Magnet diagnostics: capabilities and examples

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U.S. MAGNET DEVELOPMENT PROGRAM

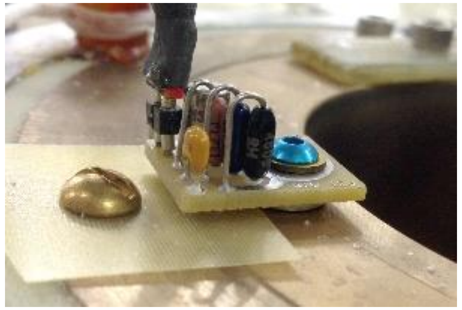
Major goals set last year and the progress made

- Understanding disturbance spectra of various quench sources
- Quench detection for subscale HTS coils and practical conductors
- Implementing active acoustic (“heartbeat”) as a standard magnet monitoring technique
- Diagnostic instrumentation for 16 T project
- Building up on active techniques for integrated detection and protection

- **We have conducted CCT4 test, and using collected high-frequency data made some important steps toward understanding training and event identification**
- **We validated QD for HTS coils, and proposed a new technique**
- **We implemented the pulsed monitoring scheme in CCT4**
- **We are developing new cryogenic instrumentation for CCT5 /16 T**

Part 1: Understanding magnet training through acoustics

AE sensors on various magnet systems



CCT series

HQ series

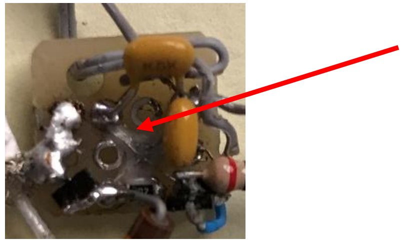
HD3

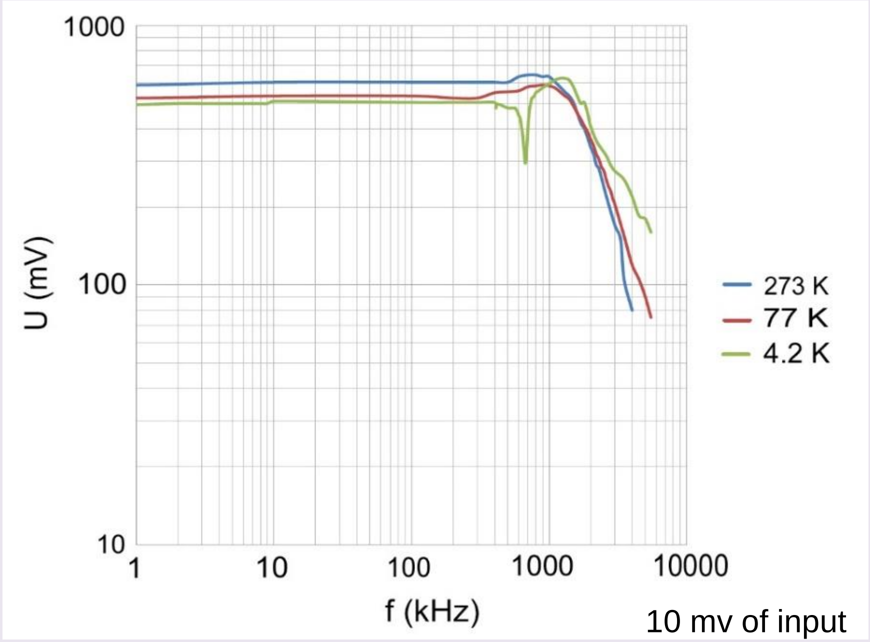
SCU

Installed on :
HQ series, HD3, SCU, CCT series (LBL)
Mu2e solenoid, MQXF LARP series (FNAL)
11 T dipole, HTS "Feather" dipole (CERN)

New development: a miniature wideband cryogenic AE sensor

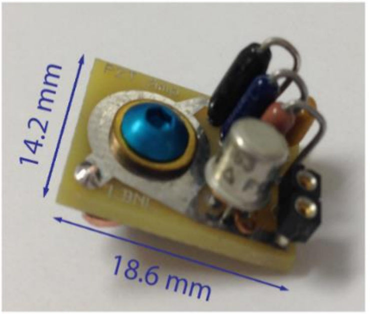
Will be installed on CCT5 and MDP's 15 T dipole





10 mv of input

Acoustic DAQ hardware

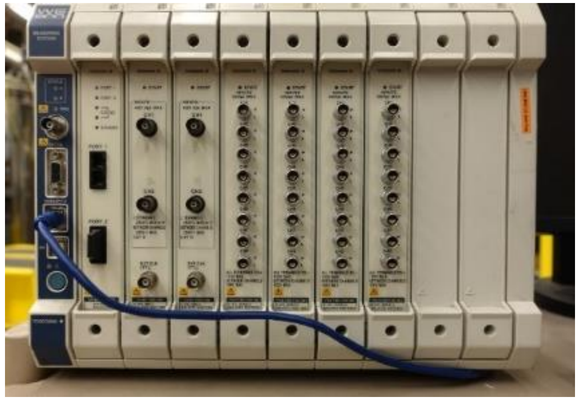


Picoscope 6404

8 bit at 5 Gs/s

Continuous streaming at 1 MHz, 4 ch
Precise axial localization and time-frequency analysis

Yokogawa WE7000



Continuous streaming at 40 kHz, 32 ch

NI PXI-6123

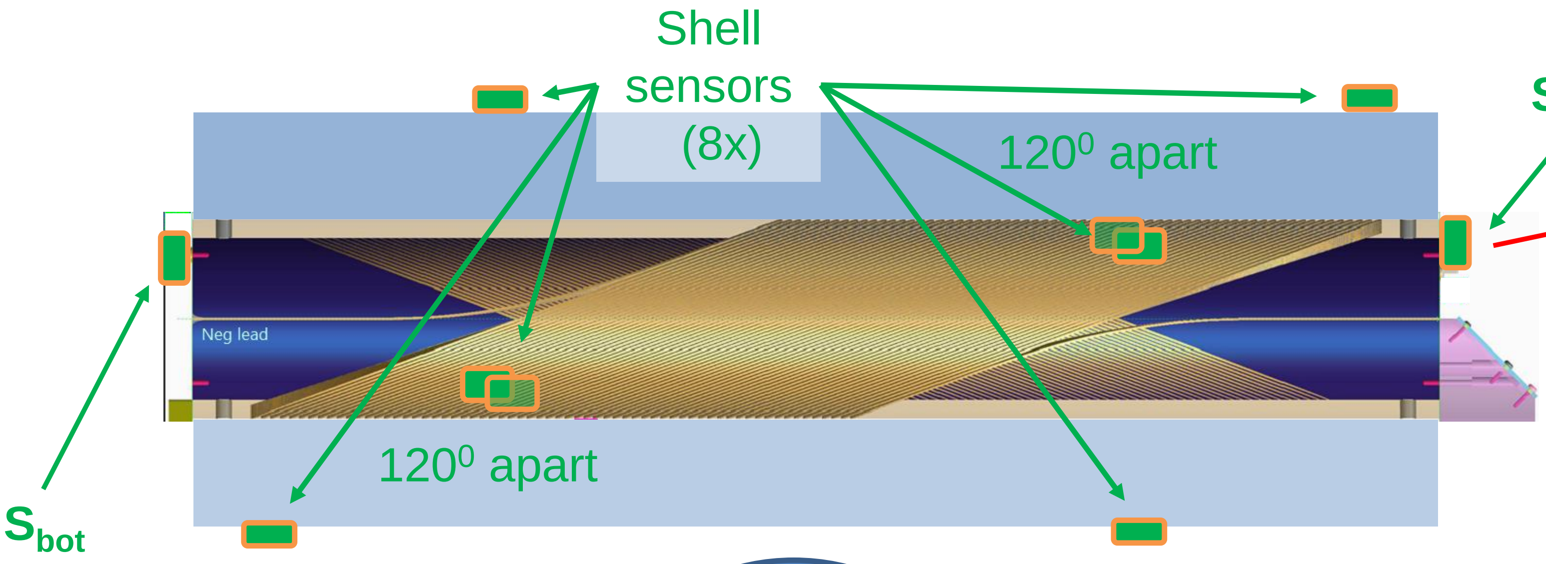
Triggered acquisition at 1 MHz, 16 ch
Axial and angular quench localization

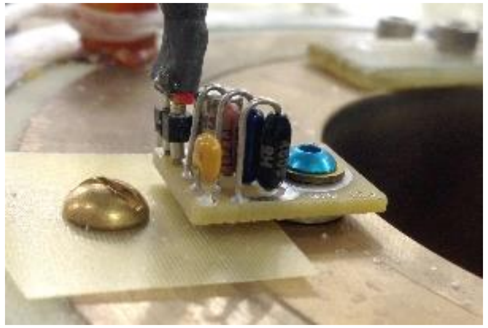
Picosope 4824

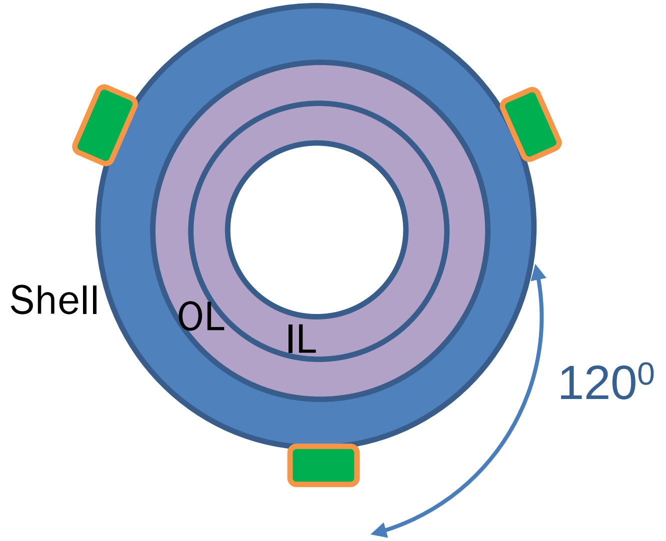
(12 bit at 80 Ms/s)

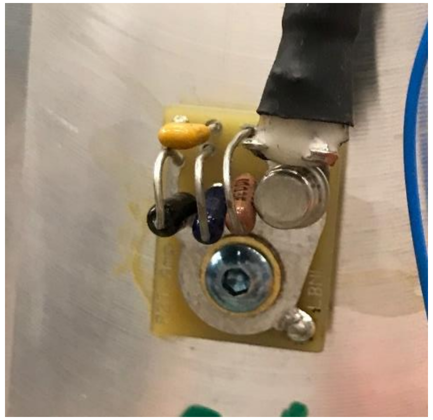
Continuous or triggered acquisition 0.5 - 10 MHz, 8 ch
"Active" mechanical integrity monitoring

Acoustic instrumentation in CCT4

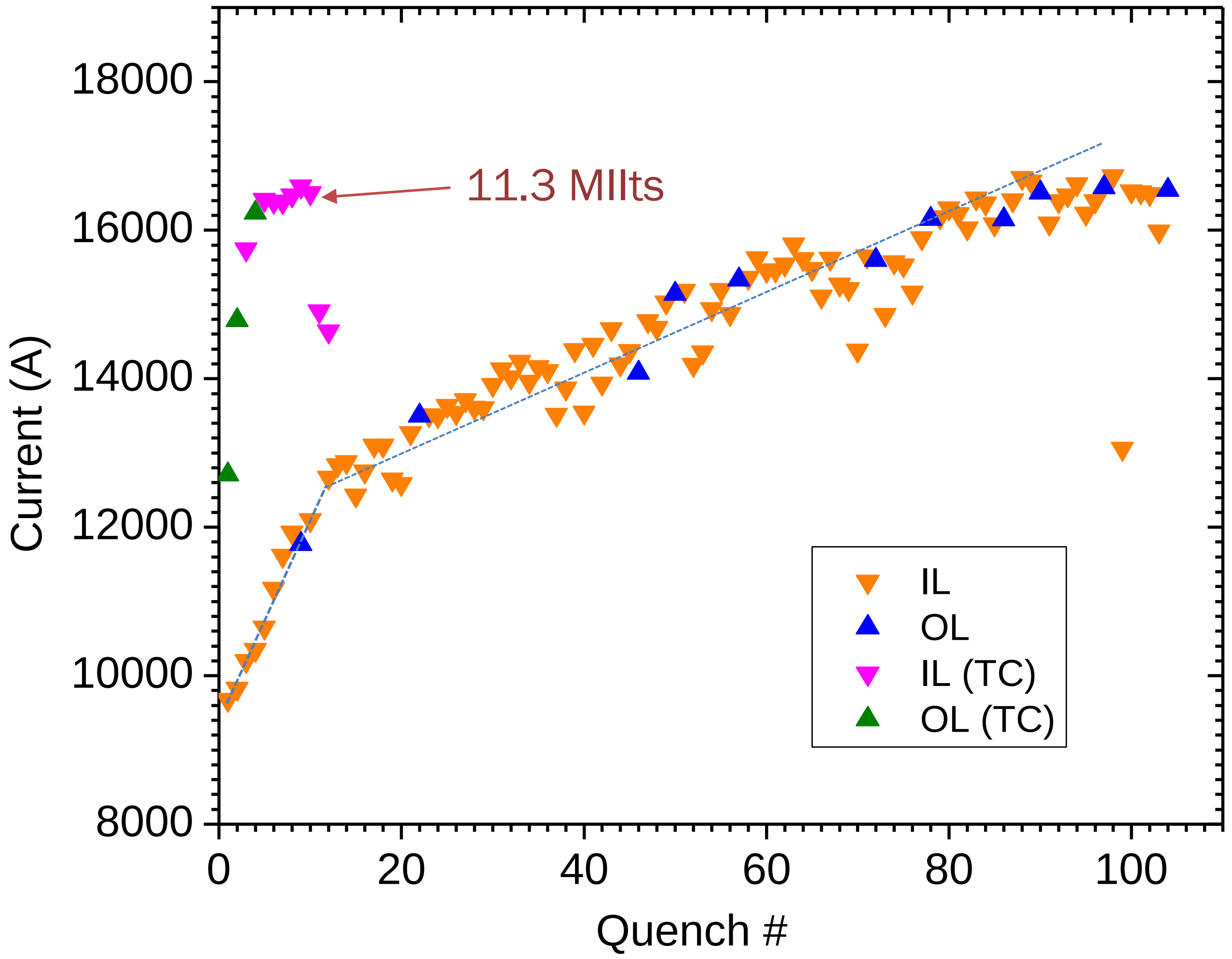








Training summary of CCT4

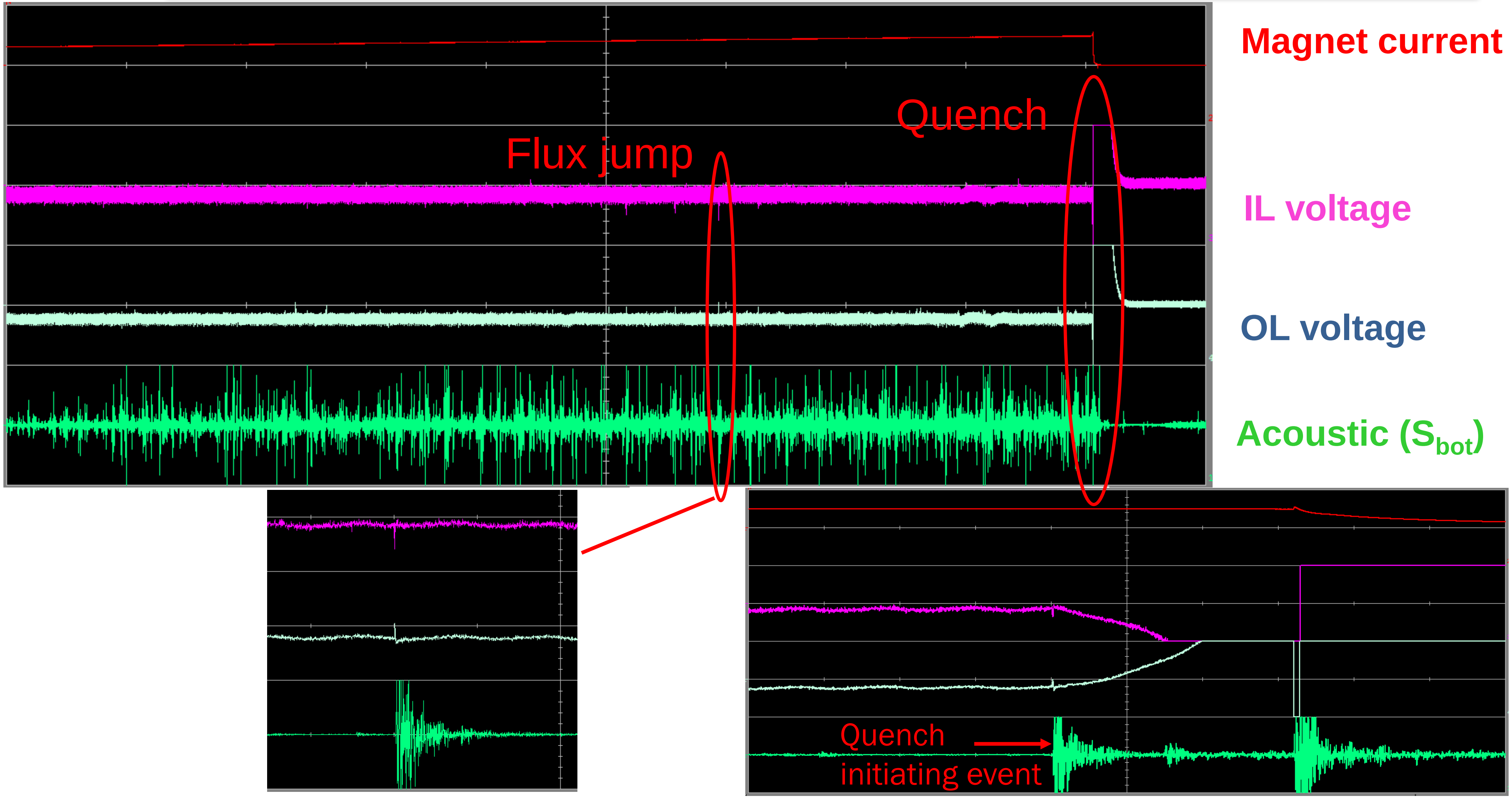


- 104 training quenches in total
- 11 quenches in the OL, the rest is IL
- Highest quench current: **16731 A**
- Bore dipole field: **9.14 T**
- Field at the conductor: 10.32 T
- “Short sample” limit: 19.3 kA (4.5 K)

