REBCO diagnostics developments

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U.S. DEPARTMENT OF ENERGY | Office of Science

REBCO diagnostics needs

- **Early quench detection and localization of quench precursors** ➡ **Acoustic QD**
  - Providing an early warning to prevent quenching and damage due to a localized hot spot formation
  - Providing redundancy to other quench detection techniques (voltage, optical, etc.)
- **Current sharing in tape stacks and cables and stability margins** ➡ **Hall sensor arrays**
  - Establishing stability margins for a multi-tape conductor and identifying critical parameters
  - Allowing for a better utilization of the conductor, compensating for local degradation in individual tapes
  - Predicting current re-distribution across cable cross-section on the magnet field quality
- **In-situ monitoring of conductor performance degradation** **Future work**
  - Identifying and quantifying damage along the REBCO layer edges caused by magnetization currents
  - Identifying delamination's and crack formation in tapes due to excessive (repetitive) stress
  - Detecting voids in REBCO layer responsible for local electric field anomalies / excessive flux creep
  - Understanding radiation damage

Quench detection

Why do we need a non-voltage quench detection?

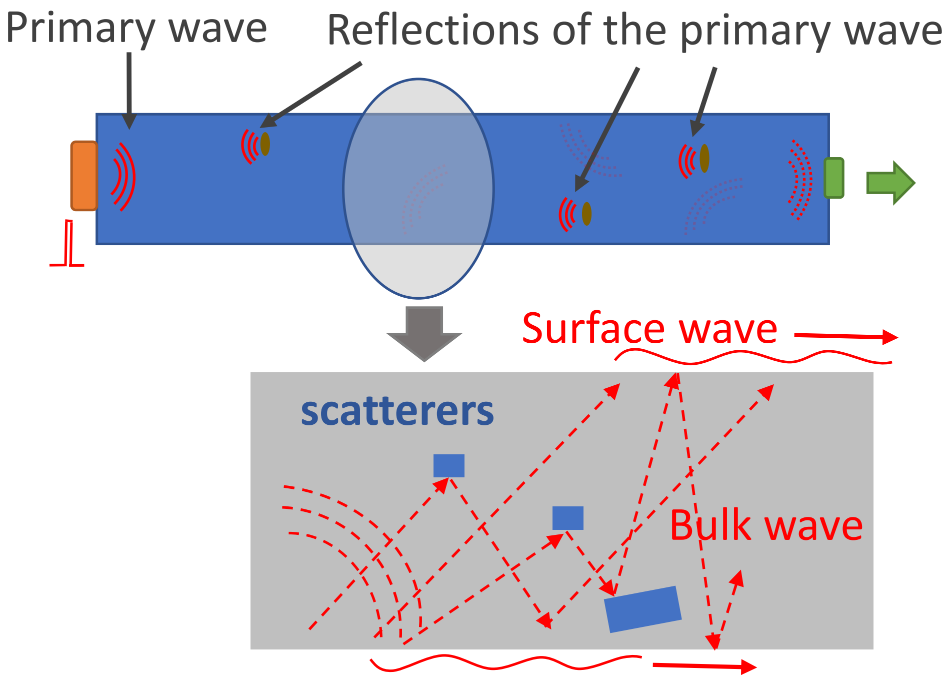
- Quench propagation velocity in HTS conductors is 1-2 orders of magnitude lower than in LTS, meaning a non-propagating hot spot may reach high temperature before voltage is detectable on top of the background noise

- For HTS applications like fusion, where large ac field or current modulation is present, the detection problem becomes even more severe

- Redundancy by a combination of different detection techniques is always desirable in critical applications

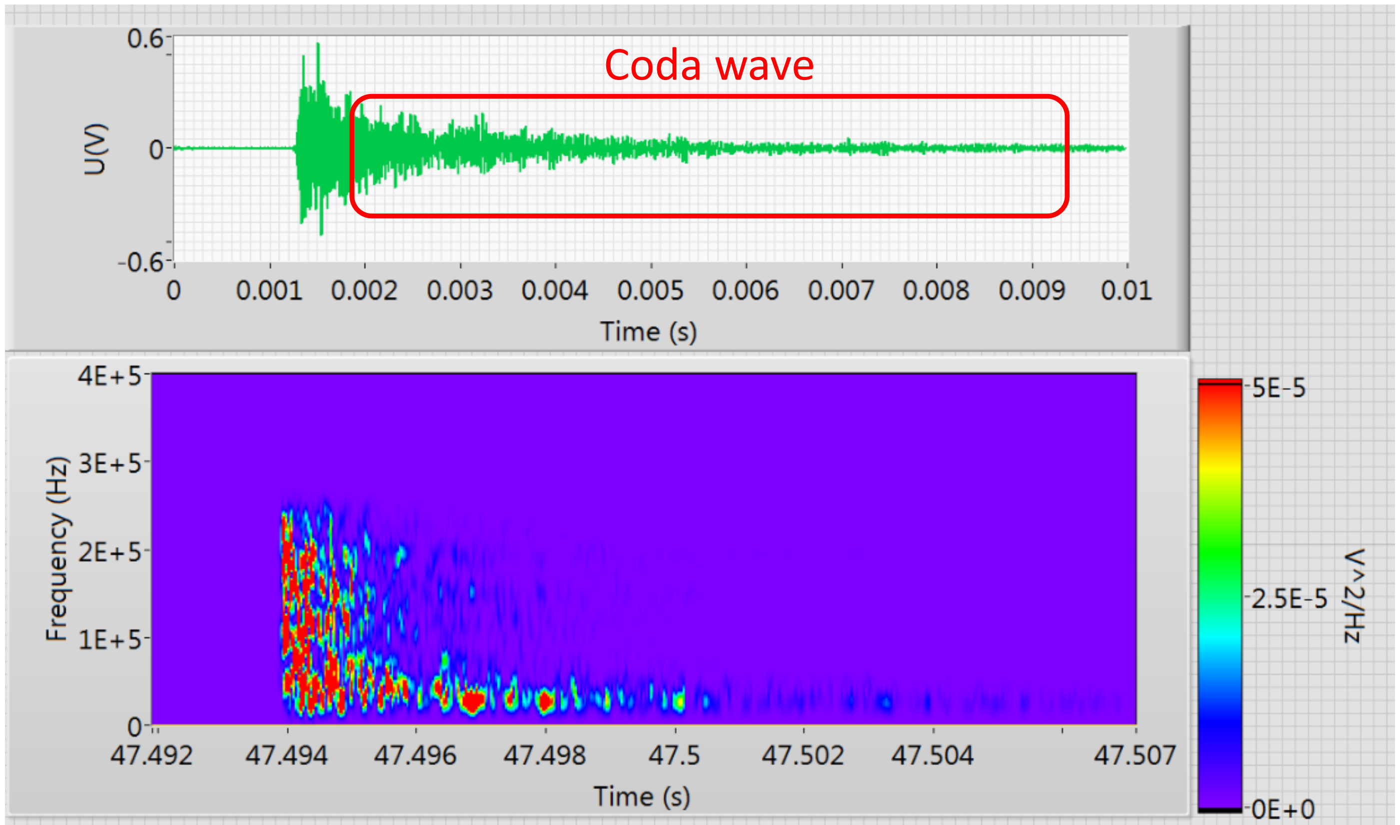
Active acoustics: using conductor itself as a distributed thermometer to detect local hot spots

Acoustic pulse “diffusion” in a complex medium: properties of the coda wave



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

A result of multiple wave scattering, mode conversions and interference of secondary waves is called “coda”.

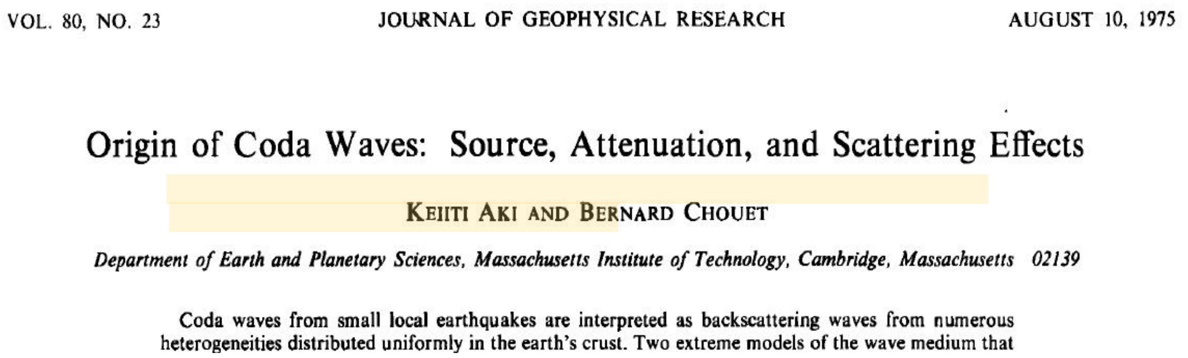


- Coda wave “samples” the specimen volumes multiple times before reaching the receiver

Coda wave is **uniquely defined** by the distribution of wave scatters and the sound velocity

Coda wave interferometry: a technique “borrowed” from seismology

- **First definition**



VOL. 80, NO. 23 JOURNAL OF GEOPHYSICAL RESEARCH AUGUST 10, 1975

Origin of Coda Waves: Source, Attenuation, and Scattering Effects

KEIITI AKI AND BERNARD CHOUET

Department of Earth and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Coda waves from small local earthquakes are interpreted as backscattering waves from numerous heterogeneities distributed uniformly in the earth’s crust. Two extreme models of the wave medium that

