Autonomous Monitoring of Wellbore Integrity Applying Time-Reverse Nonlinear-Elastic Wave Spectroscopy and Fiber Optic Sensing and Communication

Project Number (FWP-FE-853-17-FY17)

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LA-UR-22-28574

U.S. Department of Energy

National Energy Technology Laboratory

2022 Carbon Management Project Review Meeting

August 15-19, 2022

Collaborators and Background

Team

Los Alamos National Lab (project lead)

- P. Johnson (PI), C. Donahue (Co-Pi), I. Anwar, B, Euser, R. Guyer, C, Johnson, B. Carey, E. Dauson, L. Beardslee, E. Rougier, S. Boyce
- Acoustics (nonlinearity, time reversal, signals from noise); machine learning; wellbore integrity; lab-scale experiments; project integration

Lawrence Berkeley National Lab

- S. Nakagawa
- Acoustics; fiber optics

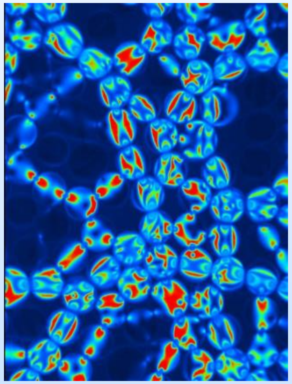
Clemson University

- L. Murdoch, L. Hua, H. Xiao, S. DeWolf
- Fiber optics, geomechanics, acoustics

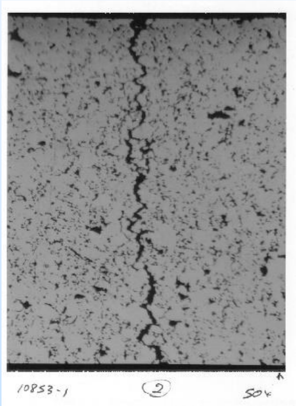
Chevron, ETC

- H. Goodman
- Field application needs

"Distributed"



"Localized"



Background to Approach

Our previous work has demonstrated:

- Machine-learning algorithms can extract small seismo-acoustic signatures from noisy backgrounds;
- Nonlinear acoustic methods can probe damage (distributed & localized) in complex earth materials;
- Acoustic time-reversal methods can be used to focus energy (including within earth materials);
- Fiber optic sensors can be used to monitor strain at high resolution;
- Microwave photonics can measure distributed strain with optical fiber using non-proprietary methods.

Project Overview

Goals and Objectives

Goals and Objective: **Development of an autonomous system that can be deployed in wells for unattended long-term (e.g., decades) to monitor both wellbore integrity and stress changes near wellbore**

- Need: affordable, robust, autonomous system for monitoring wellbore integrity, especially post closure
- Need: detect leakage signatures for long term CO_2 monitoring

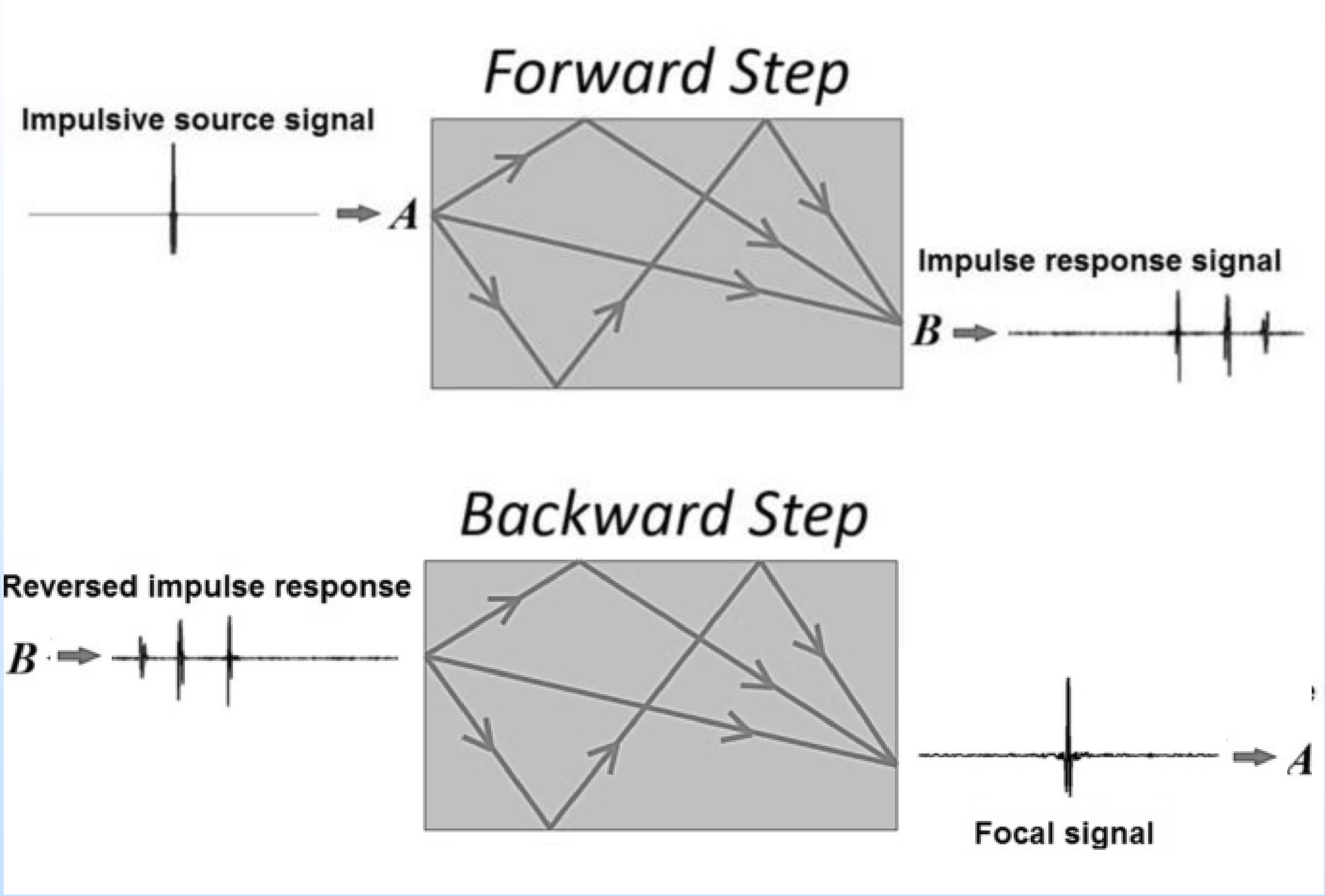
Innovation: Combination of:

(i) Fiber optic sensing to track near-borehole anomalous stress evolution associated with damage and to detect acoustic signals

(ii) Supervised machine learning to extract passive seismo-acoustic signals for long term monitoring of associated with leakage;

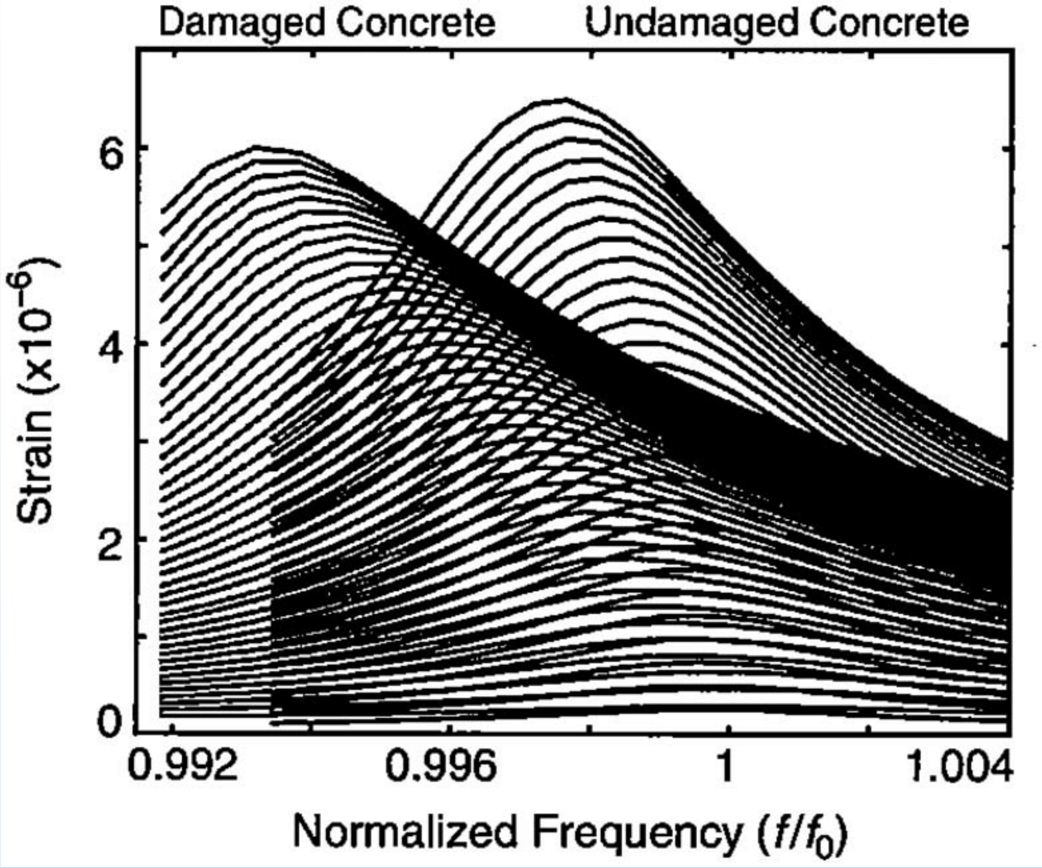
(iii) Active acoustics using embedded sensors and Time Reverse Nonlinear Elastic Wave Spectroscopy (TR-NEWS) to probe for localized damage

Time Reversal (TR)



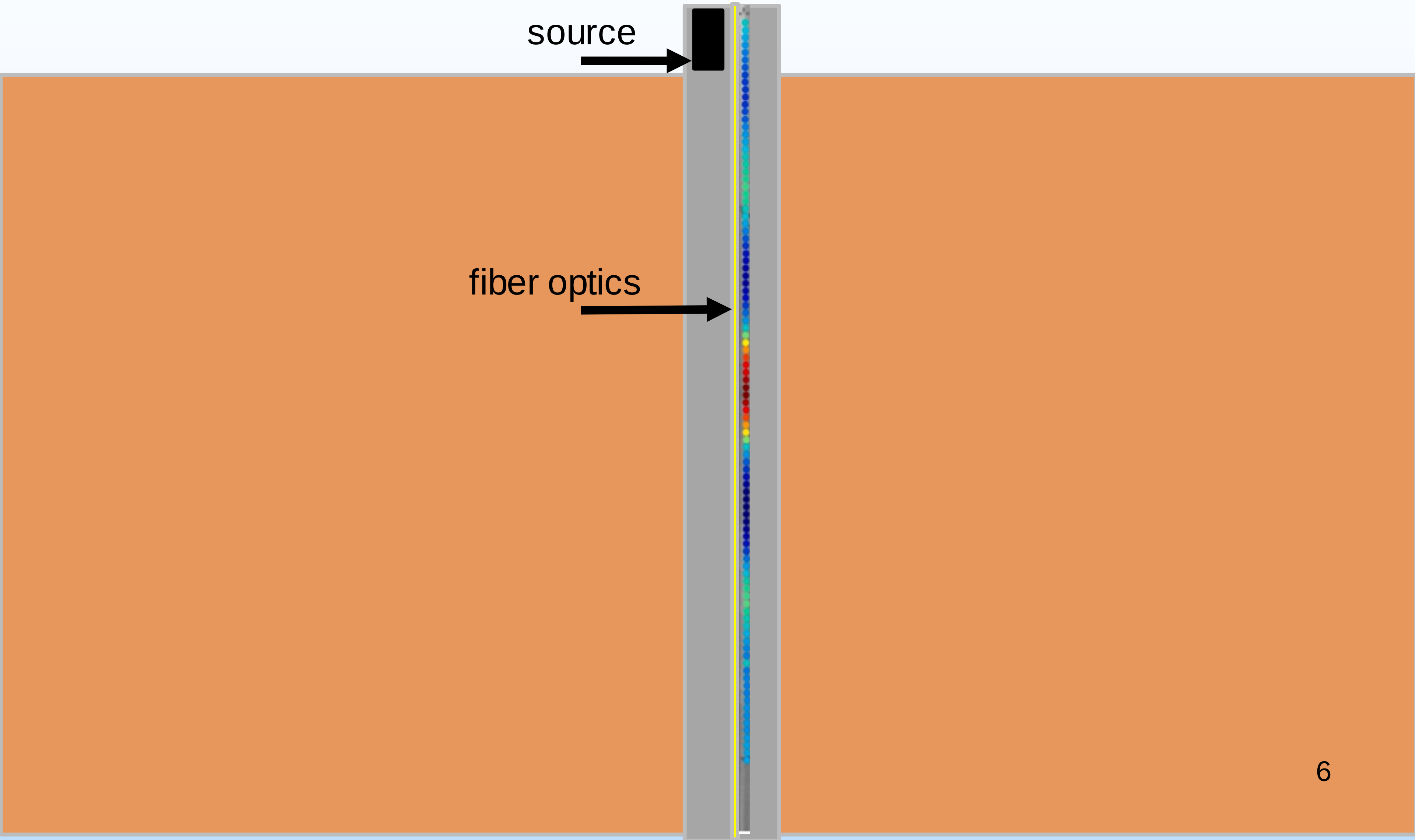
Anderson, Brian E., et al. "Time reversal techniques." *Nonlinear ultrasonic and vibro-acoustical techniques for nondestructive evaluation*. Springer, Cham, 2019. 547-581.

