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

Clean. Reliable. Nuclear.

Self-powered Wireless Through-wall Data Communication for Nuclear Environments

Advanced Sensors and Instrumentation Annual Webinar

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Project Overview

- ## Goal and Objective

  Develop and demonstrate an enabling technology for the data communications for enclosed nuclear vessels like canisters using radiation and thermal energy harvesters, through-wall ultrasound communication, and harsh environment electronics.

- ## Participants (2018)

  VT: Yongjia Wu, Kan Sun, Lei Zuo,

  UNT: Suresh Kaluvan, Haifeng Zhang,

  ORNL: Nance Ericson, Kyle Reed, Roger Kisner

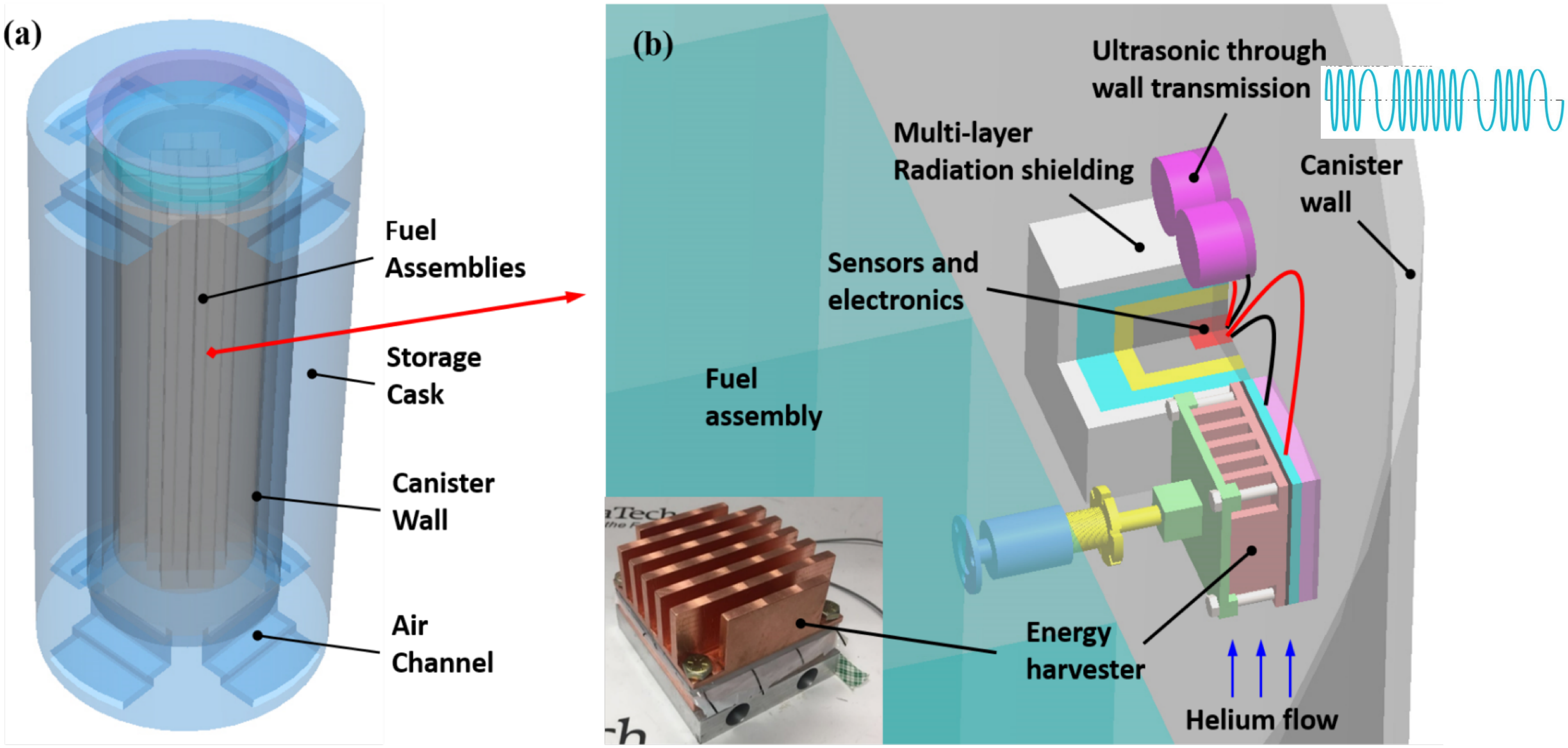
- ## Schedule

Milestone / Activity	Start Date	Finish Date
Reviewing environments and developing the functional requirements	10/1/2016	3/31/2017
Designing energy harvester and ultasonic data transmission	10/1/2016	9/30/2017
Modeling energy harvester and the ultrasonic through-wall wireless data transmission	4/1/2017	9/30/2017
Fabricating and esting the radiation energy harvesting	10/1/2017	3/31/2018
Fabricating ultrasonic through-wall data transmission, and design of electronics	10/1/2017	9/30/2018
Tesing the ultrasonic data transmission and testing electronics	4/1/2018	9/30/2018
Radiation study & shielding protection	10/1/2018	3/31/2019
System demonstration and test	4/1/2019	9/30/2019

Accomplishments

- Milestones
  - Test the radiation energy harvesters (3/31/2018)
  - Fabricating and lab testing of energy harvesters, ultrasonic through-wall data transmission, and electronics (9/30/2018)
  - Testing the ultrasonic data transmission and electronics (9/30/2018)
- Deliverable and outcomes
  - Two energy harvesters were designed and tested. The energy harvester can provide more than enough energy for the sensor powering.
  - Fabricating and lab testing of energy harvesters, ultrasonic through-wall data transmission, and electronics (9/30/2018)
  - Testing the ultrasonic data transmission and electronics (9/30/2018)

Self-powered Wireless Through-wall Data Communication for Nuclear Environments



Self-powered Wireless Through-wall Data Communication for Nuclear Environments

Goal:

Develop and demonstrate an enabling technology for the data communications for nuclear reactors and canister using **energy harvesters**, **through-wall ultrasound communication**, and **harsh environment electronics.**

Solutions:

- **Radiation and thermal energy harvesters**
- **Through-wall ultrasound communication**
- **Harsh environment electronics**
- **Radiation shielding**

Energy Harvesting for Nuclear Canisters

Energy sources available:

1. Mechanical vibration
2. Light
3. Wind, ***flow (Helium)***
4. Electromagnetic
5. ***Thermal (temperature difference)***
6. ***Radiation*** (alpha, beta, ***neutron***, and ***gamma*** rays)

Energy demand:

	Ultrasound	EMAT	Inductive
Mechanism	Ultrasound	Ultrasound	Magnetic
Media	Any	Any	Large skin depth
Power (Est.)	~1 watt	~2 watt	~1 watt
Bit rate (Max)	5M bps	1M bps	1000 bps

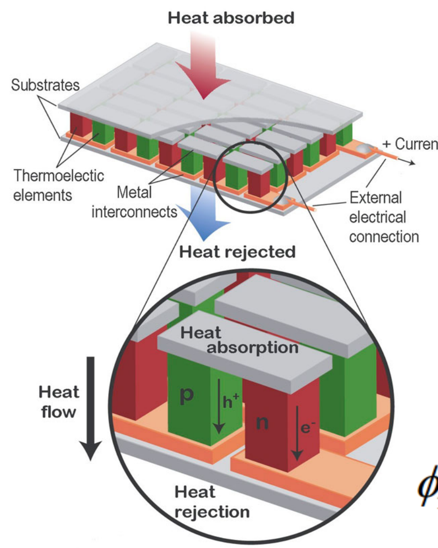
To power 1W sensing and data transmission for 3 seconds every 5 minutes, ***10mW required***.

Energy harvesting strategy:

Existing temp. gradient | **Gamma heating**

Thermoelectric energy harvesting

Thermoelectric energy harvesting:

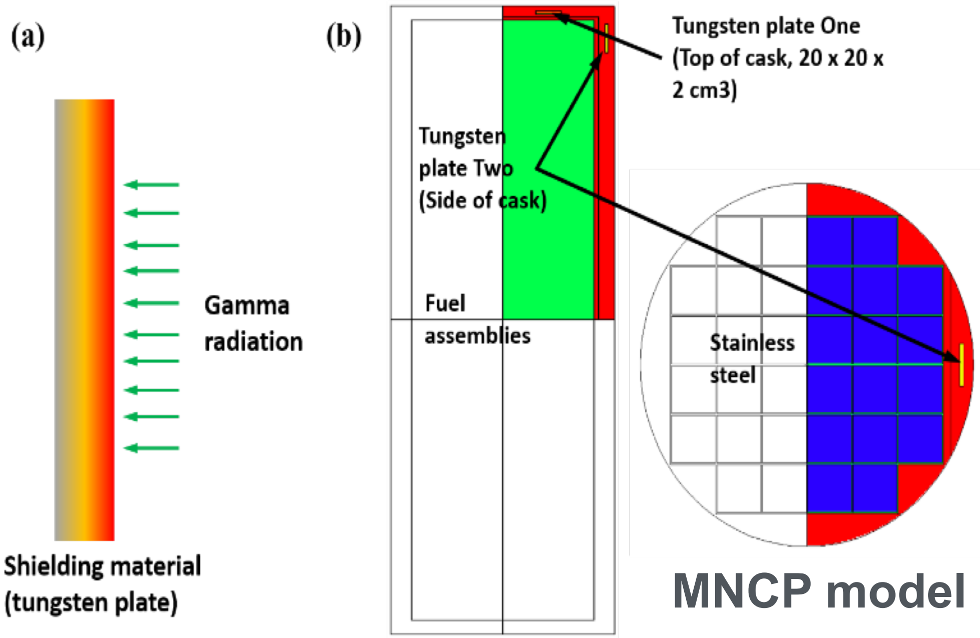


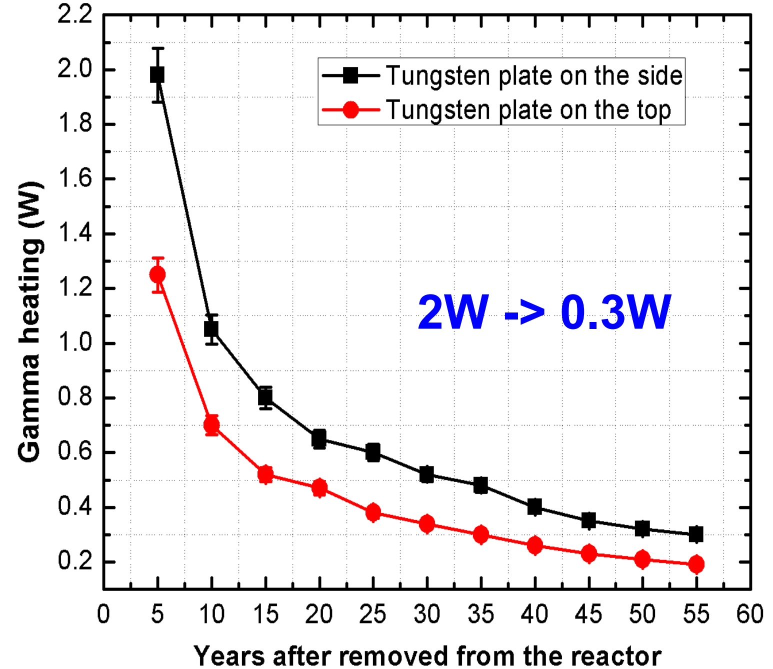
$$Z = \frac{\sigma S^2}{\kappa_e + \kappa_l},$$

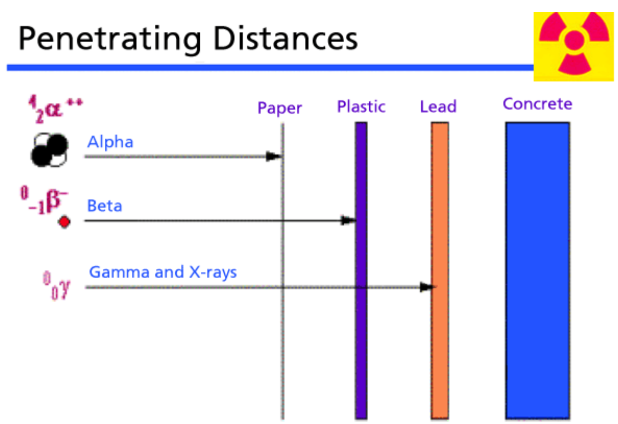
σ Electrical conductivity
α, Seebeck coefficient
κe Electron thermal conductivity
κl Phonon thermal conductivity

$$\phi_{\max} = \frac{T_1 - T_2}{T_1} \bullet \frac{(1+Z\bar{T})^{1/2} - 1}{(1+Z\bar{T})^{1/2} + T_2 / T_1}$$

