Advanced Laser Ultrasonic Sensors for Fuel Rod Characterization

Intelligent Optical Systems (IOS)

Principal Investigator: Dr. Bradley Bobbs, Senior Scientist

Advanced Sensors and Instrumentation (ASI) Program Annual Review Webinar

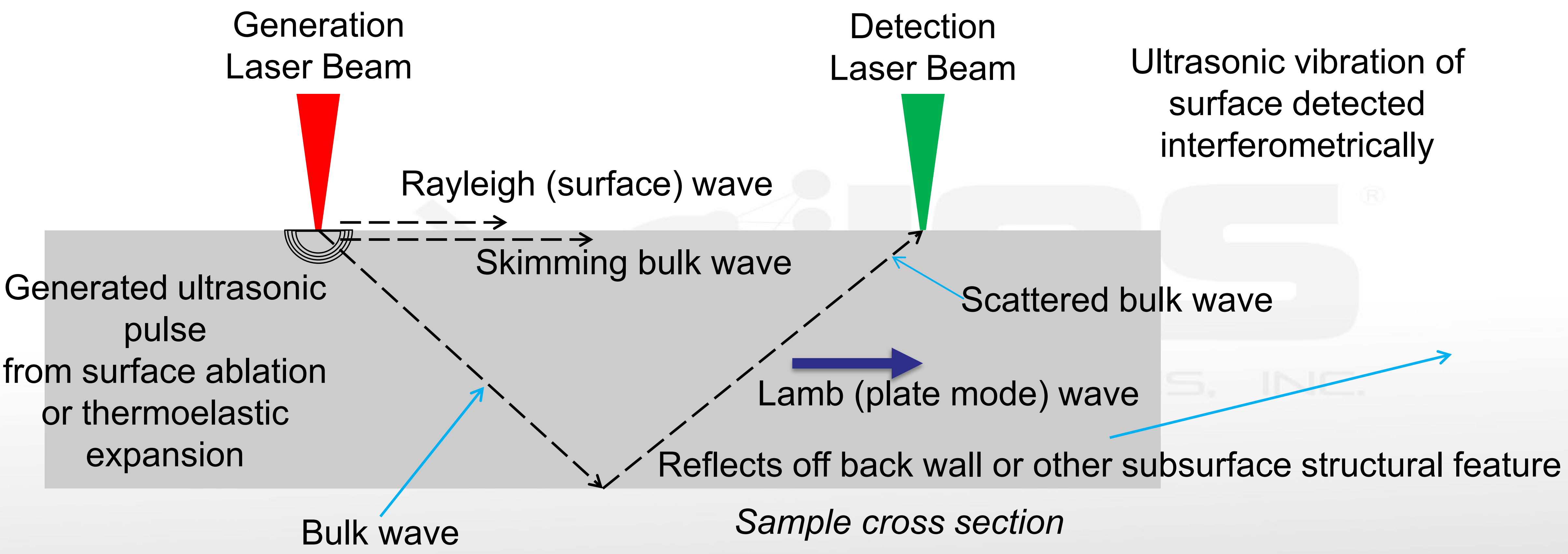
October 31, 2023

This document is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Energy, under Award Number DE-SC0020749

Outline

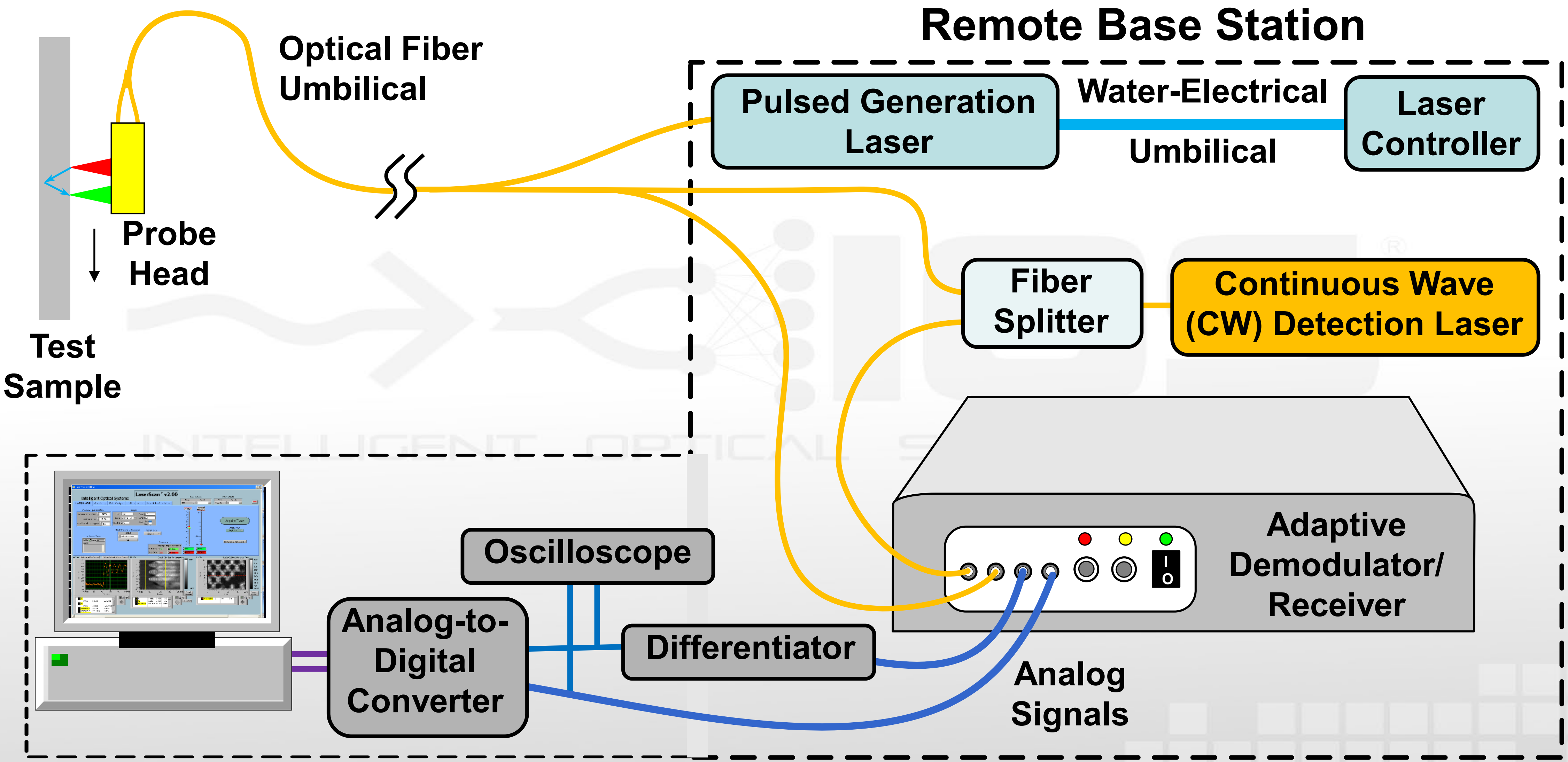
- Laser ultrasonic testing (LUT) background
- LUT measurement of nuclear fuel rod internal pressure and cladding wall thickness
  - Needs addressed
  - Methodology
  - Simulations
  - Experimental design and results
- Concluding Remarks

