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

Advanced Sensors and Instrumentation

Advanced Laser Ultrasonic Sensors for Nuclear Diagnostics

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar
October 24 – 27, 2022

Principal Investigator: Bradley Bobbs, Ph.D.

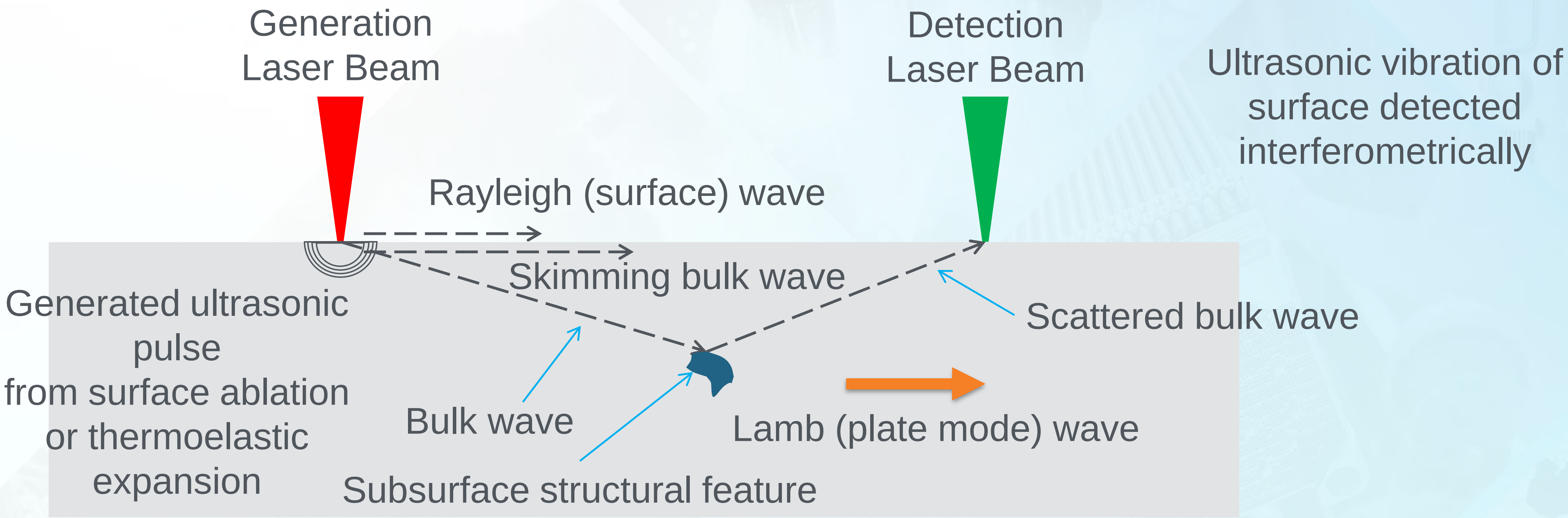
Intelligent Optical Systems

INTELLIGENT OPTICAL SYSTEMS, INC.

Outline

- Laser ultrasonic testing (LUT) overview
- Three examples of LUT sensors for nuclear diagnostics
  - Checking internal pressure and wall thickness of fuel rods
  - Monitoring flow rate in cooling pipes
  - Stress corrosion crack depth profile evaluation in nuclear waste canisters
- Concluding Remarks

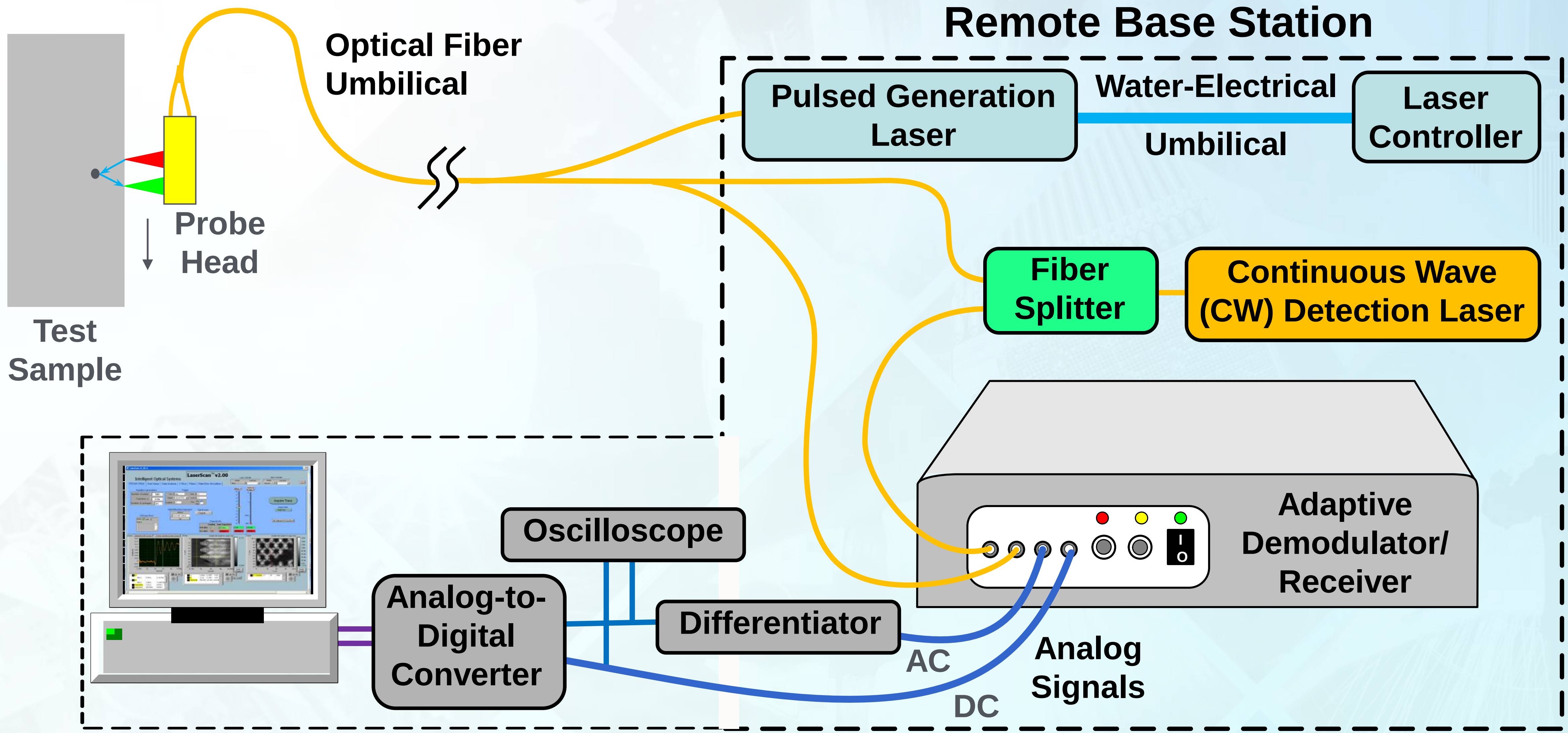
Laser Ultrasonic Testing (LUT) Principles



Sample cross section

Produces similar data to conventional transducer-based ultrasonic testing

Laser Ultrasonic Testing (LUT) System Layout



Laser Ultrasonic Testing (LUT) Advantages

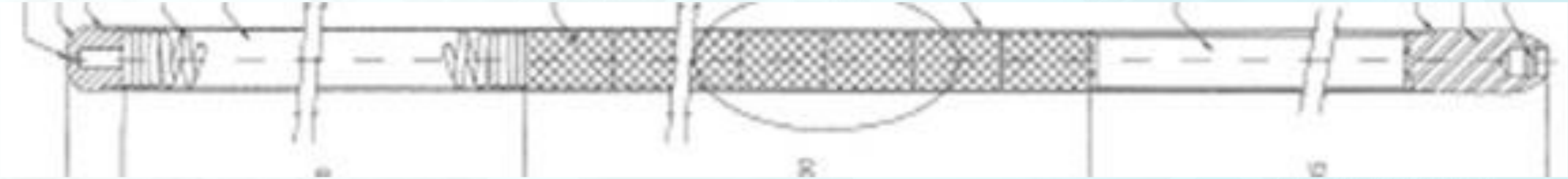
- Noncontact sensor operates on moving, rough, curved, corroded, mechanically noisy, hot surfaces
- Optical fiber connection enables access to confined spaces
- Electronics-free measurement head has high thermal and radioactivity resistance
- Small laser spots enable good spatial resolution
- High bandwidth enables accurate and sensitive measurements
- IOS nonlinear-optics-based adaptive demodulator/receiver greatly boosts signal for non-ideal surfaces