Gamma Heating Effect

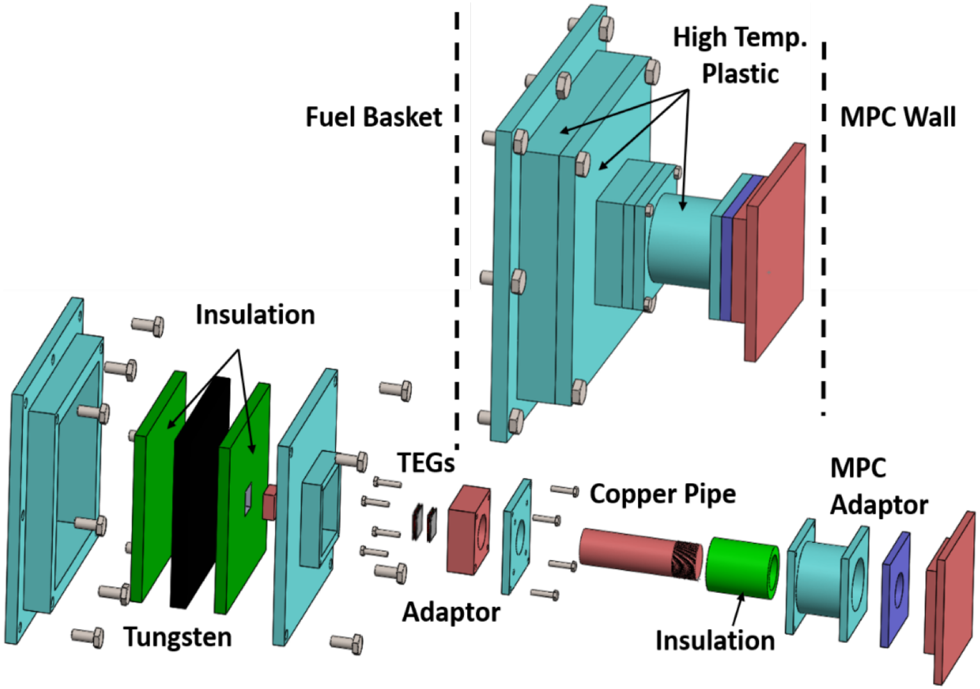




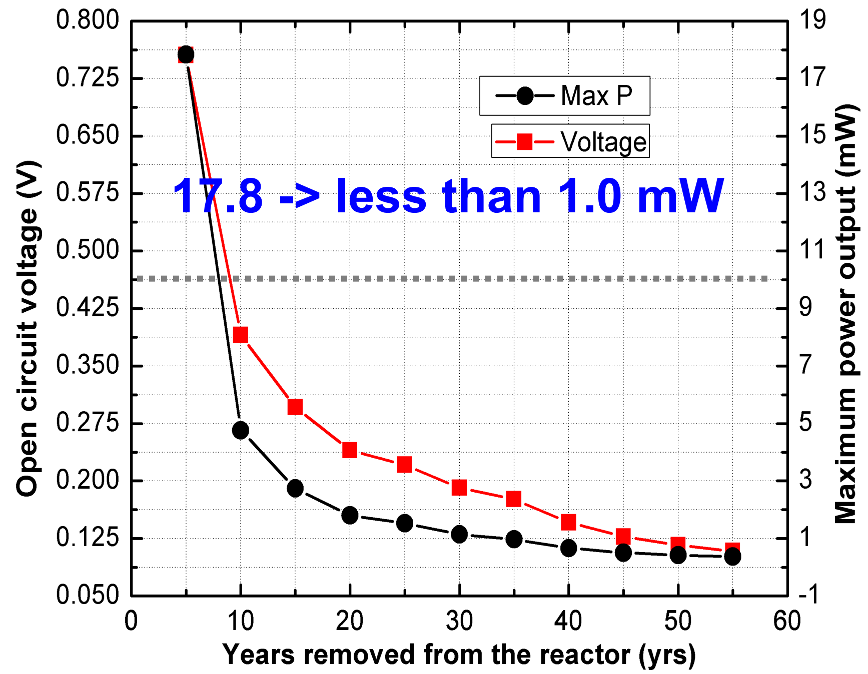


- The deposited heat from neutron heating: **~1.0 micro watt** for the year 5 case, neglected.

Design One: Energy harvester using the gamma heating effect



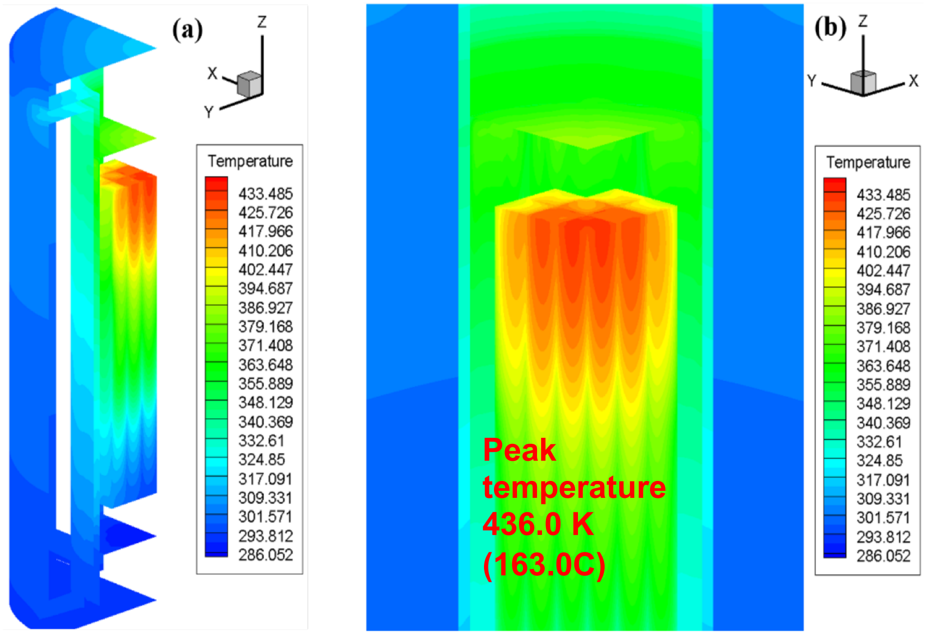
Gamma-radiation energy harvester.



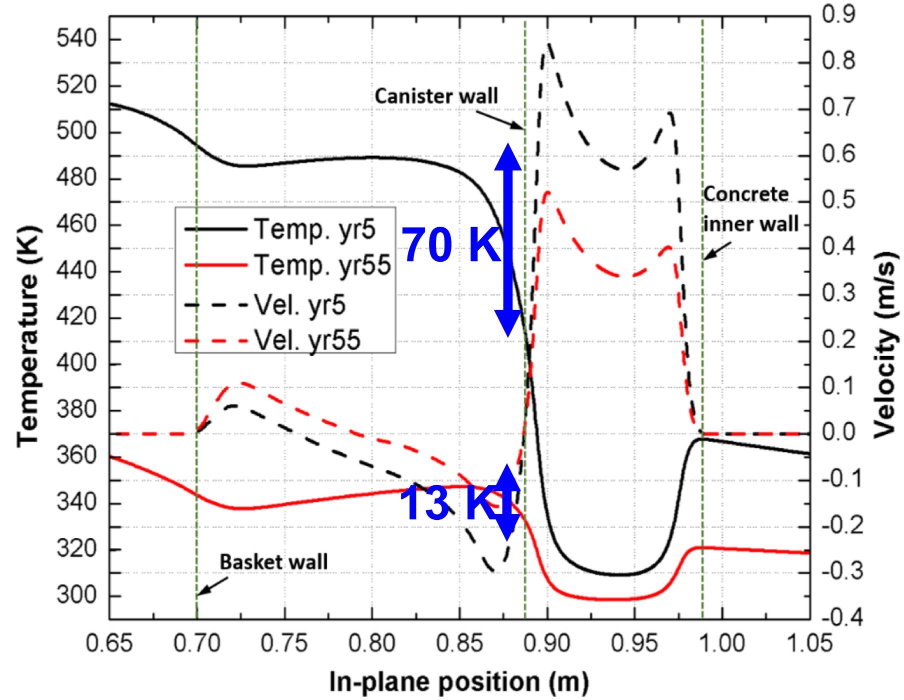
The voltage and power output of the gamma heating energy harvester during 50-years operation

- Goal: **P>=10 mW**
- Harvesting gamma radiation did not offer a complete solution.

Temperature gradient near the canister wall



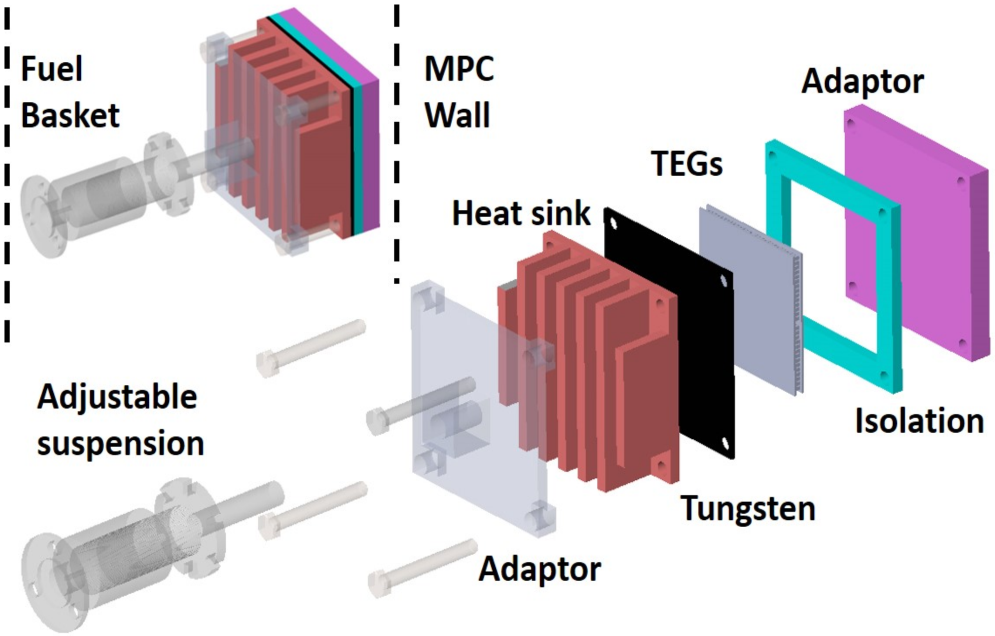
Temperature distribution within the MPC-32 canister



Temperature distribution near the canister wall

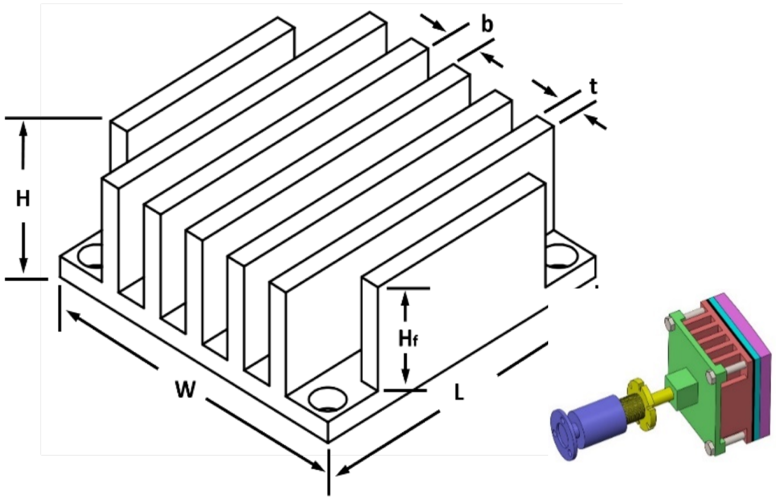
- The temperature difference is **>13 K**.
- TEG can be used for thermal energy harvesting.

Design Two: Energy harvester taking advantage of temperature gradient near the canister wall

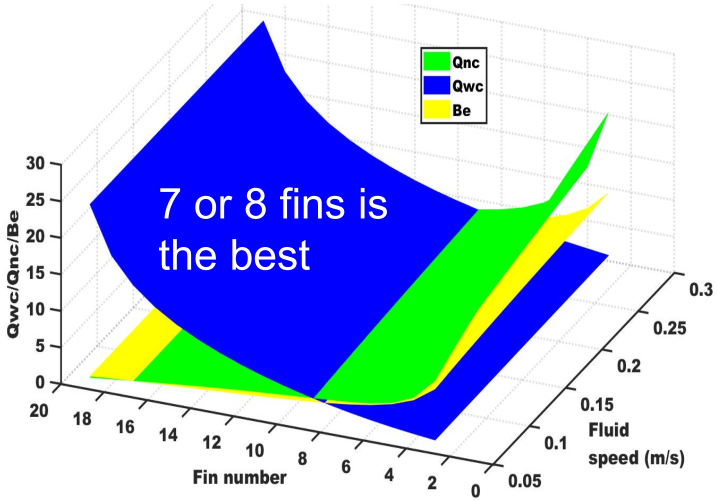


Existing temperature gradient energy harvester.