- **Thermal sensitivity first demonstrated:**

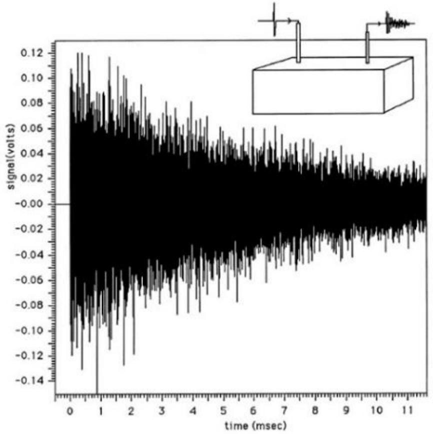
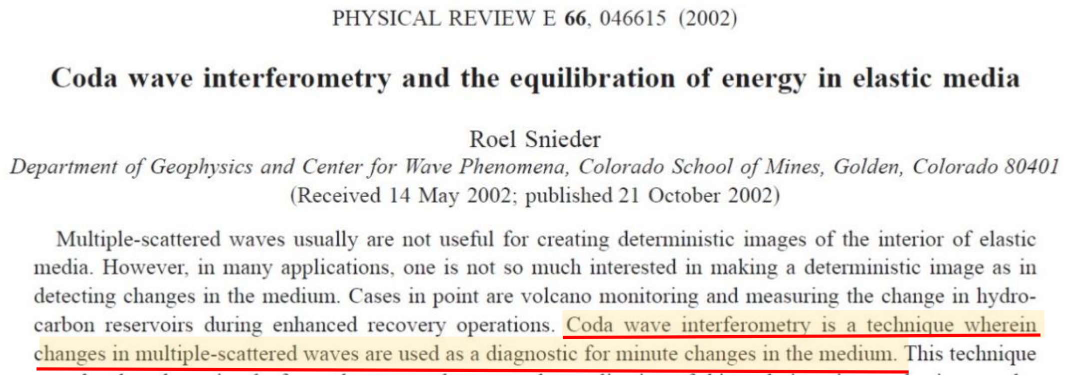


Fig. 1. A broadband impulsive source leads to a stochastic ultrasonic signal with a duration of many tens of milliseconds. This signal is robust in spite of its noisy appearance, and is obtained after 10–100 repetition averages.

- **First introduction of CWI**



PHYSICAL REVIEW E **66**, 046615 (2002)

Coda wave interferometry and the equilibration of energy in elastic media

Roel Snieder

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(Received 14 May 2002; published 21 October 2002)

Multiple-scattered waves usually are not useful for creating deterministic images of the interior of elastic media. However, in many applications, one is not so much interested in making a deterministic image as in detecting changes in the medium. Cases in point are volcano monitoring and measuring the change in hydrocarbon reservoirs during enhanced recovery operations. Coda wave interferometry is a technique wherein changes in multiple-scattered waves are used as a diagnostic for minute changes in the medium. This technique

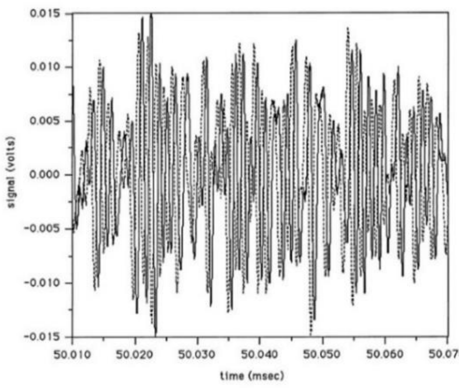


Fig. 2. A 60 μs section of the full waveform is examined at an age of 50 ms. The original signal (solid line) appears to drift to the left (dotted line) as the specimen cools, and to suffer some slight distortion.

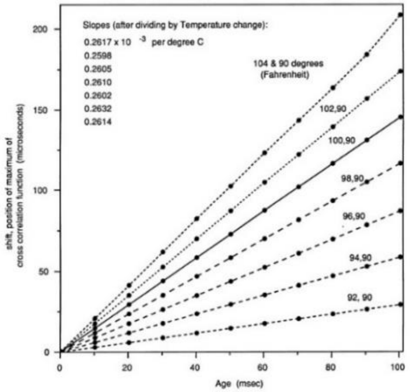


Fig. 5. The position of the cross-correlation peak is plotted as a function of age and temperature change. Its linearity with both parameters is apparent.

Richard L. Weaver, Oleg I. Lobkis, “Temperature dependence of diffuse field phase”, Ultrasonics, V. 38, pp. 491-494 (2000)

Detecting temperature change using coda waves

- Wave velocity change due to a temperature variation in the object

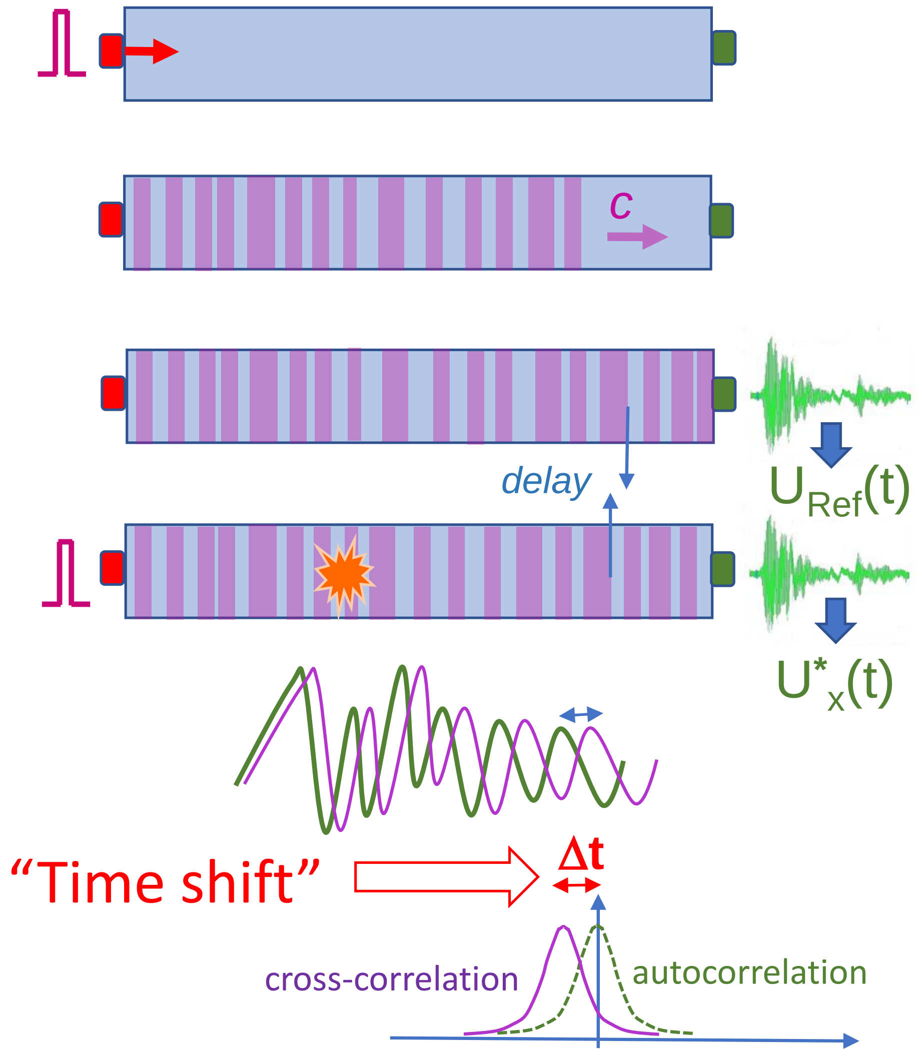
Sound velocity: $v = \sqrt{\frac{E}{\rho}}$ ➡ $E(T) = E_0 - s/\left[e^{t/T} - 1\right]$ (s, t – adjustable parameters)

The E(T) dependence is **weak**: just ~1-10 ppm/K at 77 K and even less at lower temperatures

Detecting a weak change using coda: operational principle

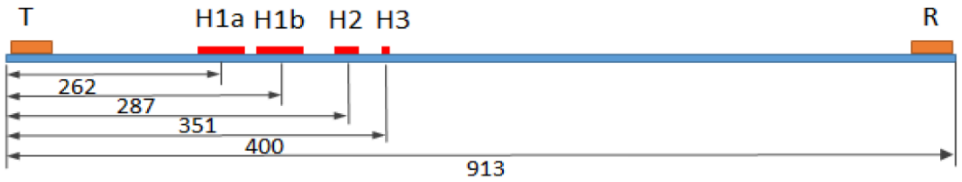
1. An object is pulsed by a sender transducer
2. The pulse propagates and reverberates multiple times
3. The coda is acquired by a receiver transducer; and **stored as “reference”** $U_{Ref}(t)$
4. Pulsing and coda acquisitions are repeated periodically; every new coda $U_x(t)$ is compared to $U_{Ref}(t)$ using cross-correlation: $A(Dt) = U_x(t+\Delta t)*U_{Ref}(t)$. The time shift Δt yielding maximal cross-correlation is calculated for every new pulse
5. When a weak change develops, sound velocity decreases/increases locally, phase shifting the wave passing through it. This proportionally **increases/decreases Δt**.