Nonlinear-Elastic Wave Spectroscopy (NEWS)

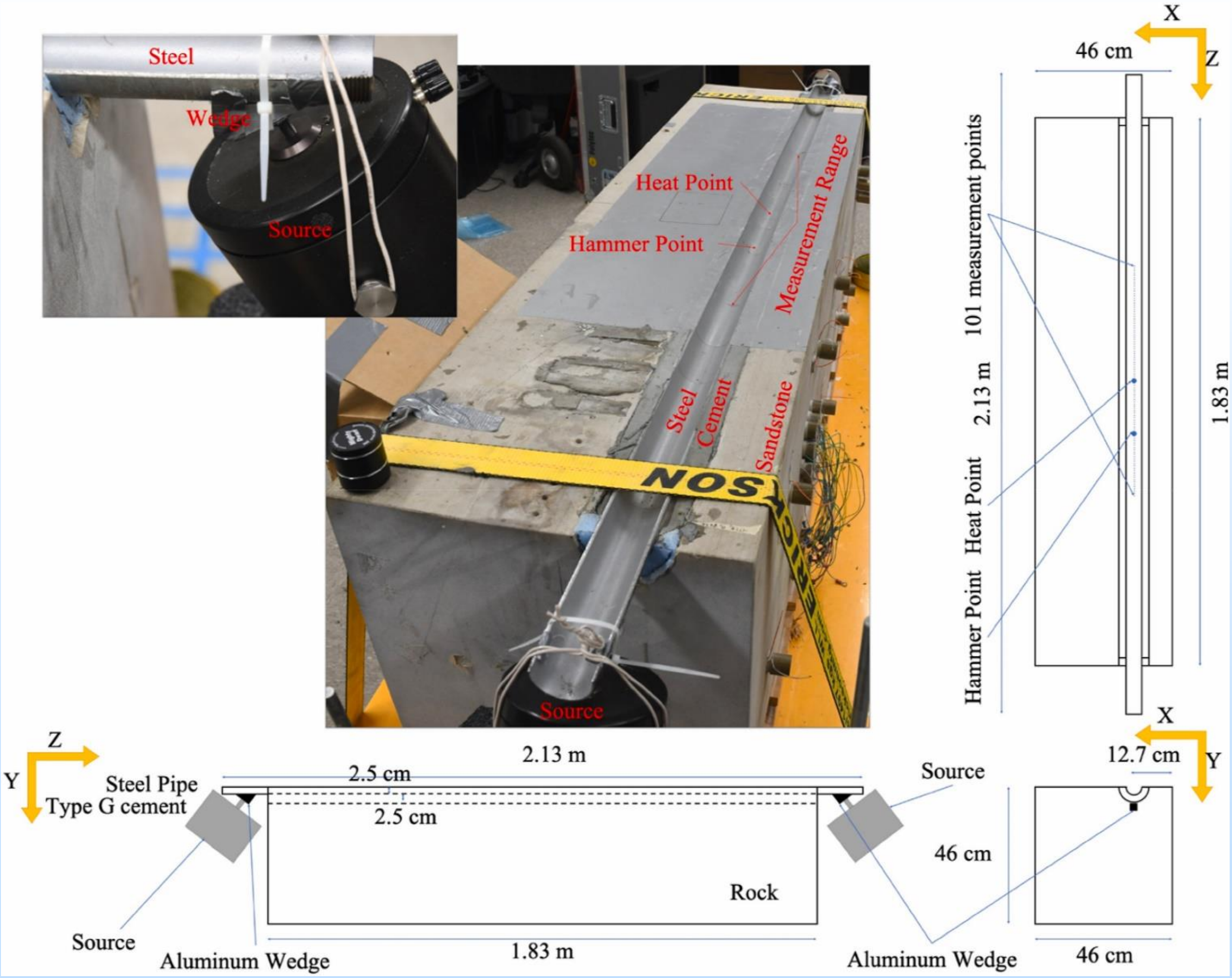


K. E.-A. Van Den Abeele, P. A. Johnson, and A. Sutin, Copyright 2000, The American Society for Nondestructive Testing

TR + NEWS + Fiber Optics

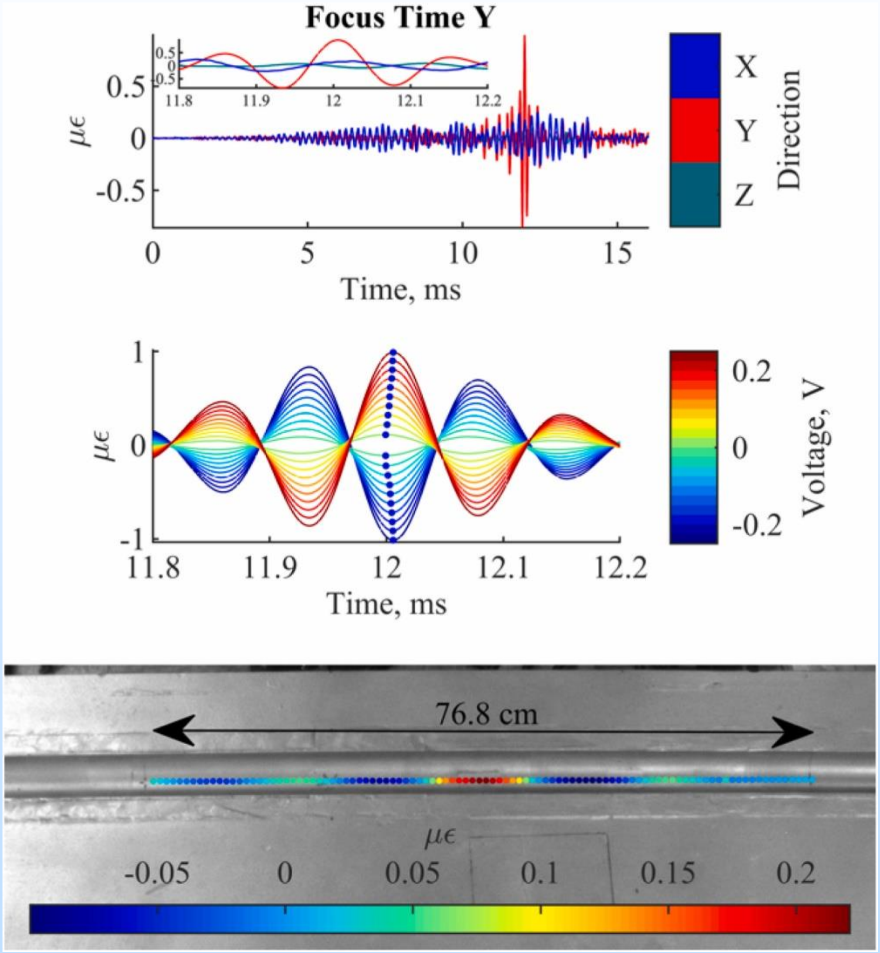


Experimental Setup



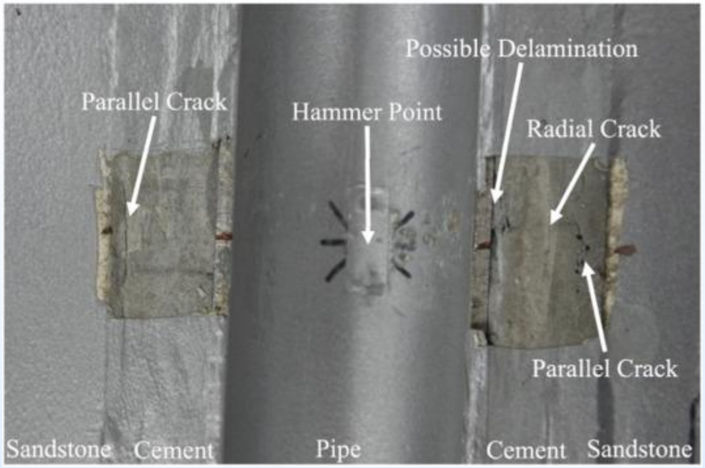
Dauson, Erin, et al. "Damage detection in a laboratory-scale wellbore applying Time Reversal and Nonlinear Elastic Wave Spectroscopy (TR NEWS)." *NDT & E International* 126 (2022): 102573.

Time Reversal Focusing

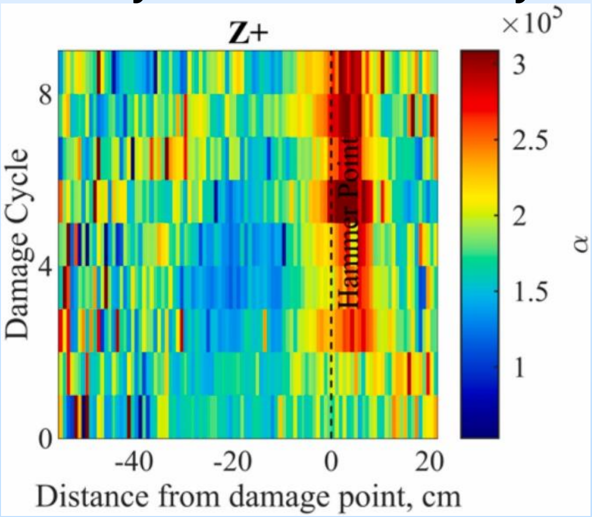


Dauson, Erin, et al. "Damage detection in a laboratory-scale wellbore applying Time Reversal and Nonlinear Elastic Wave Spectroscopy (TR NEWS)." *NDT & E International* 126 (2022): 102573.

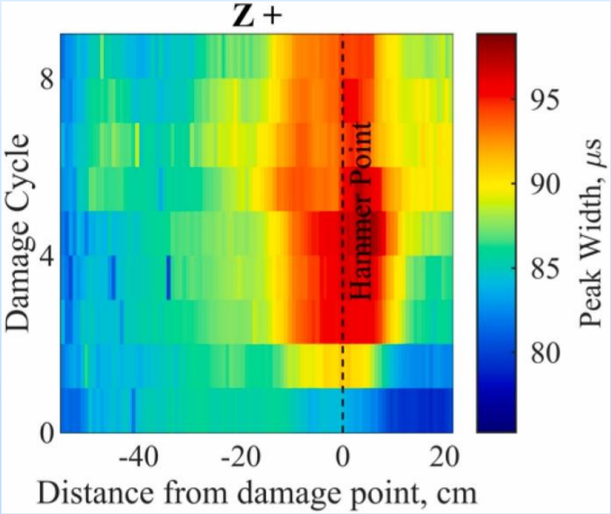
Hammer Strikes: Measuring Damage



Hysteric Nonlinearity

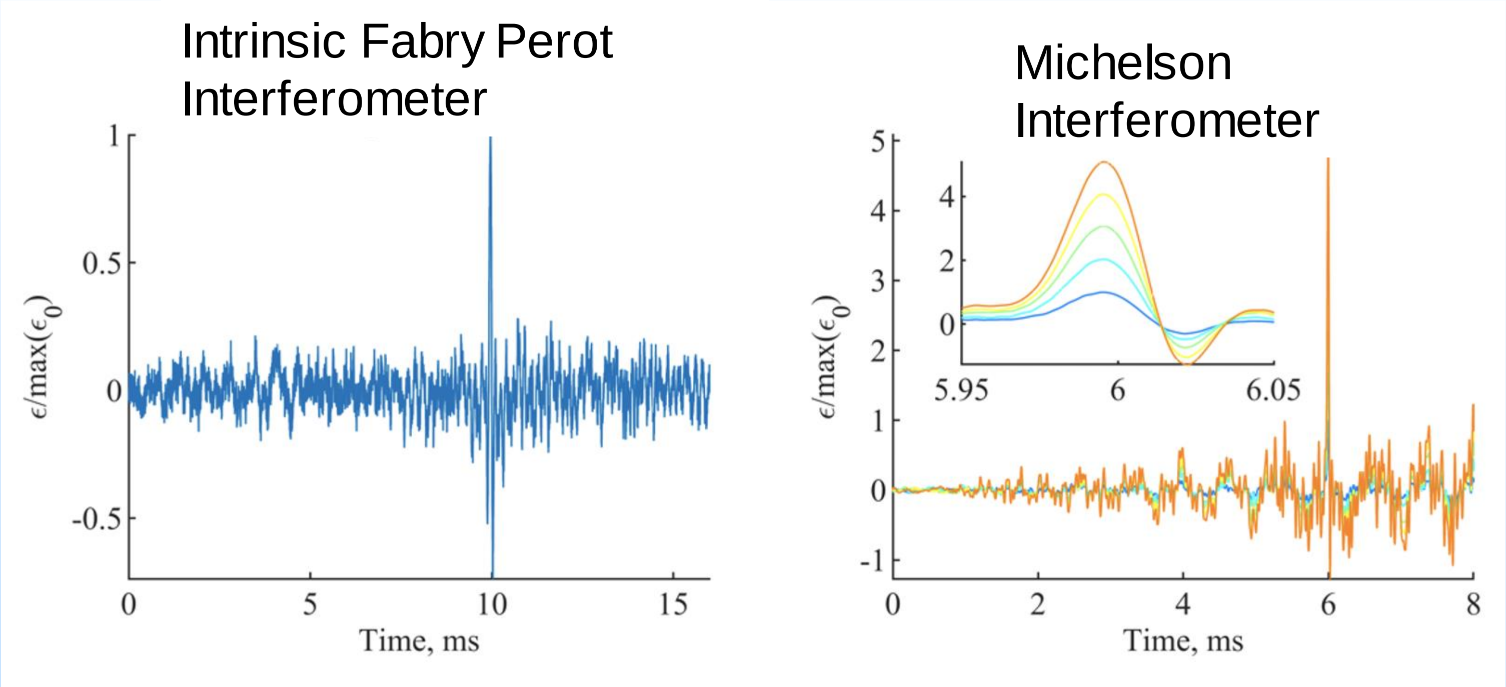


Pulse Width



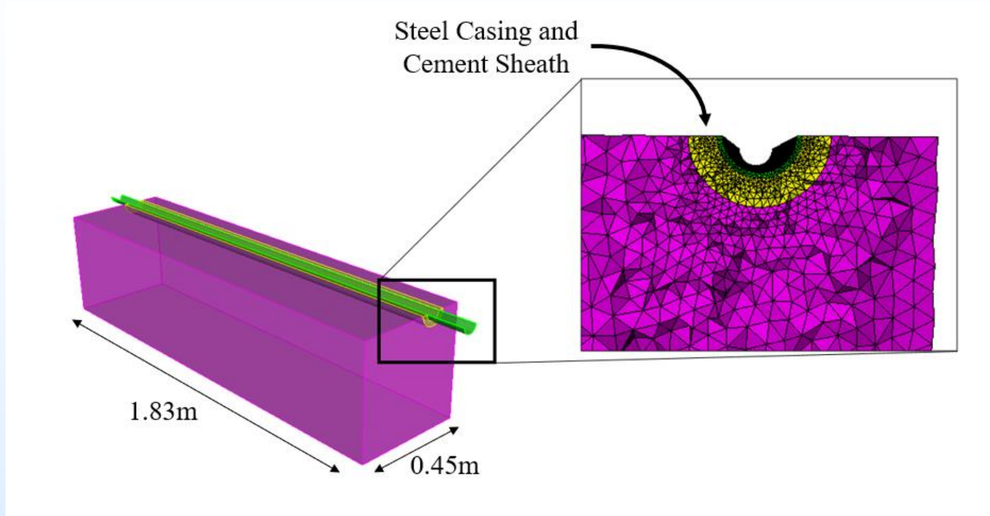
Dauson, Erin, et al. "Damage detection in a laboratory-scale wellbore applying Time Reversal and Nonlinear Elastic Wave Spectroscopy (TR NEWS)." *NDT & E International* 126 (2022): 102573.

