Real-time functional diagnostics of superconducting magnets using acoustic techniques

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Diagnostics types and goals

Operational

- Quench detection and localization
- Conductor instabilities
- Thermal monitoring
- Mechanical integrity monitoring

→ **Safety**
→ **Cost reduction**

General and predictive

- Understanding training and memory effects
- Finding design limitations
- Benchmarking of electro-mechanical models

→ **Improving magnet performance**

Acoustic diagnostics

- ✓ **Fast: sound propagation velocity is several km/s**
- ✓ **Not intrusive: sensors are at the outer surfaces**
- ✓ **Immunity to magnetic fields**
- ✓ **inexpensive, portable and adaptable to various magnet configurations**

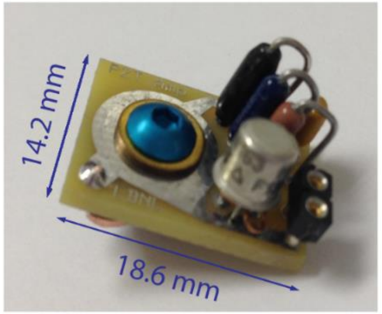
Causes of acoustic emission in magnets

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.

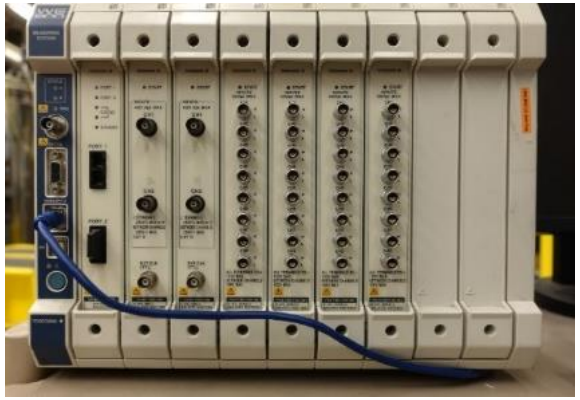
- "Acoustic emission from NbTi superconductors during flux jump", G. Pasztor and C. Schmidt, Cryogenics 19, 608 (1979).
- "Sources of acoustic emission in superconducting magnets", O. Tsukamoto and Y. Iwasa, J. Appl. Phys. 54, 997 (1983).

Acoustic sensors and DAQs



- In-house developed amplified cryogenic sensors
- Built-in GaAs MOSFET amplifiers have 300-1.9 K operational range
- Bandwidth up to ~300 kHz

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

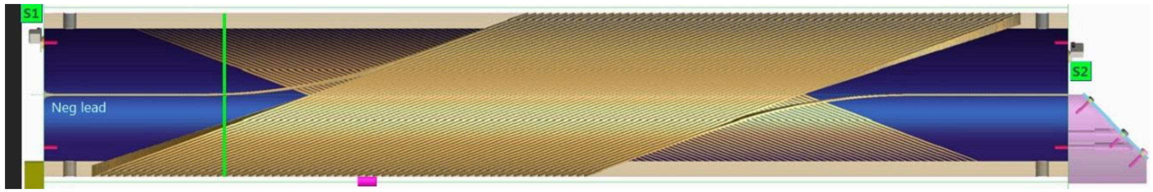


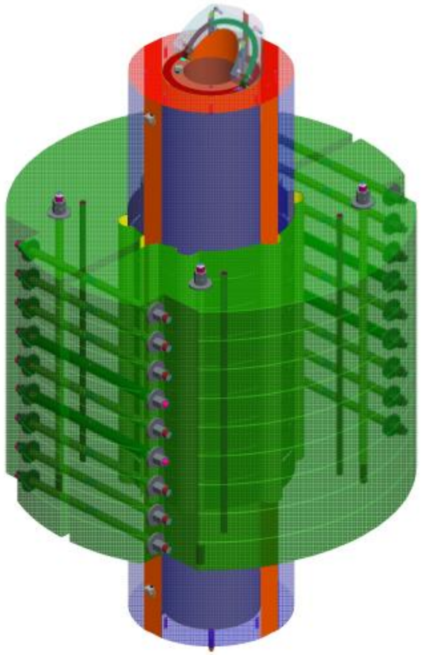
Continuous streaming at 40 kHz, 32 ch

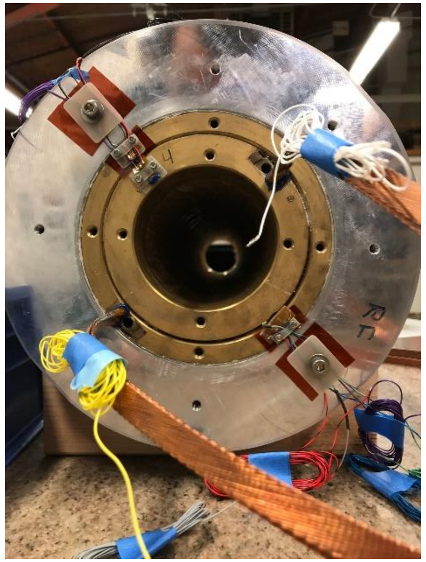
Triggered acquisition at 1 MHz, 16 ch
Axial / angular quench localization