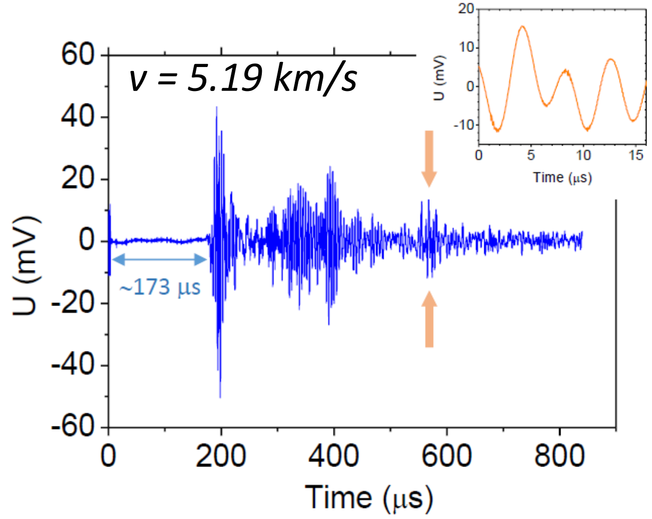
The further in time a portion of the coda is taken, the larger time shift it will experience



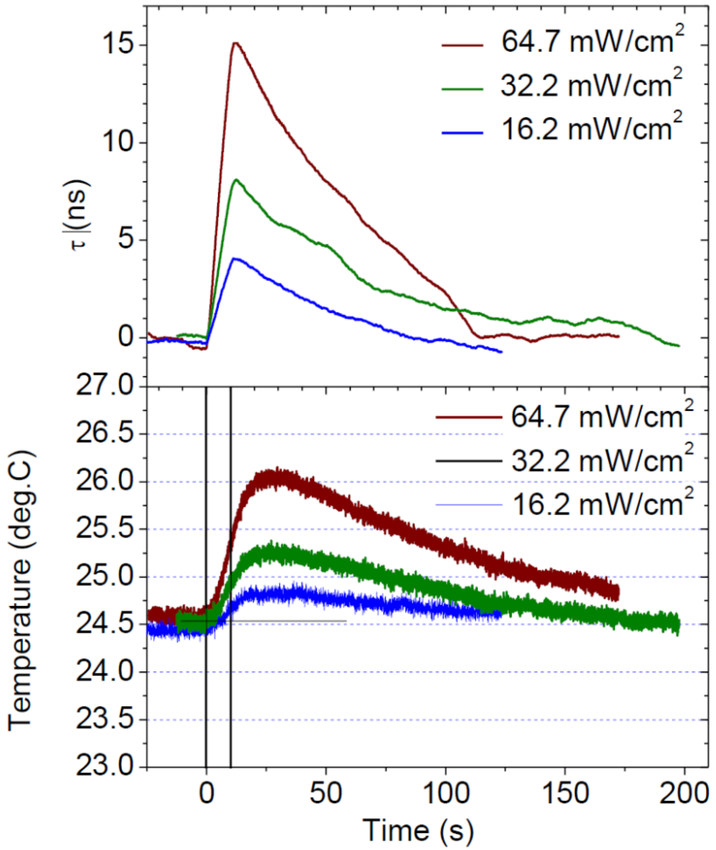
Dependence of the time shift upon the net amount of heat

A stainless (SS316) strip of 0.25 mm thickness and 16.55 mm width was instrumented with a transmitter and receiver. Local temperature was measured with a thermocouple

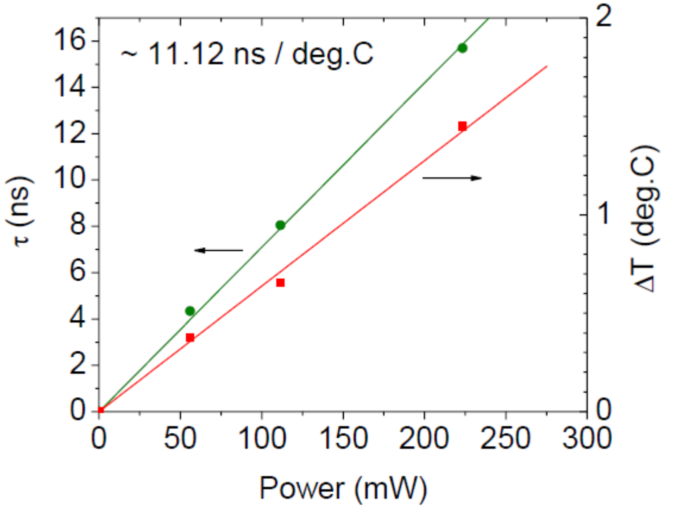




10 V p-p, 0.9 µs-long pulse

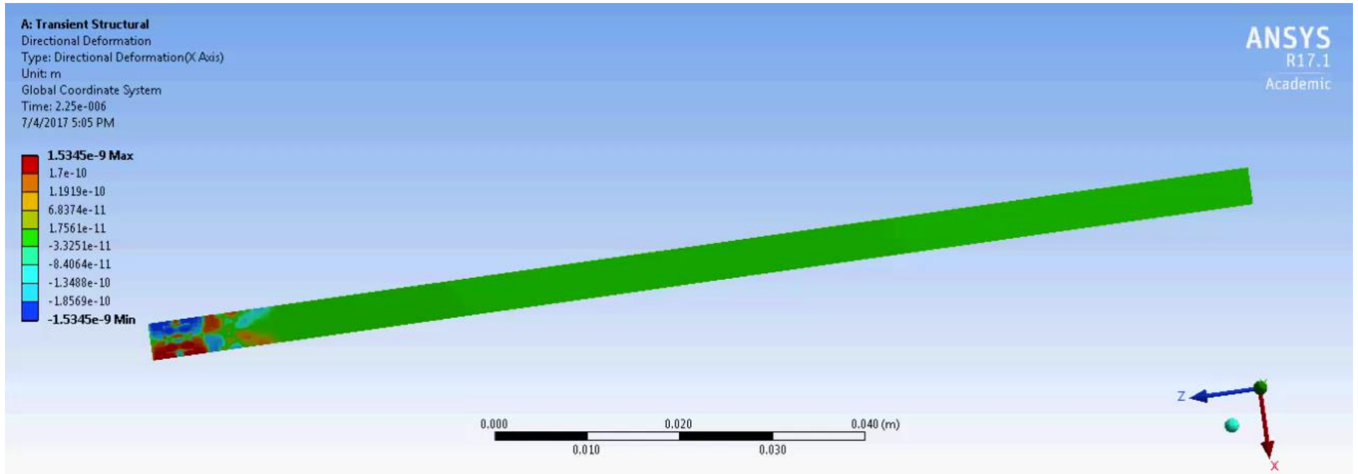


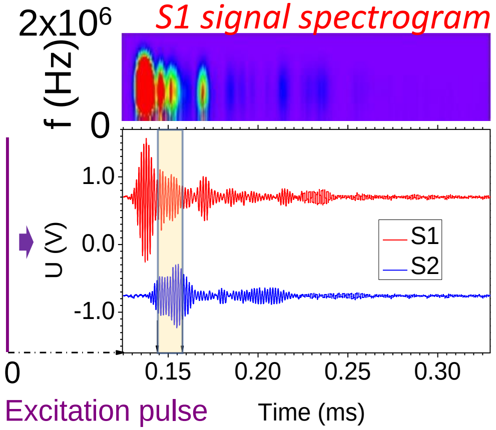
Time shifts (top plot) and temperature variations (bottom plot) during powering up of the H1a heater strip for 10 s at various heater power densities.

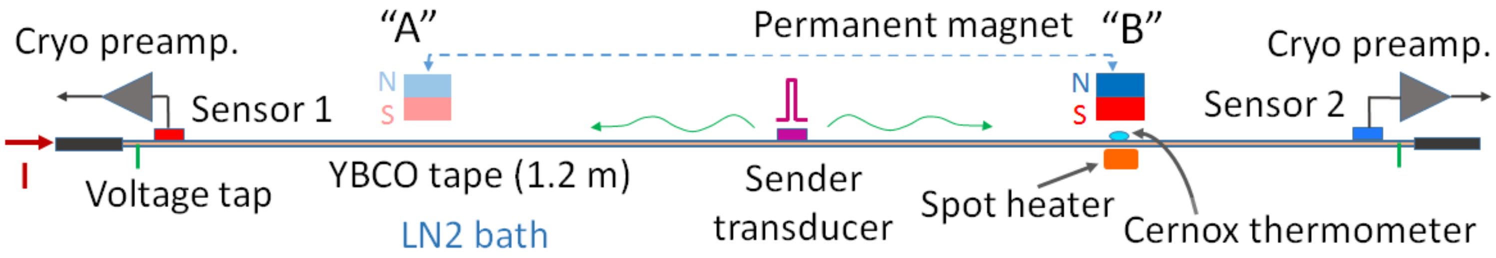


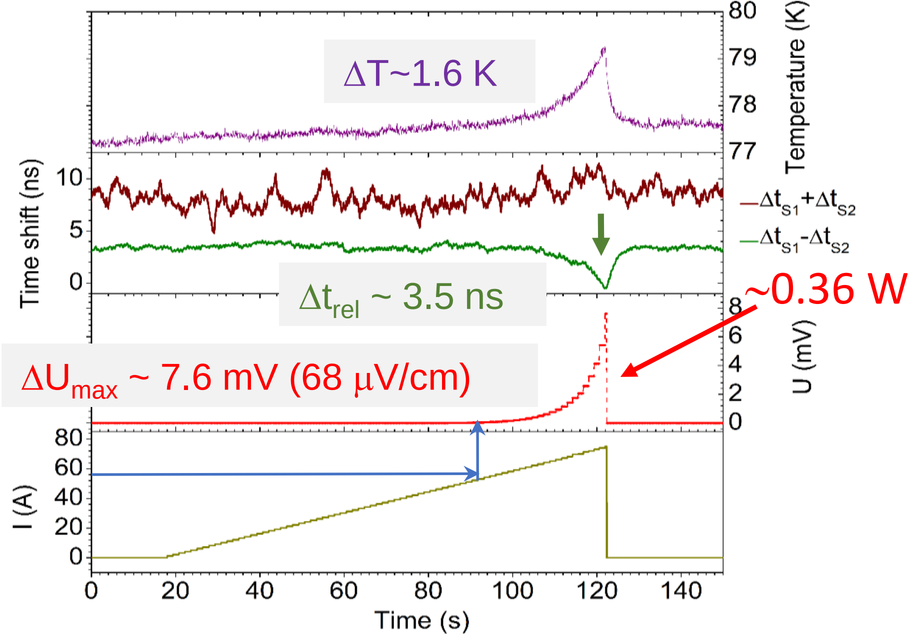
Both maximal acoustic time shift and maximal temperature rise measured by the thermocouple are **linear with the net amount of heat**; yielding acoustic sensitivity of ~11.12 ns per degree Celsius

