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# High Temperature Embedded/Integrated Sensors (HiTEIS) for Remote Monitoring of Reactor and Fuel Cycle Systems

**Advanced Sensors and Instrumentation Annual Webinar**

**October 31 – November 1, 2018**

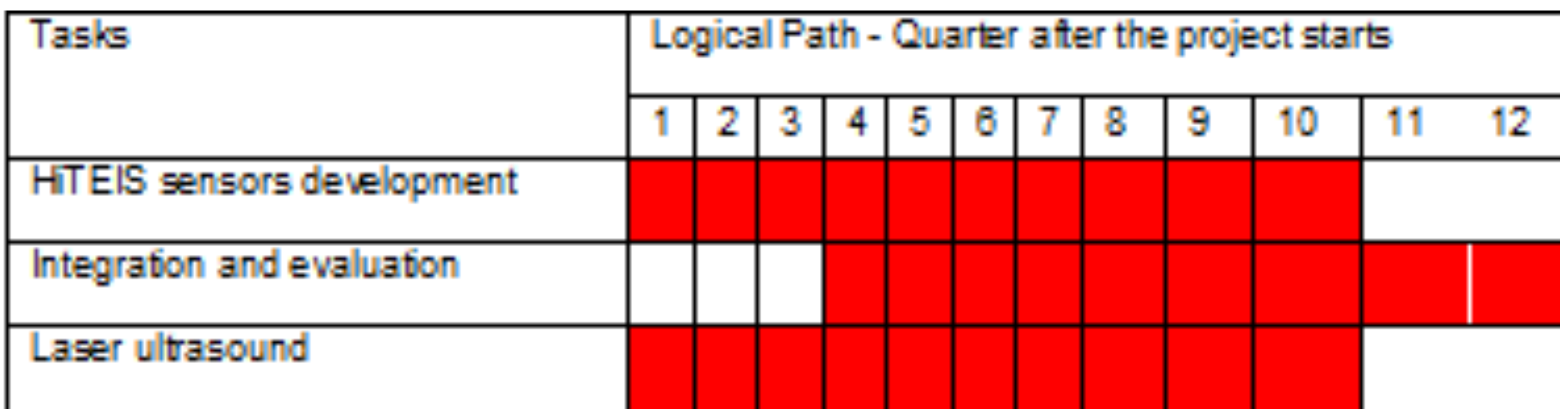
Xiaoning Jiang
**North Carolina State University**

# Project Overview

**The Objective** of this project is to develop and evaluate high temperature embedded/integrated sensors (HiTEIS) for applications in reactor and fuel cycle systems.

Specific Goals:

1) To develop high temperature (> 600 °C) embedded/integrated sensors (HiTEIS) for monitoring of temperature, vibration, liquid level, pressure and structural integrity;
2) To investigate laser ultrasound;
3) To implement nuclear environment compatible secured remote communication for HiTEIS;
4) To verify the HiTEIS technology in reactor and fuel cycle environments.



# Task I: Development of HiTEIS

**NC State (Xiaoning Jiang, Mo-Yuen Chow and Mohamed Bourham):**

- Sensor development: Xiaoning and Mohamed (Y1&Y2)
- Wireless sensor integration: Mo-Yuen and Xiaoning (Y1 & Y2)
- Embedded sensor: Mohamed and Xiaoning (Y2&Y3)
- Integrated sensor tests: Mohamed, Mo-Yuen and Xiaoning (Y3)

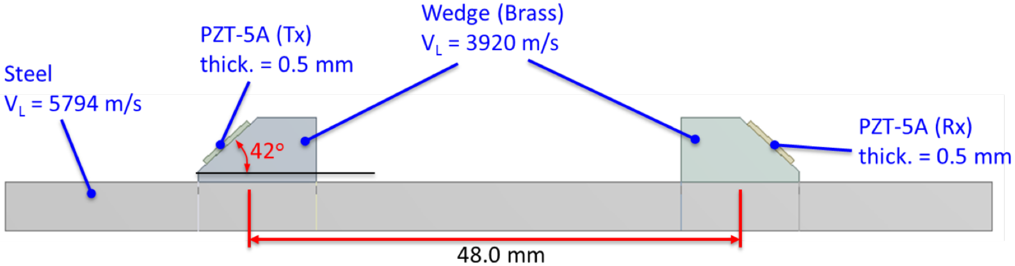
**University of Florida/Penn State and NC State (Leigh Winfrey and Mohamed Bourham):**

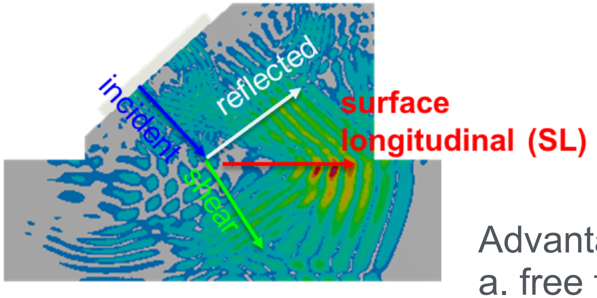
- Sensor materials evaluation: pre-and post- irradiation evaluation (Y1)
- Sensor prototype evaluation: pre-and post- irradiation evaluation (Y2&Y3)

# Stress Sensor development (1/2)

- Accomplishments:
  - FEM simulation for confirmation of technical feasibility
  - Dual 1-3 composite transducers for receiver and transmitter (4.4 MHz)
  - Concept design for high temperature stress sensing with high-power laser

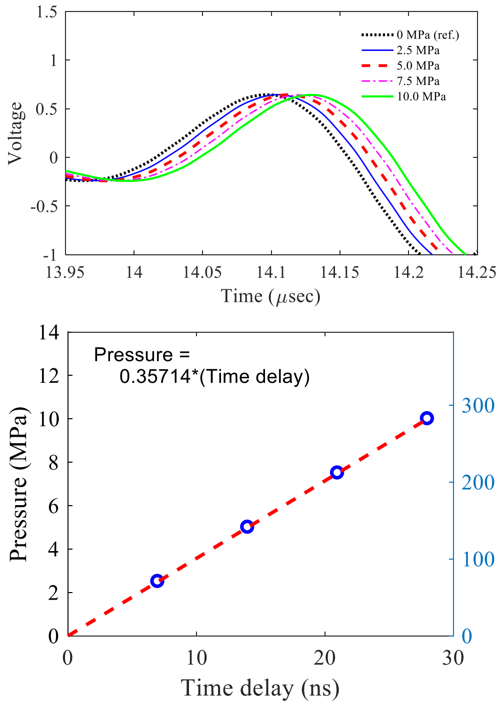
✓ **Simulation works (1)**




Advantages of SSL wave:
a. free from surface roughness
b. less influenced by internal medium

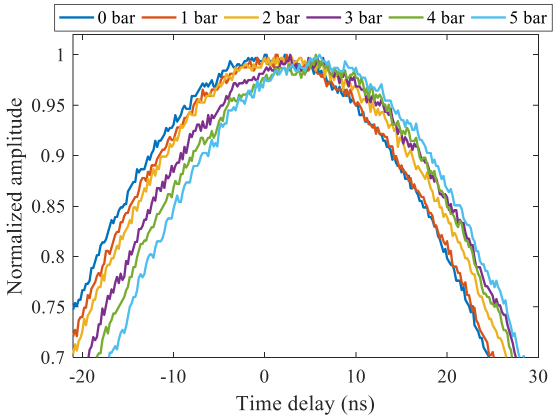
**Linear relation for stress vs. time-delay**