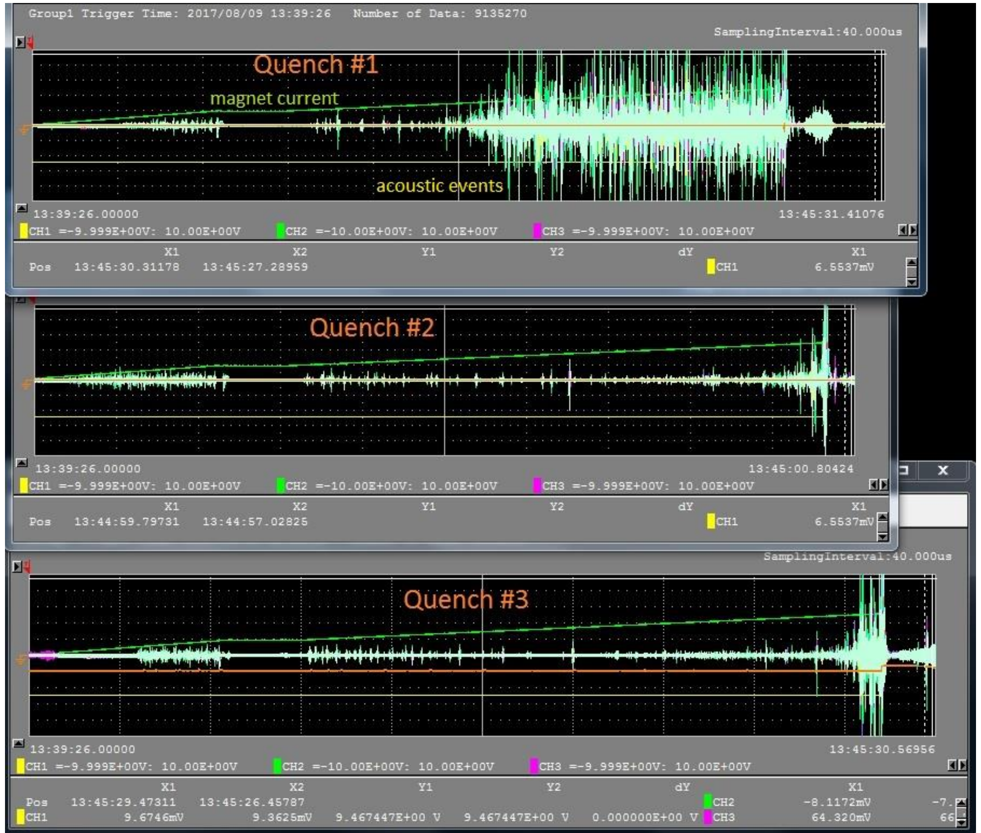
- Good quench memory after thermal cycle: reached above 16 kA in 4 quenches
- Highest quench current is 16590 A (quench #9)

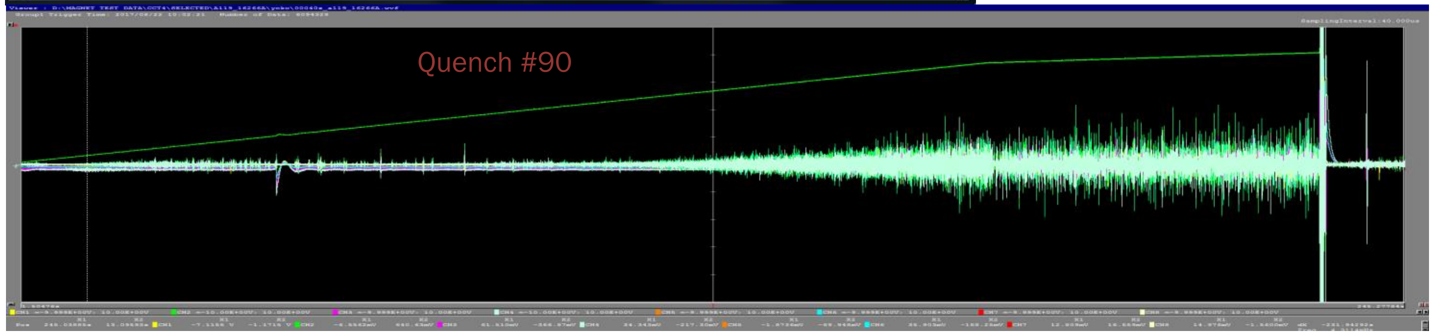
A remarkable linear trend is observed for the most part of the training, with an abrupt change of slope at ~ 13 kA

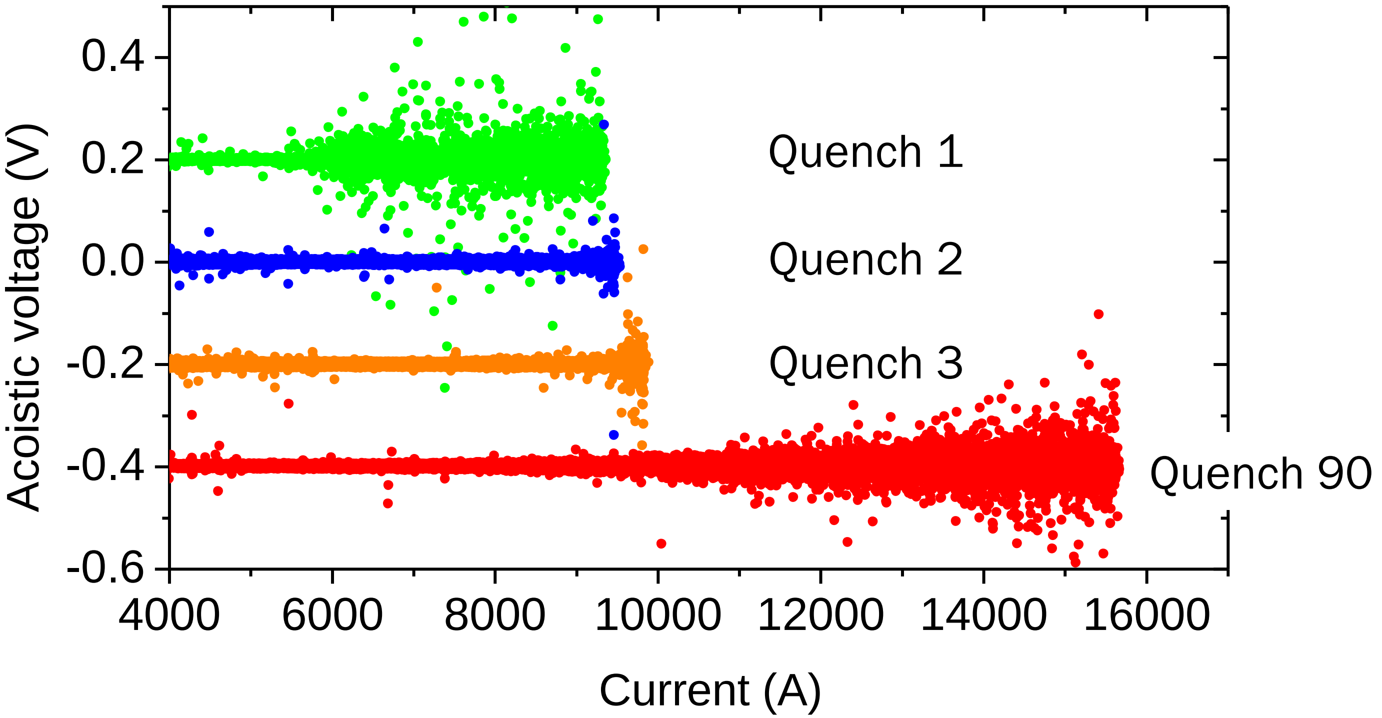
First quench in the CCT4



Mechanical memory of the magnet

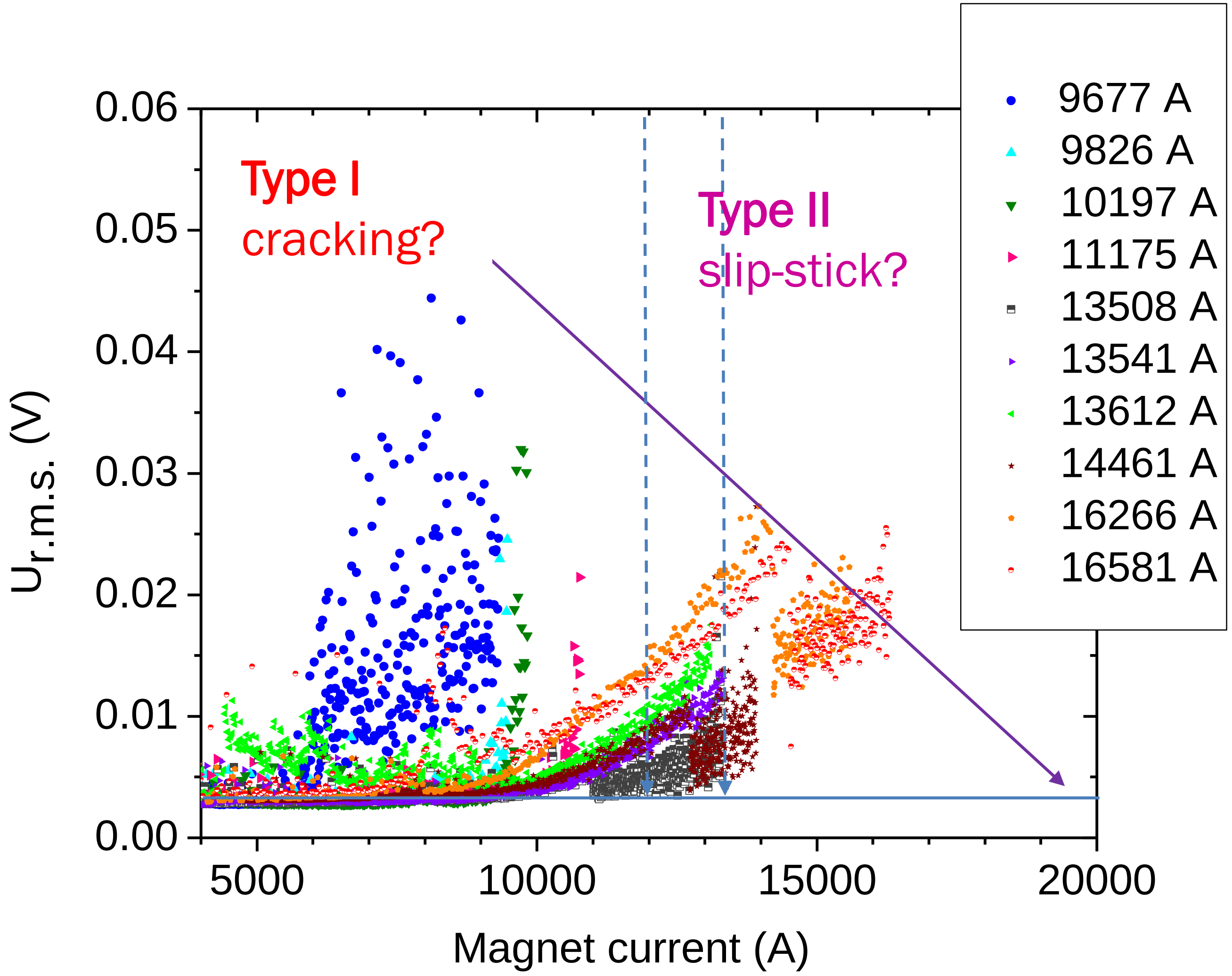


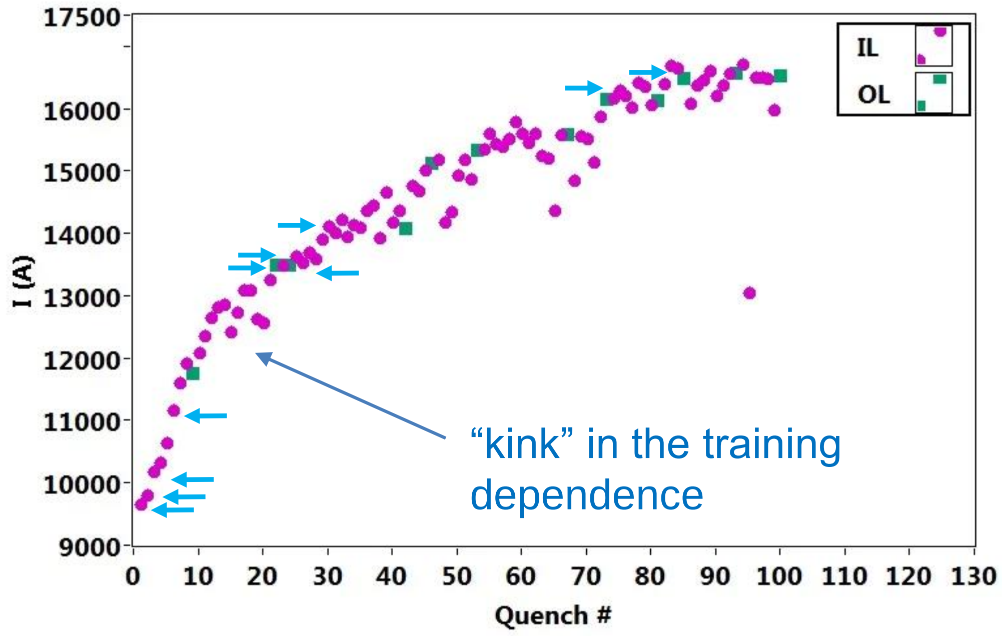




- CCT4 magnet shows mechanical memory in the initial quenches (Kaiser effect) - **“Type I” behavior**
- As training progresses, AE grows in amplitude towards the quench, erasing the memory effect. **“Type II” behavior**

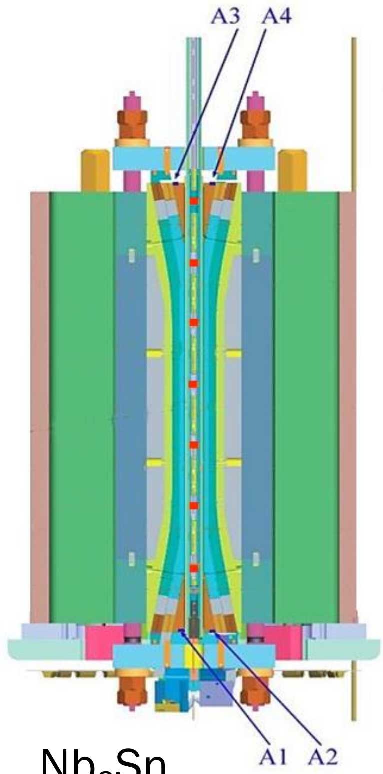
Two distinct regimes of magnet training



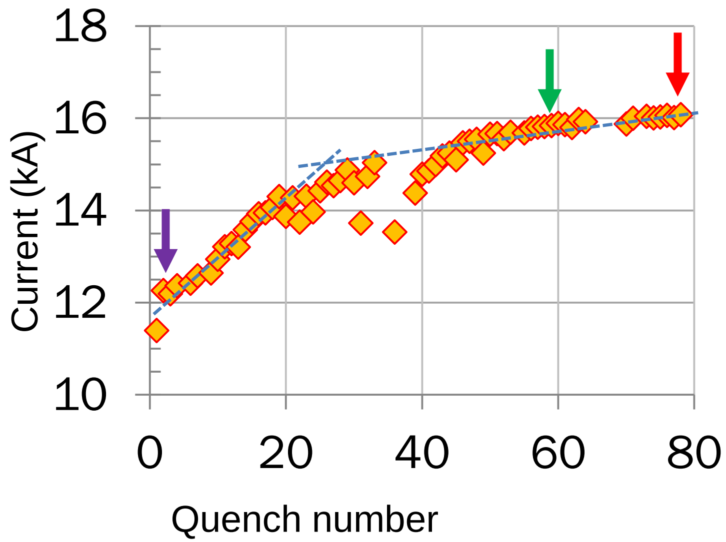


Similar behavior was earlier seen in a different kind of high-field Nb_3Sn dipole!

We have seen this before in HD3!

