Acoustic emission diagnostics for superconducting magnets

M. Marchevsky
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Outline

- Mechanical disturbances in superconducting magnets and their connection to premature quenching and training
- What is acoustic emission and how is it related to magnet disturbances?
- Basics of acoustic emission diagnostics: hardware, calibration, and data processing
- Localization of quench origin using AE
- Disturbance spectra characterization using AE
- “Inverting the problem”: using diffuse ultrasound for probing magnet interfaces and quench detection
- Distributed sensing of temperature and strain using acoustic methods

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Elastic energy stored in a superconducting magnet

It takes very little energy to quench a magnet…

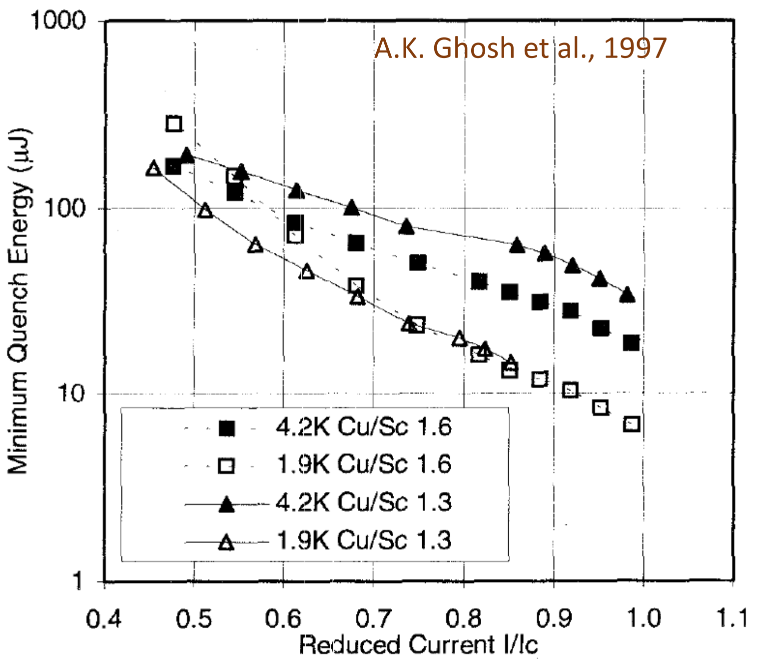


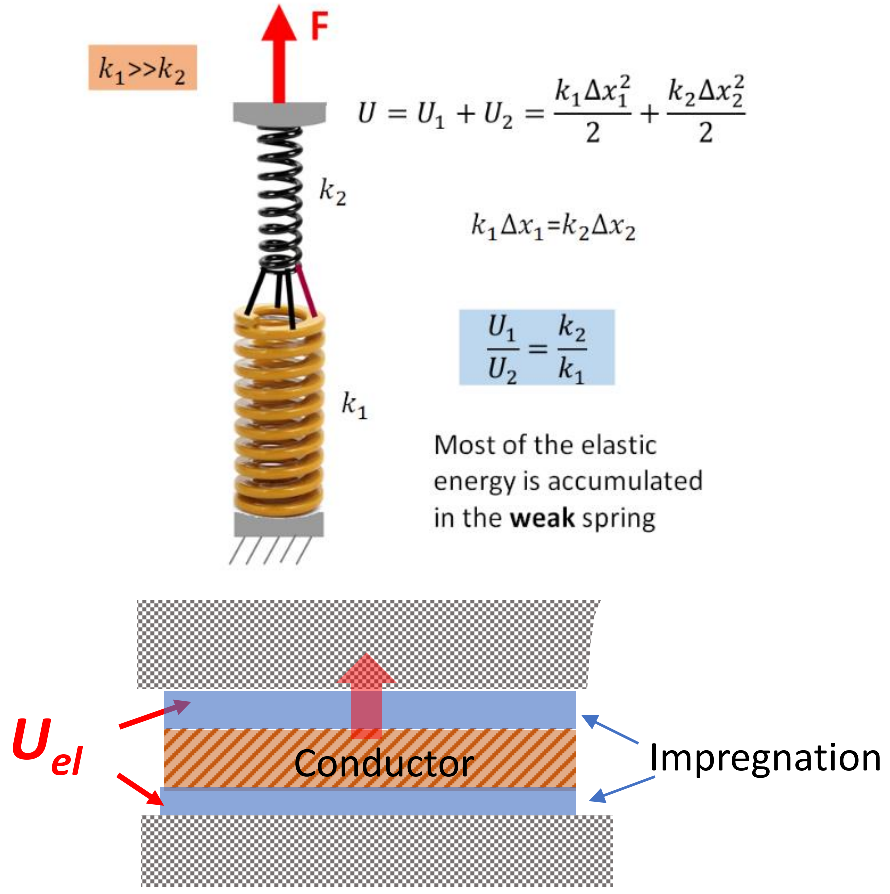
Fig. 3. MQE for two LHC type strands with different Cu/Sc ratio.

10 mJ is the kinetic energy of a staple dropped from a 3 cm height …and it is **~10[11] -10[12] times smaller** than the stored EM energy of a typical accelerator magnet!

Due to the action of Lorentz force F_L=I×B, thermal and pre-loading stress, **elastic energy is stored in the magnet** and distributed between its structural elements.

The elastic energy is proportional to the strain in a square, or magnet current in the power 4:

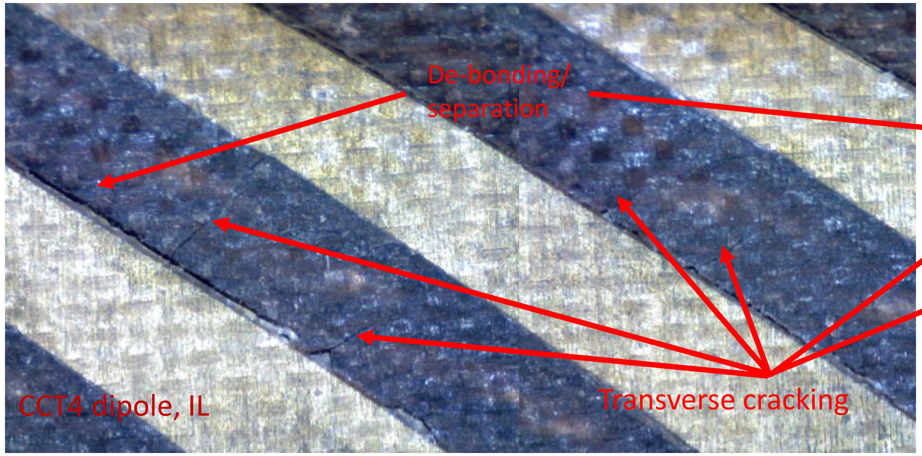
$$E_{el} \sim I_{mag}^4$$

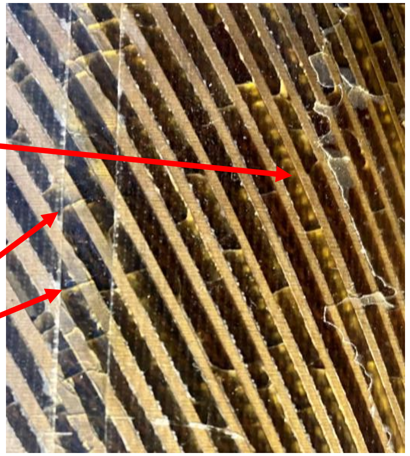


Impregnation material has a lower elastic modulus than the conductor, so it stores a significant fraction of that elastic energy…

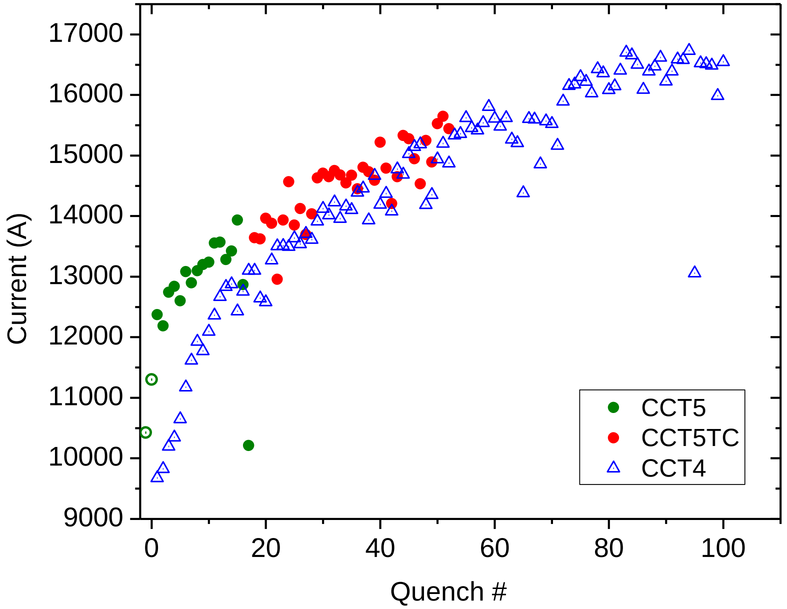
Elastic energy release causes quenching and training

Mechanical energy released: crack and de-bonding in CCT coils





Images by D. Arbelaez



Training plot of the CFT magnets tested at LBNL

- ➢ See the talk by P. Ferracin

The stored energy can be released spontaneously, causing premature magnet quenching and training…

How can we experimentally study these phenomena?
Can we associate a quench with some specific energy-release event?
Can we predict and understand magnet training and quench memory?

<u>These are the key questions for the superconducting magnet development program</u>

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Acoustic emission and its sources in magnets

- Release of elastic energy caused acoustic emission

"An introduction to acoustic emission", C. B. Scruby 1987 *J. Phys. E: Sci. Instrum.* **20** 946

Transient events	Continuous perturbations
Mechanical • Cracking / fracture of epoxy, interfacial de-bonding • Sudden mechanical motion of conductor or a structural part Known as **precursors** for premature quenching and training! Electromagnetic -> Mechanical • Flux jump, as current re-distribution in the cable leads to the local variation of the electromagnetic force	• Vibrations of coils, shell, and support structures) • Background noise (helium boiling, pumps, etc.)

- **Quench development** leads to a local thermal expansion and change in the local stress which ***may*** lead to acoustic emission. However, magnets that are conductor-limited are near-quiet acoustically at quench.

- "Acoustic emission from NbTi superconductors during flux jump", G. Pasztor and C. Schmidt, Cryogenics 19, 608 (1979)
- "Sources of acoustic emission in superconducting magnets", O. Tsukamoto and Y. Iwasa, J. Appl. Phys. 54, 997 (1983)

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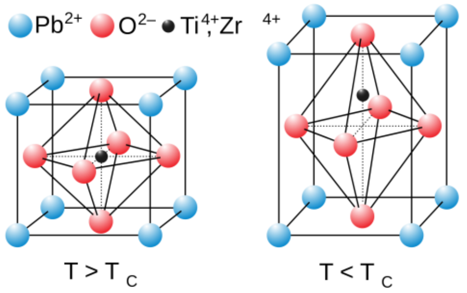
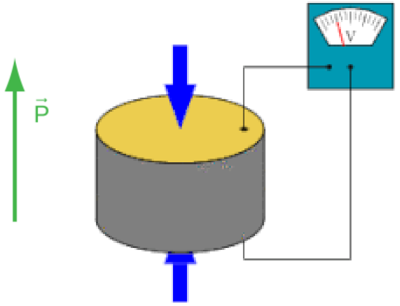
Piezoelectric sensors and transducers

- Piezoelectric effect





Source: Wikipedia

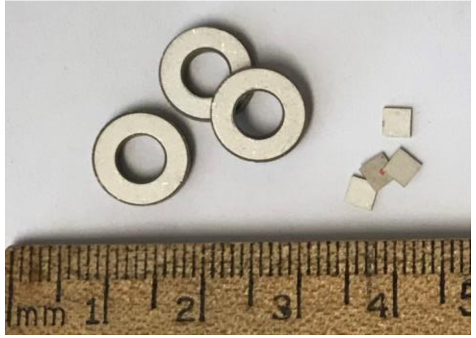
PZT $T_c \sim$ 250-300 ^{0}C

Lead Zirconate Titanate ($Pb[Zr_xTi_{1-x}]O_3$ with $0 \leq x \leq 1$)

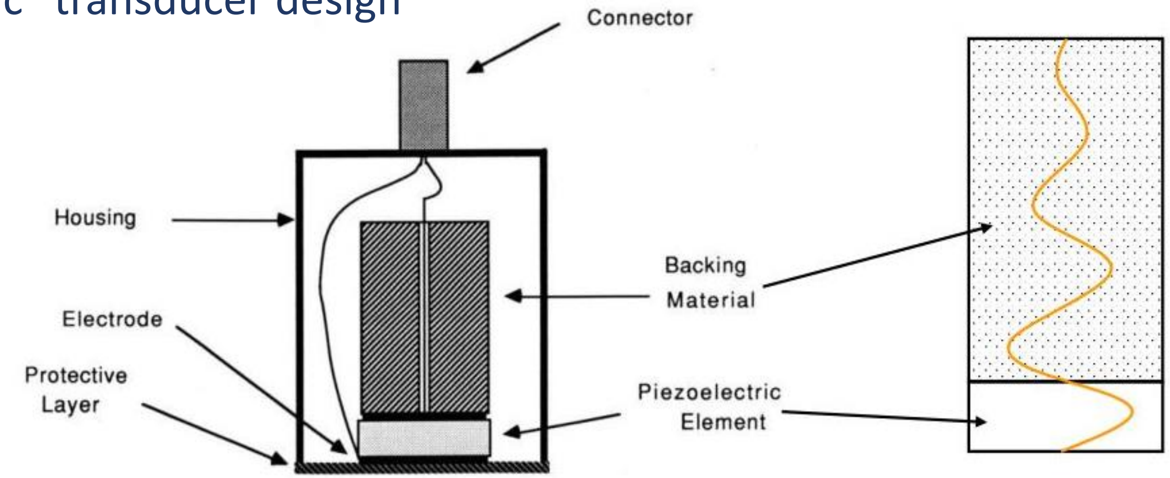
$$\frac{\Delta x}{x} = d_{33}E$$ $d_{33} \sim$ 1-3 x 10^{-10} m/V

Piezo-coefficient typically decreases ~3-5 times at liquid helium temperature

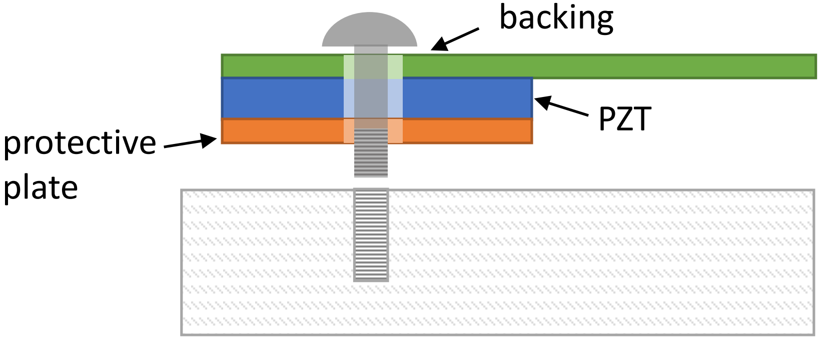
- Commercial PZT elements

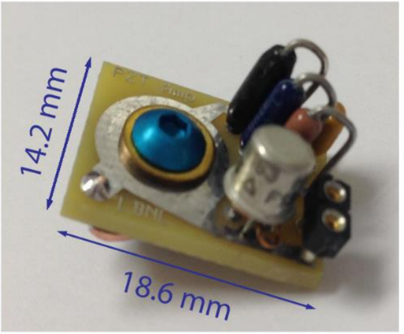


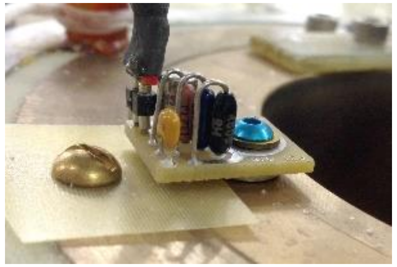
- "Classic" transducer design



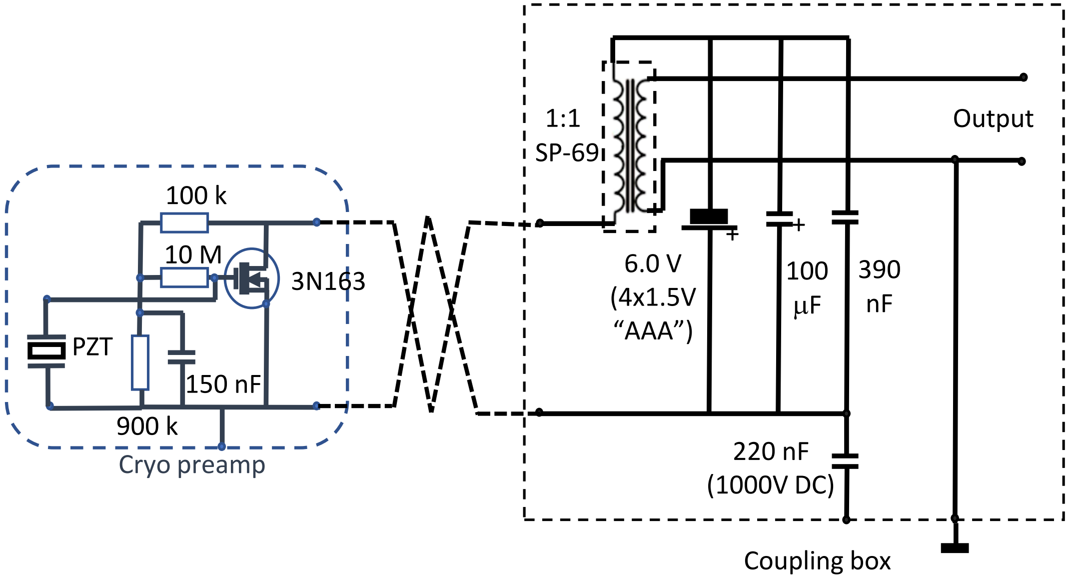
- Cryogenic AE sensor (LBNL)







