U.S. MAGNET DEVELOPMENT PROGRAM

Quench detection and localization

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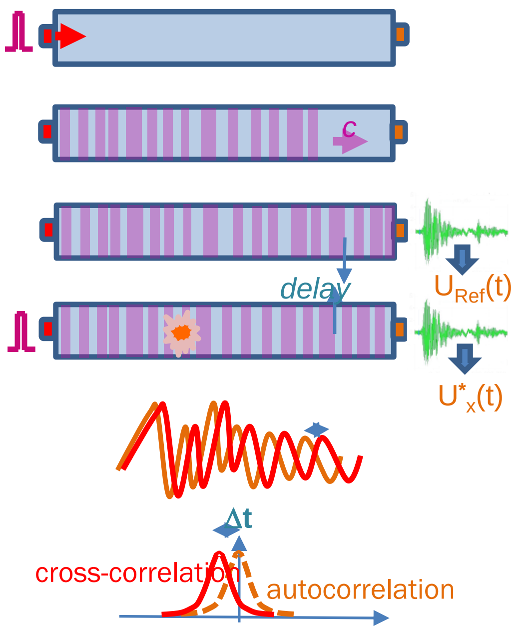
HTS quench detection challenge

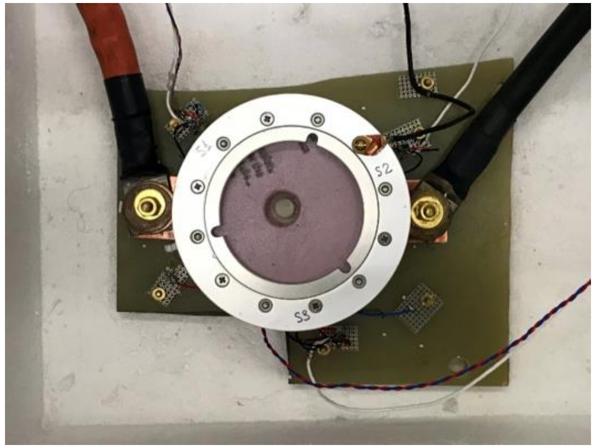
- Quench detection and localization of developing hot spots are still among most critical issues the HTS magnet technology is facing
- This problem increasingly being recognized also by the fusion community and a significant effort is diverted to a search for suitable technologies
- Non-voltage techniques in particular are actively explored to complement or replace voltage-based techniques
- None of the technologies known today can universally solve the QD problem in a way voltage taps solve it for LTS magnets. Most likely several QD technologies will be applied simultaneously and in complementary way in future HTS magnets

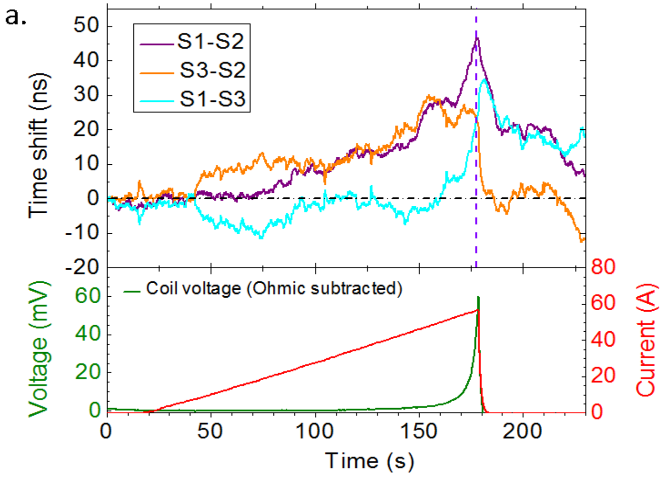
Active acoustic detection invented at LBL In 2016 has demonstrated equivalent sensitivity with the voltage detection



- STTR (ACT) - REBCO coil for US NAVY
- Sponsored project (CFS) – quench detection for fusion cable
- DOE Technology Commercialization Fund – localization of hot spots in power systems (CFS, BNL)
- ARPA-E BETHE – quench detection for CSMC (CFS)
- DOE FES Base program

