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Applied Acoustics and Additive Manufacturing

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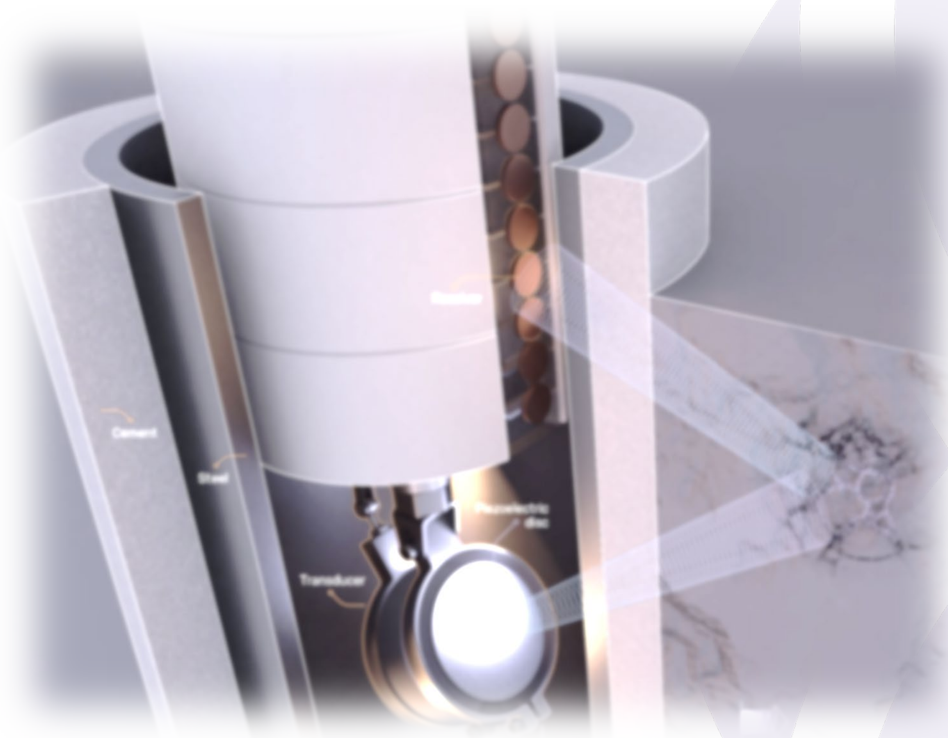
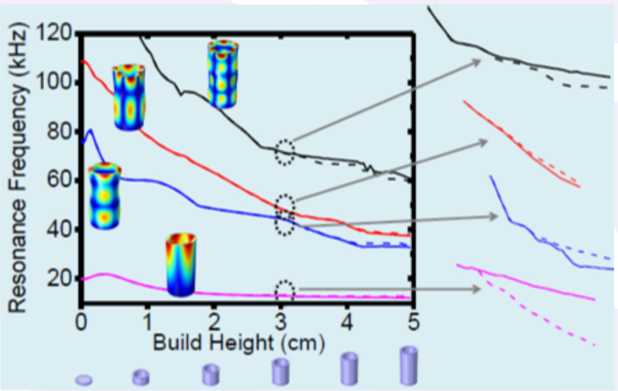
IEEE-LANNM
Hybrid (Mesa Library + GoogleMeet)
20 July 2022

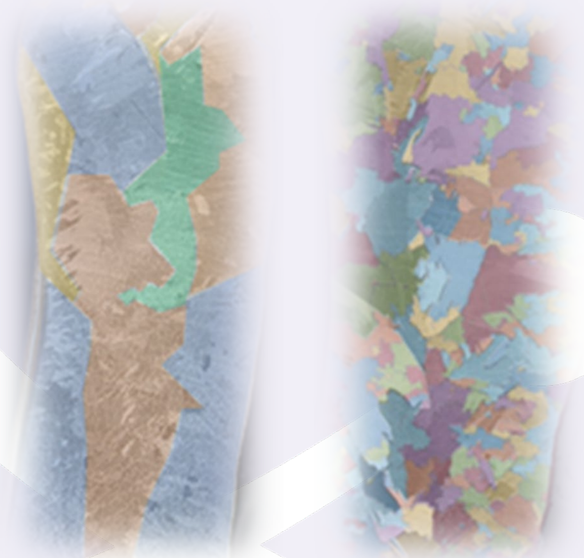
Our research - Applied Acoustics

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.)







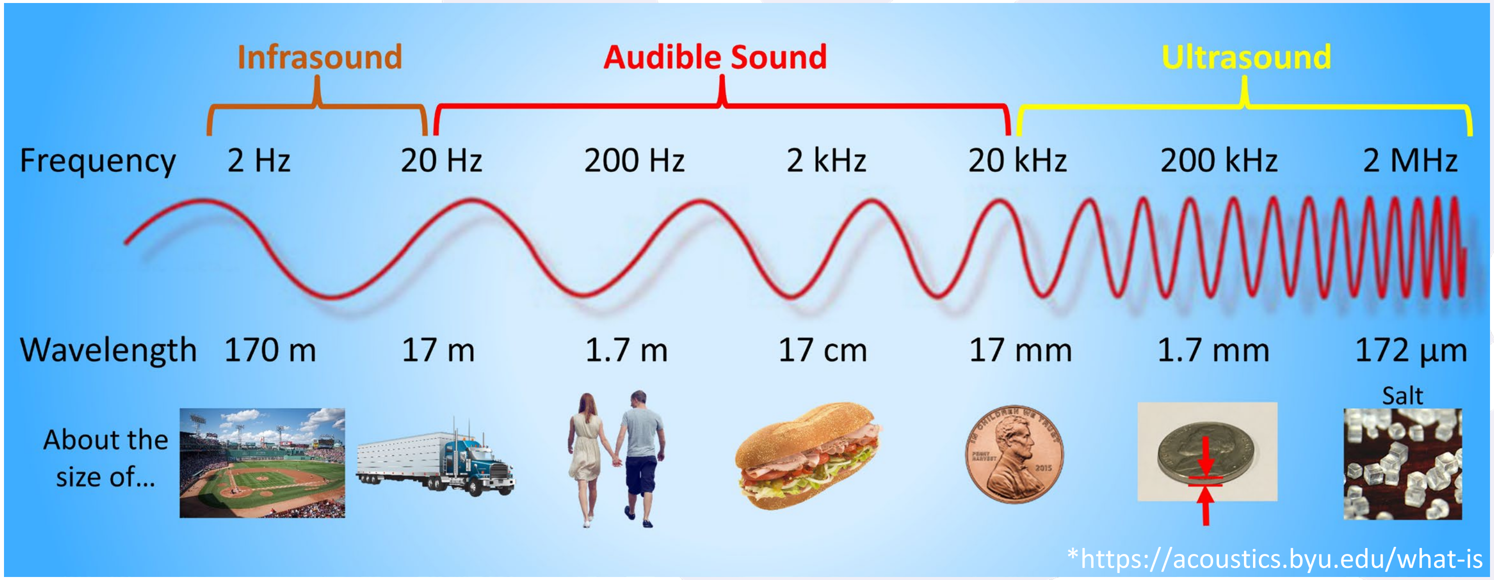
Sensing

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

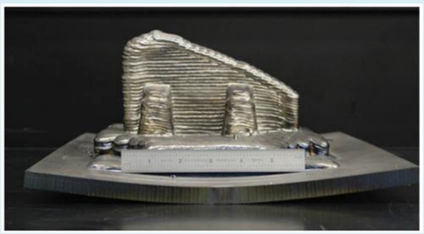
A good sound system: 35 Hz – 22 kHz

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

In situ Ultrasonic Monitoring of Additively Manufactured Structures

Background

- Stresses can arise during the AM build process
  - Large and fast (10^3-10^6 K/s) local thermal cycling
  - Can lead to deformation of part after release from build plate



Additive Manufacturing magazine

BAE Systems Advanced Technology

  - Residual stresses can lead to early and/or catastrophic part failure
- Defects (voids, microcracks, inhomogeneities) can also arise as a result of the build process
- Need techniques for monitoring for stresses and defects, *in situ*, during the build process, to enable adjustment or termination of build

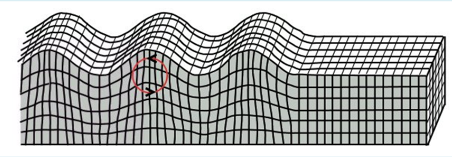
Why Ultrasonics?

- Inherently non-destructive
- Can be performed non-invasively and even non-contact
- High temperature capabilities (>1000 ^{0}C)
- Ultrasonics probe the material properties that are most affected by defects and stresses
  - Mass density
  - Elastic moduli
  - Elastic nonlinearity
- Many complementary techniques can be performed with similar equipment & materials
  - Bulk acoustic waves – traveling and standing (bulk properties)
  - Surface acoustic waves (surface stresses and defects)
  - Nonlinearity studies (presence of defects)
- Can probe the bulk of metals and other optically opaque materials

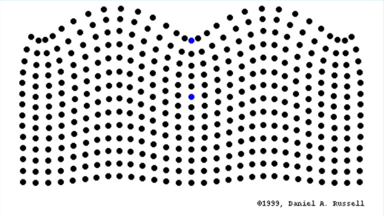
In situ Ultrasonic Monitoring of Additively Manufactured Structures

Rayleigh Waves

- Rayleigh waves (surface acoustic waves or SAWs) propagate on the surface of a structure
- Most of their energy is confined to within a few wavelengths of the surface (material deformation shown below)
  - Provides extreme sensitivity to surface defects or residual stress on surface



Rayleigh wave propagating left to right



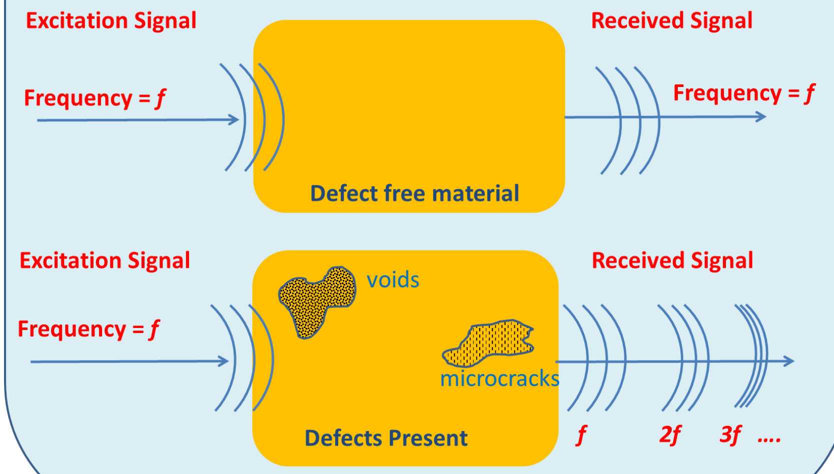
Local material deformation of a Rayleigh wave

$$c = \lambda f$$ (speed is constant)

- By varying frequency, can change the depth probed below the surface

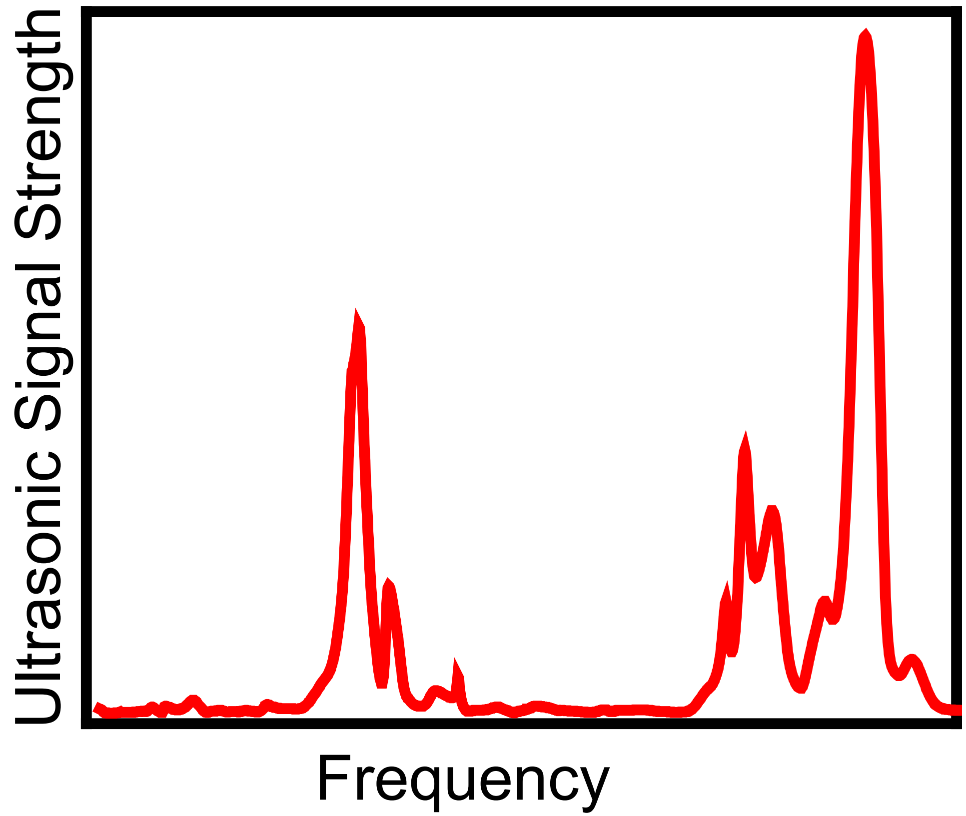
Ultrasonic Nonlinearity

- Defects produce nonlinear acoustic signals
  - (microcracks, voids, inhomogeneities)
  - Higher harmonic (2*f, 3*f, etc) generation
- Strength of the harmonic signals (degree of nonlinearity) provides a way to quantify presence of defects



