CCT4 test results: an update

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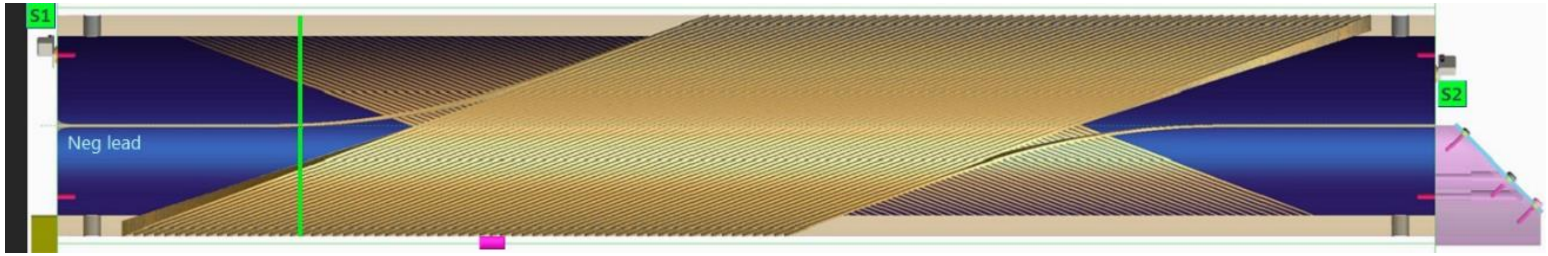
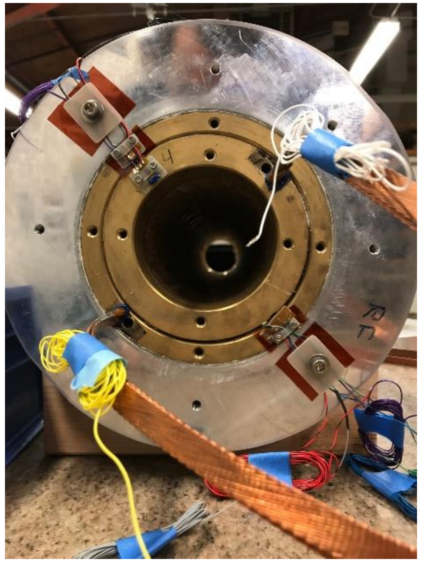
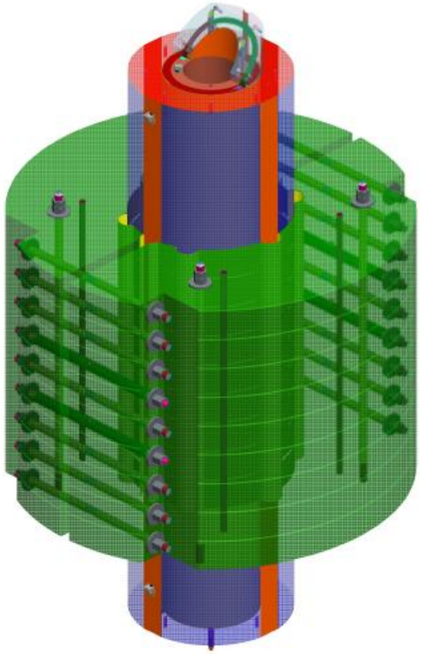
LBNL

CCT4 test timeline



- ➢ Initial cooldown was started on Jul 22, magnet was cooled to 4.2 K
- ➢ Compressor malfunction lead to a warmup to ~ 170 K
- ➢ Second cooldown to 4.2 K was started on Aug 6, two weeks of testing

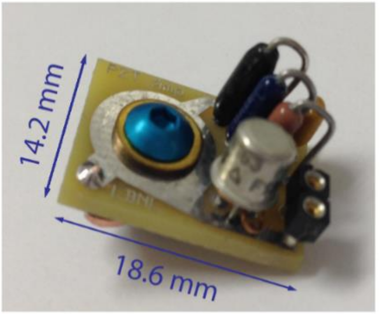




- *Lost most of the Vtaps in the IL (Kapton trace soldered to cable)*
- *Lost 1 acoustic sensor (S4, nearest to the He transfer tube)*

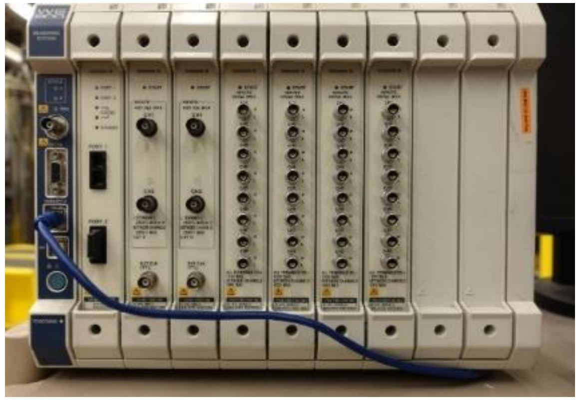
- **Training**
- **Heater (MQE) tests**
- Ramp-rate quenches at 30-200 A/s
- Forced extractions at various current levels up to 13 kA
- Magnetic measurements (z-scan and stair-step cycle)

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

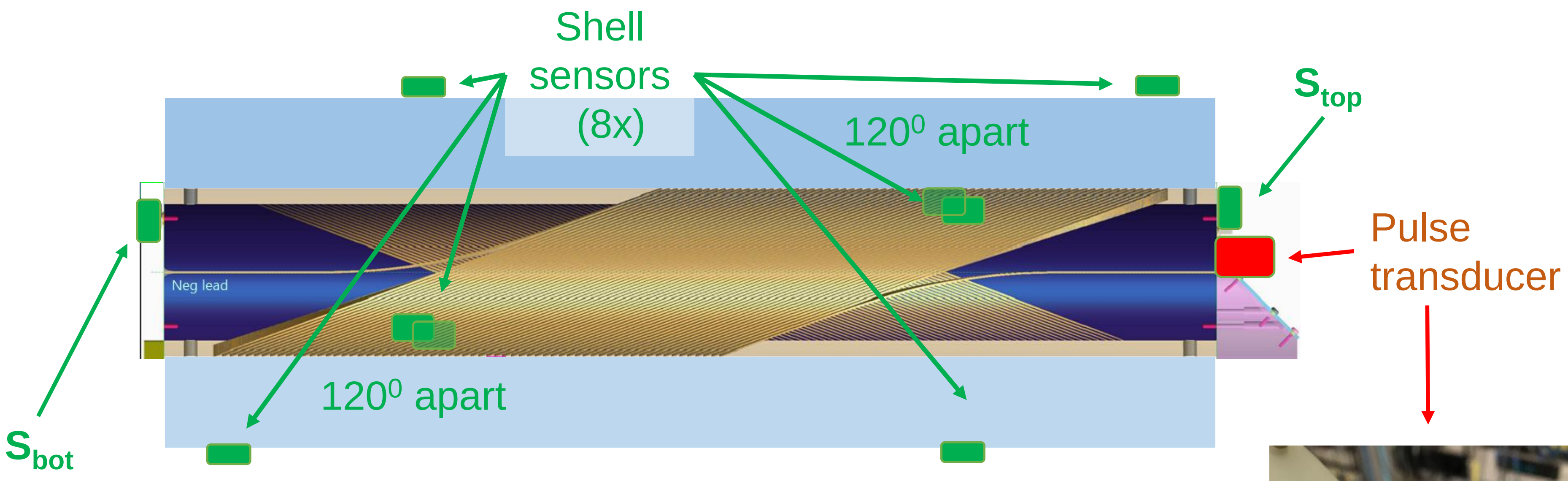


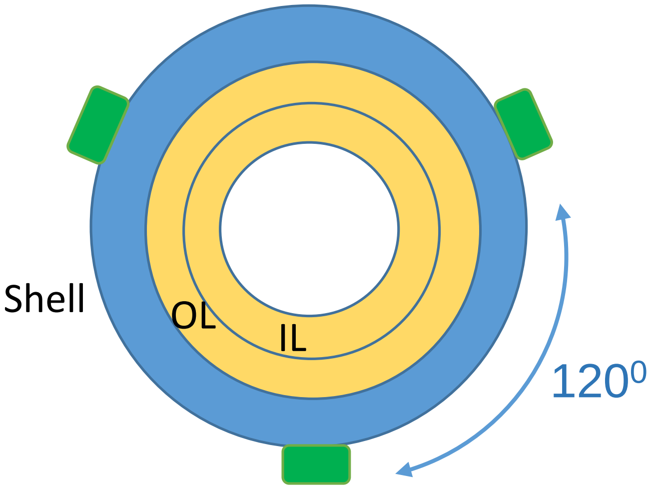
Continuous streaming at 40 kHz, 32 ch

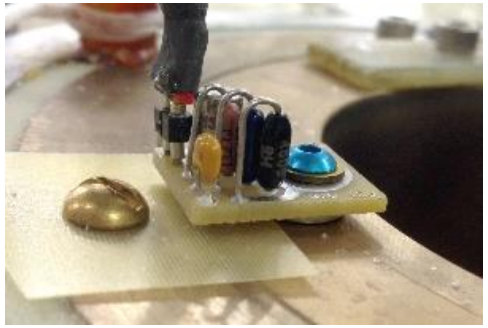
Triggered acquisition at 1 MHz, 16 ch
Axial / angular quench localization

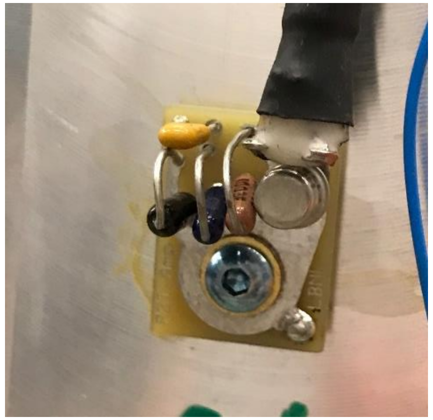
Continuous or triggered acquisition 0.5 – 10 MHz, 8 ch.
“Active” mechanical integrity monitoring

