Instrumentation and Sensors – Acoustics

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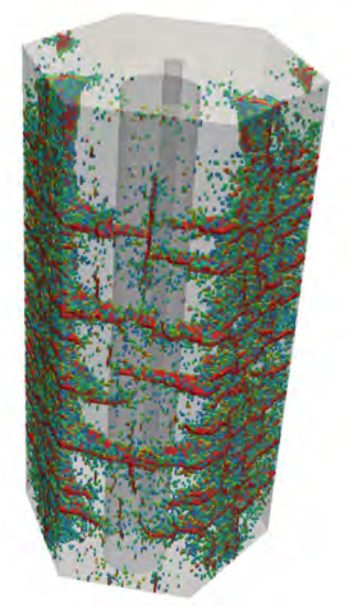
Microreactor Program Annual Winter Review

Objectives

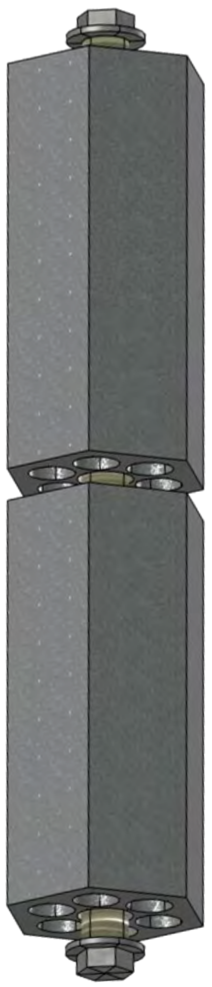
- Demonstrate acoustic defect characterization in graphite components such as those used for structural material in microreactors
- Develop machine learning (ML)-driven defect monitoring methods suitable for use with passive in situ sensors technologies (e.g. Fiber Bragg gratings in embedded fibers)

FY25 Work Scope

- Perform linear and nonlinear acoustic testing of intact and artificially damaged graphite test articles
- Use ML models to accelerate and improve damage characterization by identifying key data features, building on successful study with a stainless-steel test article



Spencer et al. (2023). “Initial Fracture Propagation Modeling of Graphite Components with Grizzly”. INL/RPT-23-74062.



