Where Sound Meets Electricity: The Acoustoelectric Effect in Biomedicine

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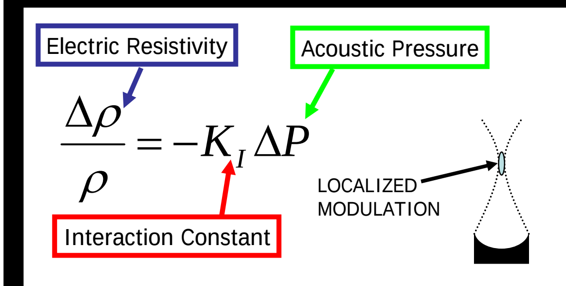
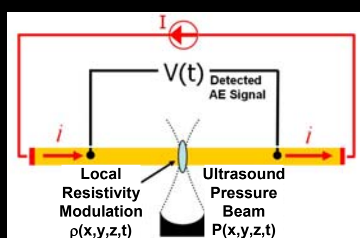
The Acoustoelectric Effect

$$\frac{\Delta\rho}{\rho} = -K_I \Delta P$$



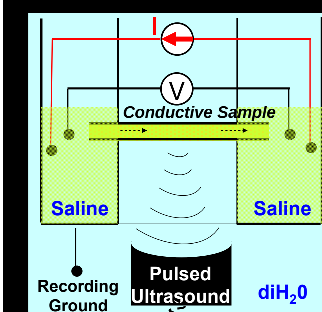
➔ Ultrasound Modulates Electric Resistivity

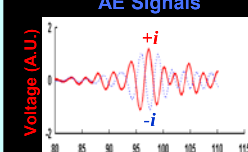
Exploiting the AE Effect Depends on Ohm's Law

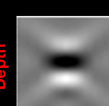


$dV = K' i \rho_0 dP$

A Setup for Detecting the AE Signal

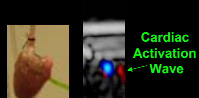






The Acoustoelectric Effect in Biomedicine

① Ultrasound Current Source Density Imaging



Ultrasound-Enhanced Electrophysiology

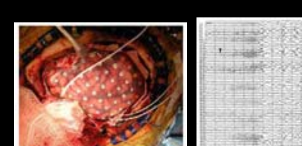
② Novel Devices to Monitor Acoustic Exposure

Mapping an US Beam During Therapy

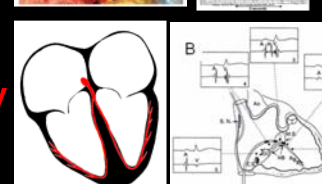
Patent Pending

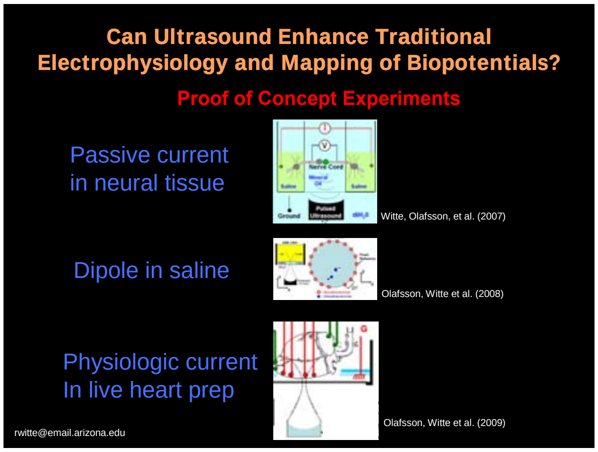
Electrical Mapping of Biopotentials: Clinical Relevance