Installation of the acoustic instrumentation

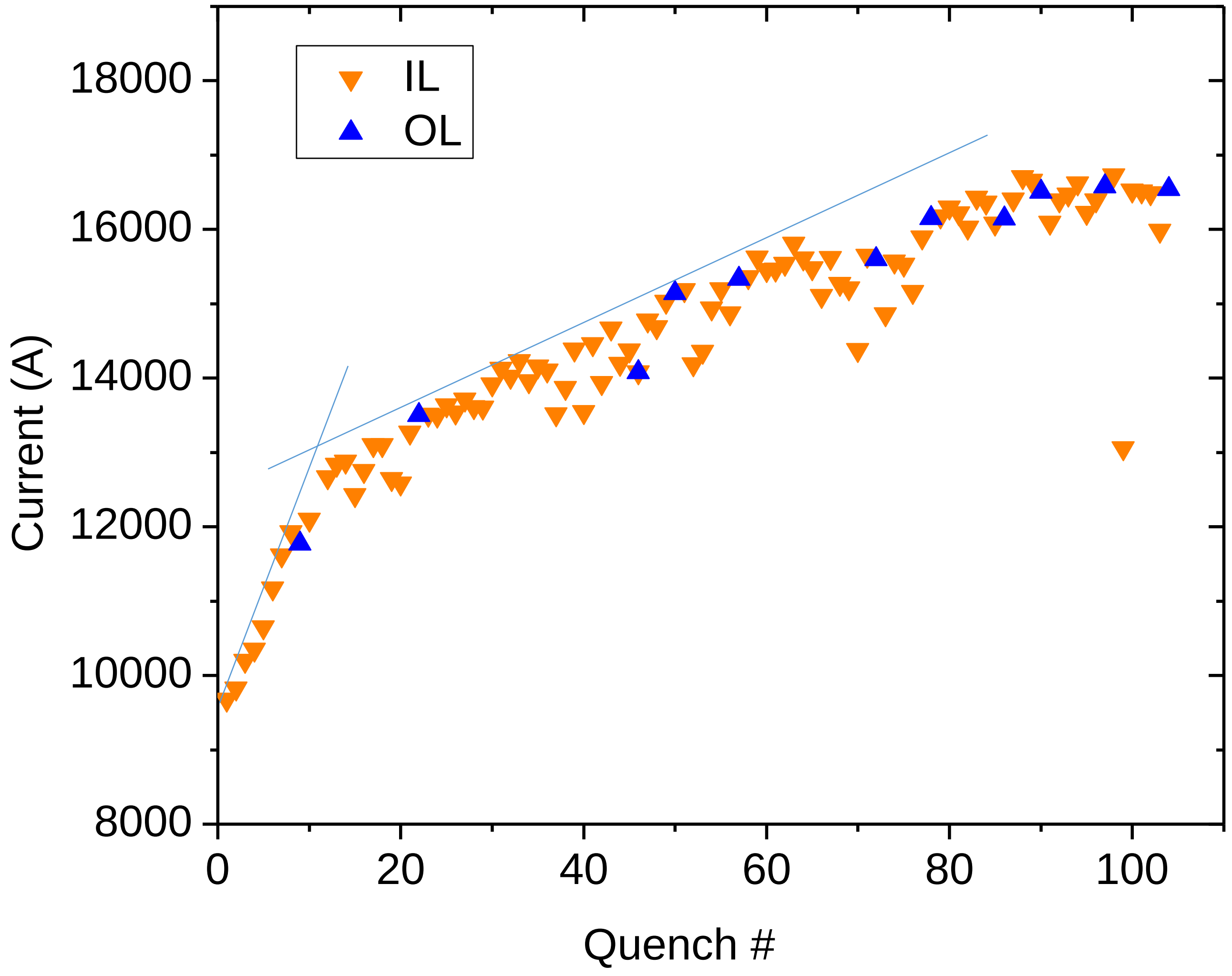








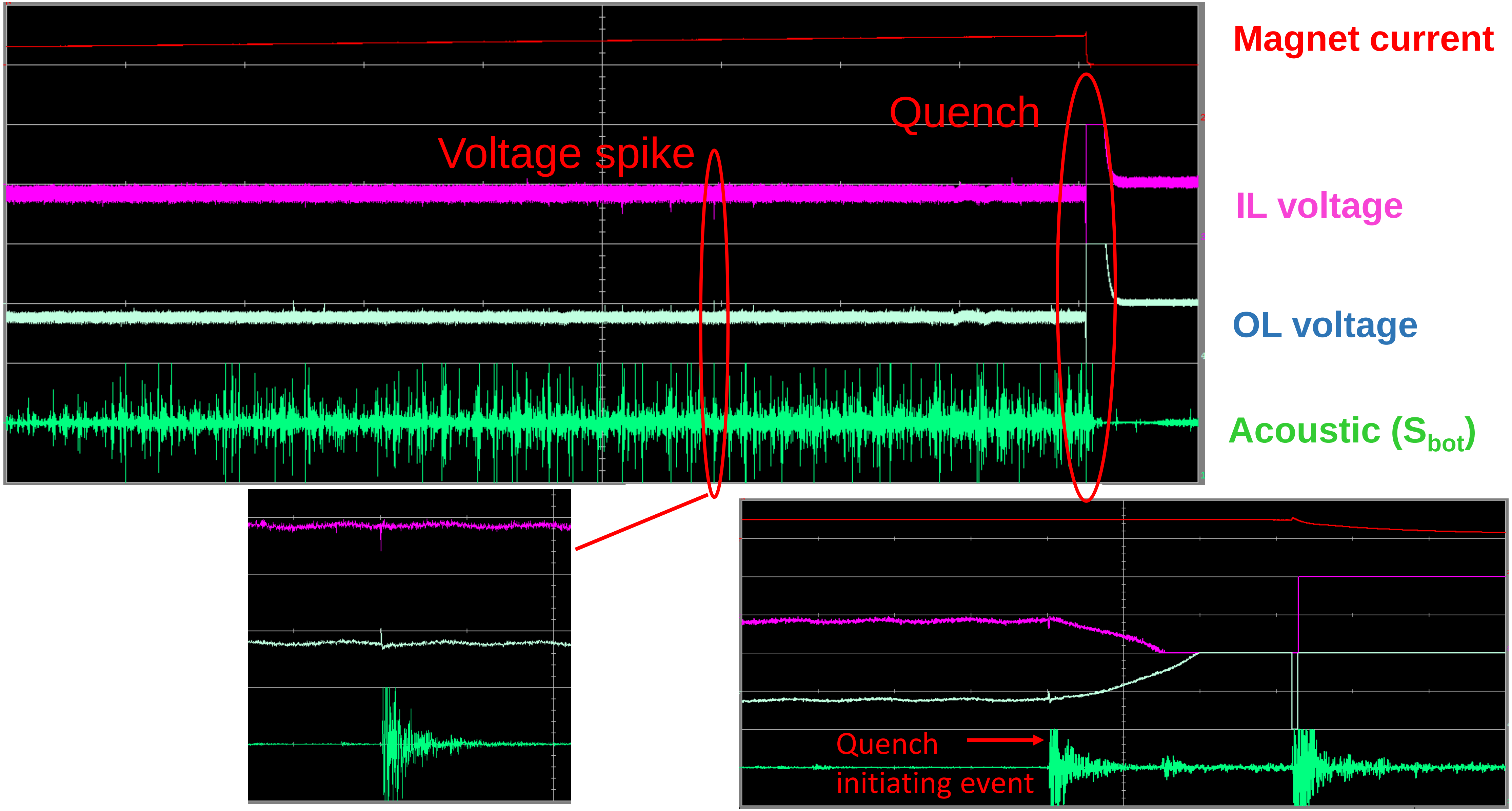
Training plot



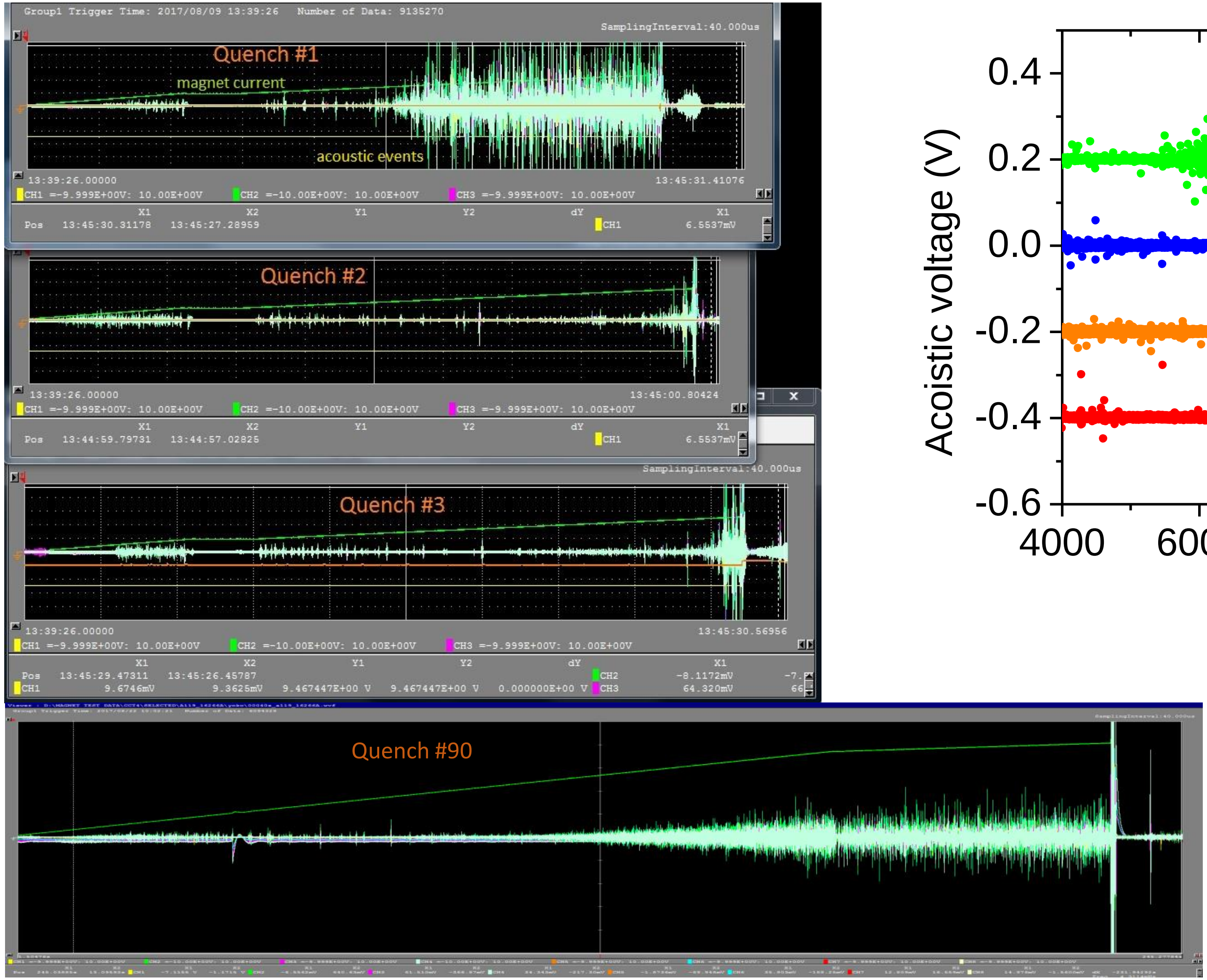
- 104 training quenches in total
- 11 quenches in the OL, the rest is IL
- Highest quench current: **16731 A**
- Bore dipole field: **9.14 T**
- Field at the conductor: 10.32 T
- “Short sample” limit: 19.3 kA (4.5 K)