In situ Ultrasonic Monitoring of Additively Manufactured Structures

Structural Resonance Evolution During Build

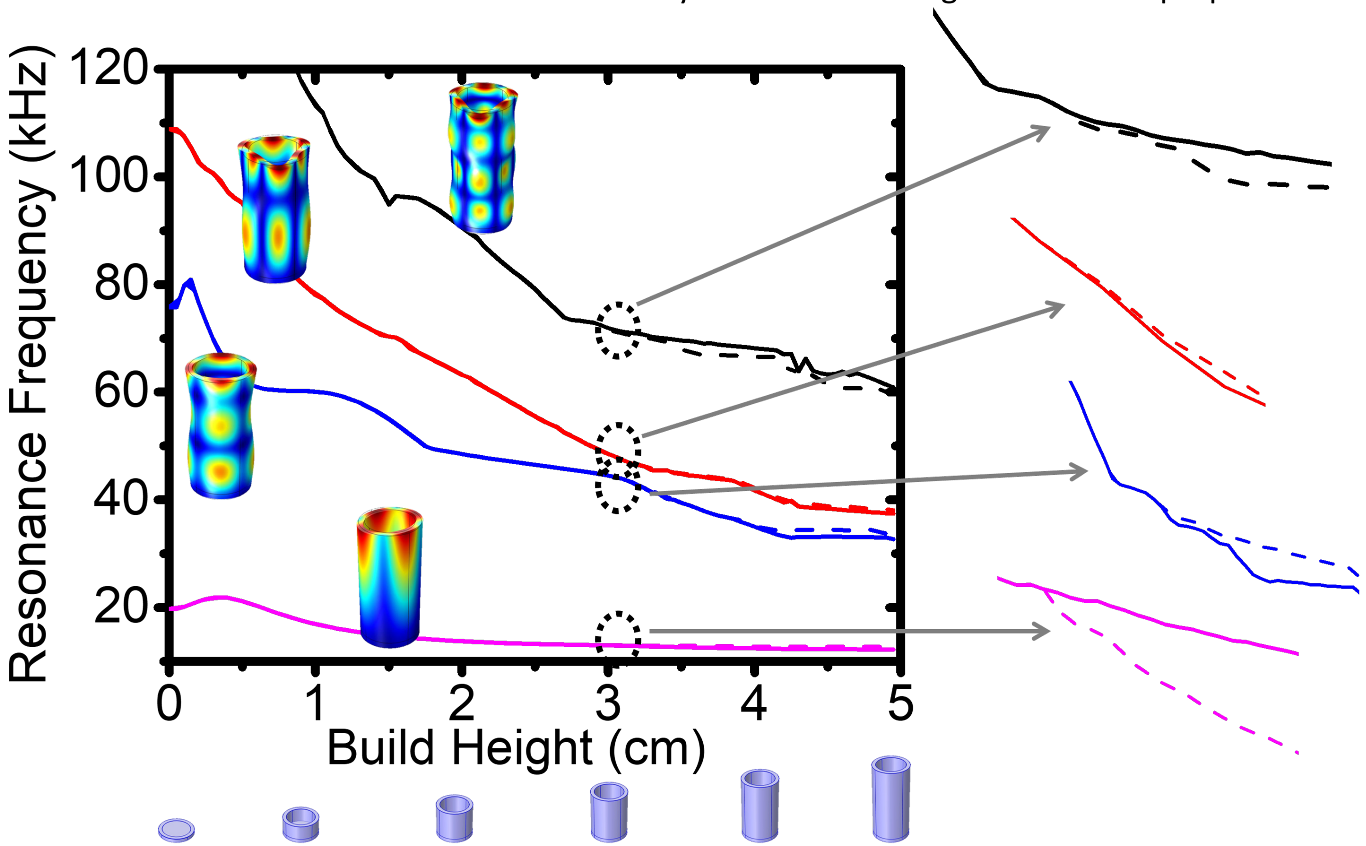


- Every solid object has a unique resonance spectrum
- Resonance peaks correspond to different structural vibration modes
- Can observe how individual resonance modes change frequency over the build process
  - Deviation from expected behavior indicates stress, defects, or damage

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

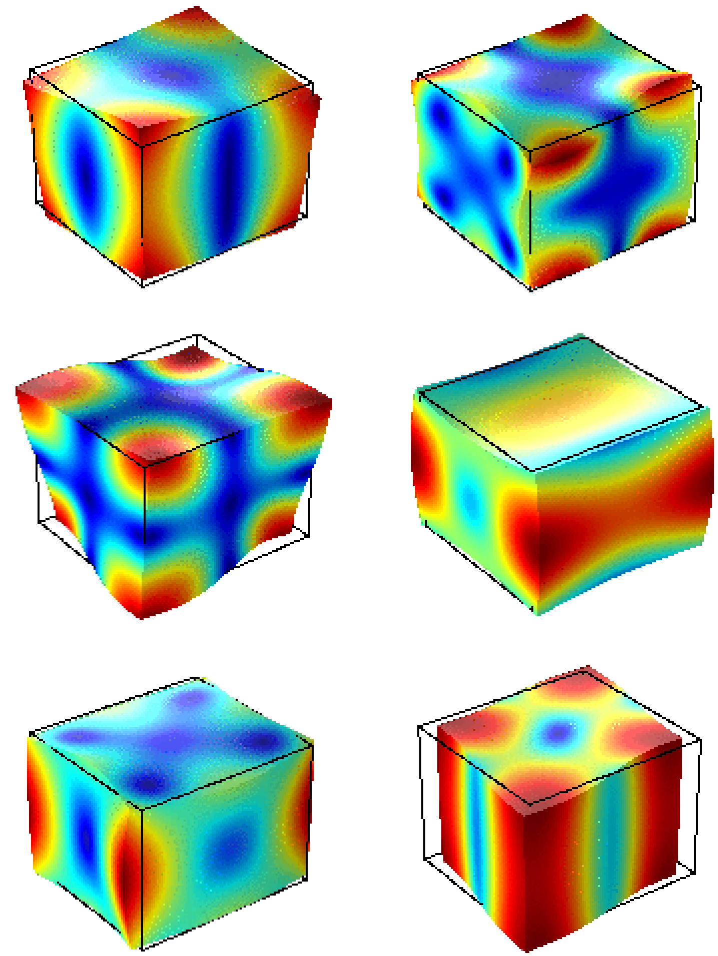
Resonant Ultrasound Spectroscopy on Steel cubes

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

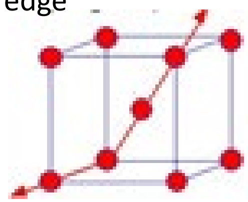
AM - TEXTURE!

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.

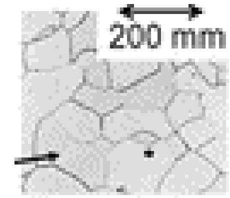
Monocrystal (BCC Fe)

E_{edge} = 125 GPa



Polycrystal (Fe)

E = 210 GPa



Grain refinement in EBAM process – improved mechanical properties

In situ Ultrasonic Grain Refinement

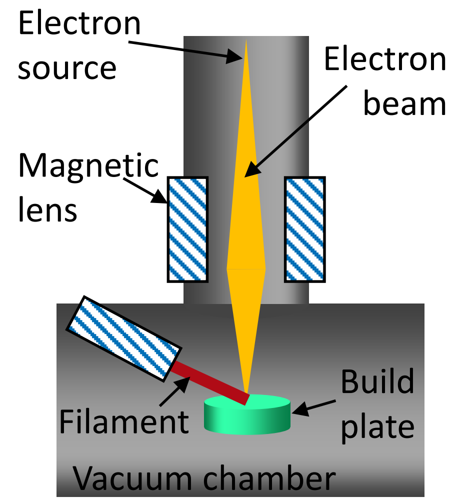
The Problem

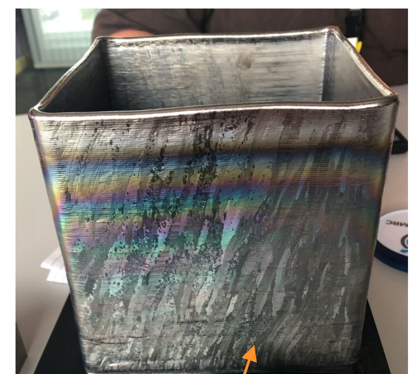
Advanced Manufacturing Development

~ 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



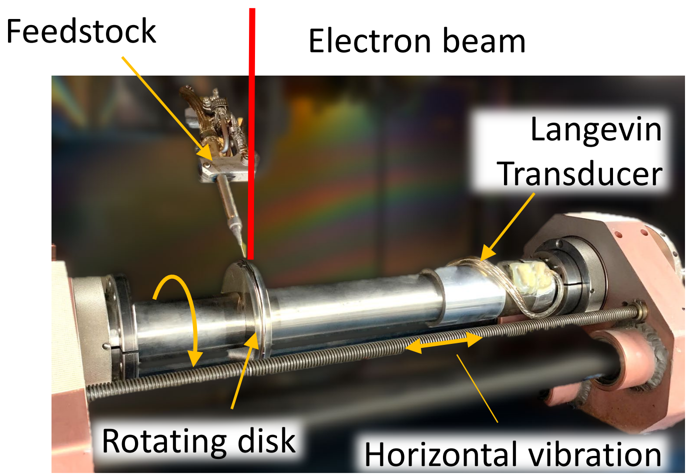


Large grains through part height

In situ Ultrasonic Grain Refinement

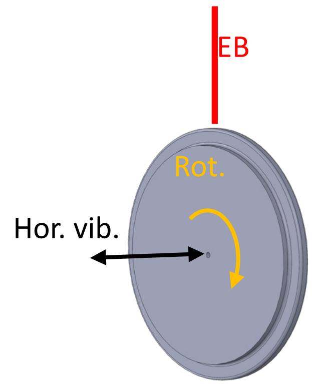
The Approach

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

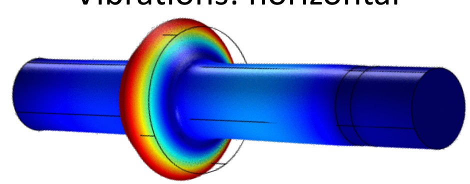


Phase 1: Ti-64

Structure: disk

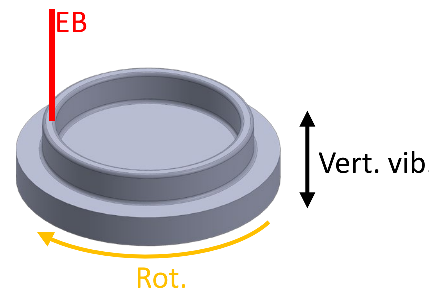


Vibrations: horizontal

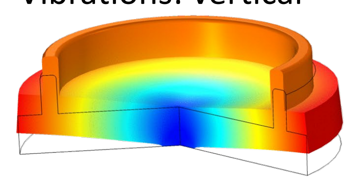


Phase 2: Pure Ti

Structure: cylinder



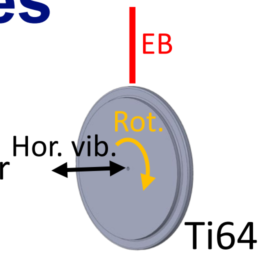
Vibrations: vertical

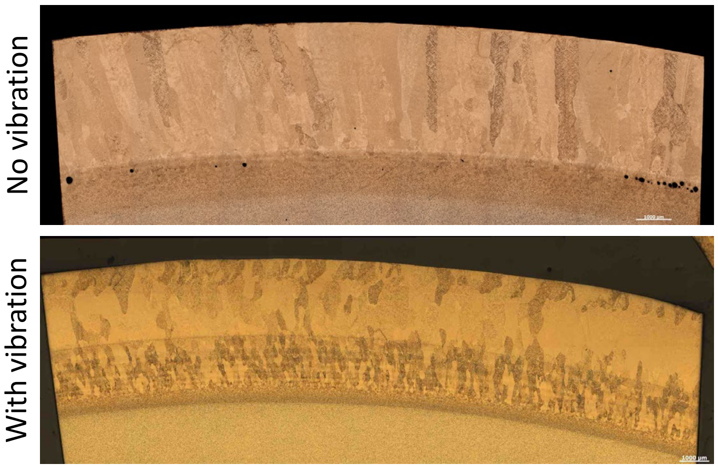


In situ Ultrasonic Grain Refinement

The Successes

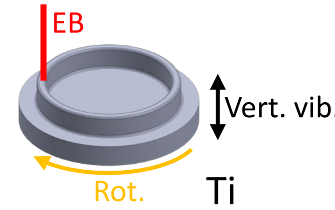
Phase I: Build disk radially, demonstrate grain reduction for single frequency and amplitude

