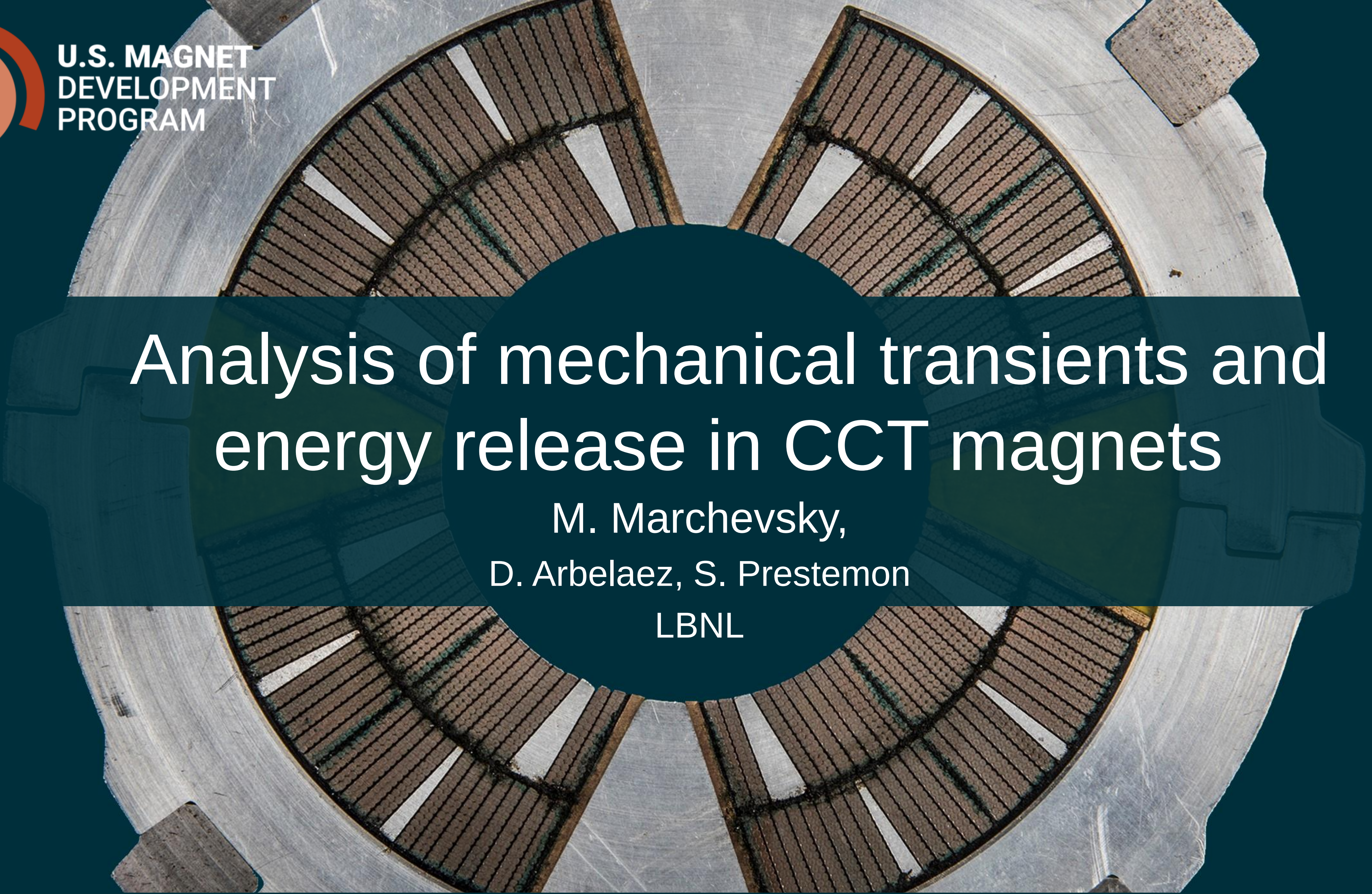
U.S. MAGNET
DEVELOPMENT
PROGRAM



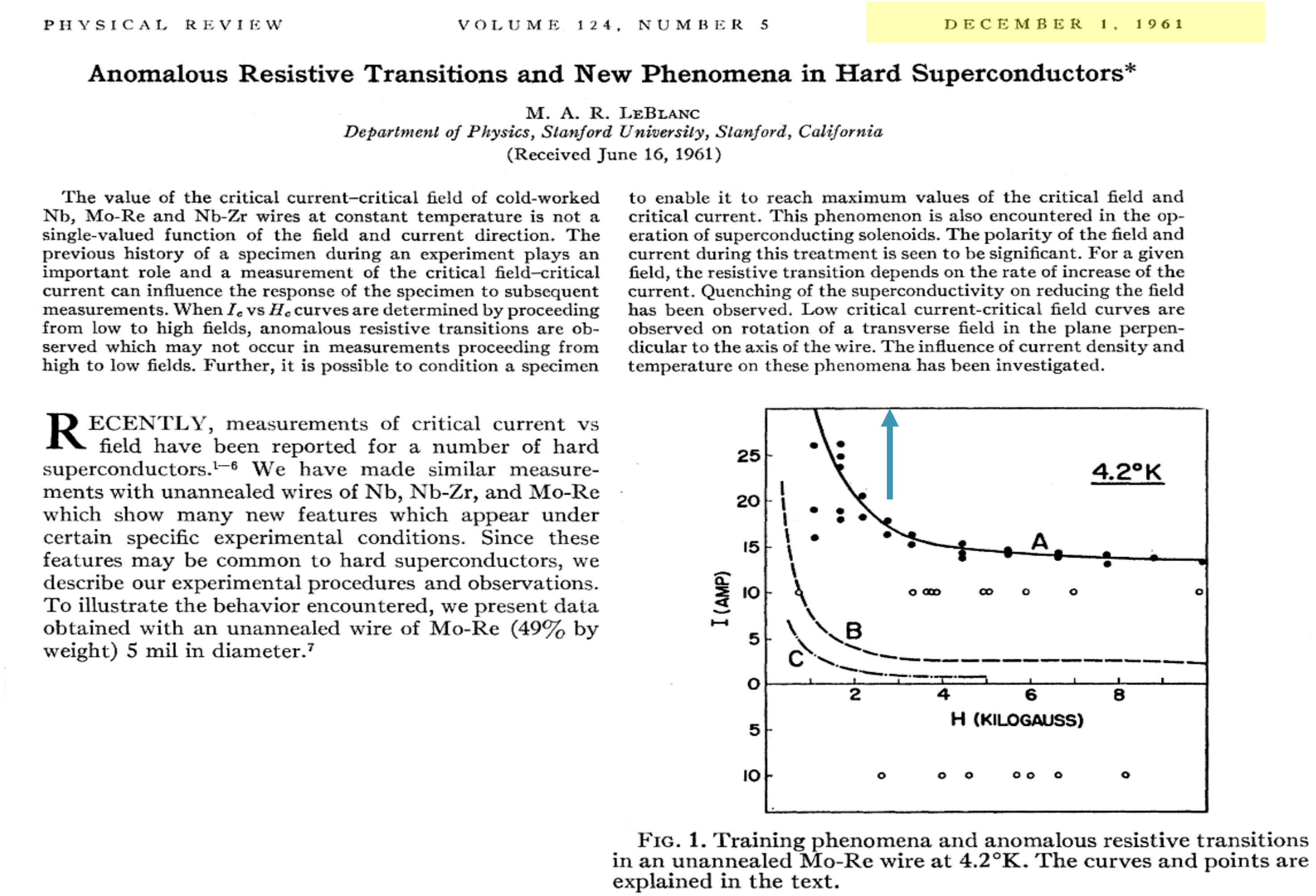
Analysis of mechanical transients and energy release in CCT magnets

M. Marchevsky,
D. Arbelaez, S. Prestemon
LBNL

Outline

- Training causes and mechanical energy release in LTS magnets
- AE instrumentation and basic analysis
- AE energy scaling and associated training regimes
- AE multiplets as evidence of stress concentrators
- Wax-impregnated CCT: preliminary diagnostics results
- Summary

First report of the training phenomenon



PHYSICAL REVIEW VOLUME 124, NUMBER 5 DECEMBER 1, 1961

Anomalous Resistive Transitions and New Phenomena in Hard Superconductors*

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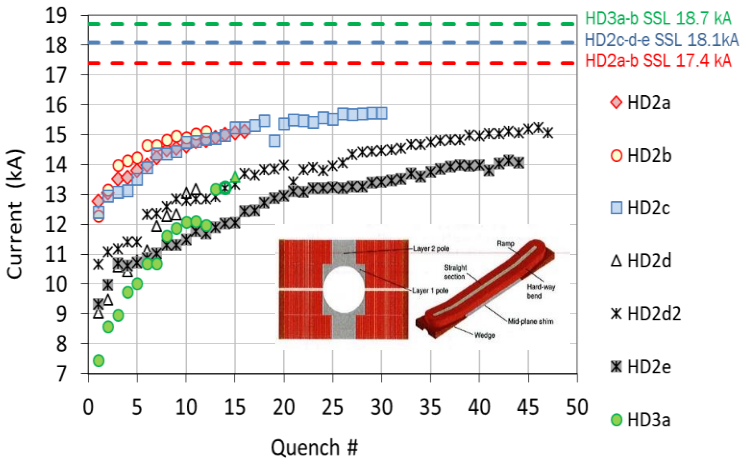
(Received June 16, 1961)