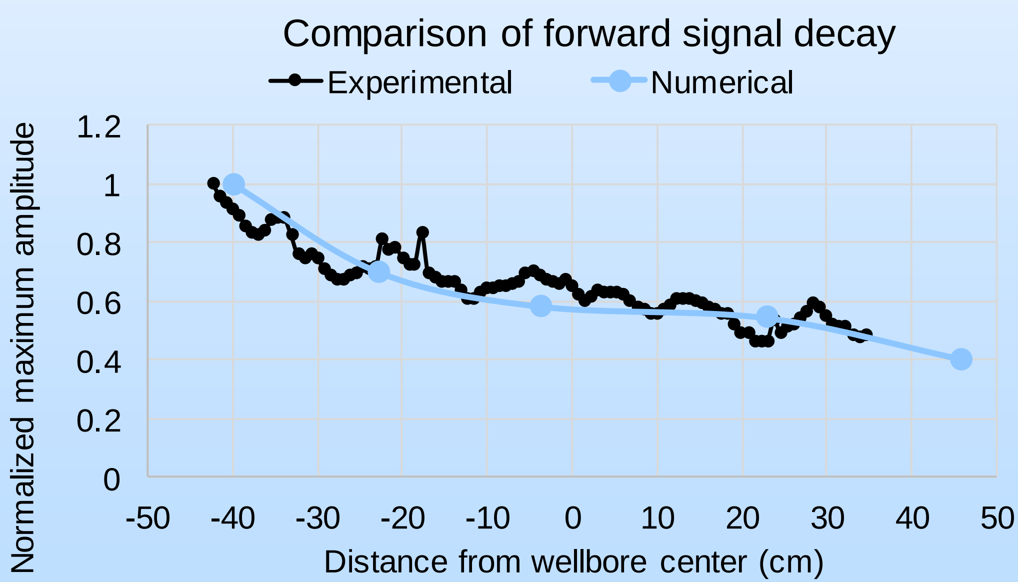
Optical Fiber for Sensors



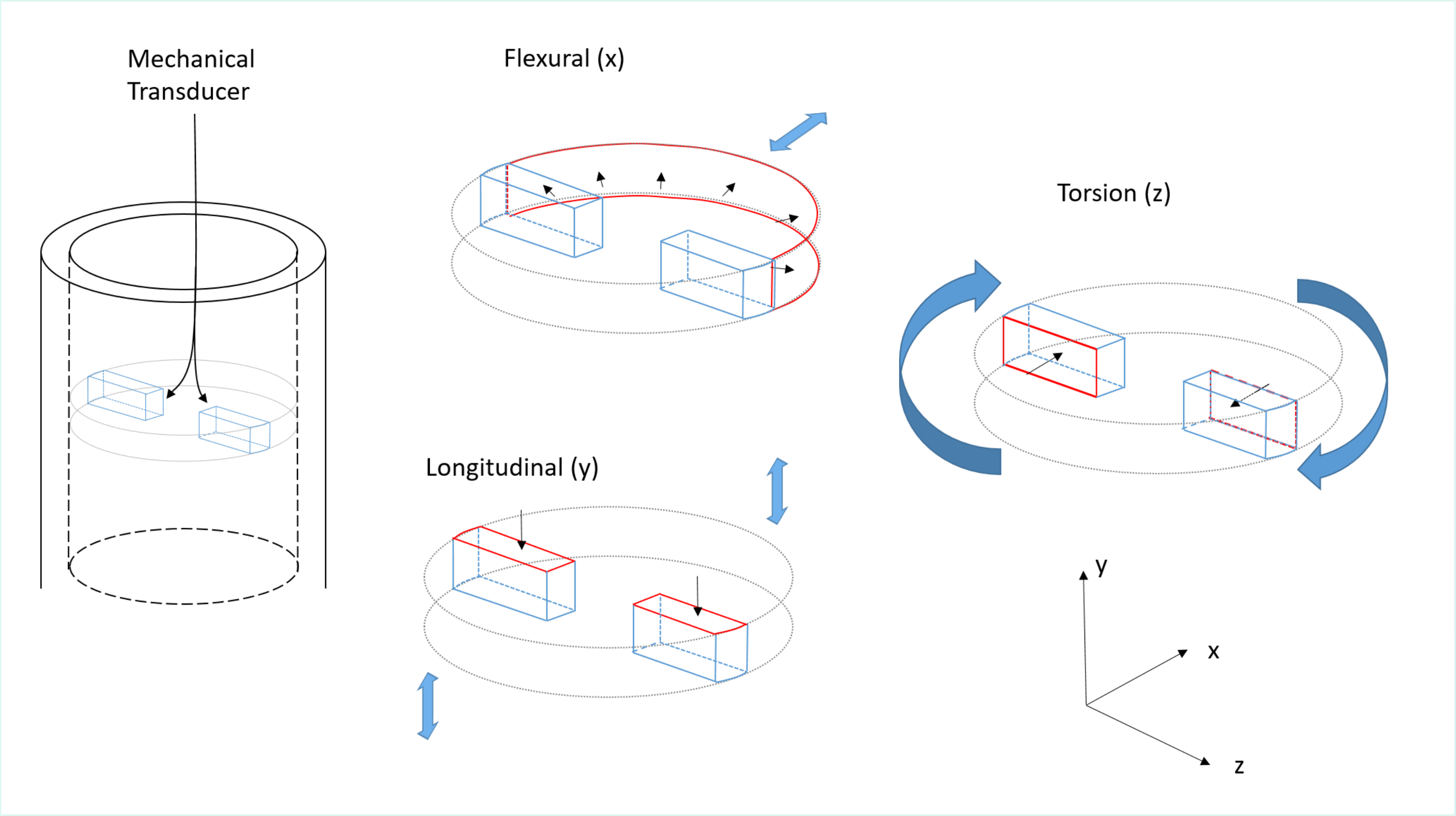
Hua, Liwei, Xuran Zhu, Baokai Cheng, Yang Song, Qi Zhang, Yongji Wu, Lawrence C. Murdoch, Erin R. Dauson, Carly M. Donahue, and Hai Xiao. "Distributed Acoustic Sensing Based on Coherent Microwave Photonics Interferometry." *Sensors* 21, no. 20 (2021): 6784.

Does Time Reversal Scale?