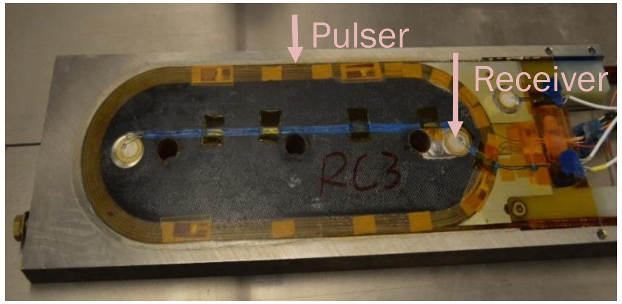
HTS coil in LN2





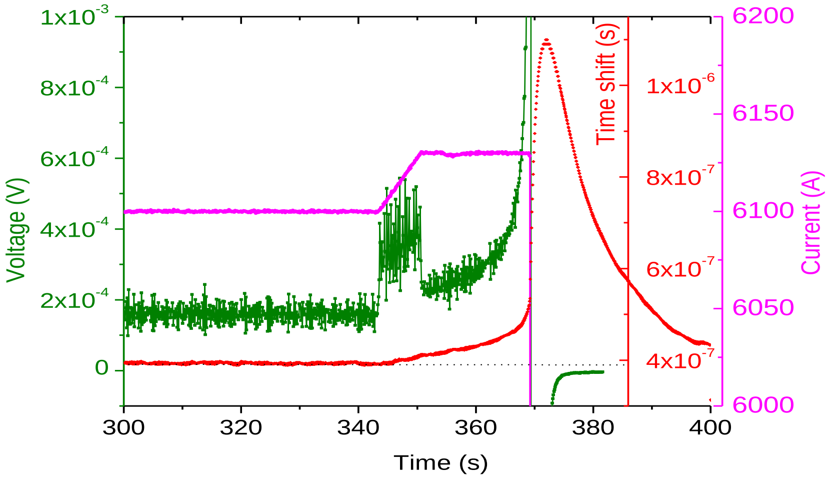
*STTR with ACT, completed March 2020

Bi-2212 coil RC3



Coil design and test by T Shen / K. Zhang

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



This is still the only example of applying this technique at 4.2 K

Localization of hot spots using diffuse ultrasound

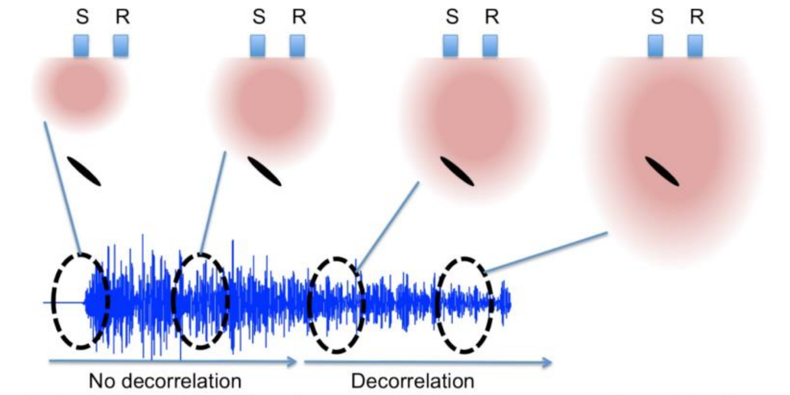
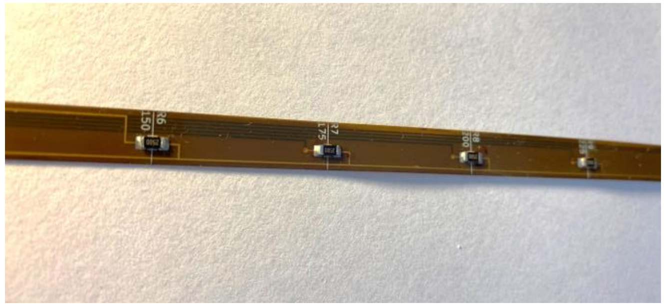


FIGURE 3. Schematic view of the spatio-temporal sensitivity of coda waves to a local change. The diffusive halo of ultrasound propagating in concrete is represented in pink (color on CD), which characteristic size is governed by the diffusion length $\sqrt{Dt}$, where D is the diffusion coefficient in concrete, and t the time in the coda. At early times in the coda (first two snapshot on the left), the waves propagating from the source S to the receiver R have hardly felt the change. Later on (two snapshots on the right), the waves have more possibly hit the defect and the coda is partially decorrelated.

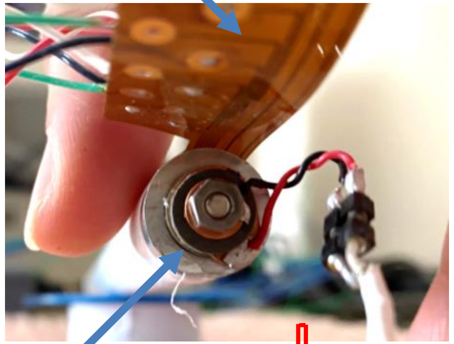
T. Planès and E. Larose, *"LOCADIFF: Locating a weak change with diffuse ultrasound"*, AIP Conference Proceedings, v. 1511, p.405 (2013)

Diffusion properties of the coda wave can be potentially explored to evaluate distance to the point of weak change or heat source

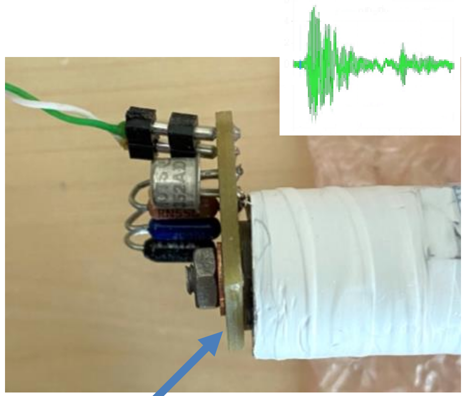


- To test the principle we have built a simple setup based on a hollow aluminum rod (="cable") instrumented with a flexible array of spot heaters, and acoustic transducers at opposite ends