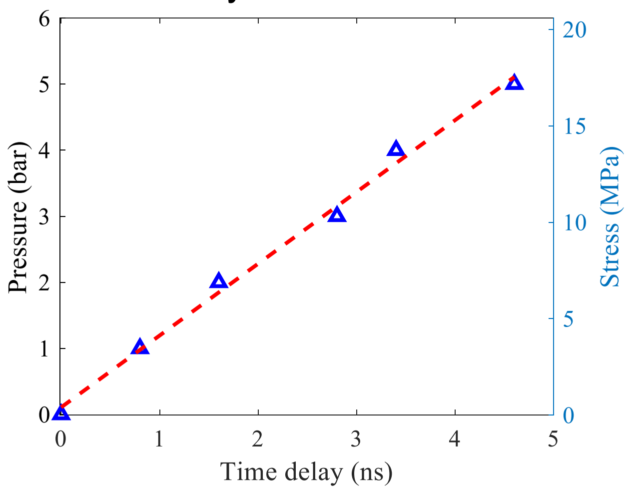
# Stress sensor development (2/2)

## ✓ Experimental results

b. Measured wave form




c. Sensitivity

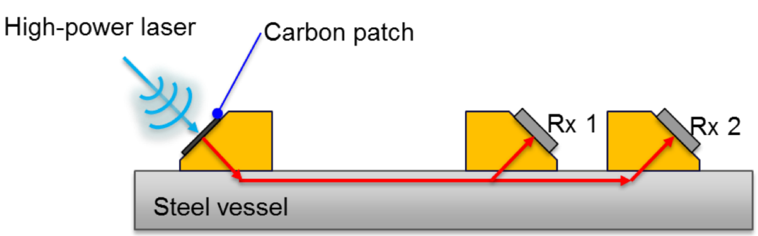



## ✓ Discussions

a. Confirmation of a linear relationship between stress and time-delay ($R^2$ = 0.99)
b. Sensitivity = 4.48 MPa/ns
c. Resolution = 1.12 MPa

## ✓ Future researches

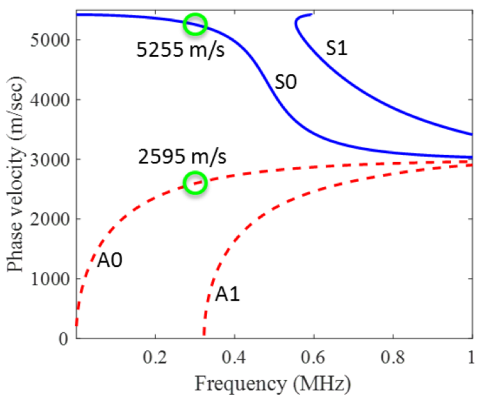
a. Temperature calibration technique
b. Laser excitation method



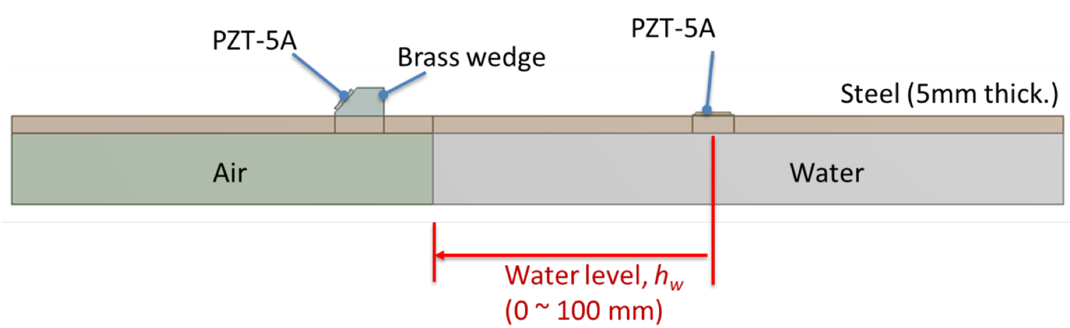
# Liquid Level Sensor development (1/1)

- Accomplishments:
  - Extensive literature survey on liquid level sensor
  - FEM simulation for technical feasibility of guide wave-based sensing