Laser Ultrasonic Testing (LUT) Principles



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

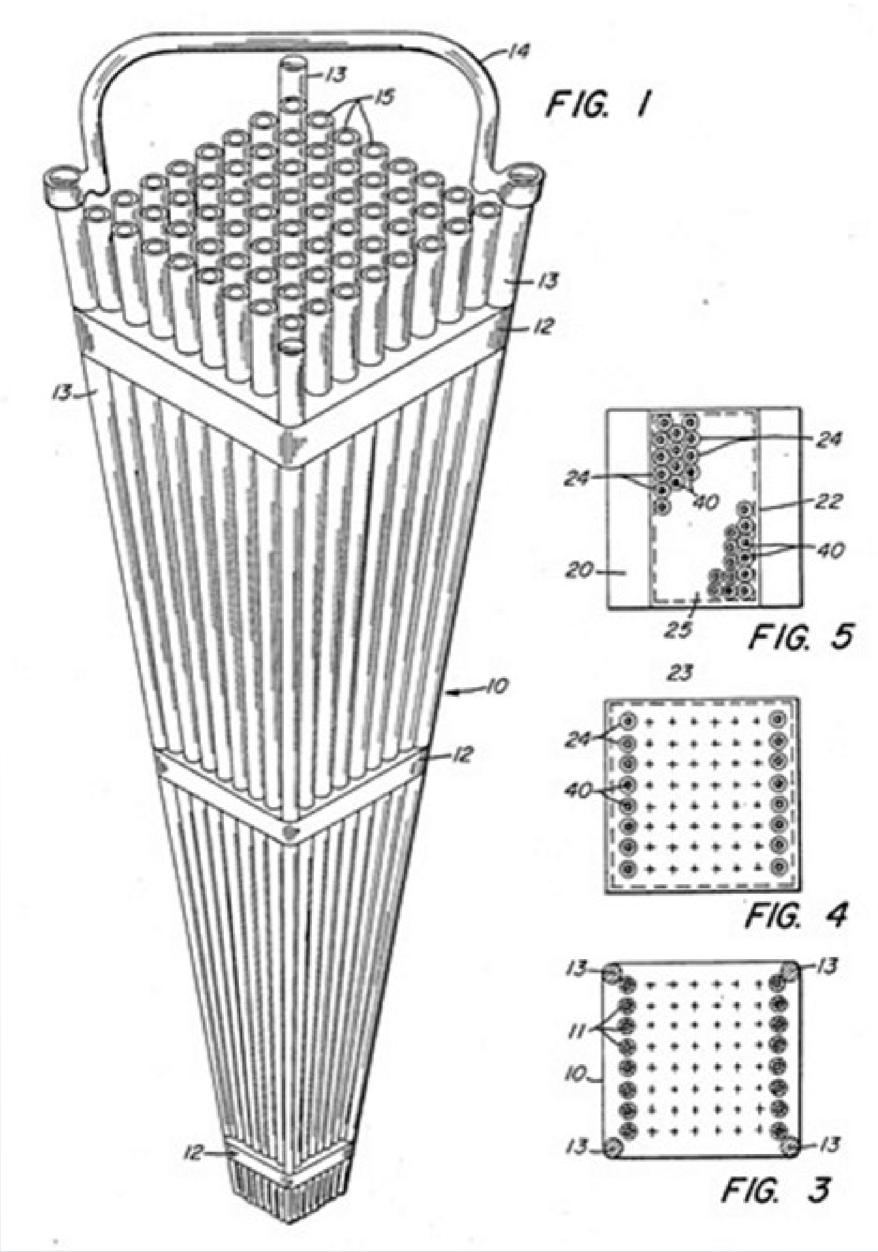
Checking Internal Pressure & Wall Thickness of Fuel Rods