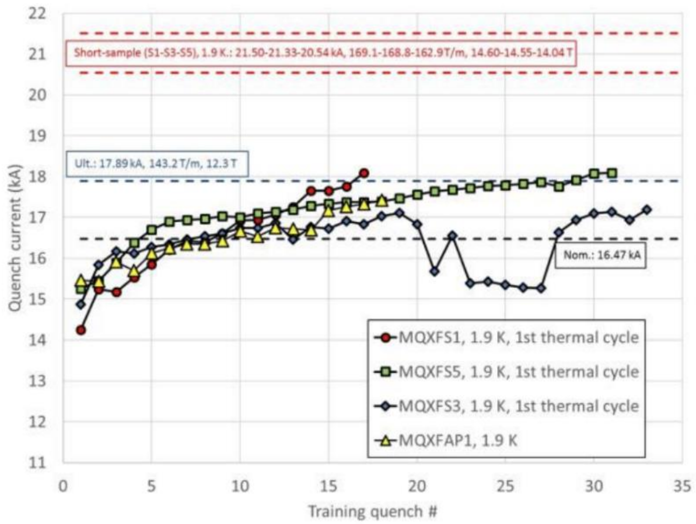
The value of the critical current–critical field of cold-worked Nb, Mo-Re and Nb-Zr wires at constant temperature is not a single-valued function of the field and current direction. The previous history of a specimen during an experiment plays an important role and a measurement of the critical field–critical current can influence the response of the specimen to subsequent measurements. When I_c vs H_c curves are determined by proceeding from low to high fields, anomalous resistive transitions are observed which may not occur in measurements proceeding from high to low fields. Further, it is possible to condition a specimen to enable it to reach maximum values of the critical field and critical current. This phenomenon is also encountered in the operation of superconducting solenoids. The polarity of the field and current during this treatment is seen to be significant. For a given field, the resistive transition depends on the rate of increase of the current. Quenching of the superconductivity on reducing the field has been observed. Low critical current-critical field curves are observed on rotation of a transverse field in the plane perpendicular to the axis of the wire. The influence of current density and temperature on these phenomena has been investigated.

RECENTLY, measurements of critical current vs field have been reported for a number of hard superconductors.[1–6] We have made similar measurements with unannealed wires of Nb, Nb-Zr, and Mo-Re which show many new features which appear under certain specific experimental conditions. Since these features may be common to hard superconductors, we describe our experimental procedures and observations. To illustrate the behavior encountered, we present data obtained with an unannealed wire of Mo-Re (49% by weight) 5 mil in diameter.[7]

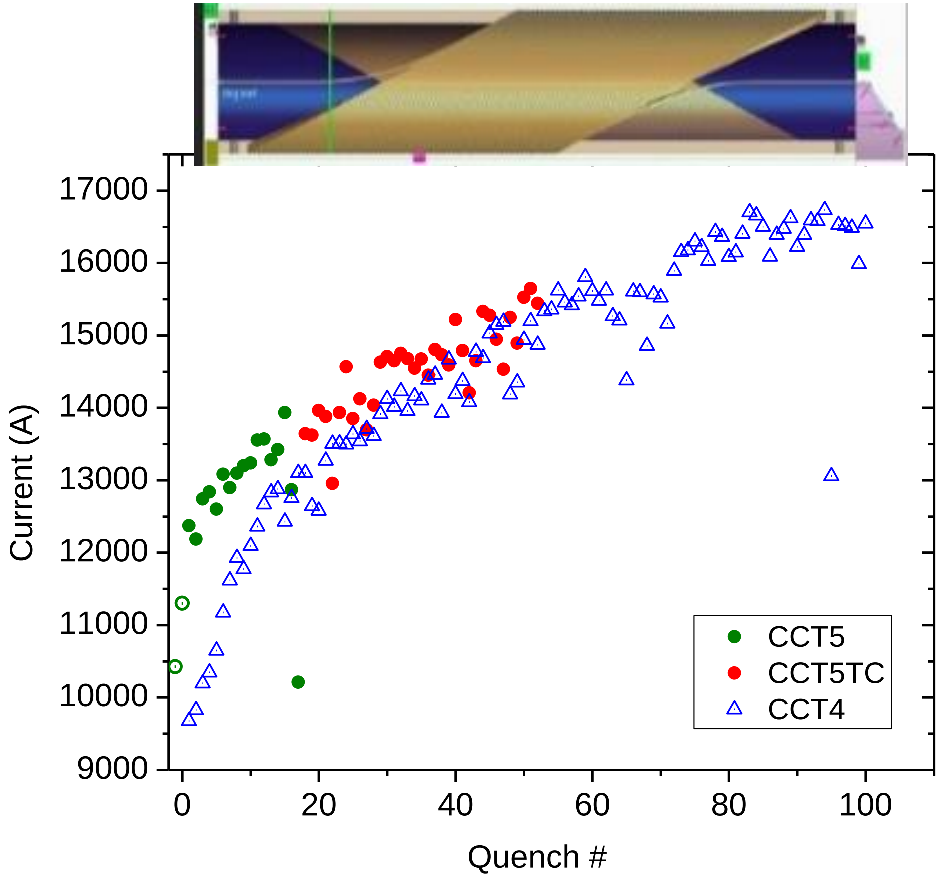
Fig. 1. Training phenomena and anomalous resistive transitions in an unannealed Mo-Re wire at 4.2°K. The curves and points are explained in the text.

Training examples





CCT

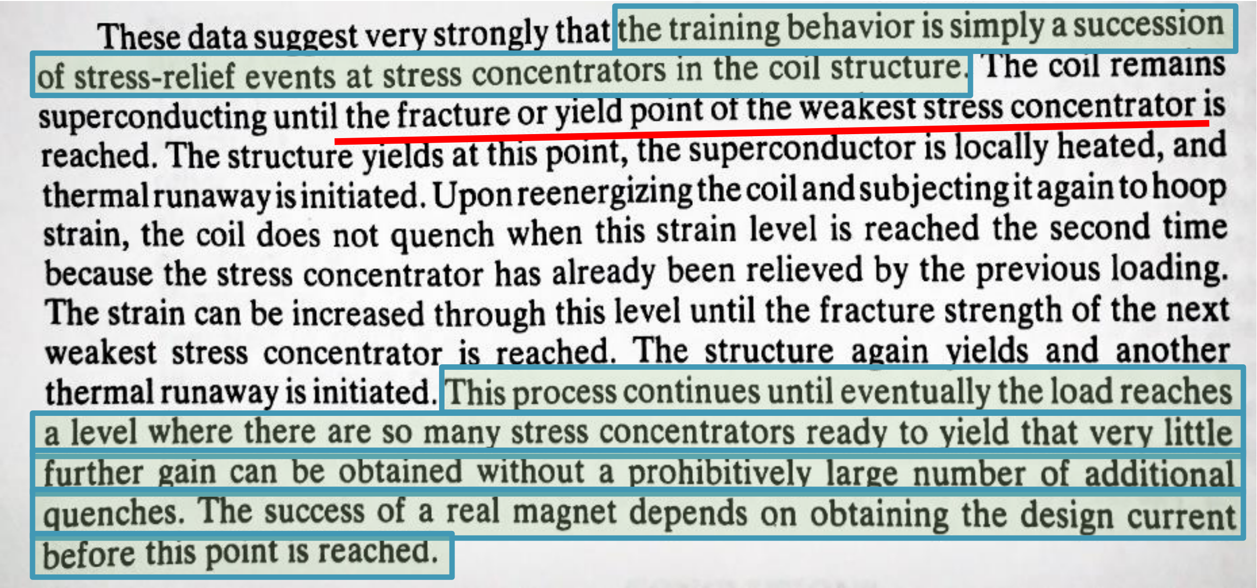


- Training can be remarkably similar in magnets of very different design

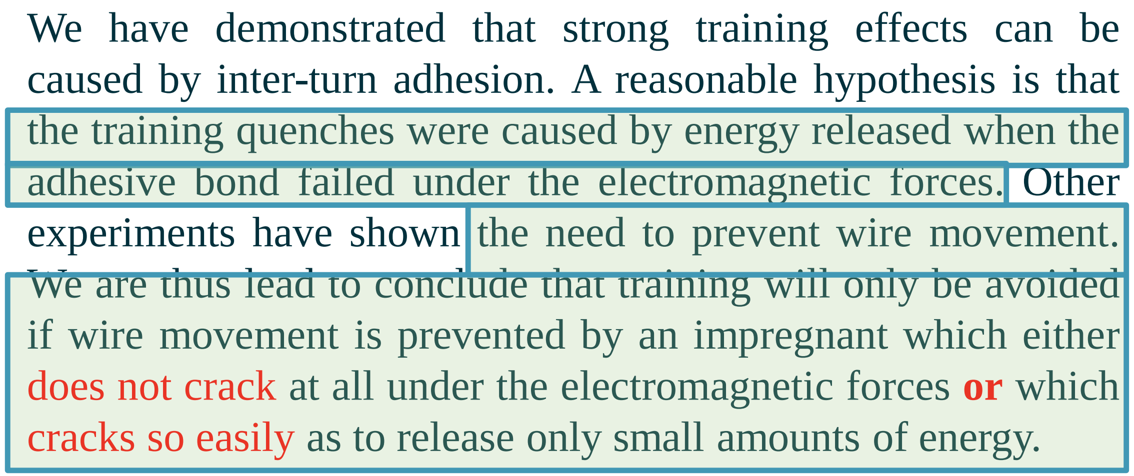
Some old papers…

“Training of Epoxy-Impregnated Superconductor Windings”, J. W. Ekin, R. E. Schramm, and M. J. Superczynski, *Advances in Cryogenic Engineering Materials*, pp 677-683, (1978)

