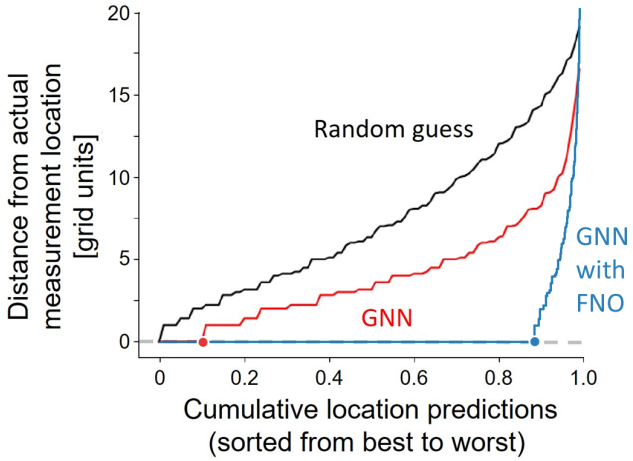


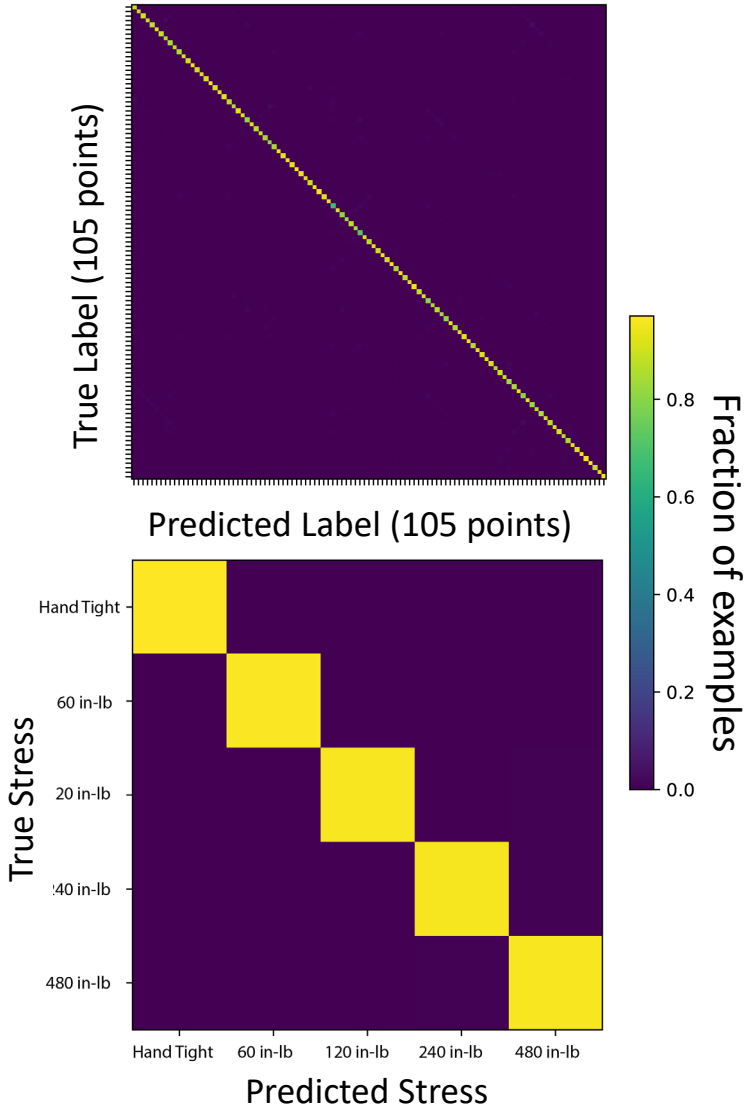


MRP Microreactor Program

Machine learning implementation





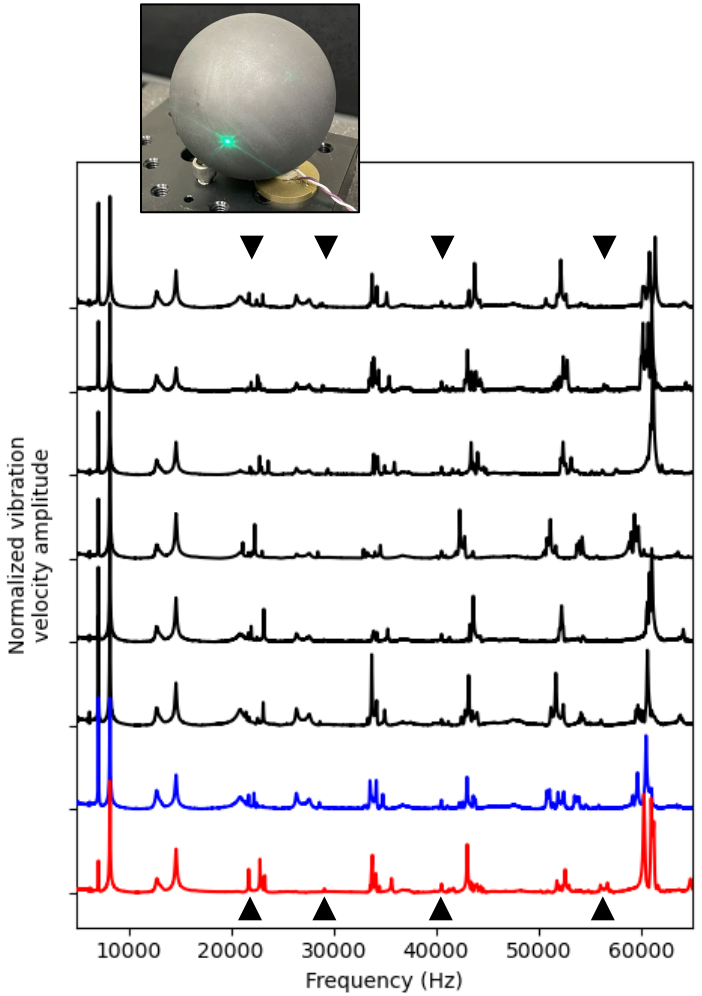


- Graph Neural Network (GNN) enables arbitrary sensor placement
- Added Fourier Neural Operator (FNO) in FY25 to better capture spectral elastic behavior
  - Neural operators learn function-to-function mappings and generalizes well across grid sizes
- Compared to previous results, greatly improved localization and characterization through coupled workflow

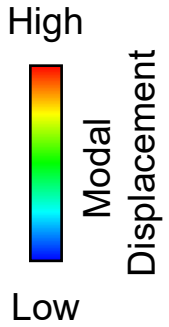
MRP Microreactor Program

Global inspection: Discrimination of sphere population using spectral features

- Prediction accuracy >99% due to small spectral differences caused by density and geometry variation
- High accuracy despite low-frequency (< 20 kHz) spectral contamination
- Material properties confirmed within spec.

