Thermo-Acoustic Simulation of a Piezoelectric Transducer for Interstitial Thermal Ablation with MRTI Based Validation

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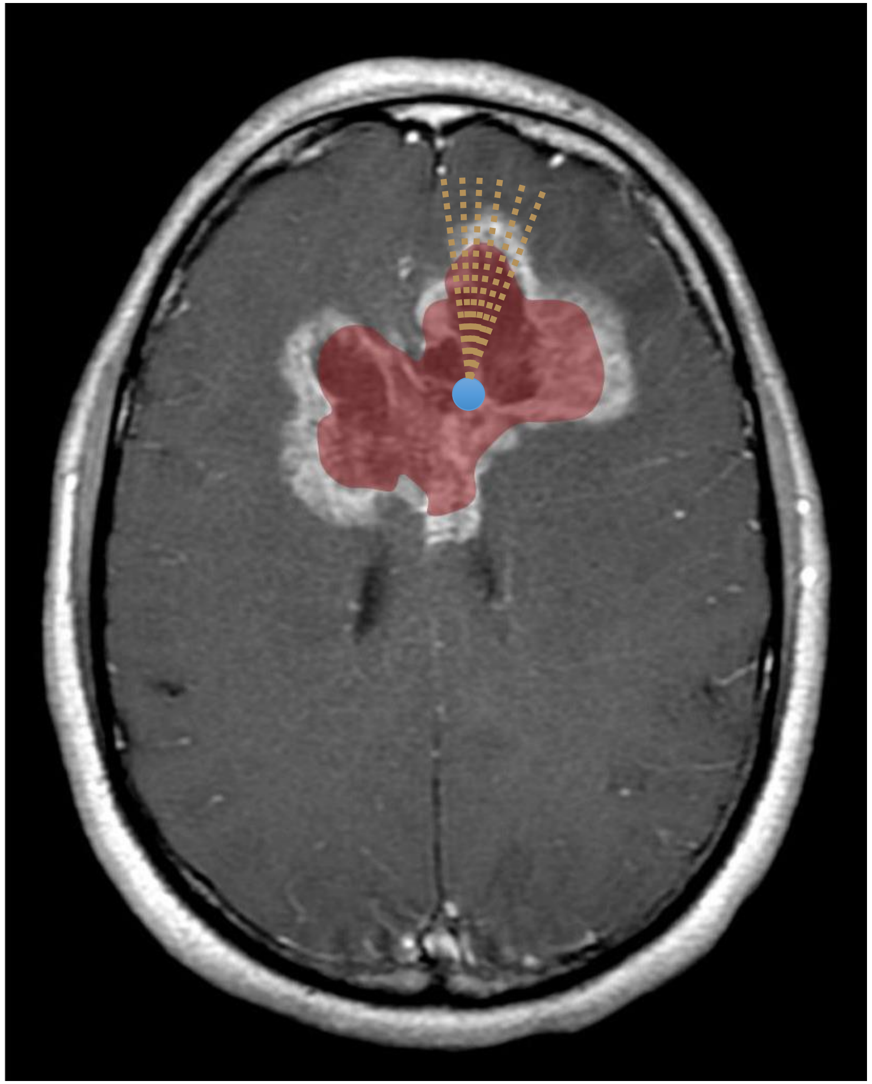
In collaboration with:

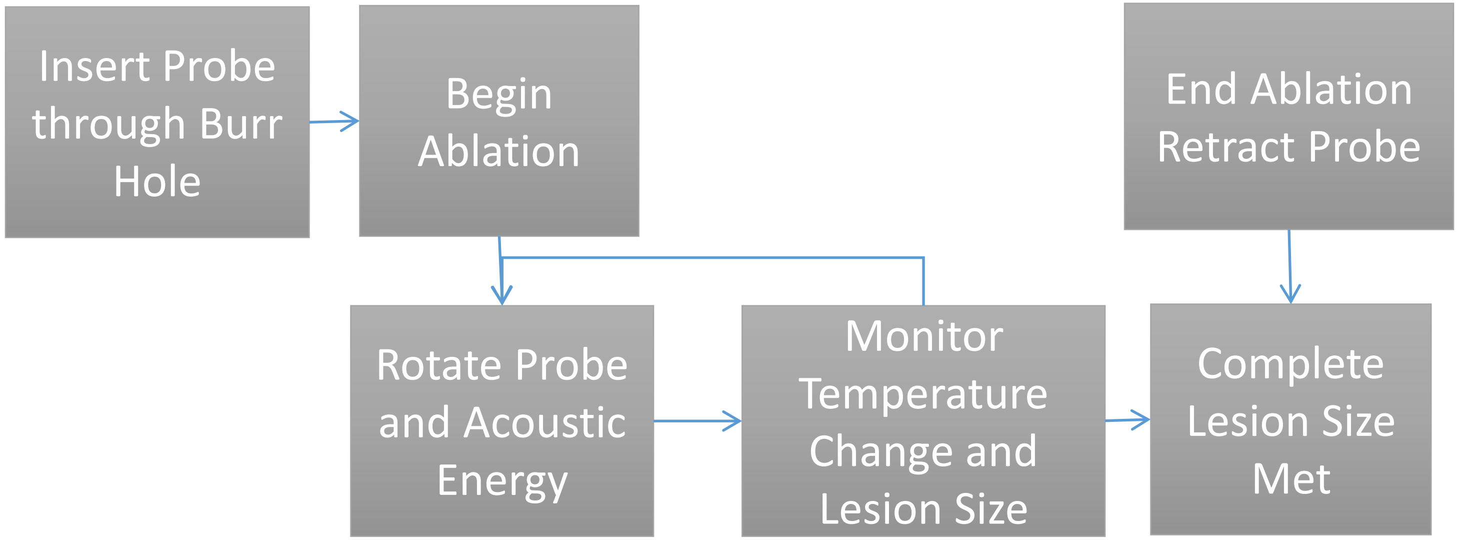
Interventions in Brain Cancer

- **Primary Objective of Cancer Treatment**
  - Remove all malignant cells while conserving healthy tissue
- **Achieving appropriate margins is vital for reducing remission [1]**
  - Tumor location, size, shape, and visibility can make this more difficult
- **Deep Brain Malignancies**
  - Unsuited for Conventional Surgical Intervention Require Other Treatment Options
    - Chemotherapy
    - Brachytherapy
    - Immunotherapy
    - Thermotherapy
    - Others

