U.S. MAGNET DEVELOPMENT PROGRAM

Novel Diagnostics Roadmap

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US Magnet Development Program

Lawrence Berkeley National Laboratory

Topics to address with diagnostics in connection with MDP goals

US Magnet Development Program (MDP) Goals:

GOAL 1:

Explore the performance limits of Nb_3Sn accelerator magnets with a focus on minimizing the required operating margin and significantly reducing or eliminating training.

GOAL 2:

Develop and demonstrate an HTS accelerator magnet with a self-field of 5 T or greater compatible with operation in a hybrid LTS/HTS magnet for fields beyond 16 T.

GOAL 3:

Investigate fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction.

GOAL 4:

Pursue Nb_3Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets.

- **Performance limits:** quench and quench precursors locations in high-field Nb_3Sn dipoles (15 T and CCT)
- **Training mechanisms:** micro-mechanics, mechanical memory, event classifications
- **HTS degradation and quench origins:** localization of hot spots in HTS magnets

Technical objectives
(MDP 2020 Collaboration Meeting planning)

1. Resolving magnet **disturbance spectra** and understanding **mechanical memory mechanisms**
   - Acoustic emission
   - Distributed heater arrays
2. Conduct spot heater studies to **improve voltage-based diagnostics** and address "silent" quenches

3 .Characterize training-like behavior in different impregnation materials under load using a Transverse Pressure Insert (TPI) measurement system

3. Mitigating **magnet training** by remote probing and manipulation of weak interfaces and cracks
   - Time-reversal acoustics

Training

4. Developing **robust quench detection and localization**
   - Standalone active acoustic QD
   - Multi-element and flexible quench antennas
   - Linear quench localization sensors
   - "Change in impedance" method

Quench
+

5. Fiber-optic based instrumentation for distributed mapping of strain variations during training and quench
6. New diagnostics to probe **stress-driven degradation** in ReBCO-based high-field HTS magnets
7. Understanding **current sharing and stability margins** in HTS coils and cables

HTS

8. Novel **non-rotating probes for magnetic measurements**
9. Cryogenic electronics, FPGAs and quantum sensors

Enabling technology

Technology roadmap

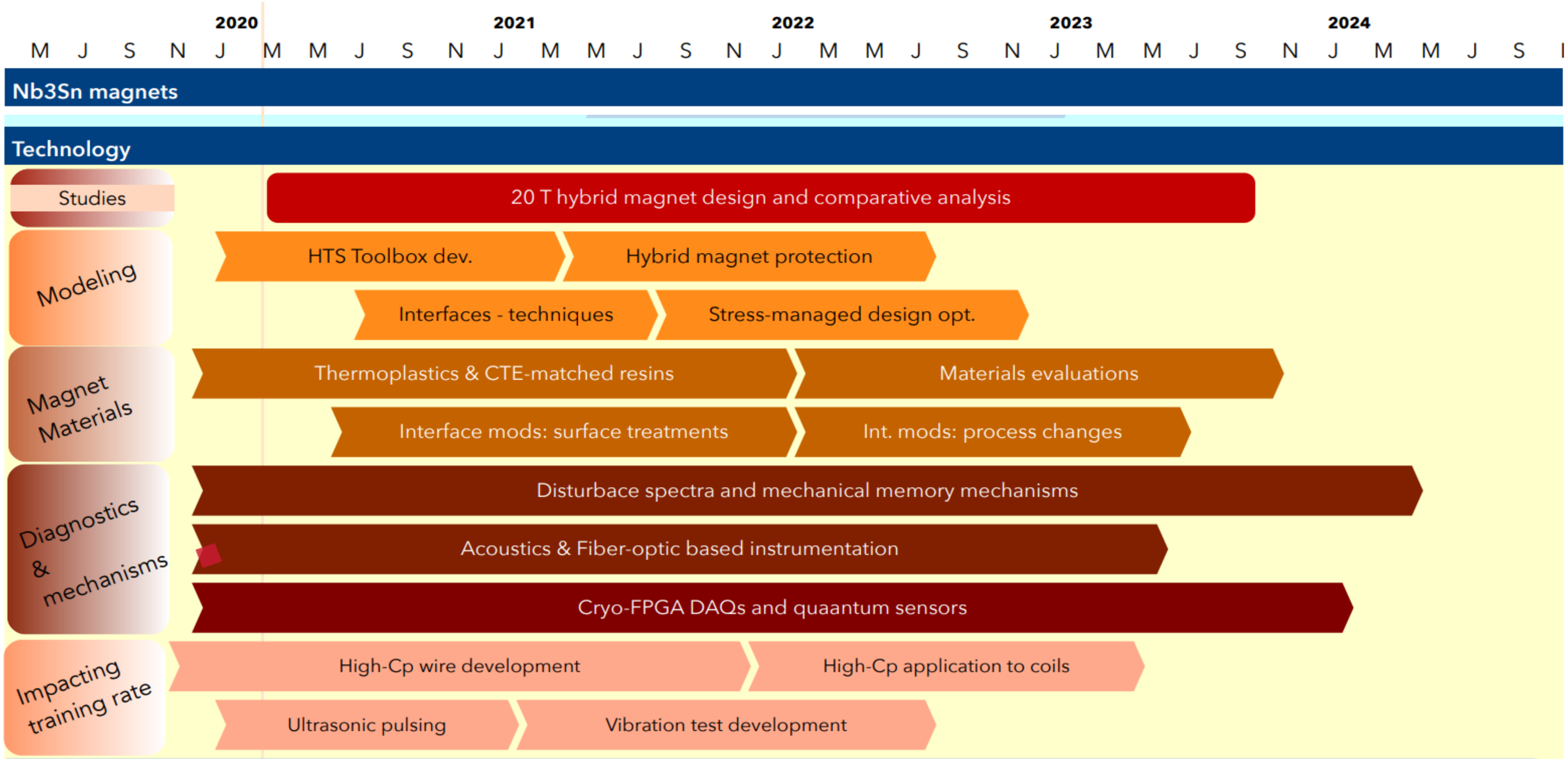

Figure 9. The updated roadmaps for the major elements of the program, including Nb_3Sn Magnets, HTS (Bi-2212 and REBCO) Magnets, and the various Technology areas. The $N_{b3}Sn$ magnet designs will focus on stress-managed structures, motivated by the need to intercept forces in magnets at high field and with large bores compatible with hybrid (HTS/LTS) configurations.

