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Los Alamos NATIONAL LABORATORY

Applied Acoustics and Applications in Additive Manufacturing

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Applied Acoustics Lab
Materials Physics and Applications, MPA-11

Worcester Polytechnic Institute
Physics Department
Solid State Physics_Spring2023
ZOOM
1 May 2023

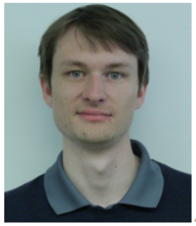
Applied Acoustics Team

http://www.lanl.gov/orgs/mpa/mpa11/AcousticsAndSensorsTeam

Cristian Pantea

Team Leader

Eric Davis



Research Scientist

Monitoring
CO_2 sequestration (DOE)
D_2O content in heavy water
3DHEAT
Acoustic Monitoring of Pu
NDE of weapons components

John Greenhall

Research Scientist

Machine Learning
3DHEAT
Defects Thermoel Wafers
NDE weapons components
Electronics design

Craig Chavez

Research Technologist

Mechanical and Electronics Design, and System Configuration

Pavel Vakhlamov

Research Technologist

Mechanical and Electronics Design, and System Configuration

Milo Prisbrey

Research Scientist

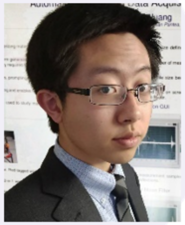
Machine Learning
Acoustic manipulation
Waveform inversion

Dipen Sinha

Lab Associate/LANL fellow

Defects Thermoel Wafers
Welding inspection
NDE of weapons components
Electronics design

Sincheng Huang



Grad Student

Instrumentation development
LabView programming
D_2O content in heavy water

Alan Graham

Research Associate

Defects detection in wafers
Welding inspection
NDE of weapons components

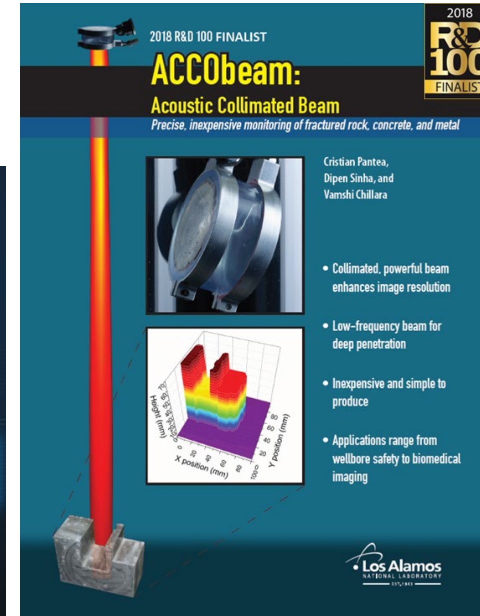
- 2 new postdocs, joining in Dec-Jan timeframe
- Norman Hunter – contractor
- Rick Rowland – RT (M-9)

- DOE NNSA Laboratory Residency Graduate Fellowship LRGF
  - **Jazmin Ley** U Nebraska-Lincoln
- DOE NNSA **MSIPP** (Minority Serving Institutions Partnership Program)
  - 4 students FIU, NMSU, UTEP
- 3 High-school students

Current Role:

- Team Leader
- Research Scientist 4
- Principal Investigator
- Acting Deputy Group Leader (May22-Jan23)

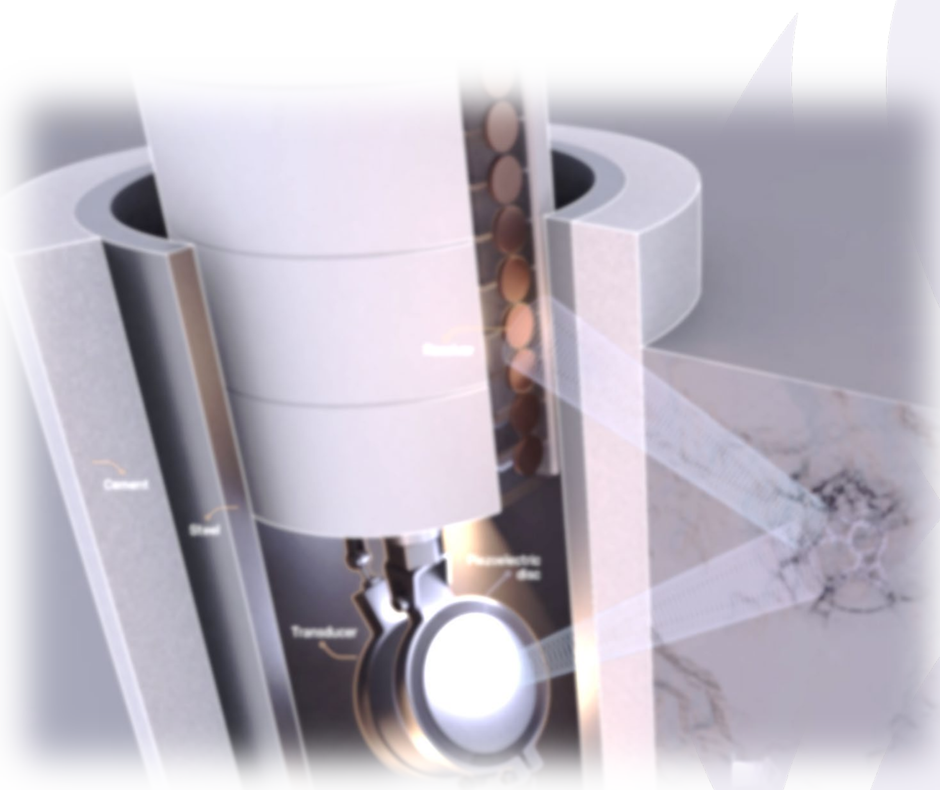
25 patents
80+ publications

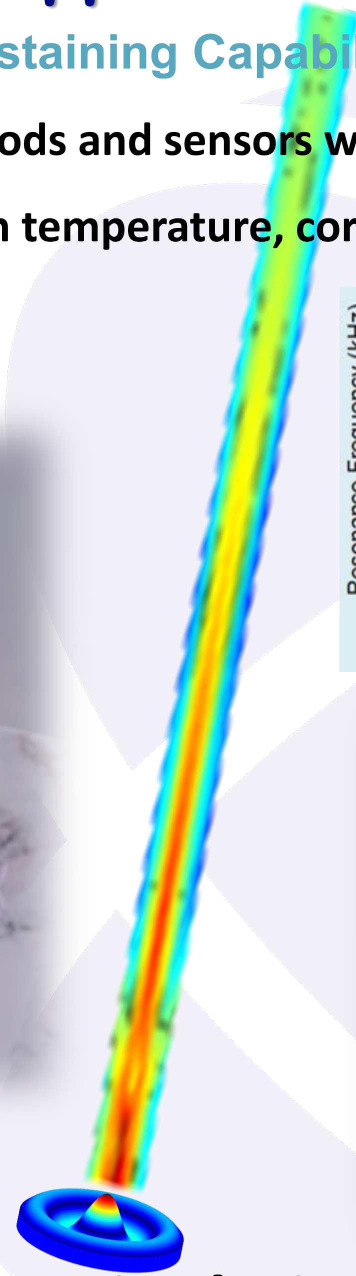


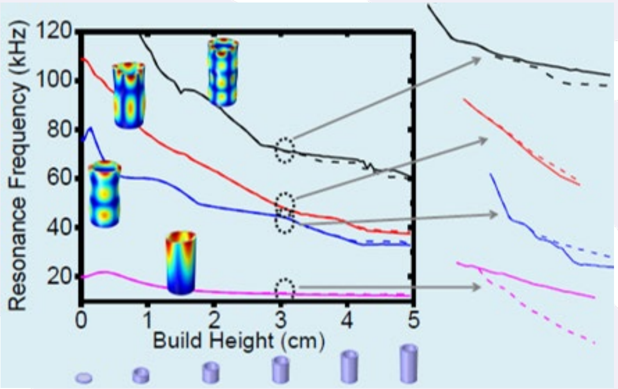
Our research - Applied Acoustics

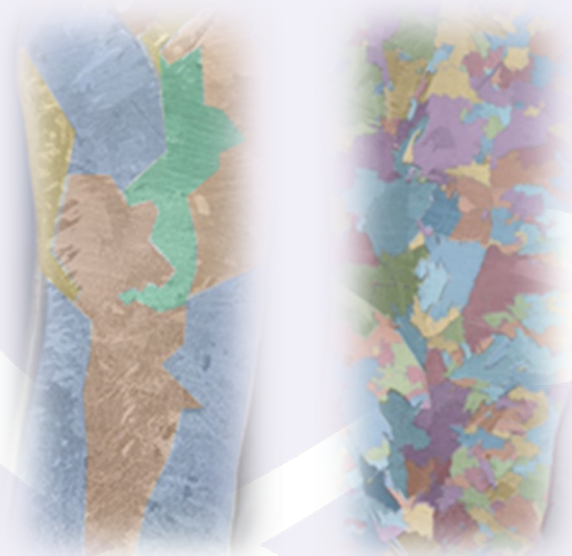
Building and Sustaining Capabilities

Development of instrumentation, methods and sensors with a focus on difficult and challenging conditions (high pressure, high temperature, corrosive media, radiation, etc.)









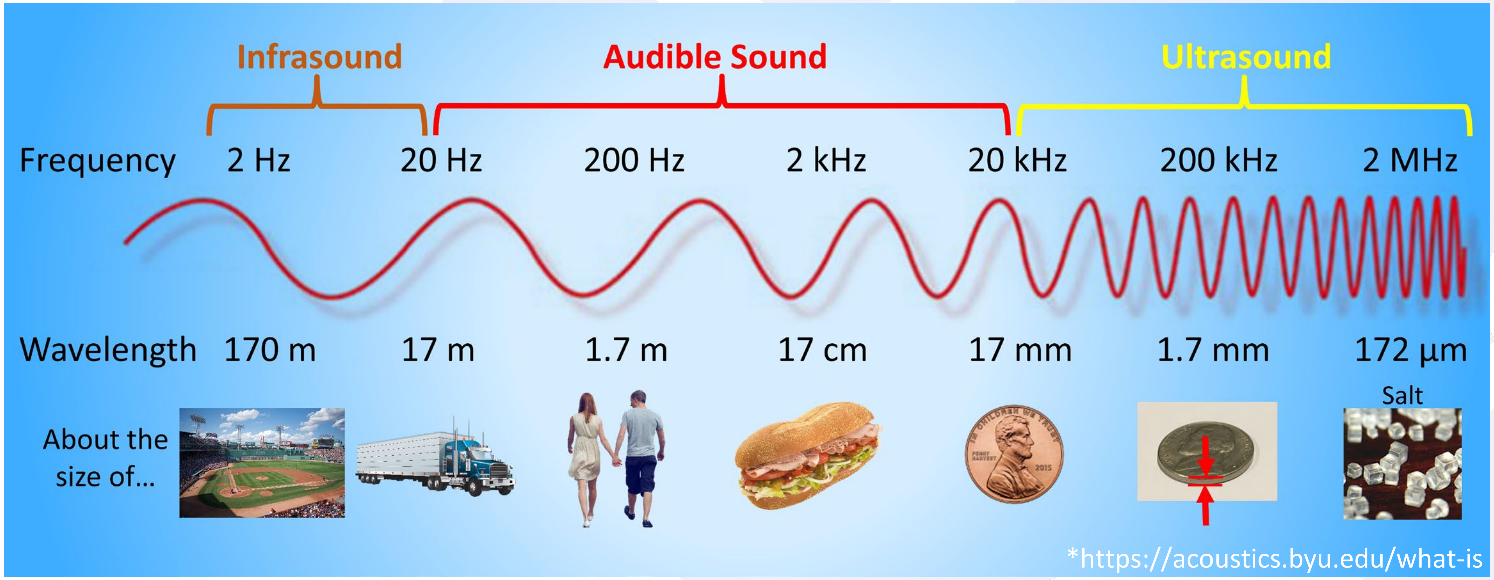
Sensing

Manipulation with sound

Acoustics

Acoustics = the branch of physics concerned with the properties of sound (Wikipedia)

Acoustics = the science that deals with the production, control, transmission, reception, and effects of sound (Merriam-Webster)