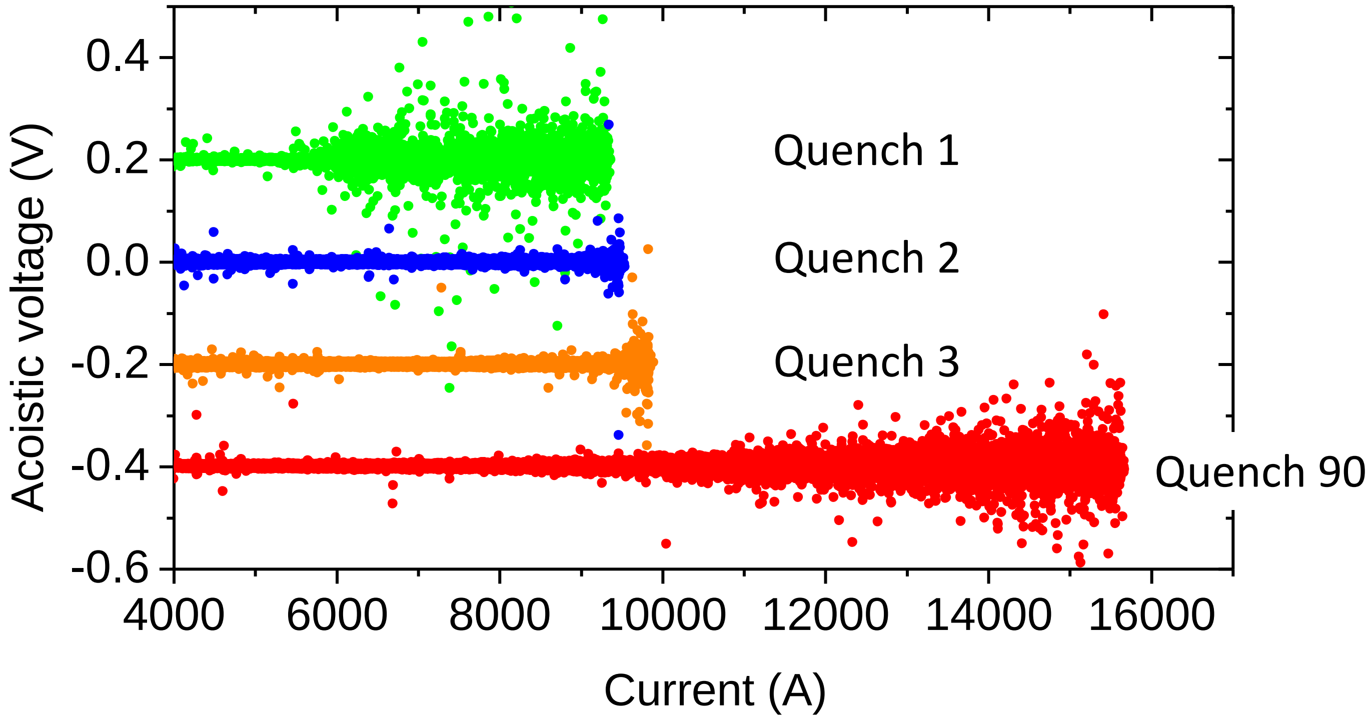
A remarkable linear trend is observed for the most part of the training, with an abrupt change of slope at ~ 13 kA

First quench in the CCT4



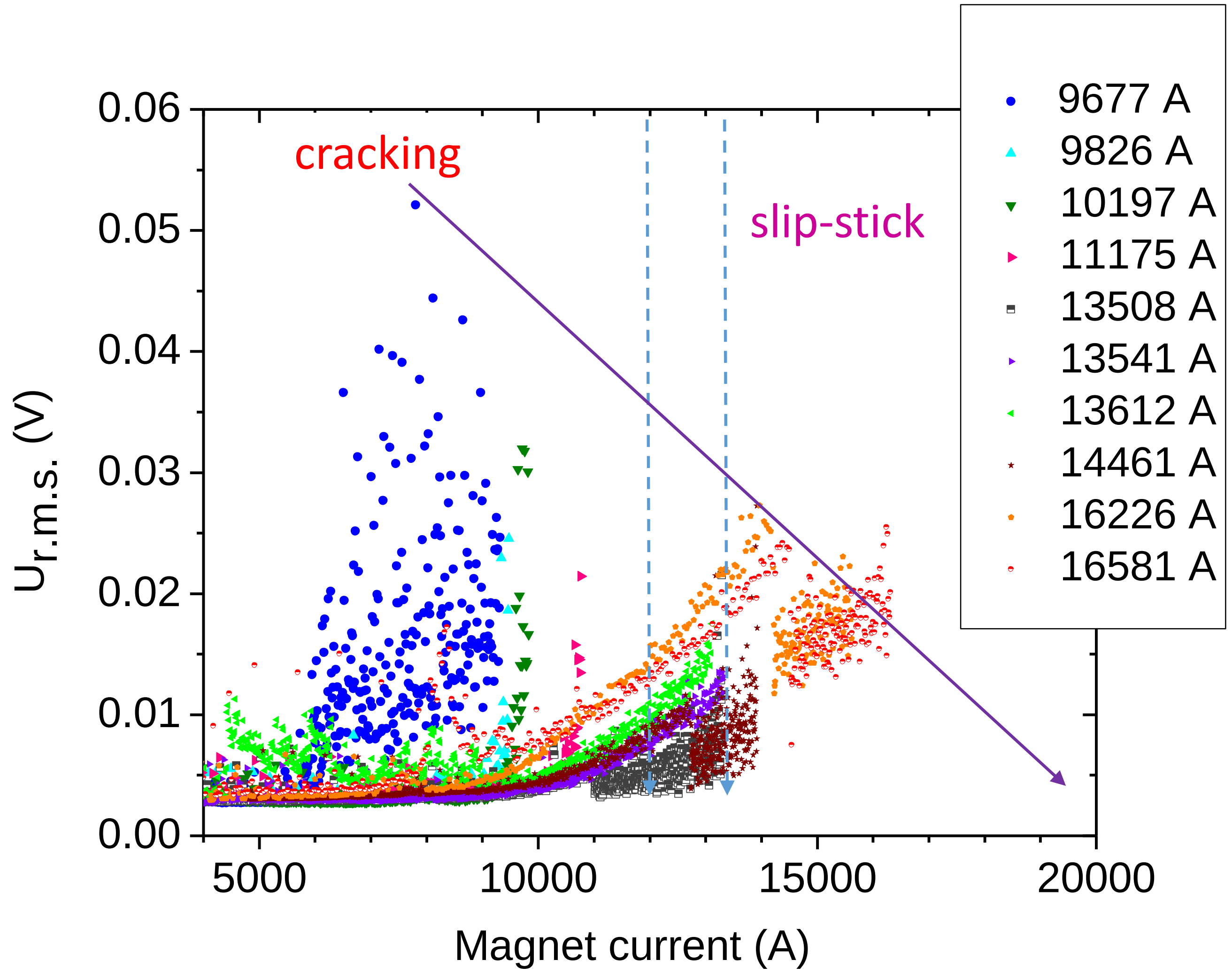
Mechanical memory of the magnet

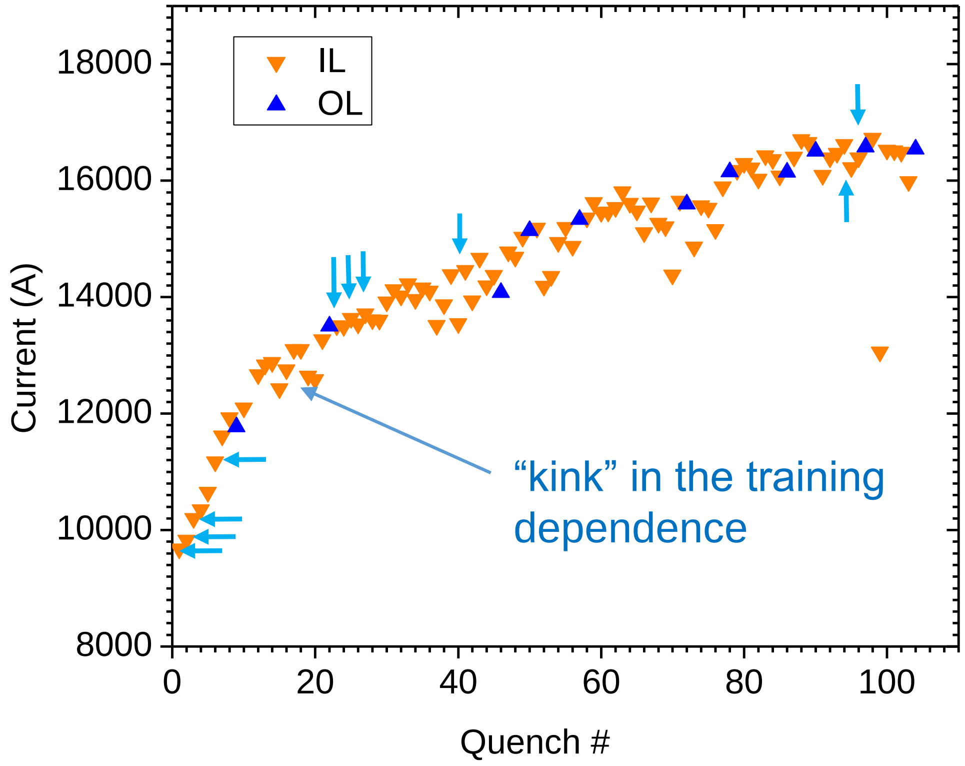




- CCT4 magnet shows mechanical memory in the initial quenches (Kaiser effect)
- However, as training progressed, acoustic emission started to increase gradually towards the quench, and the memory of the previous quench current disappeared