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Diagnostics milestone table

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Milestone #	Description	Target
AIIId-M1	Development of a new generation of self-calibrating acoustic emission diagnostics hardware	December 2020
AIIId-M2	Finalizing software algorithms for acoustic data analysis, completing analysis for the CCTs and 15T dipole	December 2020
AIIId-M3	Development and test of a linear quench localization sensor on a Bi-2212 subscale and/or ReBCO CCT series	March 2021
AIIId-M4	Test of a large-scale Hall array and imaging current distribution in HTS tape stacks and coils	May 2021
AIIId-M5	Completing spot heater studies to improve voltage-based diagnostics and address “silent” quenches	July 2021
AIIId-M6	Demonstration of inverse acoustics-based probing of interfaces in a dedicated small-scale coil	September 2021
AIIId-M7	Development of multi-element and flexible quench antennas and localization of quenches in using flexible quench antenna arrays	September 2021
AIIId-M8	Characterization of training-like behavior in different impregnation materials under load using a Transverse Pressure Insert (TPI) measurement system	December 2021
AIIId-M9	Development and test of a standalone acoustic quench detection and localization FPGA-based system	December 2021
AIIId-M10	Development and test of a non-rotating new magnetic probe prototype	December 2021
AIIId-M11	Demonstration of a programmable fully-cryogenic FPGA “smart” sensor core with digital readout and analog front-end (SQUID) amplifiers	December 2021
AIIId-M12	Calibration of FBG fibers in a small cryostat. Installation on an MDP magnet and strain measurement during a quench. Design a proof of principle experiment for quench 3D spatial detection and coil azimuthal strain mapping and install fiber on MDP magnet. Use fibers for energy spectrum analysis and HTS quench detection.	December 2022

- **Next generation acoustic hardware (LBNL)**
- **Acoustic data analysis completed for 15 T (LBNL), CCT4 and subscale 2 – in progress (LBNL). New ML algorithms for quench precursors (FNAL)**
- **In progress, new developments (LBNL)**
- **Hall array hardware built, tested on CORC (LBNL)**
- Talks in progress at FNAL for implementing these studies
- TBD (LBNL)
- **MQXFA QA built and delivered, warm bore tube QA structures are ready as well (FNAL). CCT subscale antennas (LBNL)**
- New tests with matrimid and organic resins mixed with high-Cp ceramics are planned at FNAL
- **Non-FPGA portion was built and tested (LBNL, BNL). Upgrade to FPGA TBD towards the target date**
- TBD (LBNL, FNAL) – likely early 2022
- **New DAQ boards, performance characterized for various cryo-parts. One channel cryo-system to be tested by the end of 2021 (LBNL)**
- **Progress with early tests. Modifications to vertical test facility to integrate fibers. (FNAL, BNL)**

Diagnostics publications of 2020-21

- *"Stray-Capacitance as a Simple Tool for Monitoring and Locating Heat Generation Demonstrated in Three HTS Magnets"*, D. Davis, T. Shen, M. Marchevsky, and E. Ravaioli, Supercond. Sci. Technol., submitted
- *"Design and Evaluation of Deep Cryogenic Hybrid and Digital Circuits Based on Field Programmable Gate Arrays"*, M. Turqueti, M. Marchevsky, A. Marchenkov, R. Maydra and A. Tselikov., 2021 IEEE 14th Workshop on Low Temperature Electronics (WOLTE) (accepted, April 2021)
- *"Quench detection using Hall sensors in high-temperature superconducting CORC®-based cable-in-conduit-conductors for fusion applications"*, D. Weiss et al., 2020 *Supercond. Sci. Technol.* **33** 105011
- ''CORC® cable terminations with integrated Hall arrays for quench detection", 2020 *Supercond. Sci. Technol.* **33** 095009
- *"Intelliquench: Real-time detection of magnet quenches"*, D. Hoang, C. Boffo, N. Tran, S. Krave, S. Kazi, S. Stoynev, and V. Marinozzi., IEEE Trans. Appl. Supercond., submitted
- *"Using an autoencoder to study events during superconducting magnet training".* L. Stephey , M. Mustafa and M. Marchevsky, poster presentation at the ai4science Workshop, Amsterdam, July 2020
- "*Structural diagnostics of superconducting magnets using diffuse field ultrasound*", M. Marchevsky, D. Arbelaez and S. Prestemon., *IEEE Trans. Appl. Supercond*., 10.1109/TASC.2020.2981299 (2020)
- "Nanometer-Scale Deformations of Berea Sandstone Under Moisture-Content Variations", E. Ilin, M. Marchevsky, I. Burkova, M. Pak, and A. Bezryadin, *Phys. Rev. Applied* 13, 024043 (2020)
- "Nanoscale detection of metastable states in porous and granular media", E. Ilin, Y. Li, E. V. Colla, K. T. Christensen, M. Sahimi, M. Marchevsky, S. M. Frailey, and A. Bezryadin, *J. Appl. Phys*. 127, 024901 (2020); doi: 10.1063/1.5135321
- "A cable-scale experiment to explore new materials for optimizing superconductor accelerator magnets", C. J. Kovacs, E. Z. Barzi, D. Turrioni, A. V. Zlobin, M. Marchevsky, *Cryogenics* 106, 103025 (2020), https://doi.org/10.1016/j.cryogenics.2019.103025
- "A new quench detection method for HTS magnets: stray-capacitance change monitoring", E Ravaioli, D Davis, M. Marchevsky, G. Sabbi, T. Shen, A. Verweij and K Zhang, *Phys. Scr.* 95, 015002, (2020), https://doi.org/10.1088/1402-4896/ab4570

Acoustic diagnostics update

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A broad scope of acoustic diagnostic techniques and current milestones

Passive acoustics

- Spatially localizing mechanical transients and quench locations using time of flight techniques
- Measuring local energy release in those transients by relying on the known calibration methods
- Classifying various mechanical event using advanced spectral analysis techniques and deep learning

Active acoustics

- Accessing interfacial stability during magnet energization and training cycle
- Measuring real-time temperature variations in the bulk of the magnet
- Spatially localizing heat sources (under development)

Potential future use

- Focusing ultrasonic excitation into a particular target volume within the magnet winding using time-reversal principles and probe local non-elasticity (= dissipation) at a specified location
- Affecting magnet training behavior by enabling or facilitating local slip stick-motion with ultrasonic vibrations

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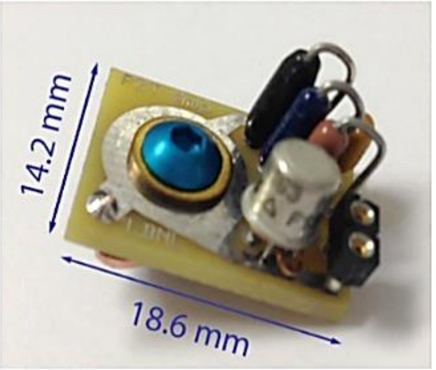
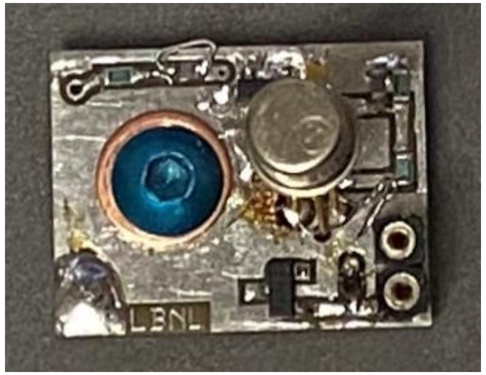
Cryogenic acoustic emission sensors

Generation 1 (2013)



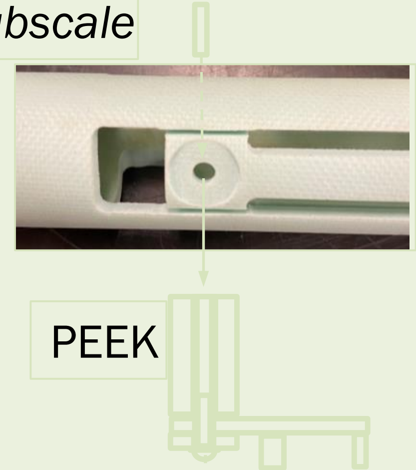


A robust "workhorse" sensor developed and used at LBL on most of our magnets. It is now also used by FNAL for the 15 T dipole, and by other labs (BNL/AUP, CERN) and projects (GE, ACT, CFS).

A self-calibrating version that can be pulsed externally was built in 2020.