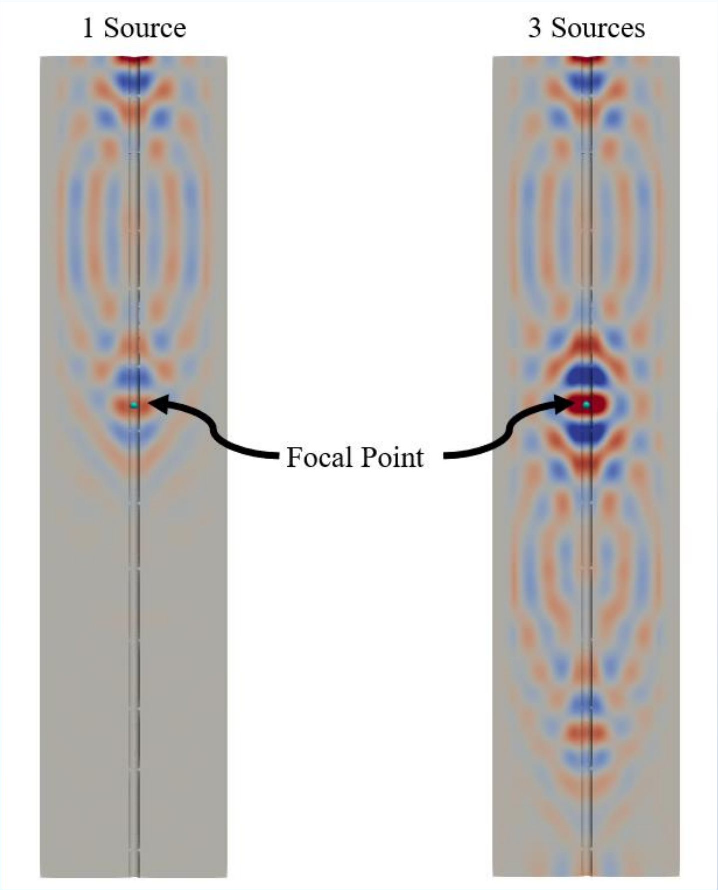


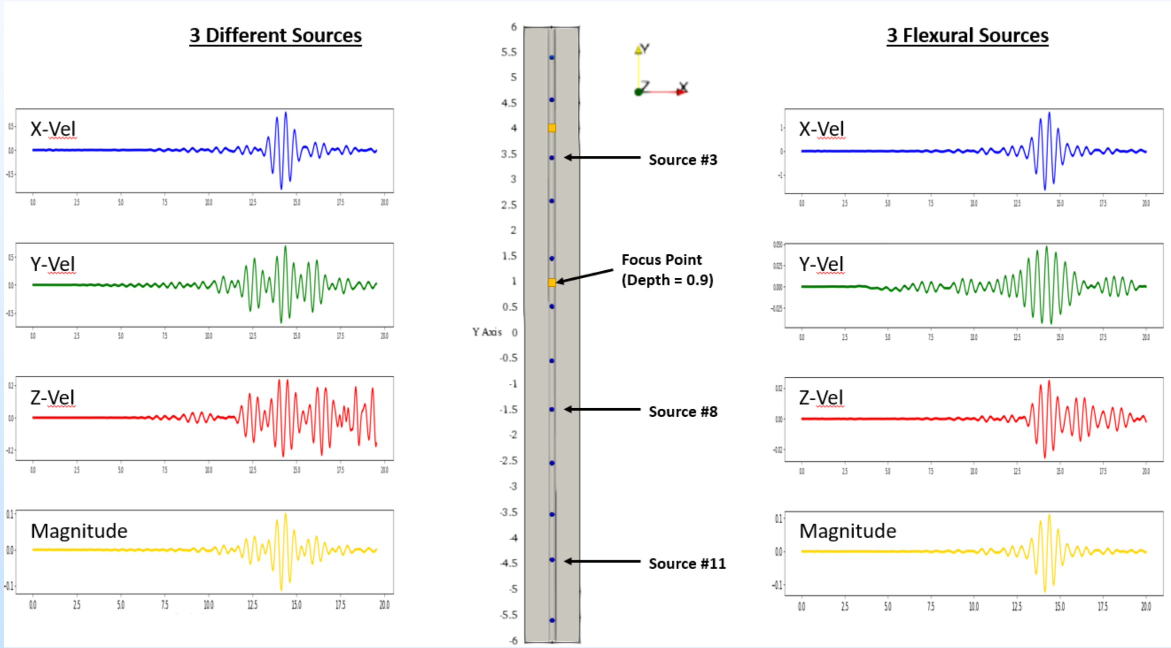


Types of Sources for Different Modes in the Wellbore



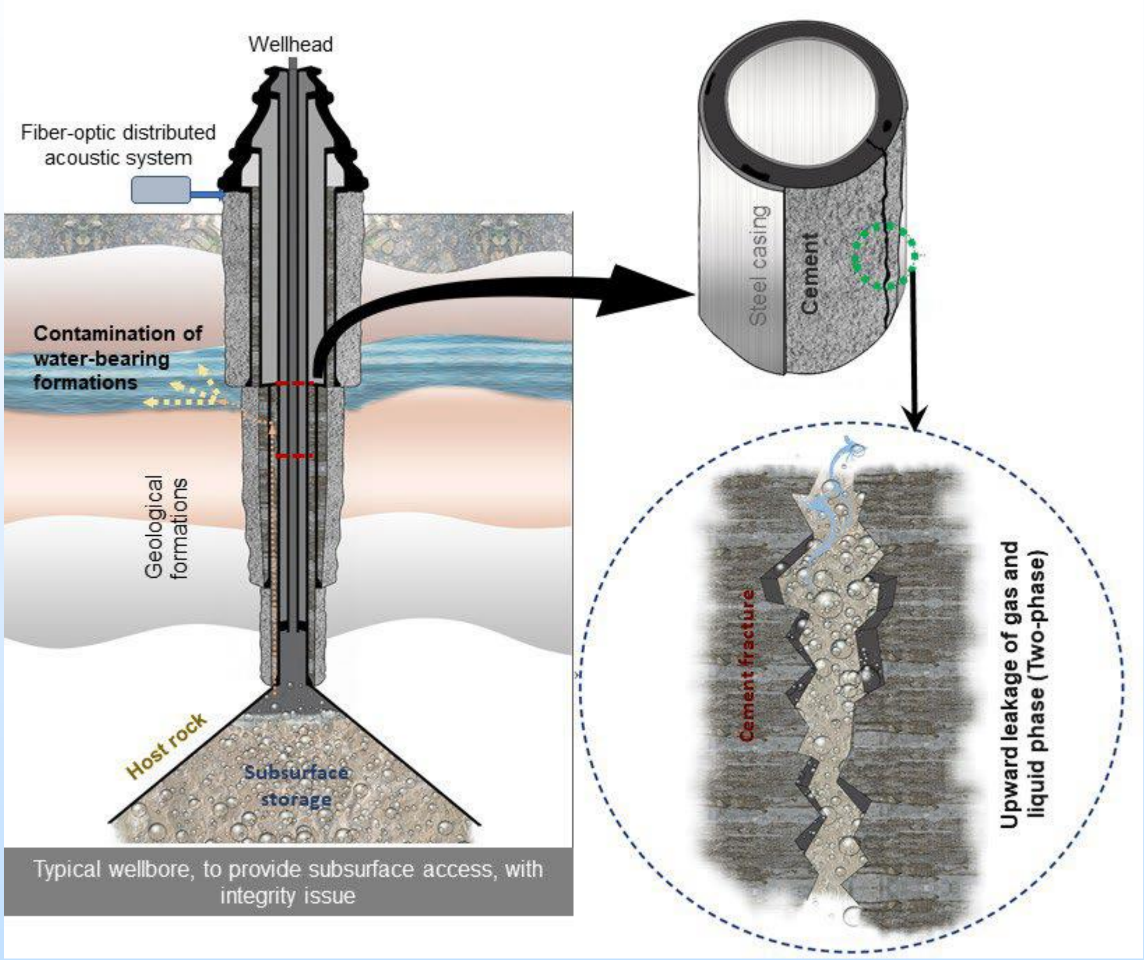
TR Focusing in a Wellbore





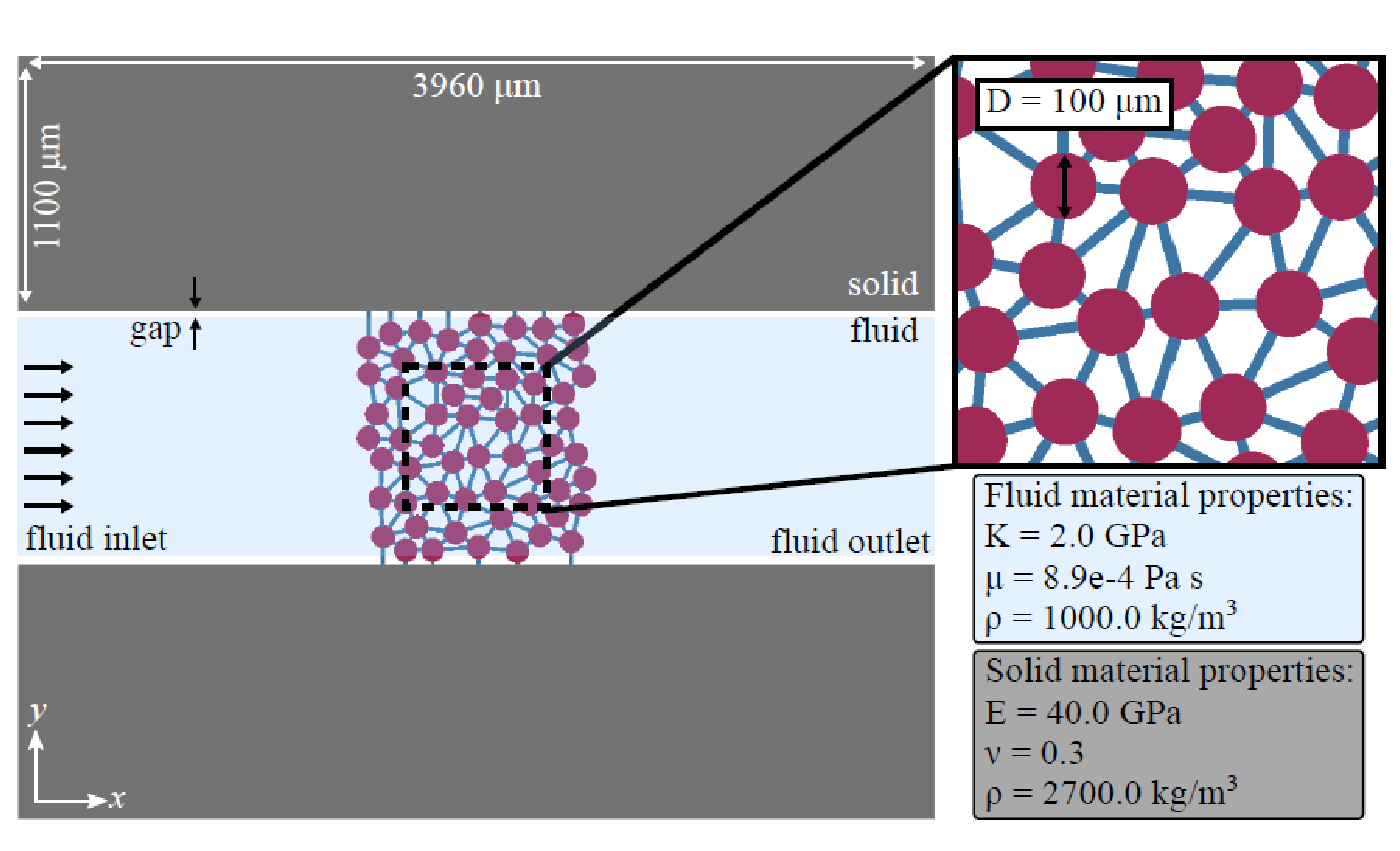
Boyce, S., et al. “Time Reversal Simulations in a Wellbore”, In Preparation.

Flow Characteristics



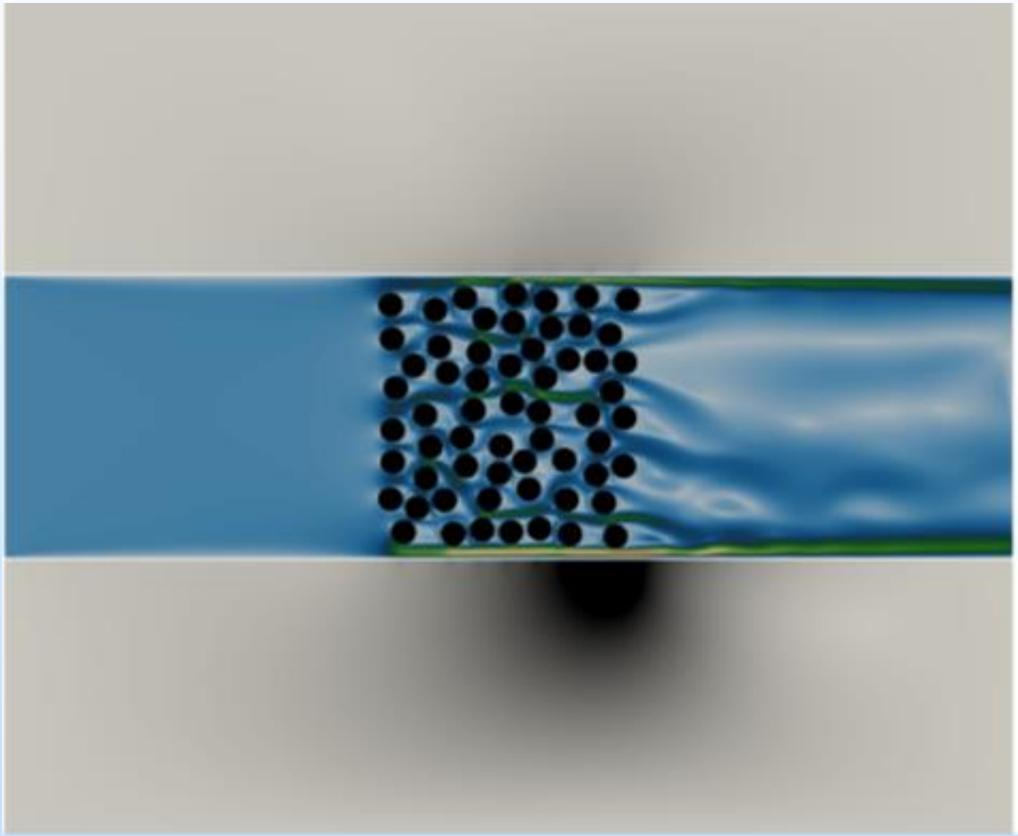
$$k(U) = \mu L \frac{U}{\Delta P(U)}$$

Simulation Setup



Euser, B, C W. Johnson, R Guyer, E Rougier, C M Donahue, G Guthrie, A Munjiza, and P A Johnson. "Straining to Learn Permeability." Submitted (2022).

Simulations of Fluid Through Porous Media



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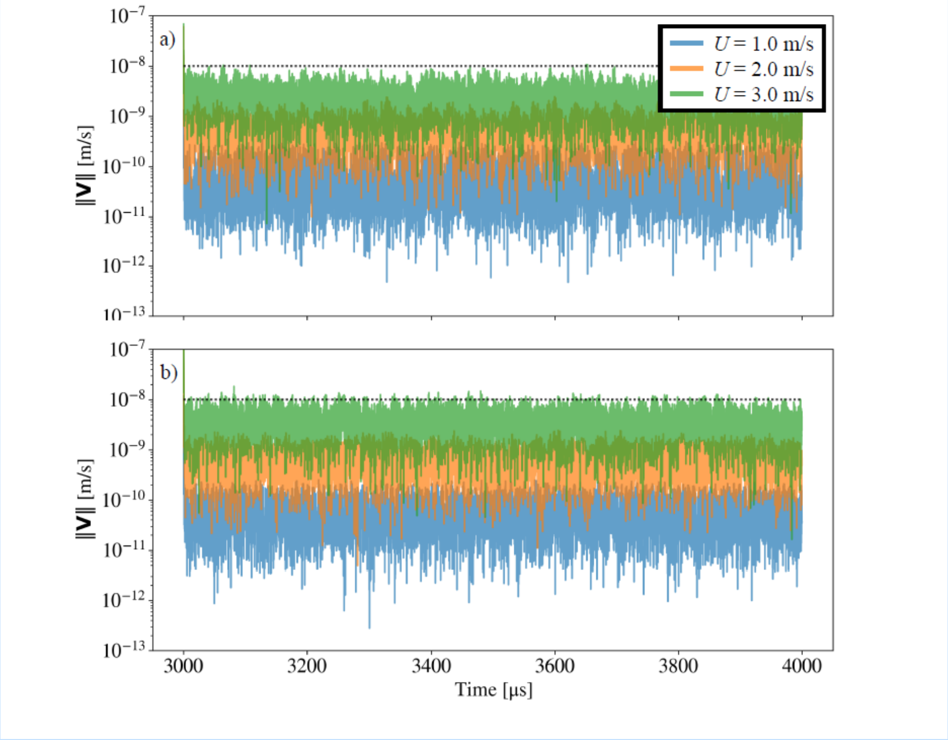
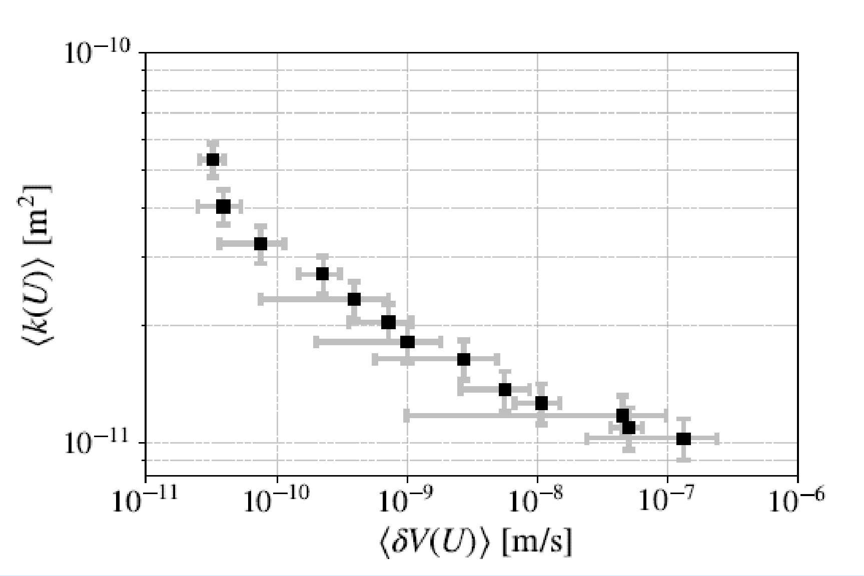
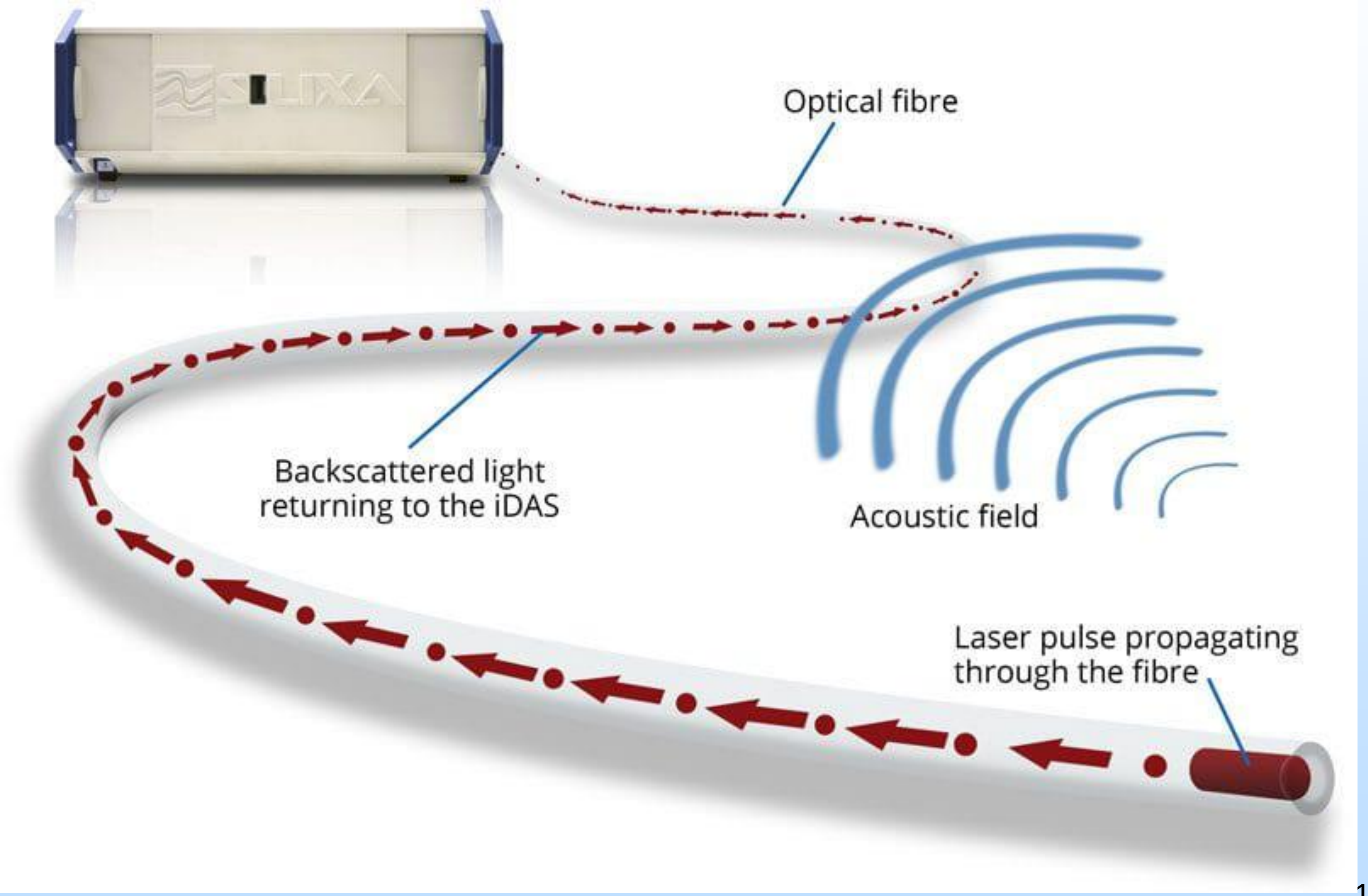