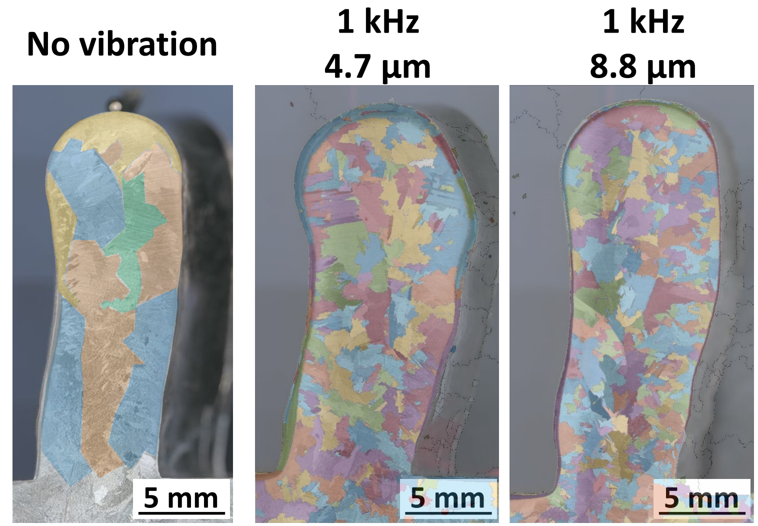




- ○ Smaller grains
- ○ Void reduction

Phase II: Build cylinder, evaluate vibration parameters





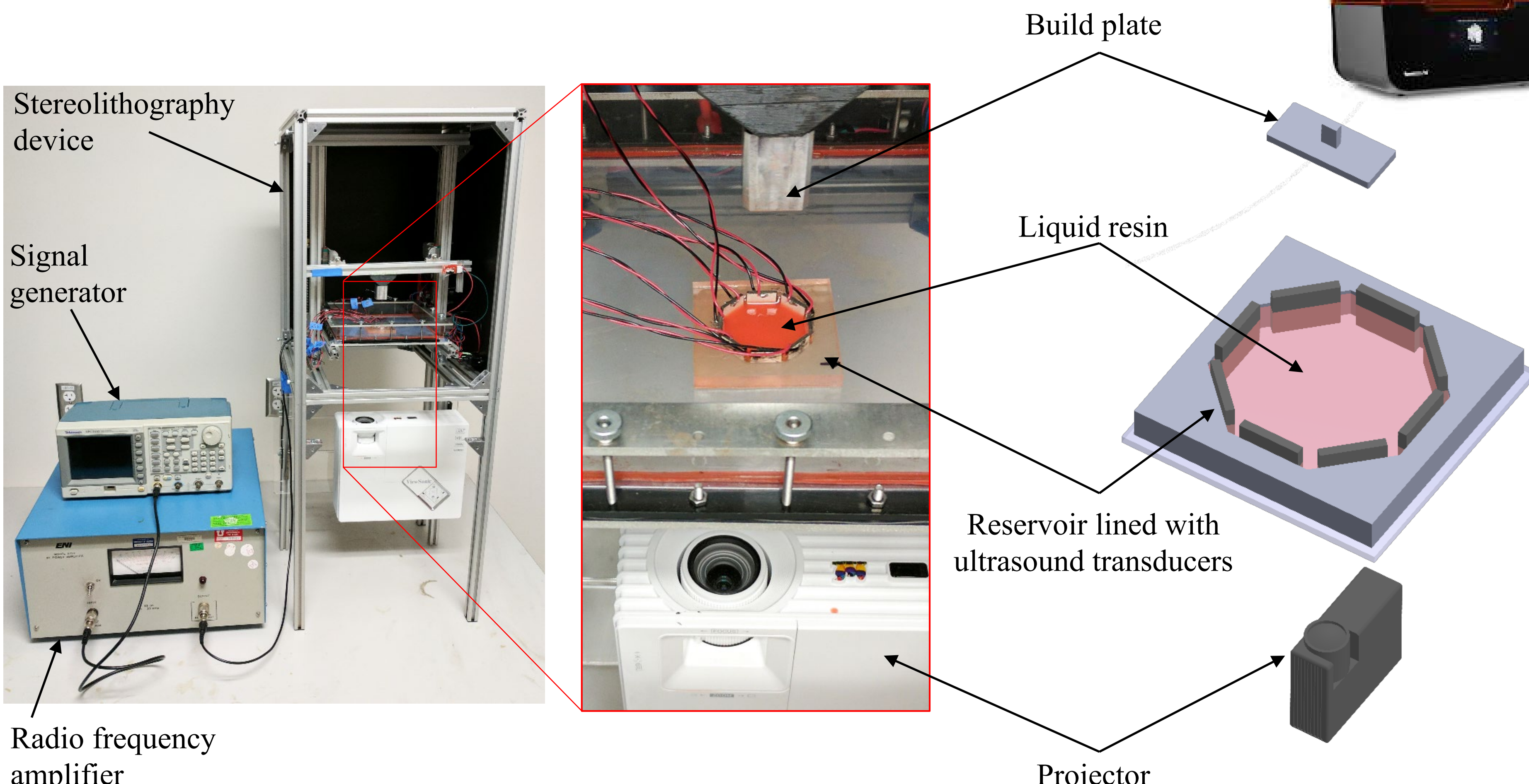
- Best grain enhancement near f = 1 kHz
- Increasing amplitudes lead to further grain refinement

New capability:

in-situ **grain refinement in Additive Manufacturing of metals**

Ultrasound DSA with SLA: Manufacturing apparatus

- Integrate ultrasound DSA reservoir lined with ultrasound transducers into existing SLA device (mUVe 1.1 DLP)

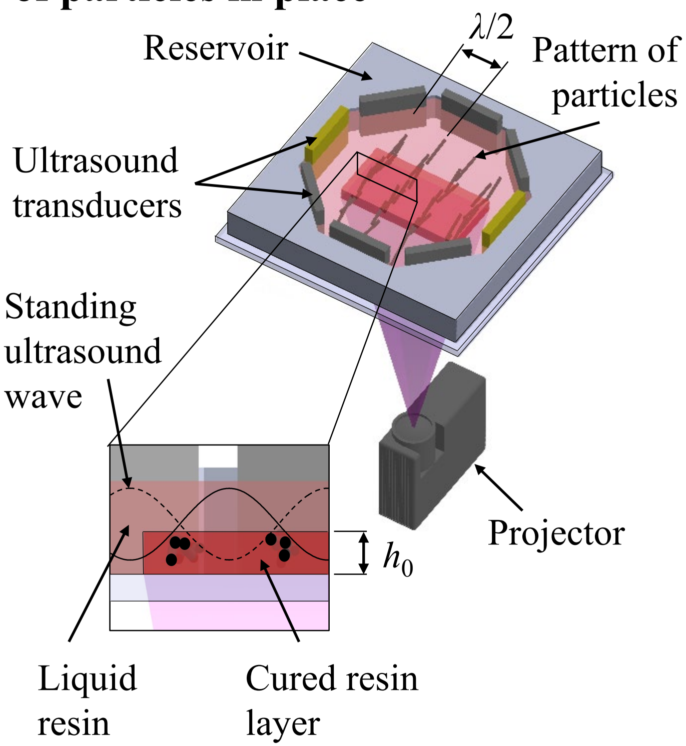


DSA - directed self-assembly
SLA - stereolithography

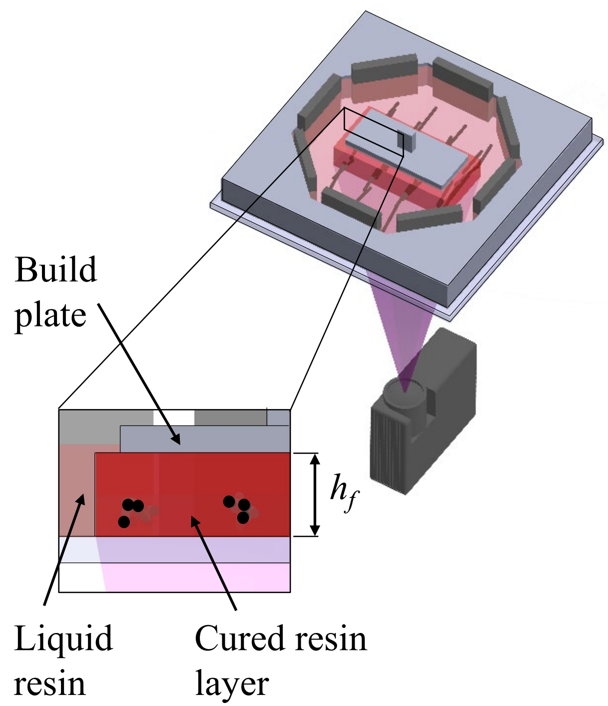
Ultrasound DSA with SLA: Manufacturing process

- 3D print engineered materials containing user-specified patterns of particles via three step process

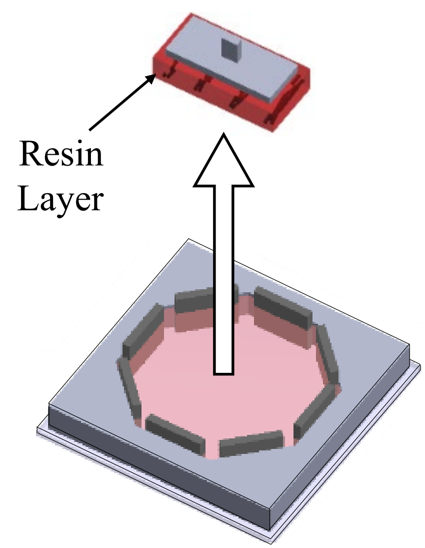
Step 1: Organize and fixate pattern of particles in place



Step 2: Adhere cured resin layer to a build plate

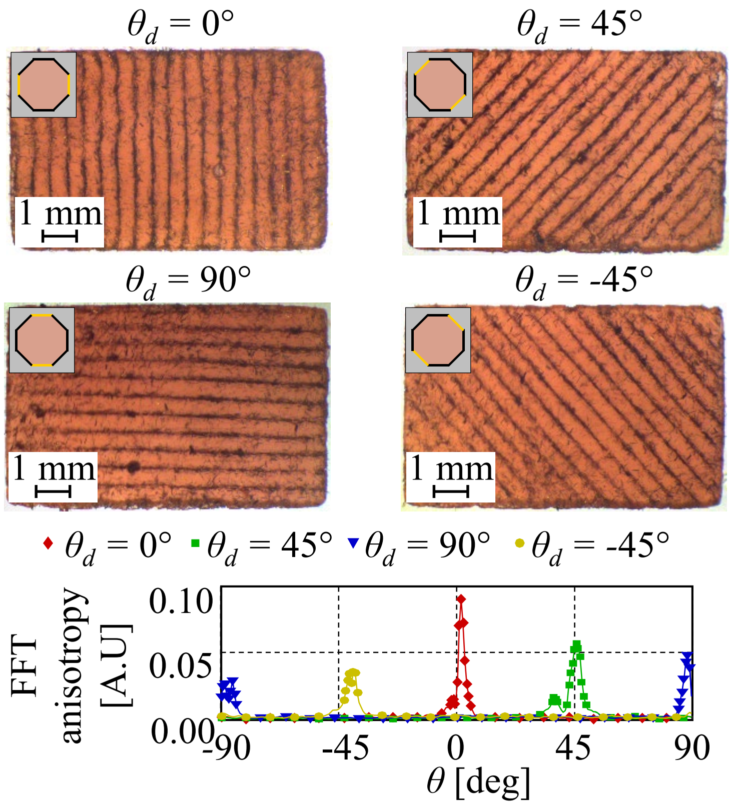


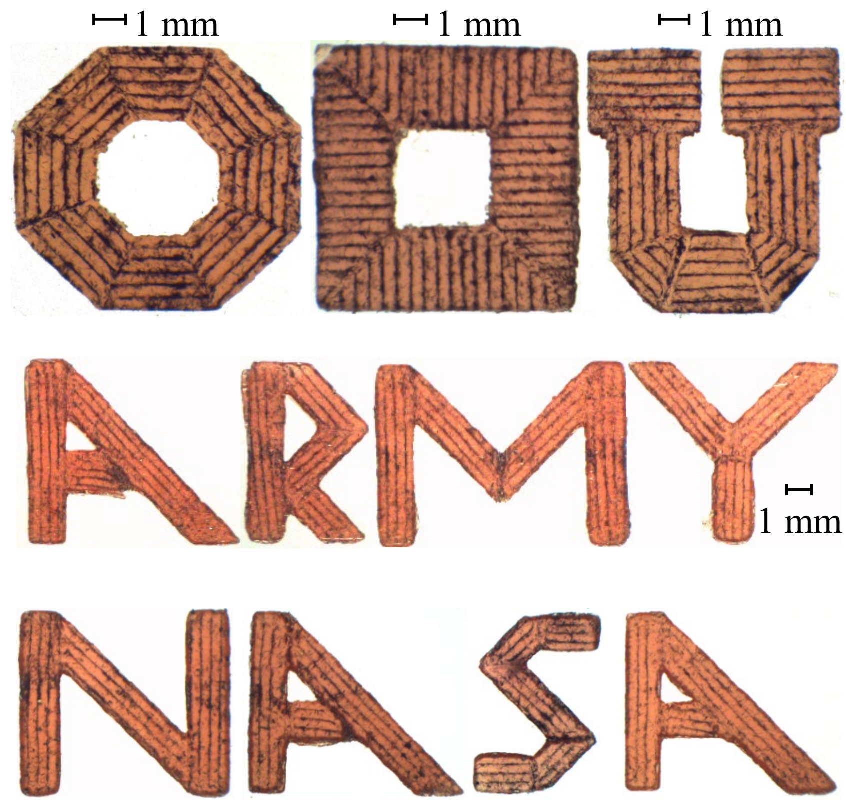
Step 3: Lift build plate and resin layer from reservoir