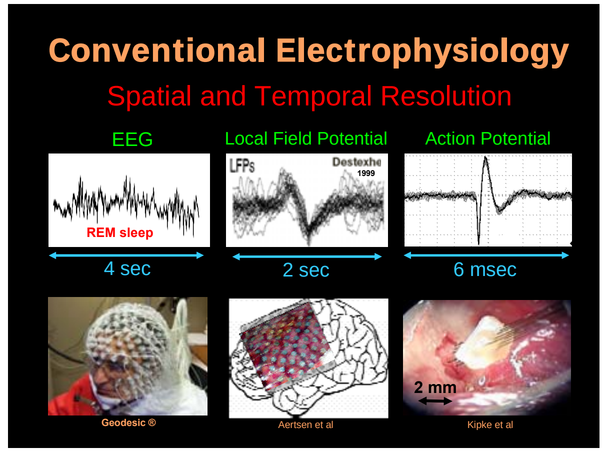
Neurosurgery
(Epilepsy, Parkinsons)

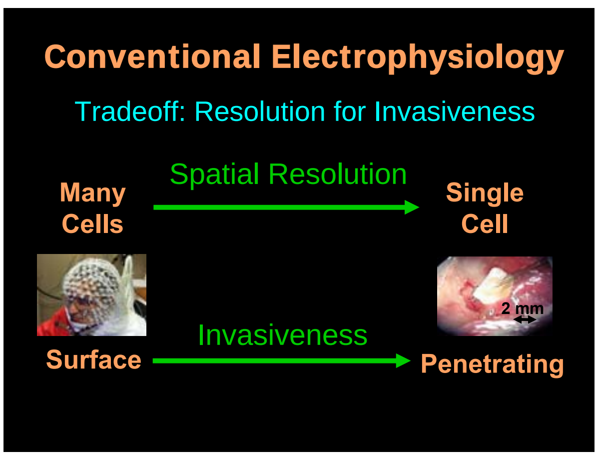


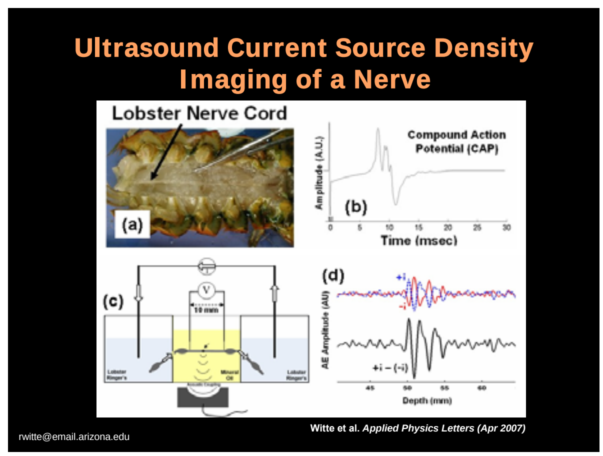
Cardiac Surgery
(Arrhythmia)

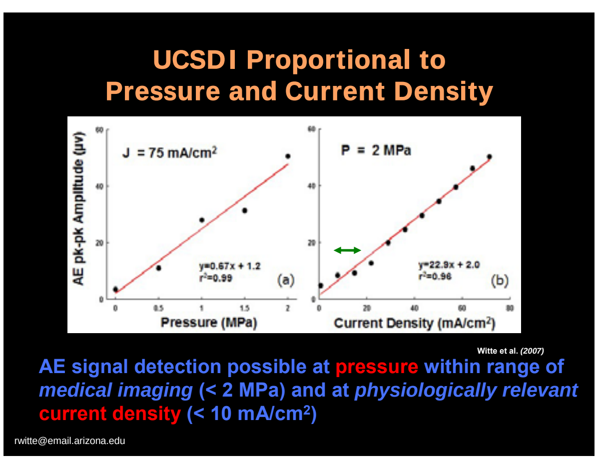



Can Ultrasound Enhance Traditional Electrophysiology and Mapping of Biopotentials?
Proof of Concept Experiments
Passive current in neural tissue
Witte, Olafsson, et al. (2007)
Dipole in saline
Olafsson, Witte et al. (2008)
Physiologic current In live heart prep
Olafsson, Witte et al. (2009)
rwitte@email.arizona.edu


Conventional Electrophysiology
Spatial and Temporal Resolution
EEG
Local Field Potential
Action Potential
REM sleep
LFPs
Destexhe 1999
4 sec
2 sec
6 msec
2 mm
Geodesic ®
Aertsen et al
Kipke et al