Heater array



Pulser piezo



Acoustic sensor

New software to monitor time shift simultaneously over multiple coda segments

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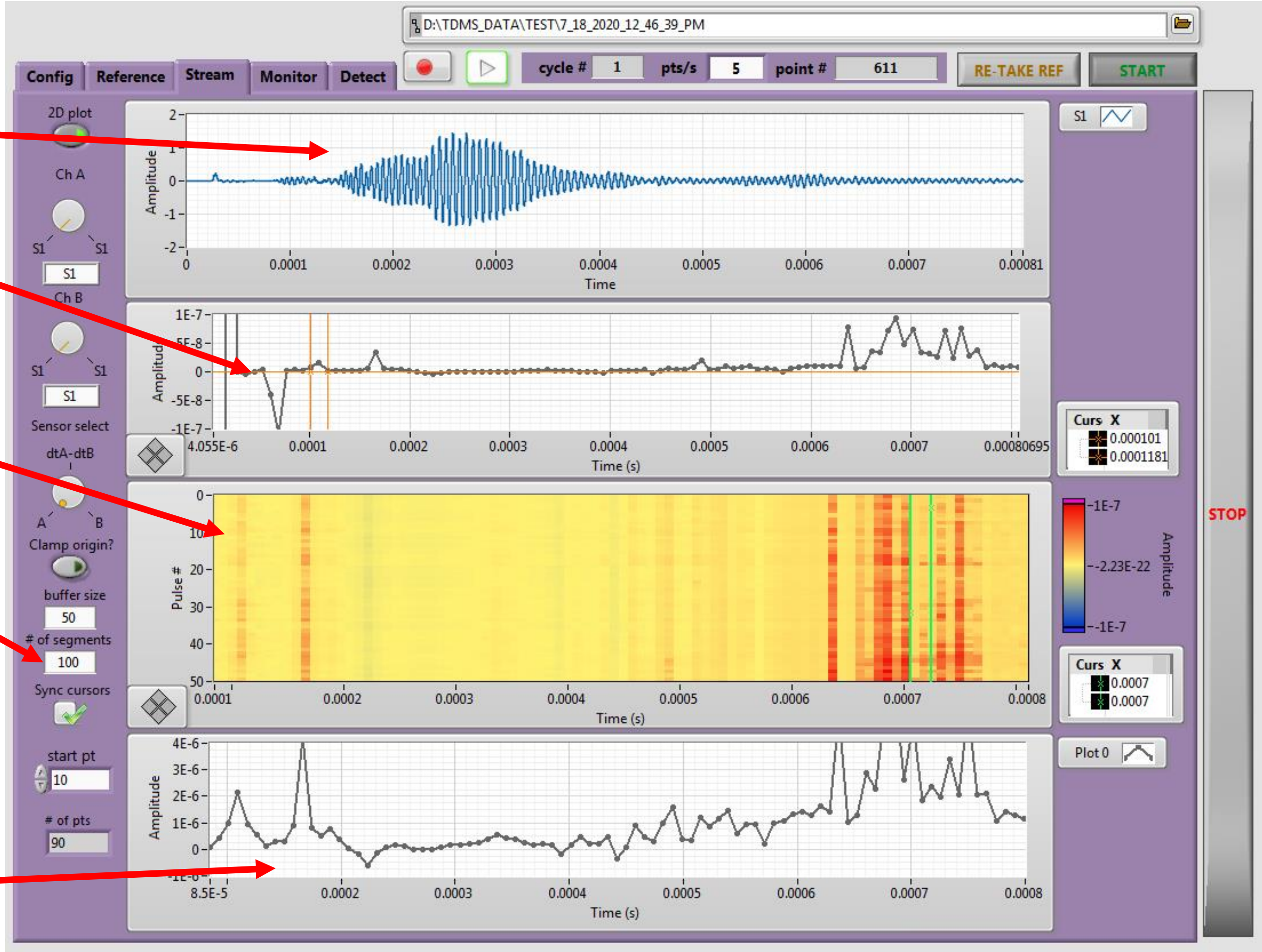
Coda

“Instant“ (per pulse) time shift measured along the coda

“Waterfall plot” of time shift vs time

Number of segments to calculate time shift

Average time shift per segment



We expanded our original quench detection software to include calculation of time shift along the pre-selected number of intervals along the coda, plot is as a waterfall plot as function of number of pulses (=time), and also calculate average variation of the time shift for those pre-defined segments as it accumulates over time.