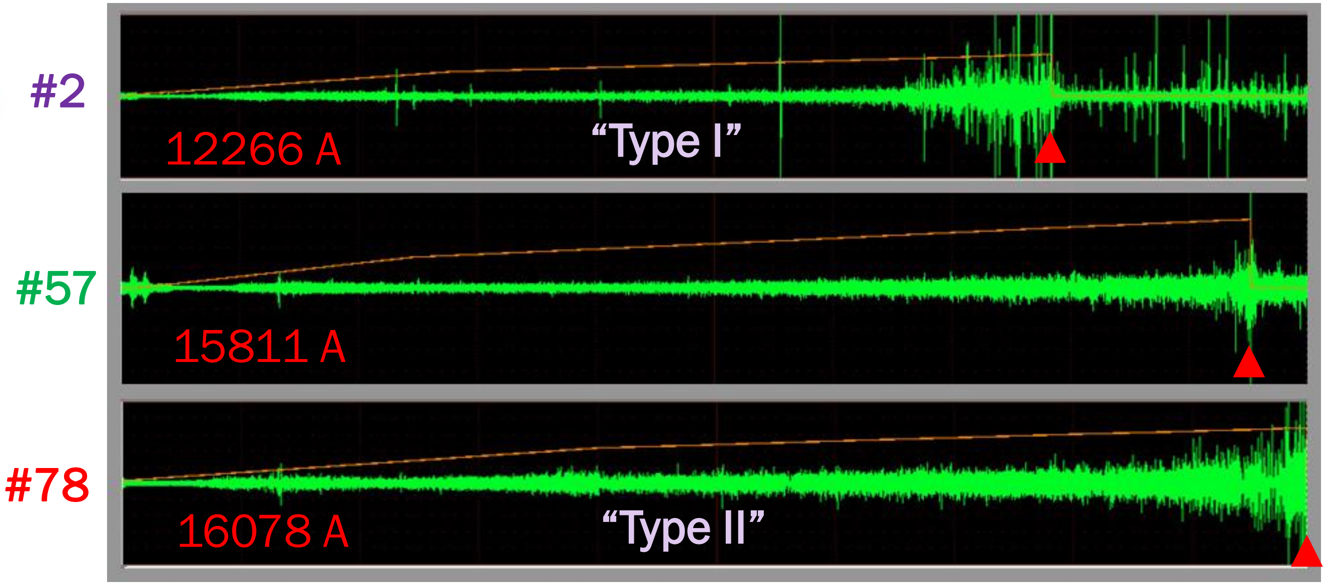


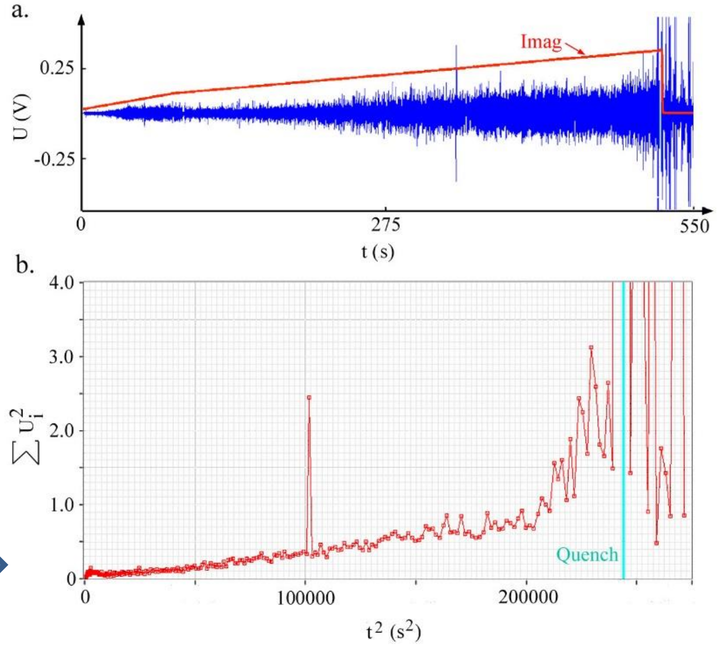
Nb$_3$Sn block dipole HD3



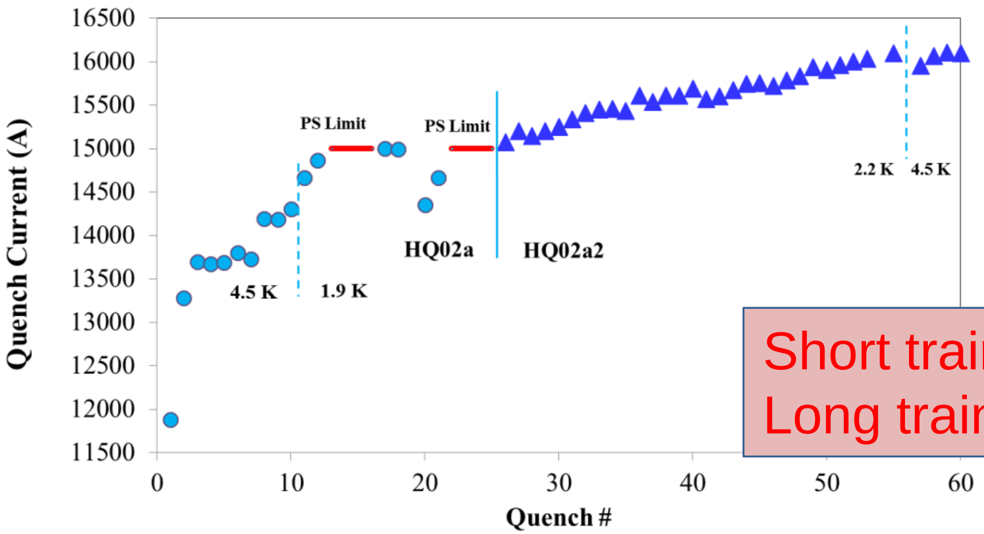
- Untrained: mostly quiet, then large spikes starting ~30-40 s and growing in amplitude prior to the quench
- Partially trained: small spikes seen from low currents, gradually increasing in amplitude; few large spikes ~5-10 s prior to the quench
- Fully trained: small spikes gradually increase in amplitude from low current, then become more sporadic and form a growing in amplitude envelope towards the quench

M. Marchevsky, et al., Cryogenics 69, 50 (2015), DOI: 10.1016/j.cryogenics.2015.03.005

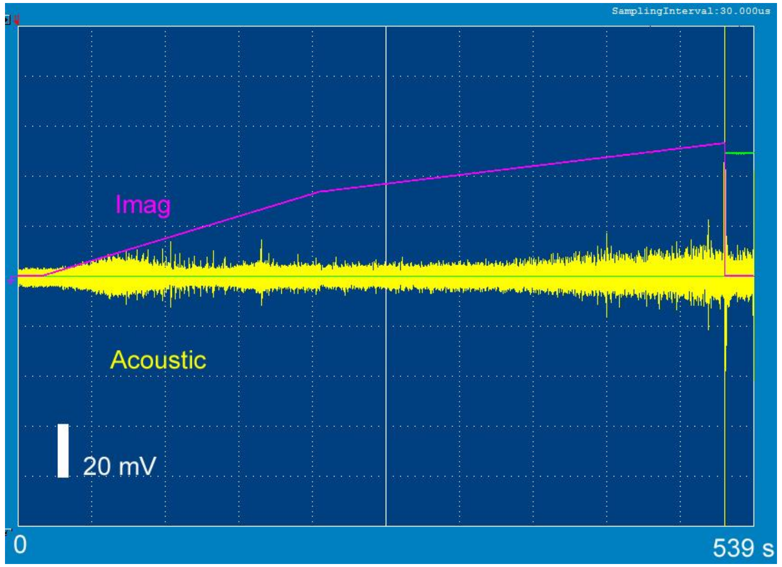




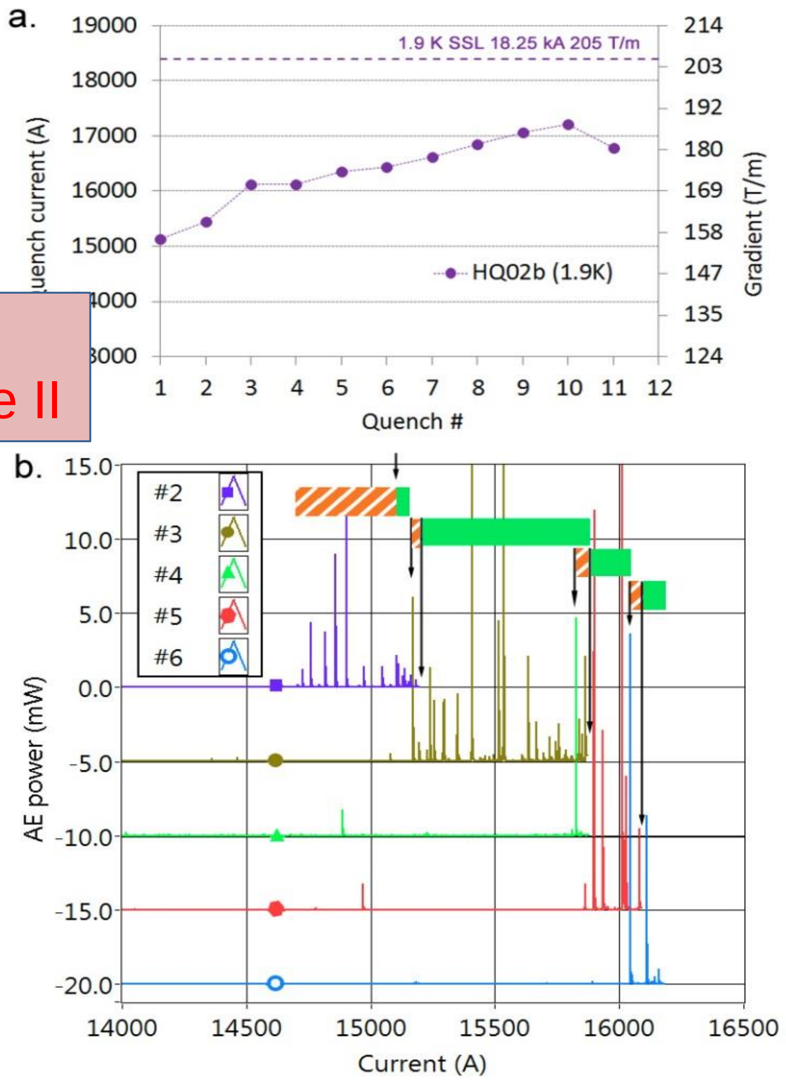
Another example: HQ02a and HQ02b



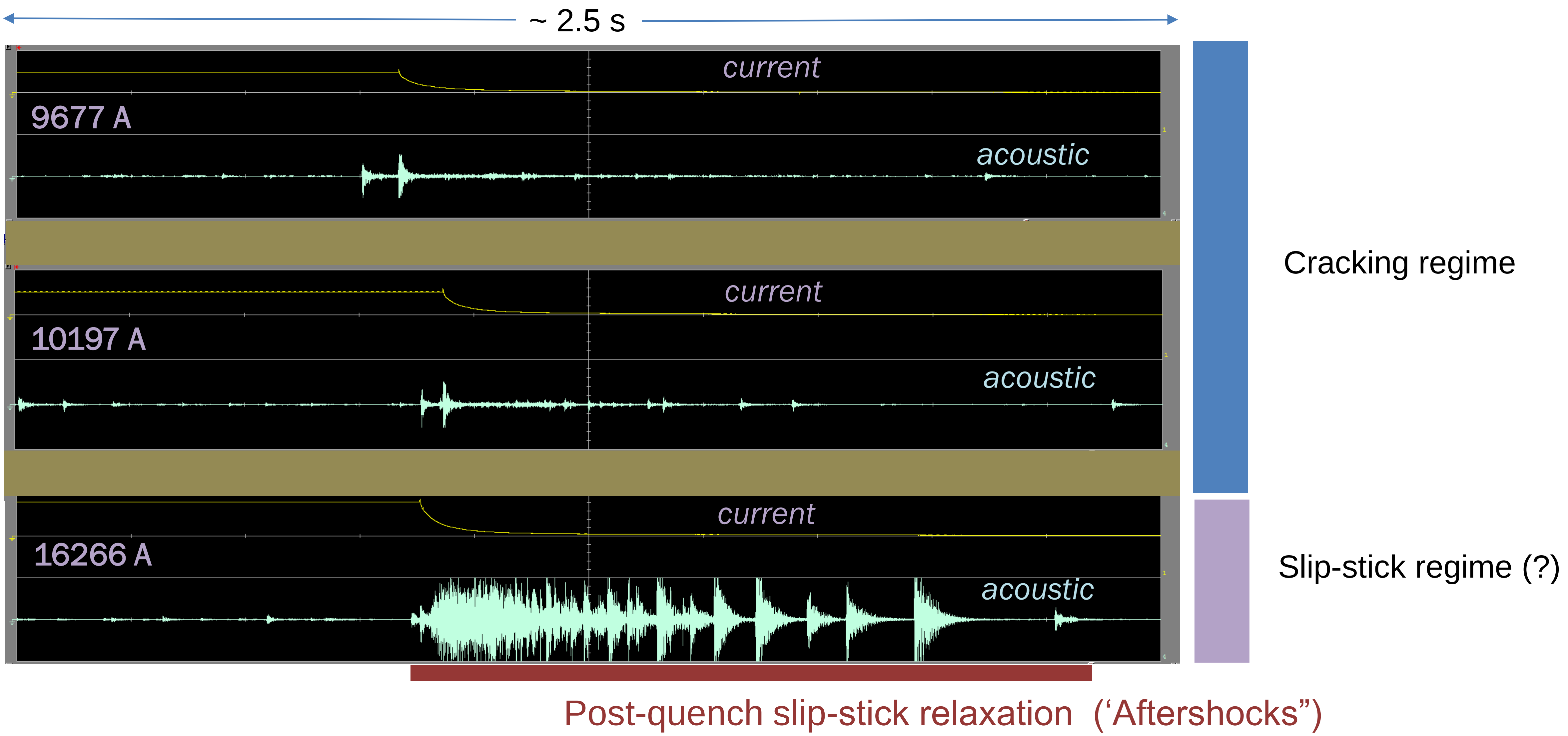
Short training => AE memory, type I
Long training => no AE memory, type II



Quench #45 at 16098 A in HQ02a2. Increasing spike envelope towards the quench is observed.

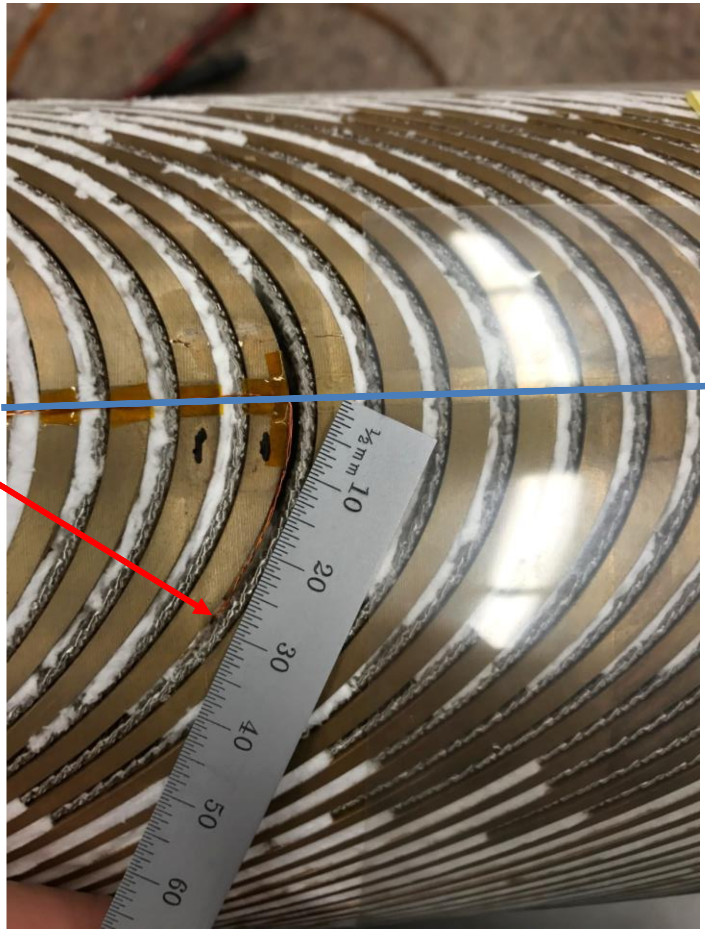


Mechanical relaxation after the quench



Temperature monitoring inside the coil

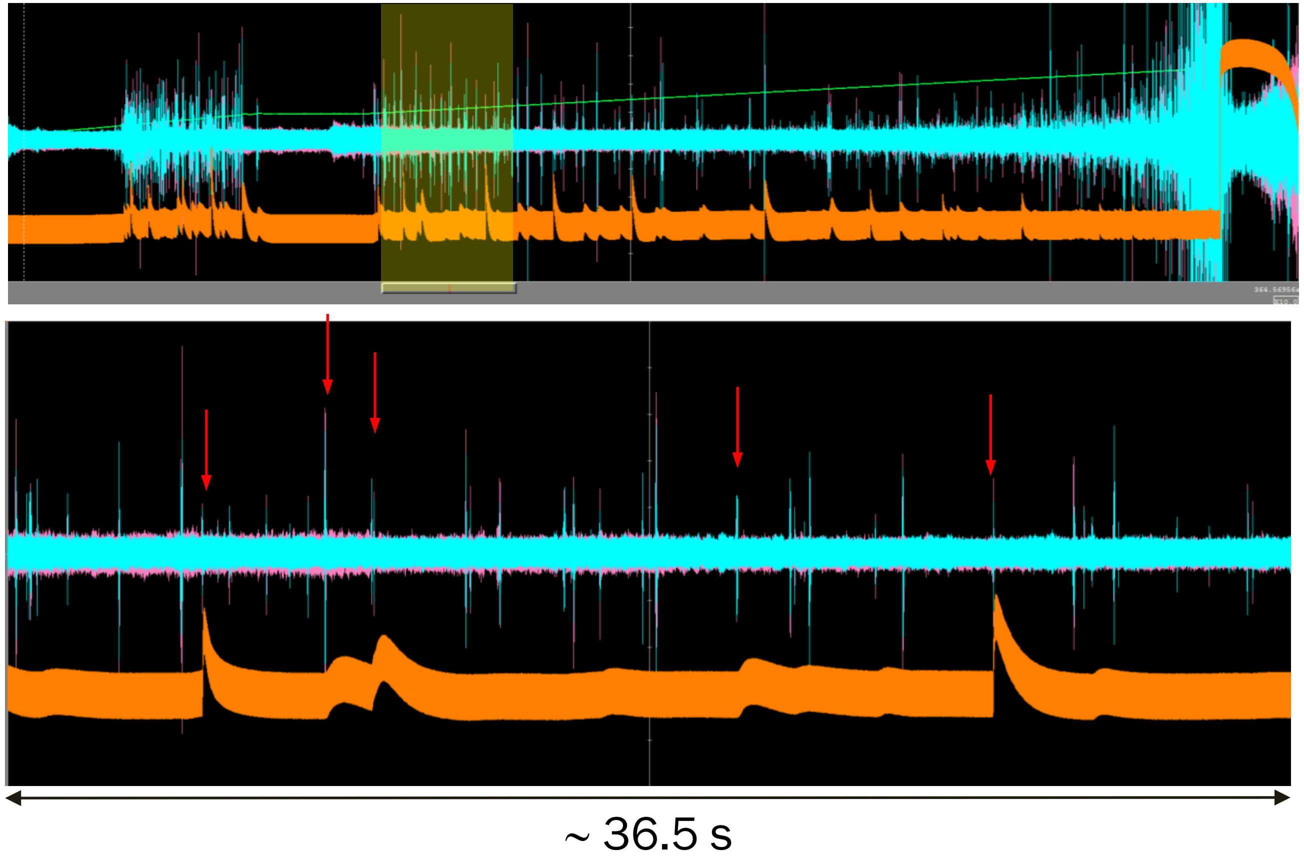
A thermometer of ~1 mm^2 size was installed directly in the cable groove in the magnet outer layer, prior to impregnation