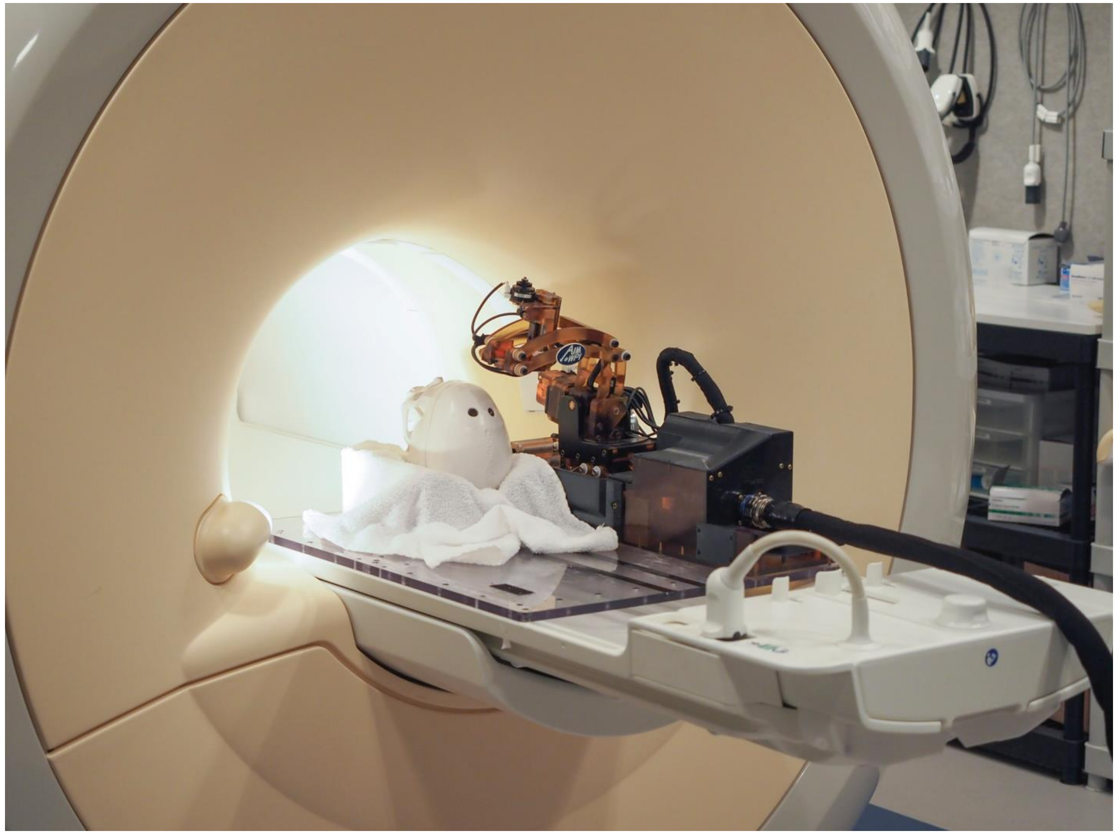
Conformal Ablation



- **Needle Based Therapeutic Ultrasound (NBTU)**
  - Cylindrical Segmented Piezoelectric Transducer
    - Produces directed ultrasound
    - Localized heating caused by absorbed acoustic energy
  - Rotating produced beam for Conformal Ablation
    - Thermal dosage can be monitored using MRTI

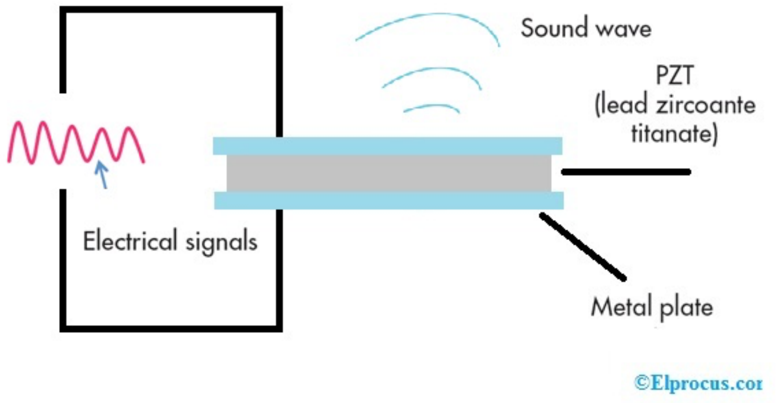


MRI Compatible Surgical Robots

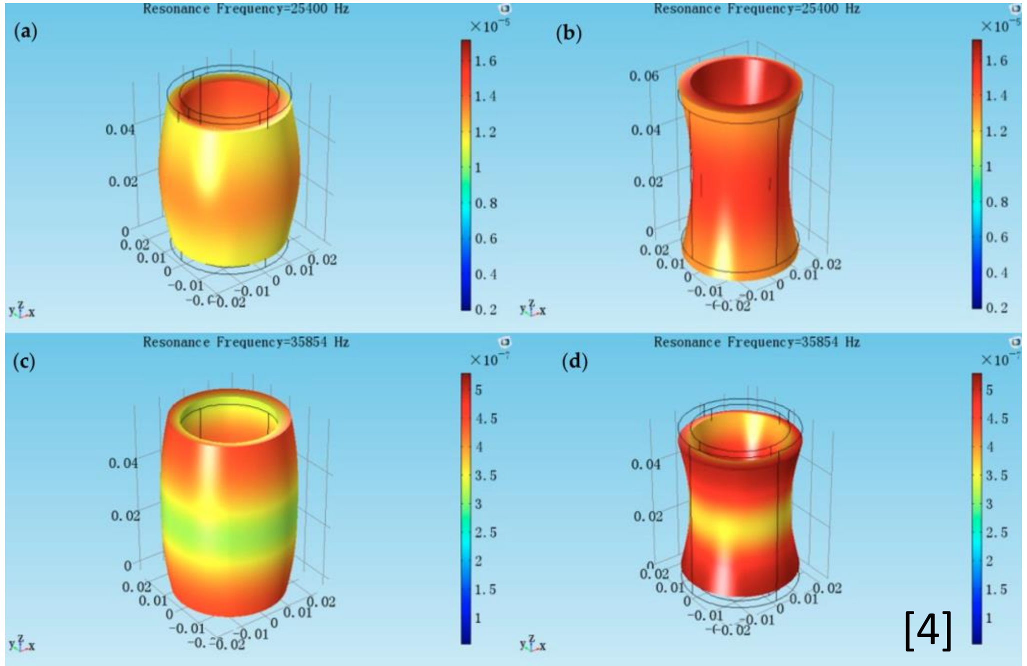


- **MRTI Compatible Robotics for NBTU [2]**
  - Accurate Probe Placement
  - Precise Rotation Control of Acoustic Beam
- **Towards Closed Loop Ablation Control**
  - Robotic Path Planning
  - Model Based Thermal Propagation
  - MRTI Feedback
- **COMSOL 5.3a Simulation of NBTU Probe**
  - Two Dimensional Model of Static Probe
  - Experimental Validation