Examples for different heaters producing time shift at different positions along the coda waveform

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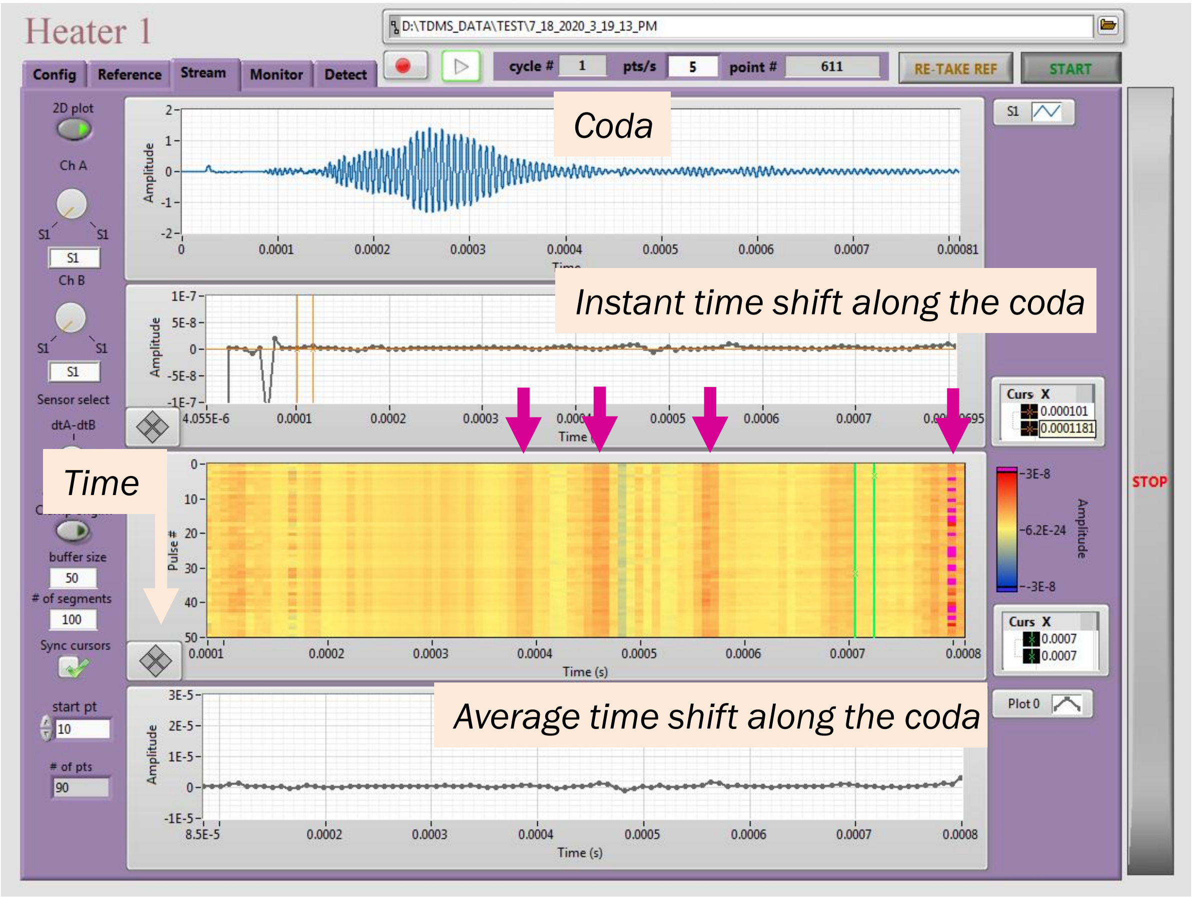
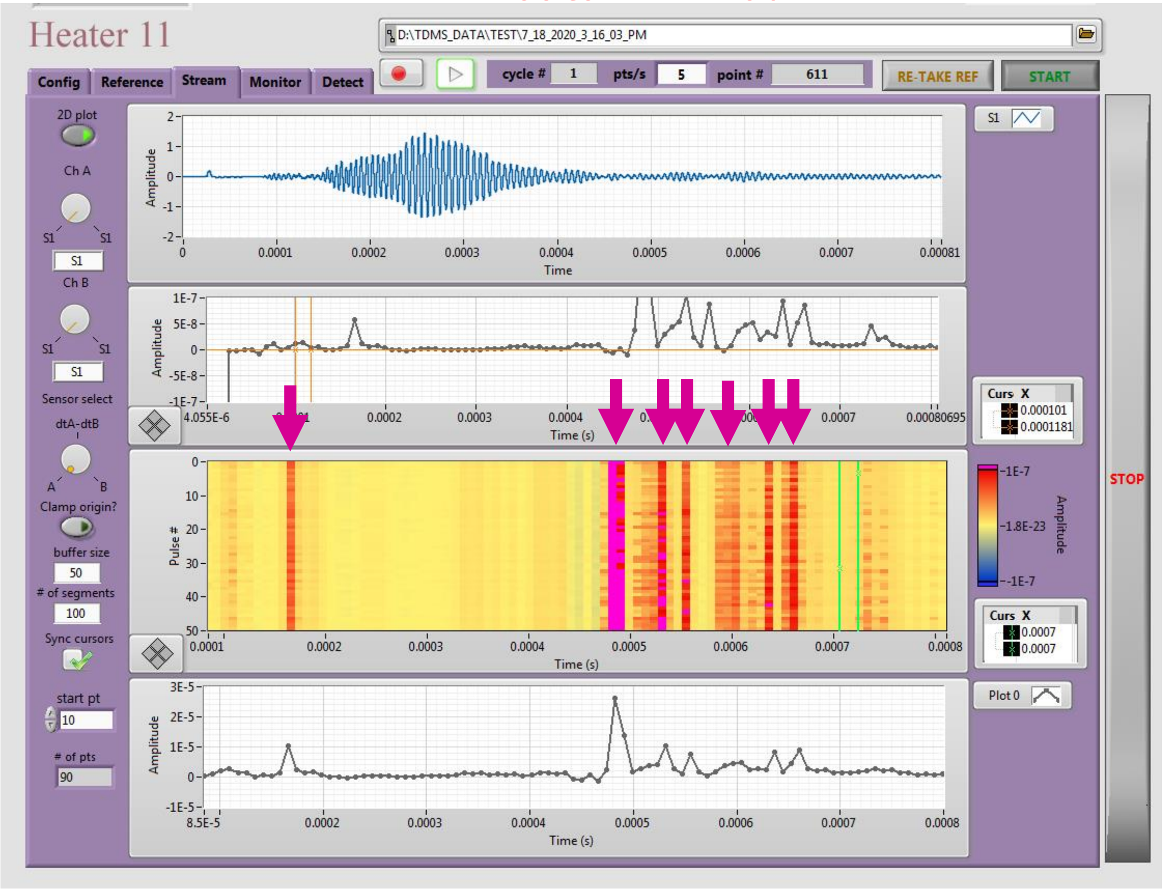
Heater 1 fired