Project Overview: Checking Internal Pressure & Wall of Fuel Rods

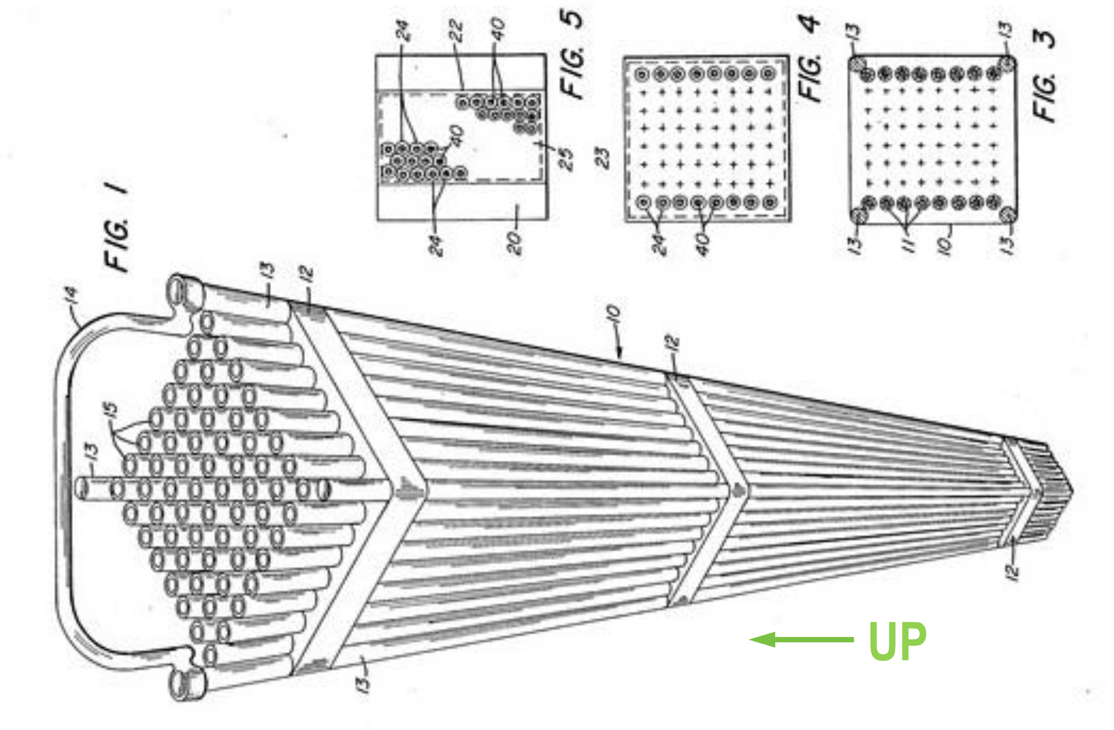
- Apply LUT to measure shifts in resonant frequencies of a fuel rod, and relate these shifts to internal pressure and wall thickness
- Currently ~one year into Phase II of DOE SBIR
- Participants
  - Current PI: Bradley Bobbs
  - Past PI & current consultant: Marvin Klein
  - Collaborator: Electric Power Research Institute (EPRI)
  - Subcontractor: Westinghouse Nuclear Services
  - Consultant: Prof. Peter Nagy, University of Cincinnati

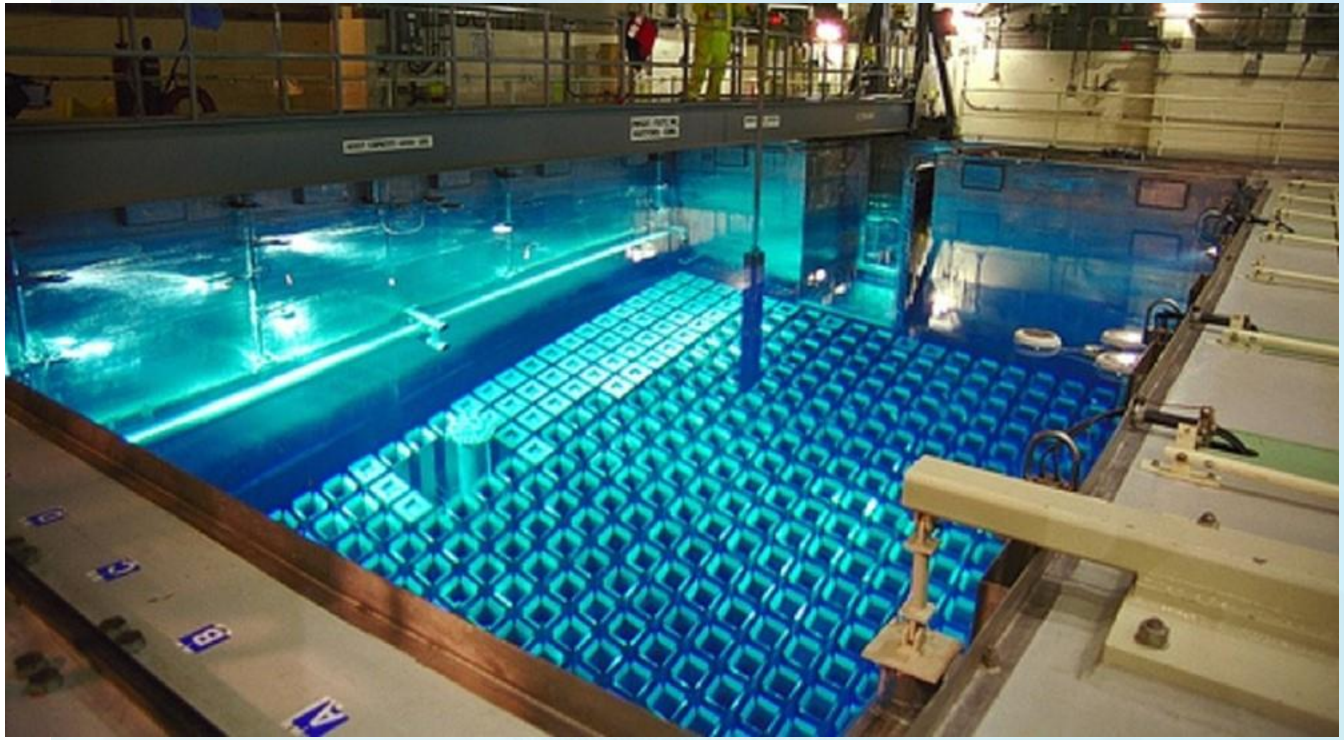
Technology Impact: Needs Addressed (1 of 2)

- Verify integrity and safety of fuel rods during periodic maintenance
  - Evidence of cracks, pinholes, and other defects causing gas leakage, pressure loss, and possible water ingress
  - Overpressure from excess reaction gasses in high burnup conditions
  - Changes in free volume can cause pressure increase or decrease
  - Wall thickness can decrease by corrosion or increase by oxide buildup



Technology Impact: Needs Addressed (2 of 2)





- Measurement needs to be *in situ* while rod array assembly is immersed in a water cooling pool (~30' deep)
- Large savings in time and cost would result for measurements made without removing the rods from their array assembly

- Validate theoretical models and simulations for future reactor development

Technology Impact: Method Comparison

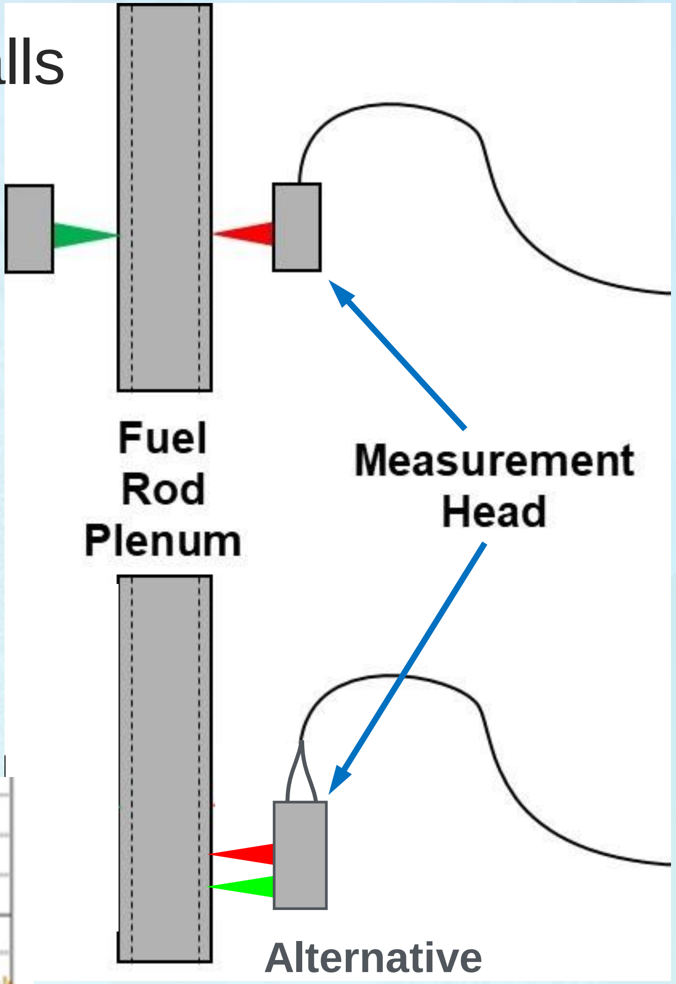
- Current methods detect leaks only
- Most current methods require removing rods from array
- Current transducer-based ultrasonic method can make measurements without rod removal from their array,
  but only senses the presence of internal water when a leak is present
- Our method will allow **direct measurement of pressure without removing the rods from their array**
  - Underpressure from gas leakage
    - **No internal water need be present**
  - **Overpressure from excessive generation of fission gases**
  - Measure in the plenum region where radiation is lower
- Our method **additionally measures rod cladding wall thickness**
  - Accuracy <0.2% demonstrated
  - May be useful for assessing corrosion or oxide buildup

