Investigation on Pyroelectric Ceramic Temperature Sensors for Energy System Applications

Ricardo Martinez

Department of Mechanical Engineering
University of Texas at El Paso

Grant: FE0011235,HBCU/MI
Project Manager: Richard Dunst

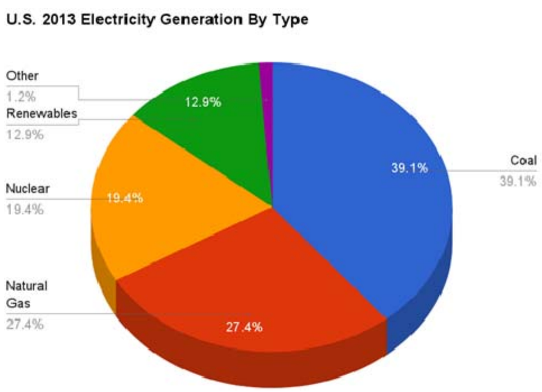
Co-PI: Norman Love, Ph.D.
PI: Yirong Lin, Ph.D.

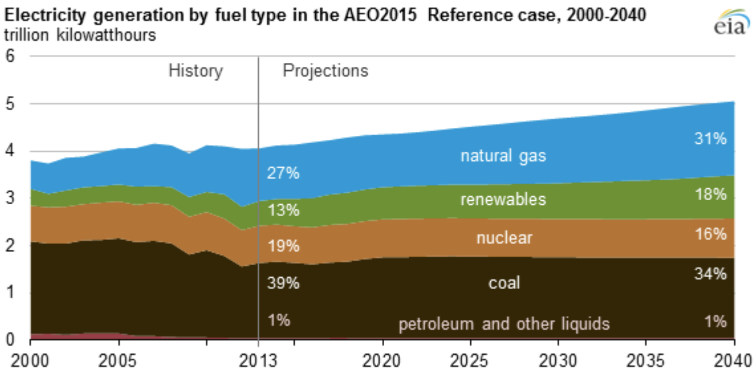
Agenda

- Introduction and Background
- Objectives
- Technical Approach
- Results
- Summary
- Future Work

Introduction

- Temperature sensing is critical in modern power plants and energy systems
  - Higher efficiencies in energy conversion
  - Lower emission for near-zero emission power plants
  - Enhanced material systems safety





Introduction

- **Project Goal**

  Design, fabricate, and demonstrate a *low cost self-powered wireless* temperature sensor for energy system applications

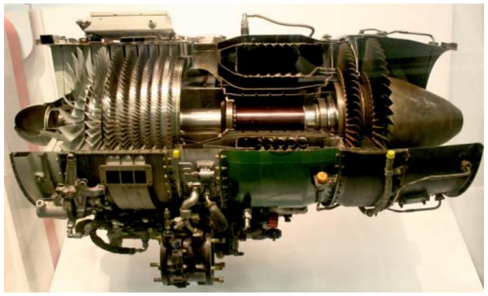
- **Expectation**

  Provide a complete set of documentation for sensor manufacturing, testing and characterization

- **Benefit**

  Energy conversion areas where continuous temperature monitoring required to achieve higher performance

Coal-Gasification Power Plant

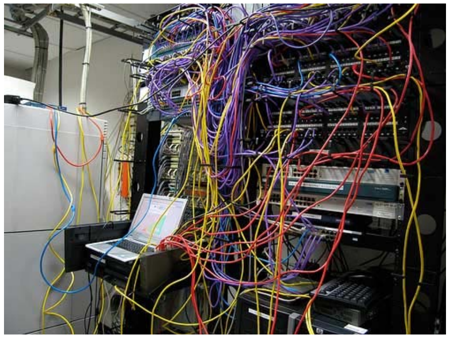


Gas Turbine

Oxy Fuel Combustion

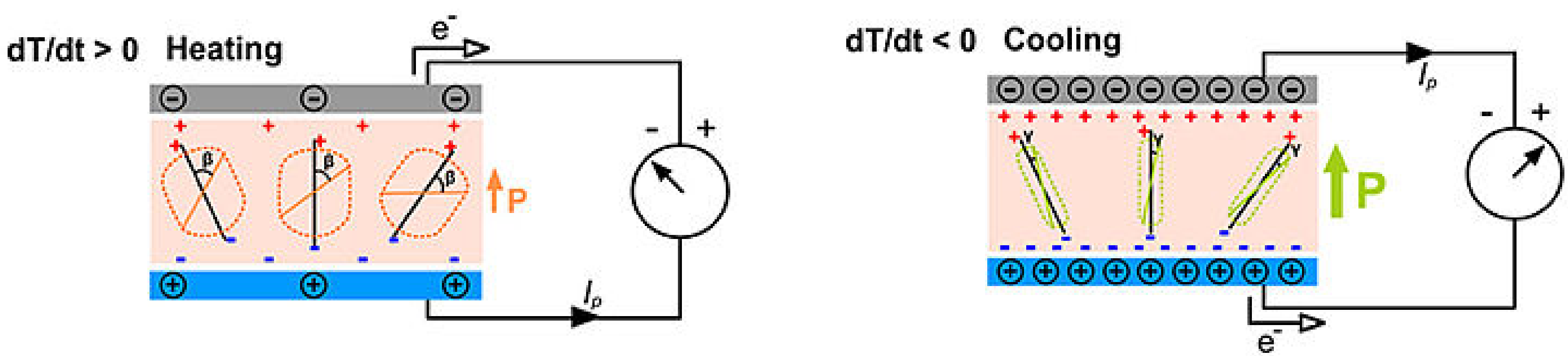
Overview and Rationale

- **Wired temperature sensors**
  - High cost materials required (Sapphire, laser)
  - Complicated sensing systems lead to high cost and maintenance
  - Typically require special coupling connection
- **Wireless temperature sensors**
  - Require built-in electronics
  - High temperature limitation
  - Complicated sensor design



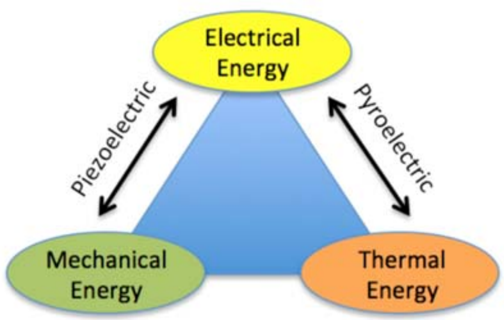
Background

- ❑ Pyroelectric material is heated
  - ➢ Spontaneous polarization reduced through reduction of dipole moment
  - ➢ Quantity of bound charges at the electrodes decreases
  - ➢ This subsequent redistribution of charges results current flow through the external circuit
- ❑ Pyroelectric material is cooled
  - ➢ Spontaneous polarization increased
  - ➢ Current sign is reversed



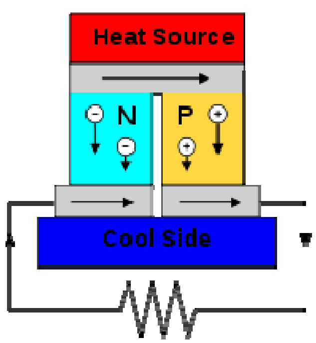
Background

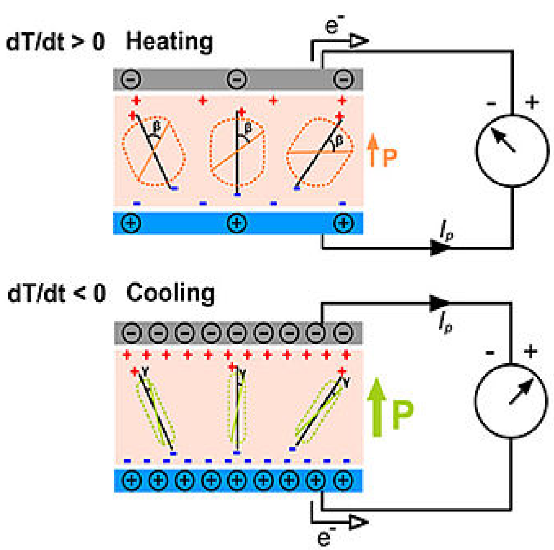
- ❑ Coupling thermal energy and electrical energy
- ❑ Different from thermoelectric, one piece
- ❑ Current proportional to temperature change



$$i_p = \frac{dQ}{dt} = Ap\frac{dT}{dt}$$

$$T_f = -\frac{1}{pA}\int_{t_i}^{t_f} I\,dt + T_i$$



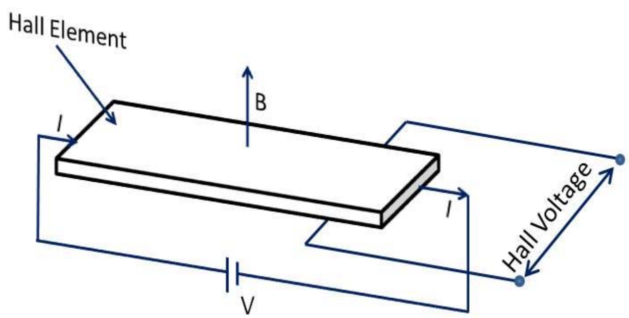


Background

Sensing of Magnetic Field

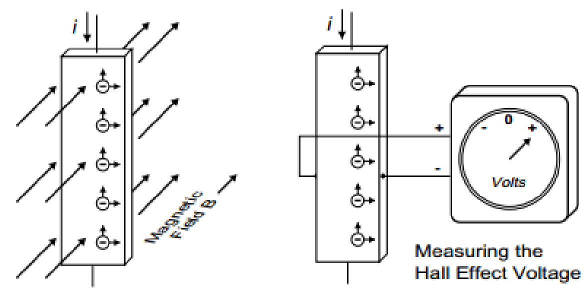
❑ Hall Sensor

- A hall effect sensor is a 3 wired sensor with reference voltage, a ground and a signal terminal



- Hall effect sensor is a transducer that varies its output voltage in presence of magnetic field

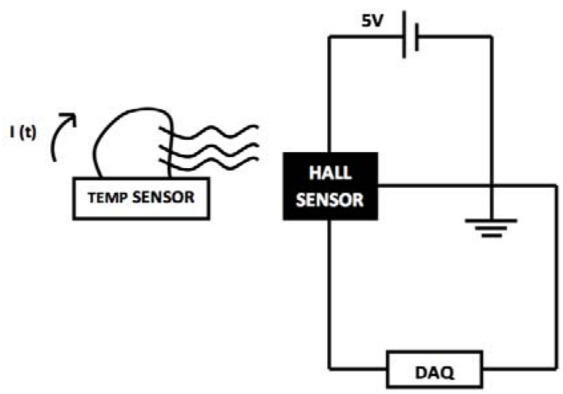
- Current flowing through a conductor in magnetic field perpendicular to the current flow would generate voltage perpendicular to both current flow and magnetic field

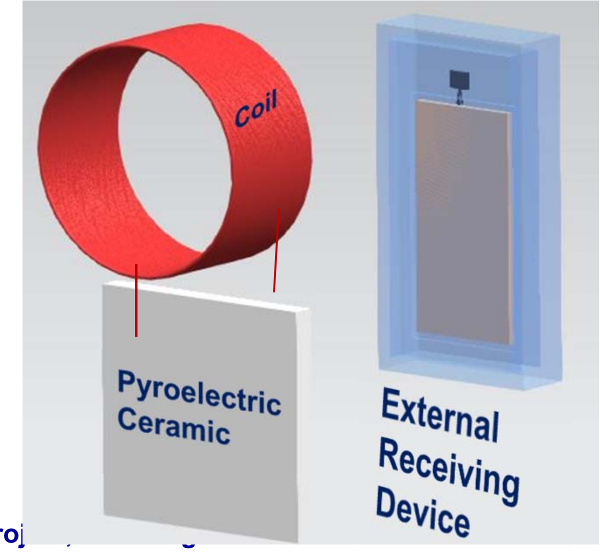


Introduction

Project Concept

- ❑ Low cost self-powered wireless temperature sensor
- ➢ Sensing mechanism is based on ***pyroelectric ceramic***
- ➢ Pyroelectric ceramic ***generates current*** upon temperature changes
- ➢ Generated current will be converted into ***magnetic flux*** by connecting the ceramic to an inductive coil and measured wirelessly by an ***external receiving device***





Technical Approach

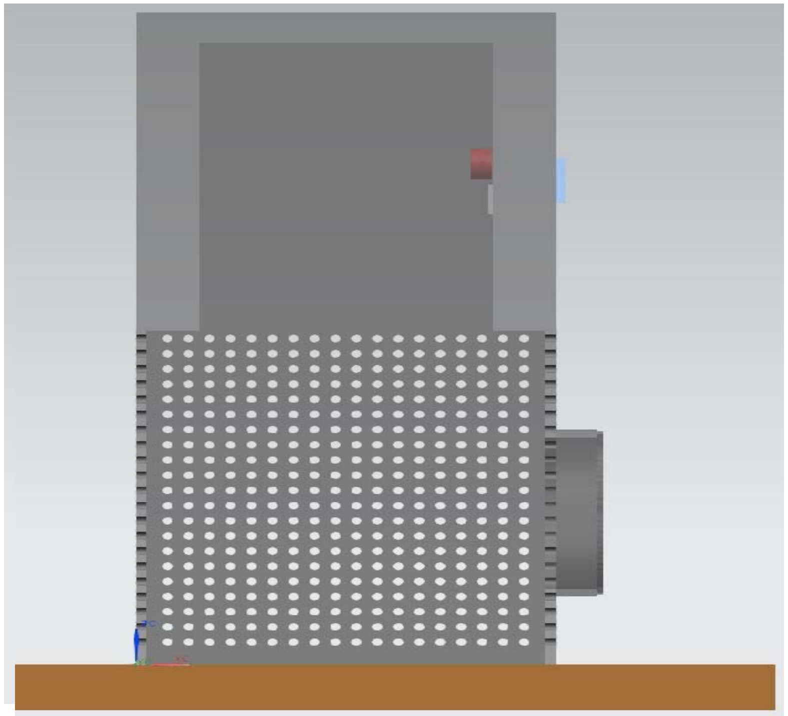
Sensing Method

- The relation between magnetic flux and current can be described as below

$$T(f) = \frac{1}{pA}\int_{t_o}^{t_f} I dt + T(0)$$

$$\varphi = \frac{\mu_0 NIA}{w}$$

- Sensing device and processing unit



- Left side: wireless signal (Current induced magnetic flux) generated by sensor
- Right side: External receiver (Hall sensor) and Data acquisition unit

Objectives

1. Determination of appropriate pyroelectric ceramics

2. Construct the wireless sensor system and demonstrate the wireless temperature sensing capability

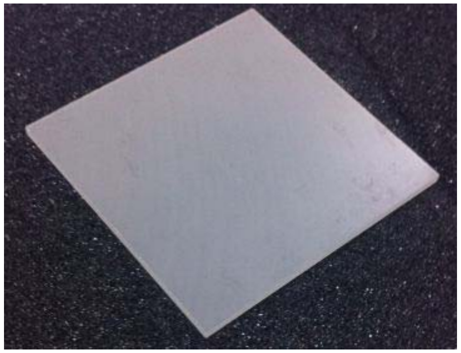
3. Development of temperature sensor using pyroelectric properties of Lithium Niobate