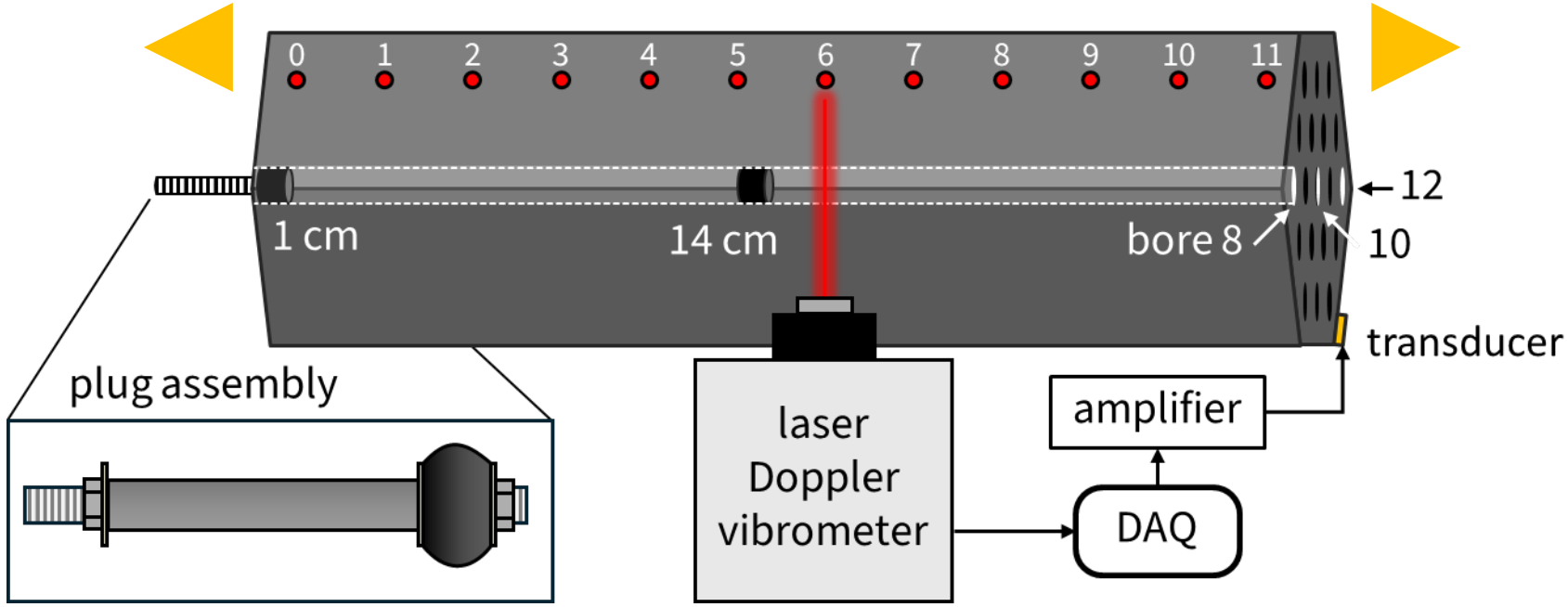


	Forward Model E=11.5 GPa, v=0.17	Sphere A	Sphere B
Mode 1 [kHz]	22.092	21.986 (-0.5%)	21.409 (-3.1%)
Mode 1 (degenerate) [kHz]	22.093	22.819 (+3.3%)	21.721 (-1.7%)
Mode 3 [kHz]	28.640	29.005 (+1.3%)	28.564 (-0.3%)
Mode 7 [kHz]	40.869	41.683 (+2.0%)	41.102 (+0.6%)
Mode 13 [kHz]	55.111	56.015 (+1.6%)	54.596 (-0.9%)