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

CCT4: canted-cosine-theta Nb_3Sn dipole

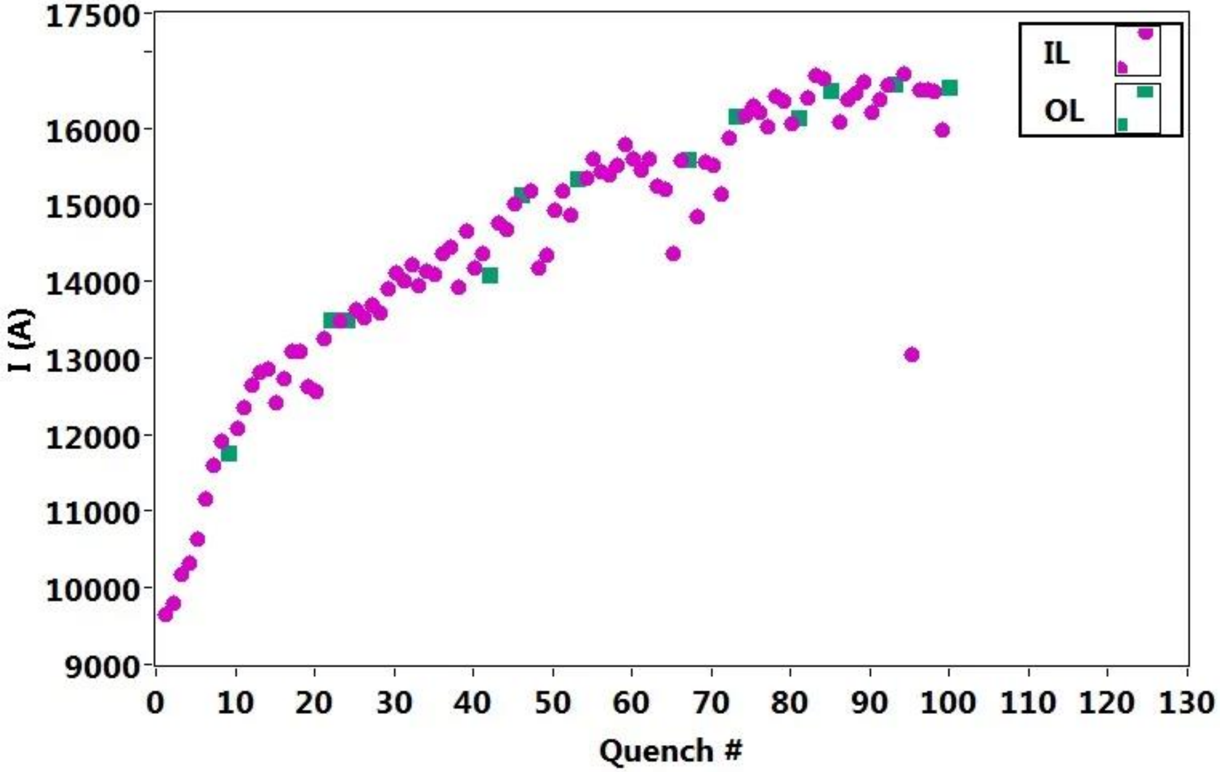






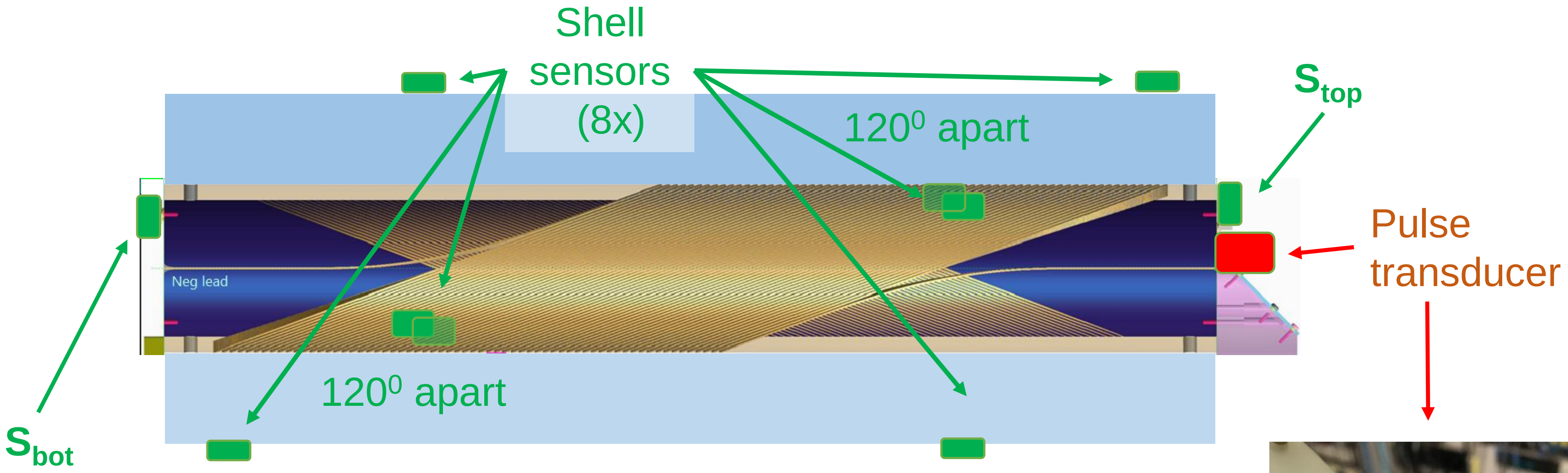
- Highest quench current: 16731 A
- Bore dipole field: 9.14 T
- Field at the conductor: 10.32 T
- “Short sample” limit: 19.3 kA (4.5 K)

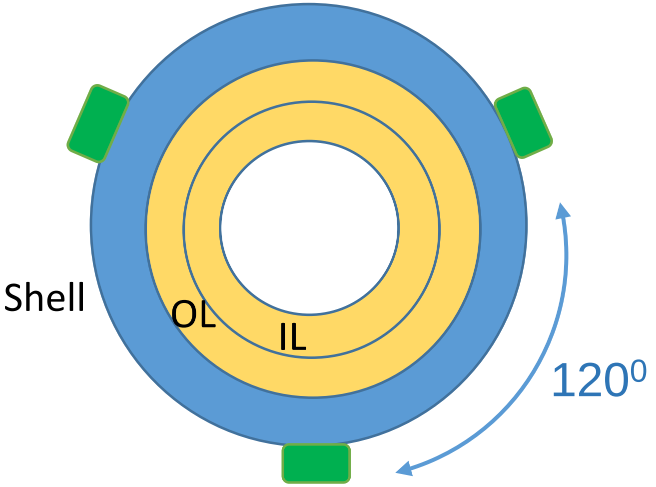
Training plot

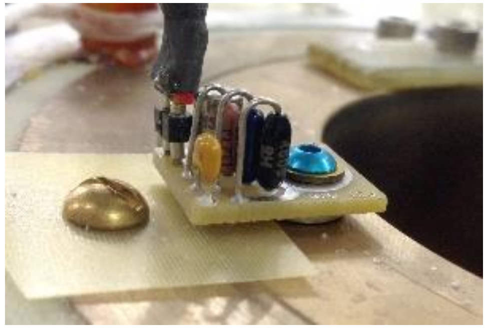


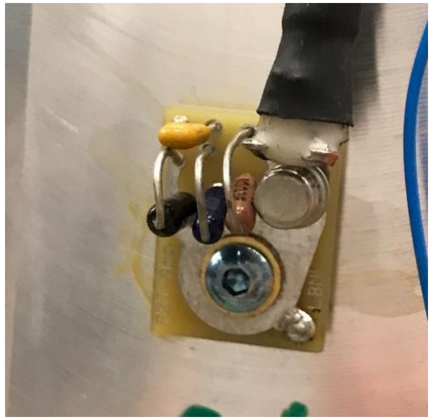
D. Arbelaez : Mon-Af-Or7, CCT4 design and test results
L. Brower : Tue-Af-Po2.10, CCT magnet modeling

Installation of the acoustic instrumentation









U.S. MAGNET DEVELOPMENT PROGRAM

First quench in the CCT4

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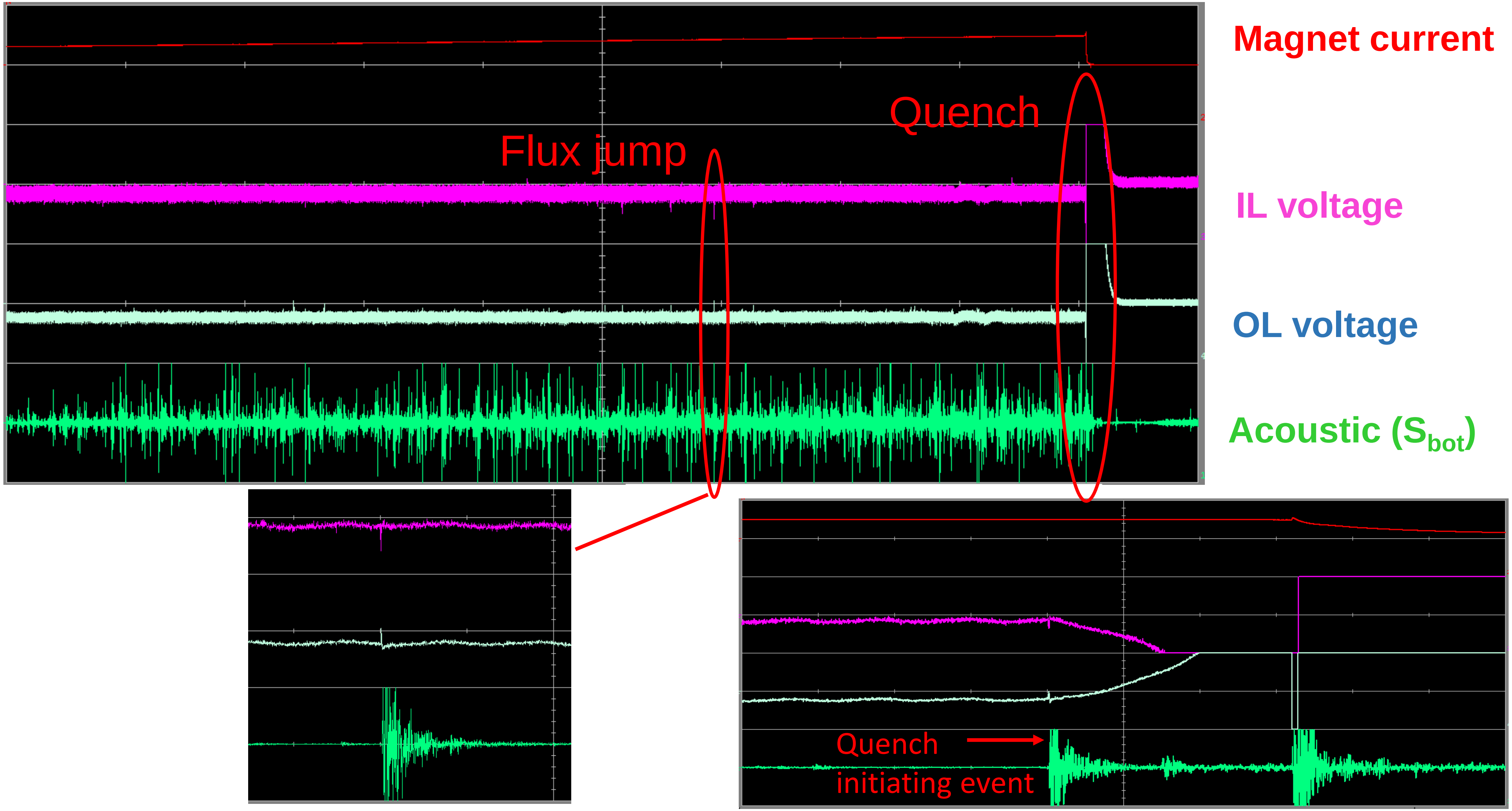

