Instrumentation and diagnostics

M. Marchevsky, LBNL

Credits to: D. Arbelaez, M. Turqueti, R. Teyber, E. Hershkowitz, T. Shen, K. Zhang, X. Wang, P. Bish, J. Swanson, S. Gourlay, S. Prestemon and all members of the Superconducting Magnet Group and Diagnostics Workgroup of MDP

Goals of magnet diagnostics

General and predictive

- **Understanding training and memory effects in magnets through disturbance spectrum analysis**
- Finding weak spots and design limitations and feeding back to magnet designers
- Benchmarking of models on stress, internal voltages, protection, ac losses, etc.

→ **Improving performance**

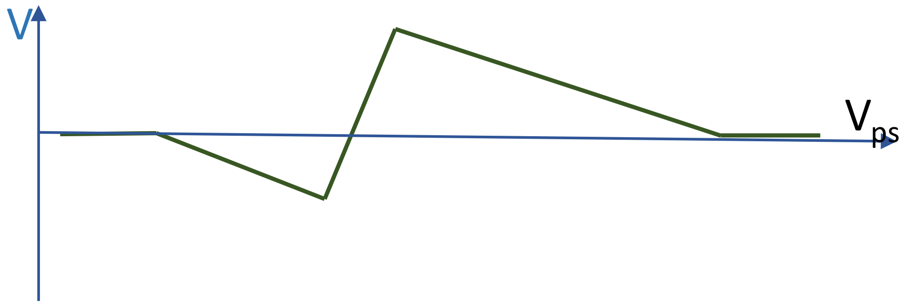
Operational

- **Quench detection**
- **Quench locations and NZPV**
- **Flux jumps and conductor instabilities**
- **Mechanical stability monitoring**

→ **Detecting problems, preventing damage**

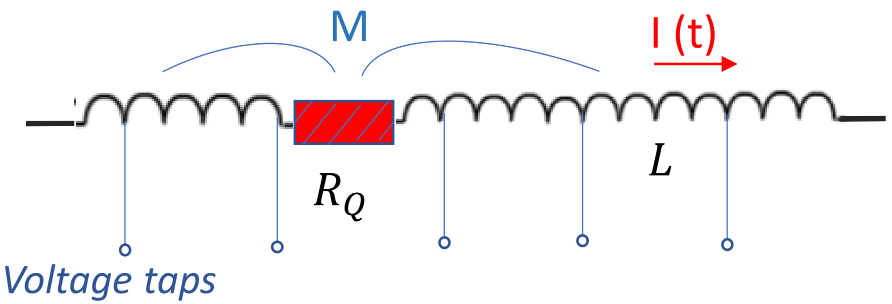
Voltage diagnostics

Voltage detection: the "traditional" technique



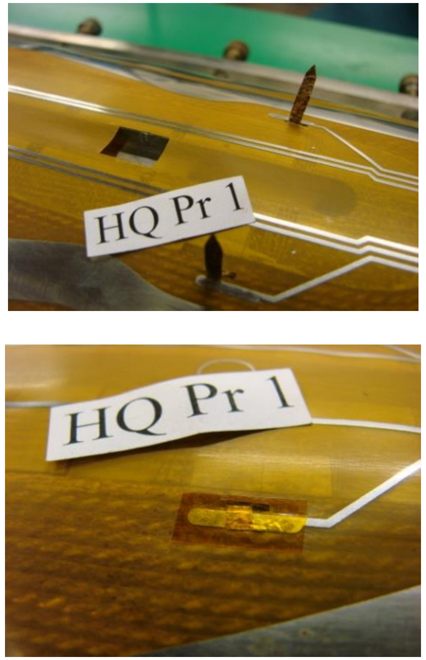
$$V_Q(t) = I(t)R_Q(t) - M\frac{dI(t)}{dt}$$

$$L\frac{dI(t)}{dt} \cong I(t)R_Q(t)$$



$$V_Q(t) = I(t)R_Q(t)(1 - \frac{M}{L})$$

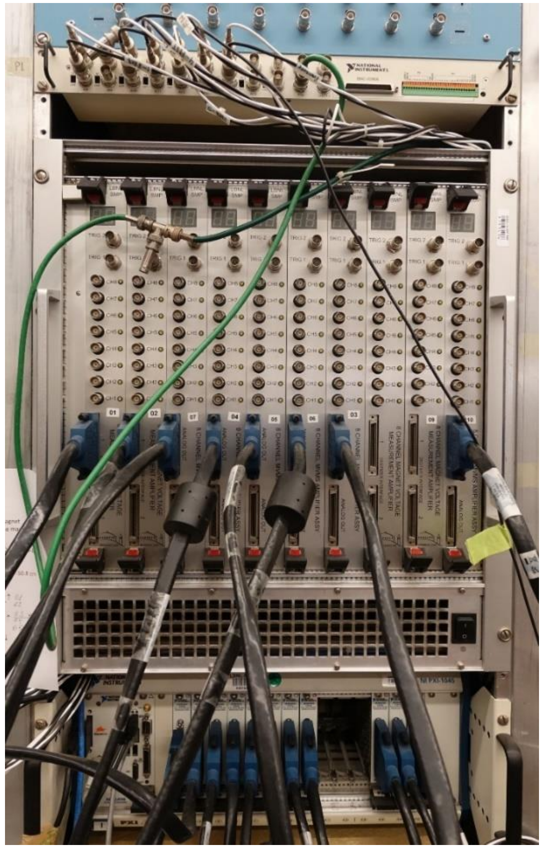
$V_Q(0) = V_Q(\infty)$ =0 => peaks during the quench



Voltage taps examples

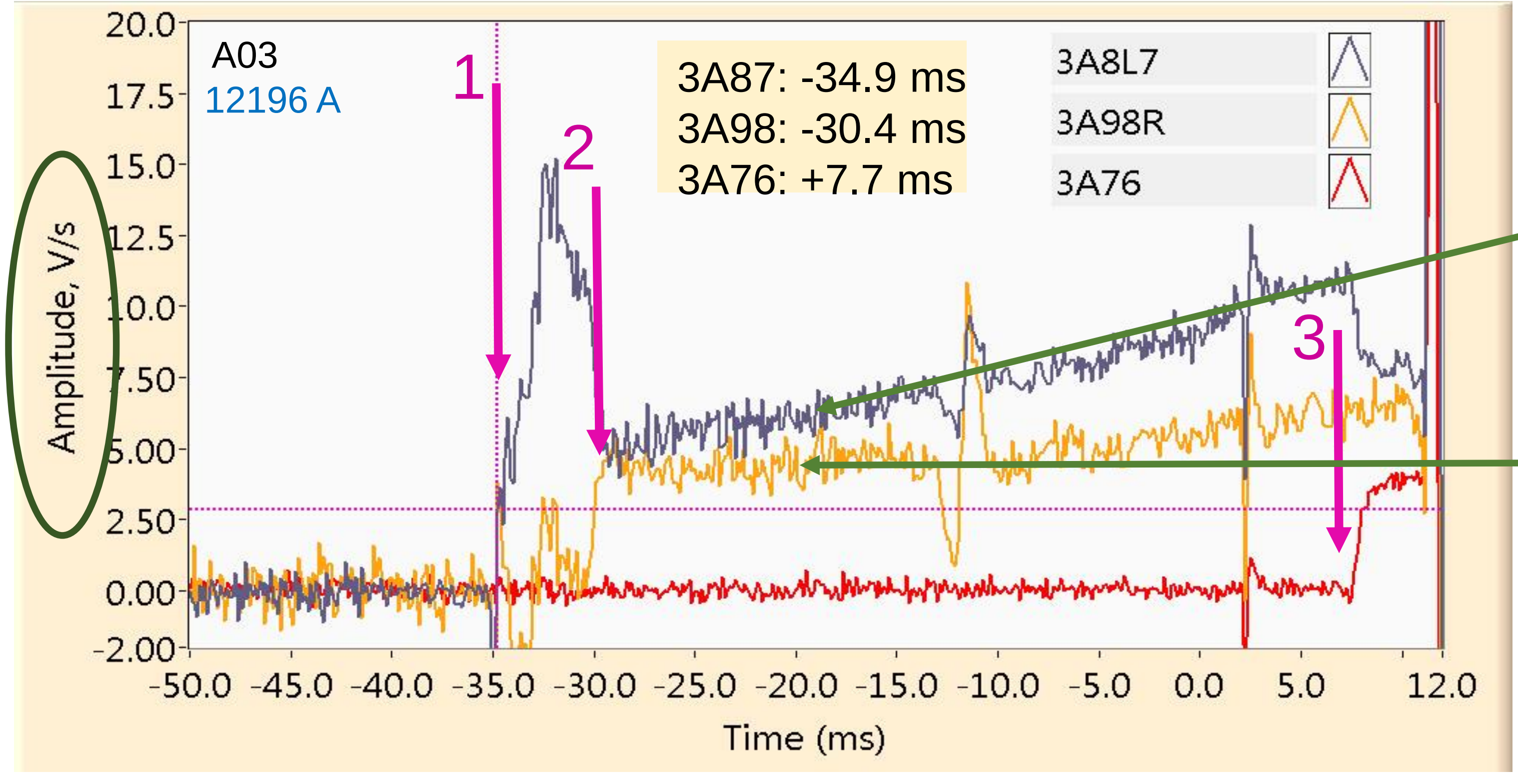
"Magnet Voltage Measurement System" (MVMS)

- 160+ DAQ channels at 500 kHz
- National Instruments PXI-6123 cards interfaced to remotely programmable custom built HV (1000 V to ground) buffer amplifiers



Internal magnet voltage during quench may reach several hundreds of volts!

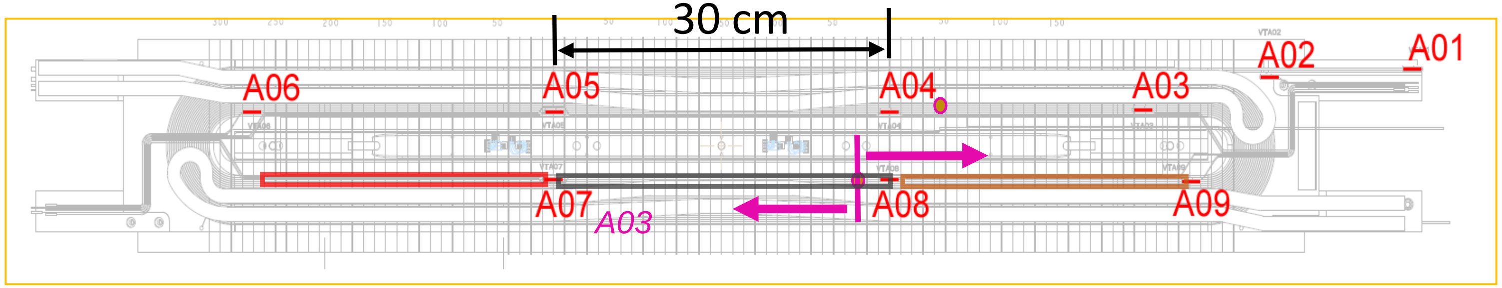
Voltage-based localization and quench propagation velocity



Acquisition is triggered by the quench detection system (trigger arrives at time “0”)

Accelerated propagation

Steady propagation



L_{A87}= 30 cm;
dt = (4.5 + 42.6) = 47.1 ms
=> V = 6.3 m/s

Quench starts ~ 3 cm from the A8 Vtap in the A87 segment segment

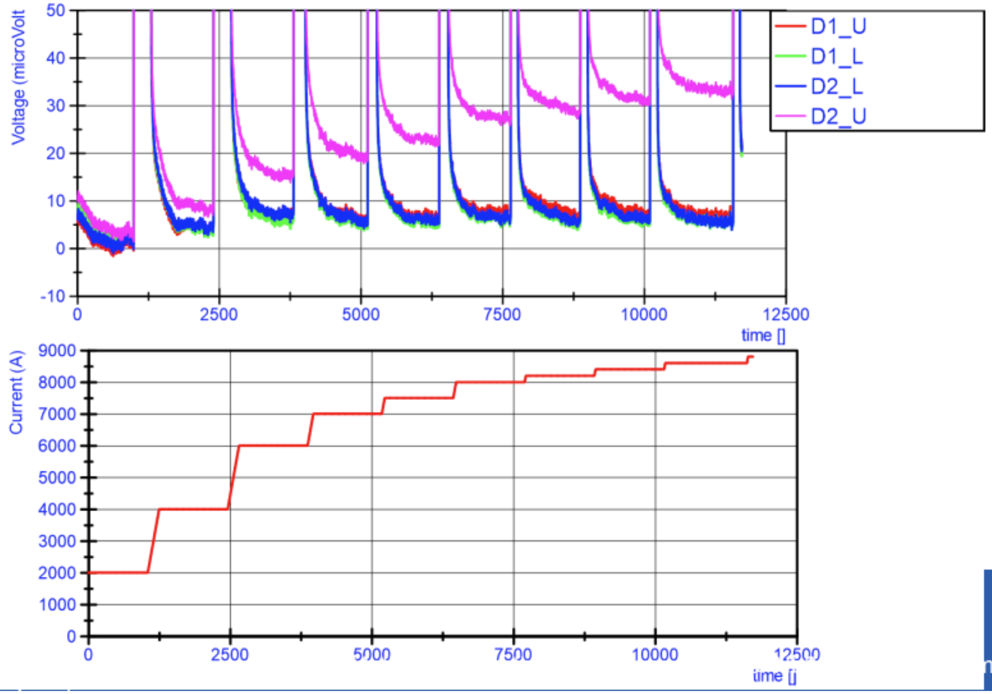
Low-level voltage measurements reveal conductor degradation

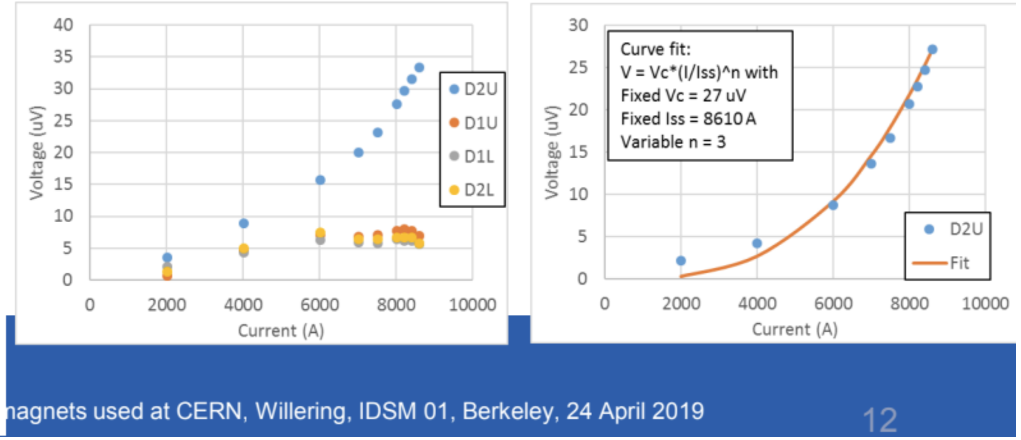
Challenge: Voltage measured over full 5.5 meter 56 turn coils (600 meter of cable)
Large effects of inductance and decay effects after each ramp!

Solution: Increase plateau duration to 20 minutes (3h measurement)
& compare 4 coils measurements

1 coil is clearly showing a resistive voltage buildup, of up to 30 uV at 8.8 kA.
The V-I curve, see below, can be fitted with linear curve, rather than the expected high n-value.

It proves a clear conductor degradation already showing at low current.





G. Willering, presentation at IDSM01 Workshop

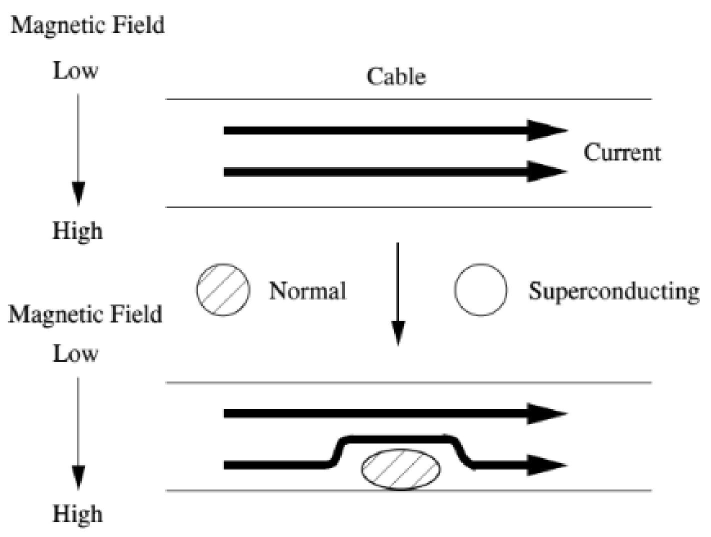
Magnetic quench antennas

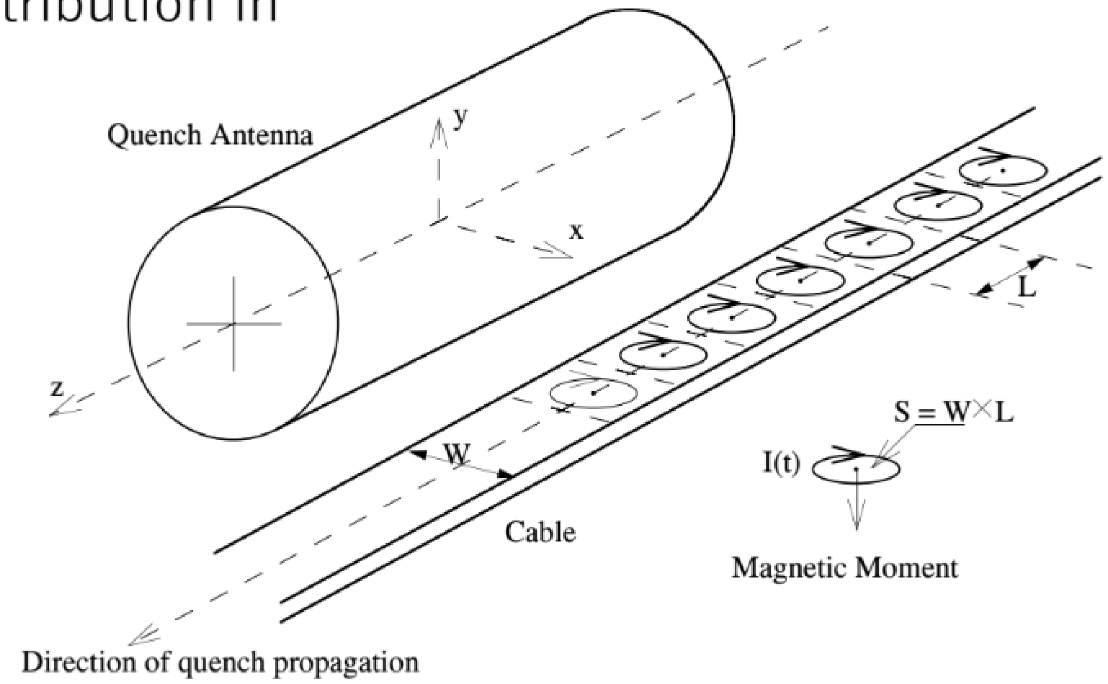
Principle of operation

Magnetic Quench Antenna

Issue:
How to cancel noises due to main field fluctuation

- Detect Magnetic Field Perturbation caused by current redistribution in quench front



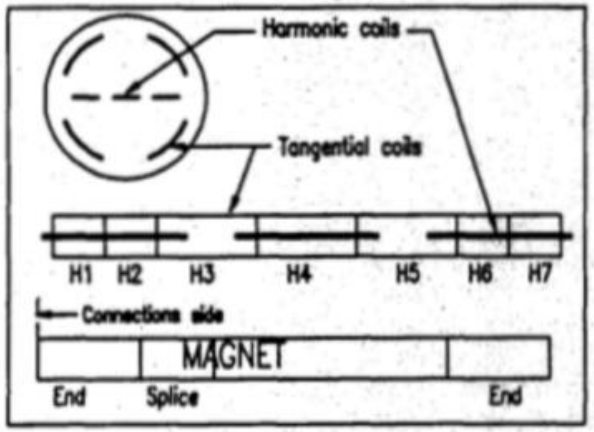


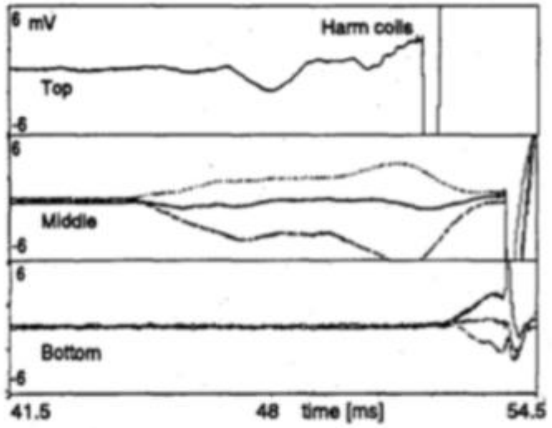
T. Ogitsu, presentation at IDSM01 Workshop