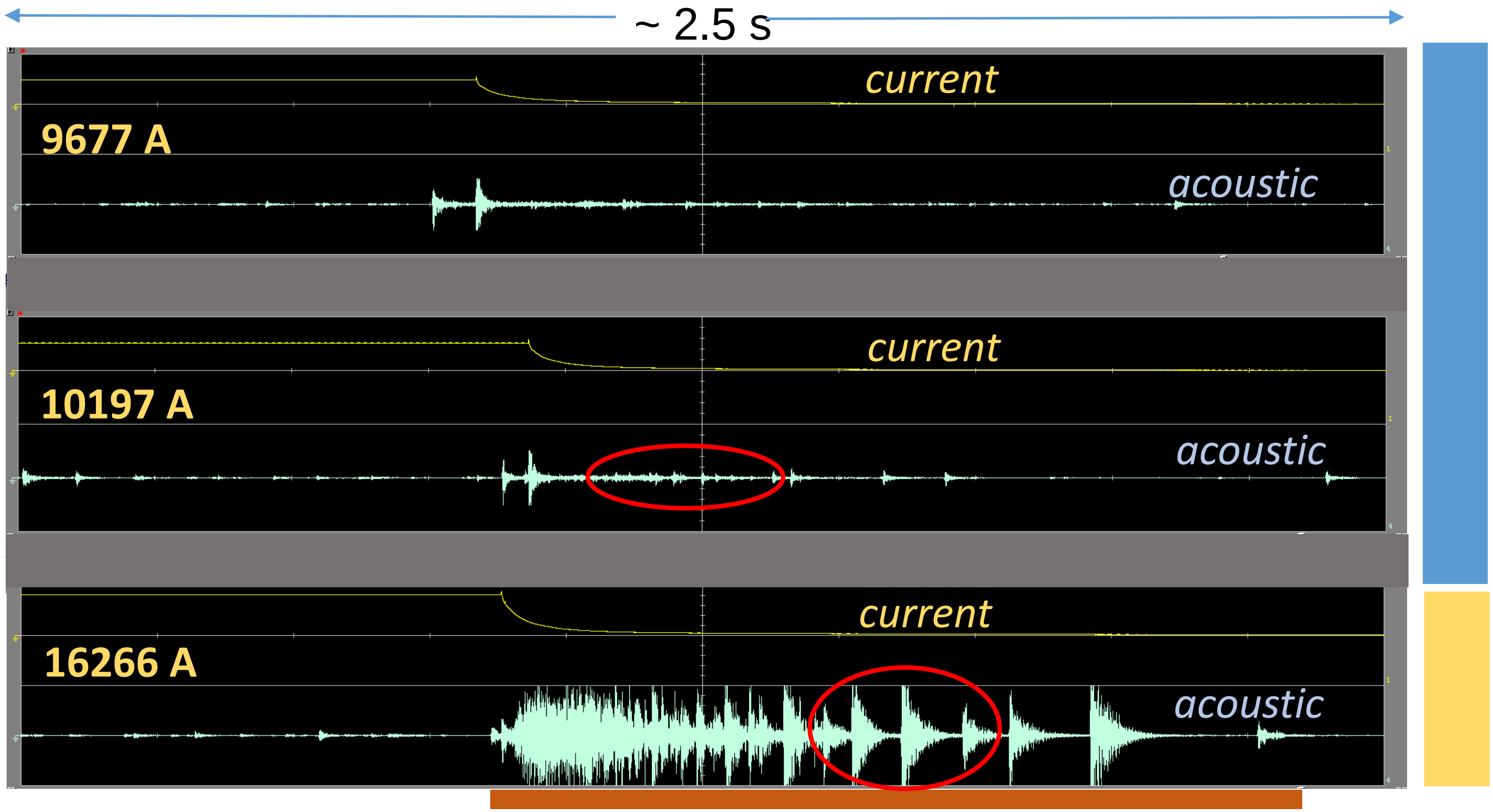
Two distinct regimes of magnet training





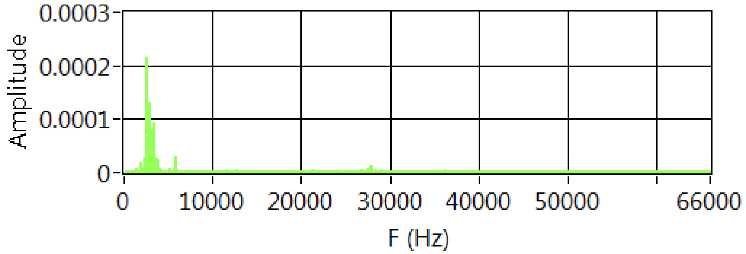
Similar behavior was earlier seen in a different kind of high-field Nb_3Sn dipole; see M. Marchevsky, et al., Cryogenics 69, 50 (2015), DOI: 10.1016/j.cryogenics.2015.03.005

Mechanical relaxation after the quench



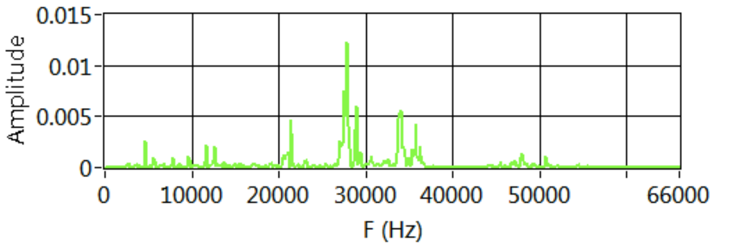
Post-quench slip-stick relaxation

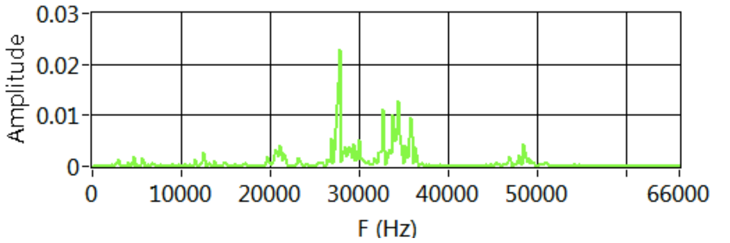
Cracking regime



Mandrel (bulk) vibrations

Slip-stick regime





Rib vibrations?

Training scenario

Cracks develop -> Cracks grow and interconnect -> Cracks percolate the structure

Structure is rigid, parts held together by solid interfaces

Deforms mostly elastically upon stress

Structure is weakened, parts held together by solid interfaces and internal friction

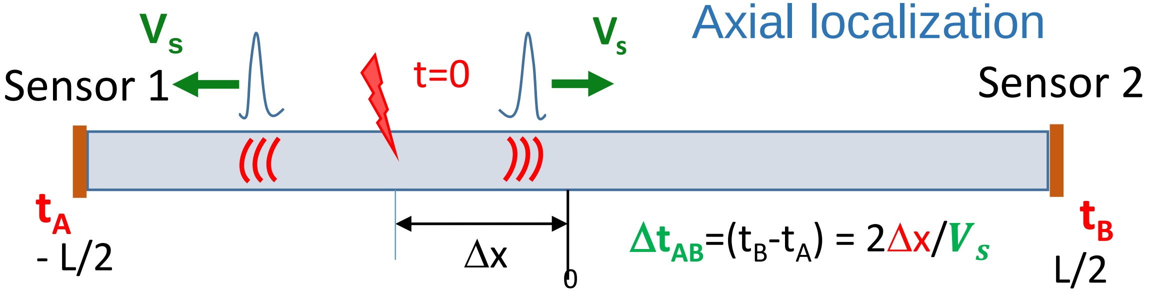
Deforms elastically and plastically, slips along the crack interfaces

Structure is semi-rigid, parts held together largely by the internal friction

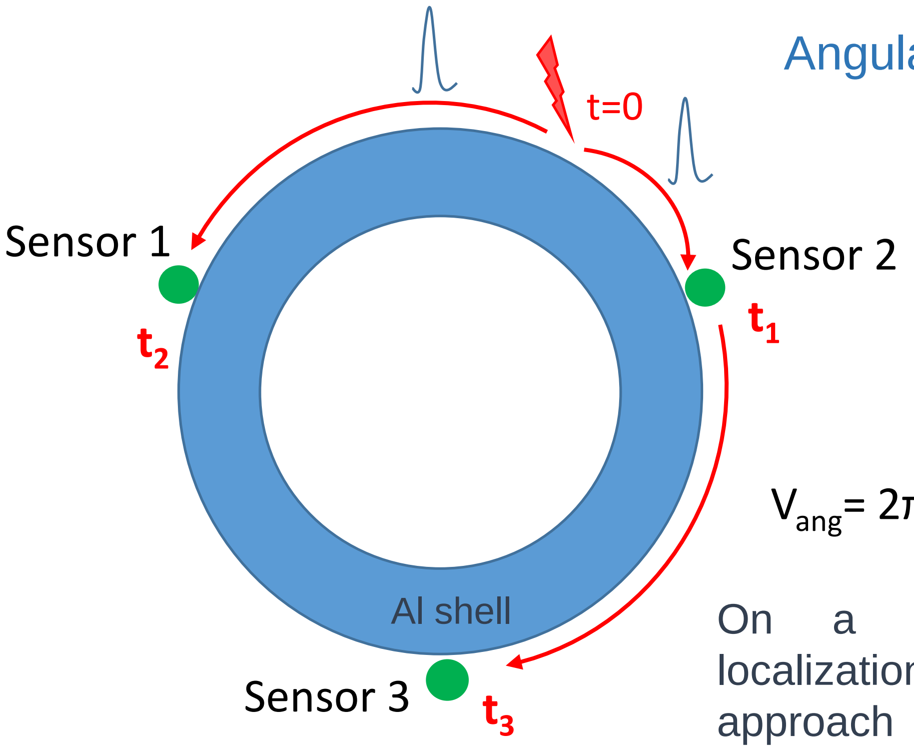
Deforms primarily via slip-stick motion along the interfaces