Acoustic detection of a hot spot in ReBCO tape in LN2









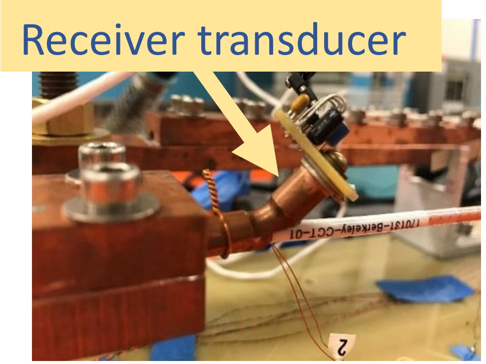
"Quench Detection for High-Temperature Superconductor Conductors Using Acoustic Thermometry", M. Marchevsky, E. Hershkovitz, X. Wang, S. A. Gourlay, S. Prestemon, *IEEE Trans Appl. Supercond*. 28 (2018) DOI: 10.1109/TASC.2018.2817218

Quench detection in a subscale CCT coil using CORC© conductor at LN2

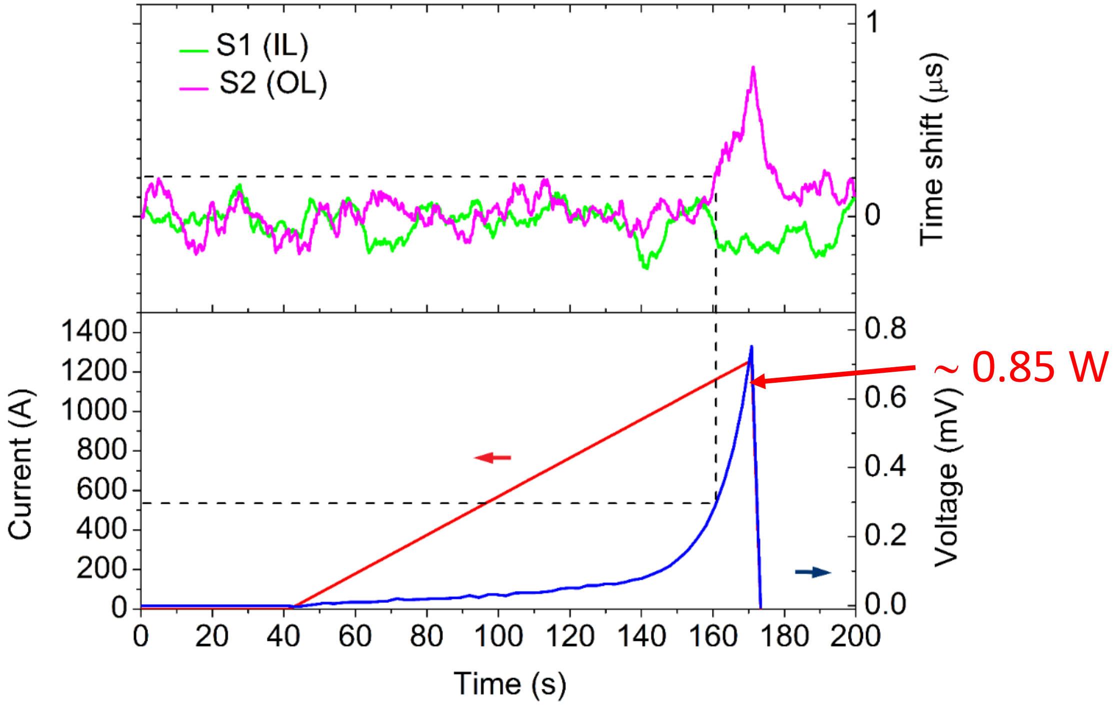
CORC© cable: 29 REBCO tapes distributed around a 2.56 mm diameter copper core wire

- Tapes are 2 mm wide, and have 30 mm-thick substrate
- Cable diameter is 3.63 mm, length is 2.25 m, including out-of-mandrel portions

Sender transducers

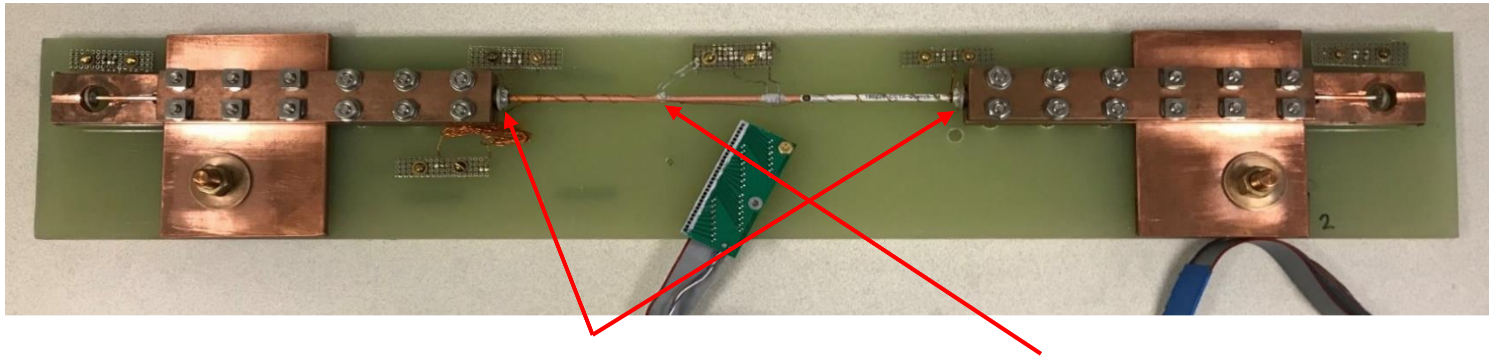


Receiver transducer

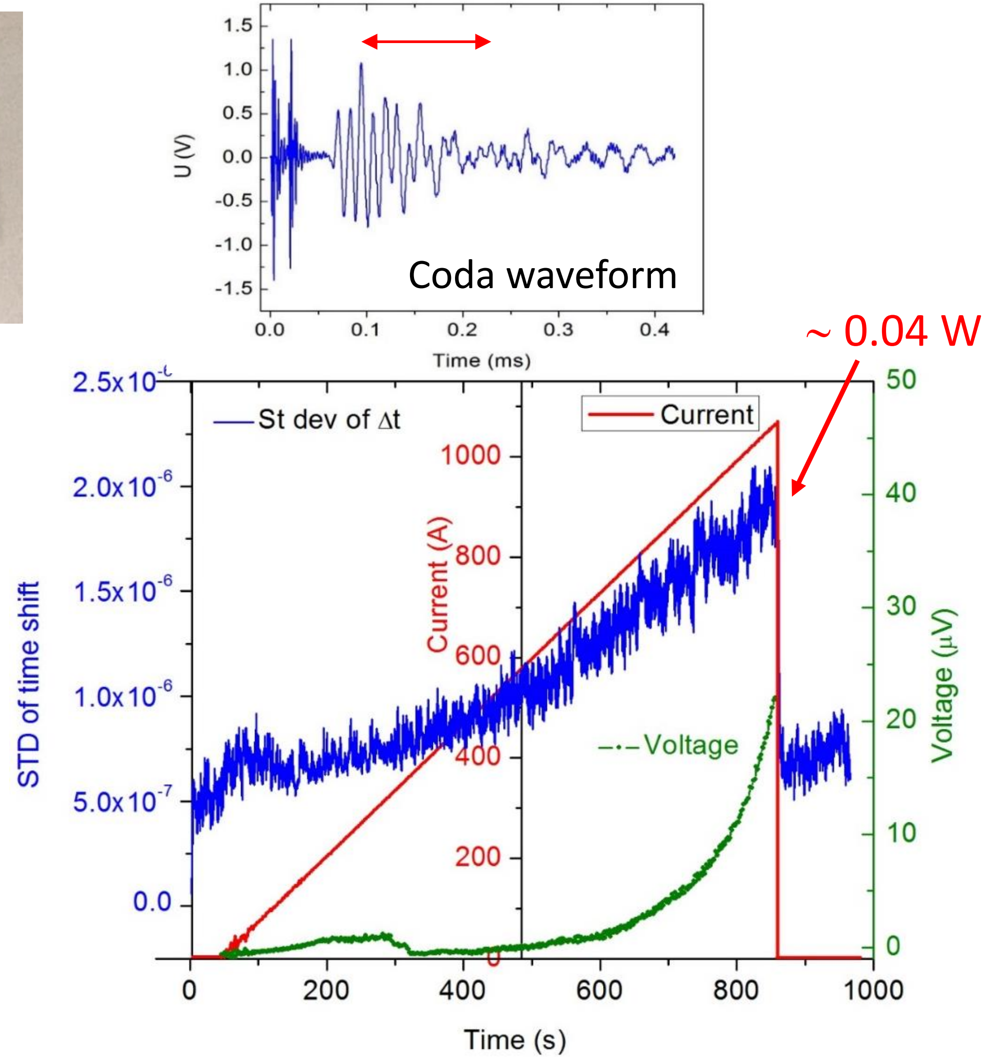


Coil design and test by X. Wang

Short sample of CORC© experiment: StDev of the time shift gives cleaner thermal signal



16-tape CORC® wire; 20 cm long section with 15 cm long terminals



The architecture of the CORC© makes acoustic quench difficult, as even minor deformations alter the wave paths through tape interfaces…

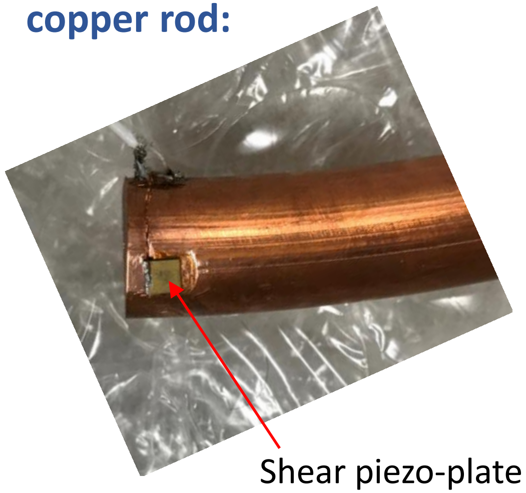
In collaboration with

Advanced Conductor Technologies LLC
www.advancedconductor.com

If standard deviation of Δt is plotted versus the applied current, a dependence closely resembling the I-V curve is recovered.