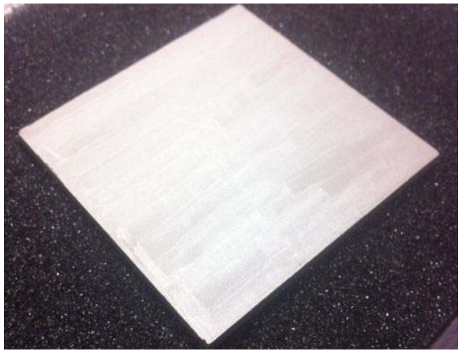
   - Development of energy harvester using pyroelectric properties

4. Determine the wireless sensing performance in energy systems

Technical Approach

Objective 1: Determination of appropriate pyroelectric ceramic



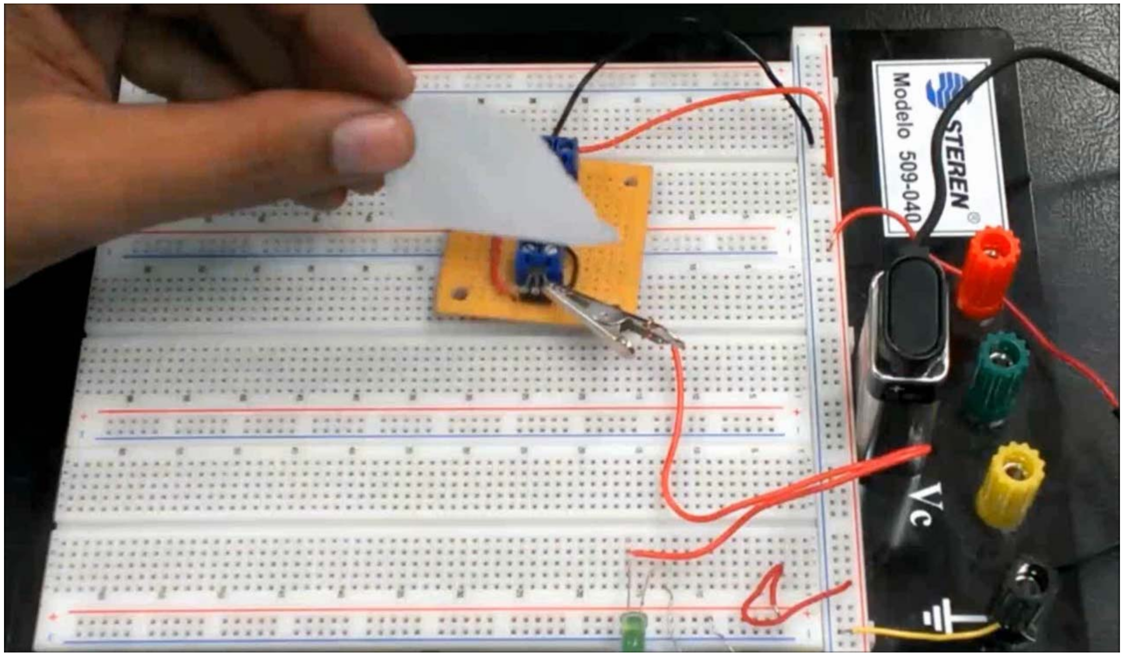


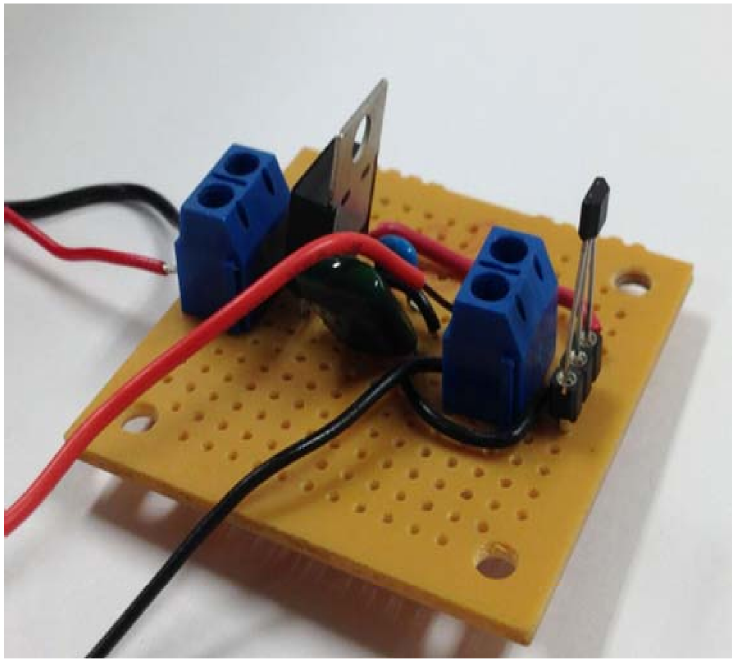
- Pyroelectric materials include
  - Crystal (Lithium Tantalate)
  - Polymer (PVDF-Polyvinylidene Fluoride)
  - Ceramic (Lithium Niobate)
  - Biological materials
- Choice of pyroelectric materials depends on
  - Size & density
  - Availability and reliability
  - Maximum operation of temperature
  - Pyroelectric coefficient

Dimension ($LiNbO_3$)	50.8×50.8 cm and 2 mm in thickness
Density	4.65 g/cm^3
Curie Temperature	1142.3±0.7º C
Dielectric Constant (@ 25º C (unclamped <500 KHz)	ε_{11} = 85, ε_{33} = 28.7
Pyroelectric Coefficient (@ 25º C)	-8.3×10^{-5} C/ºCm^2
Piezoelectric Strain Coefficients (@25ºC ×10^{-12} C/N)	d_{12}= 69.2 d_{31}=0.85 d_{22}=20.8 d_{33}=6.0
Thermal Conductivity (@ 25º C)	10^{-2} cal/cm.sec.ºC

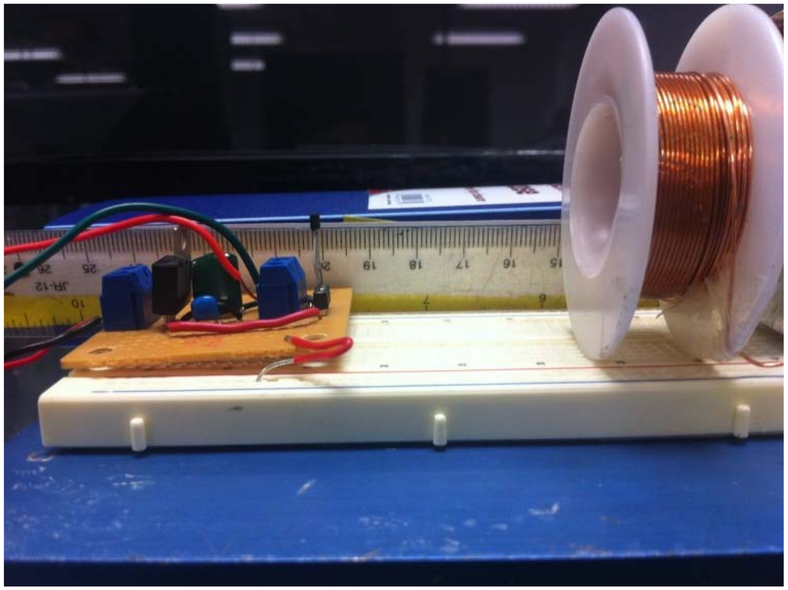
Objective 2: ***Construct the wireless sensor system*** and demonstrate the wireless temperature sensing capability

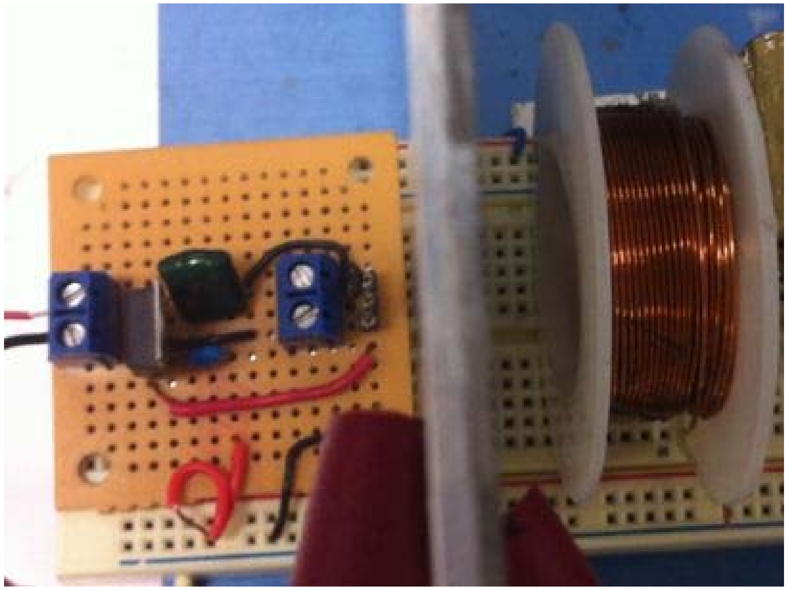
5.0 mV/Gauss ratiometric linear analog commercial Hall sensor from Alegro Micro Systems





Technical Approach





Objective 2: Construct the wireless sensor system and ***demonstrate the wireless temperature sensing capability***

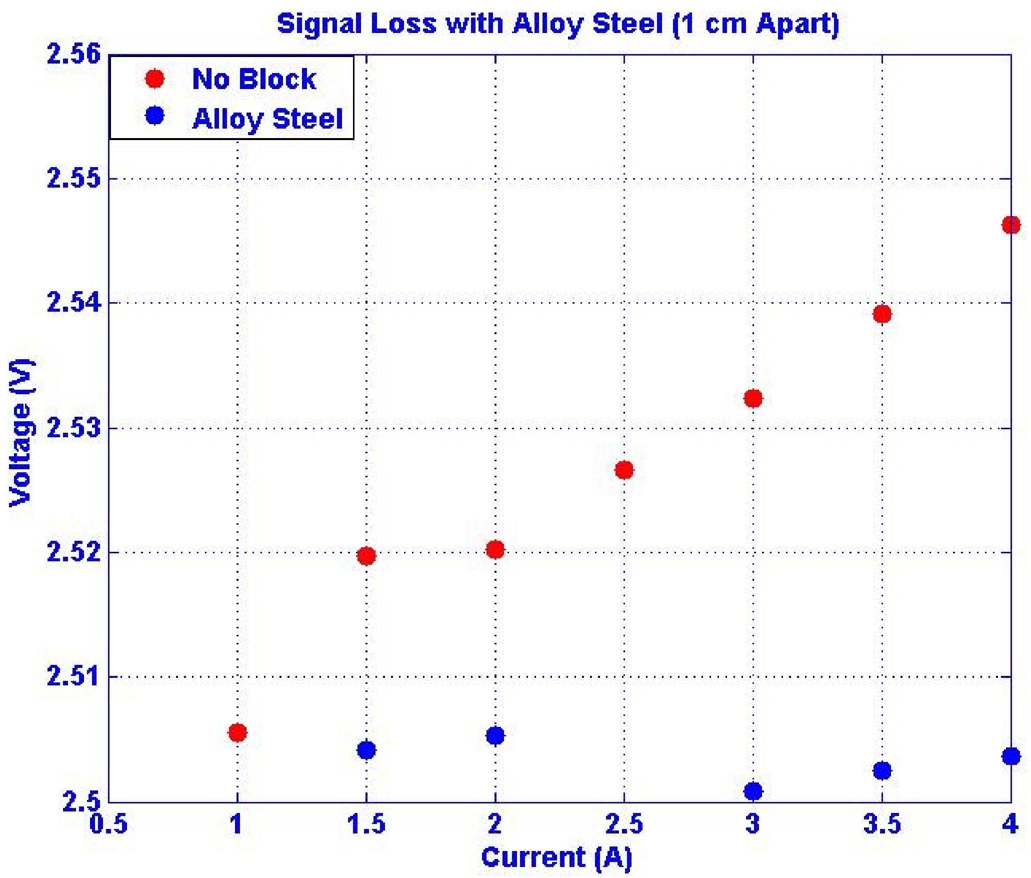
- ❑ Task

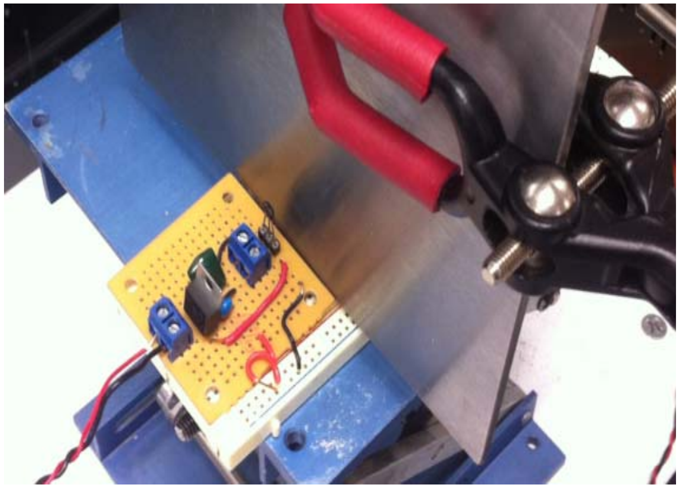
Magnetic Field Detection by Hall Effect Sensor

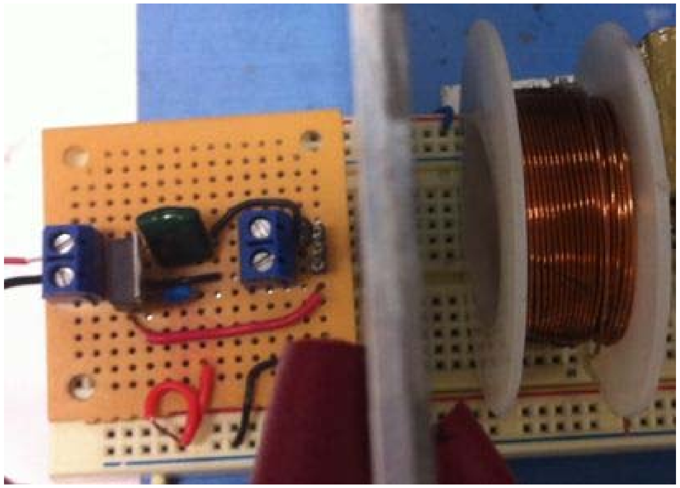
- ➢ Through Distances
- ➢ Through Material Blocks