Axial and azimuthal quench localization

Axial localization



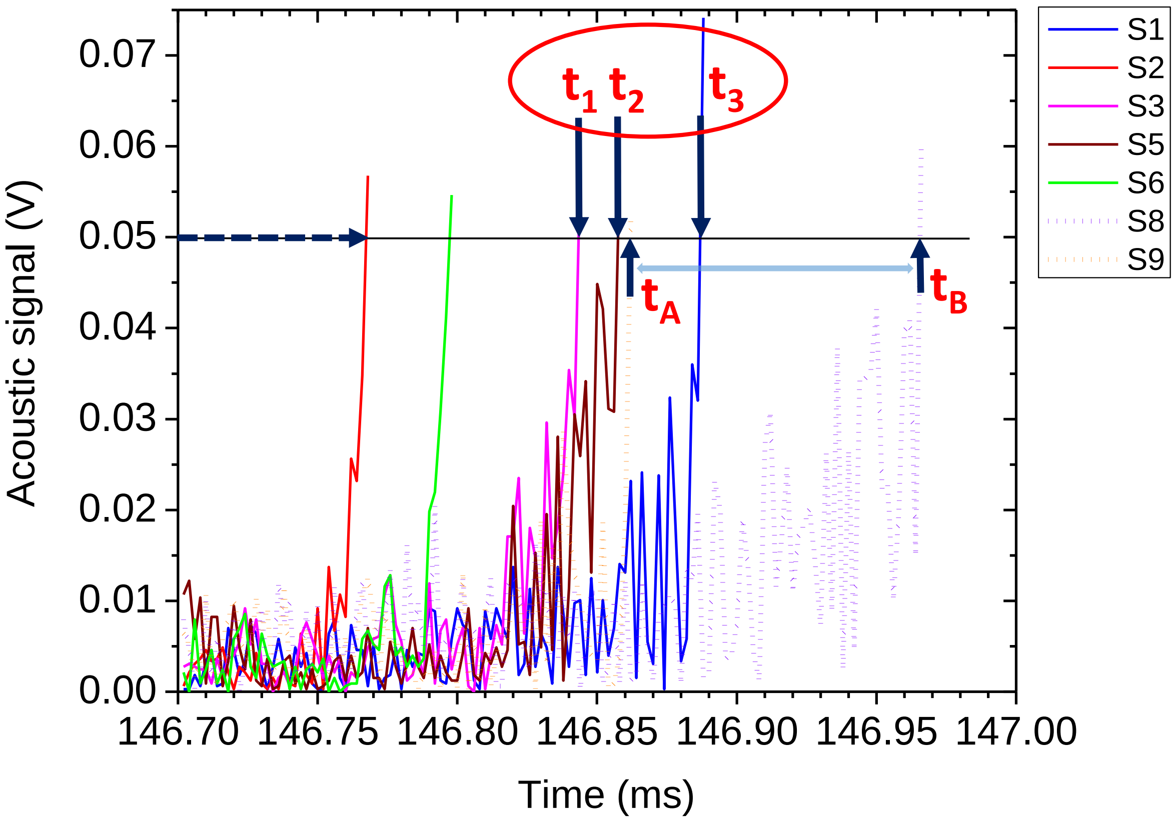
Angular localization



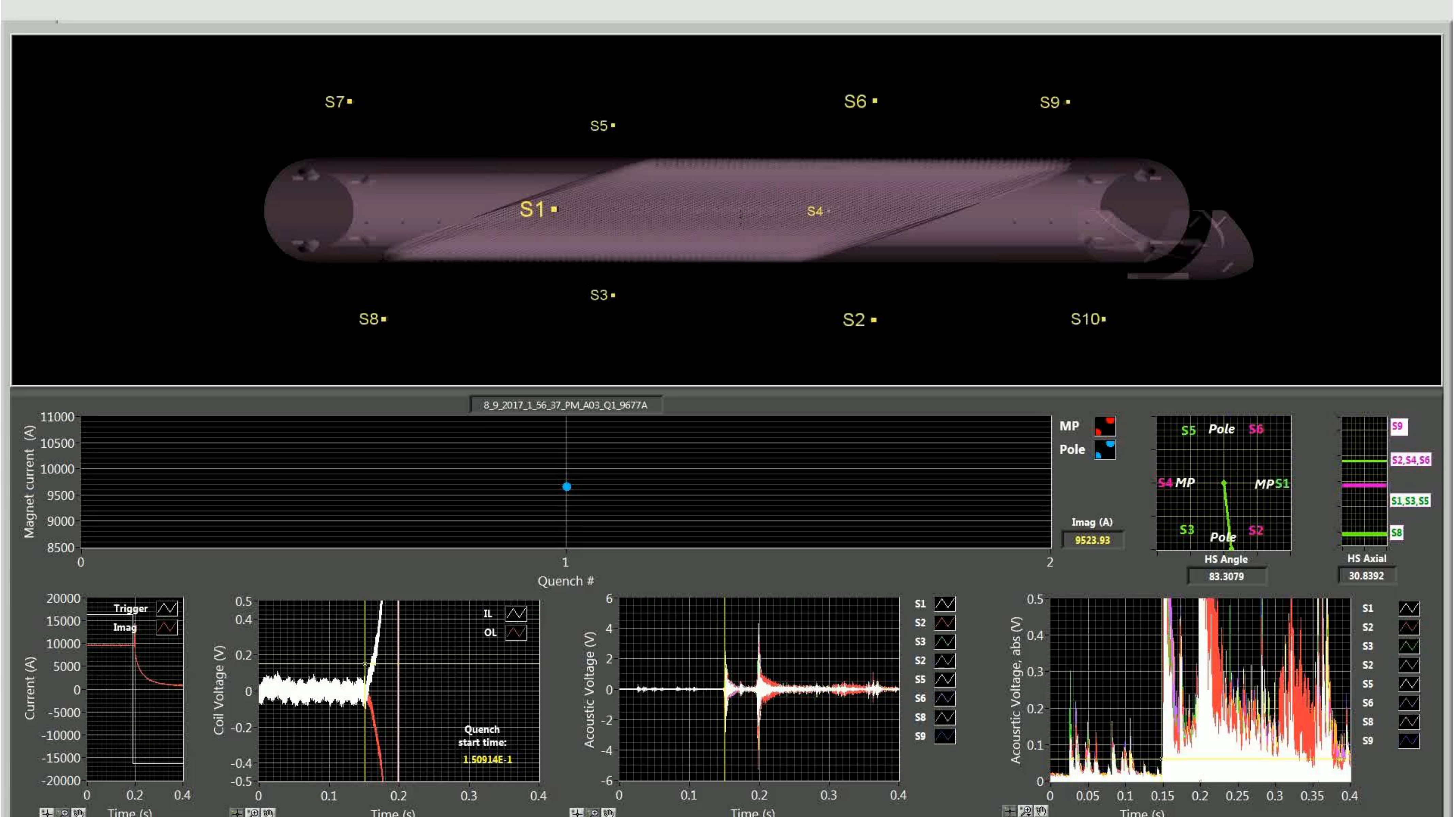
$V_{ang}= 2\pi/3 * (t_3-t_1)$

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

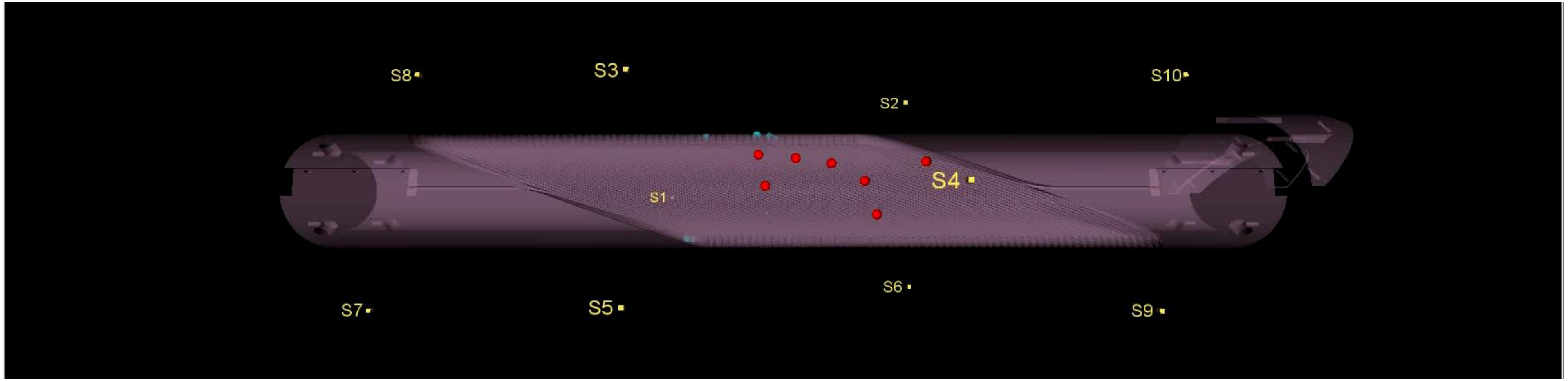
Example: quench #2 at 9826 A

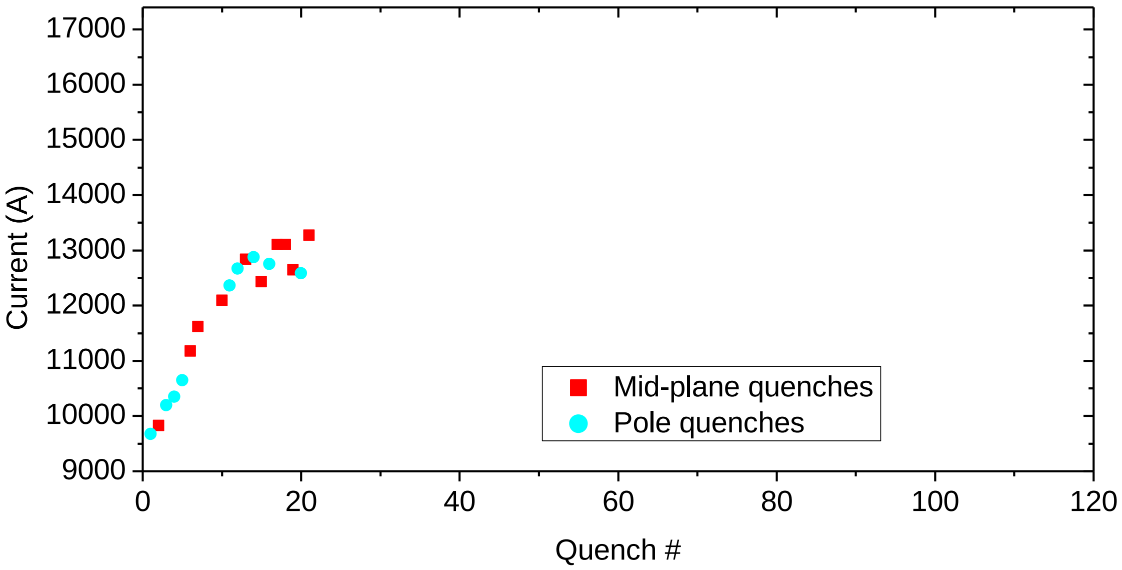


Quench locations: beginning of training

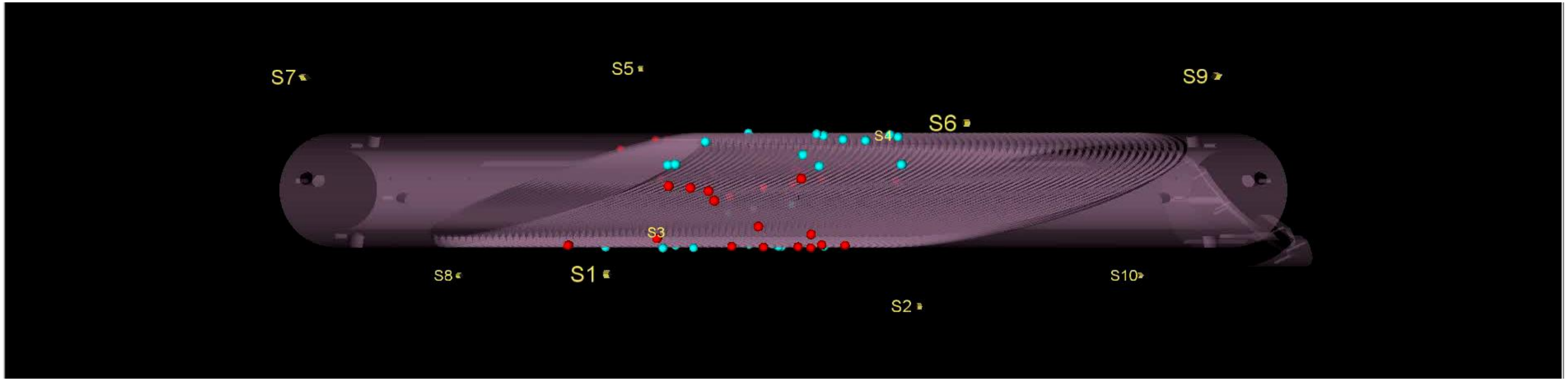


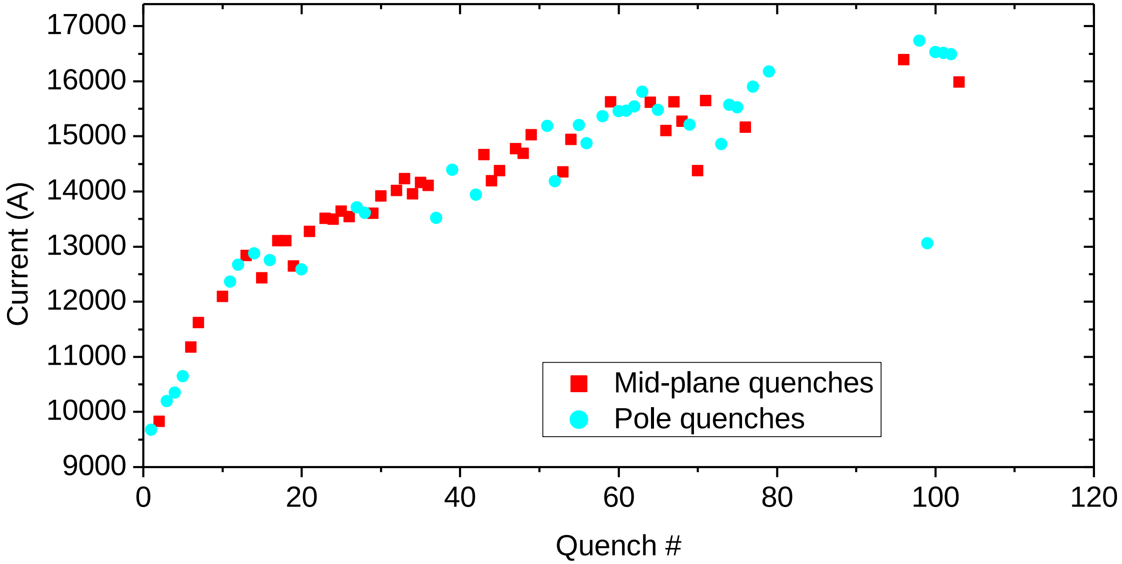
Quench locations in the IL: beginning of training



