RYERSON UNIVERSITY

Ultrasound Mediated Imaging Methods For Electrical Properties Of Biological Tissues

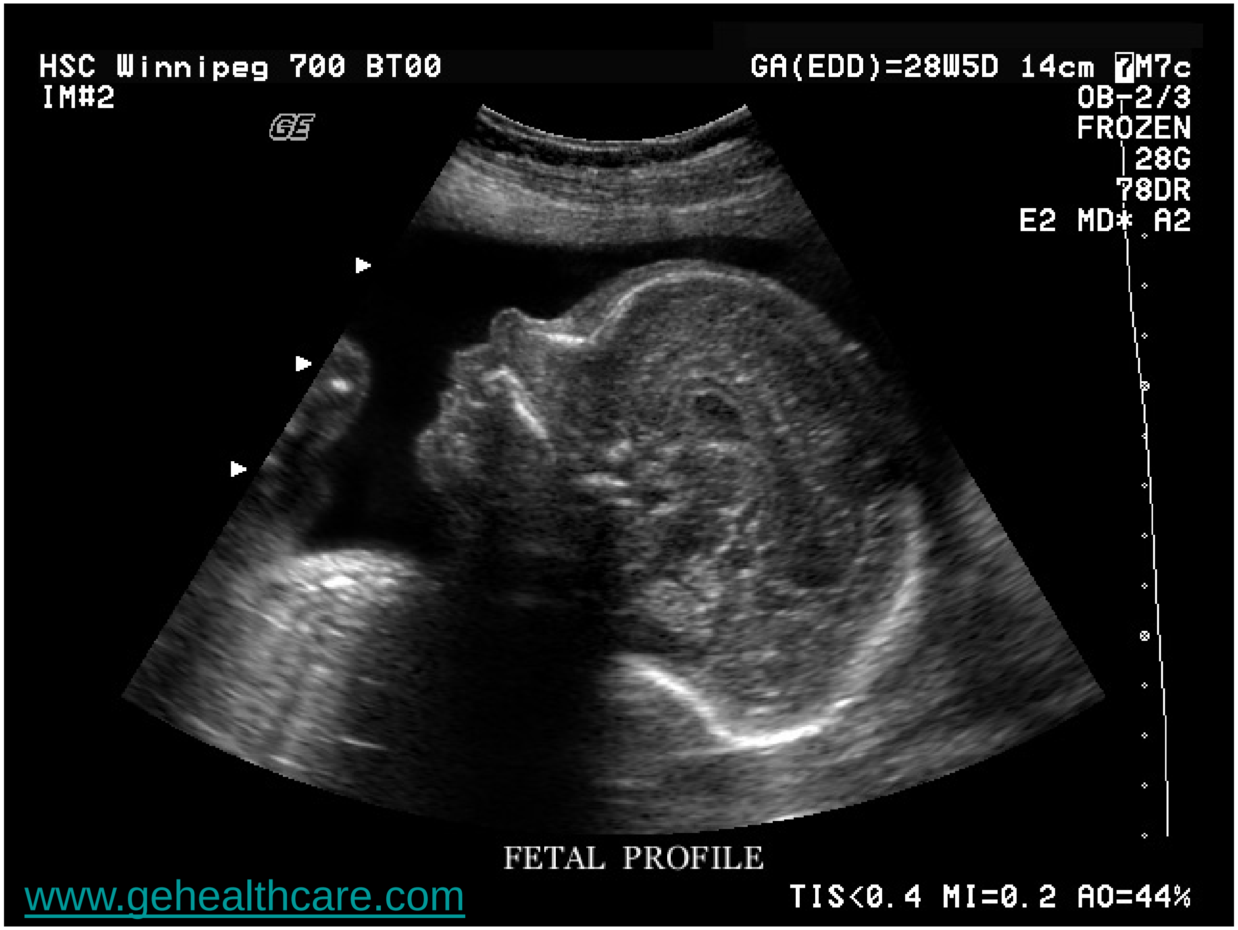
Ryerson University

Department of Physics

Laboratory of Ultrasound mediated imaging

Dr. Yuan Xu

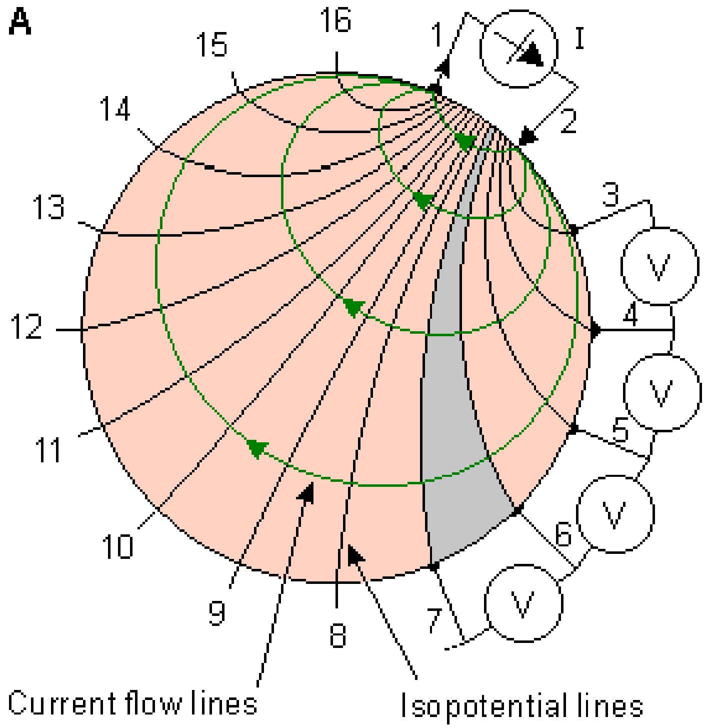
Ultrasound imaging



Limited Contrast (Backscattering coefficient of tissues)

Good Spatial resolution (scalable with imaging depth)

Principles of Electrical Impedance Tomography (EIT)



- Strength of EIT
  - Electrical conductivity and permittivity are correlated with the physiological and pathological status of tissues
  - Good temporal resolution

- Disadvantage:
  - Poor spatial resolution

Motivation

Good Contrast + High resolution

Optical Imaging

Microwave Imaging

Electrical impedance tomography

Ultrasound Imaging

Interaction between ultrasound and electric field

- The effect of electrical current in biological tissues on ultrasound echoes
- Ultrasound-induced electrical potential difference in biological tissues
  - **Magneto-acousto-electrical tomography**
  - **Ultrasound-modulated electric impedance tomography**
  - **Ultrasonic vibration potential in biological tissues**
- Ultrasound induced by electric current in biological tissues
  - **Magnetoacoustic tomography with magnetic induction**
  - **Magnetoacoustic tomography (Hall effect imaging)**

Part I: The Effect of Electrical Current in Biological Tissues on Ultrasound Echoes

- There are net charges on cell surfaces.
- An external electrical field can change the shape and orientation of cells.
- Hypothesis
  - Electric field will alter the reflected ultrasound pulses from the cells.

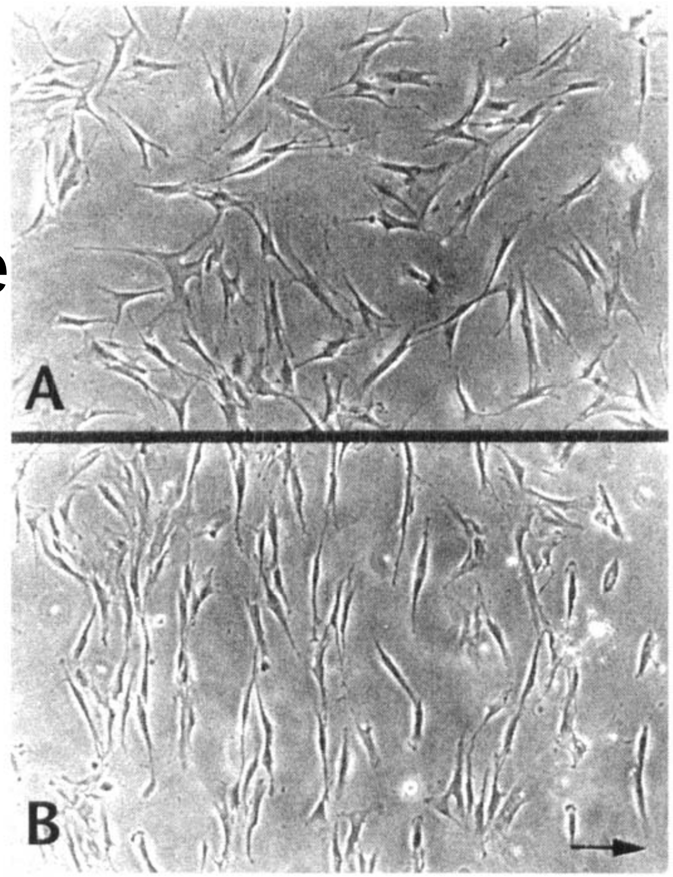
(Xu &Doganay)

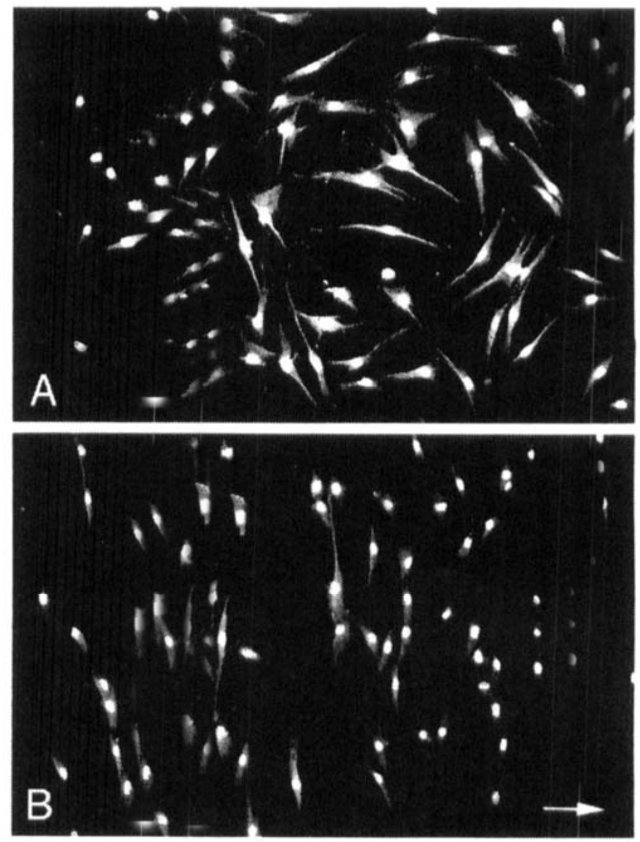
Reorientation of Human Skin Cells after an exposure to a DC Electric Field of 1-4V/cm *In Vitro*

A **fibroblast** is a type of cell that synthesizes the extracellular matrix and collagen, the structural framework for animal tissues.