“The effect of adhesion between turns on the training of superconducting magnets”, W. Edwards and M.N. Wilson, *Cryogenics*, Vol.18, Issue 7, p. 423, (1978)



These data suggest very strongly that the training behavior is simply a succession of stress-relief events at stress concentrators in the coil structure. The coil remains superconducting until the fracture or yield point of the weakest stress concentrator is reached. The structure yields at this point, the superconductor is locally heated, and thermal runaway is initiated. Upon reenergizing the coil and subjecting it again to hoop strain, the coil does not quench when this strain level is reached the second time because the stress concentrator has already been relieved by the previous loading. The strain can be increased through this level until the fracture strength of the next weakest stress concentrator is reached. The structure again yields and another thermal runaway is initiated. This process continues until eventually the load reaches a level where there are so many stress concentrators ready to yield that very little further gain can be obtained without a prohibitively large number of additional quenches. The success of a real magnet depends on obtaining the design current before this point is reached.

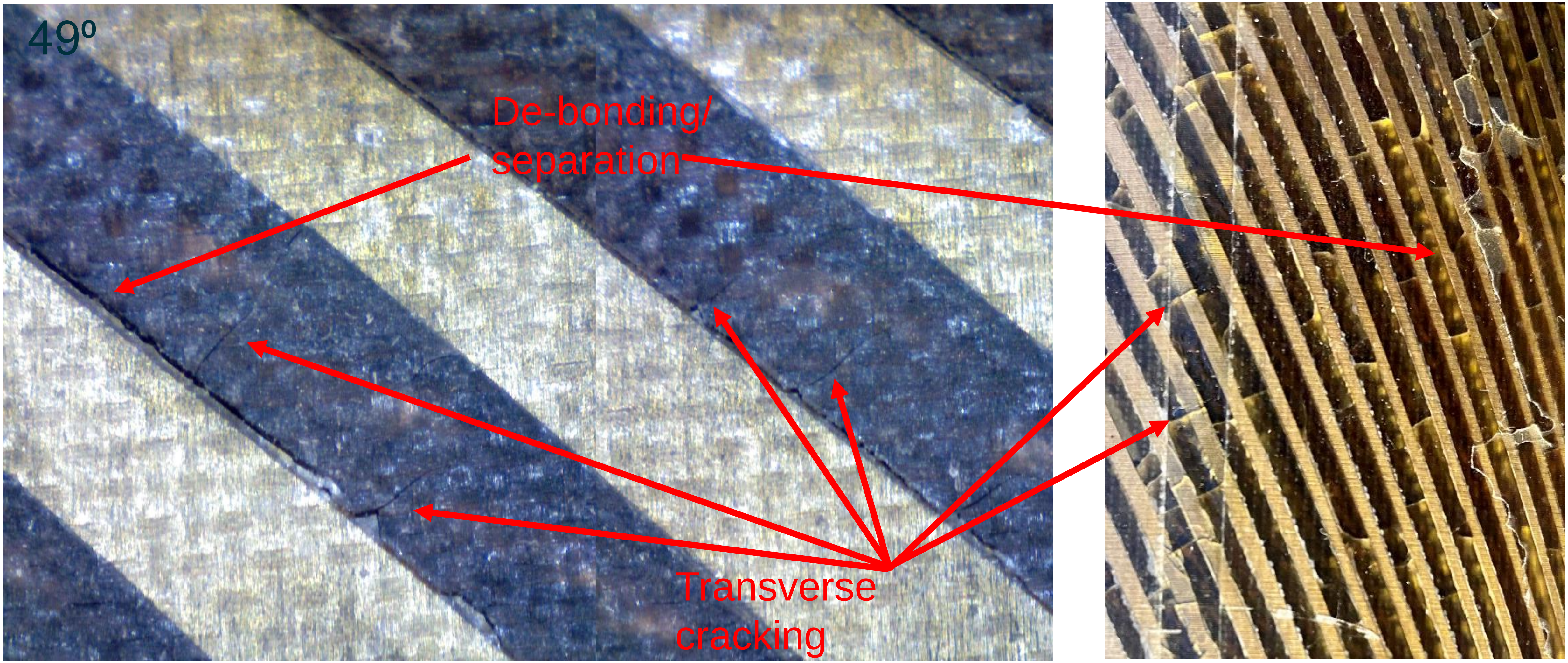


We have demonstrated that strong training effects can be caused by inter-turn adhesion. A reasonable hypothesis is that the training quenches were caused by energy released when the adhesive bond failed under the electromagnetic forces. Other experiments have shown the need to prevent wire movement. We are thus lead to conclude that training will only be avoided if wire movement is prevented by an impregnant which either does not crack at all under the electromagnetic forces **or** which cracks so easily as to release only small amounts of energy.

Causes of training (1978):

- **Epoxy cracking**
- **Wire motion (slippages, slip-stick)**
- **Stress concentrators**

Visible coil defects after testing of the CCT4 dipole



D. Arbelaez, LBNL

CCT4 dipole, IL

Modeling training by means of energy balance

…it seems that the most natural way is to assume that the releasing energy of each event E_r is proportional to the density of elastic energy, the σ^2, where σ - mechanical stress at the pulse. It is evident that for magnets this a is equivalent to $E_r \sim J^4$ or $E_r \sim B^4$ where J – is the

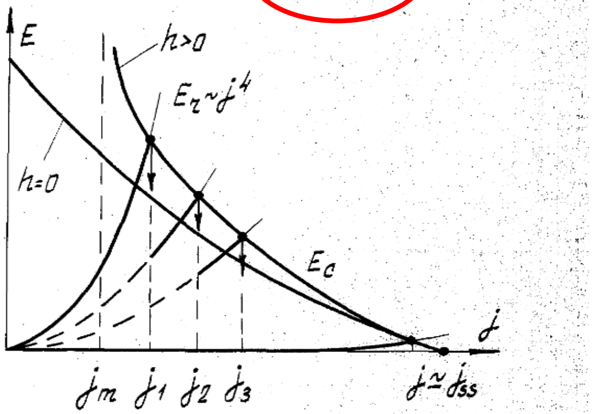


Fig 1 Critical (E_c) and releasing (E_r) energies vs current density j of the winding. The intersection points correspond to subsequent quenches.

IEEE TRANSACTIONS ON APPLED SUPERCONDUCTIVITY, VOL. 3, NO. 1, MARCH 1993 297
EXPLANATION OF MAIN FEATURES OF SUPERCONDUCTING WI TRAINING BY BALANCE OF ACTING AND PERMISSIBLE DISTURBANSES
V.E.Keilin

"Moreover, as expected, the total frictional energy dissipated during excitation varied linearly with the Lorentz force, i.e. quadratically with the current, and strongly depends on the friction factors."

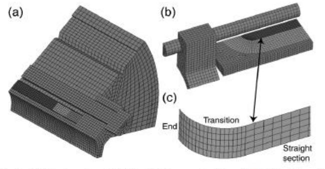


Fig. 5. Finite element model of the SQ02 geometry (a), with details of the coil end support (b), and of the contact region between coil and island (c).

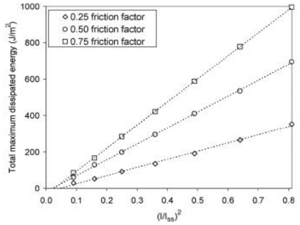


Fig. 7. Computed total frictional energy dissipated during a current ramp.

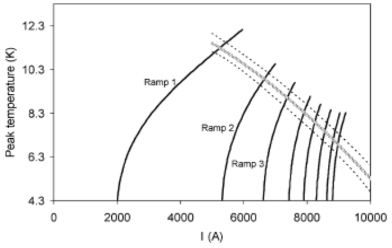


Fig. 10. Peak temperature of the superconductor induced by frictional energy computed during consecutive current ramps (solid black lines). The gray line represents the temperature of current sharing vs. current.

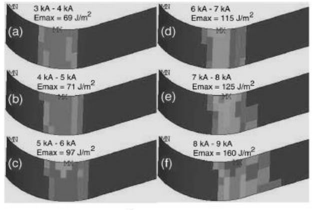
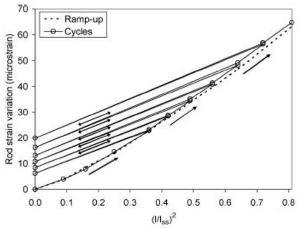


Fig. 6. Frictional energy (J/m²) dissipated during excitation from 3 kA to 9 kA in steps of 1 kA. E_{max} is the peak frictional energy dissipated in one step.