Conventional Electrophysiology
Tradeoff: Resolution for Invasiveness
Many Cells
Spatial Resolution
Single Cell
2 mm
Invasiveness
Surface
Penetrating


Ultrasound Current Source Density Imaging of a Nerve
Lobster Nerve Cord
(a)
Compound Action Potential (CAP)
Amplitude (A.U.)
(b)
Time (msec)
(c)
(d)
AE Amplitude (AU)
Depth (mm)
rwitte@email.arizona.edu
Witte et al. Applied Physics Letters (Apr 2007)


UCSDI Proportional to Pressure and Current Density
AE pk-pk Amplitude (µV)
J = 75 mA/cm²
y=0.67x + 1.2
r²=0.99
(a)
Pressure (MPa)
P = 2 MPa
y=22.9x + 2.0
r²=0.96
(b)
Current Density (mA/cm²)
Witte et al. (2007)
AE signal detection possible at pressure within range of medical imaging (< 2 MPa) and at physiologically relevant current density (< 10 mA/cm²)
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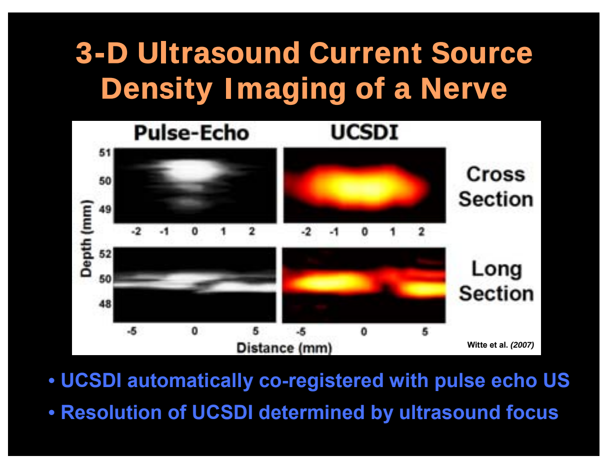
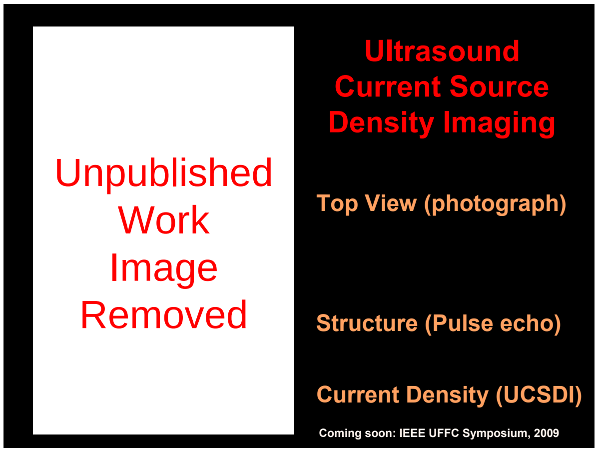
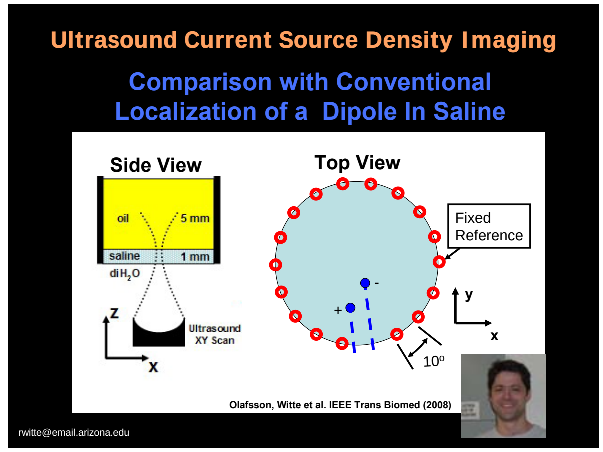
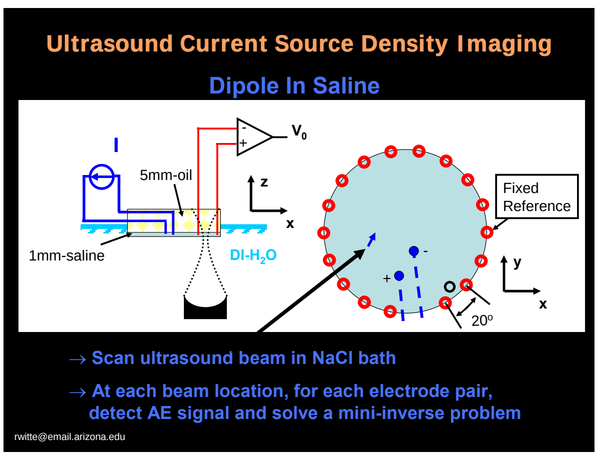
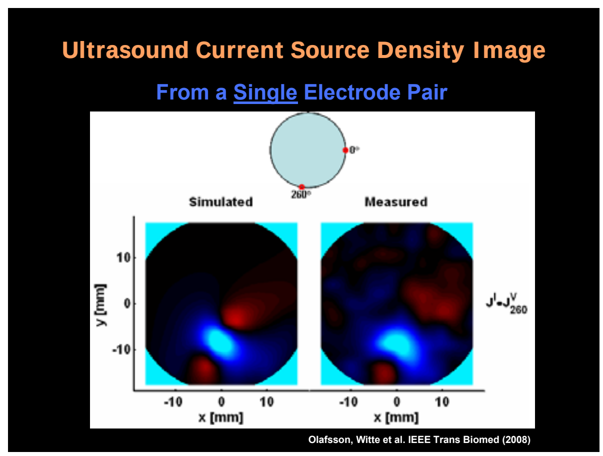
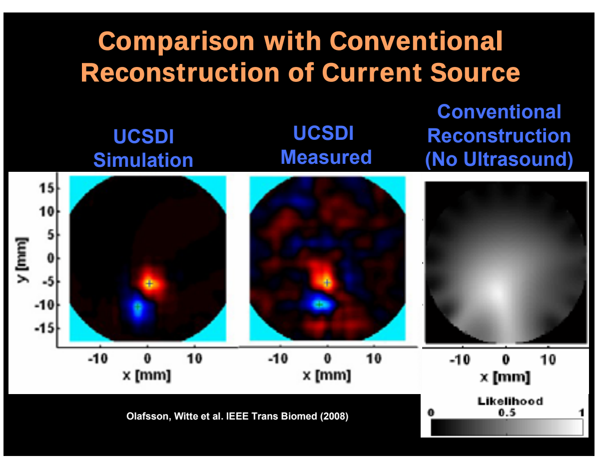