Simulations and tests of acoustic quench detection for a mock-up fusion cable

- **ANSYS simulation of acoustic wave propagation and scattering in the fusion cable geometry**
- **Tabletop test on a mock-up “cable”: a 50 cm-long copper rod:**



Shear piezo-plate

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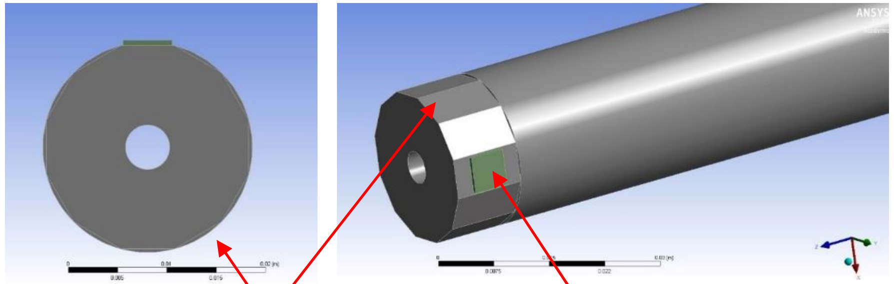
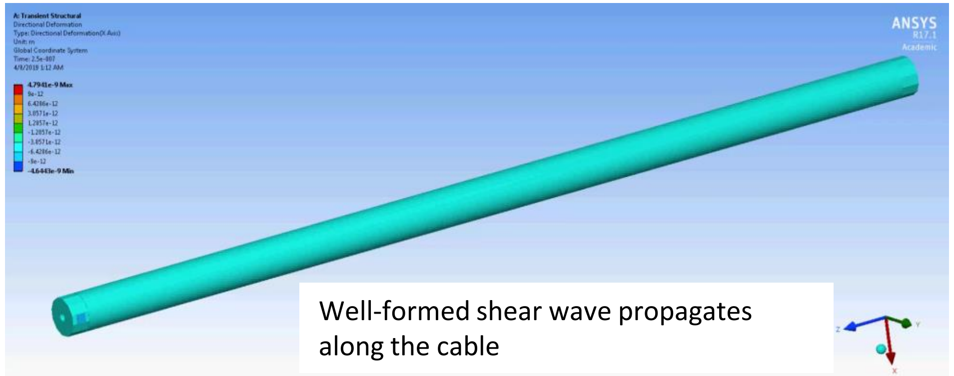
COMMONWEALTH FUSION SYSTEMS

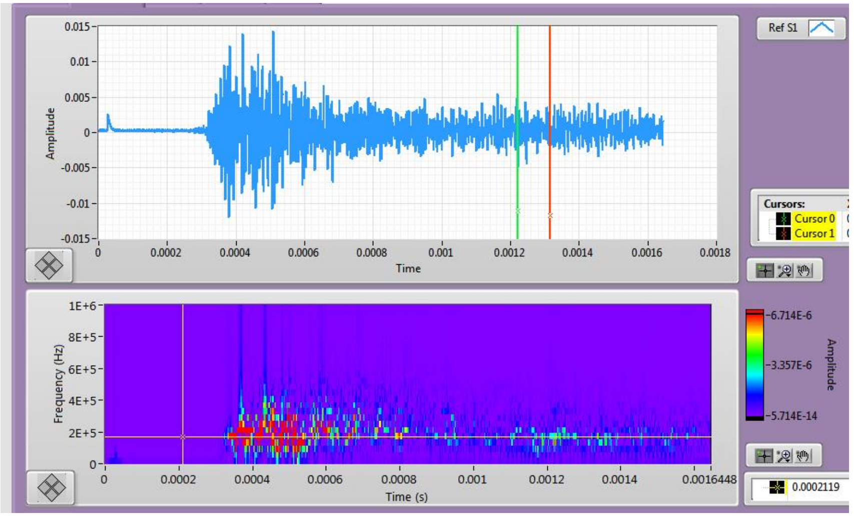


Copper rod with a central flow channel and flattened end

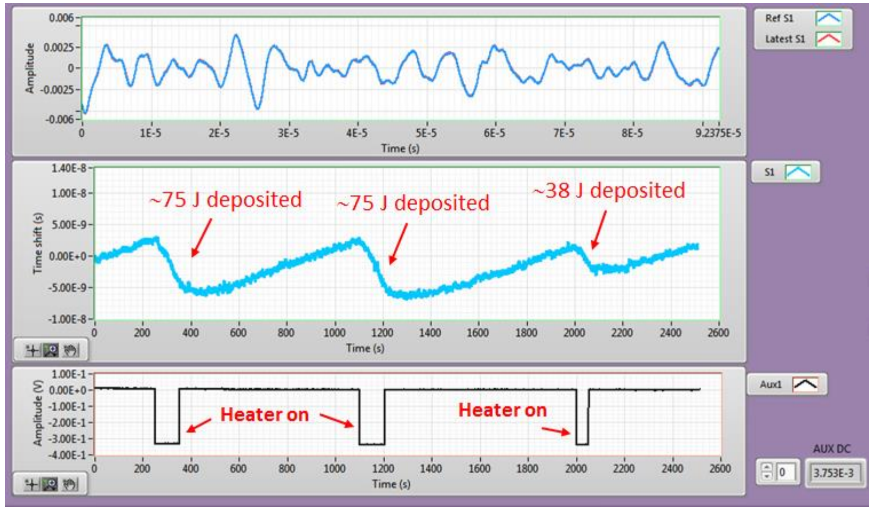
Shear piezo-plate



Well-formed shear wave propagates along the cable



Pulses of 2.3 μs duration were applied 5 Hz repetition rate. Pulse amplitude is ~40 V p-p.

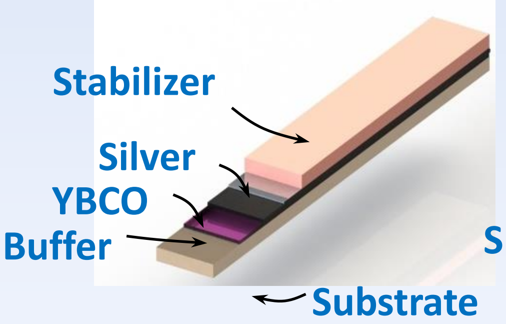


Heater was placed at the middle of the cable (~25 cm from the ends; its power is 0.753 W. Heater was on for 100 s, 100 s and 50 s respectively

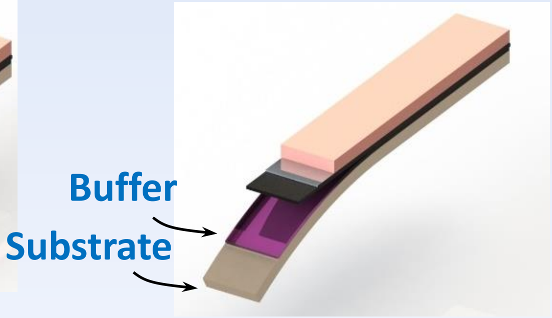
Current sharing studies using Hall sensor arrays