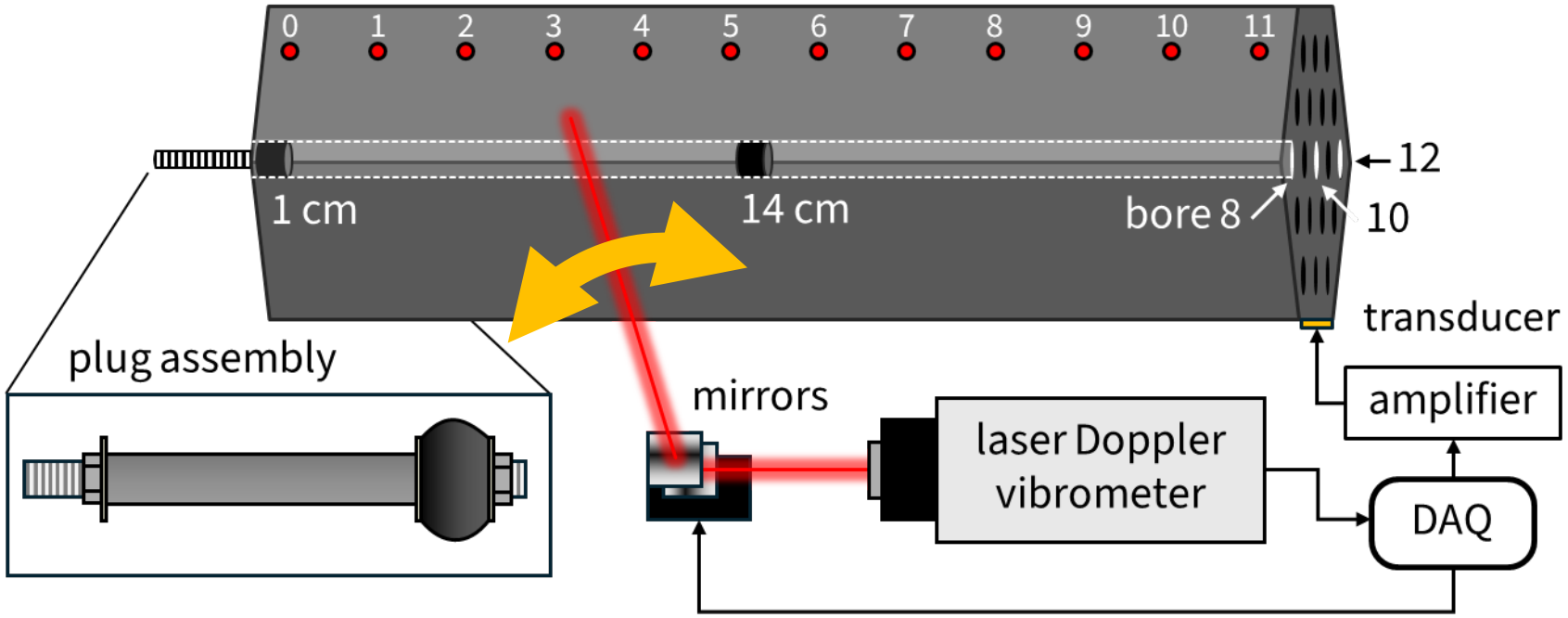
MRP Microreactor Program

Localized anomaly Experimental setup 1: Stationary vibrometer, moving sample



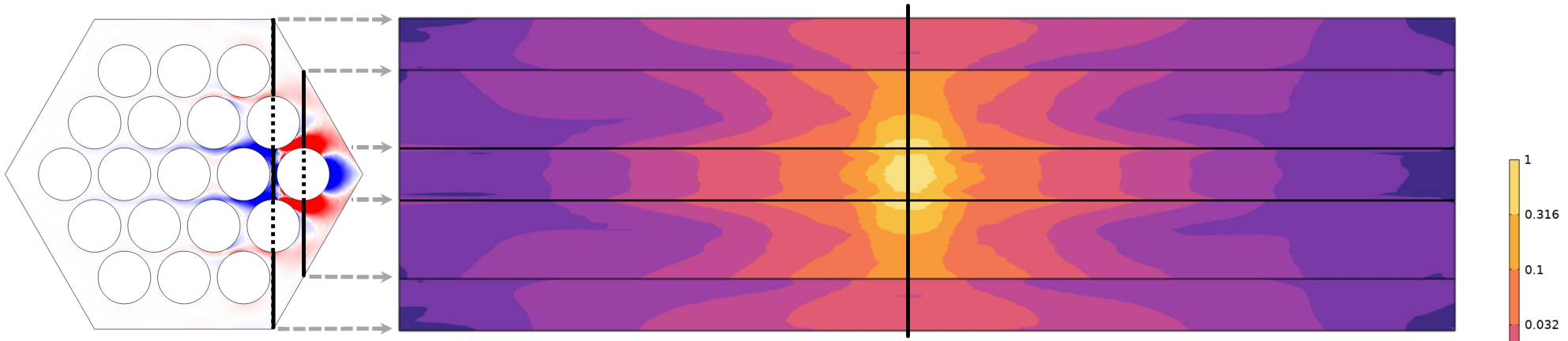
MRP Microreactor Program

Localized anomaly Experimental setup 2: Scanning laser vibrometry, stationary sample



MRP Microreactor Program

Local vs. uniaxial distribution of applied stress anomaly



Current: localized compression in graphite

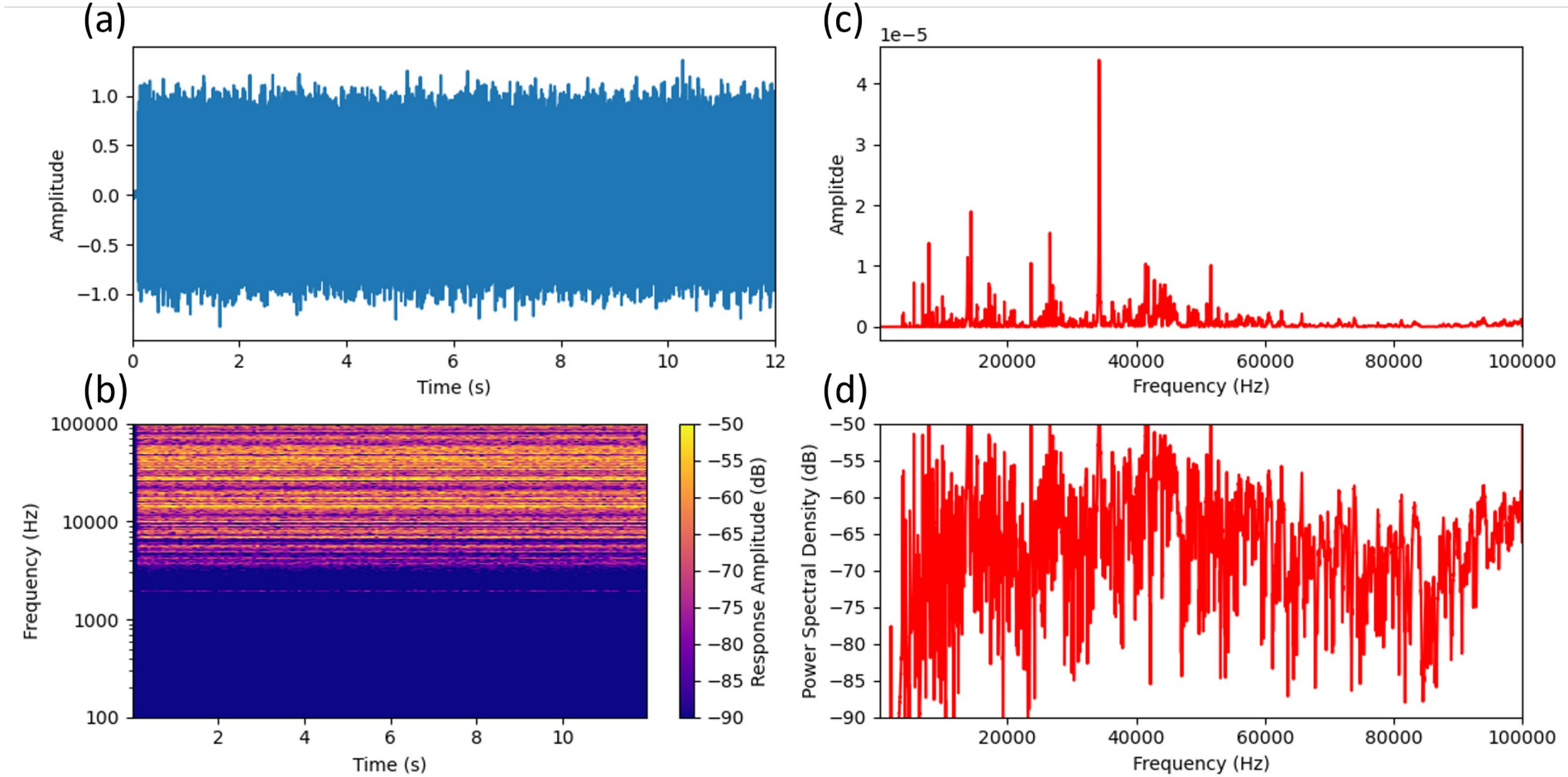
- Larger volume fraction impacted by uniaxial loading (bottom) as compared to localized load
  - Produces spatially complex pattern of **compressive** and **tensile** stresses

Previously: uniaxial compression in steel

MRP Microreactor Program

Preliminary data collection and processing (Approach 1)

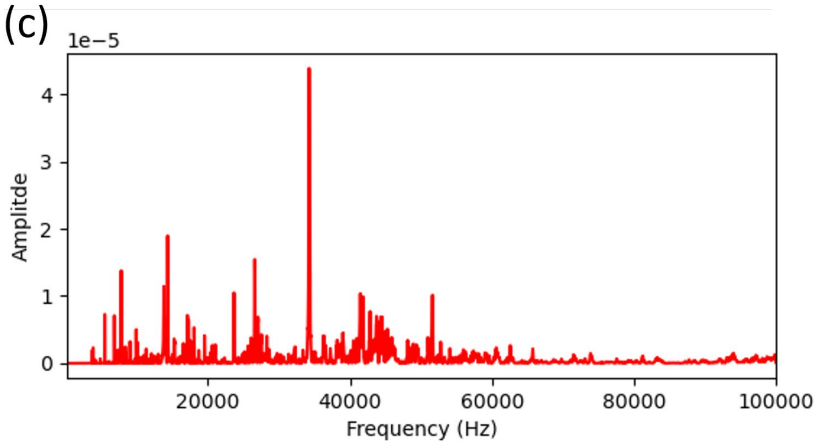
a) Time series
b) Spectrogram
c) Linear spectrum
d) Power spectrum