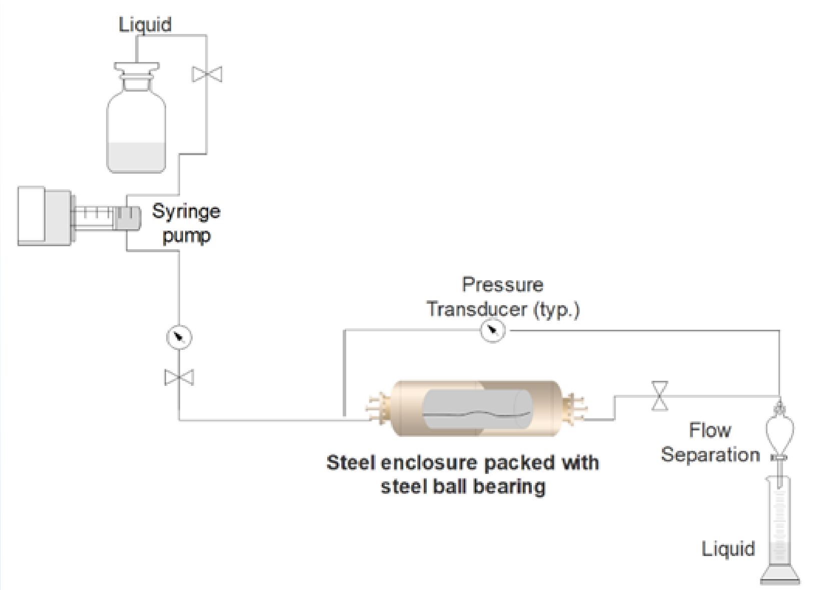
Euser, B, C W. Johnson, R Guyer, E Rougier, C M Donahue, G Guthrie, A Munjiza, and P A Johnson. "Straining to Learn Permeability." Submitted (2022).

Silixa iDAS

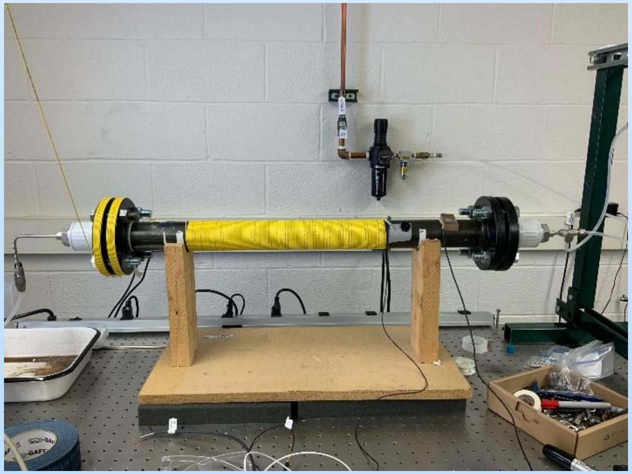


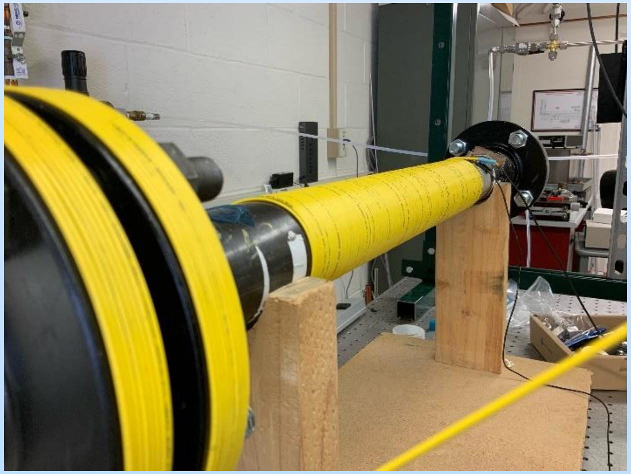
Optical fibre
Backscattered light returning to the iDAS
Acoustic field
Laser pulse propagating through the fibre

Experimental Setup

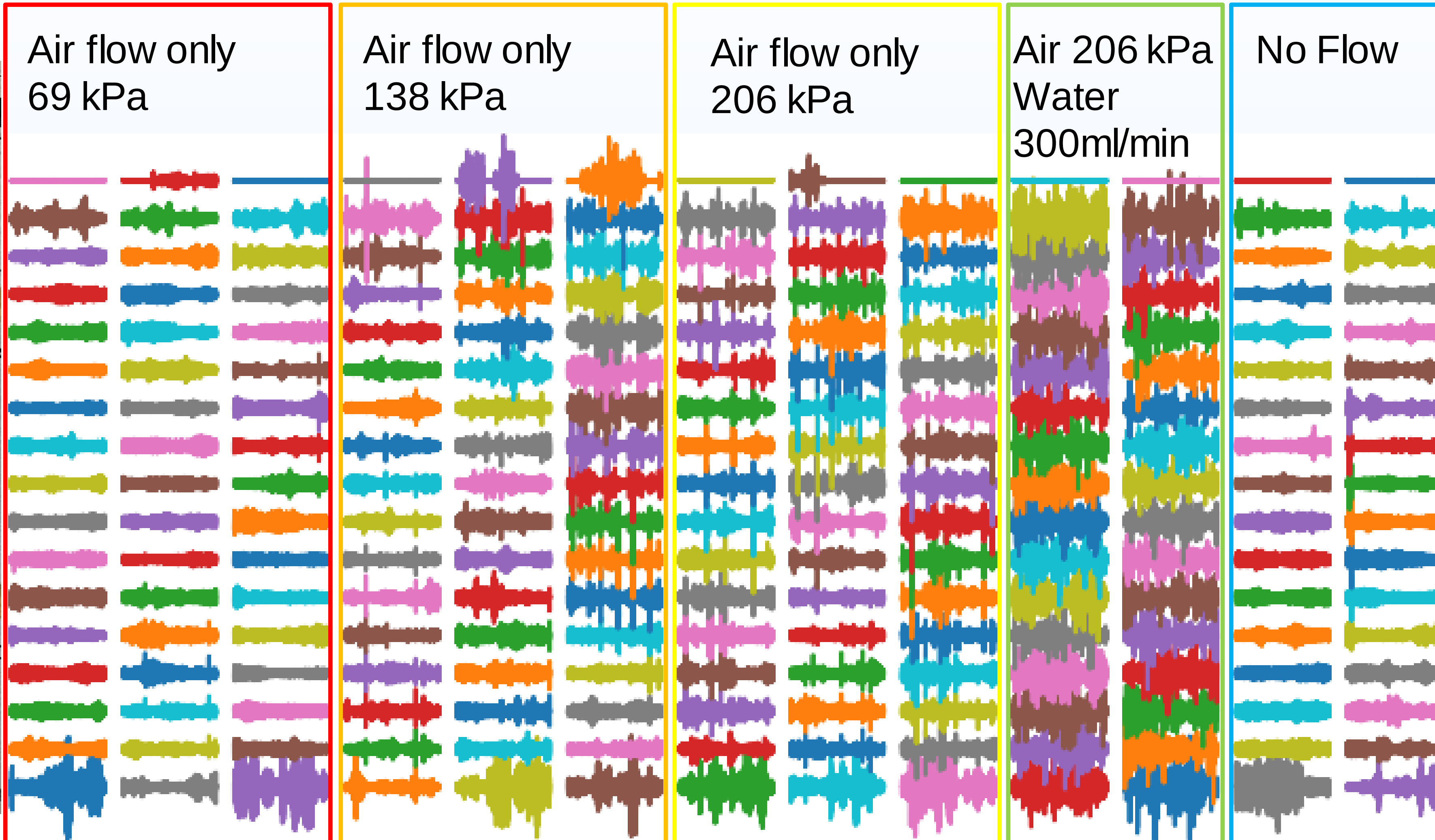


Steel Ball Bearing Dia.	**6 mm**
Diameter of Pipe	**5.1 cm**
Length of Pipe	**76.2 cm**



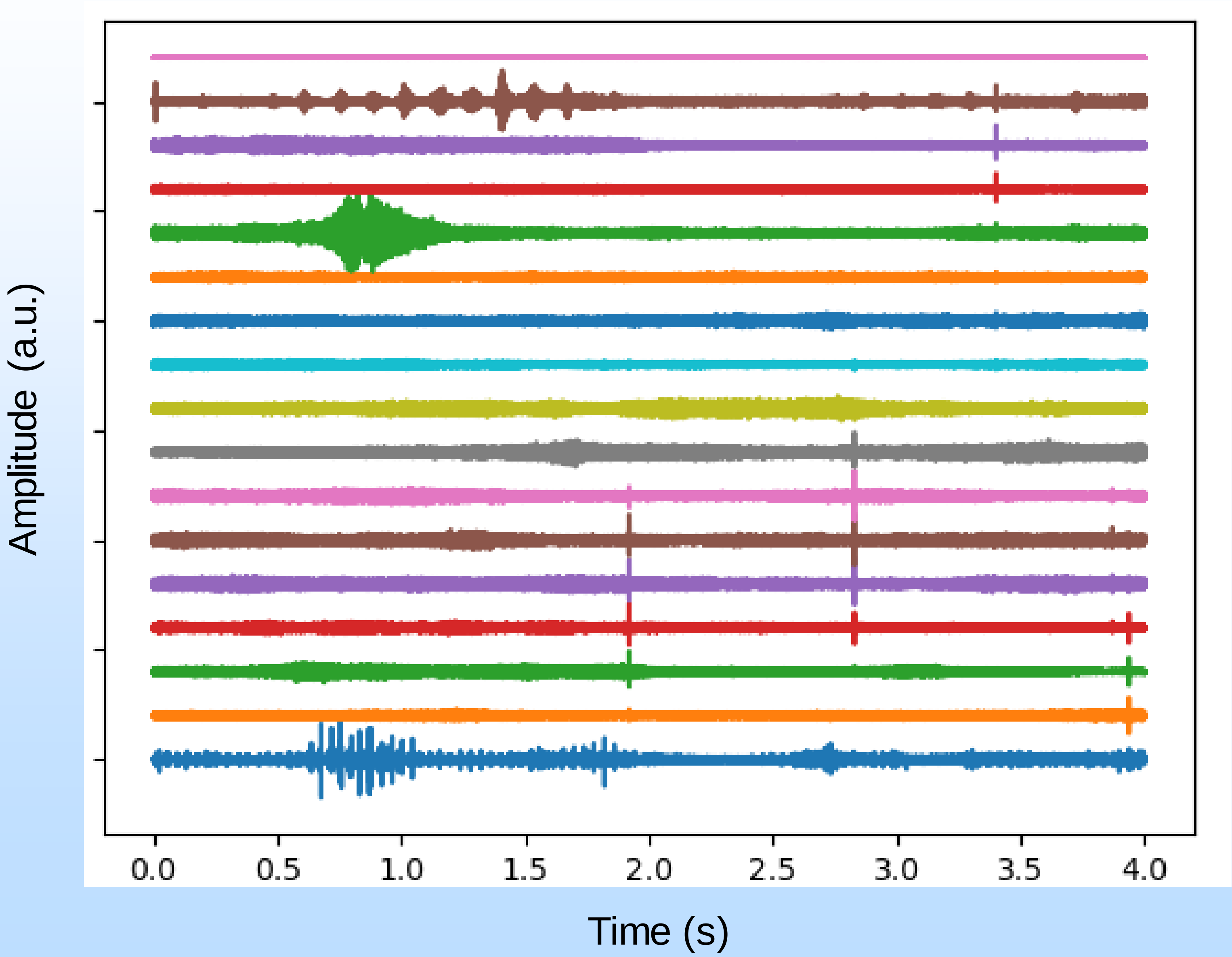


iDAS data



Time (each segment is 20 sec)

iDAS data: 206 kPa



Accomplishments to Date

- Demonstrated TR NEWS on half pipe with successive damage
- Showed that OF-DAS can be used as a sensor in Time Reversal
- Simulated TR on field scales
- Simulated fluid flow through porous media
- Setup experiment of fluid flow through porous media and showed there are signatures related to flow velocity