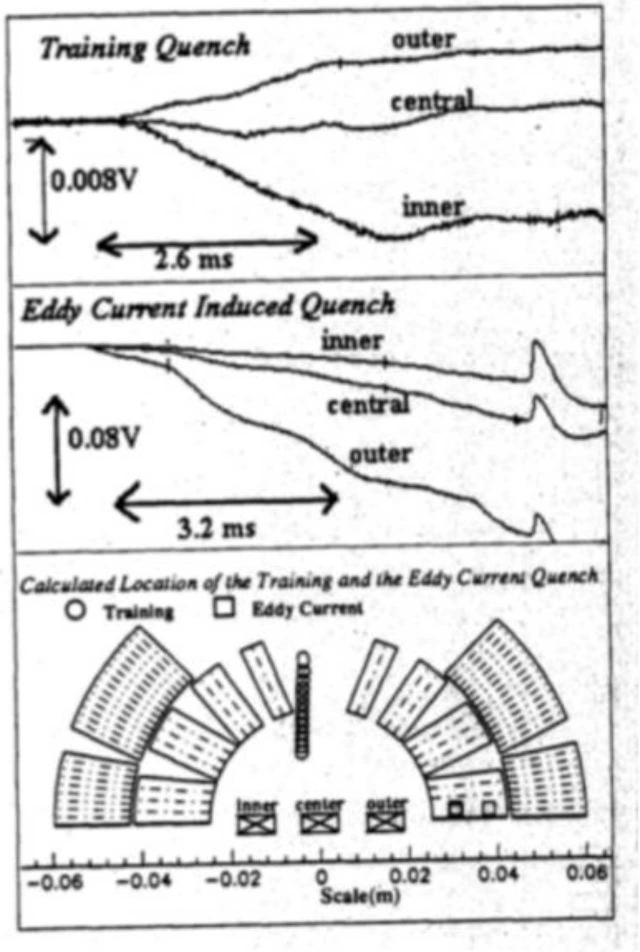
First quench antennas

Beginning of Quench Antenna

- First concept is proposed by Jacek Krzywinski in early 1990's
  - "Quench Observation in LHC Superconducting One Meter Dipole Models by Field Perturbation Measurements," D. Leroy et.al. 1993
  - Adapted for two in one magnet; use other aperture for noise cancel

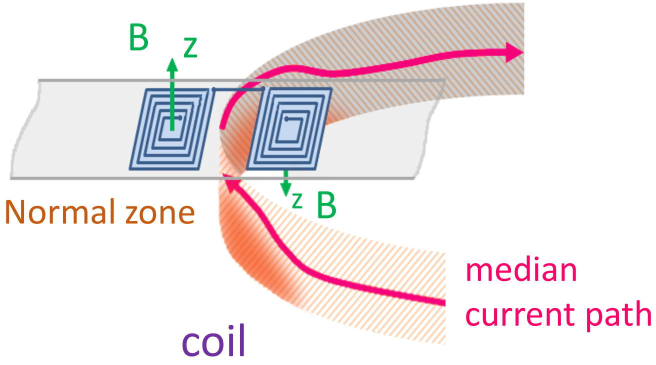


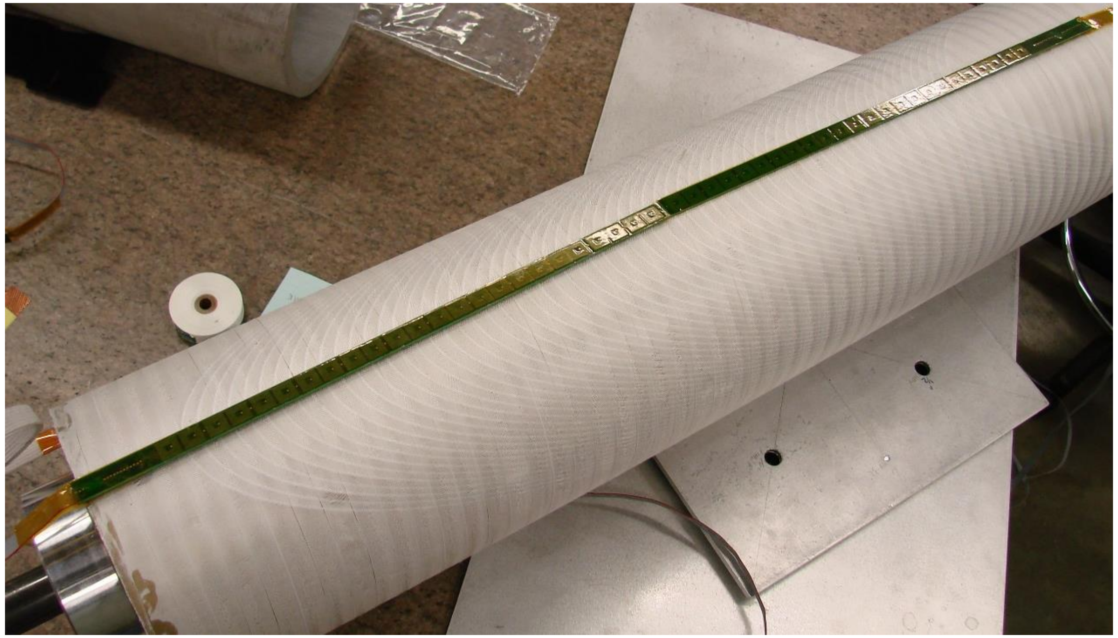




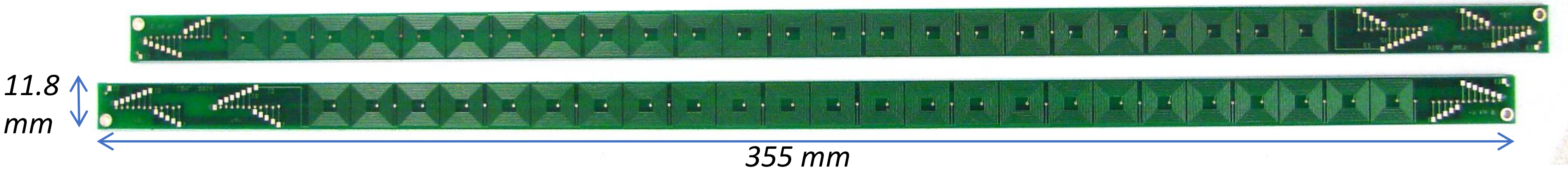
T. Ogitsu, presentation at IDSM01 Workshop

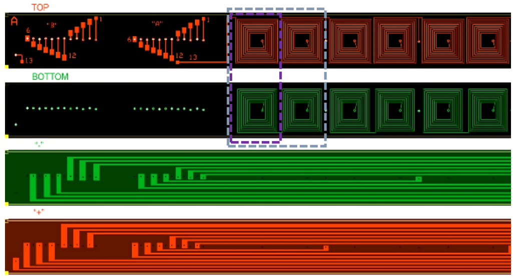
Linear array PCB antenna (CCT)





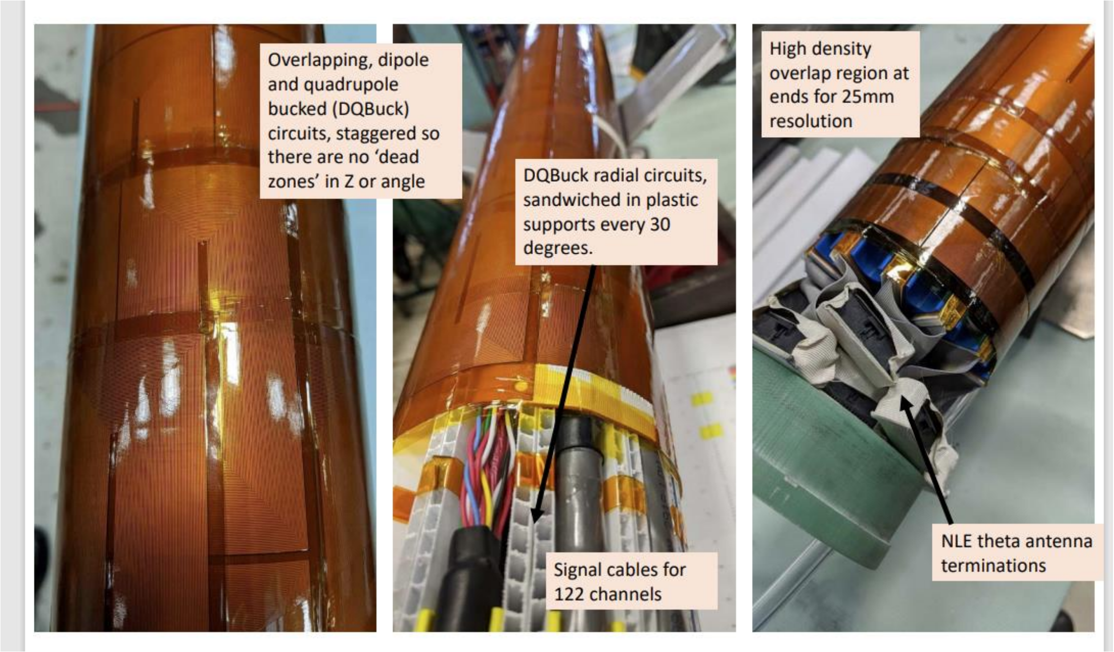
A linear array of 24 printed square coils (each is 2 layers, ~20 turn total, ~1 cm side). Coils are dipole-bucked thus forming 12 independent sensors per array. Two arrays can be further “stacked” linearly with a flat ribbon jumper, to have all 24 sensors interfaces from one end of the assembly.





Flexible PCB-based quench antennas

R. Teyber, D. Arbelaez, LBNL



J. DiMarco, S. Stoynev, FNAL

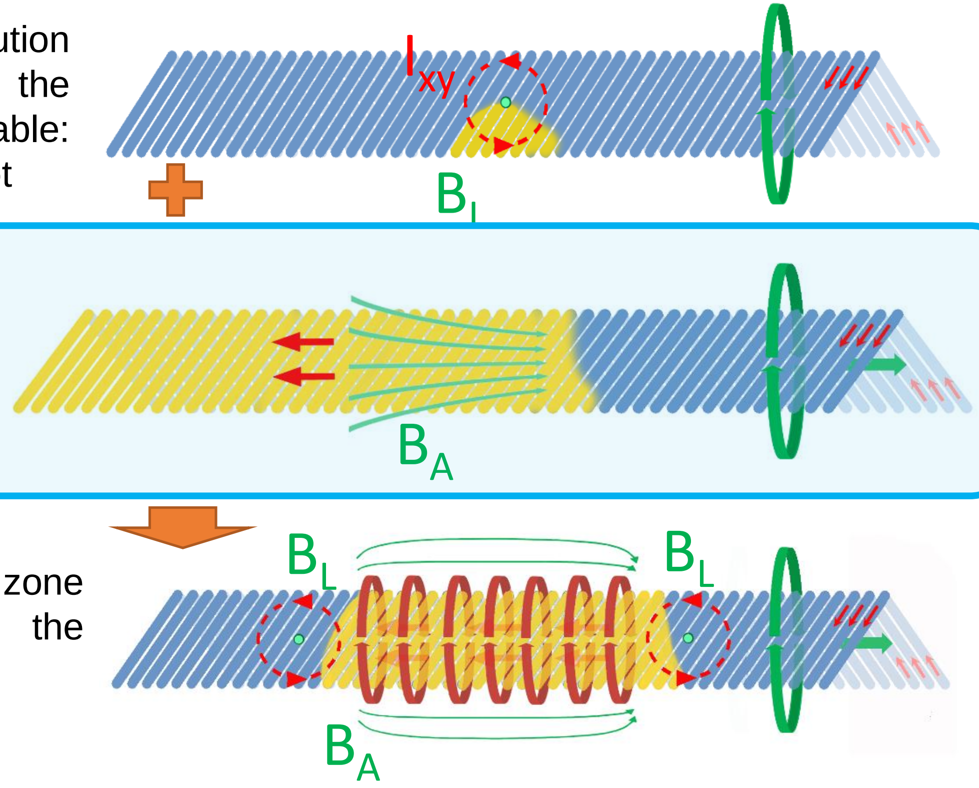
Axial field "quench antenna": the principle of operation

Field variation due to a developing quench:

1. Current re-distribution in-plane of the superconducting cable: avoiding the hot spot

2. Breakdown of a solenoidal current path in the cable

3. Normal zone expands along the cable



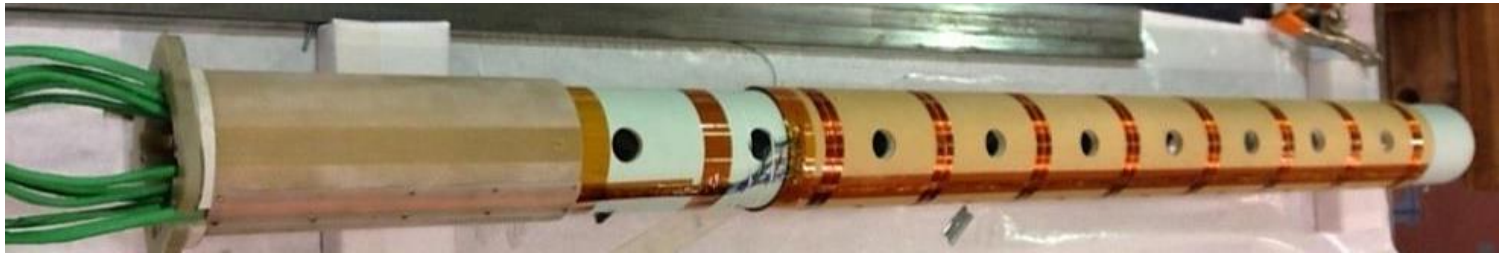
"Magnetic Detection of Quenches in High-Field Accelerator Magnets", M. Marchevsky, J. DiMarco, H. Felice, A. Hafalia, J. Joseph, J. Lizarazo, X. Wang, G. Sabbi, *IEEE Trans. Appl. Supercond.* 23, 9001005 (2013), DOI: 10.1109/TASC.2012.2236379

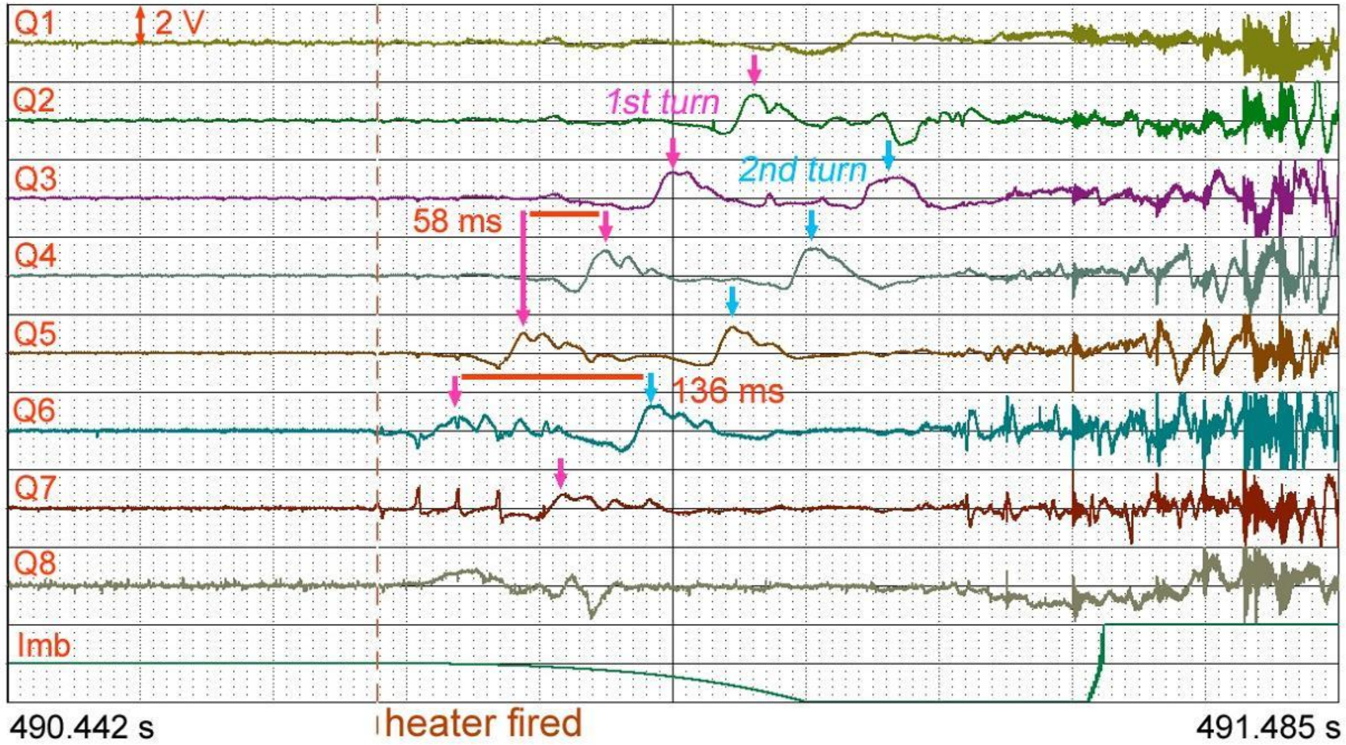
Relying on the axial field component for quench localization has some advantages:

- Better S/N ratio (as accelerator magnets normally **do not have** axial field inside bore)
- Less shielding by the walls of the bore tube (and/or the anti-cryostat), especially at high frequencies

LBNL's first axial field quench antenna

Senses axial gradient of the axial field



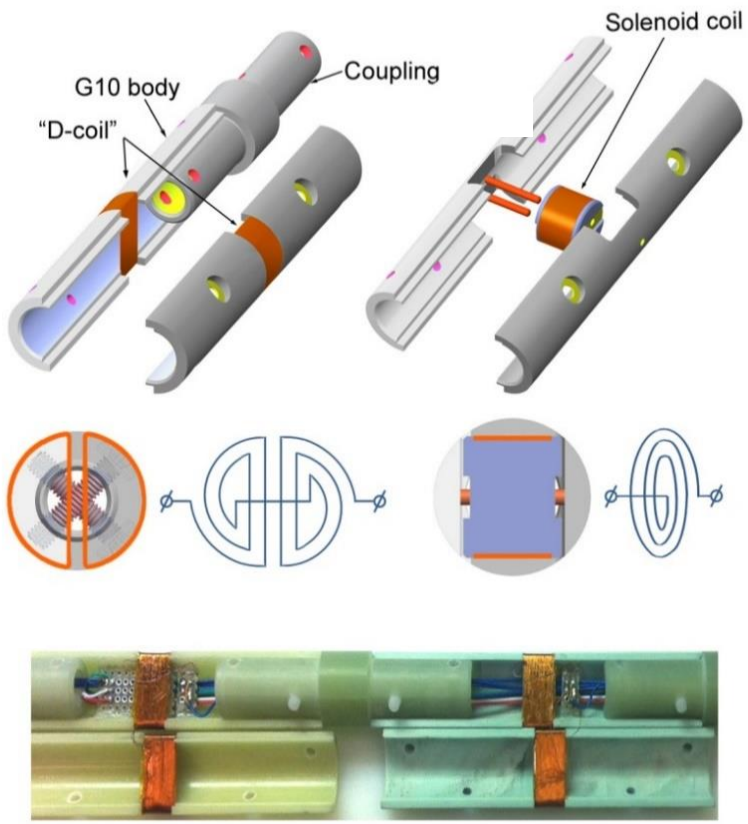


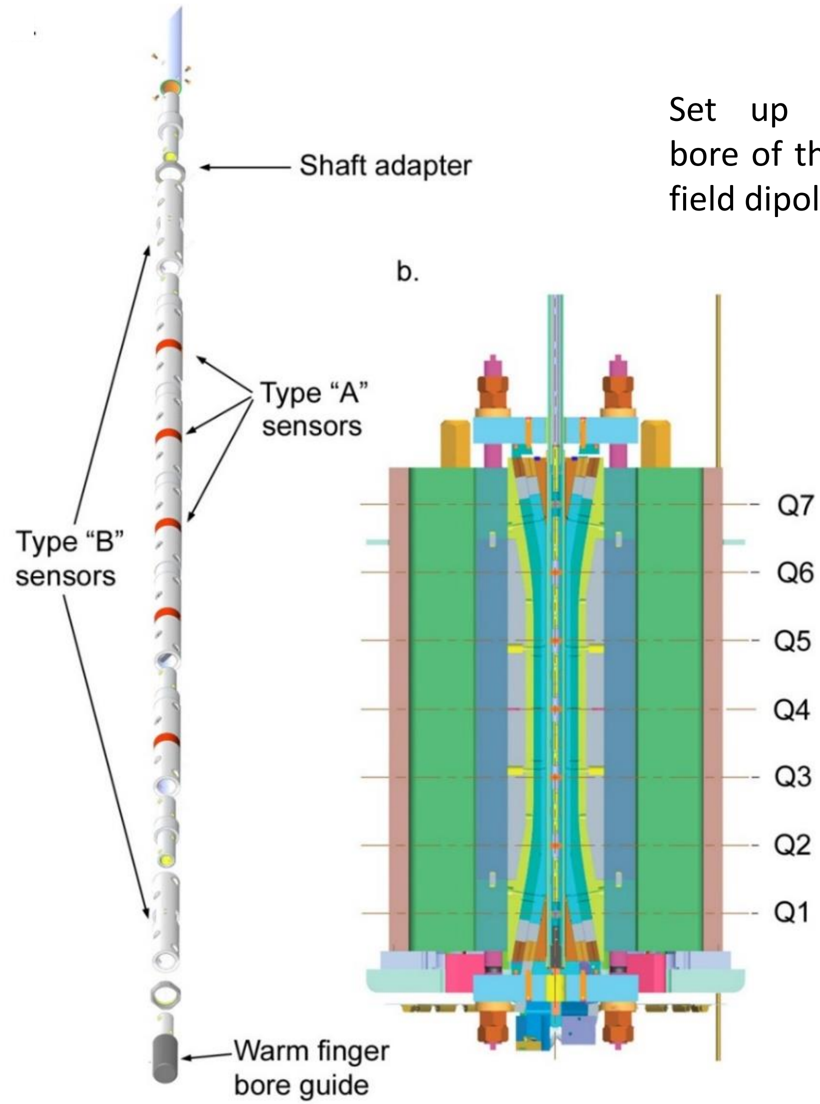
Development and propagation of a slow quench in HQ02b at 6 kA

- Does not take up space in the bore
- Easy to build and implement
- Shows excellent sensitivity and good spatial selectivity to quenches