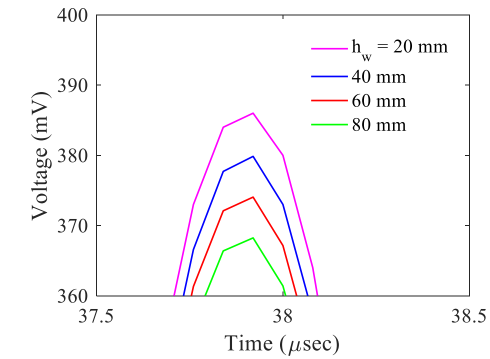
✓ **Simulation works**

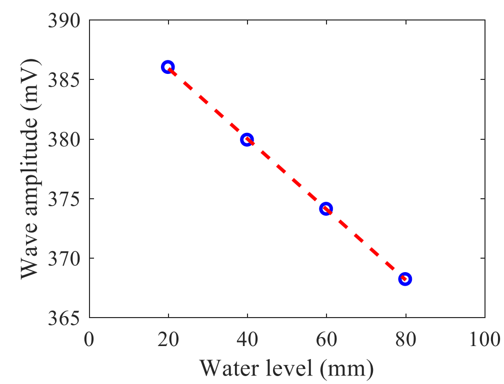



**Lamb wave dispersive curve:**
to determine the excitation frequency as well as the associated wedge angle.




**Inversely-linear relation for liquid level vs. signal magnitude**

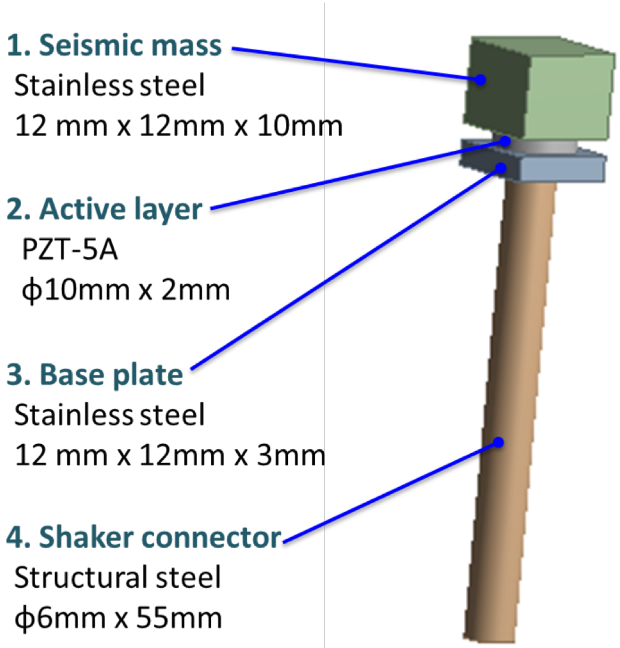


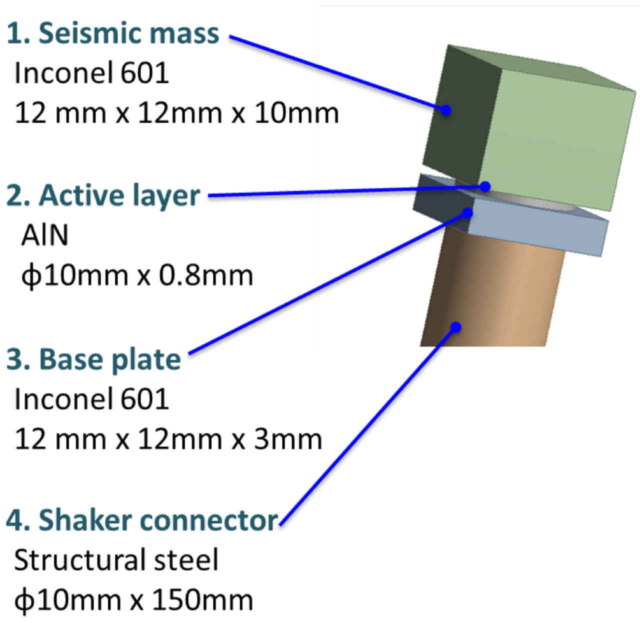
# Accelerometer (1/3)

- Accomplishments:
  - FEM simulation for technical feasibility of both room- and high-temperature transducers
  - Fabrication of room-temperature accelerometer for development of signal-conditioning circuit

**1) For room-temperature**



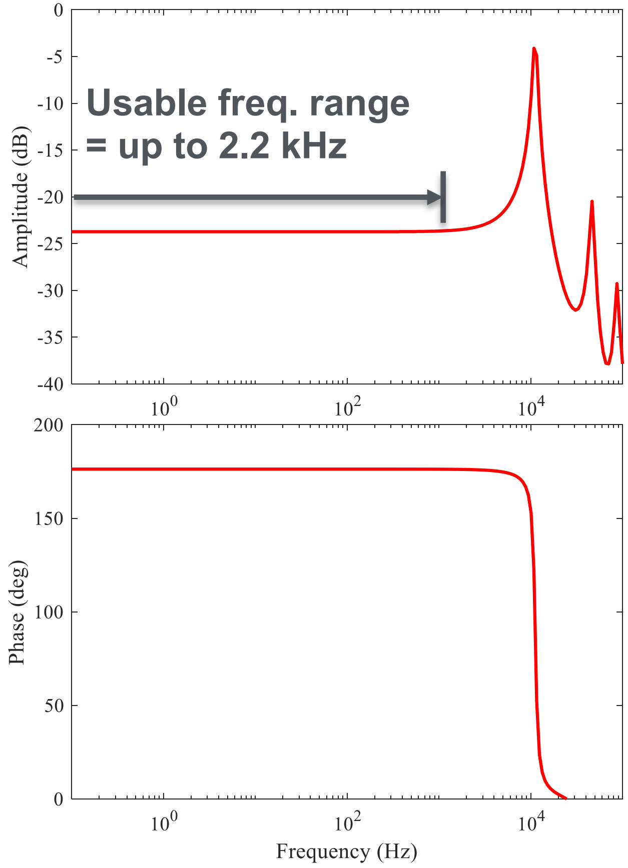

**2) For high-temperature**



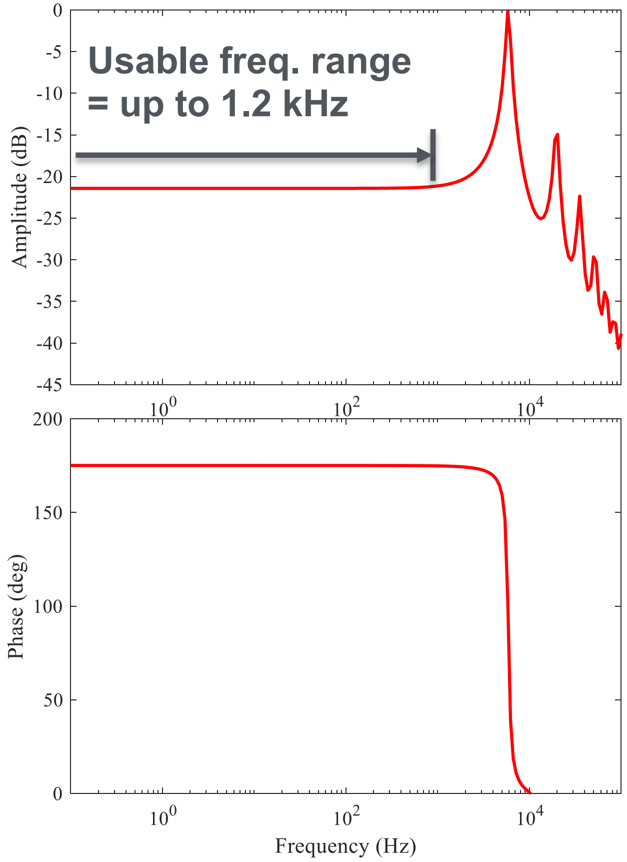
# Accelerometer (2/3)

- ✓ **FEA simulation:**
  Harmonic analysis to find the usable frequency range of each accelerometer