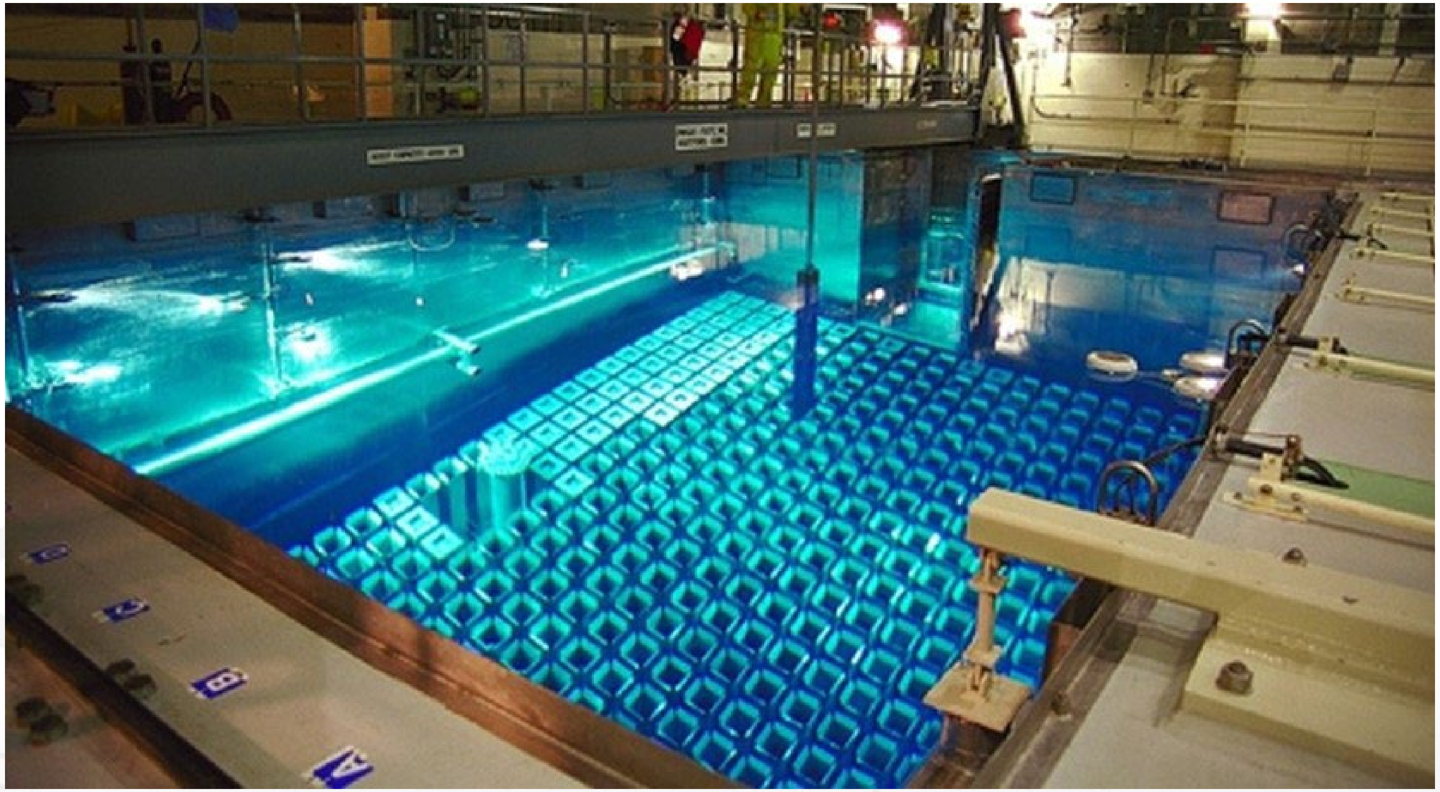
- Apply LUT to measure internal pressure and cladding wall thickness of a fuel rod
- Completed Phase II of DOE SBIR
- Participants
  - Current PI: Bradley Bobbs
  - Past PI & current consultant: Marvin Klein
  - Collaborator: Electric Power Research Institute (EPRI)
  - Subcontractor: Westinghouse Nuclear Services
  - Consultant: Prof. Peter Nagy, University of Cincinnati

Technology Impact: Needs Addressed

- 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 excessive buildup of 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
- Validate theoretical models and simulations for future reactor development

A Challenging Test Environment





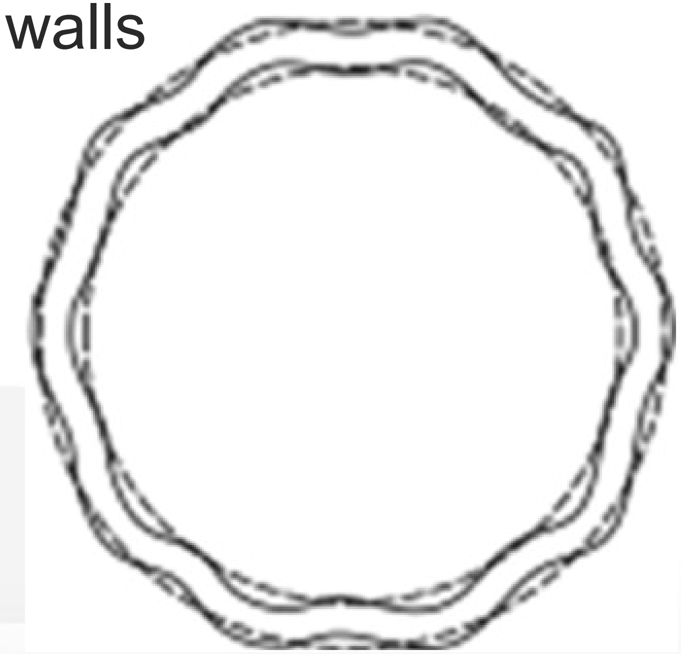
- Large savings in time and cost would result for measurements made without removing the rods from their array assembly
- Measurement needs to be *in situ* while rod array assembly is immersed in a water cooling pool (~30’ deep)