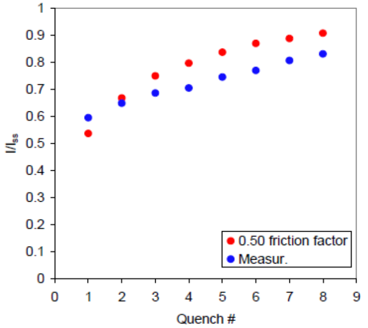
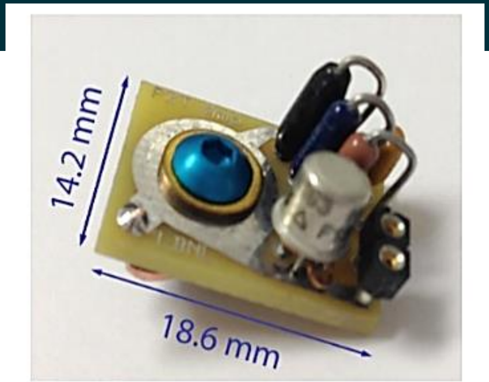


Fig. 21. Computed and measured training curve.

"Finite element model of training in the superconducting quadrupole magnet SQ02", P. Ferracin, S. Caspi, Cryogenics, V. 47, Issues 11–12, November–December 2007, Pages 595-606, https://escholarship.org/uc/item/3z22b4nk

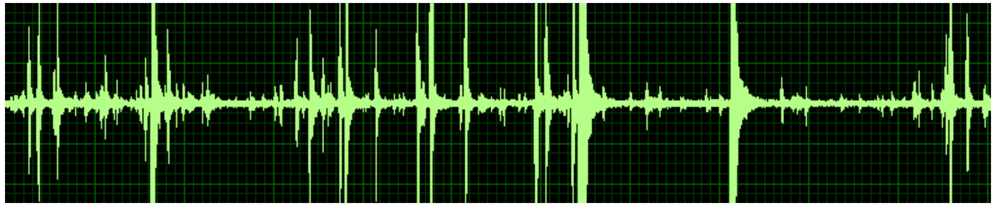
These are great examples of "mean field" modeling. However, they ignore the transient nature of the disturbances and their spatial and temporal distribution

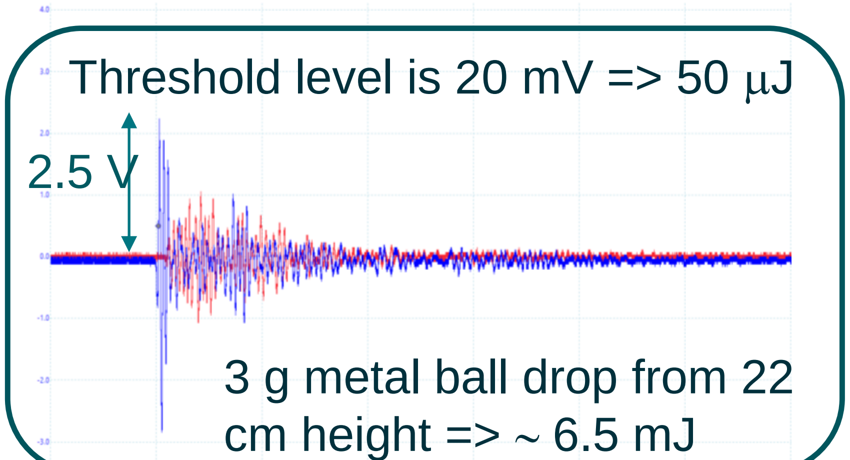
Acoustic emission as a unique tool for probing the disturbance spectrum



Event energy:

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

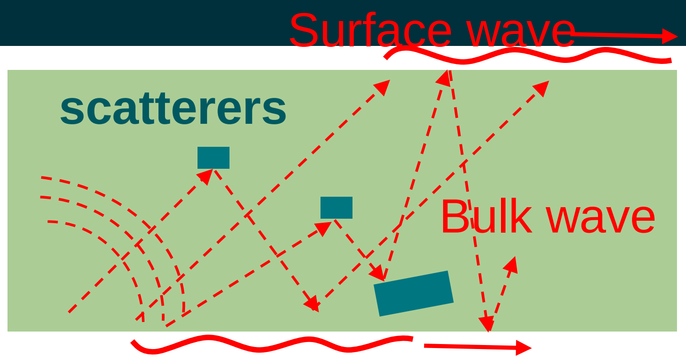


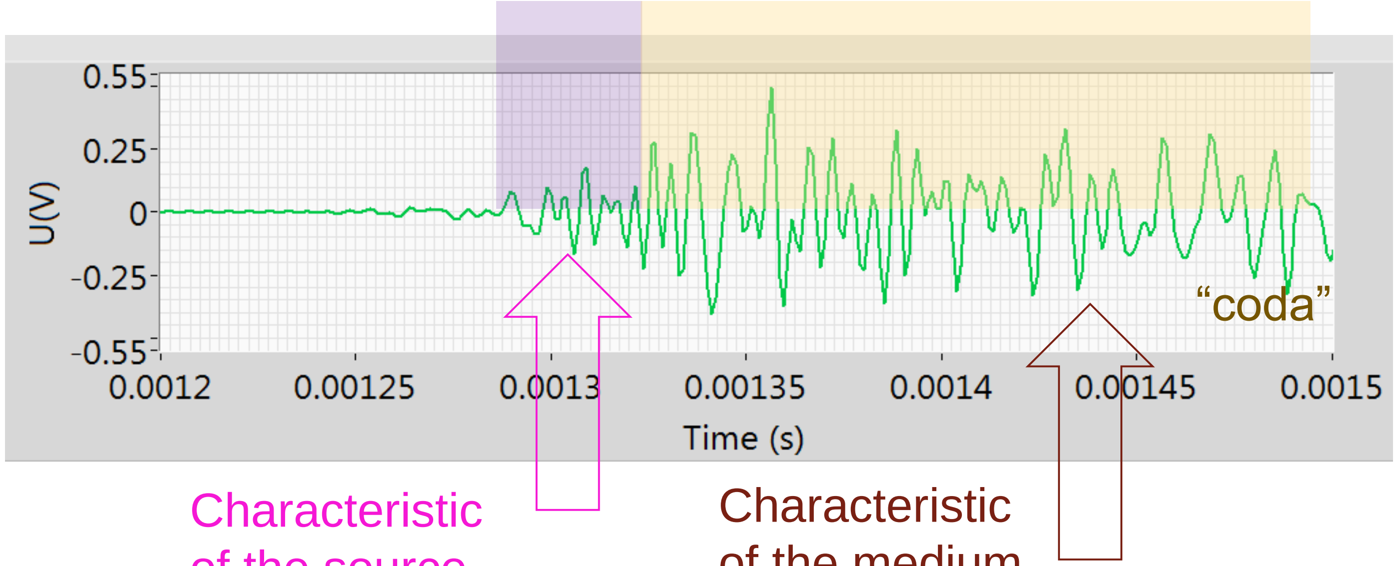


Threshold level is 20 mV => 50 μJ

3 g metal ball drop from 22 cm height => ~ 6.5 mJ

*Secondary reflections and mode conversions: wave “**diffuses**” through the medium : “coda wave”*





Characteristic of the source

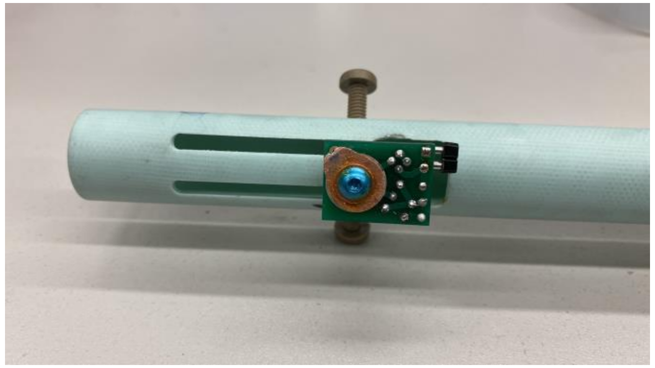
Characteristic of the medium

Coda presents an opportunity to uniquely “fingerprint” AE source location

Acoustic emission sensor hardware

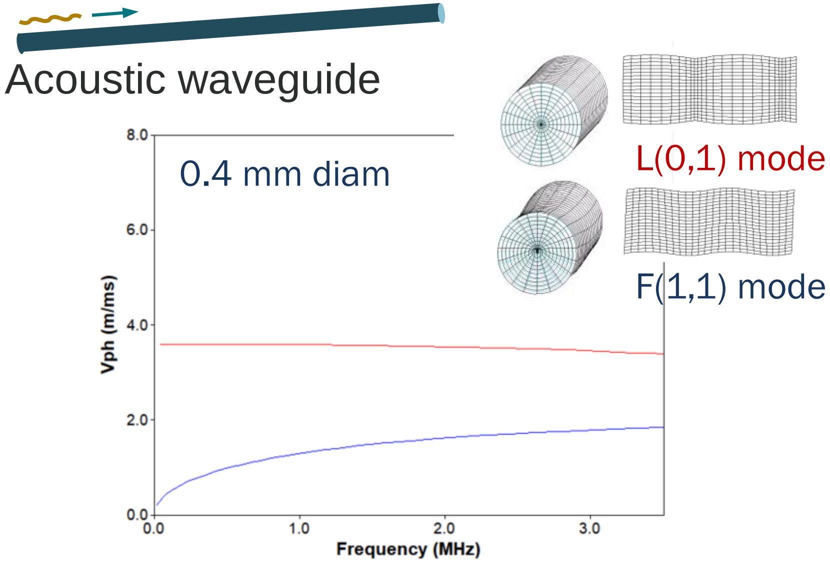
New hardware for AE measurements

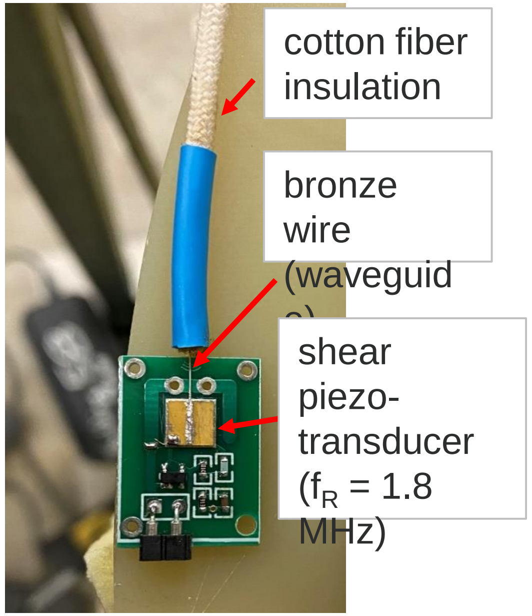
“2/3 original” amp.