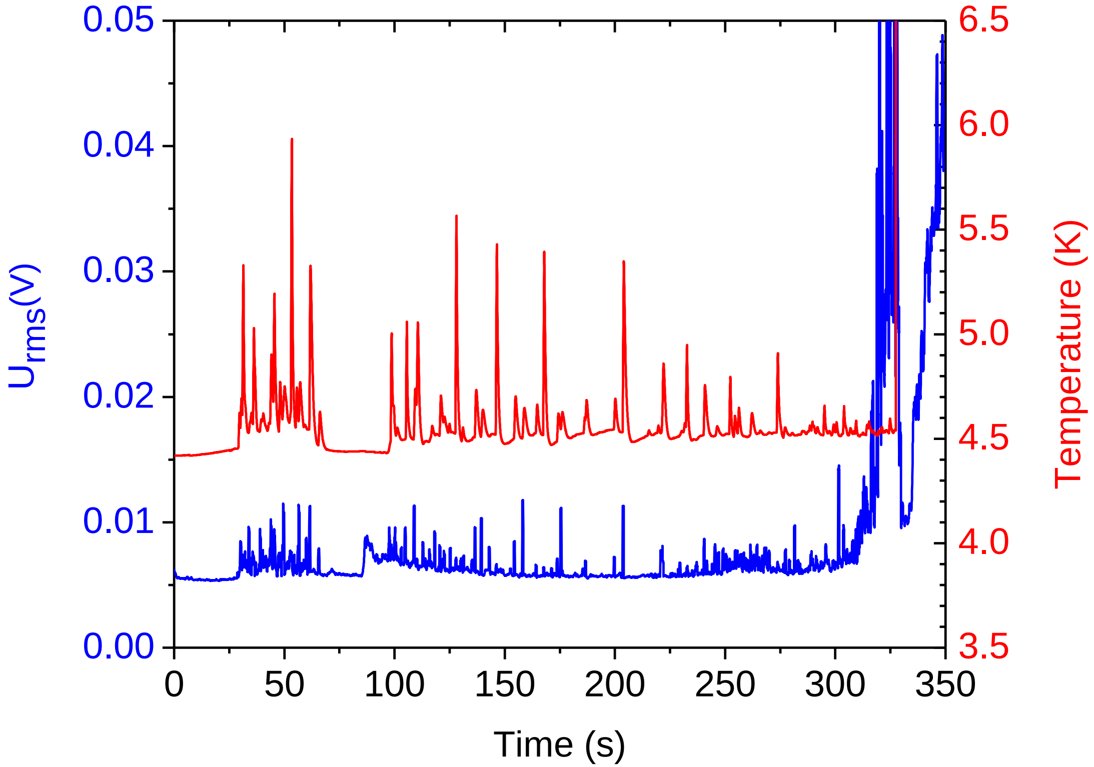


Pole location

Thermometer was powered by 10 μA bias current and monitored simultaneously with acoustic signal and coil voltages during ramps.

Thermal and acoustic spikes are correlated

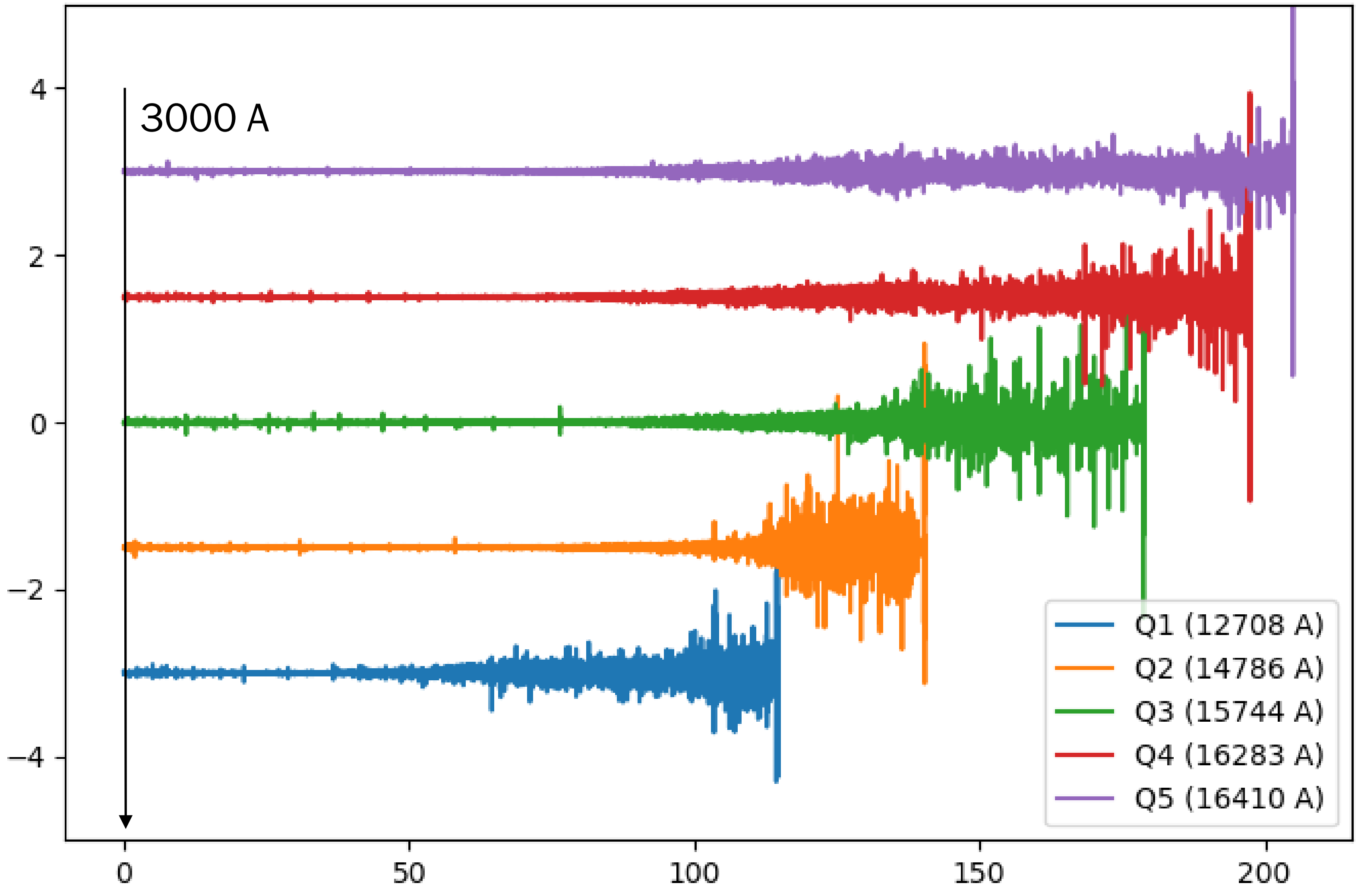




- Temperature spikes as high as 1 K are observed in the “cracking” regime. All of them are time-correlated with the acoustic events, and few also correlate with voltage spikes on the coils
- Surprisingly, only a minor (< 20 mK) temperature rise is seen in the “slip-stick” regime prior to quenching

So what is driving a quench in the “type II” training regime???

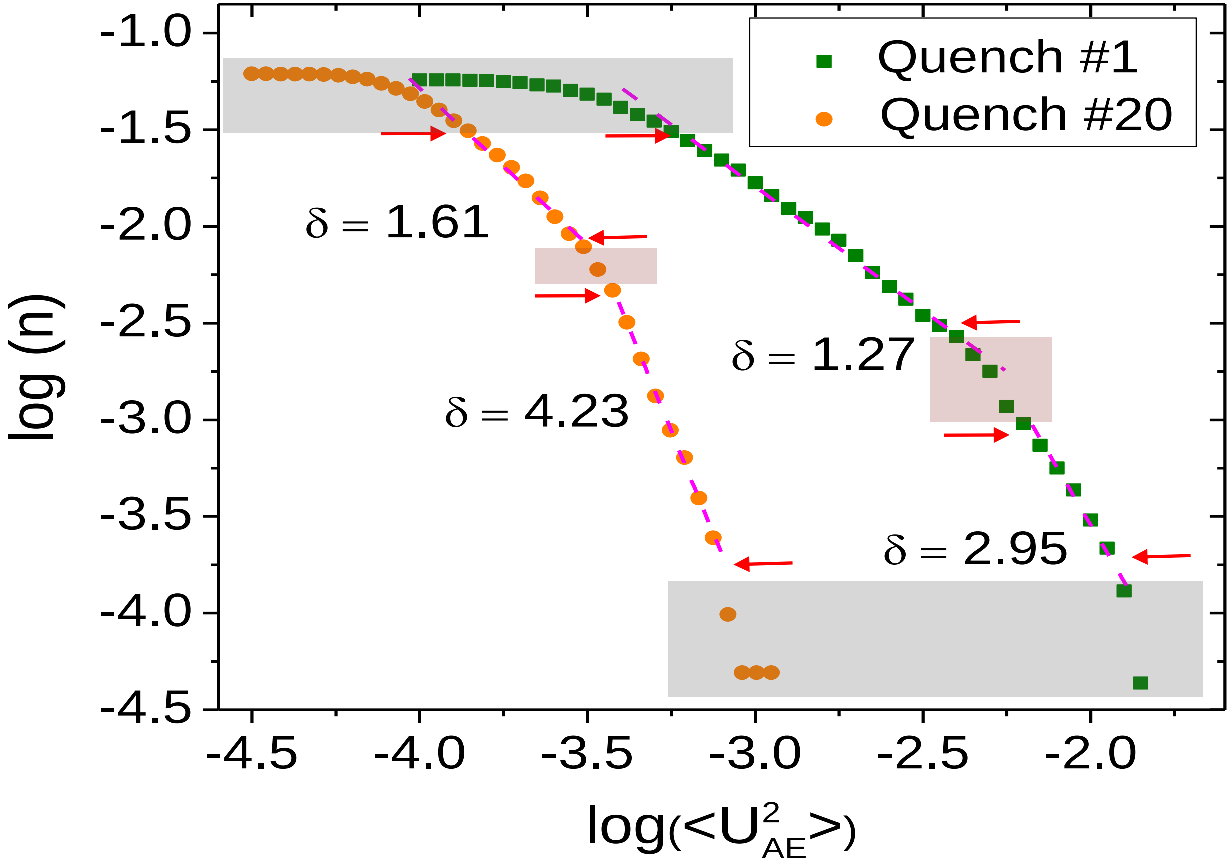
Thermal cycle: "type II behavior starting from quench #2



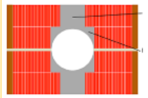
- In quench 1 AE starts early, but still follows an amplitude envelope increasing towards the quench (unlike quench #1 in the virgin magnet)
- From quench #2 the clear "type II behavior is observed"

Possible explanation: a large accumulated slippage during thermal cycle, that gets "cleared" in quench 1

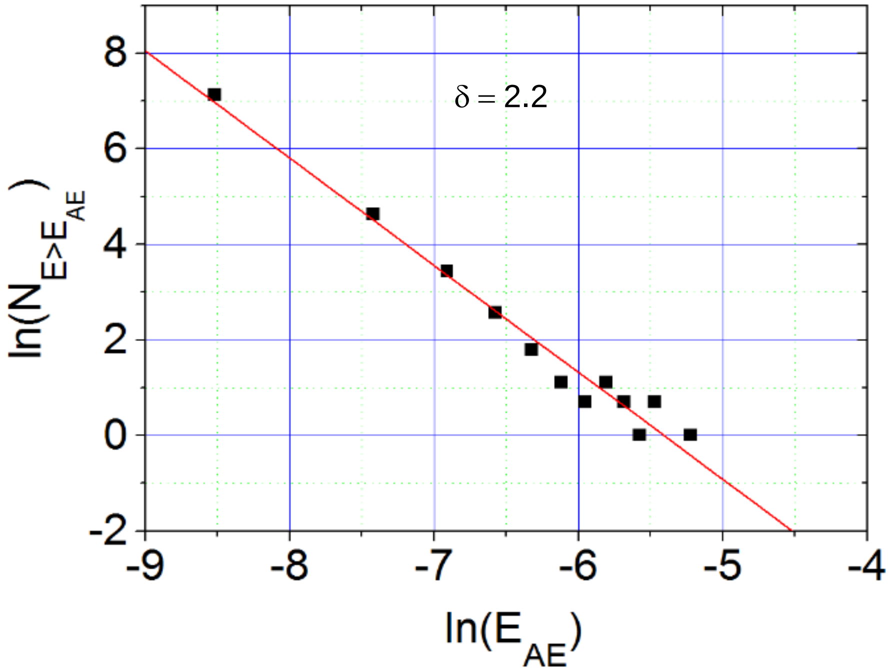
Power law scaling implies critical dynamics



Normalized number of the AE events of energy E > E_{AE} in CCT4 magnet during ramp #1 and ramp #20 to quench plotted versus E_{AE}. (E_{AE}= $<U^2_{AE}>$)



$N(E) \sim E^{-\delta}$



Cumulative number of the AE events of energy E > E_{AE} in Coil "1" oh HD3b during ramp #72 to quench, plotted versus E_{AE}. The linear fit is a power-law dependence with exponent $\delta = 2.2$.

Possible mechanism behind these observations

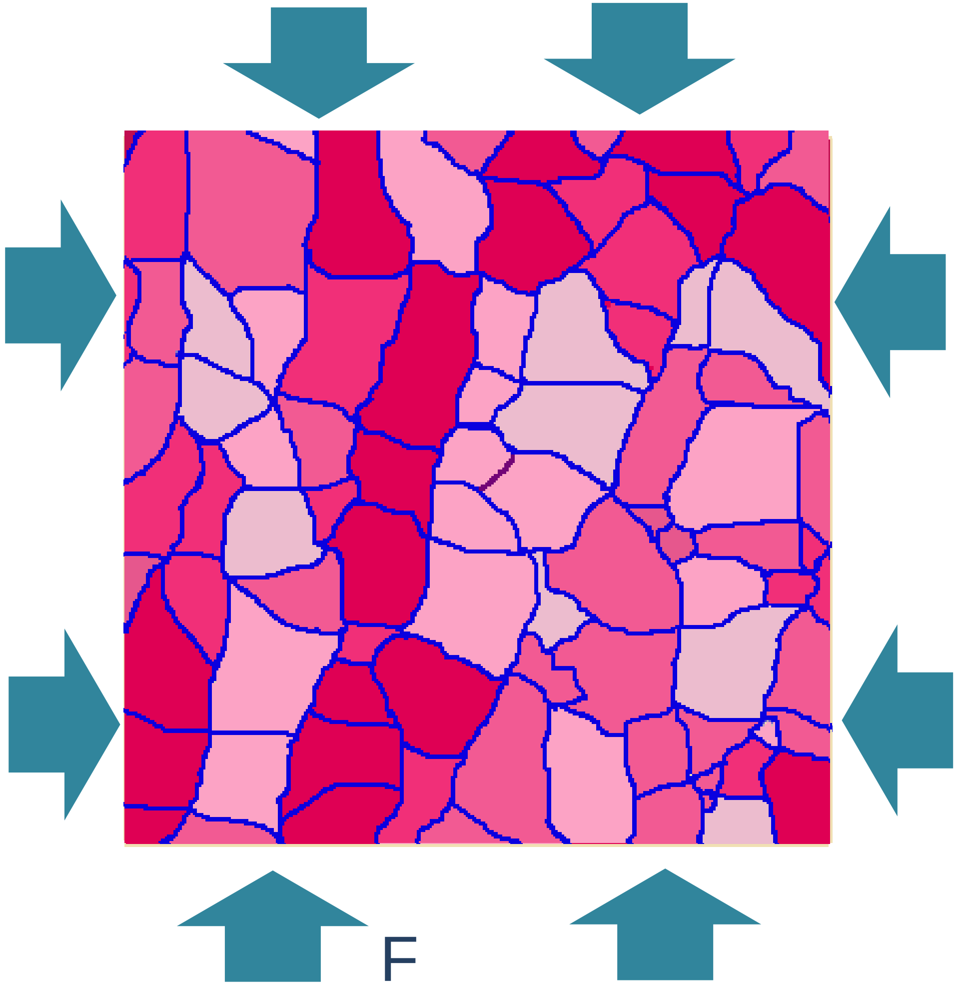
Cracks develop => grow and interconnect => percolate => slip-stick between grains

Type I

Structure is rigid

Structure is weakened by cracks

Deforms elastically and plastically as a solid body, with no internal "slippages"



Type II

Stress distribution is non-uniform at the micro-scale. Enters a "critical" state.