Axial field quench antenna II (dipole adapted)

Senses off-axis gradient of the axial field



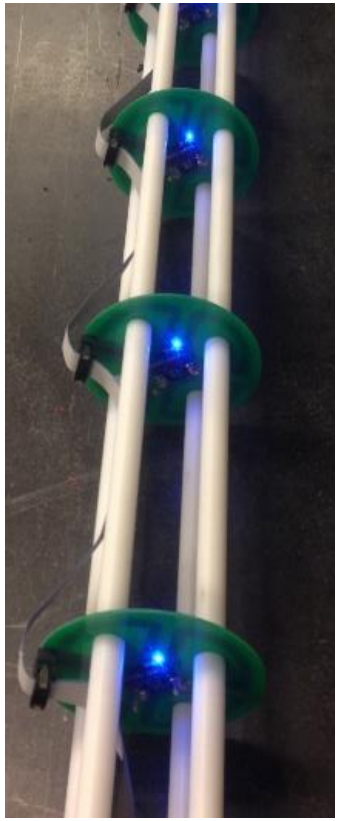


Set up in the bore of the high-field dipole HD3b

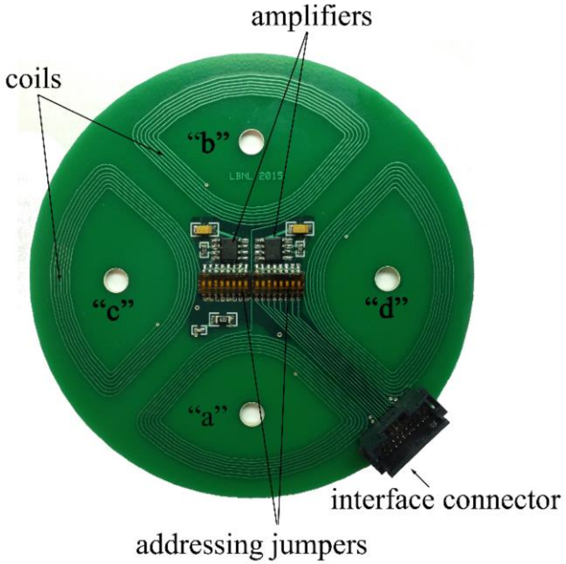
"Axial-Field Magnetic Quench Antenna for the Superconducting Accelerator Magnets", M. Marchevsky, A. R. Hafalia, D. Cheng, S. Prestemon, G. Sabbi, H. Bajas, G. Chlachidze, *IEEE Trans. Appl. Supercond.* 25, 9500605 (2015), DOI: 10.1109/TASC.2014.2374536

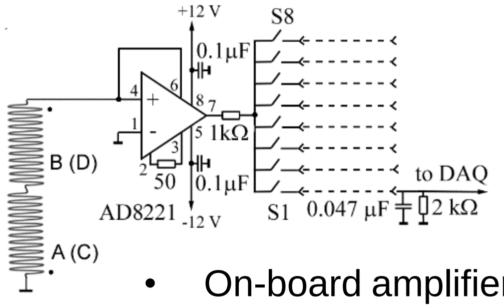
Round PCB antenna (QXF quadrupole adapted)

Senses <u>off-axis</u> gradient of the axial field

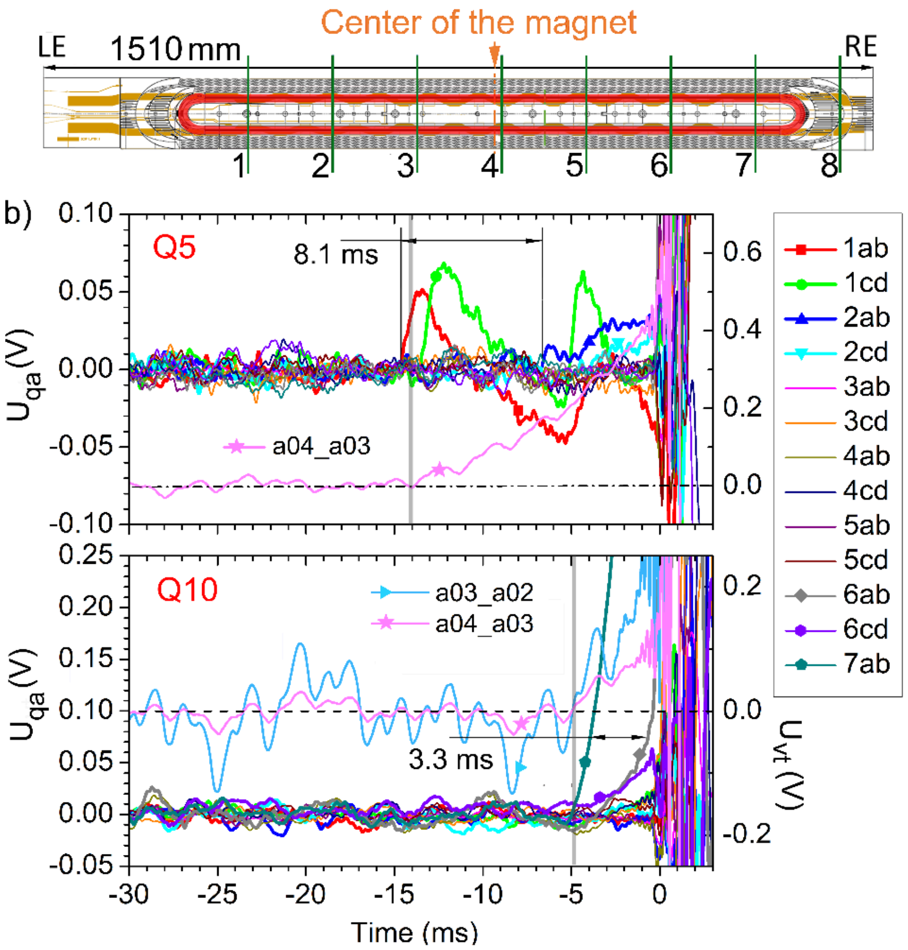


- Modular design





- On-board amplifier

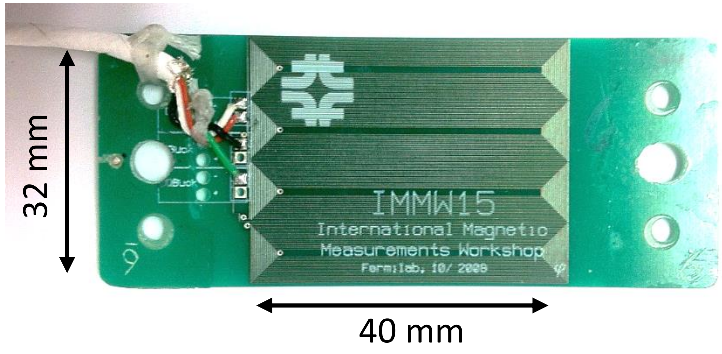


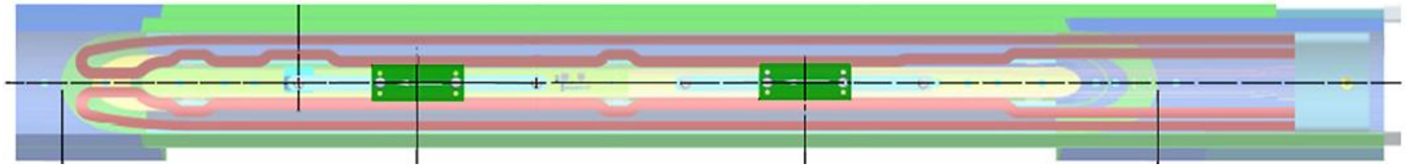
Quench localization in MQXF-S quadrupole

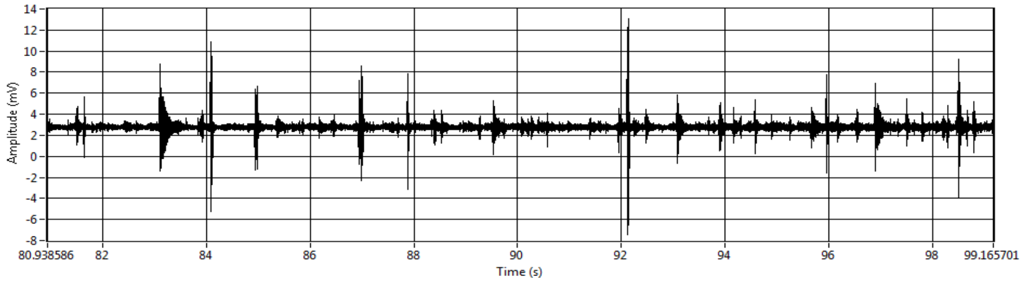
"Magnetic Quench Antenna for MQXF quadrupoles", M. Marchevsky, G. Sabbi, S. Prestemon, T. Strauss, S. Stoynev and G. Chlachidze, IEEE Trans. Appl. Supercond. 27, v. 4, 9000505 (2017), DOI: 10.1109/TASC.2016.2642983

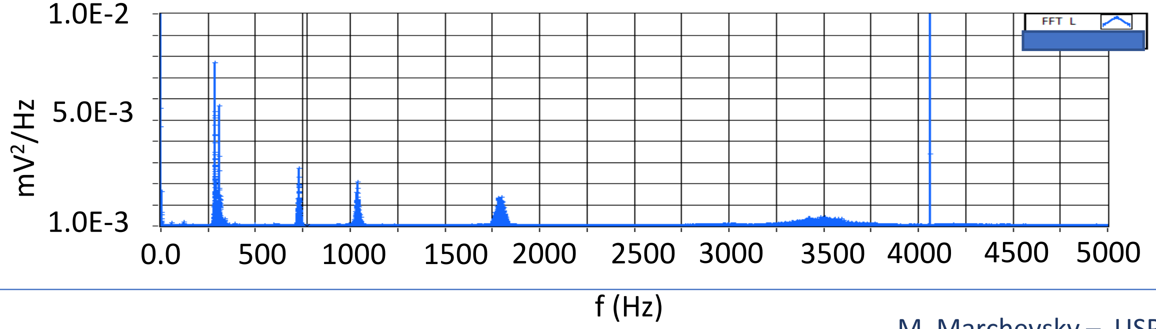
PC board “quench antennas”

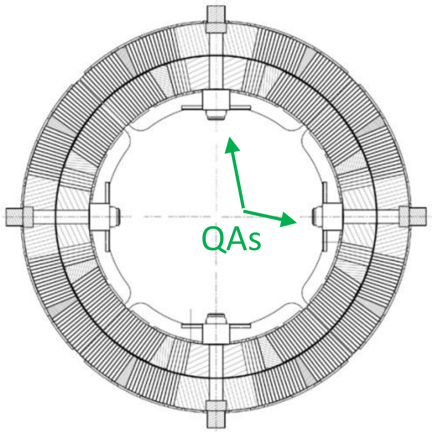
Magnetic measurement boards developed by J. DiMarco at FNAL were adapted as “inductive “pickup” sensors in HQ01d quadrupole test

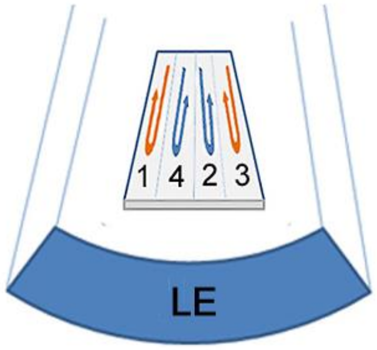












Direct sensing of vibrational coil modes and (possibly) conductor motion!

Acoustic emission

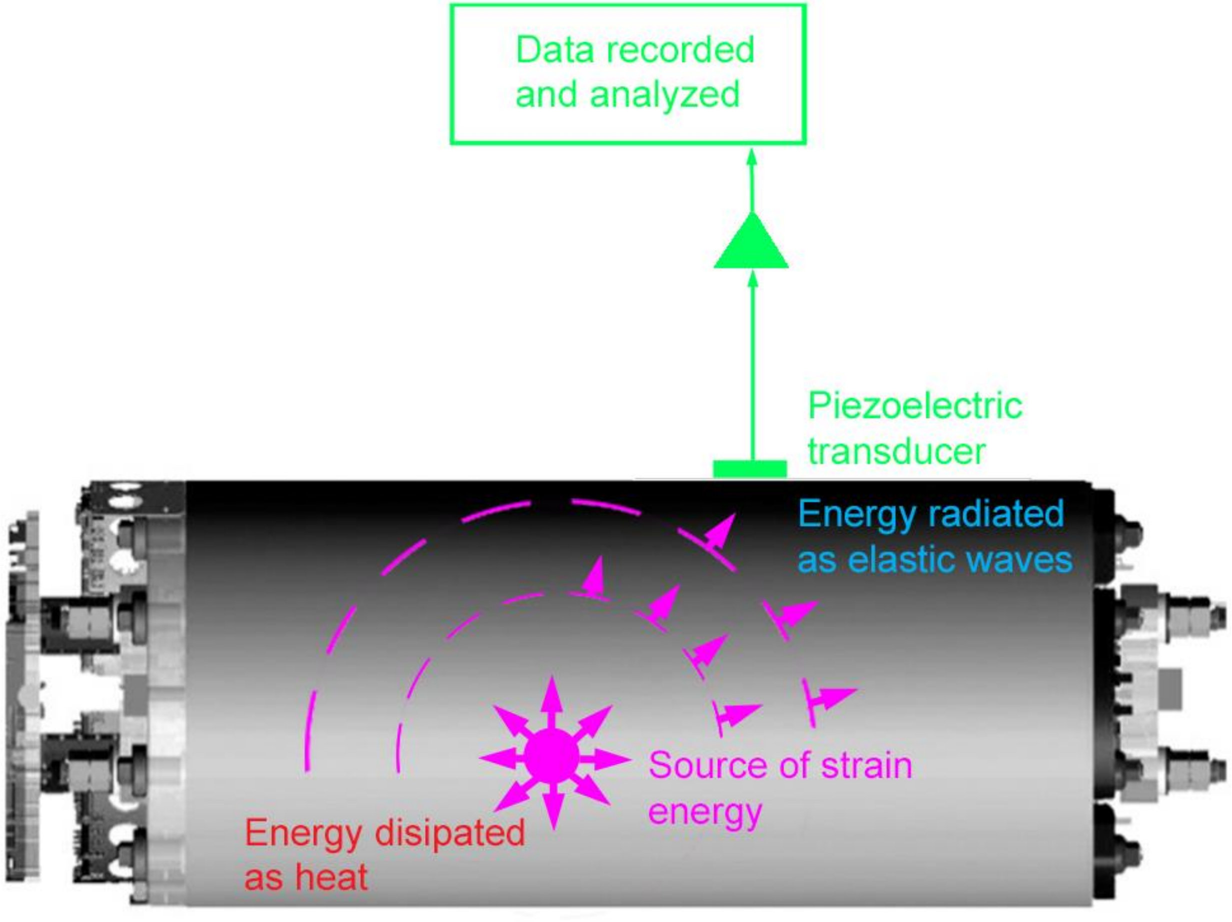
Causes of acoustic emission in magnets

Singular events	Continuous perturbations
Mechanical • Cracking / fracture of epoxy, de-laminations • Sudden mechanical motion of conductor or structural part **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 at sub-millisecond time scale, 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).

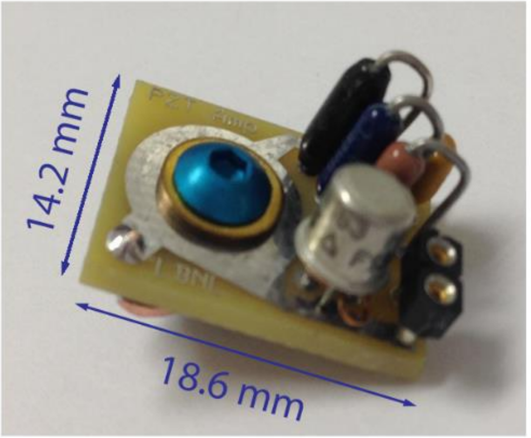
Advantages of AE diagnostics



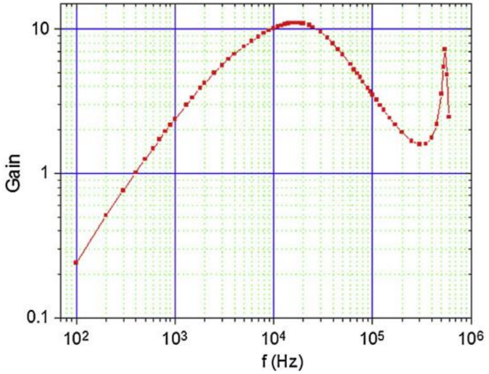
Wave conversion… absorption… acoustic impedance mismatch…

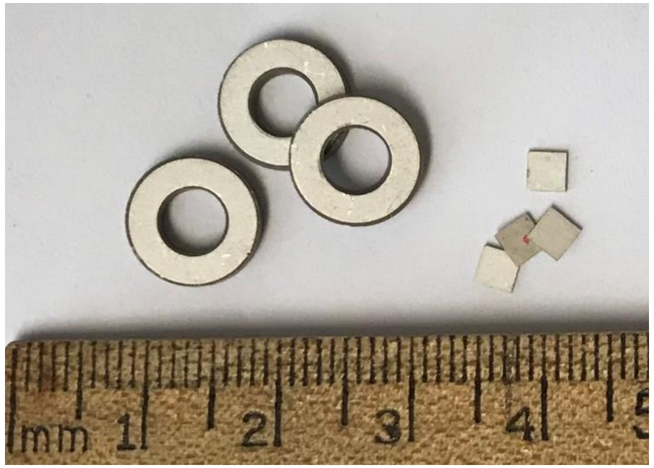
- Sound propagation velocity is several km/s), so that detection time scale is comparable (or faster) to other techniques
- Sound sources can be localized through triangulation
- Sensors can be installed on the outer surfaces – non-intrusive
- Immune to magnetic fields
- Sensors and acquisition hardware are relatively inexpensive, portable and easily adaptable to various magnet configurations

Amplified piezo-sensors for AE studies

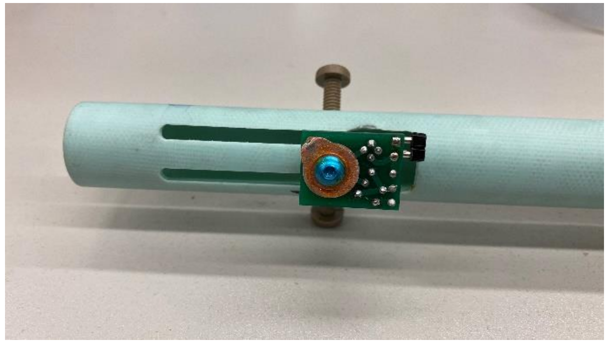


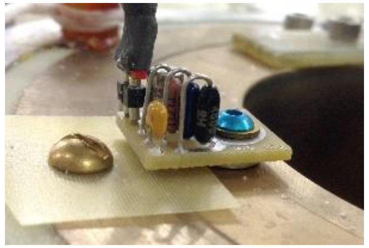
Cryo-amplifier board





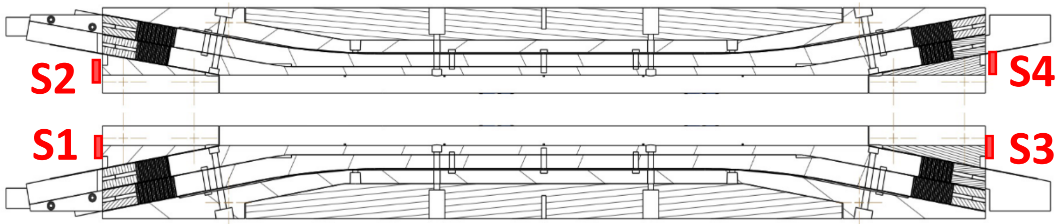
Piezoelectric transducers





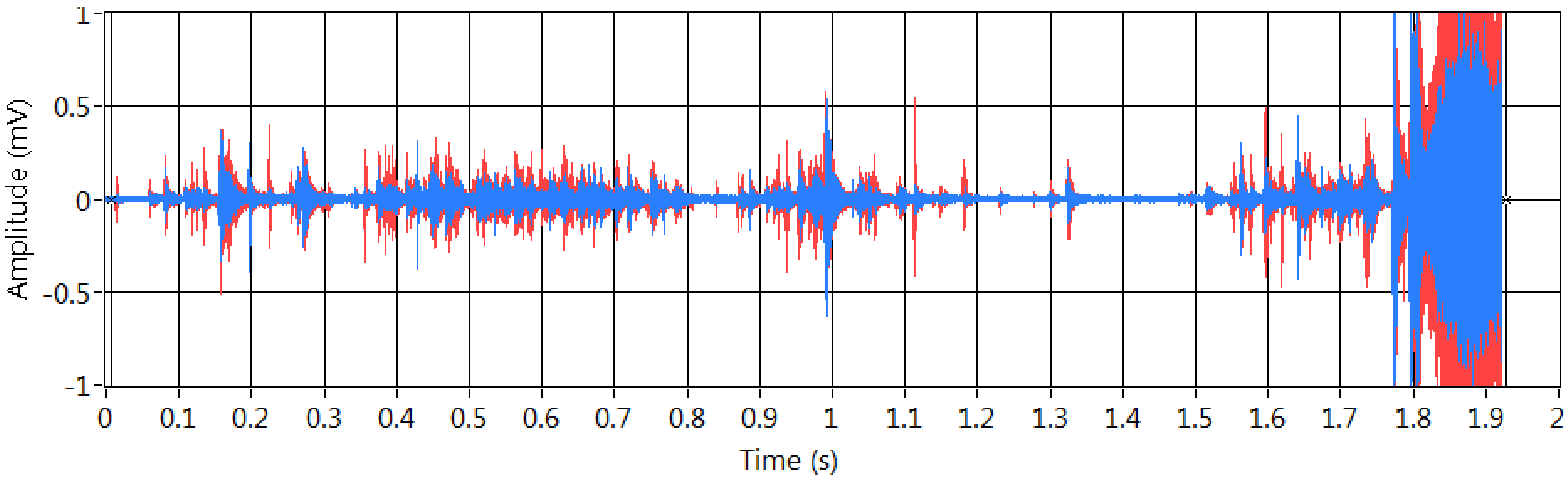
Various AE sensors and mounting hardware (LBNL)