Acoustics

Audio range: ***20 Hz – 20 kHz***

Musical notes:
e.g. guitar

Note	E	A	D	G	B	E
Frequency (Hz)	82	110	147	196	247	330

Voice - speech: 85 - 155 Hz (male) 165 - 255 Hz (female) 250 - 300 Hz (child)

Piano: 27 Hz – 4.2 KHz

Voice – singers: 65 Hz (deep bass voice) 1.3 kHz (soprano)
* female high-pitched scream: 3 kHz

Whistling: 2-4 kHz

A good sound system: 35 Hz – 22 kHz

My hearing range: ***30 Hz – 15 kHz***

Sensing applications

Applications of Acoustic Techniques

Acoustics – typical experimental arrangement:

Sample:

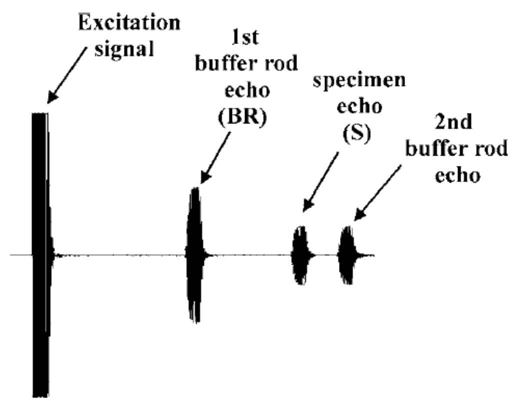
any form (solid, liquid, or gas)

Transmitter/Receiver:

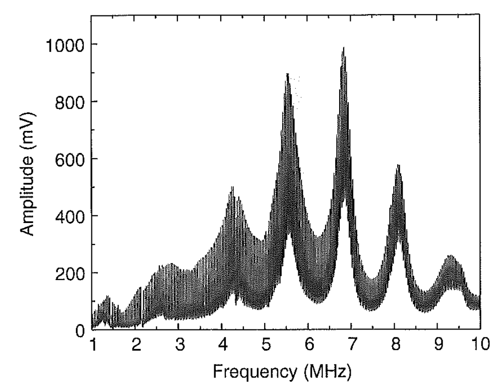
piezoelectric transducer

Two main experimental approaches:

- **Time-domain measurements**
  - Pulse - Echo
  - Pitch - Catch
  - Transmit - Receive



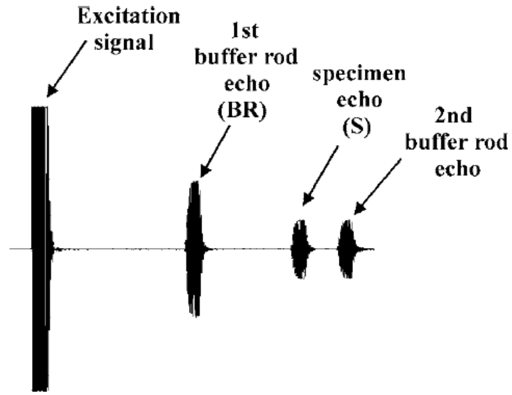
- **Frequency domain measurements**
  - Resonant Ultrasound Spectroscopy
  - Swept-Frequency Acoustic Interferometry
  - Acoustic Resonance Spectroscopy

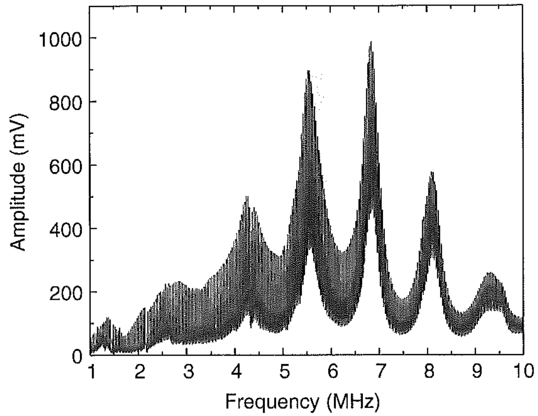


Applications of Acoustic Techniques

What one measures:

- Time of Flight
- Resonances





What one can determine:

Elastic properties of materials:

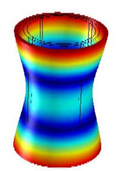
- Bulk Modulus
- Shear Modulus
- Young's Modulus
- Anisotropy
- Poisson ratio
- Acoustical Nonlinear Parameter β
- Higher-Order Elastic Moduli
- Sound Attenuation
- Viscosity
- Density

Applications of Acoustic Techniques

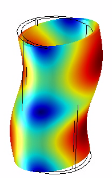
Observe mechanical resonances of objects to extract physical properties of fluids and elastic properties of materials

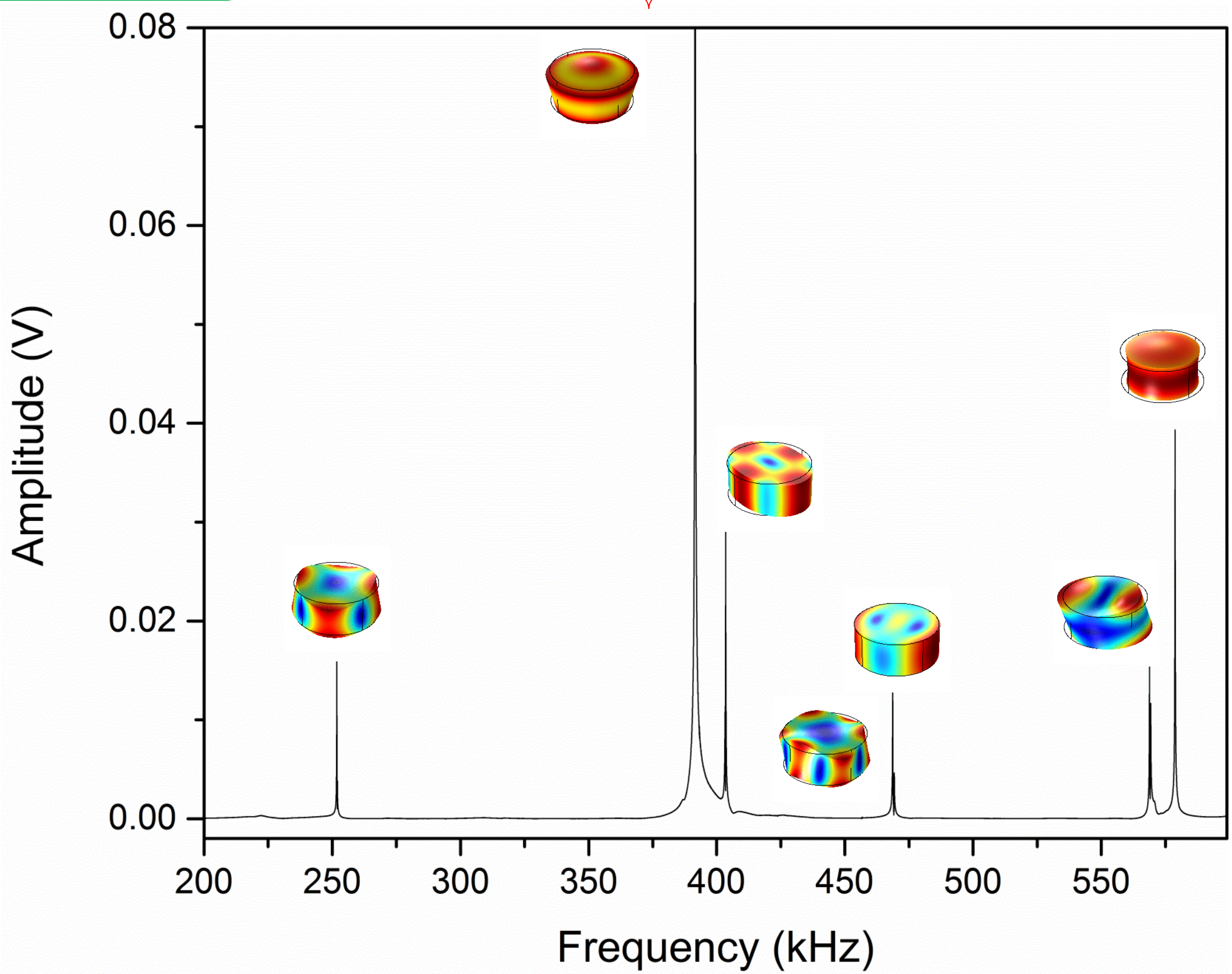
Fluid inside pipe

Eigenfrequency=32267 Hz, Surface: Displacement, RMS (mm)



Eigenfrequency=20283 Hz, Surface: Displacement, RMS (mm)



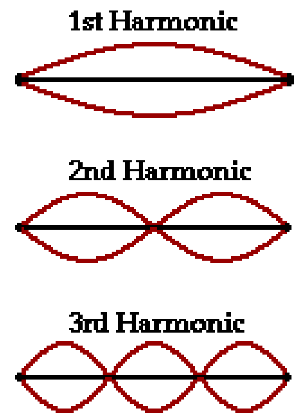


Standing Waves and Resonances in a Fluid medium inside a cavity:

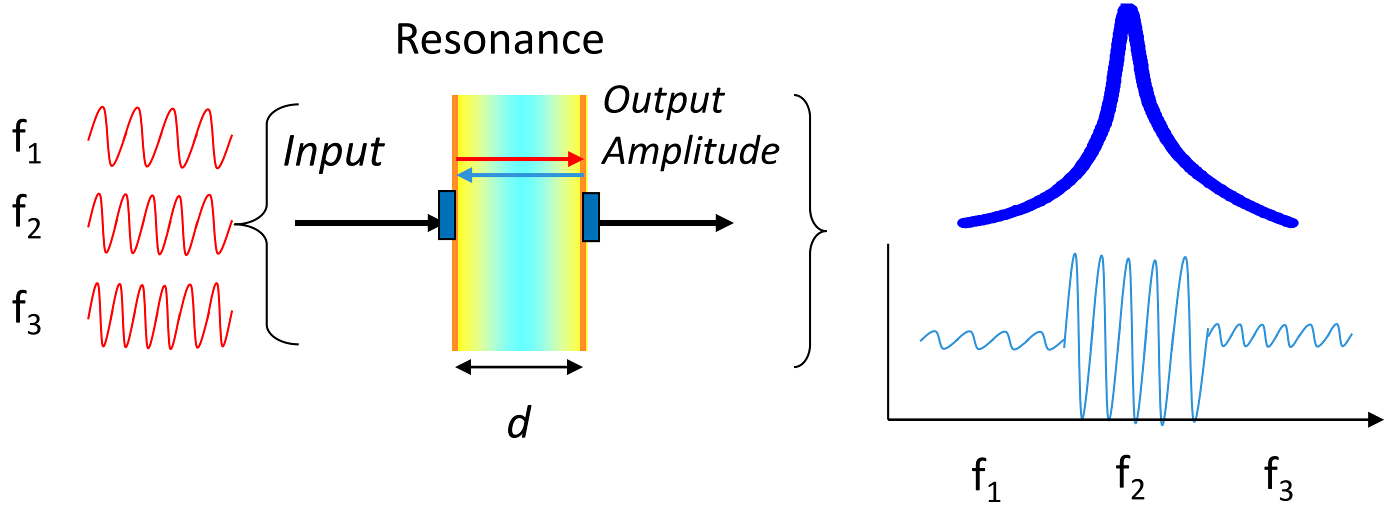
Resonance occurs when:

$$d = n.(\lambda/2)$$

n=1, 2, 3…
λ=wavelength

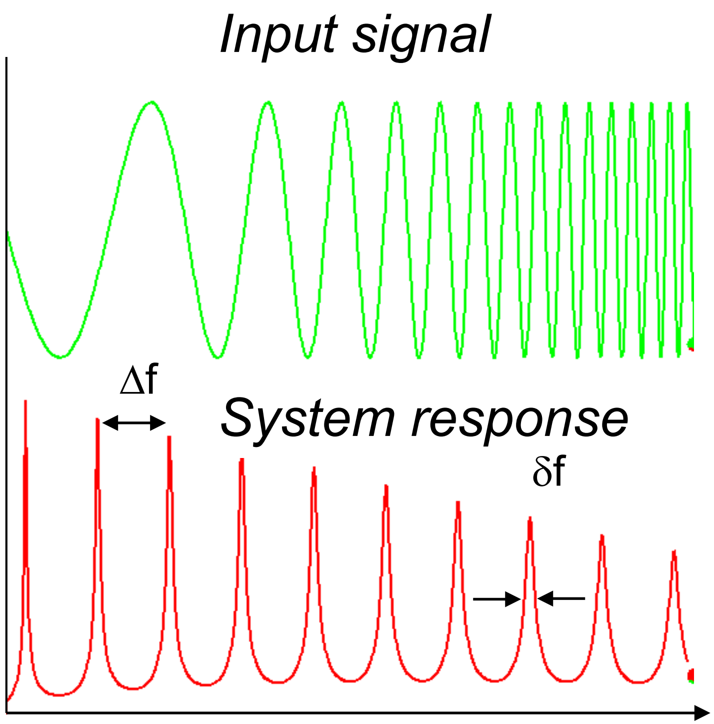


Examples of standing wave when resonance occurs



Resonance occurs when the ***forward*** *sound wave and the* ***reflected*** *wave meet exactly in phase and* ***interfere***

How can fluid properties be determined using swept frequency and acoustic interferences?