Method Comparison

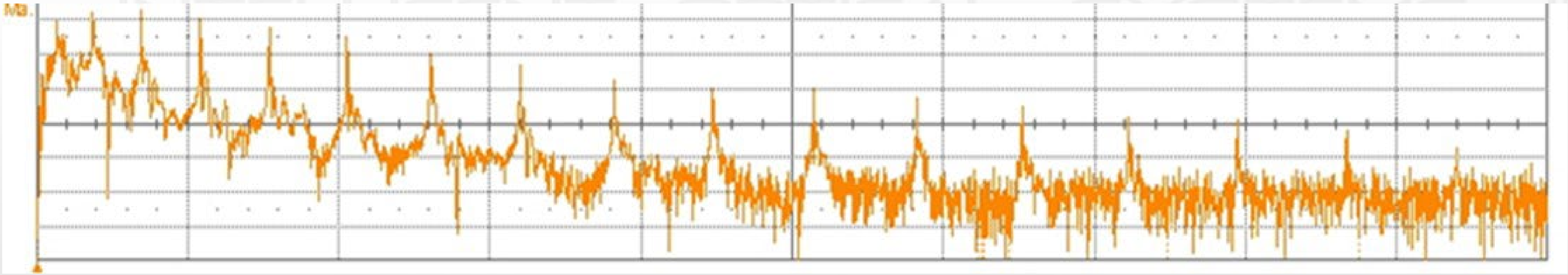
- Current methods detect leaks only
- Most current methods require removing rods from array
  - Current transducer-based ultrasonic method can make measurements without rod removal from their array, **but only senses the presence of internal water when a leak is present**
- Our method will allow **direct 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

Methodology: Measure Resonance Frequencies

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



Exaggerated circumferential deformations in rod wall for 10th order resonance



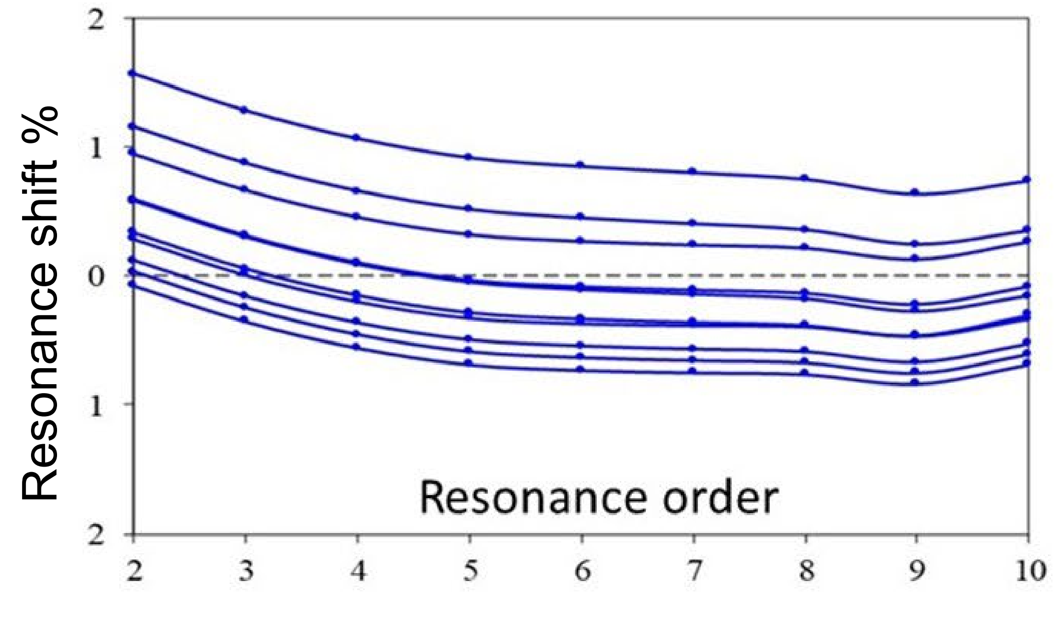
Typical Fourier-transformed circumferential wave frequency spectrum for orders 2-17

Methodology: Signal-processing

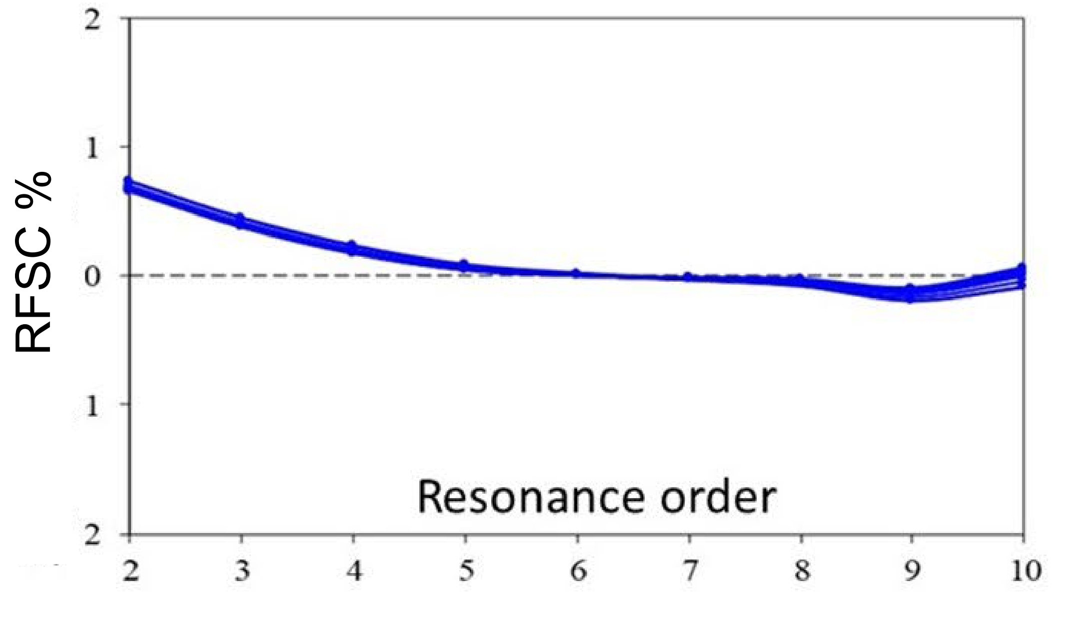
- Compare relative frequency shifts for multiple orders
- Take combination of relative shifts which, according to simulations, compensates for random non-pressure-dependent variations that are common to different orders
  - Otherwise, random variation noise is sufficiently large to render pressure determination impossible
- This defines a “Resonant Frequency Shift Contrast” (RSFC) metric with linear dependence on internal pressure
- **This methodology reduces simulation and experimental test results to a single slope calibration constant** (for a given rod type)
  - Pressure = RFSC / slope