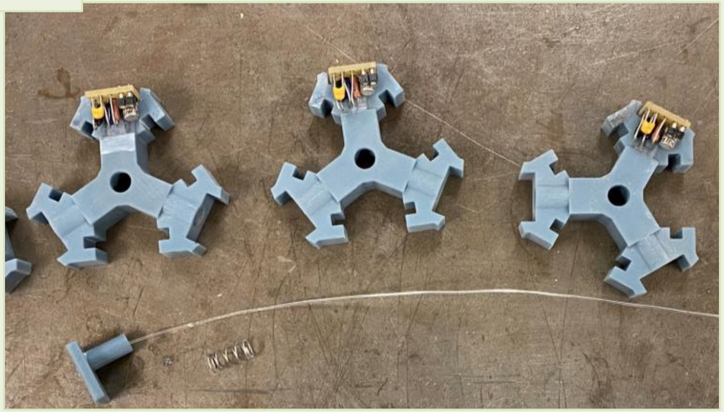
- Bandwidth is < 300 kHz
- 2-3 mV rms of noise
- **Uses an obsolete part**
- **Somewhat bulky for cable or subscale tests**

CCT subscale



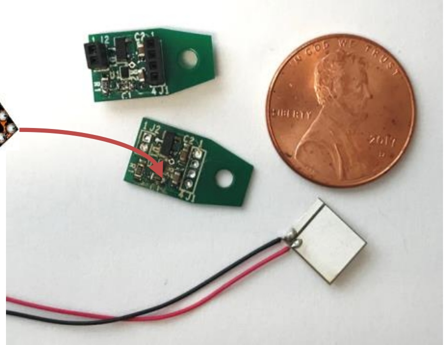
PEEK

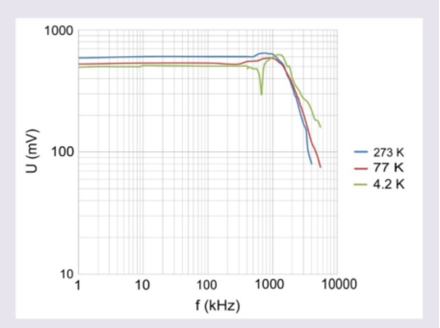
PSI



R. Teyber, M. Maruszewski

Generation 2 (2018)





- Needs one extra wire for powering
- **More installation work**
- **Requires additional in-line resistors to power up cold below 15K**

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Acoustic waveguide concept

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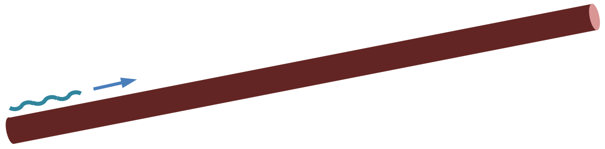
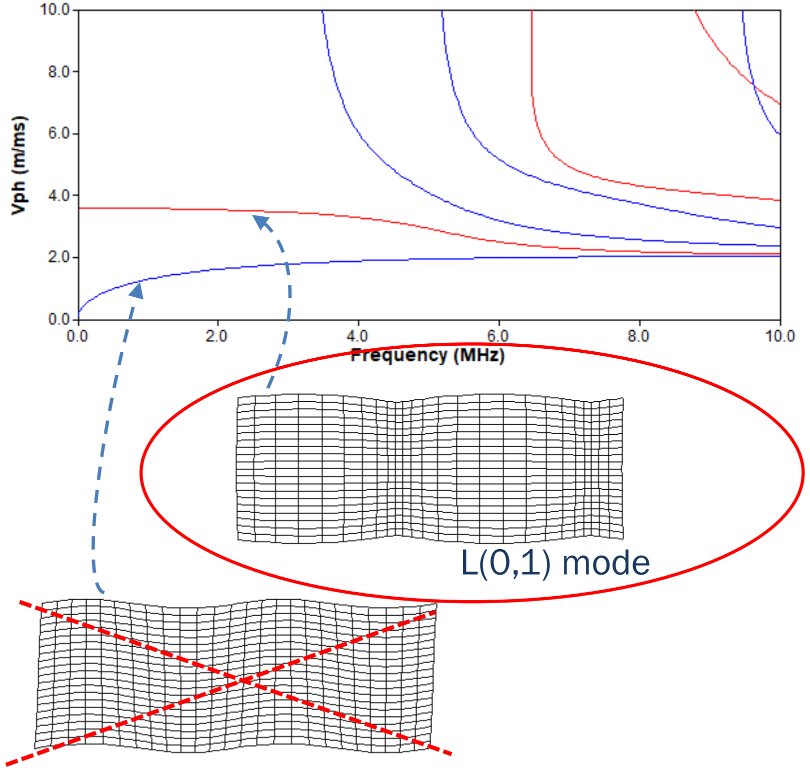
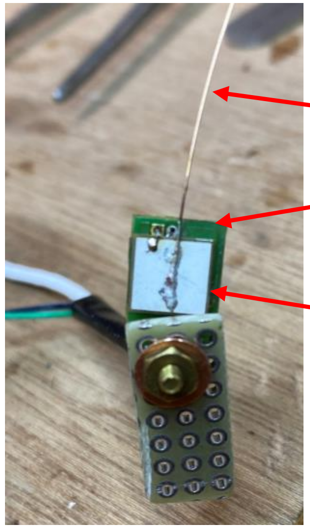


Dispersion plot for traveling acoustic waves in a 0.4 mm diam. brass rod



F(1,1) mode

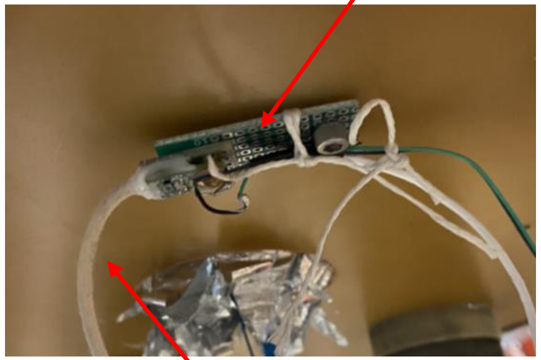


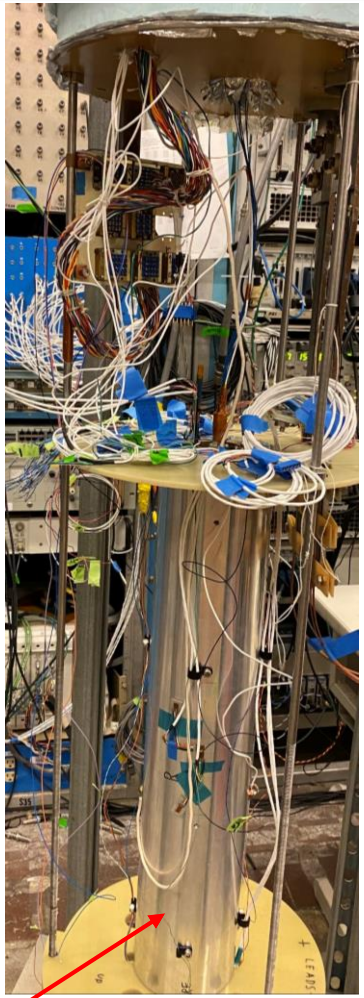
0.009” wire (waveguide)