Ultrasound DSA with SLA: Single-layer materials

- Single-layer material specimens containing patterns of nickel-coated carbon fibers



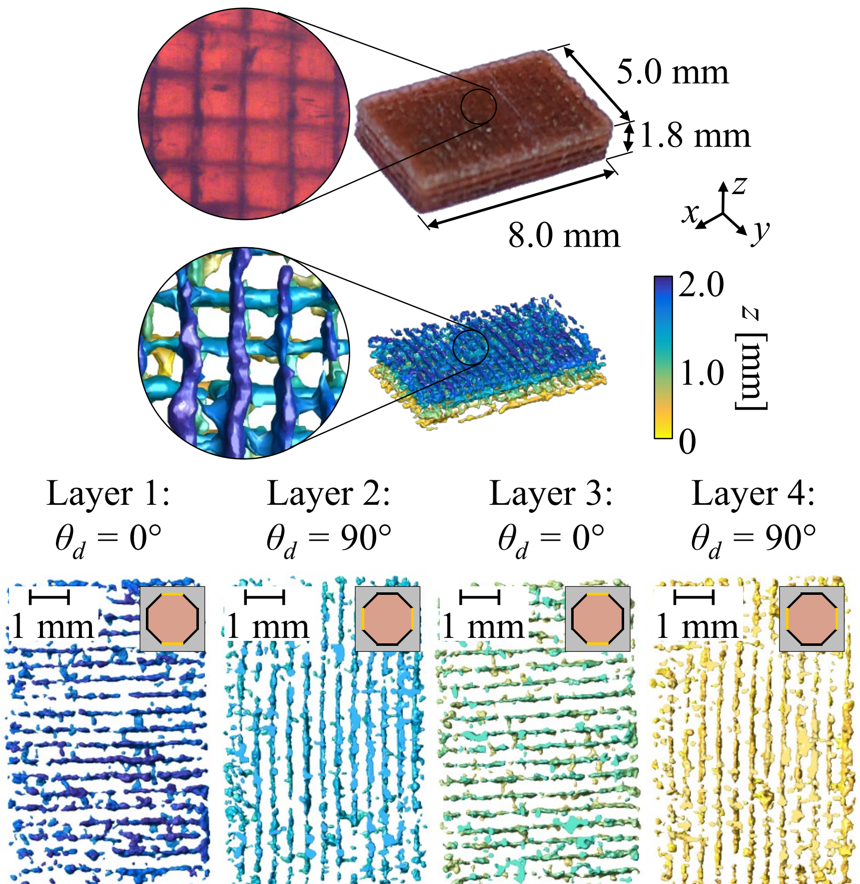


- Ultrasound DSA/SLA manufacturing process enables organizing user-specified patterns of particles over macroscale areas

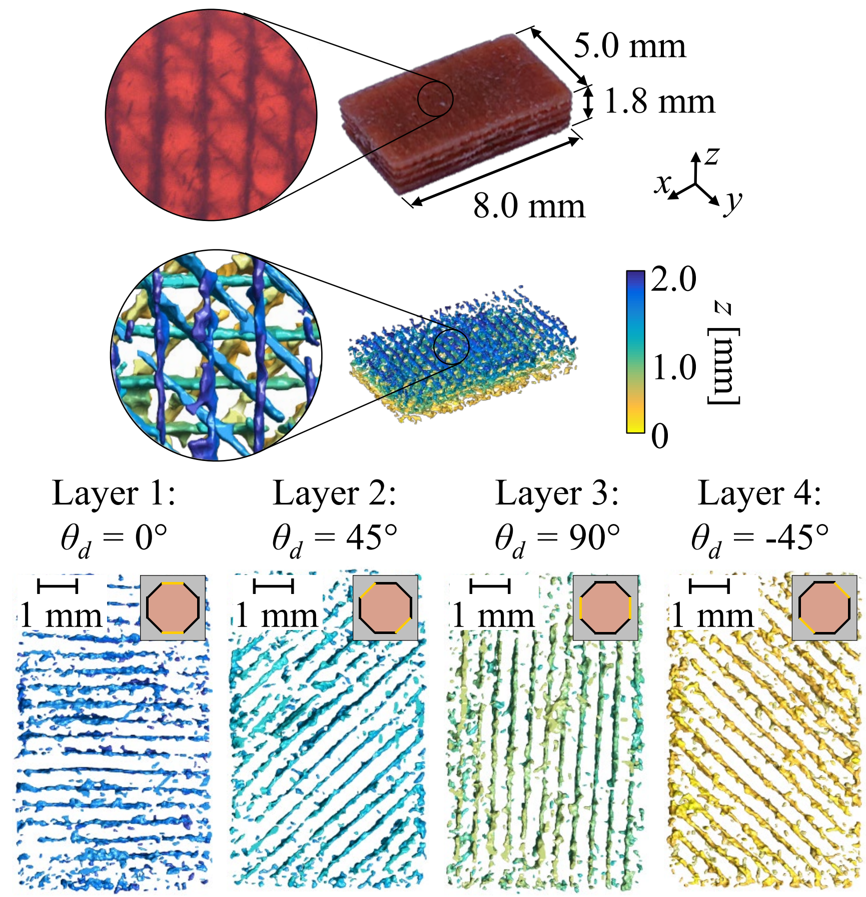
Ultrasound DSA with SLA: Multi-layer materials

- Multi-layer material specimens containing Bouligand microstructure of nickel-coated carbon fibers

90° increments

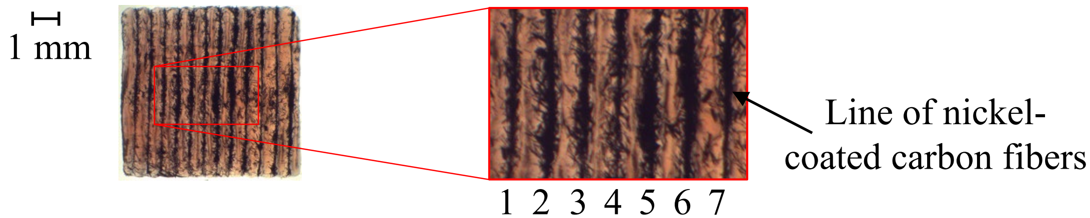


45° increments



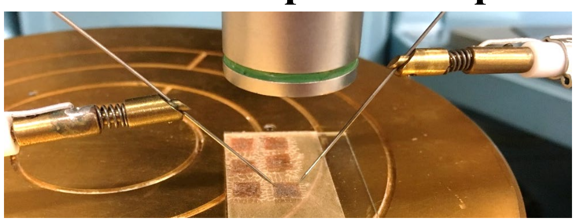
Ultrasound DSA with SLA: Functional materials

- Fabricate material specimen containing a pattern of electrically conductive lines of nickel-coated carbon fibers