Heater 11 fired



Segments of the coda along the time axis that are exhibiting largest time shift in response to a heater firing are marked with arrows. The “bar code” pattern in Time Shift vs Time waterfall plot are clearly different for different heaters, showing a potential for using this property for hot spot localization.

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Automated sampling and localization software

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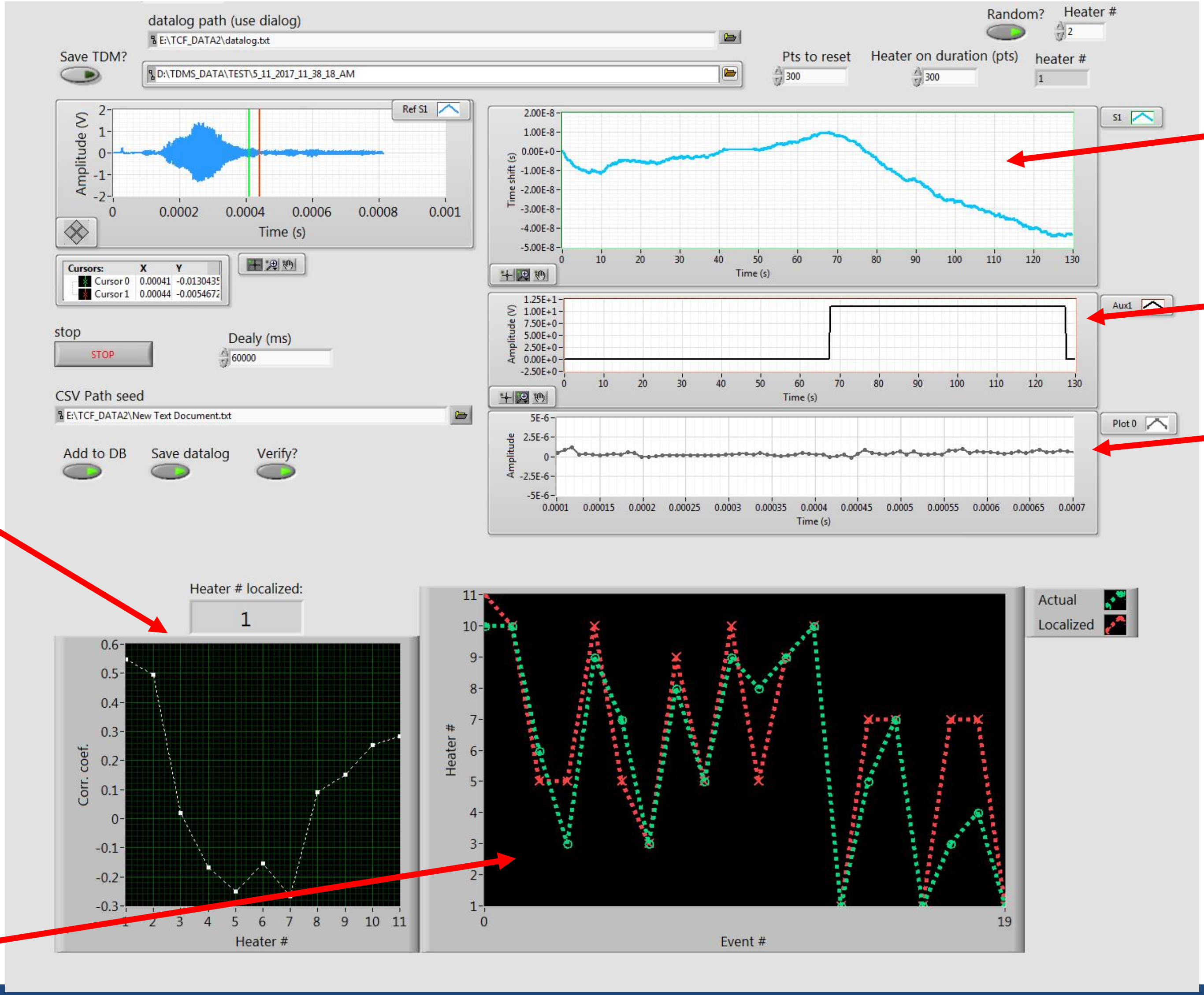