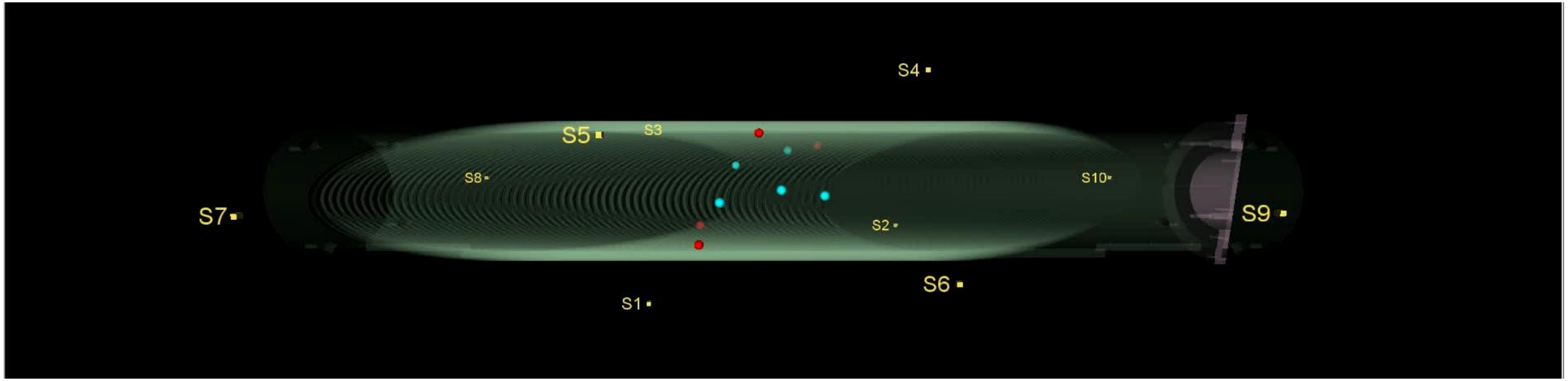


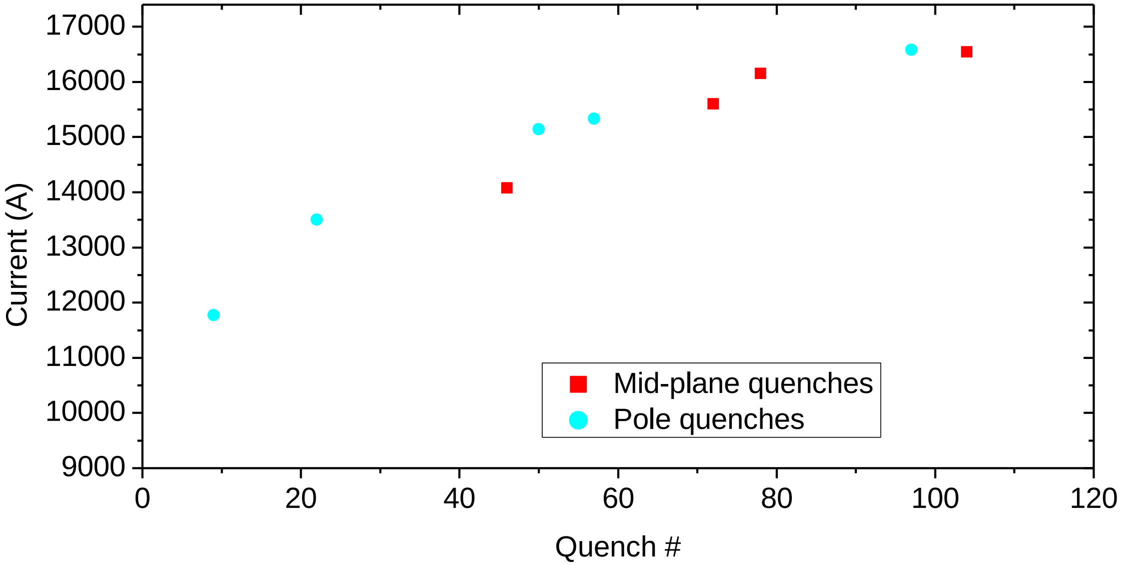
All IL quench locations





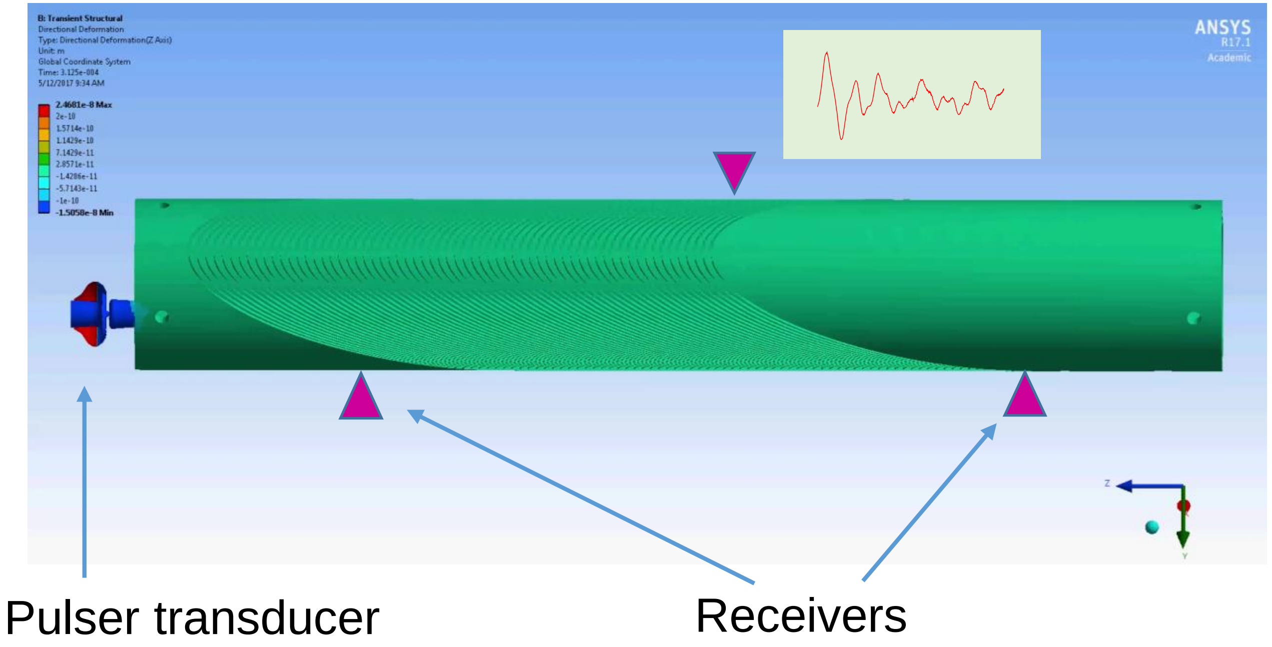
All OL quench locations





Active monitoring of mechanical integrity

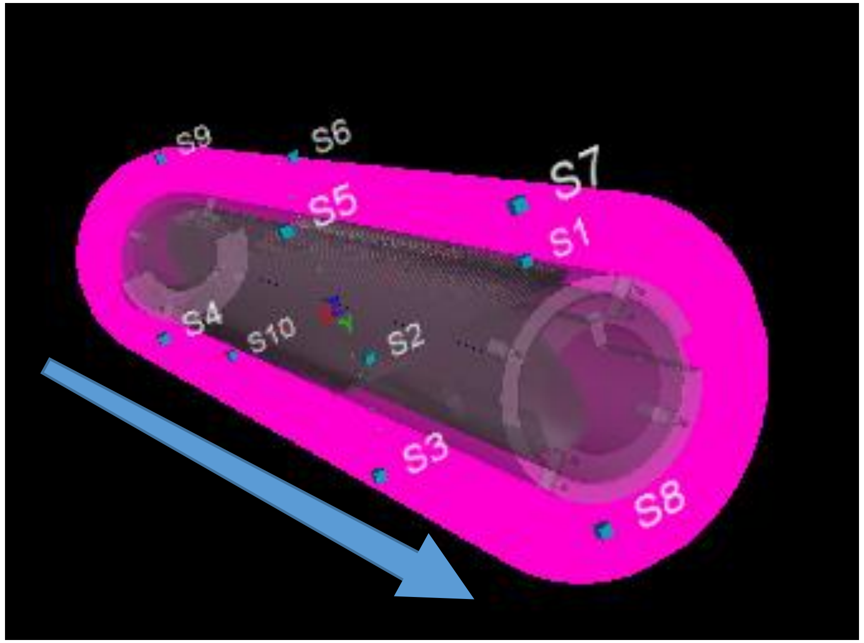
ANSYS simulation of transient deformation in the CCT mandrel upon pulsing a piezo-transducer