Before

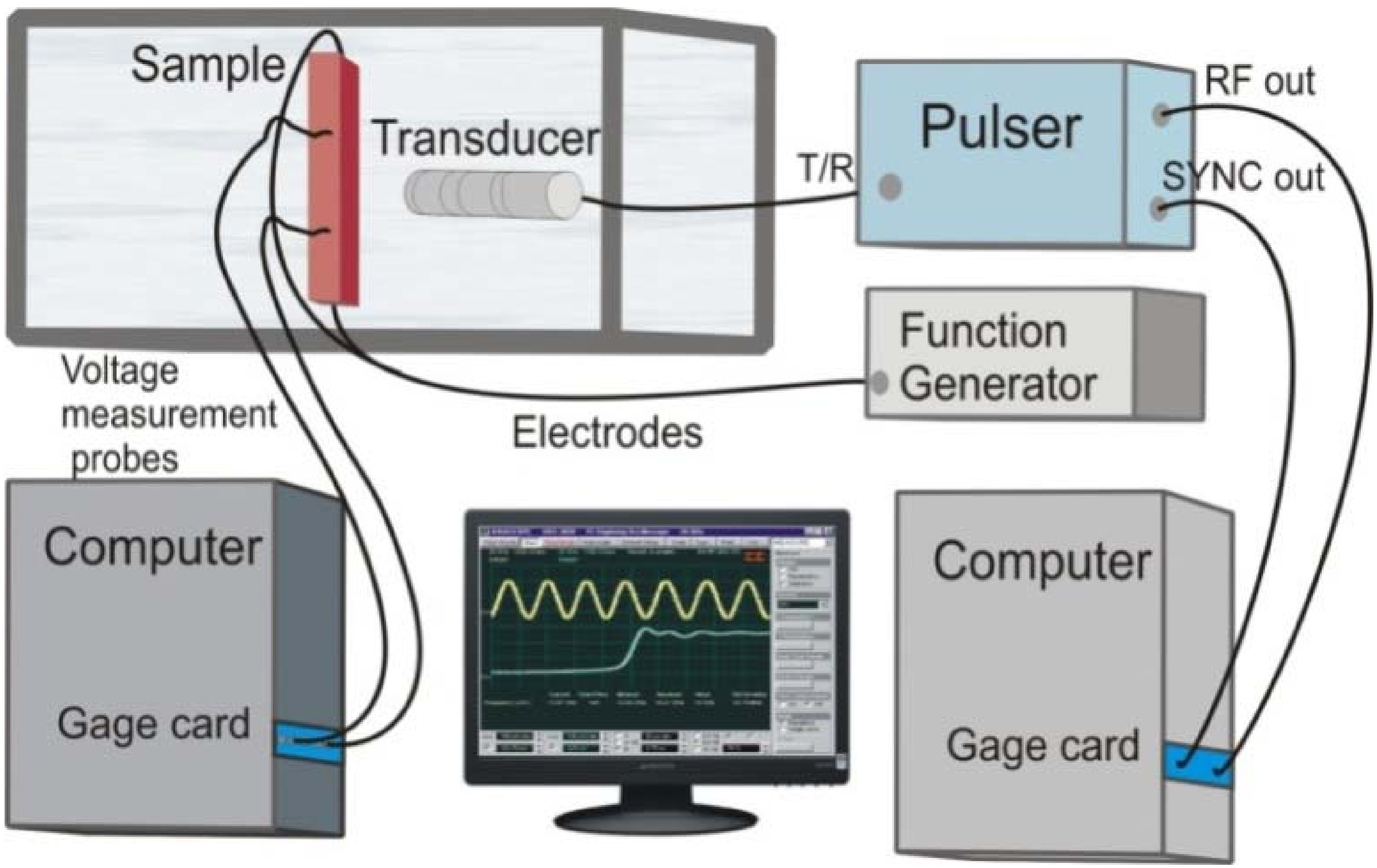
After



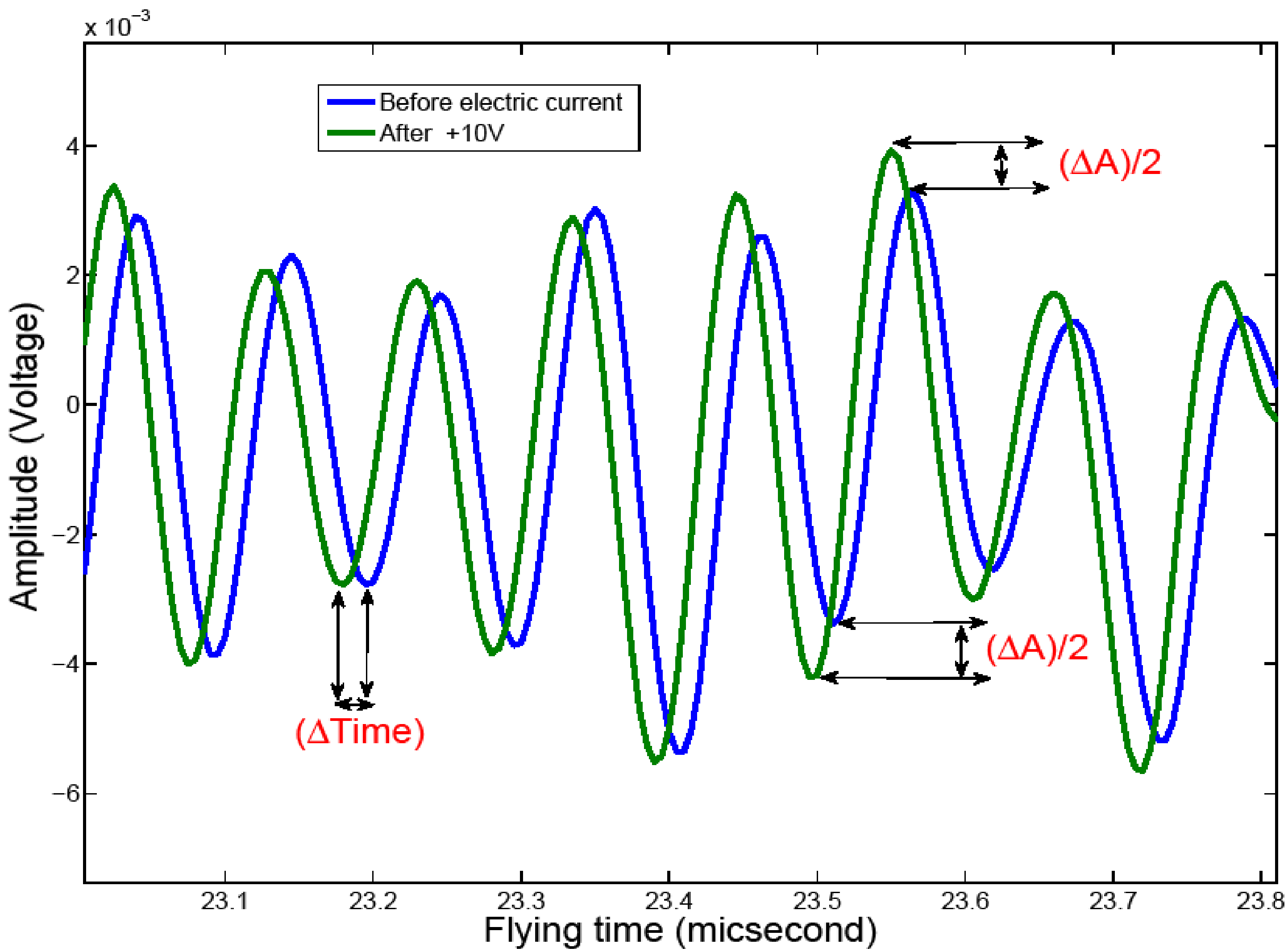


- **Stephane Methot ,Veronique Moulin, Denis Rancurt, Michel Bourdages,**

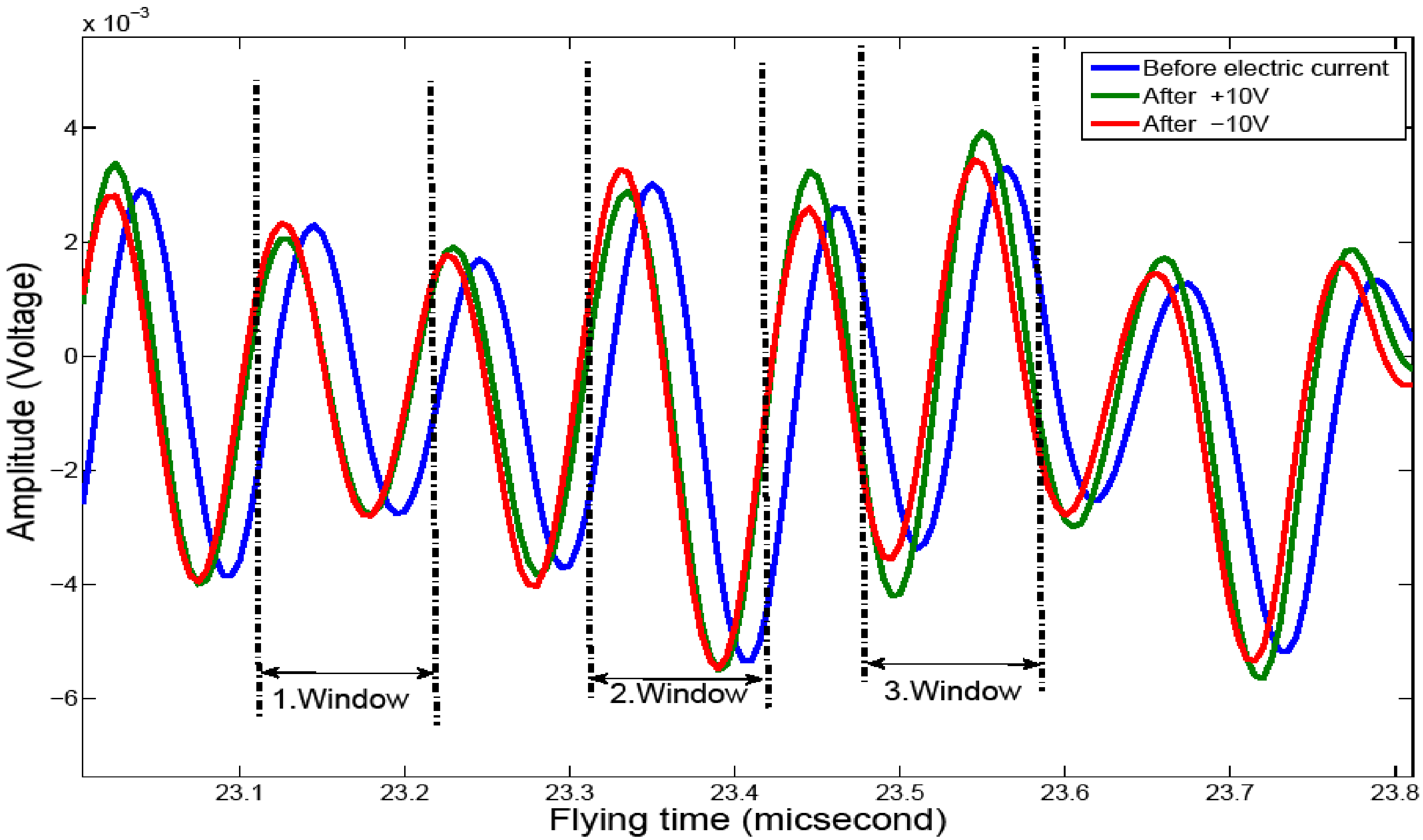
Diagram of the Experiment Setup



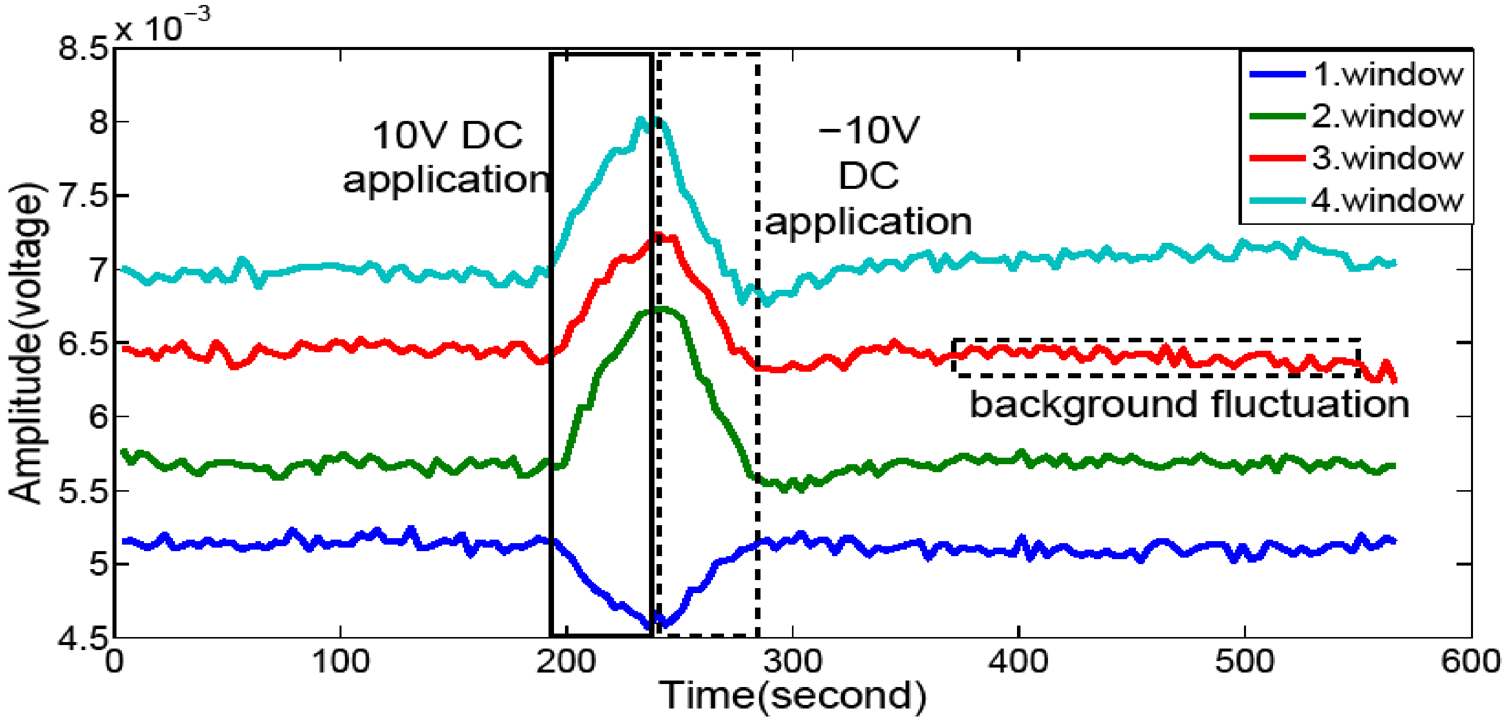
Ultrasound signals from a piece of porcine heart tissue before and after applying +10V



Choosing small windows to analyze changes



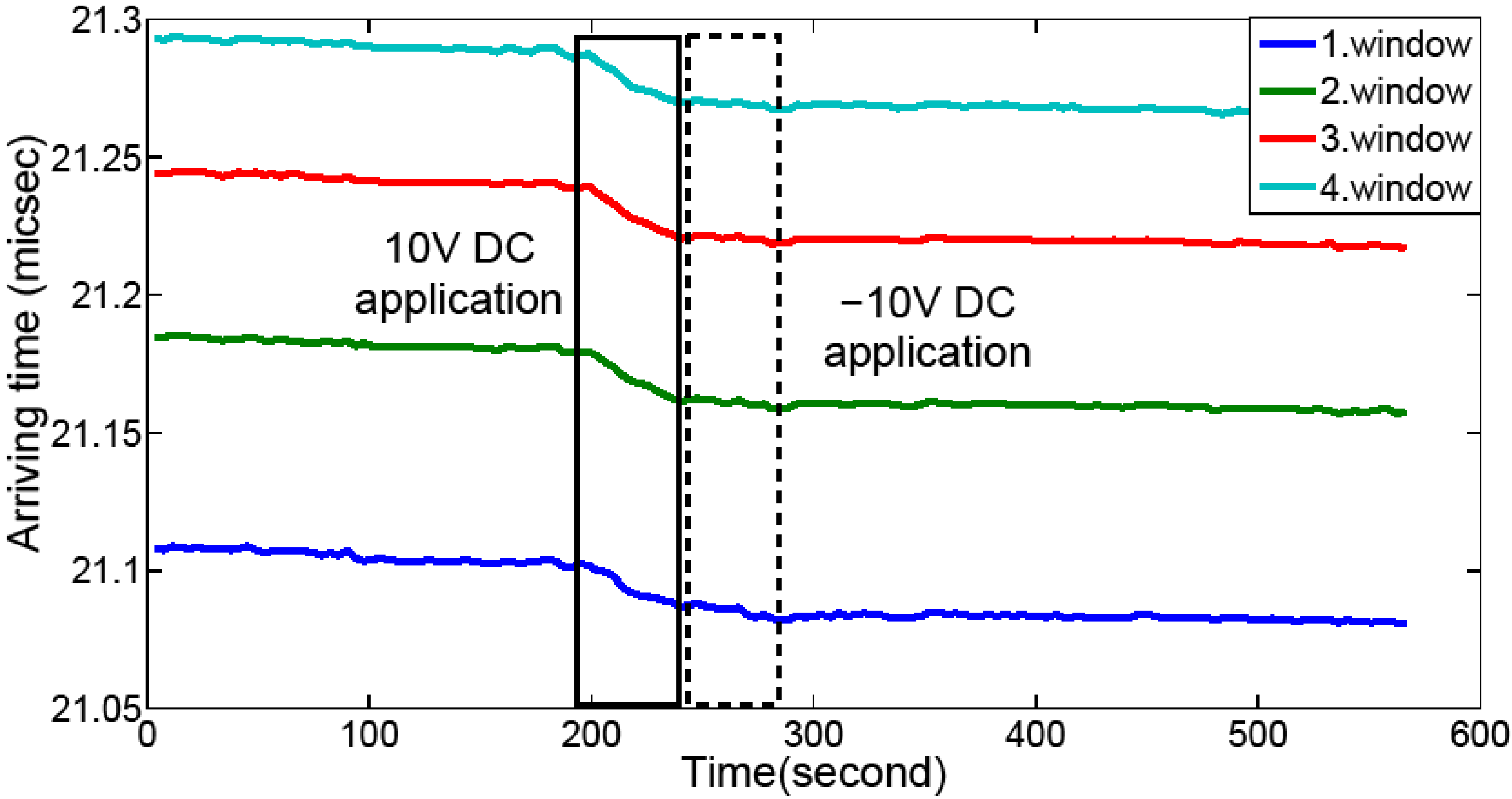
Peak-to-peak length on the amplitude in 4 windows