Sound speed = $2d\Delta f$

Sound absorption ⌒ δf

Δf =frequency spacing

δf =peak width

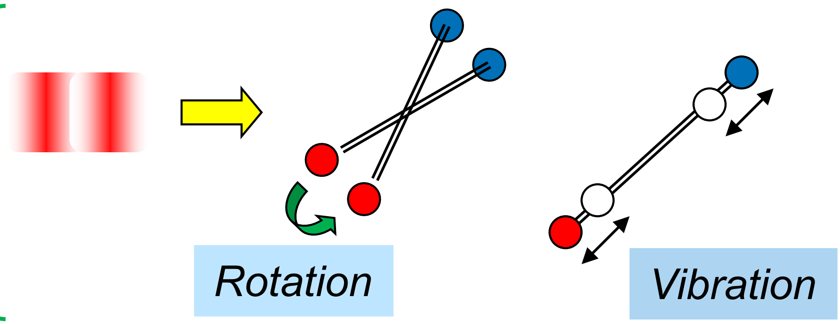
There can be hundreds of such resonance peaks in a typical spectrum

Swept Frequency Acoustic Interferometry (SFAI)

SFAI

Physical Parameters That Can Be Determined Using SFAI:

- Sound speed — $\sqrt{\text{Bulk Modulus}/\text{Density}}$
- Sound attenuation — Viscous drag, thermal effects, scattering
- Molecular Relaxation

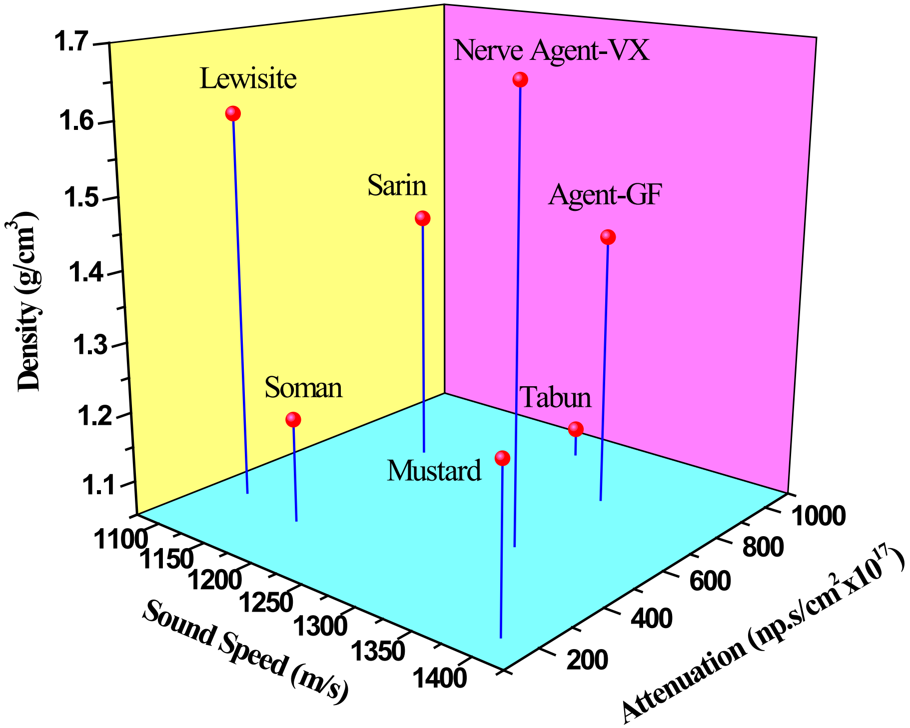


- Density
- Viscosity
- Acoustic Nonlinearity — Sound speed varies with pressure in liquids and solids.

Liquids, gases, mixtures, emulsions, suspension, etc.

Noninvasive Identification of CW Agents

SFAI Measurements of CW Agent Physical Properties



ACCObeam

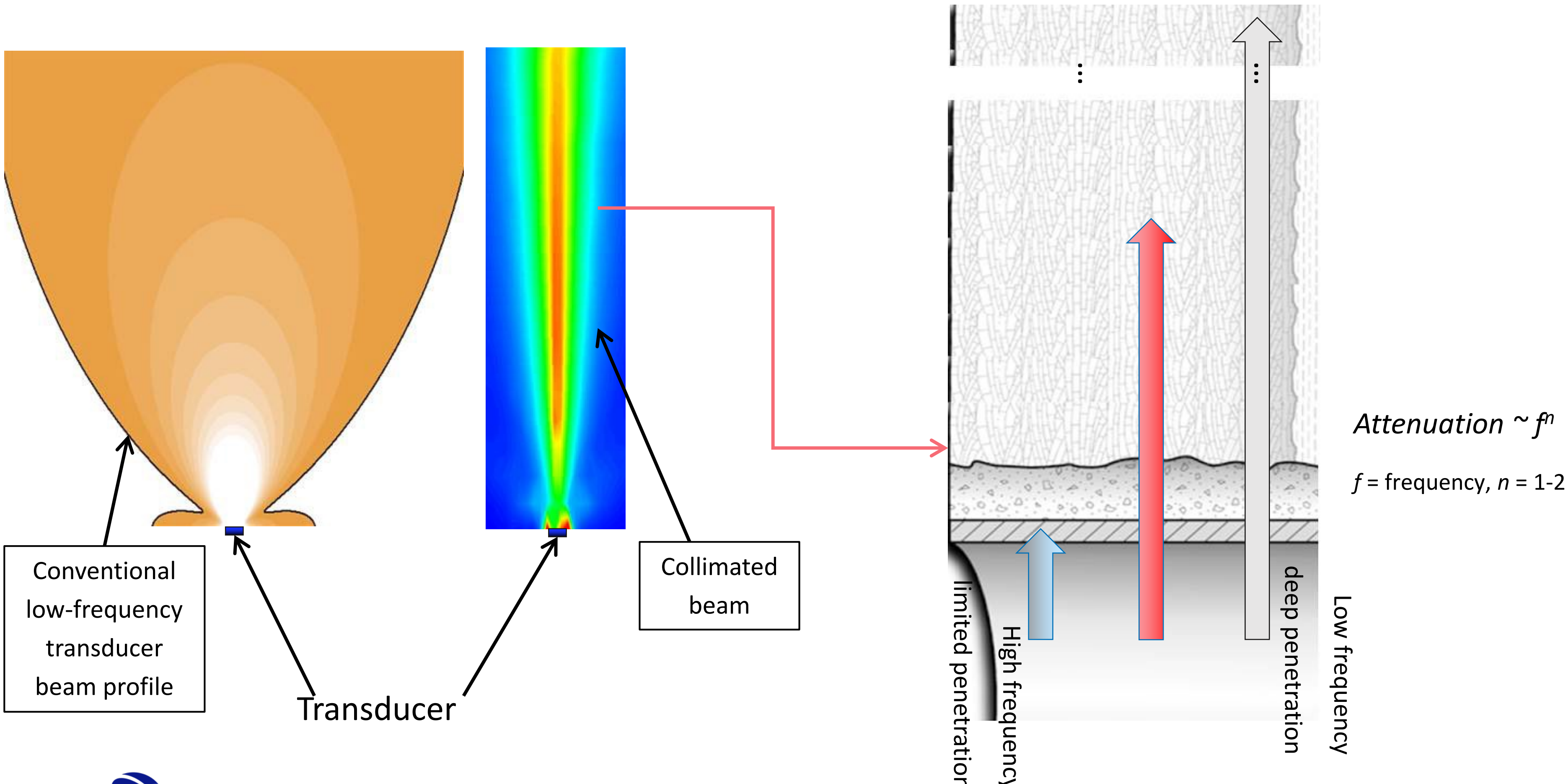
Proposed Approach:

Detect defects

using a low-frequency, collimated beam.

1. Collimated beam for increased resolution

2. Low frequency for deeper penetration

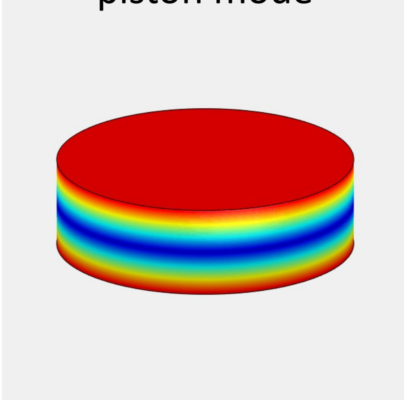


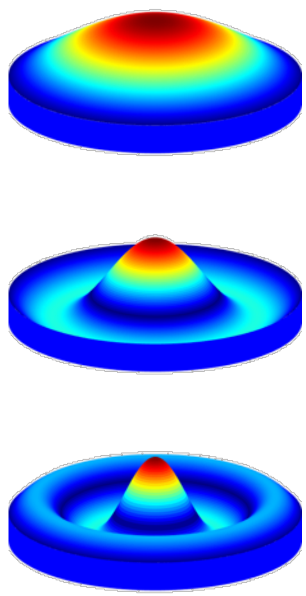
Slide 2

ACCObeam

- Generate collimated beam by exciting radial modes of piezoelectric disk
- Clamp disk edges to focus energy into collimated beam

Traditional acoustic source
“piston mode”





Radial mode 1

Radial mode 2

Radial mode 3

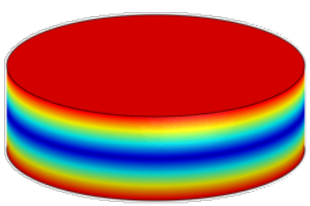
Clamped piezoelectric disk

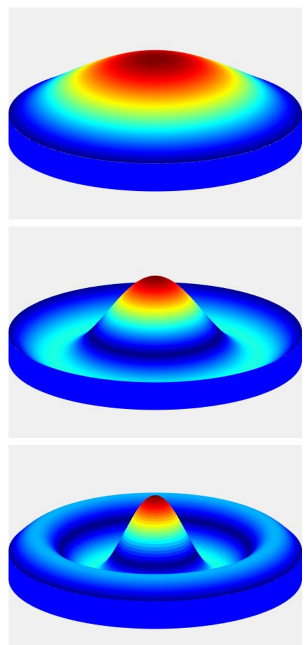
Slide 2

ACCObeam

- Generate collimated beam by exciting radial modes of piezoelectric disk
- Clamp disk edges to focus energy into collimated beam

Traditional acoustic source
"piston mode"