- The fin number is optimized.
- 4 TEG1-PB-12611-6.0 from TECTEG MFR are used.

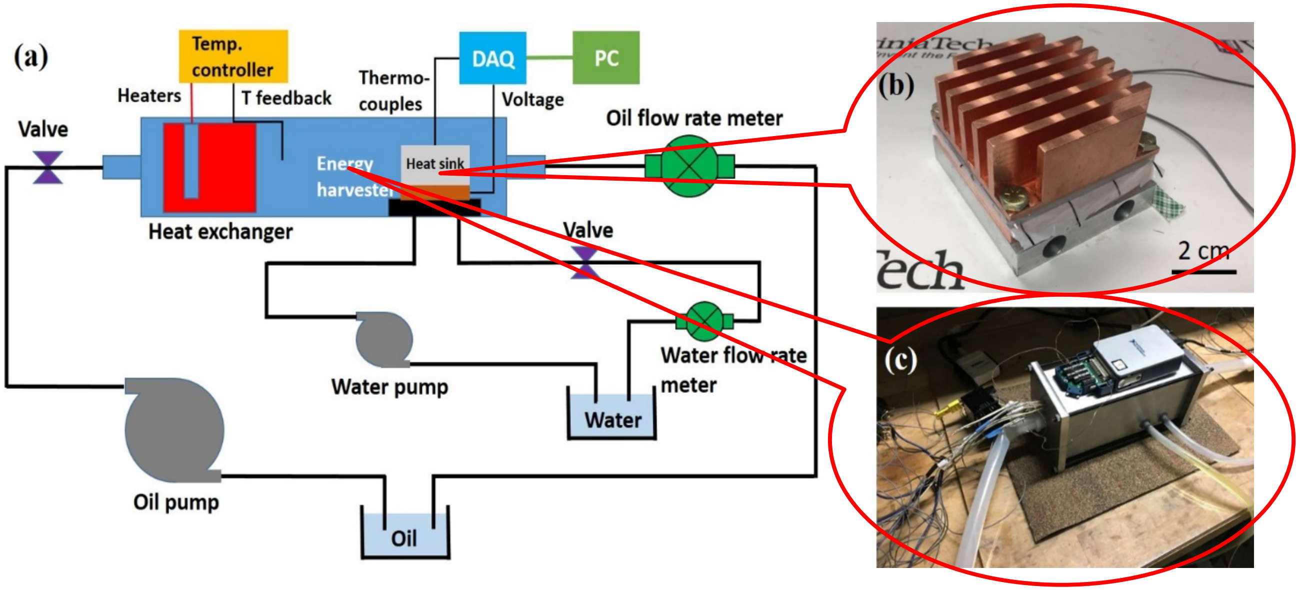


The geometry configuration of a heat sink

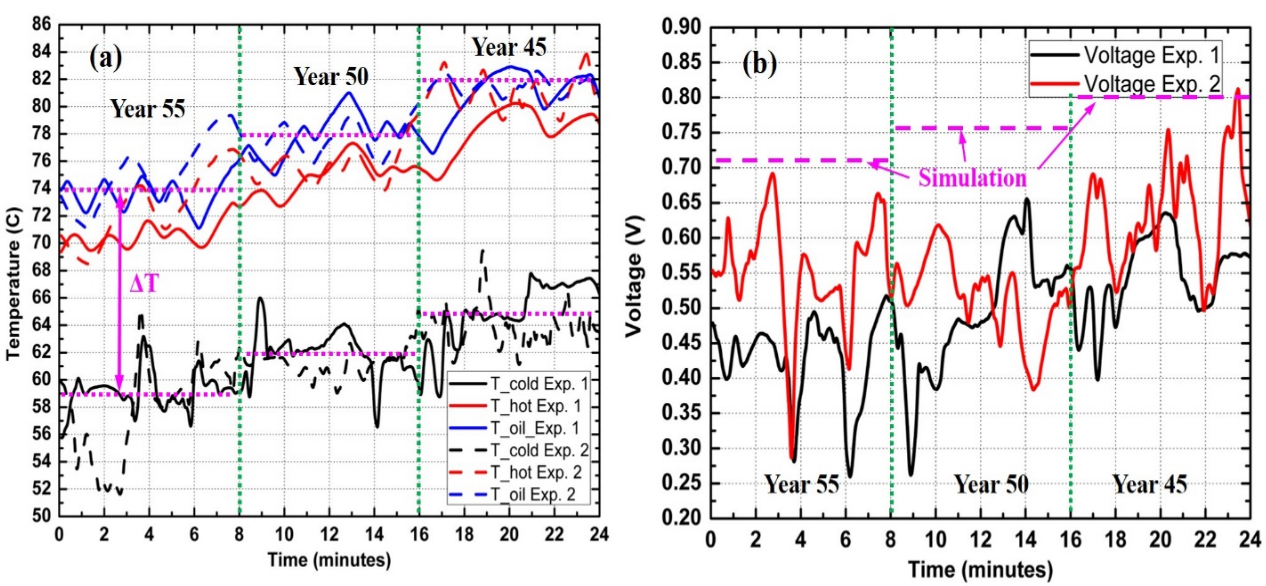


Optimization of fin number

Design Two: Energy harvester taking advantage of temperature gradient near the canister wall



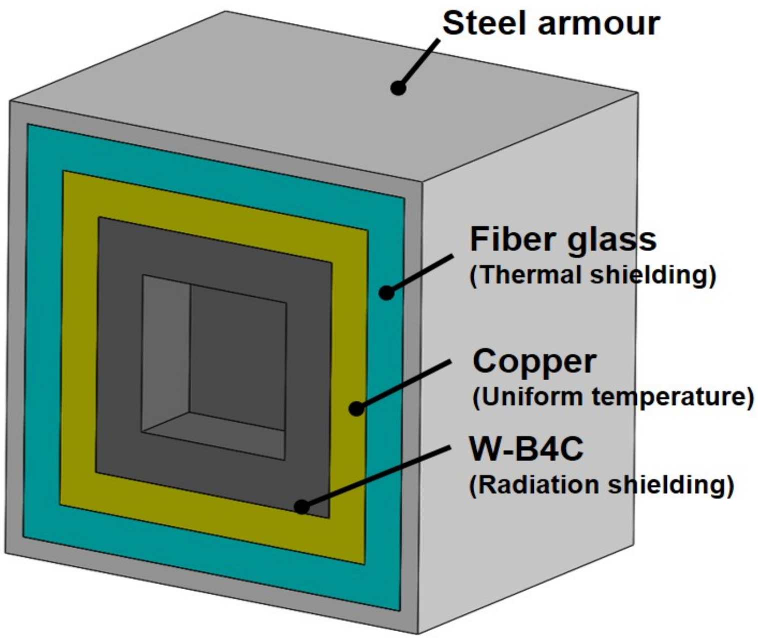
(a) The overall experimental setup in the lab, (b) The energy harvester, and (c) the oil channel to simulate the helium environment.

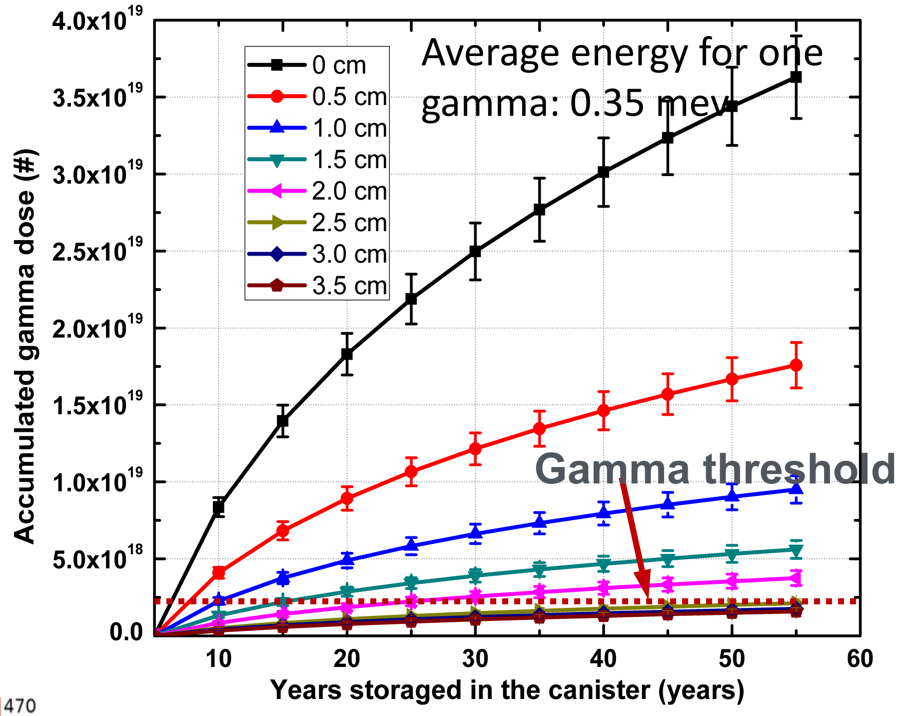


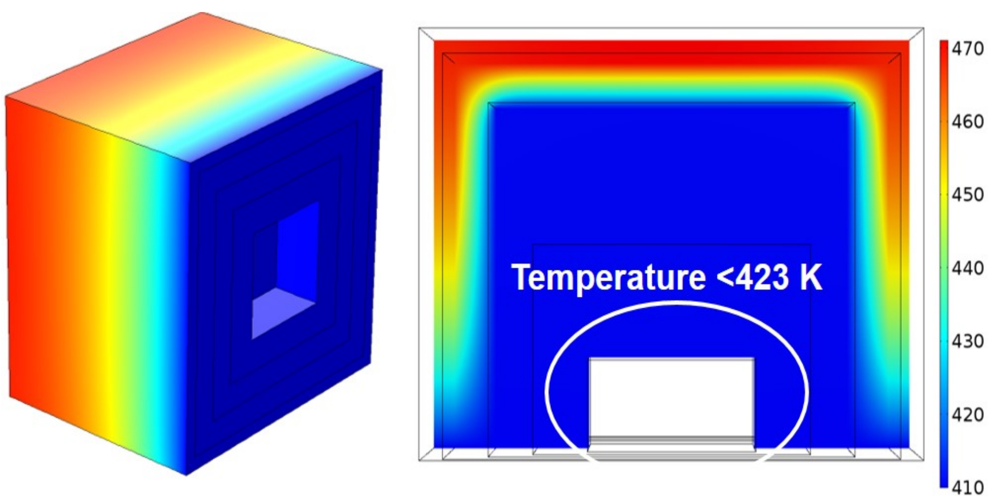
Experimental result

energy >=46.3 mW

Radiation shielding





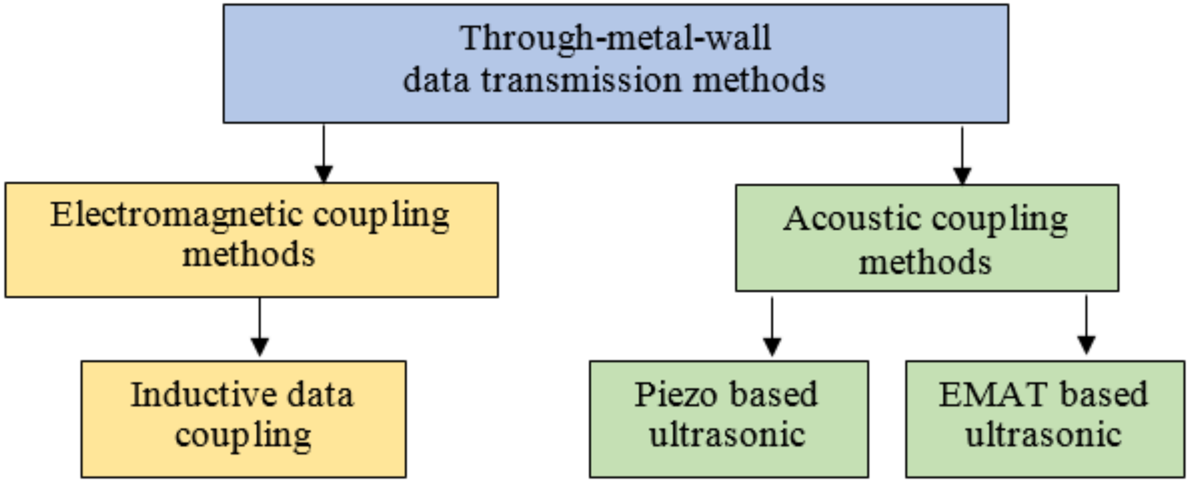


- The minimum thickness requirement for shielding material (W-B4C) was 2.5 cm.
- The temperature is less than 423 K within the chamber to install electronics.