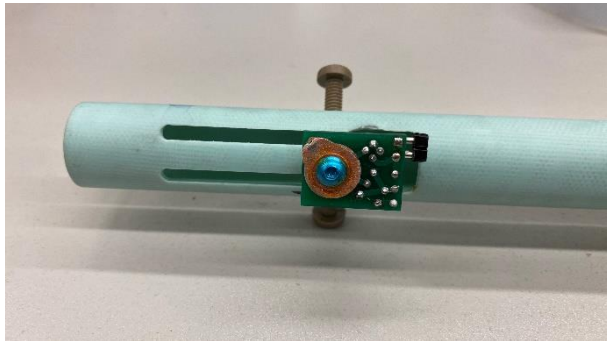
- Cryogenic pre-amplifier



1-300 kHz usable bandwidth

~ 6 mW of dissipated power

- Mounts for sensor installation in the magnet bore



- Data acquisition

NI PXI-6123

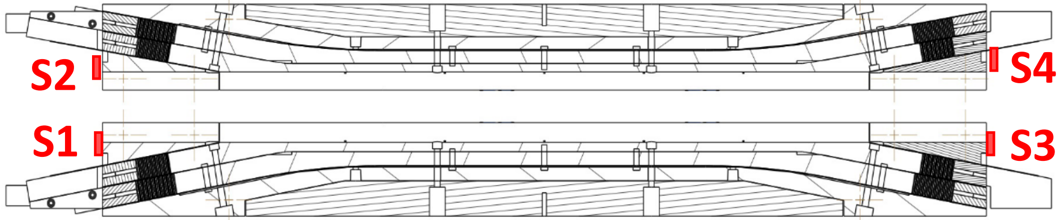
Picosope 4824

Triggered acquisition around the quench or
Streamed continuous acquisition at 0.5-1 MHz

M. Marchevsky, G. Sabbi, H. Bajas, S. Gourlay, *Cryogenics* 69, 50 (2015), DOI: 10.1016/j.cryogenics.2015.03.005

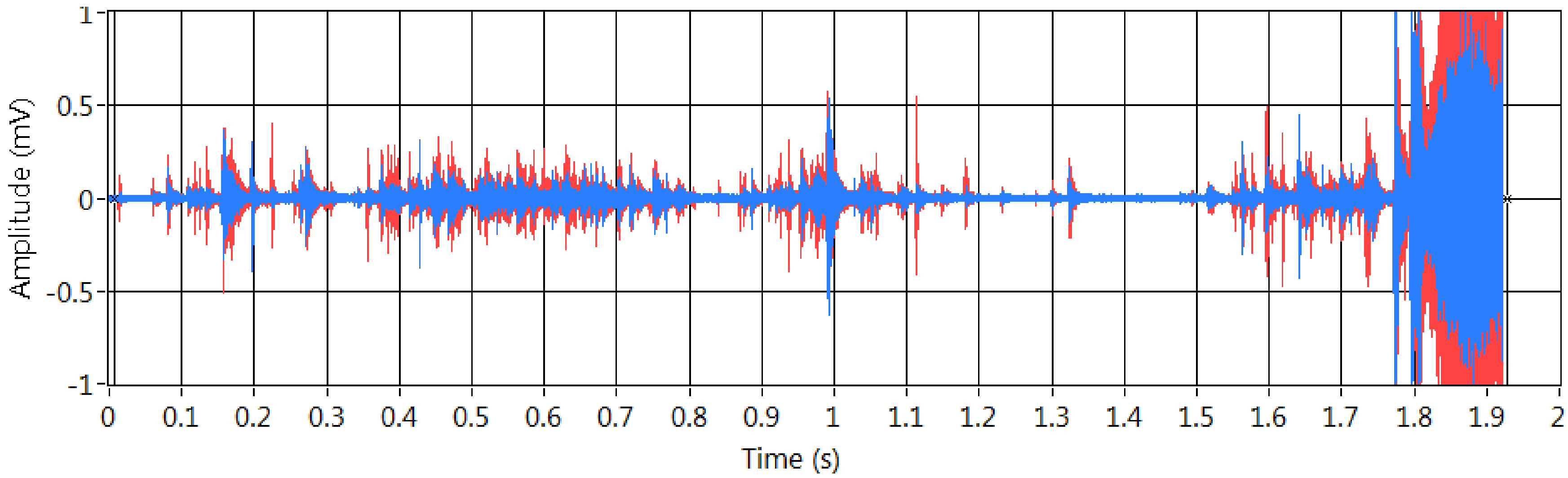
Nb_3Sn dipole quench sound example

HD3 dipole



Quench A76 at 16042 A

Sensors are installed at the ends of each 1-m long dipole coil. Multiple acoustic events are recorded during ramping



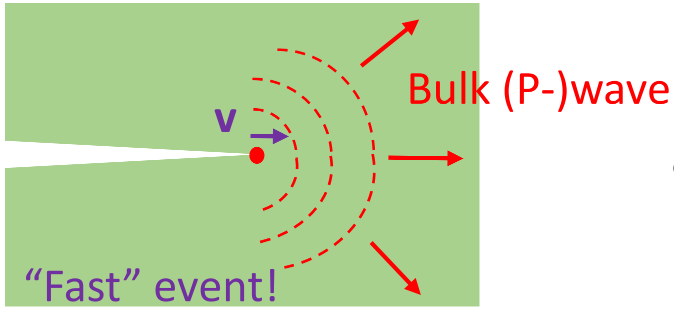
Original sound slowed down 10 times

Sensor S1 (blue) -> Left sound channel
Sensor S4 (red) -> Right sound channel

Typically we observe 10^3-10^4 AE events per each current ramp

Various acoustic wave modes can be generated simultaneously

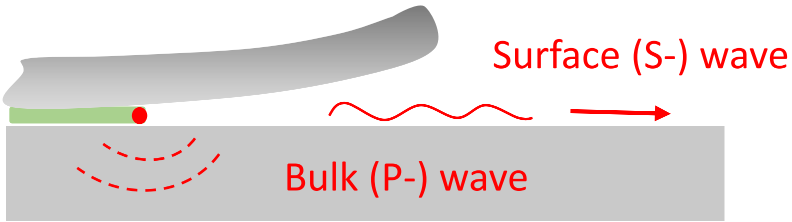
- Crack development



$$c_p = \sqrt{\frac{K + \frac{4}{3}G}{\rho}}$$

K is the bulk modulus
G is the shear modulus
ρ is the density

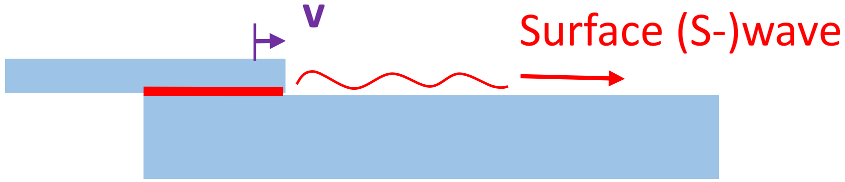
- Interfacial de-bonding



$$c_s = \sqrt{\frac{G}{\rho}}$$

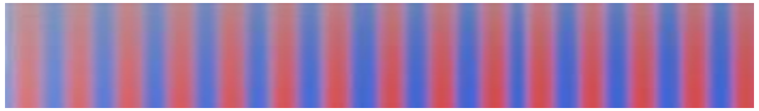
Acoustic waves travel in the bulk and along separating surfaces

- Slip-stick motion

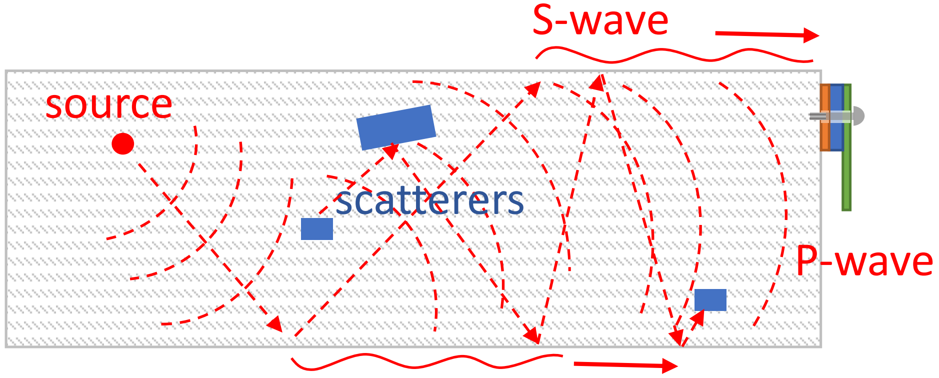


“Slow” event!

- Structural vibration



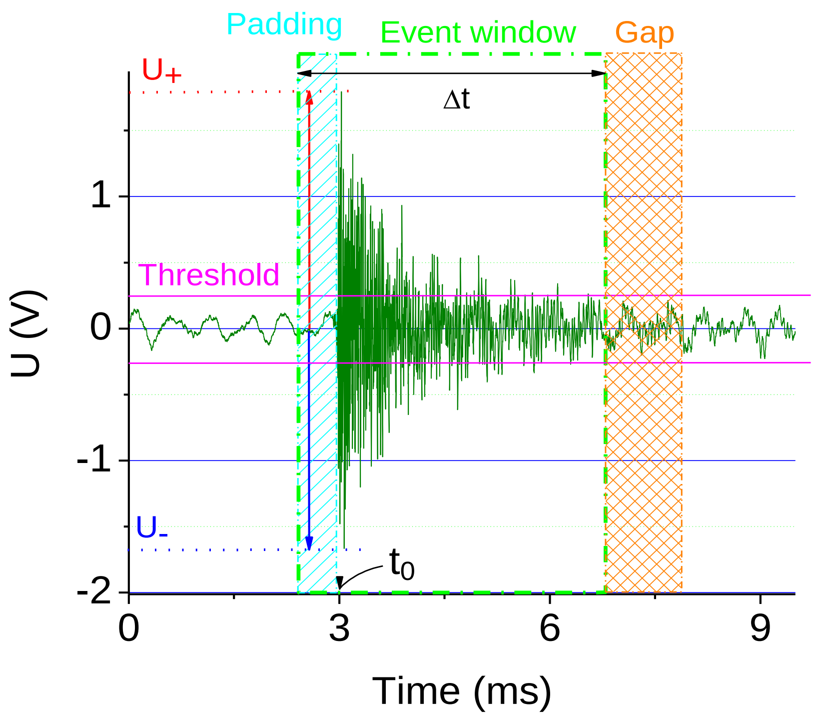
Low-frequency bulk structural resonances



Multiple reflections and mode conversions! The wave “diffuses” through the complex propagation medium

AE event separation. Features of a typical transient AE signal.

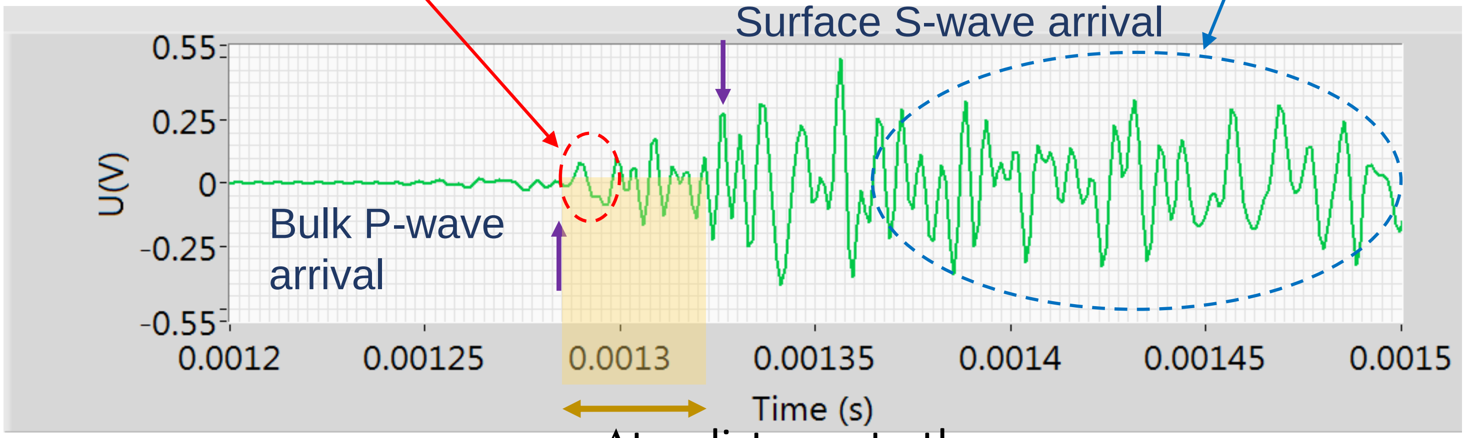
Individual “event” separation



Event threshold, padding, duration (window), and the gap between consecutive events are used by the script that separates events from the recorded data stream

Information about the event source (?)

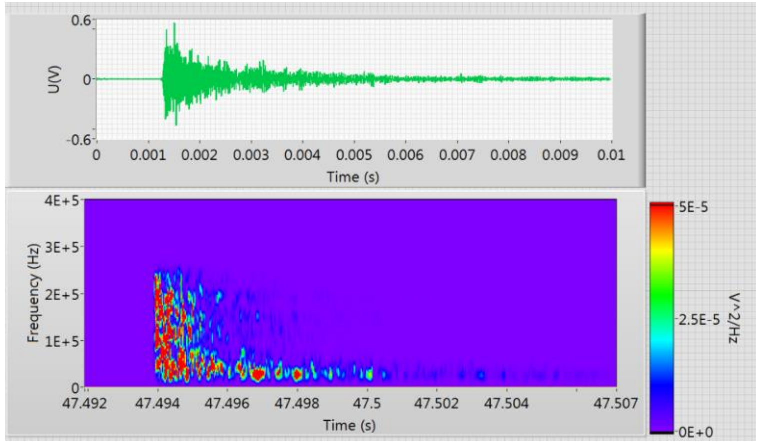
“Coda” is <u>uniquely defined</u> by the distribution of scatters in the propagation medium and the sound velocity



Δt ~ distance to the source

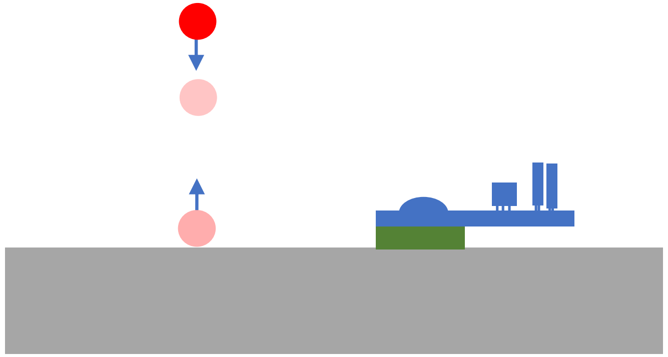
The bulk P-wave travels faster and reaches the AE sensor first

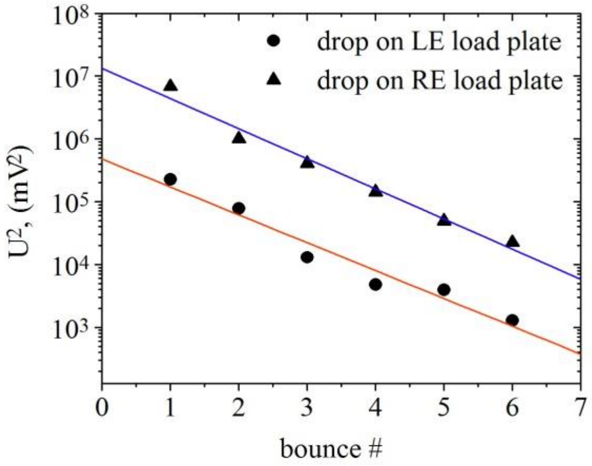
The surface S-wave travels slower and arrives later



Frequency response

➢ AE voltage in a square in known to be proportional to the energy released in the transient event. This can be verified in a simple experiment





A metal ball dropped on the magnet surface normally bounces several times, each time reaching progressively lower height h_n, until all its energy has been transferred to the structure. Assuming same energy fraction is transferred at every consecutive bounce, E_n for the n-*th* bounce can be expressed as $E_n = E_0 \alpha^n$

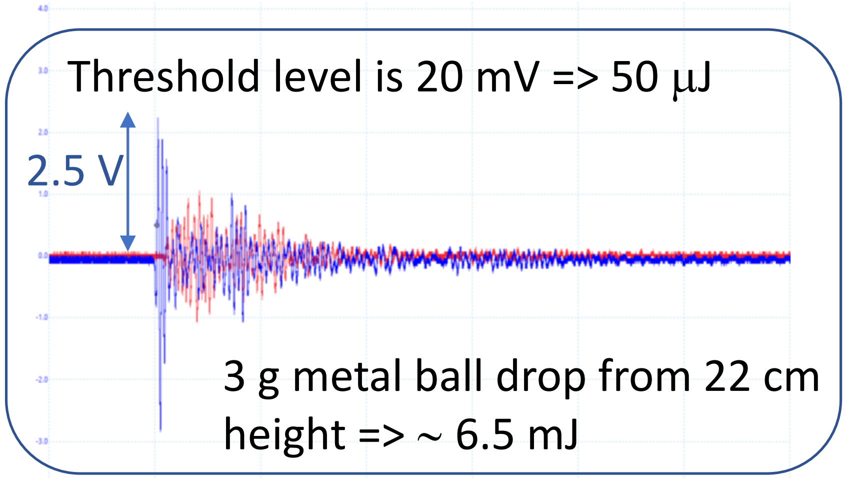
➢ Attenuation of the acoustic wave in the material follows a universal behavior: $A(x) = A_0 e^{-\beta x}$