Radial mode 1

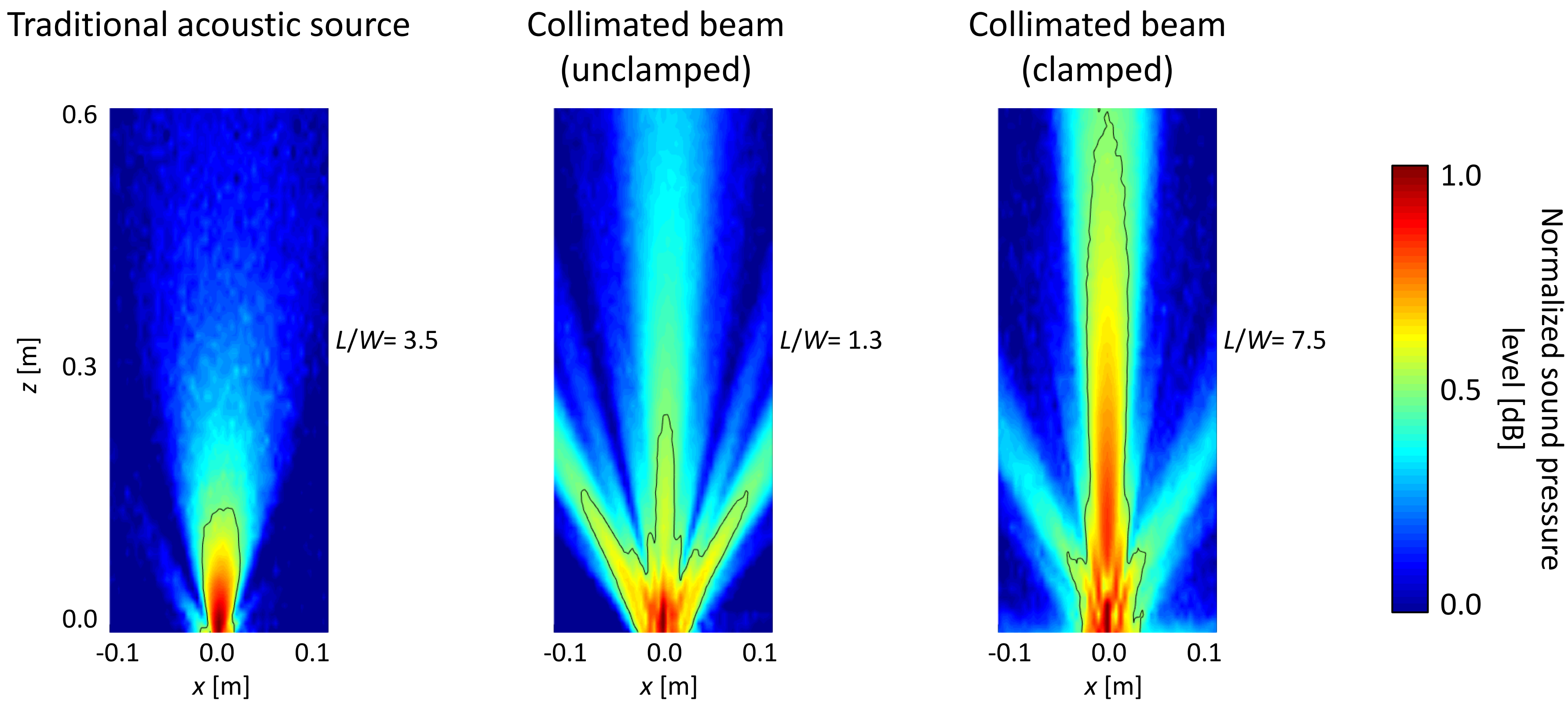
Radial mode 2

Radial mode 3

Clamped piezoelectric disk

ACCObeam - Radial Modes Clamping

Beam profile in water for the 3rd radial mode RM-3

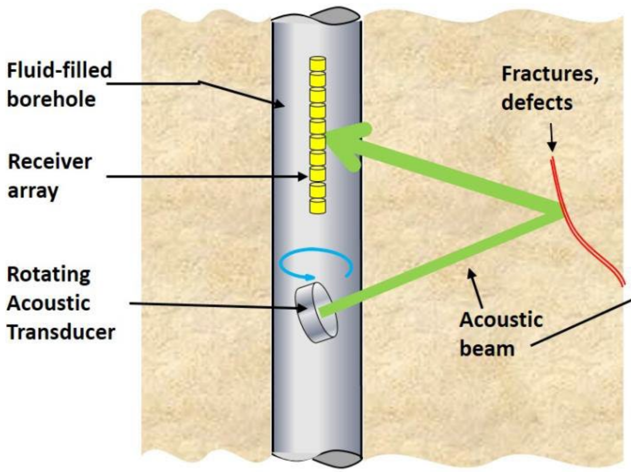


- Collimated beam provides:
  - Reduction in beam width → higher image resolution, more control over directivity
  - Increased beam length → longer detection/communication range

Appl. Phys. Lett., vol. 110, issue 6, (2017), 064101

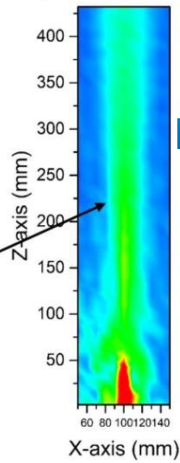
ACCObeam

Schematic representation of the 3D imaging system:



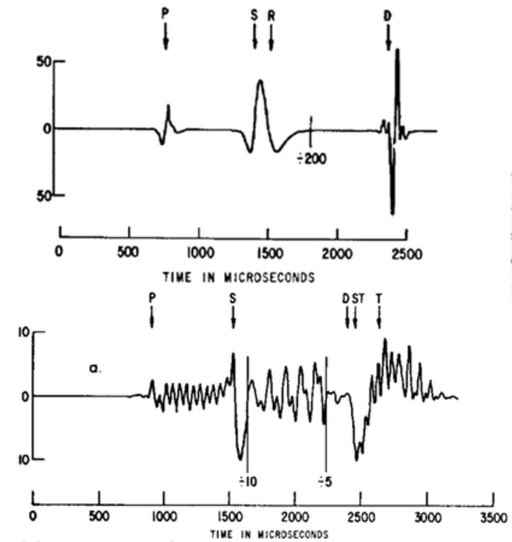
360 degree imaging

Low frequency Collimated beam (10-250 kHz)

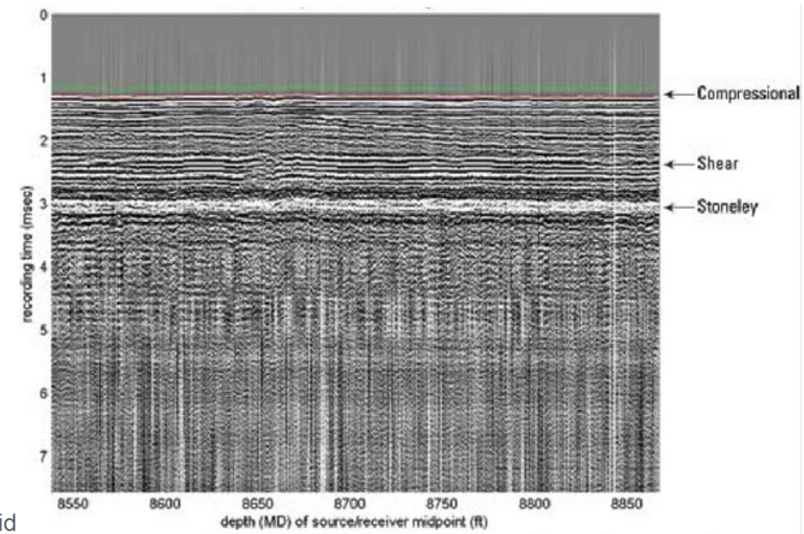


No side-lobes

Sound speed data:



* from J.H. Rosenbaum, Geophysics, vol. 39, no. 1, (1974), p. 14-32



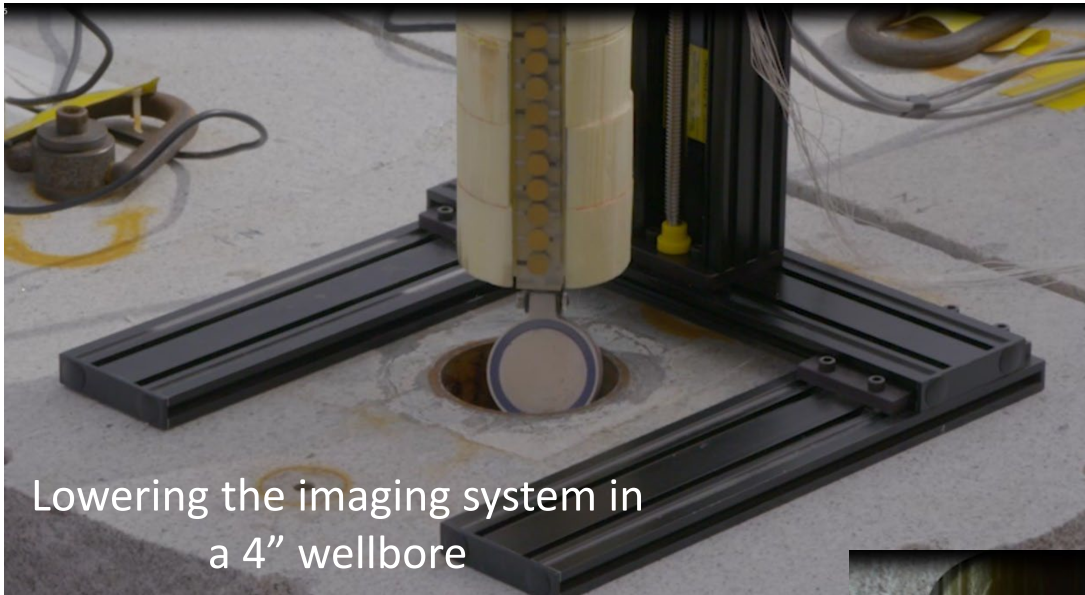
* from B.U. Jakob et al, First Break, vol. 28, Jul 2010

P – compressional wave
S – shear wave

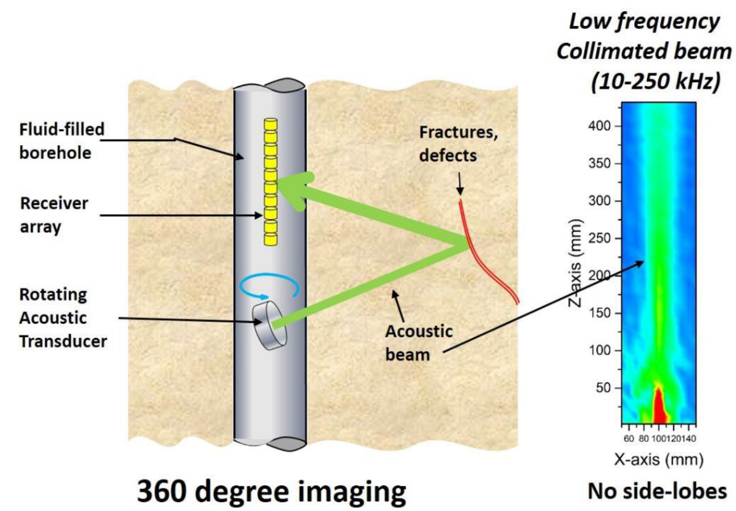
R – pseudo-Rayleigh waves
ST – Stoneley wave