Time shift vs time monitored for an arbitrary chosen coda segment (shown on the left)

Spot heater voltage vs. time

Accumulated average time shift per coda segment (100 pts)

Kendall's Tau coefficient for the current waveform comparing it to the waveforms in the database corresponding to different heaters

Localized vs actual heater location. Heaters are fired randomly

The program randomly fires the heaters using USB relay card, collects time shift variation data, update the database and localize the heater based on the data that is already in the database.

Actual vs localized heater locations

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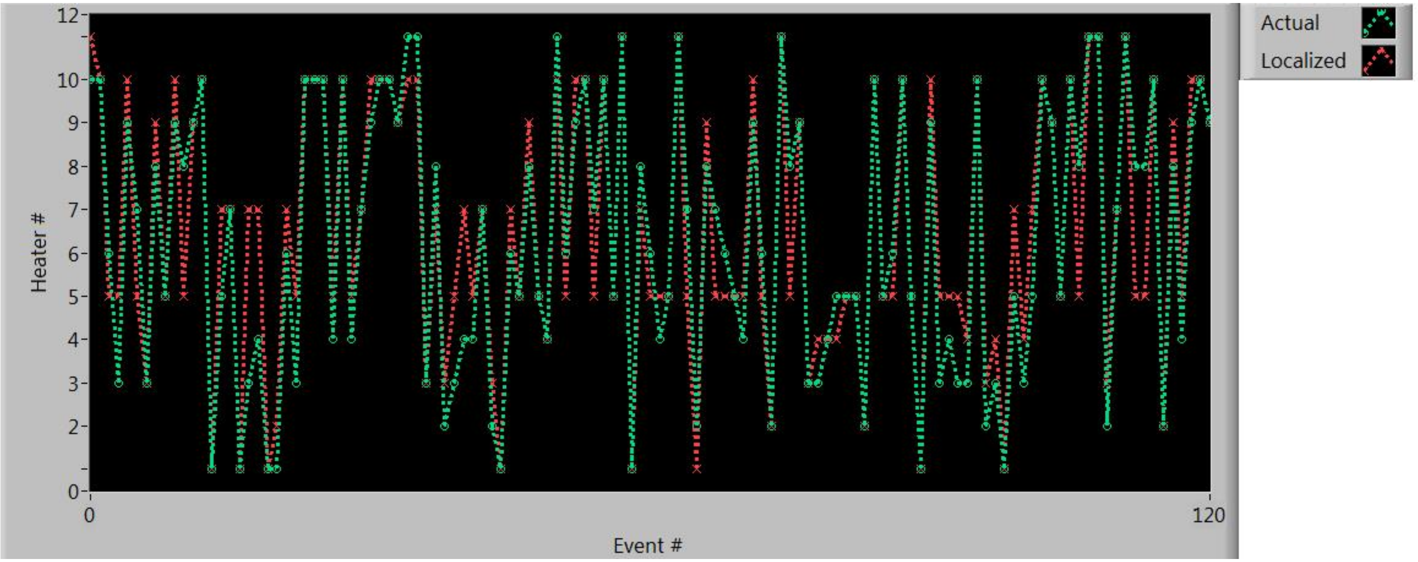
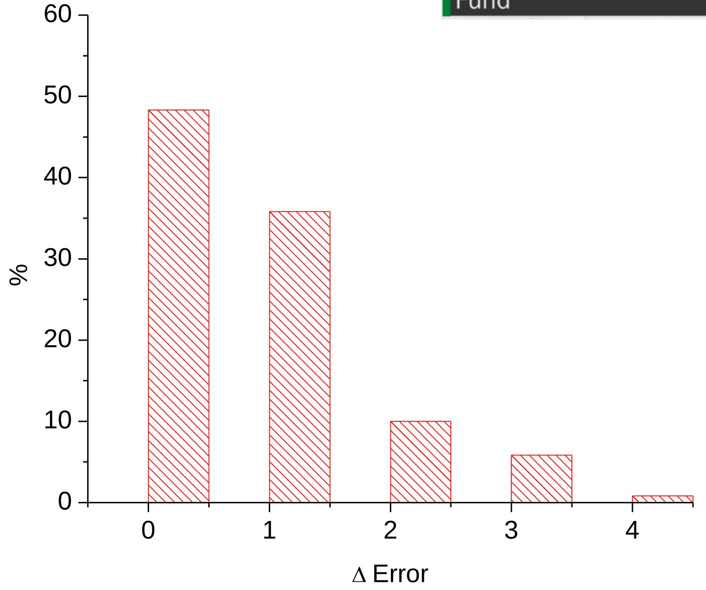