- **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**

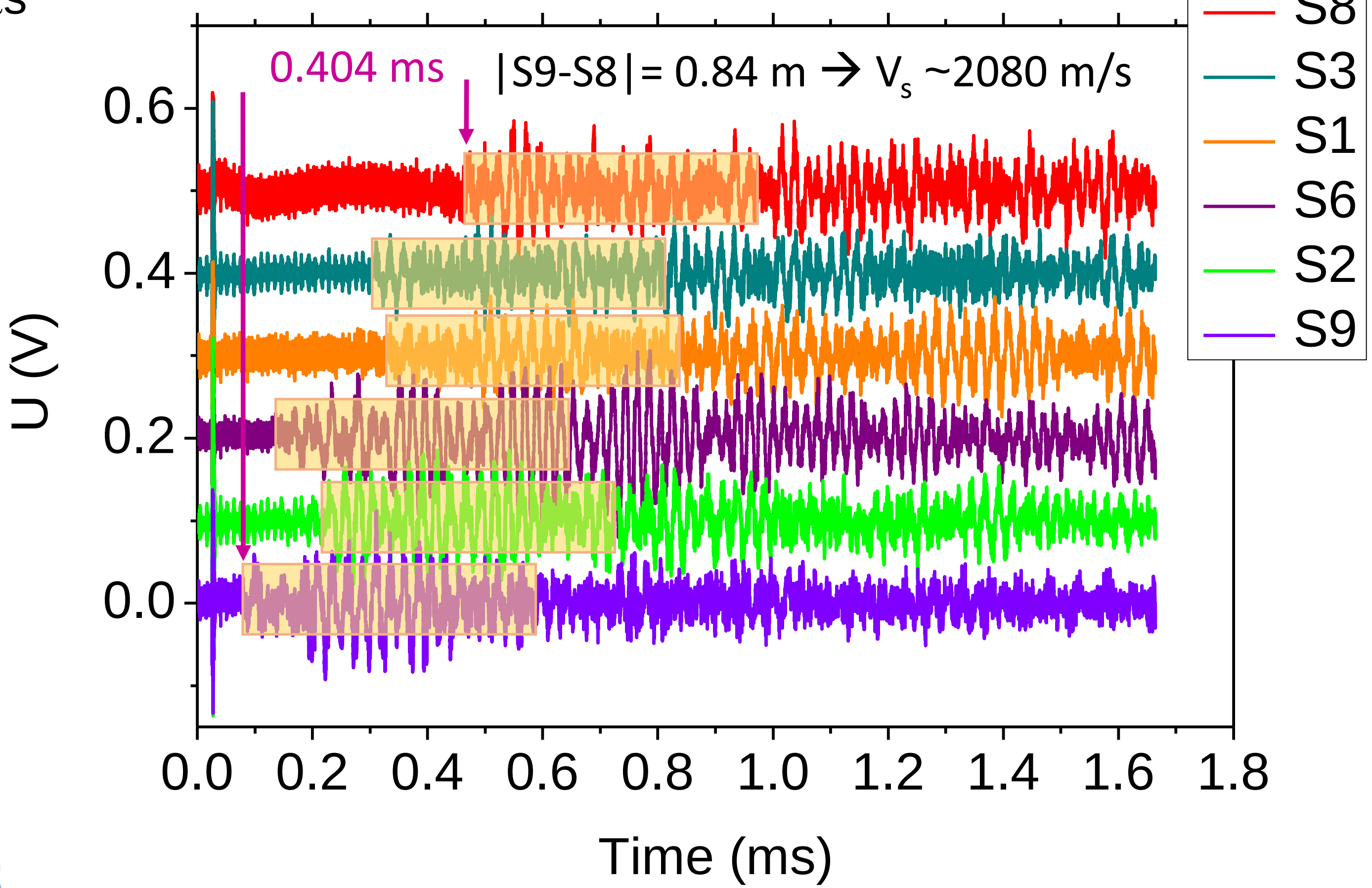
Pulse propagation in the CCT4 magnet

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



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

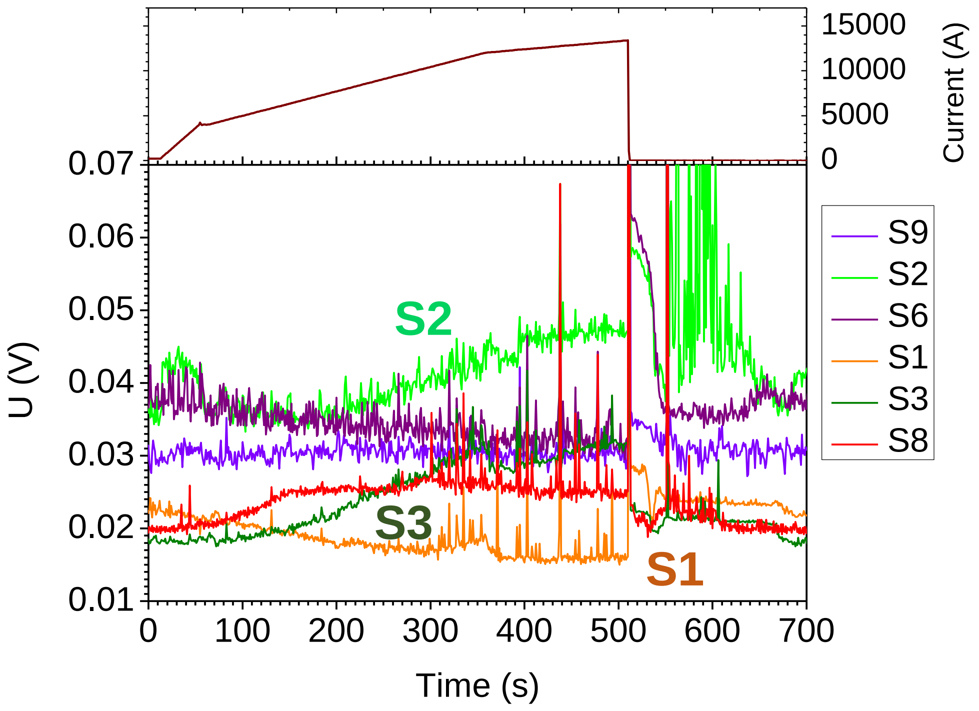
Waveforms are offset by 0.1 V on y-axis for clarity



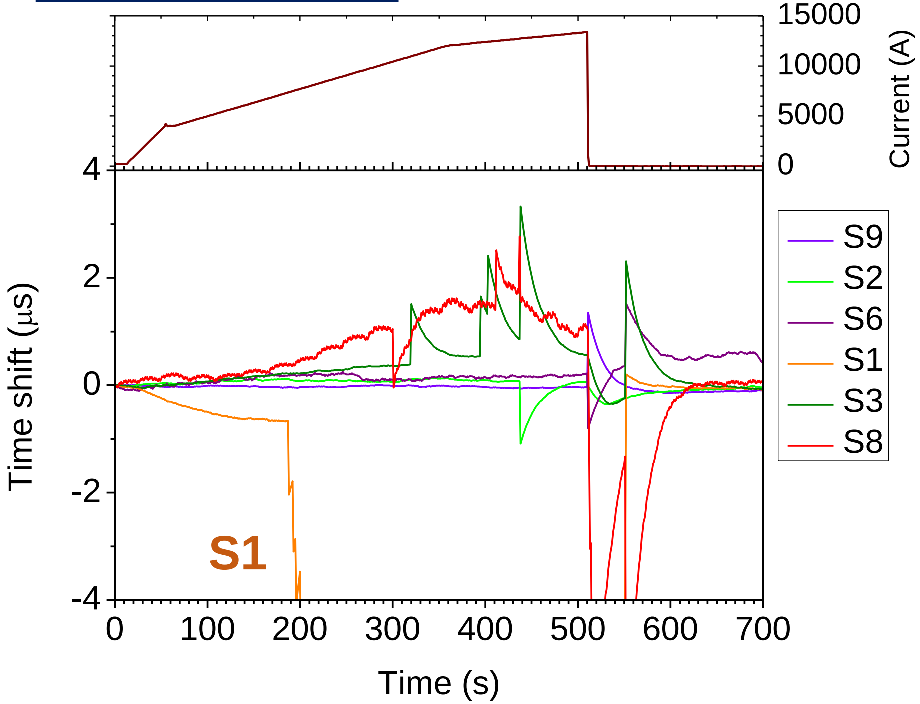
0.5 ms window is set individually for each waveform, and then periodically monitored with each pulse

Locating variation of the mechanical contacts

Transmitted pulse amplitude



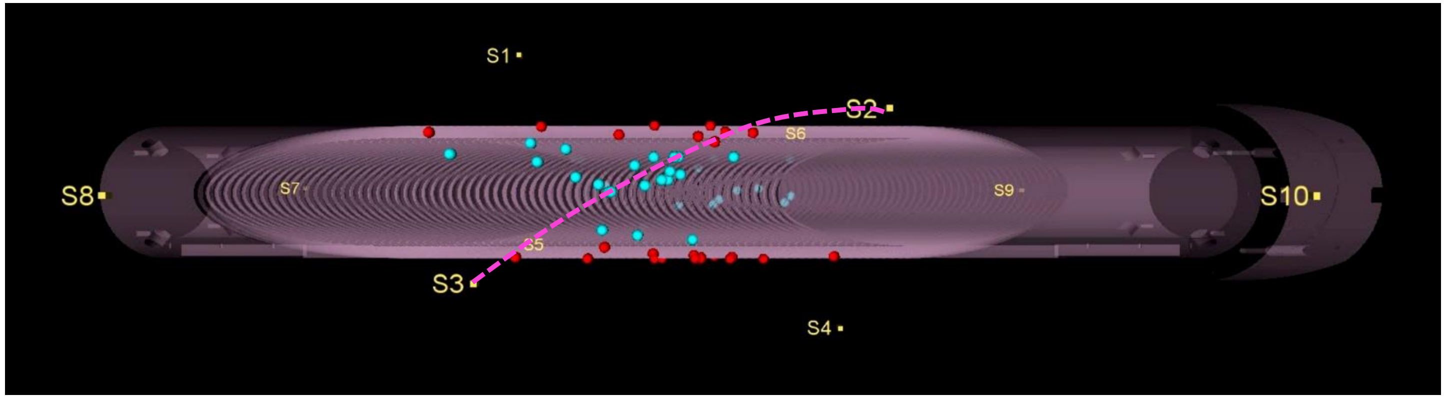
Relative time shift



Time shift is found by cross-correlating the initial “reference” waveforms with the consecutive ones.

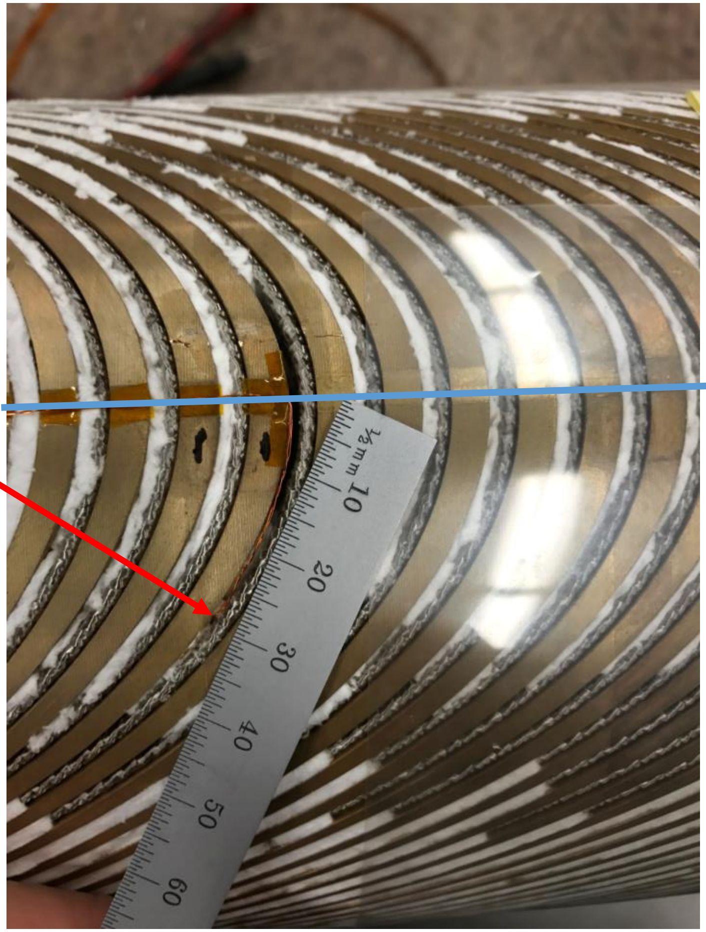
Same principle as in:. *M. Marchevsky and S.A. Gourlay, Appl. Phys. Lett. 110, 2017 doi:10.1063/1.4973466*

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



Temperature monitoring inside the coil

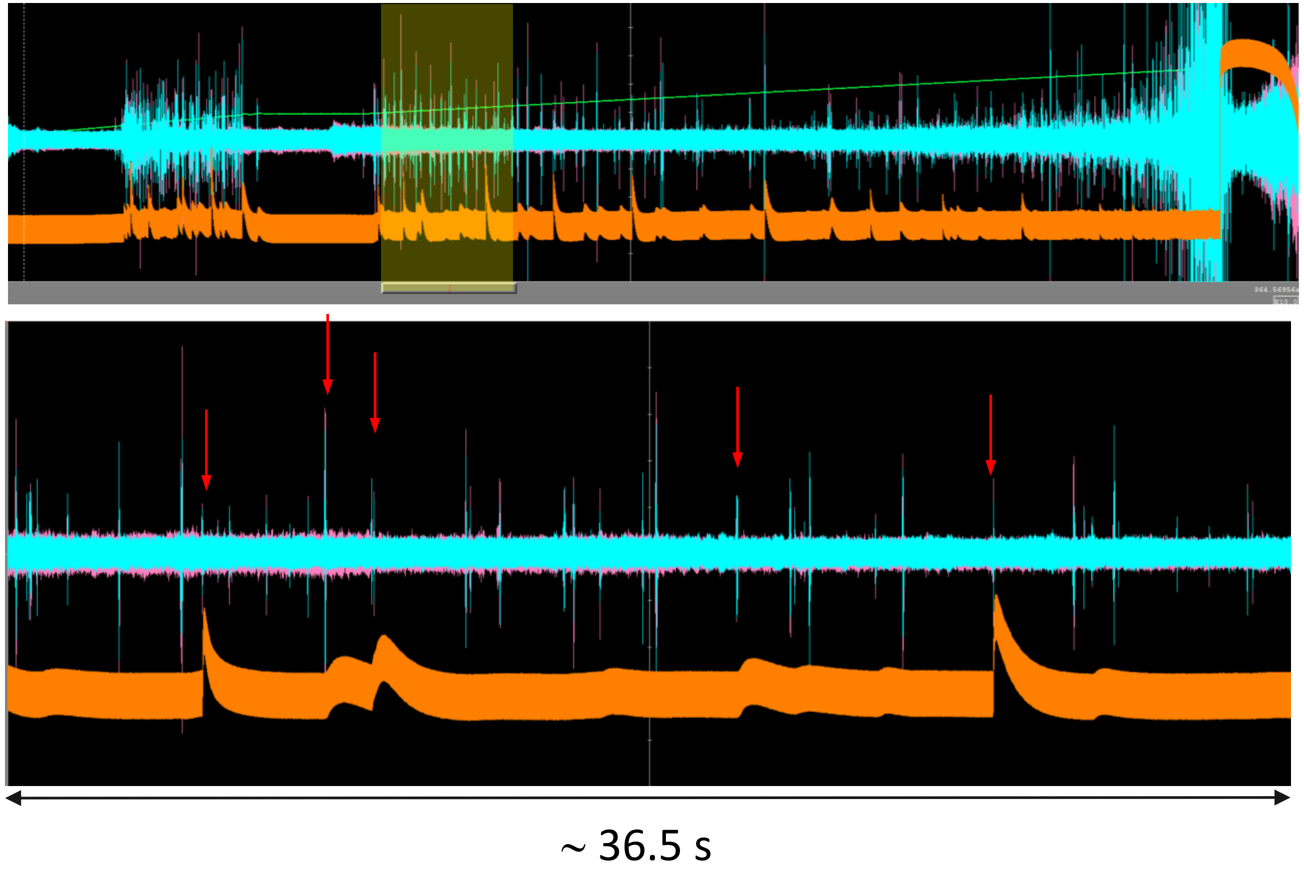
A thermometer of ~1 mm^2 size was installed directly in the cable groove, in the magnet outer layer, prior to impregnation