Using two sensors at the opposite ends of the magnet one can estimate energy release as $E_{AE} = \gamma U_i U_j$, where γ is a universal scaling factor combining sensor sensitivities and the medium attenuation coefficient, and U_i and U_j are the acoustic sensor voltages

Event energy:

$$E = \int_{t_0}^{t_0+\Delta t} U^2(t)dt$$

(integrated over event window)



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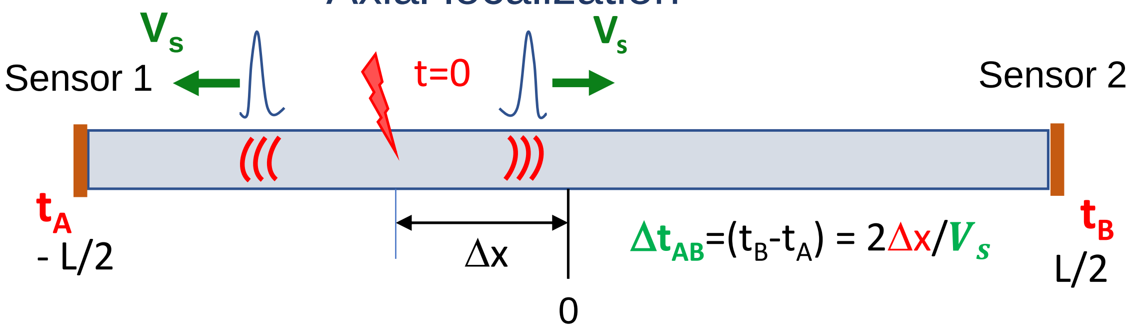
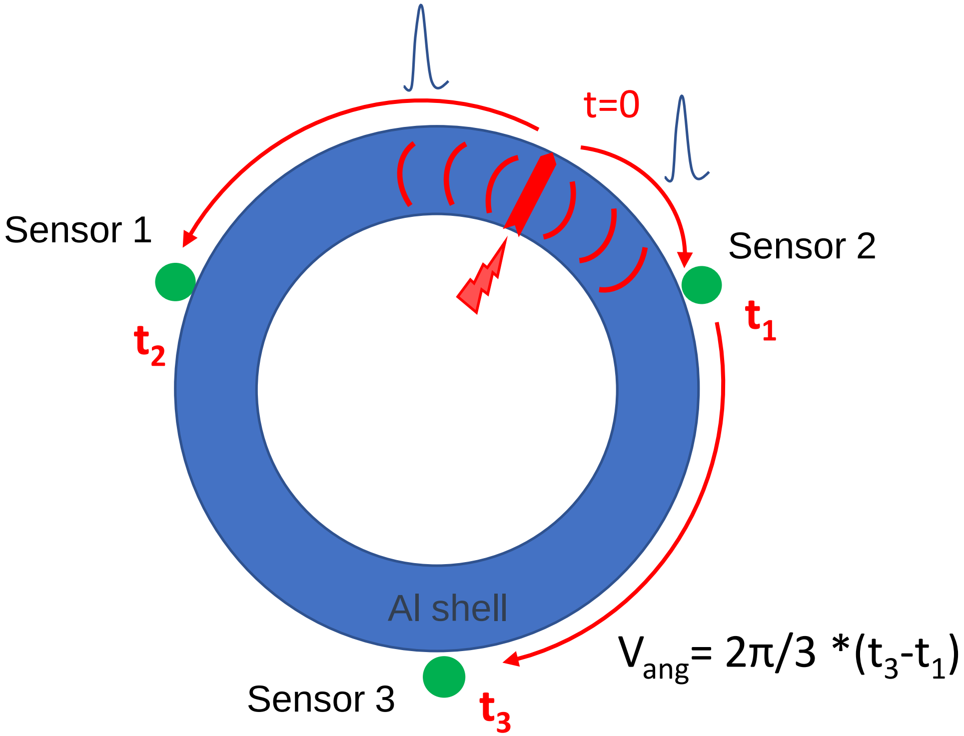
Axial and azimuthal quench localization

We rely on bulk (P-) waves for localization purposes. This implies that the very onset of the acoustic signal should be detected, and improving the signal/noise ratio is essential.

Axial localization



Angular localization

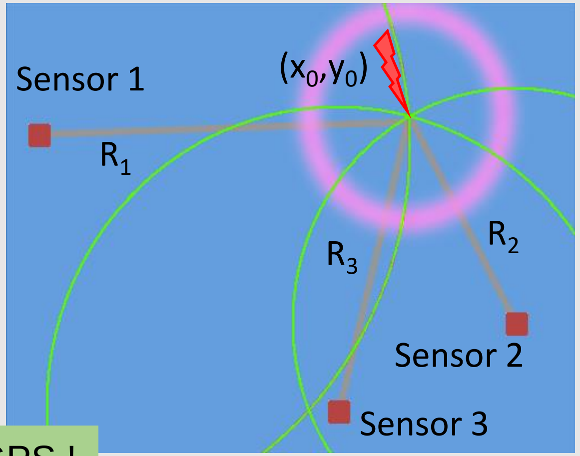


On a cylindrical surface localization using the quasi-2D approach can be sufficiently accurate

2D (3D) localization

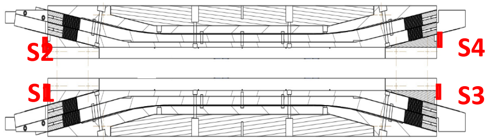
2D

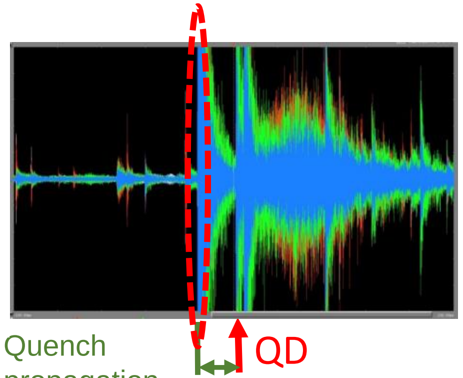
$$\begin{cases} (x_0-x_1)^2+(y_0-y_1)^2=R_1^2 \\ (x_0-x_2)^2+(y_0-y_2)^2=R_2^2 \\ (x_0-x_3)^2+(y_0-y_3)^2=R_3^2 \\ |R_1-R_2|=V_s\Delta t_{12} \\ |R_1-R_3|=V_s\Delta t_{13} \end{cases}$$

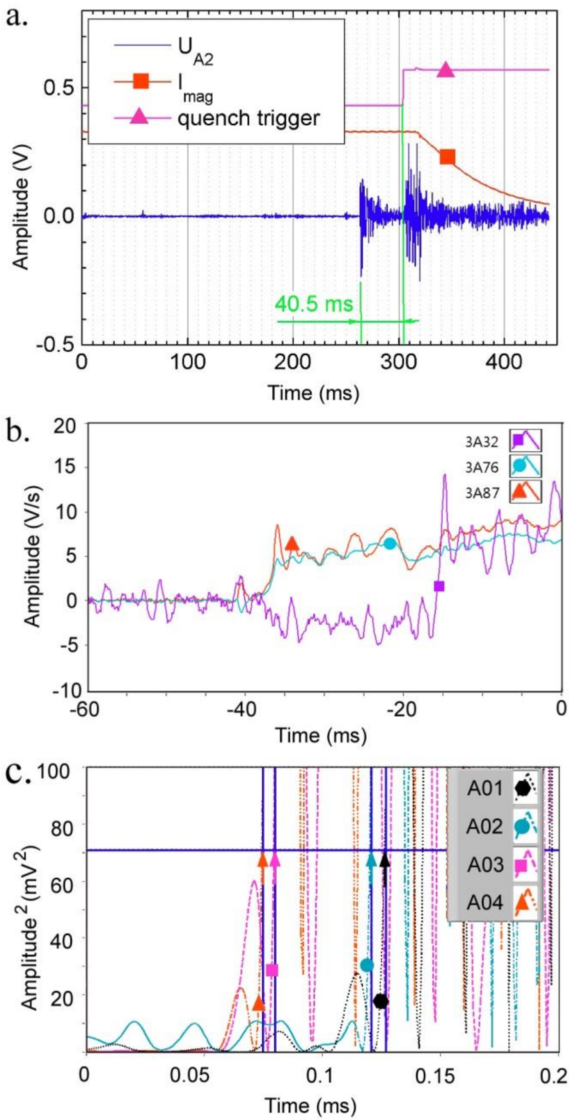


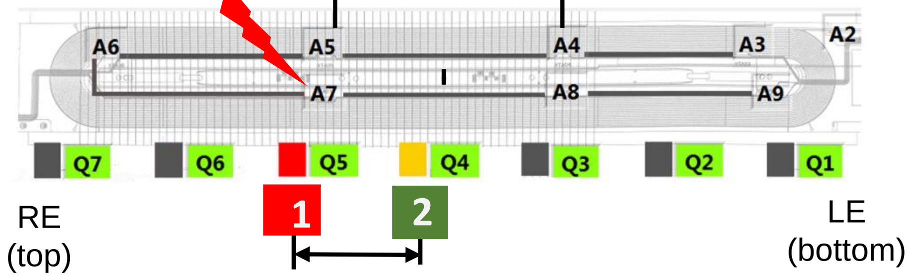
Think GPS !

2D acoustic quench localization in HD3 dipole





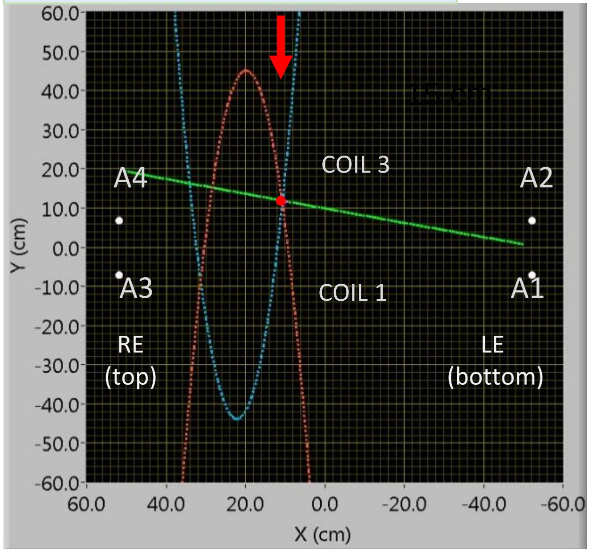




t_1	0.075 ms
t_2	0.08 ms
t_3	0.121 ms
t_4	0.127 ms

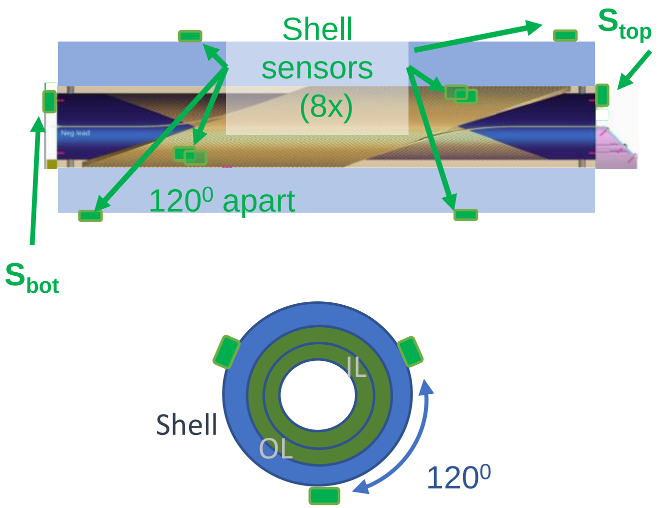
v_s= 4.3 km/s

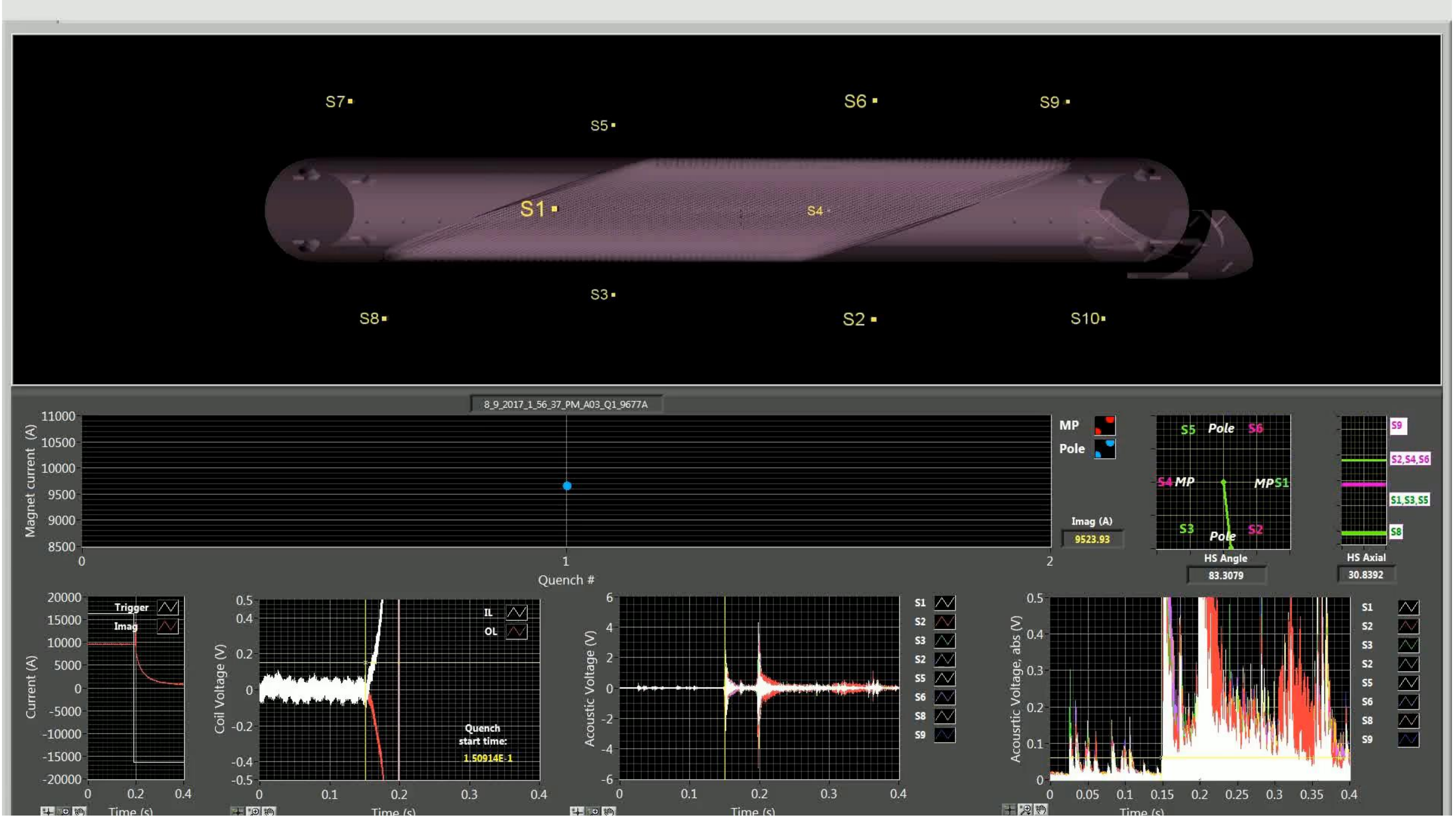
X= **+10 cm** (towards RE)



Typically voltage and acoustic data yield quench locations within ~5-10 cm from each other