Simulation: Suppression of Variations

- Suppression of pressure-independent variations based on contrast in dependence among different orders
- 10 measurements simulated with ±0.5% rod diameter variation
  - BWR rods filled with 350 psi Helium
- Pressure determination from data changes from impossible due to excessive noise (left) to accurate (right)



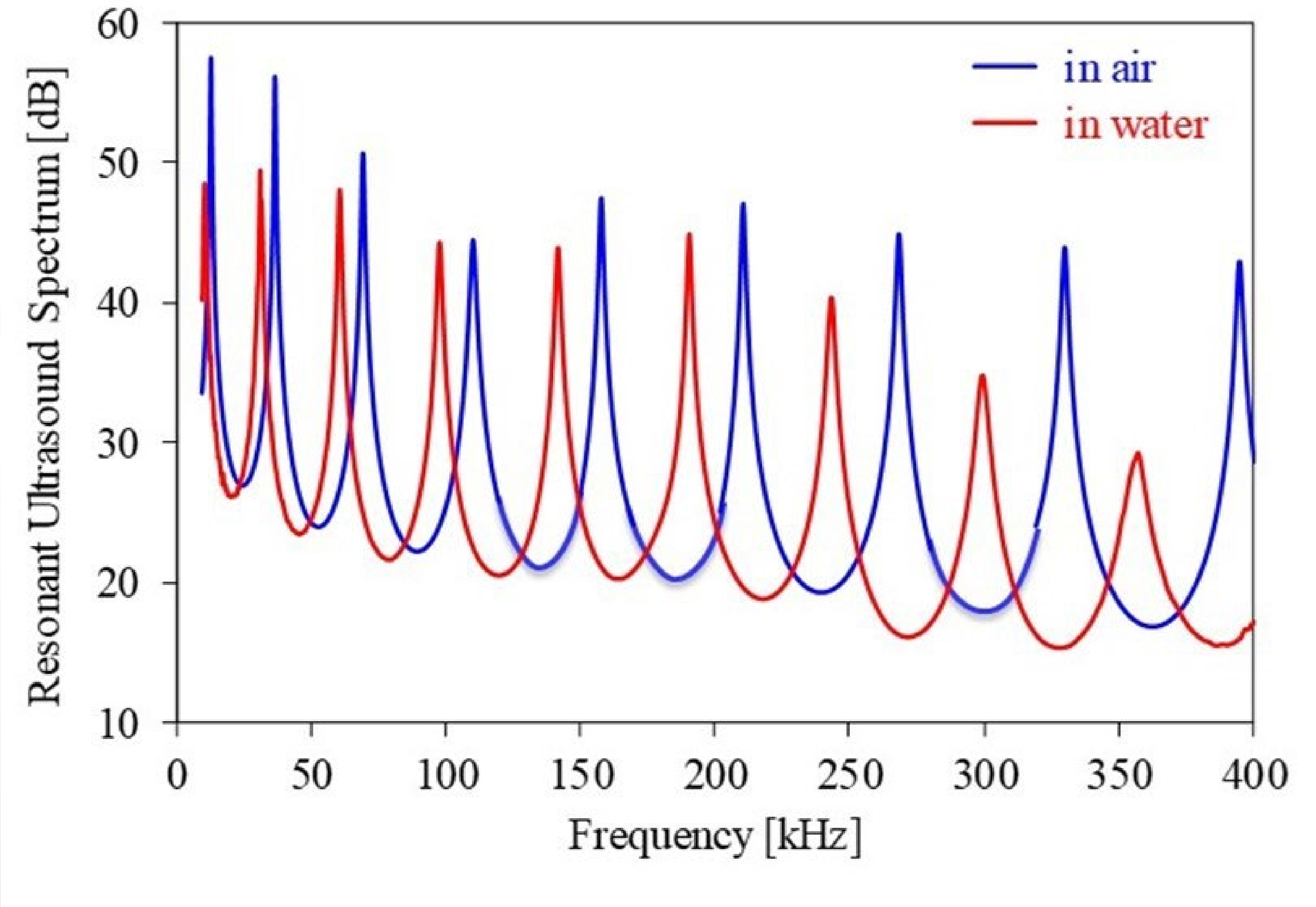
Random variation makes pressure determination impossible



Algorithm metric compensates for random variation to enable pressure determination