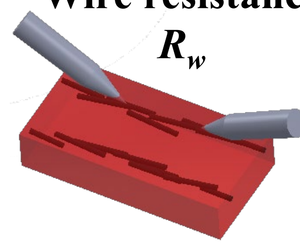


- Measure electrical resistance

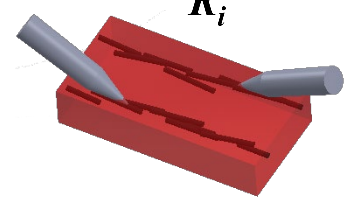
Two-microprobe setup



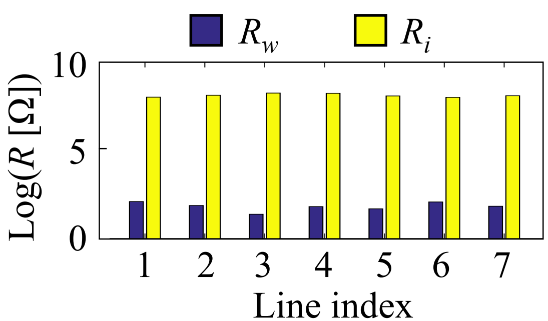
“Wire resistance” R_w



“Insulator resistance” R_i

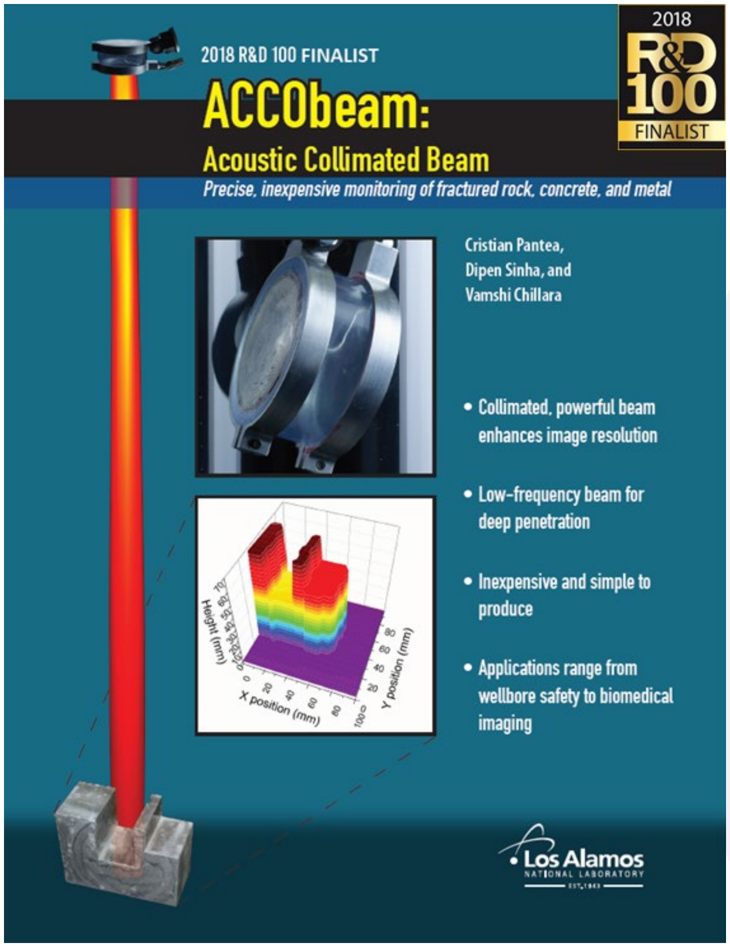


- Results



	Mean	Std. deviation
R_w	59.7 Ω	14.5 Ω
R_i	112.7 MΩ	23.2 MΩ

Thank you



2018 R&D 100 FINALIST
ACCObeam:
Acoustic Collimated Beam
Precise, inexpensive monitoring of fractured rock, concrete, and metal
2018
R&D 100
FINALIST
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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Chutes and Sensors
Making Biorefineries Commercially Viable
Apply acoustic sensors to measure moisture content of feedstock in real-time
Minimize biorefinery downtime and reduce operating costs
Integrage sensors and "smart" chutes to discard unacceptable material
Enhance the commercial viability of biorefineries
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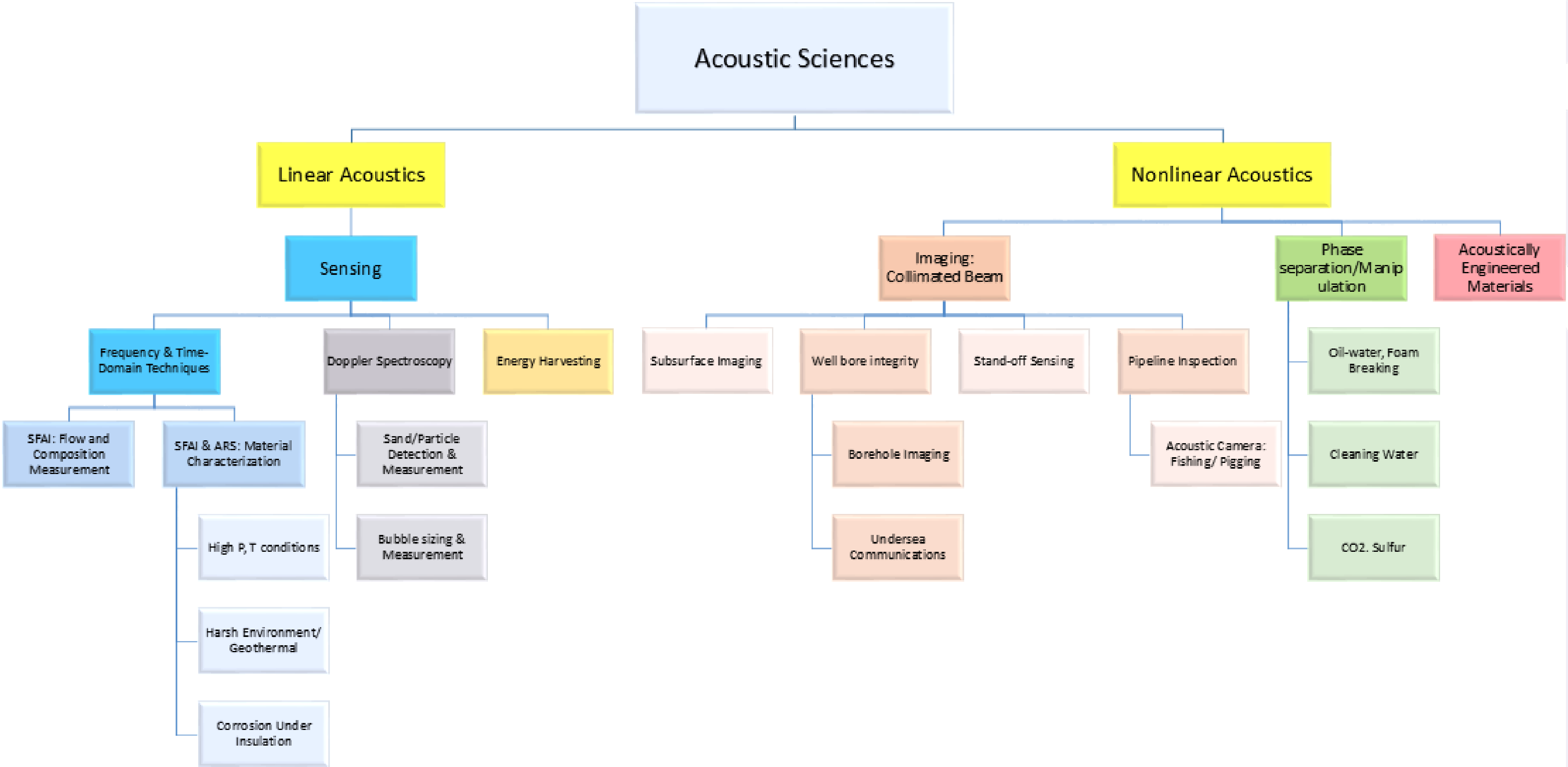
Background slides

Applied Acoustics Lab Capabilities



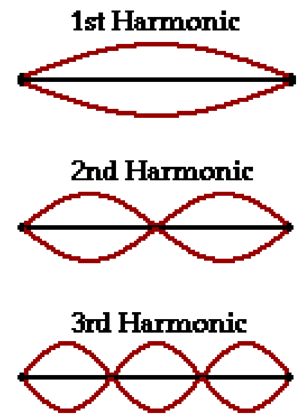
Standing Waves and Resonances in a Fluid medium inside a cavity:

Resonance occurs when:

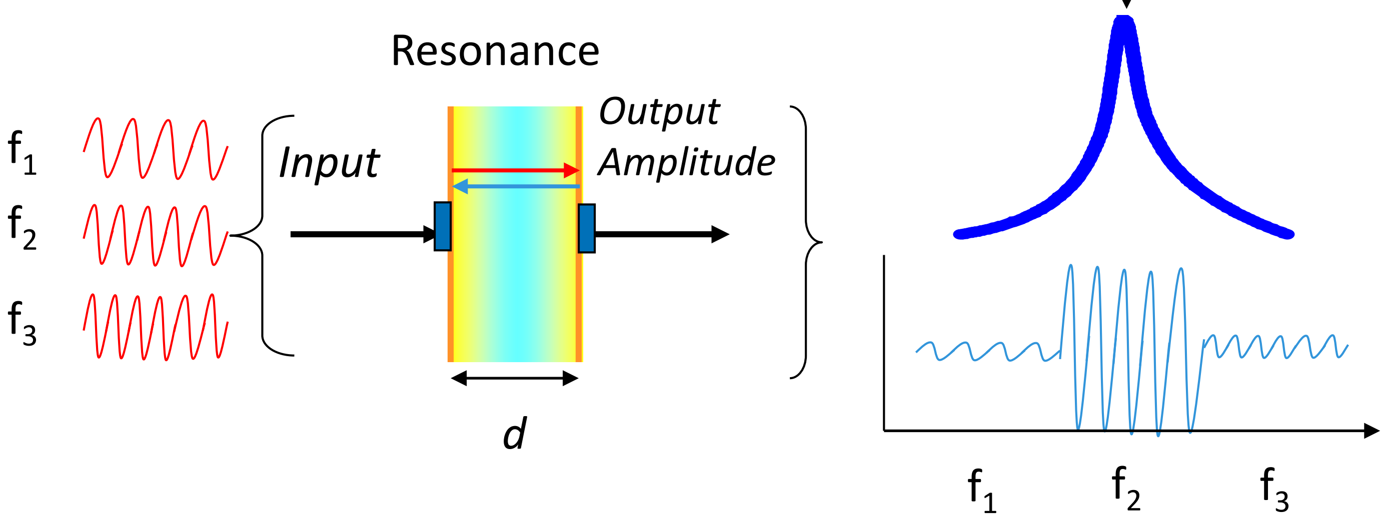
$d = n.(\lambda/2)$

n=1, 2, 3…

λ=wavelength

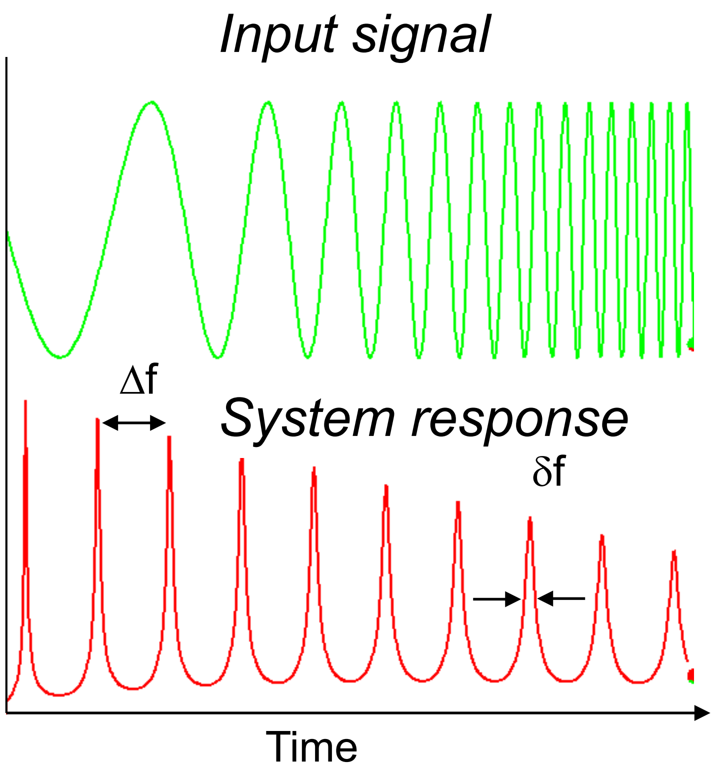


Examples of standing wave when resonance occurs



*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

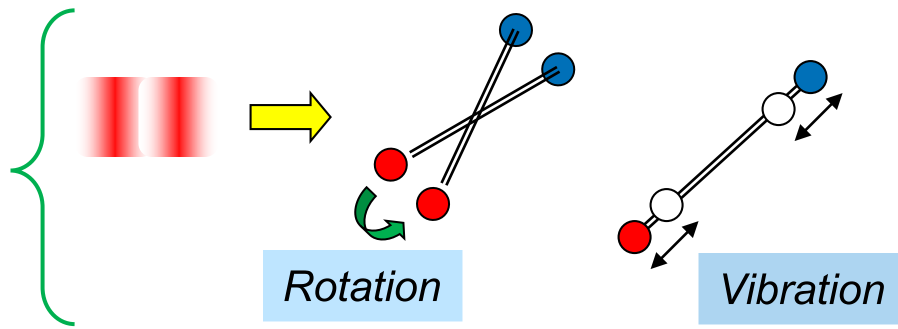
δf =peak width

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

Swept Frequency Acoustic Interferometry (SFAI)

Physical Parameters That Can Be Determined Using SFAI:

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

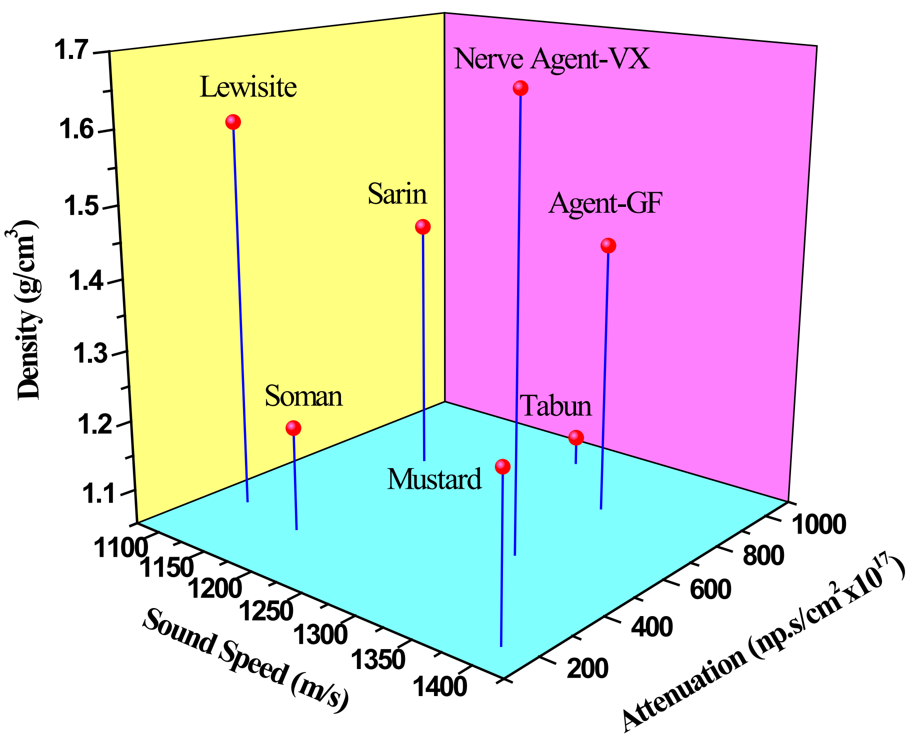


- **Density**
- **Viscosity**
- **Acoustic Nonlinearity** — Sound speed varies with pressure in liquids and solids.

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

Noninvasive Identification of CW Agents

SFAI Measurements of CW Agent Physical Properties

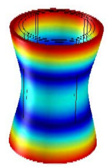


Elastic properties determination

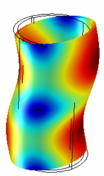
Observe mechanical resonances of objects to determine physical properties of fluids and elastic properties of materials