Acoustic mounts

- 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 event “fingerprinting”
- Waveguide sensors are directional: they can be used to pick up specific wave mode and thus used to find a direction to the source

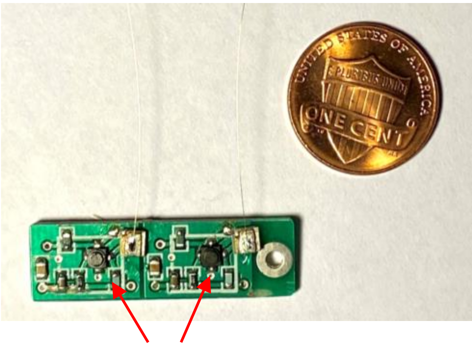




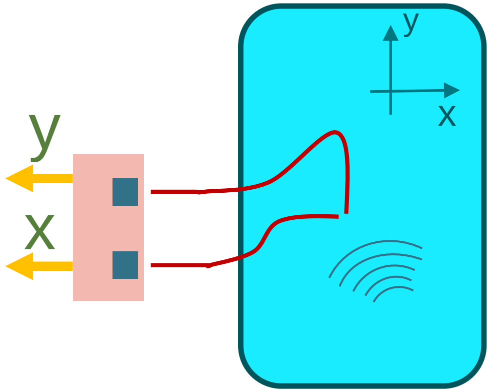
cotton fiber insulation

bronze wire (waveguide)

shear piezo-transducer (f_R = 1.8 MHz)

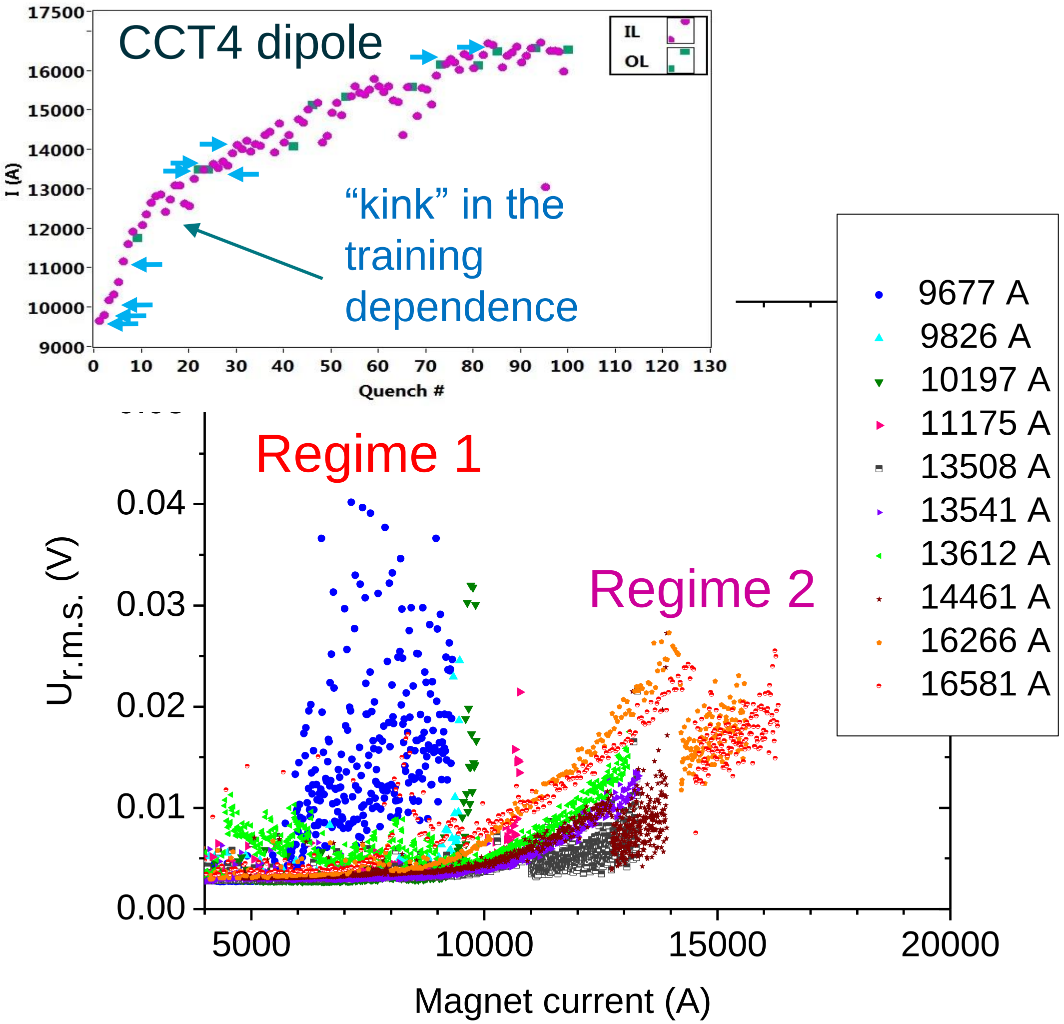


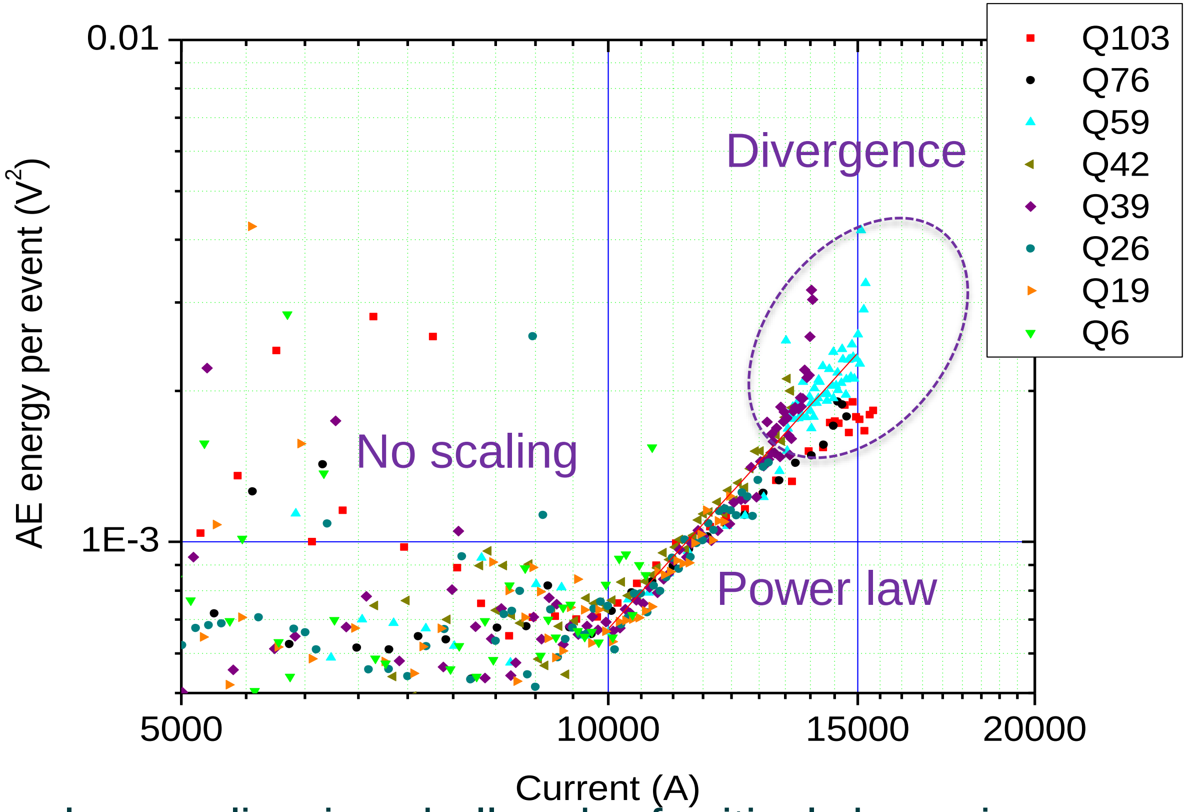
Ultra-low noise GaAs MOSFET amplifiers (< 1 nV/$\sqrt{Hz}$ at 1 MHz)