Quench localization in CCT4 dipole

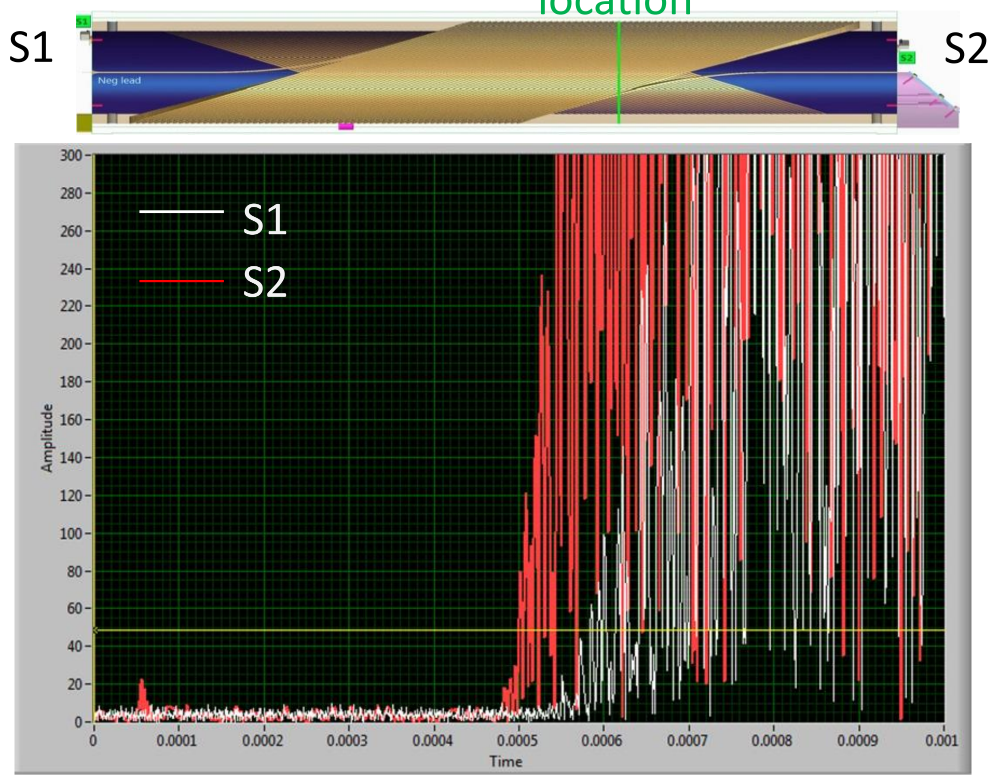




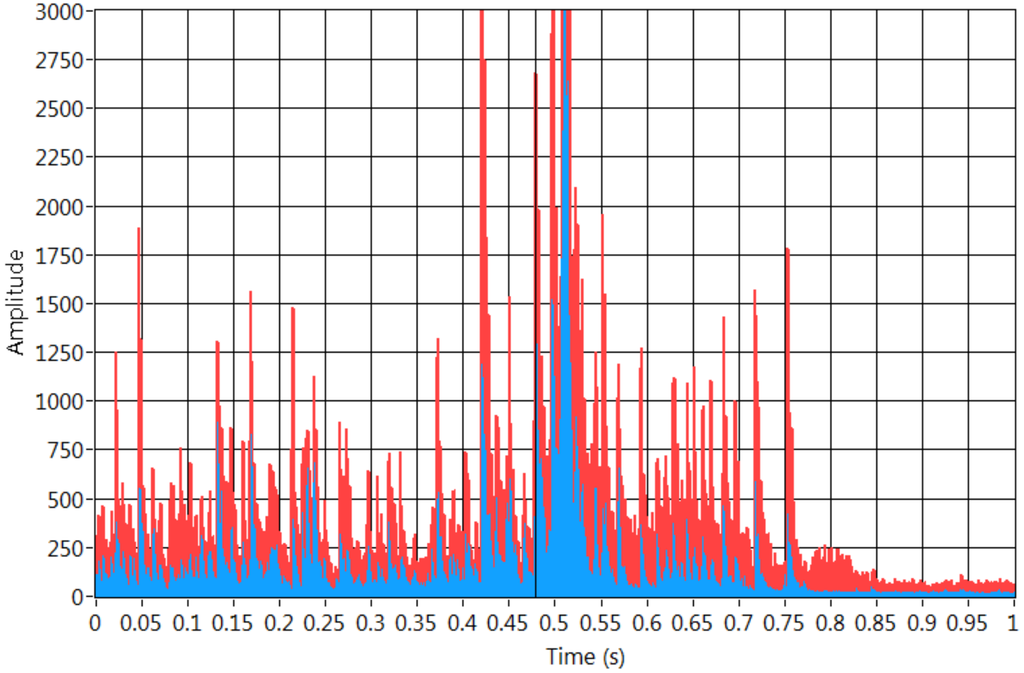
Sound slowed down 10 times

Localized vs distributed AE sources

A transient event: localization is possible



A “continuous” event…. No localization



- “Crude” localization – relies on AE signal thresholding
- “Advanced” localization uses various techniques to improve SNR: bandpass filtering, wavelet filtering, “Akaike information criterion”, etc.

For example: *Al-Jumaili et al., “Acoustic emission source location in complex structures using full automatic delta T mapping technique”, Mechanical Systems and Signal Processing, V. 72–73, pp 513-524 (2016)*

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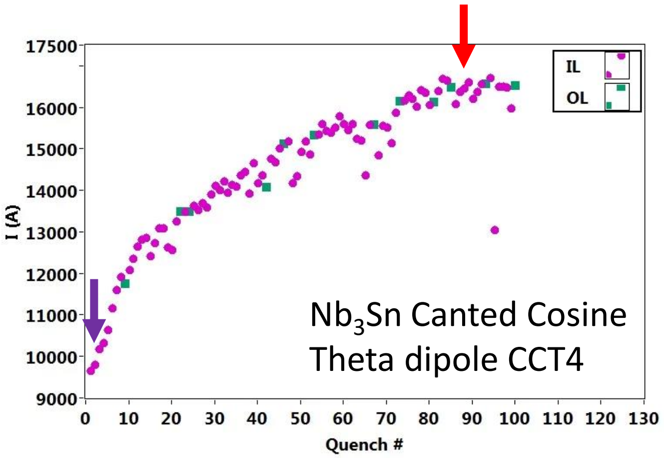
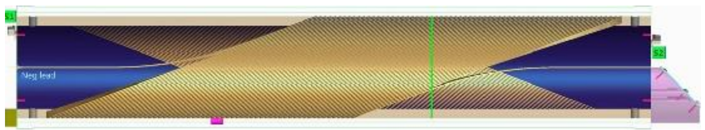
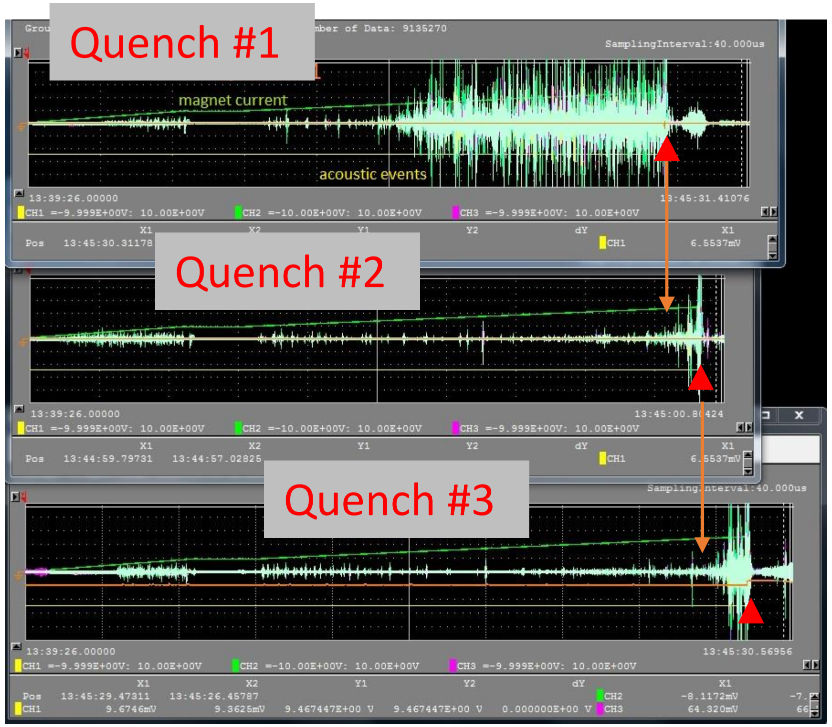
Kaiser effect: mechanical memory of the magnet

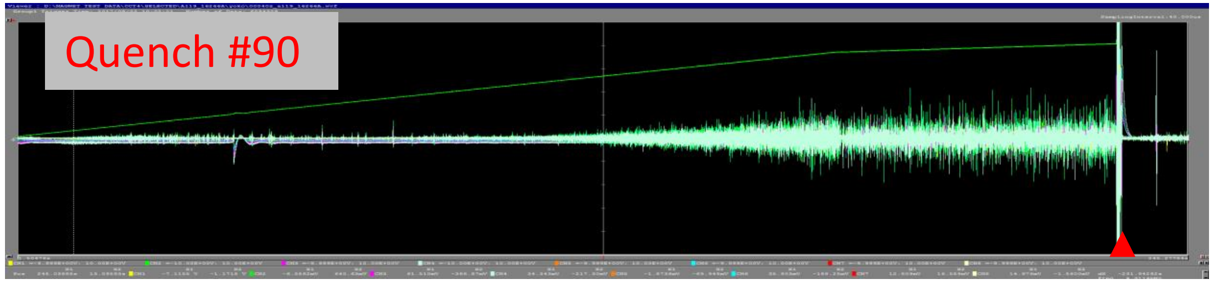




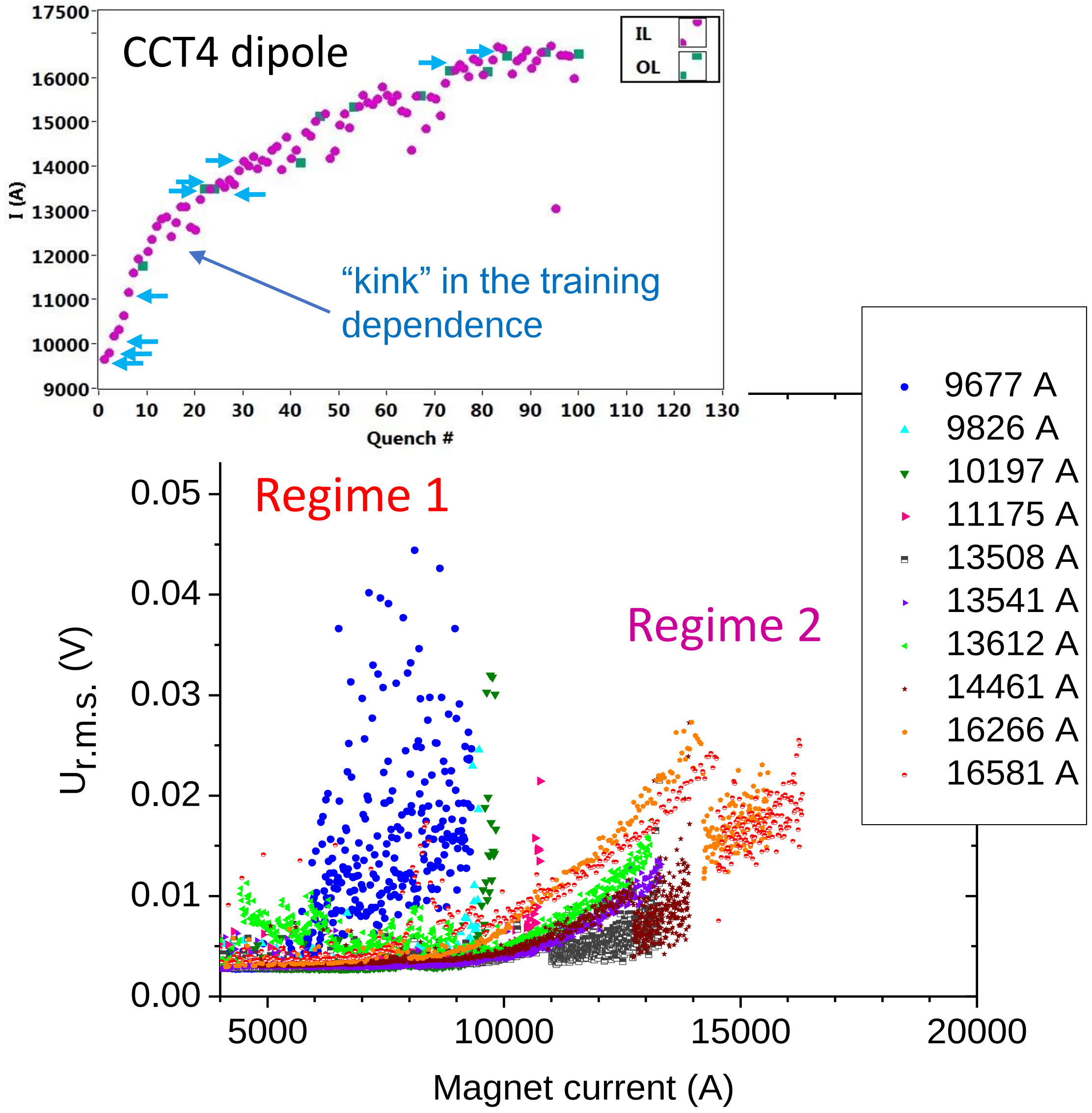


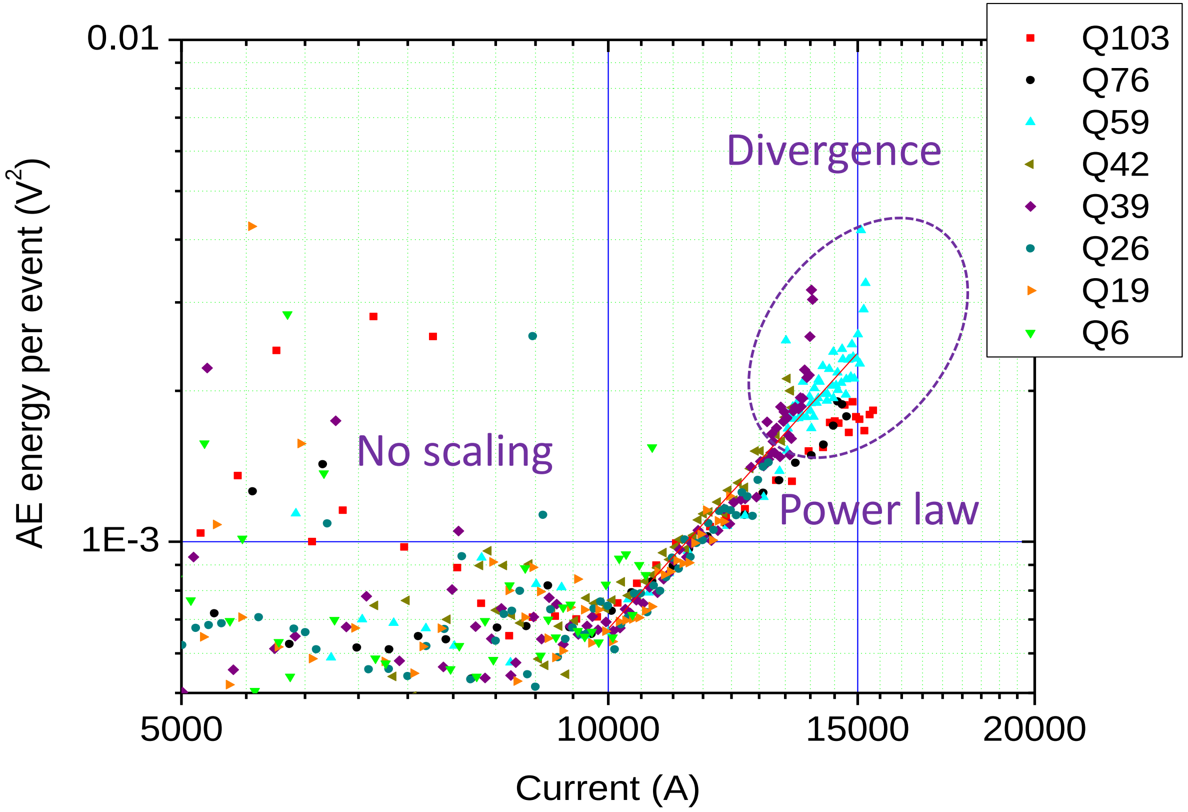
Magnet remembers the stress level reached in the previous ramp and is mostly quiet acoustically below that level. AE resumes when stress is increased past the previously achieved level.

After many quenches, the memory is lost and the magnet emits AE in every ramp starting from approximately the same level of stress



Distinct regimes of training from AE

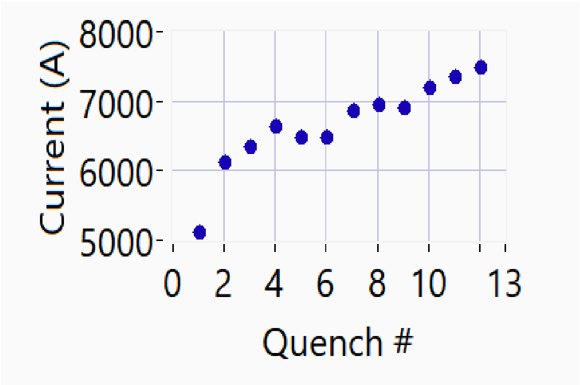


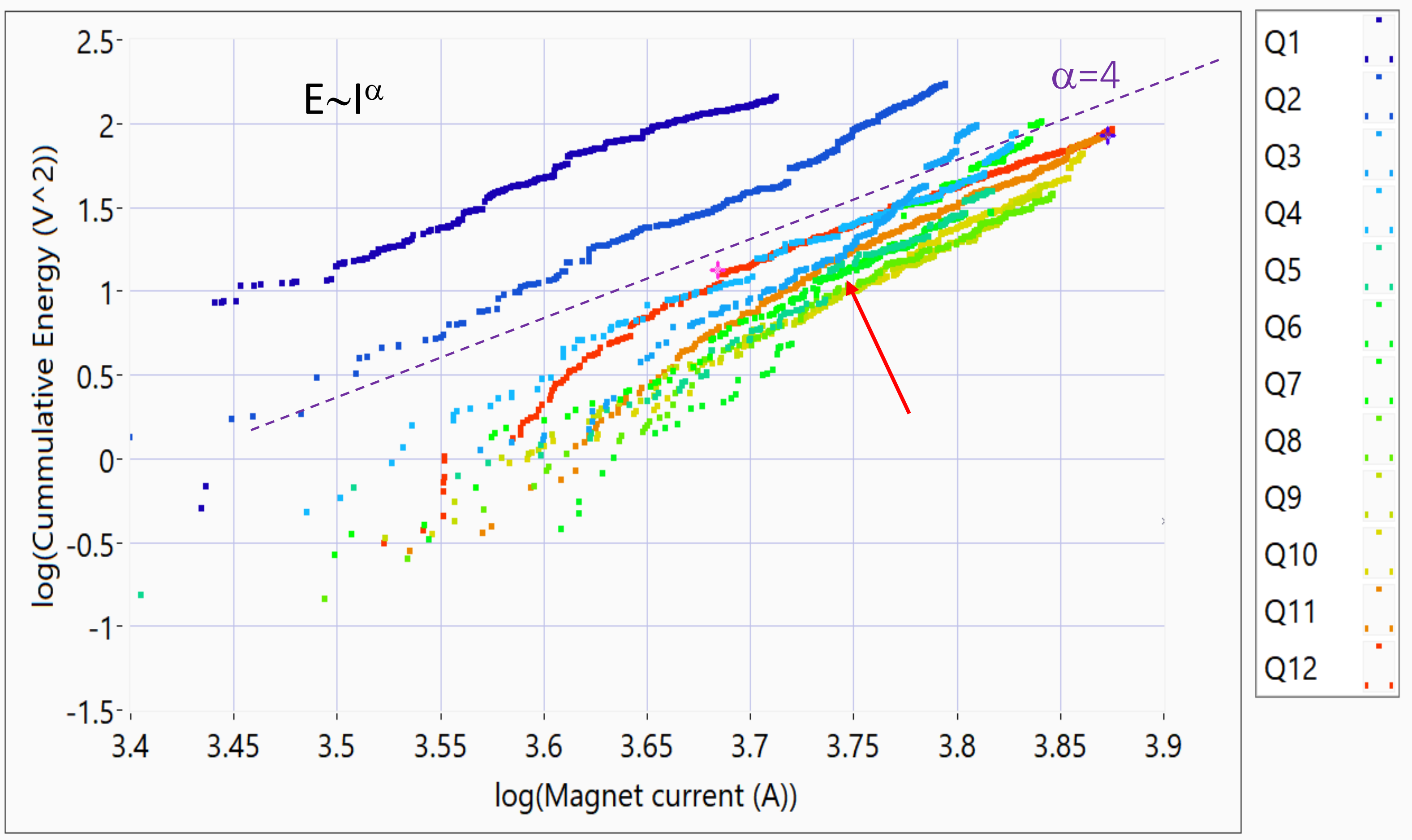


- A steep divergence from the power law develops a few seconds before quenching for some ramps. Could be used as a precursor (?)