Axial and azimuthal quench localization

U.S. MAGNET DEVELOPMENT PROGRAM

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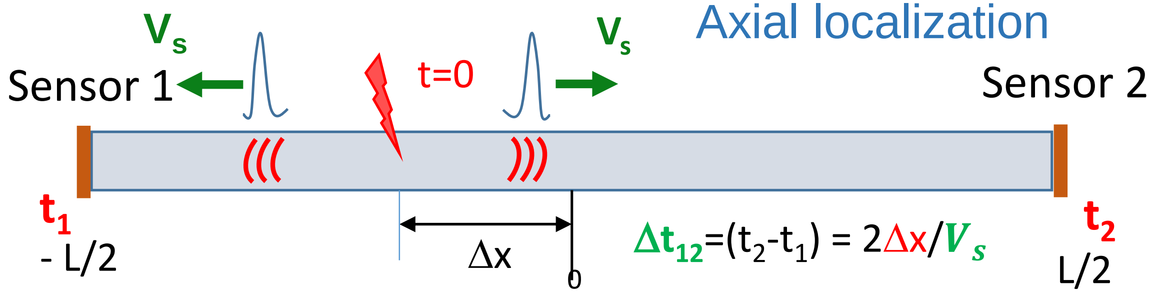
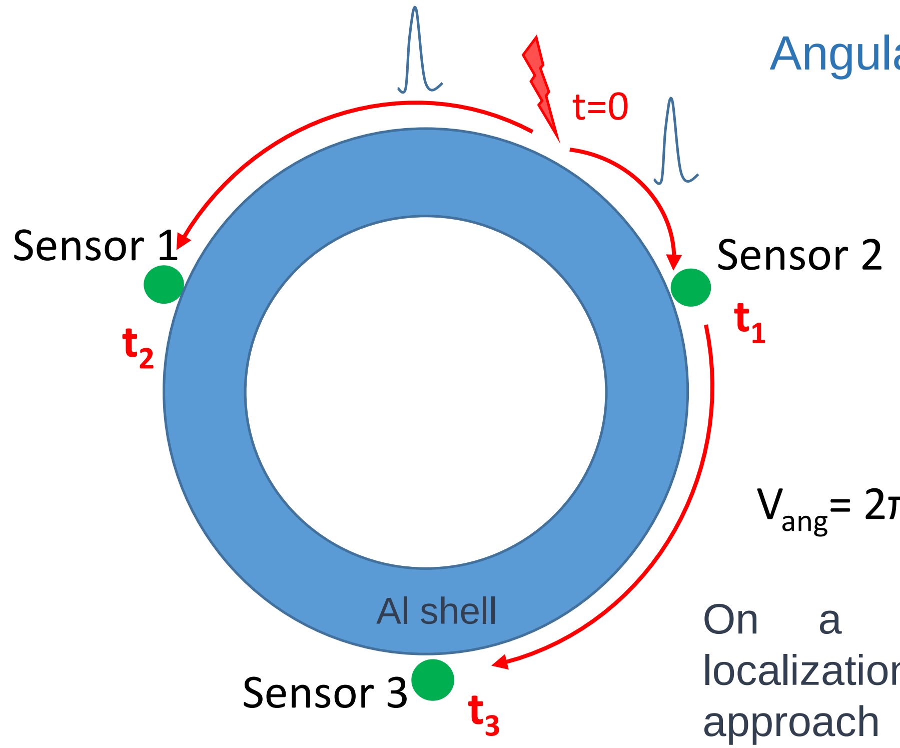
Axial localization