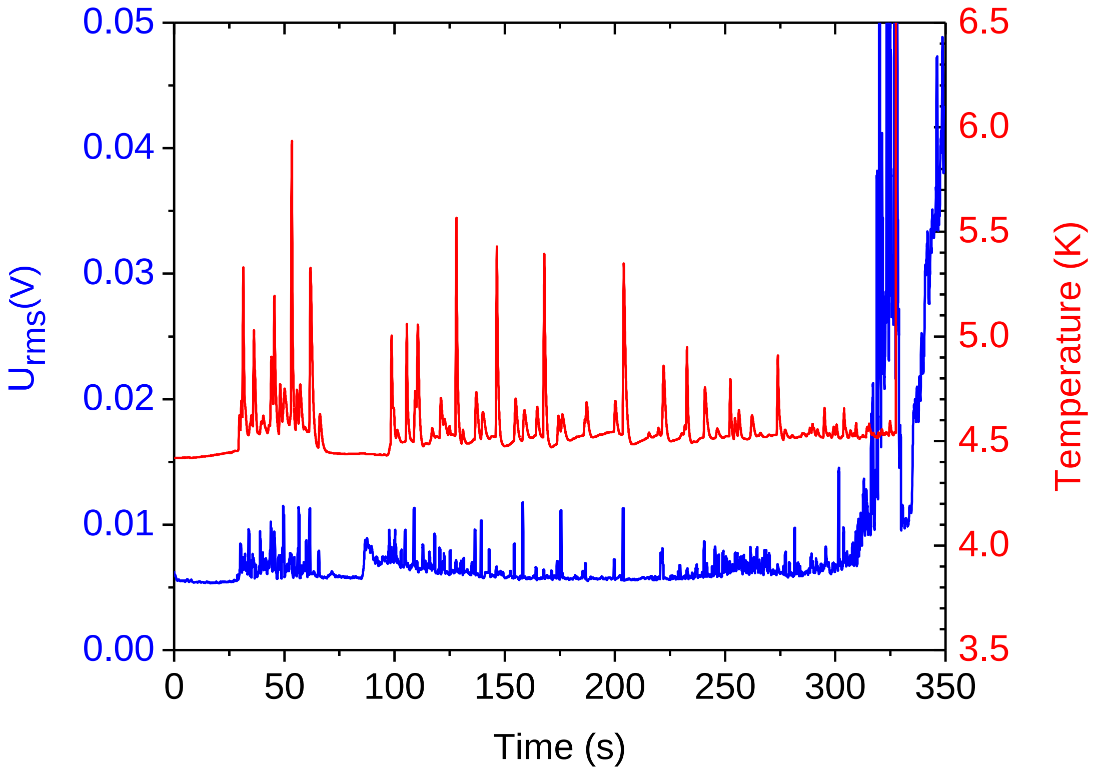


Pole location

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

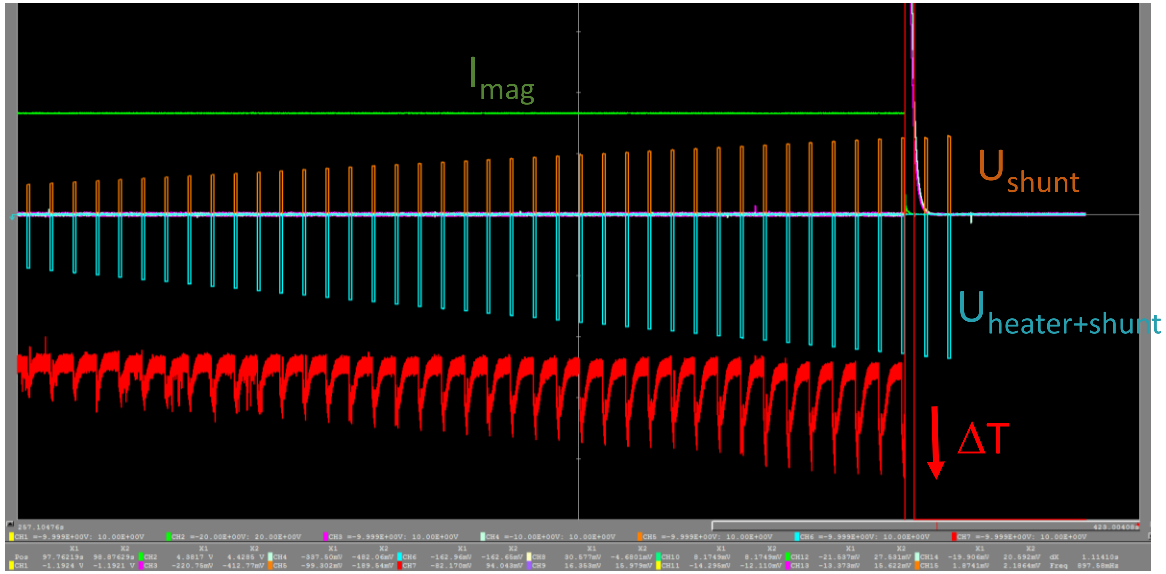


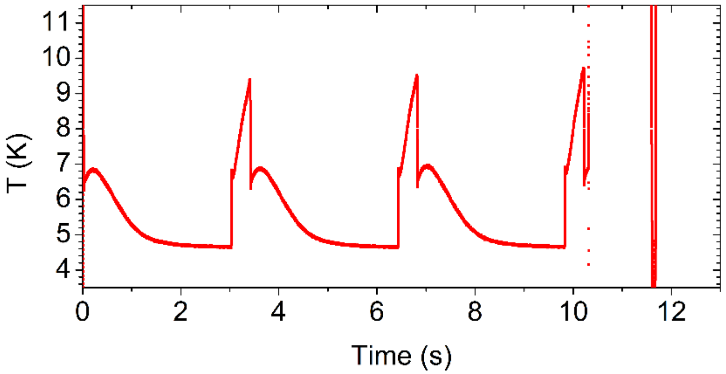


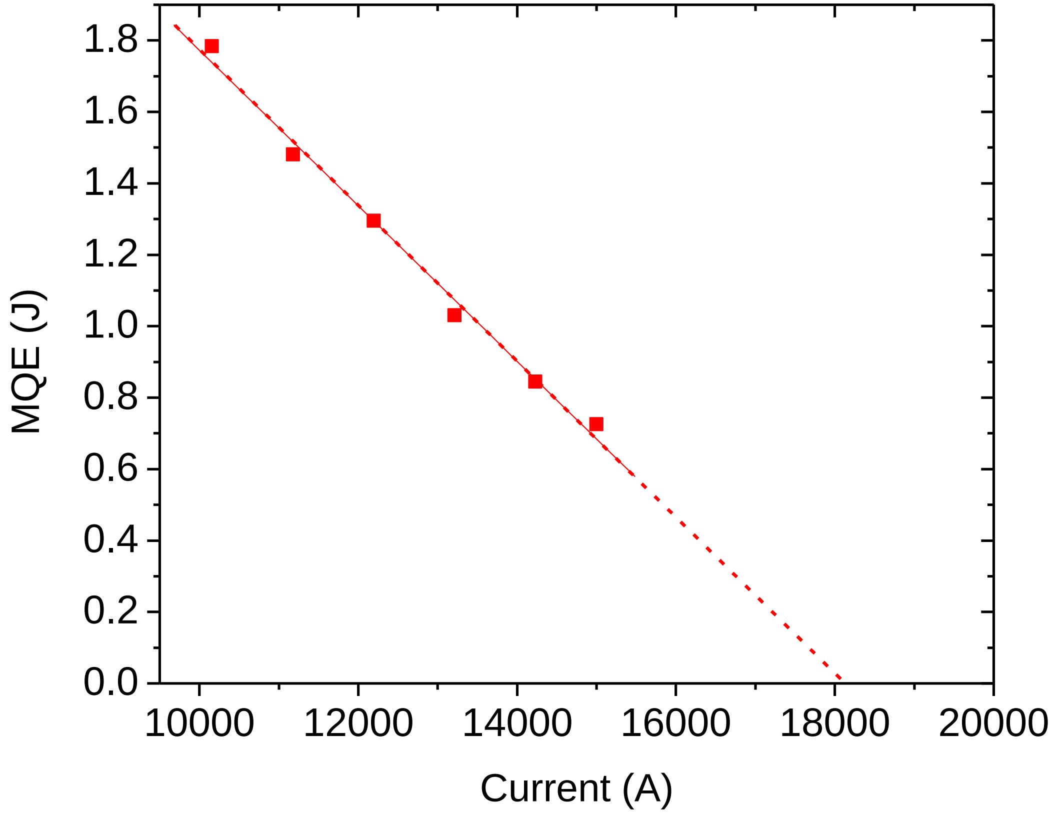
- Temperature spikes as high as 1 K are observed in the "cracking" regime. All of them are time-correlated with the acoustic events, and few also correlate with voltage spikes on the coils
- A minor (< 20 mK) gradual temperature rise, or none at all is seen in the "slip-stick" regime prior to quenching

Minimal quench energy measurements

Spot heater was fired periodically for 400 ms at 3 s intervals, gradually increasing the power.







We can now cross-check MQE and thermal data against the crack-induced heating, and compare with the temperature margin I_{cs} (B,T)

Conclusions

- 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 monitoring identifies locations of intermittent mechanical contact within magnet structure
- Thermal spikes associated with epoxy cracking were observed
- MQE has been measured

Work in progress on analyzing high-frequency acoustic data for event type sorting according to their associated disturbance spectra and deposited energy,. We also work on correlating thermal and acoustic measurements with models to understand impact of cracking and slip-stick to quench performance limitation.