D – direct wave through fluid
T – tube wave

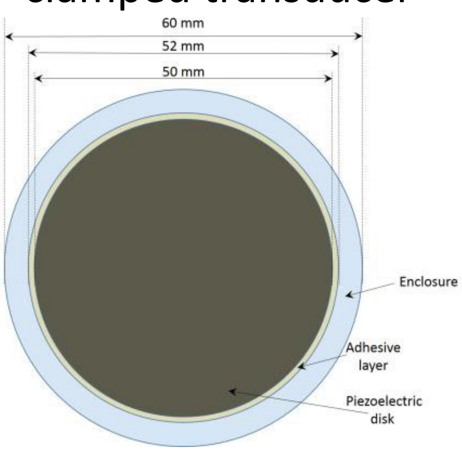
Clamped transducer and experiments



Lowering the imaging system in a 4” wellbore



Drawing of front face of clamped transducer



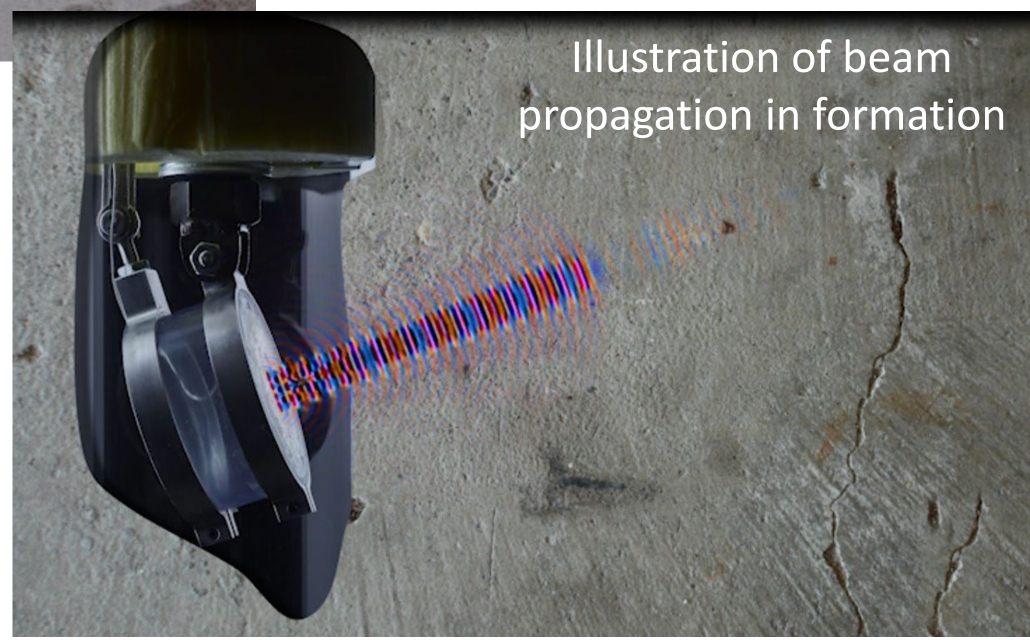
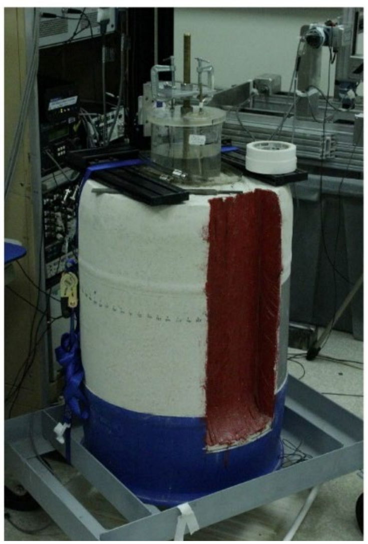
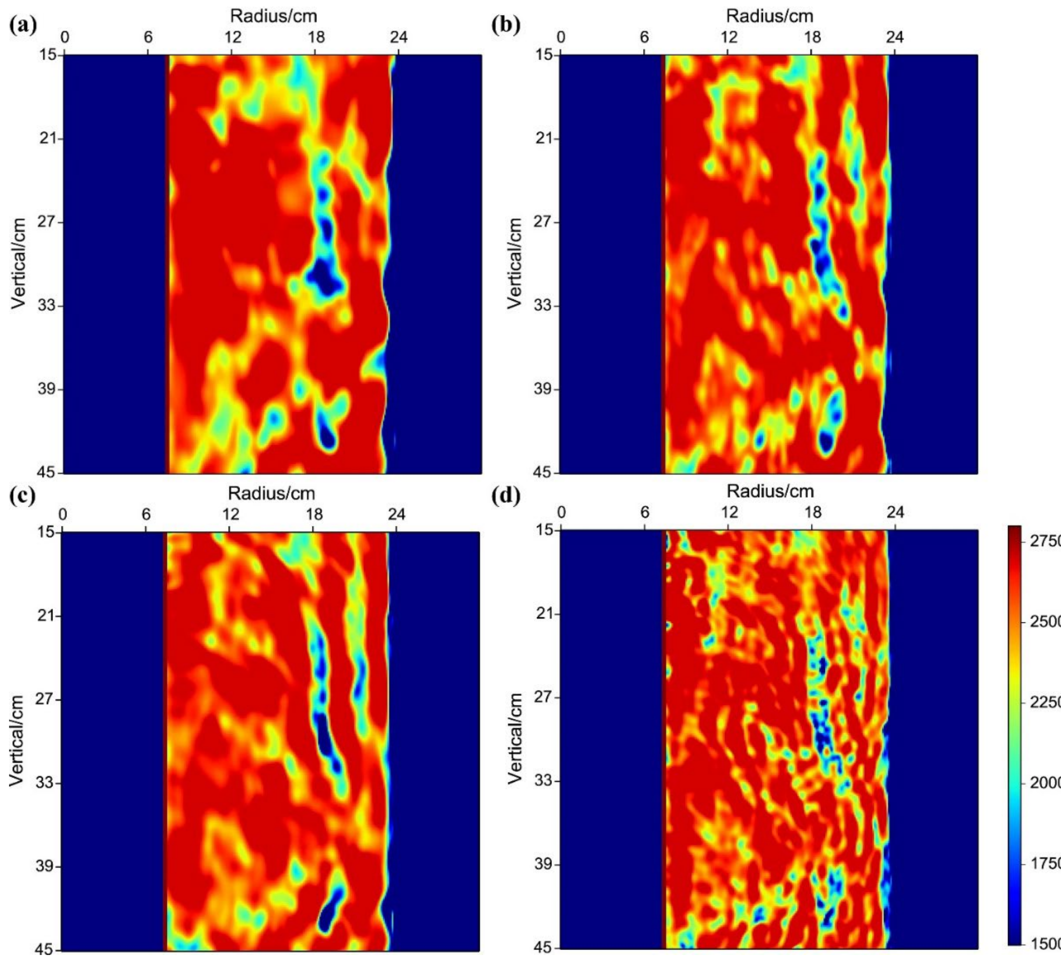


Illustration of beam propagation in formation

ACCObeam - Acoustic Inversion and Imaging

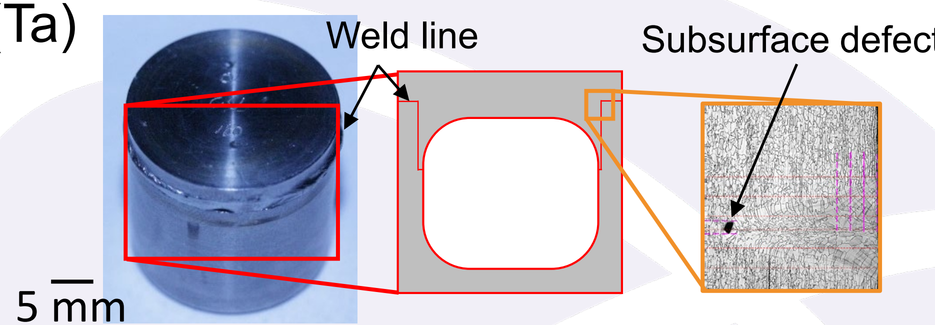
Velocity model for the long-radius profile from acoustic inversion using (a) 29 kHz data, (b) 42.4 kHz data, (c) 58 kHz data, and (d) 111.85 kHz data.



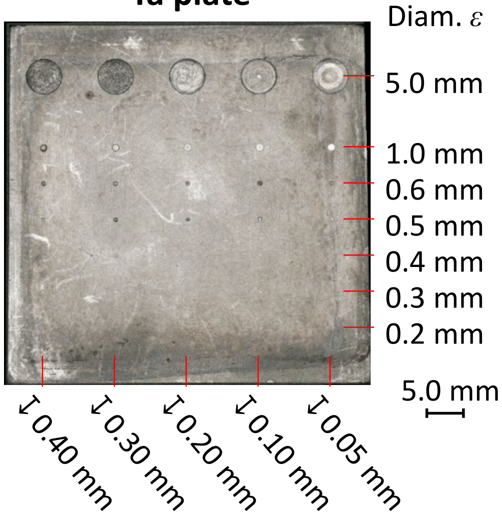


Acoustic weld defect detection

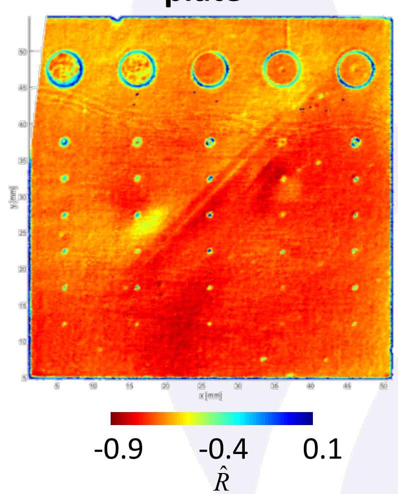
- Weld detection in dense materials (Ta) challenging for radiography
- Solution: scanning acoustic microscopy



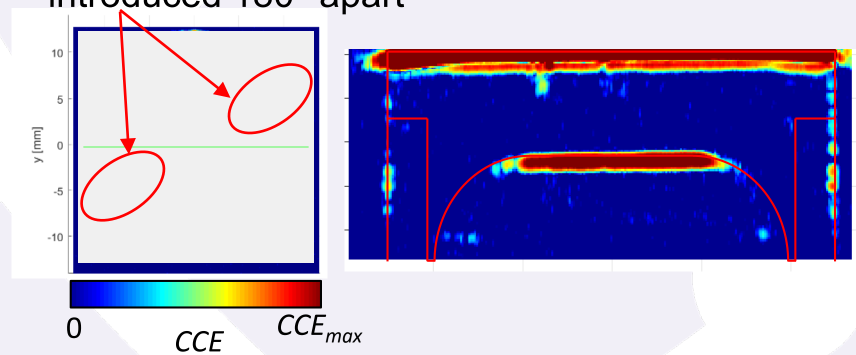
Optical microscopy of Ta plate



Acoustic microscopy of Ta plate

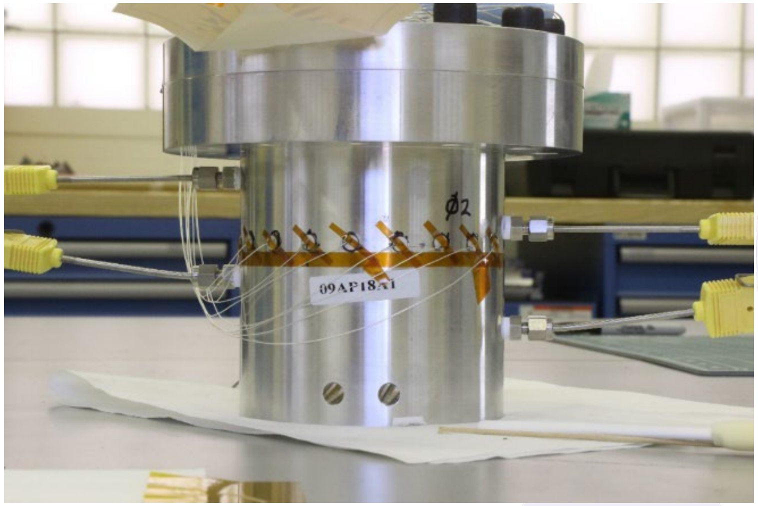


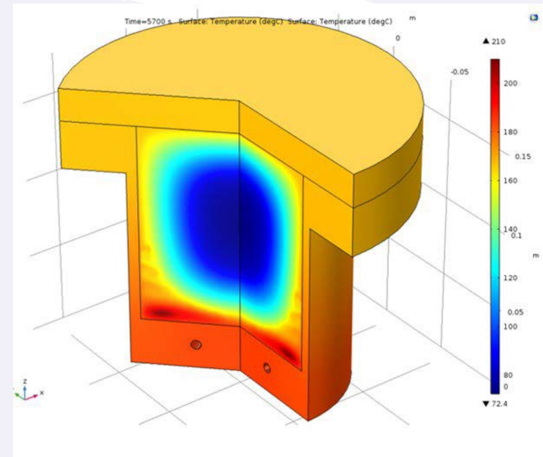
Inclusions intentionally introduced 180° apart



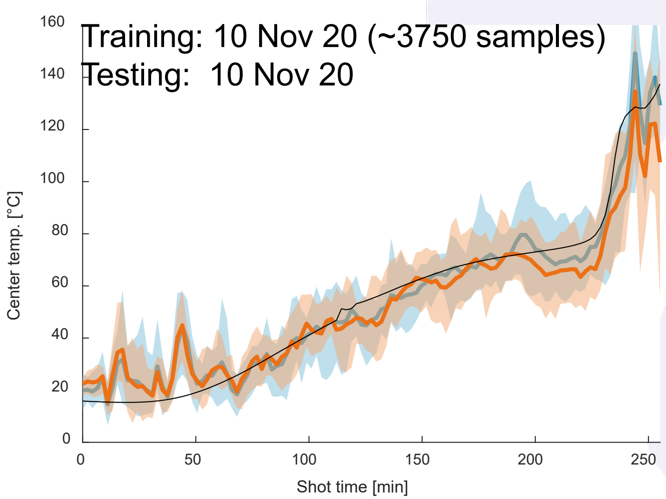
3DHEAT (3 dimensional high explosive acoustic temperature)