**1) For room-temperature (PZT-5A)**

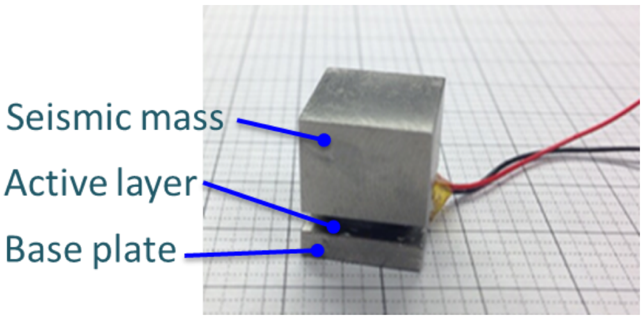


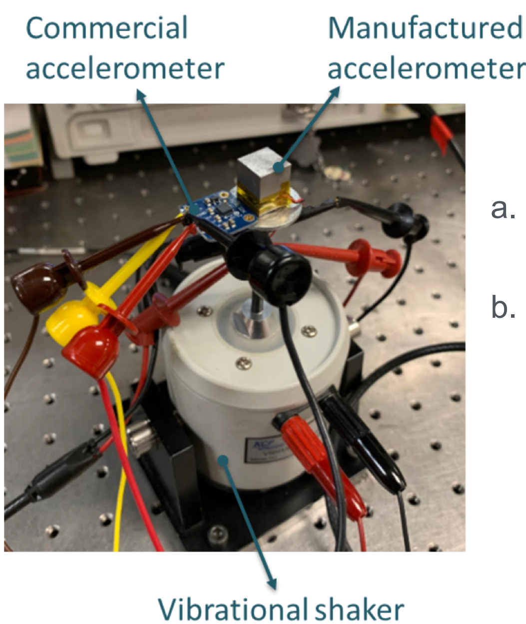

**2) For high-temperature (AlN)**



# Accelerometer (3/3)

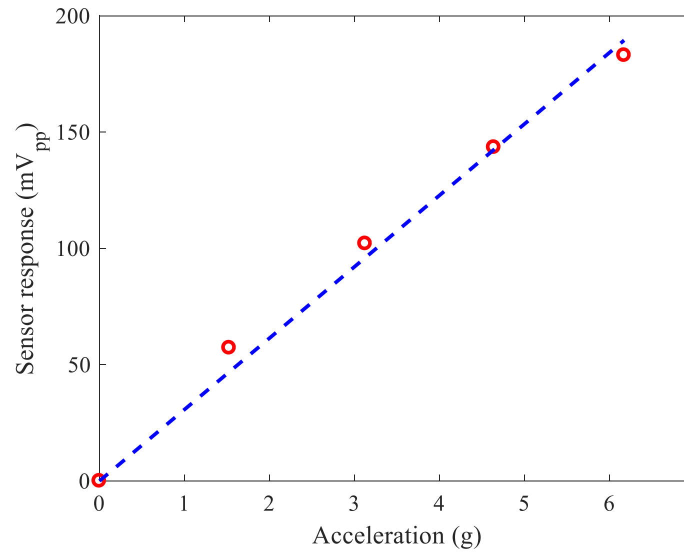
## ✓ Experimental validation




a. The commercial accelerometer used for the reference.

b. Use of a signal conditioning circuit



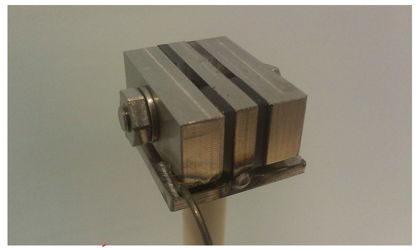

a. Linearly proportional relationship
b. Sensitivity: **30.70 mV/g**

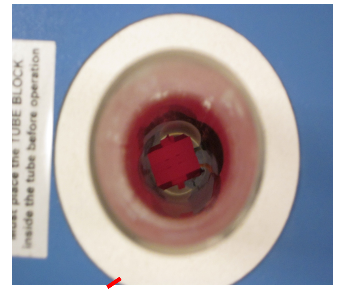
## ✓ Future researches

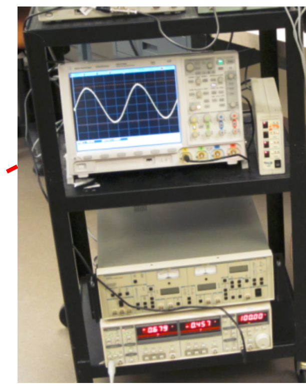
a. Fabrication of high-temperature accelerometer
b. Embedding on a miniaturized nuclear reactor