Directional AE sensing

Distinct regimes of training from AE

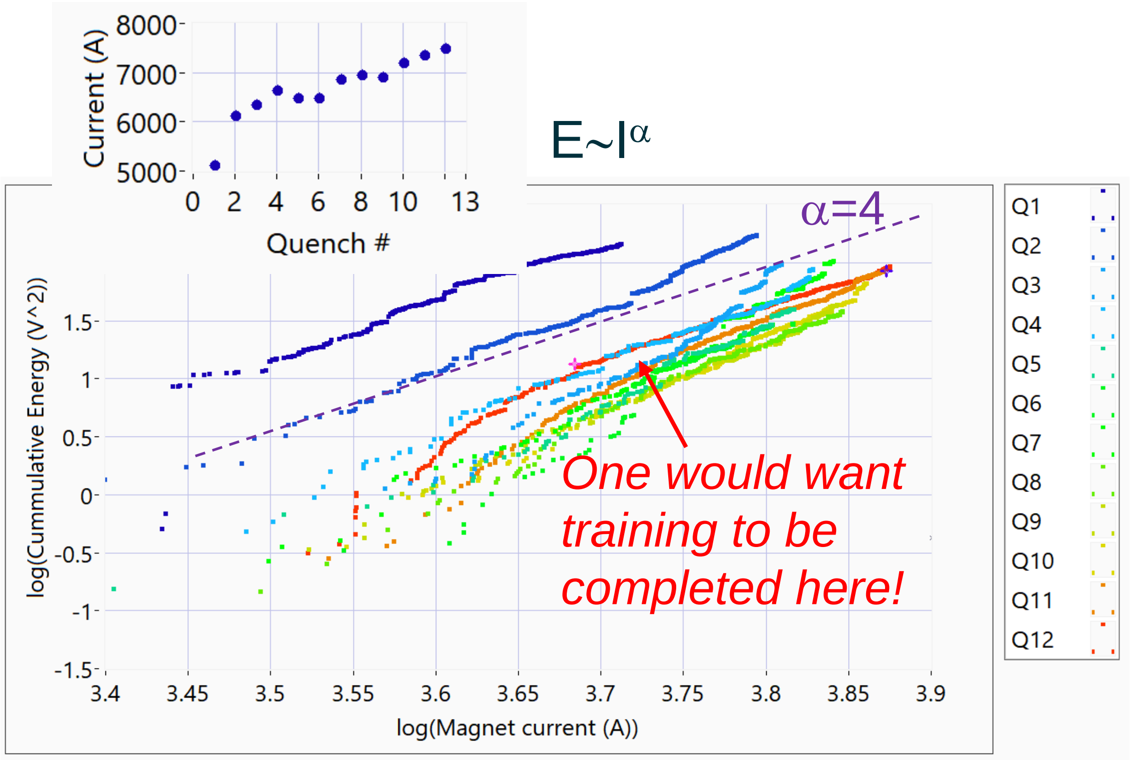




- Power–law scaling is a hallmark of critical dynamics seen in many physical systems including superconductors, magnetics, geoscience, etc.
- A steep divergence from the power law develops a few seconds prior to quenching for some ramps.

CCT Sub 4 energy release evolution

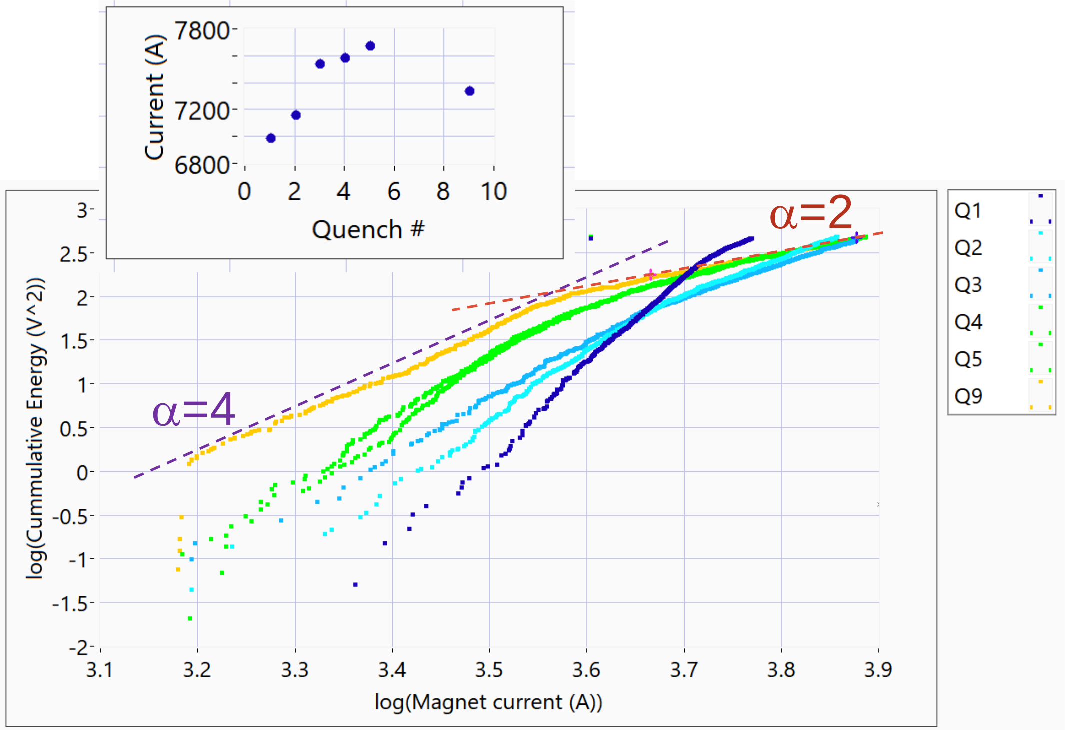
$E \sim I^{\alpha}$



One would want training to be completed here!

1st

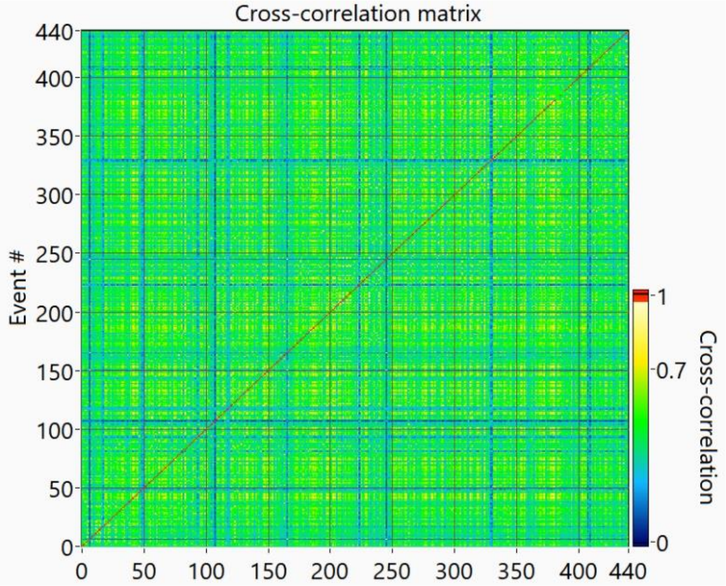
TC



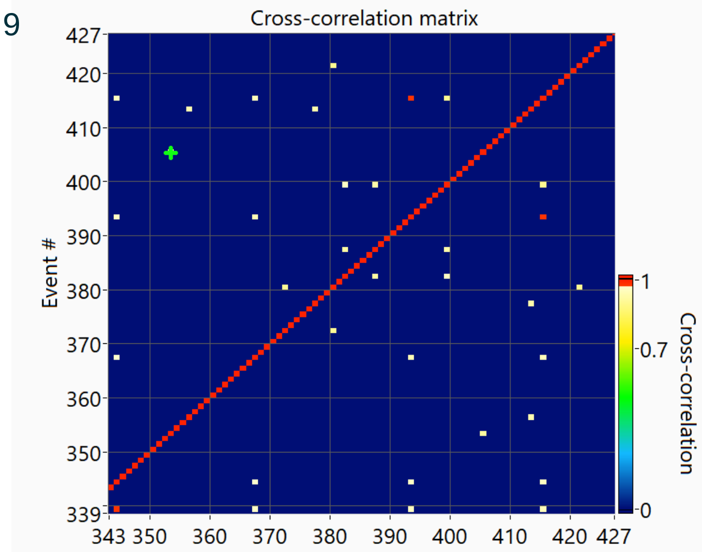
- ➢ In the first training cycle elastic energy is released proportionally to accumulation **(~ I^4)**
- ➢ Post thermal cycle, ~I^4 release rate is recovered over the first couple quenches, then transitions to ~ I^2 scaling

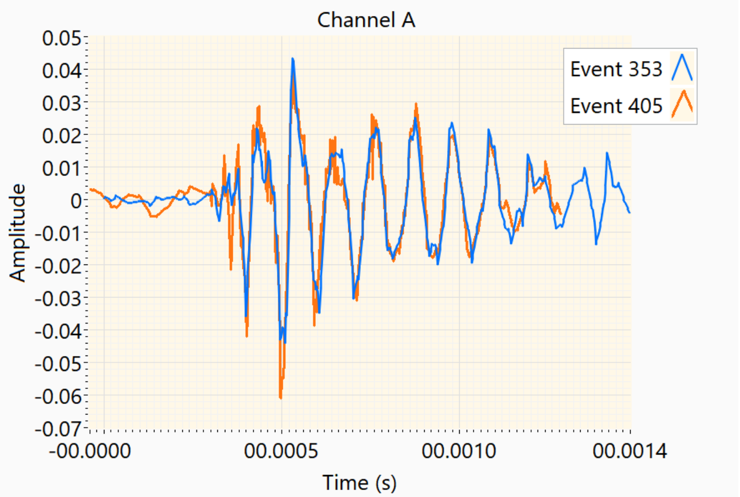
Cracking -> slip-stick?