Gen 2 sensor

Piezo-element

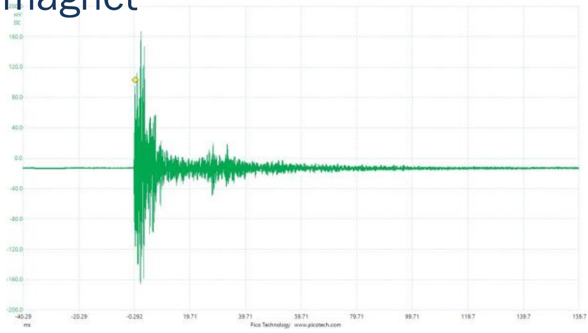
Board mounted on the cryostat header G10 plate



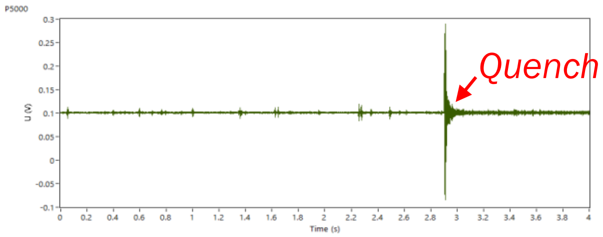


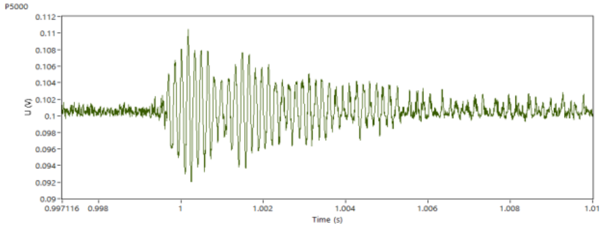
Waveguide wire in a sleeve

4.2 K tests, liquid helium level at ~5” above the top of the magnet



Tapping with a metal tool on the cryostat



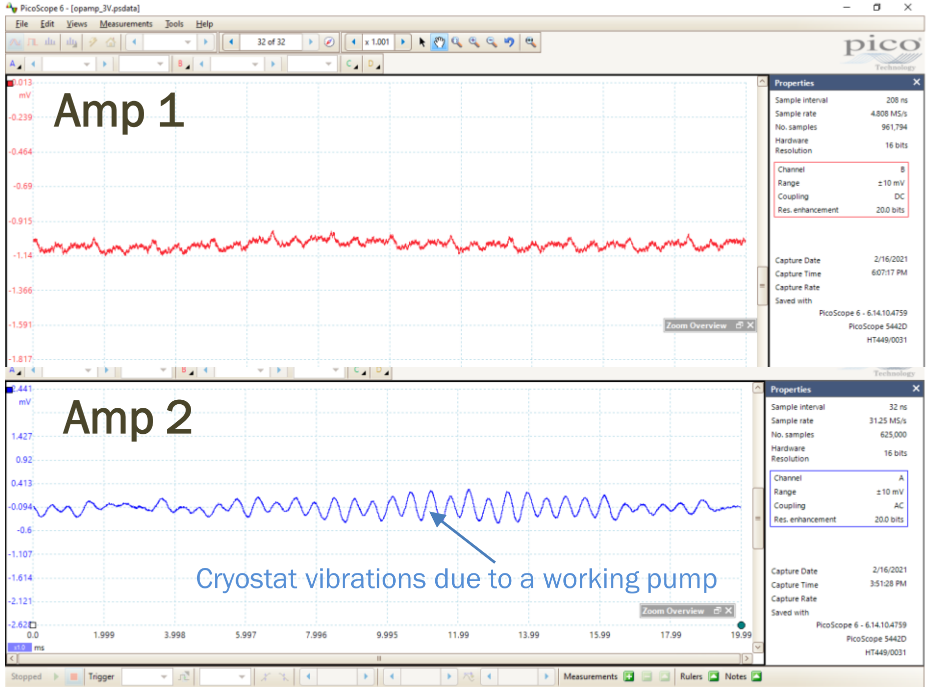


AEs during ramping to a quench

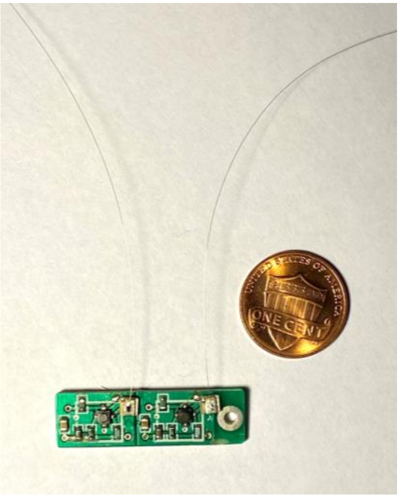
“Acoustic taps”

New cryogenic amplifiers been developed and tested at 4.5 K:

- Extremely low noise (< 1 nV/$\sqrt{Hz}$ at 1 MHz), uniform performance 300 K-> 4.2 K
- Ultra wide bandwidth, limited by the piezo-transducer Single-ended and differential amplification possible
- 50 Ohm output

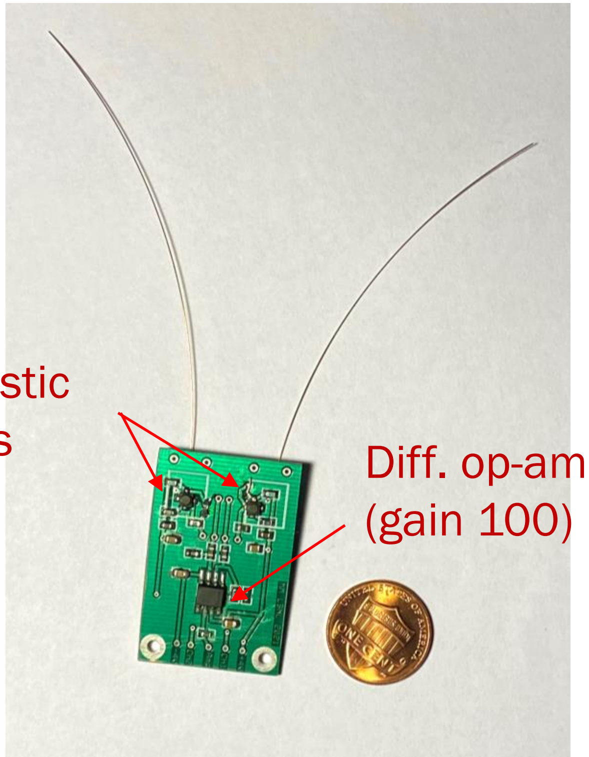


Waveguide acoustic sensors



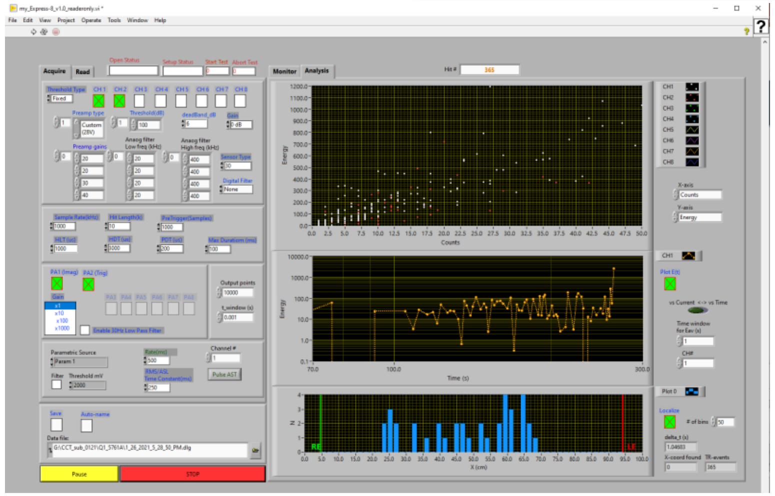
- Installation and test with CCT Subscale 3 is imminent