Summary#1: Energy Harvesting

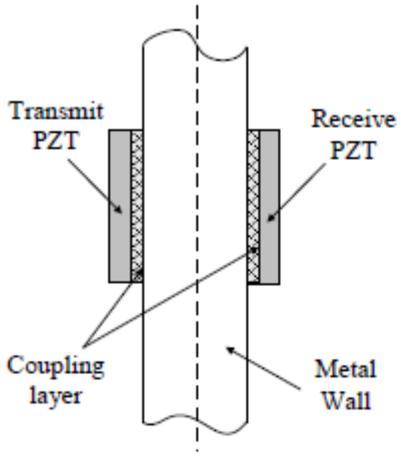
- **Goal:** Harvest **10 mW** energy from the local environment for electrics powering.
- **Deposited gamma heat: 2W -> 0.3W,** making this an increasingly difficult energy to harvest.
- **A conceptual gamma radiation energy harvester**: Voltage **0.756-> 0.12 V**, Power output **17.8 -> 1.0 mW.**
- **A second energy harvester** was conceptualized and tested which utilizes the **existing temperature gradient** in the canister:
    - Simulation: Voltage**>=2.848 V**, energy **>=93.9 mW**.
    - Experiment: Voltage**>=2.0 V**, energy **>=46.3 mW**.
- Radiation and thermal shielding design were developed.

Through wall data communication techniques

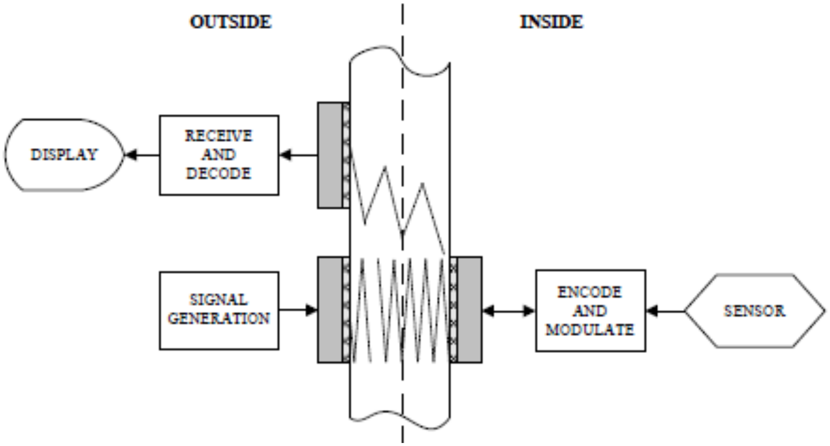


	Ultrasound	EMAT	Inductive
Mechanism	Ultrasound	Ultrasound	Magnetic
Media	Any	Any	Large skin depth
Power (Est.)	~1 watt	~2 watt	~1 watt
Bit rate (Max)	5M bps	1M bps	1000 bps

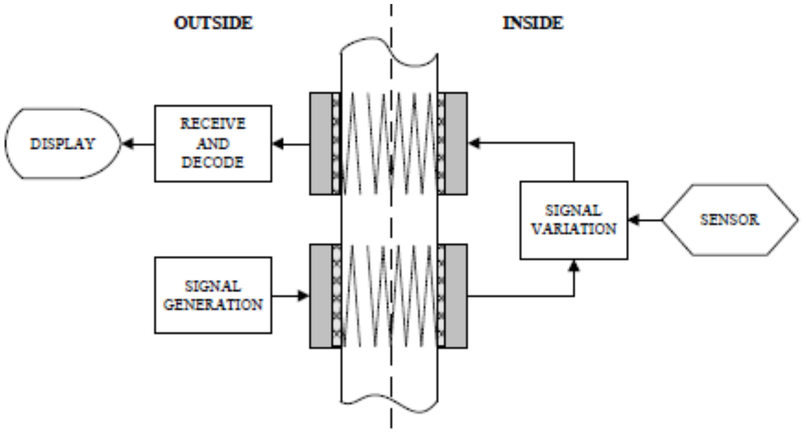
PZT configurations for through wall data communication



Pair transducer configuration through wall data communication

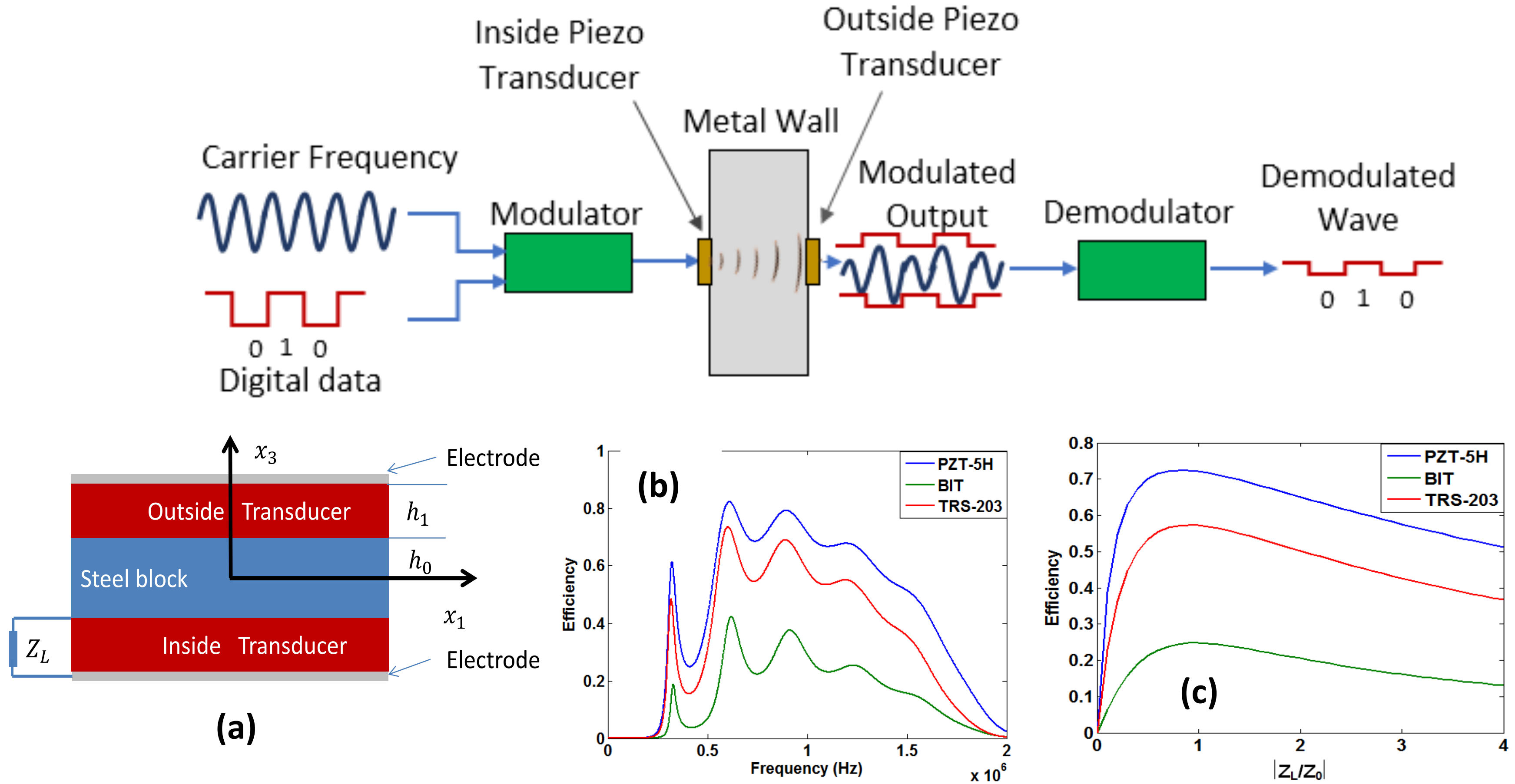


Three transducer configuration through wall data communication



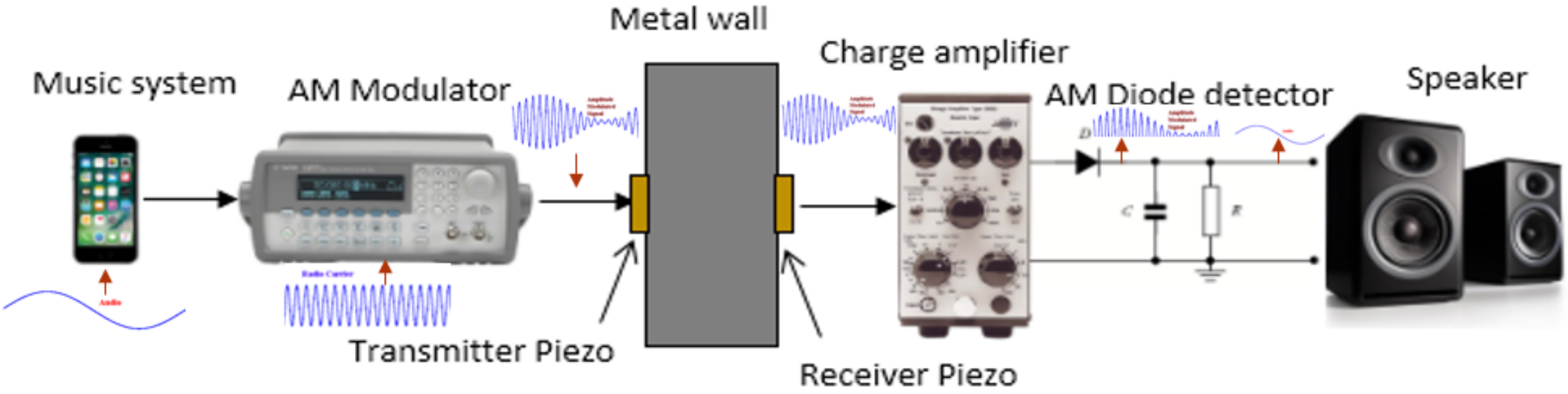
Two pair transducer configuration through wall data communication

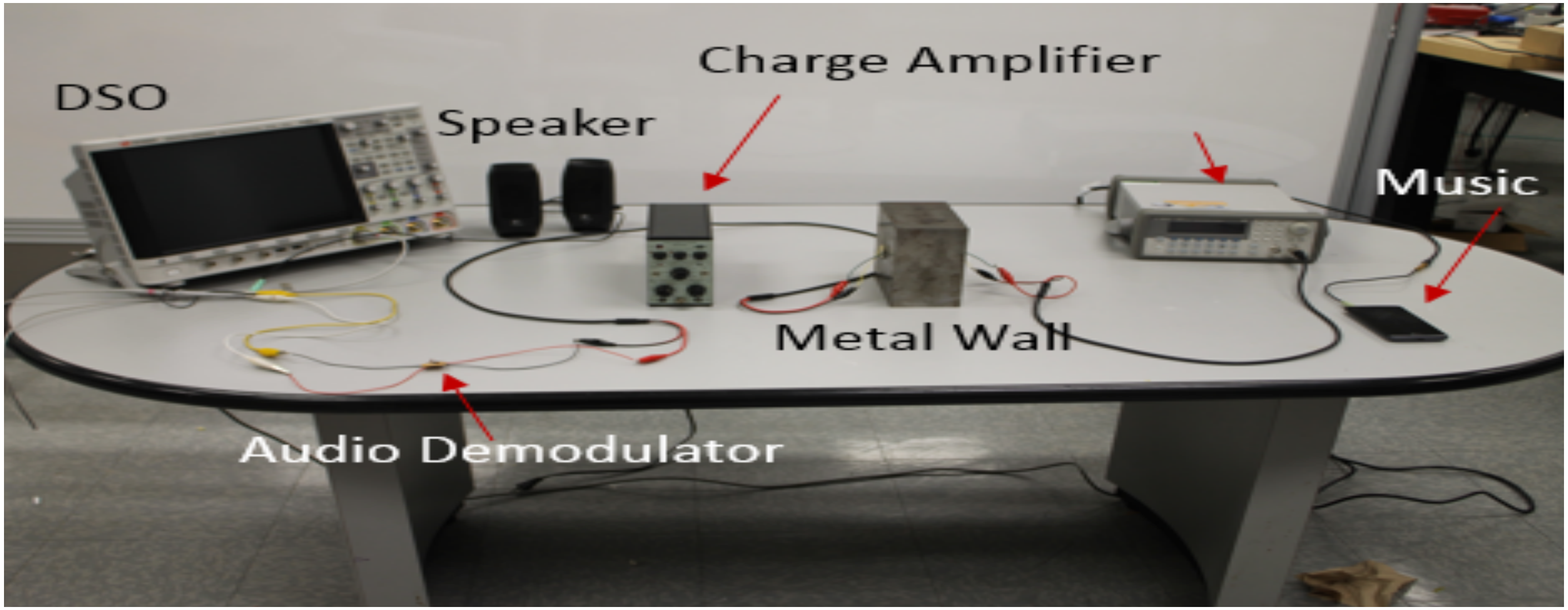
Principle of ultrasonic through wall communication