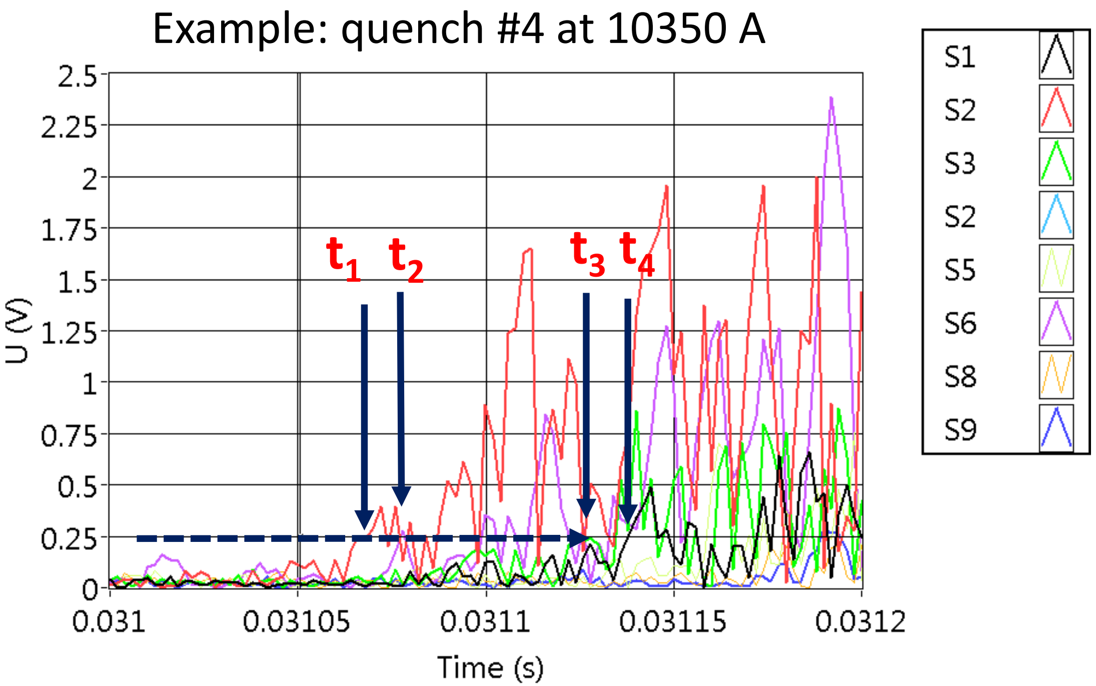


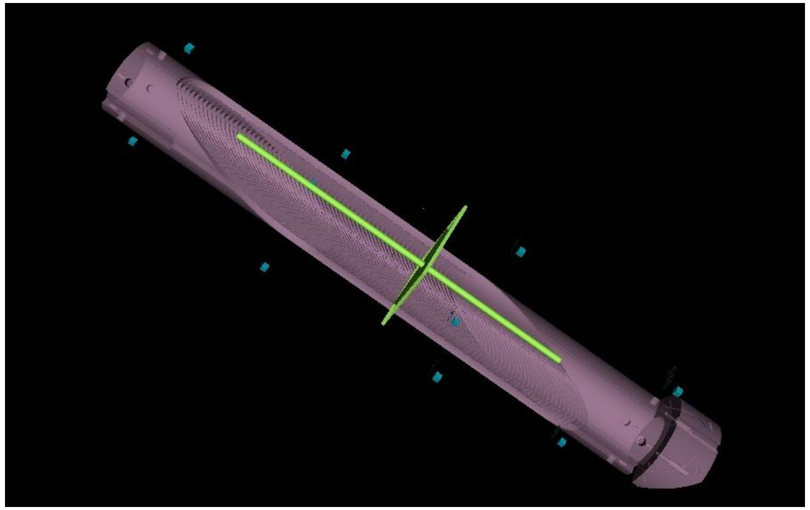
Angular localization



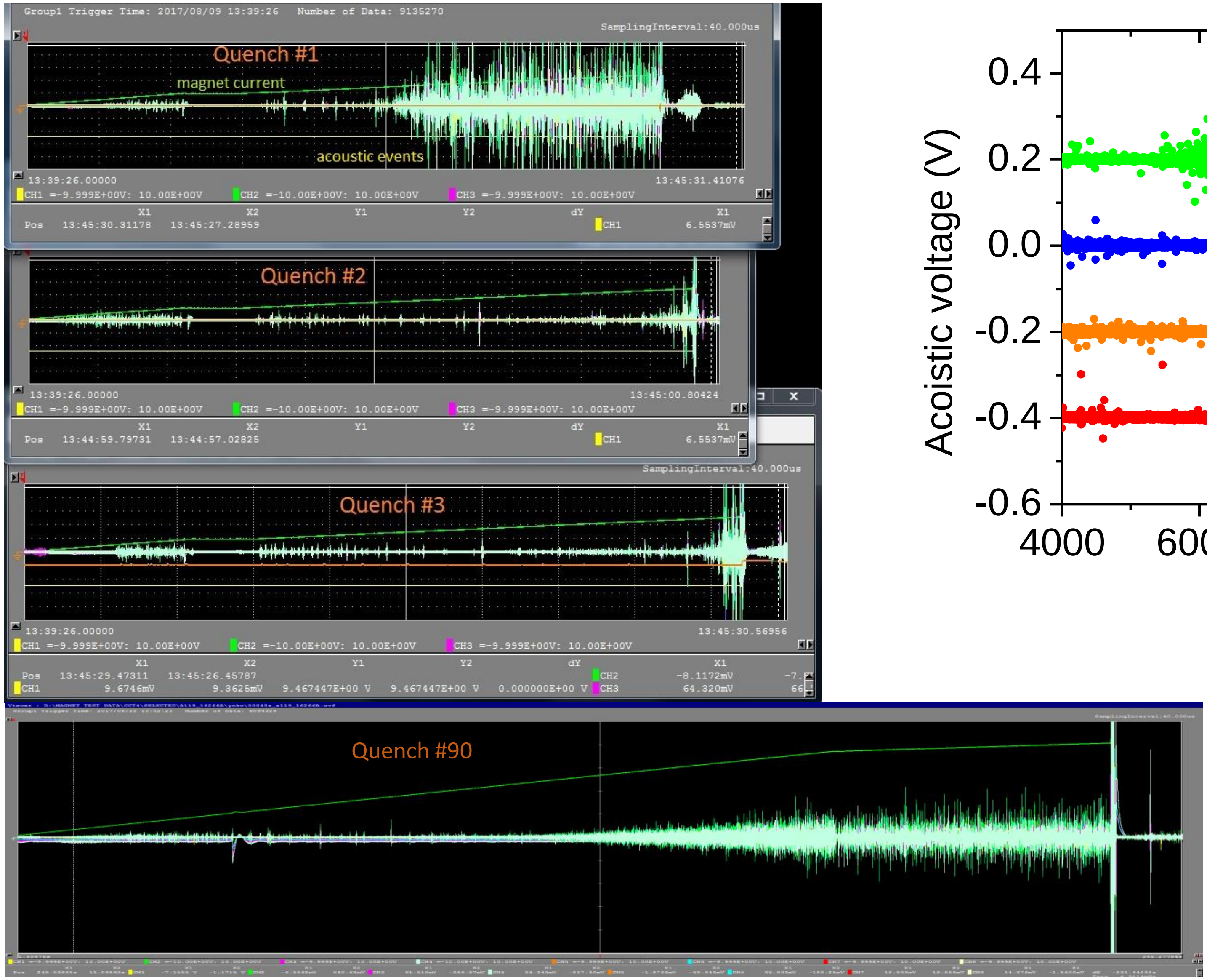
$V_{ang}= 2\pi/3\ (t_3-t_2)$

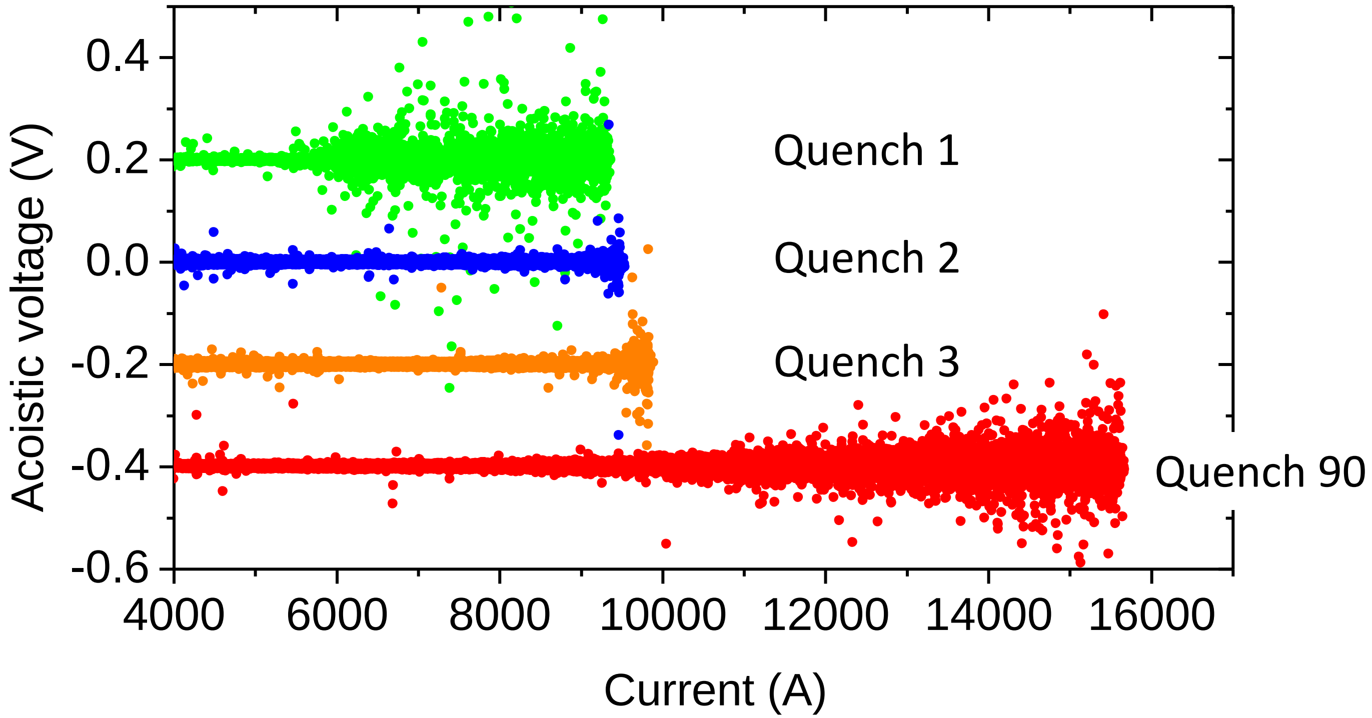
On a cylindrical surface localization using quasi-2D approach can be sufficiently accurate