Results

Signal Loss with Various Materials



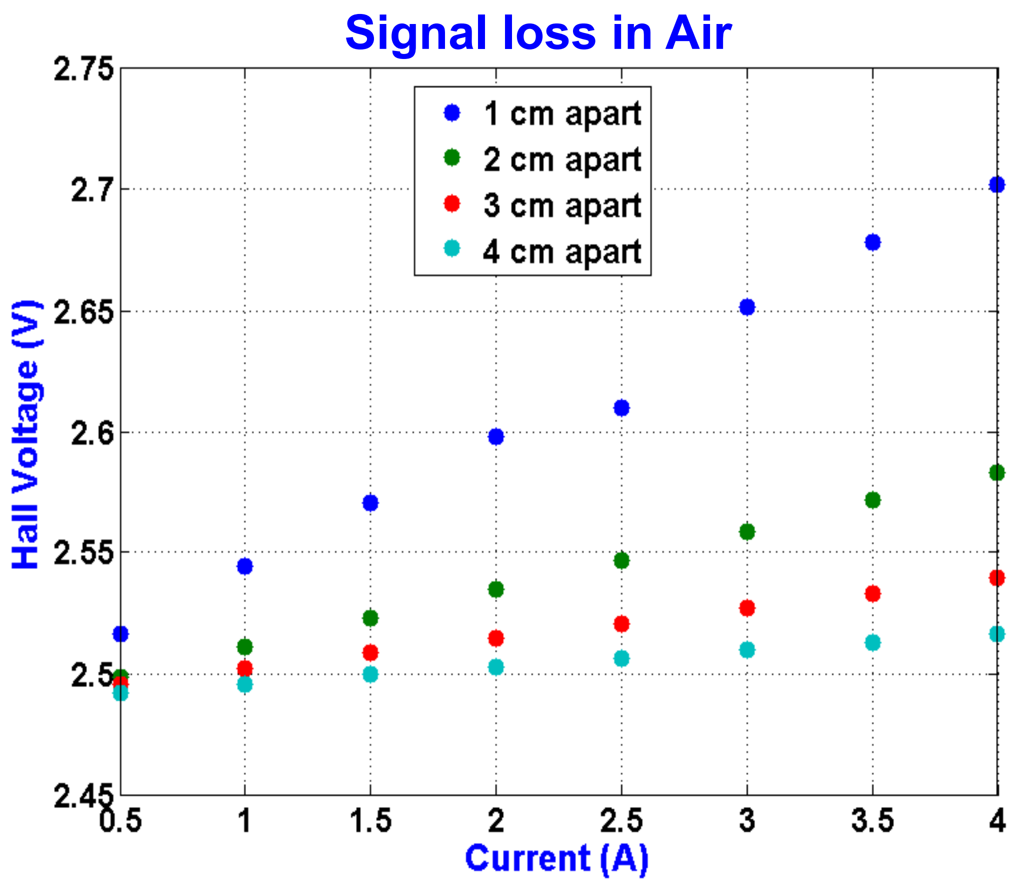


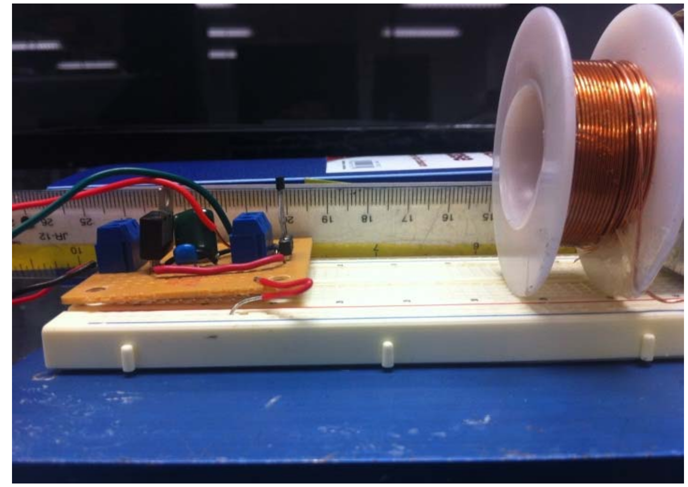


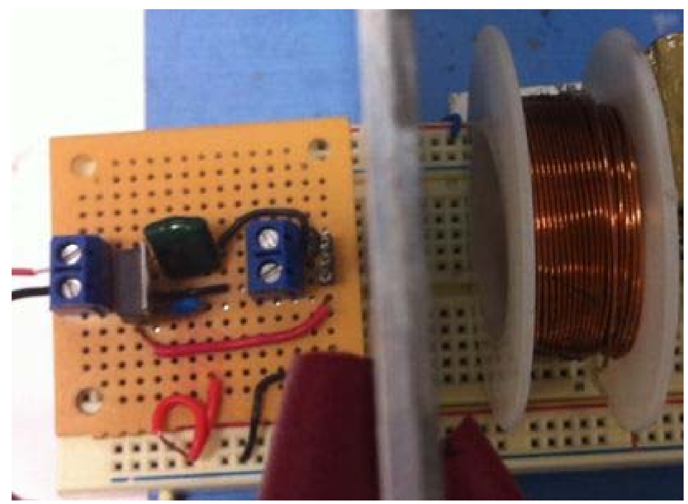
- ❑ Current supplied to winded coil from external power supply

Results

Signal Loss for Various Distances



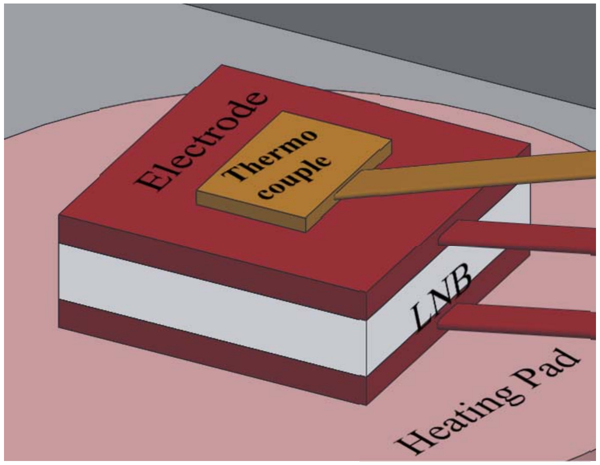


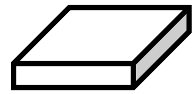


- ❑ **Current supplied to winded coil from external power supply**

Technical Approach

Objective 3: Development of temperature sensor using pyroelectric properties of Lithium Niobate

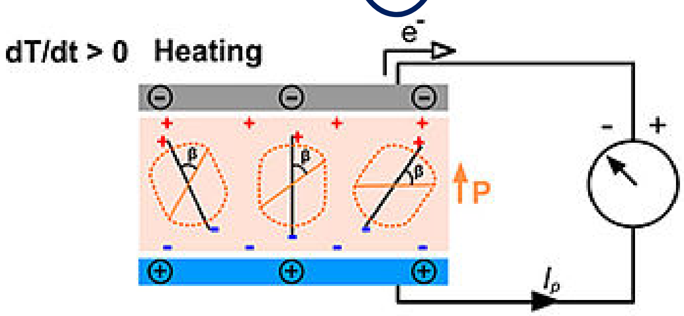


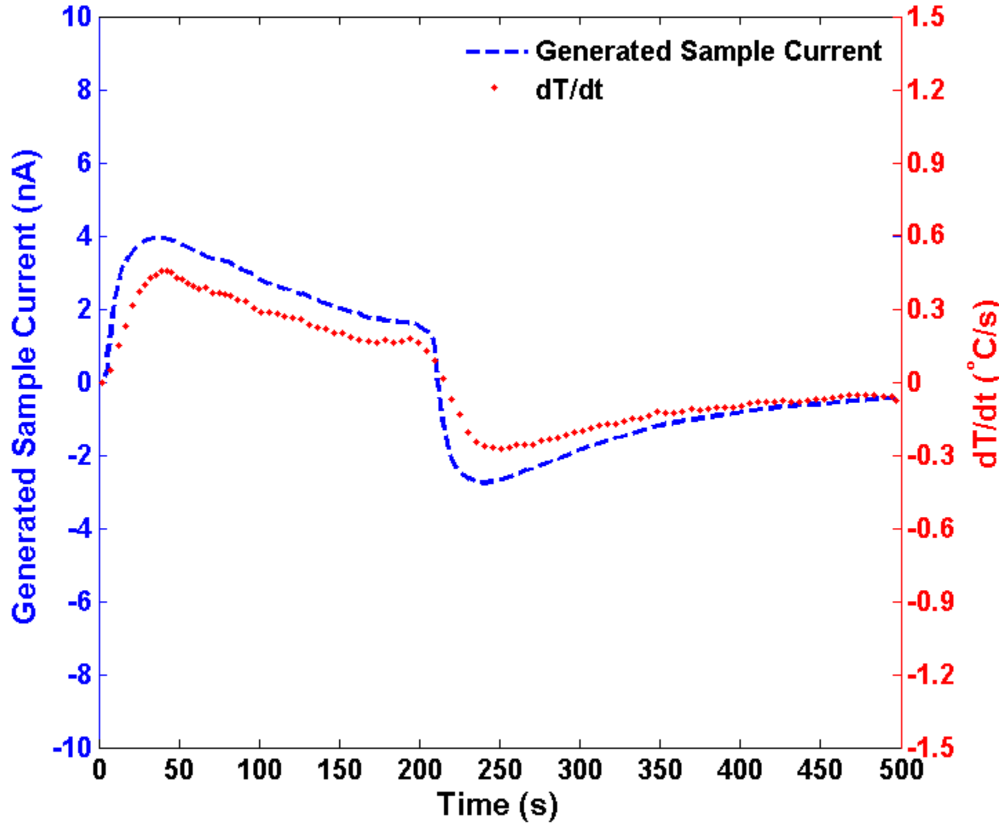


10×10x2 mm
10×10x1 mm

Pyroelectric Current

$$I = -pA\frac{dT}{dt}$$





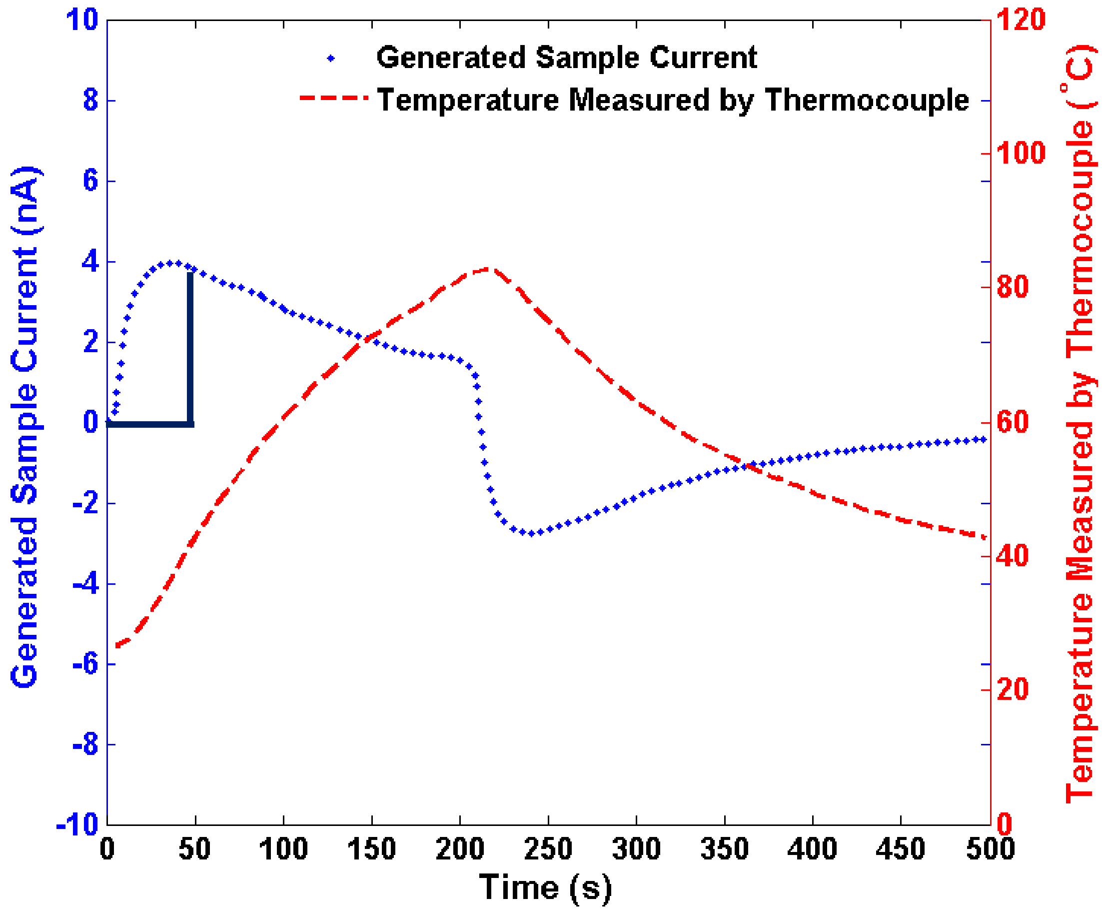
Technical Approach

Pyroelectric Current

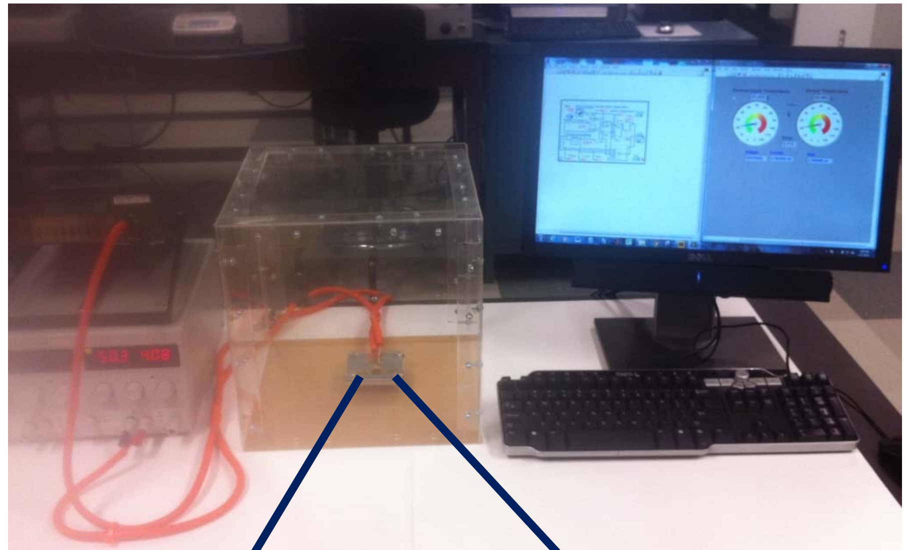
$$I = -pA\frac{dT}{dt}$$

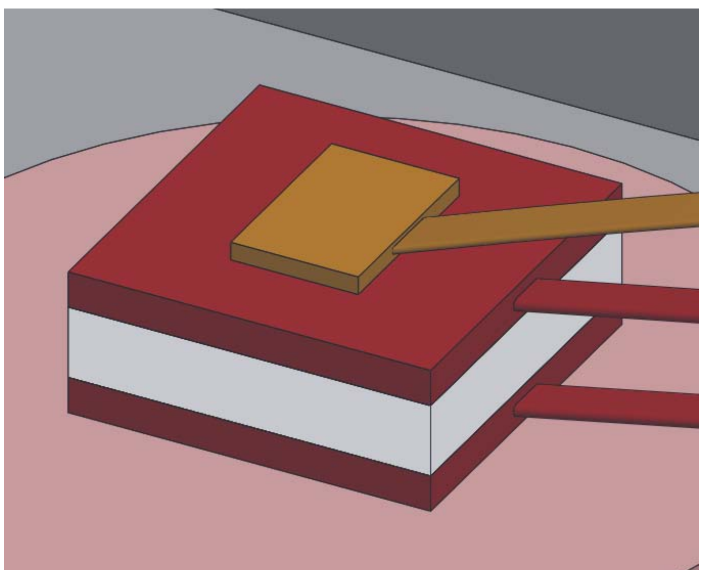
50s

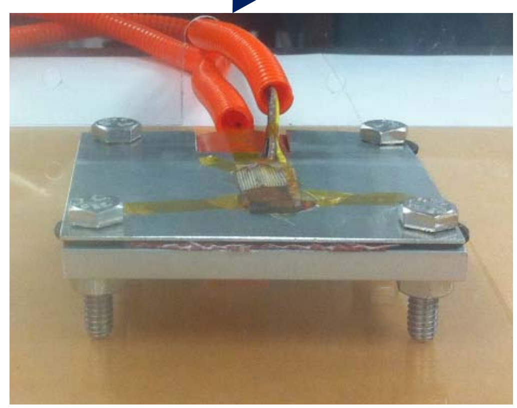
$$T_f = -\frac{1}{pA}\int_{t_i}^{t_f} I\,dt + T_i$$