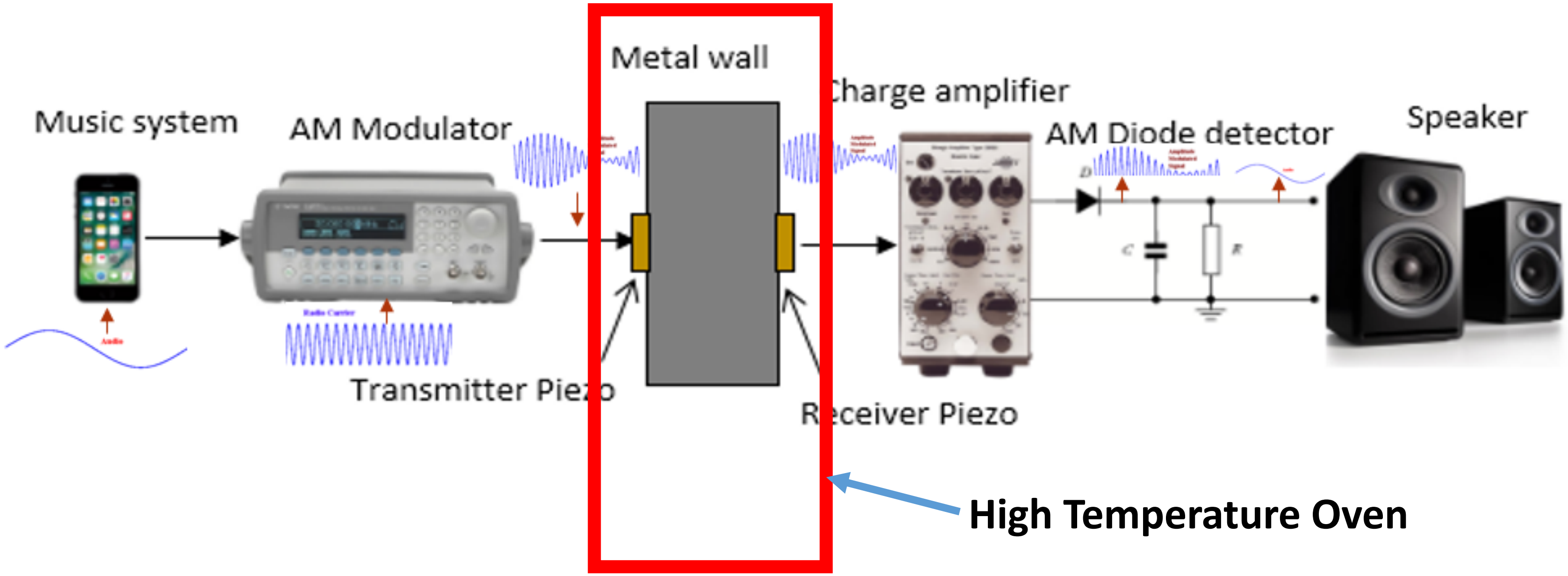
The acoustic modelling results; (a) the steel block sandwiched by two piezoelectric transducers. (b)The ultrasound transmission system efficiency versus driving frequency; (c) The system efficiency versus normalized load circuit impedance.

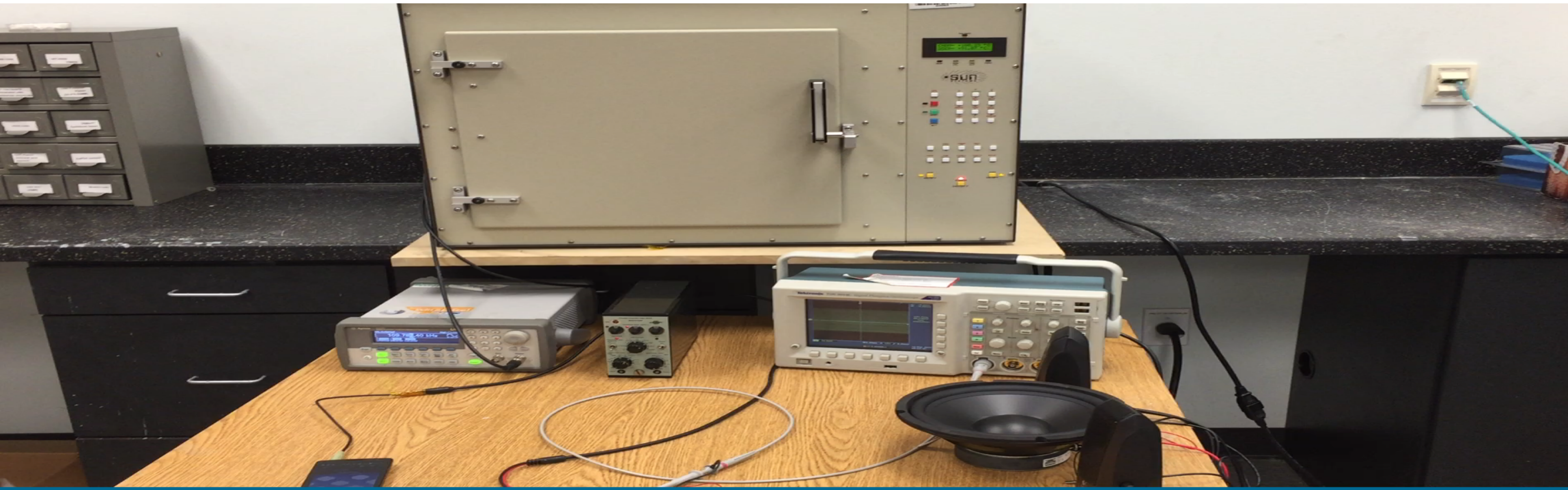
Demonstration of audio signal through-wall transmission



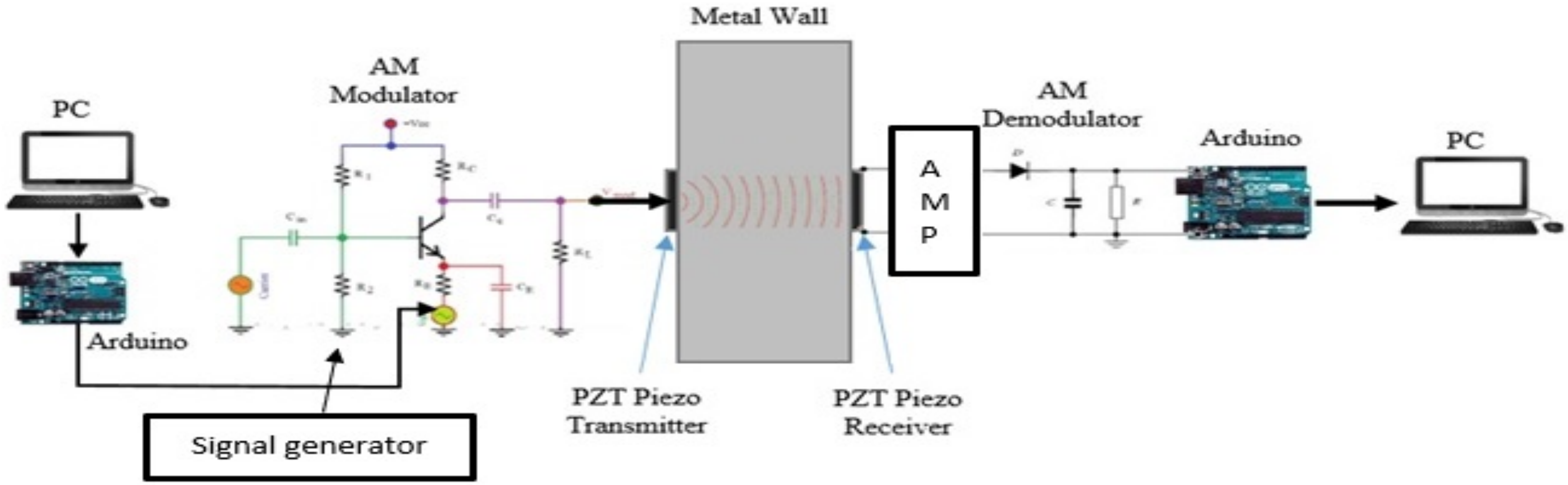


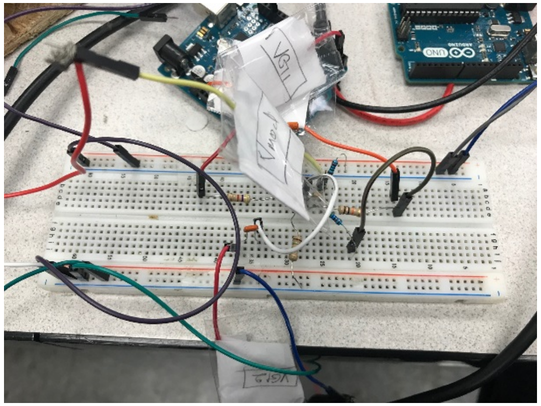
Demonstration of high temperature audio signal through-wall transmission