Nb_3Sn dipole quench sound example



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

Quench A76 at 16042 A

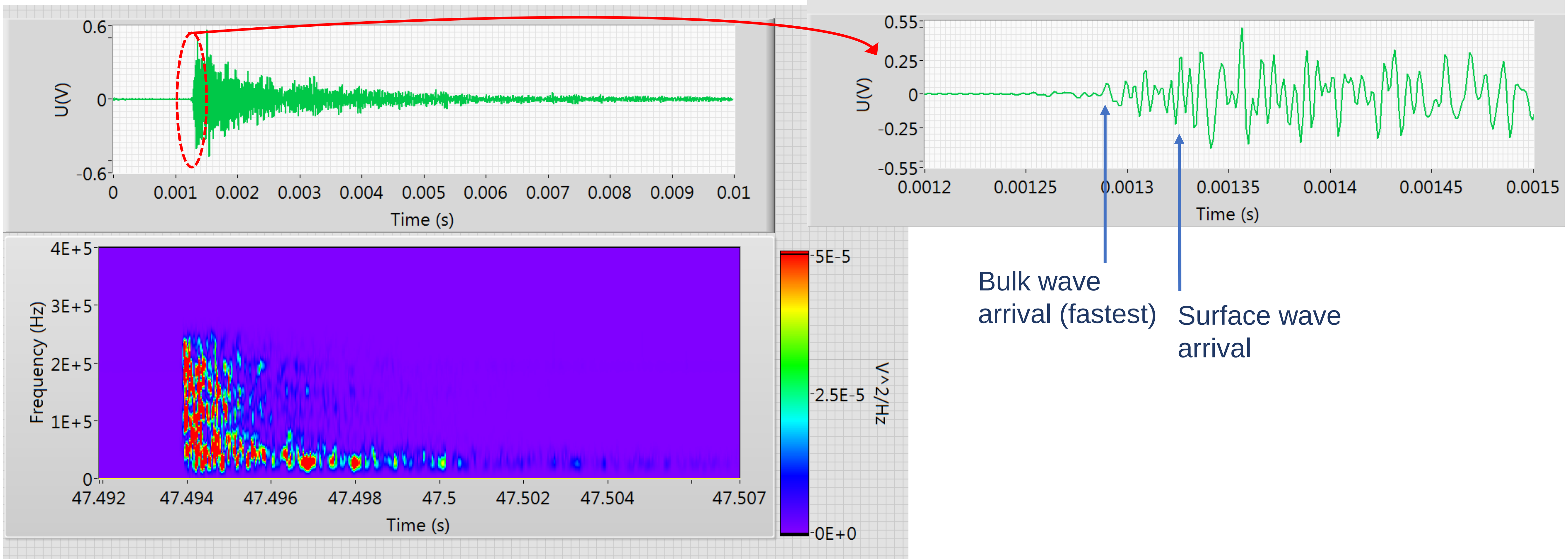


Sensor S1 (blue) -> Left sound channel
Sensor S4 (red) -> Right sound channel

Original sound slowed down 10 times

Spectrogram of a typical acoustic transient

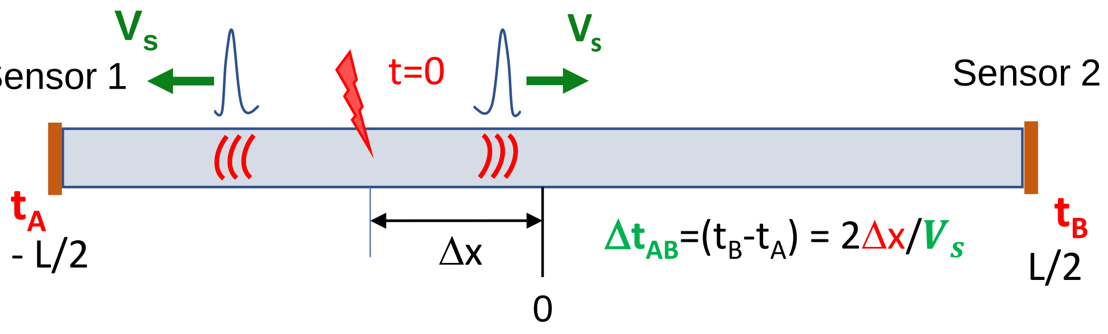
CCT4, ramp to quench #1



- Frequencies up to ~250 kHz are present
- “Ring down” with a characteristic timescale of 1-5 ms
- Low-frequency “tale”

Quench localization using AE

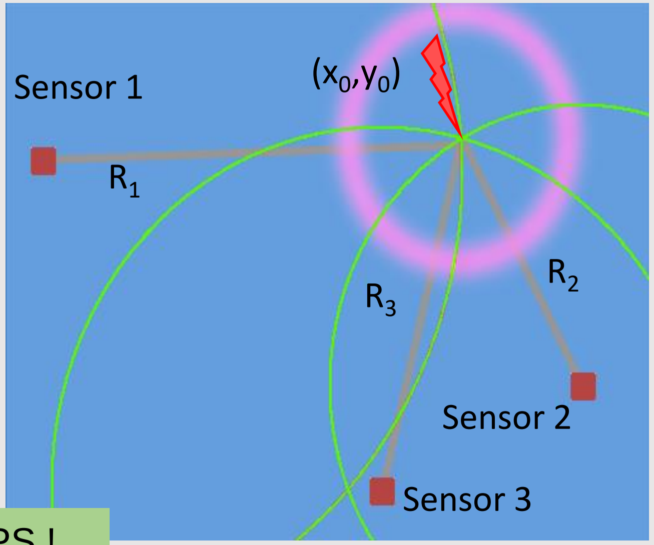
Axial localization



2D (3D) localization

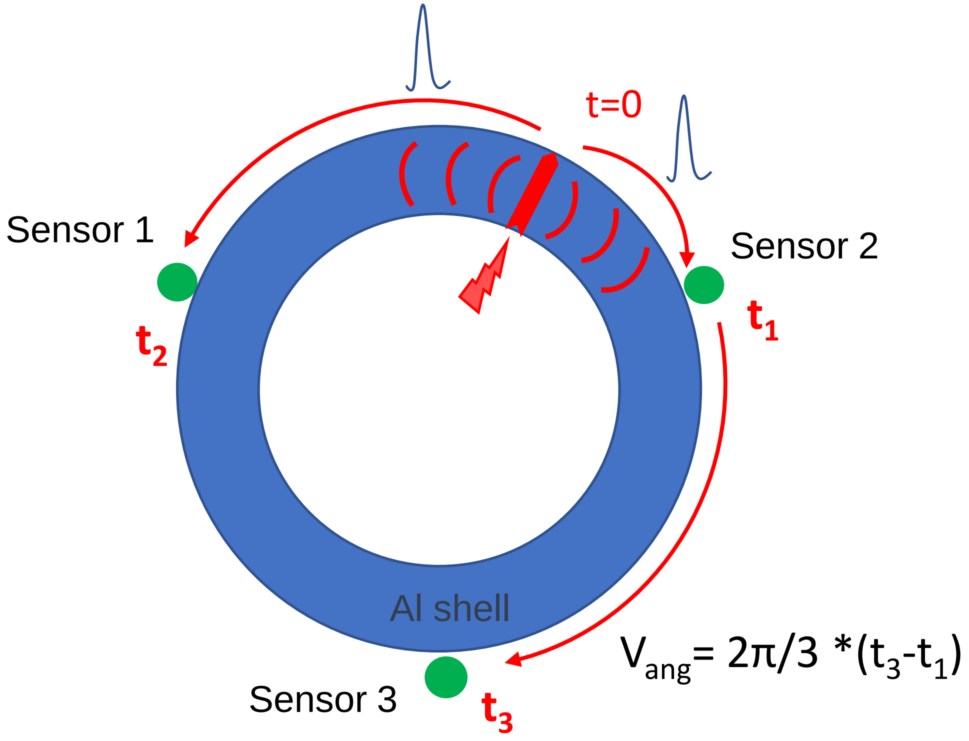
2D

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



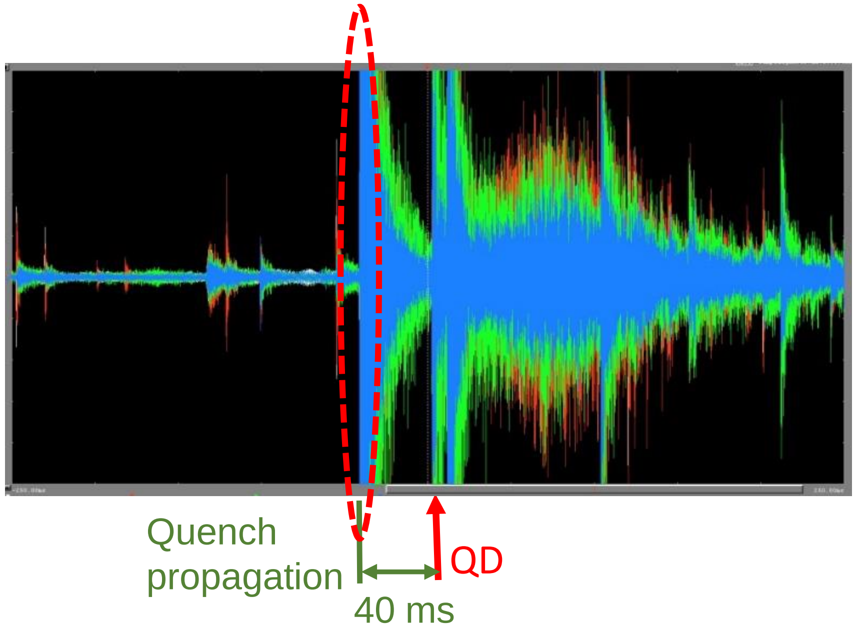
Think GPS !

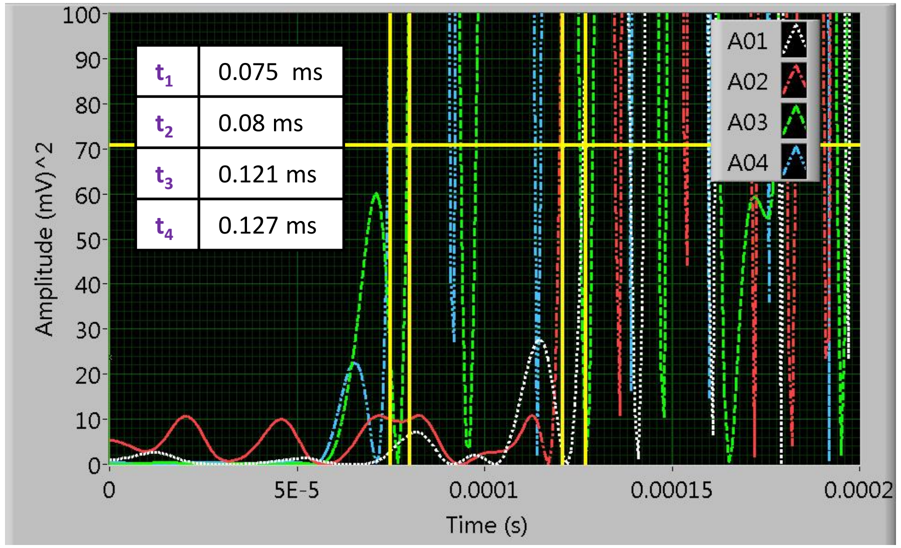
Angular localization

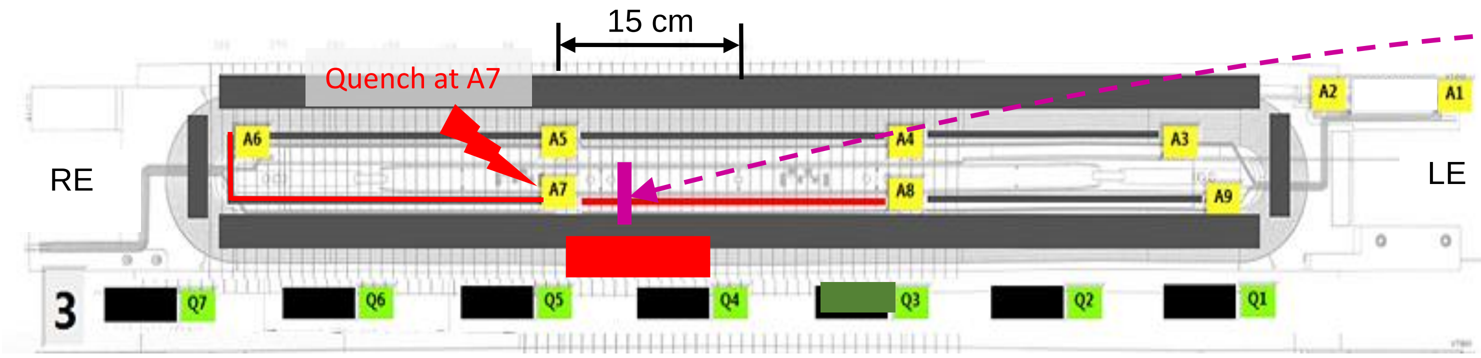


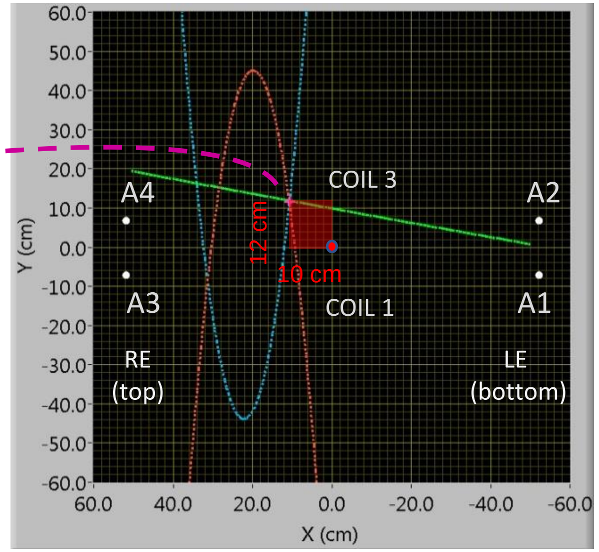
On a cylindrical surface localization using quasi-2D approach can be sufficiently accurate