Technology Impact: Stakeholders

- Rod inspection service companies
- Nuclear utilities
- Fuel vendors

Methodology: Measure Resonance Frequencies

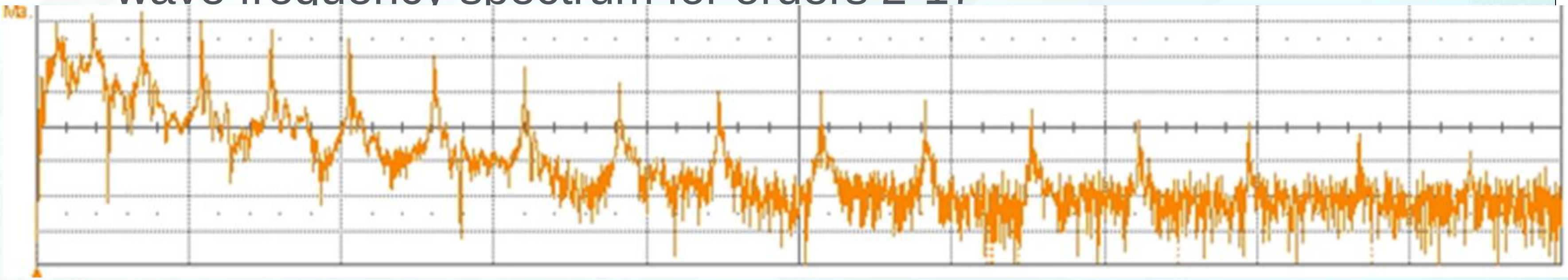
- Excite ultrasonic standing wave deformations inside rod walls
  - Circumferential waves for pressure measurement
  - Radial waves for wall thickness measurement



Alternative configuration with same-side access

Exaggerated circumferential deformations in rod wall for 10th order resonance

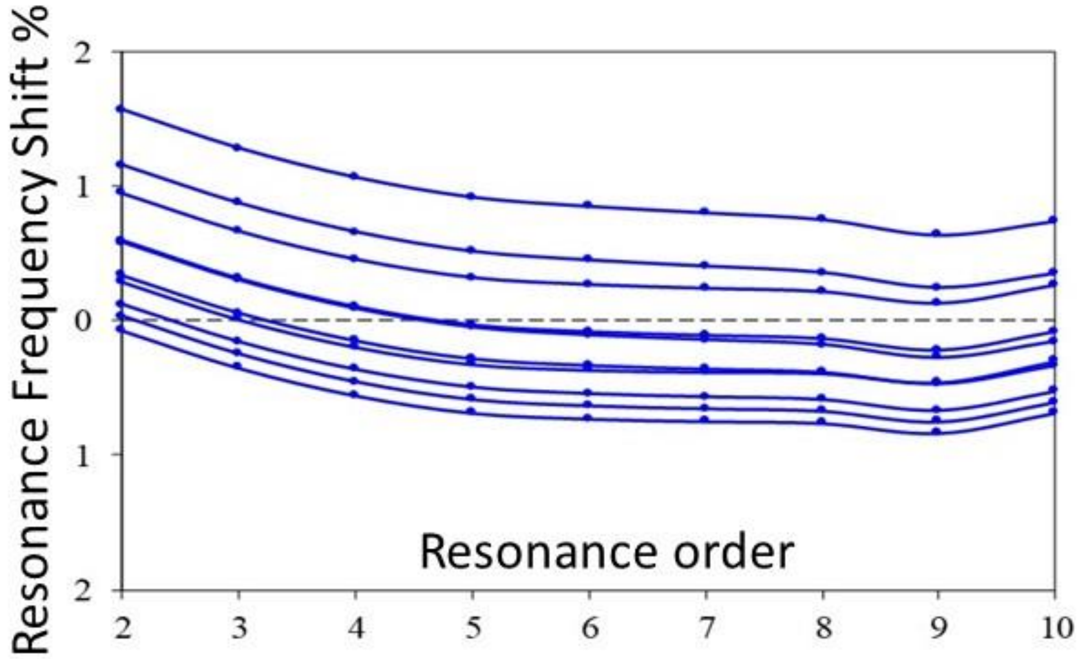
Typical Fourier-transformed circumferential wave frequency spectrum for orders 2-17



0 MHz 0.5 MHz 1 MHz

Methodology: Simulation and Signal-processing

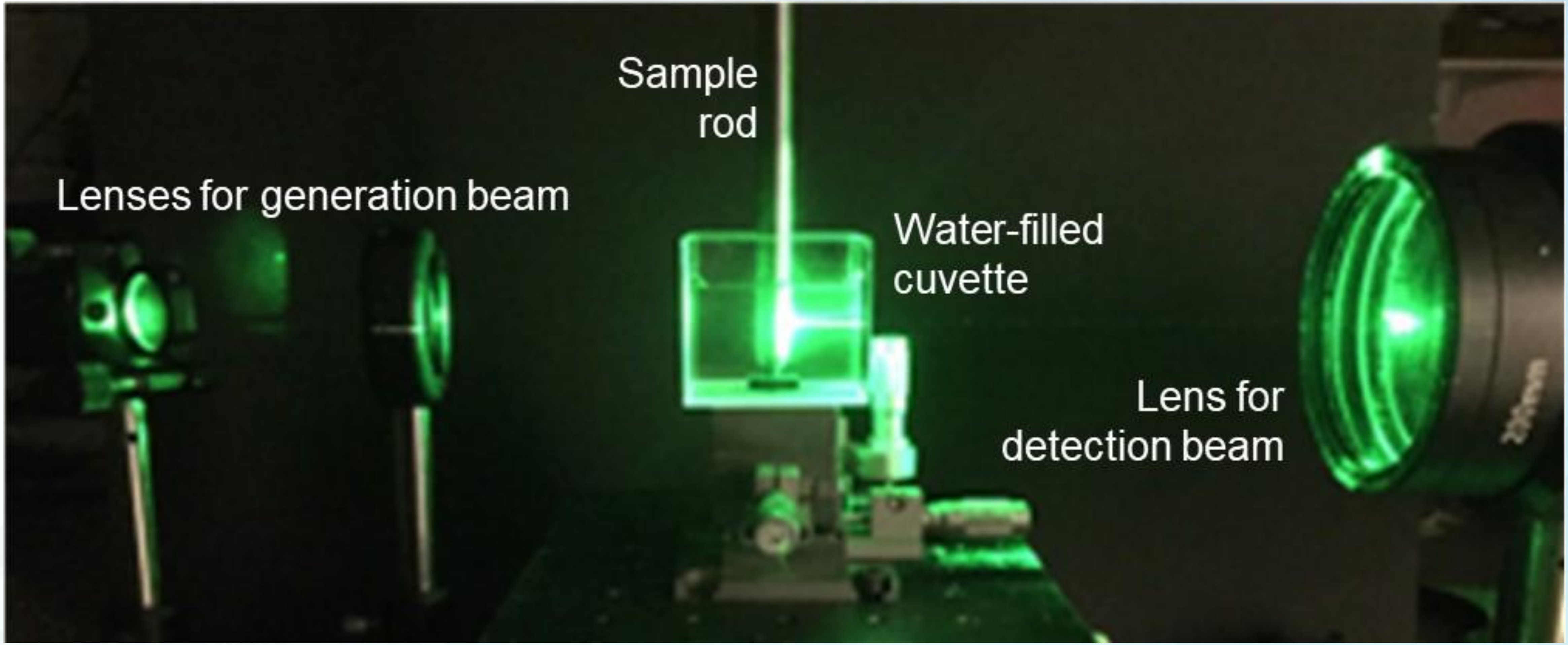
- Signal-processing algorithm compensates for pressure-independent variations
  - Illustrated below with simulation example of 10 random measurements
    - BWR rods filled with 350 psi Helium
    - ±0.5% random rod diameter variation



Random variation makes pressure determination impossible

Algorithm metric compensates for random variation to enable pressure determination