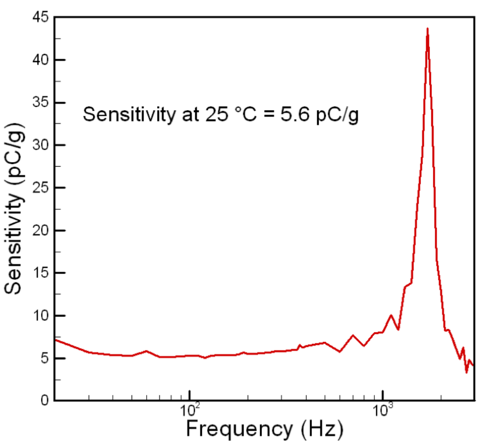
# HT Vibration Sensor

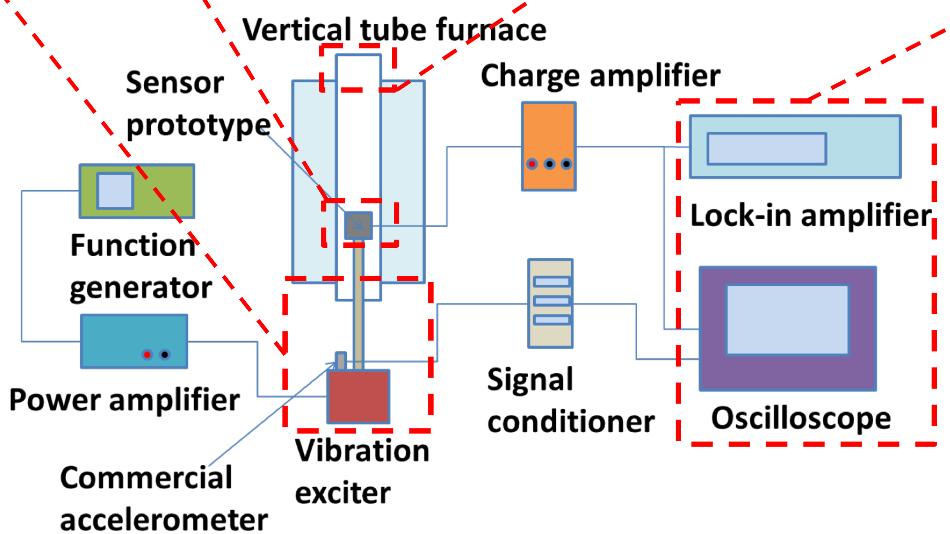




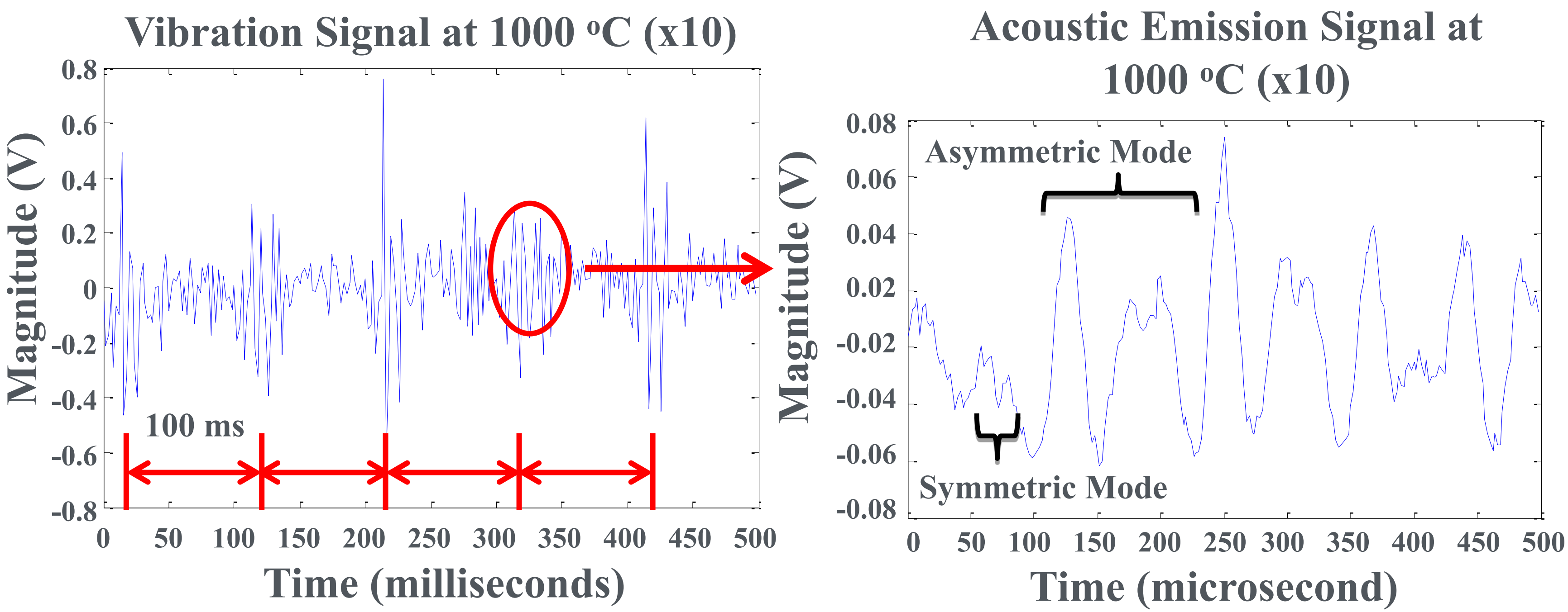






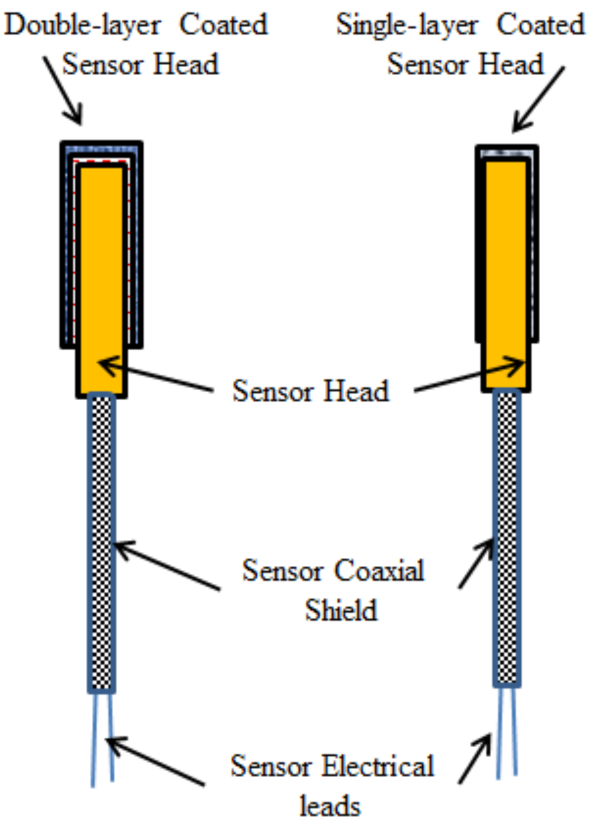
# Acoustic Emission Sensing




- High frequency AE wave only visible with small time window
- Magnitude of high frequency component less prevalent – shown in frequency domain

# Protective Coating for Sensors

- Initiating preliminary study on materials that can provide protective coating on sensors head
- Evaluating single versus multi layered coatings
- Looking into methods for coating on sensors head
- Looking into materials for corrosion protection (Zirconium, Titanium and Aluminum compounds)
- Designing experiments to assess corrosion

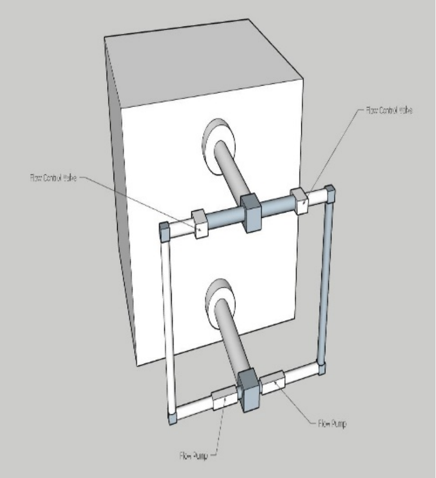


# Benchtop Mock-up

- **Recent Accomplishments:**
  - Designed and assembled a circulatory flow system to test sensor response to changes in various parameters:
    - Flow rate changes are controlled via the bottom inlet flow valves.
    - Temperature is controlled using a thermal controlled inserted into one of the various ports on the tank.
    - Water level will also be measured by changing the input volume of water.
  - Utilized PVC piping, flow gate valves, and pumps to create a closed loop flow system.

Tank with multiple inlet ports


Temperature controller



Flow system simulation

Flow circulation system assembled

# Sensors in radiation environment

- Recent Accomplishments
  - Characterization of piezoelectric materials in irradiation condition

✓ **Sample information**

| Material | Mode | Transition Temp. (°C) |
|---|---|---|
| AlN | d33(PLA) | ~2826 |
| | d15(TS) | |
| YCOB | d26(TS) | >1500 |
| | d12(LAT) | |
| CTGS | d12(LAT) | ~1350 |
| LGT | d12(LAT) | ~1470 |

* PLA (Planar), TS (Thickness shear), LAT (Lateral)

# Task II: Nuclear Environment Compatible Secured Remote Communication Integration

The goal is to develop a secured remote wireless communication system for the developed sensors.

a. To develop a wireless transmitter/receiver for harsh environments
b. To integrate the communication system with sensors

Expected results: The sensor telemetry system positioned in high temperature/radiation conditions will exhibit the reasonable power level, telemetry distance (> 5 m) and SNR (>10 dB) over a broad range of temperatures.

# Task II: Nuclear Environment Compatible Secured Remote Communication Integration



**NC State (Mo-Yuen Chow, Mohamed Bourham and Xiaoning Jiang):**

- Identification of wireless transmitters and receivers: Mo-Yuen and Mohamed (Y1)
- Wireless sensing system: Mo-Yuen and Xiaoning (Y1 & Y2)

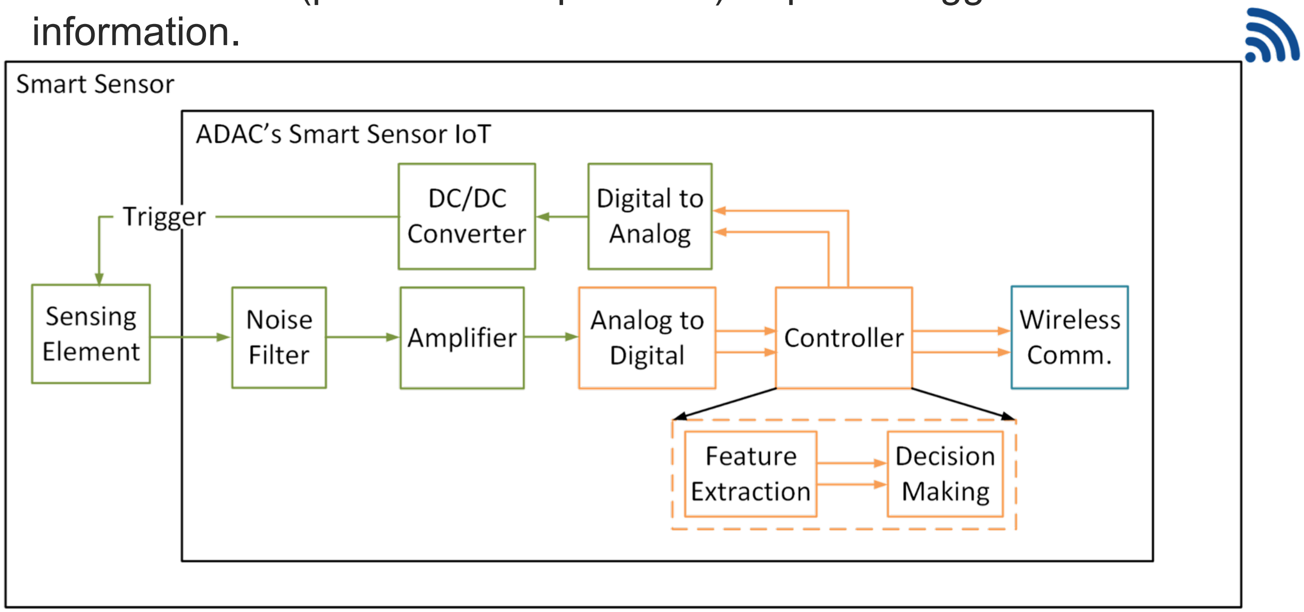
**University of Florida/Penn State and NC State (Leigh Winfrey and Mohamed Bourham):**