Triangulating a quench in 2D



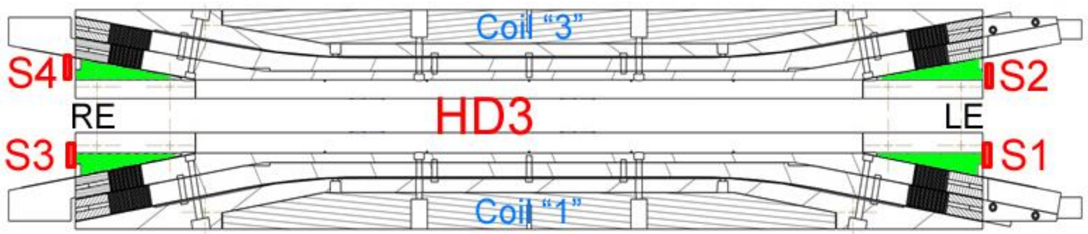


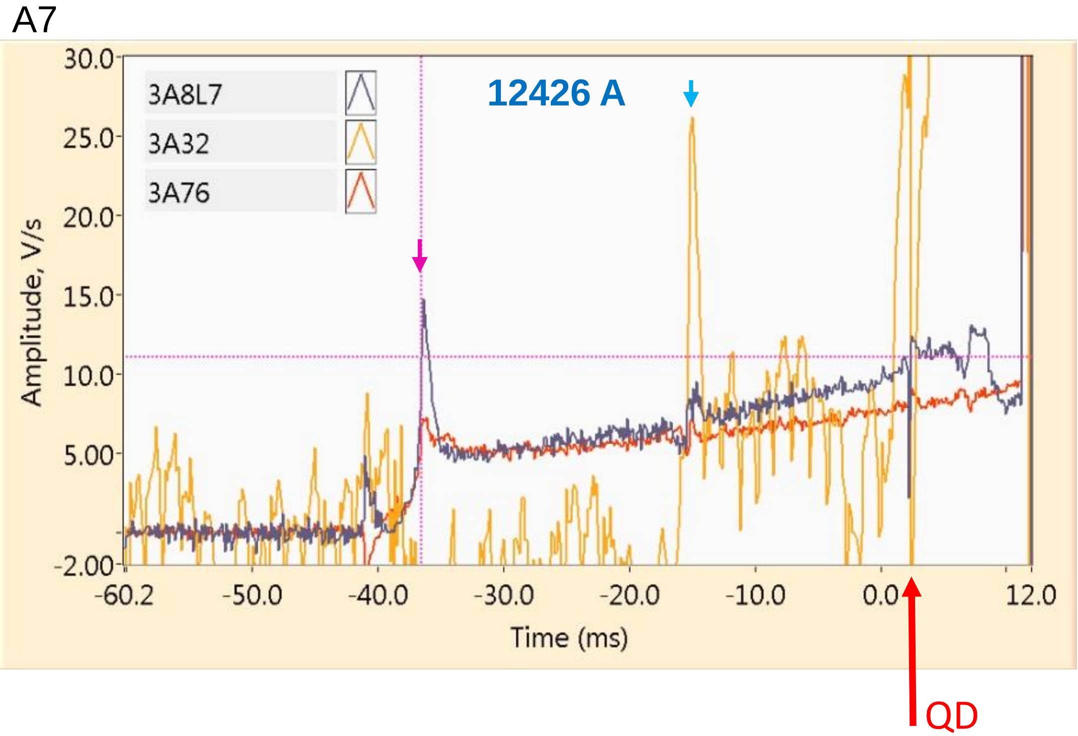


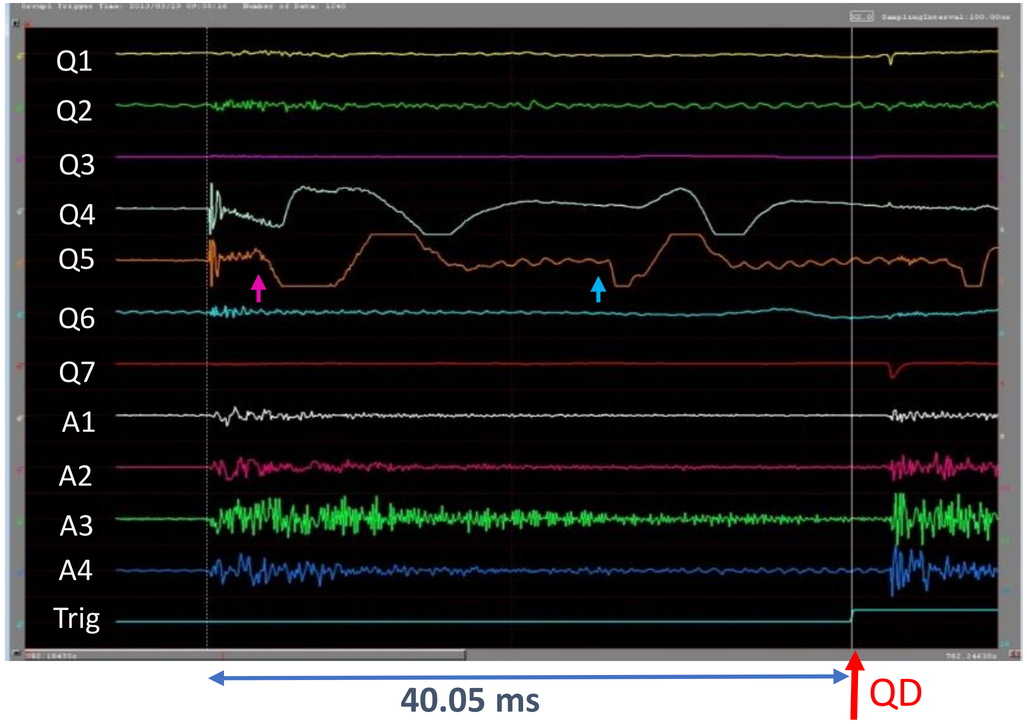


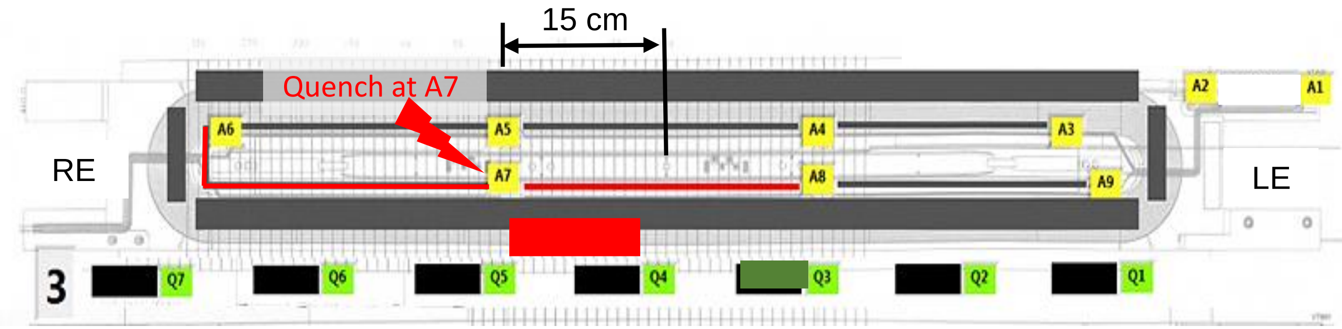
v_s= 4.3 km/s

Combined diagnostics for quench studies

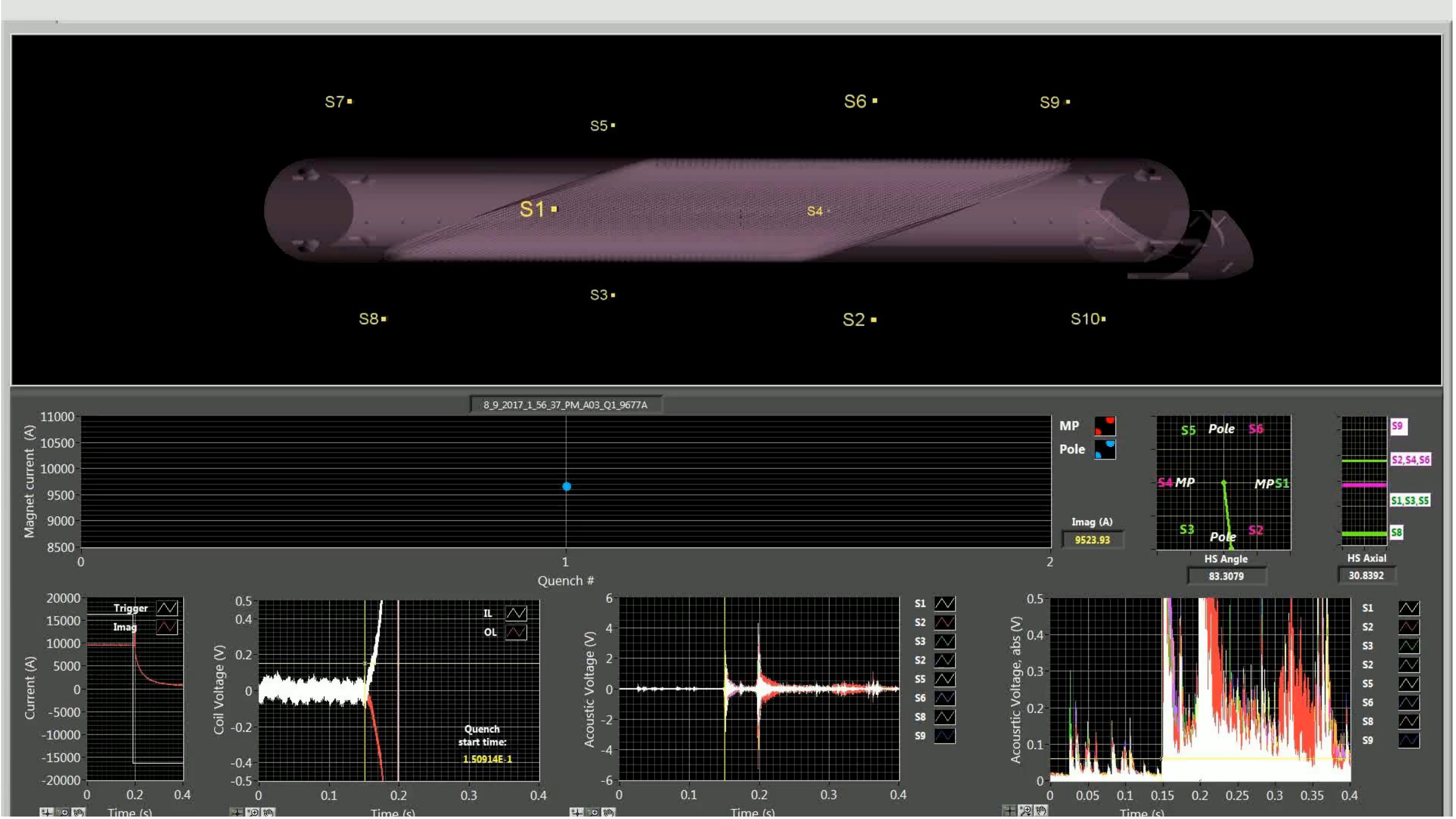






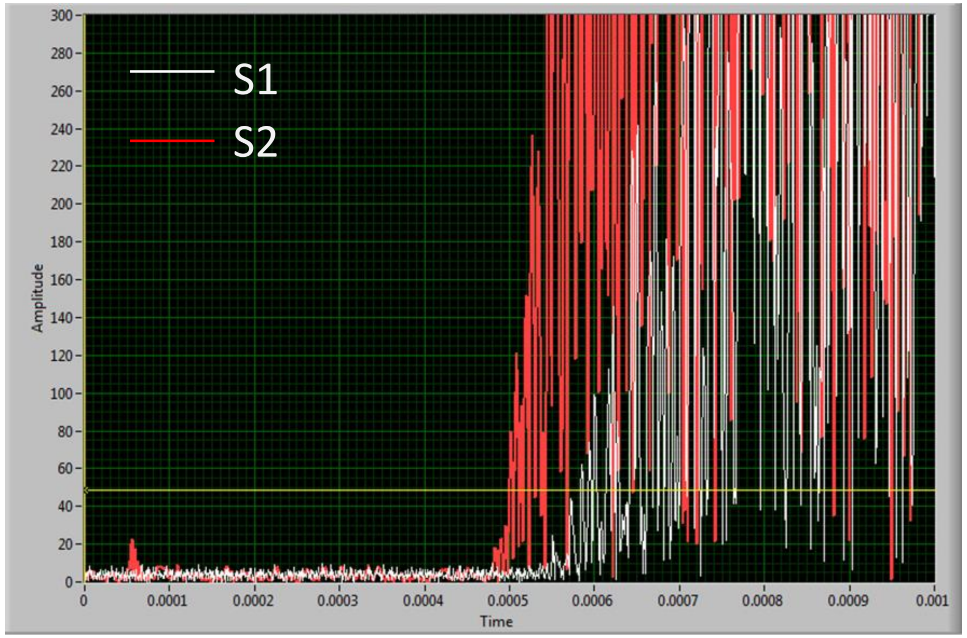


Example: quench localization in a CCT dipole

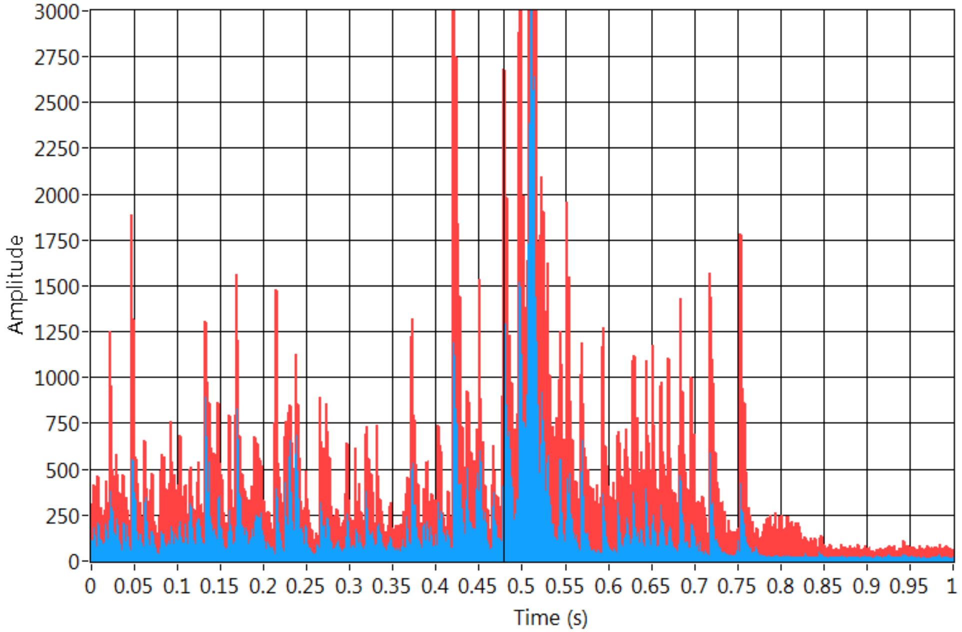


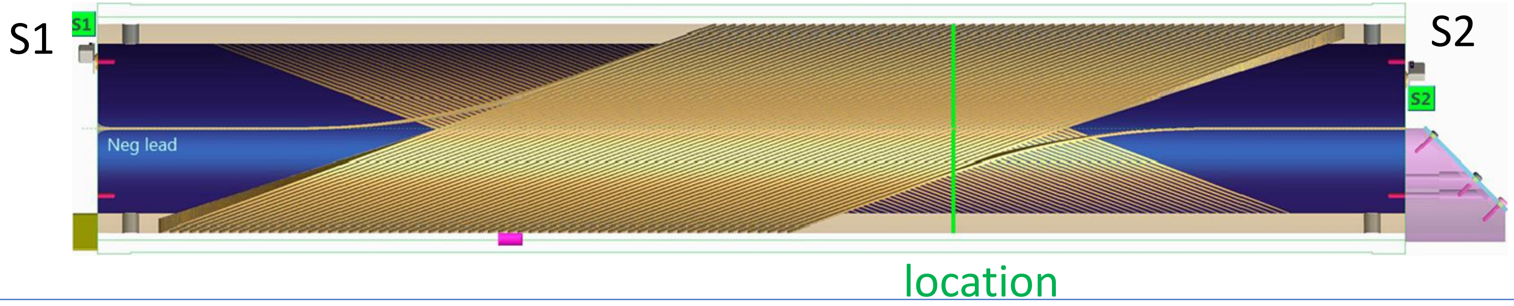
Localized vs distributed AE sources

A localized event: information on the azimuthal location

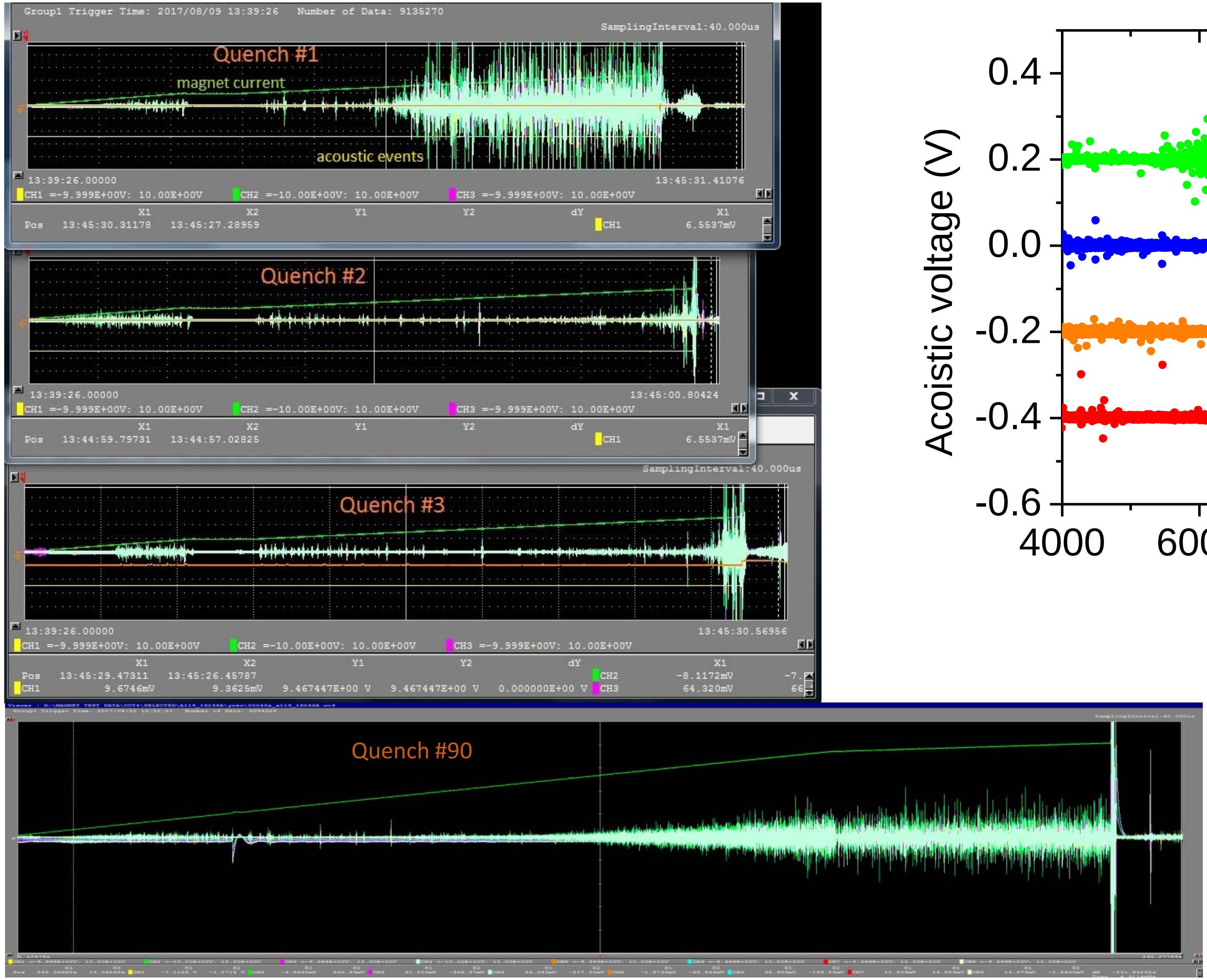


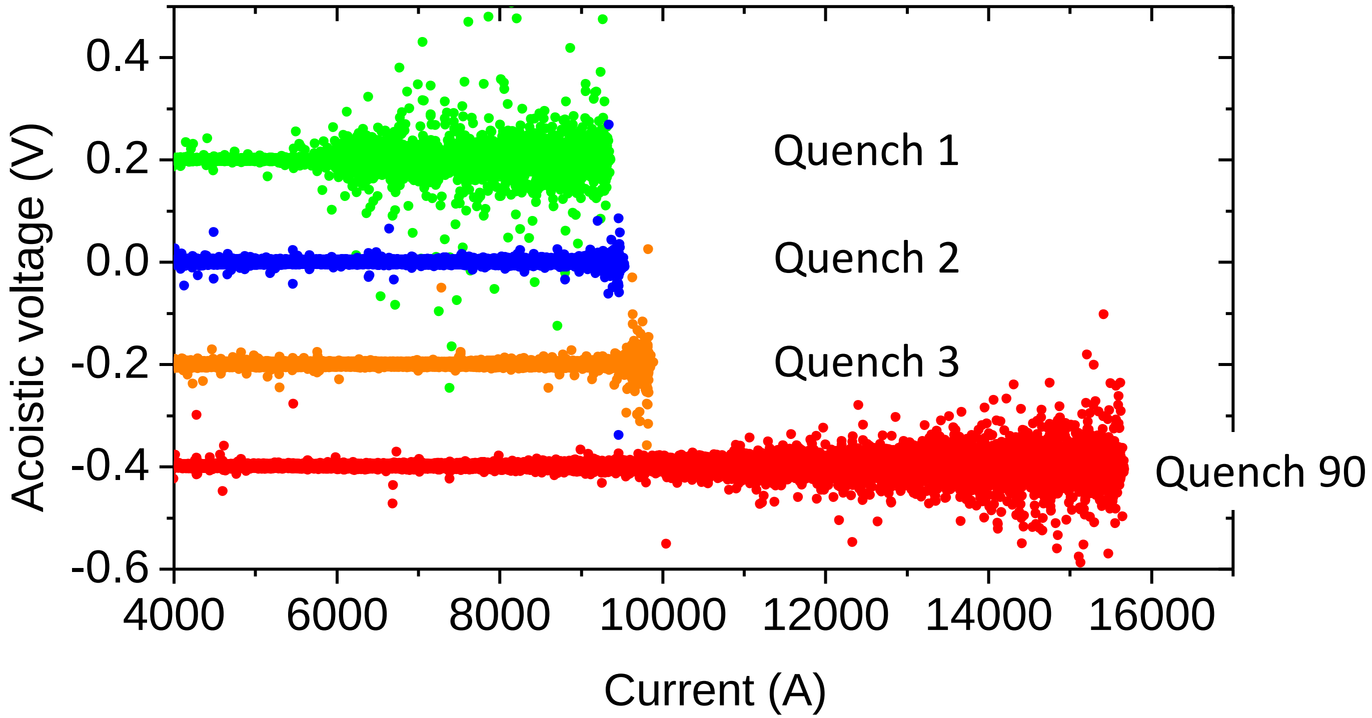
A "distributed" event…. No localization





Mechanical memory of the magnet

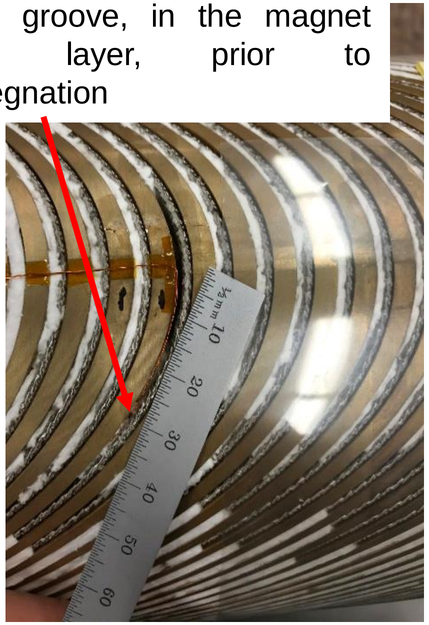


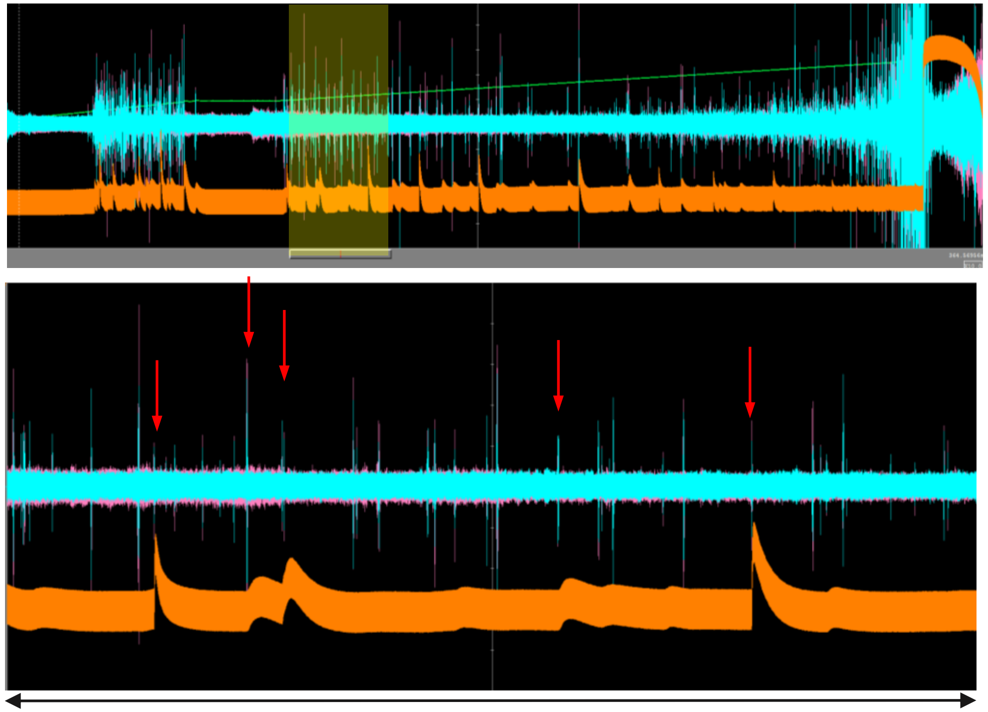


- CCT4 magnet shows mechanical memory in the initial quenches (Kaiser effect)
- However, as training progressed, noise grows in amplitude towards the quench, erasing the memory effect.