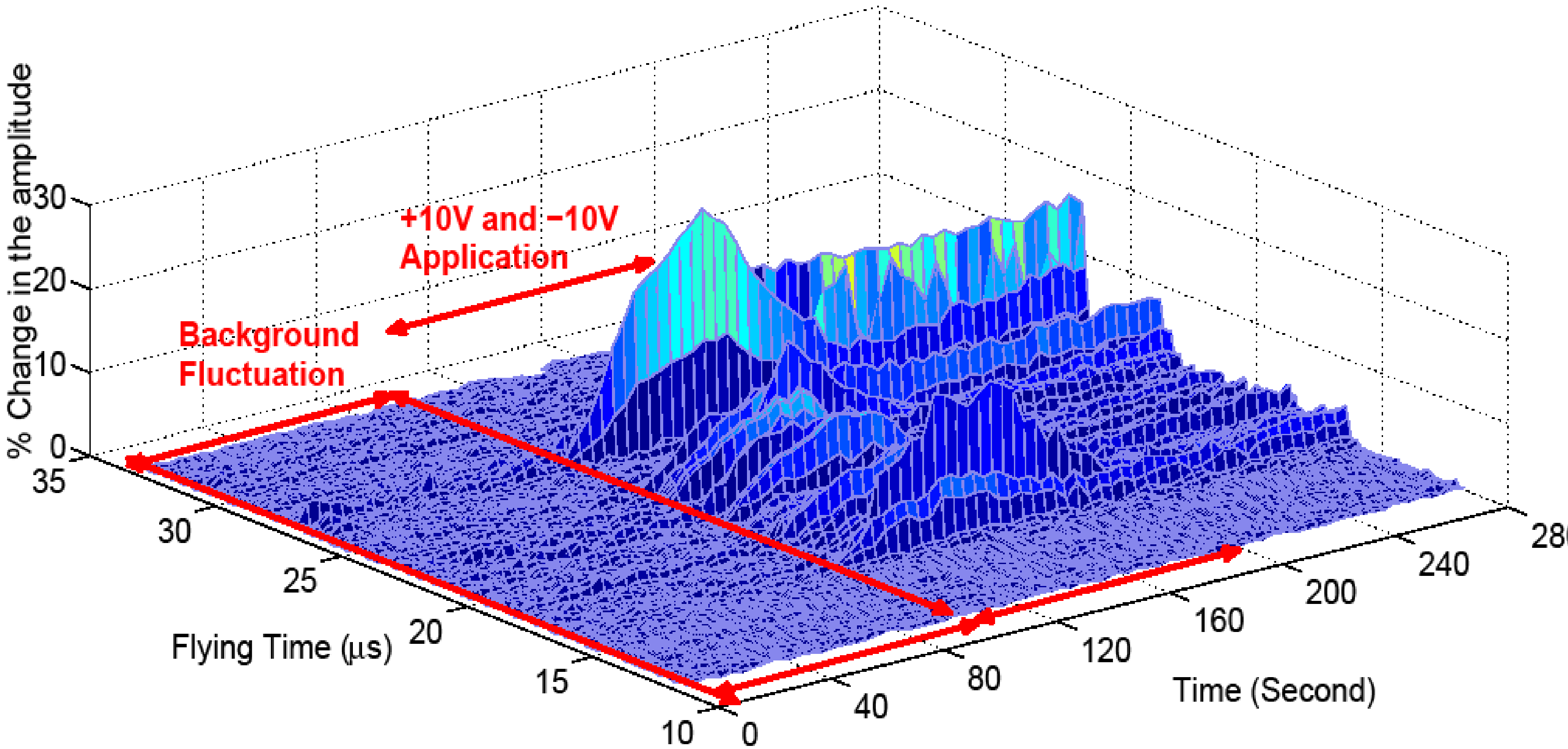
- Upon the +10V application, the amplitude of the signal increased
- Reversed DC polarity, the amplitude of the signal decreased

$$\Delta T = (\sigma / \rho c) E^2$$

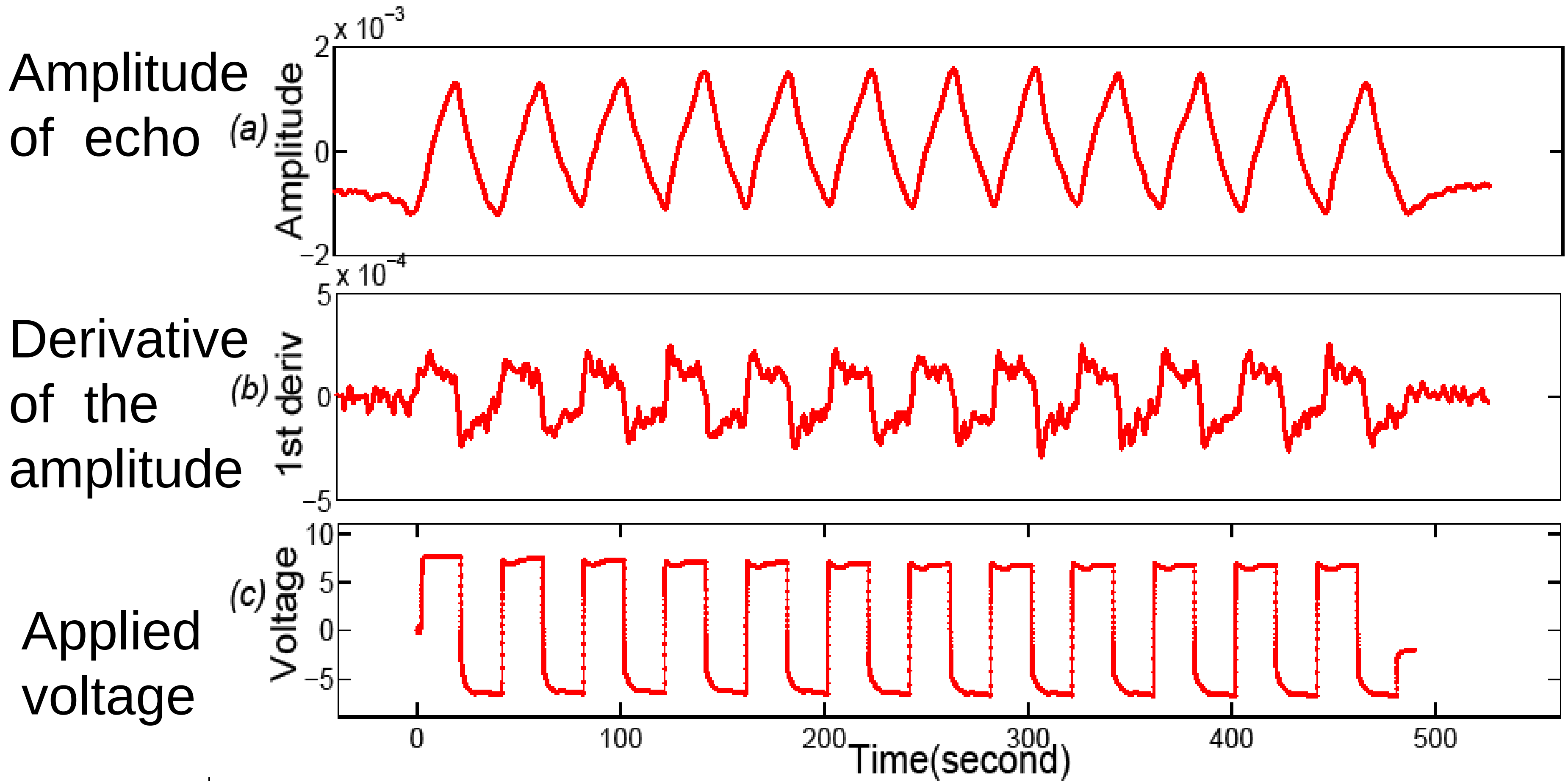
Peak positions in 4 windows : Shifting



Amplitude change in the echo signals



Correlation between the echo amplitude and the applied voltage



Joule heating due to Applied Electric Field

Tissue heating

$$\Delta T = (\sigma / \rho C) E^2$$

For 5V DC application;

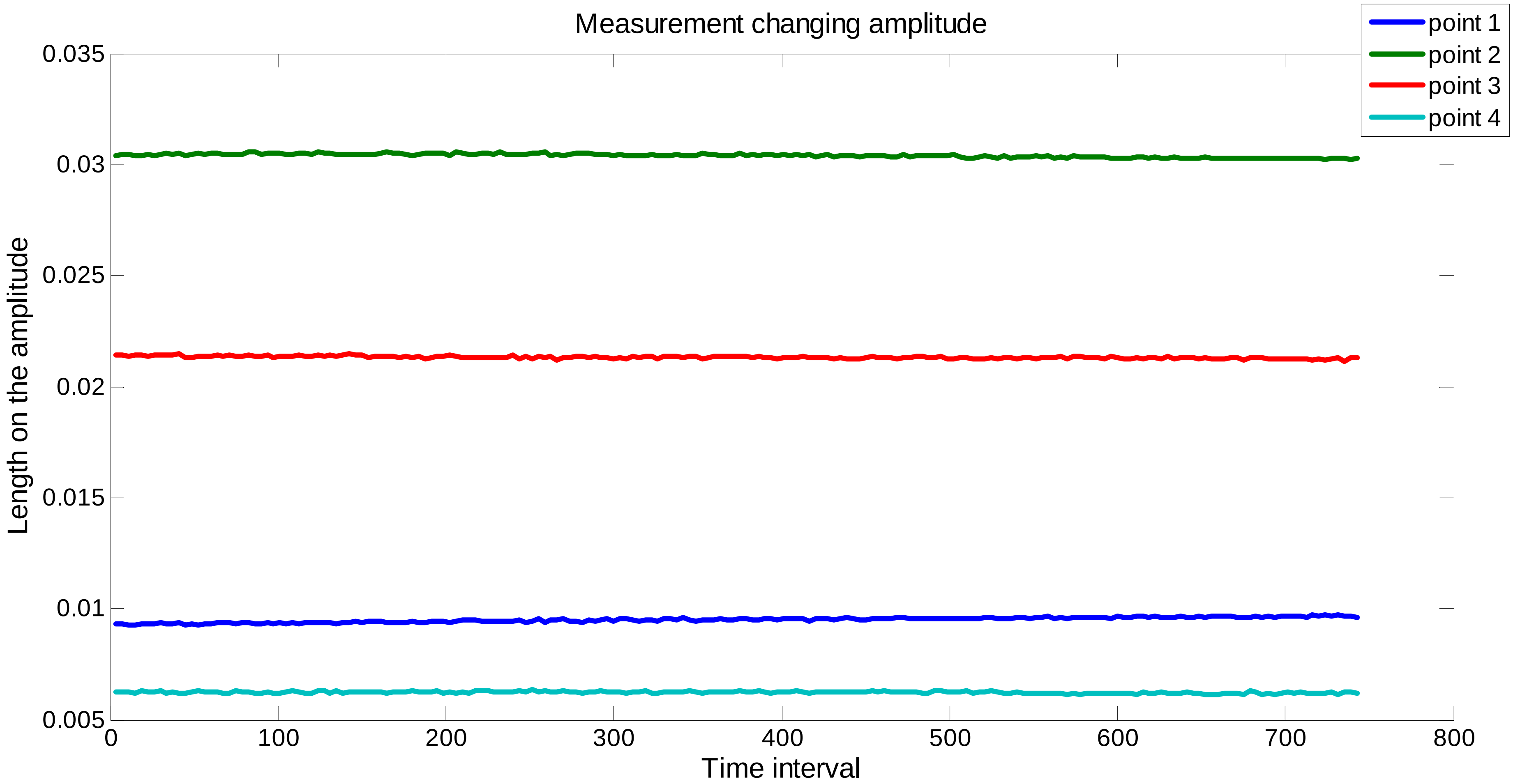
The rate of temperature increase is approximately

$$\Delta \mathrm{T} = 3.75 \cdot 10^{-4}\ ^{\circ}\mathrm{C}/s$$

Temperature increase for 1 minute DC application

$$\Delta \mathrm{T} = 0.02\ ^{\circ}\mathrm{C}$$

Effect of 0.2 °C temperature increase in tissue on echo amplitude



Summary of part I

- Local changes are observed in the echo signal upon the electric current application.

- For muscle, liver, heart, and fat tissue, similar changes at different magnitudes are observed.