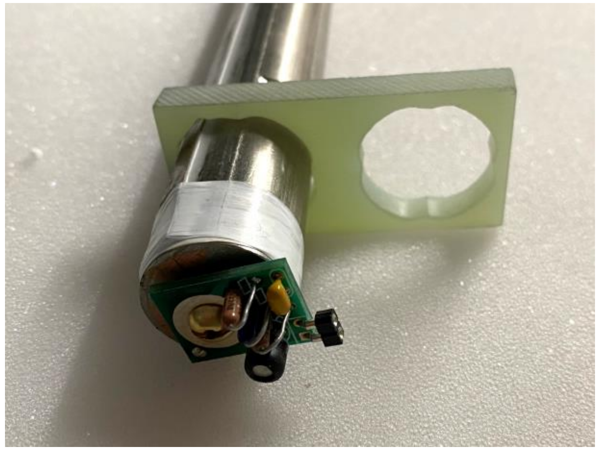
Heaters were fired at random 120 times and localization was performed. The result is plotted above.



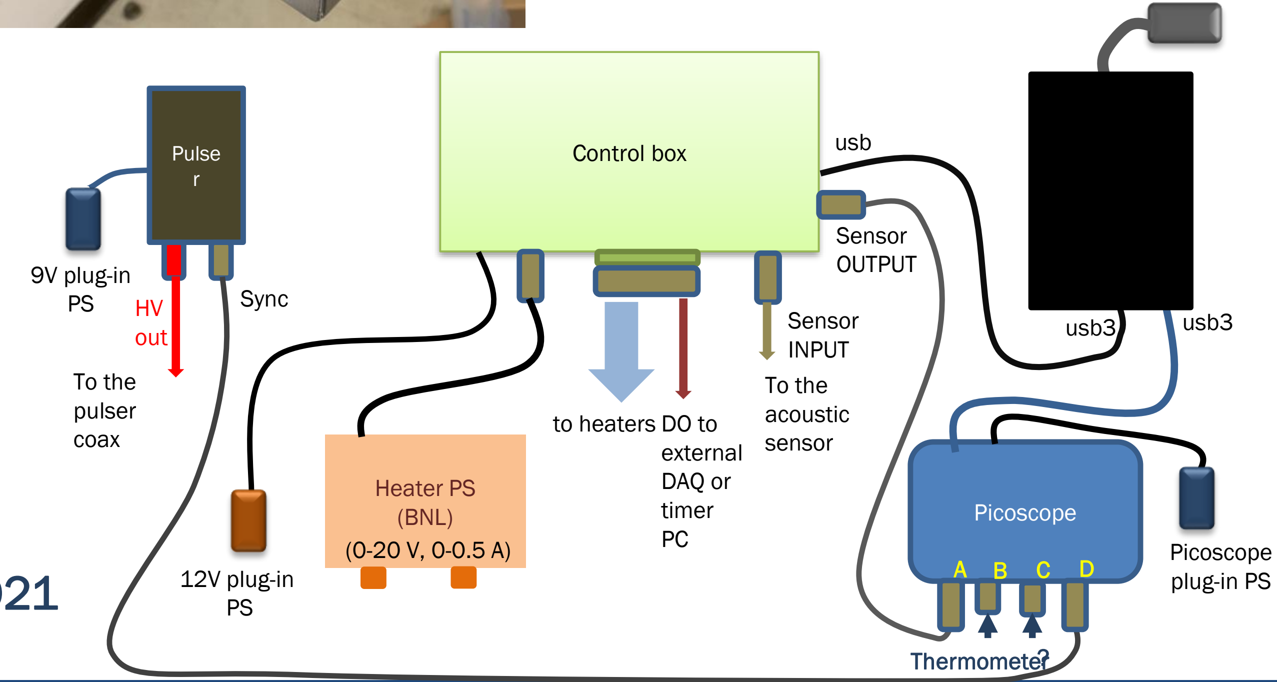
Percentage of cases plotted vs absolute error

In 48% of cases heater firing location was determined exactly, in another 36% of cases heater firing location was determined with a +/- 1 accuracy, corresponding to an inter-heater distance of 26 mm. This clearly demonstrates feasibility of our localization approach. As number of event in the “database” increases with each consecutive heater firing, the accuracy of localization increases as well. Further improvement can be made using more advanced classifier methods based on machine learning algorithms, and we plan to adapt it for future experiments.