Operating Principles of Piezoelectric Transducers



[3]



[4]

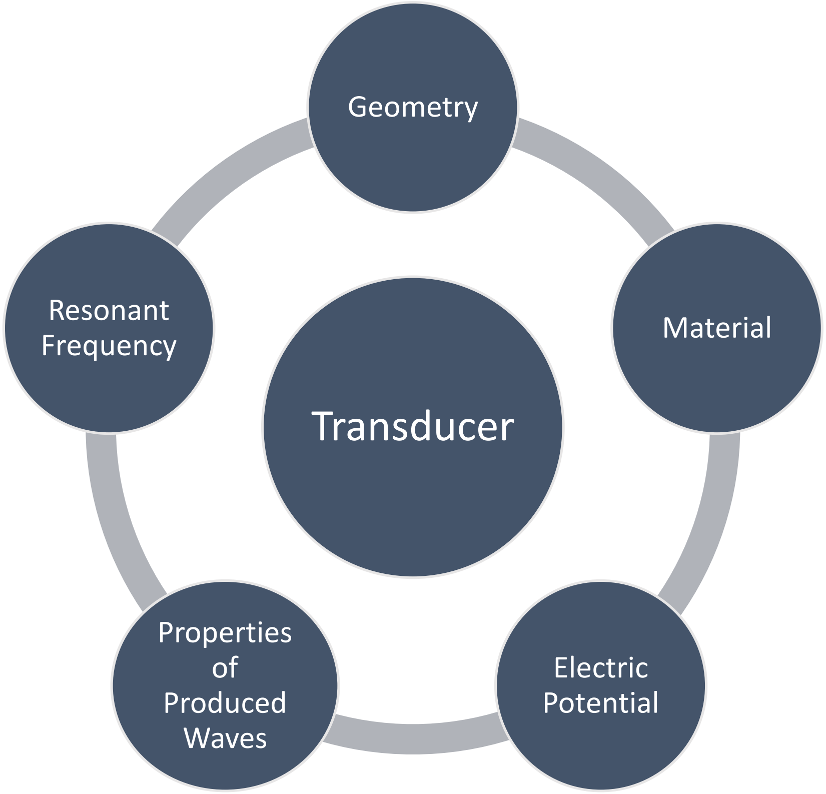
- **Inverse Piezoelectric Effect**
  - The capability of certain materials to strain when subject to an electric potential.

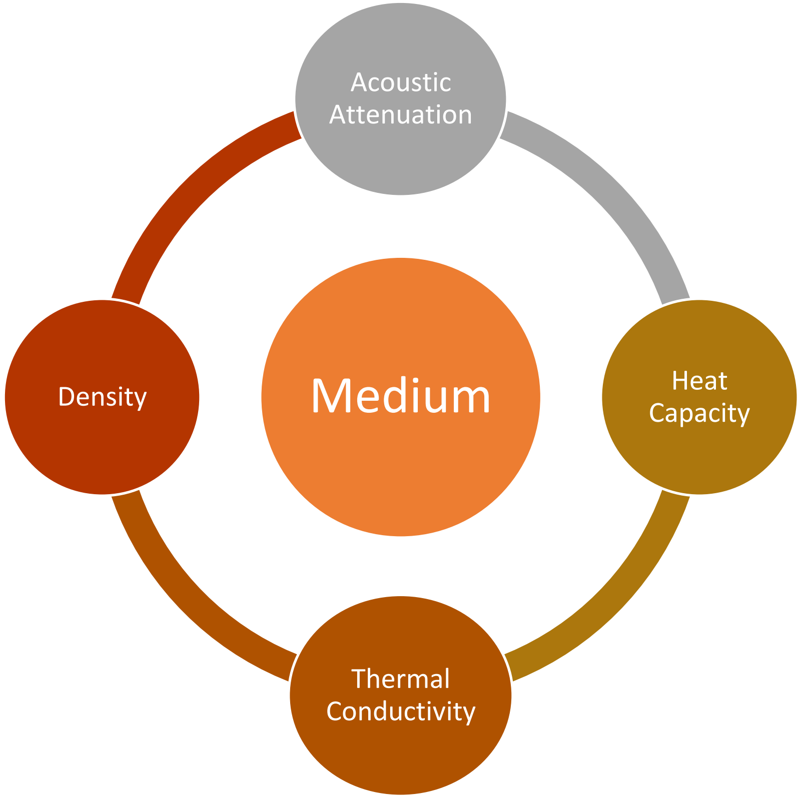
- **Cylindrical Transducers**
  - Rapid oscillating deformation under applied alternating field

- **Produces Acoustic Waves**
  - Transducers geometry and material determines ideal resonant frequency and wave properties such as beam shape, directionality, and intensity