3-D Ultrasound Current Source Density Imaging of a Nerve
Pulse-Echo
UCSDI
Cross Section
Depth (mm)
Long Section
Distance (mm)
Witte et al. (2007)
• UCSDI automatically co-registered with pulse echo US
• Resolution of UCSDI determined by ultrasound focus

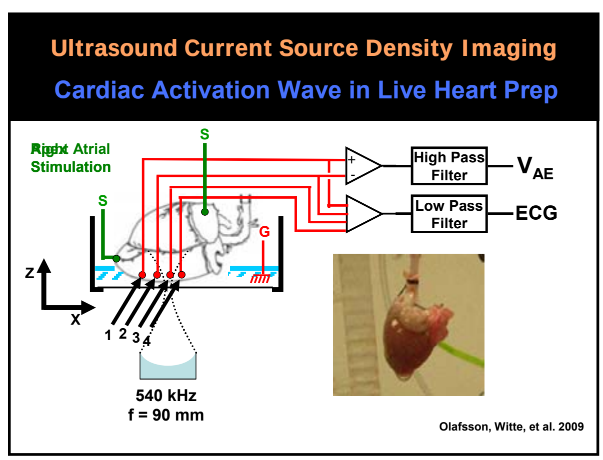

Unpublished Work Image Removed
Ultrasound Current Source Density Imaging
Top View (photograph)
Structure (Pulse echo)
Current Density (UCSDI)
Coming soon: IEEE UFFC Symposium, 2009