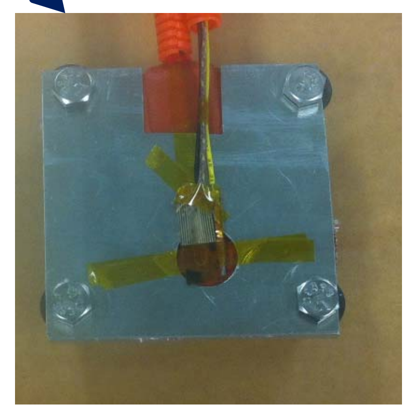


Experimental Setup

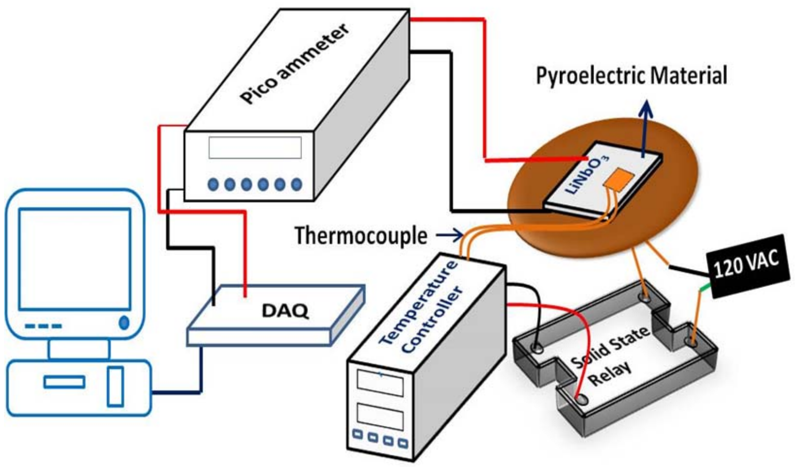




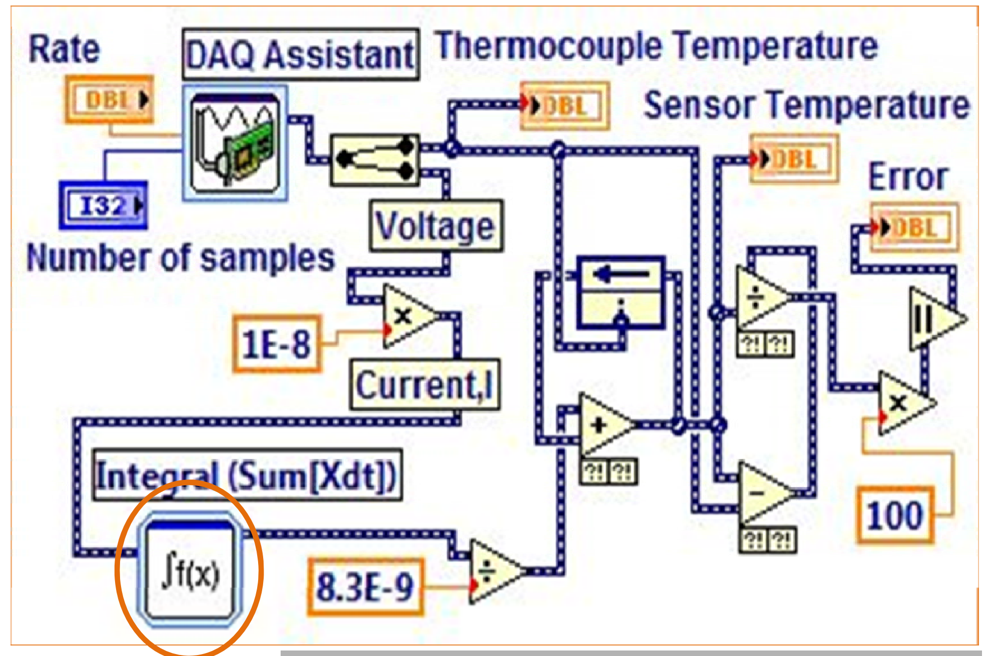


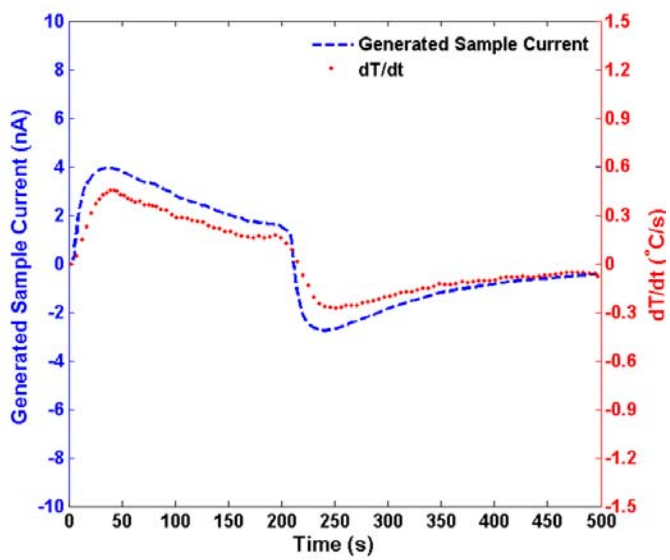


Experimental Setup

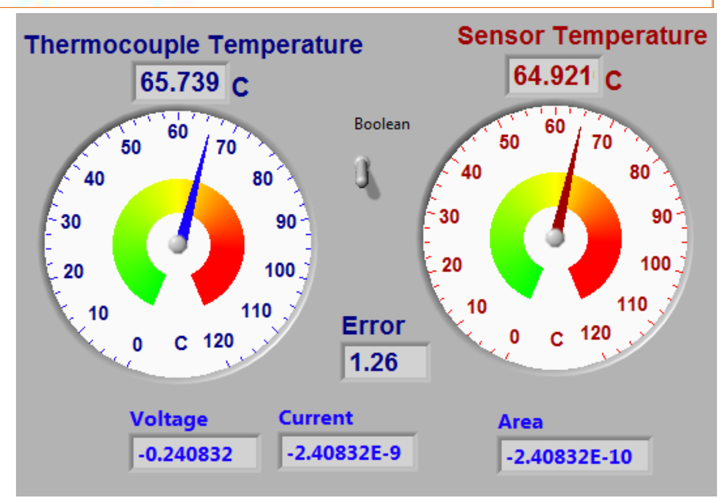


- Data Acquisition

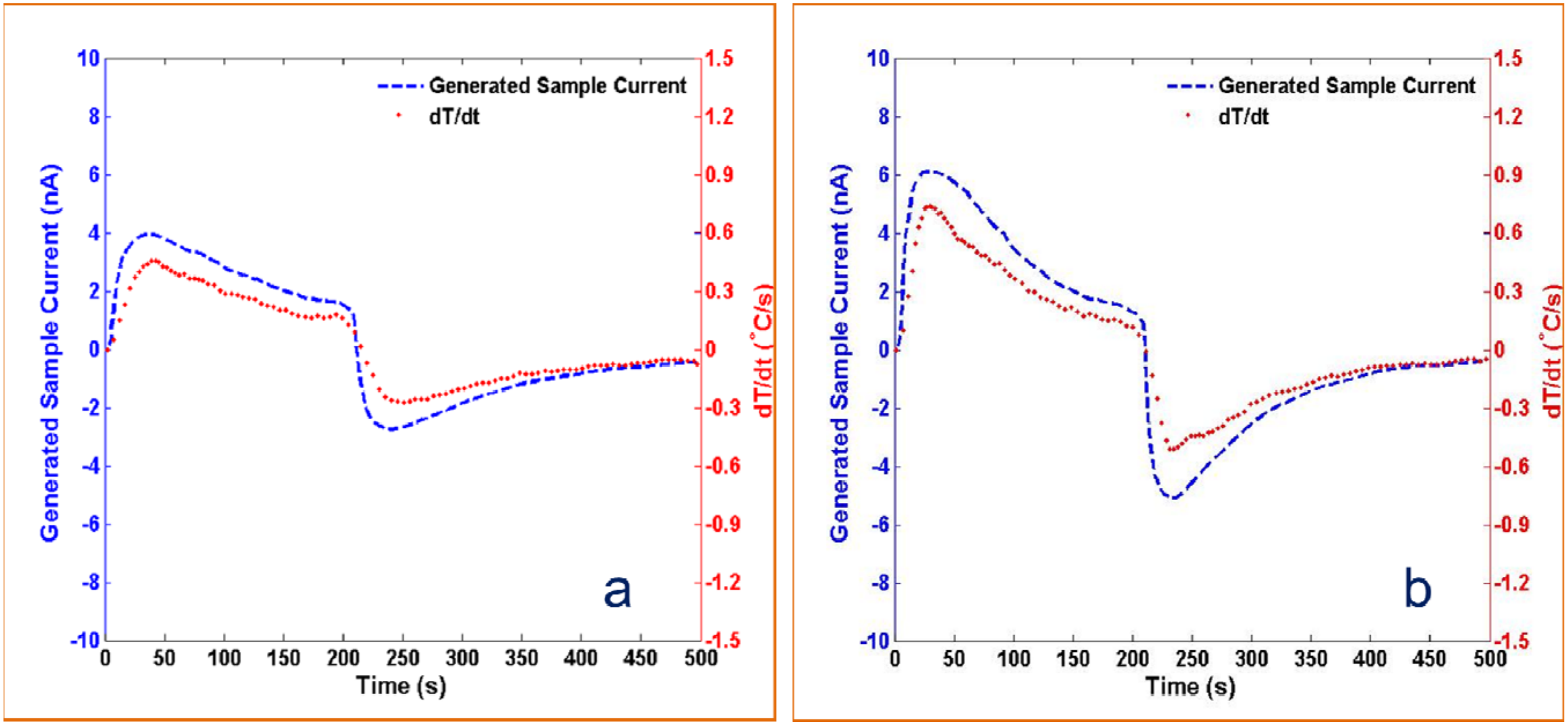




$$T_f = -\frac{1}{pA}\int_{t_i}^{t_f} I dt + T_i$$

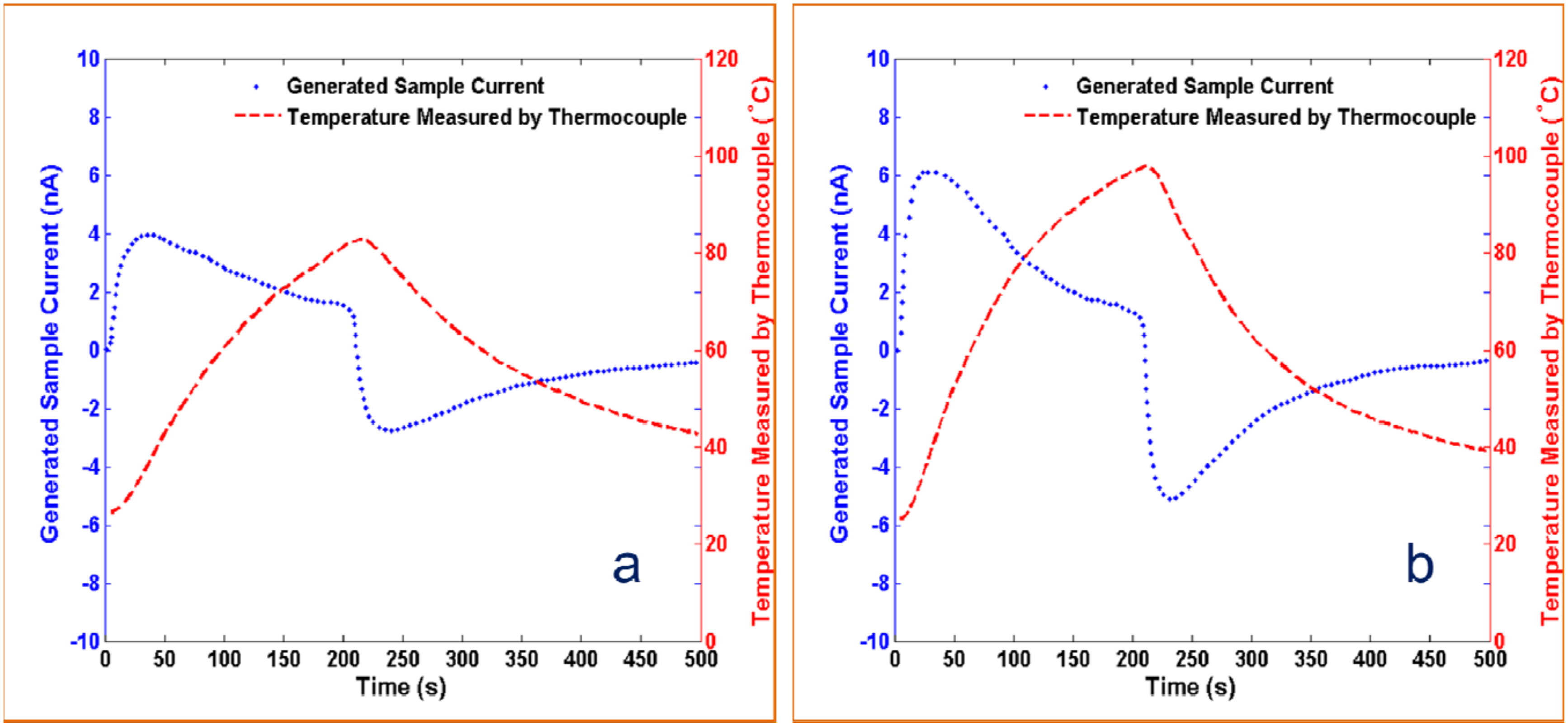


Results



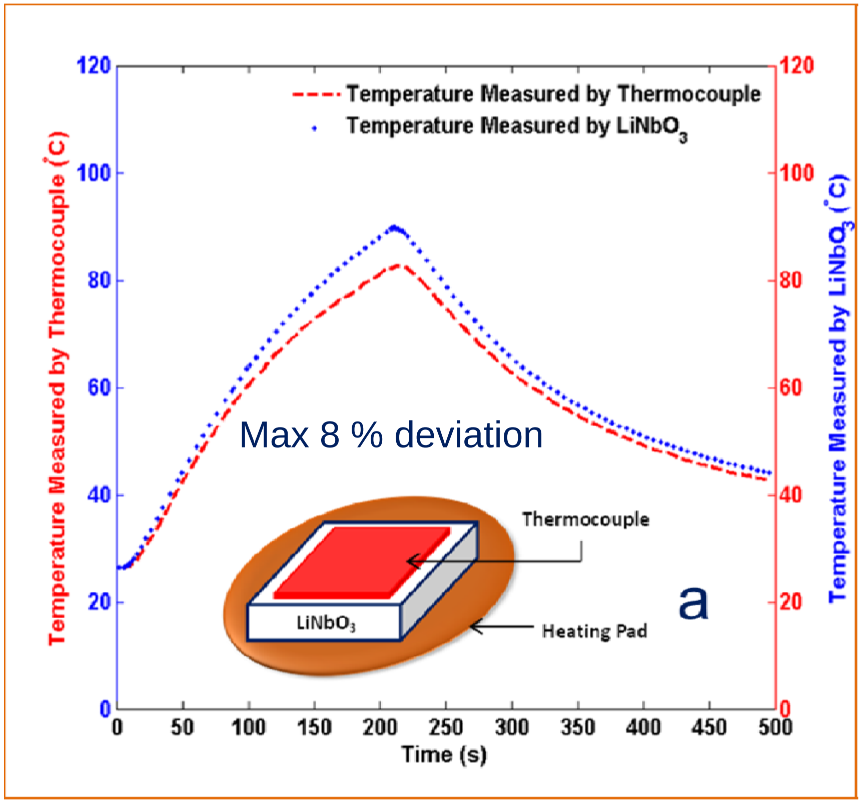
Generated current by $LiNbO_3$ and rate of temperature change of thermocouple mounted on top of (a) 2 mm and (b) 1 mm thick $LiNbO_3$