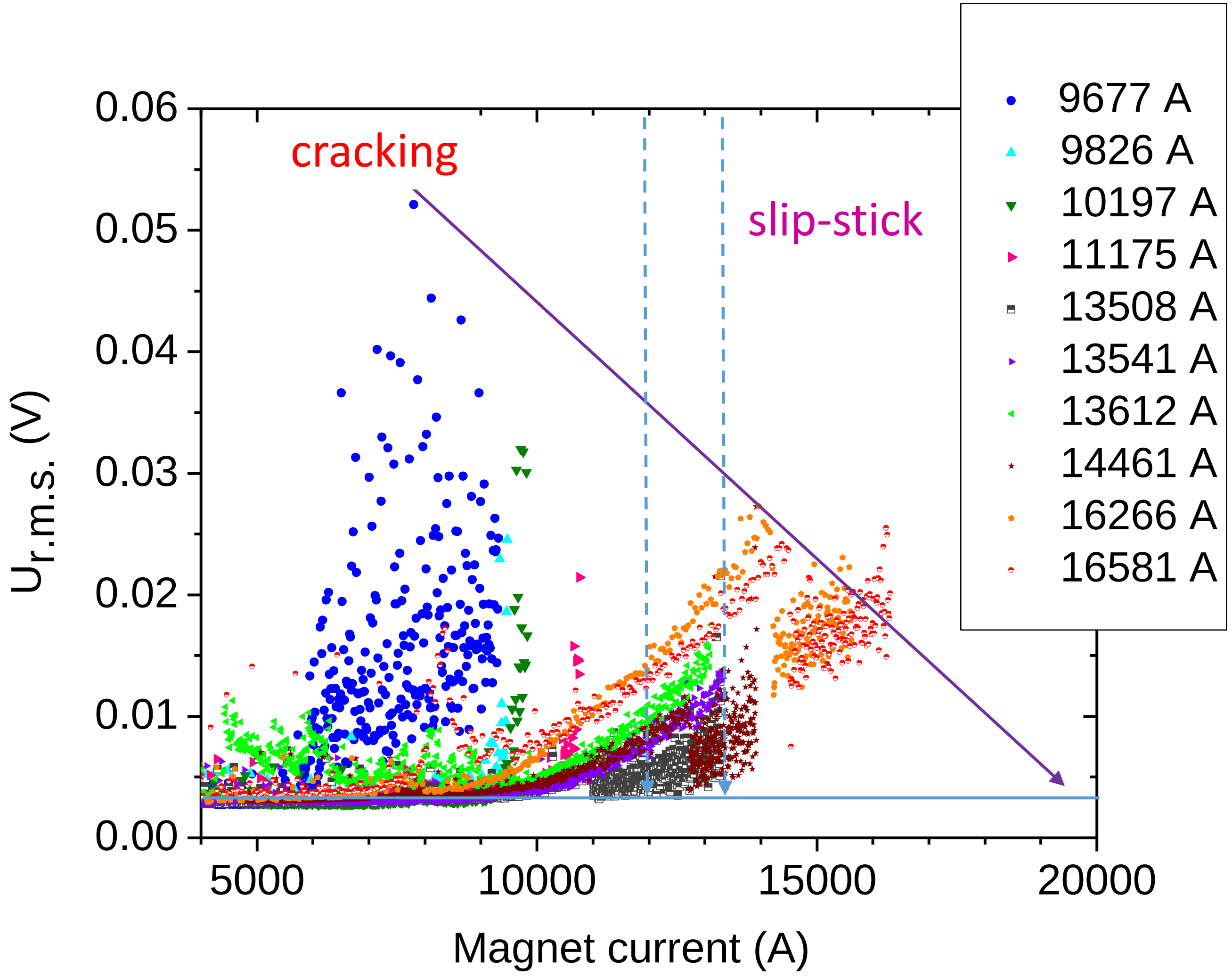
Mechanical memory of the magnet

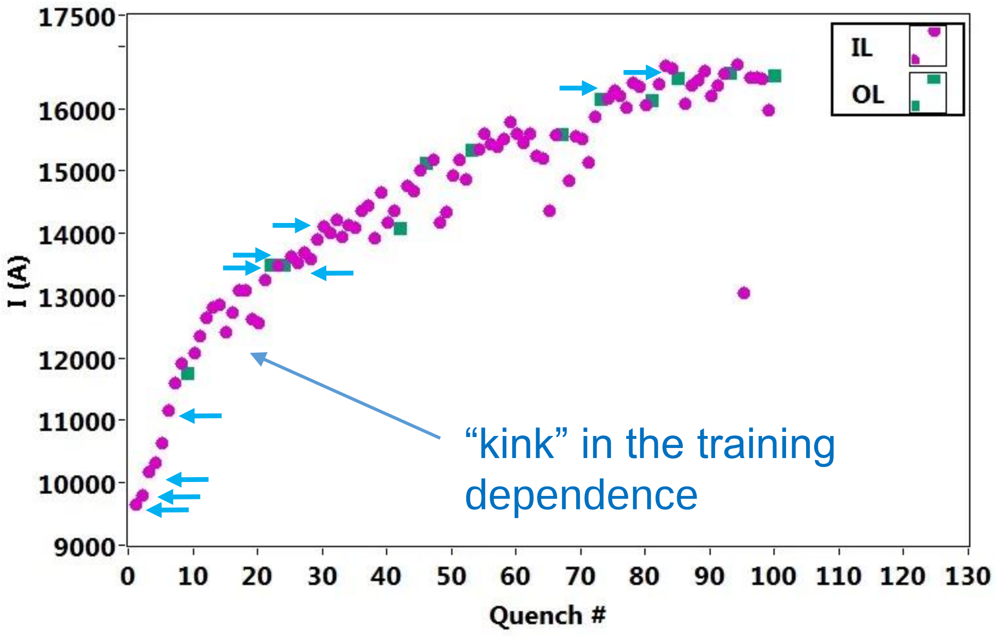




- CCT4 magnet shows mechanical memory in the initial quenches (Kaiser effect)
- However, as training progressed, noise grows in amplitude towards the quench, erasing the memory effect.