Setup For Proof-of-Concept Demonstration

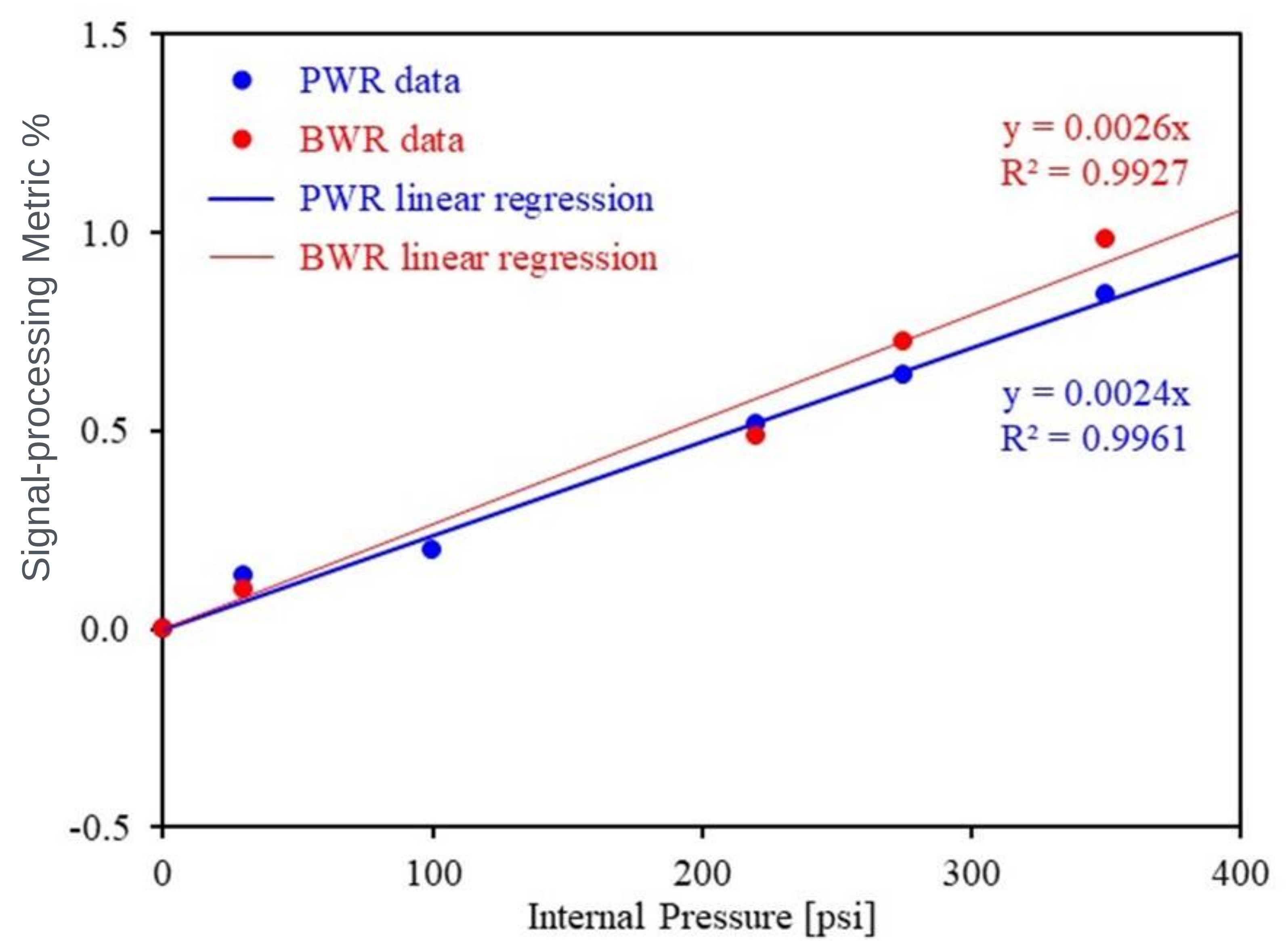


Free-space laser beams – no fibers

Infrared (1064 nm) generation beam

Visible (532 nm) detection beam

Experimental Results: Internal Pressure



Series of surrogate rods (PWR and BWR types loaned by EPRI) with fixed, known internal pressures of Helium fill gas

Initial results shown for measurement in air

Slightly different slope (calibration constant) as expected for two rod types

Experimental Results: Rod Cladding Wall Thickness

Sample type	Resonance f_h [kHz]	LUT-determined thickness h [mm]	Experimental uncertainty	Discrepancy LUT vs nominal h
BWR	3830	0.623	0.13 %	-0.12 %
PWR	3167	0.758	0.40 %	0.14 %

Project Overview: Monitoring Flow Rate in Cooling Pipes

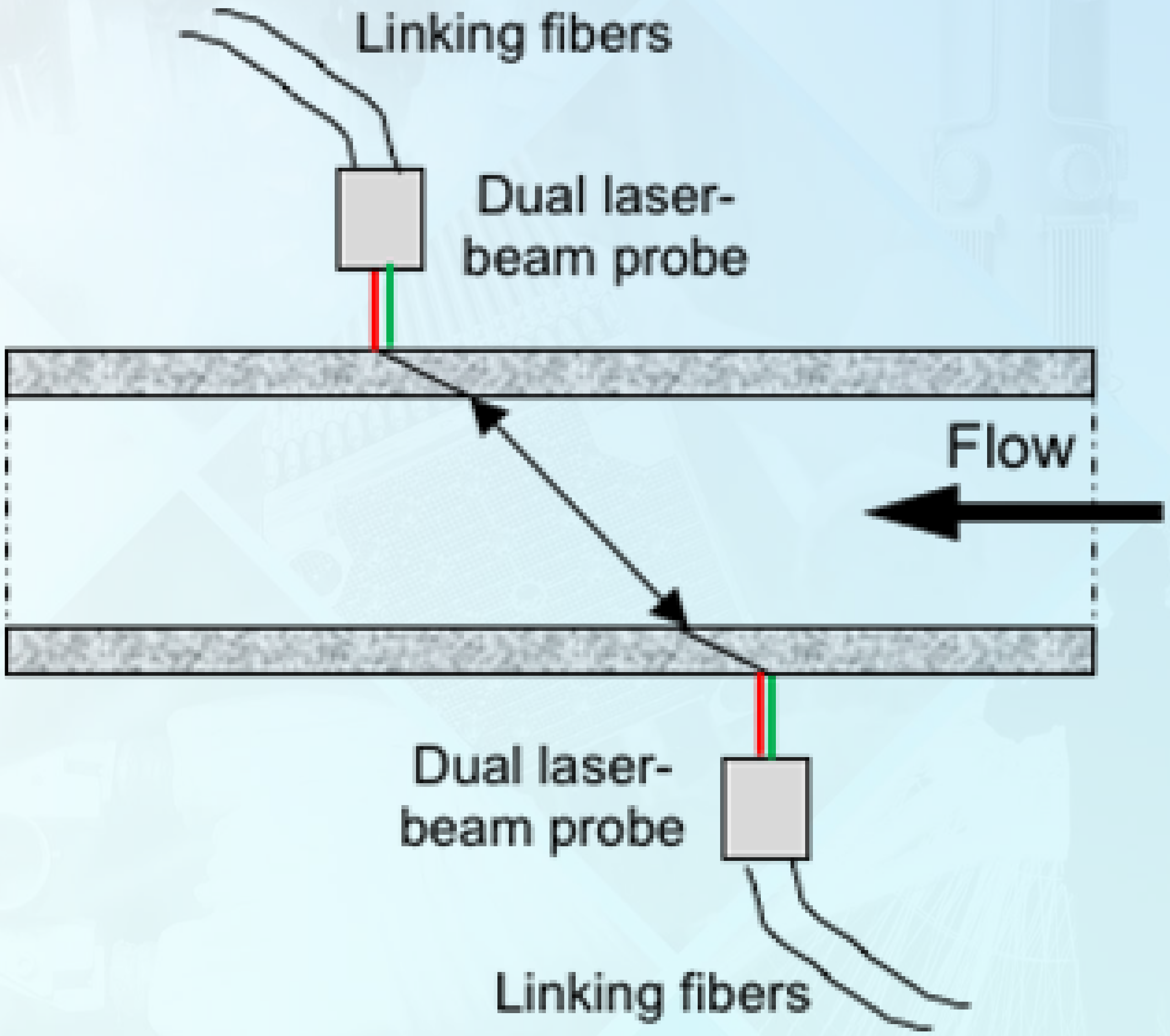
- Apply LUT to measure difference between phase shifts in upstream and downstream flow, and relate this difference to flow rate
- Phase I of DOE SBIR completed in 2020
  - Currently seeking opportunities to continue development
- Participants
  - PI: Marvin Klein
  - Subcontractor: Oregon State University

Technology Impact: Needs Addressed

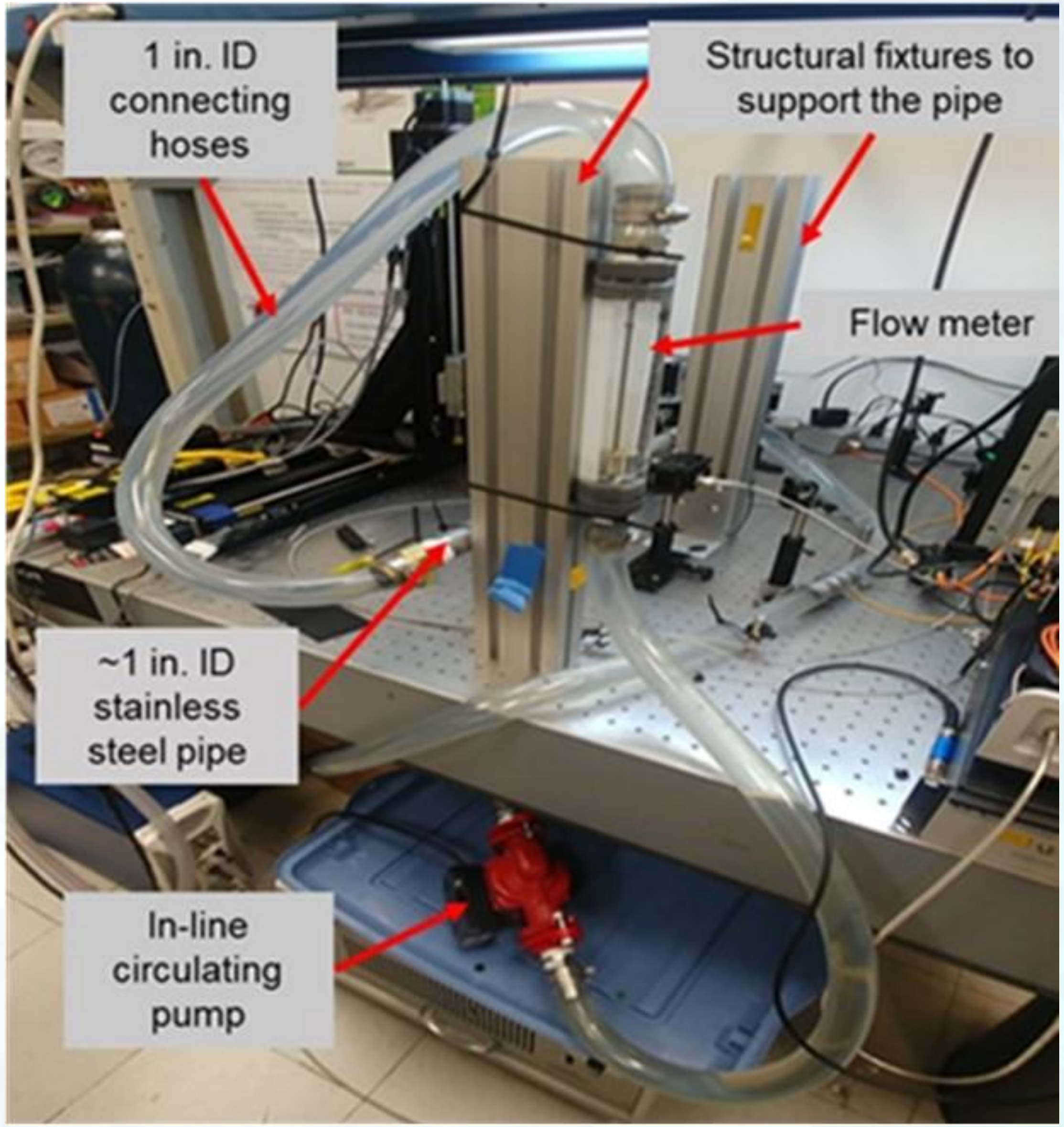
- Cooling pipe flow-rate measurements are needed for testing and monitoring
- Current flow-rate instrumentation is limited to temperatures < 600°C
  - Makes contact with pipe
- Next generation nuclear reactors will require cooling and dissolved-fuel delivery pipes up to 800°C
  - Molten chloride or fluoride salts