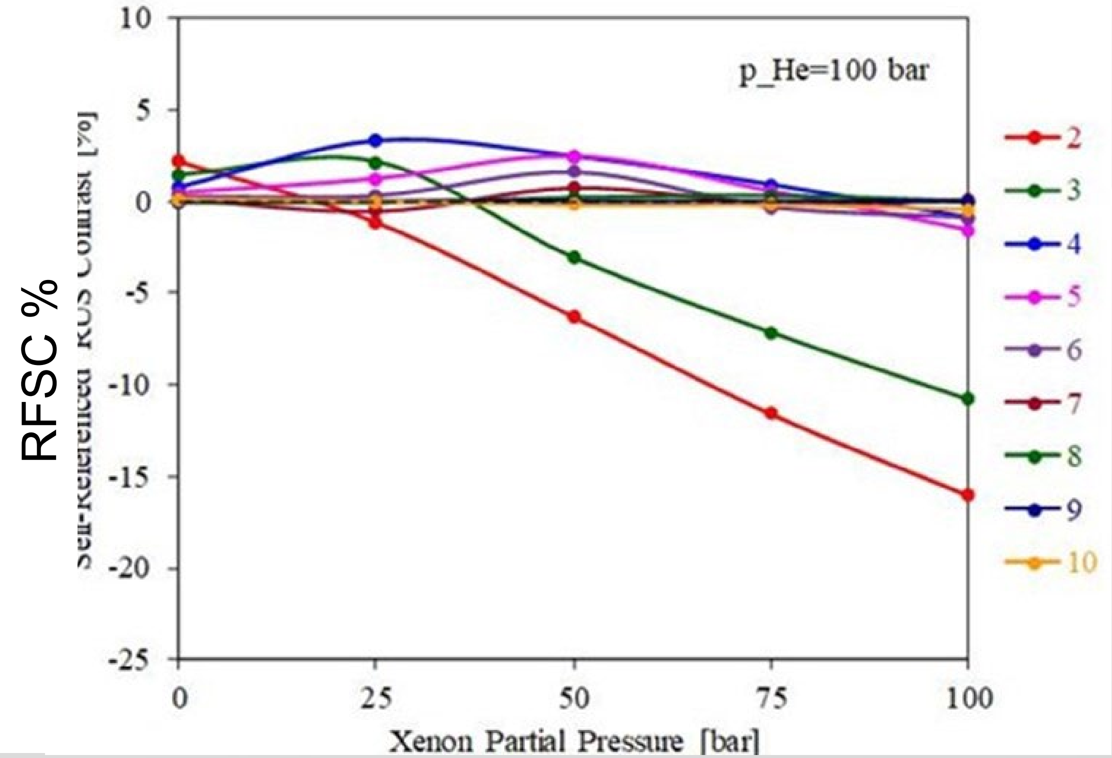
Simulation: Compare Resonances in Air and Water

- Methodology for measurement in water is same as in air, but with parameter modifications
  - Weak dependence on water pressure / depth

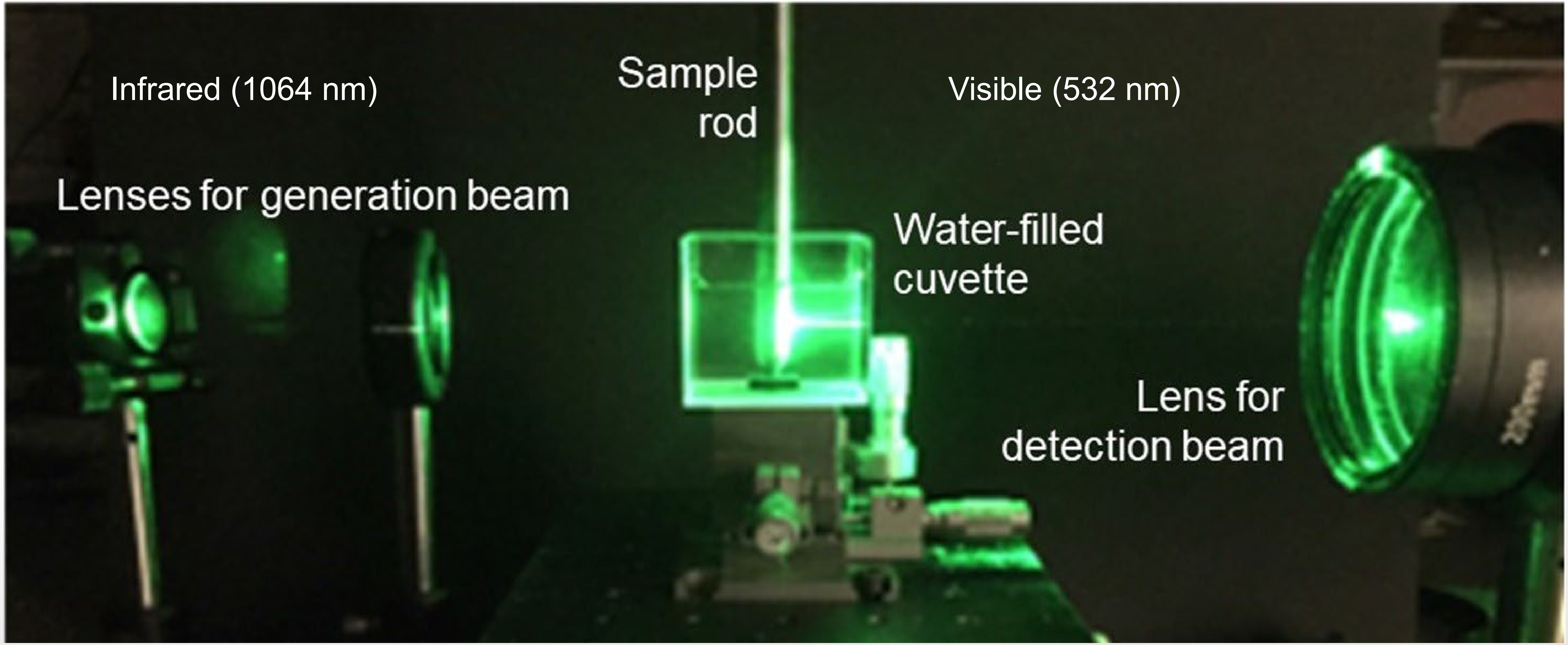


Simulation: Impact of Xe fission gas

- Complex RFSC dependence on Xe ⇒to ambiguous double-solution regions
  - Avoided in more clear-cut regimes, e.g.
    - When He dominates, detecting leakage before much fission gas is generated
    - When Xe dominates, detecting unacceptably high pressure due to fission gas buildup
    - Some solutions can be ruled out by *a priori* information
  - Negligible contributions from Ar and other fission gases