Cumulative energy release

In a series of training ramps the cumulative AE energy release asymptotically reaches $E \sim I^4$ scaling, i.e. proportional to the accumulated elastic energy





Connecting AE energy and thermal energy release

Several papers demonstrated that integral thermal dissipation is proportional to the cumulative energy of acoustic emission for crack propagation…

A N Vshivkov et al 2017 IOP Conf. Ser.: Mater. Sci. Eng. 208 012012, doi:10.1088/1757-899X/208/1/012012

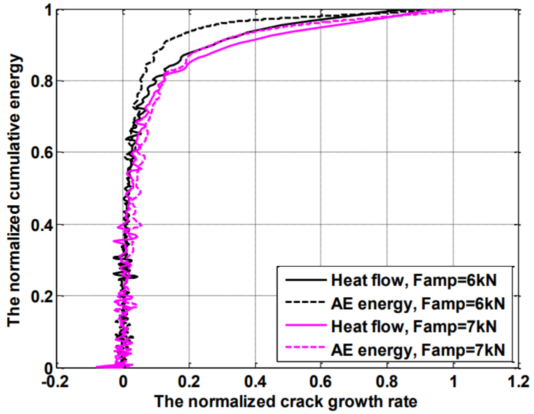
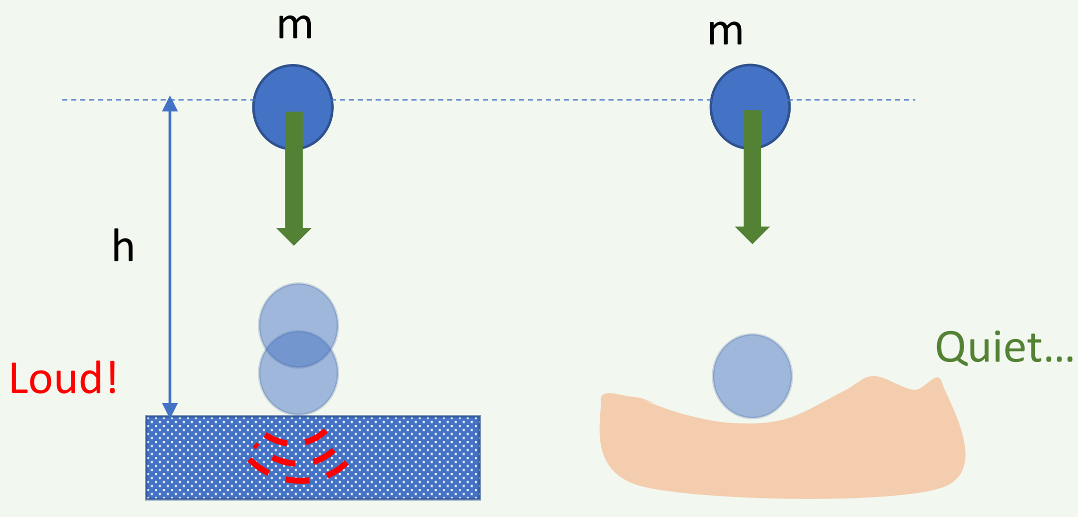


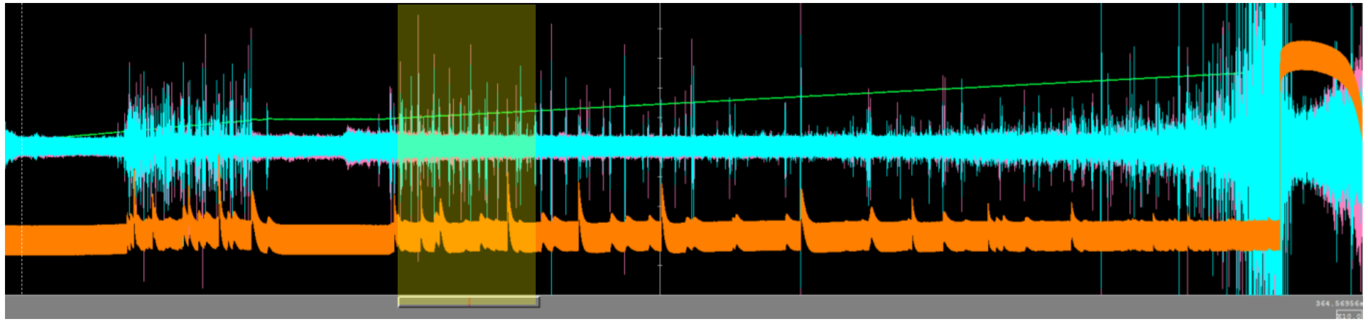
Figure 11. The comparison of the integral dissipated thermal energy and the cumulative energy of the acoustic emission.

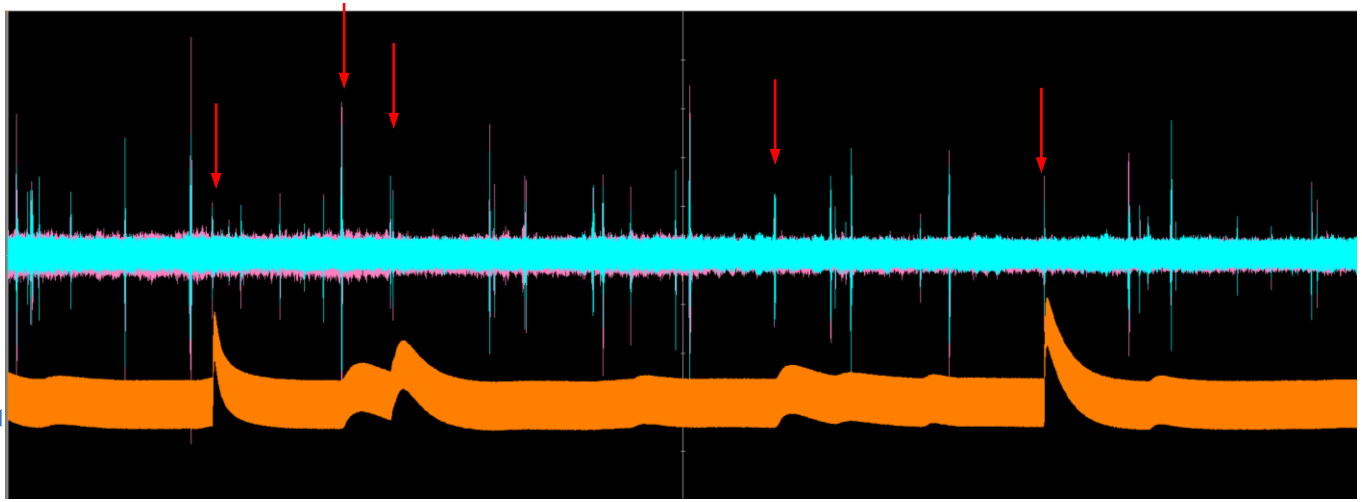
However, it is intuitively clear that the fraction of elastic energy converted to heat **locally** depends on the properties of the impregnation material…

A simple analogy: ball drop



Temperature “spikes” coincide in time with the AE spikes



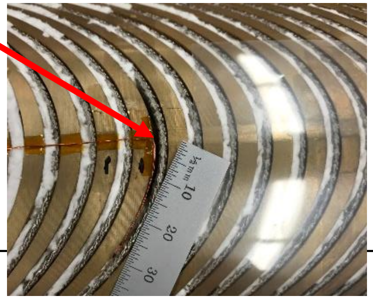


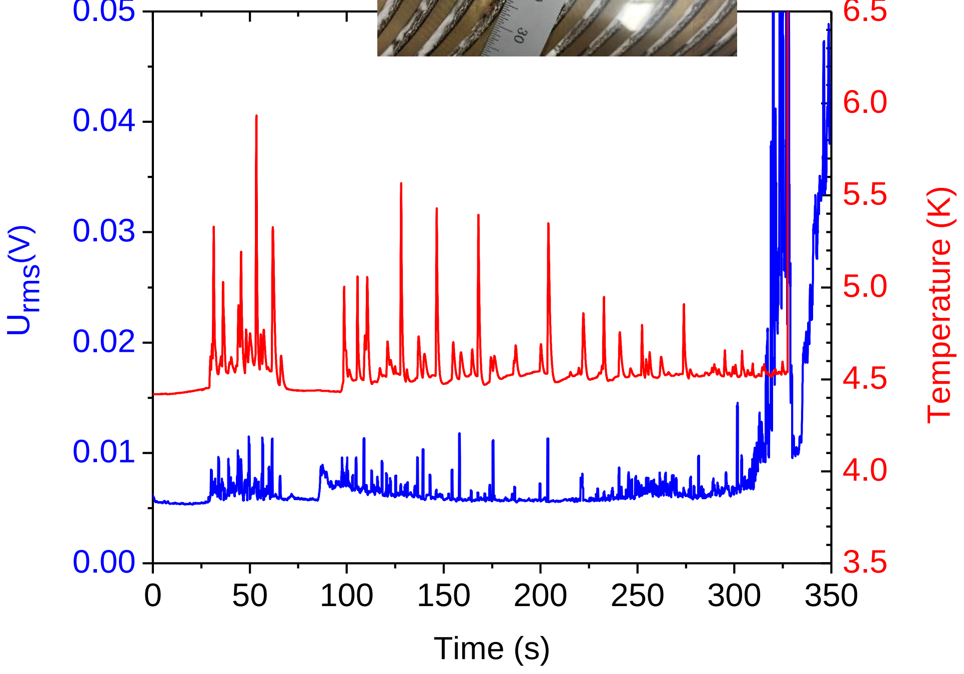
AE

Thermometer voltage

~ 36.5 s

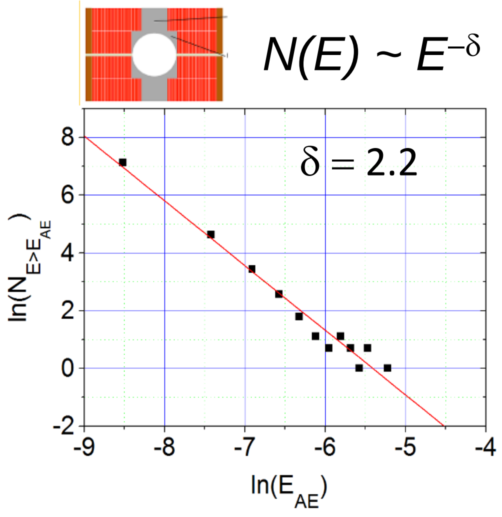
A thermometer of ~1 mm^2 size was installed directly in the cable groove before impregnation



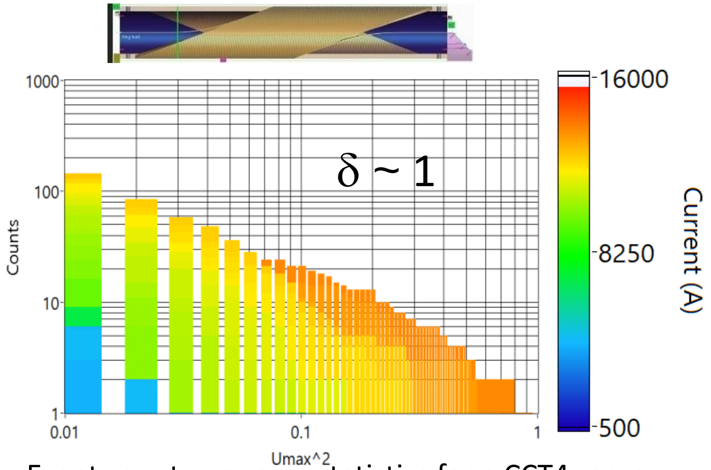


Temperature spikes as high as 1 K are time-correlated with acoustic events, and few correlate with voltage spikes on the coils. A potential way for doing in-situ calibration of energy release.

Magnets “crackle”: a self-organized criticality?

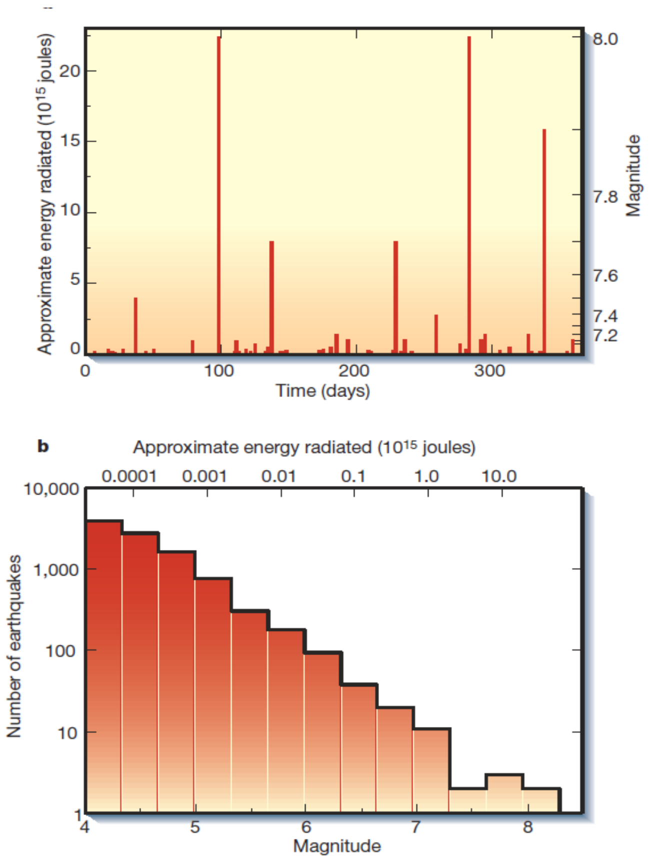


A cumulative number of the AE events of energy E > in HD3b magnet ramp to quench, plotted versus E_{AE}. The linear fit is a power law with the exponent d = 2.2.



Event count vs energy statistics for a CCT4 ramp

Earth crackles (Gutenberg–Richter law for earthquakes)



“Crackling noise:, P. Sethna et al., Nature **410**, 242–250 (2001)

Same event statistics in:

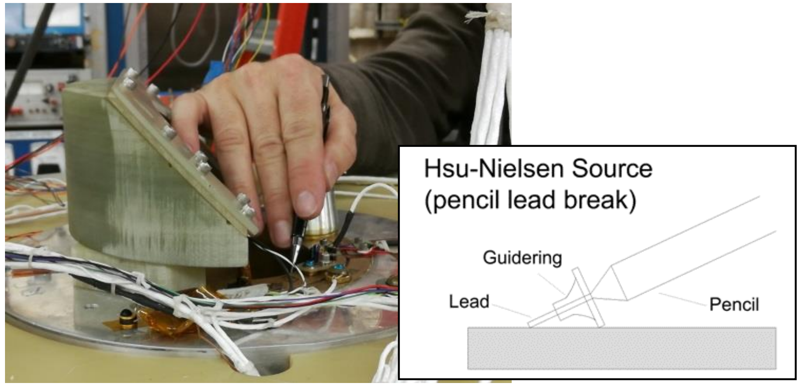
- AE from candy wrappers
- fluctuations in the stock market
- solar flares
- cascading failures in power grids
- group decision-making
- fractures in disordered materials
- etc… etc…

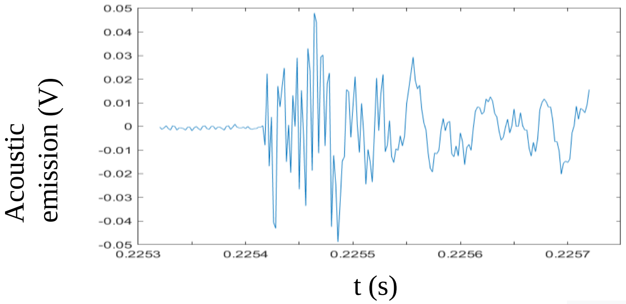
Power law implies statistical self-similarity of energy release on **all length scales.**

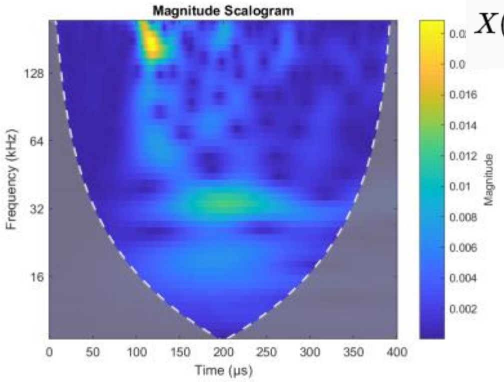
Does this mean nothing should be “special” about that particular AE event associated with a quench?..