“ExoCable”, two directions for current sharing

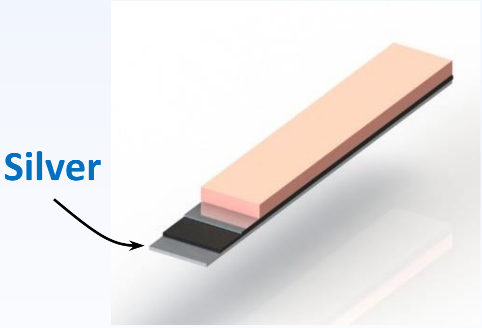
AMSC tape



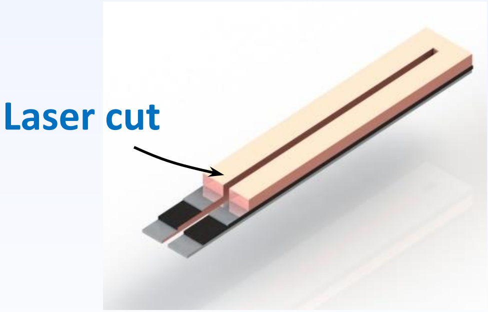
Exfoliation

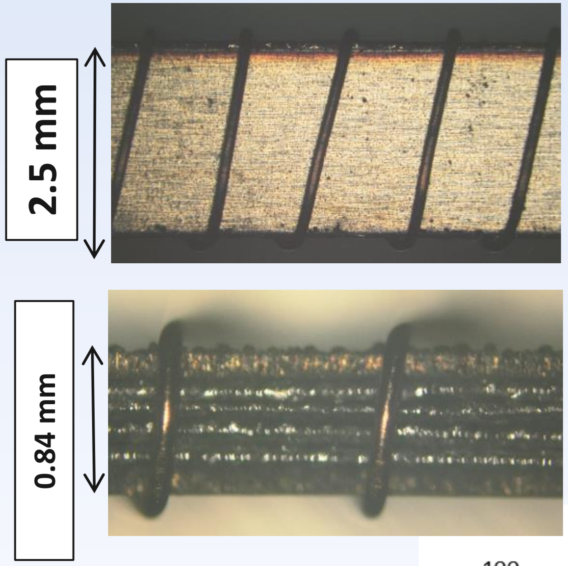


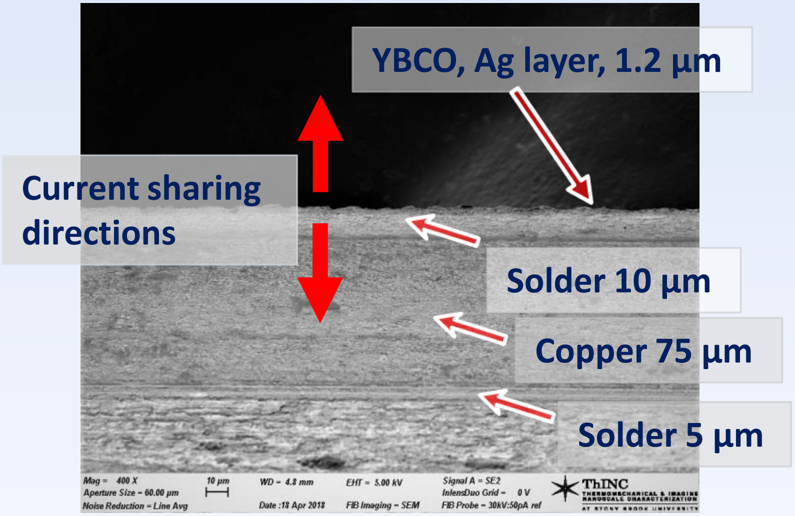
Laser slicing



Protective silver

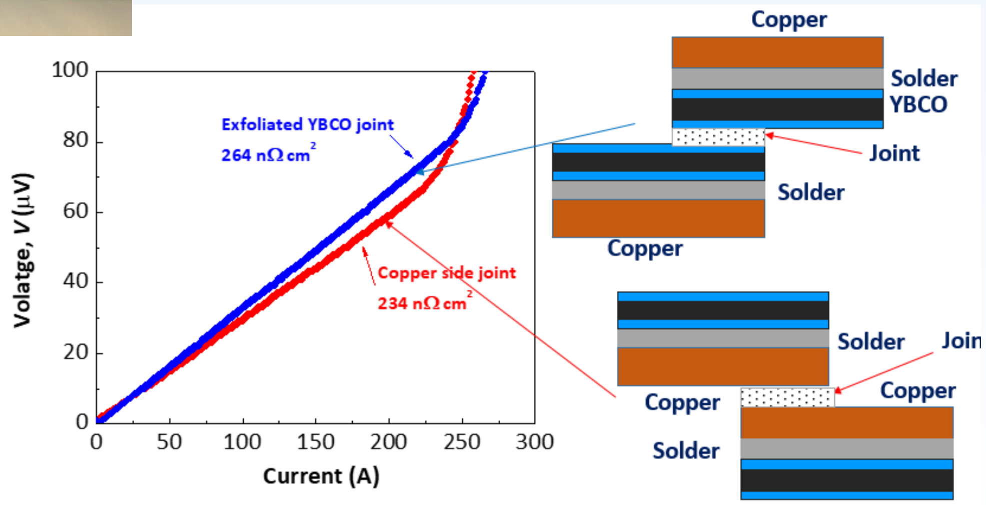






Courtesy of Slowa Soloviev, BTG

- ✓ The filament stack is YBCO-metal composite

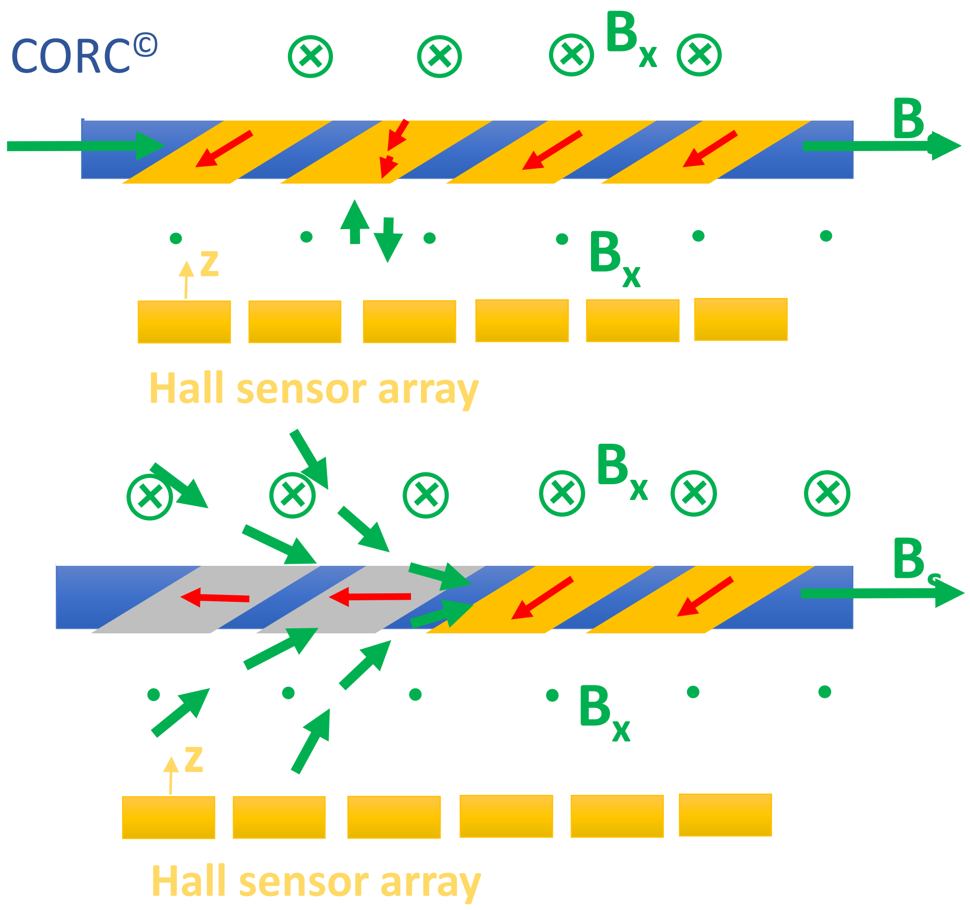


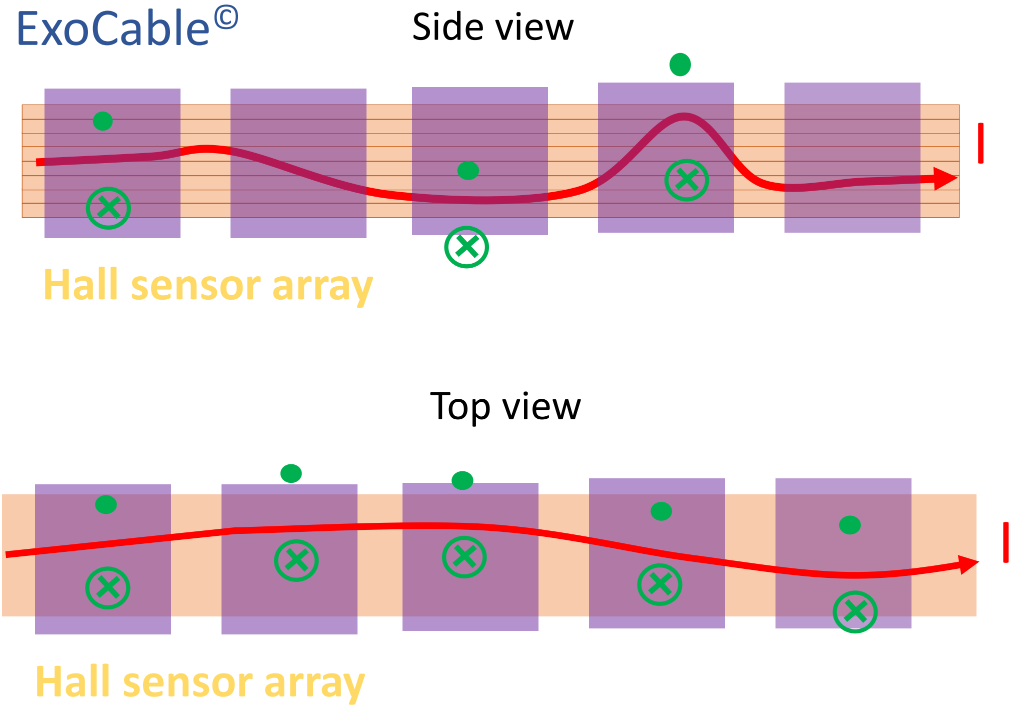
Brookhaven Technology Group

- ➢ We study an 8-tapes ExoCable stack sample

Measuring current sharing and quench propagation with a Hall sensor array

- Normally, current sharing can be studied by measuring voltage drop across individual tapes in the cable. Alternatively one can measure magnetic field re-distribution.