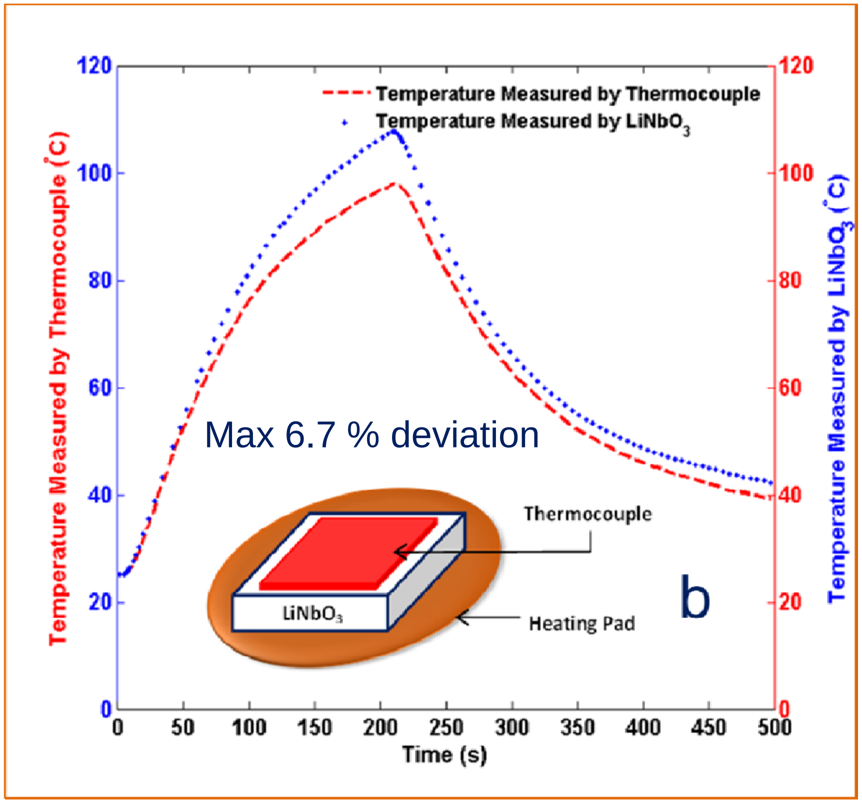
Results



Generated current by $LiNbO_3$ and temperature of thermocouple mounted on top of (a) 2 mm thick $LiNbO_3$ and (b) 1 mm thick $LiNbO_3$

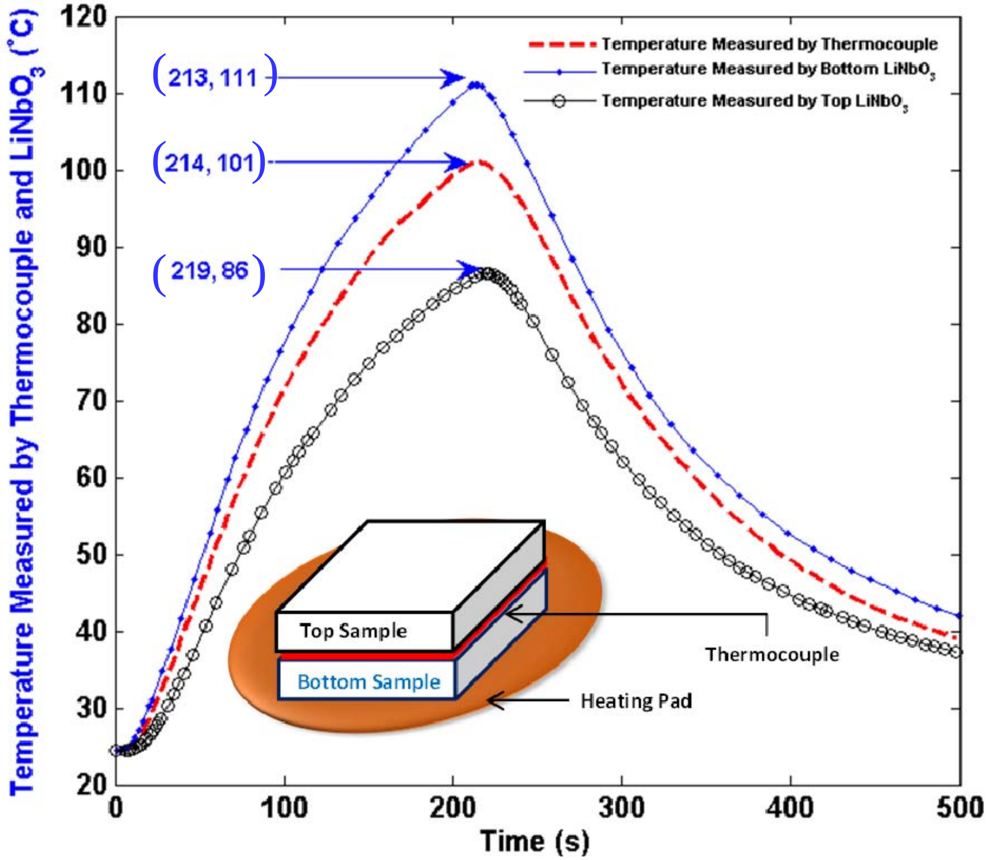
Results





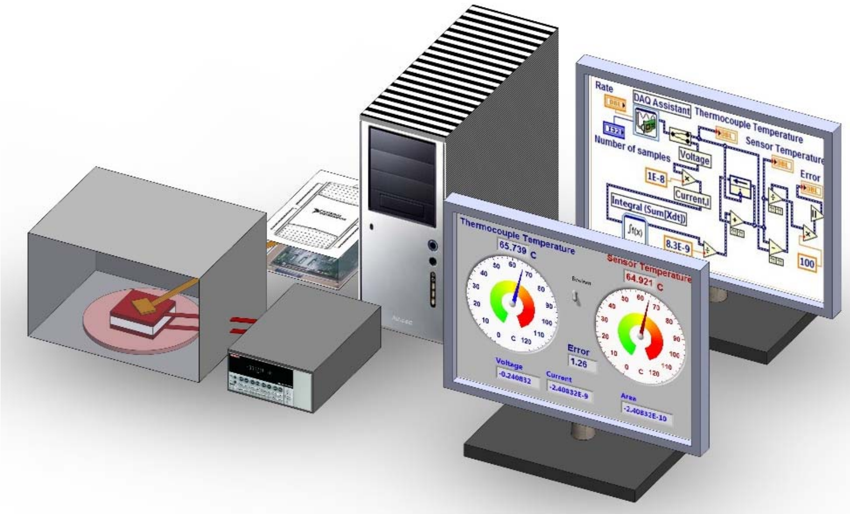
Temperature measured by thermocouple and (a) 2 mm thick and (b) 1 mm thick $LiNbO_3$

Results



Temperature measured by the thermocouple and 1 mm thick sandwich structured $LiNbO_3$