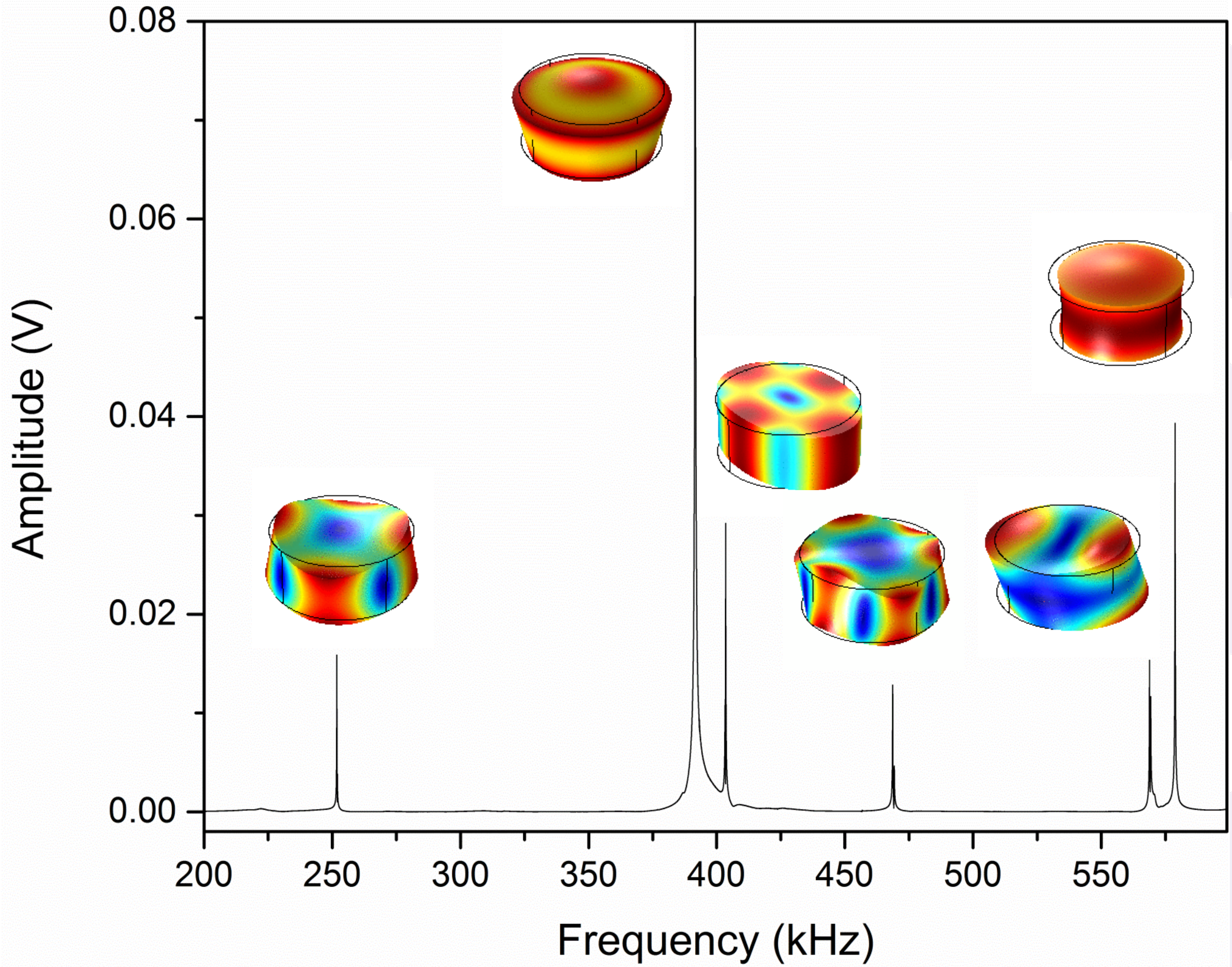
Fluid inside pipe

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



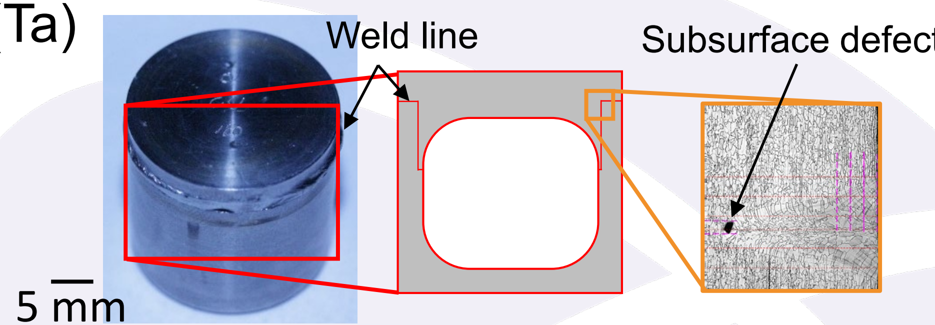
Eigenfrequency=20283 Hz, Surface: Displacement, RMS (mm)



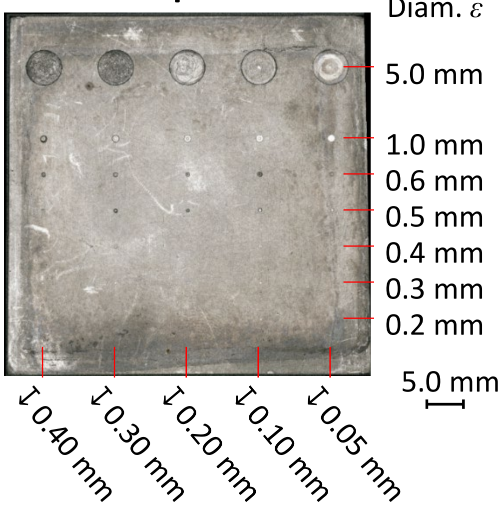


Acoustic weld defect detection

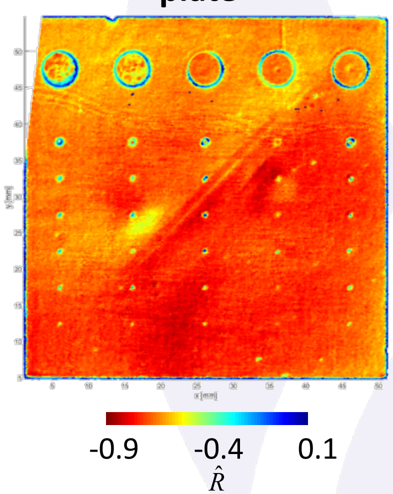
- Weld detection in dense materials (Ta) challenging for radiography
- Solution: scanning acoustic microscopy



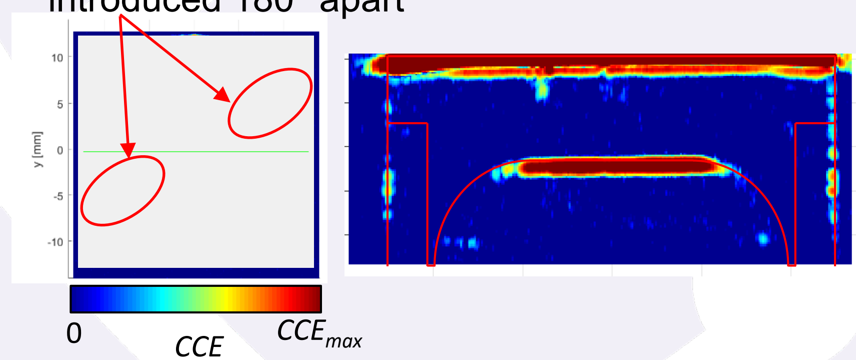
Optical microscopy of Ta plate



Acoustic microscopy of Ta plate

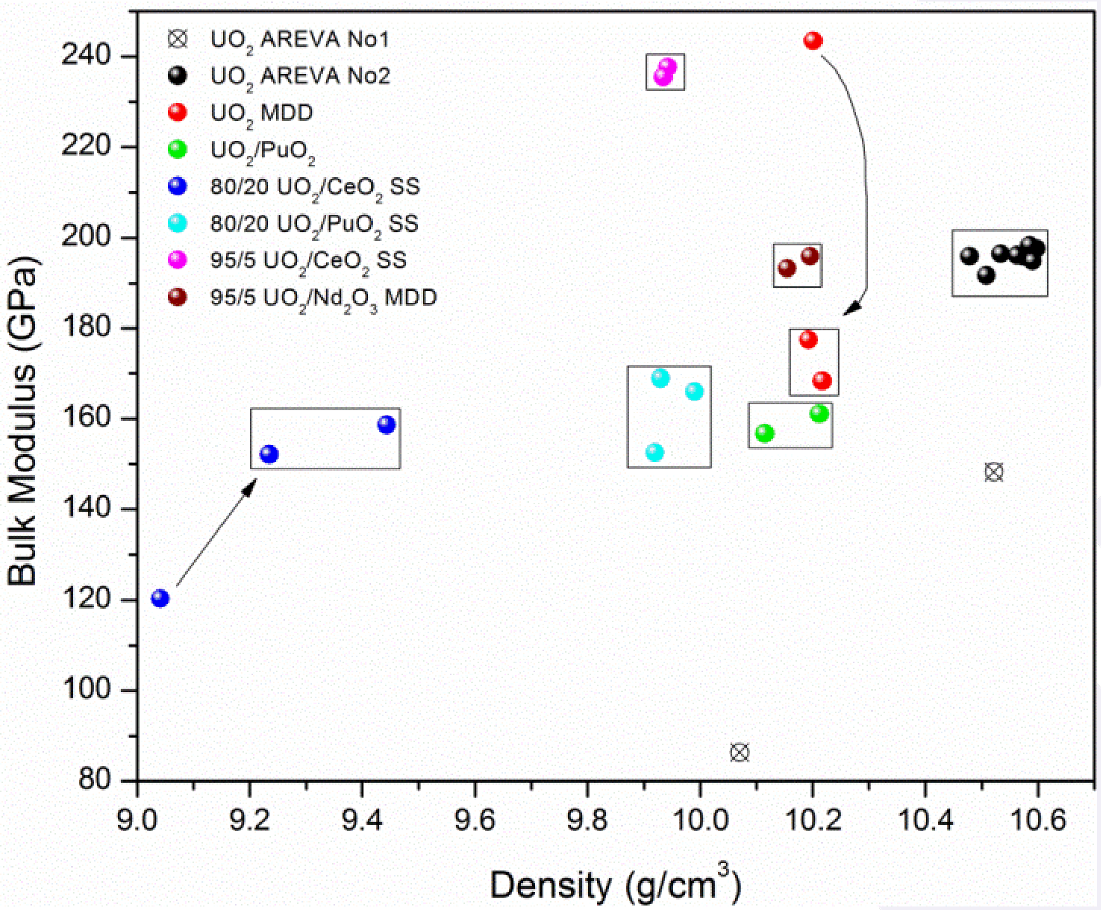


Inclusions intentionally introduced 180° apart



Nuclear materials identification

- RUS - a nondestructive, very difficult to spoof, well-tested measurement method.

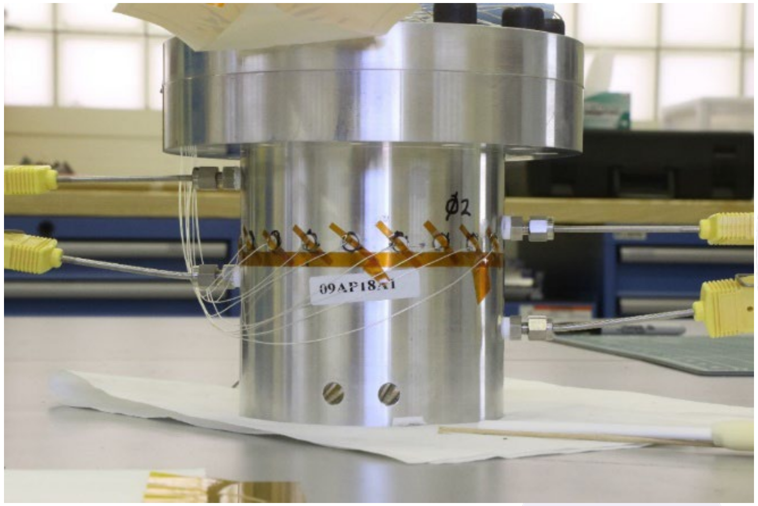


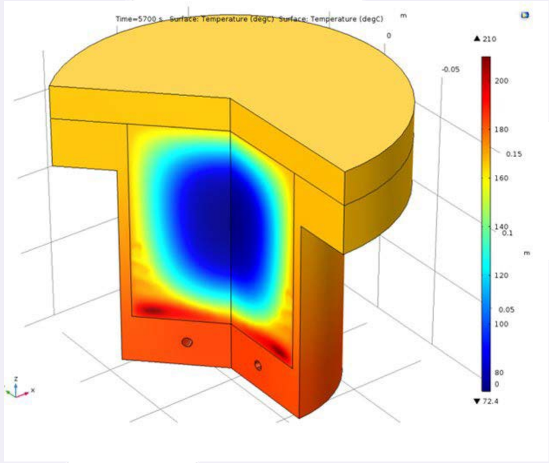
Good correlation between the elastic moduli and density for samples of different compositions/origins.

Able to identify nuclear material composition, fabrication method and source by measuring its RUS properties.

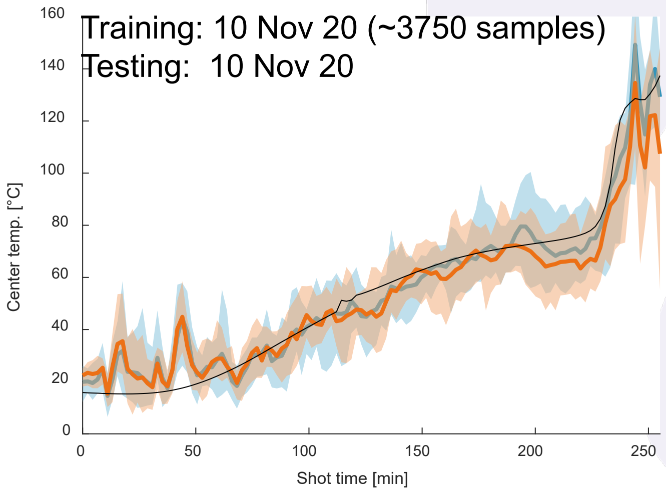
3DHEAT (3 dimensional high explosive acoustic temperature)

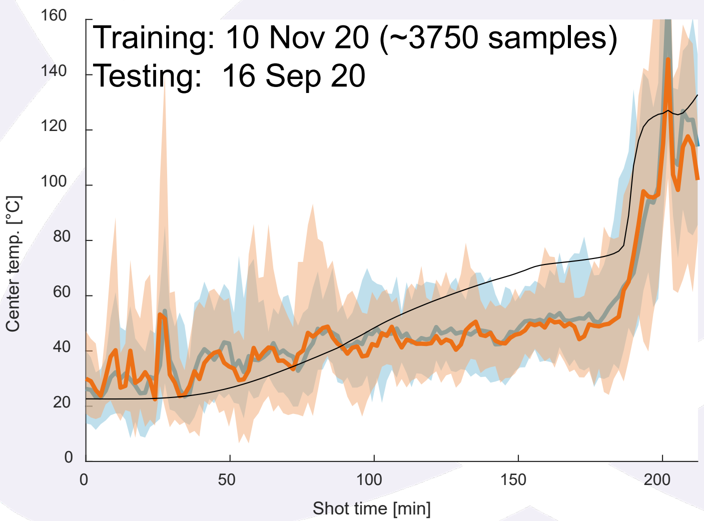
Acoustics diagnosis of thermal damage in Pentolite