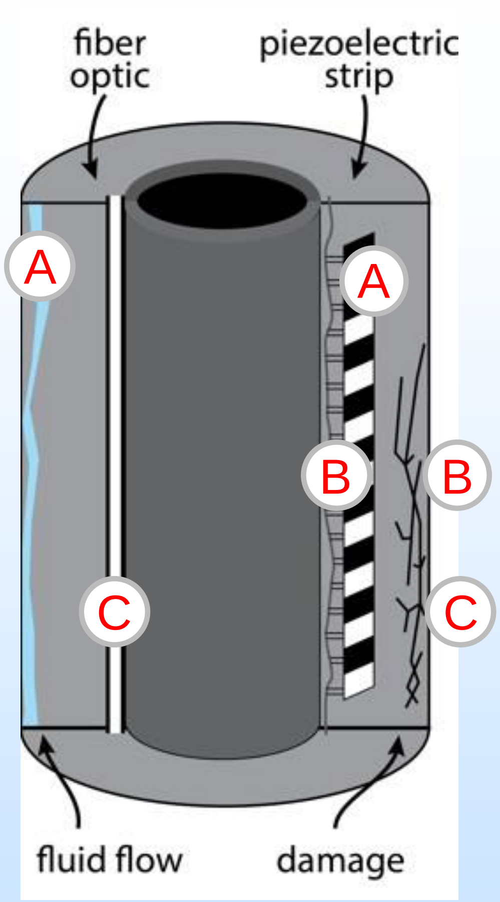
Lessons Learned

- Safety considerations have delayed fluid listening experiments
- Must be careful not to train Machine Learning on other signals, such as pump noise
- Need sufficient reflectors in open hole for time reversal
- Difficult to create damage for evaluation in case wellbore
- Drilling and casing a hole requires months of preparation, particularly for safety

Bibliography

- Dauson, Erin, Carly Donahue, Scott DeWolf, Liwei Hua, Hai Xiao, Lawrence Murdoch, and Paul Johnson. "Damage detection in a laboratory-scale wellbore applying Time Reversal and Nonlinear Elastic Wave Spectroscopy (TR NEWS)." *NDT & E International* 126 (2022): 102573.
- Hua, Liwei, Xuran Zhu, Baokai Cheng, Yang Song, Qi Zhang, Yongji Wu, Lawrence C. Murdoch, Erin R. Dauson, Carly M. Donahue, and Hai Xiao. "Distributed Acoustic Sensing Based on Coherent Microwave Photonics Interferometry." *Sensors*21, no. 20 (2021): 6784.
- Anwar, Ishtiaque, Carey, William, Johnson, Paul and Donahu, Carly "Detecting and characterizing fluid leakage through wellbore flaws using Fiber-Optic Distributed Acoustic Sensing." American Rock Mechanics Association, Conference Proceeding (2022).
- Euser, Bryan, Christopher W. Johnson, Robert Guyer, Esteban Rougier, Carly Michelle Donahue, George Guthrie, Antonio Munjiza, and Paul A. Johnson. "Straining to Learn Permeability." Submitted (2022).
- Boyce, S., Rougier, E., Donahue, C., "Time Reversal Simulations in a Wellbore", In Preparation.

Supplementary Slides



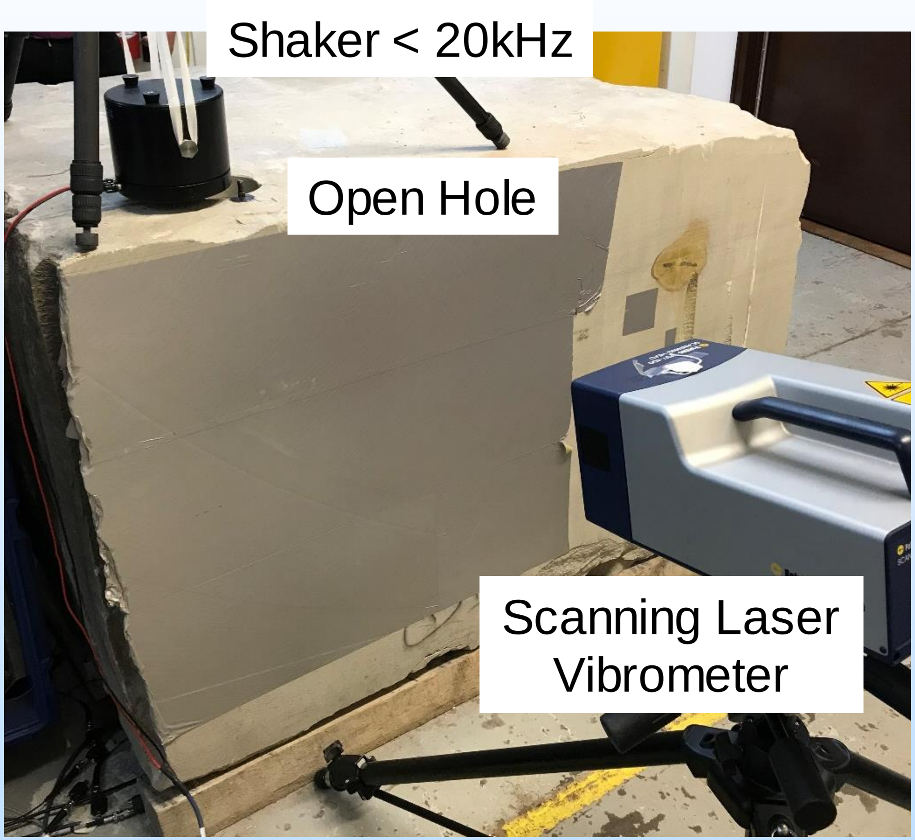
Approach

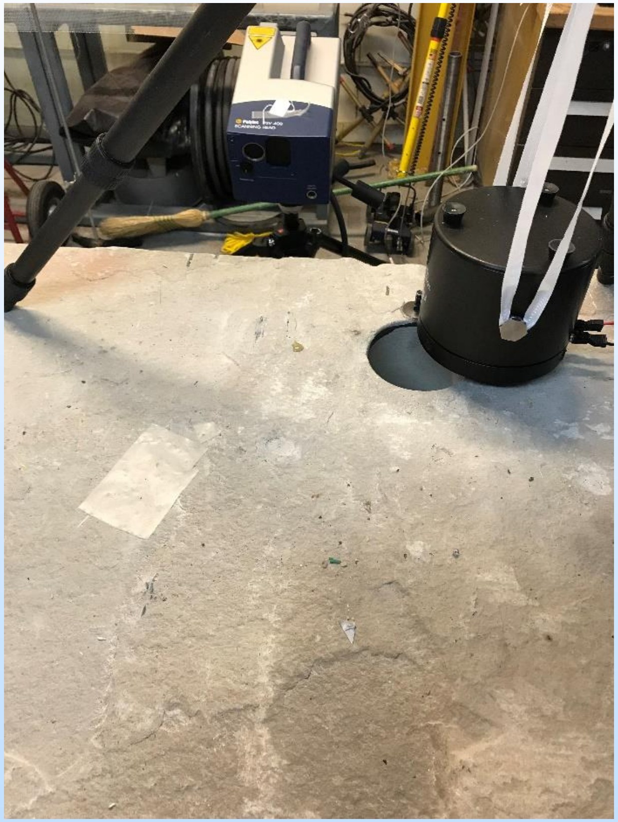
A. **<u>Listen</u> for leakage related signatures in the near-wellbore region using passive acoustic methods (specific objective 1; task 3)**
   i. Identify/discover signatures
   ii. Evaluate ability of embedded acoustic sensors to detect signature(s)
   iii. Develop machine-learning algorithms to extract signature(s) autonomously, including the extraction of signal from noise

B. **<u>Interrogate and locate</u> damage regions with time-reversal nonlinear elasticity wave spectroscopy (TR-NEWS)**
   i. Demonstrate the ability to focus acoustic energy at specific points along a wellbore using time reversal (specific objective 2; task 4)
   ii. Identify/discover nonlinear elastic signatures associated with damage zones and leakage pathways (specific objective 3; task 5)

C. **<u>Monitor</u> strain/stress evolution in near-wellbore region using fiber optic sensing**
   i. Demonstrate the ability of an embedded fiber optic cable to detect strain tied to loss of integrity in the near-wellbore region (specific objective 4; task 6)
   ii. Evaluate the feasibility of measuring distributed strain and acoustic spectra using non-proprietary fiber optic techniques