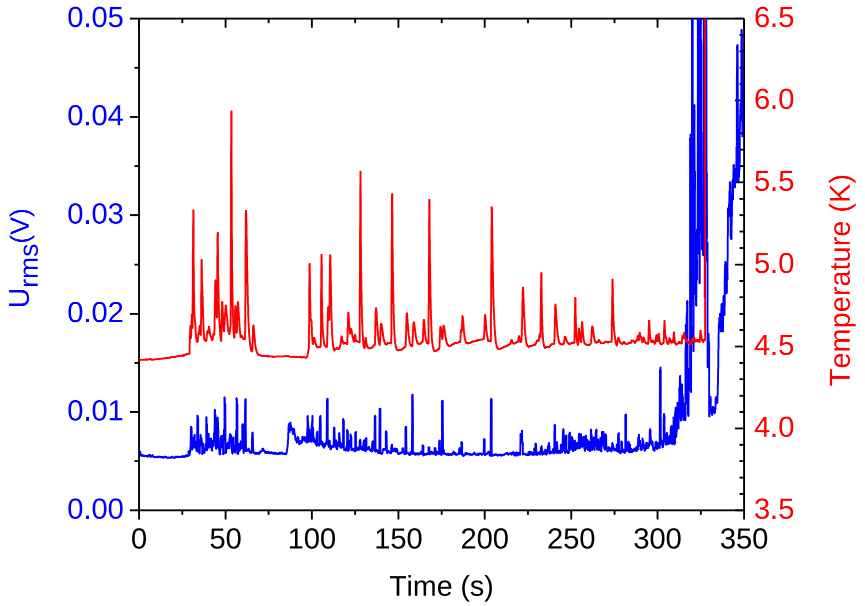
Thermal and acoustic spikes are correlated

A thermometer of ~1 mm^2 size was installed directly in the cable groove, in the magnet outer layer, prior to impregnation





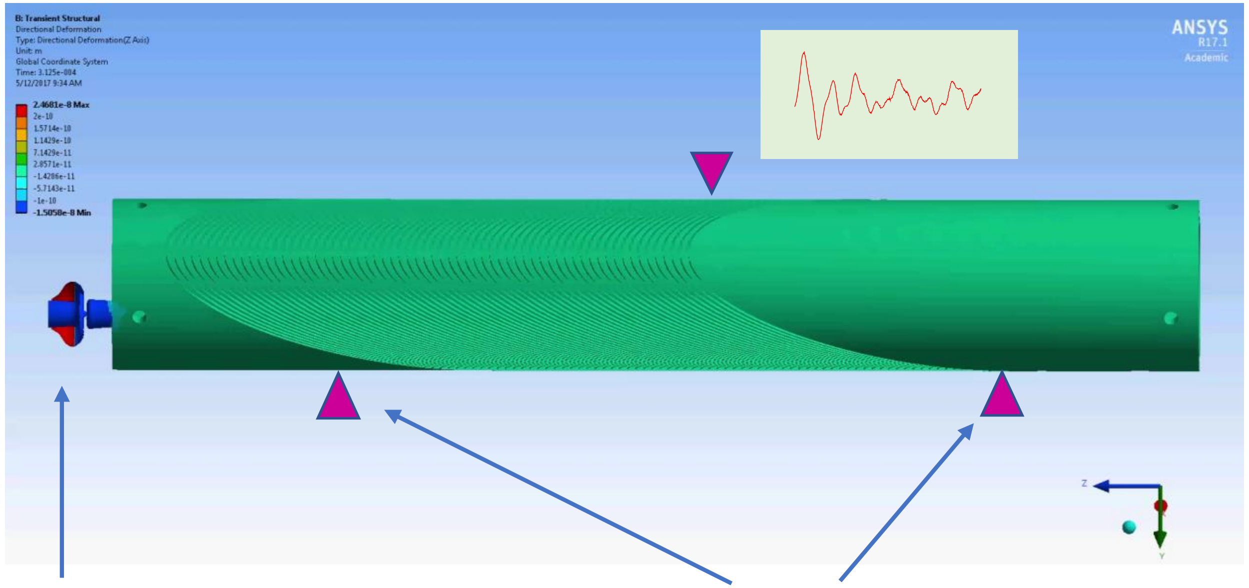
~ 36.5 s



- Temperature spikes as high as 1 K are observed in the "cracking" regime. All of them are time-correlated with the acoustic events, and few also correlate with voltage spikes on the coils
- A minor (< 20 mK) gradual temperature rise, or none at all is seen in the "slip-stick" regime prior to quenching

Active monitoring of mechanical integrity

ANSYS simulation of transient deformation in the CCT mandrel upon pulsing a piezo-transducer



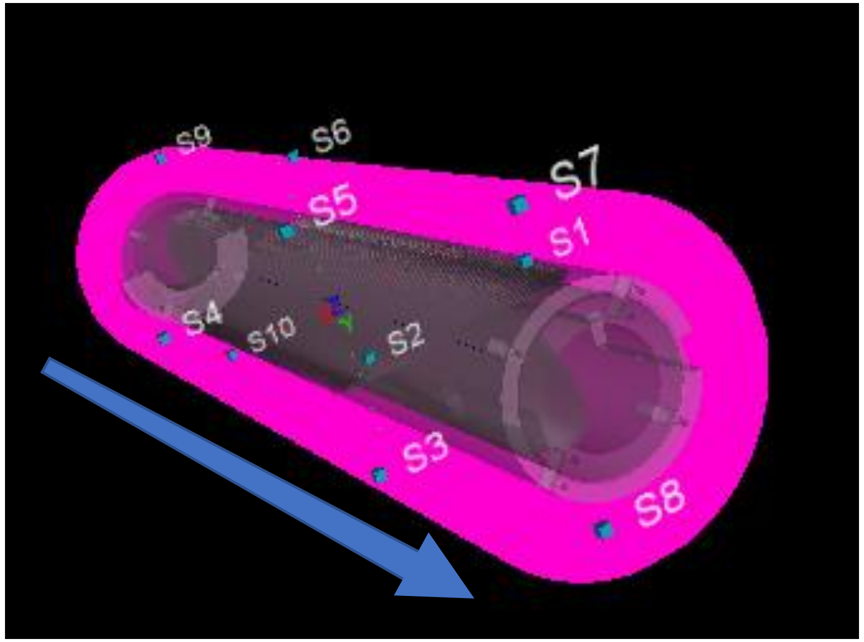
Ultrasonic pulser transducer

Receivers

- **Coil is pulsed using a piezo-transducer, and resulting perturbation is recorded by sensors distributed along the magnet**
- The ring-down deformation x(t) at any location is **uniquely defined** by the magnet geometry, Young's moduli of the materials, and their mutual **interfaces**
- Acoustic wave reverberates multiple times thus allowing to **detect structural perturbation** anywhere in the magnet
- Technique is **non-invasive,** and be **adapted to existing magnet systems**

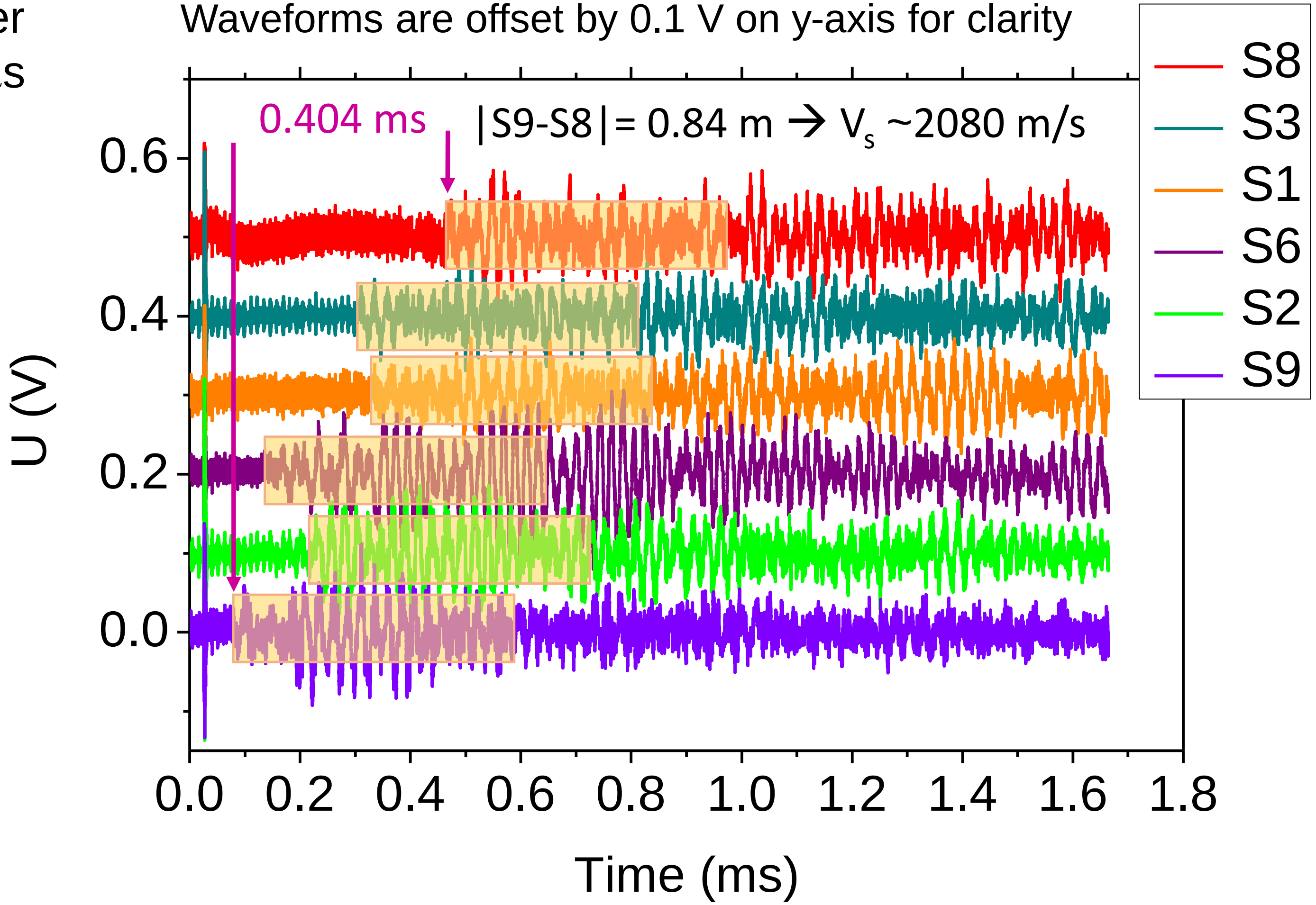
Example: ultrasonic pulse propagation in the CCT4 dipole

Transducer is mounted on the inner layer mandrel; powered with a 100 V / 14 μs rectangular pulse at 1-10 Hz repetition rate



Pulse propagation:
S9 –> (S2 S4 S6) –> (S3 S2 S7) -> S8

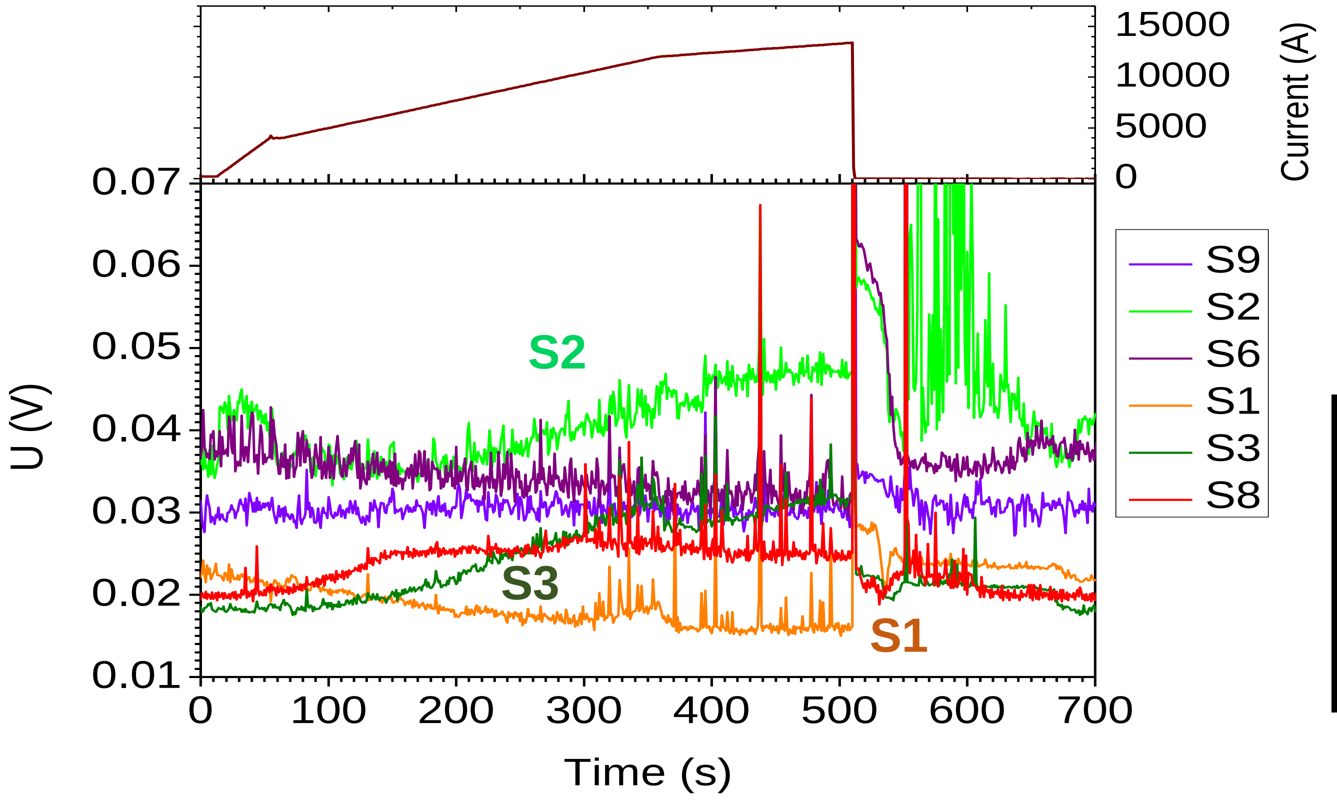
Waveforms are offset by 0.1 V on y-axis for clarity



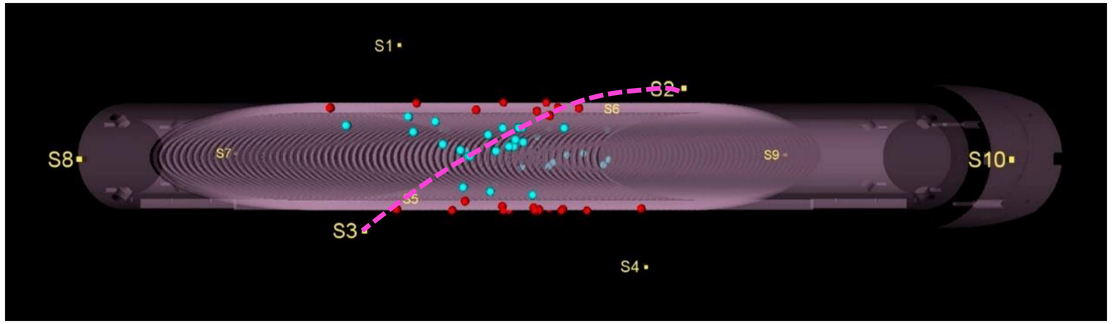
0.5 ms window is set individually for each waveform, and then periodically monitored with each pulse

Monitoring mechanical interfaces

Transmitted pulse amplitude



Ultrasonic pulse propagates through interfaces between the inner layer and outer layer -> mandrel of the magnet. When the magnet is energized, interfacial contact changes due to Lorentz forces on the coils

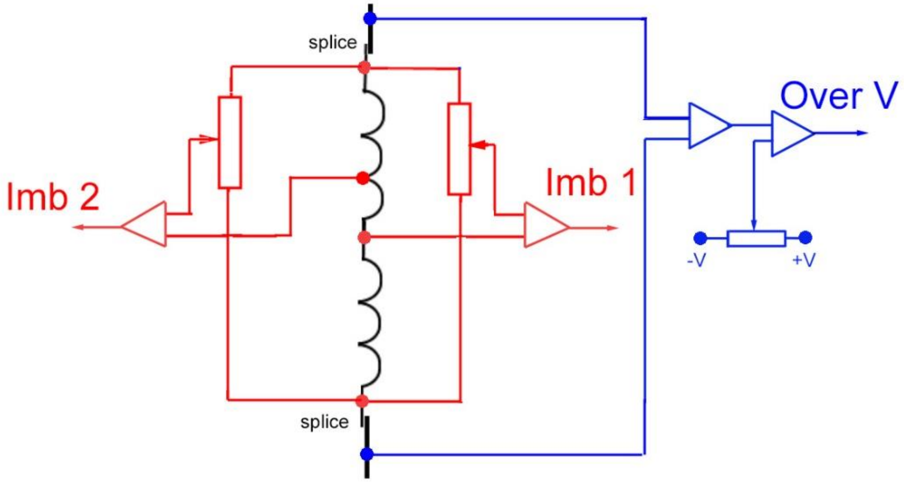


- As magnet deforms under stress, sensors S2 and S3 are seeing an improving mechanical contact between shell and inner / outer layers, while S1 is seeing a loss of mechanical contact.

Quench detection

“Traditional” voltage-based quench detection

Quench detection circuit example



Typically, voltage detection threshold for large accelerator magnets is ~100 mV

If the quench propagates very slowly, a hot spot may reach a high temperature while the voltage rise (proportional to the normal volume) will still be very small.. => a high risk of damaging the conductor.

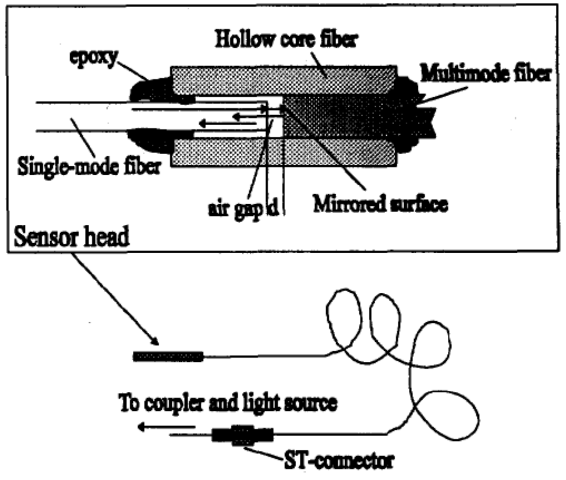
A problem for HTS conductors, as there NZPV is 1-2 orders of magnitude slower than in LTS!

Alternative: monitoring temperature variations

Optical techniques

Optical sensing: based on detecting local stresses generated by a hot spot

Fiber-optic interferometer



J.M. van Oort, R.M. Scanlan and H.H.J ten Kate., *"A Fiber-optic Strain Measurement and Quench Localization System for Use in Superconducting Accelerator Dipole Magnets", IEEE Trans. Appl. Supercond. 5, 882 (1995)*

The sensitivity of the fiber optic sensors for absolute readout is in the order of 50 -100 nm, which yields a strain resolution of the order of 10x10^{-6} in the longitudinal and radial direction. The pressure resolution in the transverse direction is in the order of *5* MPa.

Rayleigh scattering

W.K. Chan, G. Flanagan and J. Schwartz, *"Spatial and temporal resolution requirements for quench detection in (RE)Ba2Cu3Ox magnets using Rayleigh-scattering-based fiber optic distributed sensing",* Supercond. Sci. Technol. 26 105015 (2013).

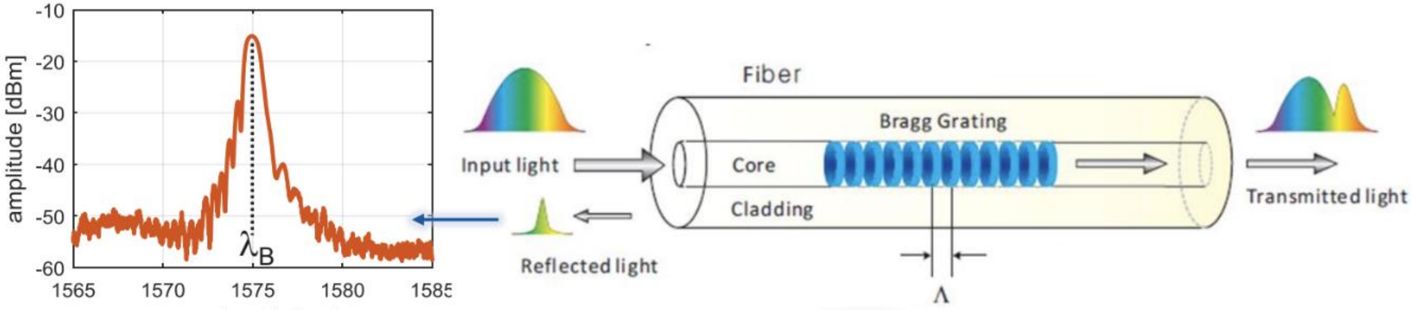
Fiber Bragg gratings (FBG)

F. Hunte et al., "Fiber Bragg optical sensors for YBCO applications", Proceedings of PAC09, Vancouver, BC, Canada

Pro: immune to EM interference. High sensitivity. Proven to work on small coils.
Con: requires co-winding optical fiber with the conductor + an increasingly powerful data processing for detecting quenches in long coils. Detection time is ~1s.

Fiber Bragg Gratings for quench detection

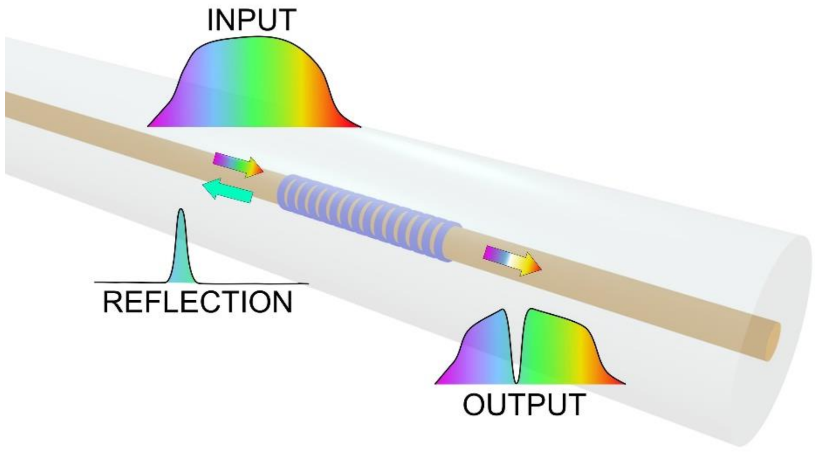
Acts as a band-stop **filter** passing all wavelengths that are not in resonance with the grating and reflecting wavelengths that satisfies the Bragg condition



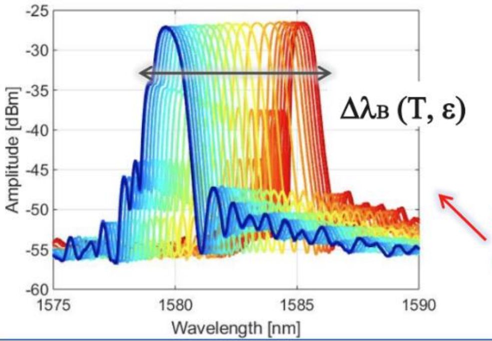
$$\lambda_B = 2\, n_{eff}\, \Lambda$$

Temperature and strain dependent

- n_{eff} = effective refractive index of the core
- Λ [nm] = grating period



The FBG is sensitive to both temperature (T) and strain (ε). **A change in these parameters leads to a shift** in the Bragg wavelength due to the effect they induce on both the refractive index **n_{eff} (T, ε)** and the grating period **Λ(T, ε)**.



$$\Delta\lambda_B = \frac{\partial\lambda}{\partial T}\Delta T + \frac{\partial\lambda}{\partial\varepsilon}\Delta\varepsilon$$

Sensors can be interrogated and then monitor the Bragg wavelength over time

B. Castaldo et al.,
presentation at the IDSM01 workshop

Detecting heating through coil mechanical resonances

Monitoring changes in vibrational frequency spectra and structural resonances due to local heating within the windings

- T. Ishigohka et al., "*Method to detect a temperature rise in superconducting coils with piezoelectric sensors*", Appl. Phys. Lett. 43 (3), pp. 317-318 (1983)
- A. Ninomiya et al., "*Quench detection of superconducting magnets using ultrasonic wave*", IEEE Trans. Magn. 25, v2 pp 1520-1523 (1989)

- *T. Ishigohka et al., "Method to detect a temperature rise in superconducting coils with piezoelectric sensors", Appl. Phys. Lett.43, 317 (1983)*
- A. Ninomiya et al., "*Monitoring of a superconducting magnet using an ultrasonic technique*", Fusion Eng. Design 20, 305-309, (1993)

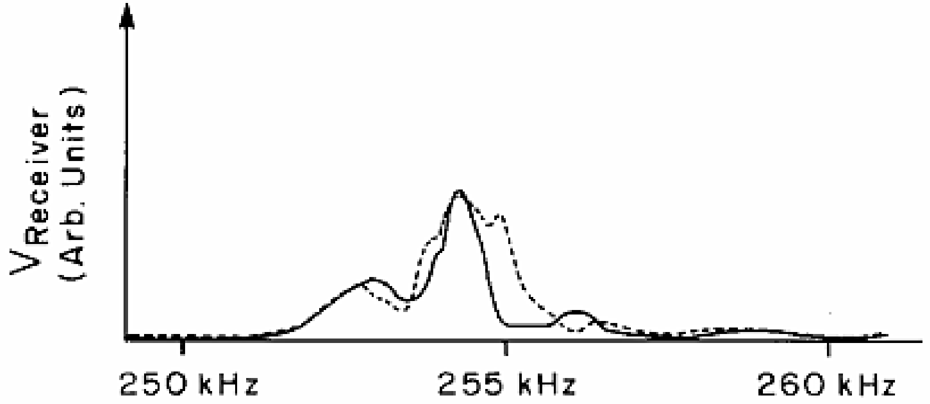


FIG. 3. Frequency spectra for the test coil immersed in a bath of liquid helium, with heater current zero (solid curve) and with heater current at 0.3 A (dotted curve).