Machine learning, CNN (convolutional neural network)

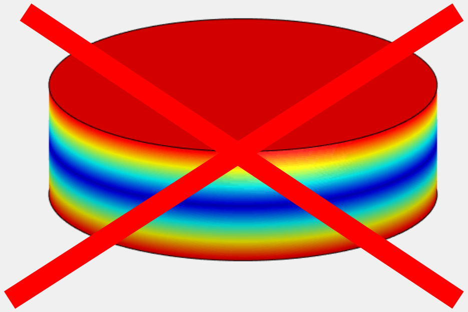




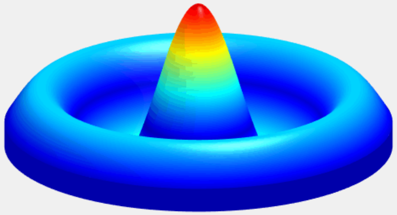
Low-Frequency Collimated Beam

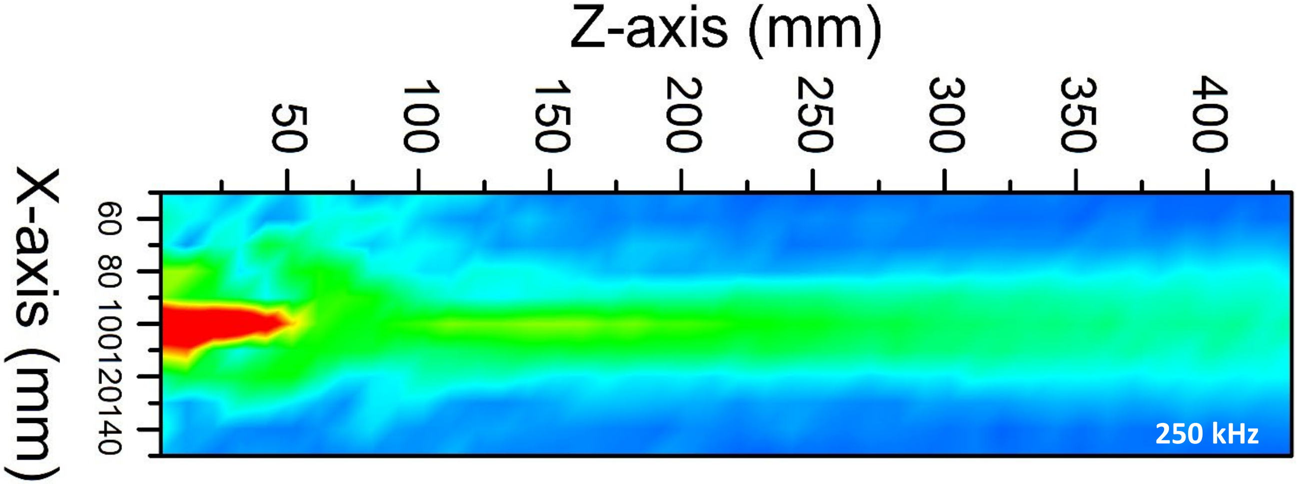
- Bessel-like Acoustic Source (ACCObeam)

Fundamental mode



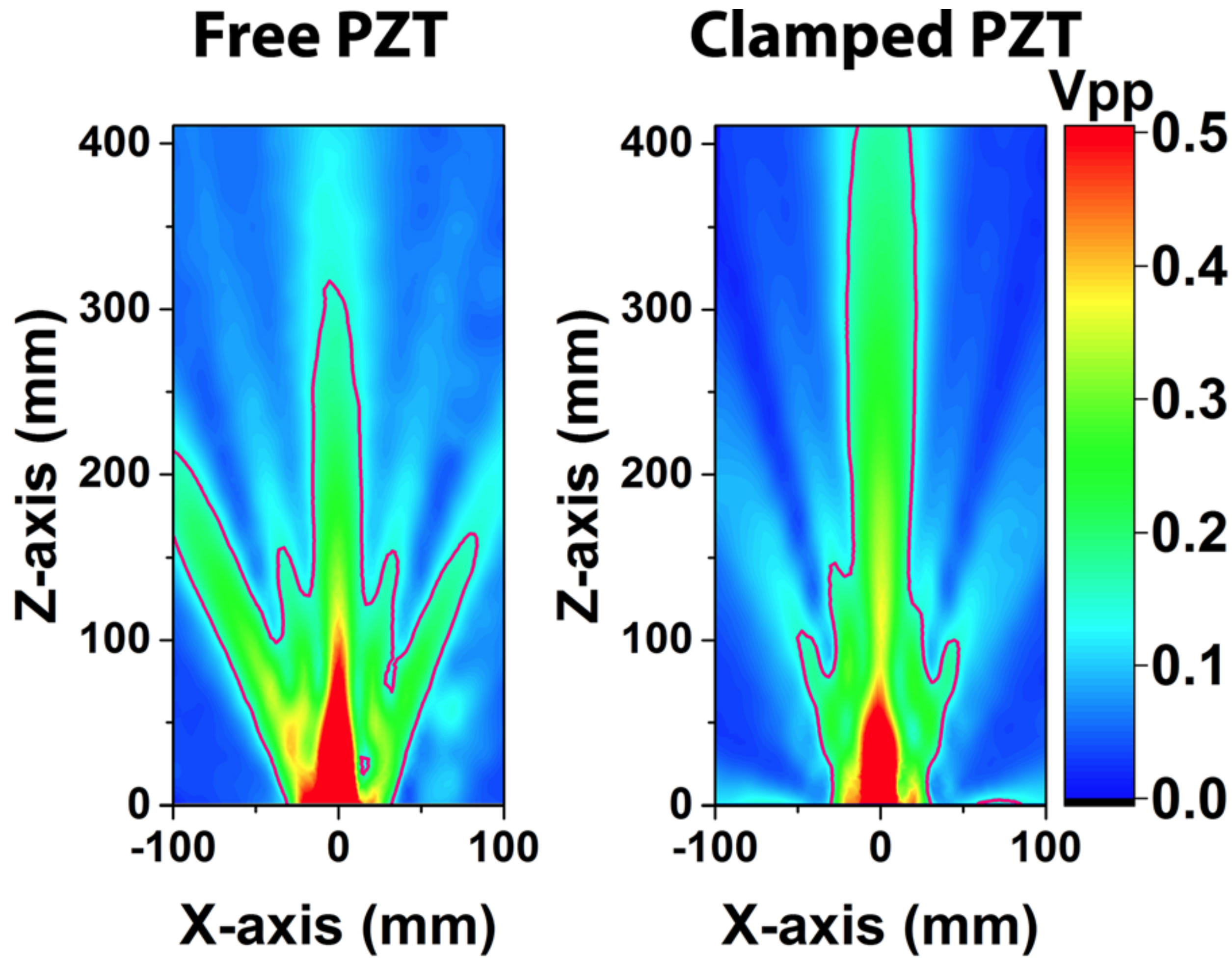
Radial mode





ACCObeam - Radial Modes Clamping

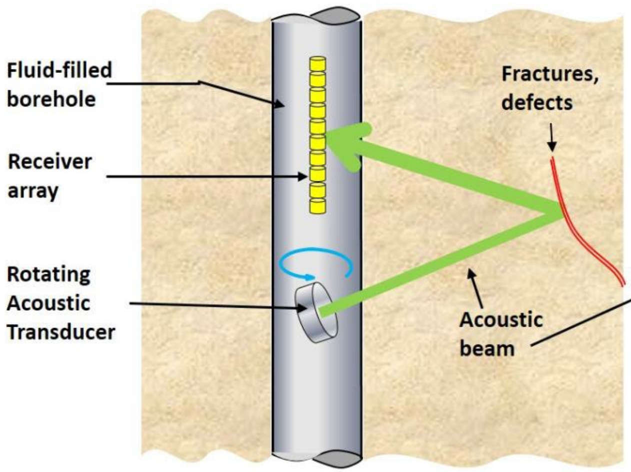
Beam profile in water for the 3rd radial mode RM-3;
free transducer (left) and clamped transducer (right)



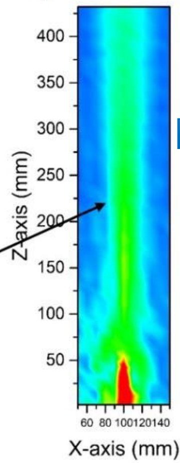
Appl. Phys. Lett., vol. 110, issue 6, (2017), 064101

ACCObeam

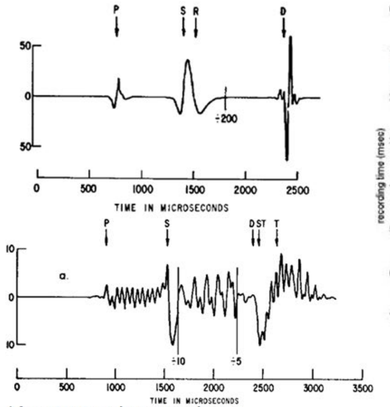
Schematic representation of the 3D imaging system:



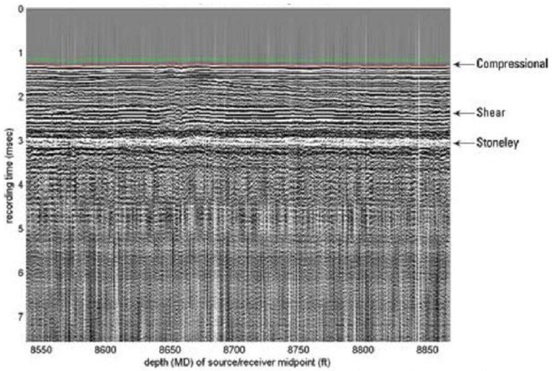
360 degree imaging



No side-lobes



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



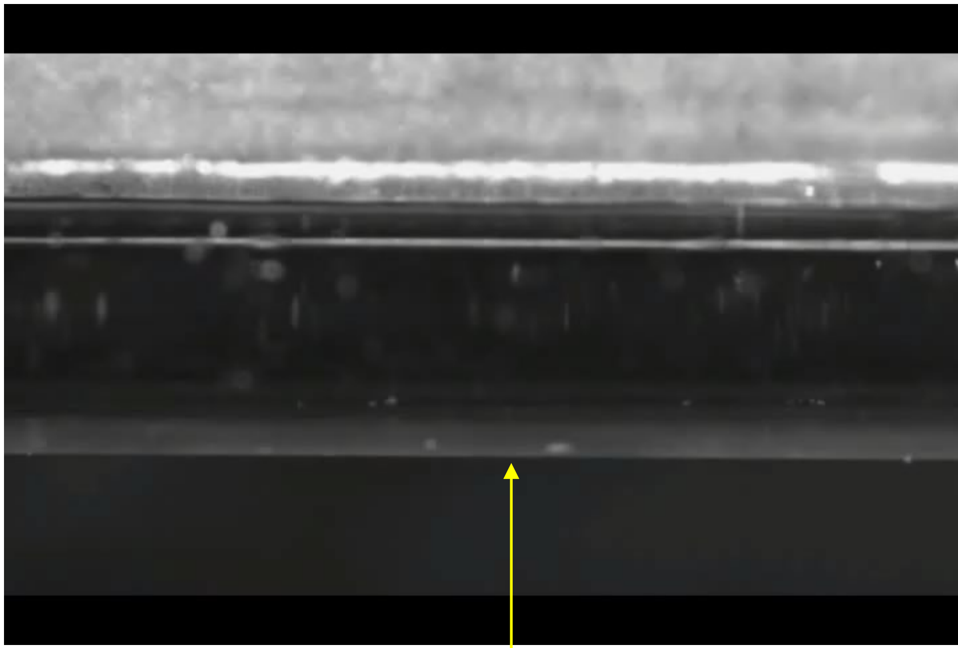
* from B.U. Jakob et al, First Break, vol. 28, Jul 2010

P – compressional wave
S – shear wave
R – pseudo-Rayleigh waves
ST – Stoneley wave
D – direct wave through fluid
T – tube wave

Concentration of Particles in a Tube

Sound field is turned ON and OFF.