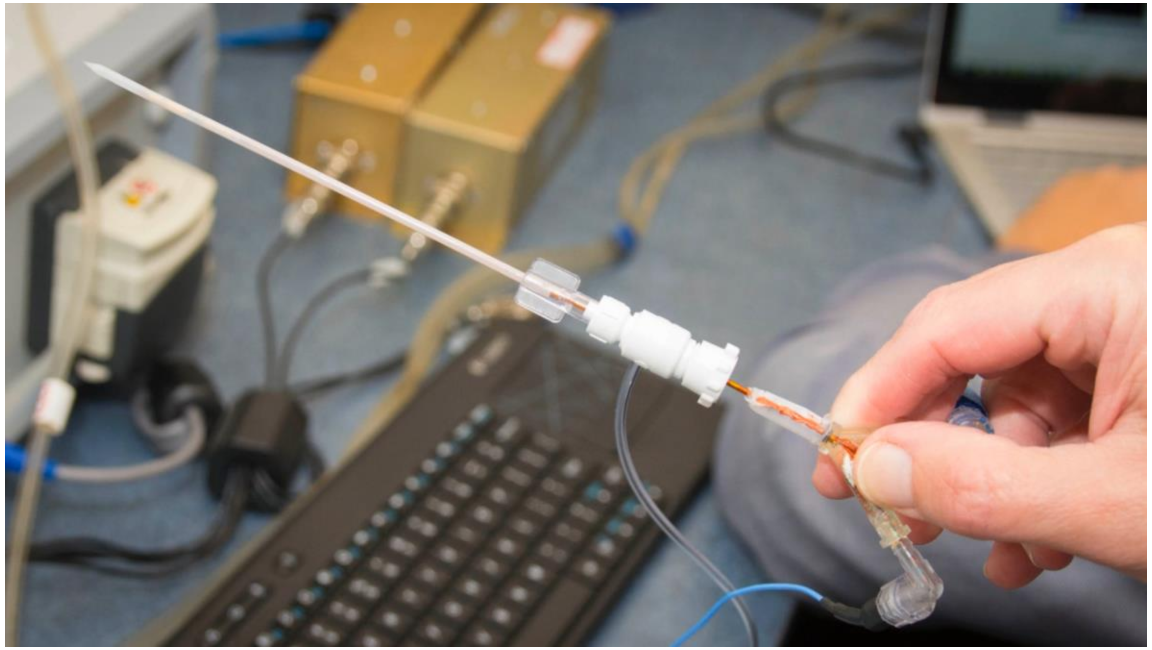
Characterizing Thermal Propagation

- Absorption of Produced Acoustic Waves produces localized heating
- Key Properties of the Transducer and Medium determine the change in temperature by NBTU probe

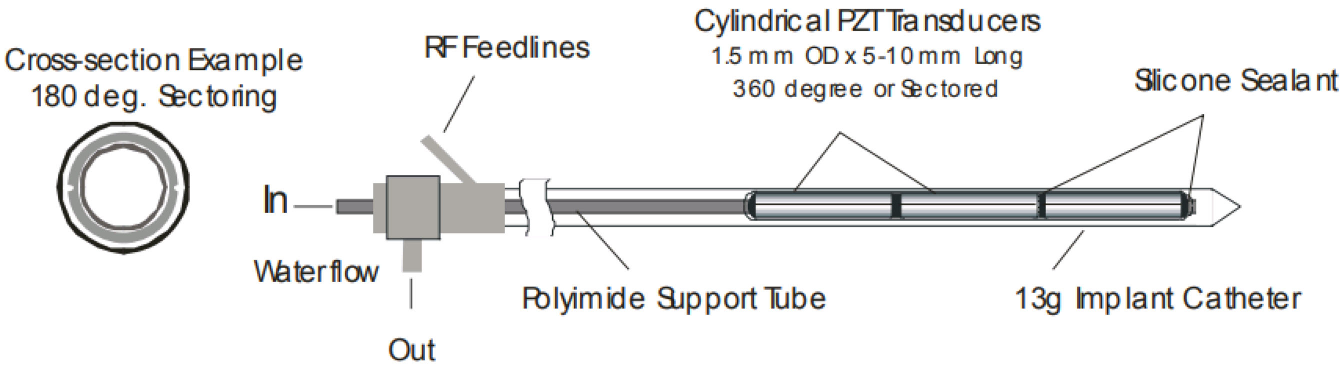




Needle Based Therapeutic Ultrasound (NBTU) Probe



- **NBTU Probe Acoustic MedSystems (AMS) Inc.**
  - Probe Specifications:
    - 1.55 mm OD x 10mm PZT-4 Transducer
    - Notched 90° Sectored Probe