Open questions

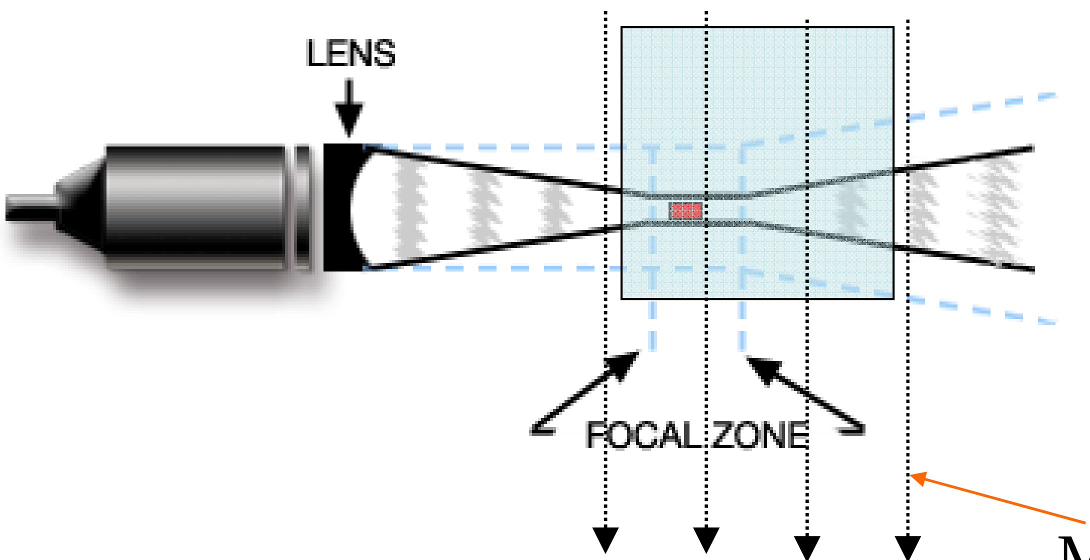
- What is the mechanism underlying the changes in the amplitudes and phases of the ultrasound echoes?
- Can we use the changes in the ultrasound echoes for medical diagnosis?

Part II: Ultrasound-induced electrical potential difference in biological tissues

- Magneto-acousto-electrical tomography
  - Static magnetic field + ultrasound (Wen, Montalibet, Xu)
- Ultrasound-modulated electric impedance tomography
  - Electric field + ultrasound (Jossinet, Zhang&Wang, Xu)
- Ultrasonic vibration potential
  - Ultrasound (Diebold)

Creat Point Source by Combining Ultrasound and Magnetic Field

- Focused Ultrasound pulse
  - Localized vibration of ions



$$\vec{F} = q(\vec{v} \times \vec{B})$$

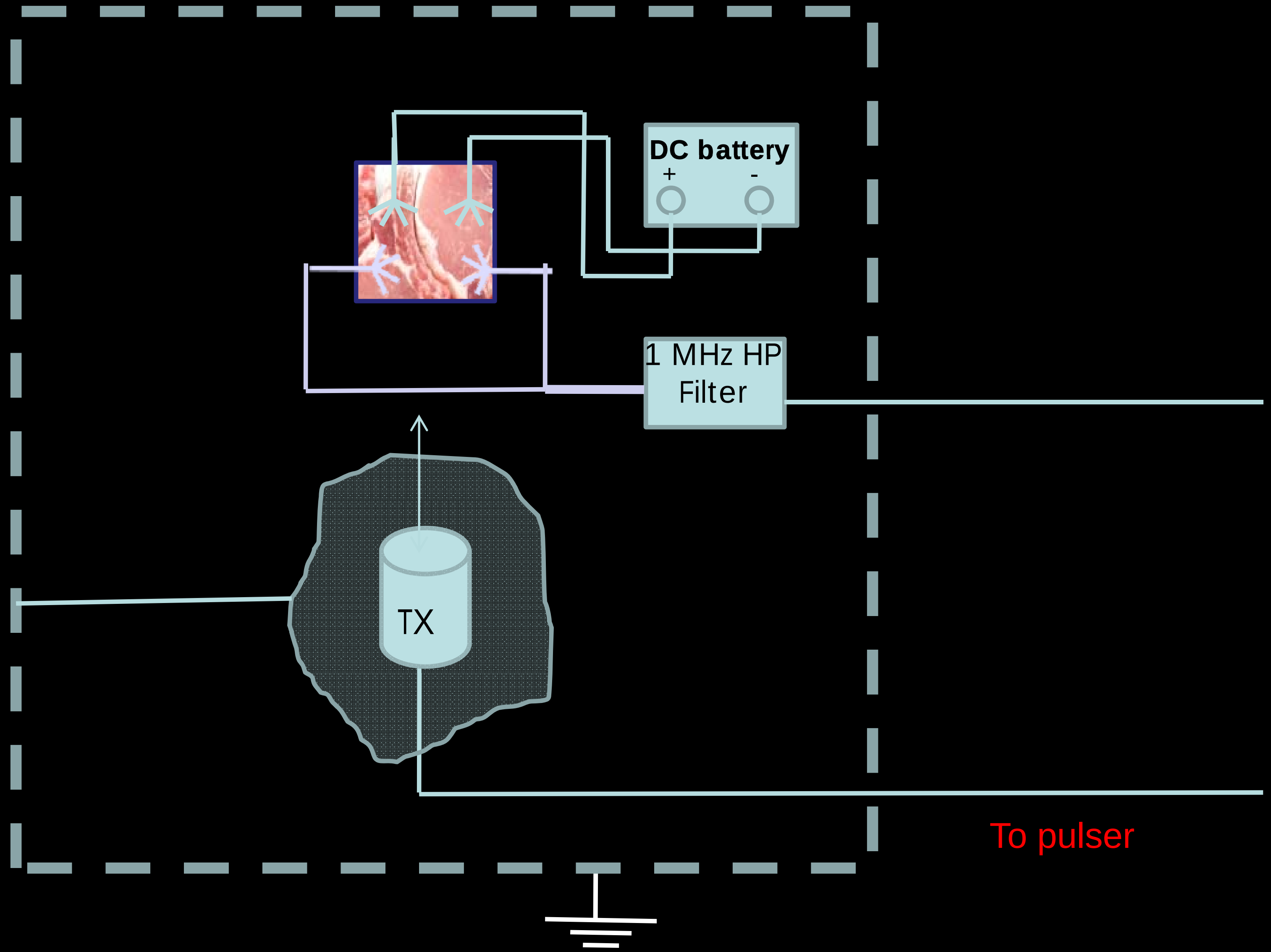
Lorentz force

Magnetic field

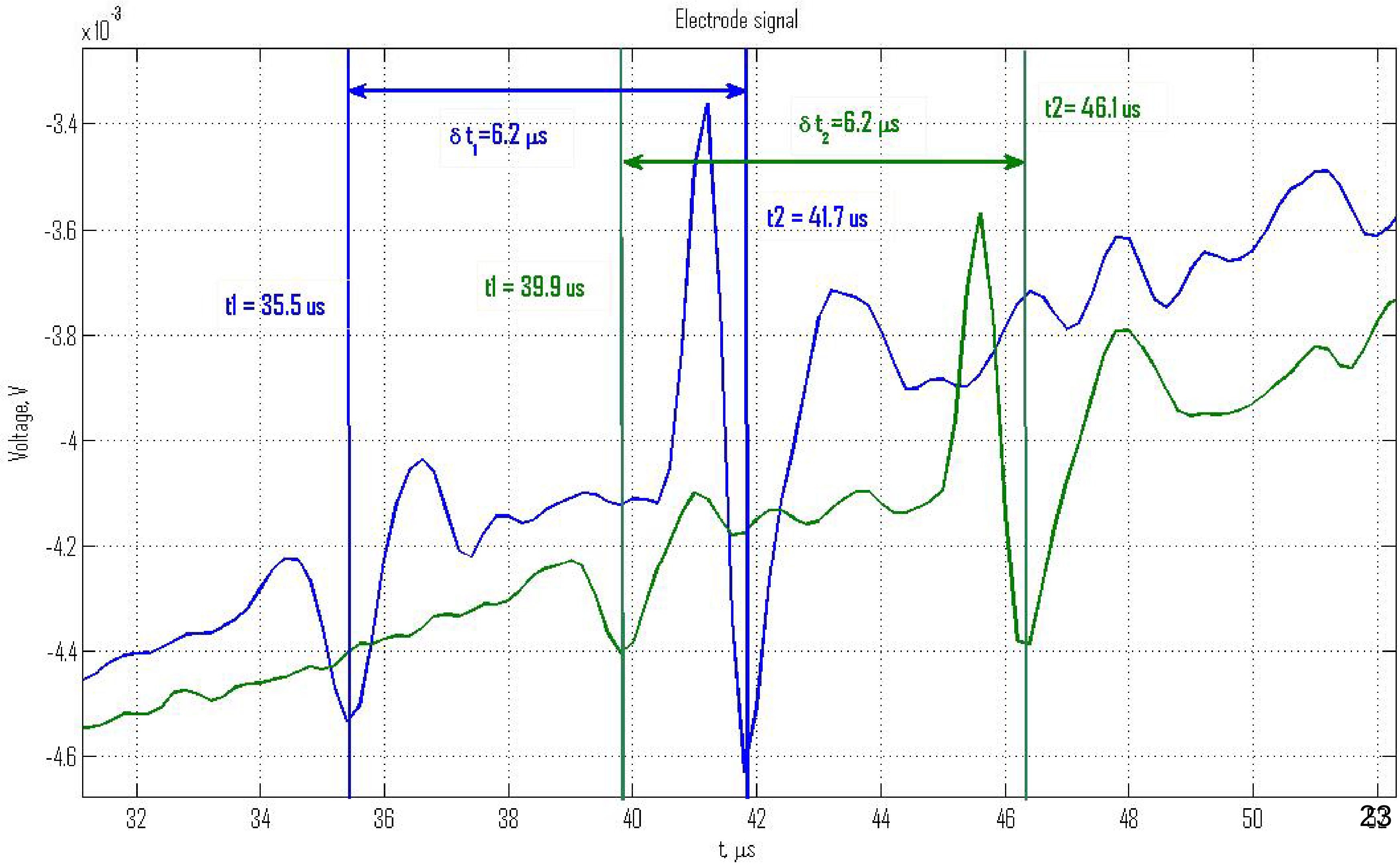
Ultrasound-modulated electric impedance tomography (UMEIT)

- Electric field + ultrasound
- Ultrasound can modulate the impedance of tissues at the ultrasound frequency.
  - Ultrasound changes the density and temperature of the medium. Consequently, the electric impedance will be changed.

Experimental setup of UMEIT

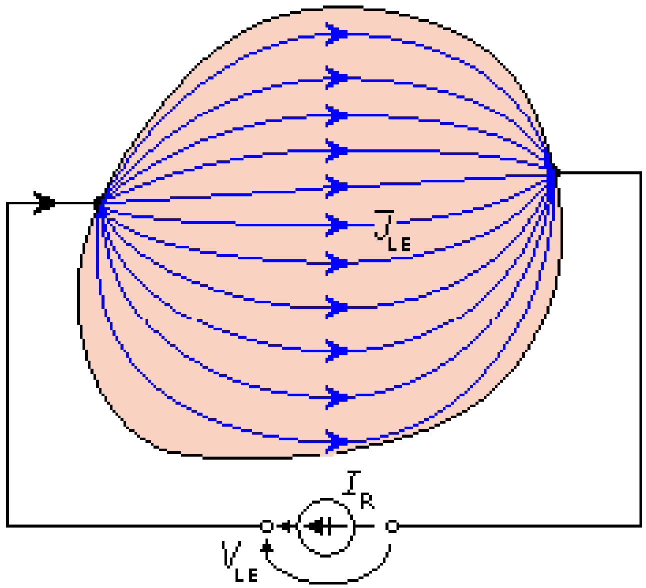


UMEIT Signals



Lead field corresponding to a pair of electrodes

- $\vec{j}_P^{\,LE}(\omega,\vec{r})$ current density when one ampere of current is injected through the electrodes
- Map the lead field current density by combining ultrasound with electromagnetic field
- High-spatial resolution images of electrical impedance can be reconstructed from the image of current density



Theory for Ultrasound-induced electrical potential difference in biological tissues

Based on the reciprocity theorem of electromagnetic waves, The voltage detected at the two points of the sample is given by

$$U(\omega, \vec{R}_P) = \int \vec{E}_{emf}(\omega, \vec{r}) \cdot \vec{j}_P{}^{LE}(\omega, \vec{r}) d^3\vec{r}$$

ω is the ultrasound frequency.

$\vec{j}_P{}^{LE}(\omega, \vec{r})$ is the current density when one ampere of current is injected through the probing electrodes.

$\vec{E}_{emf}(\omega, \vec{r})$ is the electromotive force due to ultrasound.

$U(\omega, \vec{R}_P)$ is the voltage detected by the probing electrodes

Ultrasound-induced electrical potential difference in biological tissues

- Magneto-acousto-electrical tomography
  - Static magnetic field + ultrasound

    $$\vec{E}_{emf}(\omega,\vec{r}) = \vec{v}(\vec{r},\omega) \times \vec{B}_0$$

  - Measurement gives one component of $\vec{j}_P^{\,LE}(\omega,\vec{r})$
- Ultrasound-modulated electric impedance tomography
  - Electric field + ultrasound

    $$\vec{E}_{emf}(\omega,\vec{r}) = k \cdot v(\vec{r},\omega) \cdot \vec{E}_S^{\,LE}$$

  - Measurement gives $\vec{j}_P^{\,LE}(\omega,\vec{r}) \cdot \vec{j}_S^{\,LE}(\omega,\vec{r}) / \sigma$