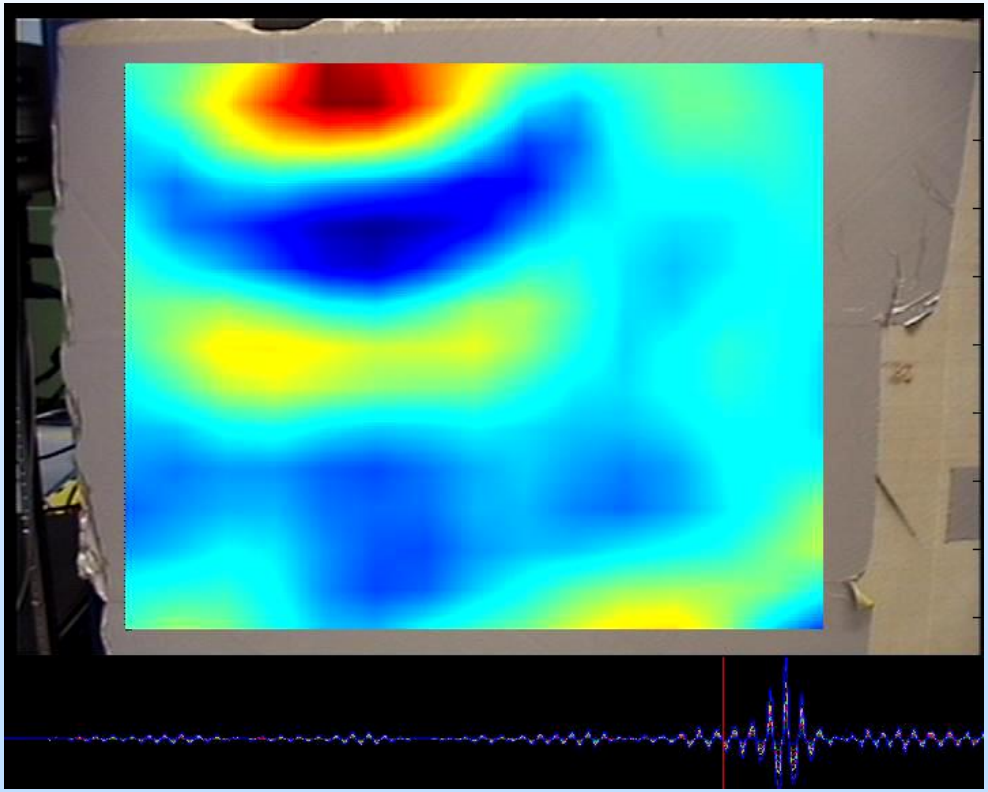
TR Focusing in open wellbore

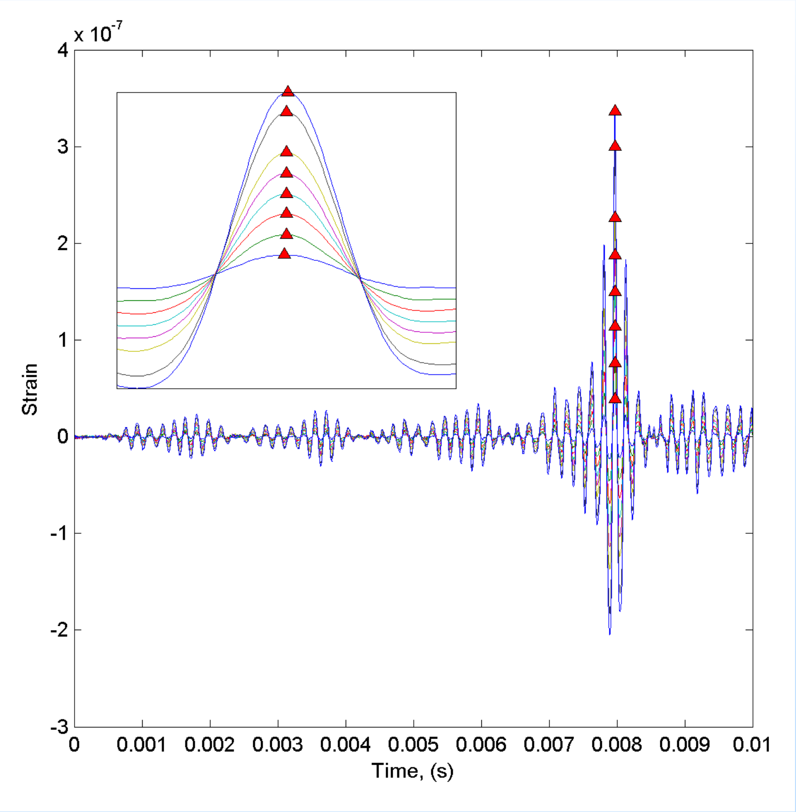




TR Focusing in open wellbore

- Focuses well in time, focuses poorly in space





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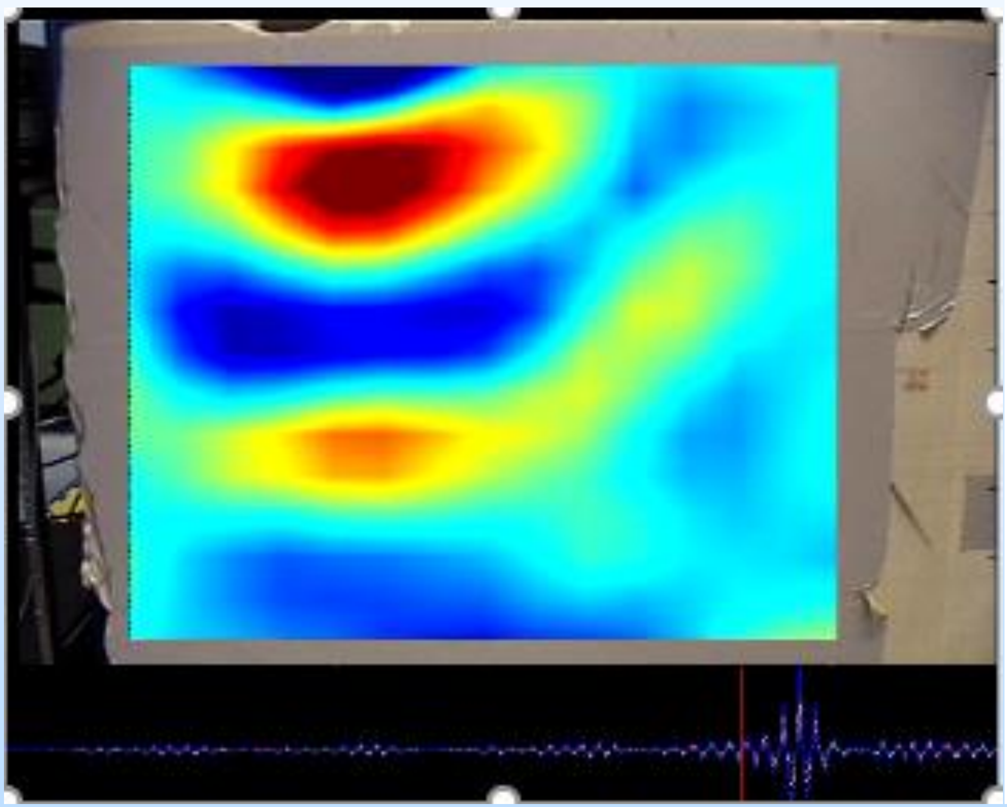

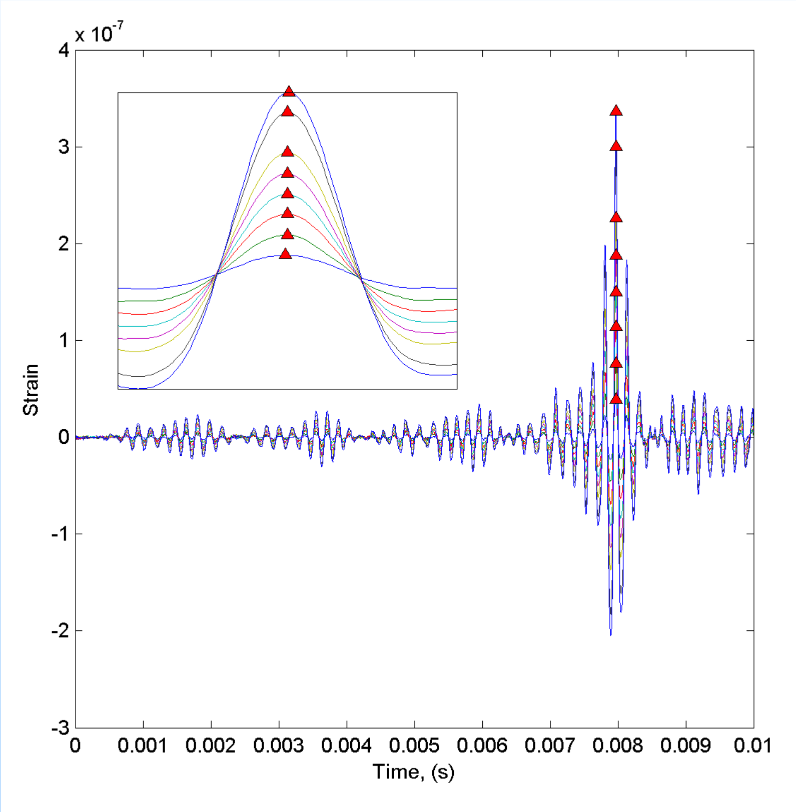

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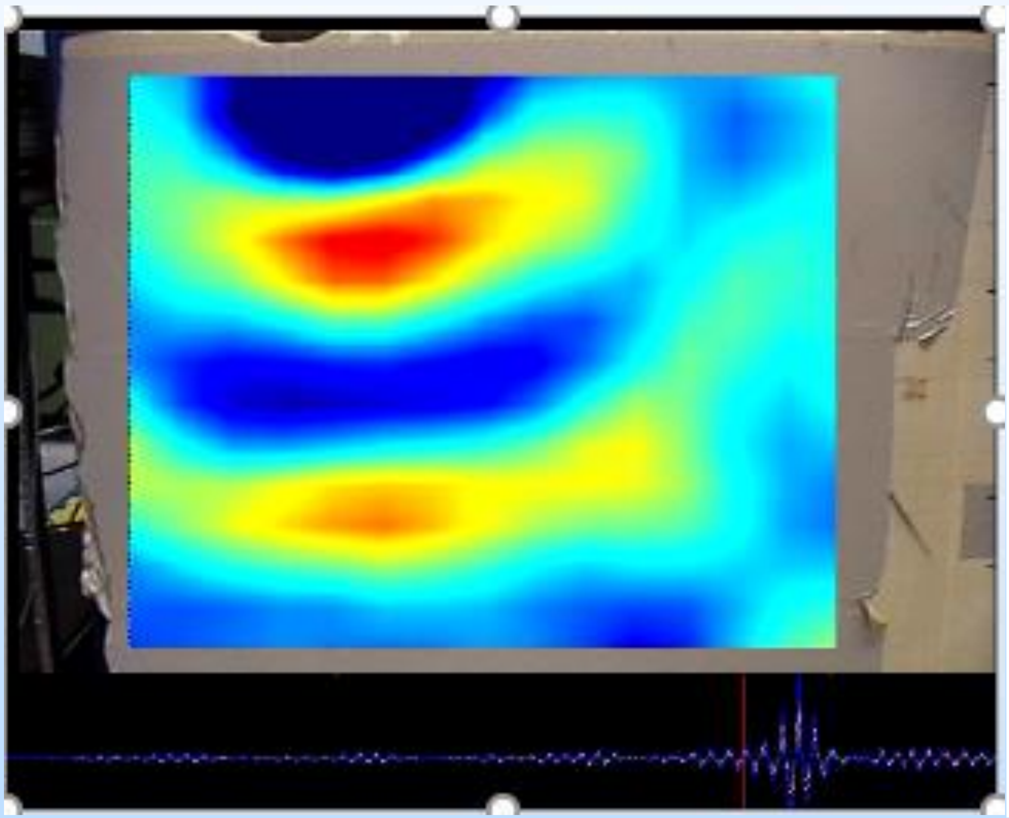

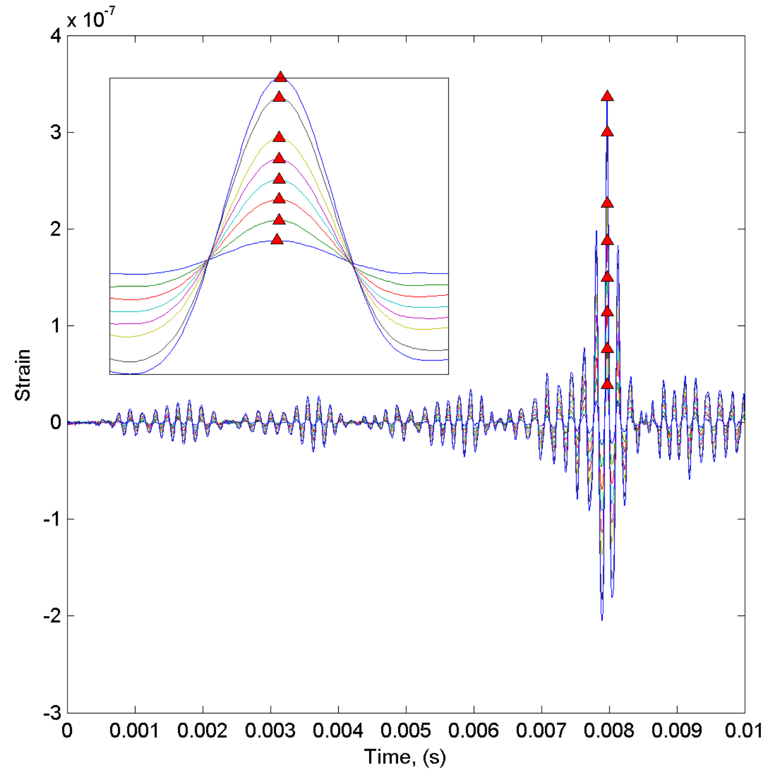

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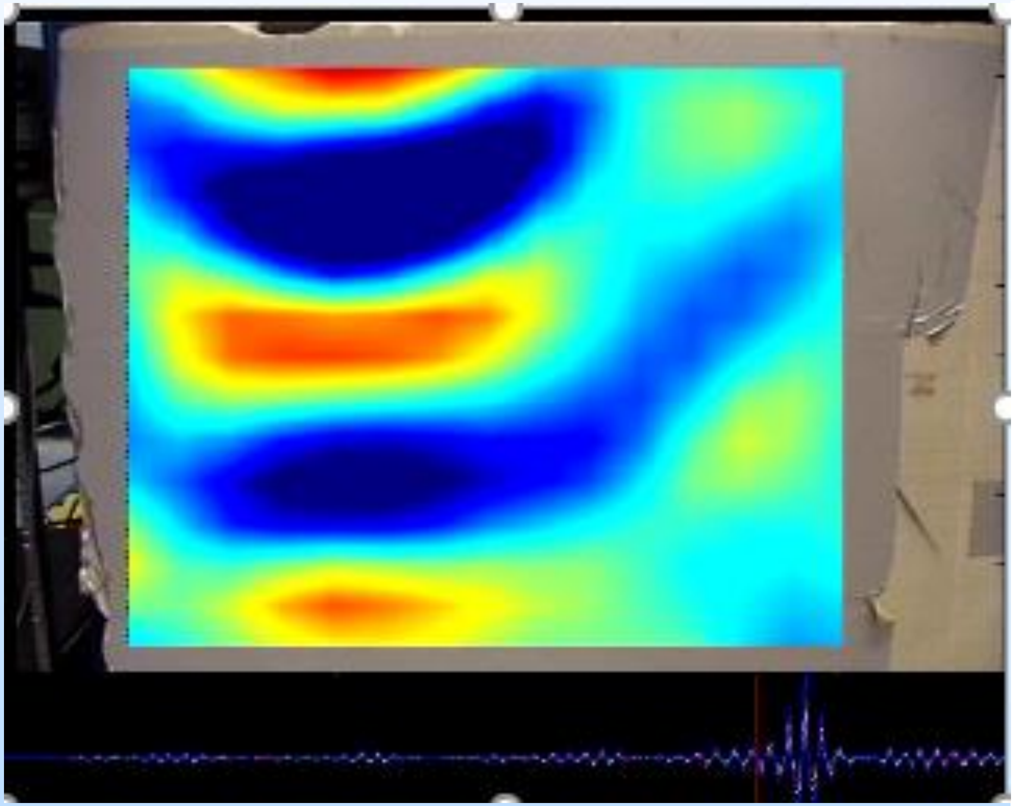