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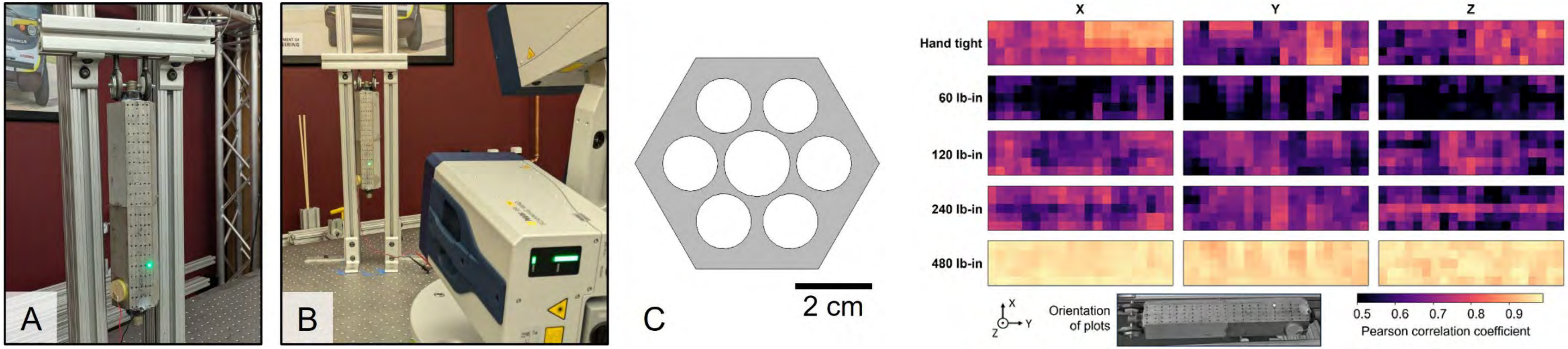
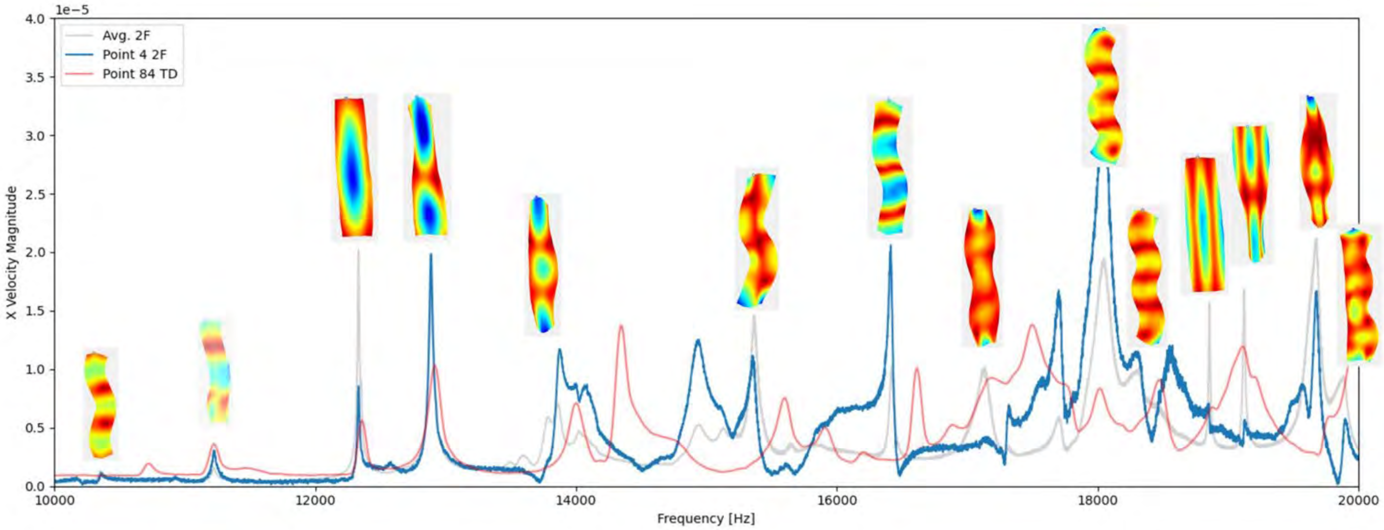
FY24 demonstration on stainless-steel test article: experimental



Resonant ultrasound spectroscopy (RUS):

Use induced vibrational resonance in sample to extract quantitative material properties