Structure is held together by internal "locking" and friction

Deforms via internal slip-stick motion accompanied by occasional formation of new cracks and voids

Possible mechanism behind these observations

Cracks develop => grow and interconnect => percolate => slip-stick between grains

Type I

Structure is rigid

Structure is weakened by cracks

Deforms elastically and plastically as a solid body, with no internal "slippages"

A "well-built" magnet should train up to the "plateau" by this point

Type II

Stress distribution is non-uniform at the micro-scale. Enters a "critical" state.

Structure is held together by internal "locking" and friction

Deforms via internal slip-stick motion accompanied by occasional formation of new cracks and voids

But can it be all happening within the conductor?

Dynamic stress effects in technical superconductors and the "training" problem of superconducting magnets

G. Pasztor and C. Schmidt, *J. Appl. Phys.* 49 (1978)

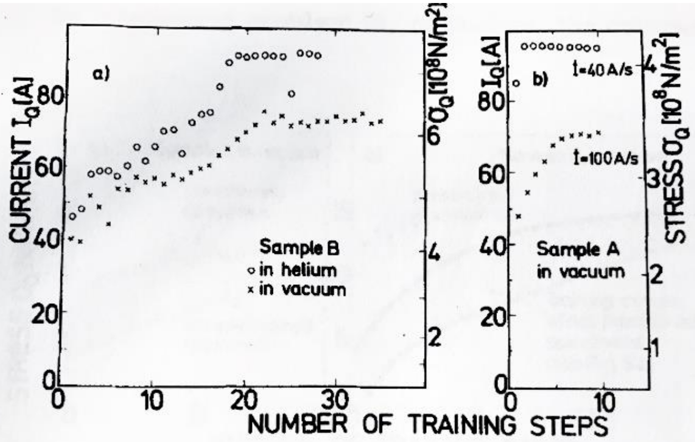


FIG. 4. Short-sample training in a transverse field of a single-core conductor (a) without and (b) with copper matrix. The plot gives the current at which the sample quenched and the corresponding stress calculated with Eq. (5) versus the number of quenches.

890 J. Appl. Phys., Vol. 49, No. 2, February 1978

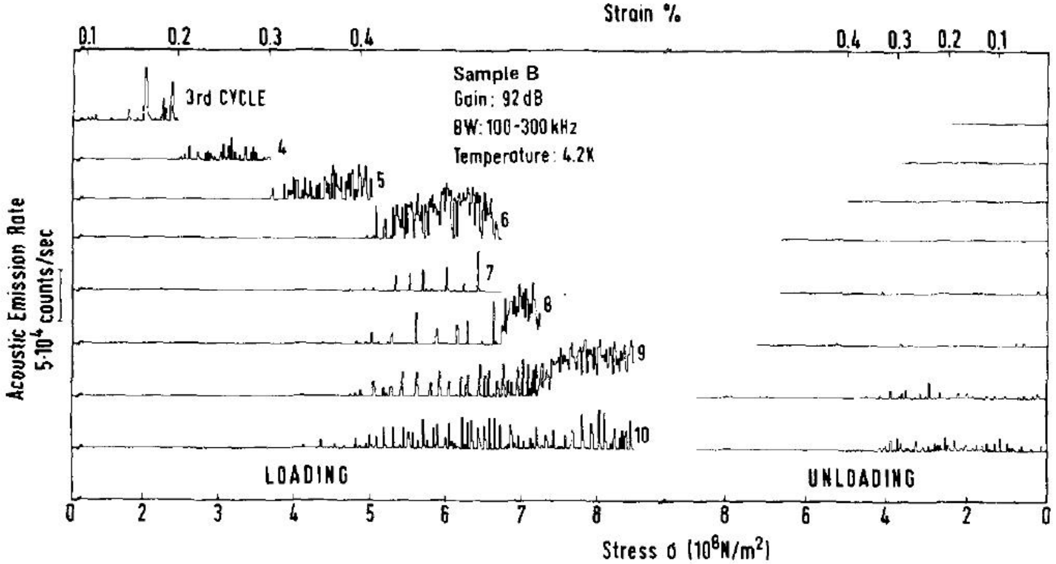


FIG. 7. Acoustic emission rate from a NbTi (50 *wt%*) wire as a function of stress during several loading-unloading cycles. The plot gives the number of oscillations per second. The stress rate is 8.5 $\times 10^8$ N/m^2 sec upon loading and 16 $\times 10^8$ N/m^2 sec upon unloading. The top scale gives the corresponding strain.

The acoustic activity involves two significant components: (i) A stress-irreversible component within the whole range of the stress-strain curve which appears in all loading cycles in Fig. 7 for stresses exceeding the previous maximum stress value. In an experiment characterized by a higher amplifier gain, irreversible emission was found to start immediately upon the application of stress. 14 (ii) A stress-reversible part starting at a stress of about 5 x 10^8 N/m^2 (corresponding to a strain of about 0.4%) which is seen for the first time in cycle 7. The stress necessary to induce the reversible emission showed the tendency to decrease with increasing number of cycles.

Can we identify event types from *individual* AE transients?

Possibly – if we can determine what are the distinctive features in their AE transients

Complexity:

- It is not clear *a priori* if acoustic signatures of slip-stick, cracking or un-sintering are really that different (they all are very short-duration events (< 1 μs), meaning we need to look into high frequencies)

- Wave propagates through the magnet and crosses multiple interfaces, so the received signal reflects properties of the medium it has traversed. Distortions due to damping, reflections and dispersion will accumulate along the wave path

A path forward

We are experimenting with wavelet transforms to develop a robust set of identifiers for the transient events

1. **Collect AE data at high rates (0.5-1 MHz is standard) during the entire test campaign**
2. ~~**Process the files to identify and time all transient events within a given amplitude window**~~
3. ~~**Normalize events for the amplitude**~~
4. **Run wavelet transforms on each event and record set of coefficients (5-7) identifying its characteristics**

Compare coefficients directly

Cross-correlate between events, and cluster them based on similarity

OR

Cross-correlate with events of distinctly different type that are either simulated or recorded in model experiments

Program a neural network

Teach it using pre-recorded AE signals of slippage, cracking, un-sintering, etc. obtained from table-top test experiments. Then apply to magnet data for clustering events by type

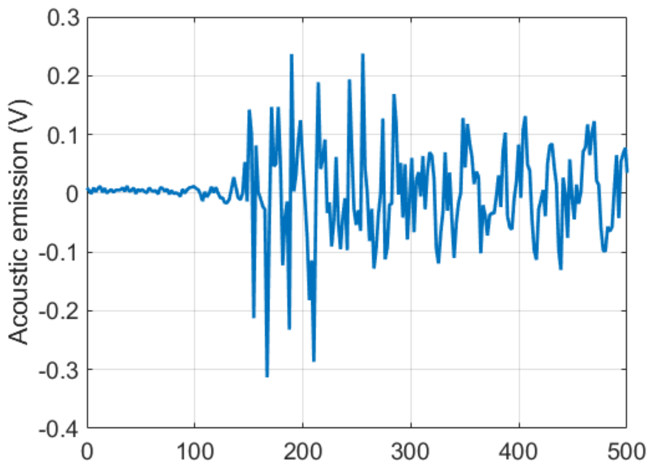
OR

Use unsupervised learning algorithms and back-propagation techniques to automatically cluster events by type

A primer on wavelet-based event identification: see Emelie Nilsson's presentation next

Characterizing acoustic events

- Transient acoustic emission (time scale ~ 1-2 ms).
- Wavelet analysis: ideal for analysis of transient signals.
  [Torrence et al., American Meteorological Society 1998]
  [Gupta et al., Ultrasonics 2017]

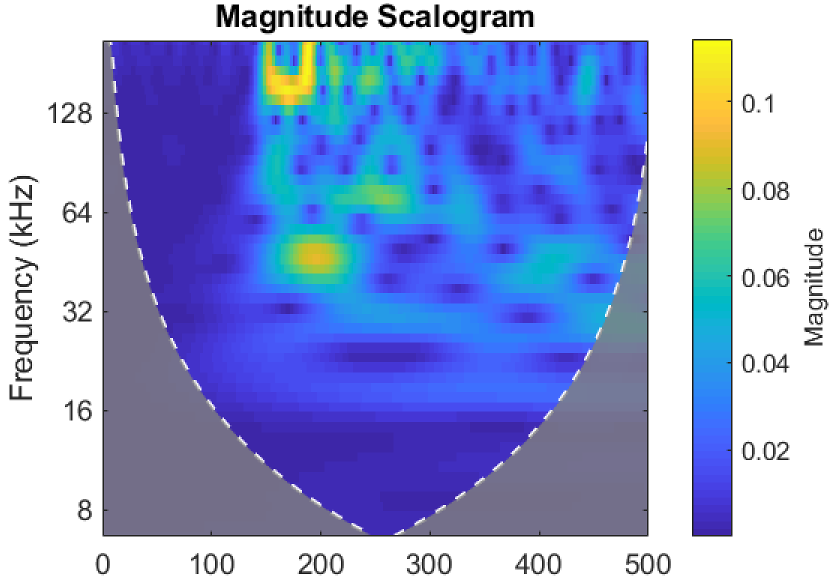


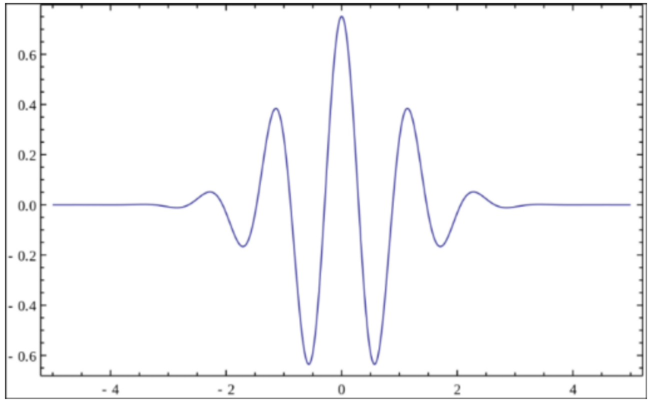
- Continuous wavelet analysis, using a wavelet base function Ψ:

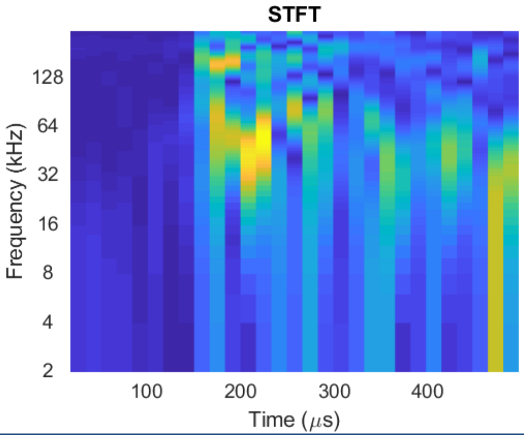
$$X(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} \overline{\Psi\left(\frac{t-b}{a}\right)}\, x(t)\, dt$$

  - Scaling factor **a**, shift in time **b**.
  - Corresponding frequency values:

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





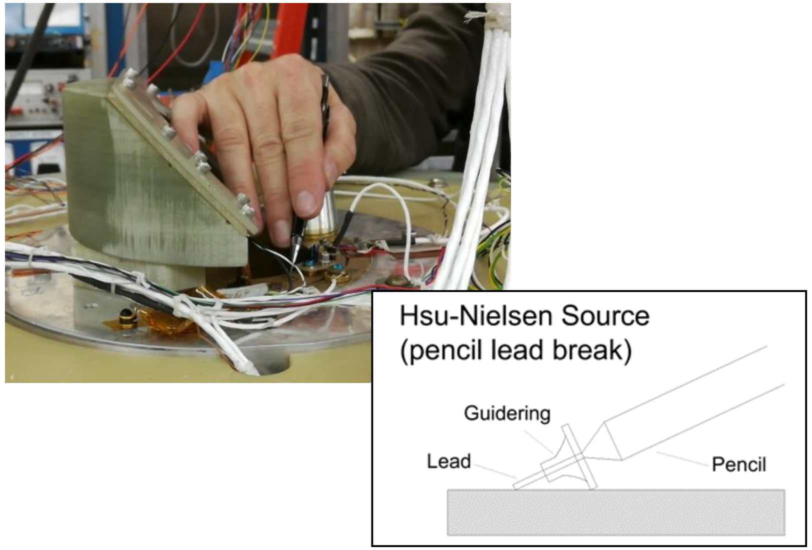


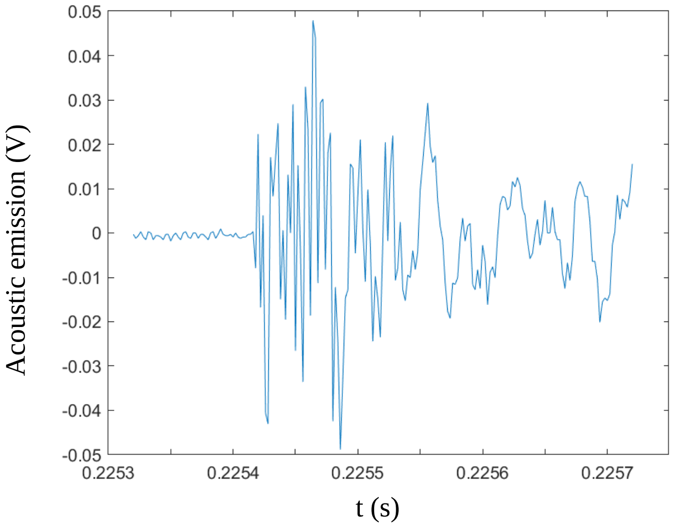
Compare with Fourier Transform:

by E. Nilsson

Pencil lead break and ball drop

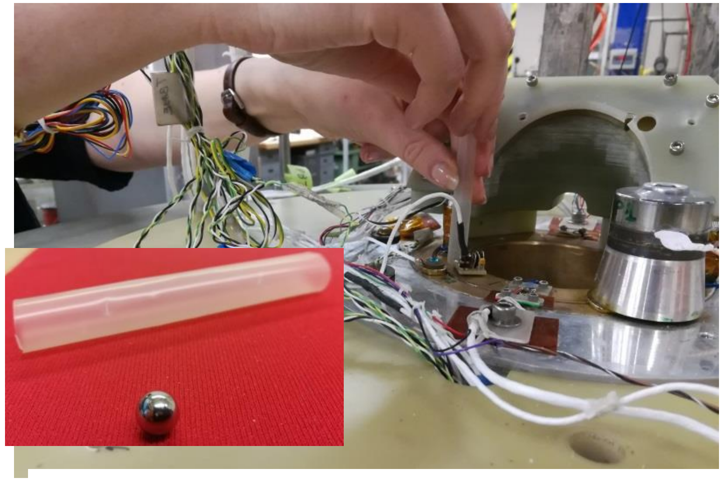
Pencil break

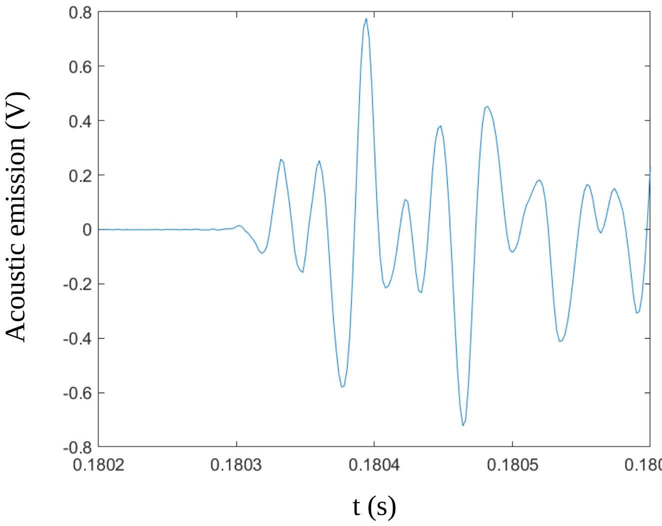




Ball drop

- 1 g ball dropped from 7.5 cm height.