- Wireless system evaluation: pre-and post- irradiation evaluation (Y2)
- Integrated wireless sensing system evaluation: pre-and post- irradiation evaluation (Y2&Y3)

# Smart Sensor IoT Design

ADAC

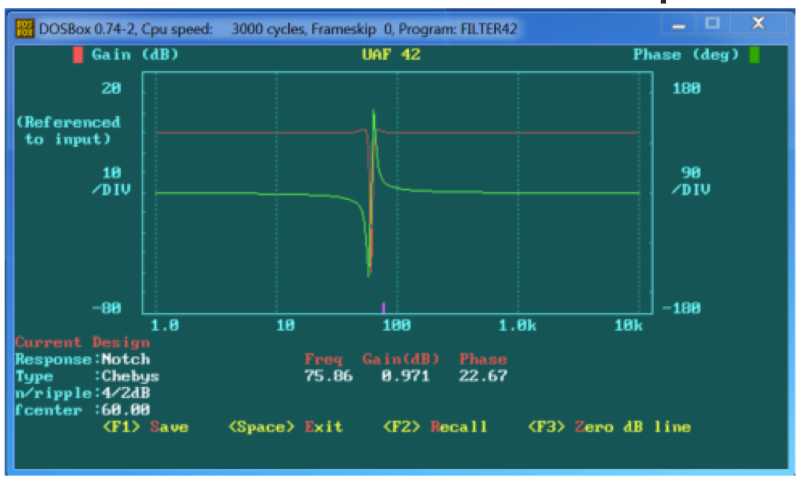
- General Block Diagram
  - Each Block will be explained in the subsequent slides
  - Some sensors (pressure or liquid level) require a trigger from the controller to read information.