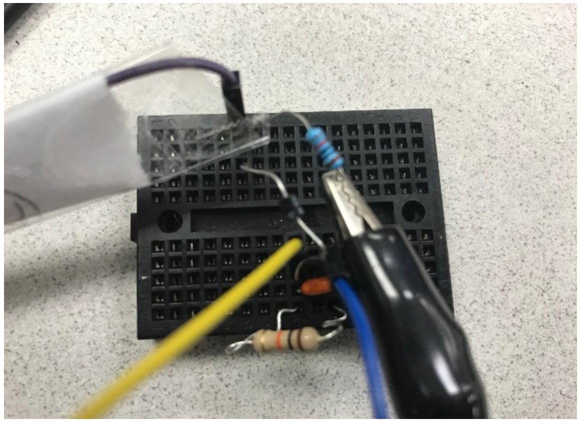


Ultrasonic TEXT Transmission System



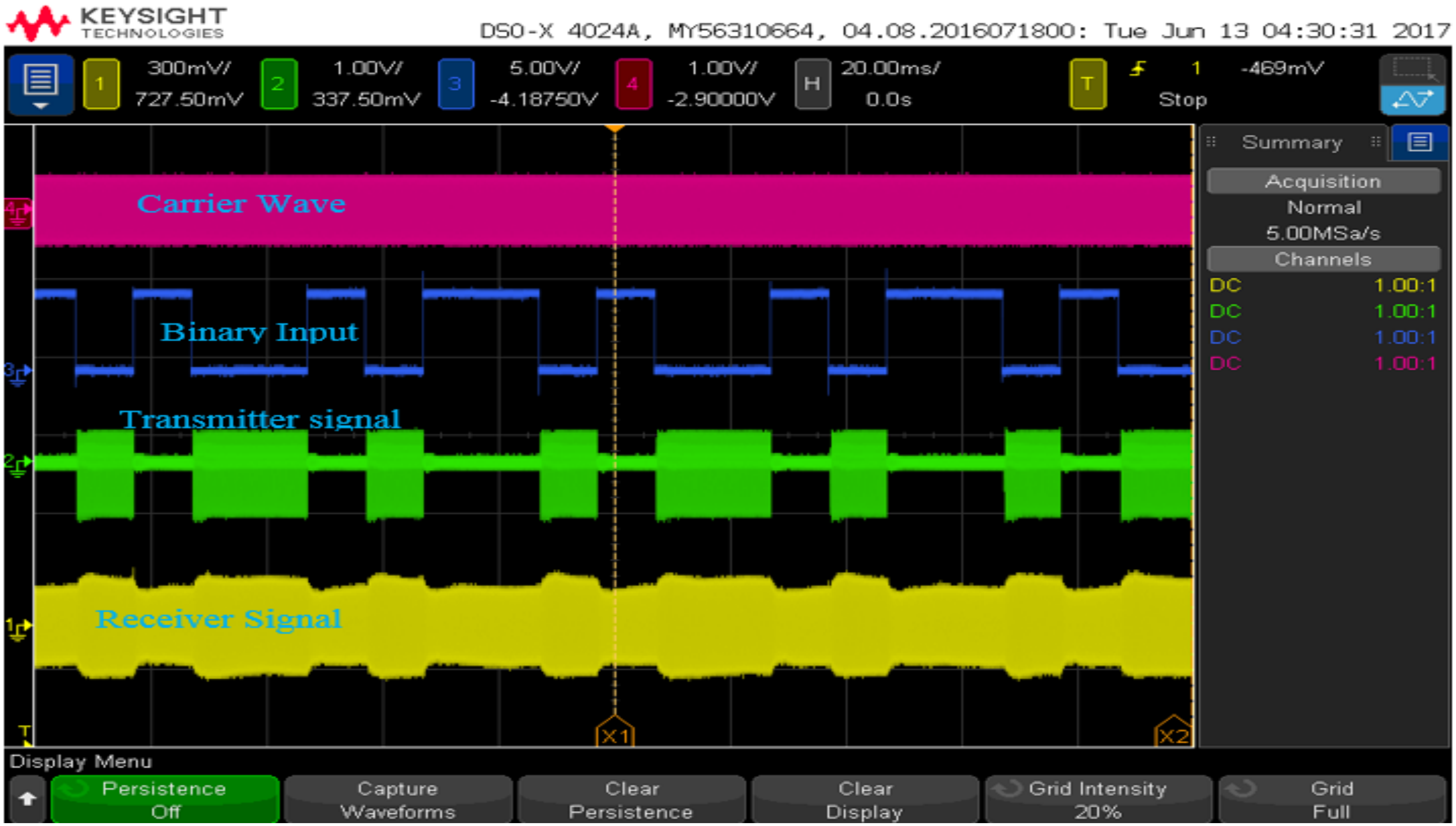


AM modulator circuit

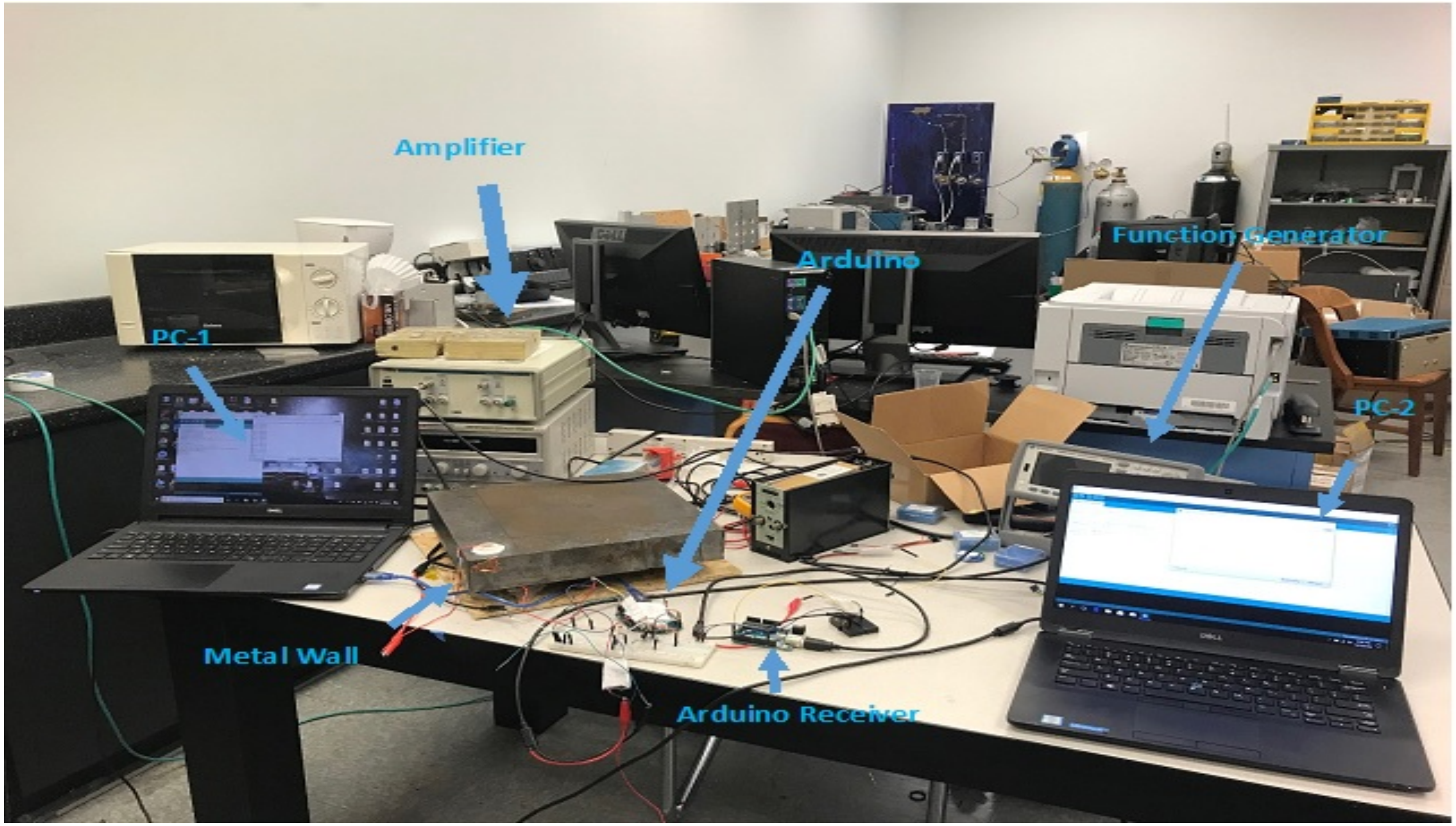


AM demodulator circuit

Experimental modulated and demodulated signal

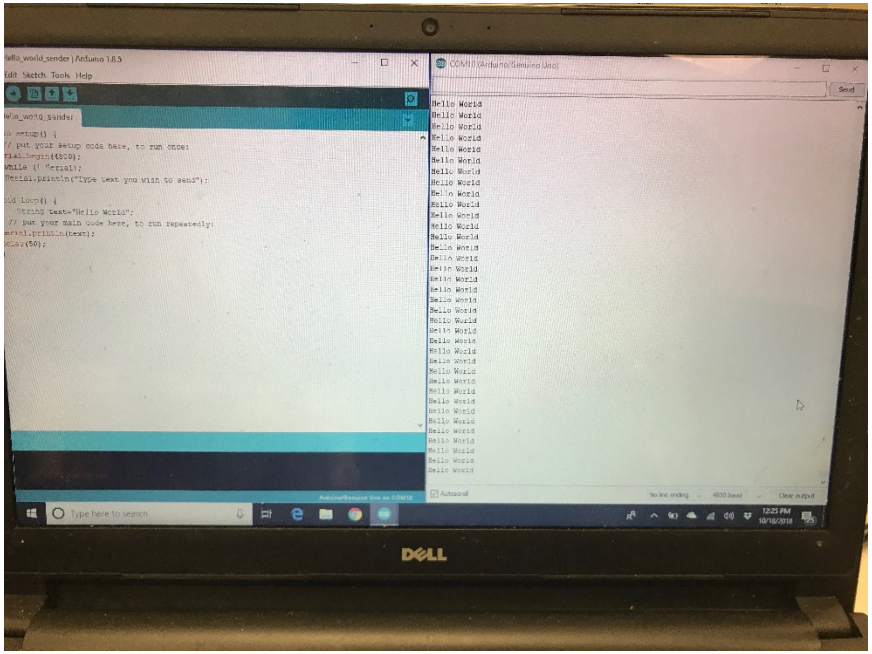


Experiment of TEXT transmission system

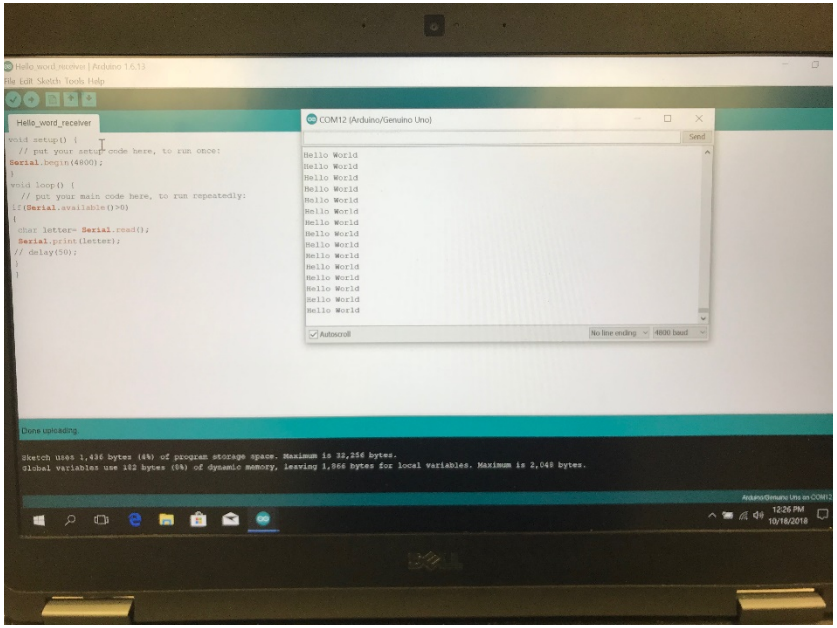


Result of Text transmission

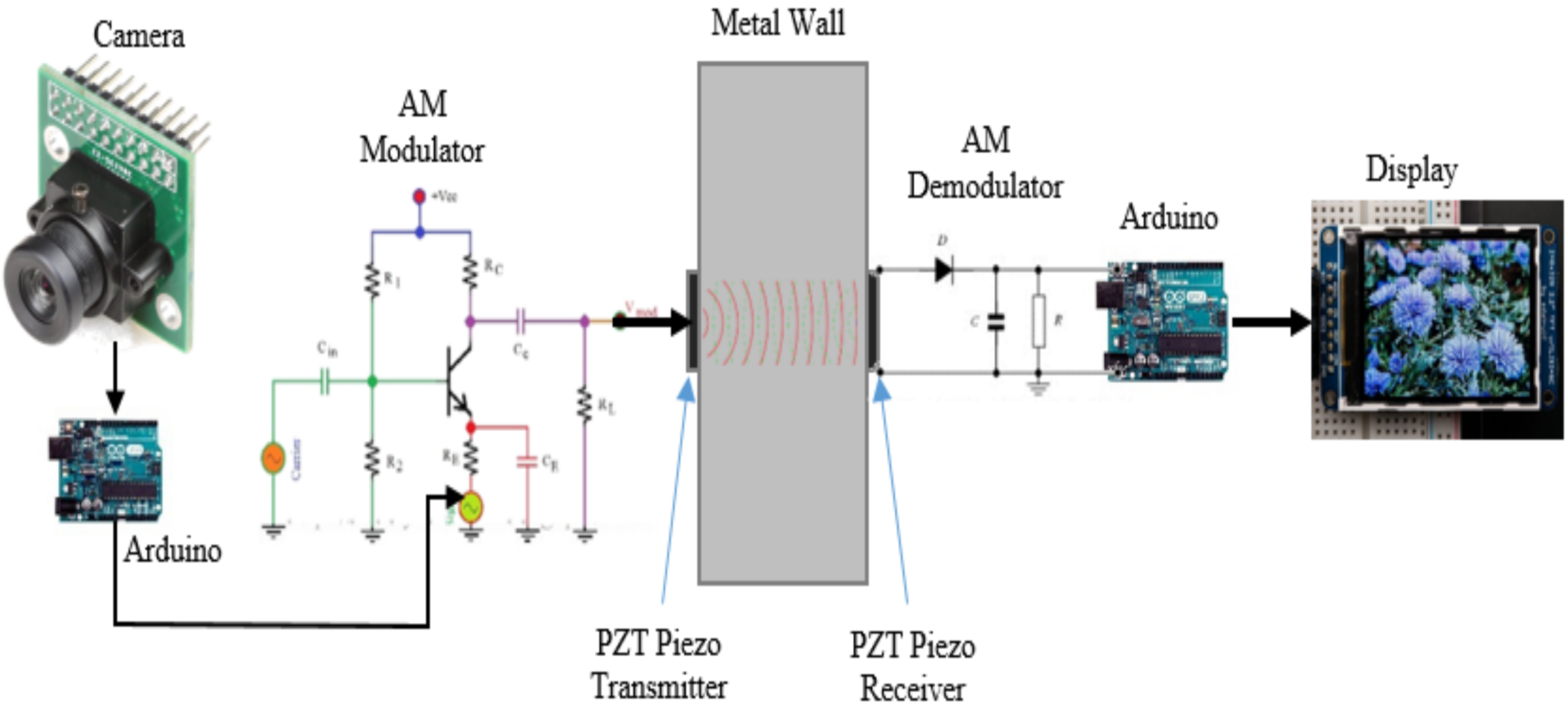
Transmitter



Receiver



Future work
Image/video transmission system



Summary #2: Ultrasound wireless communication

- **2 inch thick steel sample fabricated and PZT5H/TRS high temperature transducer was chosen for this application**

- **The audio signal is successfully transferred using PZT piezo ceramic based transducer at room temperature in a thick metal wall**