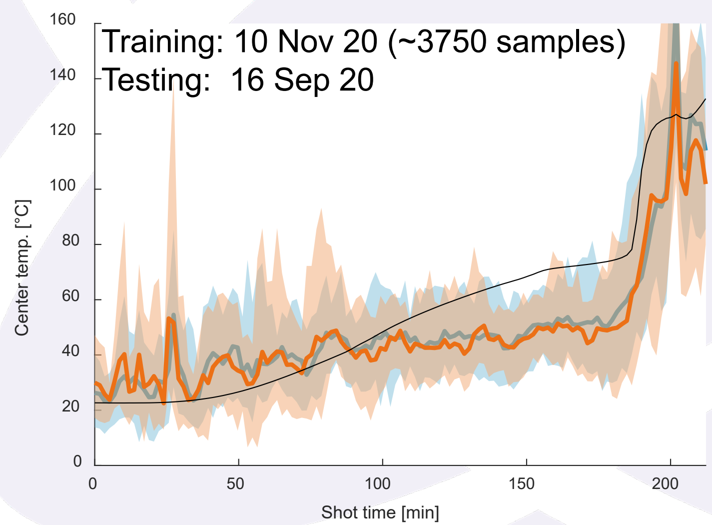
Acoustics diagnosis of thermal damage in Pentolite





Machine learning, CNN (convolutional neural network)



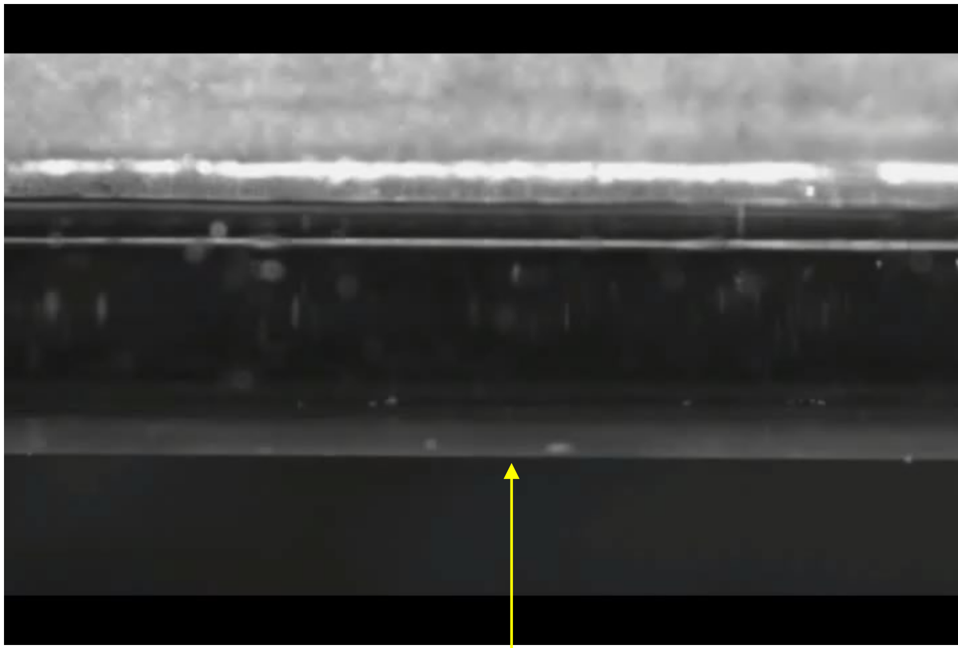


Particles Manipulation

Concentration of Particles in a Tube

Sound field is turned ON and OFF.

Piezoelectric Transducer @ 1.5 MHz

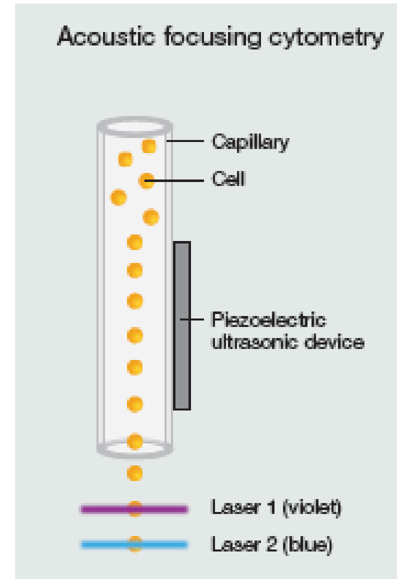


600 μm capillary, Flow~ 200 μL/min

20 μm polystyrene beads

Real Time Video

Acoustic Flow Cytometer

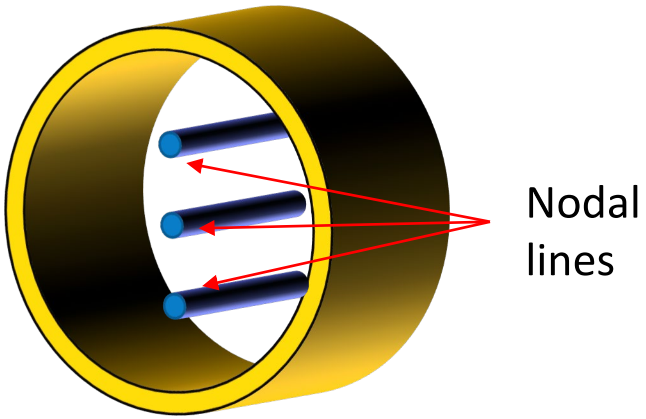


Biological cell analysis

Thermo Fisher Scientific

Acoustic Separation of Humidified Air

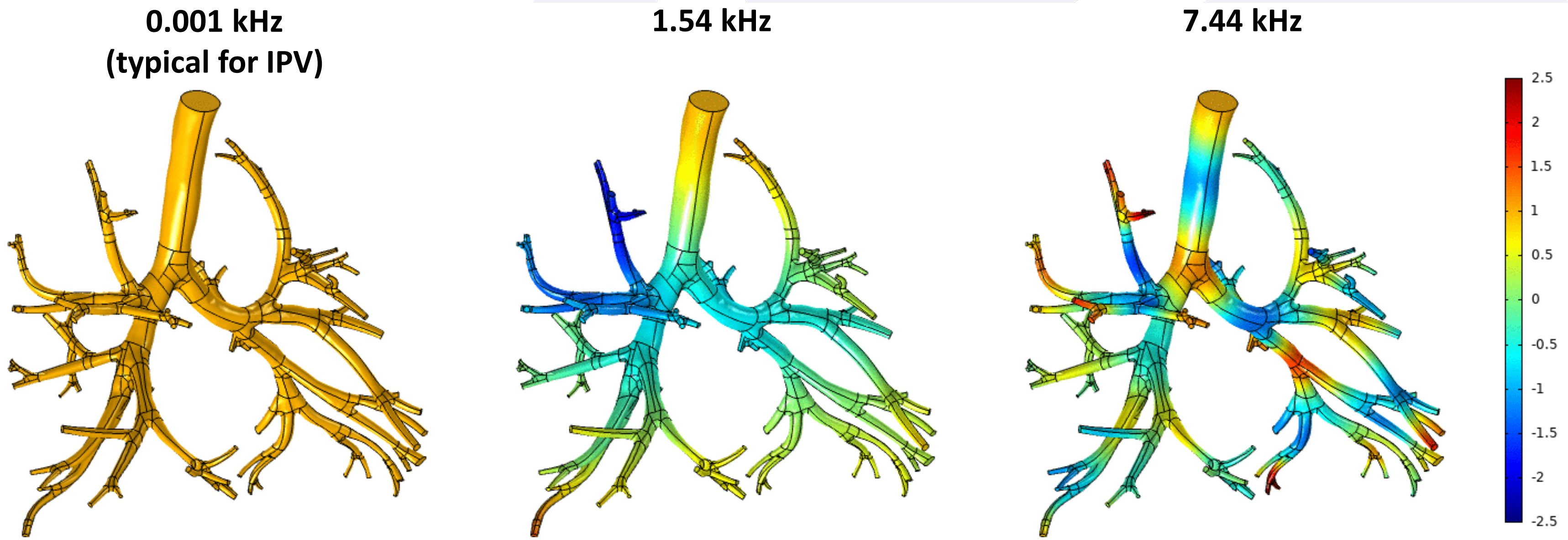
Acoustic Aerosol Concentration & Separation



The video (real-time) shows the separation of mist from humidified air and concentrating the mist acoustically inside a hollow cylinder using sound. Once the mist is concentrated, It can be taken out of the system. Various types of implementation are possible and this is simply a proof-of-concept to show what is possible with sound.

IPV – targeted excitation of lungs

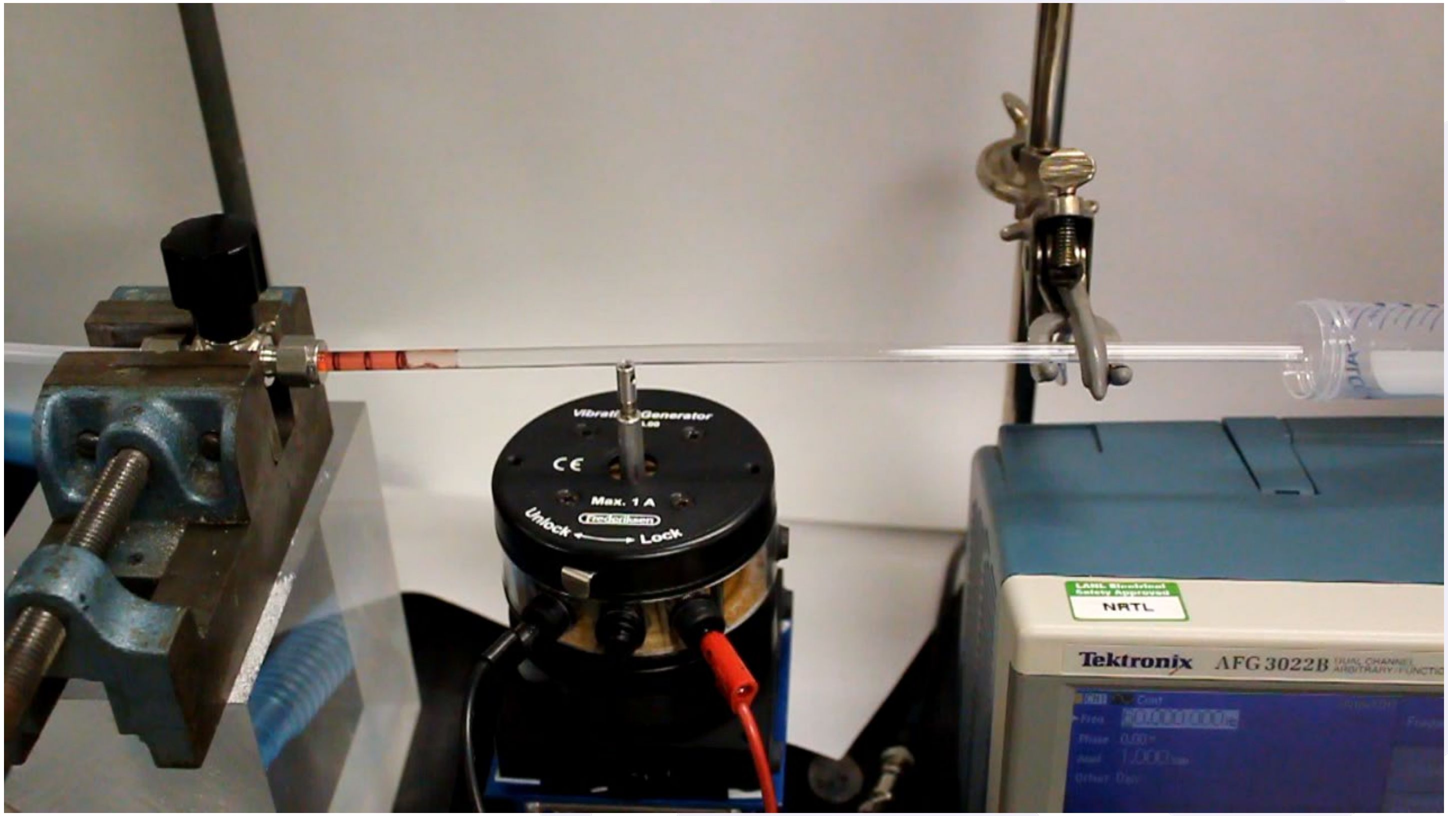
- Intrapulmonary percussive ventilation (IPV): Applies periodic bursts of air/aerosolized medication down the trachea to improve air absorption and mucus clearance
- Currently, no good understanding of optimal parameters (frequency)
- We simulate how frequency affects sound penetration in lung bronchi