“Standalone” acoustic setup for detection and localization



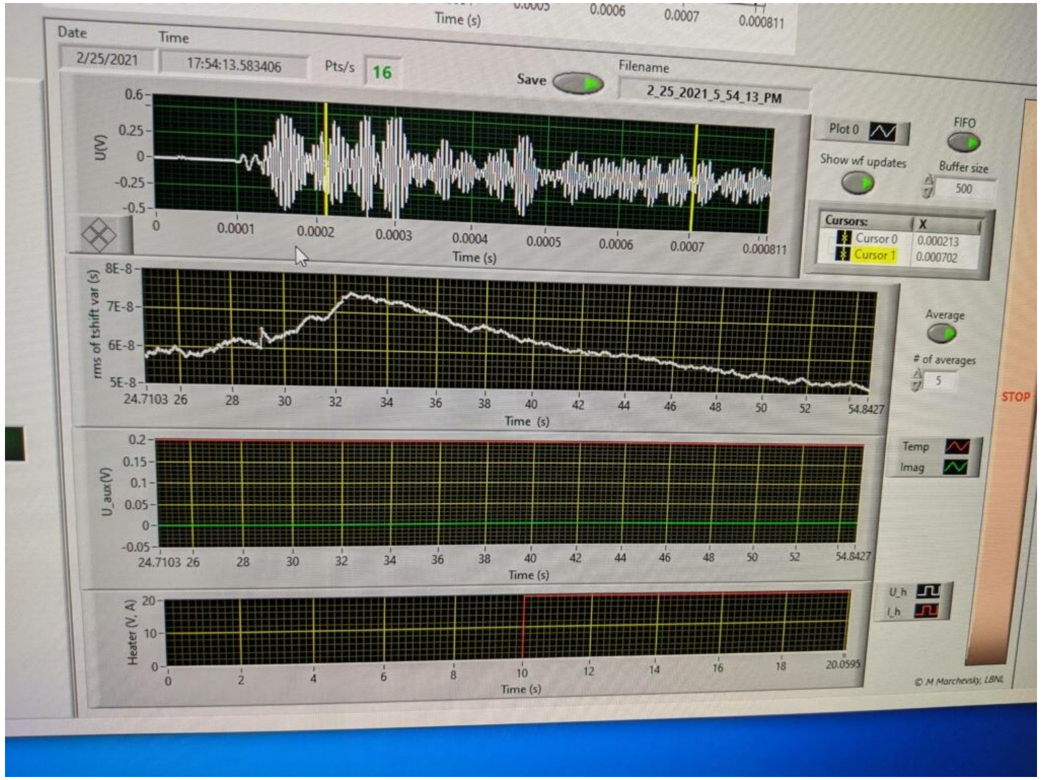
Fusion cable instrumented with acoustic hardware. It was installed in a sealed “cassette” that was mounted in the BNL common coil structure



Cryogenic test was conducted at BNL on Feb 24-25, 2021

First successful cryogenic demonstration of the method on a fusion cable

11.7 K -> 13 K



Heaters were fired along the sample at random at a background temperature of 10-20 K, and also during fast magnetic fields ramps

Localization results are to be analyzed….

This system will be used next on the CCT Subscale 3 to explore measuring temperature variation inside the magnet caused by mechanical disturbances.

C. Sanabria, D. Meichle, M. Segal (CFS), P. Joshi, S. Joshi, R. Gupta (BNL)

New quench detection concept: using ultrasonic waveguides

Etegent TECHNOLOGIES ltd

We plan to apply the acoustic waveguide technology for active quench detection. Instead of sending ultrasonic pulses directly into the magnet and measuring diffuse field signals, we will instrument it with acoustic waveguides and sense temperature variations along those waveguides using pulse-echo techniques. This approach is in many ways similar to the fiber-optic one, but expected to be:

- more robust
- less expensive
- capable of separating thermal and stress responses*

➢ We teamed up with an expert, **Etegent Technologies** who successfully applied WG temperature sensing techniques for high-temperature applications. An SBIR Phase I proposal was submitted towards FES call, aiming at delivering this technique to LBNL as a standalone solution for detecting hot spots in HTS cables and HTS subscale prototypes.

http://www.etegent.com/uploads/pdfs/Papers/2015QNDE_0211-Lobkis.pdf

Other new directions in quench detection

- RF impedance change quench detection (BNL, LBNL)
- Capacitive detection (FSU, LBNL)
- Linear sensors based on variation of resistance and/or capacitance at hot spots (based on the new cryo-electronics)
- LDRD on fiber-optics (LBNL)

Paolo Ferracin (PI), Xiaorong Wang (co-PI).

Goal is to develop and demonstrate fiber optics as an effective tool to measure strain and identify quench locations and defect in Nb_3Sn and HTS (both strain sensitive) magnets; in collaboration with Geophysics Division for exploring distributed fibers.