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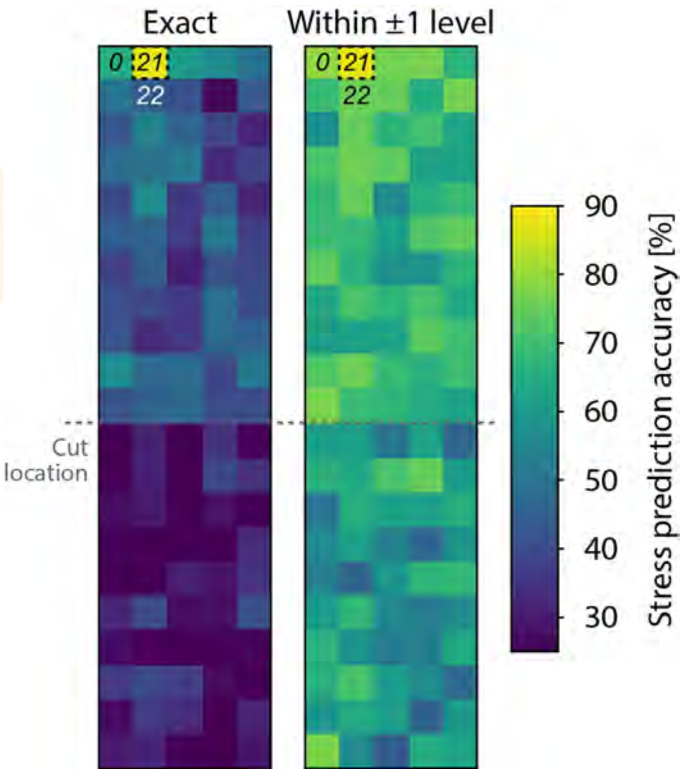
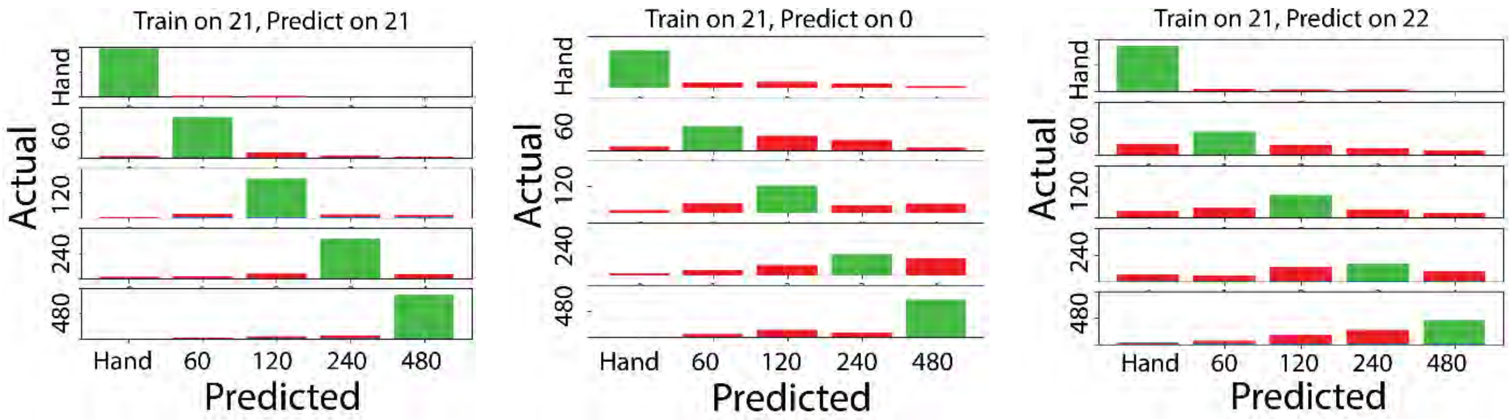
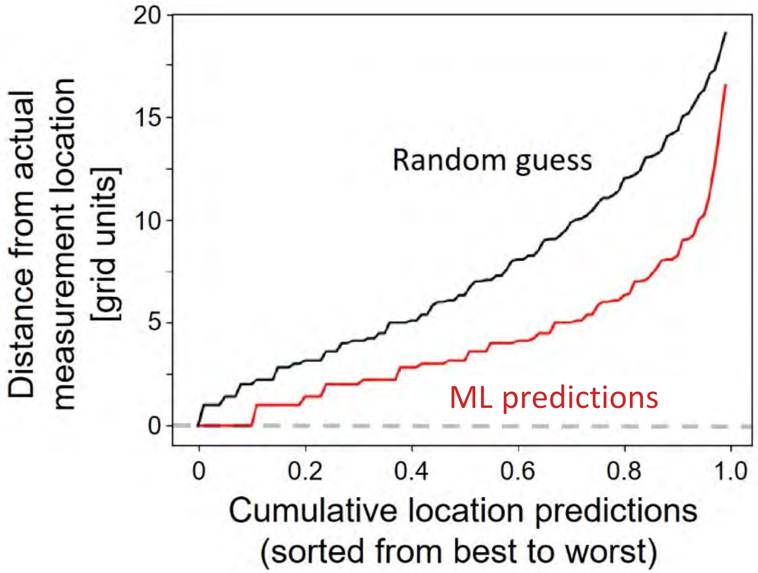
FY24 demonstration on stainless-steel test article: machine learning for localization using sparse data