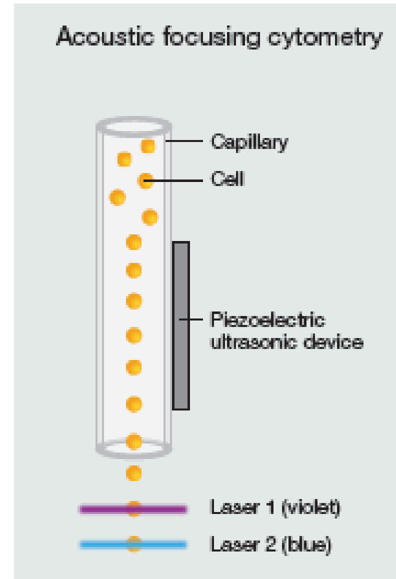
Piezoelectric Transducer @ 1.5 MHz



600 μm capillary, Flow~ 200 μL/min
20 μm polystyrene beads

Real Time Video

Acoustic Flow Cytometer

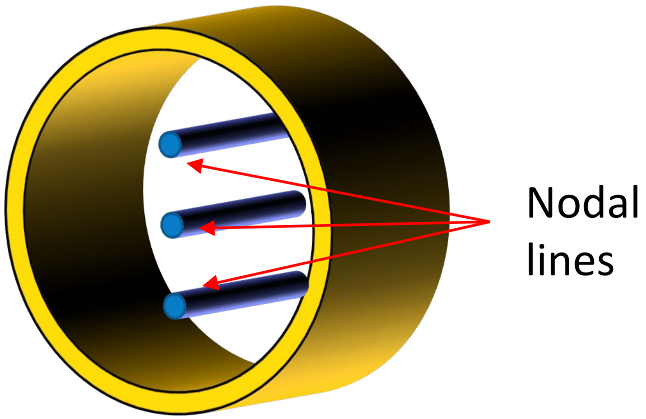


Biological cell analysis

Thermo Fisher Scientific

Acoustic Separation of Humidified Air

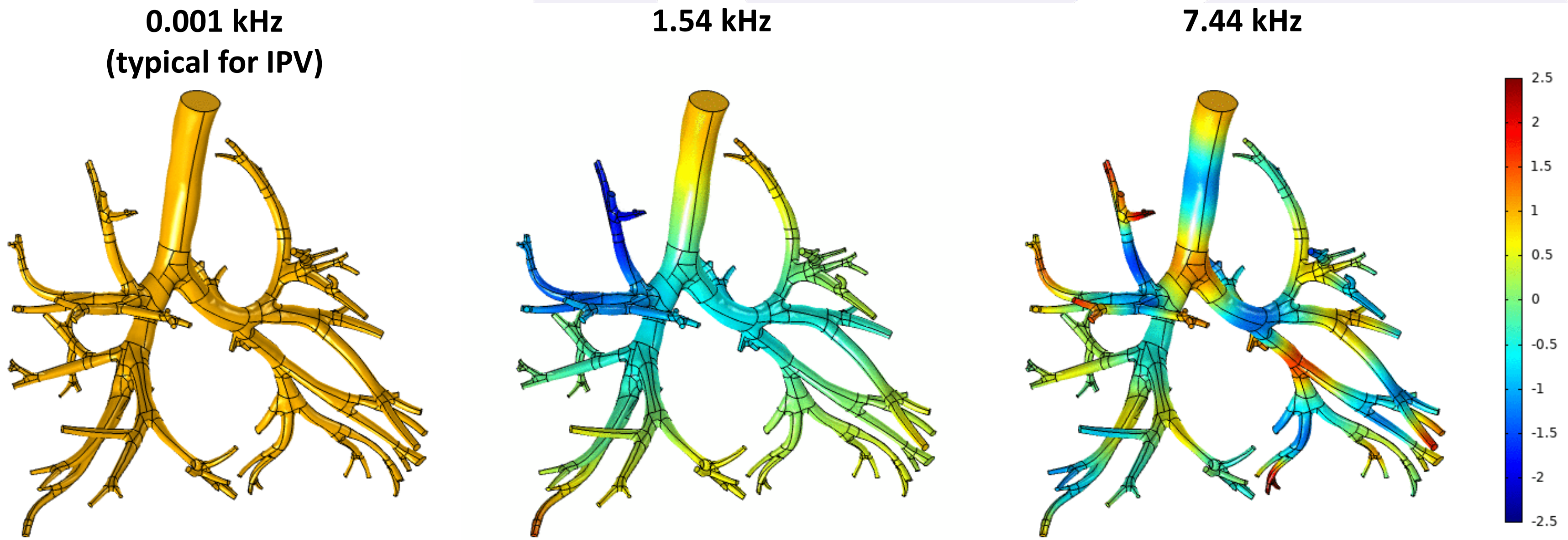
Acoustic Aerosol Concentration & Separation



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

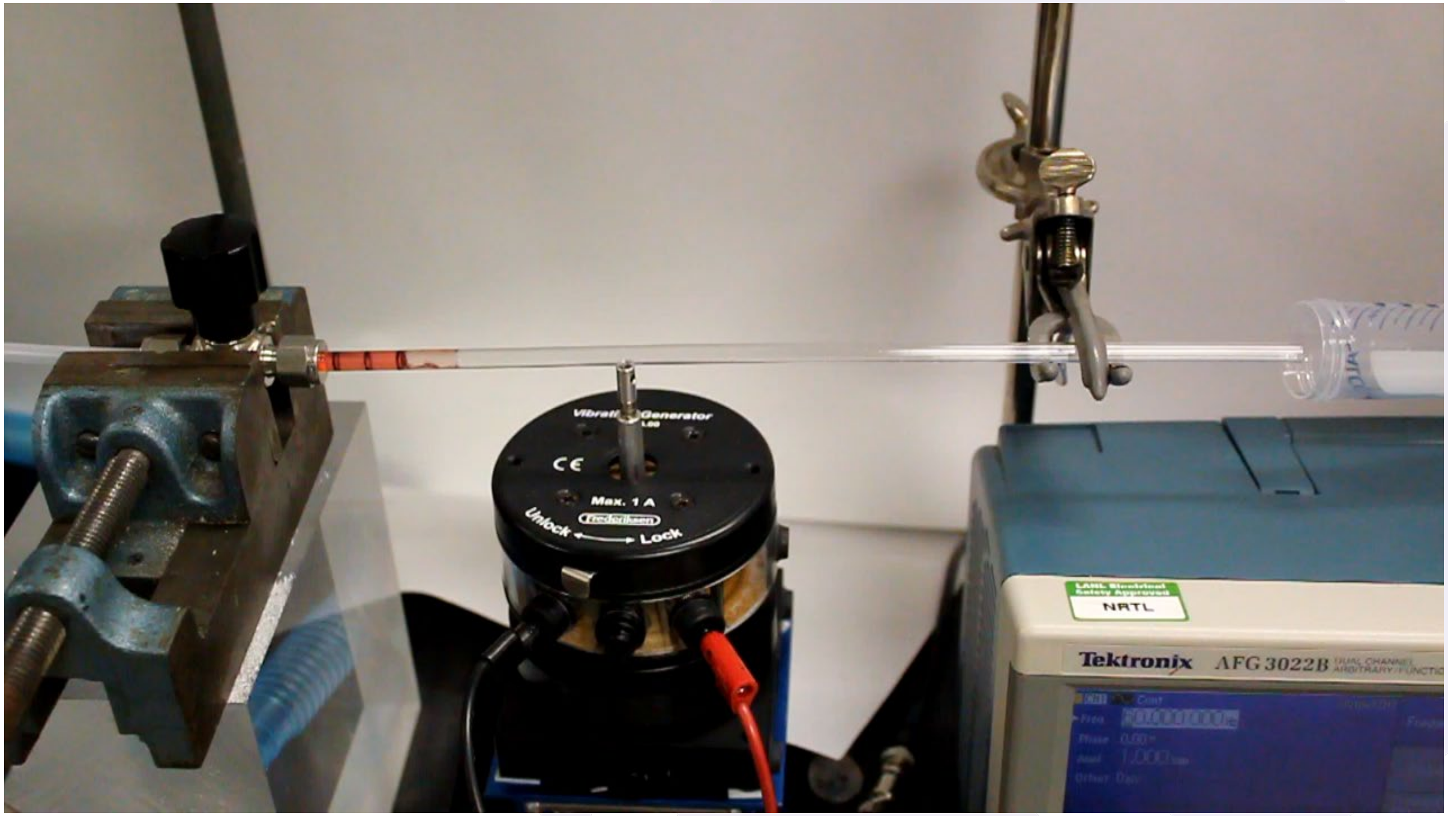
- Intrapulmonary percussive ventilation (IPV): Applies periodic bursts of air/aerosolized medication down the trachea to improve air absorption and mucus clearance
- Currently, no good understanding of optimal parameters (frequency)
- We simulate how frequency affects sound penetration in lung bronchi



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

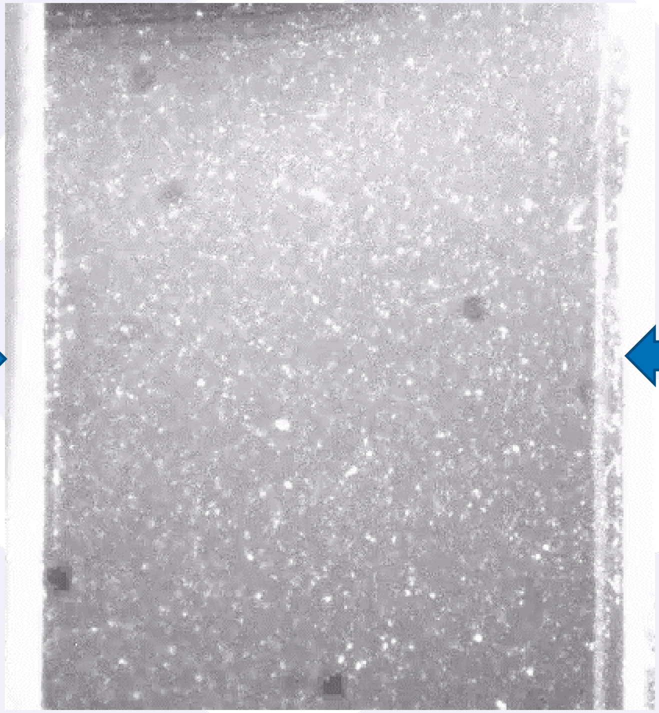


Acoustic Separation

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

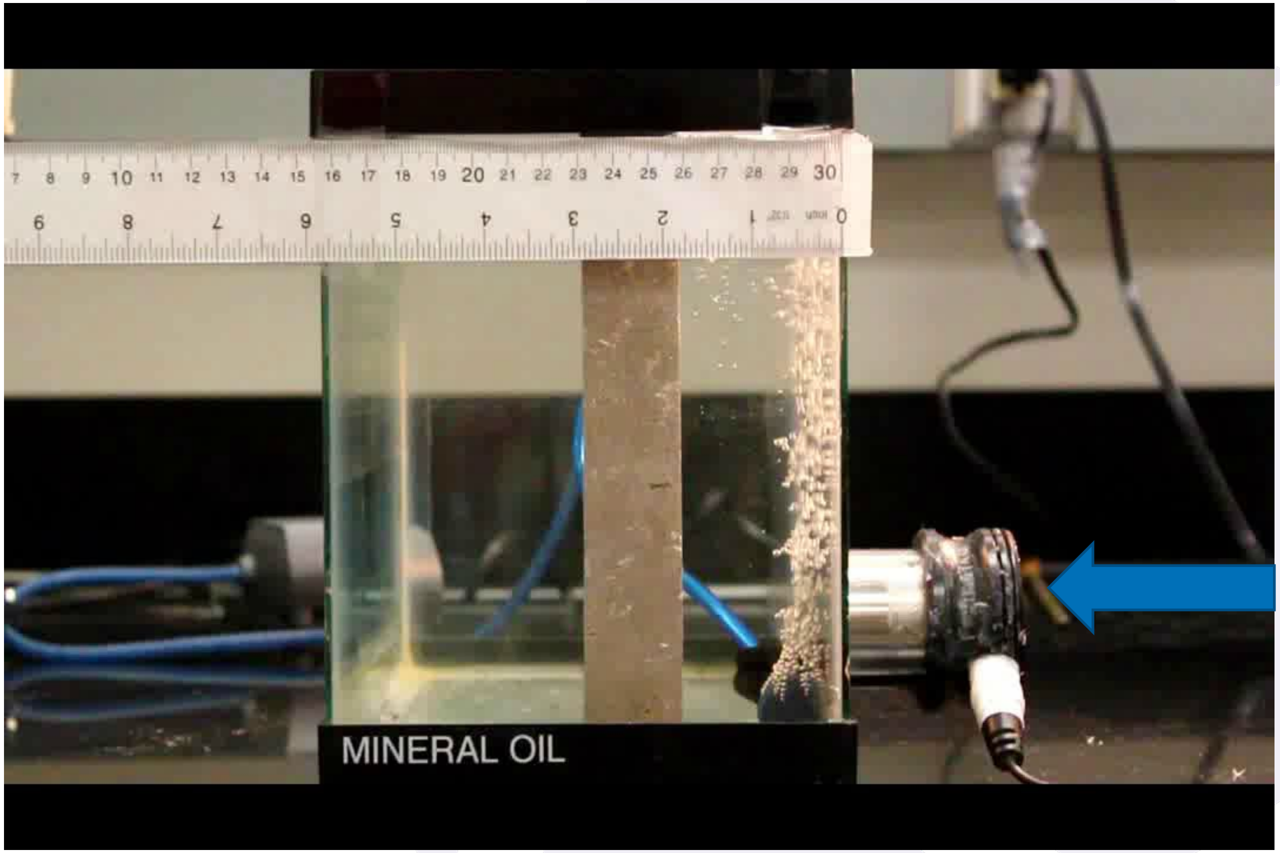
Liquid-Liquid

Solid-Liquid



Acoustic manipulation

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



Underwater manipulation with sound

Acoustic Metamaterials

Acoustic Radiation Force Based Fabrication Technique