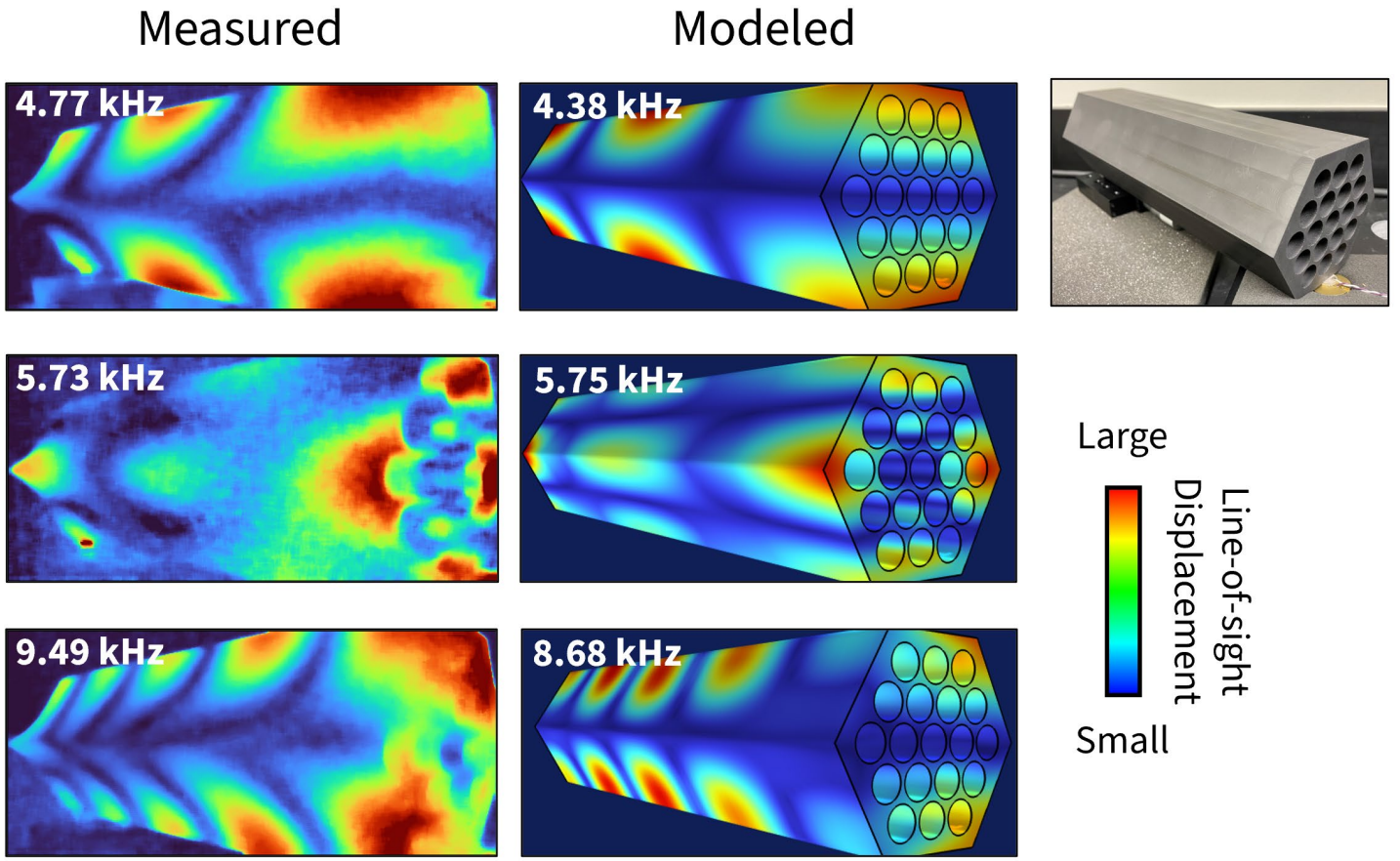


MRP Microreactor Program

Validation of spectral features using modal analysis

- Measured mode shapes correspond to identified peaks (sub-10 kHz shown)