Single damage scenario resulted in ML model learning sensor locations better than the defect characteristics

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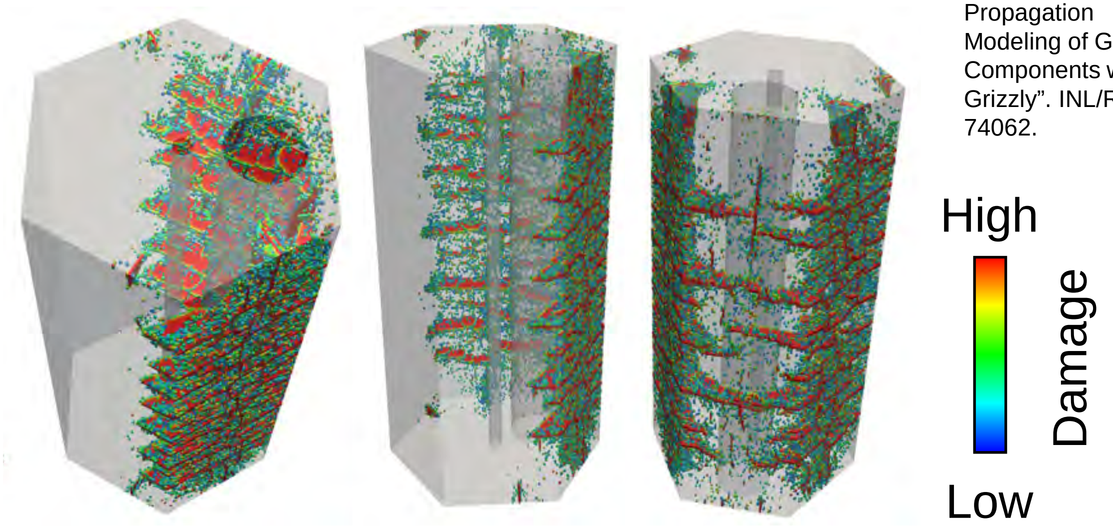
Damage mechanisms in bulk graphite components

- Irregular microstructure and high porosity produces extensive microcracking
- Creep under compression, greater microcracking (softening) under tensile stresses
  - Geometric changes due to neutron irradiation
  - Asymmetric temperatures during reactor operation
  - Residual stress from production of bulk feedstock

Nonlinear resonant ultrasound spectroscopy (NRUS)** is highly sensitive to nonlinear elastic changes due to **microcracking



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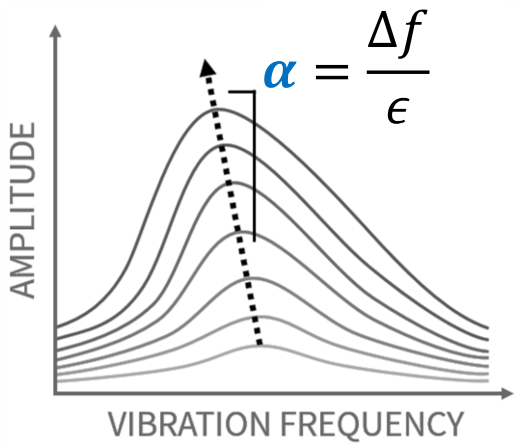