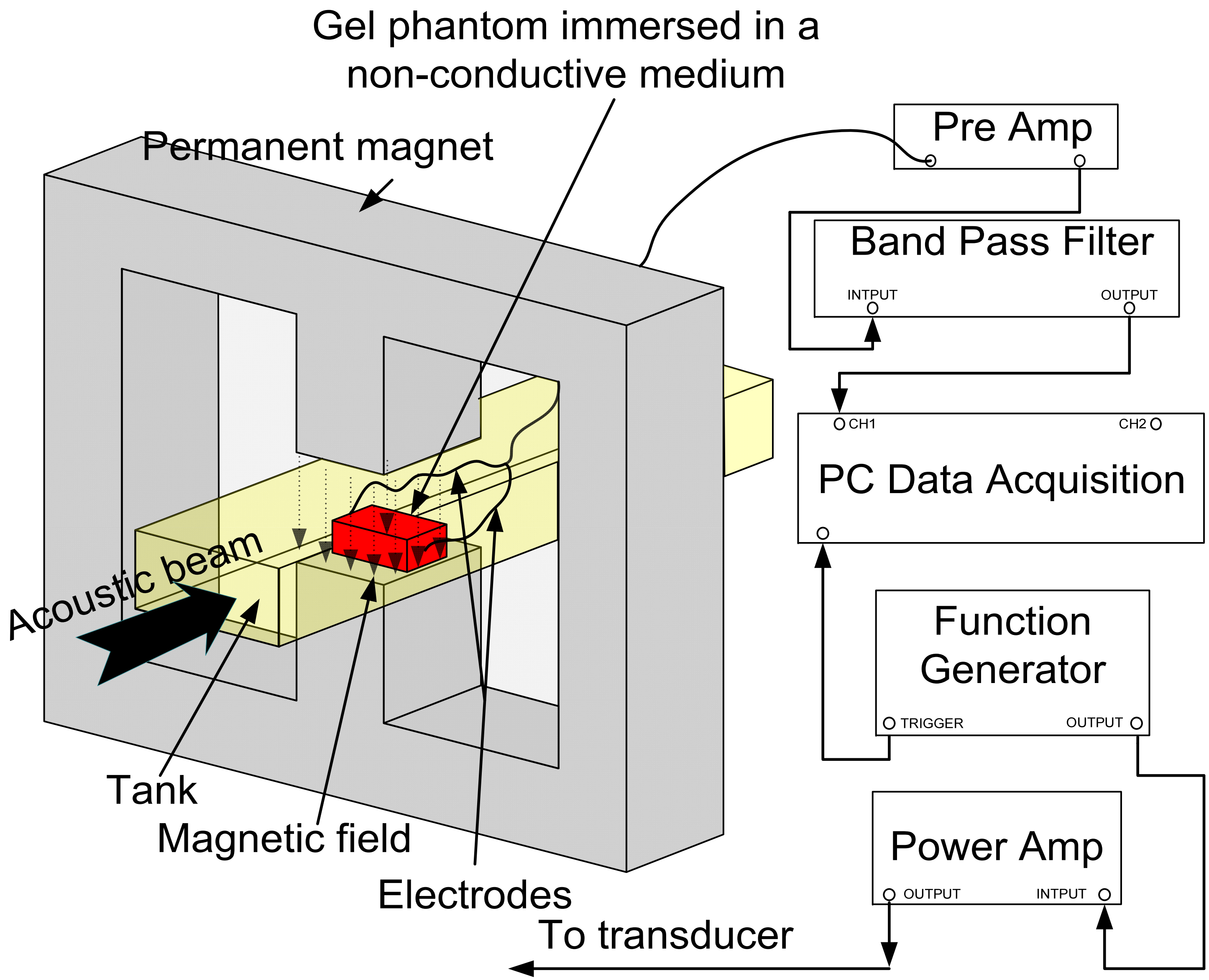
Obtaining Lead Field Current Density in MAET

- Assuming that the magnetic field and vibration velocity can be measured,

$$j^{LE}{}_{\vec{v}\times\vec{B}_0} = \frac{U}{\left|\vec{v}\times\vec{B}_0\right|\cdot\Delta V}$$

- Only the component in the direction of $\vec{v}\times\vec{B}_0$ results in the voltage.

Experimental Setup of MAET



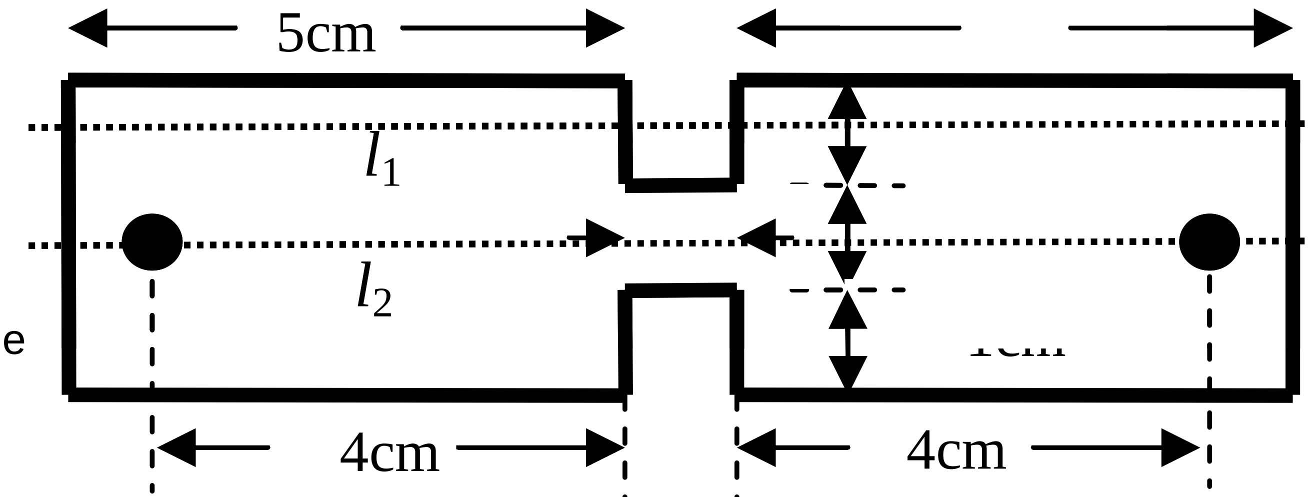
A 2-D (thin) Sample to image $\vec{j}_P^{LE}(\omega,\vec{r})$

2 mm thick

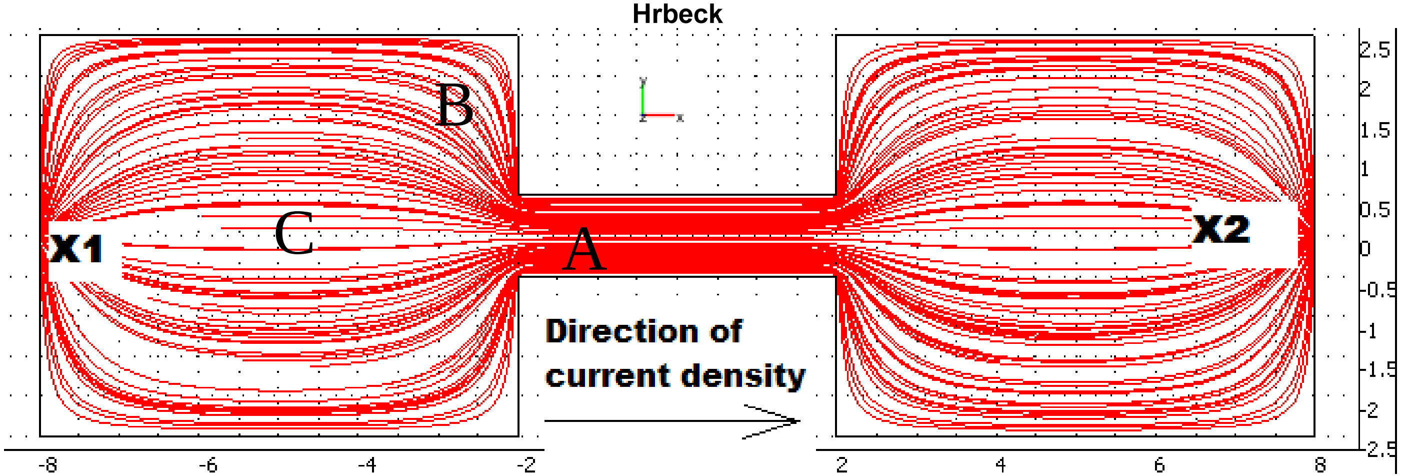
$\mathbf{B}_0$

$\mathbf{V}$ $\otimes$

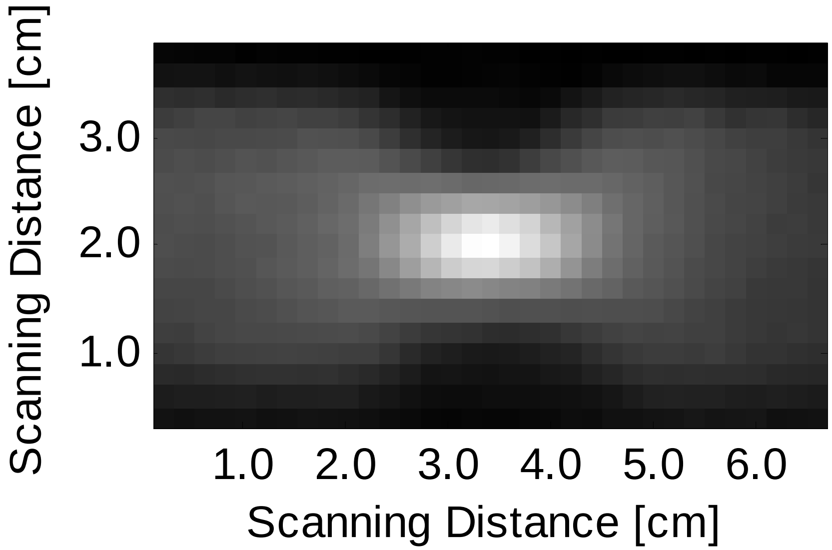
Ultrasound perpendicular to the screen



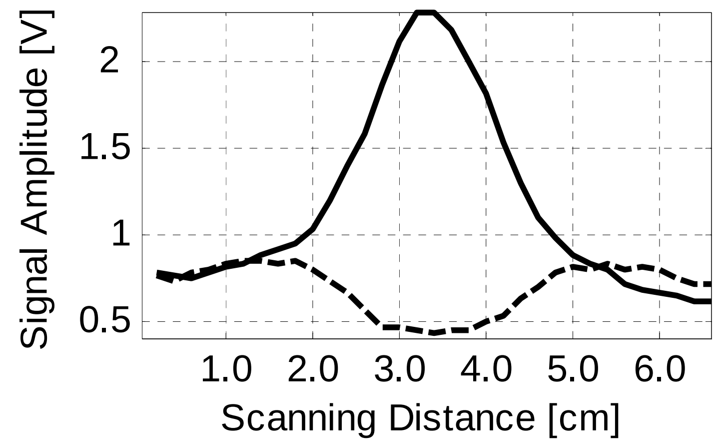
Forward simulation of Current Density distribution from a known conductivity distribution in COMSOL – Courtesy Andrew Hrbeck



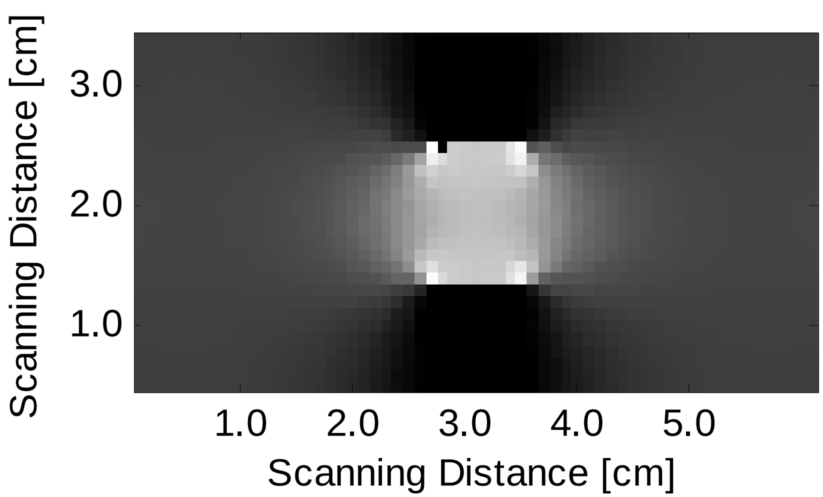
Experiment and Simulation Results



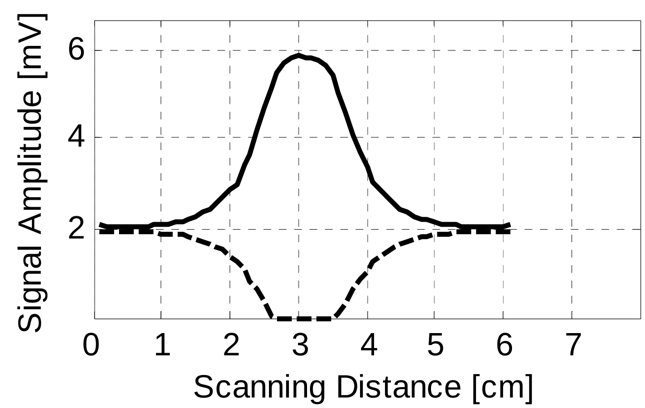
(a) Experiment image



(b) Experiment lines



(c) Simulation image



(d) Simulation lines

The Conductivity from the Lead Field Current Density

The conductivity may be found using $\vec{\nabla} \times \vec{E} = 0$ where $\vec{E} = \vec{E}_{lead}$

With the lead field current density $\vec{J} = \sigma \vec{E}$

To obtain a relation between current density and conductivity $\vec{\nabla} \times \dfrac{\vec{J}}{\sigma} = 0$

This curl may be expanded into three components

$$\frac{1}{\sigma^2}\left(J_y \frac{\partial \sigma}{\partial z} - J_z \frac{\partial \sigma}{\partial y} \right) + \frac{1}{\sigma}\left(\frac{\partial J_z}{\partial y} - \frac{\partial J_y}{\partial z} \right) = 0$$

$$\frac{1}{\sigma^2}\left(J_z \frac{\partial \sigma}{\partial x} - J_x \frac{\partial \sigma}{\partial z} \right) + \frac{1}{\sigma}\left(\frac{\partial J_x}{\partial z} - \frac{\partial J_z}{\partial x} \right) = 0$$

$$\frac{1}{\sigma^2}\left(J_x \frac{\partial \sigma}{\partial y} - J_y \frac{\partial \sigma}{\partial x} \right) + \frac{1}{\sigma}\left(\frac{\partial J_y}{\partial x} - \frac{\partial J_x}{\partial y} \right) = 0$$

← For a thin sample only this equation is needed

Expanding the curl leads to a first order PDE in the conductivity

$$\frac{1}{\sigma^2}\left(J_x\frac{\partial\sigma}{\partial y}-J_y\frac{\partial\sigma}{\partial x}\right)+\frac{1}{\sigma}\left(\frac{\partial J_y}{\partial x}-\frac{\partial J_x}{\partial y}\right)=0$$

This PDE may be converted into a system of three autonomous ordinary differential equations by using the ‘Method of Characteristics’ to make it solvable

Let $$\frac{d\sigma}{ds}=\frac{\partial\sigma}{\partial x}\frac{dx}{ds}+\frac{\partial\sigma}{\partial y}\frac{dy}{ds}$$ then

$$\frac{dx}{ds}=-J_y \qquad \frac{dy}{ds}=J_x$$ and $$\frac{1}{\sigma^2}\frac{d\sigma}{ds}+\frac{1}{\sigma}\left(\frac{\partial J_y}{\partial x}-\frac{\partial J_x}{\partial y}\right)=0$$