Ultrasound Current Source Density Imaging
Comparison with Conventional Localization of a Dipole In Saline
Side View
Top View
oil
5 mm
saline
1 mm
diH2O
Ultrasound XY Scan
Z
X
Fixed Reference
y
x
10°
Olafsson, Witte et al. IEEE Trans Biomed (2008)
rwitte@email.arizona.edu

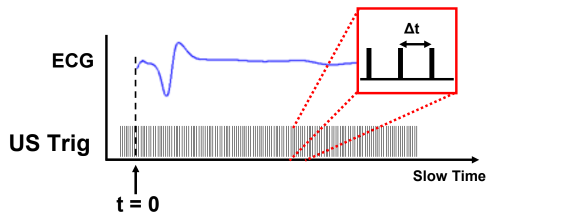

Ultrasound Current Source Density Imaging
Dipole In Saline
I
V0
5mm-oil
z
x
1mm-saline
DI-H2O
Fixed Reference
y
x
20°
→ Scan ultrasound beam in NaCl bath
→ At each beam location, for each electrode pair, detect AE signal and solve a mini-inverse problem
rwitte@email.arizona.edu


Ultrasound Current Source Density Image
From a Single Electrode Pair
0°
260°
Simulated
Measured
y [mm]
10
0
-10
-10
0
10
x [mm]
Olafsson, Witte et al. IEEE Trans Biomed (2008)


Comparison with Conventional Reconstruction of Current Source
UCSDI Simulation
UCSDI Measured
Conventional Reconstruction (No Ultrasound)
y [mm]
15
10
5
0
-5
-10
-15
-10
0
10
x [mm]
Likelihood
0
0.5
1
Olafsson, Witte et al. IEEE Trans Biomed (2008)


Ultrasound Current Source Density Imaging
Cardiac Activation Wave in Live Heart Prep
Right Atrial Stimulation
S
G
High Pass Filter
VAE
Low Pass Filter
ECG
Z
X
1 2 3 4
540 kHz
f = 90 mm
Olafsson, Witte, et al. 2009