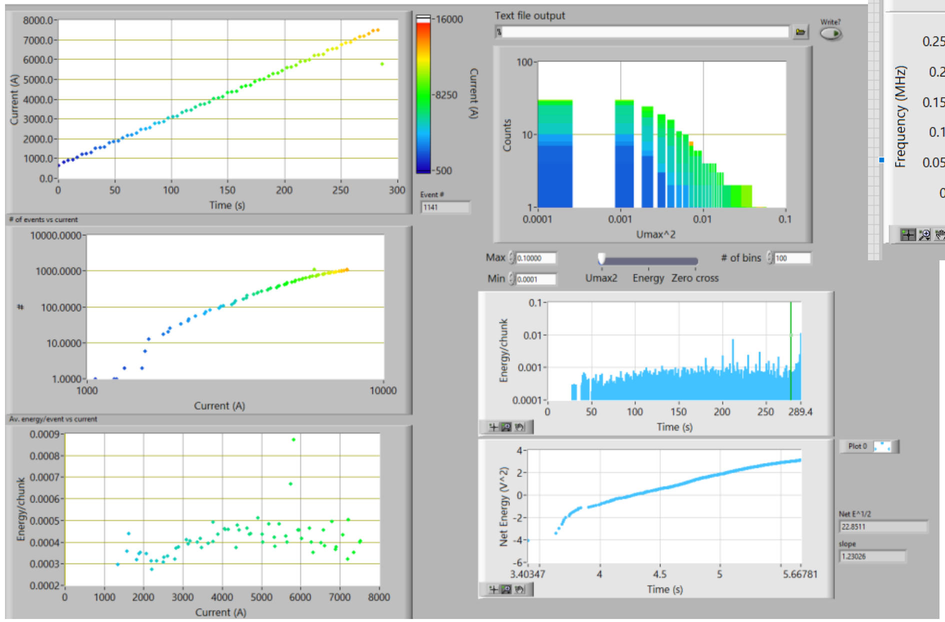
“Universal tap” board

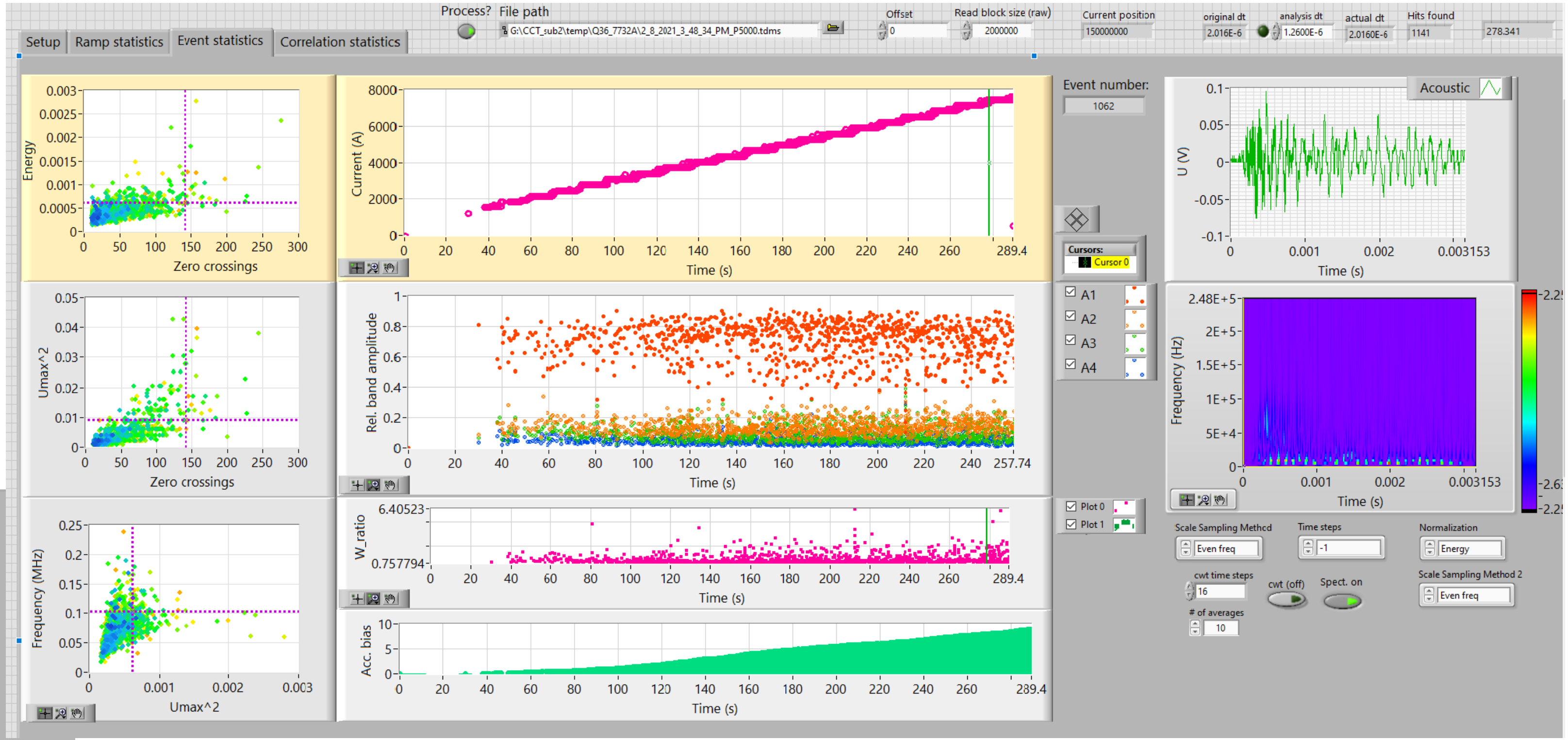


- Simultaneous measurement of differential voltages and acoustic emissions can be achieved with a single pair of taps.

Analysis software is instrumental for providing a quick feedback on the test data







- Separation of individual acoustic events from a continuous data stream
- Precise calculation of time of arrival calculation
- Triangulation of acoustic emission sources
- Energy release analysis
- Wavelet-based frequency analysis
- Statistical analysis and scaling
- Machine learning-based analysis (PCA, Random Forest, Tsne)
- DL network-based event classification (TensorFlow)