To be usable for quench detection, these techniques require mechanical modeling of the coil eigenfrequencies and transfer function that are experimentally validated prior to actual QD.

Detecting heating by measuring change in the sound propagation velocity

- Quench propagation velocity in HTS materials is < 50 mm/s at best circumstances, and typically much less (especially at LN2 temperature and below). This translates into a very localized hot spot that does not generate much resistive voltage => coil can burn before quench is detected…
- "Thermal" quench detection would solve that!

What if we use the conductor itself as distributed temperature sensor?

Sound velocity: $v = \sqrt{\frac{E}{\rho}}$, where Young's modulus E exhibits the strongest temperature dependence:

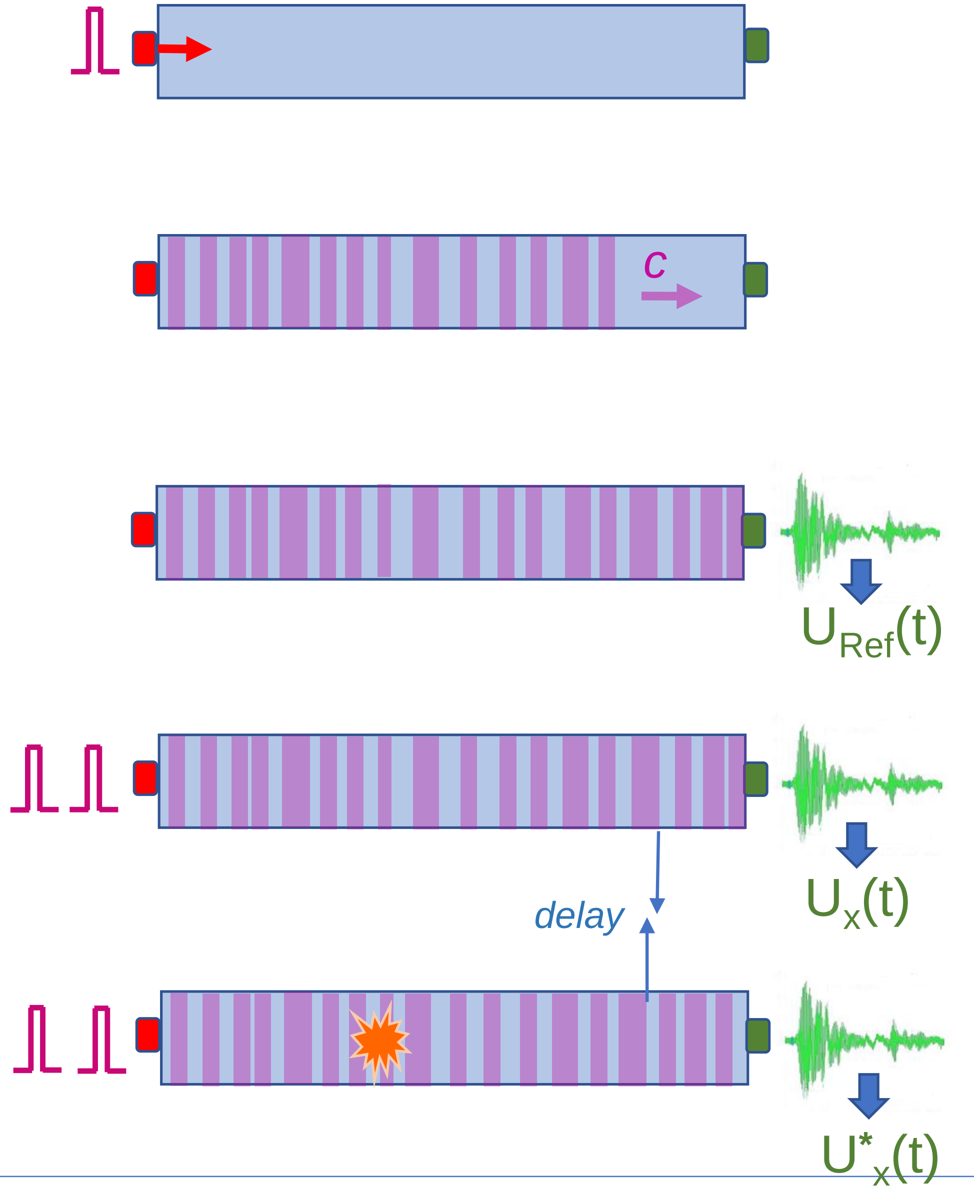
$$E(T) = E_0 - s/\left[e^{t/T} - 1\right]$$ (*s*, *t* – adjustable parameters)

The E(T) dependence is **weak**: just ~1-10 ppm/K at 77 K and even less at lower temperatures. But it is still **measurable** using high-frequency (10^5-10^6 Hz) vibrational modes, and taking advantage of high (>100) mechanical Q-factor.

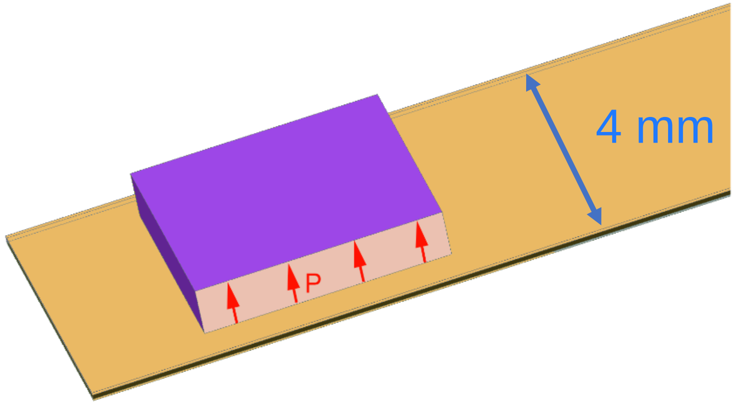
We do it by monitoring a **transient acoustic response**

Operational principle

1. A body is **pulsed** by a sender transducer
2. A **“ring-down” transient waveform propagates and reverberates** multiple times
3. Transient oscillation **is acquired** by a receiver transducer; and **stored as “reference”** U_{Ref} (t). Its shape is **uniquely defined** by the body geometry, density and elastic modulus E(T)
4. Pulsing and transient acquisitions are repeated periodically; every new transient $U_x(t)$ is compared to $U_{Ref}(t)$ using cross-correlation: $A(\boldsymbol{\Delta t}) = U_x(t+\boldsymbol{\Delta t}) * U_{Ref}(t)$. The time shift $\boldsymbol{\Delta t}$ yielding the **maximal cross-correlation** is calculated for every new pulse
5. When a hot spot develops, E(T) decreases locally, delaying the wave passing through it. This proportionally **increases $\boldsymbol{\Delta t}$**.



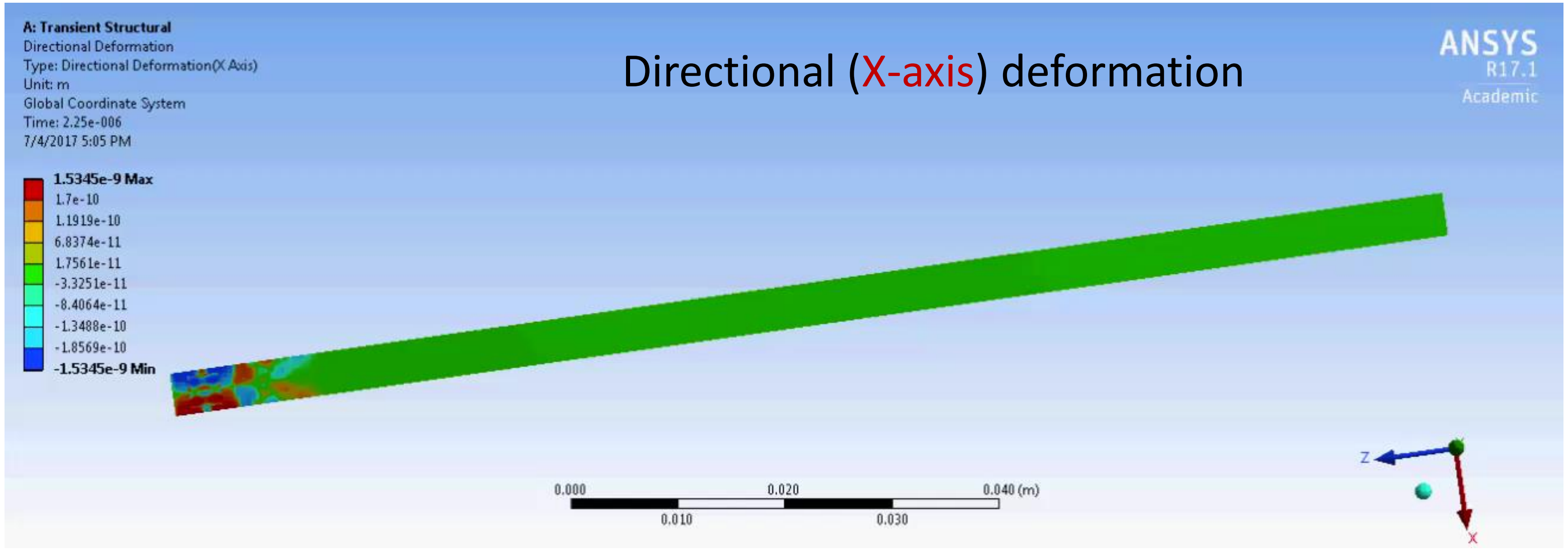
Transient mechanics of HTS tape conductor



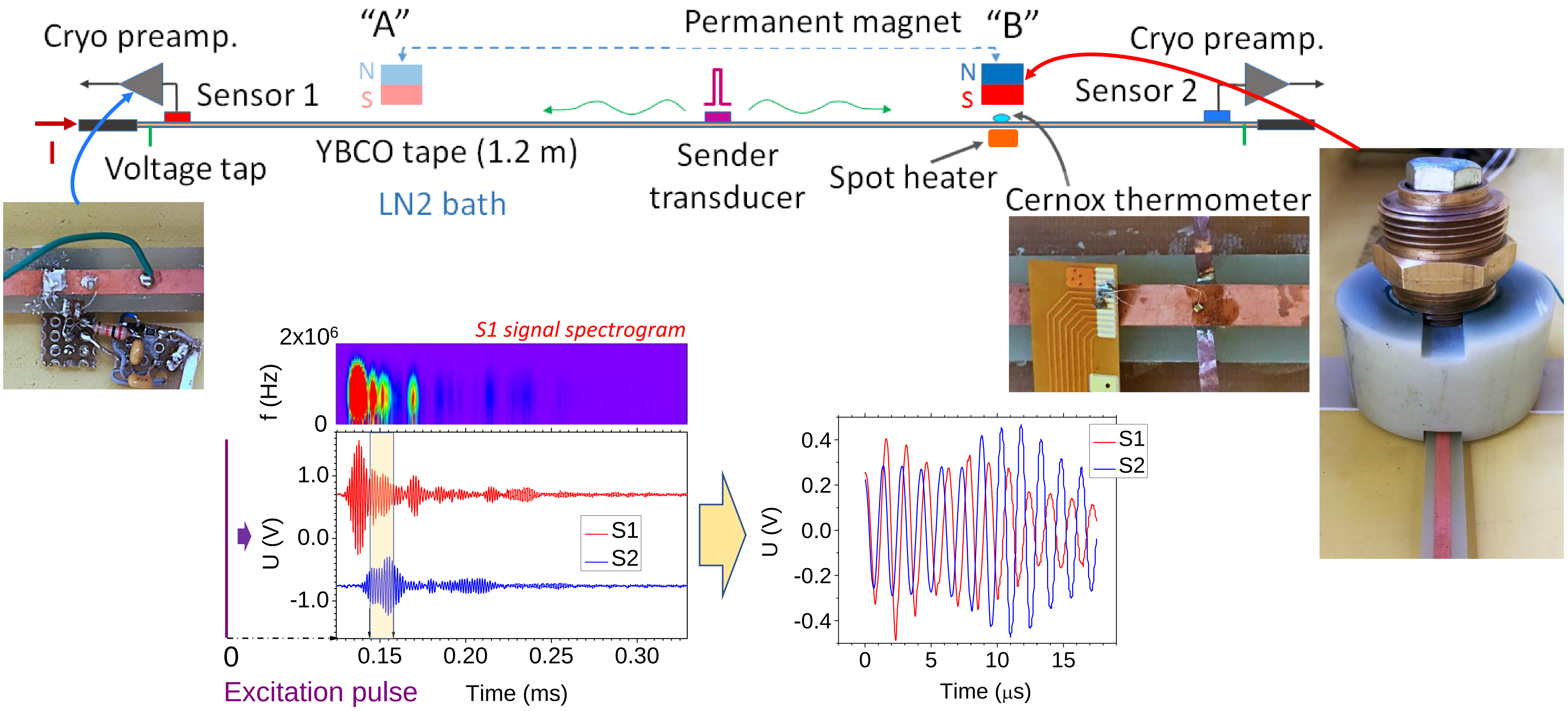
- *30 (Cu)-50 (SS)-20 (Cu) μm tape cross-section*
- *0.2 μs rectangular pulse voltage is applied to the transmitter piezo-transducer*

➢ **In-plane** shear waves and **out-of-plane** waves are excited

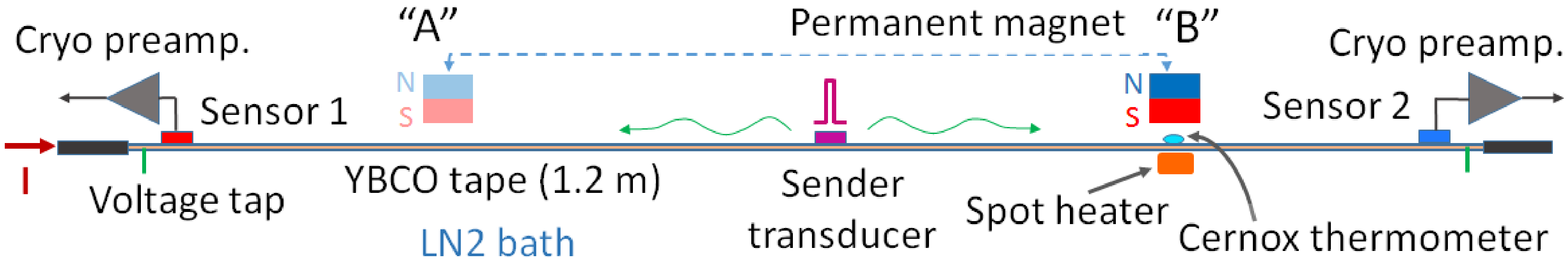
The in-plane wave modes interact less with a supporting structure and do not couple to the cryogen bath due to absence of shear vibrations in liquids. **Beneficial for the detection!**

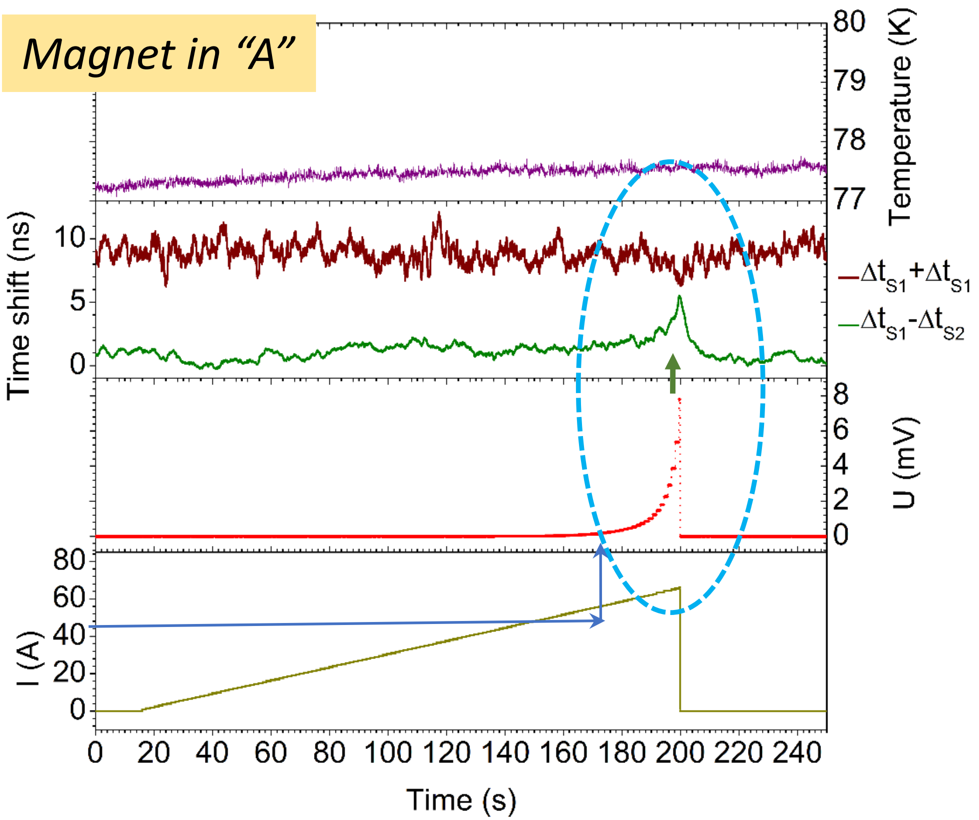


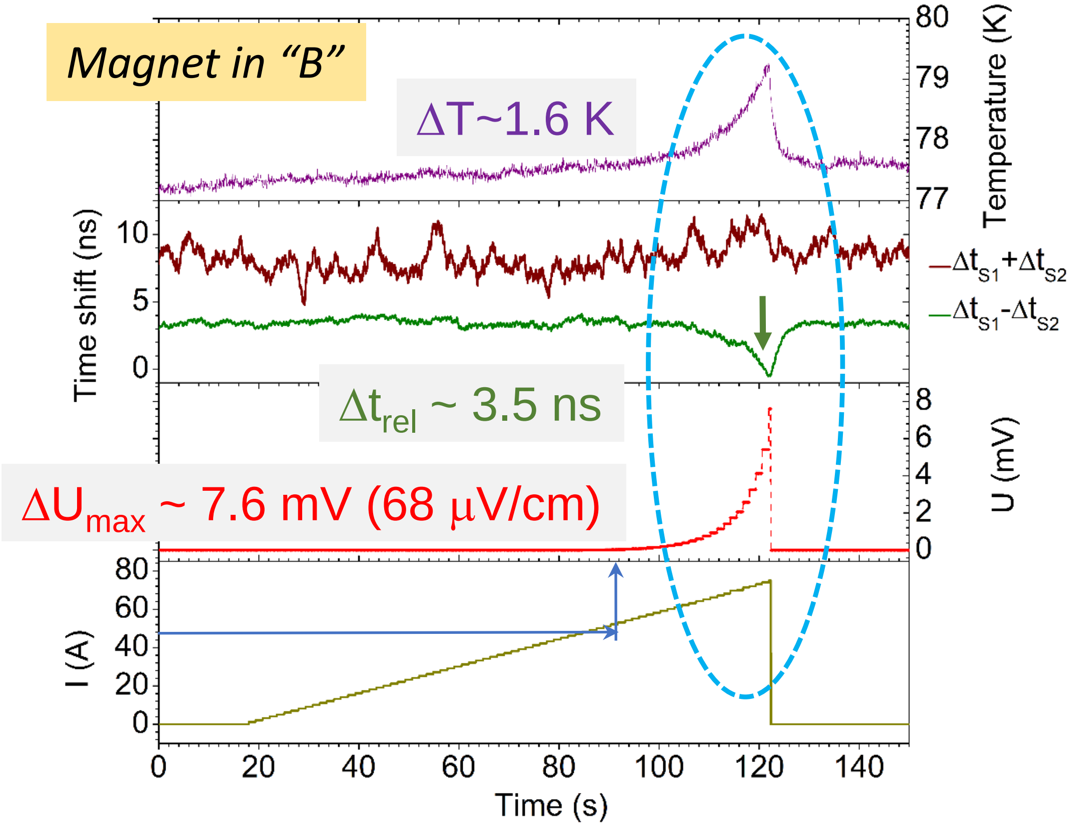
Setup for the differential acoustic quench detection