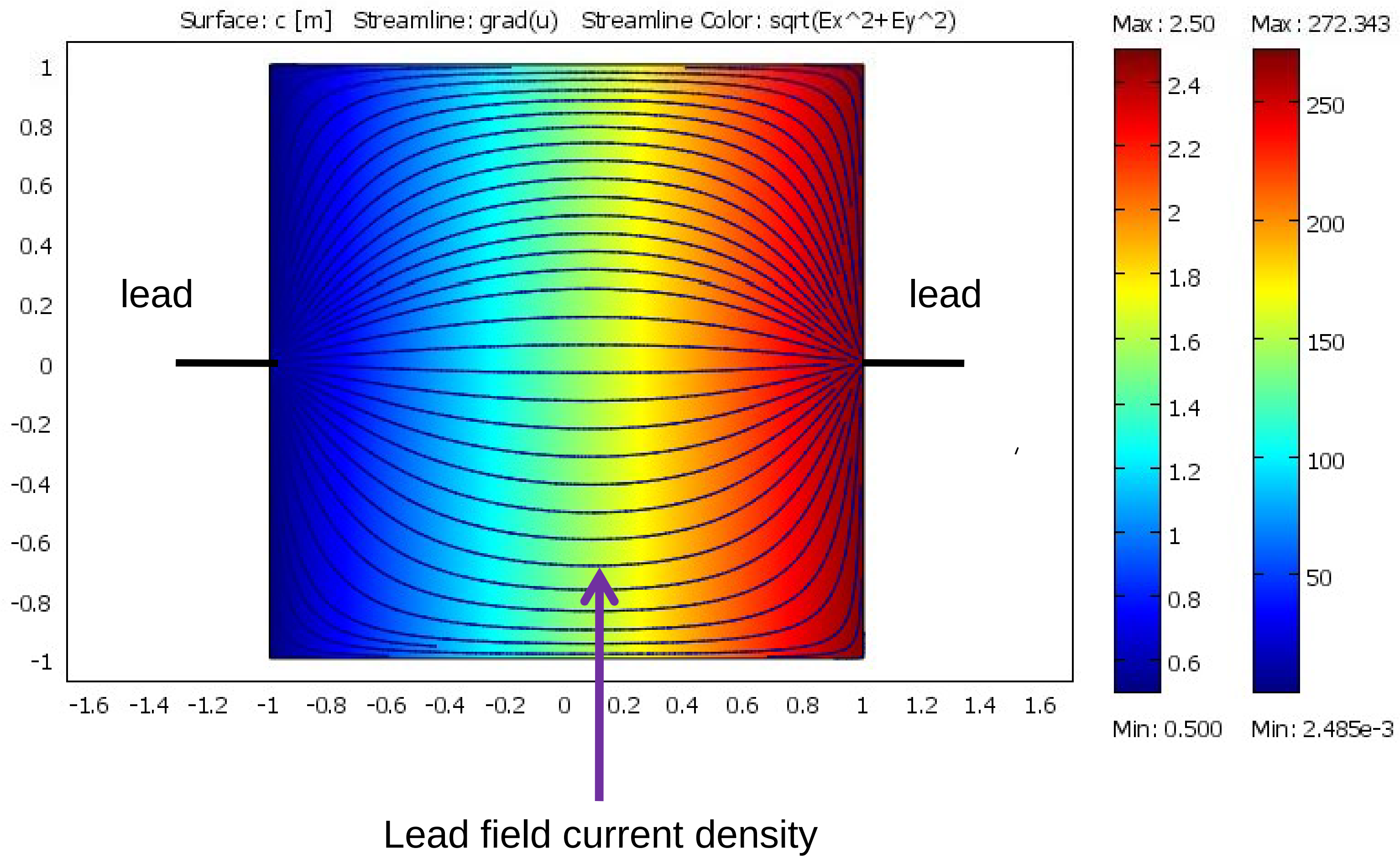
These may be written in a more conventional form .

$$\dot{x}=-J_y \qquad \dot{y}=J_x \qquad \dot{\sigma}=-\sigma\left(\vec{\nabla}\times\vec{J}\right)_z$$

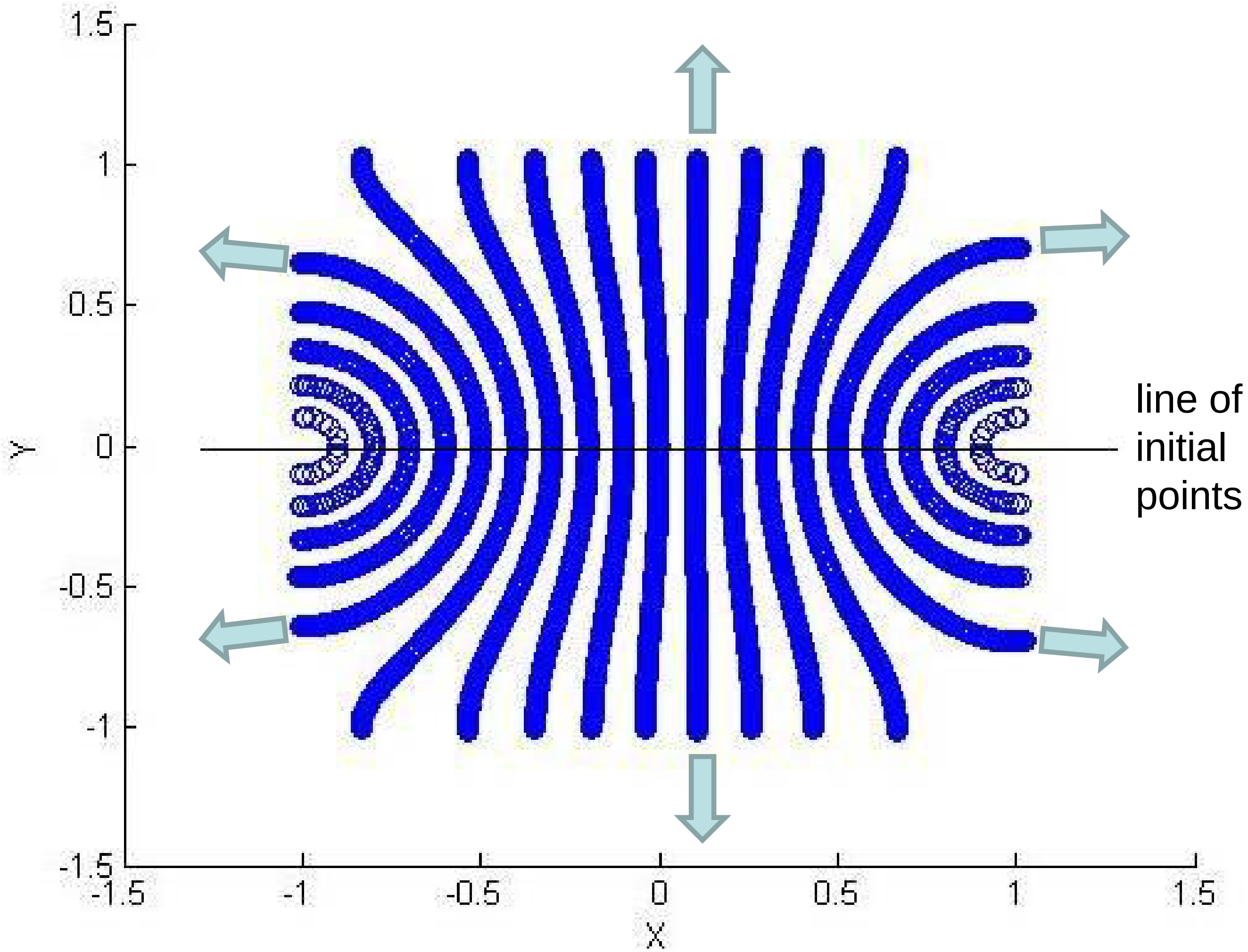
At s=0 we must give an initial x,y, and σ