Cross-correlation of AE events in a current ramp

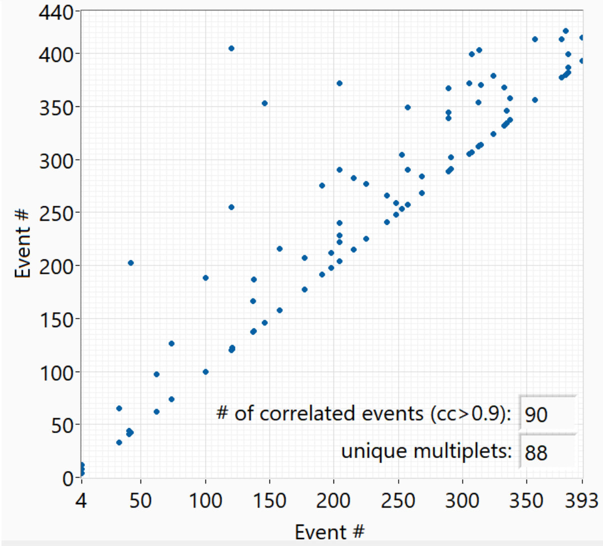


$A_{ij} > 0.9$



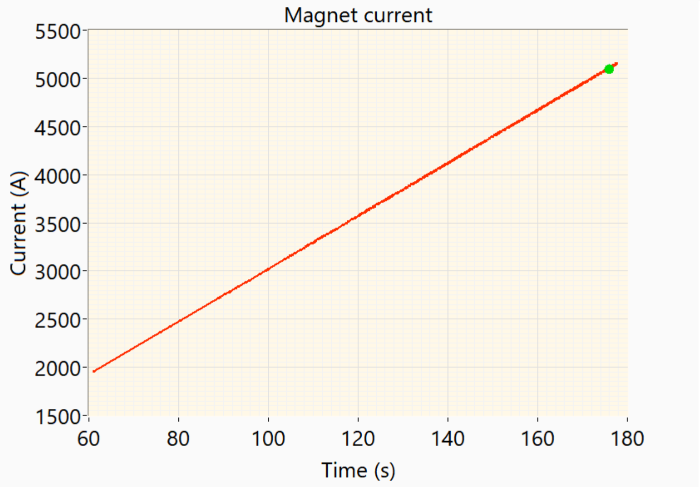


$$A_{ij} = \max_{\tau}\left\{\frac{\int U_i(t)U_j(t-\tau)dt}{\left\{\int U_i(t)U_i(t-\tau)dt\right\}^{1/2}\left\{\int U_j(t)U_j(t-\tau)dt\right\}^{1/2}}\right\}$$



\# of correlated events (cc>0.9): 90

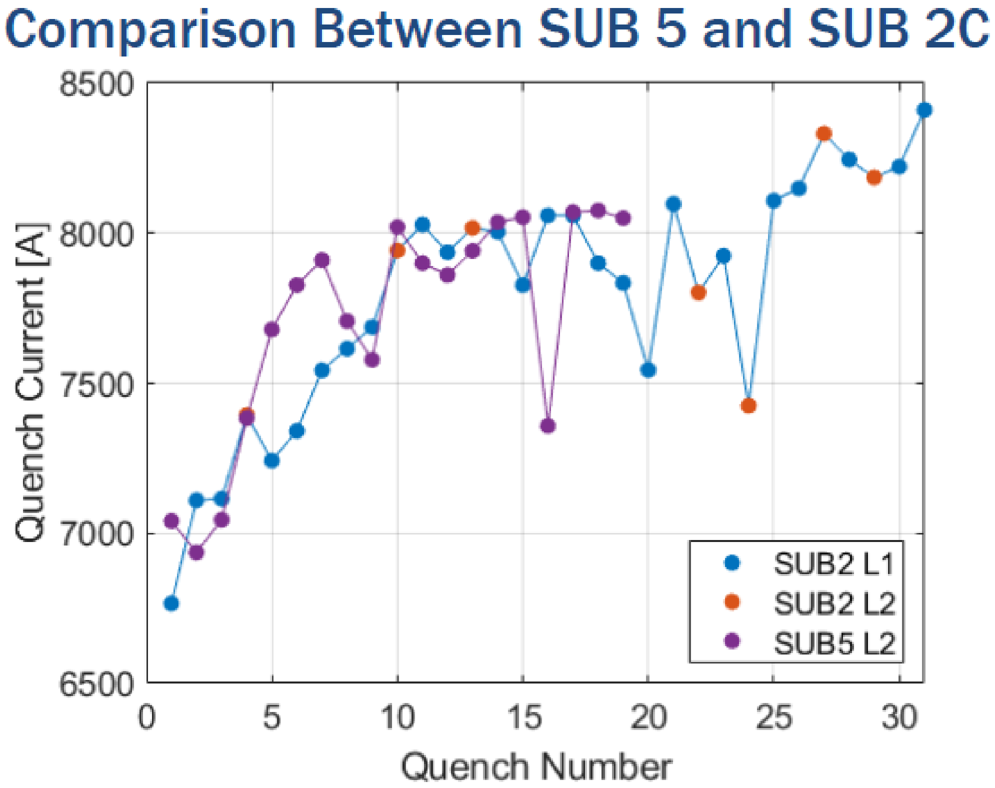
unique multiplets: 88



Magnet is "playing" some highly reproduceable AEs, suggesting they are coming from same locations within the coil.

Wax-impregnated CCT coil

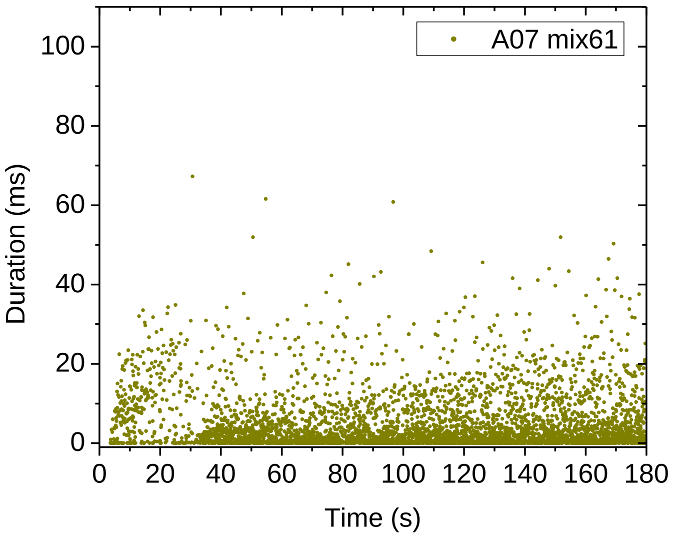
- Wax magnet inner layer was fabricated and assembled along with epoxy outer layer
- Zero training quenches occurred in the wax inner layer
- Training of magnet behaves similar to the SUB 2 after disassembly / reassembly but all training occurs in outer layer



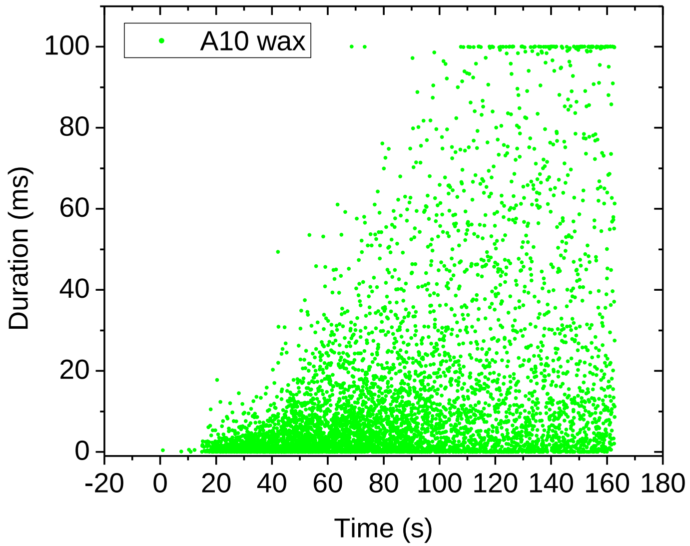
Diego Arbelaez et al.