We are now able to provide a full analysis of a quench within minutes, not days

Acoustic event count provides insight into the physics of training

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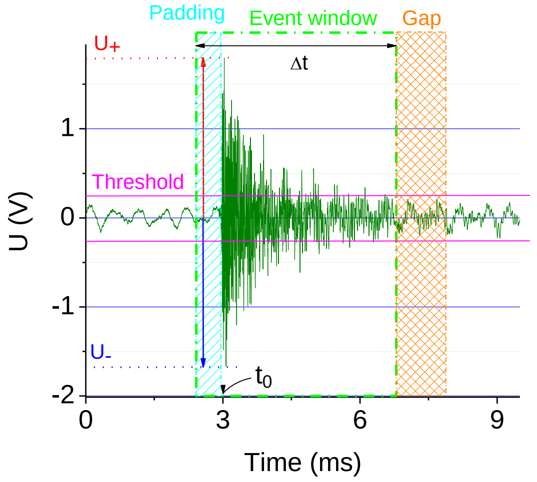
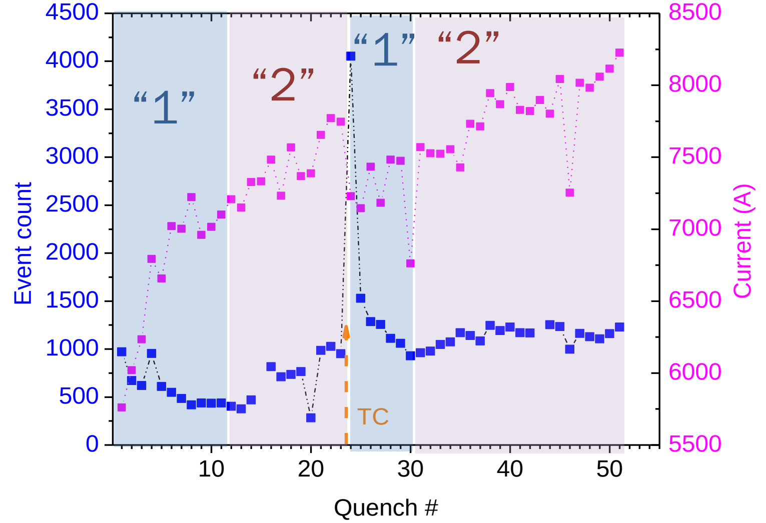
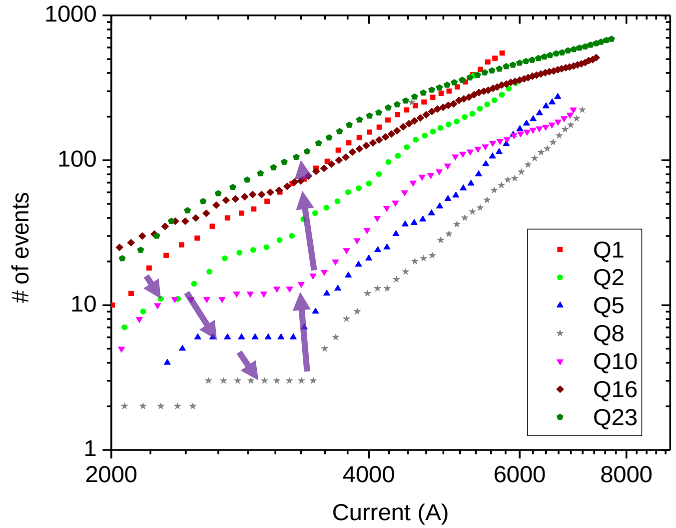


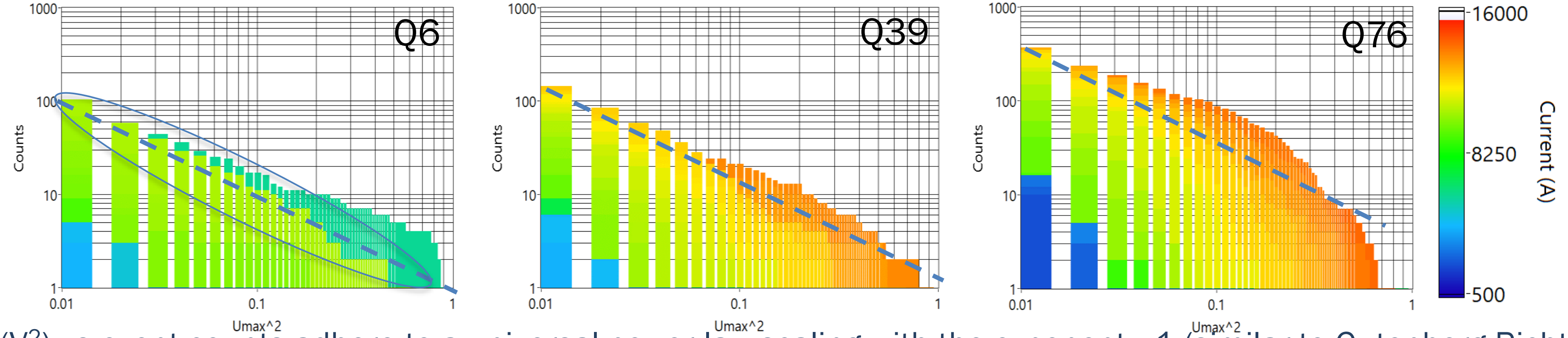
CCT Subscale 2





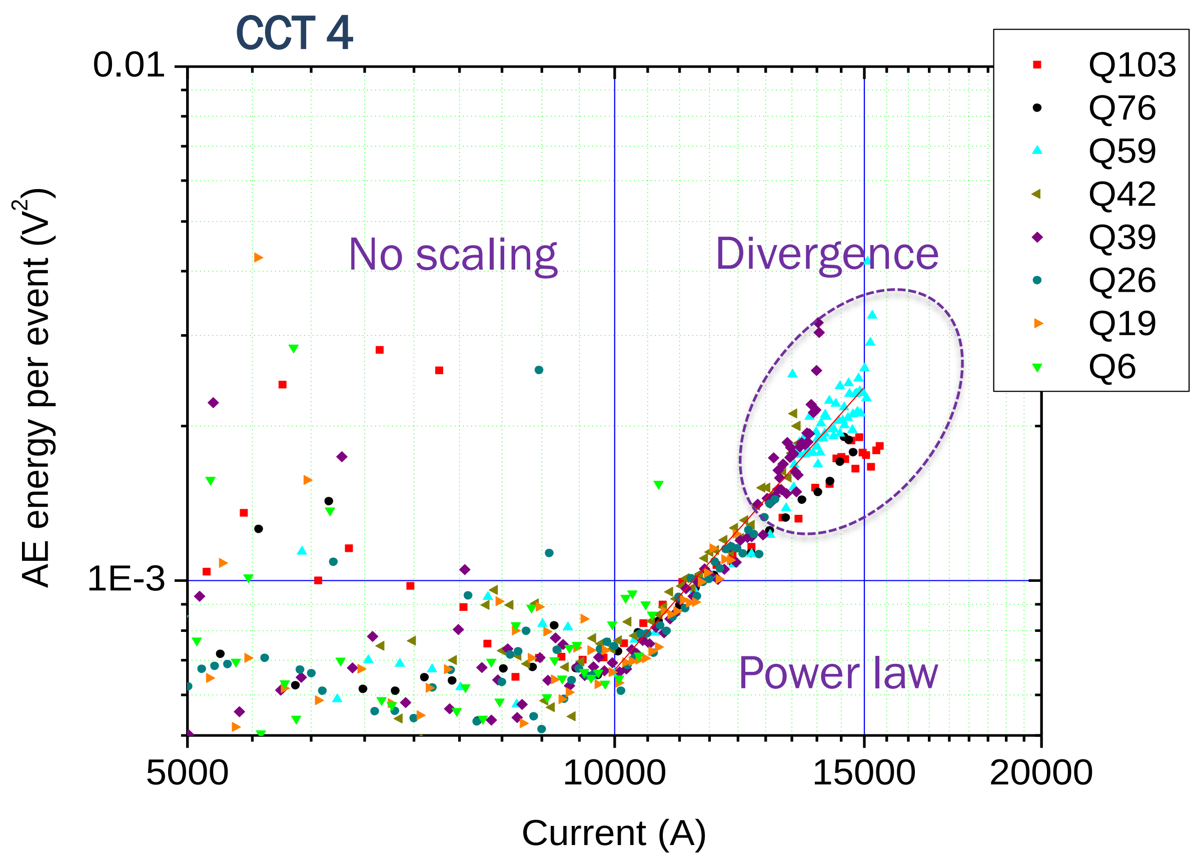
Two different training regimes can be identified in CCT Sub 2

CCT 4



Peak energy (V^2) vs event counts adhere to a universal power law scaling with the exponent ~1 (similar to Gutenberg-Richter law). However, the distribution varies in the course of training.