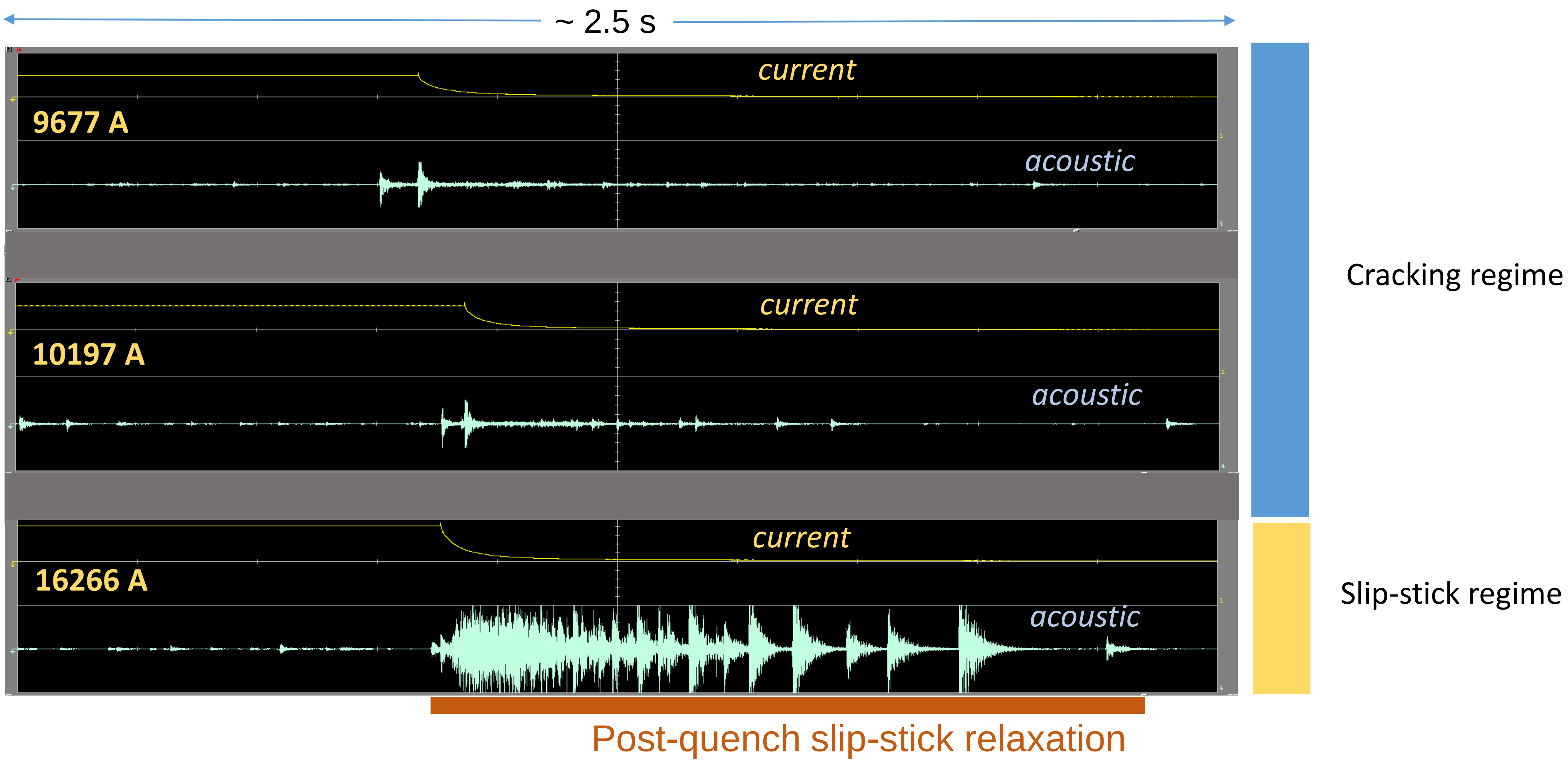
Two distinct regimes of magnet training





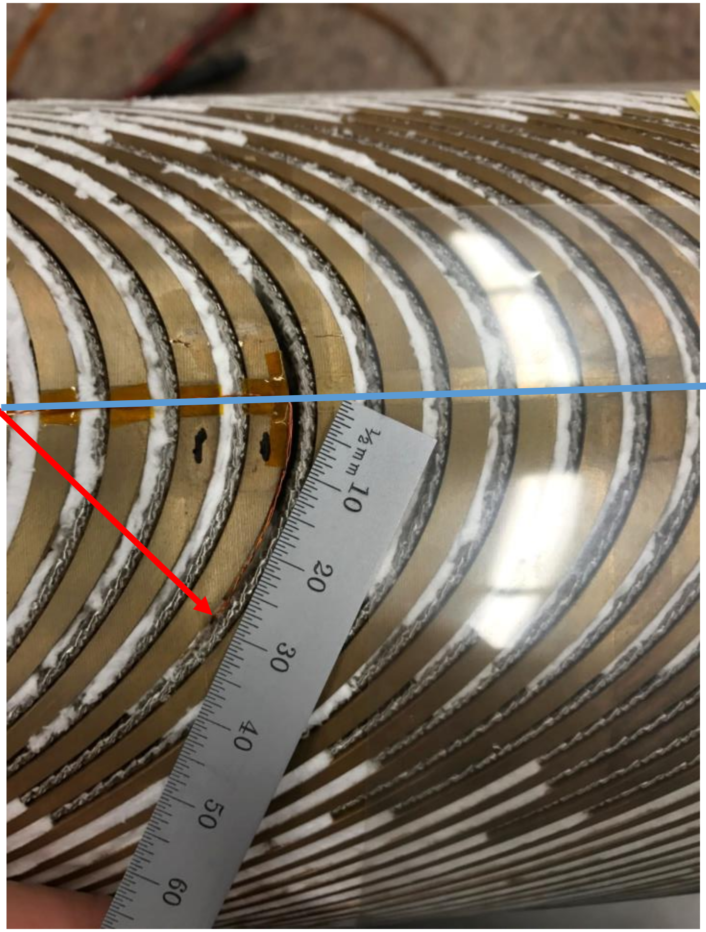
Similar behavior was earlier seen in a different kind of high-field Nb_3Sn dipole; see M. Marchevsky, et al., Cryogenics 69, 50 (2015), DOI: 10.1016/j.cryogenics.2015.03.005

Mechanical relaxation after the quench



Temperature monitoring inside the coil

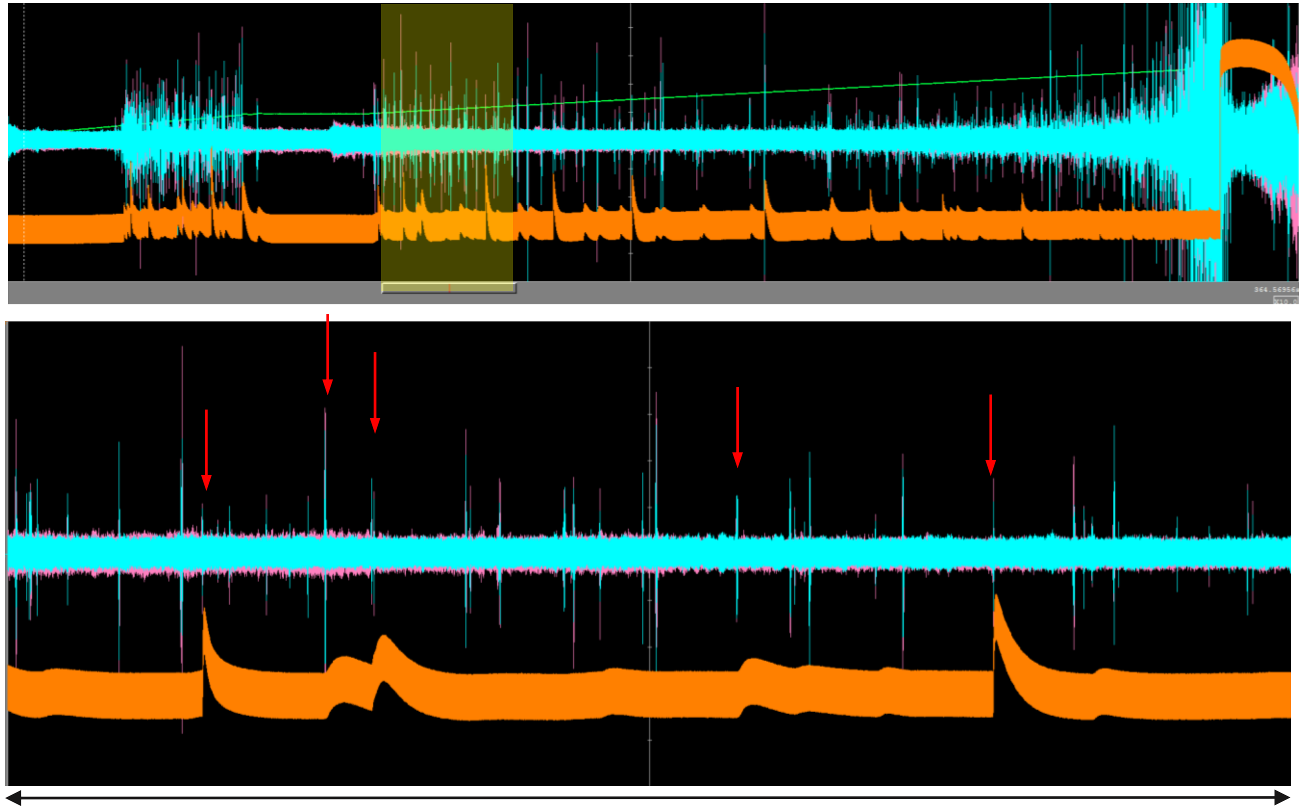
A thermometer of ~1 mm^2 size was installed directly in the cable groove, in the magnet outer layer, prior to impregnation