Funded by DOE Office of Science through the CARES Act (the Coronavirus Aid, Relief, and Economic Security Act)

IPV – targeted excitation of lungs

- Proof-of-principle: use vibrations to improve mucus clearance from a channel

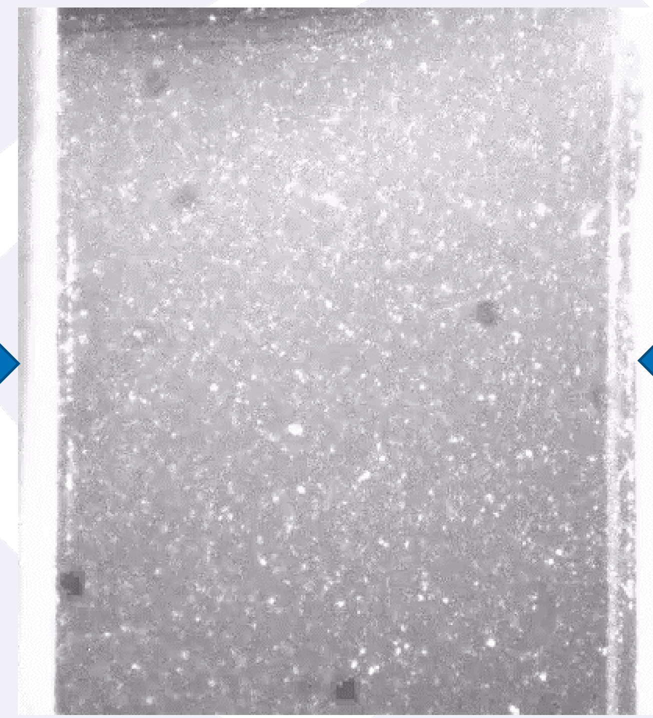


Acoustic Separation

Non-invasive mechanical separation of any two-phase system (e.g., liquid-liquid, liquid-solid, gas-liquid, etc.,) using sound

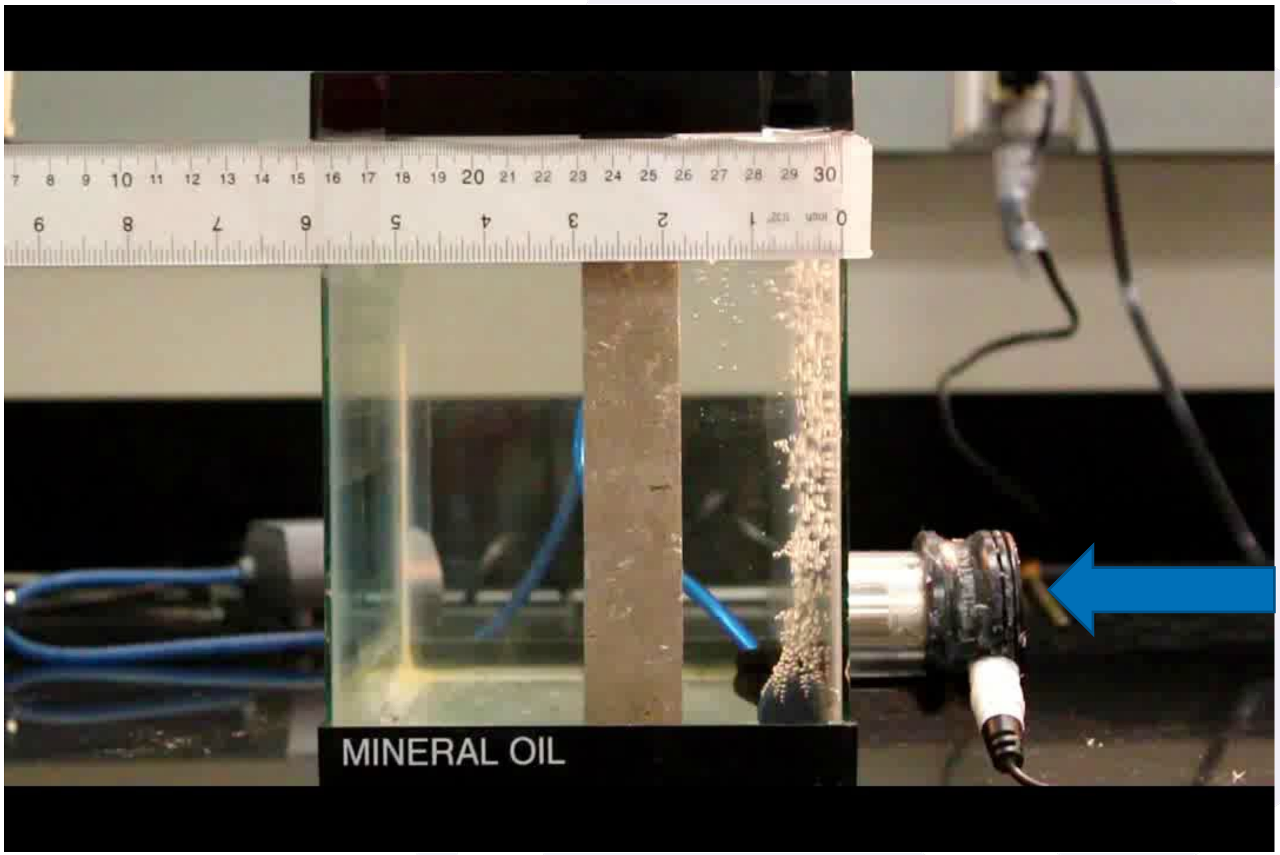
Liquid-Liquid

Solid-Liquid



Acoustic manipulation

Manipulation of gas bubbles, liquid droplets, and solid particles with sound



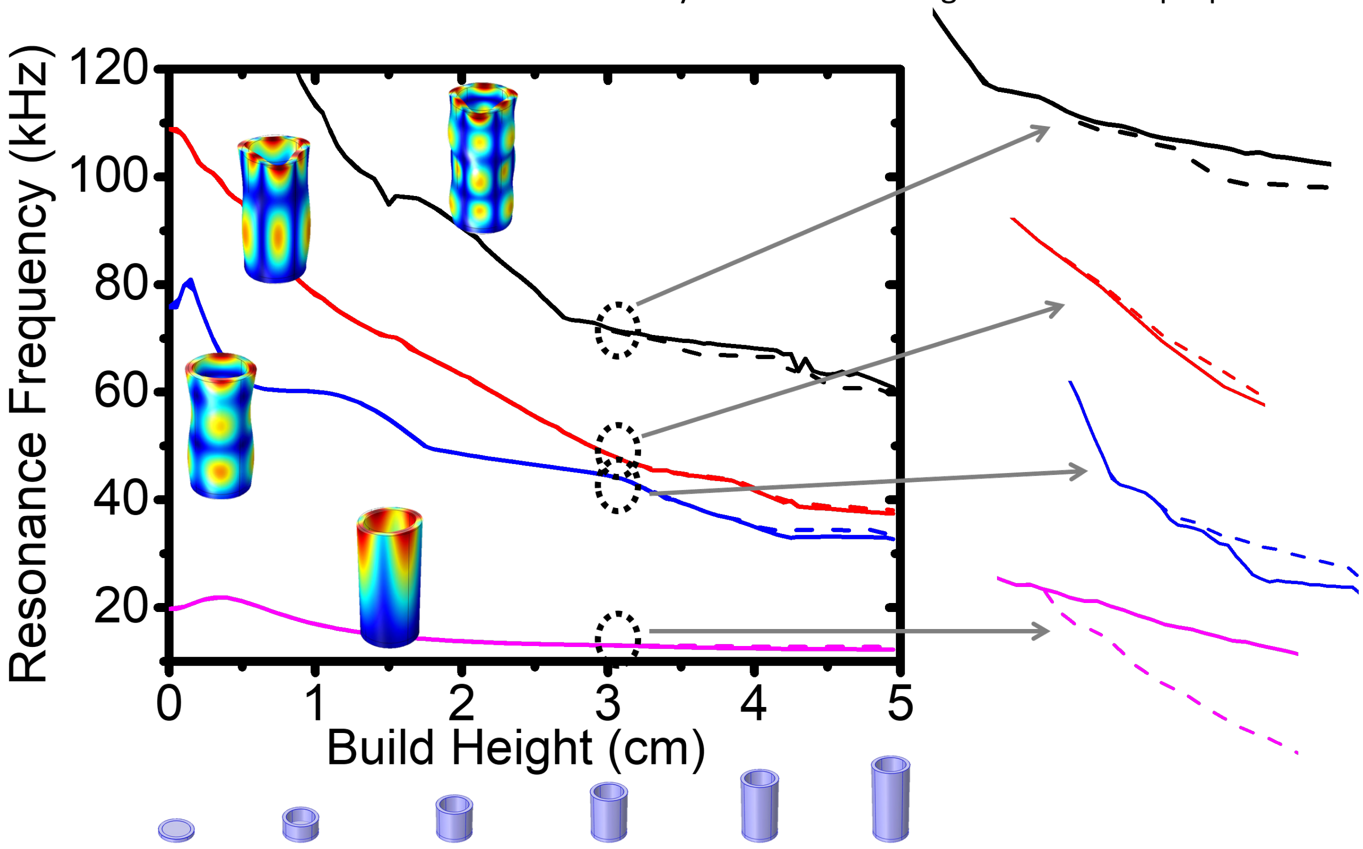
Underwater manipulation with sound

Applications in Additive Manufacturing

In situ Ultrasonic Monitoring of Additively Manufactured Structures

Finite Element Modeling

- Tracked individual resonance peaks throughout the build process
  - Build is of a 5 cm tall stainless steel hollow cylinder with an endcap
- At 3 cm, artificially changed elastic modulus of material (mimics residual stress)
- Observed resonance frequency shift from that of a “good” part (constant elastic modulus)
- Different resonance modes have different sensitivity to different changes in material properties



(dashed lines show how resonances change when elastic modulus changes @ 3cm)

Can detect changes of <1% in elastic modulus

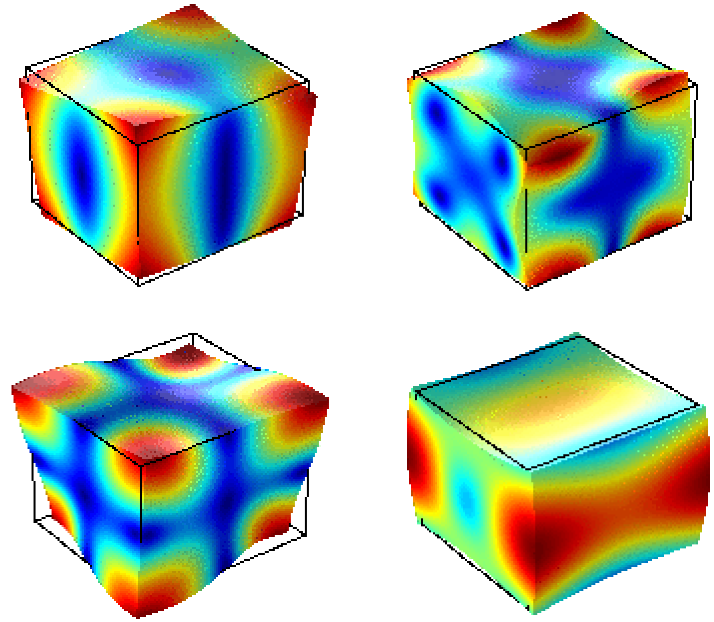
Resonant Ultrasound Spectroscopy on Steel cubes

LANL RPRcode Ver. 6.0
Steel cube
free moduli are c11, c44
rho= 7.071 gm/cc

Bulk Modulus= 1.3719

c11	c33	c12	c44	c66
2.29123	2.29123	0.91226	0.68948	0.68948

d1	d2	d3
2.53600	2.54000	2.54100

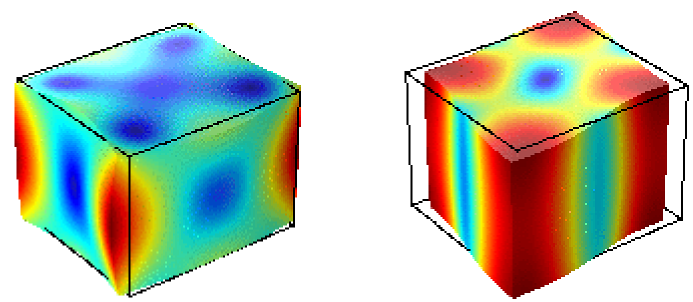


LANL RPRcode Ver. 6.0
Steel Cube As Printed
rho= 7.901 gm/cc

Bulk Modulus= 1.4411

c11	c33	c12	c44	c66
2.78076	1.82324	1.21269	0.66531	0.78404

d1	d2	d3
2.54402	2.65699	2.50477

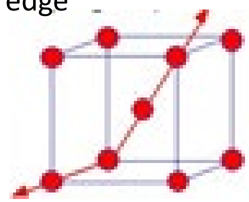


AM - TEXTURE!