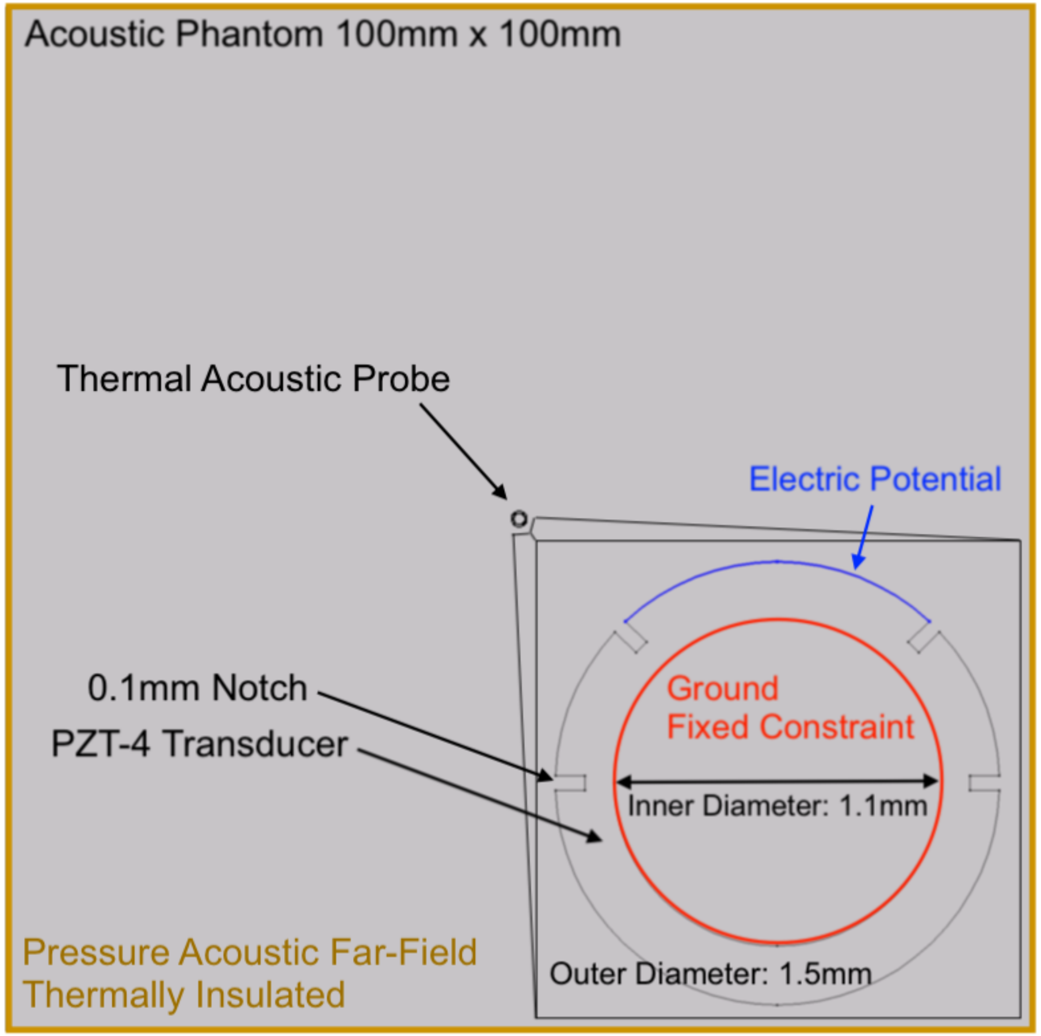


TheraVision Tabletop System

Acoustic MedSystems TheraVision Integrated Interventional System

COMSOL 5.3a Simulation – Model Setup

Model Setup



- **2D COMSOL Component**
  - Built in Geometry Tools
- **NBTU Transducer Design**
  - Difference of two concentric circles
  - Four notches producing a 90 and 180 degree segments
  - Lead Zirconate Titanate (PZT-4)
- **Acoustic Medium**
  - 100mm x 100mm square
  - Blank Material with Properties based on [5]
    - Heat Capacity at Constant Pressure: 3451 J/(Kg*K)
    - Thermal Conductivity: 0.53 W/(m*K)
    - Density: 1058 Kg/m^3
    - Speed of Sound in Medium: 1551 $m/s

COMSOL 5.3a Simulation – Physics Interfaces

- **Acoustic Piezoelectric Interaction – Frequency Domain Multiphysics**

Physics Interfaces

Solid Mechanics

- Piezoelectric Material
- Fixed Constraint
- Probe Poling by applying a Cylindrical Base Coordinate System

Electrostatics

- Applied to NBTU Probe
- 7.8V Applied to 90 degree segment
- Inner circumference defined as ground

Pressure Acoustics

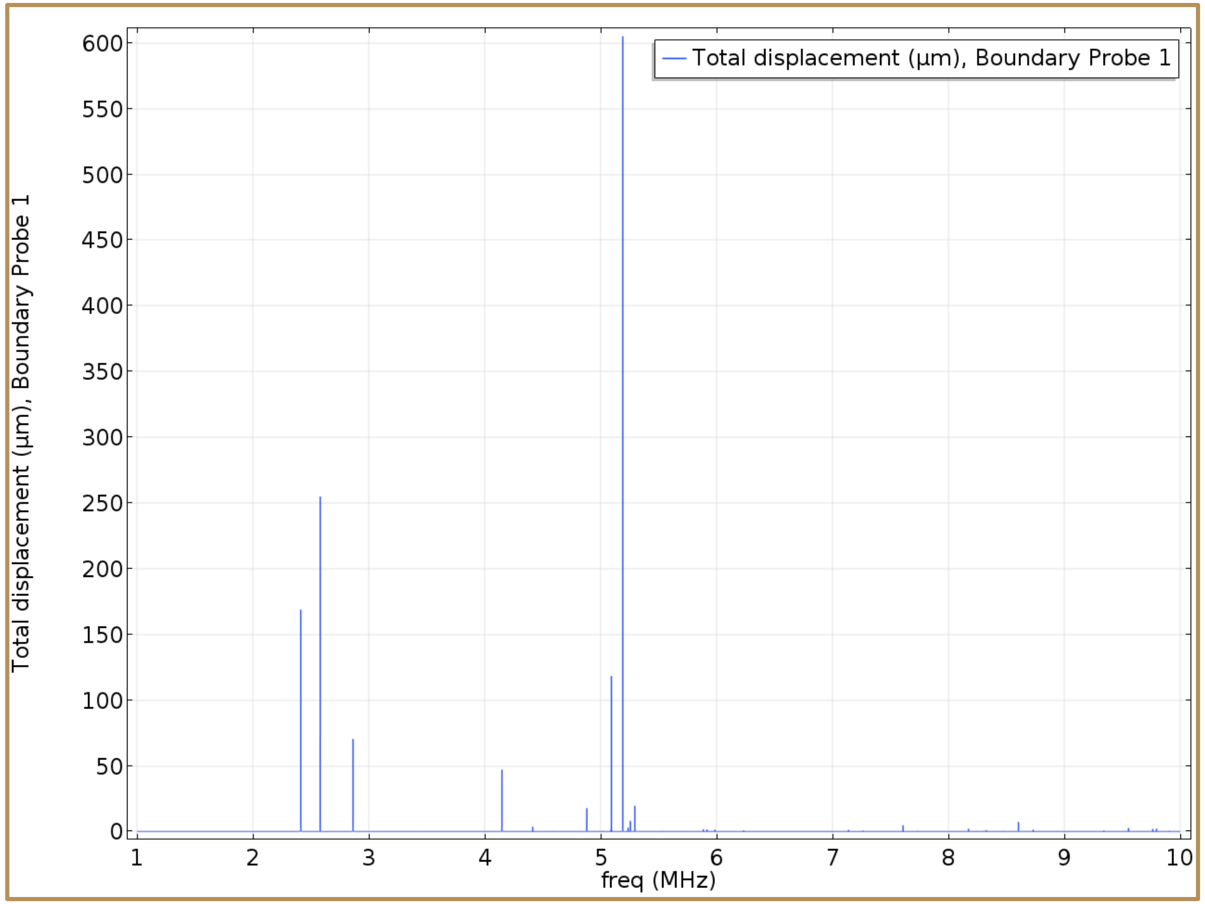
- Applied to Acoustic Medium
- Attenuation Coefficient of 31.96 Np/m
- Far-field and Cylindrical Radiation

Bioheat

- User Defined Heat Source
- Q = acpr.Q_pw ∗ step(t−t_probeOn)
- Penne’s Bioheat Transfer Equation