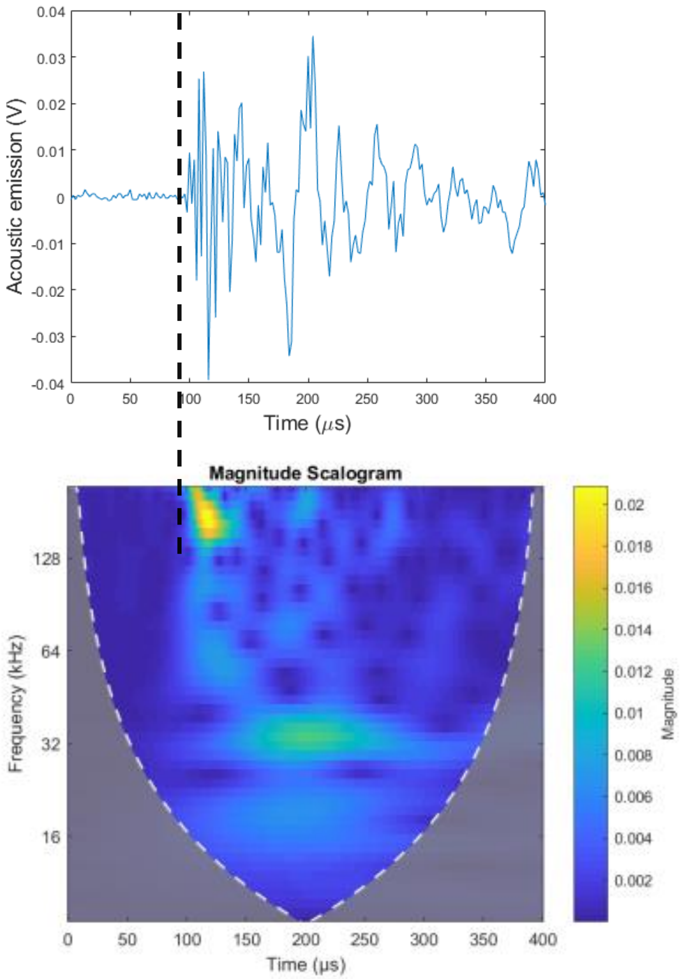


by E. Nilsson

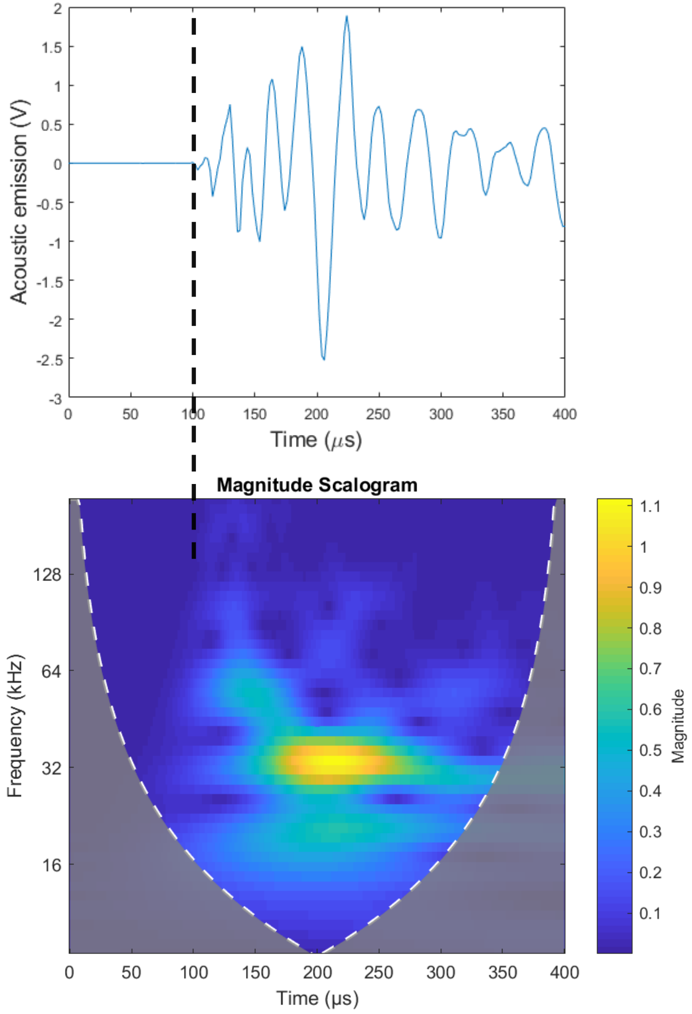
Time-frequency analysis

- **Events have different frequency content:**

Pencil lead break:



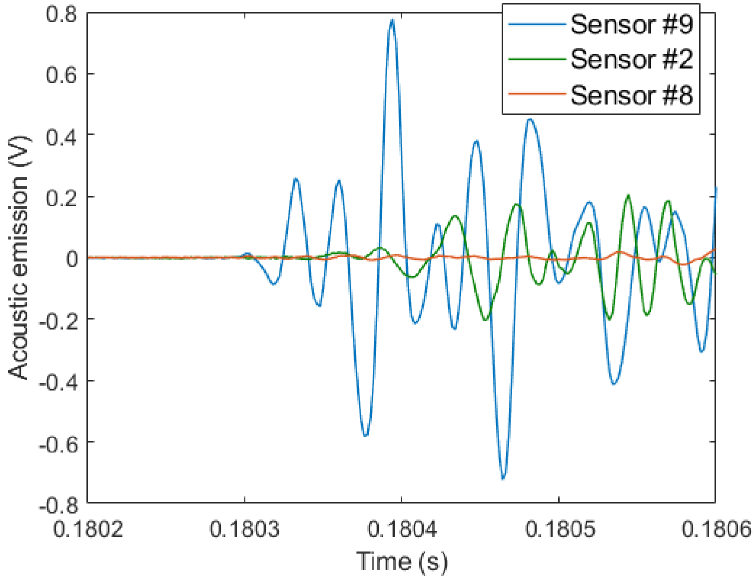
Ball drop:

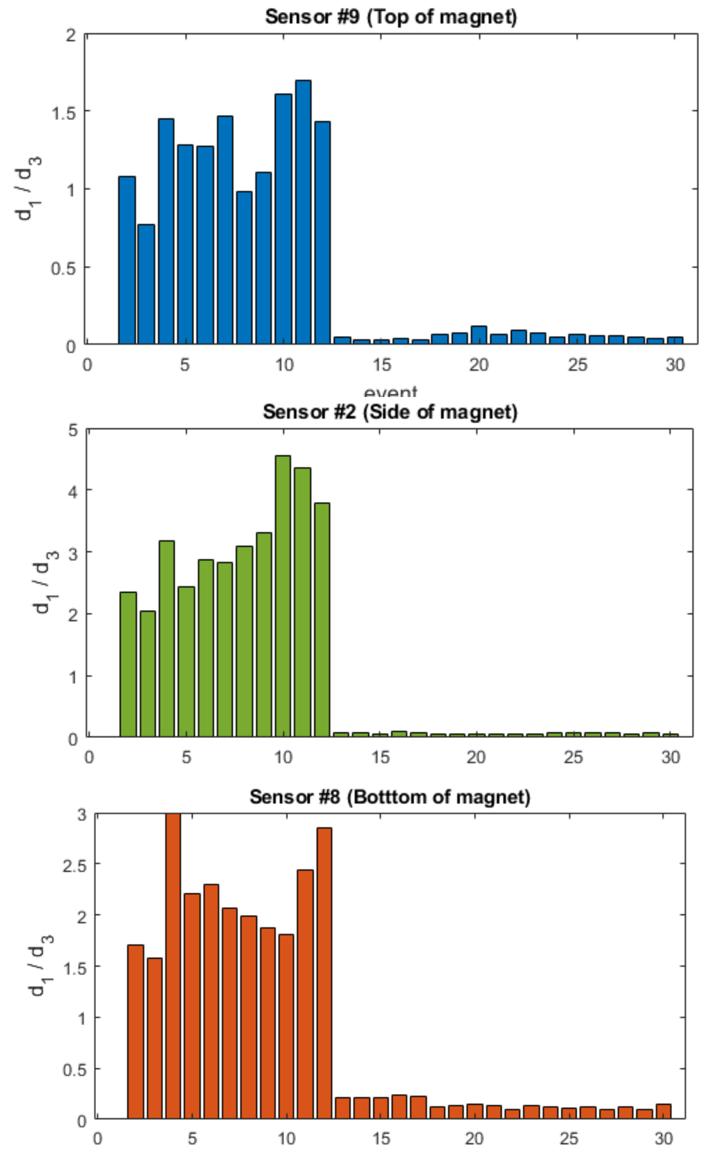


by E. Nilsson

A parameter for event identification

- A fast and reliable way to characterize these reference events is based on high frequency vs lower frequency content with discrete wavelet analysis:
  - d_1/d_3 , where d_n is the n^{th} scale of discrete wavelet decomposition.
- Order of magnitude difference between pencil lead break (events 2-12) and ball drop (event 13-30), detected <u>on all eight sensors</u> (even the ones far away from the event, with weak signal)

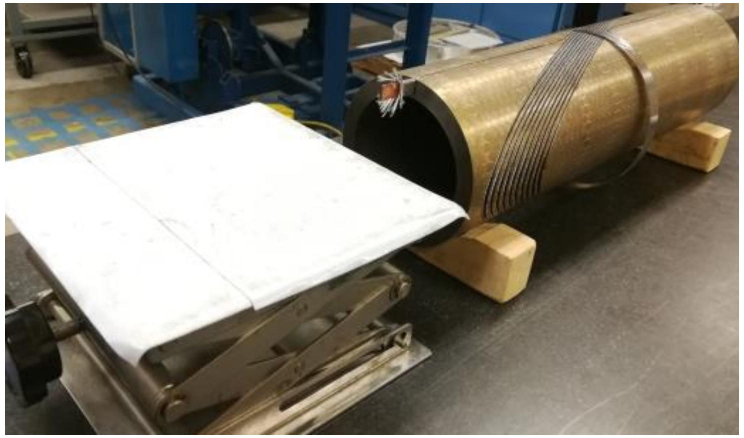


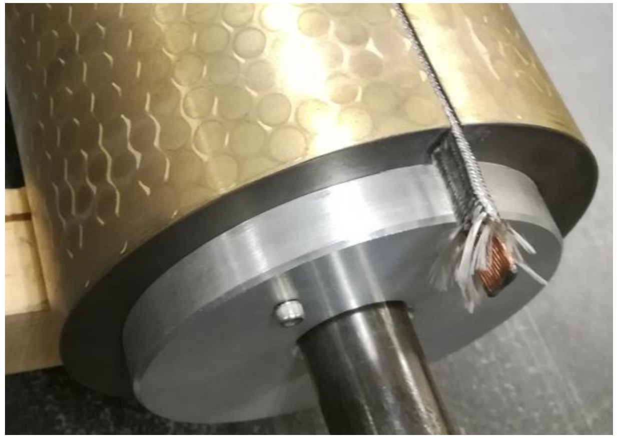


by E. Nilsson

Characterization of acoustic emission in CCT

- Epoxy cracking (*Tengming Shen).*
- Stick-slip between interfaces in magnet.
- On the cable level: Debonding of sintered (typically from heat treatment) strands in cable. Acoustic signature to be tested.





The challenge:

- Events in the magnet are more similar to each other than ball drop and pencil lead crack.

by E. Nilsson

Part 2:
Quench detection effort update

Progress on the quench detection

Last year we reported a new technique for quench detection in HTS, and demonstrated its working on a small (10 cm-long) impregnated stack of HTS tapes

"Acoustic thermometry for detecting quenches in superconducting coils and conductor stacks", M. Marchevsky and S. A. Gourlay, *Appl. Phys. Lett.* 110, 012601 (2017); DOI: 10.1063/1.4973466

This year:

- **Validated the technique on 1.2 m long ReBCO conductor immersed in liquid nitrogen, calibrated its sensitivity with respect to absolute temperature change**

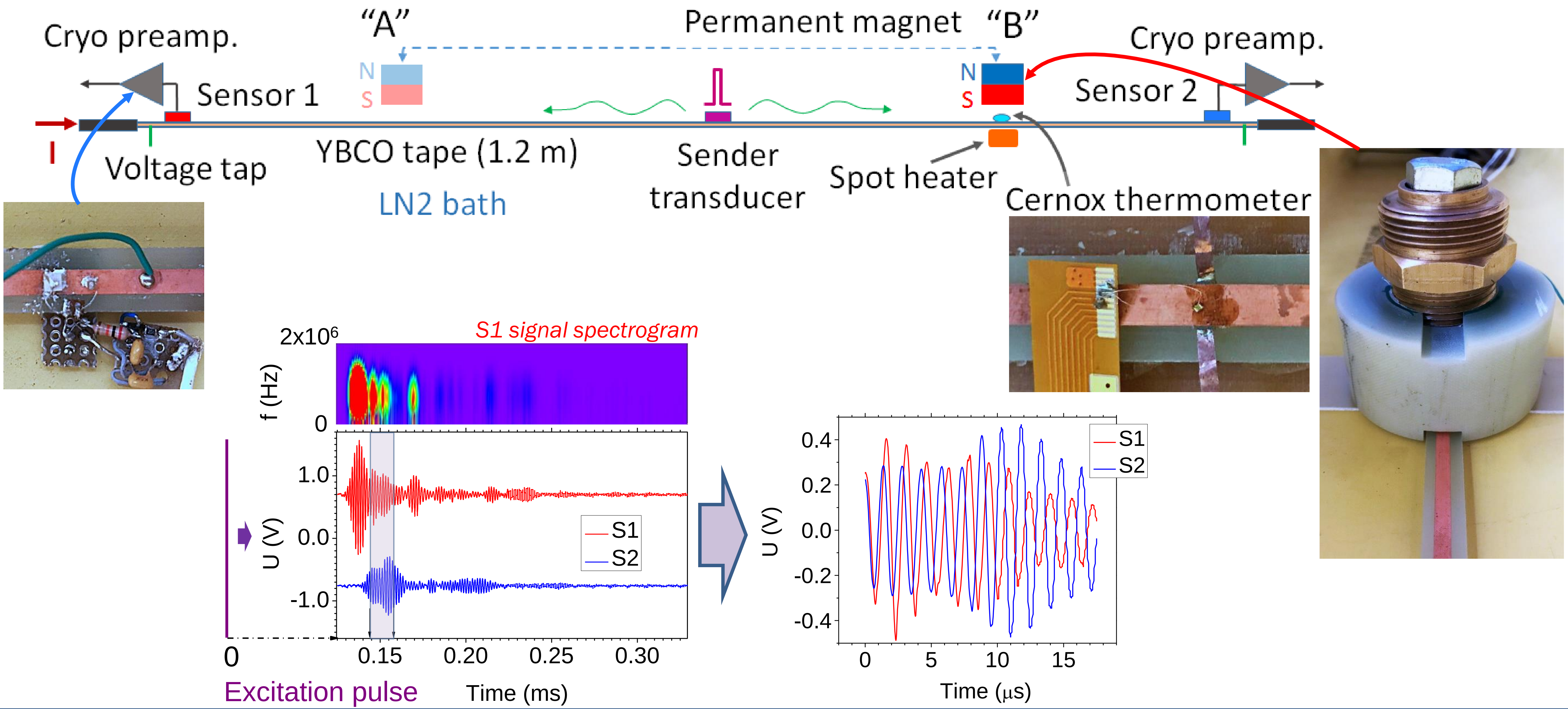
  "Quench detection for HTS conductors and coils using acoustic thermometry",
  M. Marchevsky, E. Hershkovitz, X. Wang, S. A. Gourlay and S. Prestemon, EUCAS 2017, submitted

- **Demonstrated practical quench detection in CORC-wound CCT coils at 77 K (with X. Wang) and in subscale Bi-2212 coils at 4.2 K (with T. Shen and K. Zhang)**

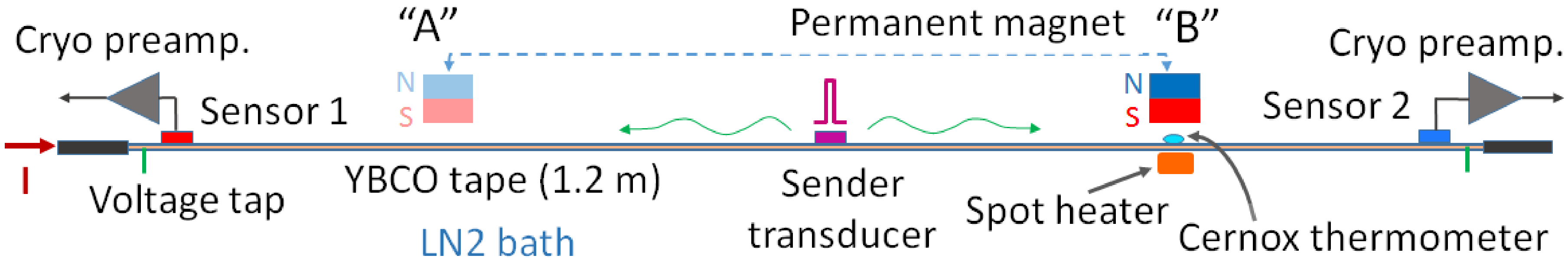
- **Proposed new capacitive QD technique (E. Ravaioli and MM), validated in in subscale Bi2212 coils at 77K and 4.2 K (with T. Shen and K. Zhang)**

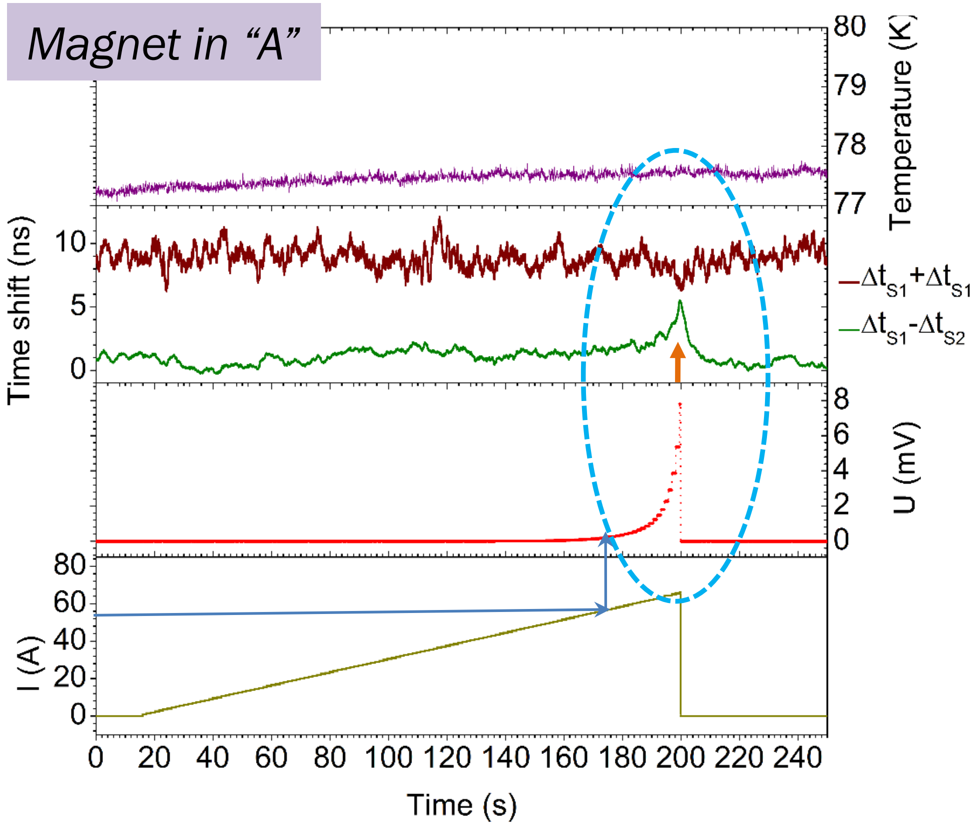
  "Quench Detection Utilizing Stray Capacitances"
  E. Ravaioli, M. Marchevsky, GL. Sabbi, T. Shen, and K. Zhang, EUCAS 2017, submitted