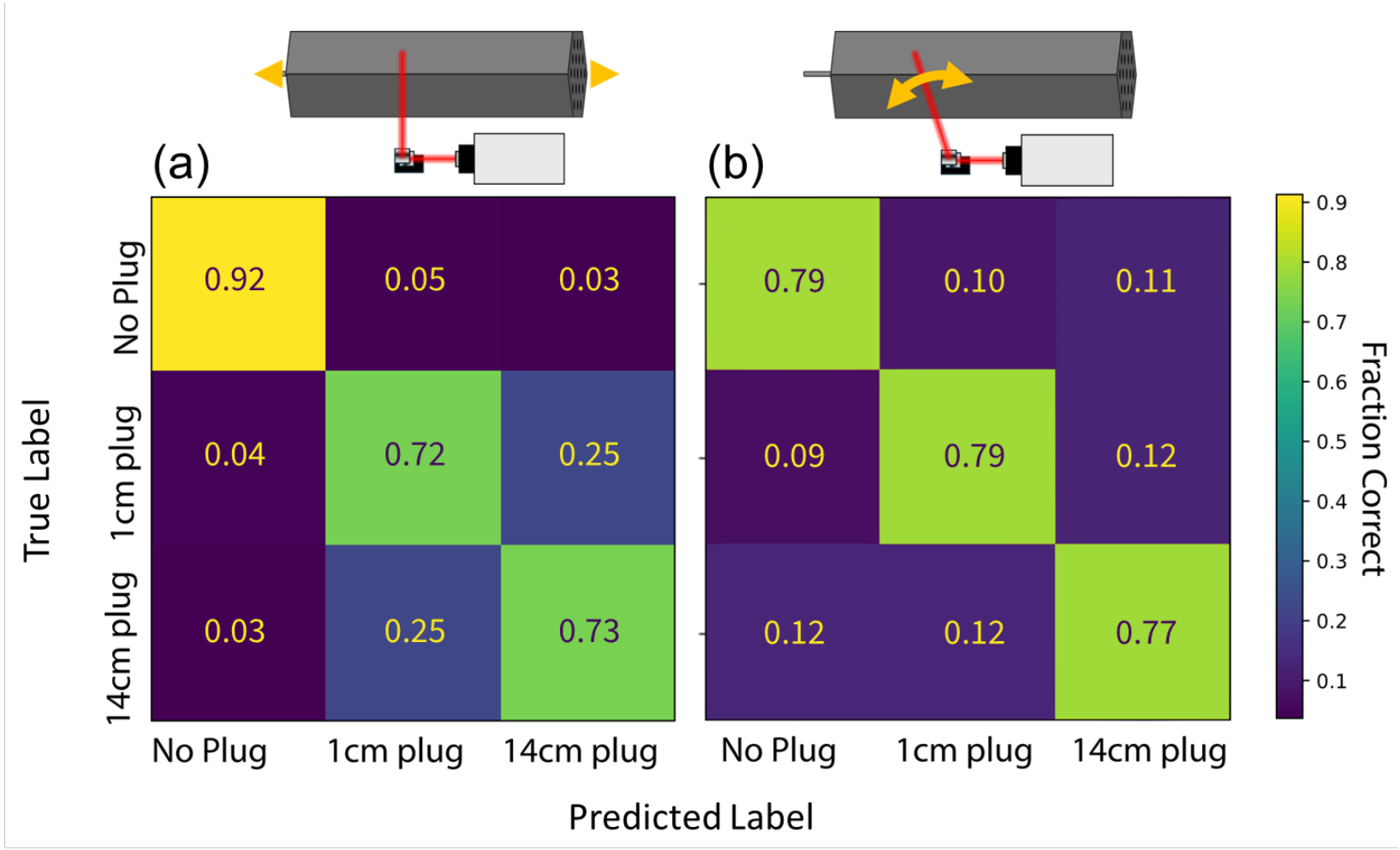




MRP Microreactor Program

1D localization of blind anomaly

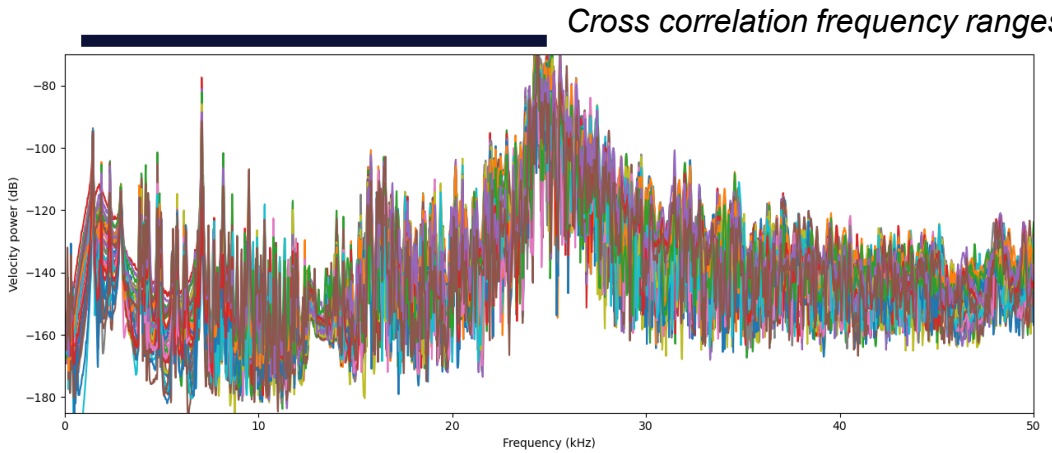
- Comparable accuracy for both testing approaches (off-axis values)
- Approach 2 preferred due to higher testing repeatability

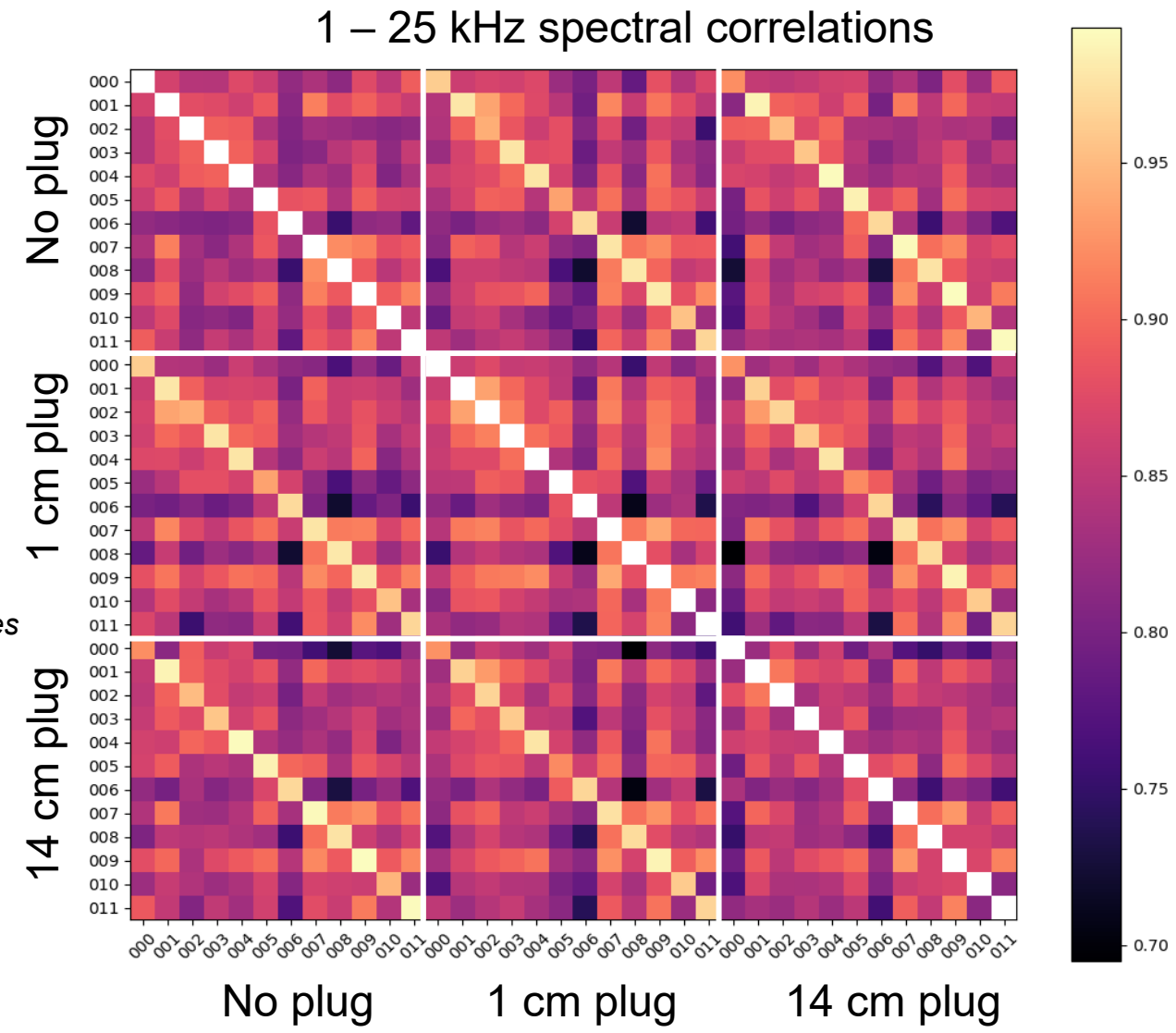


MRP Microreactor Program

Cross correlations provide insights into model's learned features

- Strong location similarity (main and secondary diagonals)