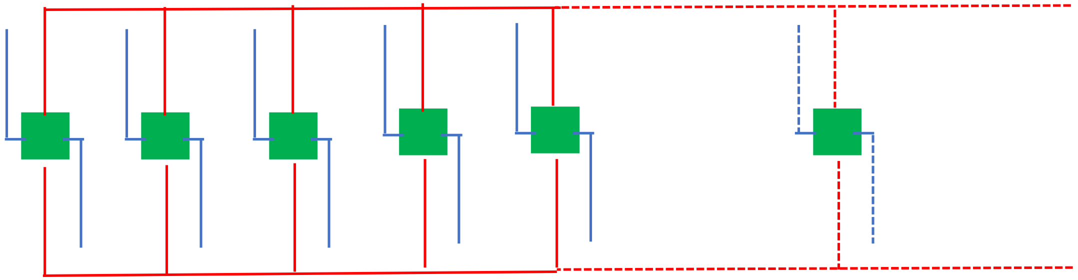




- ➢ Current deviation from the "median path" will create additional local modulation of the magnetic field that can be monitored with the Hall sensor array

Hall sensor array design

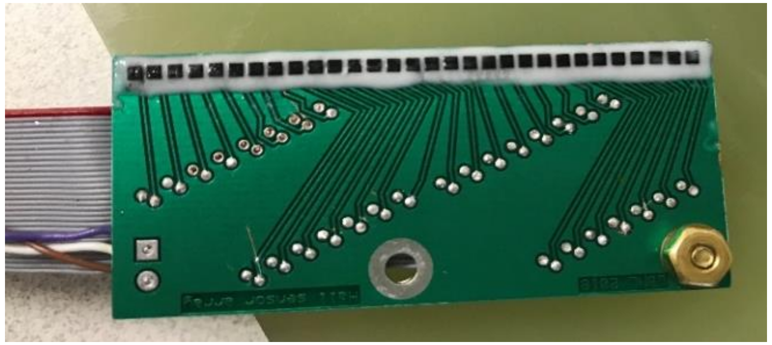
- Commercial GaAs ion-implanted Hall sensors: work well down to cryogenic temperatures (sensitivity actually increases with cooling)



6V DC / ~300 mA at 77 K (60 mW per probe)

Sensitivity is ~1.2 mV/mT

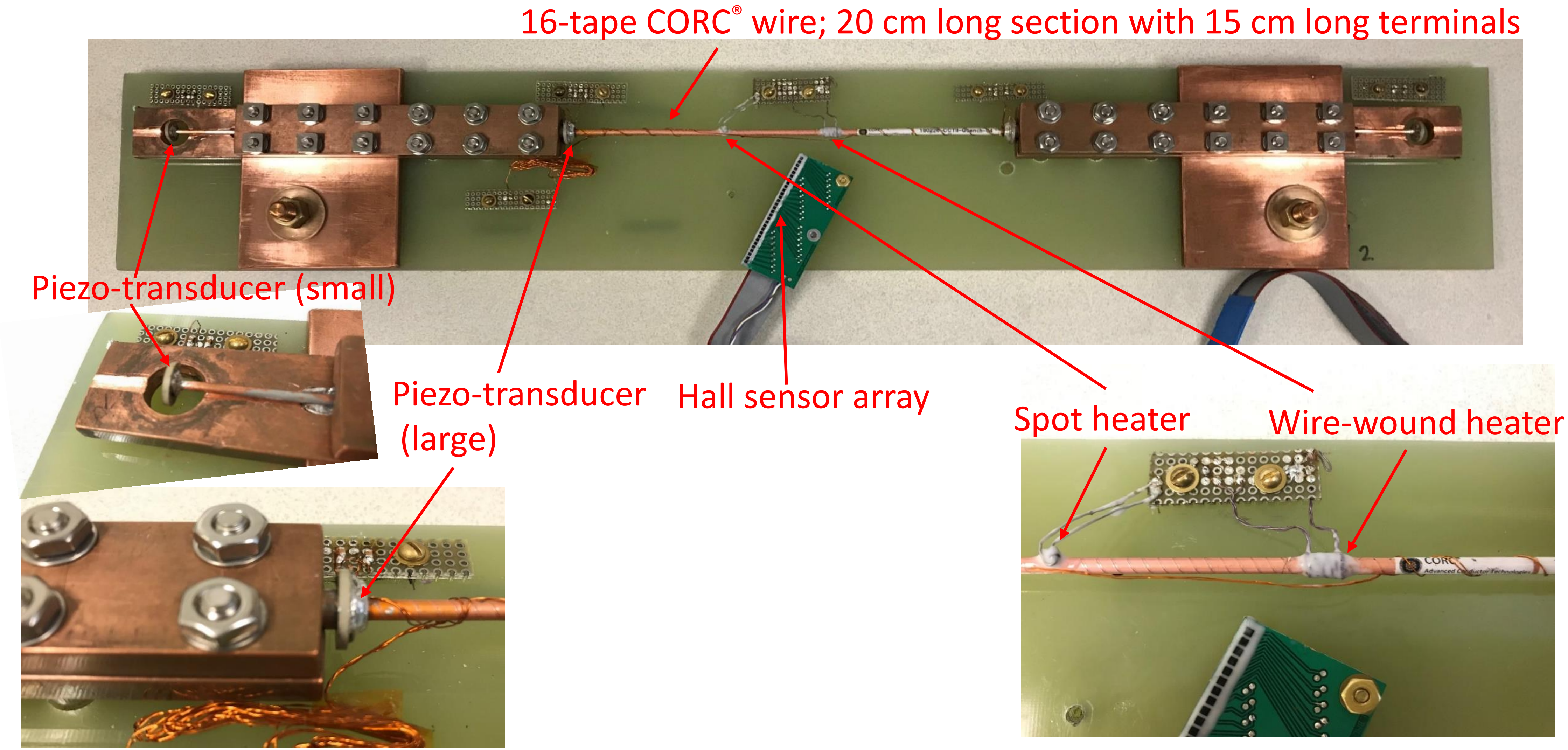
Linear period is 1.9 mm



- A simple 2-layred PCB board designed to integrate sensors in an array

- Yokogawa WE700 DAQ with 32 simultaneous 16-bit channels with hardware-selectable range down to 10 mV and speed up to 100 kHz used for data acquisition

Experimental arrangement for the CORC © cable measurements



16-tape CORC® wire; 20 cm long section with 15 cm long terminals

Piezo-transducer (small)

Piezo-transducer (large)

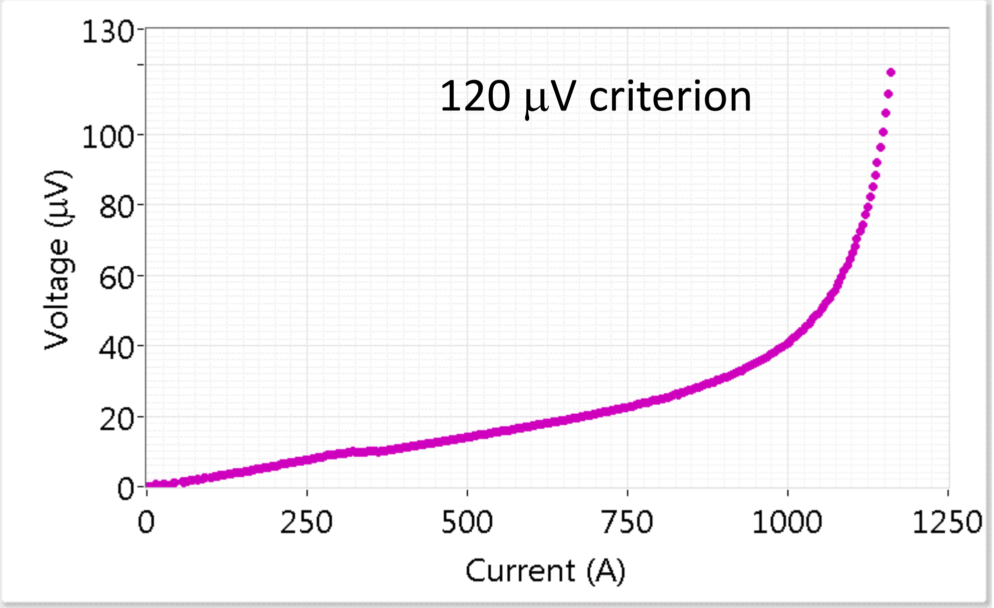
Hall sensor array

Spot heater

Wire-wound heater

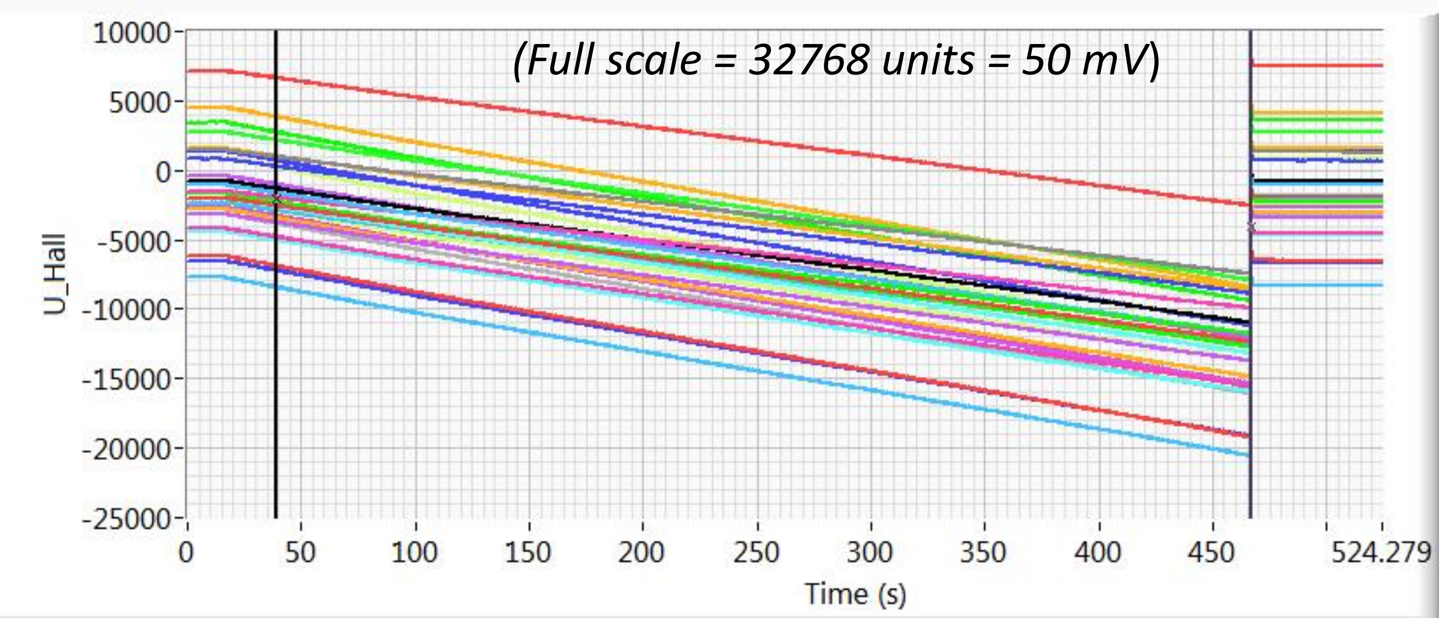
Current-Voltage characteristic and raw Hall signals

Liquid nitrogen bath conditions



Linear current ramp to 1150 A.