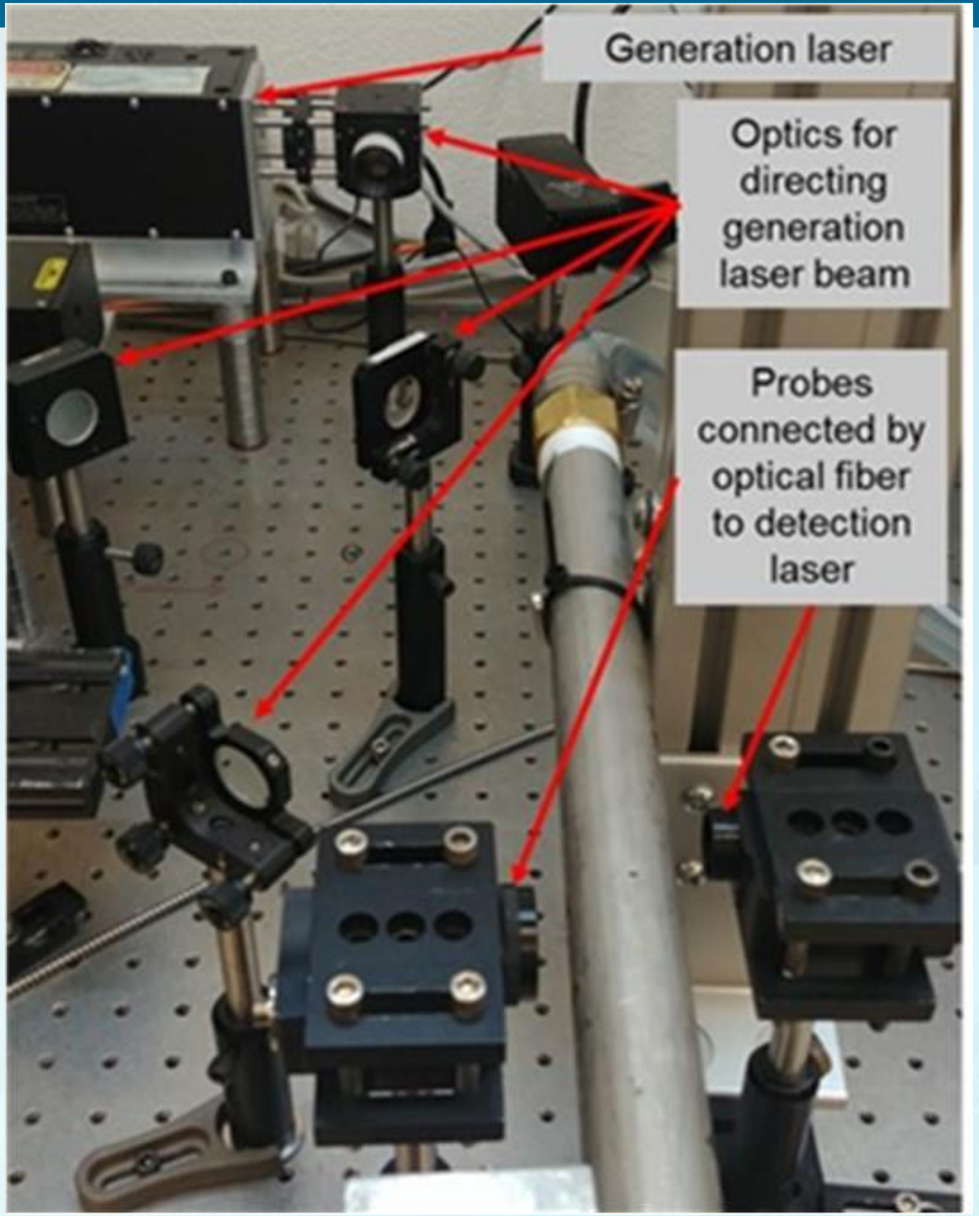
Methodology

- Path, and hence phase, of LUT signal through the flow is shifted by the flow
- Phase difference between upstream and downstream LUT signals cancel out all other asymmetries, leading to high flow sensitivity
- Compare to finite-difference simulation results