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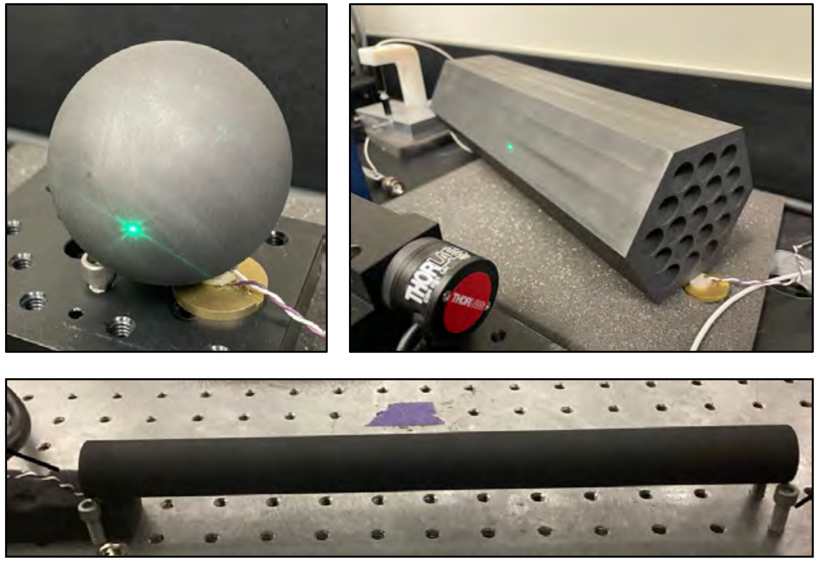
Experimental testing design



Benchtop vibrational testing of multiple geometries under baseline and various damaged conditions

- Scanning laser vibrometry enables multiple measurement locations and mode shape captures
- High-strength, fine-grain commercial graphite grades (isotropic, low porosity, <20 μm grains)
  - **Spheres** (Φ6 cm):
    - Planned damage: calibrated impacts of varying severity across a batch of nominally identical samples
  - 19-hole **hexagonal block** as a relevant, complex geometry
    - Planned damage: expanding collet in bore to generate localized stress
  - **Rods**: common geometry in (N)RUS literature to enable material comparisons
  - Ultra-fine-grain (3 μm) sheet to test effect of grain size on elastic linearity