Sensitive only to *changes* in conductivity

A thin domain with a linearly varying conductivity

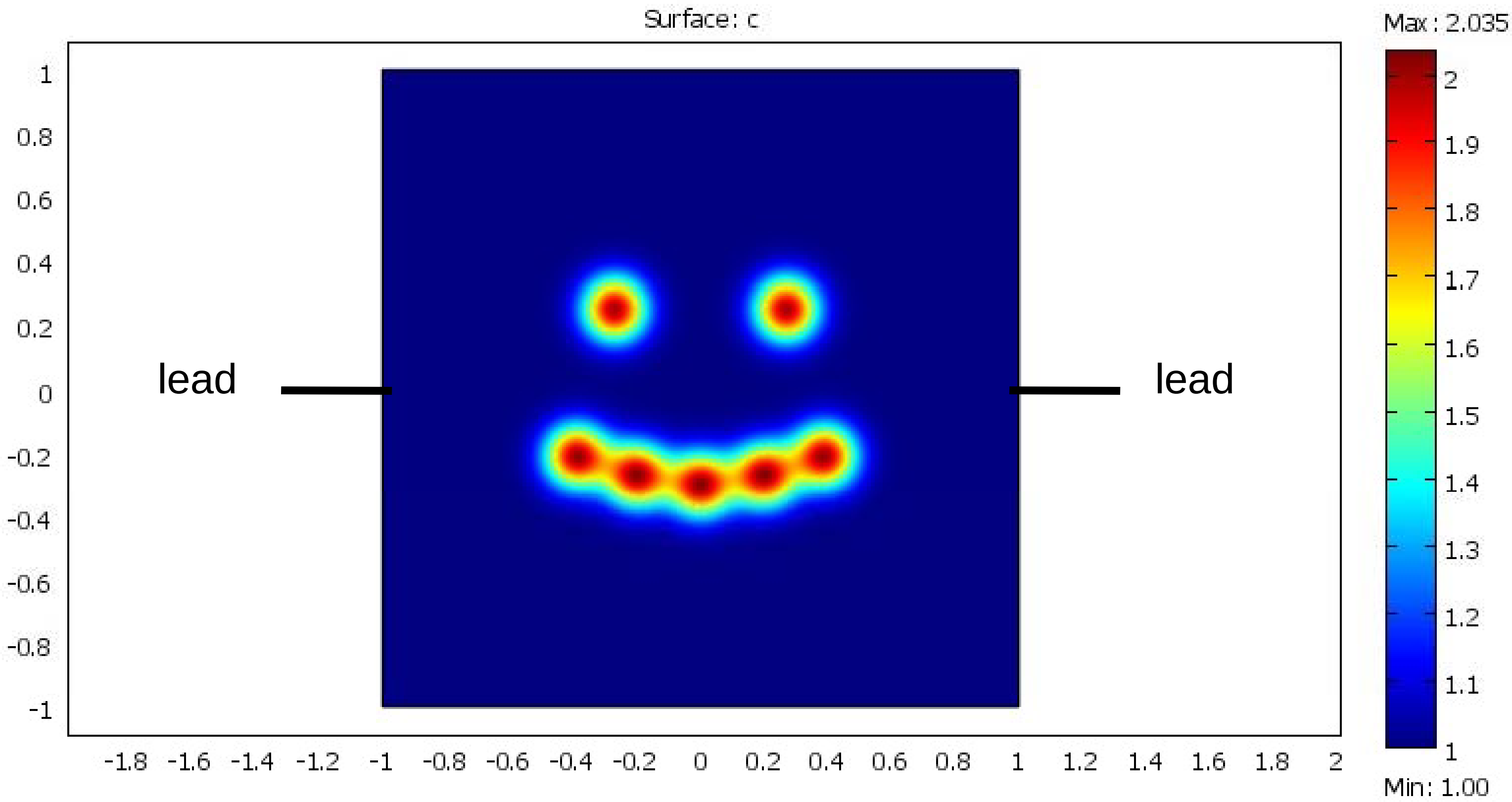


The characteristic curves are perpendicular to the lead field current

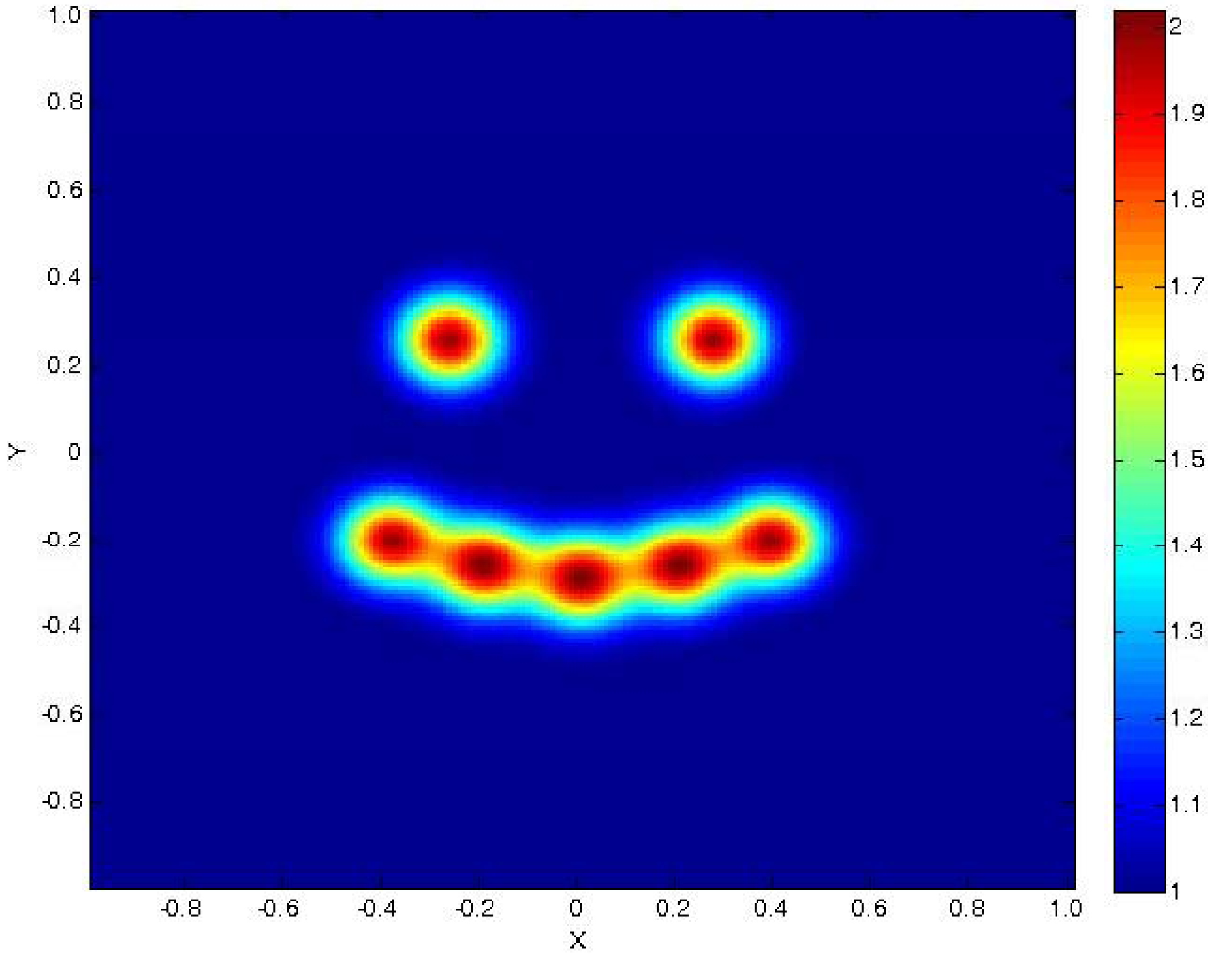


The arrows indicate the direction of the trajectories

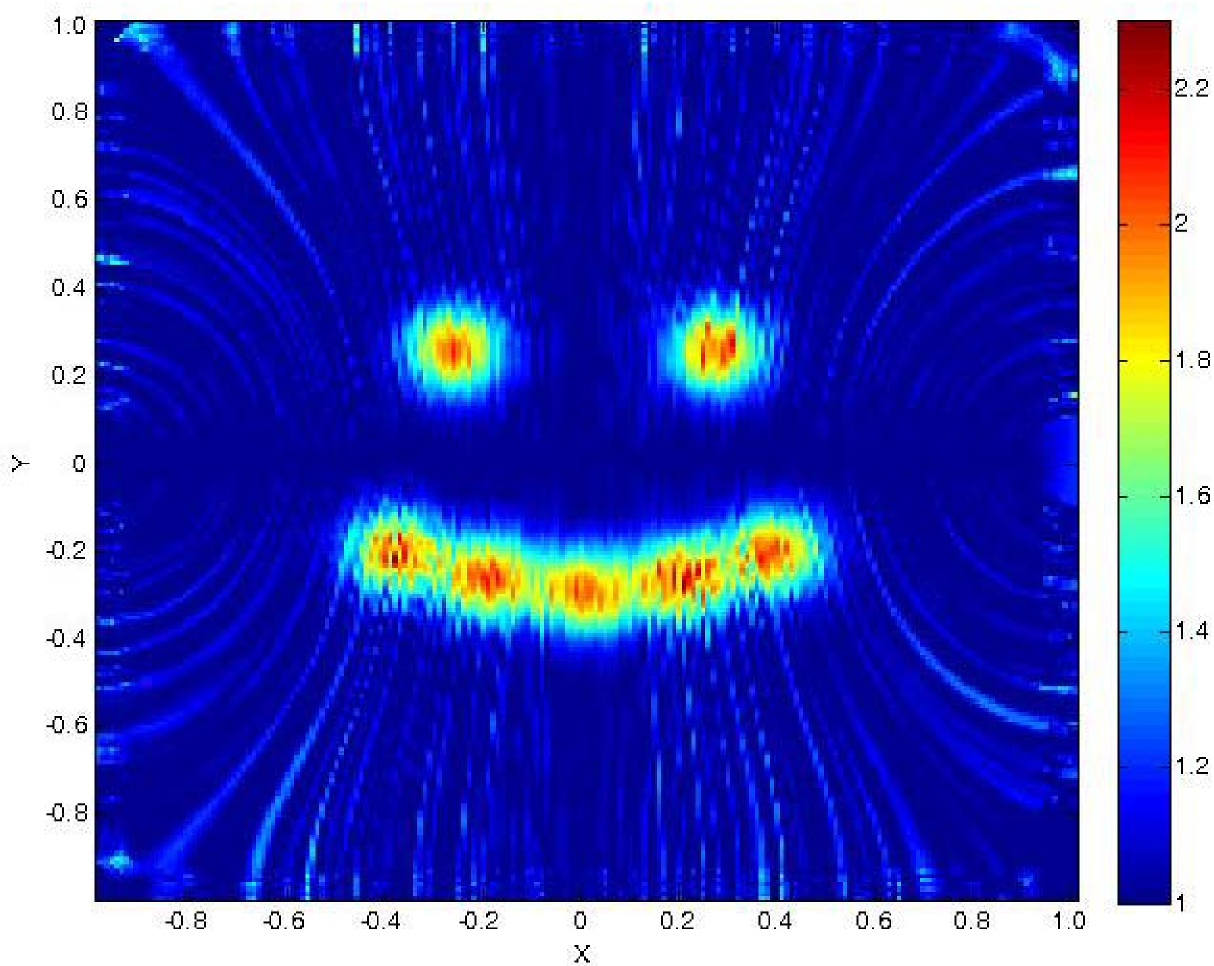
Consider a happyface conductivity distribution



The correct distribution is returned if the background conductivity (blue) is known

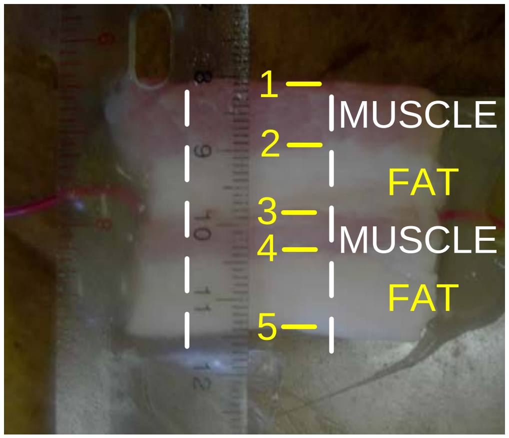


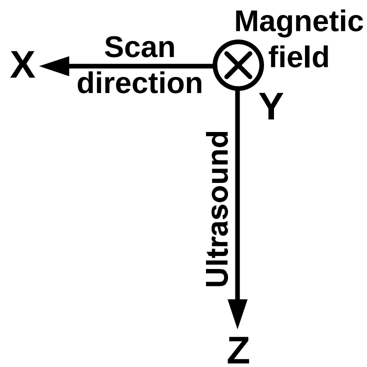
Addition of 10 percent noise to the lead field current density reveals the characteristic curves



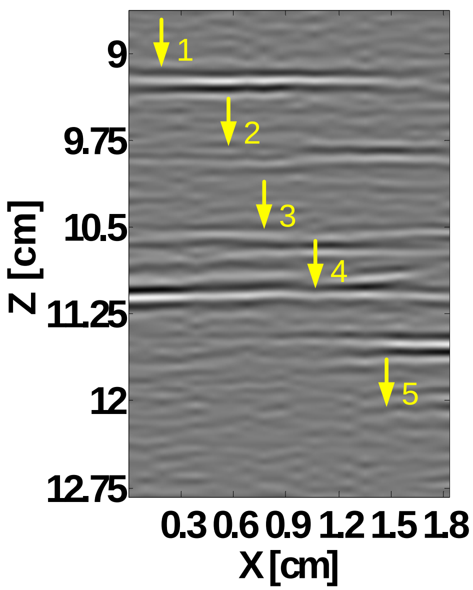
2D MAET images of a biological sample

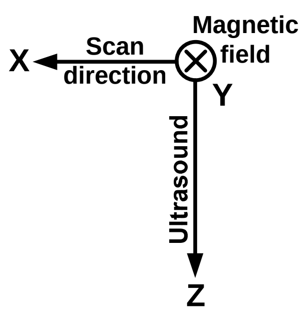
1MHz Transducer





Thickness of tissue along Z-axis is 3.5cm.





Thickness of tissue along Y-axis is 0.9cm

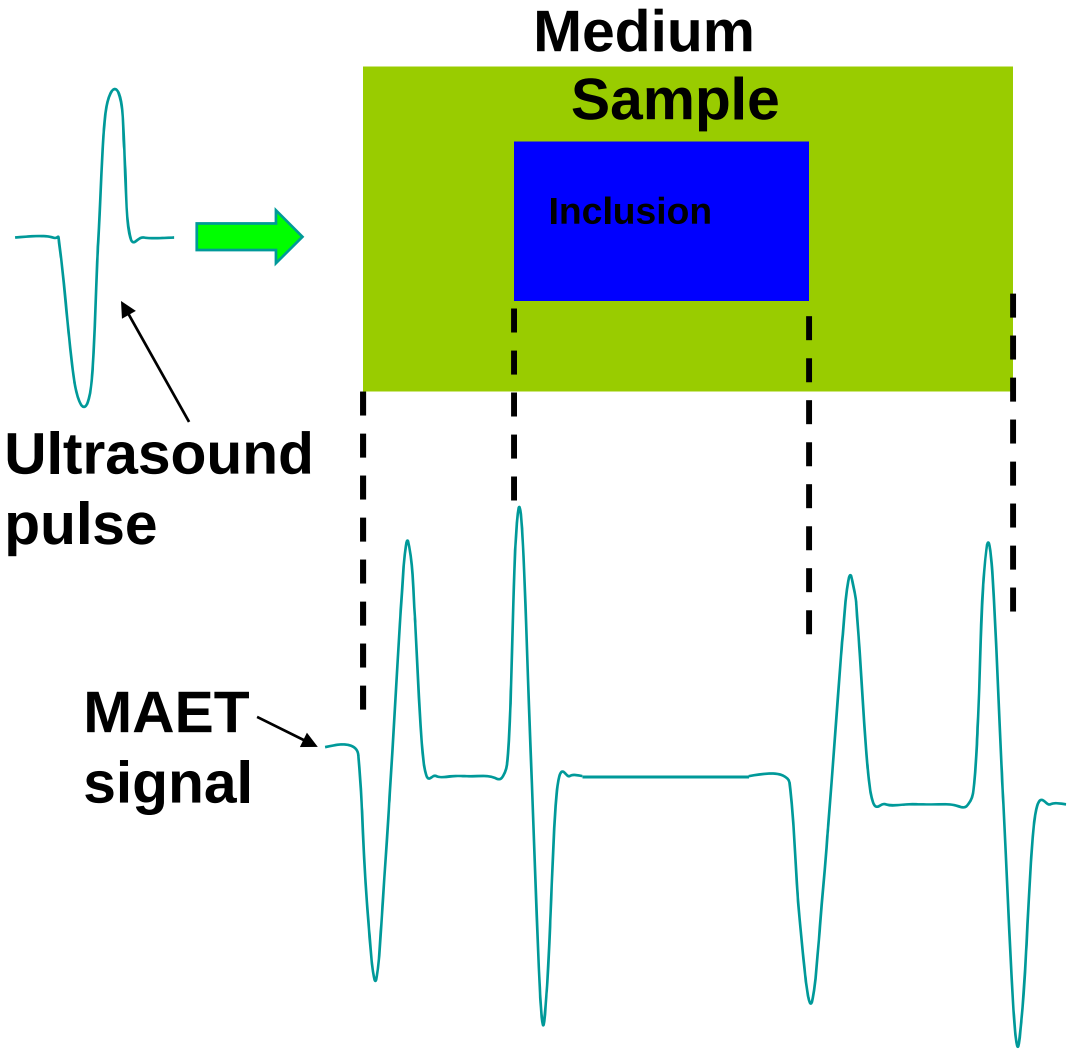
Challenges in Ultrasound-induced electrical potential difference

- Signals are weak compared with the electronic noise.
  - Signal amplitude proportional to the lead field current density of the probing electrodes.

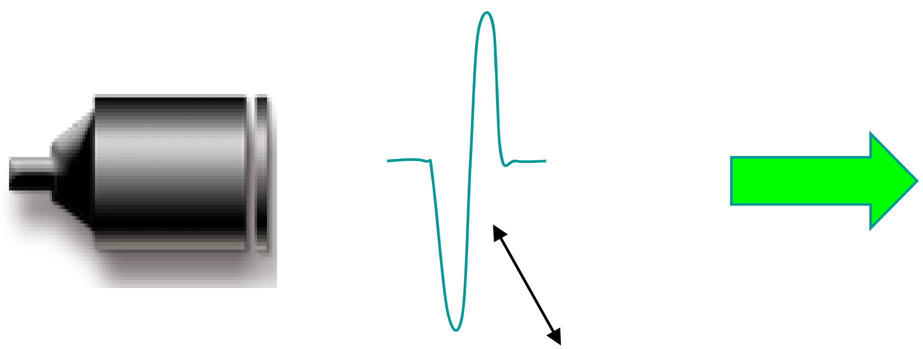
$$U(\omega,\vec{R}_P)=\int \vec{E}_{emf}(\omega,\vec{r})\cdot\vec{j}_P(\omega,\vec{r})d^3\vec{r}$$

- Signals are observed only at interfaces.