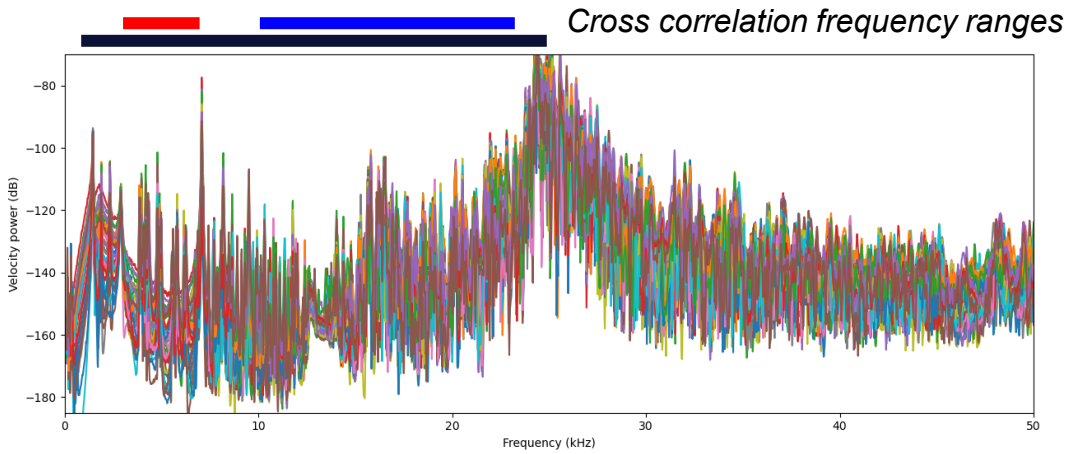


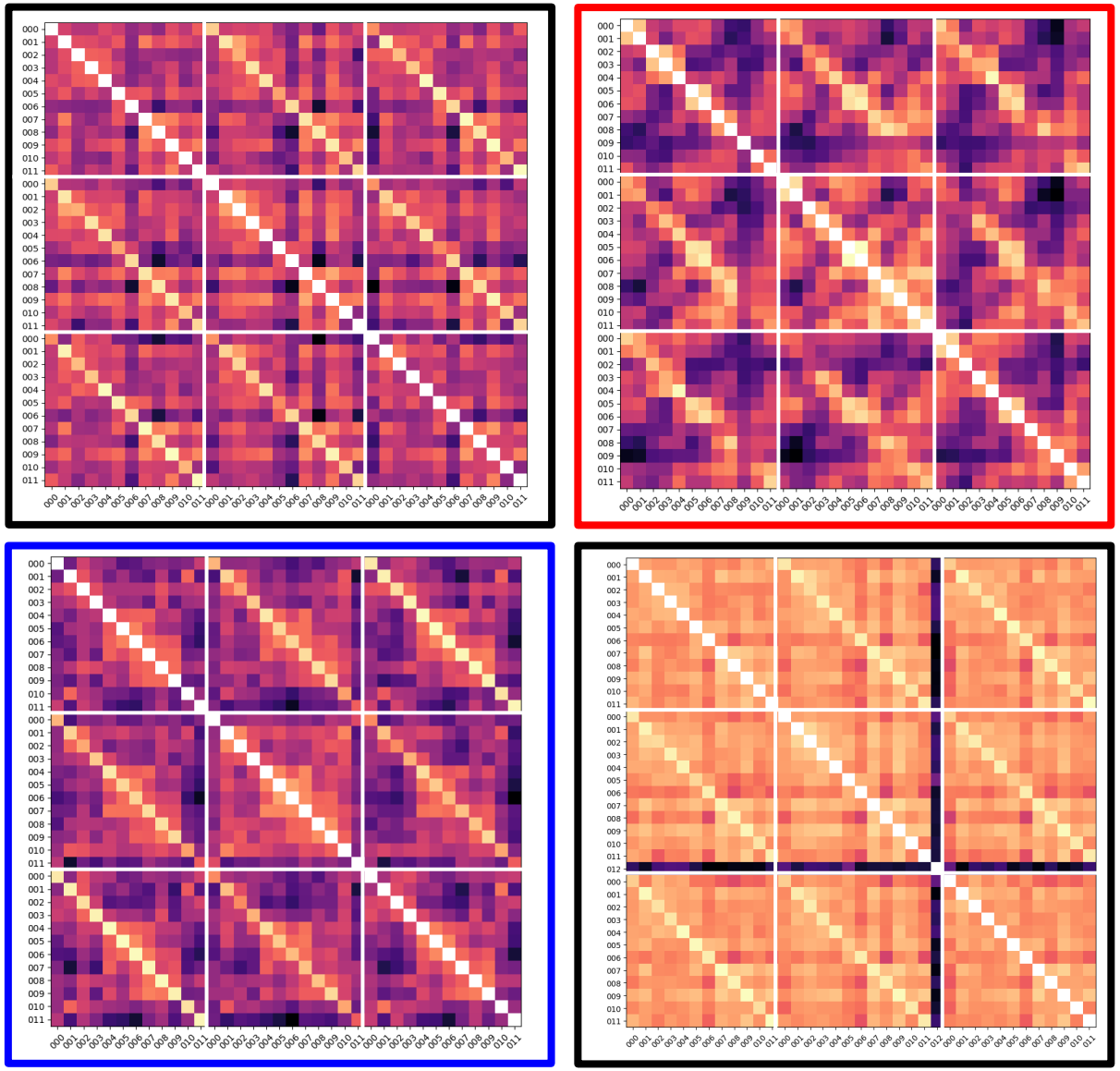


MRP Microreactor Program

Cross correlations provide insights into model's learned features

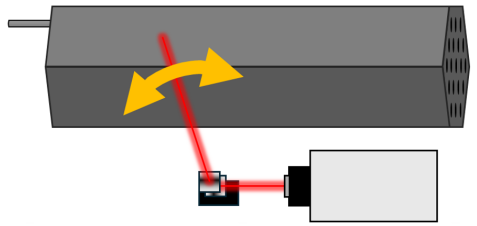
- Strong location similarity (main and secondary diagonals)
- Easily detects non-component spectral information (bottom right)