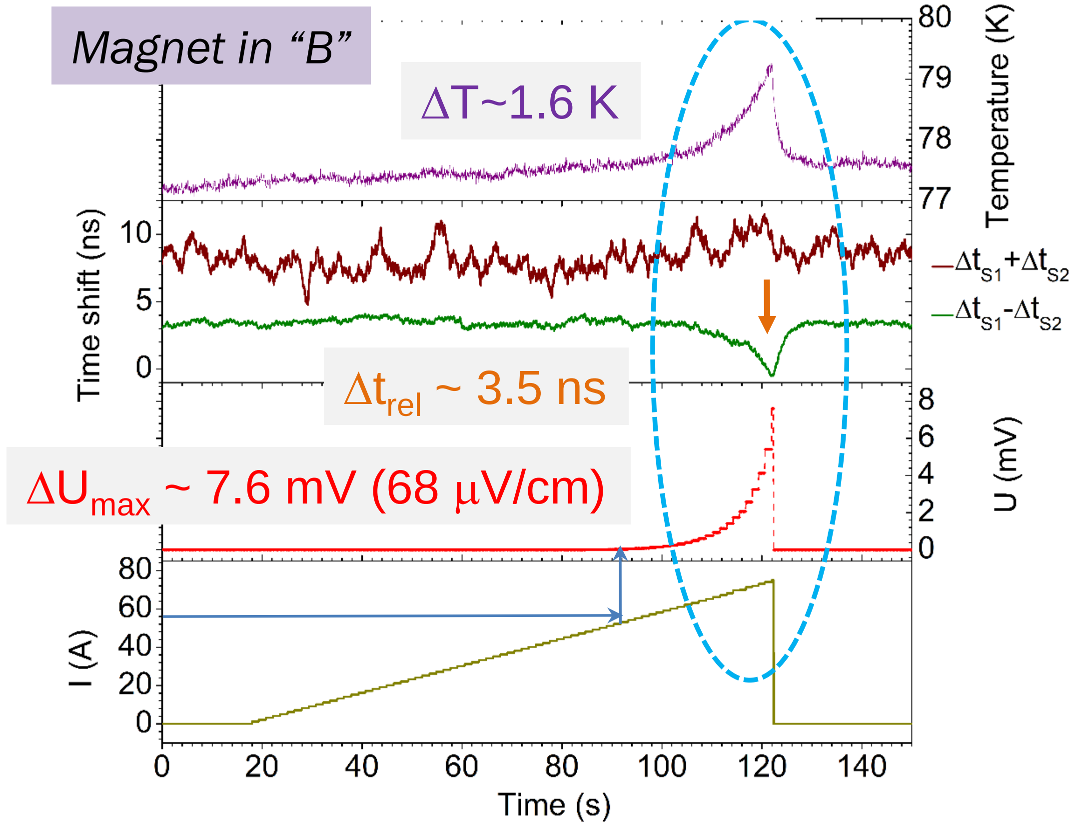
Setup for the differential acoustic detection



Differential acoustic quench detection: results

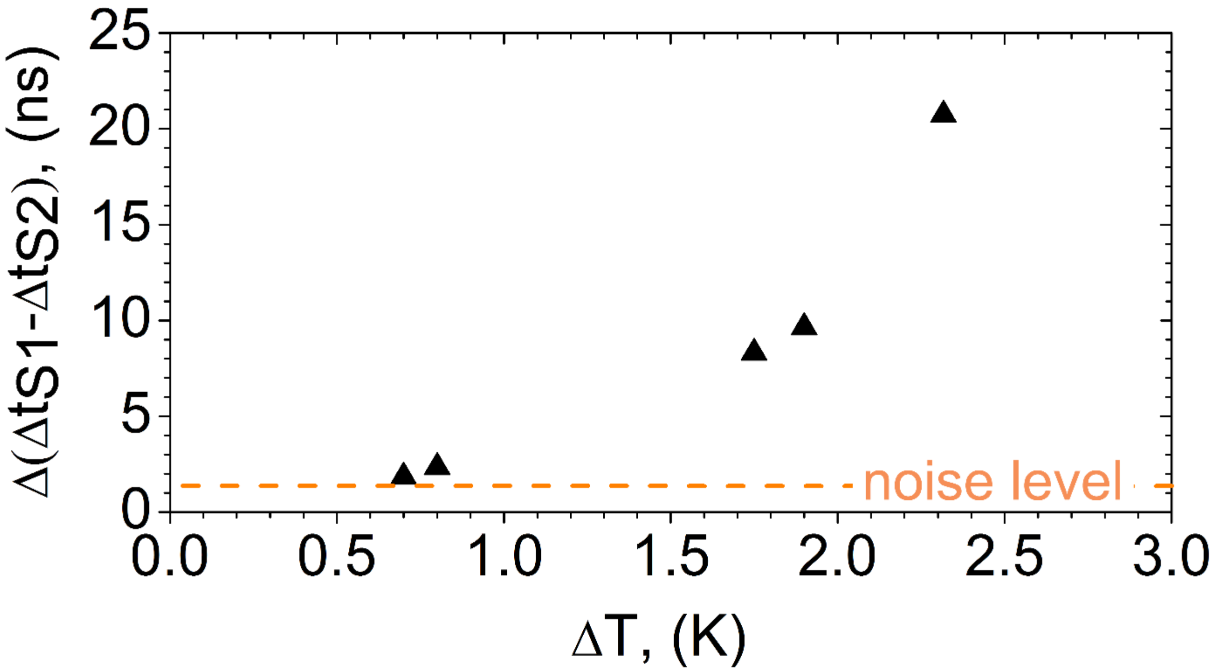






Sensitivity calibration using spot heater

- Spot heater was fired at 4.0, 4.6, 4.8, 5 and 6 V; for 5-8 s, until temperature and acoustic signal equilibrated
- No current in the tape and permanent magnet removed

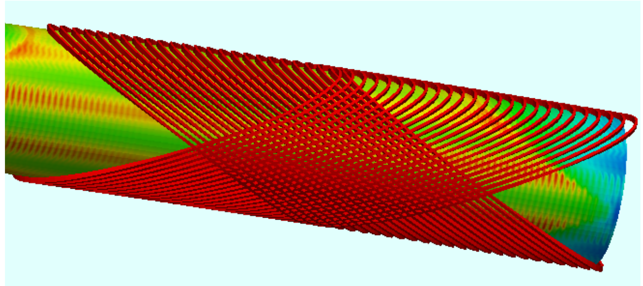


Thermal contribution to the acoustic time shift is clearly distinguishable above the noise background for ΔT > 0.7 K

CCT sub-scale coil using CORC conductor

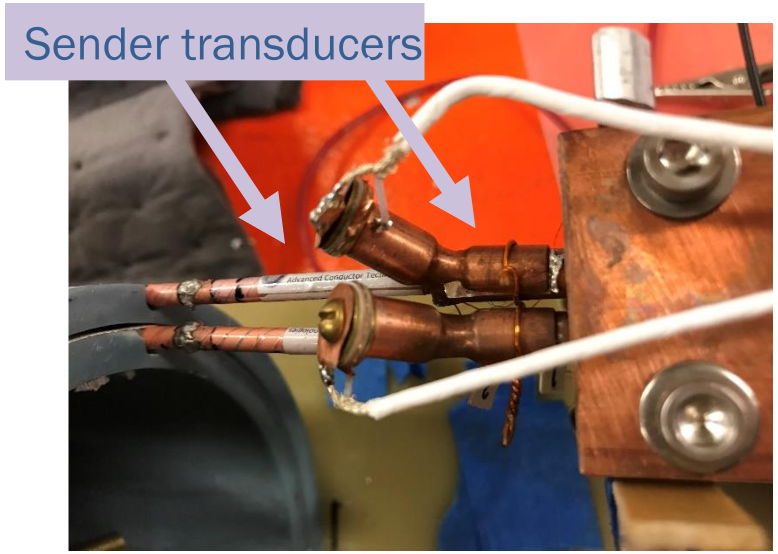
Coil design and test by X. Wang

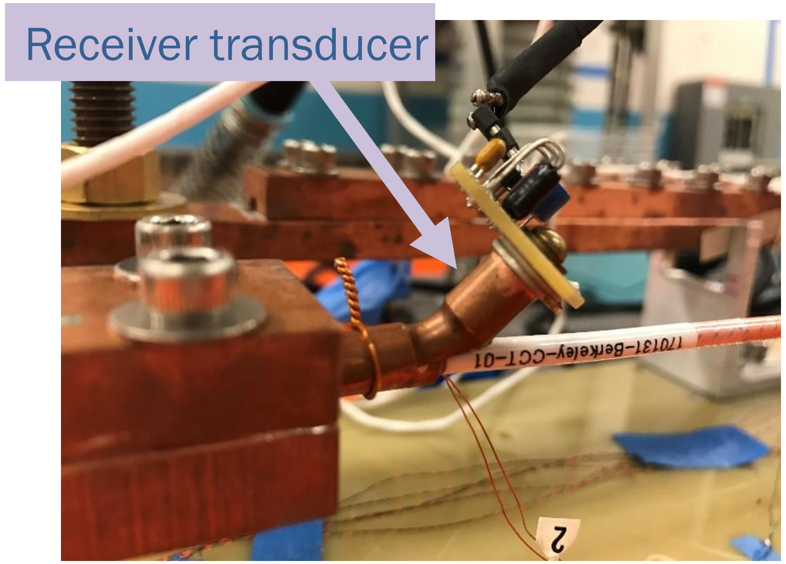
- CORC-based HTS dipole sub-scales are built by LBNL in the framework of US Magnet Development Program, and in collaboration with Advanced Conductor Technologies.



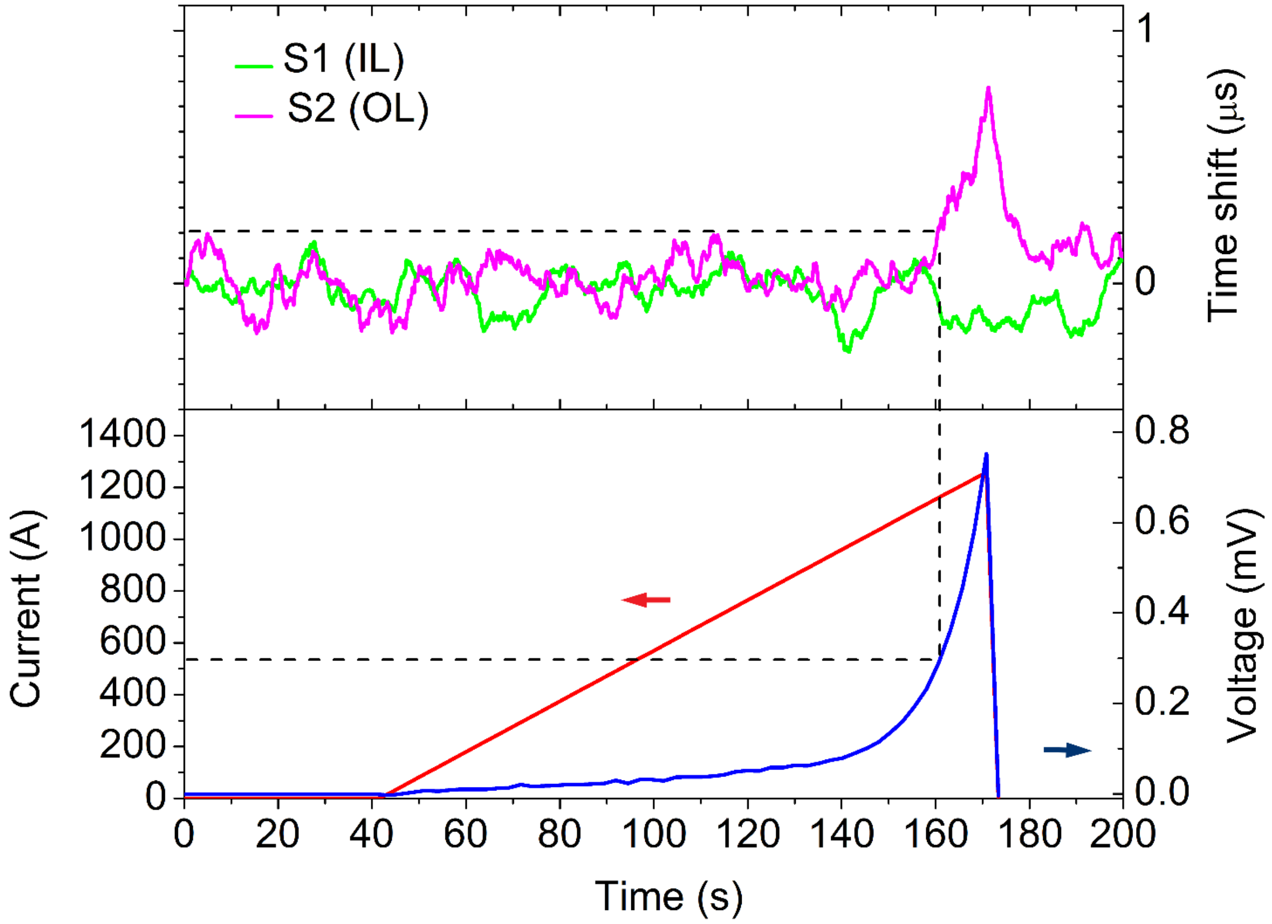
- CORC® conductor :

29 REBCO tapes distributed around a 2.56 mm diameter copper core wire.
- Tapes are 2 mm wide, and have 30 mm-thick substrate.
- Cable diameter is 3.63 mm, length is 2.25 m, including out-of-mandrel portions





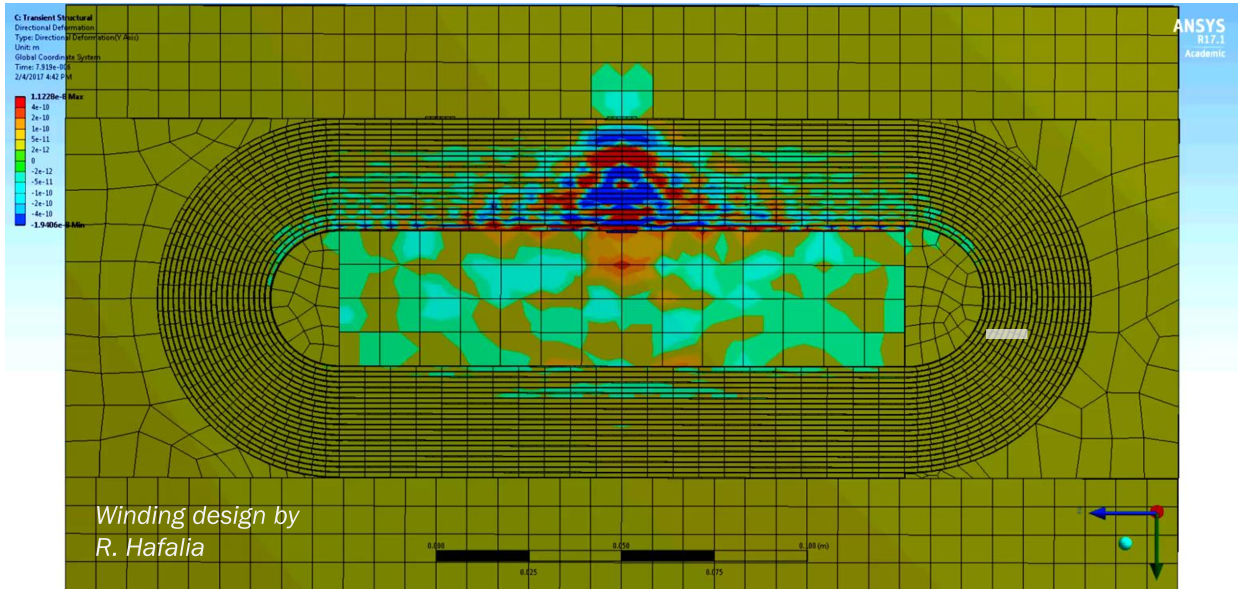
Quench detection in the CORC coil



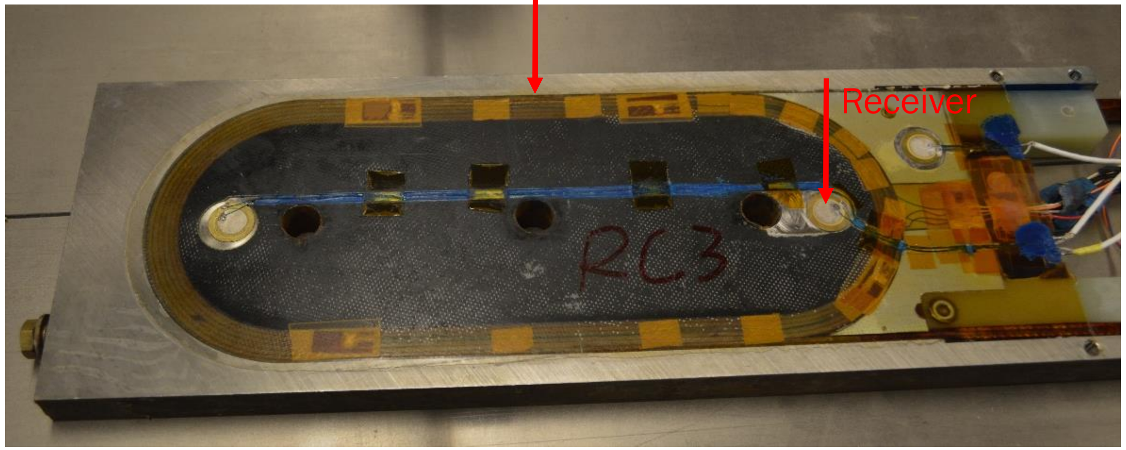
The acoustic time shift signal rises above background noise level at I=537 A which corresponds to the coil voltage of 0.3 mV and power dissipation of 0.16 W in the cable.