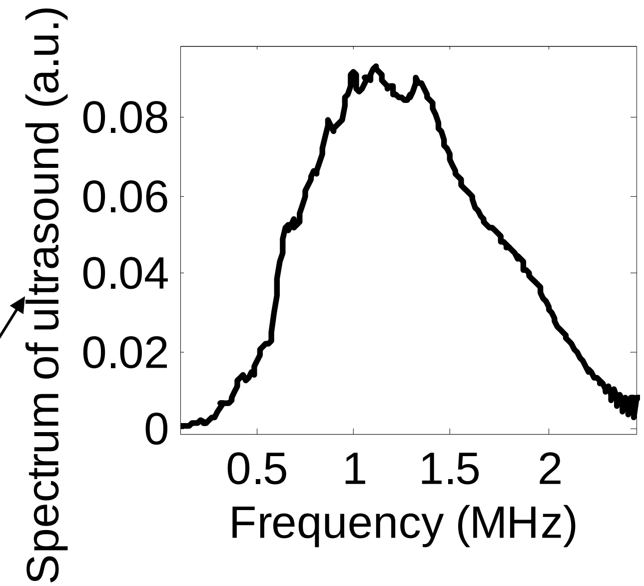
Signals are observed only at interfaces



Filtering Effect of the Ultrasound Transducer



Ultrasound pulse



$$S(\omega) \propto R(\omega) \cdot J_{\mathbf{v}\times\mathbf{B}}(\omega)$$

spectrum of the measured electrical signal

ultrasound spectrum

Summary of Part II

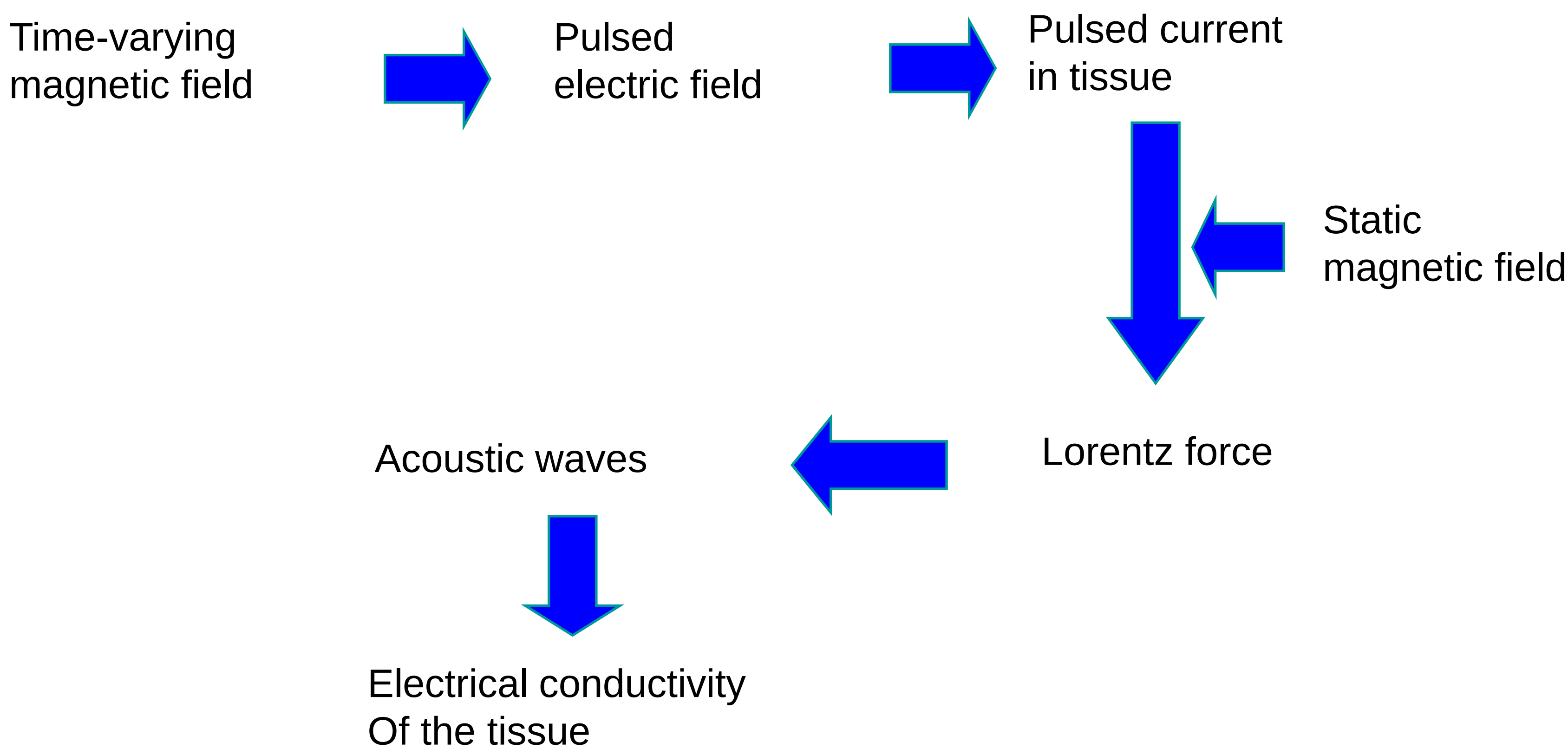
- A filtered version of one component of the current density can be mapped using the ultrasound-induced electrical potential difference in biological tissues

- Signal-noise-ratio of the ultrasound-induced electrical potential difference needs to be improved to make the technique practical.

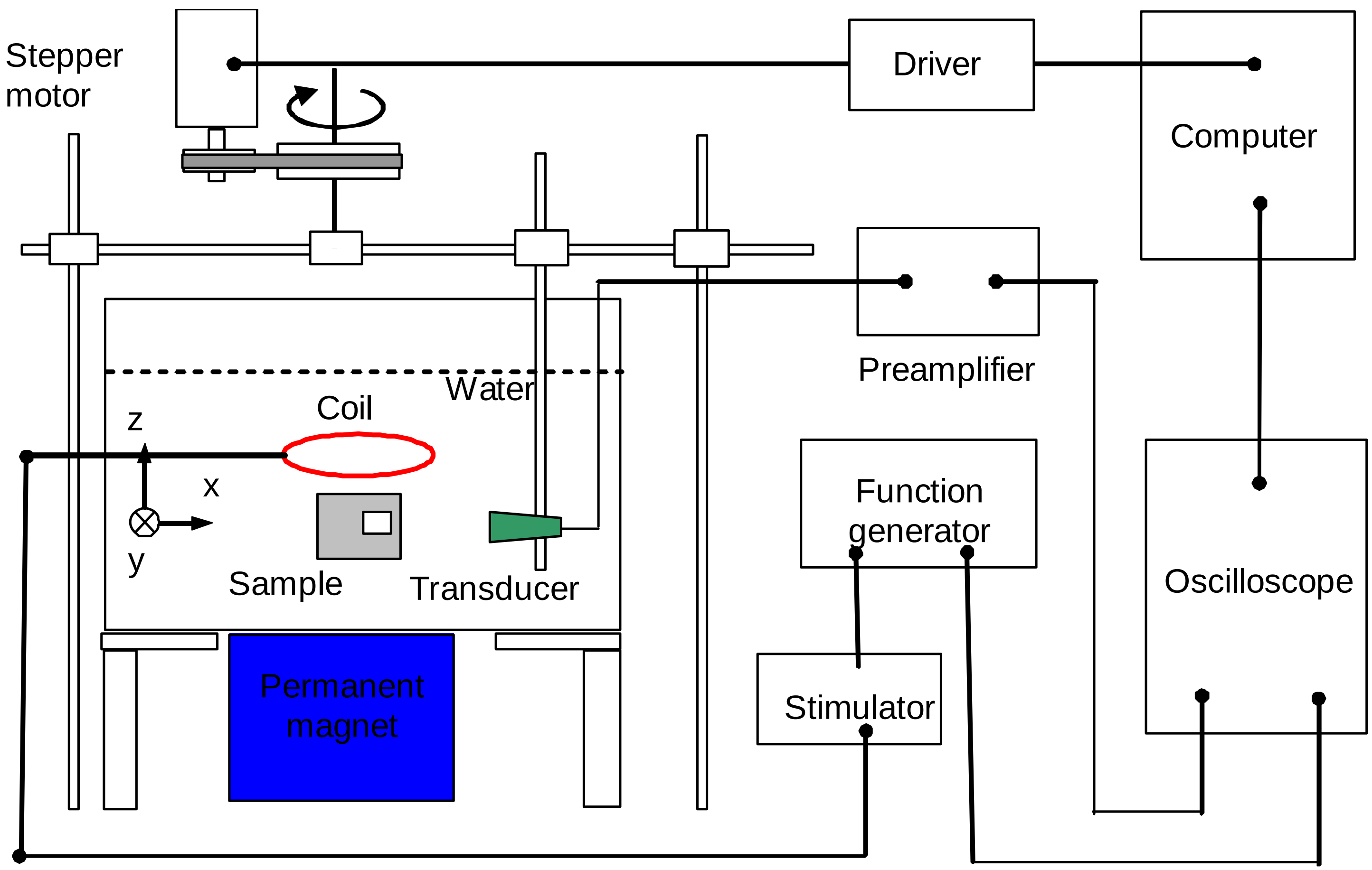
Part III: Ultrasound induced by electric current in biological tissues

Magnetoacoustic Tomography with Magnetic Induction (MAT-MI) (Xu and He)

Principle of MAT-MI



Experimental Setup of 2-D MAT-MI



Wave Equation in Forward Problem

Pressure

Source term

$$\nabla^2 p - \frac{1}{c_s^2}\frac{\partial^2 p}{\partial t^2} = S(\mathbf{r},t),$$

Delta function

Static magnetic field

$$S(\mathbf{r},t) = \varphi(\mathbf{r})\delta(t),$$

$$\varphi(\mathbf{r}) = \mathbf{B}_0 \cdot [\nabla \times \mathbf{J}(\mathbf{r})]$$

$$\mathbf{J}(\mathbf{r}) = \sigma(\mathbf{r})\mathbf{E}(\mathbf{r})$$

Two Steps in Reconstruction

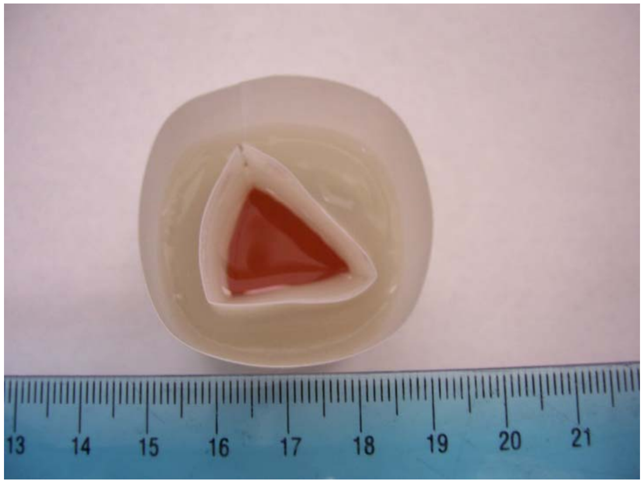
1. $$p(\mathbf{r},t) \Rightarrow S(\mathbf{r},t)$$

$$S(\mathbf{r},t) = \varphi(\mathbf{r})\delta(t),$$

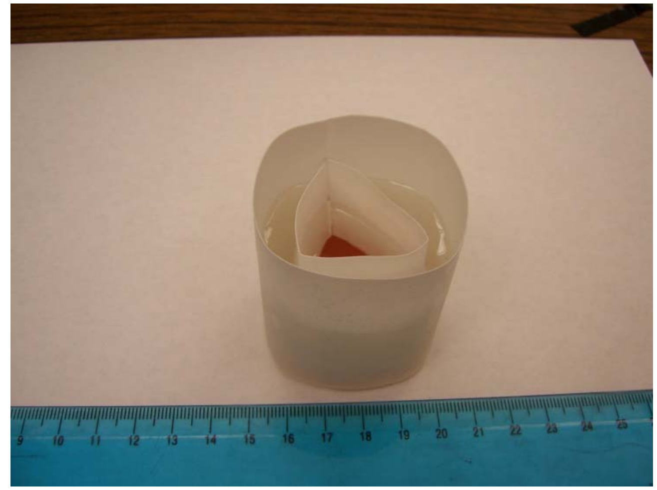
$$\varphi(\mathbf{r}) = \mathbf{B}_0 \cdot [\nabla \times \mathbf{J}(\mathbf{r})]$$

2. $$\mathbf{B}_0 \cdot [\nabla \times \mathbf{J}(\mathbf{r})] \Rightarrow \sigma(\mathbf{r})$$

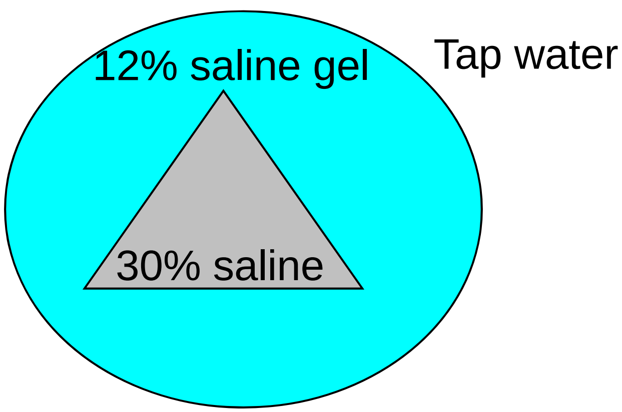
Image and Photo of Saline Gel



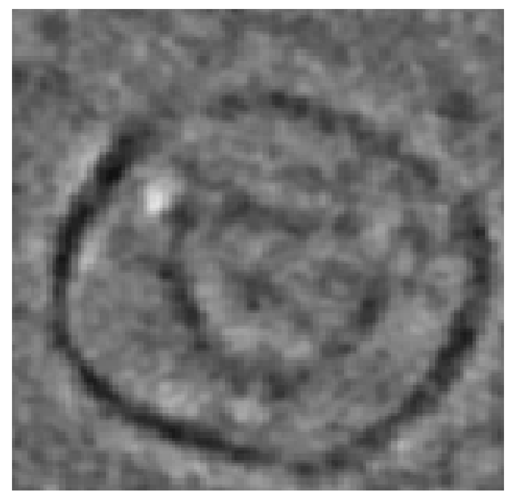
(a) Photo of the sample



(b) Photo of the sample

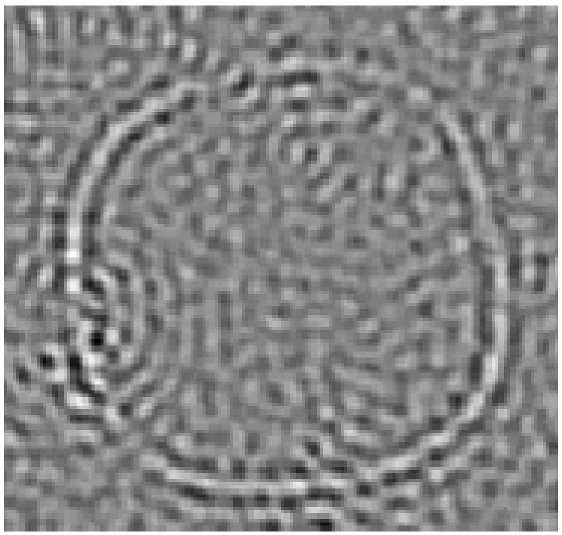


(c) Diagram of the sample



(d) MAT-MI image

Image and Photo of Pork Muscle



1 CM

CM

(a) **(b)**

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