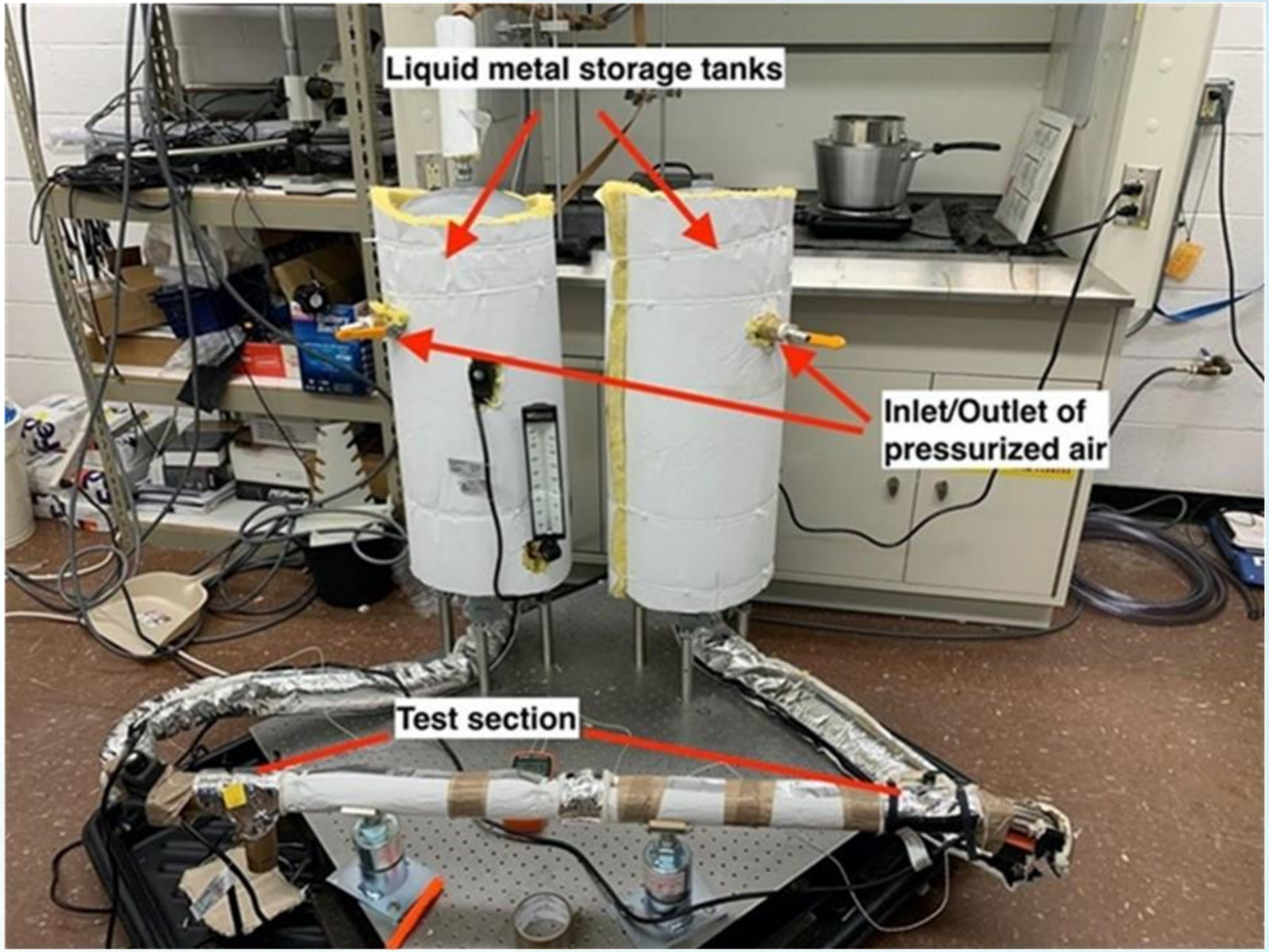


Setup For Proof-of-Concept Demonstration in R.T. Water



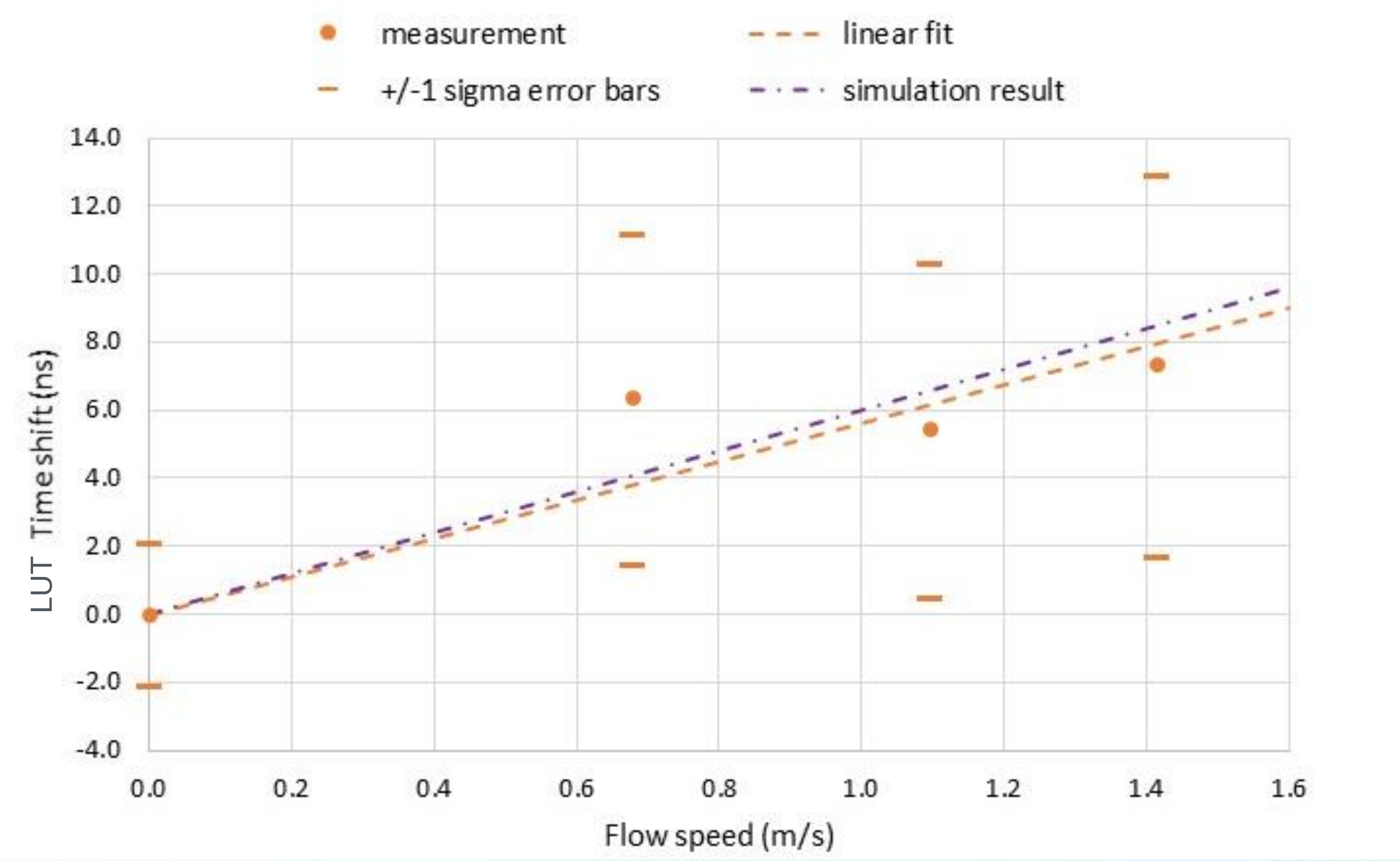


Setup For Proof-of-Concept Demonstration in Molten Wood’s Metal



Courtesy of Prof. Haori Yang at Oregon State University

Experimental Results in Room-Temperature Water



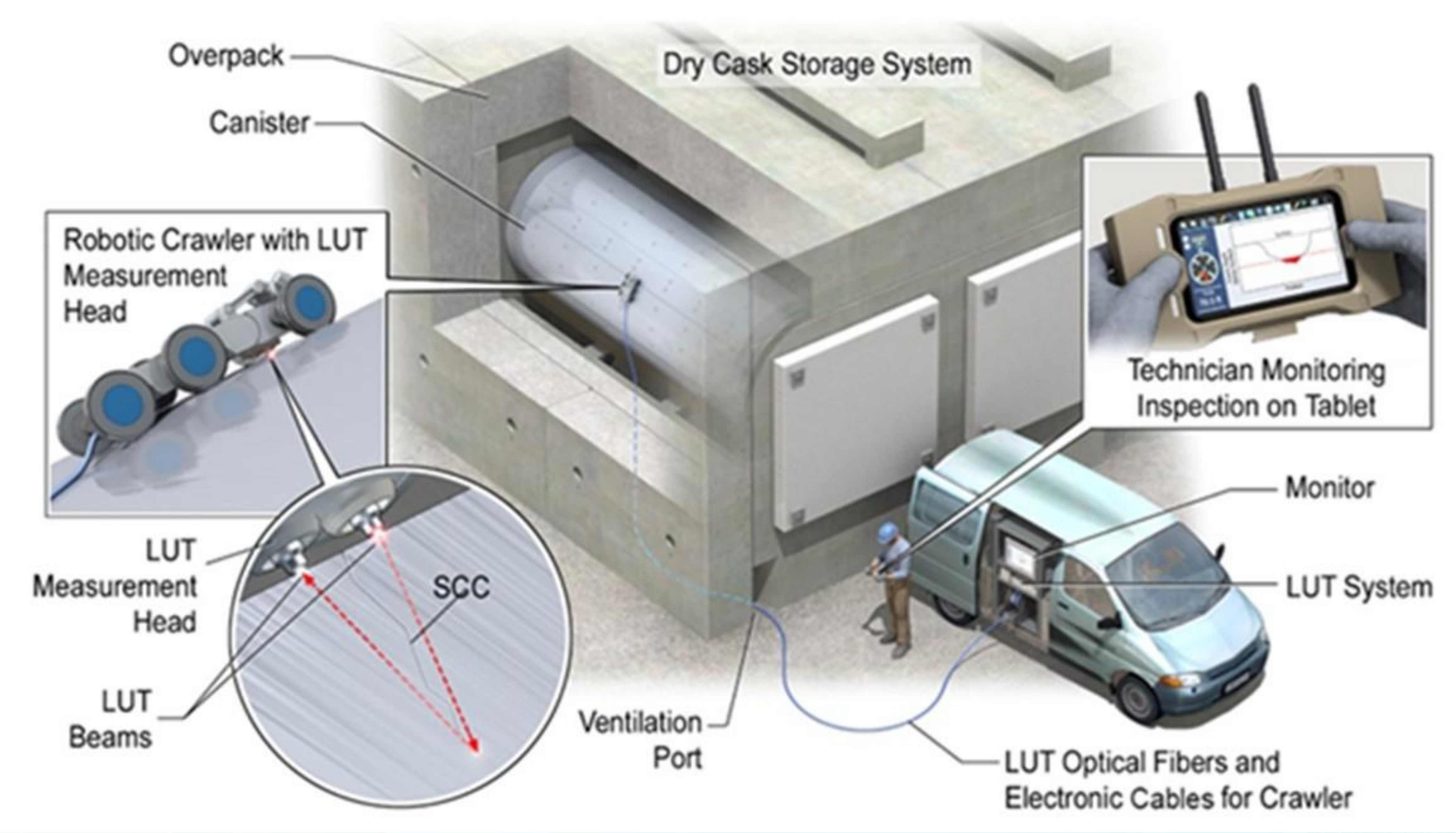
Project Overview: Stress Corrosion Crack Depth Profile Evaluation

- Apply LUT to measure time-of-flight of an ultrasonic pulse diffracted by a stress corrosion crack in a nuclear waste canister, and relate this to crack depth profile
- Phase II of DOE SBIR completed in 2020
  - Currently seeking opportunities to continue development
- Participants
  - PI: Marvin Klein
  - Collaborator: Pacific Northwest National Laboratory (PNNL)
  - Subcontractor: Electric Power Research Institute (EPRI)
  - Subcontractor: Robotic Technologies of Tennessee
  - Consultant: Jason Van Velsor, Structural Integrity

Technology Impact: Needs Addressed

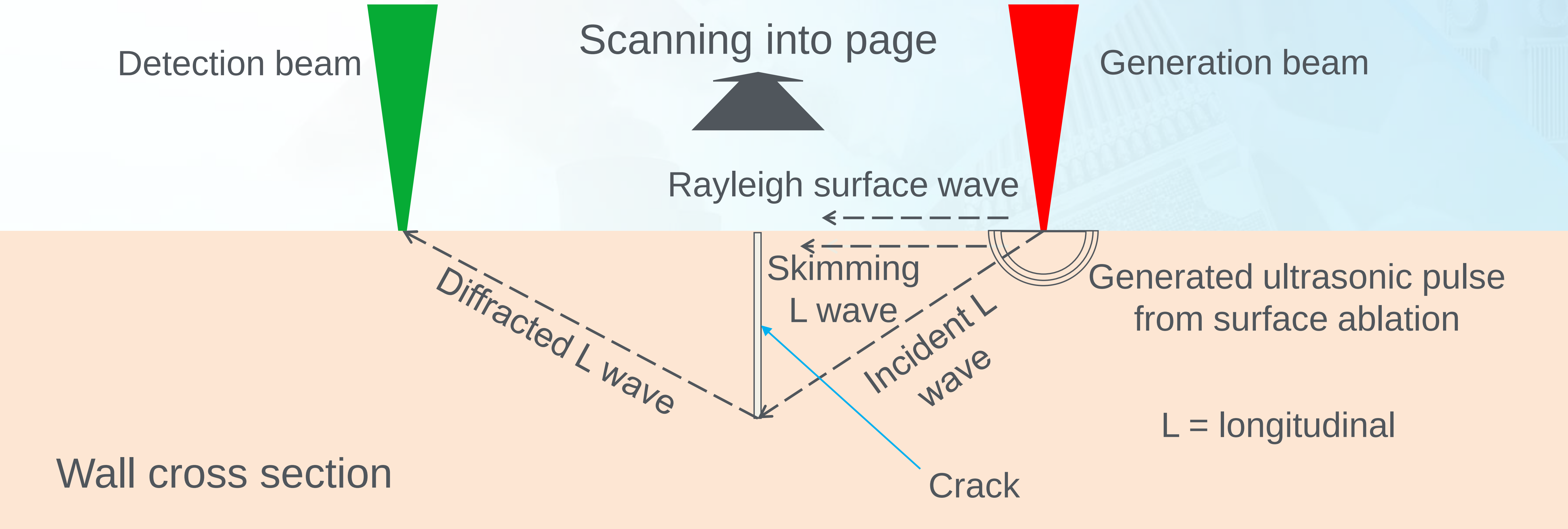
- Nuclear waste canisters must be periodically monitored for formation of stress corrosion cracks that could lead to leaks
  - Dry cask storage system
- Personnel and non-radiation-hardened electronics must be kept far from the canisters
- Limited access to canisters
  - Enter canister area via ventilation ports
  - Fit between canisters in space as small as 2”