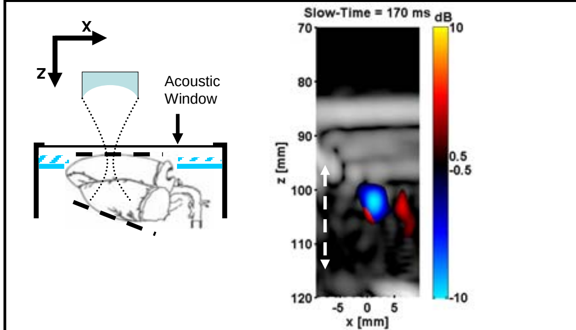
Experimental Timing



- Heart Pacing Rate (PRF) = 3 Hz
- BDM used to limit cardiac motion

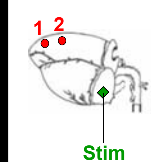
Olafsson, Witte, et al. 2009

Orientation



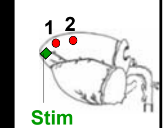
Olafsson, Witte, et al. 2009

B Mode Movie 1: Atrial Stimulation



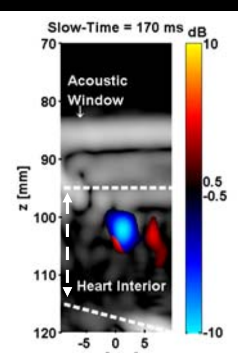
Olafsson, Witte, et al. 2009

B Mode Movie 2: Apical Stimulation



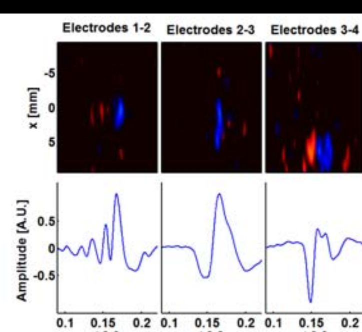
Olafsson, Witte, et al. 2009

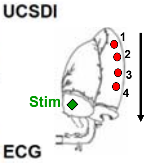
M-mode Imaging



Olafsson, Witte, et al. 2009

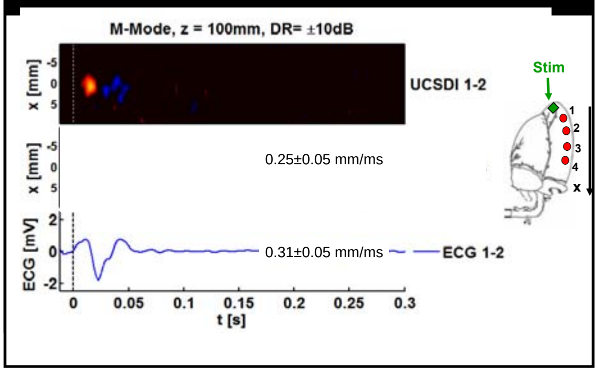
AE is spatially separable



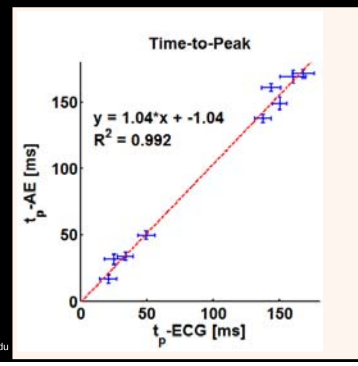


Olafsson, Witte, et al. 2009

AE is temporally separable



Correlation: UCSDI vs. Conventional ECG



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Olafsson, Witte, et al. 2009

UCSDI compared with conventional electrophysiology (no ultrasound)

Potential advantages of UCSDI

- Direct imaging of biopotentials and current flow in 4D
- Spatial resolution determined by US focus (<1 mm^3)
- Fewer assumptions (e.g., conductivity, sources, etc.)
- Less invasive with possibly fewer electrodes
- Automatic co-registration with pulse echo ultrasound

Major Challenges:

- Sensitivity
- Instrumentation

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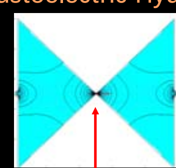
UCSDI Patent Pending

What if the ultrasound beam pattern *P(x,y,z,t)* was the unknown, but you had control of the current density *J(x,y,z,t)*?

The Acoustoelectric Hydrophone:



Sensitivity Zone

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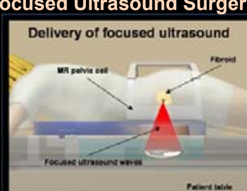
Why Monitor Medical Ultrasound Exposure?

1) Ensure Safety
2) *Guide Treatment*

- Lithotripsy
- Uterine Fibroids
- Tumor Therapy
- Thrombolysis
- Drug/Gene Delivery

Focused Ultrasound Surgery



insightec.com

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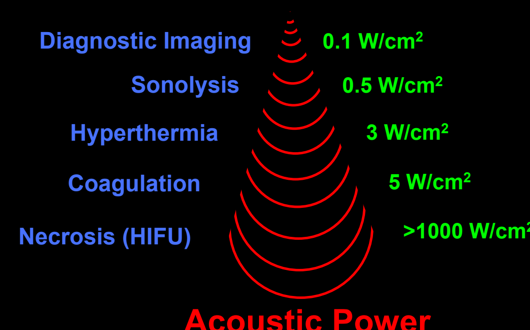
Novel Devices to Monitor Acoustic Exposure