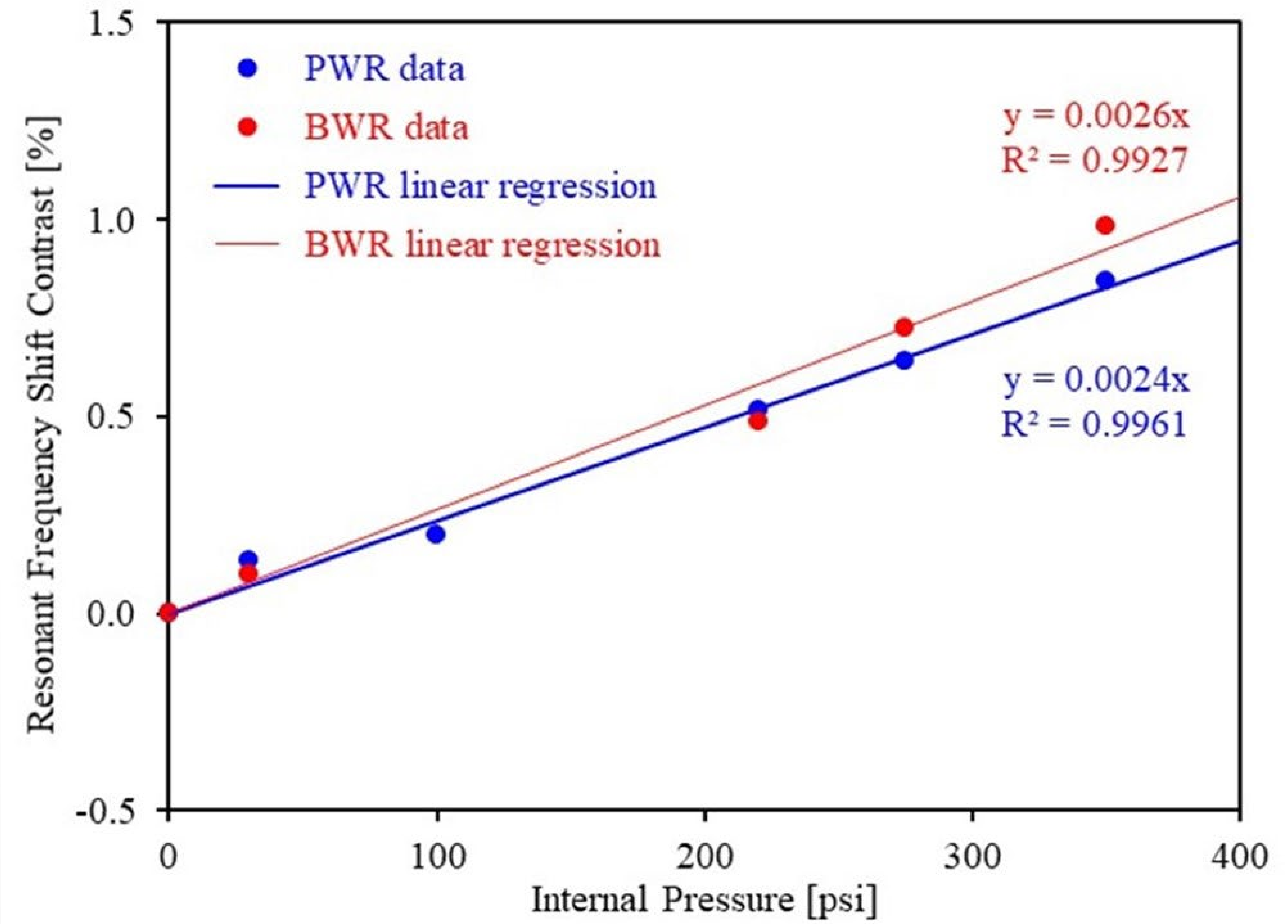


Setup For Proof-of-Concept Demonstration



Free-space laser beams – no optical fibers – in initial setup

Initial Experimental Results: Internal Pressure



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

Initial results shown for measurement in air

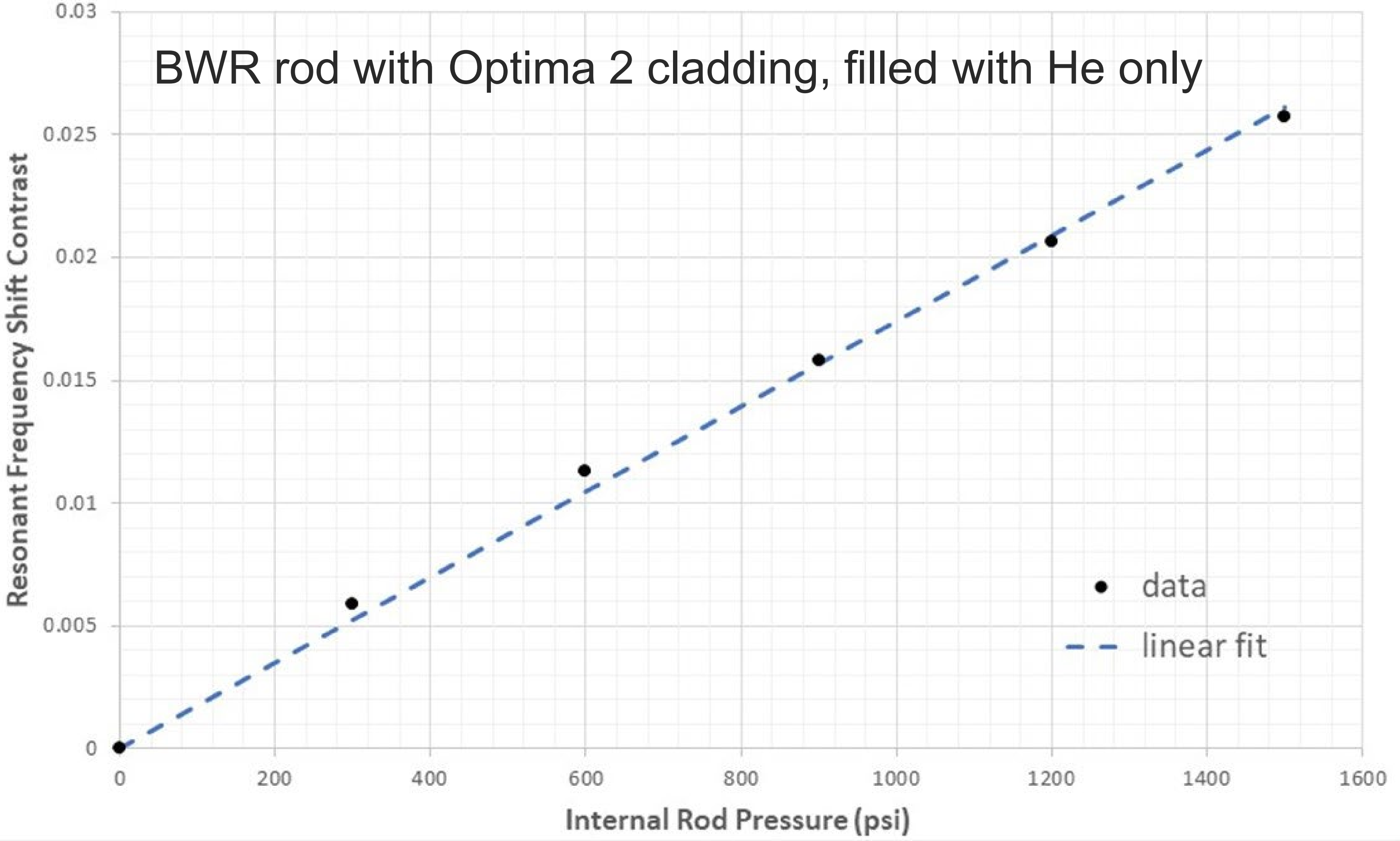
Slightly different slope (calibration constant) as expected for two rod types