Technology Impact: LUT Concept

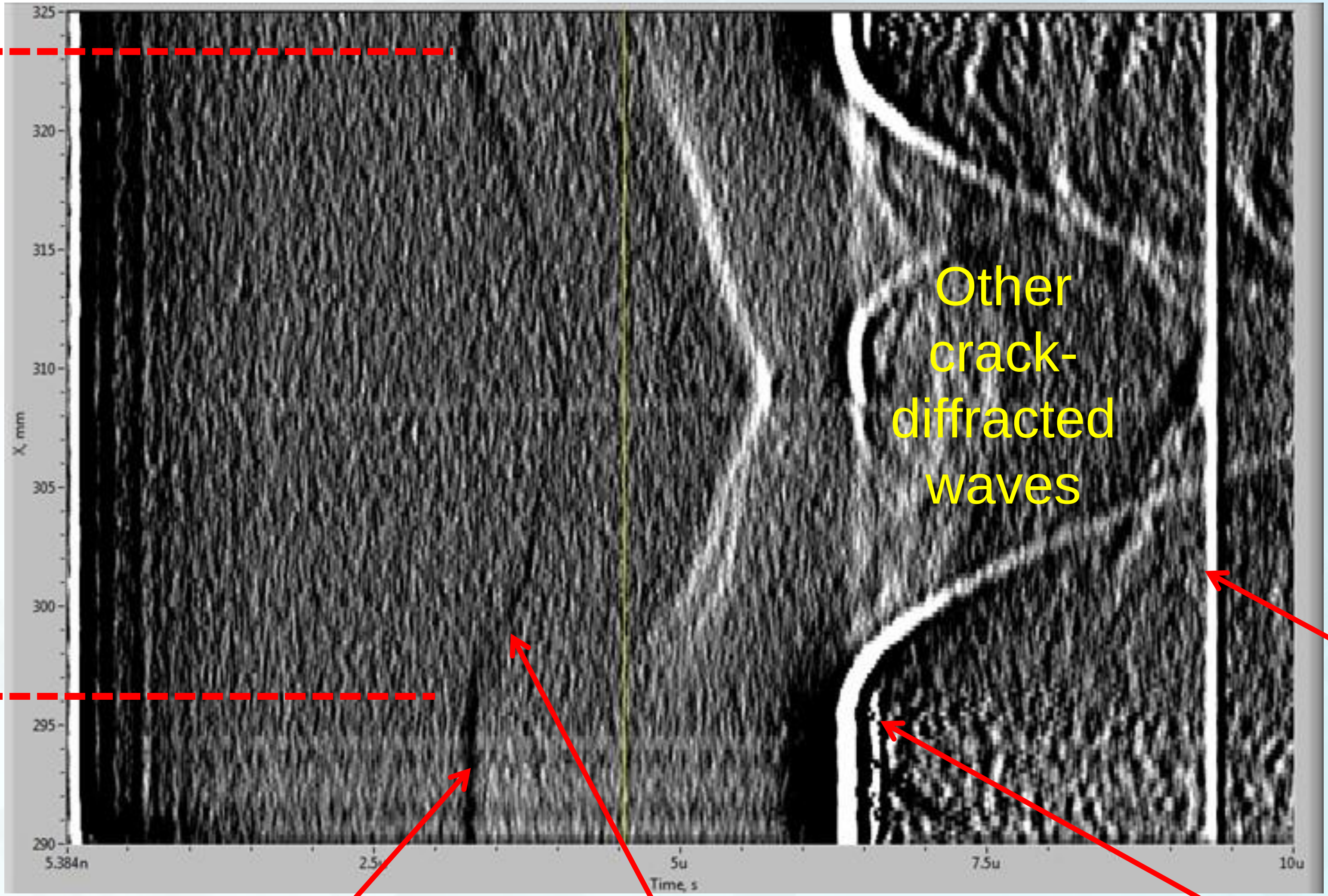


Methodology

- Crack depth determined from time of flight of ultrasonic pulse diffracted by crack bottom



Experimental Results: Test Crack LUT B-Scan



Physical extent of crack (skimming wave interrupted)