Event classification based on AE frequency response

Pencil break





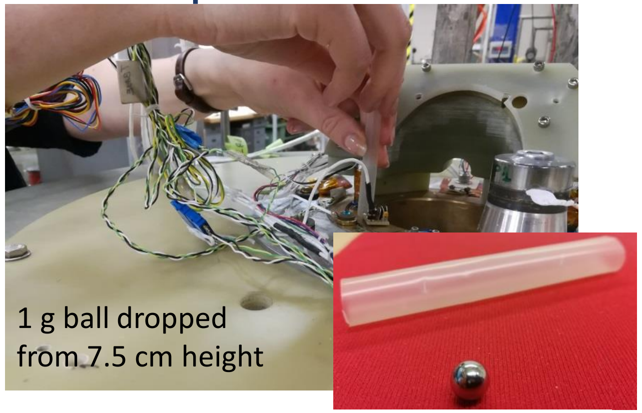


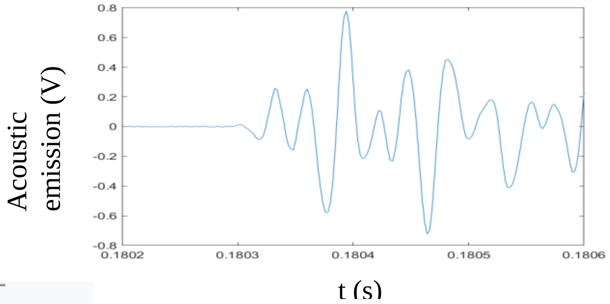
$$X(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} \overline{\Psi\left(\frac{t-b}{a}\right)} x(t)\, dt$$

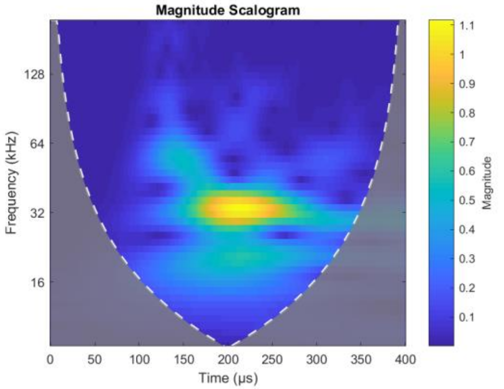
$$f_a = \frac{f_c}{a \cdot dt}$$

Measurements by E. Nilsson

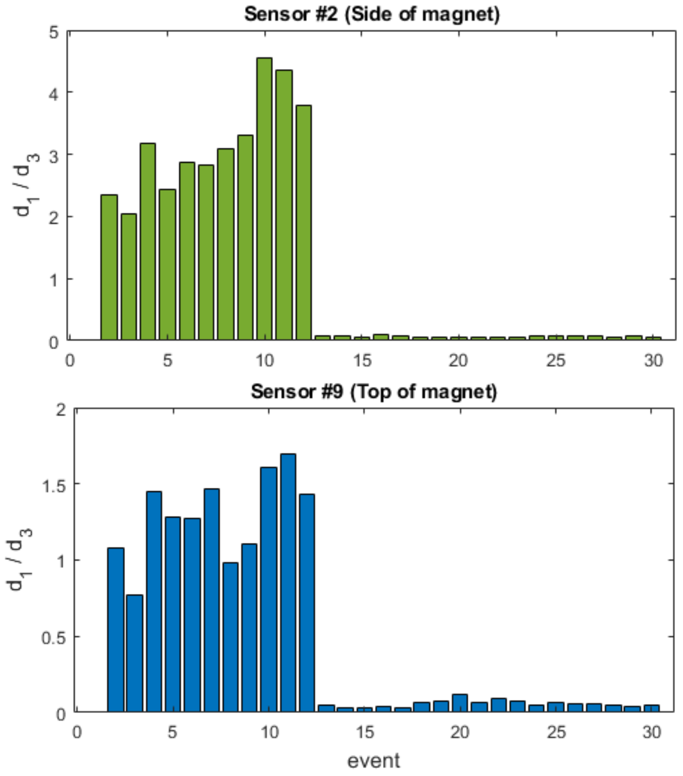
Ball drop



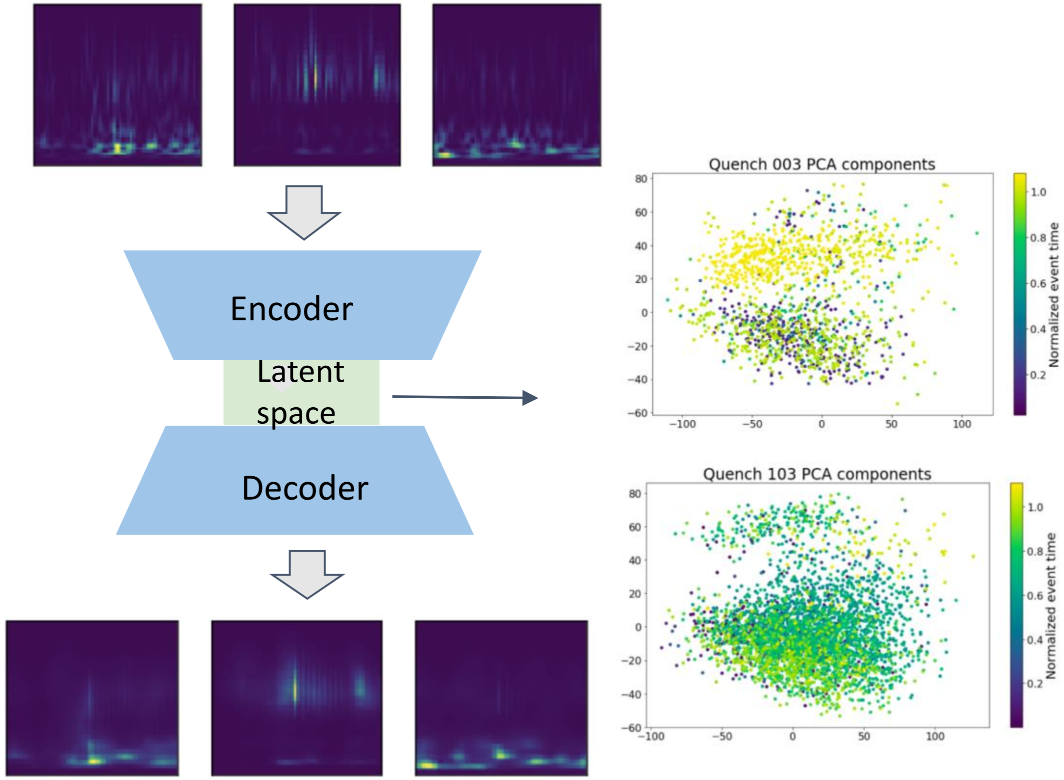




A fast and reliable way to characterize these reference events is to calculate high-frequency vs lower frequency content with discrete wavelet analysis: d_1/d_3 , where d_n is the n^{th} scale of the discrete wavelet decomposition.



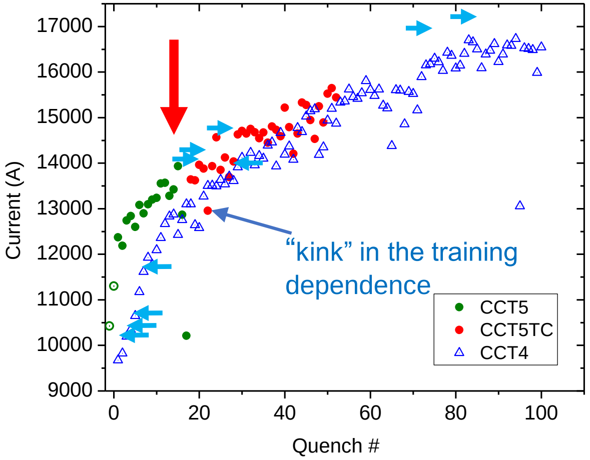
Machine learning for event type clustering and identification of quench precursors

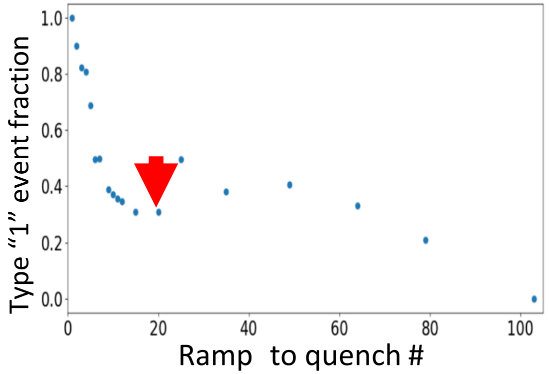


Reconstructed scalograms

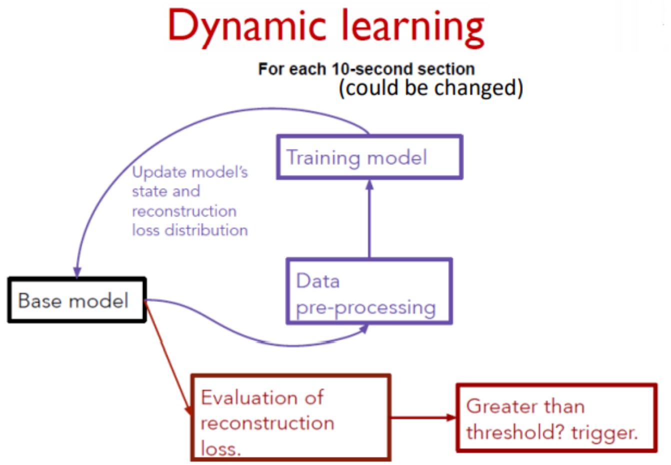
Some encouraging first results of unsupervised event-type clustering using deep learning

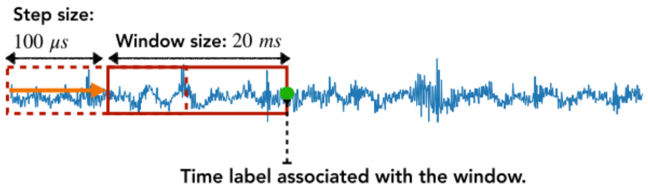
L. Stephey et al. NERSC





The "Random Forest" classifier was used to identify event fractions based on frequency content; dependence coincides with the transition from training fast training to a slow training regime. MM, EUCAS 2017





D. Hoang et al., "Intelliquench: An Adaptive Machine Learning System for Detection of Superconducting Magnet Quenches," in IEEE Transactions on Applied Superconductivity, vol. 31, no. 5, pp. 1-5, Aug. 2021, Art no. 4900805, doi: 10.1109/TASC.2021.3058229.

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Coda wave interferometry: a technique "borrowed" from seismology

- First definition

VOL. 80, NO. 23 JOURNAL OF GEOPHYSICAL RESEARCH AUGUST 10, 1975

Origin of Coda Waves: Source, Attenuation, and Scattering Effects

KEIITI AKI AND BERNARD CHOUET

Department of Earth and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Coda waves from small local earthquakes are interpreted as backscattering waves from numerous heterogeneities distributed uniformly in the earth's crust. Two extreme models of the wave medium that

- First introduction of CWI

PHYSICAL REVIEW E **66**, 046615 (2002)

Coda wave interferometry and the equilibration of energy in elastic media

Roel Snieder

Department of Geophysics and Center for Wave Phenomena, Colorado School of Mines, Golden, Colorado 80401

(Received 14 May 2002; published 21 October 2002)

Multiple-scattered waves usually are not useful for creating deterministic images of the interior of elastic media. However, in many applications, one is not so much interested in making a deterministic image as in detecting changes in the medium. Cases in point are volcano monitoring and measuring the change in hydrocarbon reservoirs during enhanced recovery operations. Coda wave interferometry is a technique wherein changes in multiple-scattered waves are used as a diagnostic for minute changes in the medium. This technique

- Thermal sensitivity first demonstrated:

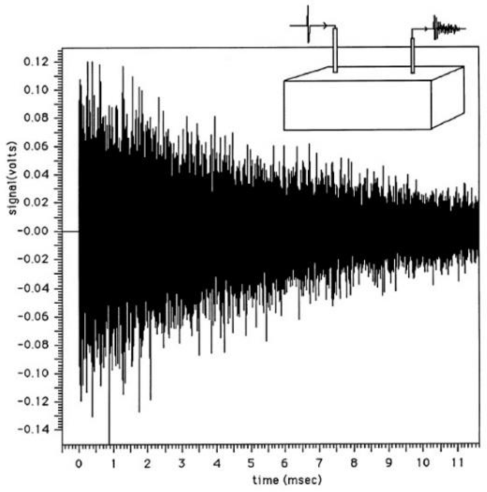


Fig. 1. A broadband impulsive source leads to a stochastic ultrasonic signal with a duration of many tens of milliseconds. This signal is robust in spite of its noisy appearance, and is obtained after 10–100 repetition averages.

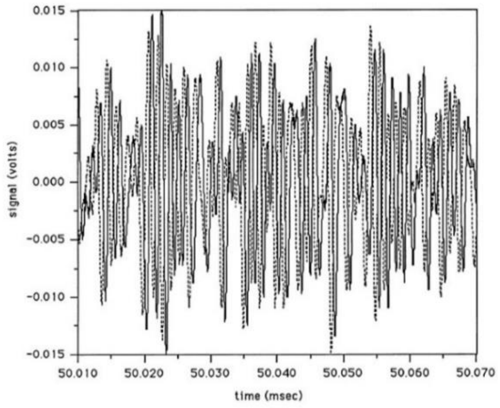


Fig. 2. A 60 μs section of the full waveform is examined at an age of 50 ms. The original signal (solid line) appears to drift to the left (dotted line) as the specimen cools, and to suffer some slight distortion.

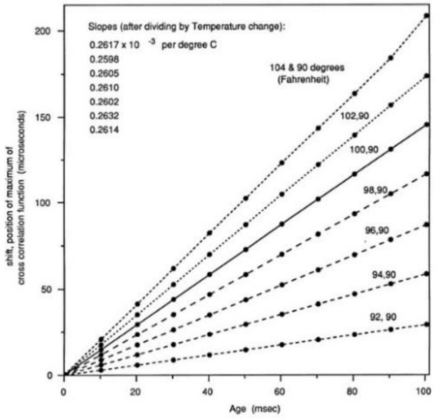


Fig. 5. The position of the cross-correlation peak is plotted as a function of age and temperature change. Its linearity with both parameters is apparent.

R. L. Weaver, O. I. Lobkis, "Temperature dependence of diffuse field phase", Ultrasonics, V. 38, pp. 491-494 (2000)

Detectable quantities using coda waves

- Wave velocity change due to a temperature variation in the object

Sound velocity: $v = \sqrt{\frac{E}{\rho}}$ ⇨ $E(T) = E_0 - s/\left[e^{t/T} - 1\right]$ (s, t – adjustable parameters)

The E(T) dependence is **weak**: just ~1-10 ppm/K at 77 K and even less at lower temperatures

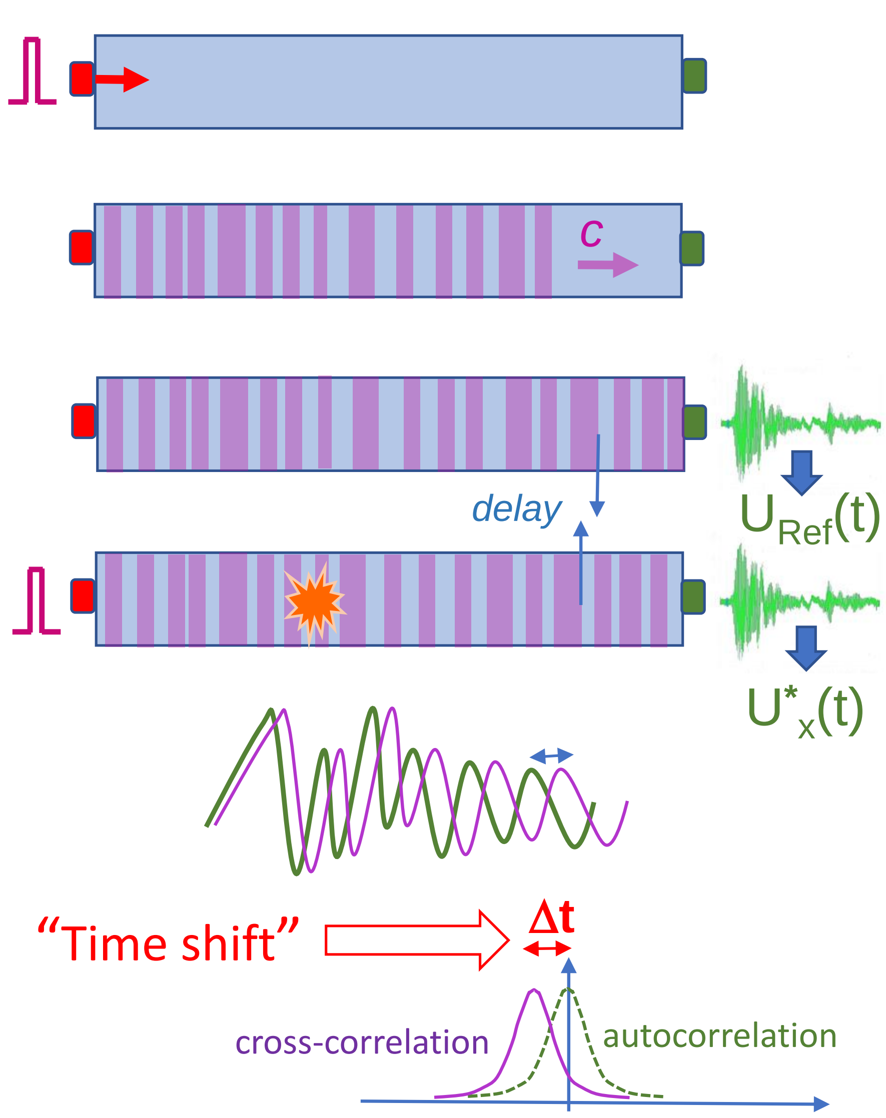
- Wave path change due to an interfacial coupling variation between object parts