COMSOL 5.3a Simulation – Resonant Frequency

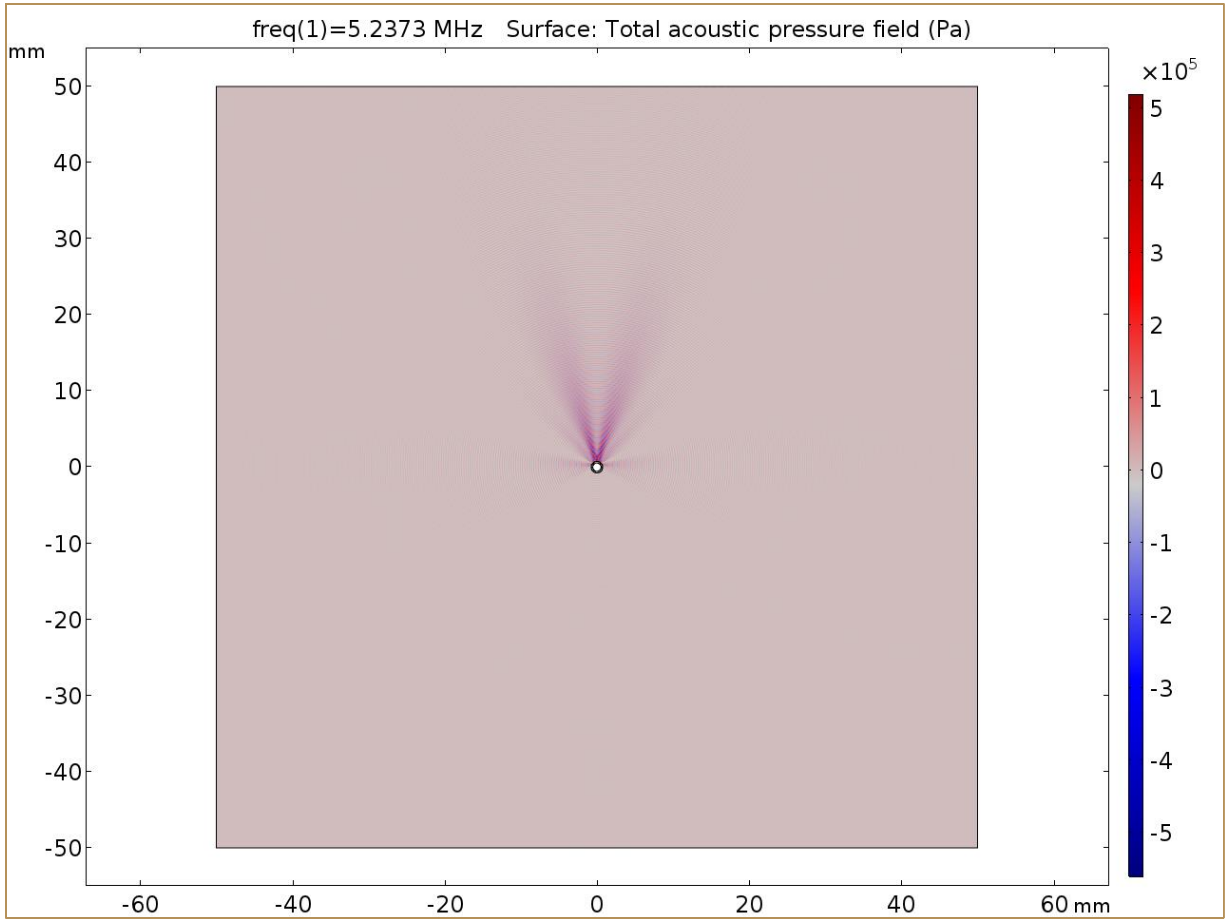
Frequency vs Probe Deformation



- **Resonant Frequency, or Natural Frequency**
  - Amplitude of probe deformation is at a relative maximum
- **COMSOL Boundary Probe**
  - Measuring total displacement of the probe on the outer circumference of the transducer
- **Frequency Domain Study**
  - Sweep from 1MHZ to 10MHz at 0.1 kHz steps
  - Solid Mechanics and Electrostatics Interfaces
  - Qualitative analysis of peaks based on intensity and direction
  - Resulting selected resonant mode was 5.237 MHz