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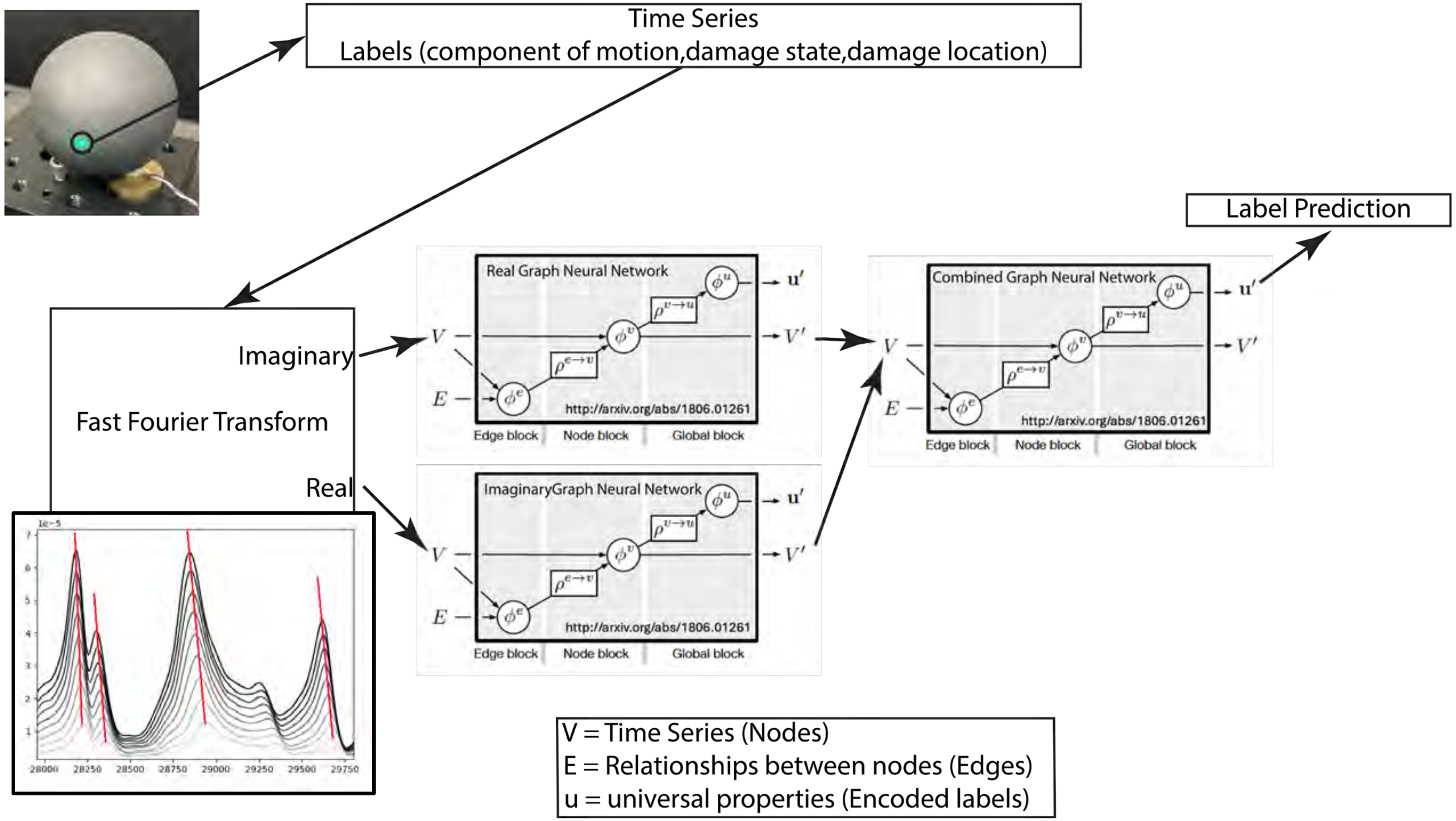
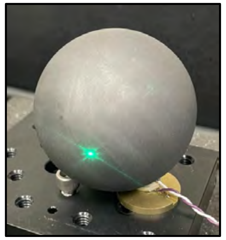
Machine learning for efficient identification of defect-related features in vibrational data

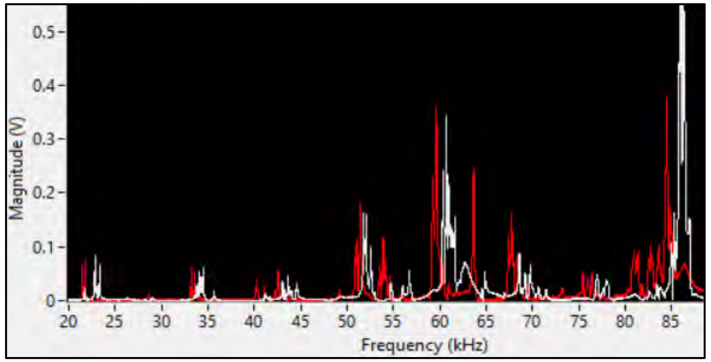
Graph neural network architecture enables flexible and/or sparse data inputs for training and defect prediction

- Adaptable approach for defect detection across various test articles
- Suitable for large datasets and near-real-time monitoring if given enough realistic defect examples
- New dedicated ML-optimized server for spring 2025 will increase training speeds by 1-2 orders of magnitude