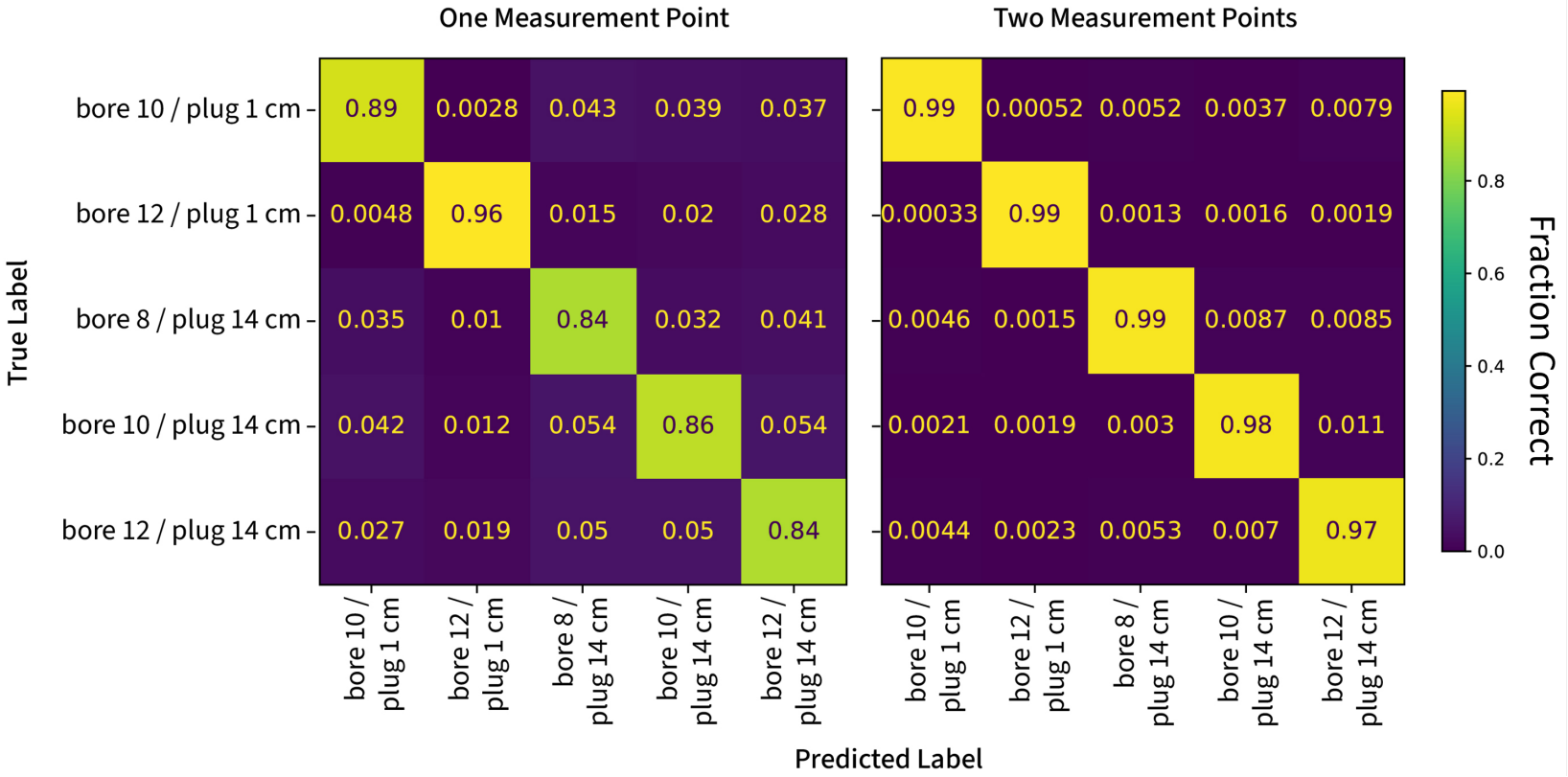


MRP Microreactor Program

2D and pseudo-3D localization of blind anomaly



- Approach performs well using a single-station graphs
- Error reduced from ~12% to ~1.5% when second measurement point added to graph
- Approach is scalable for larger sensor graphs (e.g. distributed acoustic sensing, optical fibers, etc.)

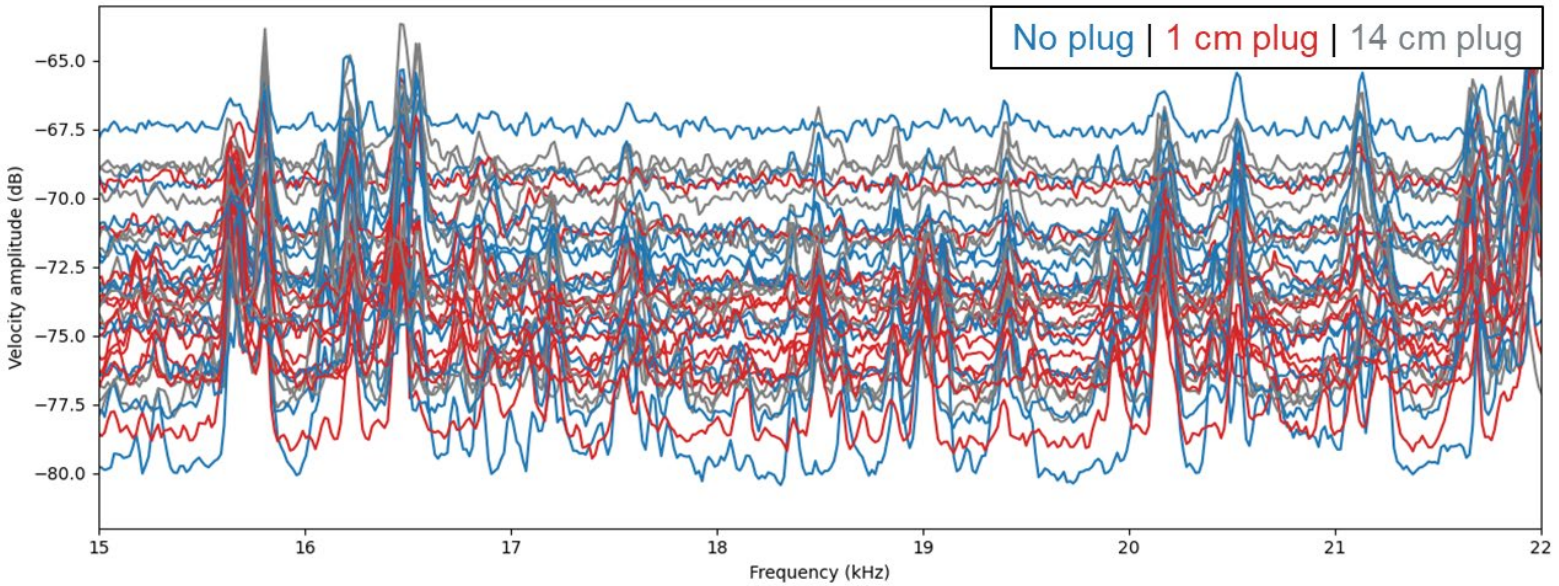


Typical training times of ~1-10 hours
1 epoch took < 10 minutes

MRP Microreactor Program

Impact of fluctuating noise levels within training data

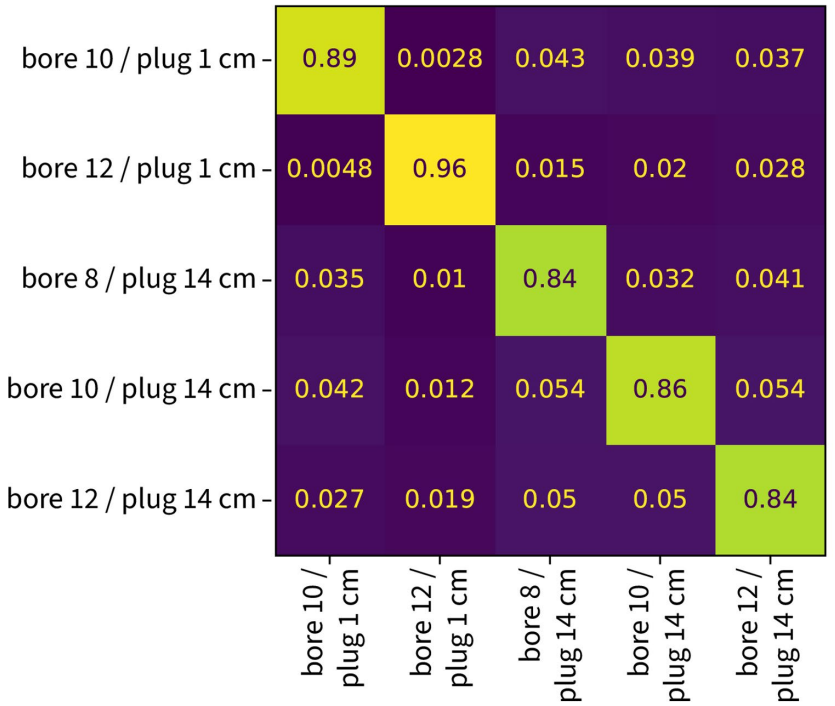
- Baseline noise differences may bias model towards improved predictions
  - But median noise level was nearly identical (± 1 dB) across plug configurations, so this explanation is insufficient
- Addressed in most recent rounds of testing via bonded transducer and recalibrated laser