- Wave path change due to structural deformation of the object

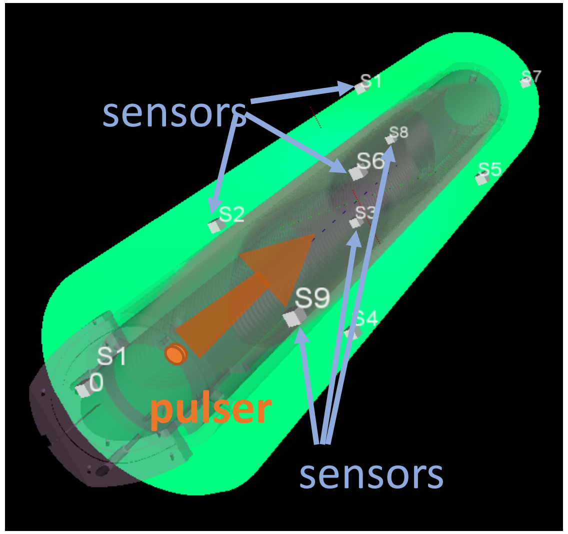
Detecting a weak change using coda: an operational principle

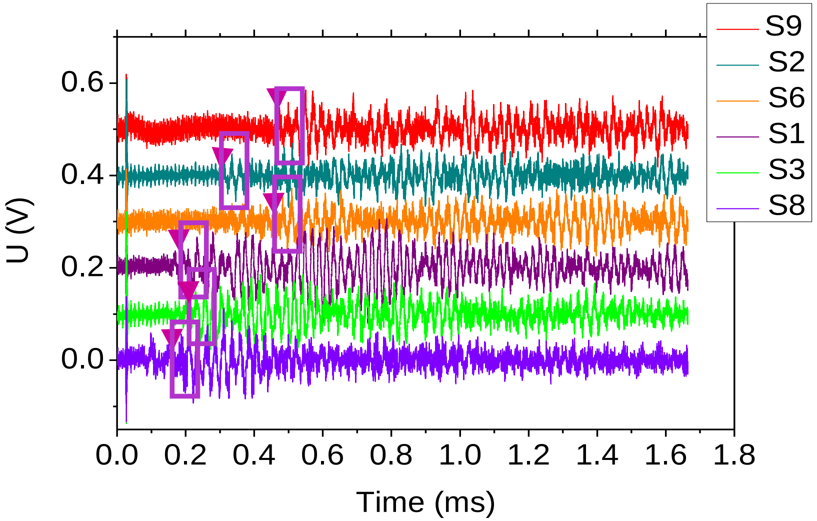
1. A sender transducer pulses the object
2. The pulse propagates and reverberates inside the object multiple times
3. The coda is acquired by a receiver transducer, and **stored as “reference”** $U_{Ref}(t)$
4. Pulsing and coda acquisitions are repeated periodically; every new coda $U_x(t)$ is compared to $U_{Ref}(t)$ using cross-correlation: $A(Dt) = U_x(t+\Delta t)*U_{Ref}(t)$. The time shift Dt yielding maximal cross-correlation is calculated for every new pulse
5. When a weak change develops, sound velocity decreases/increases locally, phase shifting the wave passing through it. This proportionally **increases/decreases Δt**.

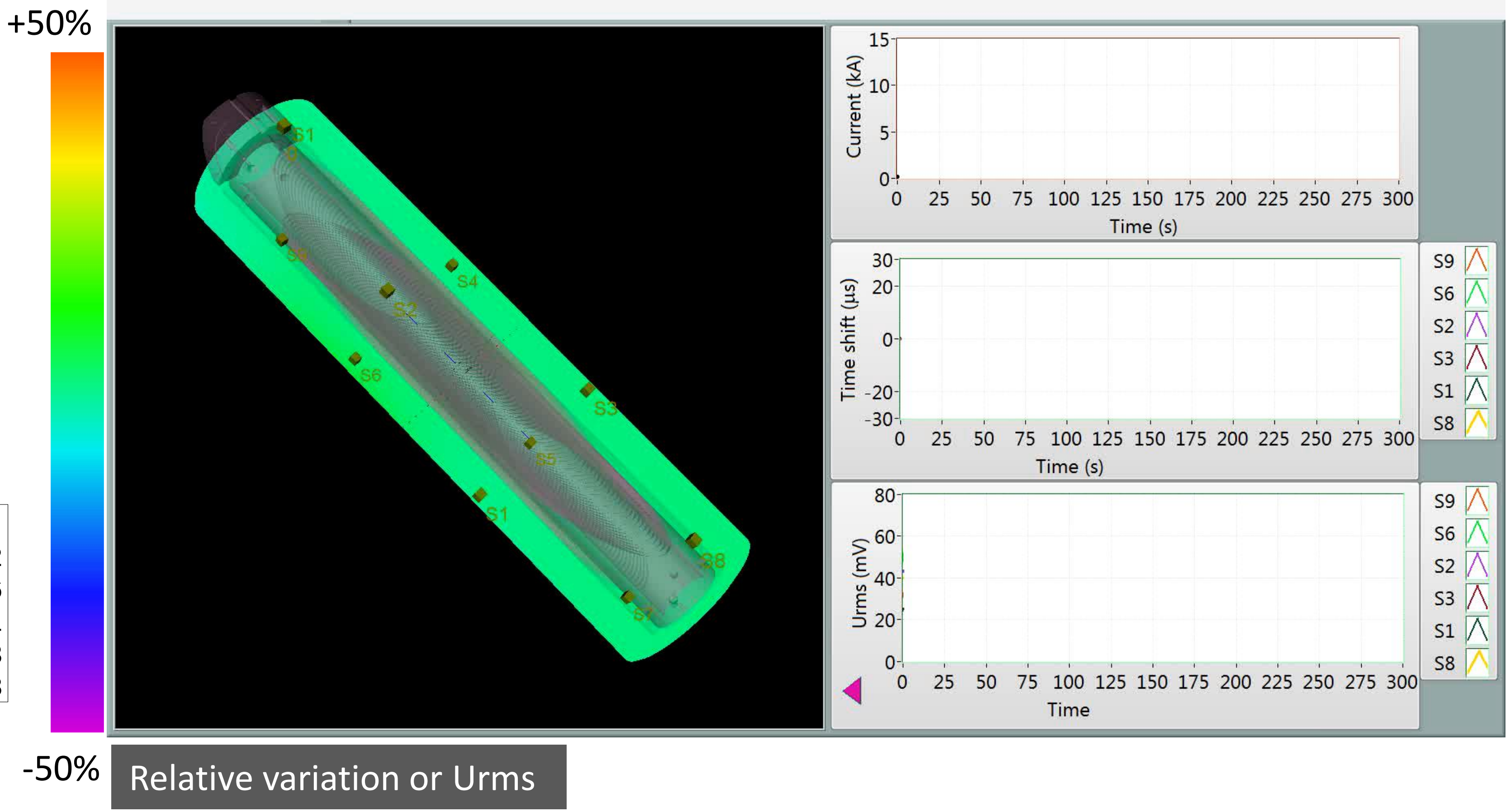
The further along the time axis the coda is sampled, the larger time shift it will experience



Mechanical interfaces evolution during ramping of CCT4 magnet

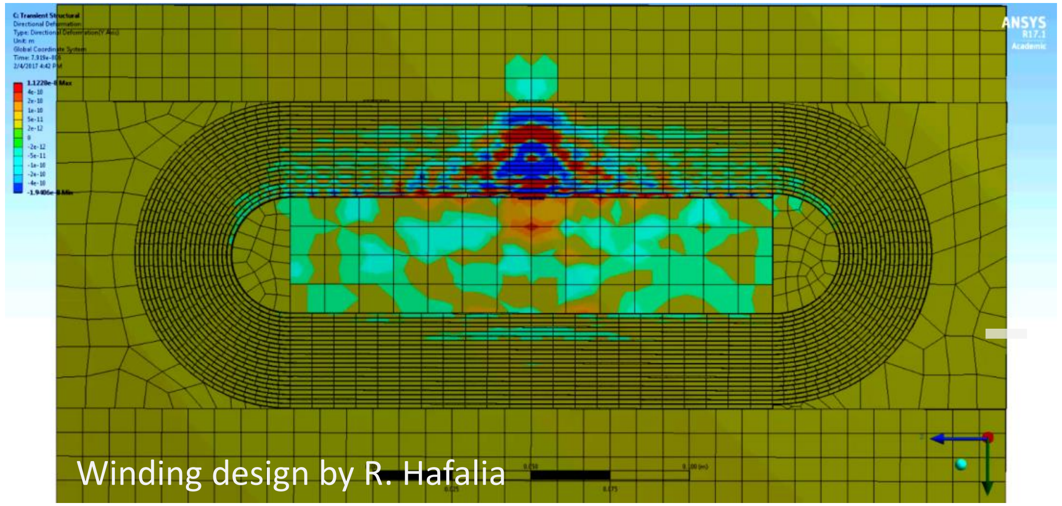


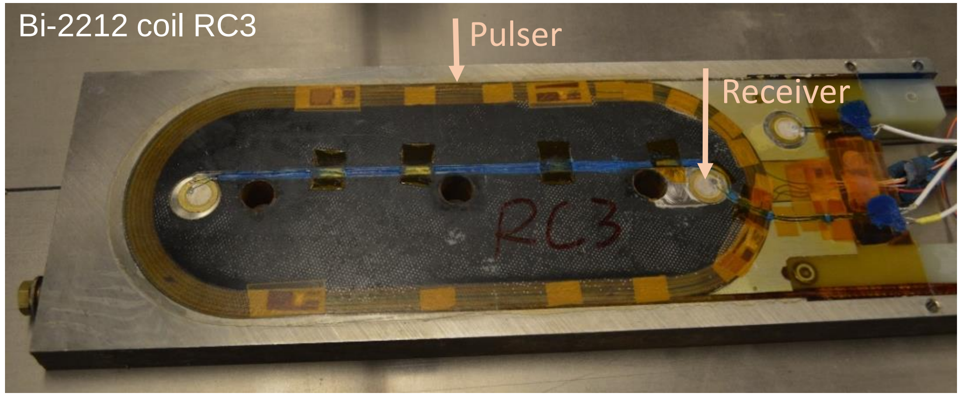




A transducer is mounted on the inner layer mandrel, powered with a 100 V / 14 µs rectangular pulse waveform at 1 Hz repetition rate; AE sensors are installed on the magnet aluminum shell

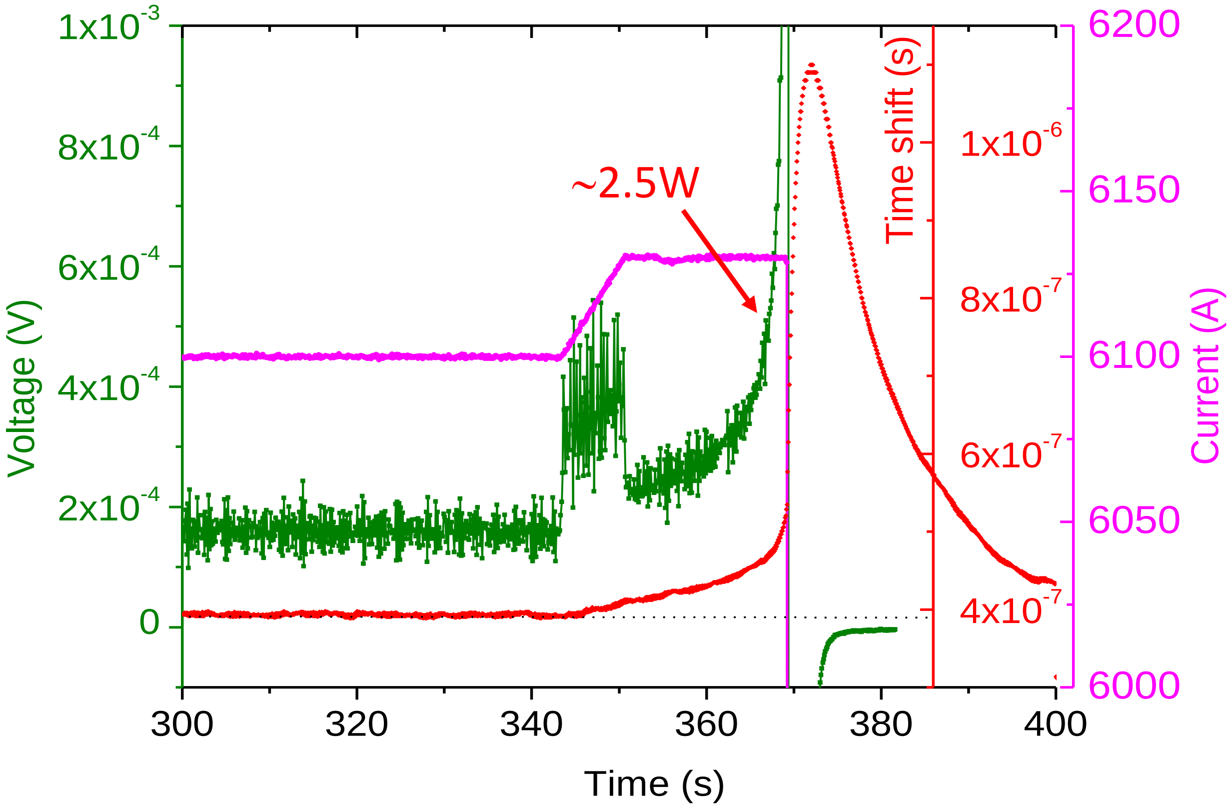
Ultrasonic quench detection in Bi-2212 HTS coil at 4.2 K





Coil design and test by T Shen / K. Zhang, LBNL

Experiment at 4.2 K. Current ramp stopped at 6100 A (stable) and then increased by 30 A (quenching)



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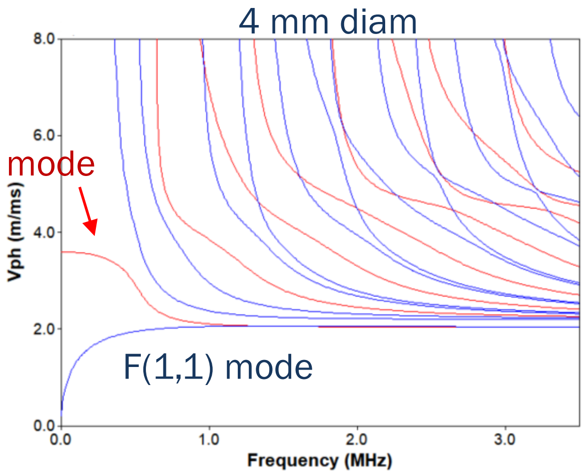
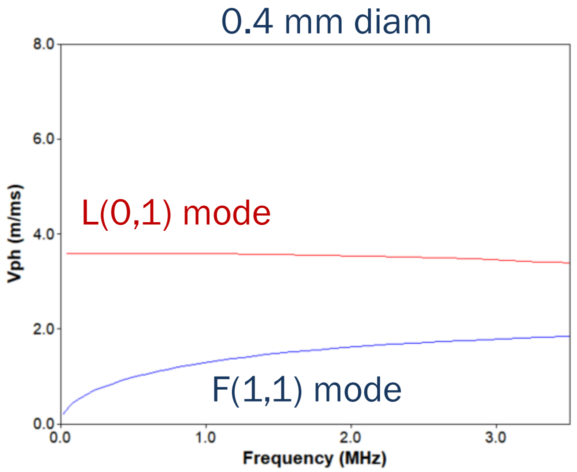
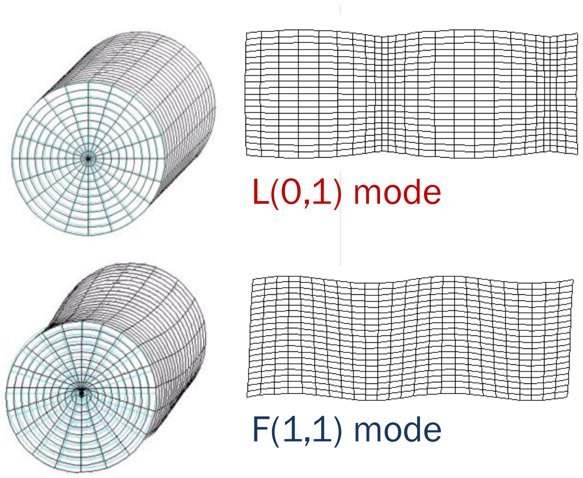
Acoustic waveguide concept