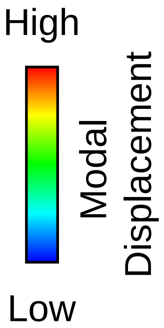


Initial RUS results from baseline testing: intact spheres



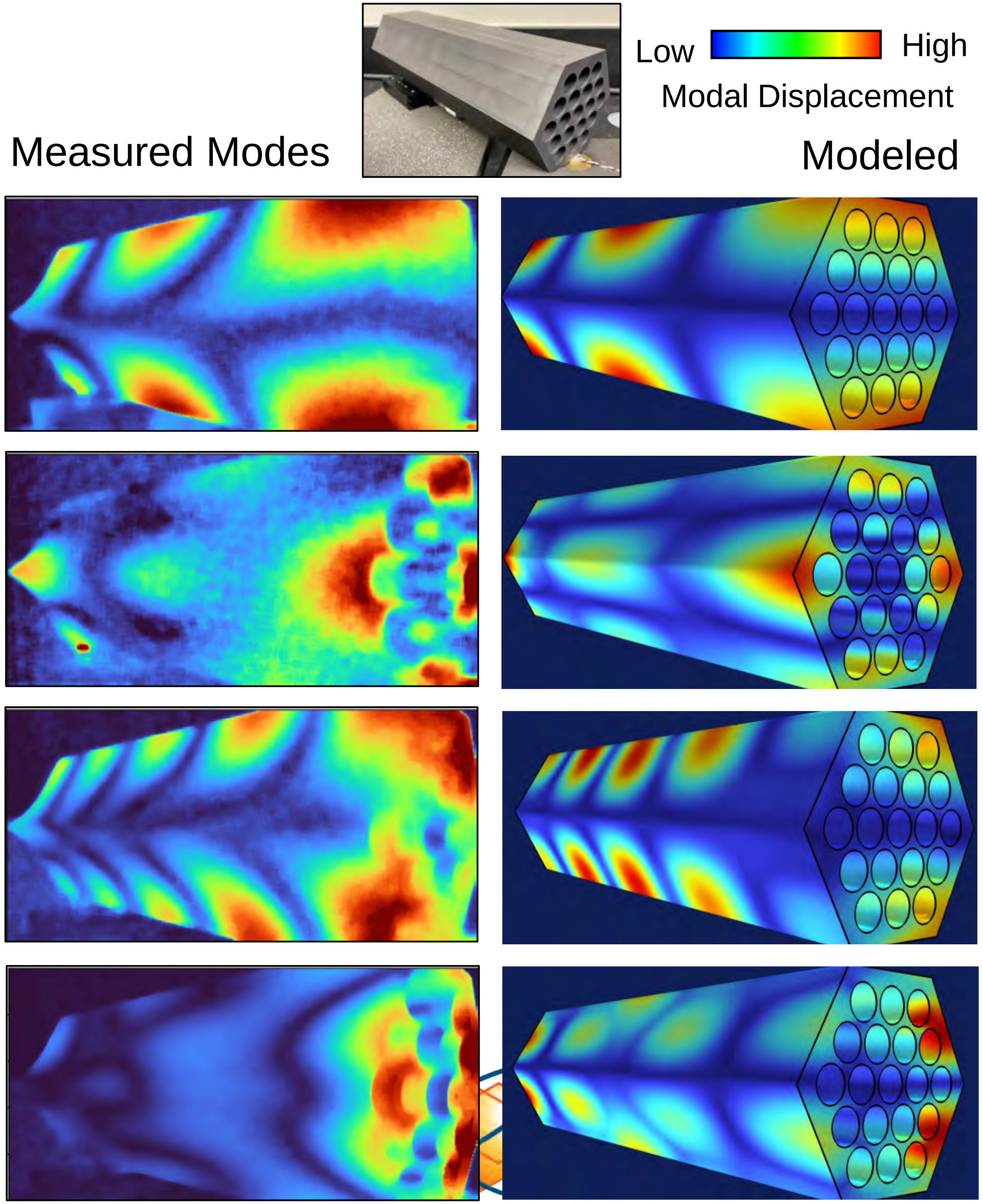


- Resonance modes identified up to 90 kHz
- Two nominally identical spheres found to have an isotropic elastic modulus difference of 4%
  - Full batch variation being quantified before introducing brittle damage
- Geometric symmetry of spheres means many damage scenarios can easily be generated for ML model training by rotating sample and retesting
  - Surface vs. blind defects
  - Data quantity needed for discrimination of “good” vs. “bad” samples?