Power-law scaling emerges as a universal feature of magnet training mechanics



- Power–law scaling is a hallmark of critical phenomena seen in many physical systems including superconductors, magnetics, geoscience, etc.
- This result suggests that critical dynamics emerges in the magnet at a certain stress level, and is sustained throughout the current ramp until the quench.
- A step divergence from the power-law develops a few seconds prior the quench for some ramps. Potentially this can be considered as a "quench precursor".

"Analysis of Acoustic Emissions During Training of the Canted-Cosine-Theta Nb_3Sn Dipole CCT4",
M. Marchevsky, D. Arbelaez and S. Prestemon, ASC 2020

Progress in identifying quench precursors

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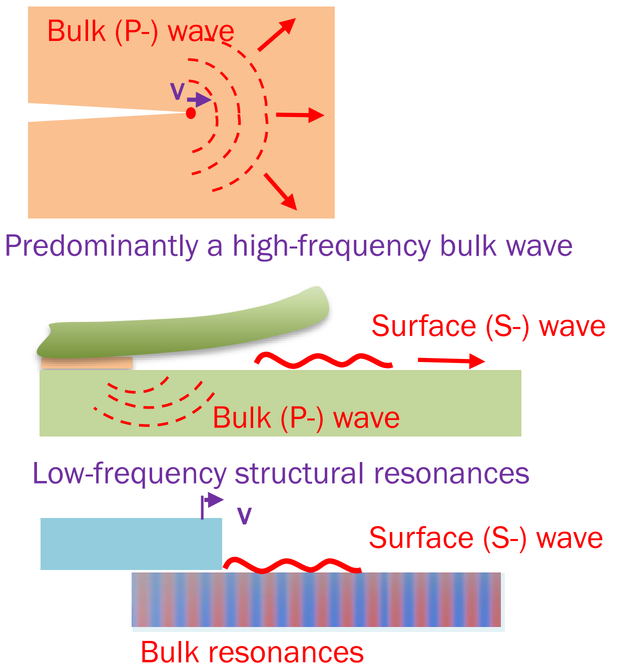
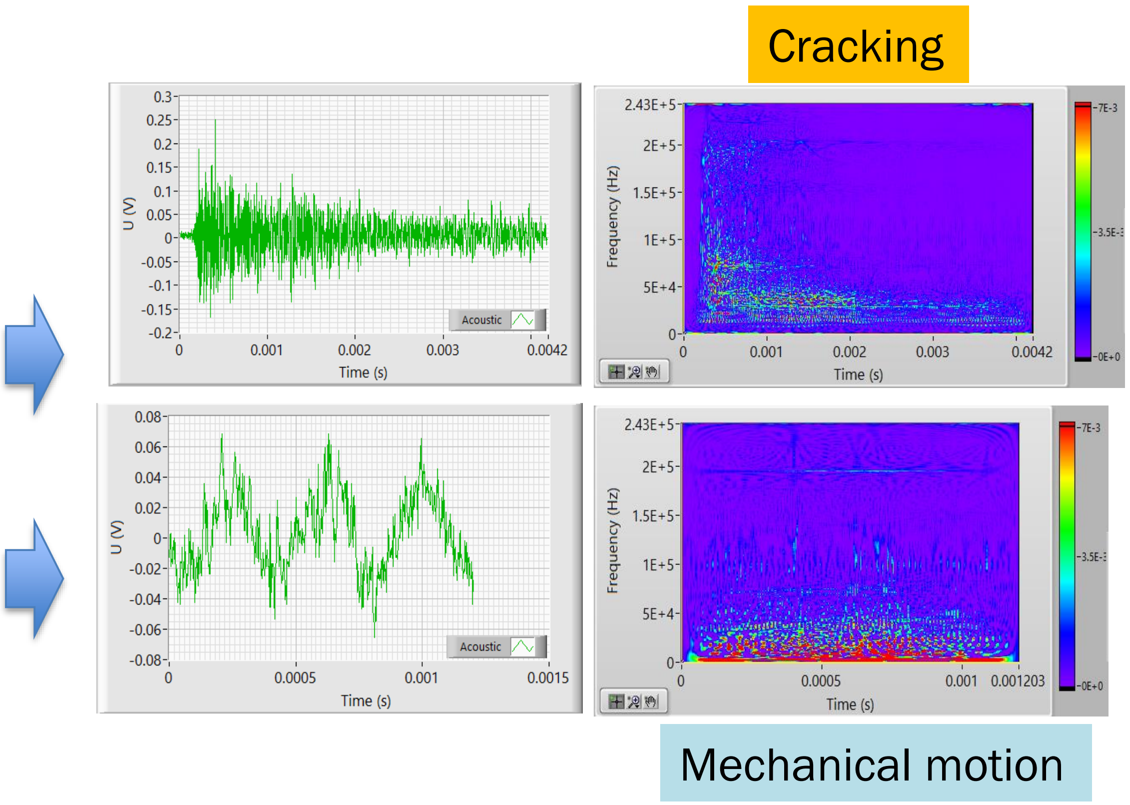
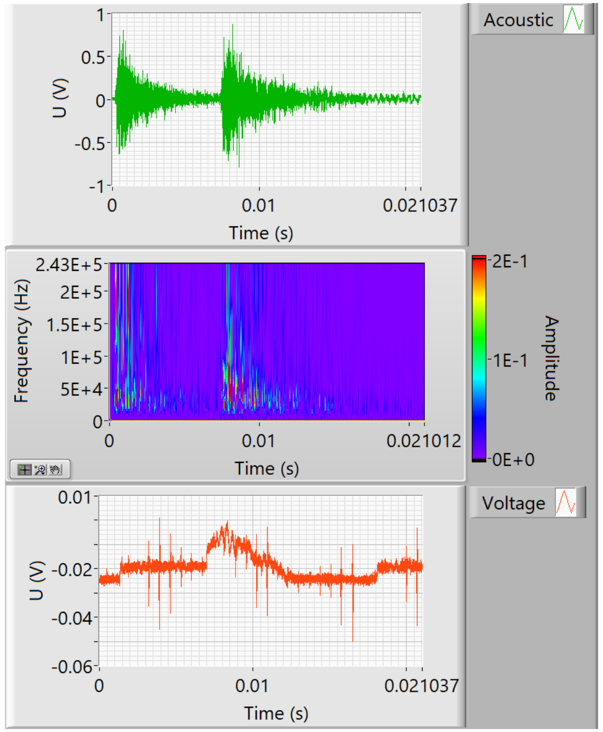