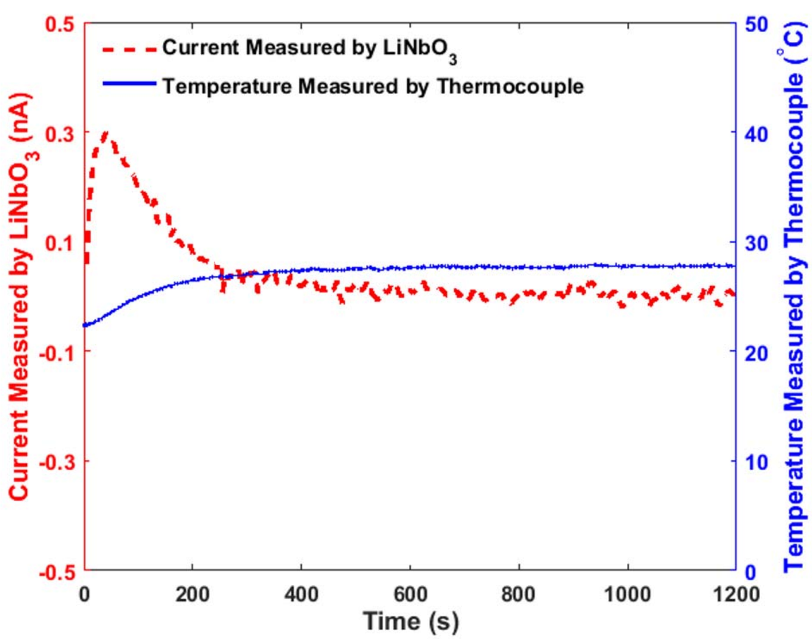
Results

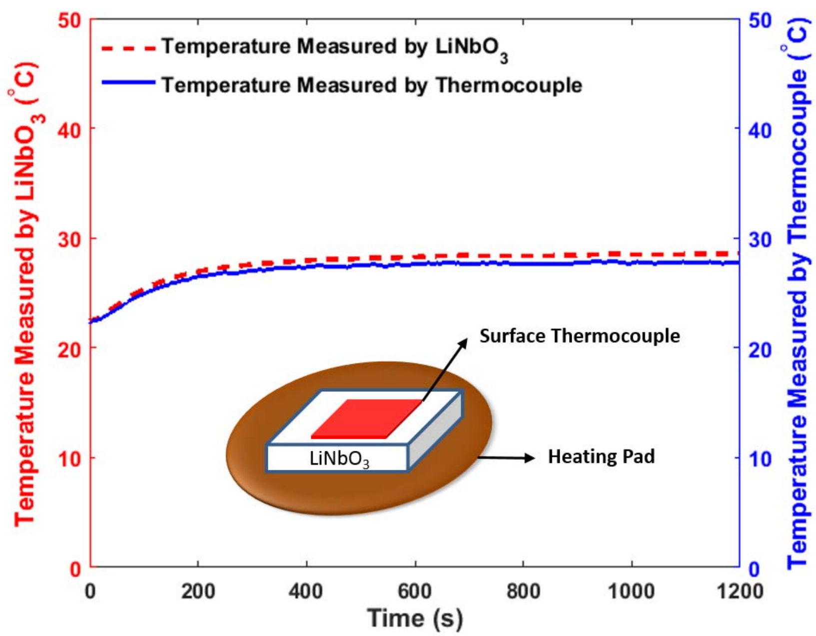


❑ Slow Heating Rate

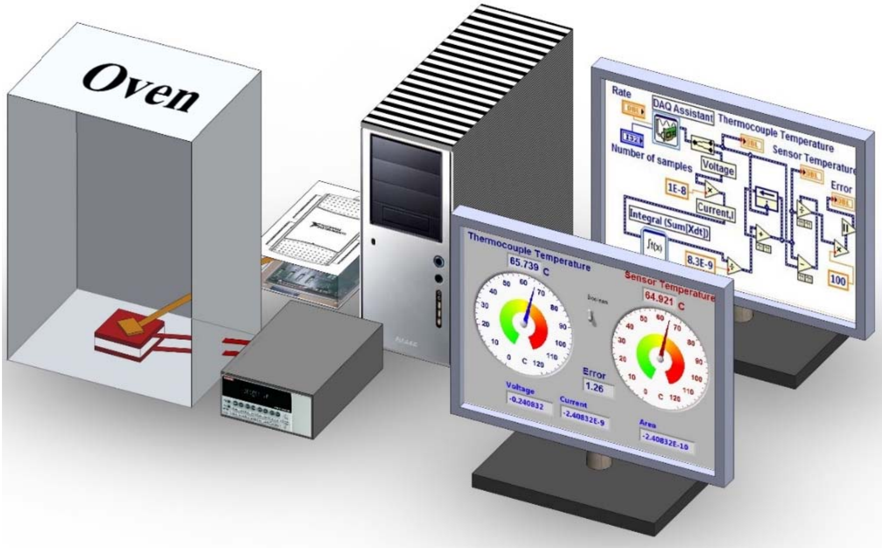
22.50 °C to 27.75 °C within 650 s

Average dT/dt = 0.008 °C/s





Results

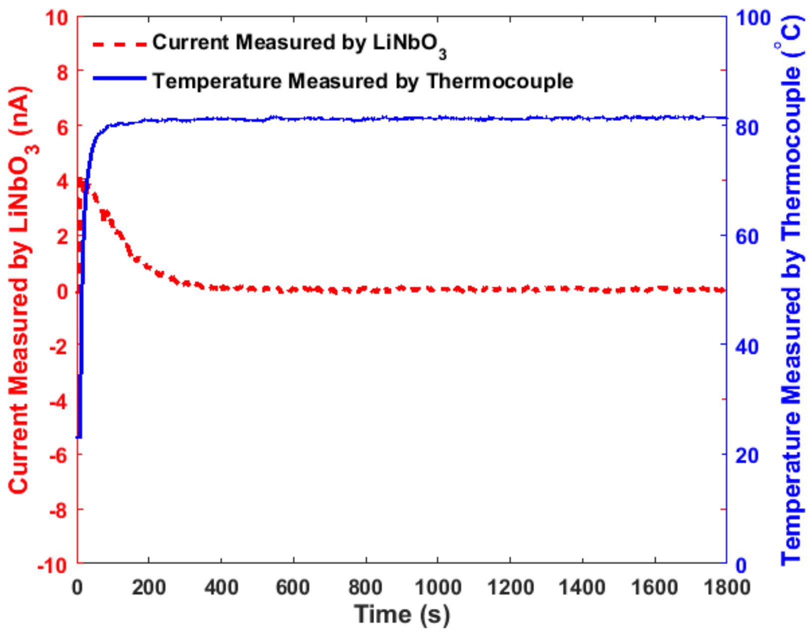


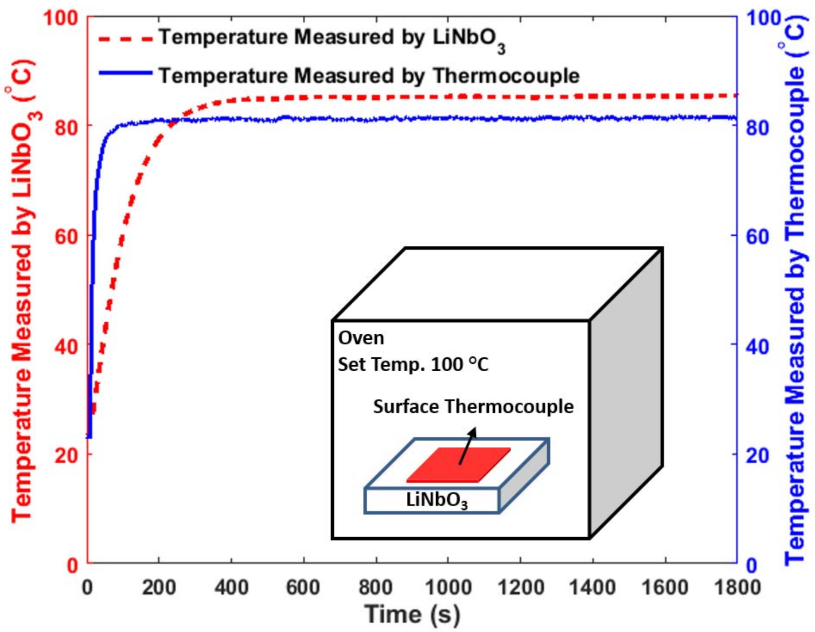
❑ High Heating Rate

25 °C to 81 °C within 190 s

Average dT/dt = 0.3 °C/s

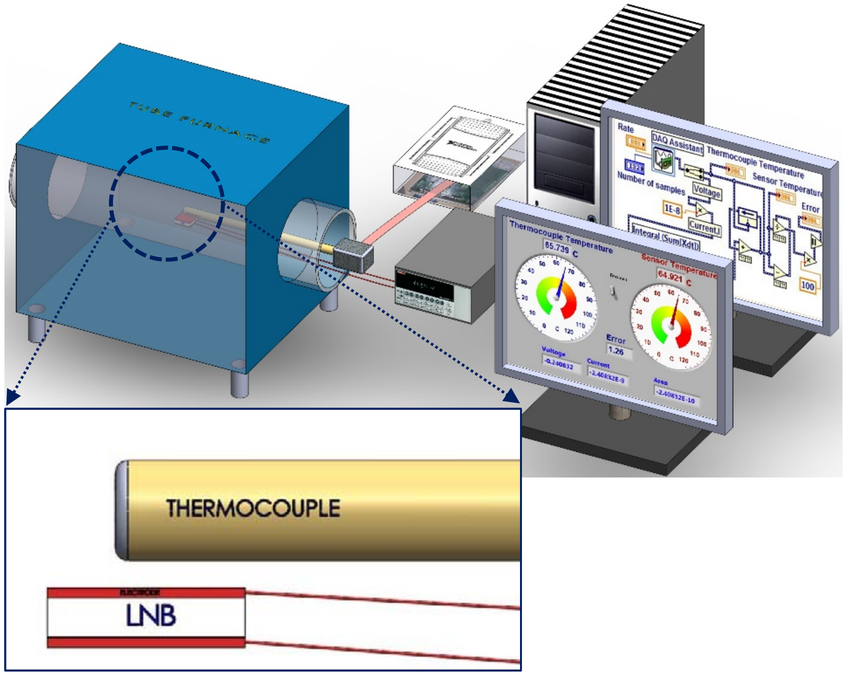
Oven Pre-heated set Temp. 100 °C





Results

❑ High temperature Measurement



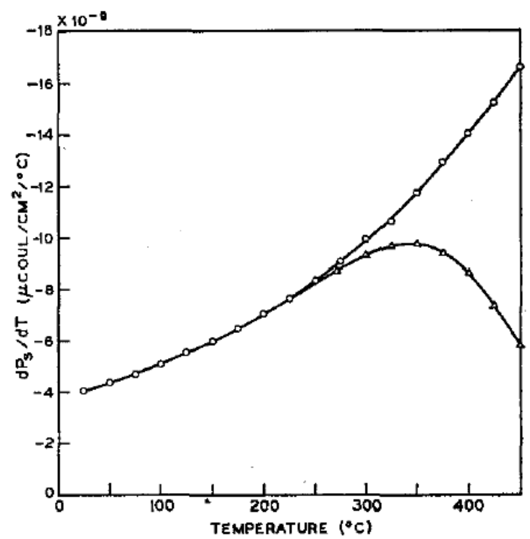
Tube furnace Set Temperature

1. **25 °C to 300 °C with 0.25 °C/s**
2. **25 °C to 400 °C with 0.25 °C/s**
3. **25 °C to 500 °C with 0.33 °C/s**

$I = -pA\frac{dT}{dt}$; $-p$ is a function of temperature

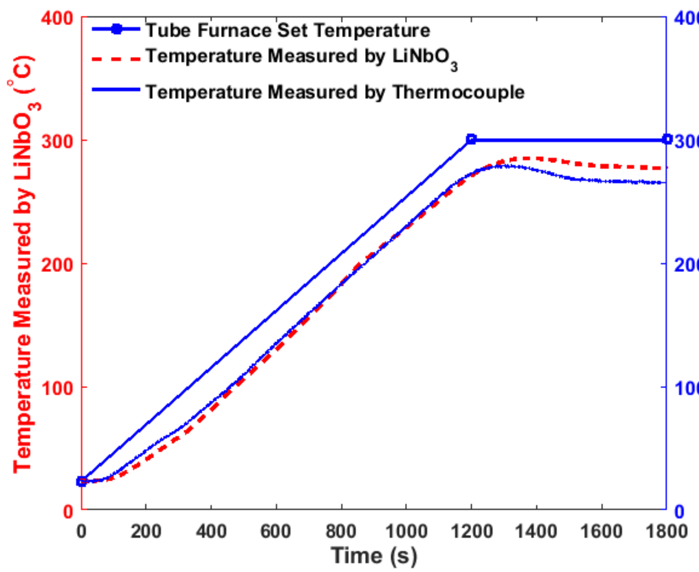
Tube Furnace

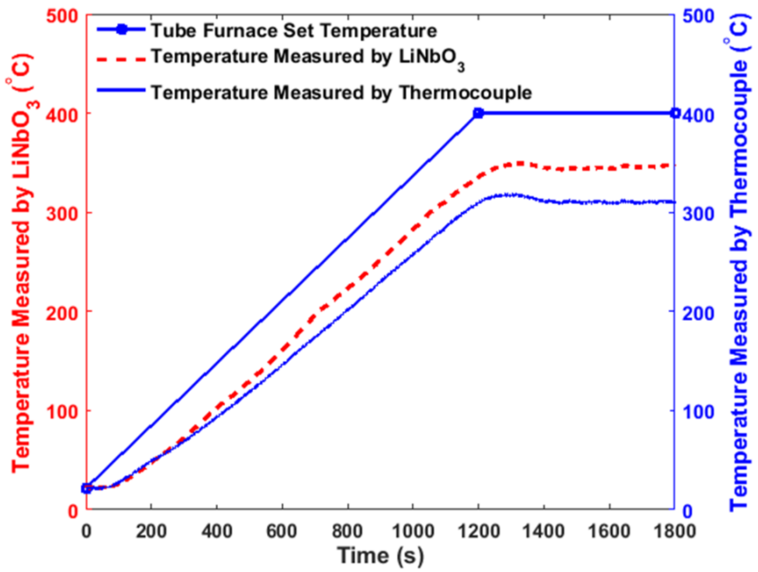
FIG. 1. Plot of the pyroelectric coefficient as a function of temperature. Triangles—dP_s/dT prior to correction for the sample resistance; circles—pyroelectric coefficient after the data had been corrected.

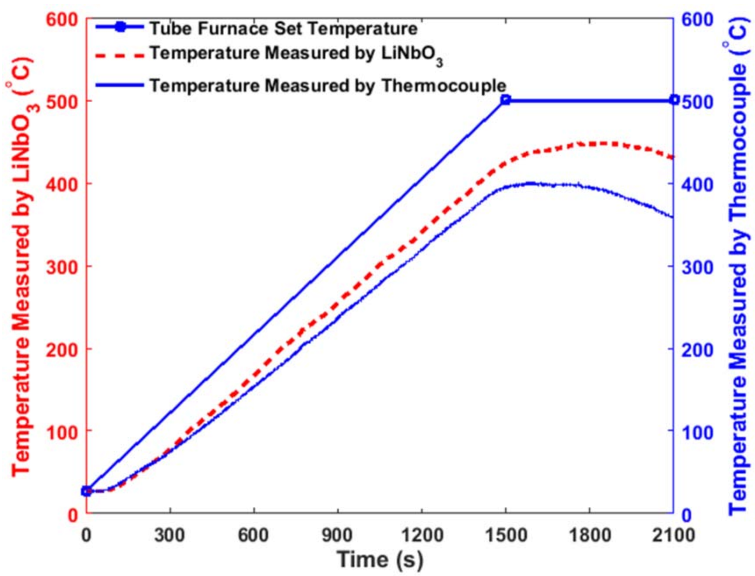


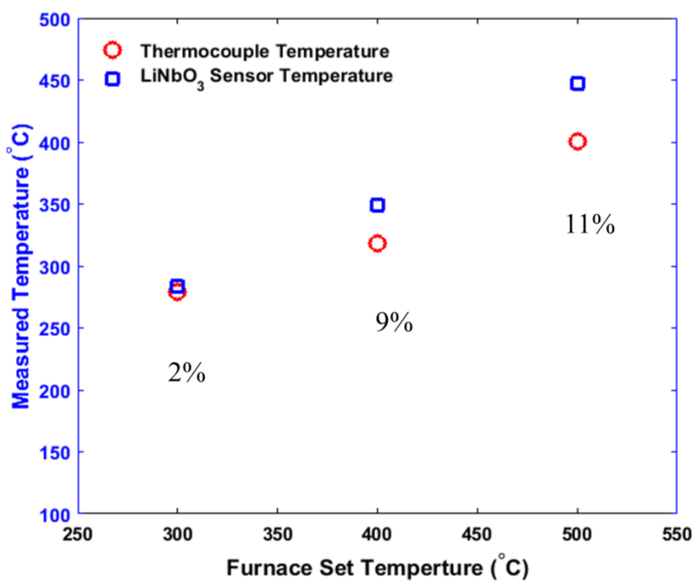
Savage, A. "Pyroelectricity and spontaneous polarization in $LiNbO_3$." *Journal of Applied Physics* 37, no. 8 (1966): 3071-3072.

Results


Tube Furnace Set Temperature
Temperature Measured by $LiNbO_3$
Temperature Measured by Thermocouple
Temperature Measured by $LiNbO_3$ (°C)
Temperature Measured by Thermocouple (°C)
Time (s)


Tube Furnace Set Temperature
Temperature Measured by $LiNbO_3$
Temperature Measured by Thermocouple
Temperature Measured by $LiNbO_3$ (°C)
Temperature Measured by Thermocouple (°C)
Time (s)

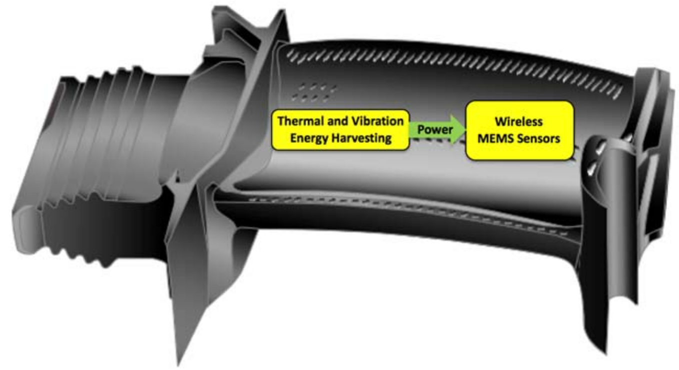

Tube Furnace Set Temperature
Temperature Measured by $LiNbO_3$
Temperature Measured by Thermocouple
Temperature Measured by $LiNbO_3$ (°C)
Temperature Measured by Thermocouple (°C)
Time (s)

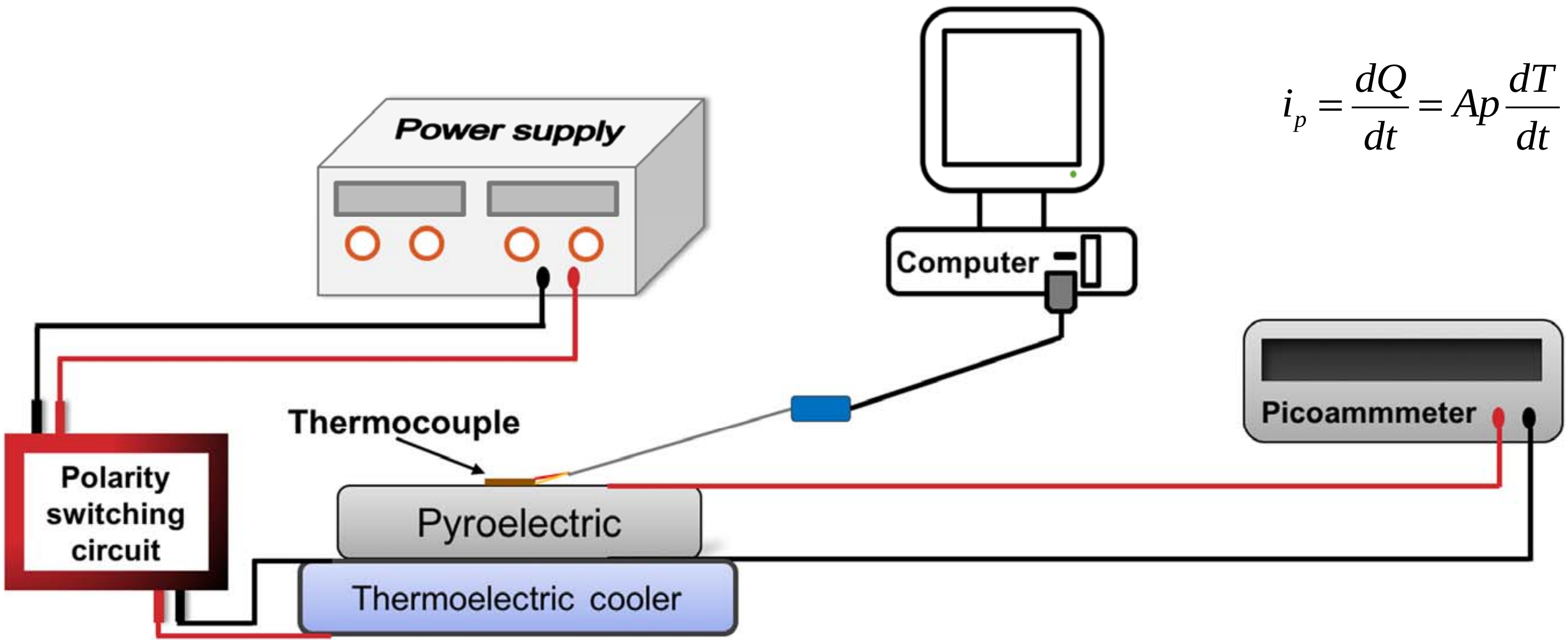

Thermocouple Temperature
$LiNbO_3$ Sensor Temperature
11%
9%
2%
Measured Temperature (°C)
Furnace Set Temperture (°C)