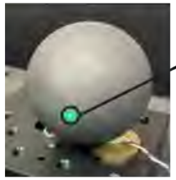


Initial results from baseline testing: hex block

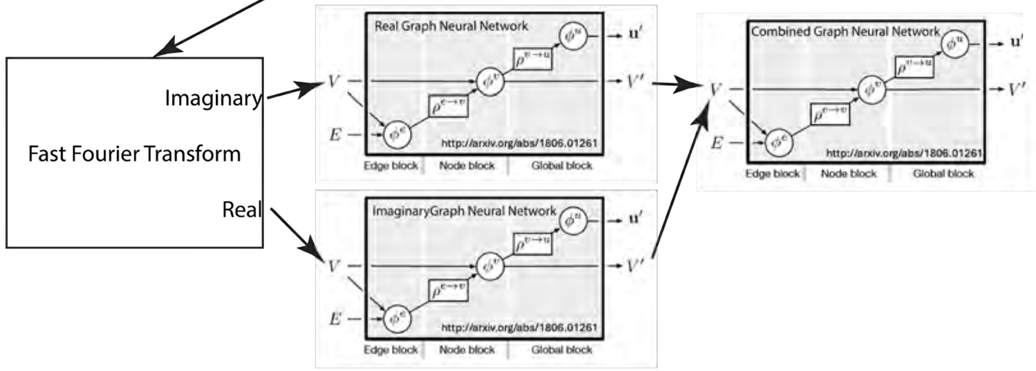
- Identifiable resonance modes measured up to 10 kHz using unbonded source transducer coupled with amplifier
  - Optimize measurement locations for sparsely sampled ML models
  - Improved modal clarity expected after bonding transducer to sample for NRUS testing
- Simple isotropic FEA model largely able to replicate modal behavior of a complex geometry
  - Can be extended to more complex assemblies



Next Steps



- Establish elastic nonlinearity of baseline graphite samples, noting correlations with grain size
- Spheres: NRUS test on suite of damaged samples, acquire CT images of induced fractures
- Hex block:
  - Use expanding collet to apply localized stress at various bore locations (outer vs. inner bore locations, shallow vs. deep)
  - Build training dataset to determine sensitivity of ML model for defect localization within component
- Quantify limits (sensitivity and localization) of material defect characterization using current ML workflow with graph neural networks and spatial vibration information



FY25 Deliverables

Milestone Title	Description	Status
Vibrational testing for machine-learning defect characterization in bulk graphite samples	M4 memo: preliminary and planned experimental acoustic testing of bulk graphite for structural health monitoring	Completed January 30, 2025
Non-destructively detect and characterize graphite damage	M3 report: Defect characterization results for multiple graphite components of varying damage states using resonance-based acoustic methods and deep-learning models	Expected completion September 26, 2025
Complete damage detection analysis from summer FY25 experiments	M4 memo: technical insights and conclusions obtained from FY25 summer experiments on damaged graphite samples	Expected completion November 20, 2025

Recent & upcoming presentations:

- "Passive Monitoring of Nonlinear Behavior" A. A. Delorey, C.W. Johnson, P.R. Geimer, and T.J. Ulrich. International Conference on Nonlinear Elasticity in Materials (June 2024). Prague, Czech Republic.
- "Acoustic monitoring of component condition for microreactor applications" R. Bose, A.A. Delorey, T.J. Ulrich, and P. Geimer. Shock and Vibration Symposium (Nov 2024). Dallas, TX.
- "Leveraging nonlinear hysteretic response for structural characterization" P. R. Geimer, A. A. Delorey, T.J. Ulrich, R. Bose. Acoustical Society of America (May 2025). New Orleans, LA.

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