MRP Microreactor Program

Opportunities for technique maturation

- Improve and streamline model to enable clear, floating-point predictions of unseen conditions
  - Ex. arbitrary anomaly locations (“12.2 cm”)
  - Focus for remainder of FY26
- Expand to larger variety of sensor types
  - Optical fibers (distributed acoustic sensing, fiber Bragg gratings, etc.)
- Test model against greater variety of damage scenarios and noise levels (steel vs. rubber insert)
- FNO implementation now published as Python module by paper authors (NeuralOperator), removing implementation barriers



“A structural change has occurred in Zone 4 (87% probability)”

MRP Microreactor Program

Summary

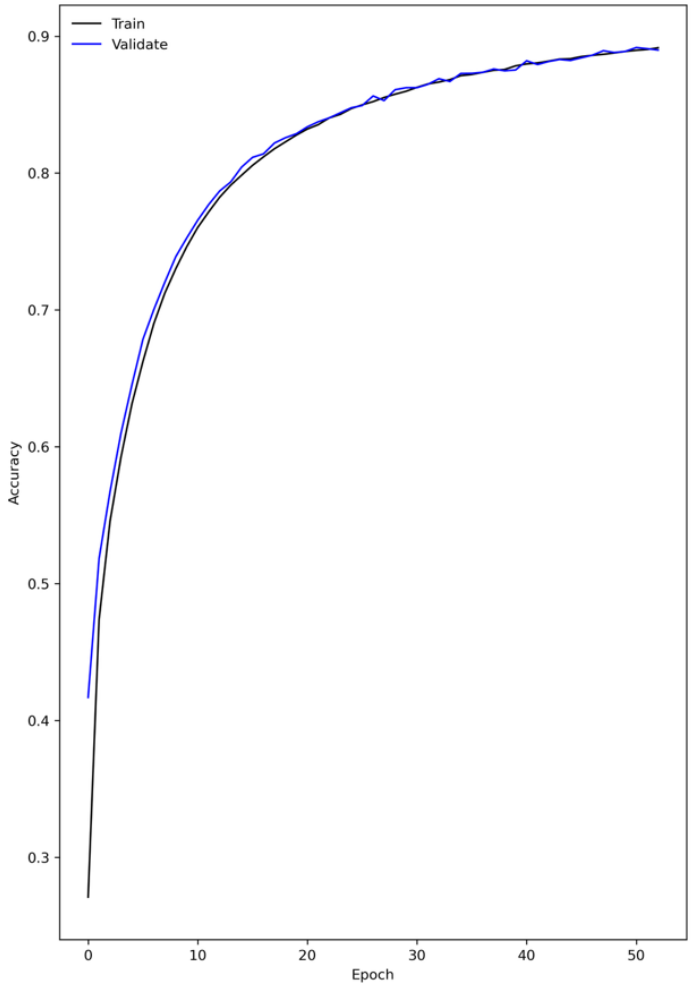
- Measured elastic-acoustic properties of graphite components using principles of modal analysis and machine learning
- Trained model predicted blind internal anomaly within graphite hex block
  - Encouraging performance in both 1D and 2D situations
  - Expansion of ML graph approach provides robust improvement in prediction accuracy

Recent Project Documentation

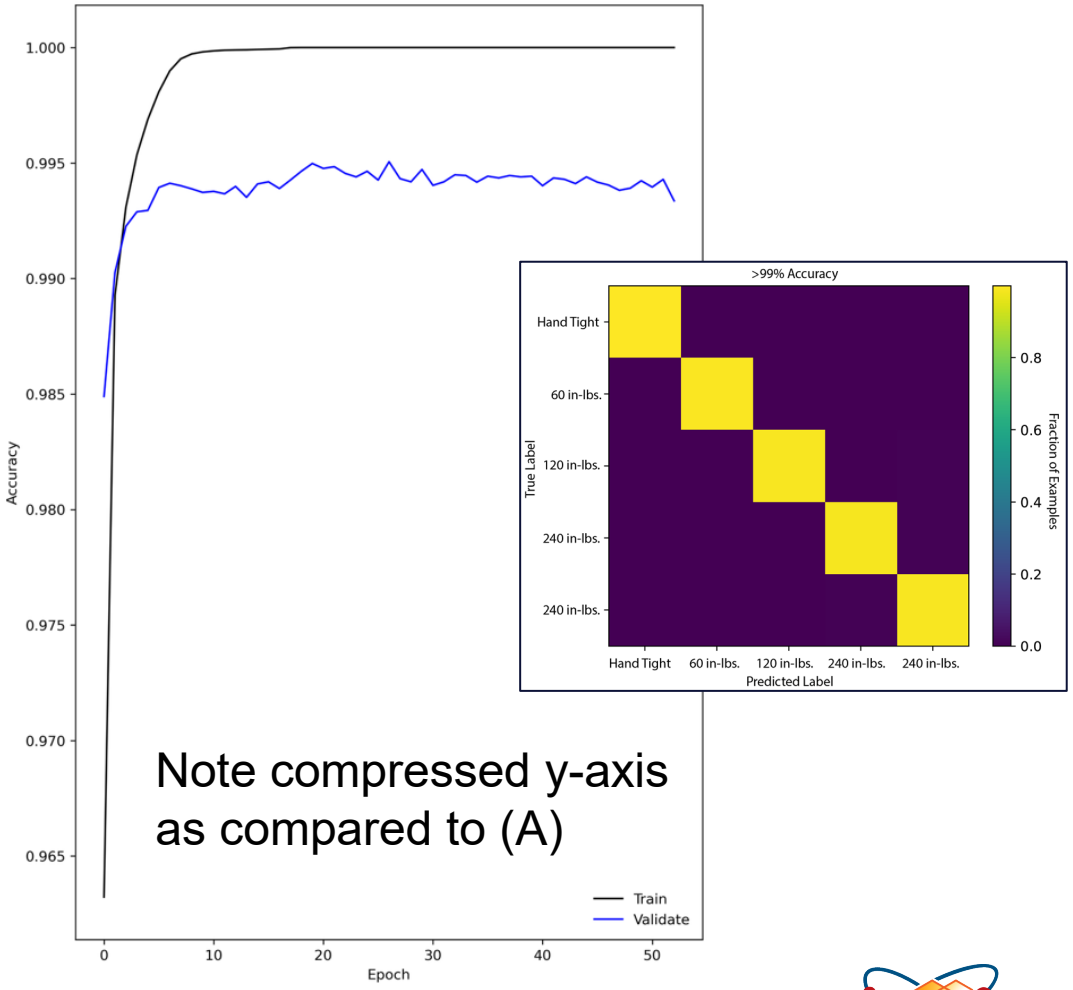
- M3 report from January 2026: “Graphite structural assessment through acoustic resonance and machine learning”
- End of FY25 report: “Non-destructive structural characterization of graphite components using mechanical resonance and deep learning”
- Manuscript in preparation for *Nondestructive Testing & Evaluation International*

Typical training and validation of FNO-GNN model

A: Sensor Location



B: Stress condition



MRP Microreactor Program