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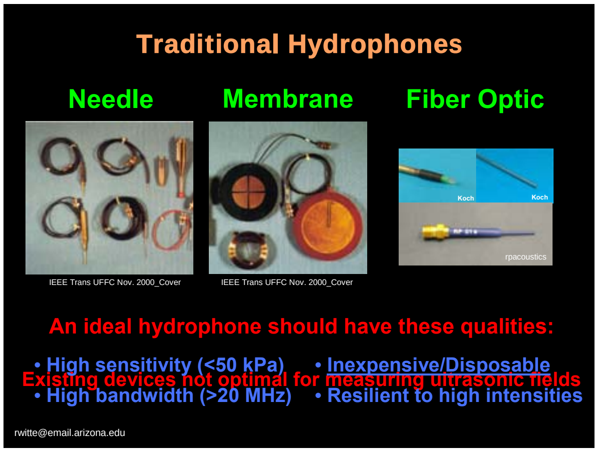
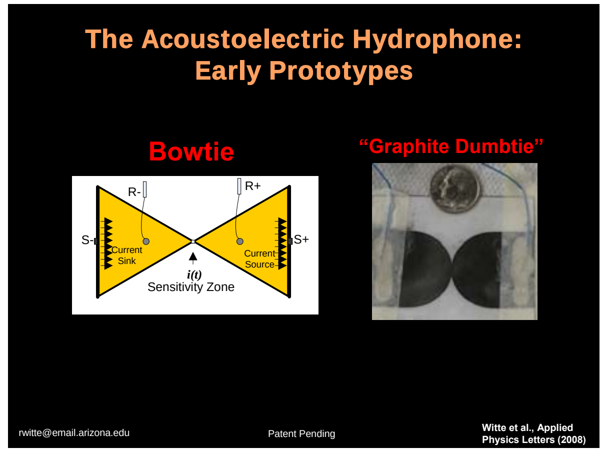
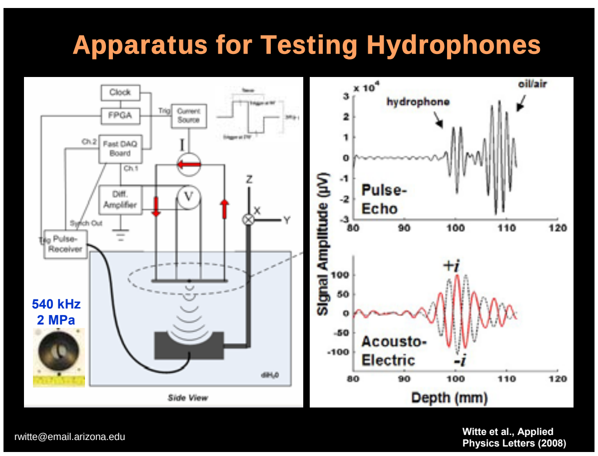
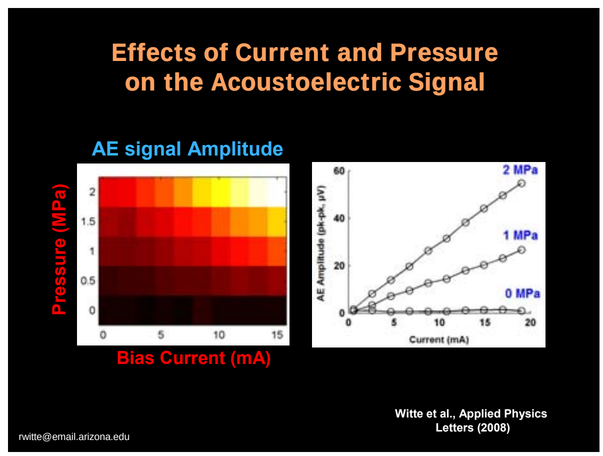
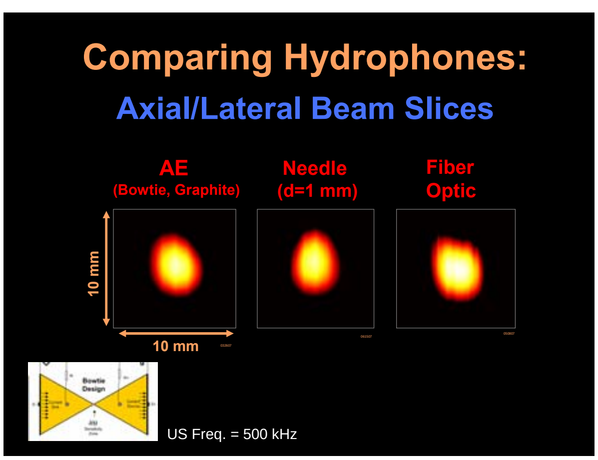
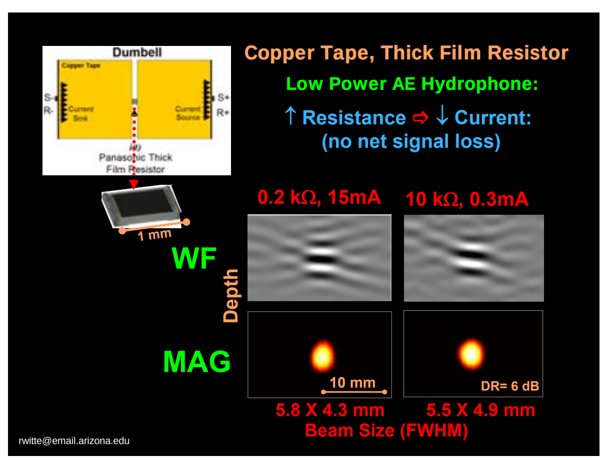