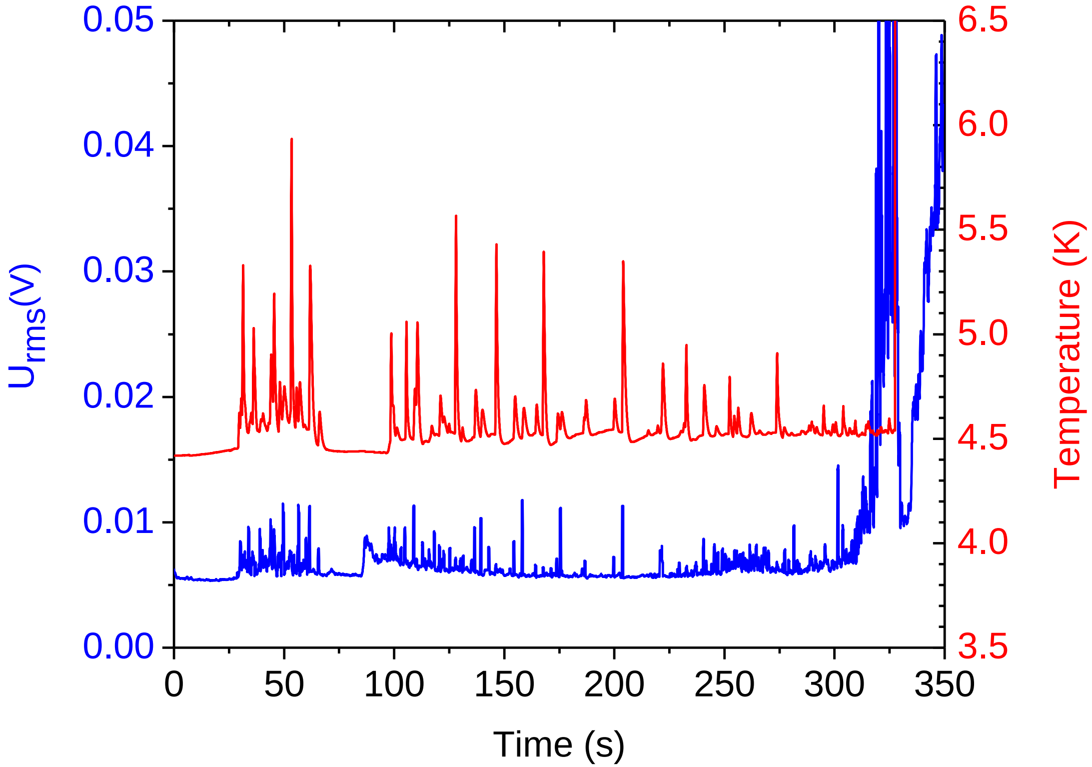


Pole location

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

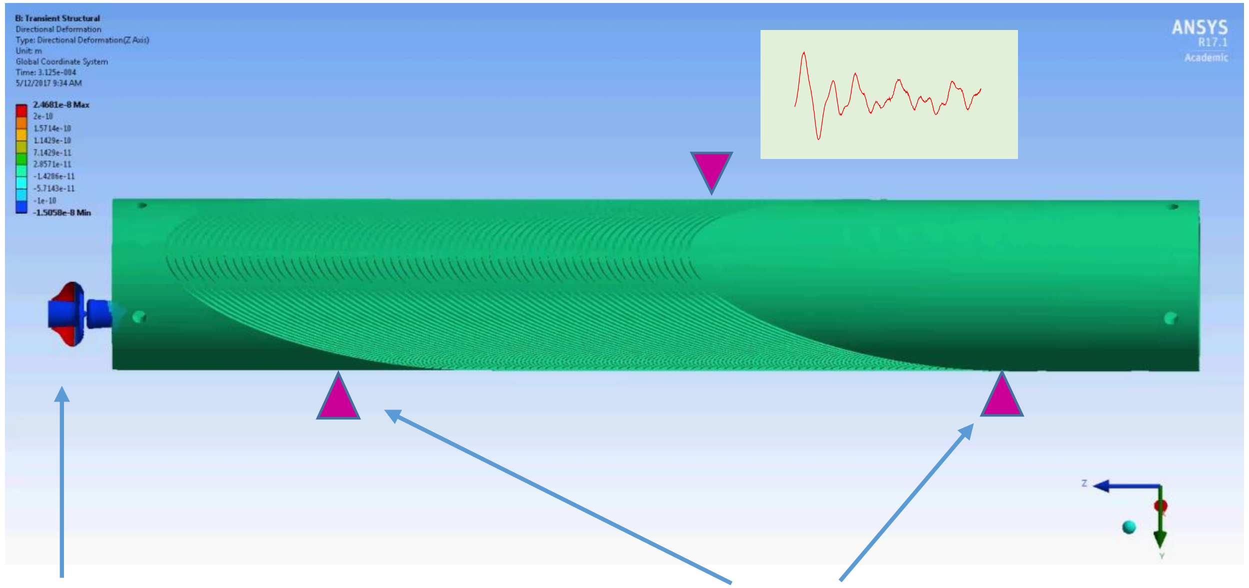




- Temperature spikes as high as 1 K are observed in the "cracking" regime. All of them are time-correlated with the acoustic events, and few also correlate with voltage spikes on the coils
- A minor (< 20 mK) gradual temperature rise, or none at all is seen in the "slip-stick" regime prior to quenching