Development of Energy Harvesting

Direct sensing: Temperature sensing

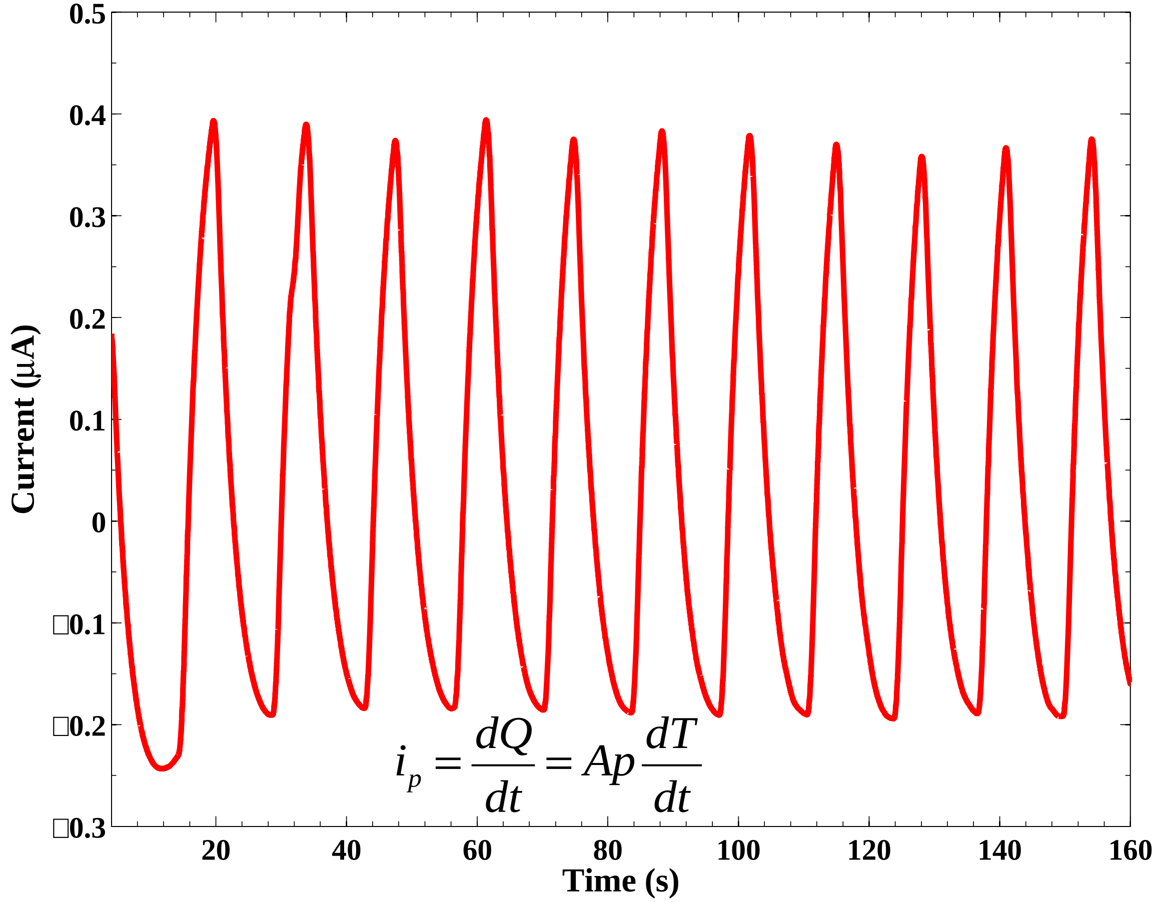
Indirect sensing: Energy harvesting





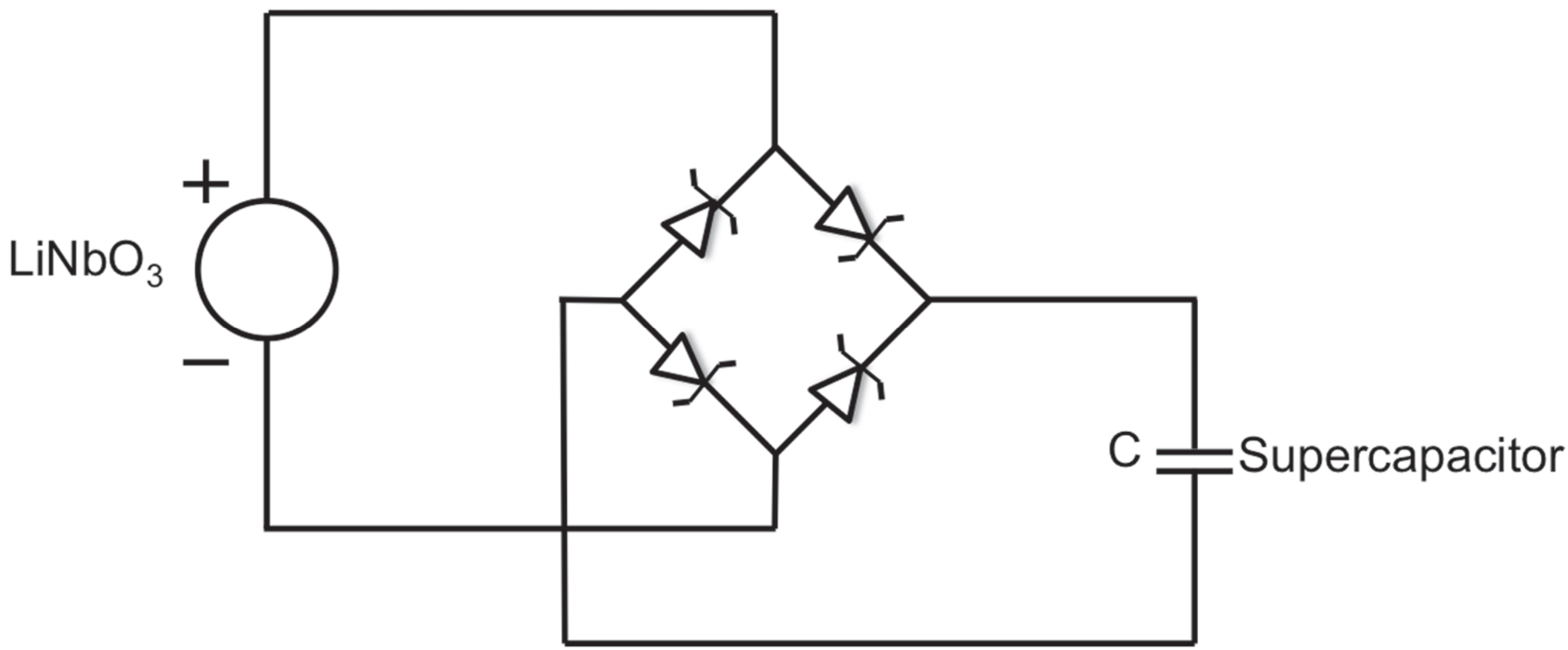
$$i_p = \frac{dQ}{dt} = Ap\frac{dT}{dt}$$

Results - Harvesting



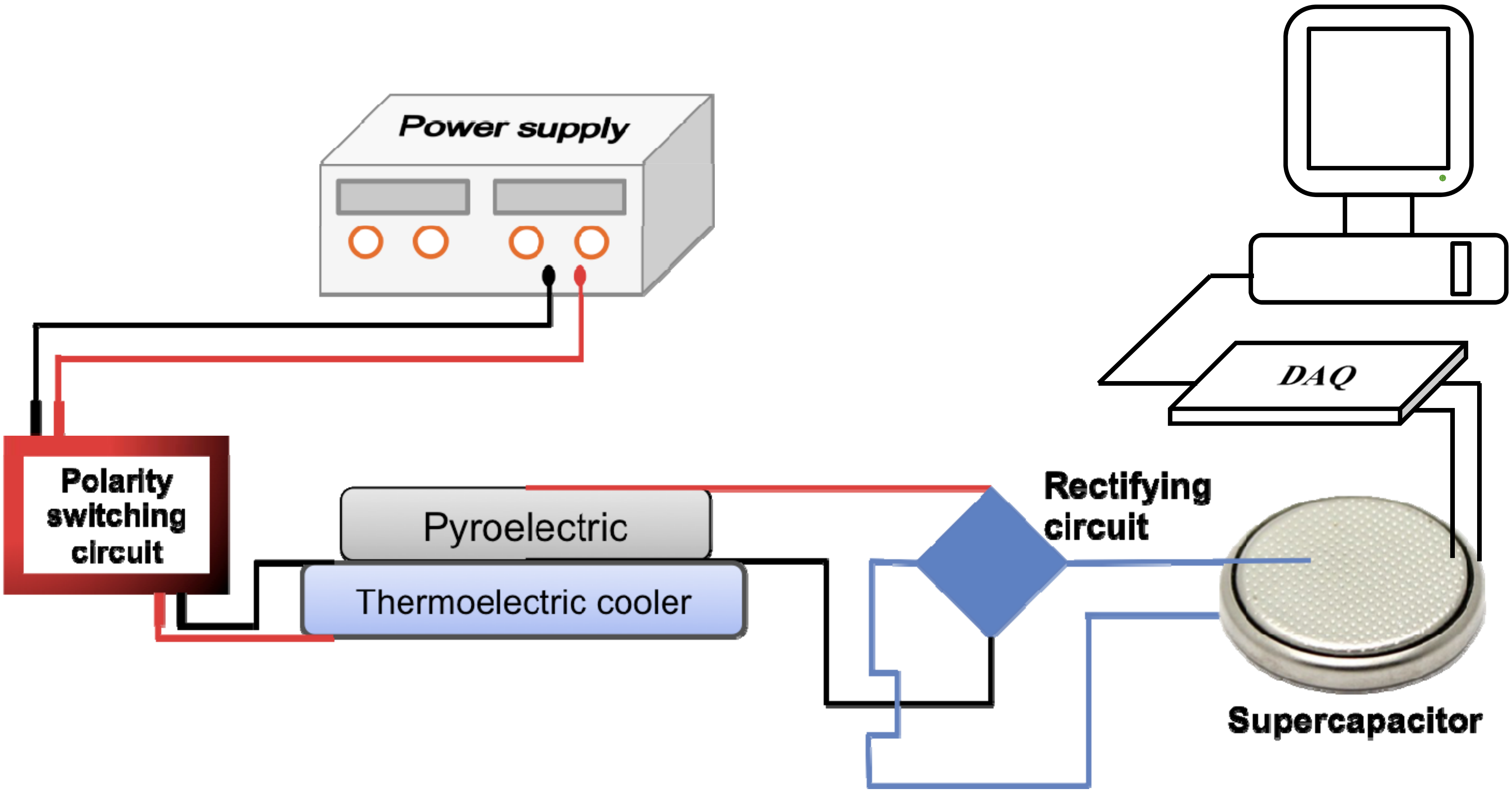
Current generated from $LiNbO_3$ with continuous heating and cooling

Results – Harvesting Circuit



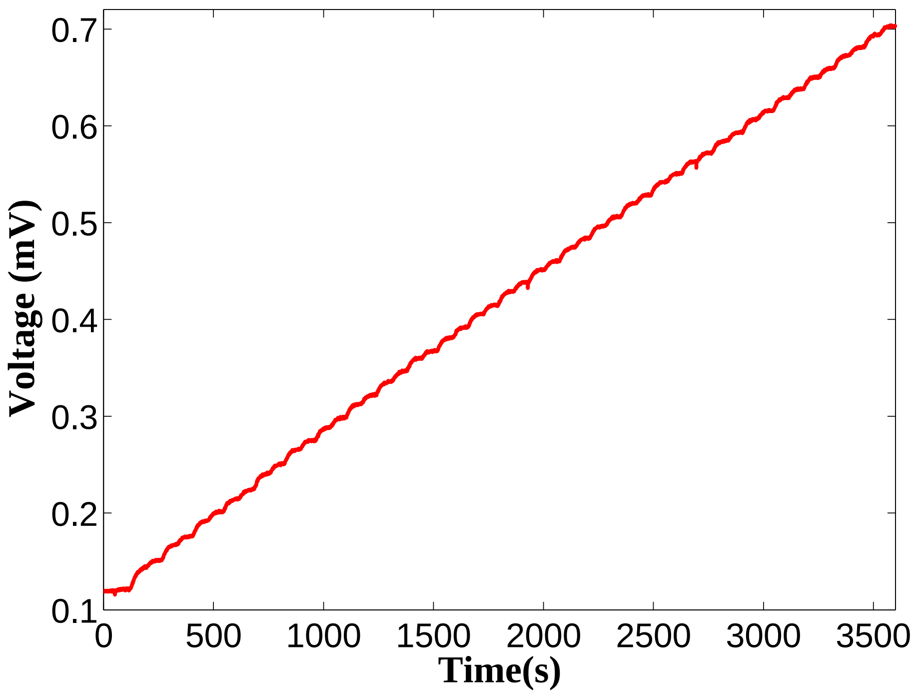
Results - Harvesting

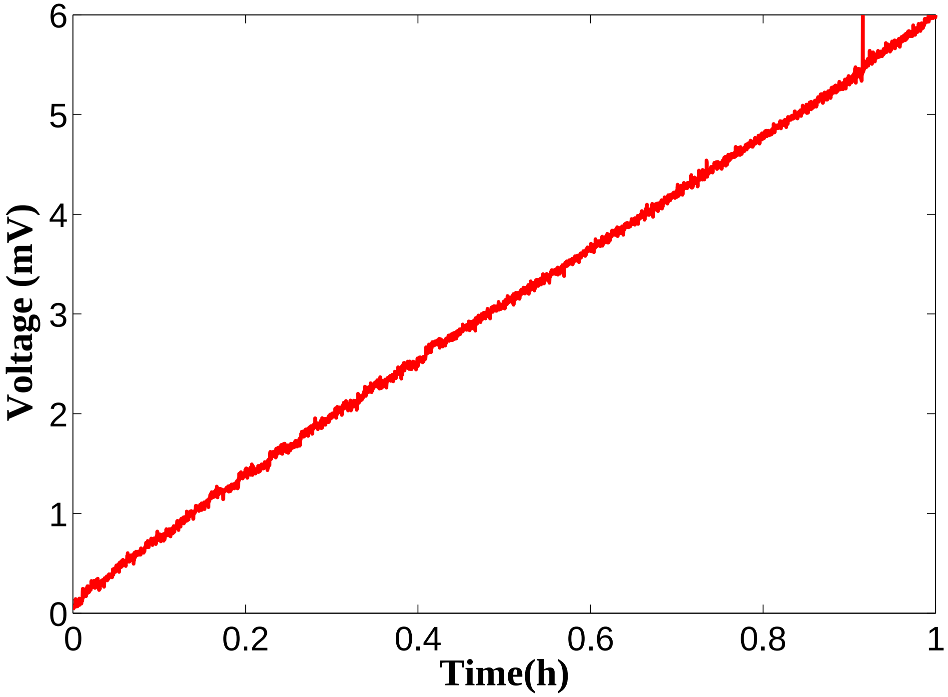
Experimental setup for Supercapacitor charging