Traditional Hydrophones
Needle
Membrane
Fiber Optic
IEEE Trans UFFC Nov. 2000_Cover
IEEE Trans UFFC Nov. 2000_Cover
Koch
Koch
rpacoustics
An ideal hydrophone should have these qualities:
• High sensitivity (<50 kPa)
• Inexpensive/Disposable
Existing devices not optimal for measuring ultrasonic fields
• High bandwidth (>20 MHz)
• Resilient to high intensities
rwitte@email.arizona.edu


The Acoustoelectric Hydrophone: Early Prototypes
Bowtie
"Graphite Dumbtie"
R-
R+
S-
S+
Current Sink
Current Source
i(t)
Sensitivity Zone
rwitte@email.arizona.edu
Patent Pending
Witte et al., Applied Physics Letters (2008)


Apparatus for Testing Hydrophones
Clock
FPGA
Current Source
Fast DAQ Board
Diff. Amplifier
Pulse-Receiver
540 kHz
2 MPa
Side View
hydrophone
oil/air
Pulse-Echo
Acousto-Electric
+i
-i
Signal Amplitude (μV)
Depth (mm)
rwitte@email.arizona.edu
Witte et al., Applied Physics Letters (2008)


Effects of Current and Pressure on the Acoustoelectric Signal
AE signal Amplitude
Pressure (MPa)
Bias Current (mA)
2 MPa
1 MPa
0 MPa
AE Amplitude (pk-pk, μV)
Current (mA)
rwitte@email.arizona.edu
Witte et al., Applied Physics Letters (2008)


Comparing Hydrophones:
Axial/Lateral Beam Slices
AE
(Bowtie, Graphite)
Needle
(d=1 mm)
Fiber
Optic
10 mm
10 mm
Bowtie Design
US Freq. = 500 kHz


Dumbell
Copper Tape
Current Sink
Current Source
Panasonic Thick Film Resistor
1 mm
Copper Tape, Thick Film Resistor
Low Power AE Hydrophone:
↑ Resistance ⇨ ↓ Current:
(no net signal loss)
0.2 kΩ, 15mA
10 kΩ, 0.3mA
WF
MAG
Depth
10 mm
DR= 6 dB
5.8 X 4.3 mm
5.5 X 4.9 mm
Beam Size (FWHM)
rwitte@email.arizona.edu

Next Generation: MEMS-based AE Hydrophones

Unpublished Work
Image
Removed

rwitte@email.arizona.edu

Patent Pending

Key advantages of AE Hydrophone

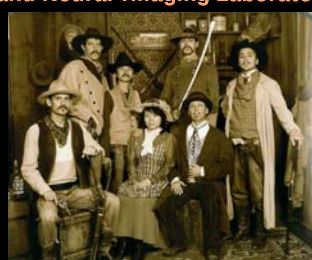
- Disposable hydrophone based on *conduction*
- Sensitivity (<20 kPa) proportional to bias current
- Faithful reproduction of US beam pattern

Focus of ongoing work

- Optimize material composition and design
- Test high bandwidth devices (10+ MHz)
- Evaluate damage threshold at high intensities

Acknowledgements

Experimental Ultrasound and Neural Imaging Laboratory



"The Posse"

rwitte@email.arizona.edu