We are looking to improve mechanical coupling between transducers and the central core of the cable to rely on its transverse travelling wave mode.

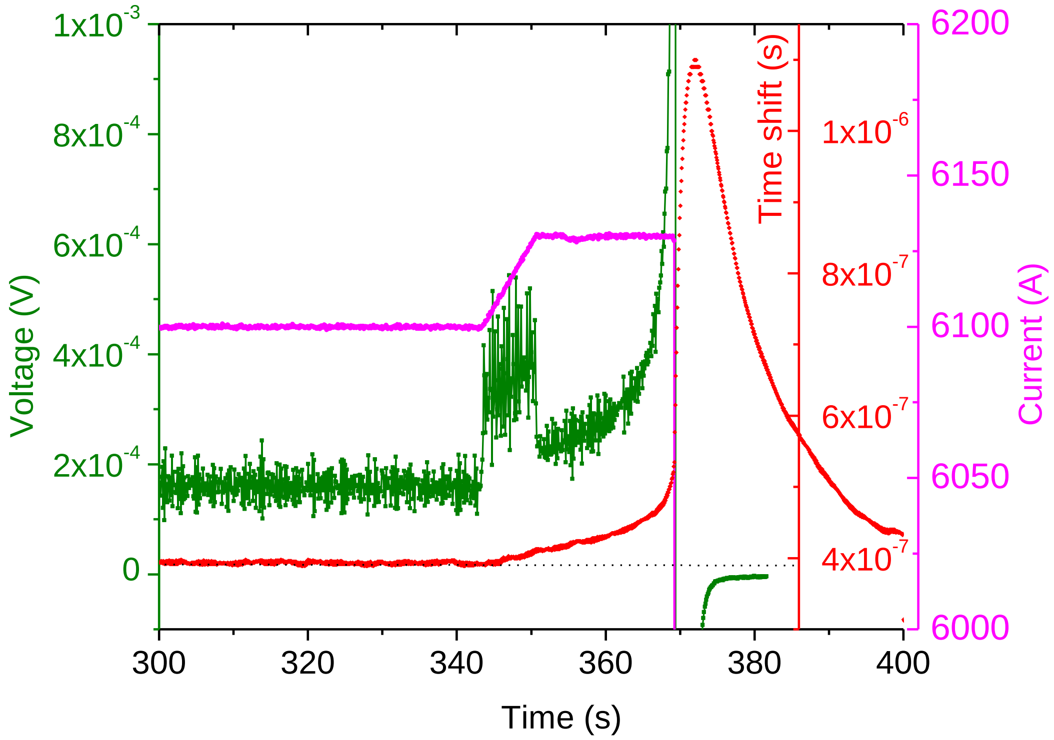
Quench detection in Bi-2212 HTS coil



Bi-2212 coil RC3



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



Coil design and test by T Shen/ K. Zhang

Capacitive quench detection

A new idea proposed by E. Ravaioli:

Utilizing change of stray capacitance between magnet structure parts to detect a quench

Why would it work?

Consider a flat capacitor:

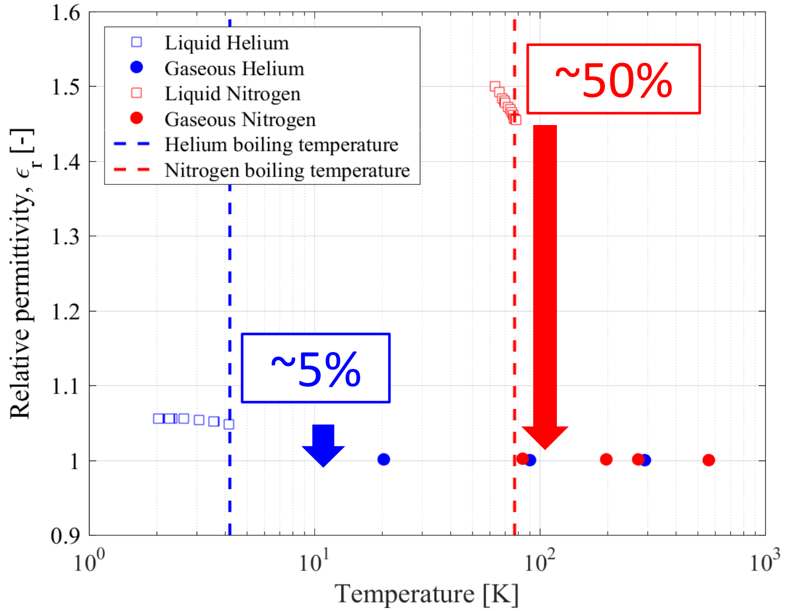
$$C = \varepsilon_0 \varepsilon_r S/s$$

ε_0=const

$\Delta C \rightarrow \Delta\varepsilon_r? \ \Delta S? \ \Delta s?$

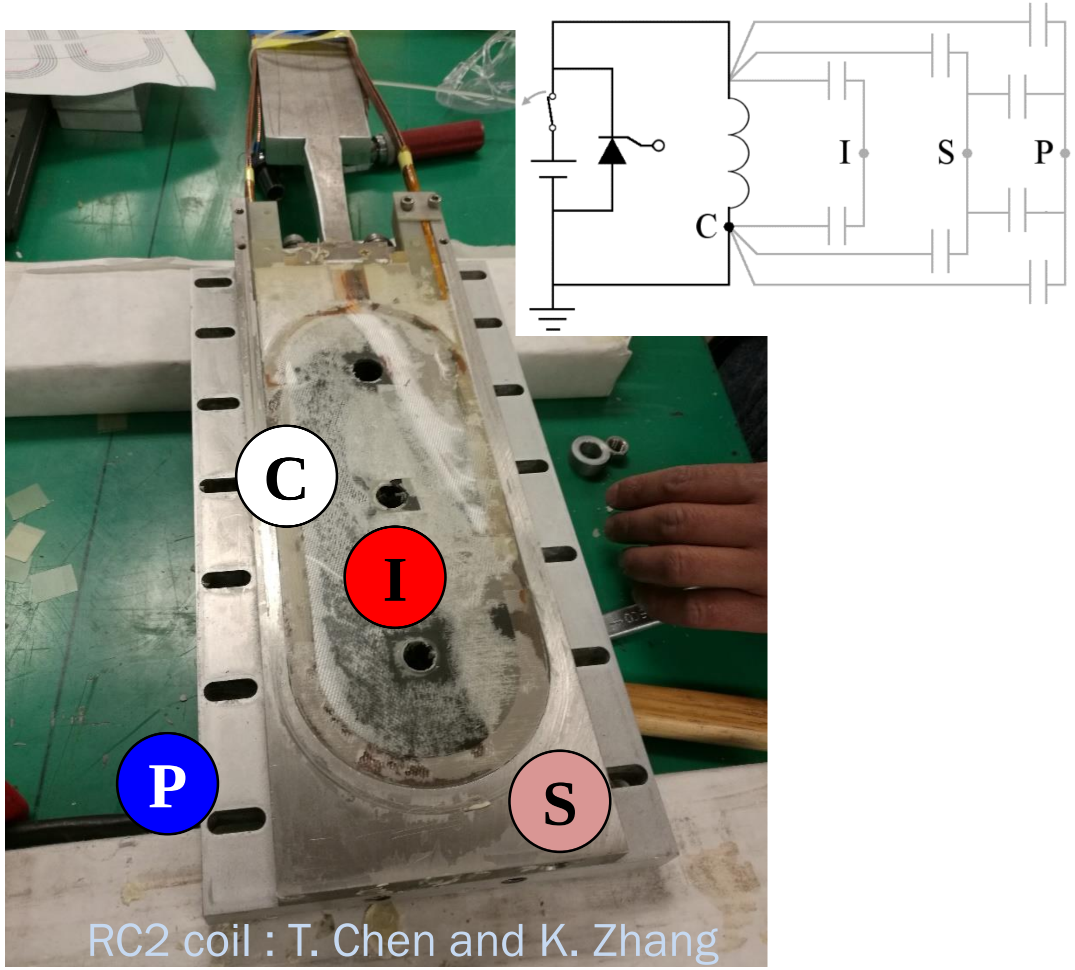
Heating

- Temperature dependence of ε_r
- Thermal expansion -> Δs?
- Mechanical movement -> Δs?
- Cryogenic liquid boiling -> $\Delta\varepsilon_r$? ΔS? Δs?



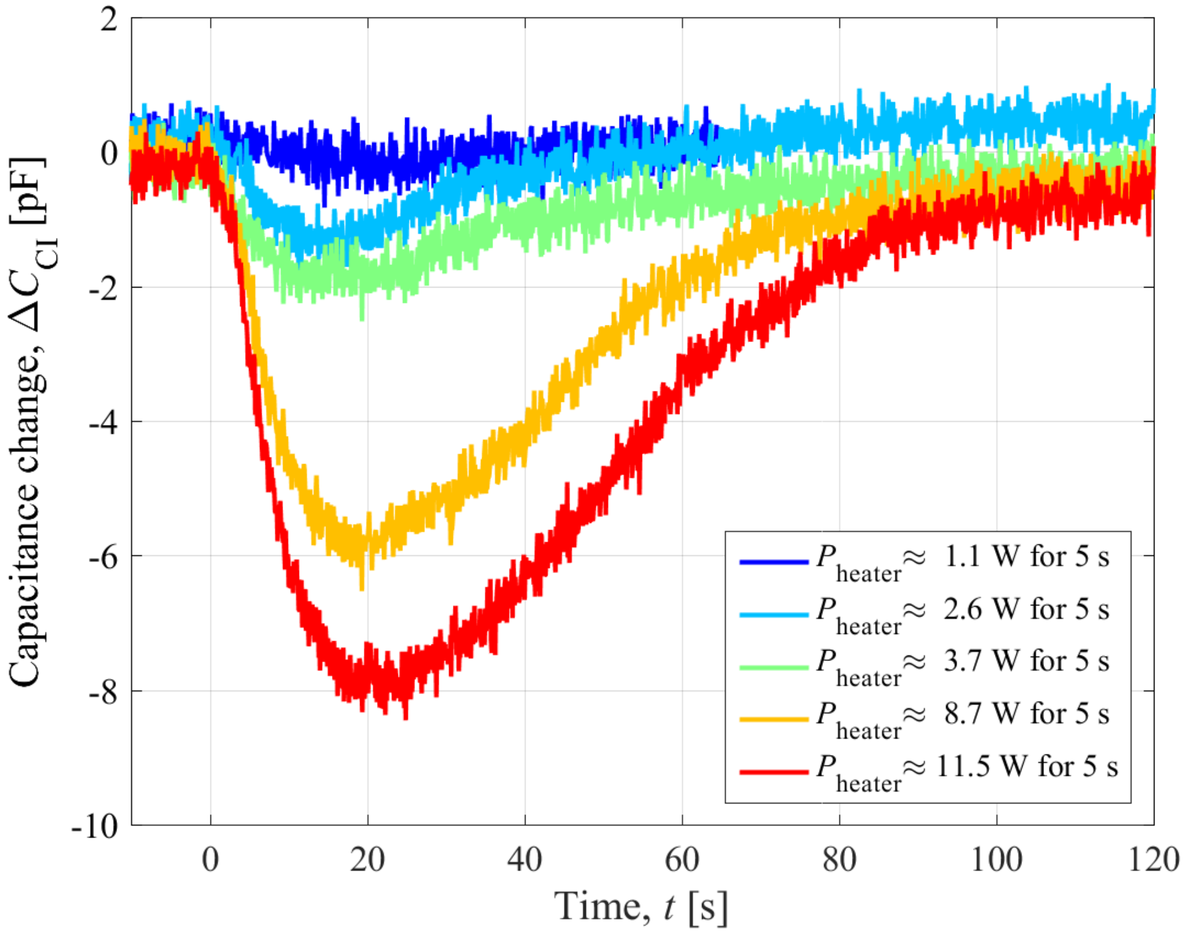
The most likely mechanism leading to stray capacitance change just before quench is the decrease of cryogen fluid's electrical permittivity ε_r when the phase change occurs.
This happens when the fluid impregnating the insulation boils off (N: T>77 K, He: T>4.5 K).

First tests in liquid nitrogen

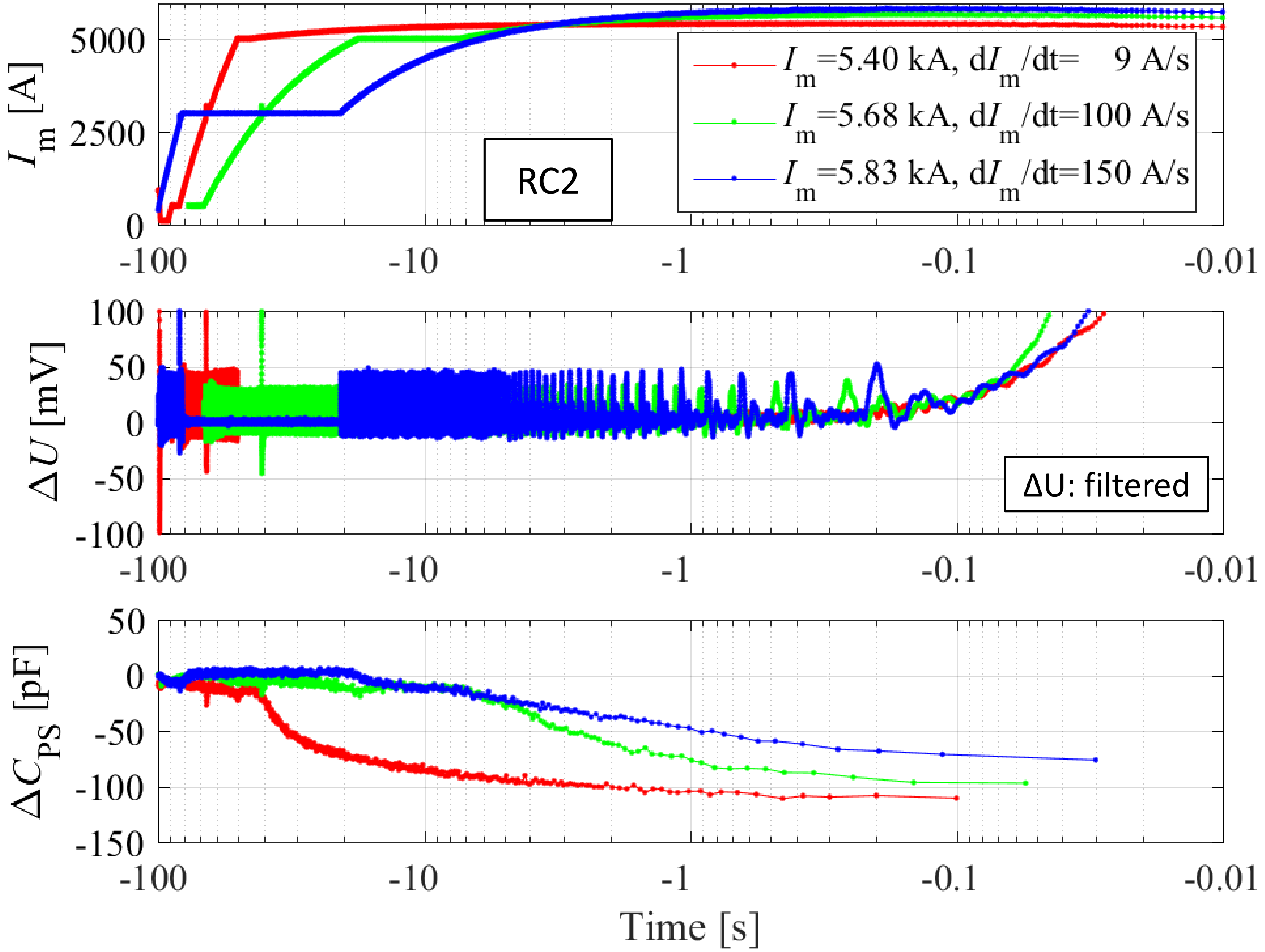


Stray capacitance can be measured between any metallic component electrically insulated from the others

Base capacitance C_{CI} = 2.130 nF



RC2 – Quench detection while ramping current



- The technique was shown to work very well in tests of Bi-2212 racetrack coils, detecting onset of heating well before voltage was detected across the coil
- Details of the sensitivity mechanism still need to be clarified in test experiments done in a well-defined geometry and thermal conditions
- Given high sensitivity of the technique and multiple possible sources contributing to *ΔC*, elimination of false positives may need to be addressed in the future

Future plans and milestones

- Collect "signature" signals from various sources: epoxy cracking, slip-stick motion, strand un-sintering, short-sample training experiments, other magnets... Develop identification algorithms. Collaborate with US labs and CERN on implementing this technology for magnet diagnostics

- Provide data analysis expertize for the community. Develop a database of magnet "events" : please please contribute with your data!

- Instrumentation:
  - ➢ Complete development of next generation sensors (acoustic, inductive) for CCT5 and 16 T project.
  - ➢ We seek to implement a multi-channel (64-128) system for combined magnet monitoring (mechanical contacts, AE, quench locations, thermal) .Open source commercial ultrasonic systems are available for the task (~ 50 k$ investment)

- Implement acoustic quench detection for longer CORC CCTs and larger HTS magnets

- Establish new collaborations outside of MDP to promote and expand use of our technology in other fields and applications