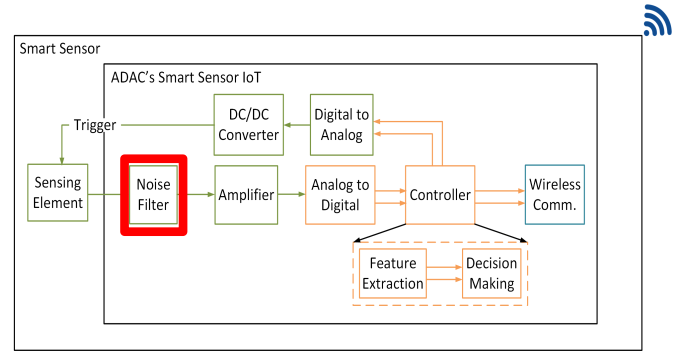
# Smart Sensor IoT Design

## ADAC – Noise Filtering

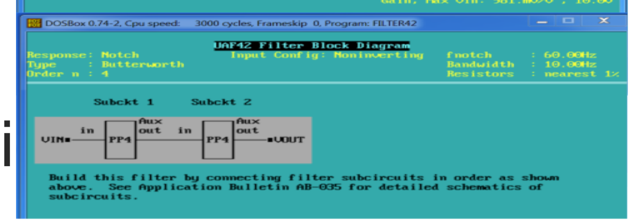
- Butterworth Filter Response




- Components required for Filter Desi



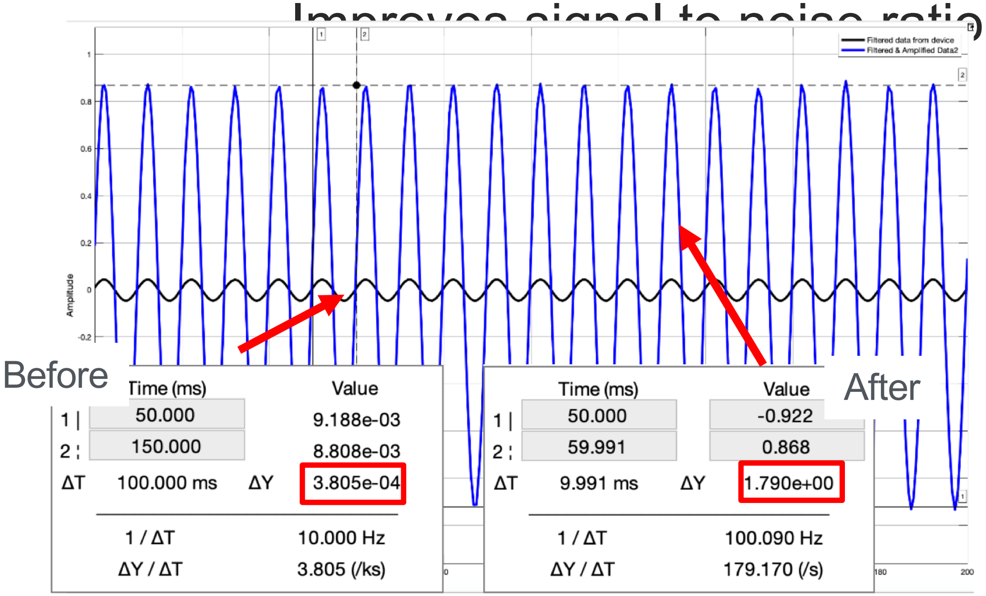


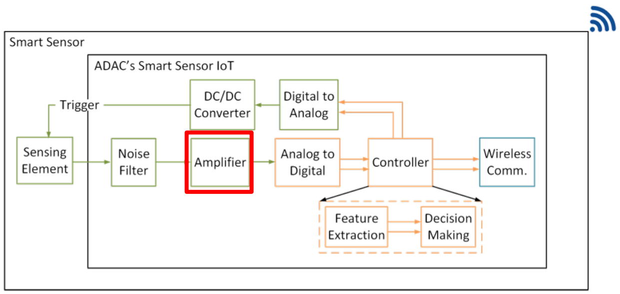


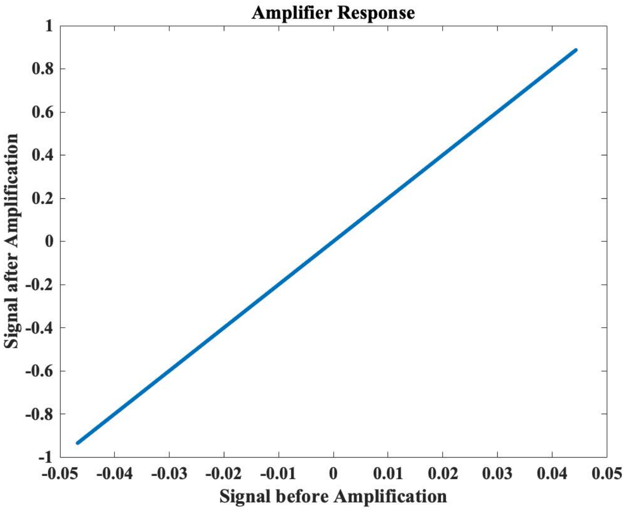
# Smart Sensor IoT Design

## ADAC - Amplifier

- Amplifier
  - Increases signal strength
  - Improves signal to noise ratio



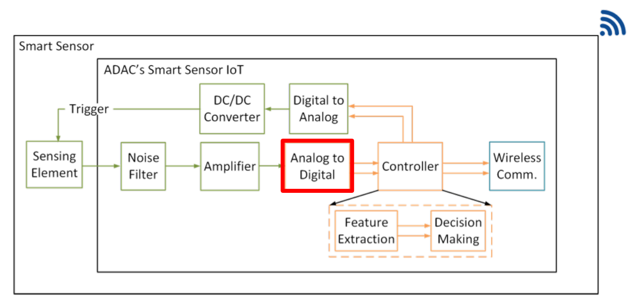



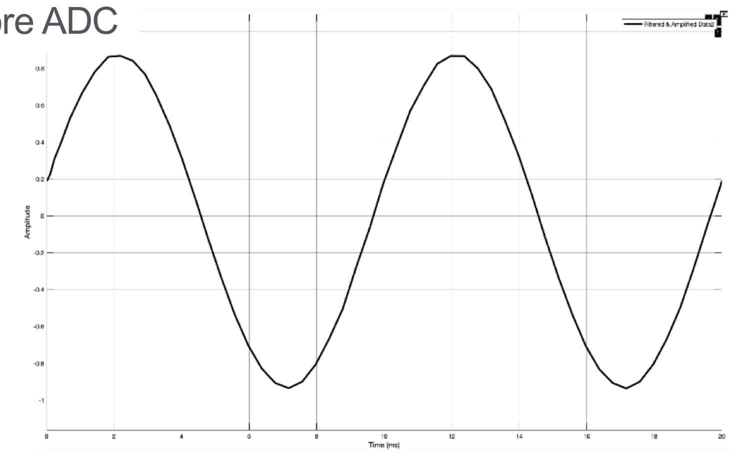
# Smart Sensor IoT Design

## ADAC – Analog to Digital Converter

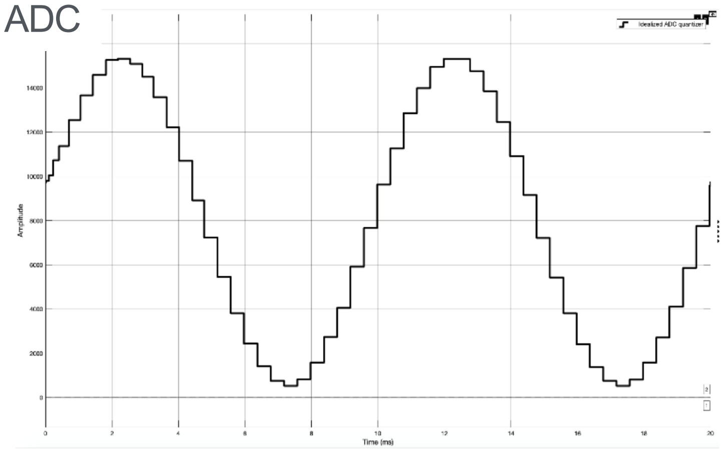
- Analog to Digital Converter
  - – The Most Significant Bit (MSB) is used to represent the sign of the signal and the rest of the bits are used for representation of absolute value




Before ADC



After ADC

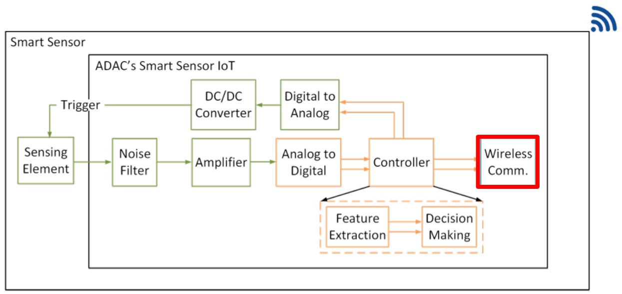


# Smart Sensor IoT Design

- Wireless Communication

ADAC – Wireless Communication

| IEEE Standard | Industry Name | Operational Frequency | Characteristics | Common Application |
|---|---|---|---|---|
| 802.11 | Wi-Fi | 2.4 GHz<br>5.7 GHz | High Data Rate<br>Local Area Network | Network/Internet Connectivity |
| 802.15.1 | Bluetooth | 2.4 GHz | Low Data Rate<br>Personal Area Network | Peripheral Wireless Devices |
| 802.15.3 | UWB WiMedia | ~5 GHz | High Data Rate<br>Personal Area Network | Video Transmission |
| 802.15.4 | Zigbee, ISA100.11a and Wireless Hart™ | 868/915 MHz<br>2.4 GHz | Low Data Rate<br>Personal Area Network | Sensor Networks |
| 802.16 | WiMAX | 2-11 GHz<br>10-60 GHz | High Data Rate<br>Wide Area Network | Broadband Wireless Access |



# Task III: Laser Ultrasound

**NC State (Xiaoning Jiang, Mo-Yuen Chow, and Mohamed Bourham):**

- Laser ultrasound transducer development: Xiaoning (Y1)
- Laser ultrasound integrated with wireless acoustic emission sensors: Xiaoning and Mo-Yuen (Y1 & Y2)
- Structural NDT using laser ultrasound: Mohamed, Xiaoning and Mo-Yuen

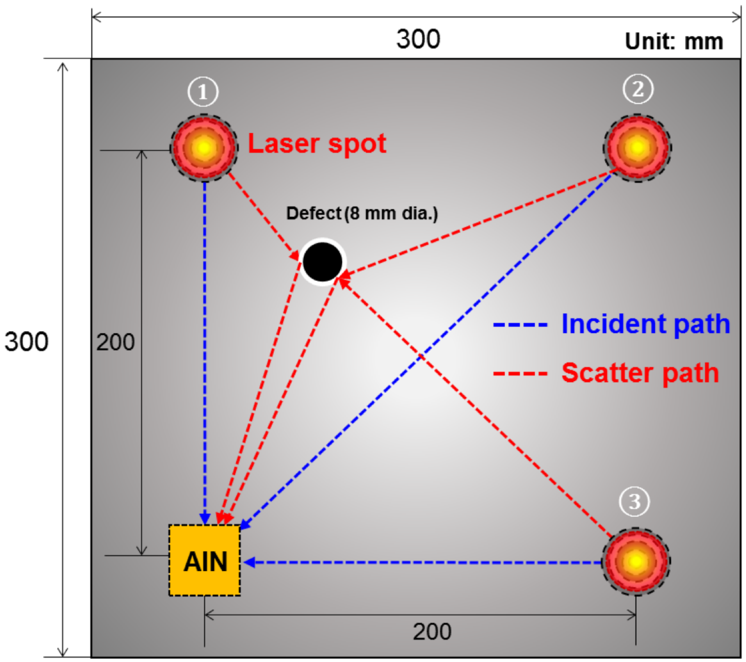
**University of Florida and NC State (Leigh Winfrey and Mohamed Bourham):**