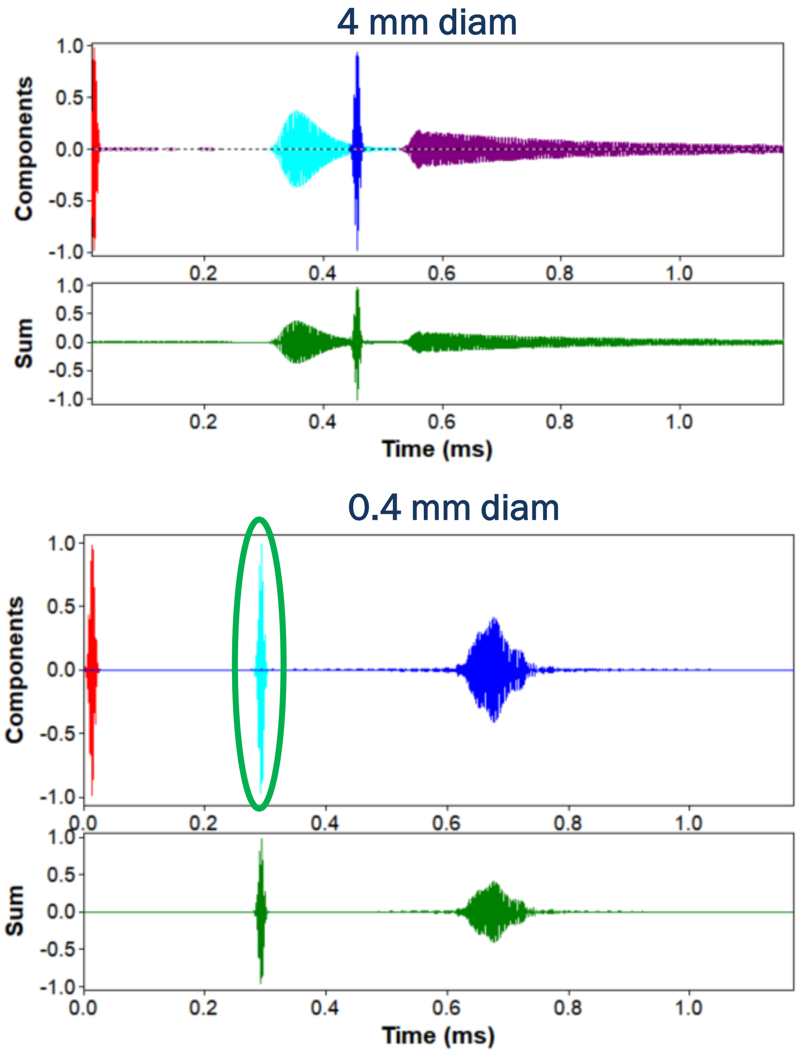




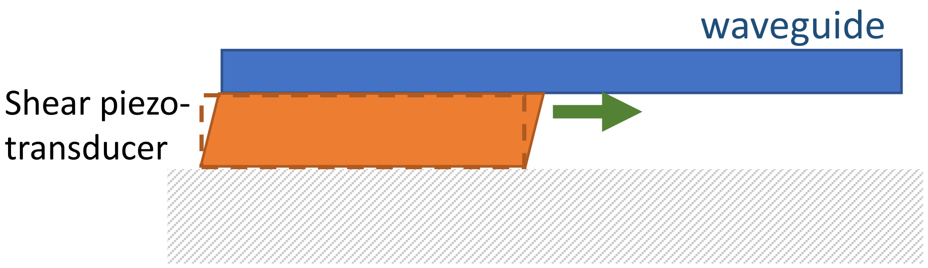
Traveling acoustic waves in a brass rod



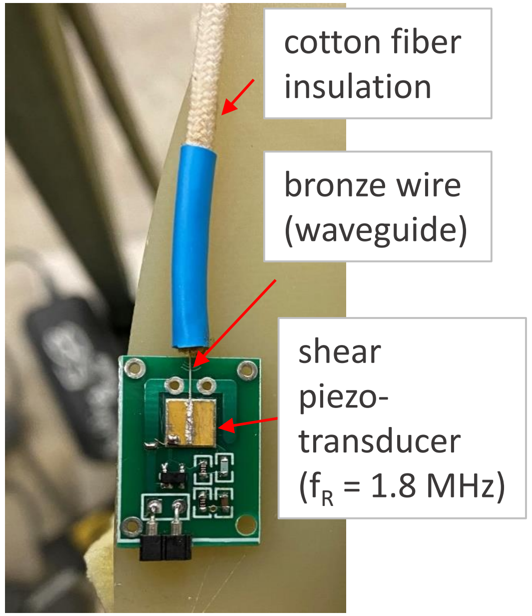
Time domain signals in transmission mode for a 1 m long bronze waveguide at frequency 350 kHz for waveguides of different diameters.

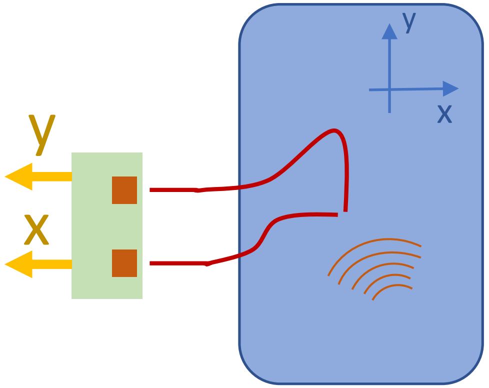


Acoustic waveguide-based sensor instrumentation



Shear piezo-transducers allow for efficient excitation of the L(0,1) mode

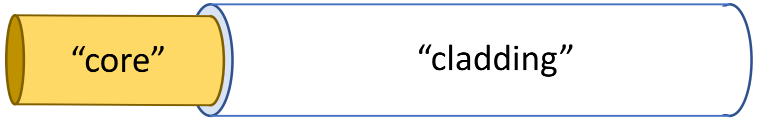


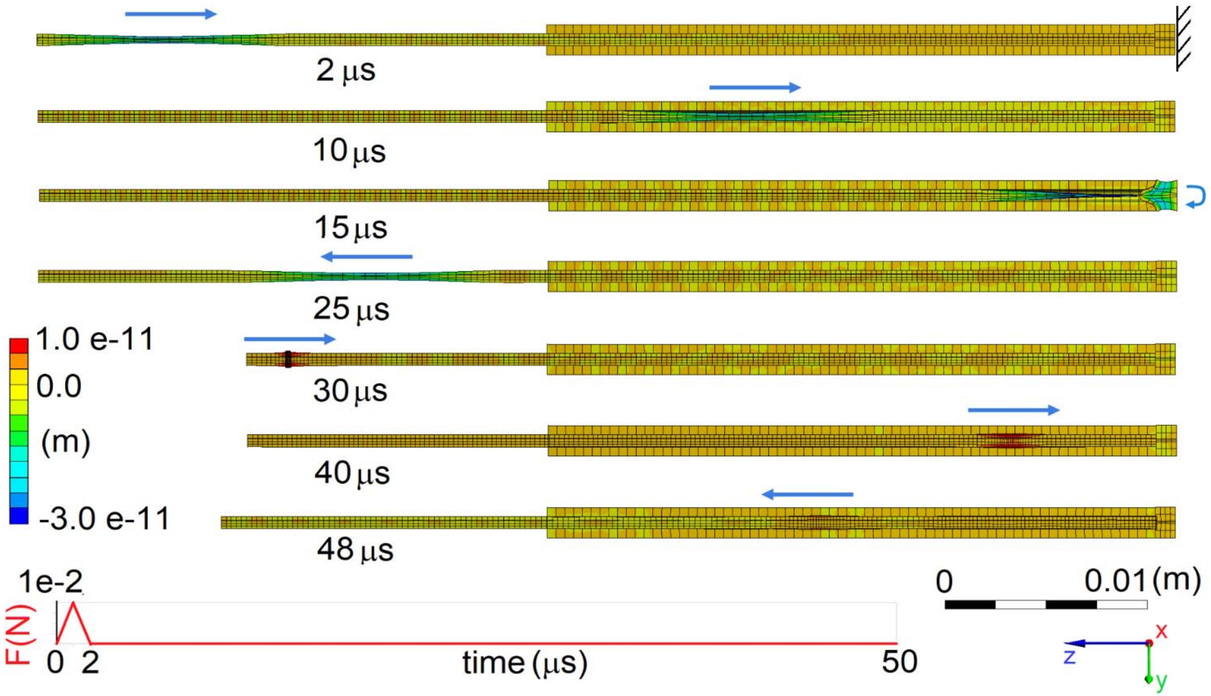


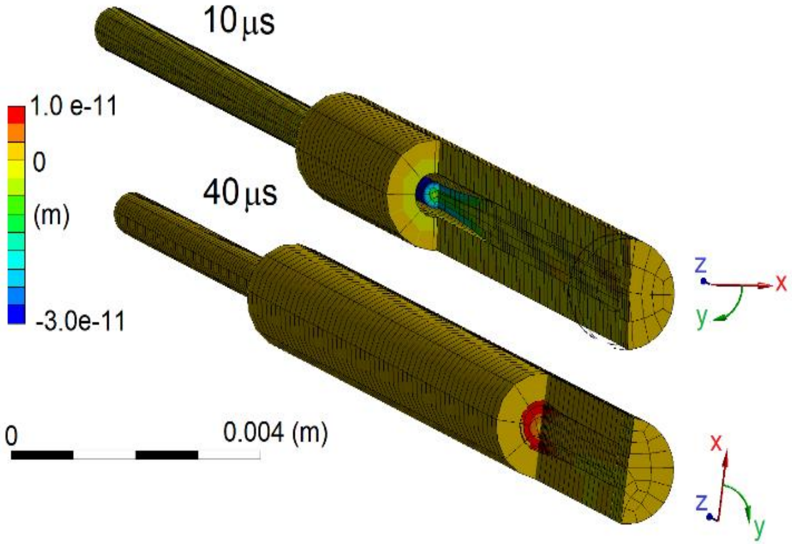
Directional AE sensing

- Sensors can be installed outside of the magnet
- Waveguide can pick up AE from surfaces/locations within magnet structure that are otherwise inaccessible for instrumentation
- High fidelity signal: critical for the event “fingerprinting”
- Waveguide sensors are directional: they can be used to pick up specific wave modes and thus used to find a direction to the source

Adding cladding enables a non-leaky operation of the waveguide



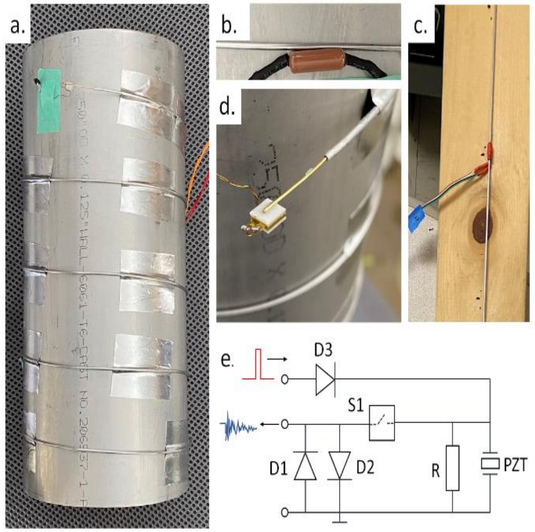


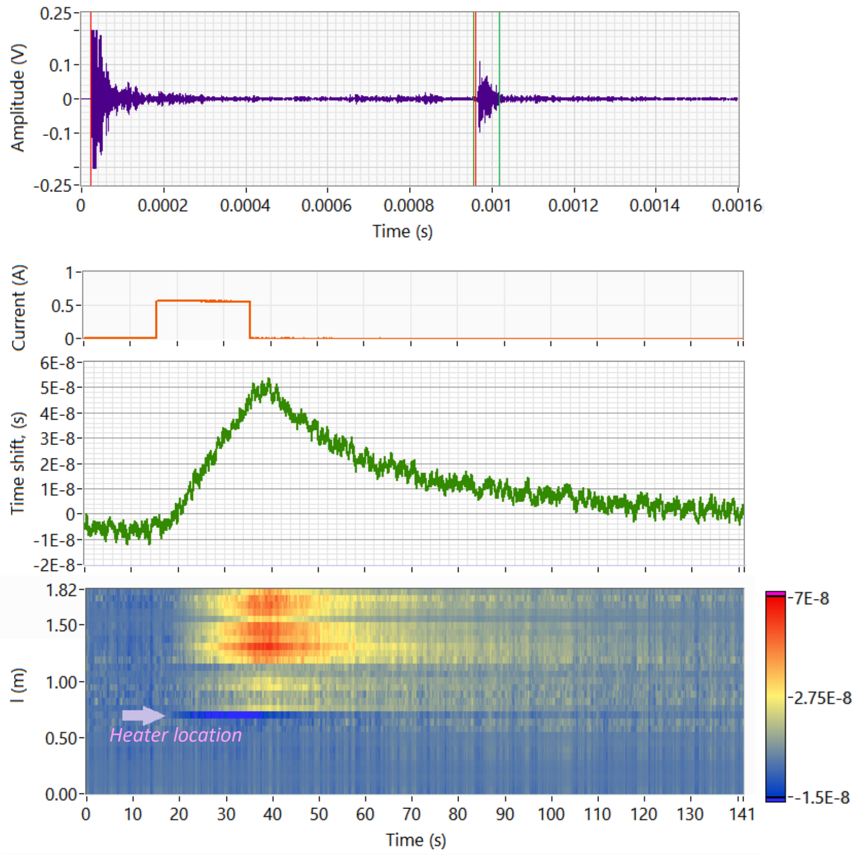


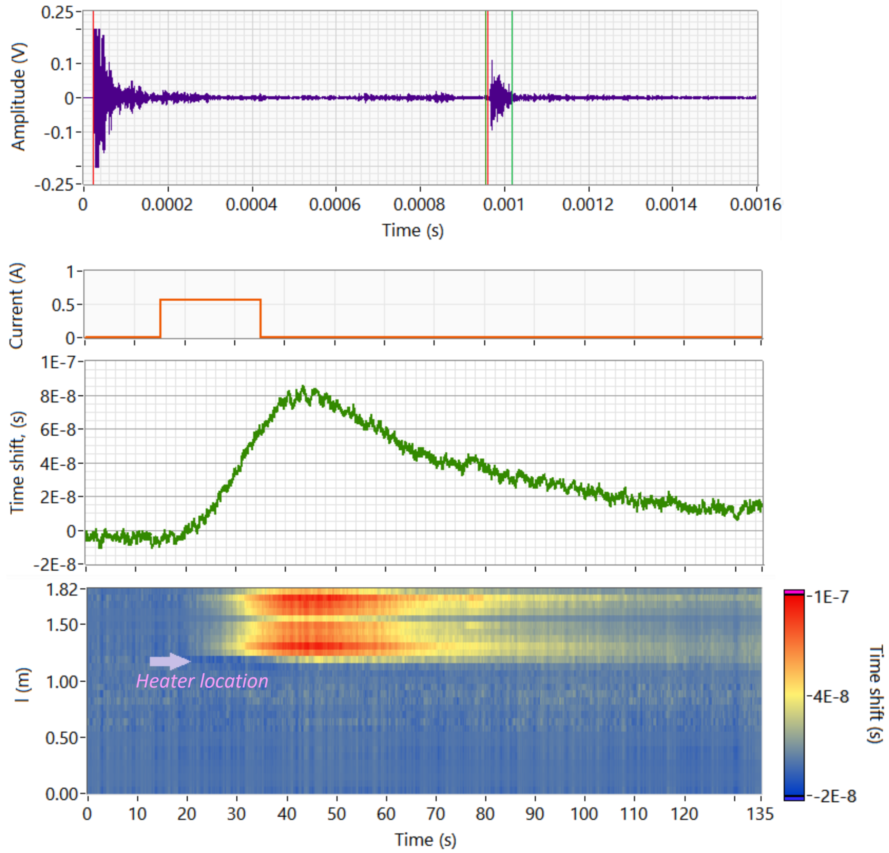
A propagating longitudinal excitation in the waveguide also leads to local transverse deformation (Poisson effect). The latter “detaches” the waveguide from the inner wall of the cladding, allowing for a non-leaky propagation.

The non-leaky waveguide sensor can then be readily integrated with magnets without loss to the transmission

The "non-leaky" acoustic waveguide is suitable for the practical integration of distributed thermometry in magnets

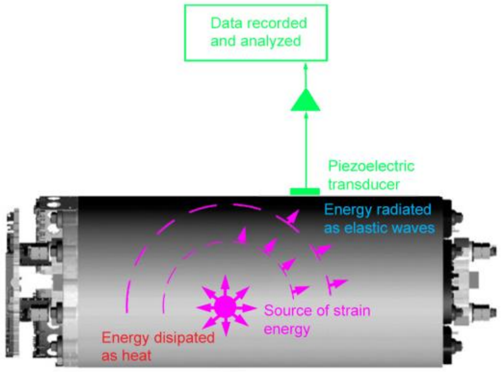






"Distributed thermometry for superconducting magnets using non-leaky acoustic waveguides", M. Marchevsky and S. Prestemon, Supercond. Sci. Technol. 36 045005, doi:10.1088/1361-6668/acb23a

Summary



- **Acoustic emission diagnostics is a unique technique to access magnet micromechanics *in situ* and probe the disturbance spectra.** AE instrumentation is non-intrusive (can be installed on the outer surfaces), immune to magnetic fields, inexpensive, and easily adaptable to various magnet configurations
- Disturbances and quench locations can be localized through AE triangulation
- AE energy release trends and event statistics open a unique window into magnet micro-mechanics and facilitate the search for quench precursors and causes of training
- Diffuse ultrasound methods enable in-situ monitoring of interfacial debonding and heating in magnet coils
- Acoustic waveguide approach offers an attractive, simple, and robust way of distributed sensing of temperature for quench detection and hot spot localization

More to do on:

- ML/AI approach for event classification and quench precursors/ quench detection
- Quantitative analysis and energy calibration
- Synergistic analysis of AE and other diagnostic data
- Implementation of long-length ultrasonic waveguide sensors into magnets

Thank you!