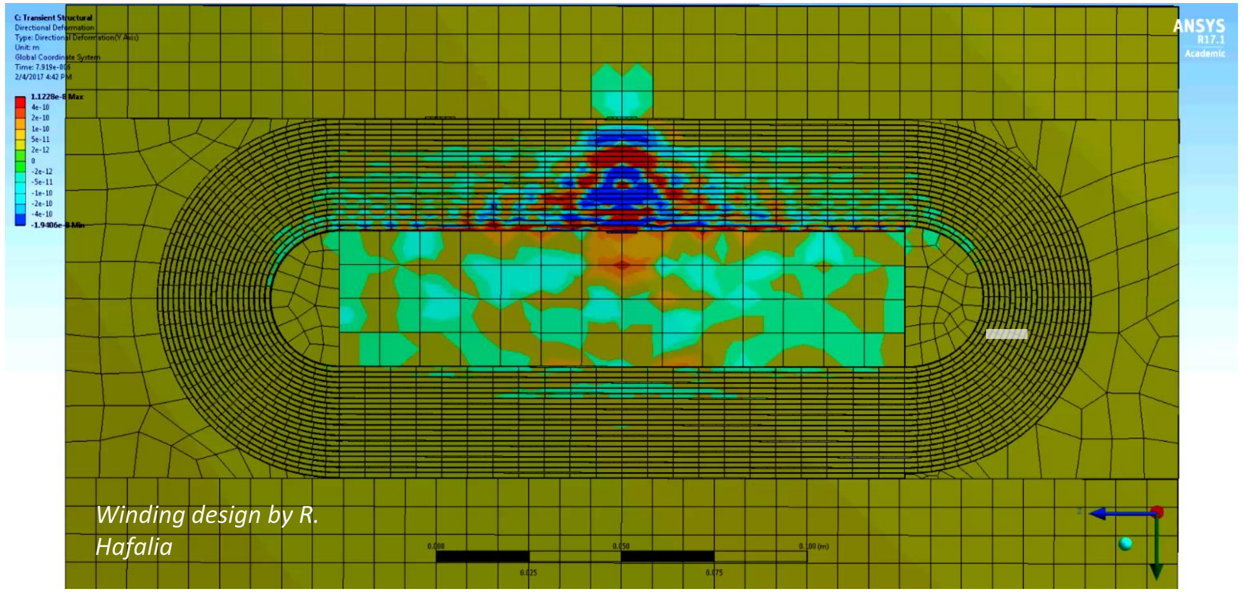
Differential acoustic quench detection: results







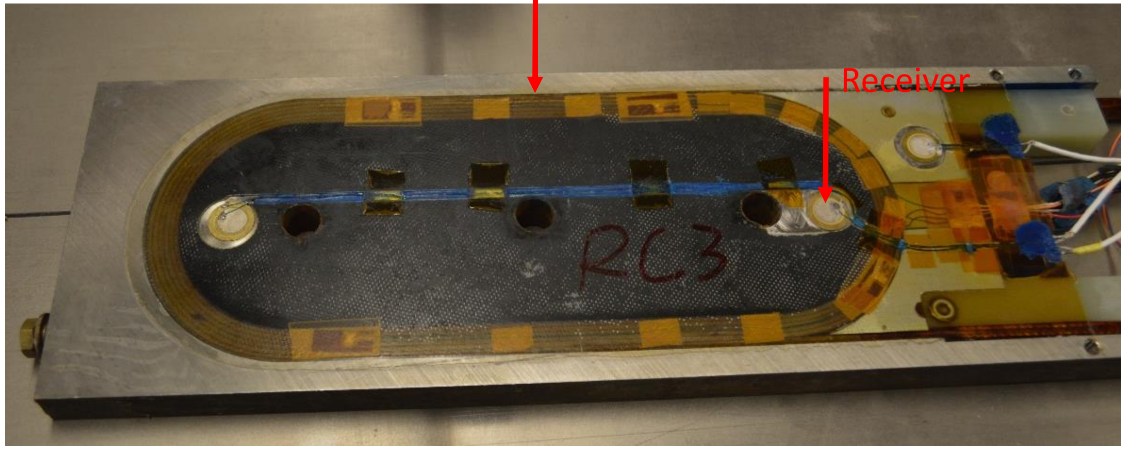
Acoustic quench detection in Bi-2212 HTS coil



- Flat coil model: PET-insulated (0.2 mm thick) stainless tape (1.25 mm thick), stainless structure.
- Piezo-transducer is installed at the interface between central island and the first pole turn; pulsed with a 0.2 μs duration pulse; and displacement along "y" is calculated with 0.1 μs time step.

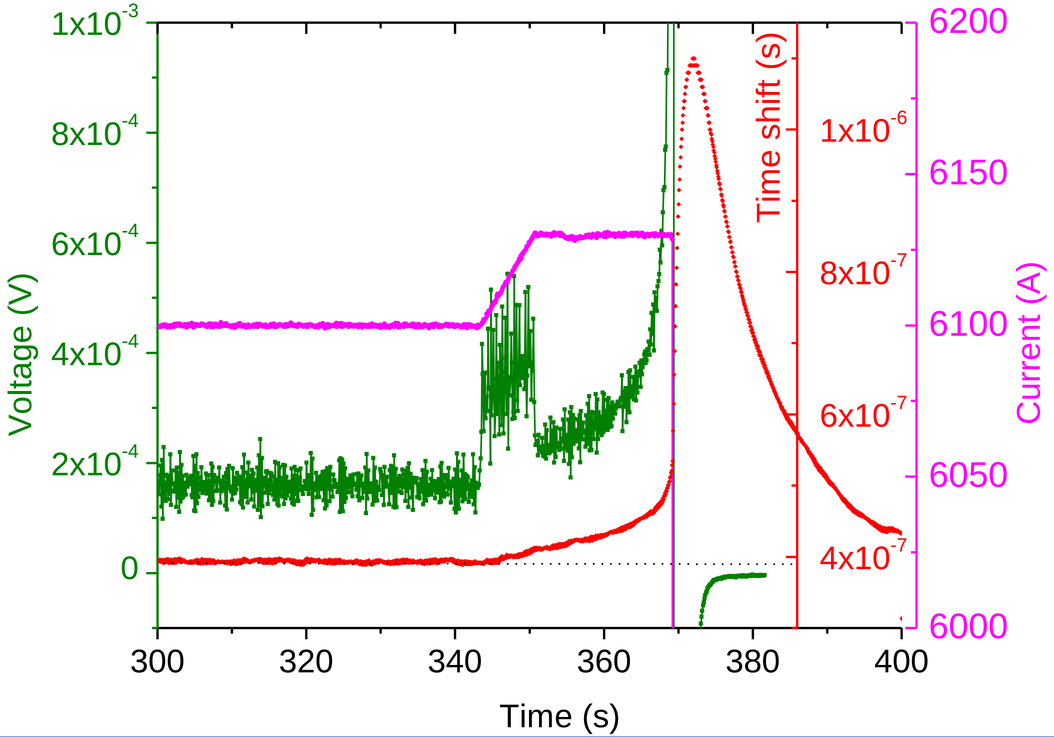
Bi-2212 coil RC3

Pulser embedded in the winding

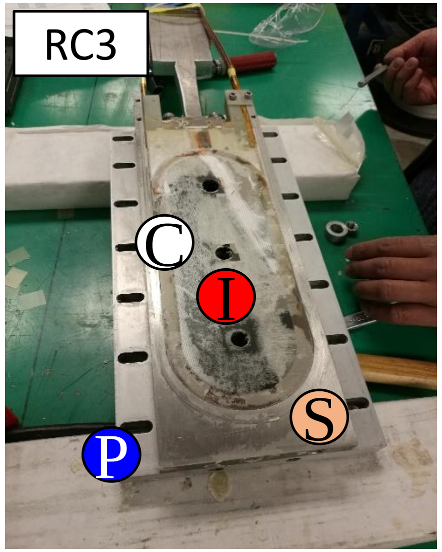


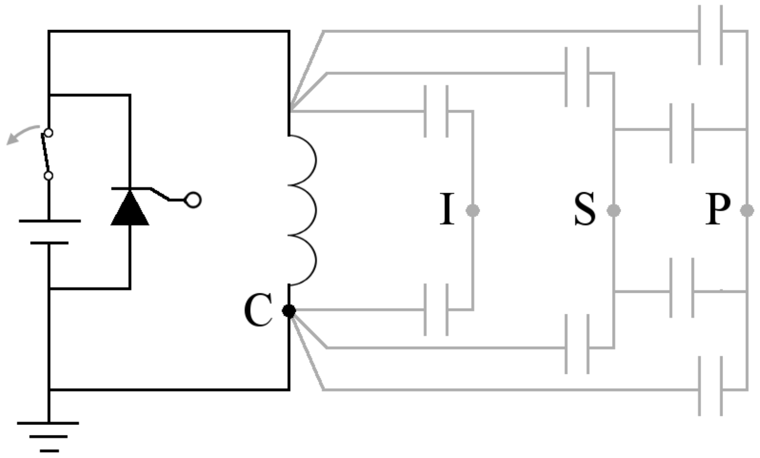
K. Zhang, T. Shen

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



Capacitive quench detection technique





Stray capacitance can be measured between any metallic component electrically insulated from the others

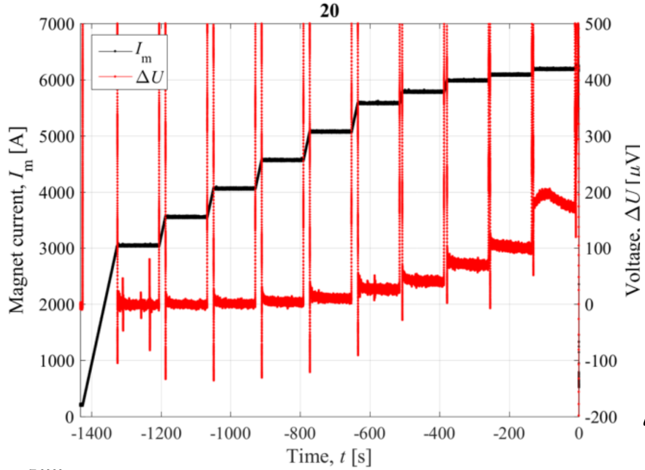
$C = \varepsilon_0 \varepsilon_r S/s$

ε_0=8.854 10^{-12} Fm^{-1}

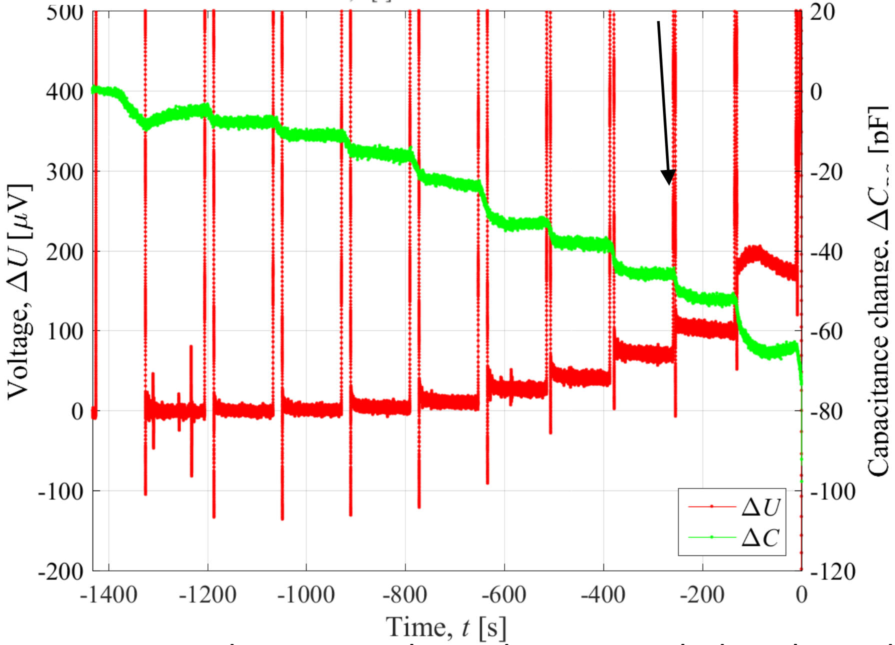
ε_r rel permittivity

S contact surface

s distance



ΔU: 1 s moving average



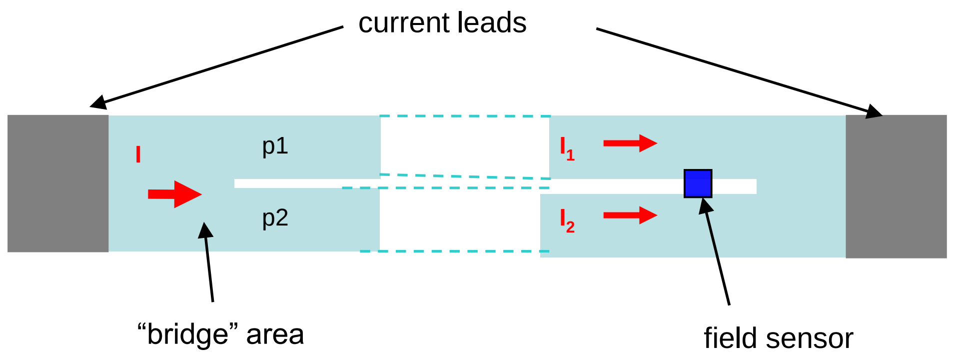
Measured magnet voltage does not include voltage drop across the splices

The mechanism leading to stray capacitance change just before quench is the decrease of cryogen fluid's electrical permittivity ε_r when the phase change occurs.

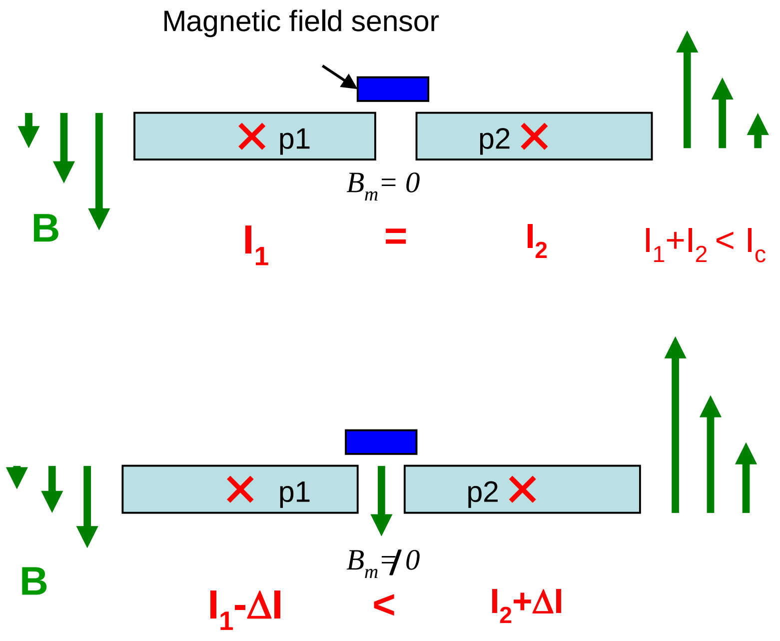
This happens when the fluid impregnating the insulation boils off.

"Quench Detection Utilizing Stray Capacitances", E. Ravaioli, et al., IEEE Trans. Appl. Supercond. 28, 4702805 (2018)

Detecting quench by monitoring current re-distribution in a split conductor



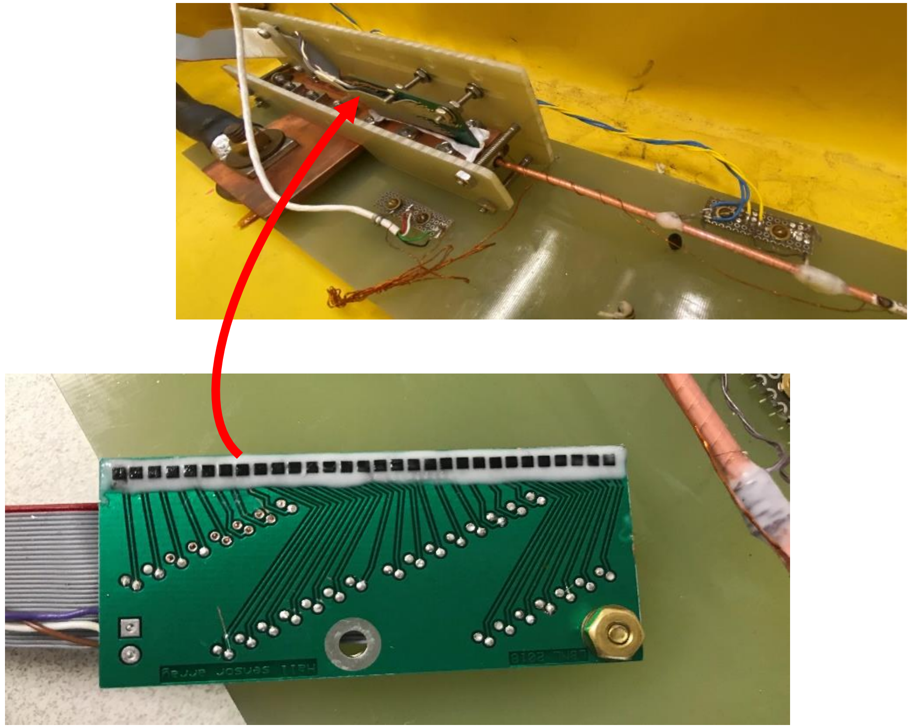
Quench detection using split wire or otherwise two conductors following same geometrical path and electrically separated from each other except at the ends.



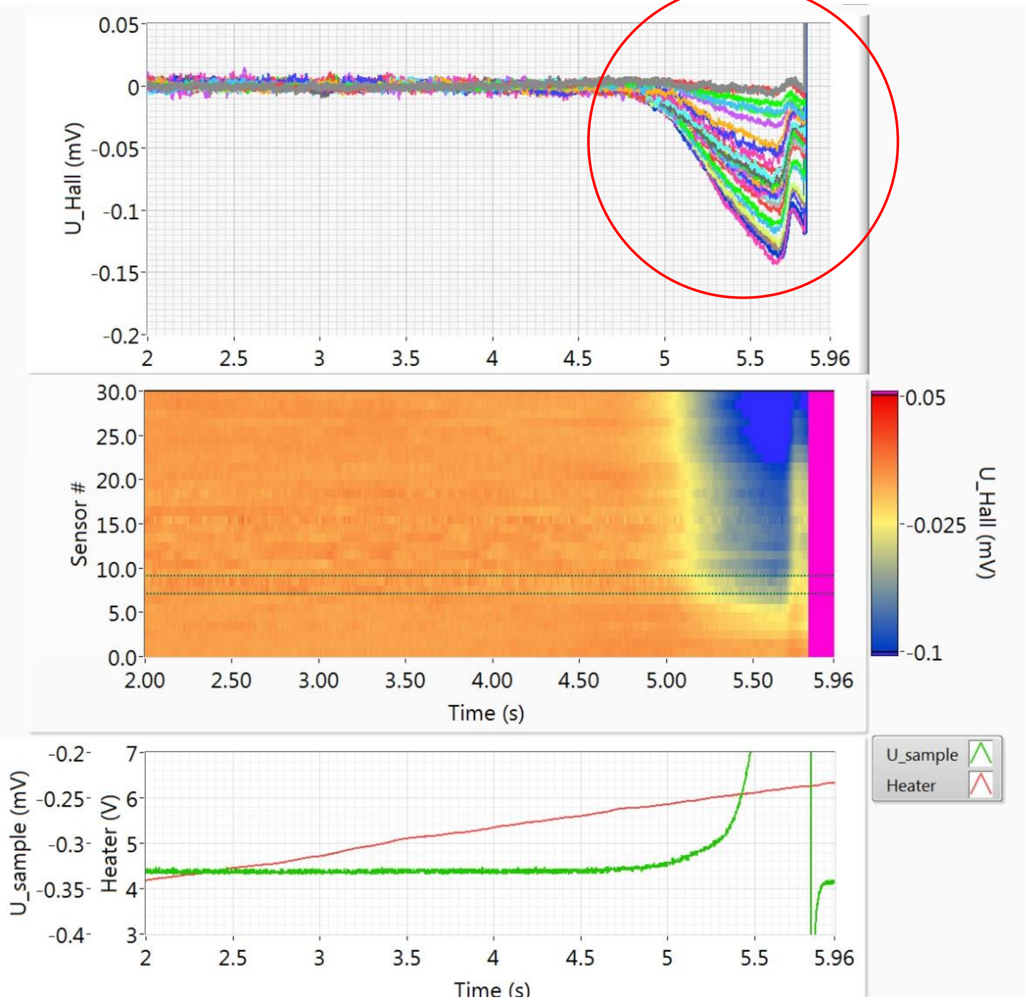
- **Sensitivity is in 10^{-12} Ohm range** for superconducting end joints, and ~10^{-8}-10^{-9} Ohm for non-superconducting joints - way superior to voltage detection!
- The technique **can sense heating at the very onset of resistance, $I \ll I_c$ (!)**

Hall sensor arrays for quench detection

CORC® HTS conductor



Current re-distributes along the terminal when resistance appears in the HTS cable



Additional material

First Workshop on Diagnostics and Instrumentation of Superconducting Magnets: https://idsm01.lbl.gov/

Thank you!