AE event duration and amplitudes (mix 61 vs wax)

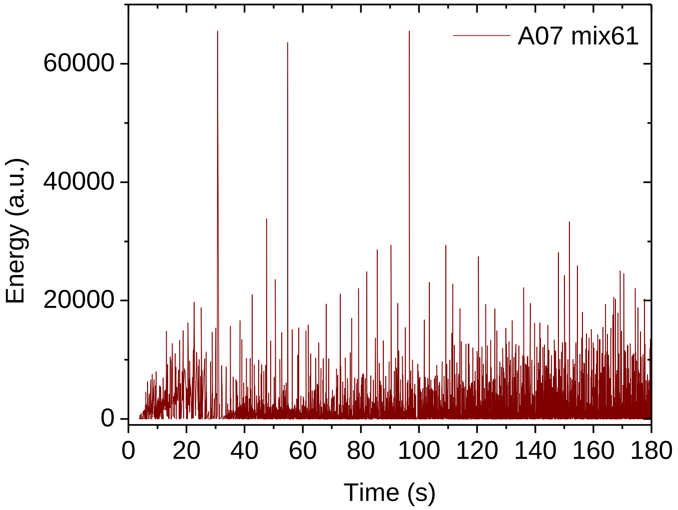
Mix61 (sub2)

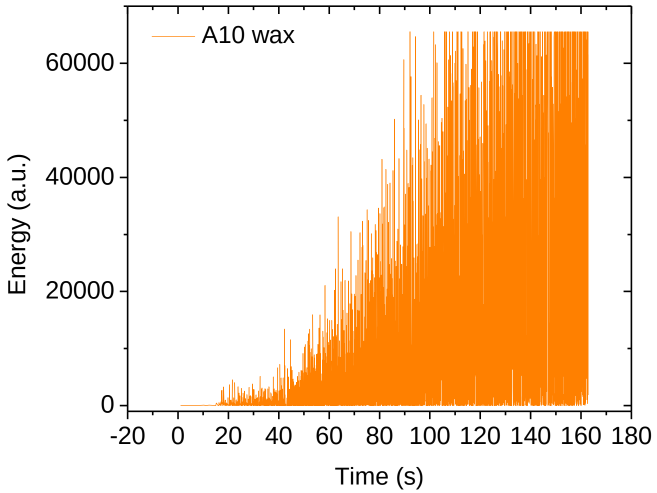


Wax (sub5)



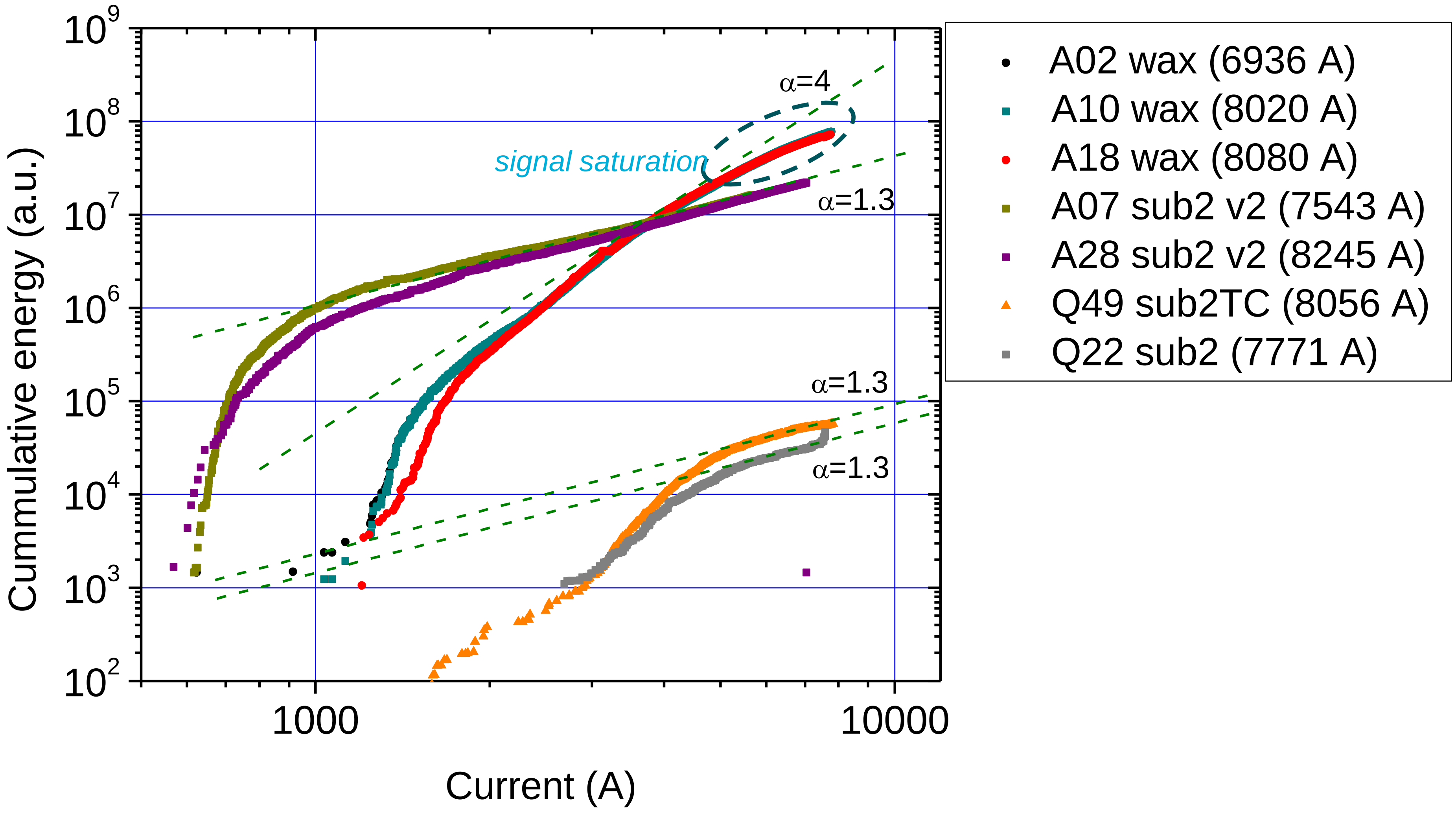
AE events are very long





Very noisy!

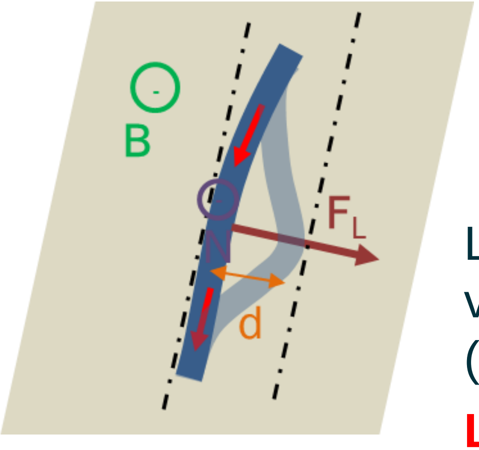
Cumulative energy release in the wax-impregnated CCT



Wax impregnation – what is special about it?

Wax-impregnated magnet appears to release elastic energy at the same rate as it is being accumulated.
Energy releases are not quenching the coil…. even so AE amplitude seems higher than in case of mix61 epoxy.

Work done on the conductor moving over **d** under Lorenz force: $A = (\mathbf{I} \times \mathbf{B})\,\mathbf{d}$



$$A = \mu N\, d + E_{AE}$$

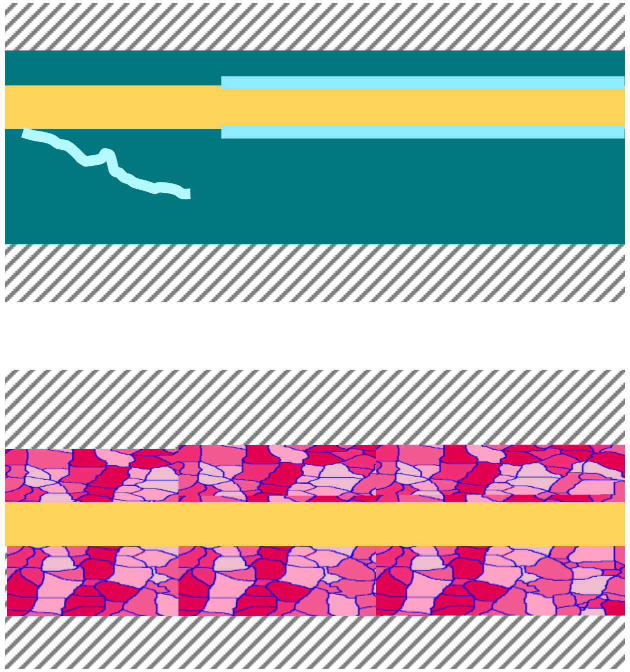
Lattice vibrations (heat)

LOCAL

Structural vibrations, AE

NON-LOCAL

For a given A, larger AE energy release means less conductor heating



Wax shrinks when cooled and becomes a powder-like substance, This creates multiple interfaces **distributed along the bulk of the granular impregnation material.** Heat is being dissipated at these interfaces over entire bulk of that impregnation material.

Summary

- AE energy release in CCT sub-scales exhibit characteristic scaling pointing to a change in the physical mechanism responsible for energy dissipation, as training progresses

- Both epoxy and wax-impregnated magnet emit AE “multiplets” - markers of highly concentrated and repeatable energy release points (strass concentrators)

- Density and distribution of the multiplets evolve with training, allowing for the first time to quantify how similar or different the micro-mechanical states of the magnet are across the training process

- A wax impregnated magnet seems to release elastic energy at a rate is being accumulated and a much more significant fraction of it is being converted into structural vibrations rather than heat