COMSOL 5.3a Simulation – Acoustic Pressure Field

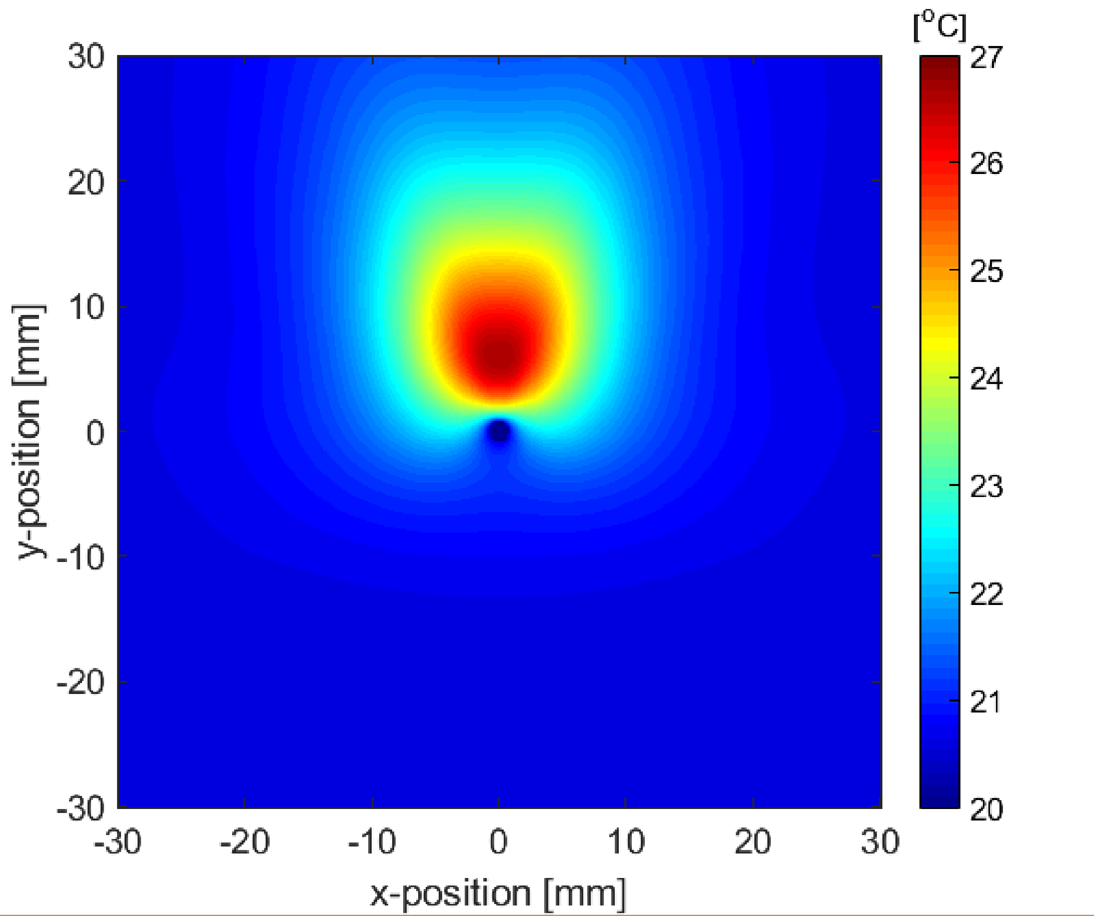
Acoustic Pressure Field



- **Acoustic Pressure Field**
  - Used to derive Acoustic Intensity
  - Used to Calculate Thermal Propagation
- **Frequency Domain Study**
  - Study conducted at resonant mode
  - Pressure Acoustics, solid mechanics, and electrostatics interfaces
  - Results depict a focused 90 degree beam

COMSOL 5.3a Simulation – Thermal Propagation

Thermal Propagation (240 seconds of insonation)

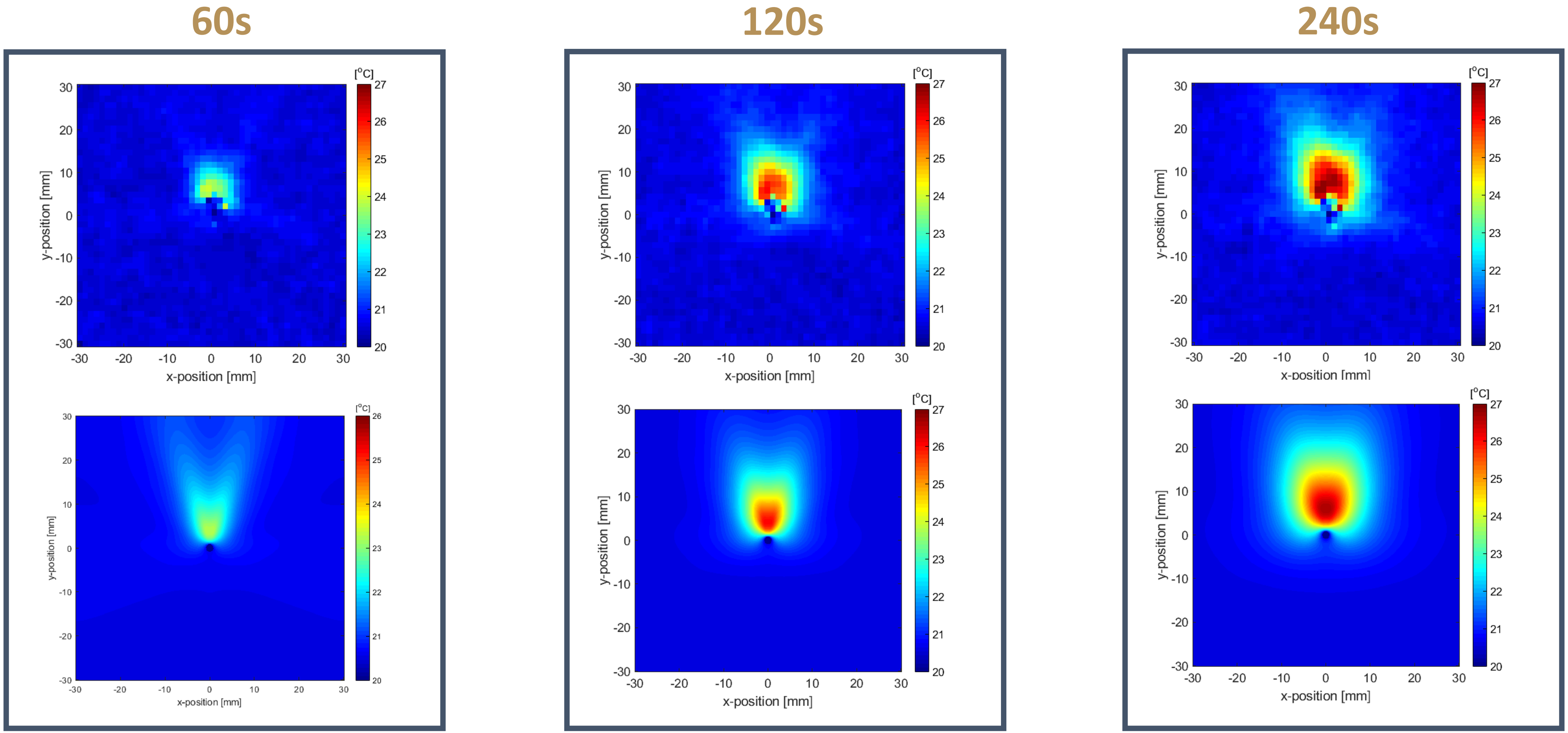


- **Time Domain Study**
  - Bioheat Transfer interface
  - Previous study used as a dependent variable
  - Study Conducted over 480 seconds
    - First 240 seconds the transducer was ON
    - Second 240 seconds the transducer was OFF