2L Backwall reflection

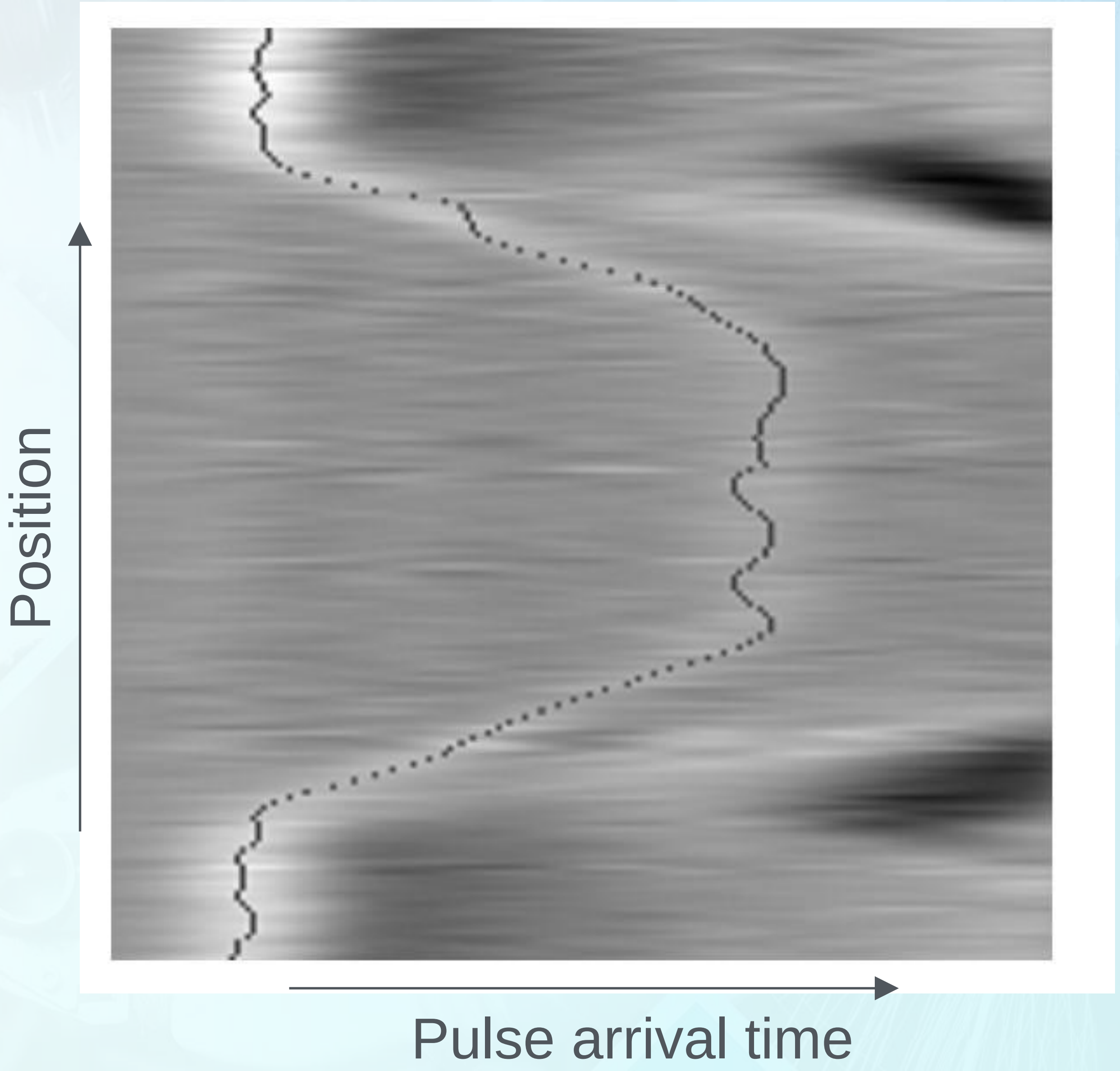
Skimming L wave

Crack-diffracted L wave

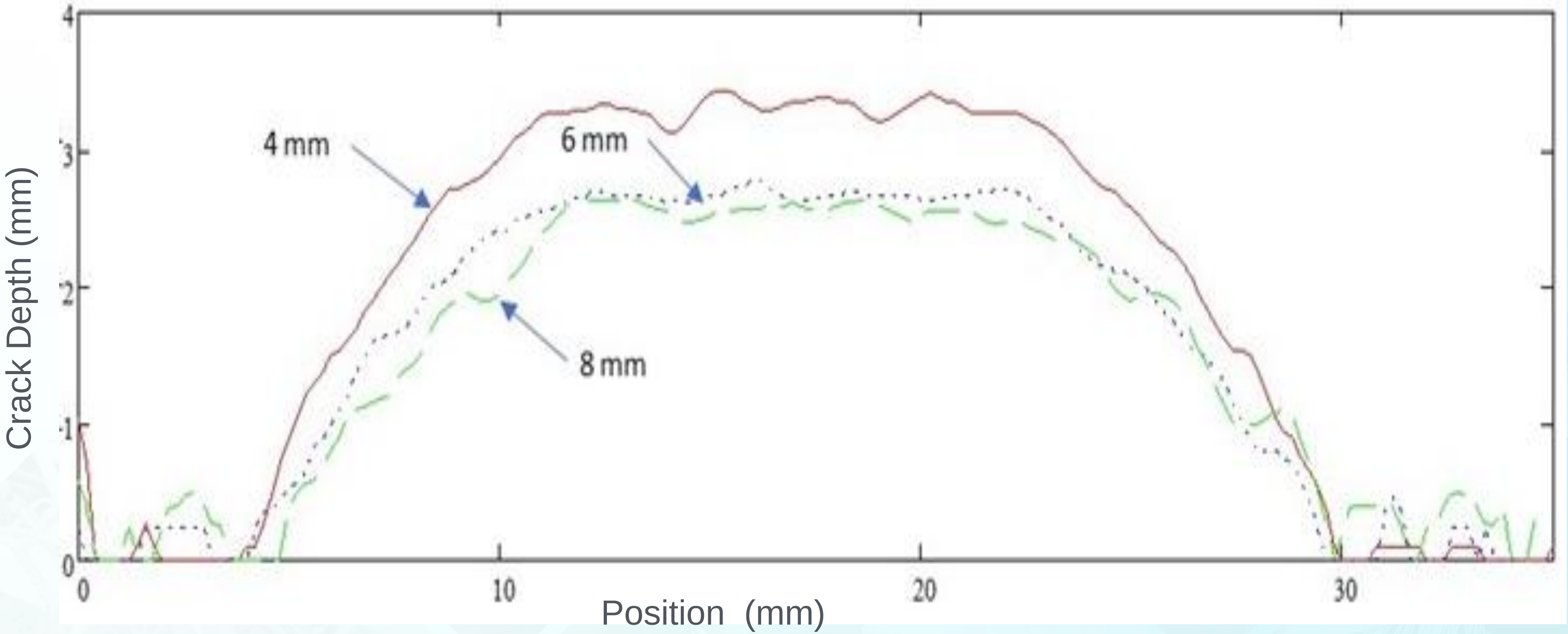
Rayleigh wave is interrupted over crack

Experimental Results: Automated Tracking of Crack-Diffracted Wave

- Digital near-real-time data-processing achieves large SNR enhancement
- Tracked wave converts directly to crack-depth profile

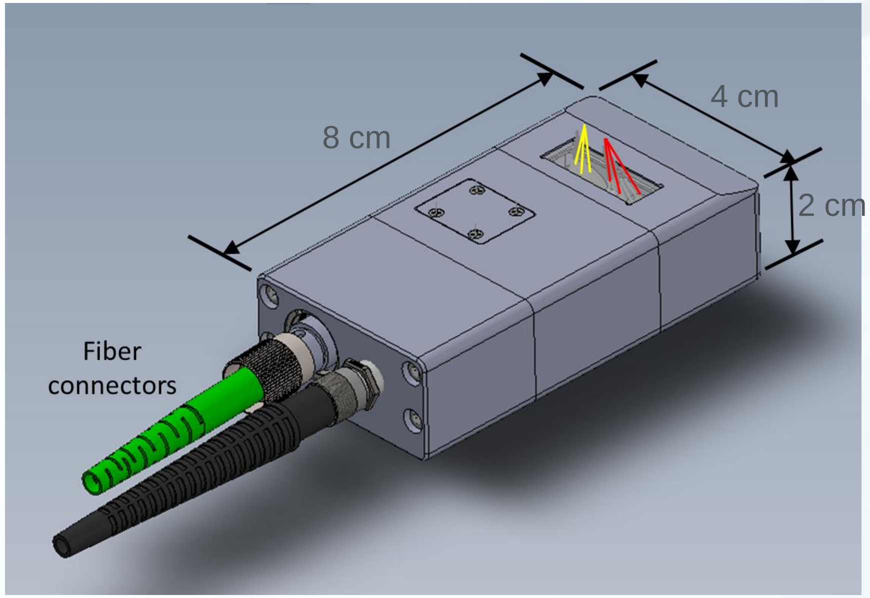


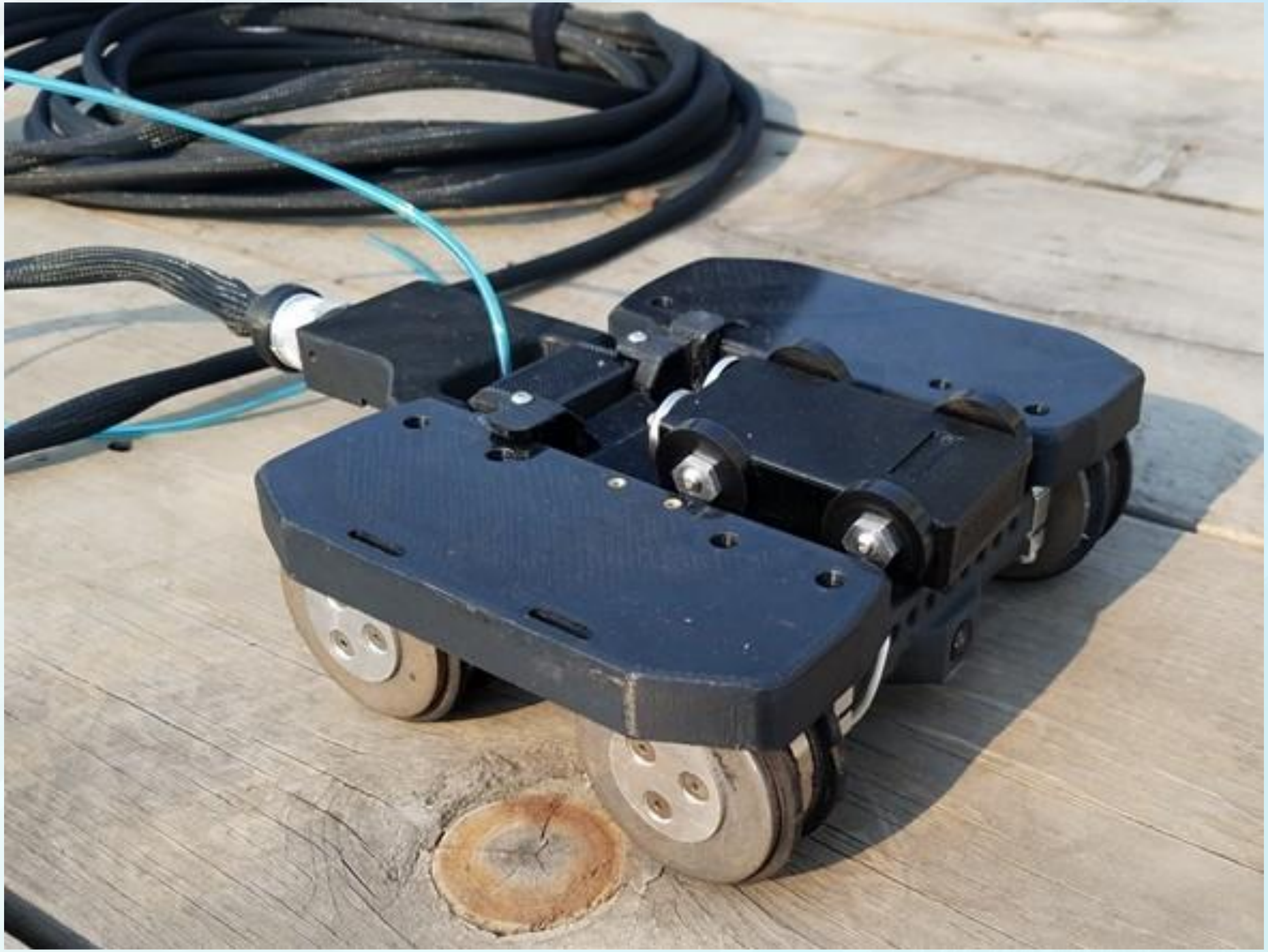
Experimental Results: Automated Tracking of Crack-Diffracted Wave



- Consistent profile obtained for three laser beam separations

Accomplishment: Integrated Miniaturized LUT Probe onto Crawler





Accomplishment: Field Demonstrations on Canister Mockup

- Mechanical tests at Pacific Northwest National Laboratory (PNNL)

Crawler with LUT probe entering vertical mockup vent

Inside vertical 2” annular space

Concluding Remarks (1 of 2)

- Checking internal pressure and cladding wall thickness of fuel rods
  - Proof-of-concept experiment demonstrates
    - Linear plot of calibrated metric vs. internal pressure
    - Measurement of wall thickness with accuracy <0.2%
  - Extensive simulations have elucidated analysis of experimental data, while data provide validation of models
  - Future work underway or planned
    - Further underwater laboratory measurements
    - Developing signal-processing metric for mixed He/Xe gases
    - Developing ultra-miniature test probe for access between the rods in an array
    - Test probes on surrogate rods in a research cooling pool at required depth (~30')
    - Demonstrate operation at expected radiation levels without excessive damage to fibers
  - Currently filing provisional patent
  - Establishing commercialization partners

Concluding Remarks (2 of 2)

- Monitoring flow rate in cooling pipes
  - Demonstrated consistent results for proof-of-concept experiment with R.T. water
  - Currently seeking opportunities to continue development
- Stress corrosion crack depth profile evaluation in nuclear waste canisters
  - Demonstrated consistent profile determination
  - Tested integration onto robot crawler in canister mock-up
  - Currently seeking opportunities to continue development
- Laser Ultrasonics has great potential for *in-situ* monitoring in nuclear installations

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Thank You