Active monitoring of mechanical integrity

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



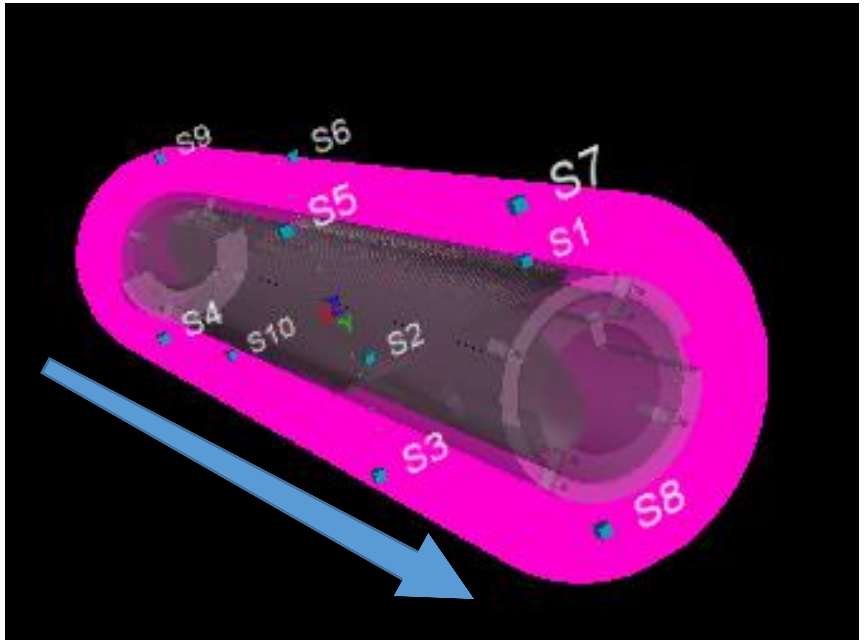
Pulser transducer

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**

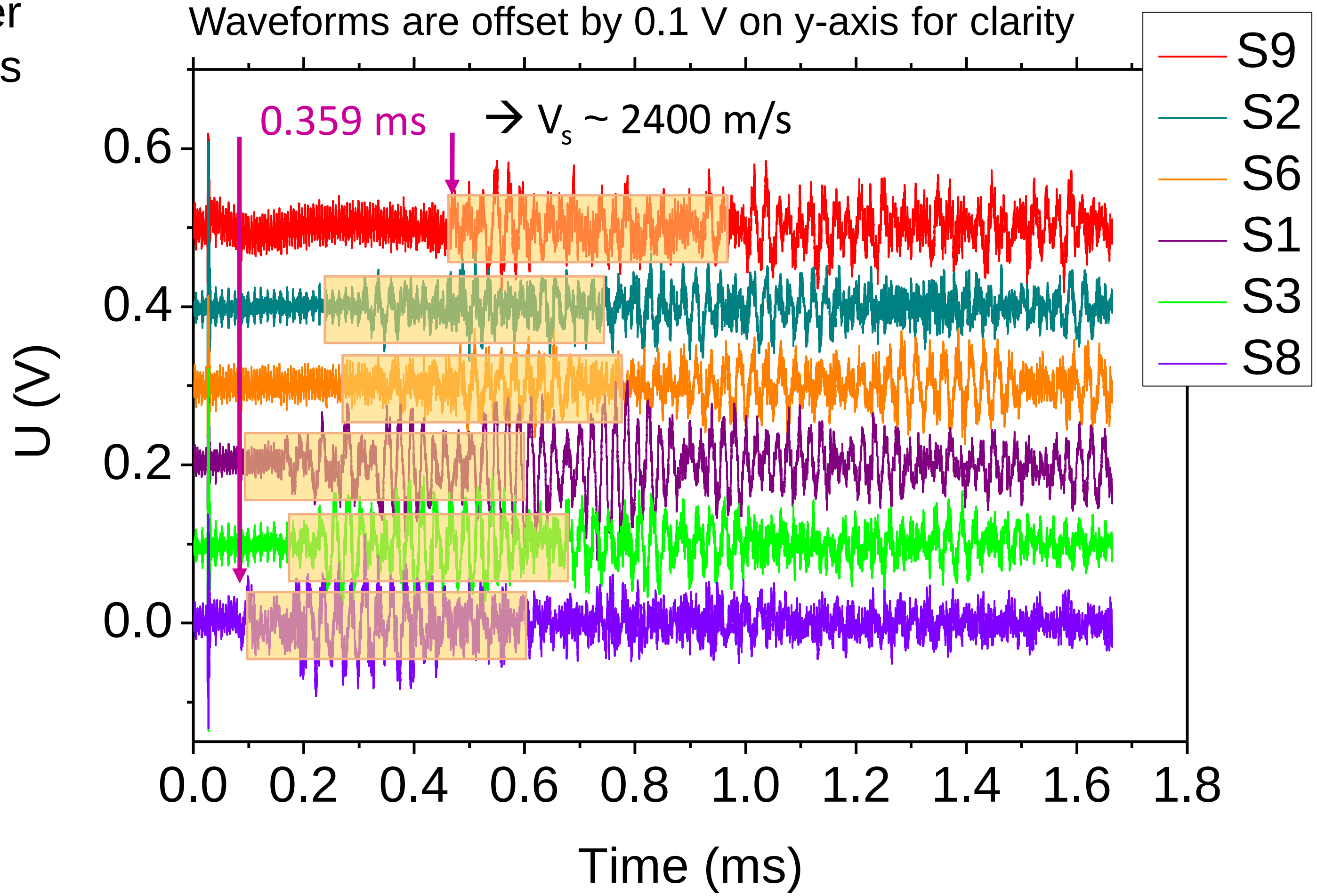
Pulse propagation in the CCT4 magnet

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



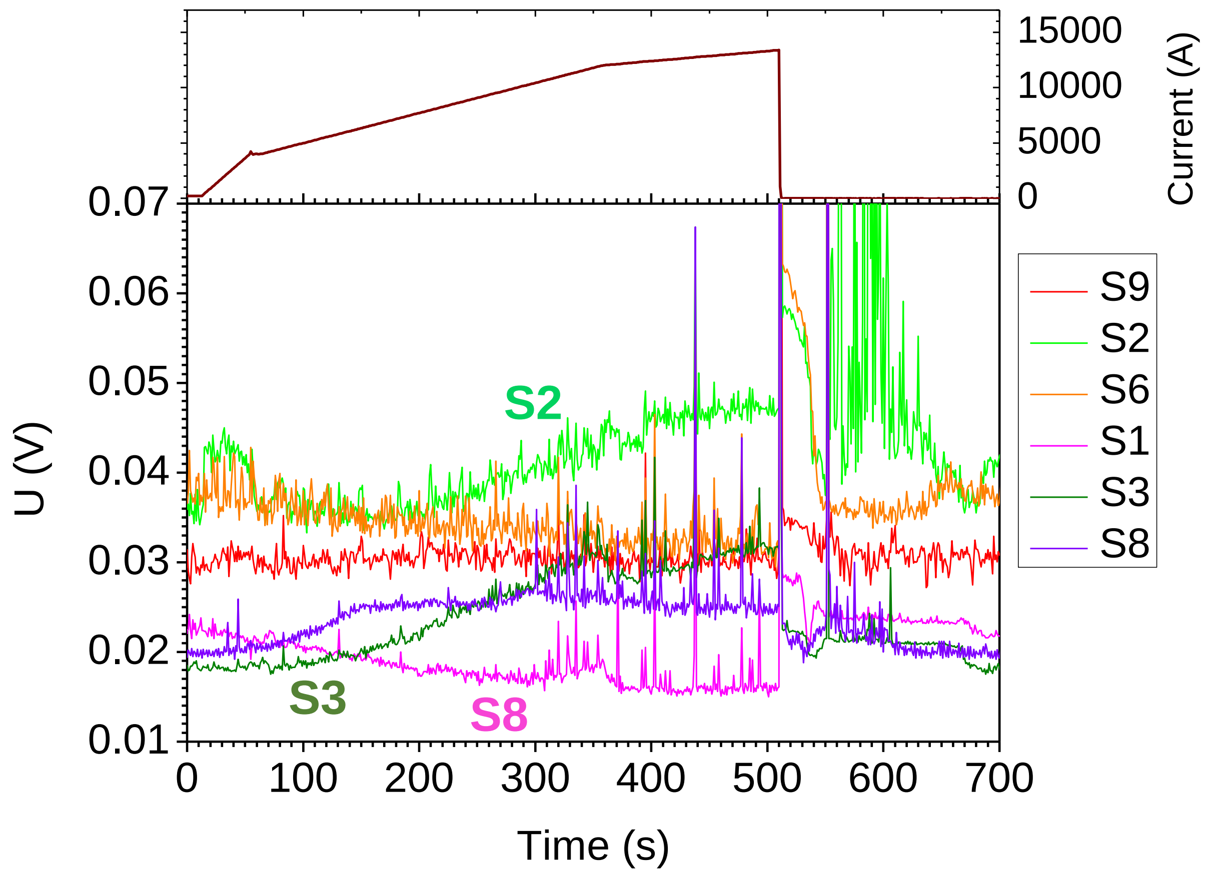
Pulse wave propagation:
S9 –> S2 S4 S6 –> S3 S2 S7 -> S8

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

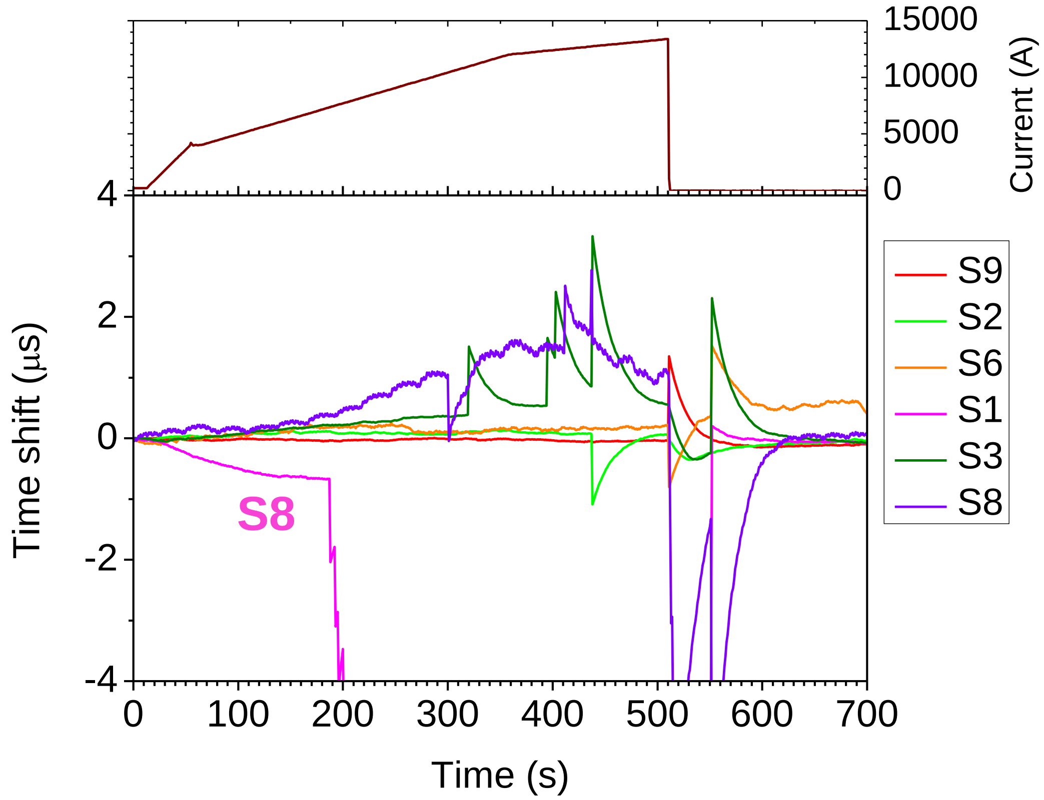


0.5 ms window is set individually for each waveform. and then periodically monitored with each pulse

Pulse intensity and time shift monitoring



Time shift is found by cross-correlating the initial "reference" waveforms with the consecutive ones. Same principle was used in ***M. Marchevsky and S.A. Gourlay, Appl. Phys. Lett. 110, 2017 doi:10.1063/1.4973466***



- 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.

Conclusions

- Localization of quenches using acoustic sensor array is a solid diagnostic tool for studying mechanically-initiated quenches
- Acoustic emission diagnostics can provide a unique insight towards understanding magnet training
- Two distinctly different slopes of CCT4 training curve can be tentatively identified as ones dominated by epoxy cracking and slip-stick motion respectively
- Active acoustic approach allows for a real-time monitoring of magnet mechanical integrity and rigidity of its interfaces

Work in progress on analyzing high-frequency acoustic data, and developing algorithms for events sorting according to their associated disturbance spectra and deposited energy.