Initial Experimental Results: Cladding 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 %

New Experimental Results: High Pressure

- Our new lab setup can produce any mix of He and Xe fission gas up to 1500 psi
  - Simulation shows other fission gases are negligible
  - Choice of two different rod cladding materials and dimensions



Compact Probe Design

- Can measure all rods *in-situ* in an array without disassembly
- Simplifies insertion into and operation in a hot cell
- All light coupling via optical fibers
- Initial experimental tests show good coupling efficiency (~10%) and consistency

Conclusion

- Laser ultrasonic testing (LUT), as being developed at IOS, can address a variety of challenging applications of *in-situ,* in-line, non-contact, non-destructive evaluation, including nuclear applications
- LUT has key advantages over alternative techniques
- Advances in LUT have enabled it to be effective under more challenging test surface and environmental conditions, such as in nuclear applications
- Simulations have elucidated analysis of experimental data, while data provide validation of models
- LUT of nuclear fuel rod internal pressure and cladding wall thickness show potential for good accuracy and *in-situ* measurements within an array

Publications and Patent

- B. Bobbs and M. Klein, “Laser Ultrasonics for In-Situ Monitoring of Physical Properties in Nuclear Installations”, Dept. of Energy Environmental Monitoring In-Situ Analysis Workshop, virtual conference, 2021.
- M. Klein and B. Bobbs, “Advanced Laser Ultrasonic Sensor for Fuel Rod Characterization”, Dept. of Energy Advanced Sensors and Instrumentation (ASI) Annual Program, virtual conference, 2021.
- B. Bobbs and M. Klein, “Applications of Laser Ultrasonic Sensing to Nuclear Applications”, Dept. of Energy Advanced Sensors and Instrumentation (ASI) Newsletter, Issue 16, pp 10-12, March 2022.
- B. Bobbs, M. Klein, P. Nagy, J. Beale, and B. Yoon, “Fuel Rod Characterization Using Laser Ultrasonics”, Fuel Reliability Program, Electric Power Research Institute, Charlotte, NC, 2022.
- “Fuel Rod Characterization Using Laser Ultrasonics”, Quantitative Non-Destructive Evaluation (QNDE) Conf., San Diego, CA, 2022.
- B. Bobbs and M. Klein, “Laser Ultrasonics for In-Situ Monitoring of Physical Properties in Nuclear Installations”, Dept. of Energy Advanced Sensors and Instrumentation (ASI) Annual Program Review, virtual conference, 2022.
- B. Bobbs, M. Klein, B. Yoon, and J. Beale, “Update on Fuel Rod Characterization Using Laser Ultrasonics”, Fuel Reliability Program, Electric Power Research Institute, Charlotte, NC, 2023.
- P. Calderoni, B. Bobbs, M. Klein, et al, “NDE Applications at Nuclear Facilities,” 8th Int’l Conf. Advancements in Nuclear Instrumentation Measurement Methods and their Applications (ANIMMA), Lucca, Italy, 2023.
- B. Bobbs, M. Klein, and P. Nagy, “Applications of Laser Ultrasonic NDE to Nuclear Facilities”, Am. Soc. Nondestructive Testing (ASNT) 30th Research Symposium, Columbus, OH, 2023.
- B. Bobbs, “Laser Ultrasonics and Spectroscopic Monitoring for Nuclear Applications”, PNNL seminar/webinar, invited speaker, Richland, WA, 2023.
- B. Bobbs, “Laser Ultrasonics for Aerospace and Nuclear Applications”, Optical Society of Southern California, invited speaker, Torrance, CA, 2023.
- Provisional patent 63/527,322 filed: Marvin Klein, Bradley Bobbs, “System and Method for Laser Ultrasonic Testing of Nuclear Fuel Rods,” 2023.

Questions?

Bradley Bobbs, Ph.D.
Senior Scientist, Laser Ultrasonics Products Group
Intelligent Optical Systems
Torrance, CA (Los Angeles area)
bbobbs@intopsys.com
Phone: 424-263-6326
intopsys.com

Thank you for your attention!
Please contact us for more information, and to arrange collaboration, testing, commercialization, and development funding opportunities