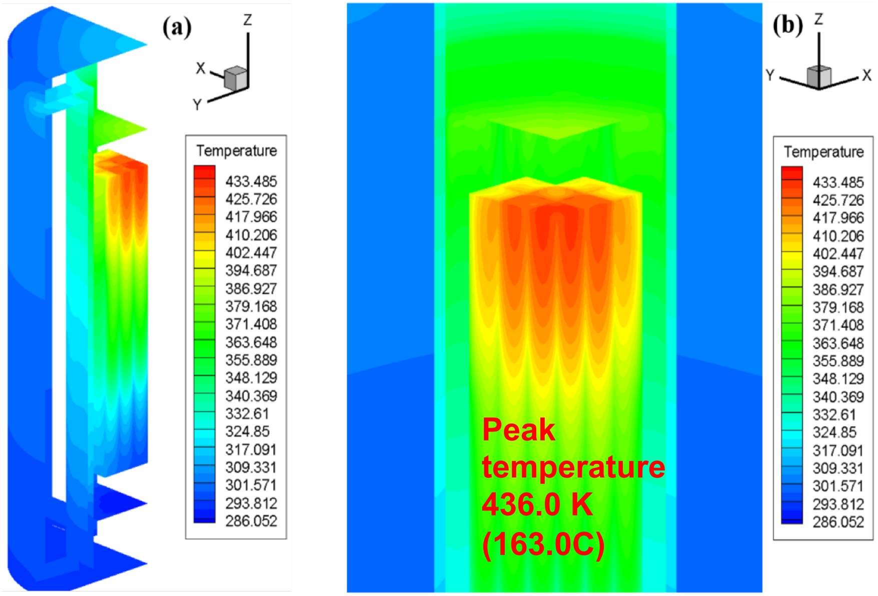
- **High-Temperature audio signal communication was also verified with the amplitude modulation technique**

- **The TEXT signal is effectively transmitted using PZT piezo ceramic based transducer at room temperature in a thick metal wall**

Temperature and Radiation Hardened Electronics for In-Cask Sensor Interfacing and Communications

Electronics Overview

- In-cask electronics system for monitoring temperature and pressure
- Sensor data is transmitted to cask exterior periodically (low reporting rate of once every ~10 minutes
- Must survive internal γ radiation dose rate of ~33 krad/h for 50-year storage cycle (~14.5 Grad TID)
- Will require the use of radiation shielding materials
- Must operate at a peak environment temperature of 200°C
- Demonstration of system via SPICE simulation (FY18) and in lab environment COTS prototype (FY19)



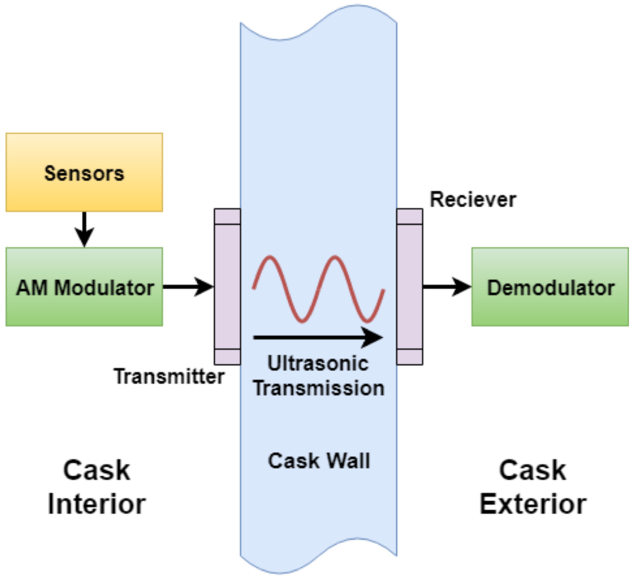
Rad-hard (1Mrad) & Rad-tolerant (300krad) Circuits - Current State-of-the-Art (*partial listing*)

Circuit Function	Classification	Suppliers	Specifics
Operational Amplifiers	Rad-tolerant / Rad-hard*	STMicroelectronics Linear Technology Texas Instruments Cobham (>1Mrad*)	Single, dual, & quad designs Supply voltages 1.5V-5V Some rail-to-rail input and output
Linear Voltage Regulators	Rad-tolerant / Rad-hard*	API Technologies Linear Technology Intersil Aeroflex STMicroelectronics Microsemi Cobham (>1Mrad*)	Positive linear regulators Negative linear regulators Some adjustable voltage Various packages
Mixer Transistors	Rad-tolerant	Intersil Analog Devices Microsemi	Multiple monolithic bipolar transistors Single transistor NPN and PNP
Analog to Digital converters	Rad-tolerant Rad-hard*	Analog Devices STMiicroelectronics Cobham (1Mrad*)	Single supply Various sample sizes Various sample rates
Microcontrollers	Rad-tolerant Rad-hard*	Atmel Microchip (in production)	

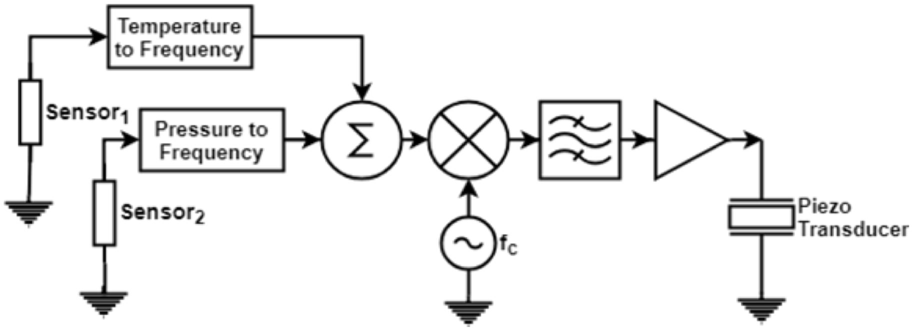
Other more complex circuit functions not directly relevant to this research are becoming increasingly available as well (FPGAs, microcontrollers, memory, communications controllers, etc.)

Electronics System Overview

- Utilizes analog-based approach to minimize active device count
- Suitable for use with temperature and pressure sensors
- Each sensor's information is encoded into an independent frequency – both signals are summed
- Summed sensor output frequencies are mixed with a carrier wave matched to the PZT resonance
- The mixer output is filtered and amplified to drive the PZT
- Utilizes straightforward methods on the cask exterior for signal detection
- Minimum device topology expands the future technology implementation options



Block diagram of full measurement system



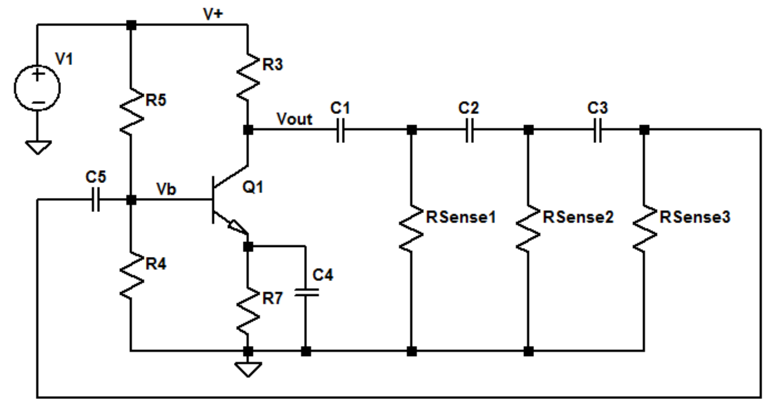
In-cask measurement and transmitter system architecture

Oscillator Designs - Sensors

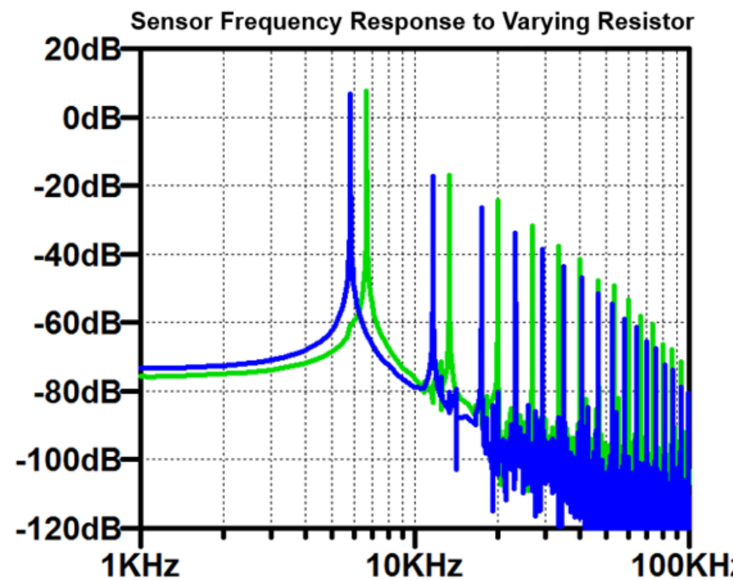
- Sensors are in the feedback path of an RC oscillator with low harmonic content
- Temperature sensors can be thermistor
- Capacitive pressure sensors can be utilized
- Oscillation frequency follows

$$f_{Sensor} = \frac{1}{2\pi RC\sqrt{6}}$$

- Biasing network must not interfere with sensor network
- Independent oscillators may be buffered to minimize interference or crosstalk



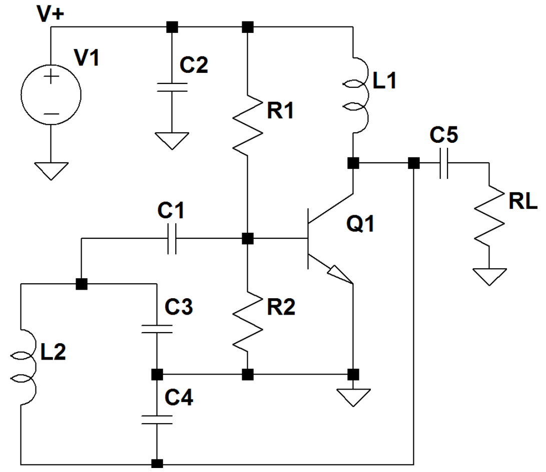
Schematic of the implemented RC-phase oscillator with resistors RSense1, RSense2, and Rsense3 as the sensing thermistors



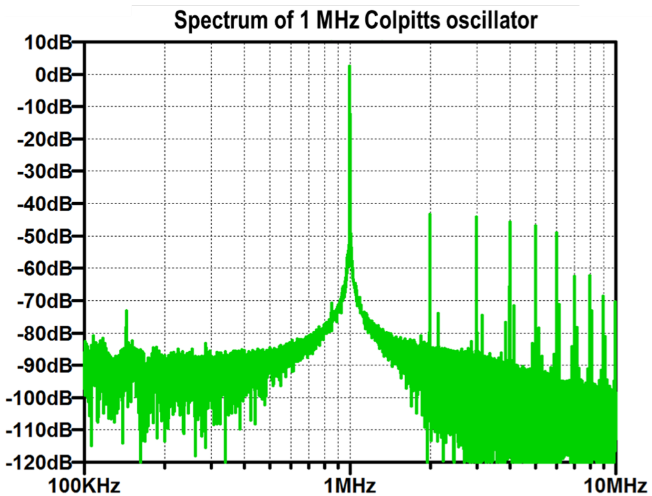
Spectrum of the RC-phase oscillator output with sense resistors set to 10 kΩ (green) and 12 kΩ (blue)

Oscillator Designs – Local Oscillator

- System uses a Colpitts oscillator for the Local Oscillator (LO) tuned to the PZT resonance
- Utilizes LC tank circuit in the feedback
- Colpitts oscillators have *low harmonic content* and high quality factor
- Oscillation frequency follows $f_{LO} = \frac{1}{2\pi\sqrt{LC}}$



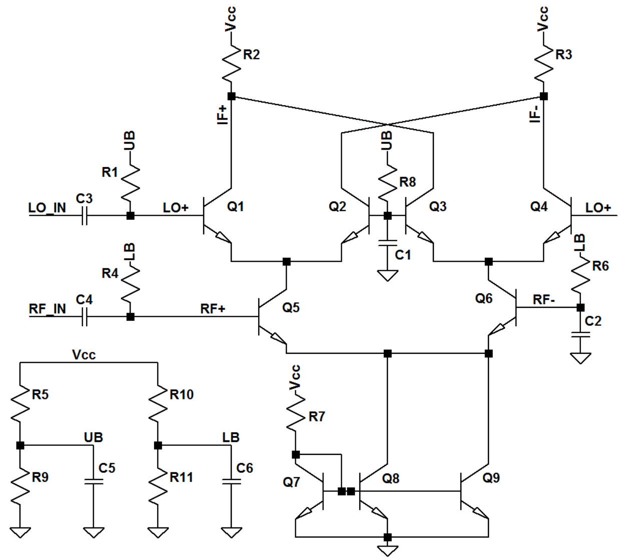
Schematic of Colpitts oscillator



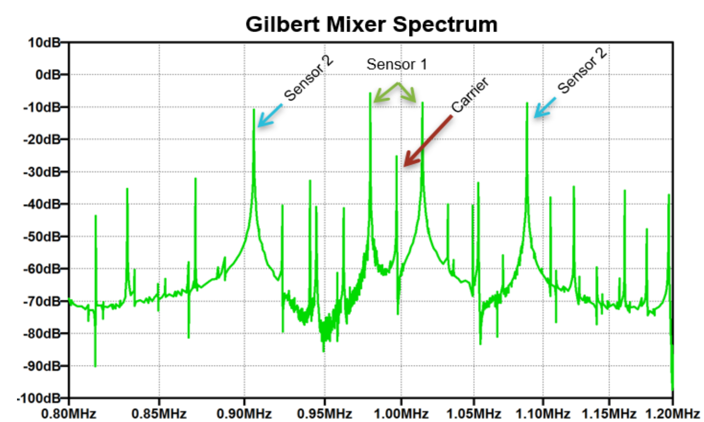
Spectrum of the Colpitts oscillator output – used for local oscillator generation