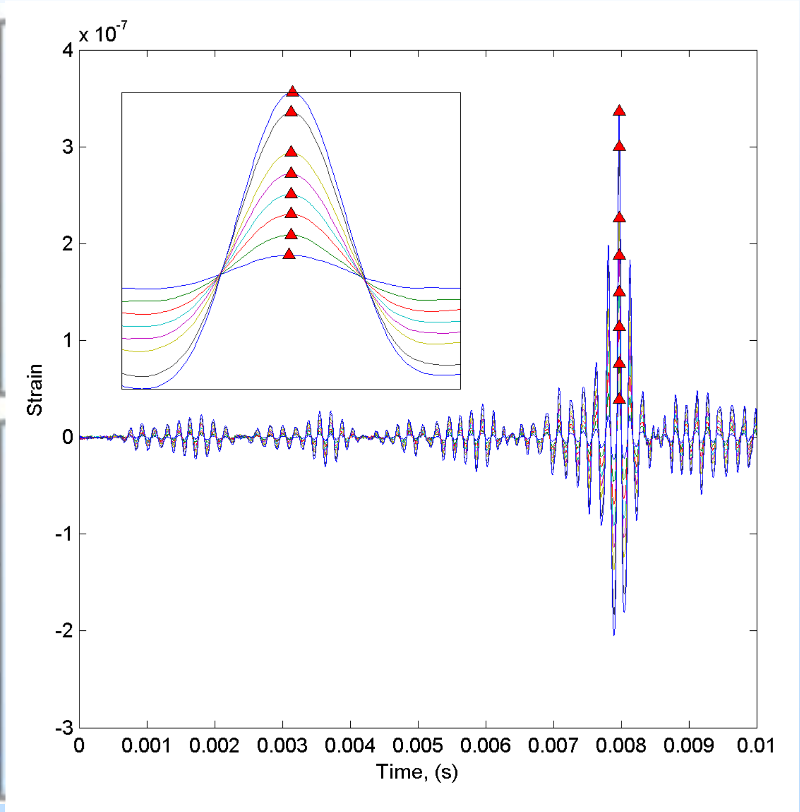

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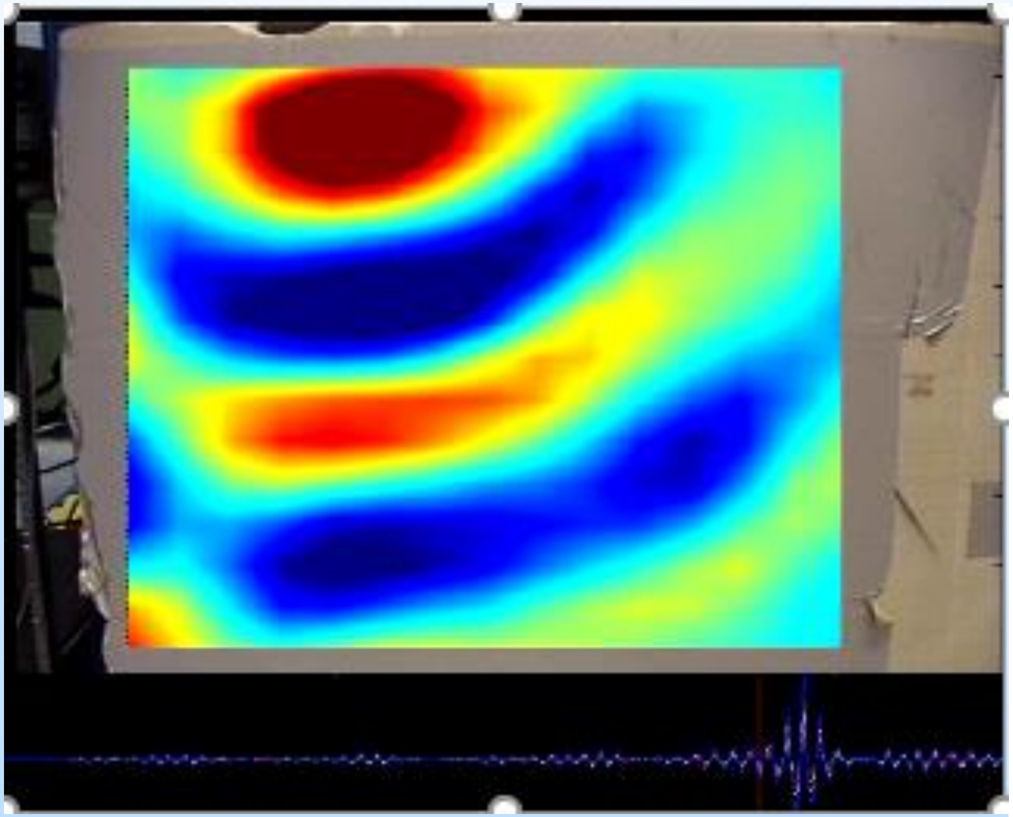

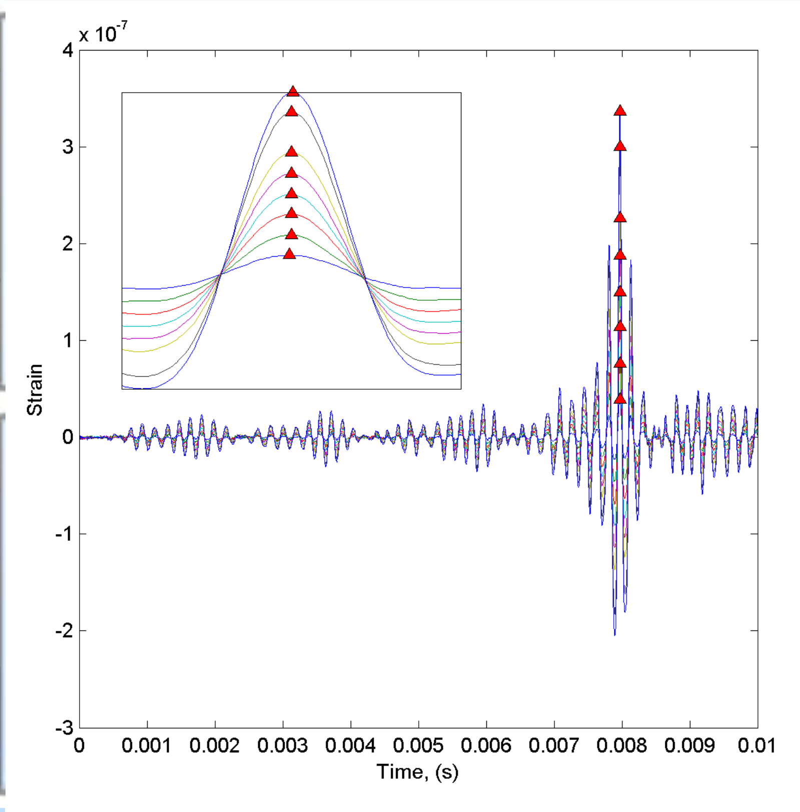

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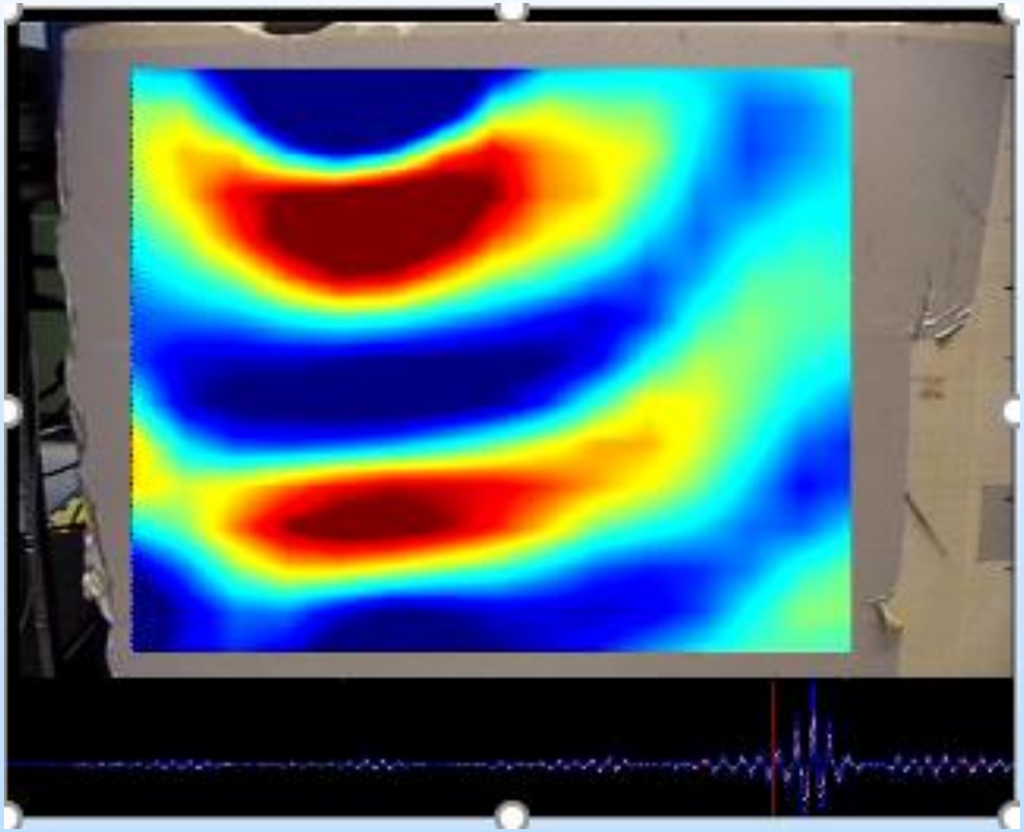
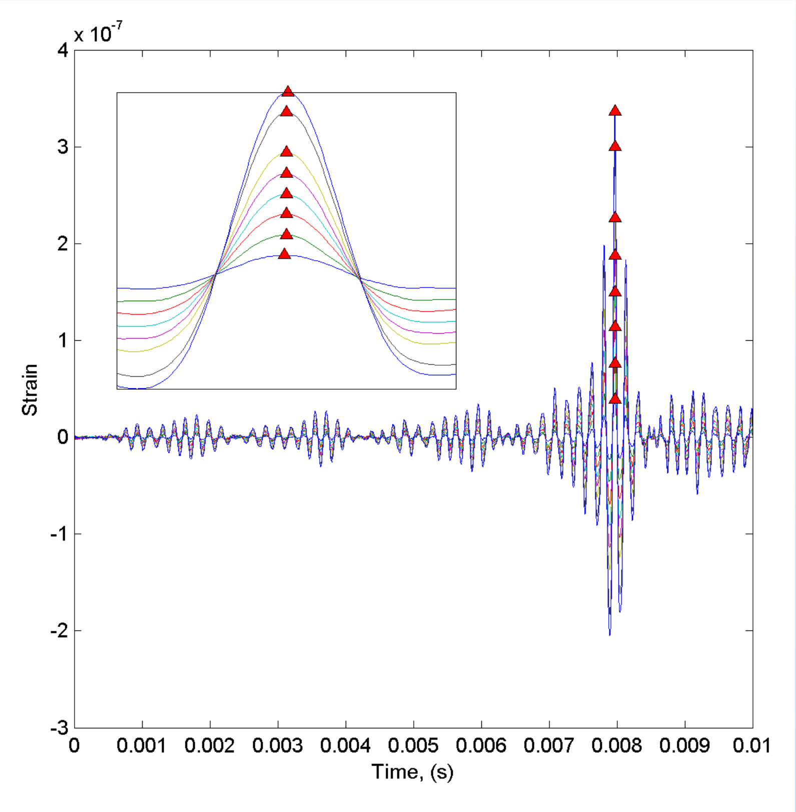
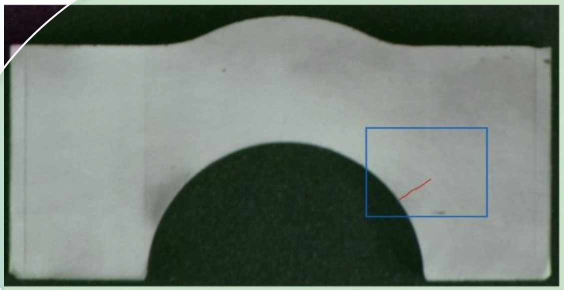
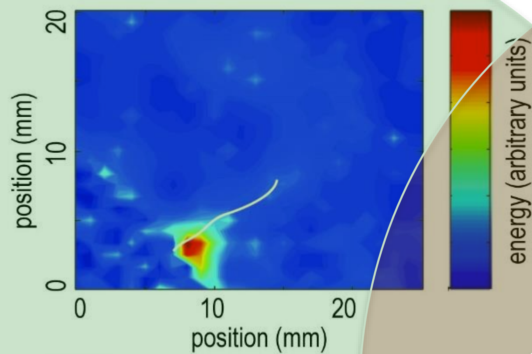




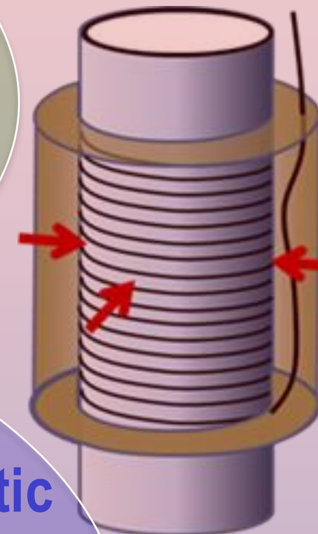
Concepts

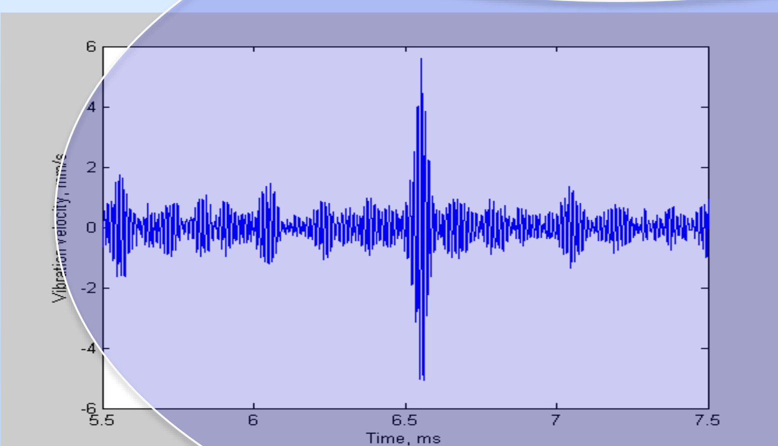




TR NEWS

Fiber optic measure of strain signals





Monitoring acoustic signals with advanced methods—machine learning, waveform coherence….