- Laser ultrasound system evaluation: pre-and post- irradiation evaluation (Y3)

# NDT Sensor development (1/2)

- Accomplishments:
  - Structural wave excitation using high-power laser and concentric carbon patches
  - Damage localization using single sensor (AlN) element

✓ **Experimental Set-Up**




➢ **Purpose**

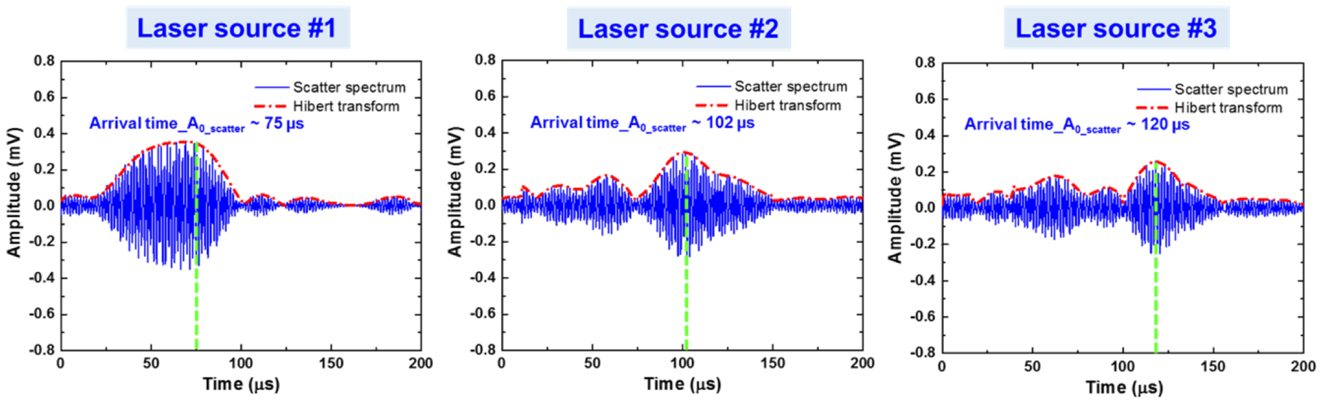
- Verify ability of defect detection
  : through scanning mode of laser system
  : 3 different signal sources (TX)
  : 1 receiver (RX)

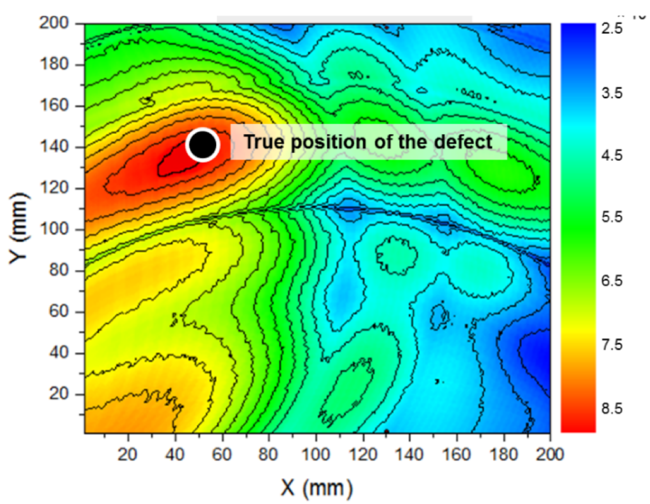
➢ **Experimental setup**

- Pulse laser energy : 30 mJ
- Target material : Aluminum (1.25 mm thick)
- Sensor : AlN ($10 \times 10 \times 0.5$ mm$^3$, TE mode)
- Concentric shape patch
- Defect : Magnetic column (8 mm dia.)

# NDT Sensor development (2/2)

✓ **Experimental Results**




**Successful damage localization (based on time-of-arrival algorithm)**

$$S(x,y) = \sum_{i=1}^{3} f_{i1}^{(s)}(t_{i1}(x,y))$$

**Future researches:**

a. More AlN patches on the structure for more accurate localization

b. Temperature compensation technique

# Milestones

***<u>Year 1:</u>***
*Major: HiTEIS design and sensor development –Technical report*
*Minor 1: High temperature and radiation resistant sensors*
*Minor 2: High temperature and radiation resistant wireless transmitter/receiver*

**<u>Year 2:</u>**
Major: HiTEIS Integration (Technical report)
Minor 1: Development of embedded sensors and laser ultrasound
Minor 2: Integration of sensors and wireless communication

**<u>Year 3:</u>**
Major: HiTEIS for structural monitoring (Technical report)
Minor 1: Mock structure with HiTEIS
Minor 2: Laser ultrasound NDT

# Publications

## ✓ Journal

1) T. Kim, J. Kim, and X. Jiang, "AlN Ultrasound Sensor for Photoacoustic Lamb Wave Detection in a High Temperature Environment," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 2018* (Accepted).

2) W. Y. Chang, S. Huang, H. Kim, and X. Jiang, "Narrow Band Photoacoustic Lamb Wave Generation for Nondestructive Testing Using Candle Soot Nanoparticle Patches," (In preparation).

3) H. Kim, T. Kim, D. Morrow, and X. Jiang, "Stress-sensing Technique using 1-3 Composite PZT Ceramics," (in preparation).

## ✓ Conference

1) T. Kim, J. Kim and X. Jiang, "High temperature ultrasound NDT using photoacoustic Lamb waves and AlN sensors," SPIE Smart Structures and NDE conference, Denver, CO, March, 2018 (Presented).

2) H. Kim, T. Kim, D. Morrow, X. Jiang, "Stress Sensing Technique via Subsurface Longitudinal Wave with Composite Transducer," NPIC & HMIT, Orlando, FL, February, 2019 (Full paper submitted).

3) H. Kim, W. Y. Chang, T. Kim, D. Morrow, and X. Jiang, "Stress Measurement of a Pressurized Vessel Using Candle Soot Nanocomposite Based Photoacoustic Excitation," SPIE Smart Structures and NDE conference, Denver, CO, March, 2019 (abstract submitted).

## ✓ Dissertation

1) T. Kim, Ph. D dissertation, Chapter 4: Novel Ultrasound NDT Method Using Photoacoustic Lamb waves and AlN sensor for high temperature applications, NC State Univ., 2018.

# Technology Impact

-A high temperature and radiation hard laser ultrasound system will provide an in-service evaluation tool for nuclear energy systems, that can improve data transmission, processing, and actuation time

-Sensors and instrumentation capable of measuring properties in opaque coolants and very high temperature coolants representative of Molten Salt and Fast Reactor technologies

-Ability to measure important parameters in radiation and harsh environments with the wireless communication

# Conclusion

- A broad range of high temperature sensors, data acquisition and wireless data transmission were demonstrated.
- HiTEIS will enable new reactor research and structural monitoring of in-service reactors and fuel processing systems.

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