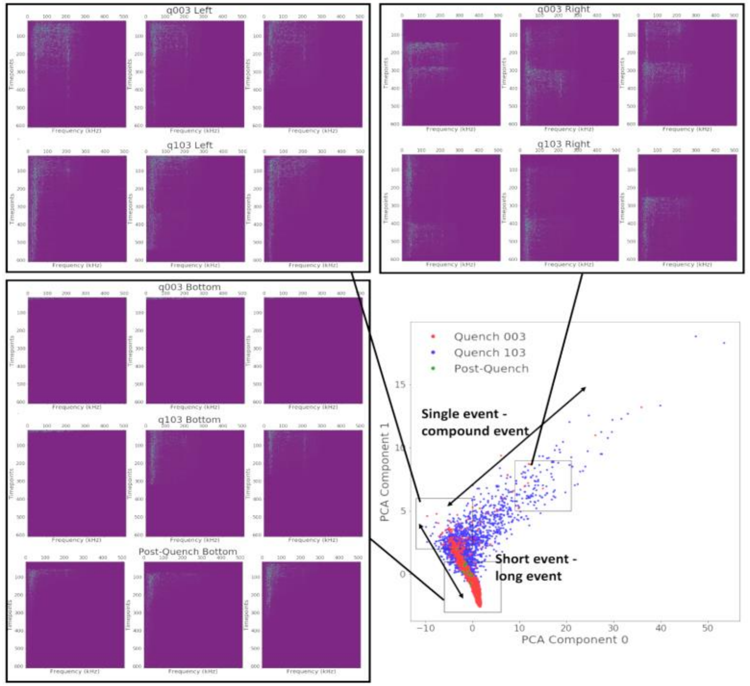


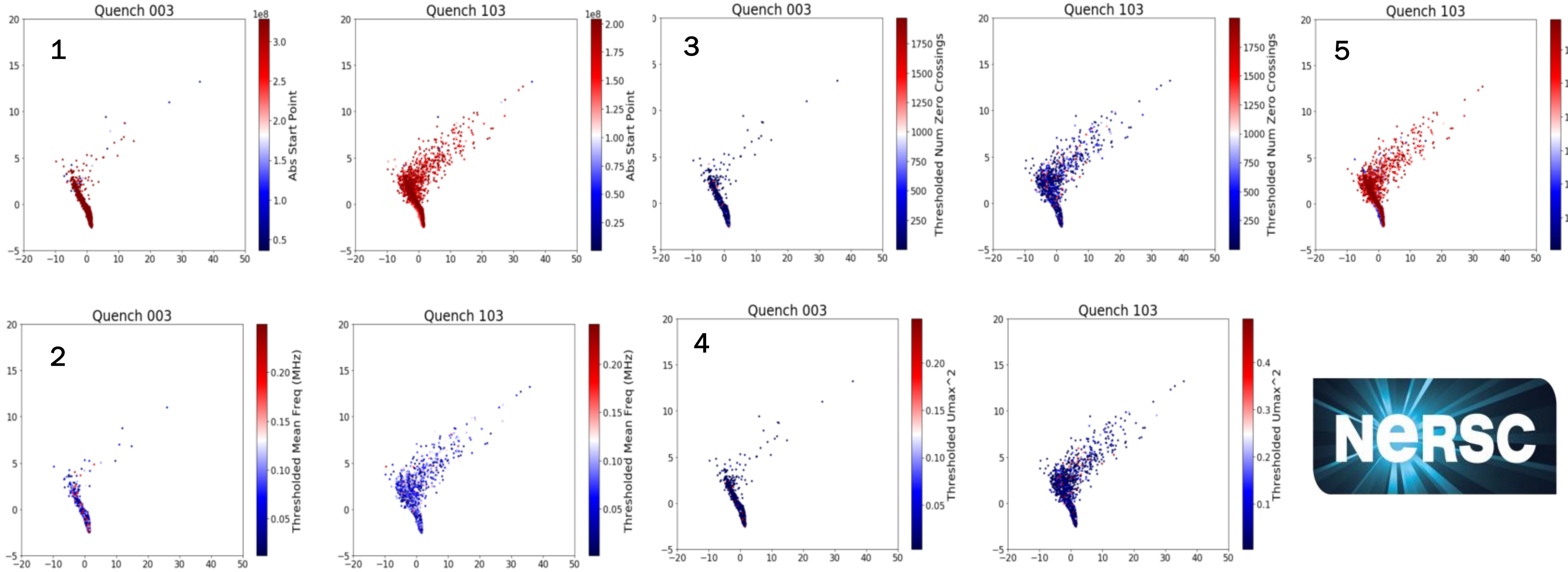


Frequency content of acoustic events can be efficiently extracted using SFFT and wavelet-based scalograms. In some cases identification of the origin is rather obvious.

“Multiplet” acoustic emissions are coming in succession, likely from the same location in the magnet. Some of them are associated with small transient voltage rise.

ML-based analysis of CCT4 quenches





L. Stephey. M. Mustafa (NERSC)

- Examining data from early training quench (q003), late training quench (q103), and post-quench (pq)
- Use autoencoder to look for clusters in the data
- Used 14 layer autoencoder (symmetrical 7 layer encoder + 7 layer decoder)
- Encoded 8-dimensional latent space
- Used binary cross-entropy loss
- Notebooks and analysis at https://github.com/lastephey/magnet-notebooks/tree/master/conv2d-autoencoder

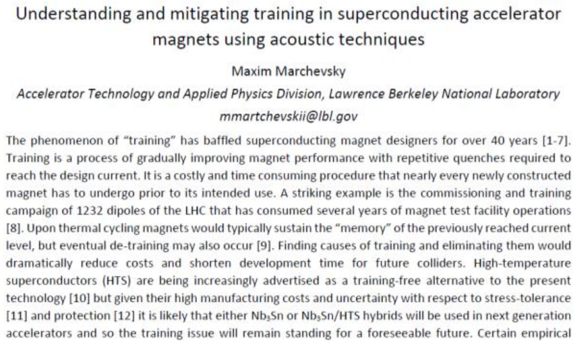
- ➢ **The early quench (q003) included both short and long events but few compound events**
- ➢ **The late quench (q103) included long, short, and a greater number of compound events**
- ➢ Based on results from additional processing for q003 and q103:
- ➢ Events late in training concentrated in the single event region
- ➢ High frequency events appeared in all regions
- ➢ Events with many zero crossings appeared in the longer, compound event region
- ➢ Events with higher energy (Umax^2) appeared at left side of PCA space
- ➢ **Events at high current (near end of training quench) lie in short, single events**

Poster presented at ai4science Workshop, Amsterdam, July 2020

Future work

- Implementation of the new generation acoustic hardware and integrating acoustic data collection with data from other sources (quench antennas, strain gauges, etc…).
- Studying quench precursors in scaling and frequency analysis and understanding their physical meaning and connection to the magnet training
- Quantitatively connecting strain accumulated in a magnet with energy release via acoustic emission
- Exploring latest machine learning techniques for time-driven data for resolving disturbance spectra and quench precursors
- Exploring passive acoustic sensing for HTS

Understanding magnet training



Understanding and mitigating training in superconducting accelerator magnets using acoustic techniques

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The phenomenon of "training" has baffled superconducting magnet designers for over 40 years [1-7]. Training is a process of gradually improving magnet performance with repetitive quenches required to reach the design current. It is a costly and time consuming procedure that nearly every newly constructed magnet has to undergo prior to its intended use. A striking example is the commissioning and training campaign of 1232 dipoles of the LHC that has consumed several years of magnet test facility operations [8]. Upon thermal cycling magnets would typically sustain the "memory" of the previously reached current level, but eventual de-training may also occur [9]. Finding causes of training and eliminating them would dramatically reduce costs and shorten development time for future colliders. High-temperature superconductors (HTS) are being increasingly advertised as a training-free alternative to the present technology [10] but given their high manufacturing costs and uncertainty with respect to stress-tolerance [11] and protection [12] it is likely that either Nb_3Sn or Nb_3Sn/HTS hybrids will be used in next generation accelerators and so the training issue will remain standing for a foreseeable future. Certain empirical

https://www.snowmass21.org/docs/files/summaries/AF/SNOWMASS21-AF7_AF0_Marchevsky-114.pdf