Experimental Setup

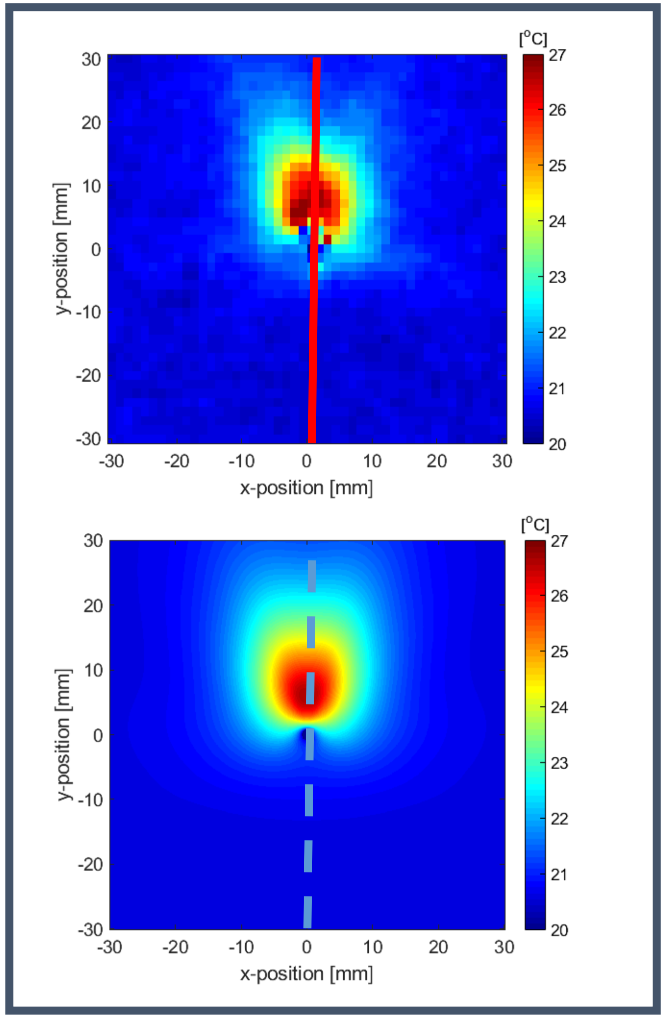
- **Acoustic Phantom Based in [5]**
- **NBTU Probe and Phantom Placed in MRI**
  - Achieva 3T (Philips, USA)
  - Two Flex Coils
  - FFE-EPI at 1.5mm cubed voxels
  - MRTI Data Collected
- **4 Minutes Ablation with 4 Minutes Cooling**

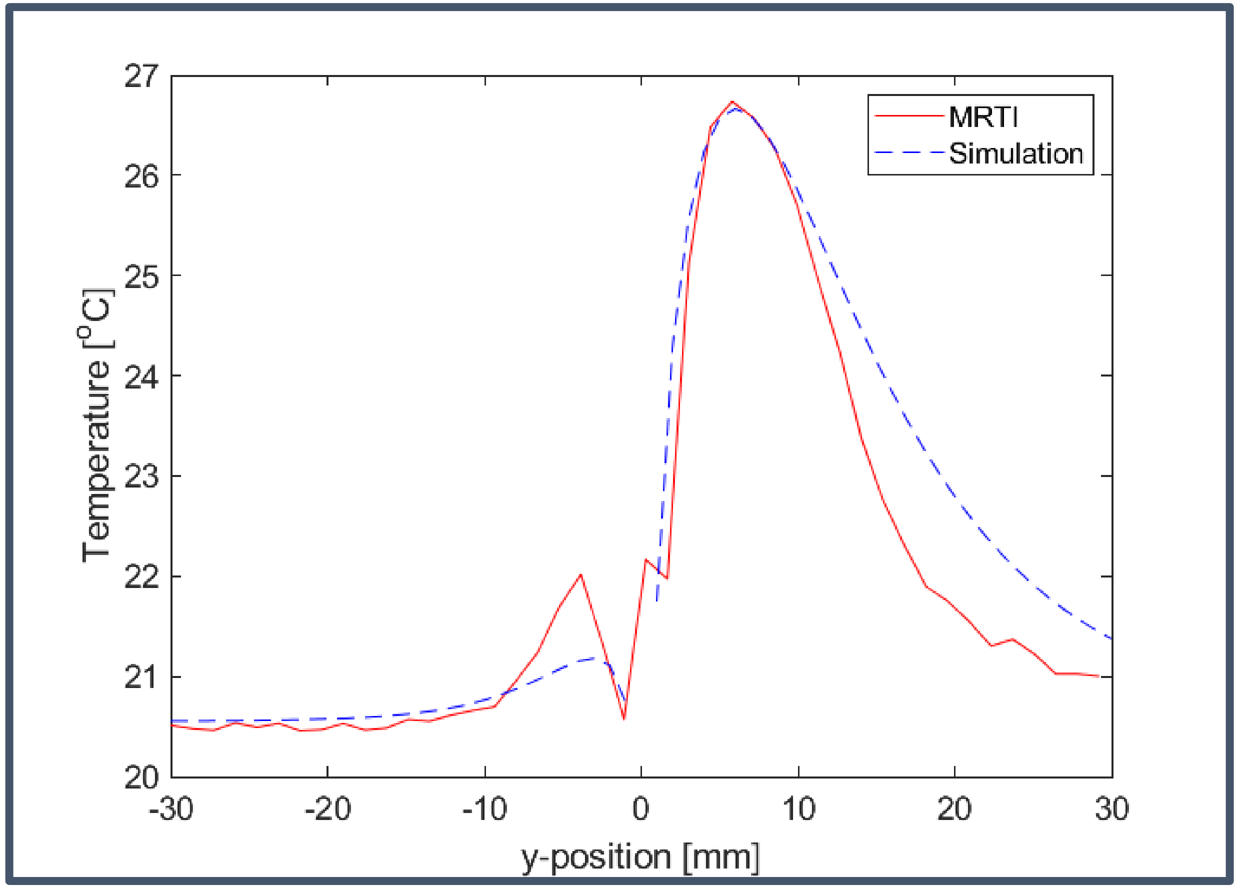
MRTI Result Comparison



MRTI Result Comparison

240s





- **RMS Error: 0.53 °C**
- **Maximum Difference: 1.54 °C**

Conclusion and Future Work

- **Multiphysics simulation of an NBTU Probe**
- **Studies conducted to calculate thermal heating**
- **Experimental validation of thermal propagation under MRTI**
- **Future Work:**
  - Explore 3D Modeling of Transducer
  - Develop Dynamic Models of Rotating Probe
  - Closed Loop Control with MRTI Feedback for Surgical Robot Systems
  - Non-static material properties and blood perfusion

Questions ?

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References

- **[1]** Lacroix, M. et al. A multivariate analysis of 416 patients with glioblastoma multiforme: prognosis, extent of resection, and survival.J.neurosurgery 95, 190–198 (2001).
- **[2]** Nycz, C. J. et al. Mechanical validation of an mri compatible stereotactic neurosurgery robot in preparation for pre-clinical trials. In 2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS),1677–1684 (IEEE, 2017).
- **[3]** https://www.elprocus.com/what-is-the-piezoelectric-effect-working-and-its-applications/
- **[4]** Xu, Jie, et al. "Analysis on coupled vibration of a radially polarized piezoelectric cylindrical transducer." Sensors 17.12 (2017): 2850.
- **[5]** Farrer, A. I. et al. Characterization and evaluation of tissue-mimicking gelatin phantoms for use with mrgfus.J. therapeutic ultrasound 3, 9 (2015).