Results - Harvesting

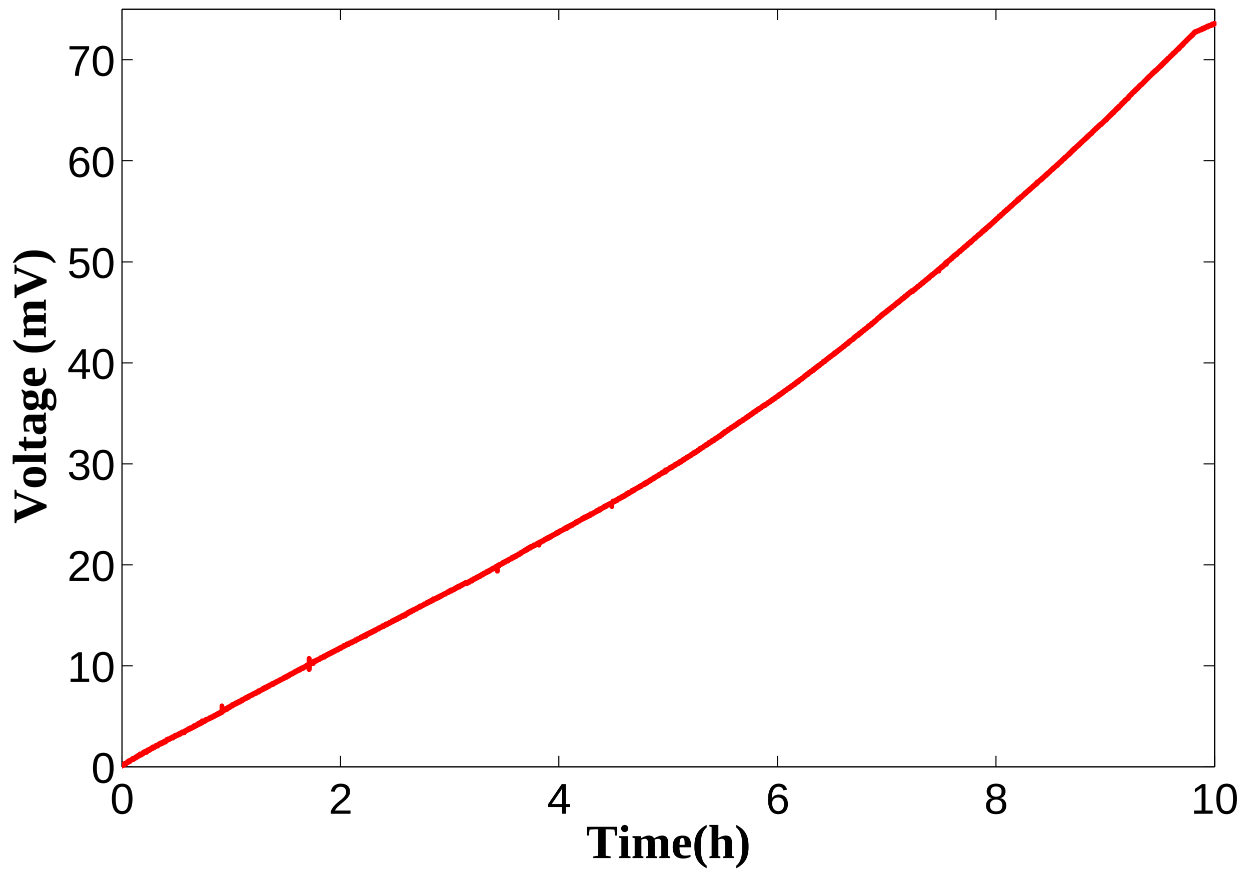
Comparison of diode NTE573 (left) vs HFA15TB60PBF (right)





Results - Harvesting

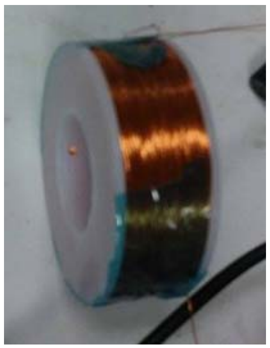
Charging commercial supercapacitor with HFA15TB60PBF diode



Technical Approach: Wireless Demonstration

Objective 4: Determine the wireless sensing performance in energy systems

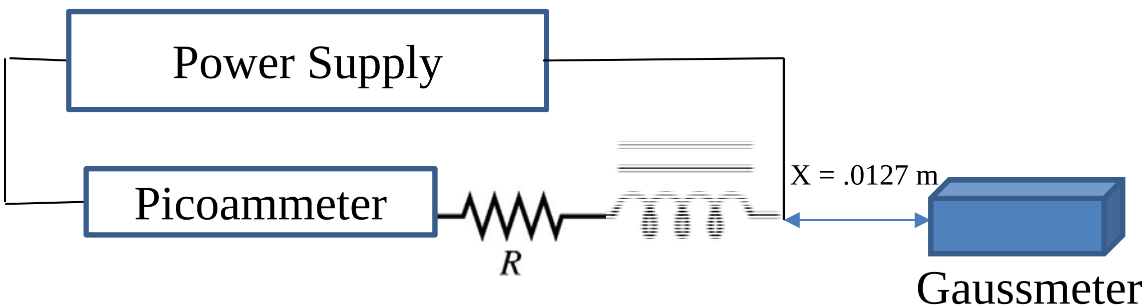
Characterizing the Coil and Gaussmeter



Length .017 m
Inner radius .0127 m
Outer radius .02413 m
Number turns 6740
Magnetic wire resistance 1100 ohm

No core material Inside the electromagnet

Applied Current.	Measured Field(milligauss)	Expected Field(milligauss)	Error %
2.50E-03	1639.2	1718.4	4.6
1.00E-03	660.5	687.36	3.91
5.00E-04	335.6	343.68	2.35
1.00E-04	77.5	68.74	12.74
5.00E-05	32.8	34.37	4.57
2.50E-05	16.7	17.18	2.79
1.00E-05	7.01	6.87	2.04
5.00E-06	3.8	3.43	10.79
1.00E-06	0.8	0.69	15.94



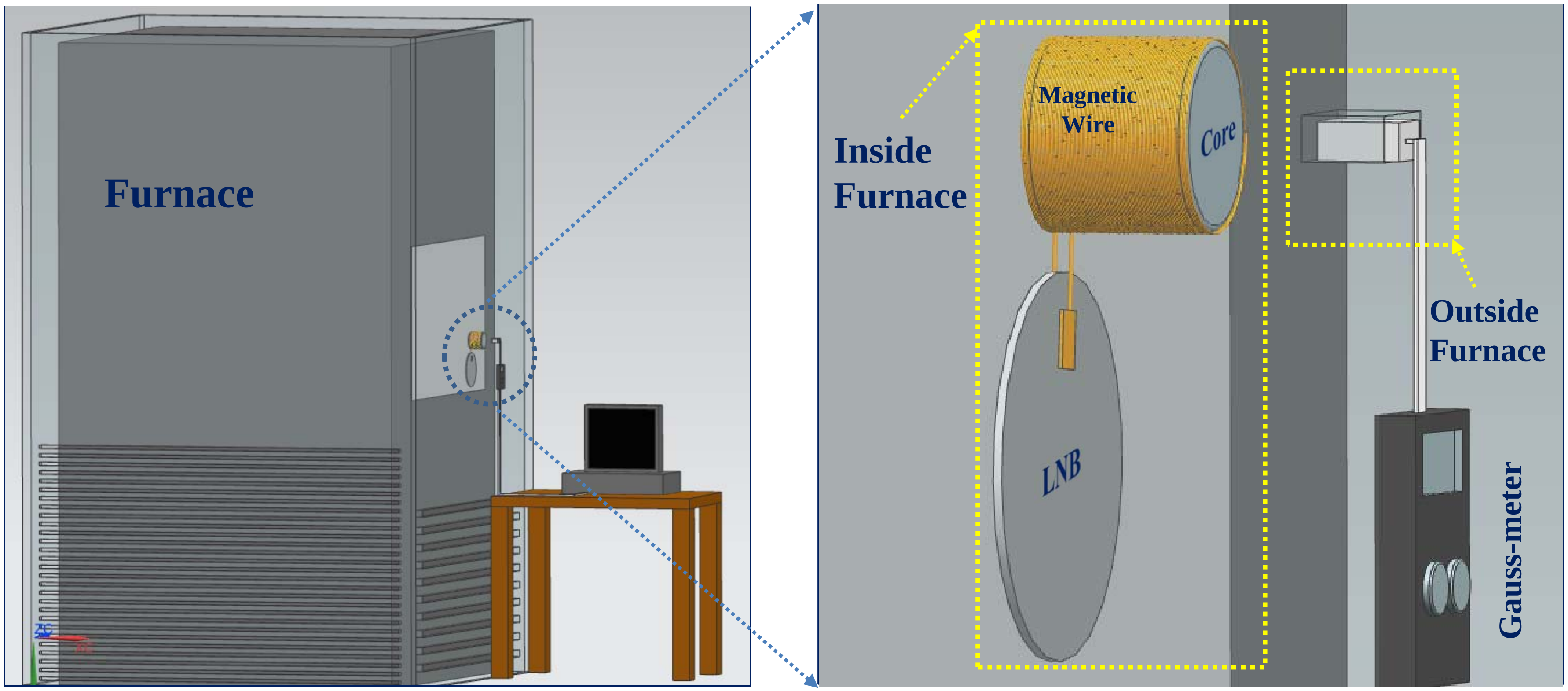
$$B = \frac{\mu_0 I N}{2L(R_2 - R_1)}\left[(L+x)\ln\frac{\sqrt{R_1^2+(L+x)^2}+R_2}{\sqrt{R_1^2+(L+x)^2}+R_1} - x\ln\frac{\sqrt{R_2^2+x^2}+R_2}{\sqrt{R_2^2+x^2}+R_1}\right]$$

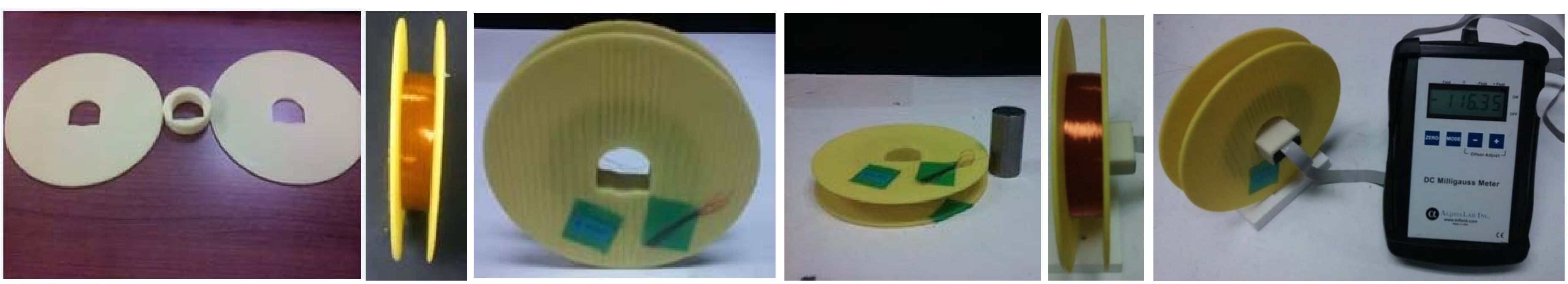
Wireless Sensing Approach

- Challenges
  - Low Magnetic field generated in the inductor coil
- Probable solutions
  - Increase the current generated by having a larger sample or stacking multiple samples together
  - Proof of wireless sensing concept using PZT-5H for low temperature applications

Future Work

- ❑Demonstration of wireless sensing mechanism





Future Work

- A simple inductance-Hall Sensor based wireless sensing mechanism
- Demonstrate effectiveness of wireless temperature sensing
- Energy harvesting at elevated temperature (> 500 ℃)
- Optimization of the energy harvesting circuit
- Evaluate different types of energy storage units (regular capacitors and supercapacitors) to find out more suitable options for low energy harvesting

Conclusion

- A lithium niobate ceramic with high Curie temperature (1142 °C) material is selected
- Hall Effect sensor was constructed and tested to measure the magnetic flux remotely through various distances and through various materials
- 1 cm x 1 cm sample of lithium niobate material with two different thicknesses (1mm and 2 mm) were characterized in terms of current generation
- Measured current from lithium niobate is compared with the theoretical current. The comparison satisfies the definition of pyroelectricity
- Pyroelectric current from the lithium niobate ceramic material due its change of temperature is taken into consideration to calculate the sample temperature
- A commercial supercapacitor of 0.2F were charged using the current generated from $LiNbO_3$
- It's possible to improve the amount of energy harvested by improving the harvesting circuit design and circuit elements

Publications and Patent

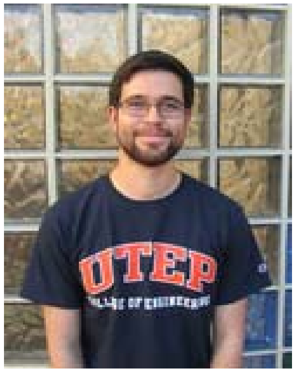
1. Sarker, R., Karim, H., Martinez, R., Love, N. and Lin, Y., "**A Lithium Niobate High Temperature Sensor for Energy System Applications**," IEEE Sensors, revision in preparation.
2. Karim, H., Sarker, M., Shahriar, S., Shuvo, M., Delfin, D., Hodges, D., Tseng, T., Roberson, D., Love, N., and Lin, Y., 2016. "**Lead free pyroelectric energy harvesting**", Journal of Smart Materials and Structures, in press.
3. Sarker, MD, Karim, H., Martinez, R., Delfin, D., Enriquez, R., Shuvo, M., Love, N., and Lin, Y., 2015, "**Temperature measurements using a lithium niobate ($LiNbO_3$) pyroelectric ceramic**," Measurement, 75, 104-110.
4. US provisional patent, **"SYSTEMS AND METHODS FOR WIRELESS TEMPERATURE SENSING"**
5. Sarker, M., Karim, H., Martinez, R., Delfin, D., Enriquez, R., Shuvo, M., Love, N., and Lin, Y., 2015, "**Temperature Measurement Using a Lithium Niobate Pyroelectric Ceramic**", 5th Southwest Energy Science and Engineering Symposium, April 4, El Paso, TX
6. Sarker, M., Sandoval S., Love, N., and Lin, Y., 2014, "**Development of a Wireless Temperature Sensor using a Lithium Niobate Pyroelectric Ceramic**", 4th Southwest Energy Science and Engineering Symposium, March 22nd, El Paso, TX

Acknowledgements

- This research was performed with the support of the U. S. Department of Energy advanced fossil resource utilization research under the HBCU/MI program with grant number of **FE0011235** Project Manager: **Richard Dunst**

- Student Involvements




THANK YOU