In-Situ Ultrasound Grain Refinement in Electron Beam Additive Manufacturing

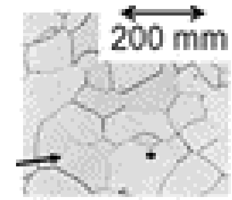
Advanced Manufacturing Development - Exploring Electron Beam Additive Manufacturing (EBAM) of metal parts with improved mechanical properties.

Monocrystal (BCC Fe)
E_{edge} = 125 GPa



Polycrystal (Fe)

E = 210 GPa



Grain refinement in EBAM process – improved mechanical properties

In situ Ultrasonic Grain Refinement

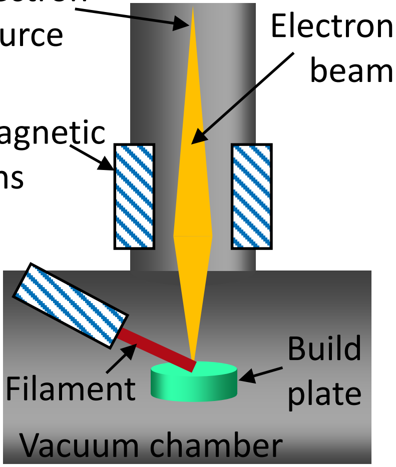
The Problem

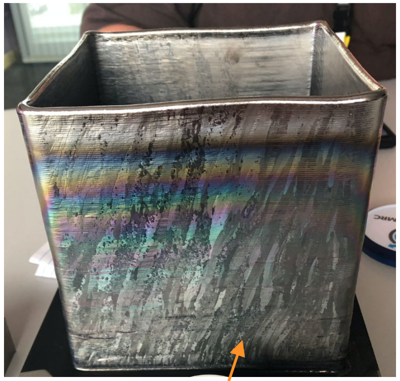
Advanced Manufacturing Development

~ Additive Manufacturing of complex shapes with improved mechanical properties ~

- **Electron Beam Additive Manufacturing (EBAM)**
  - Enables 3D printing metal, large, complex geometries
  - High deposition rate → fast, cost-effective
  - Drawback: large grains negatively impact material properties and introduce residual stress

- **Ultrasound grain refinement**
  - Demonstrated in welding processes
  - Not in AM



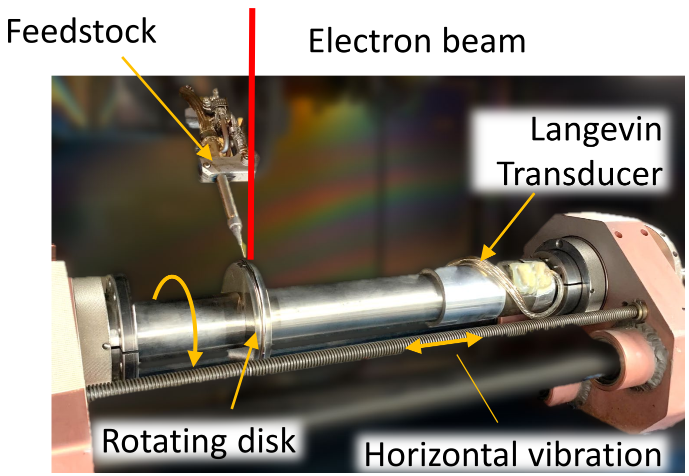


Large grains through part height

In situ Ultrasonic Grain Refinement

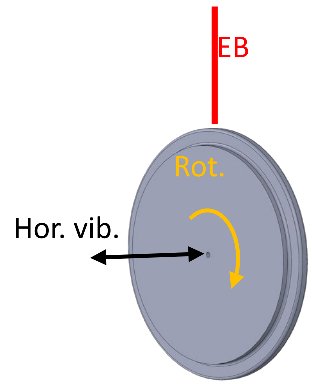
The Approach

Integrate targeted Ultrasound excitation with metal 3D printing in vacuum (EBAM)

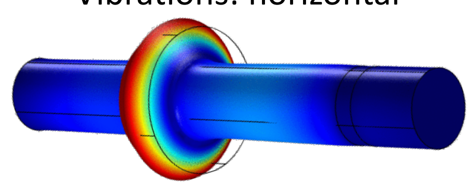


Phase 1: Ti-64

Structure: disk

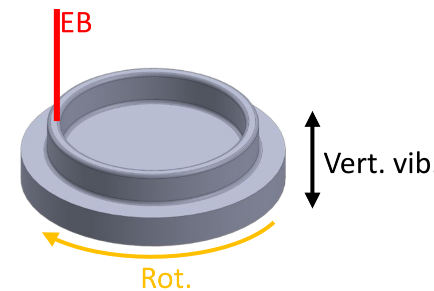


Vibrations: horizontal

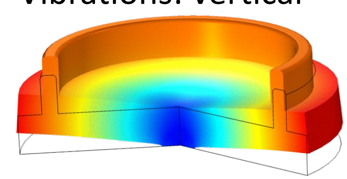


Phase 2: Pure Ti

Structure: cylinder



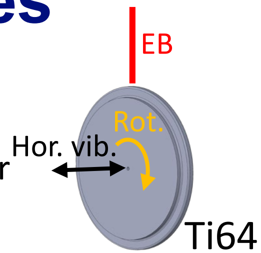
Vibrations: vertical

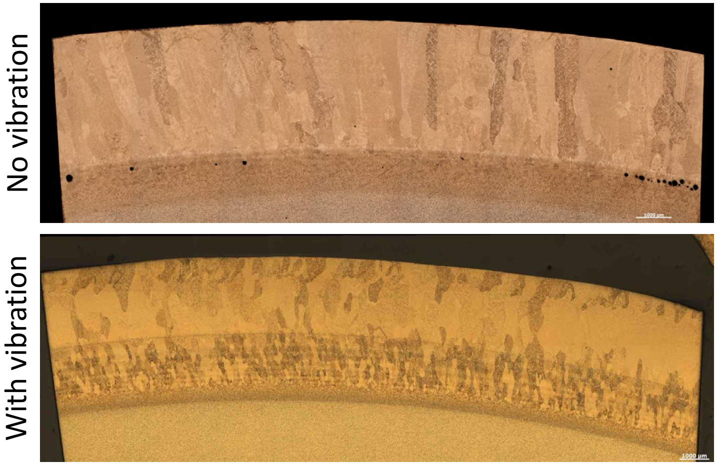


In situ Ultrasonic Grain Refinement

The Successes

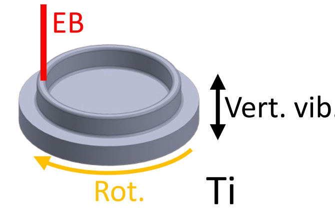
Phase I: Build disk radially, demonstrate grain reduction for single frequency and amplitude

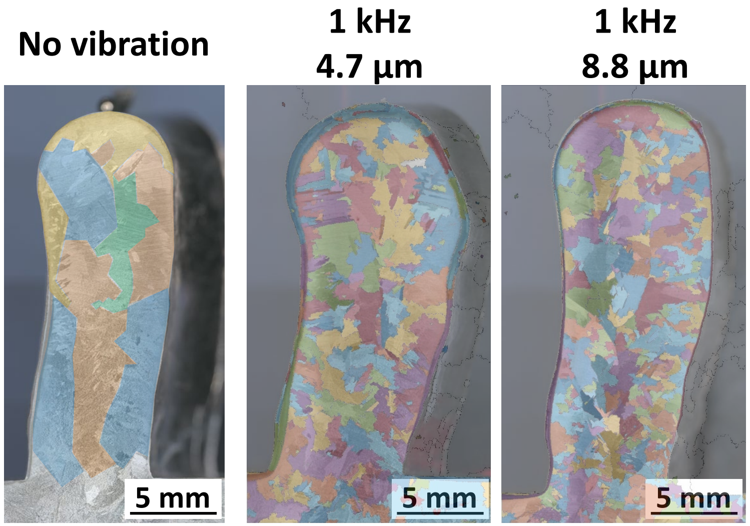




- Smaller grains
- Void reduction

Phase II: Build cylinder, evaluate vibration parameters

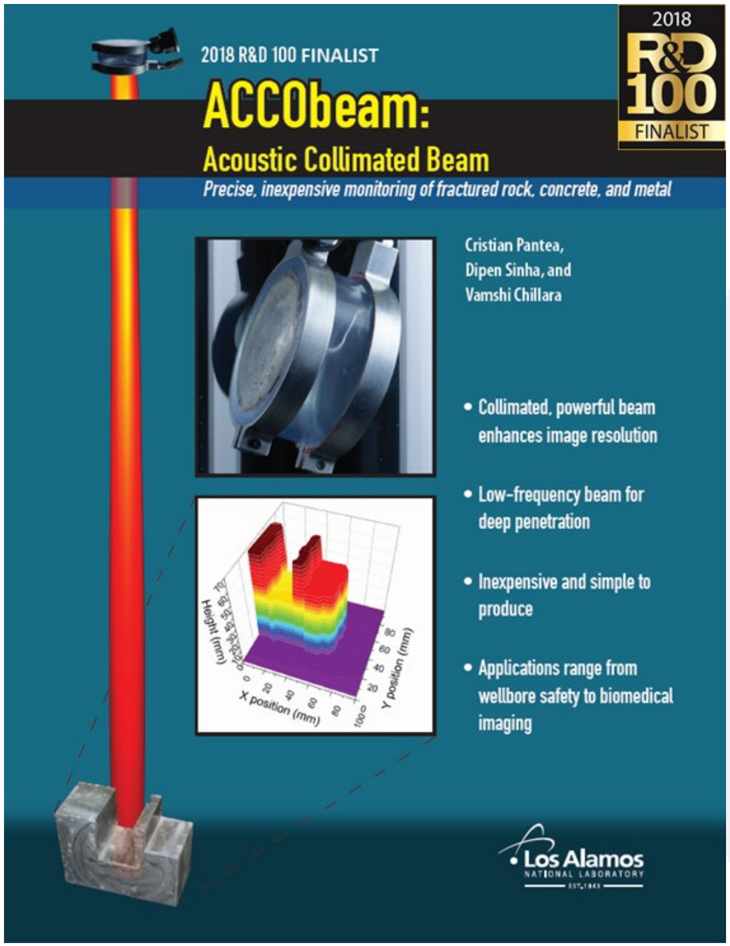




- Best grain enhancement near f = 1 kHz
- Increasing amplitudes lead to further grain refinement

New capability:
***in-situ* grain refinement in Additive Manufacturing of metals**

Thank you



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R&D 100
FINALIST
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Precise, inexpensive monitoring of fractured rock, concrete, and metal
Cristian Pantea, Dipen Sinha, and Vamshi Chillara
Collimated, powerful beam enhances image resolution
Low-frequency beam for deep penetration
Inexpensive and simple to produce
Applications range from wellbore safety to biomedical imaging
Height (mm)
X position (mm)
Y position (mm)
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