Sensor and Carrier Signals Are 'Combined' Using a Gilbert Cell Mixer

- Multiplies summed sensor frequencies by the LO frequency producing the sum and difference frequencies (mixing)
- Utilizes amplitude modulation (AM)
- Double-sideband suppressed-carrier topology reduces power utilized in the carrier
- Single-ended Gilbert mixer eliminates the need for bulky transformers
- SPICE simulations indicate clear separation of the 2 sensor signals from the carrier
  - Harmonics have >20 dB of attenuation, compared to the sensor signals
  - Carrier is suppressed to >20 dB below signal peaks
  - ~1MHz carrier shown



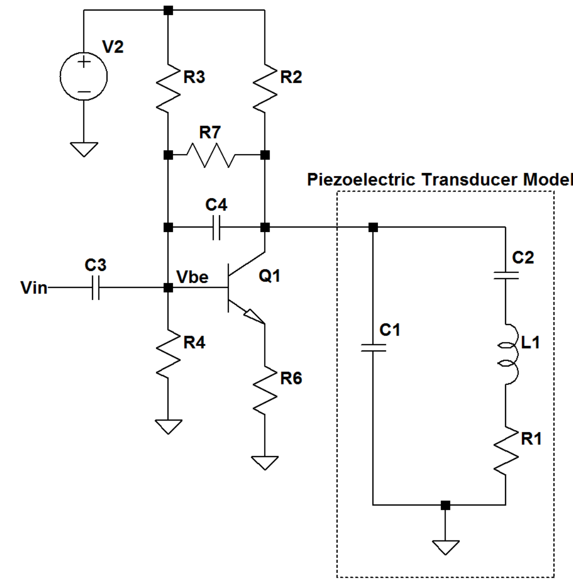
Schematic of the implemented Gilbert mixer shown



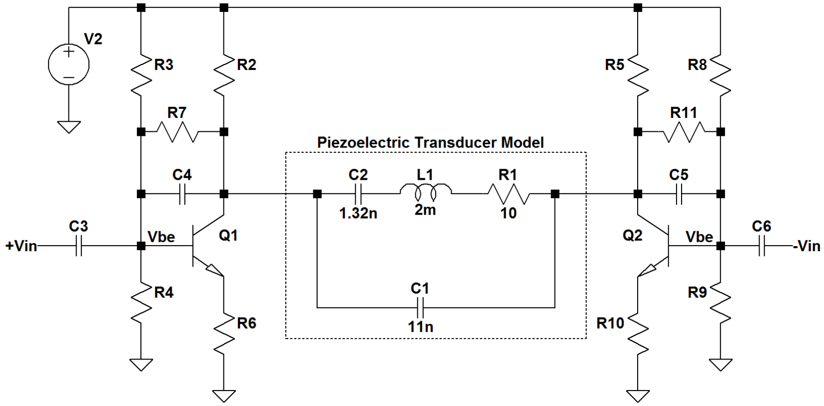
Output spectrum of SPICE simulated mixer with sensor signals and carrier labeled

Piezoelectric Transducer Driver

- Preliminary driver was designed using SPICE and approximate PZT model
- Both differential and single-ended driver topologies were investigated
  - Differential (higher gain, more devices)
  - Single-ended (lower gain, fewer devices)
- Waiting for the selected piezoelectric transducer (TRS BT200) to arrive to verify rudimentary model using an impedance analyzer
- Will revise driver cicuit as needed following PZT model generation

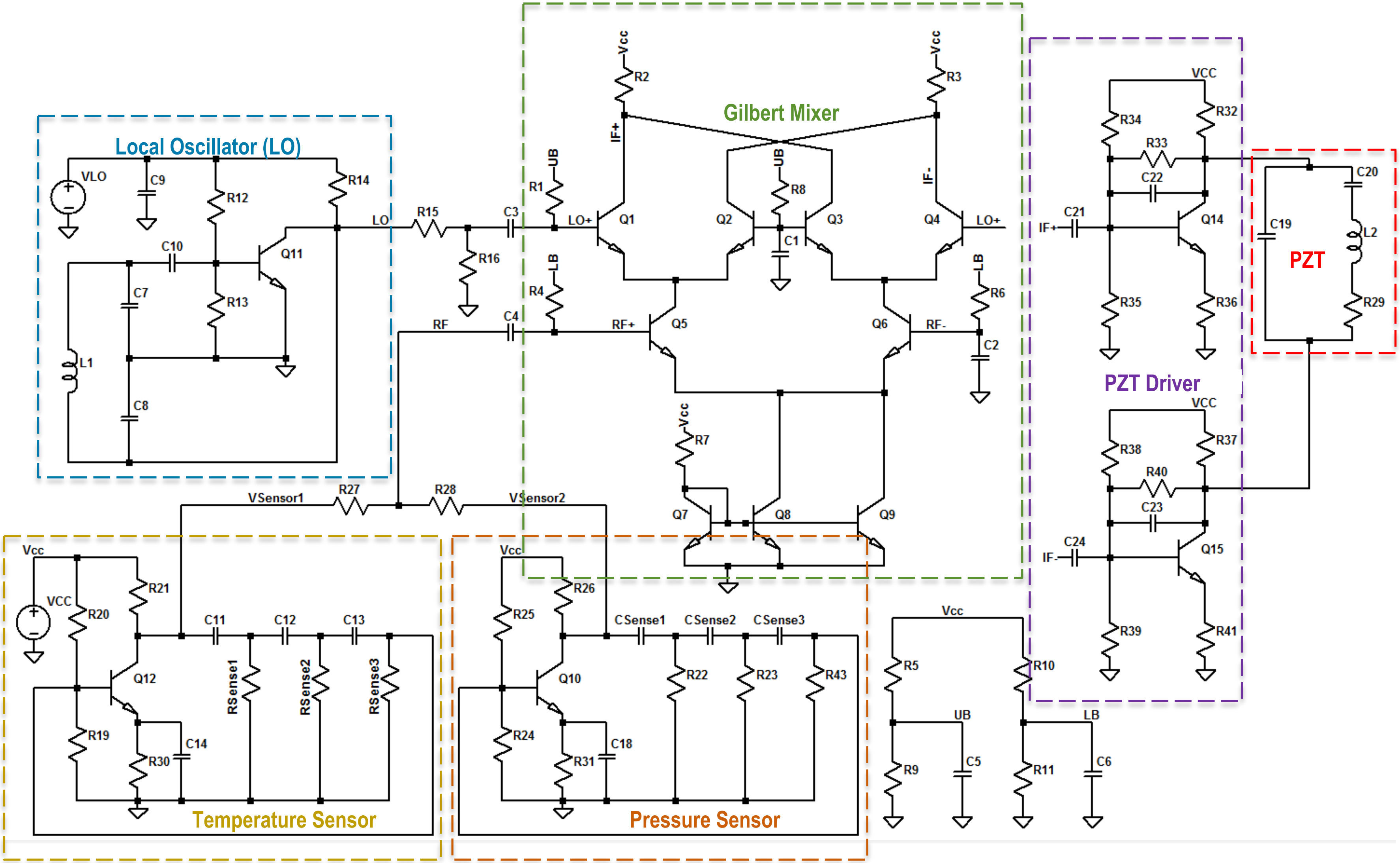


Schematic of common emitter piezoelectric transducer driver



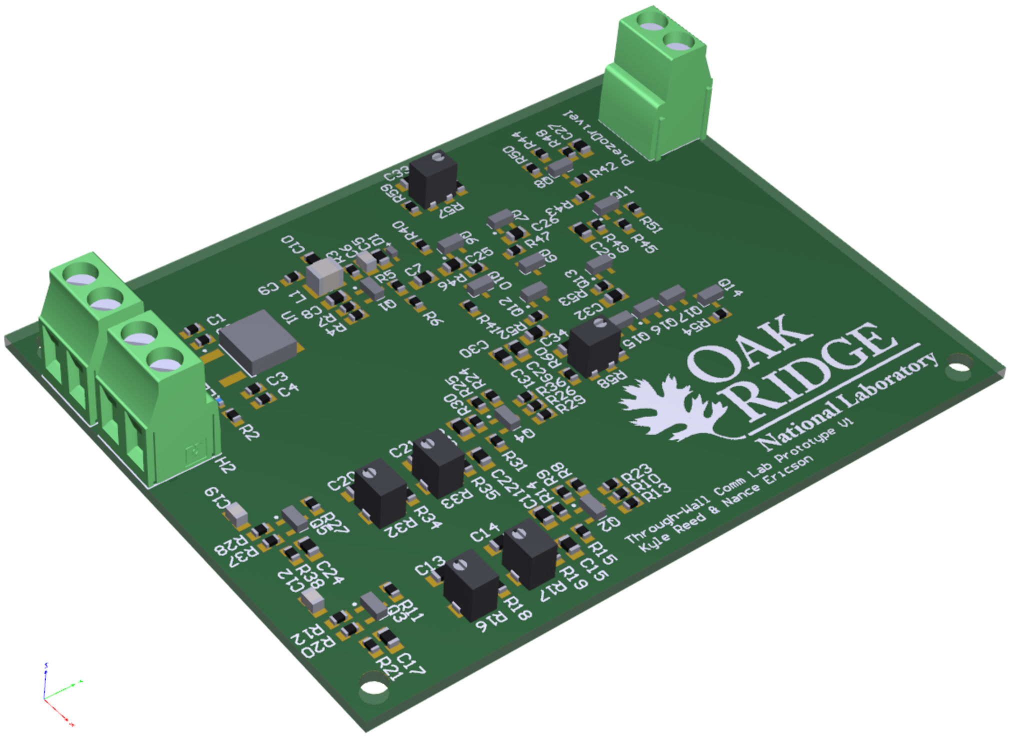
Schematic of the differential piezoelectric transducer driver

Full System Schematic



System Prototype Printed Circuit Board Preliminary Layout

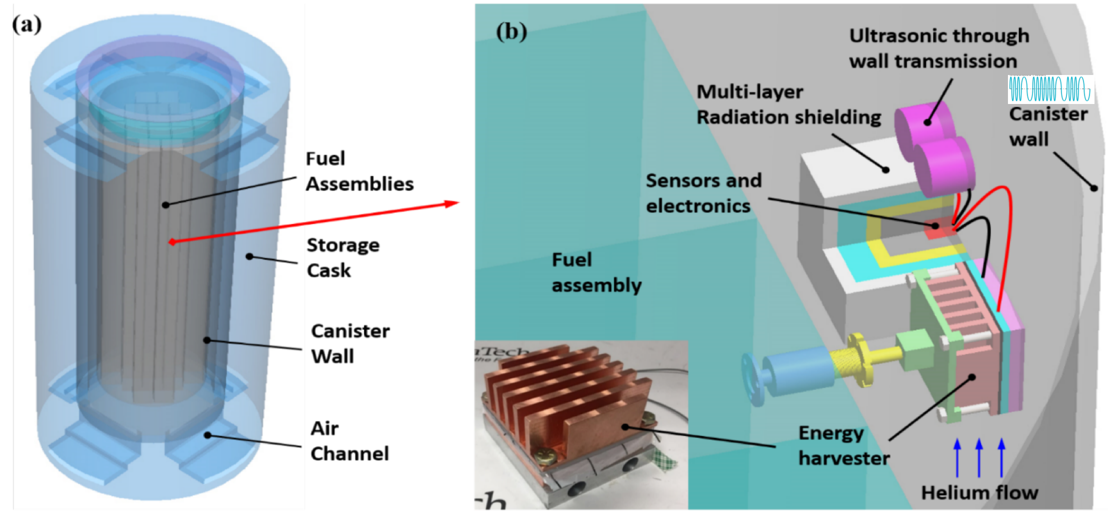
- Implemented entirely using ‘COTS’ components
- Components preliminarily placed in PCB layout using CircuitStudio
- Trace impedance will be 50Ω matched for RF traces
- LO can be tuned for different PZT resonances
- Versatility and adaptability of the test circuit have been considered
  - Potentiometers may be used in place of thermistors
  - Single-ended or differential PZT drivers can be interchanged
  - DC biasing can be adjusted



3D rendering of PCB layout for COTS lab prototype

Summary#3: Harsh environment electronics

- SPICE Simulations show favorable results for a COTs-based laboratory prototype
- Presently, the prototype is not radiation hardened
- The design approach chosen (using circuit topologies requiring a minimum number of devices) provides a path forward for potential radiation hardening (i.e. perhaps substituting BJTs with vacuum tube transistors with proper biasing)
- Considerable shielding will be required for 50-year survivability
- The external demodulation system may be placed in a much lower radiation zone enabling the use of common commercial rad-soft electronics modules



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