Signals are acquired at 1 kHz; then low-pass filtered at 100 Hz.



As Hall array is not perfectly aligned with respect to the wire, signals corresponding to B_x are still present.

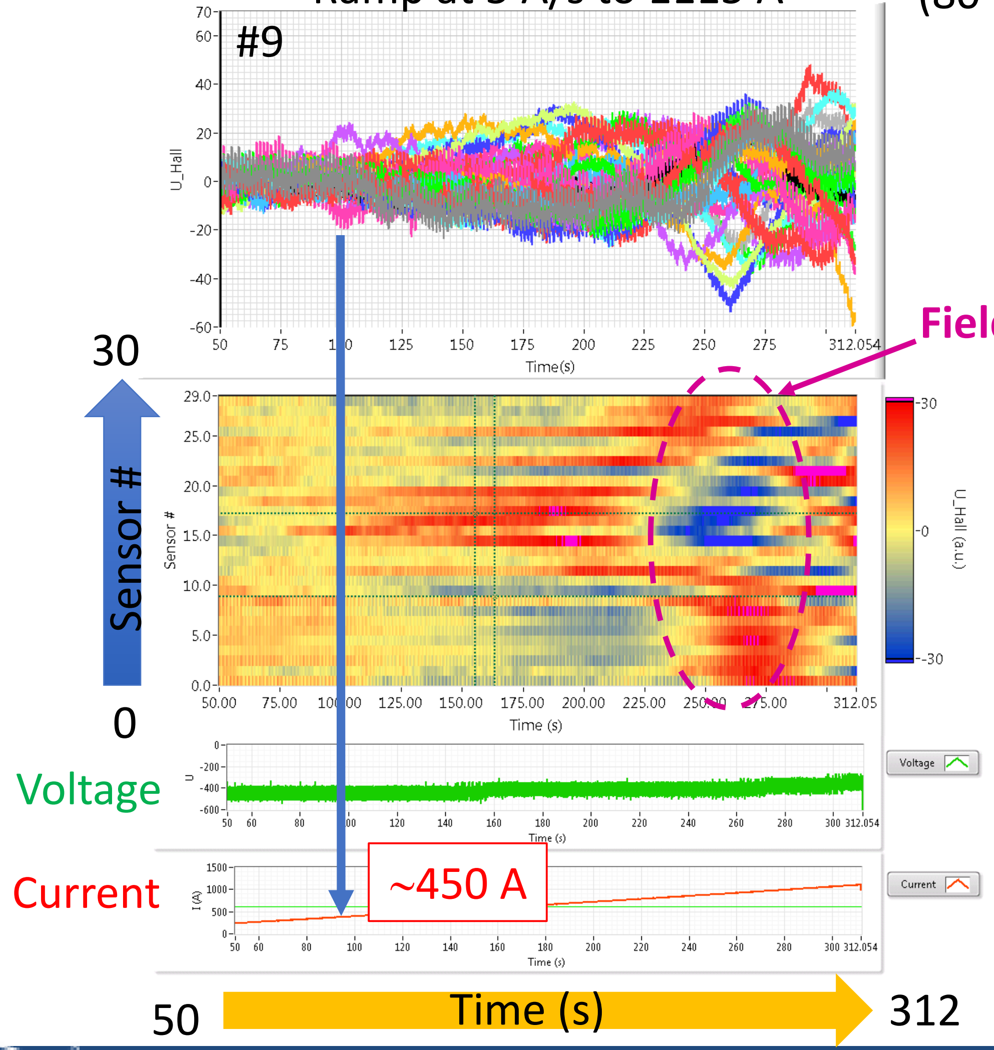
Post-processing:

- Straight line subtraction from each signal
- Remove offsets

Current re-distribution towards the transition

Ramp at 5 A/s to 1115 A

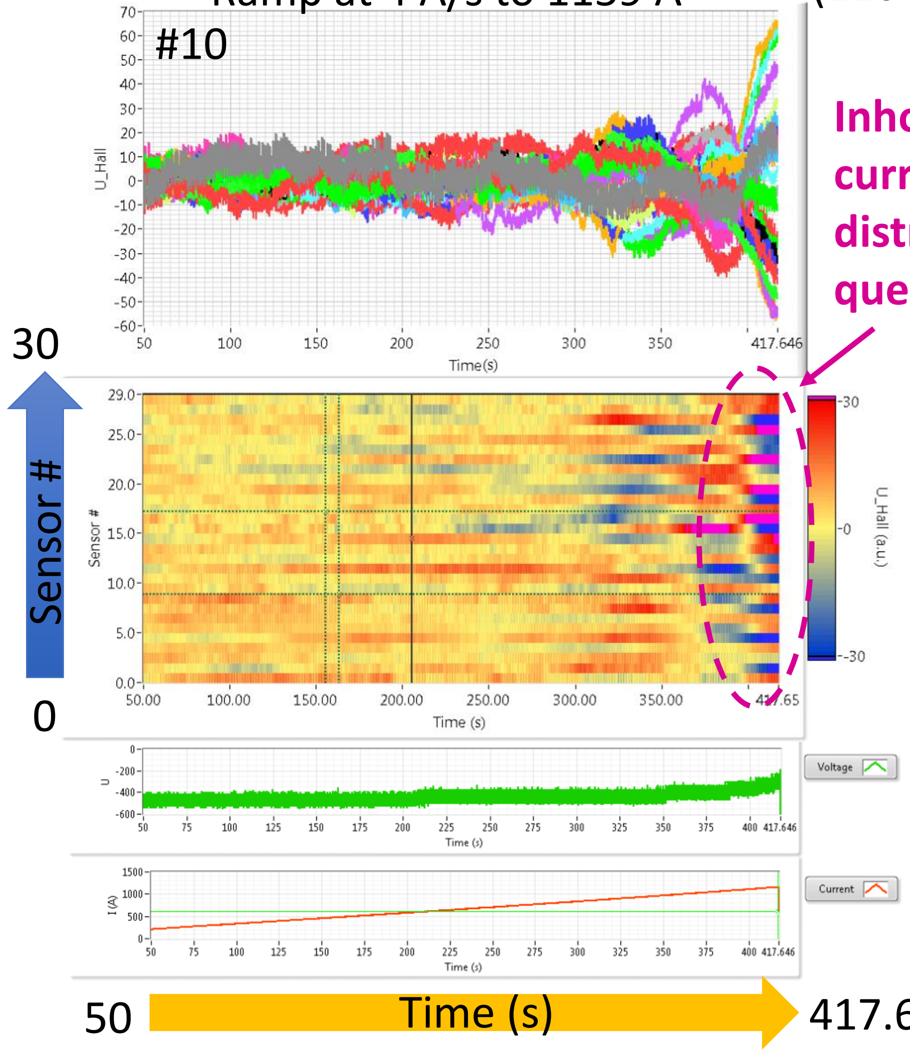
(80 μV criterion)



Field "leakage"

Ramp at 4 A/s to 1159 A

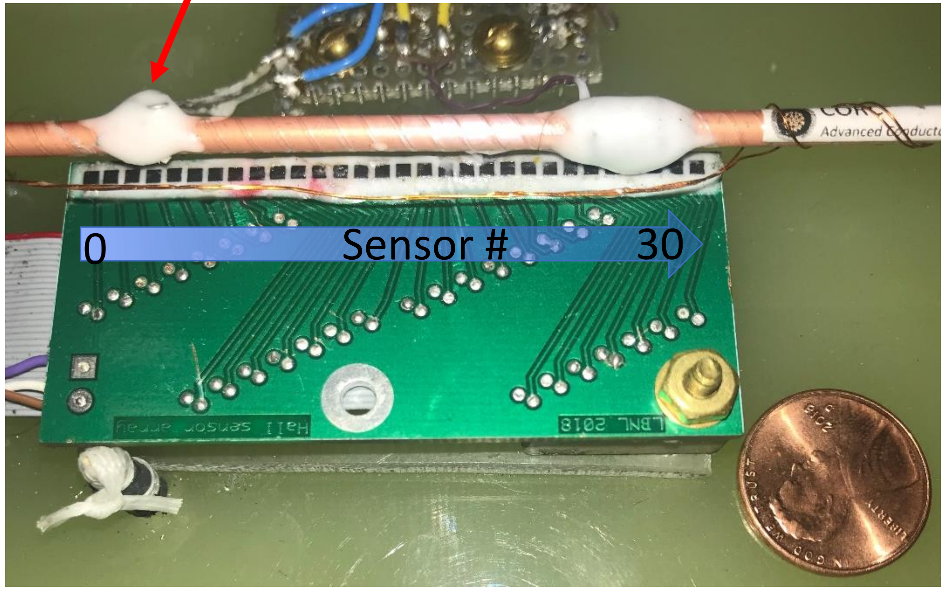
(120 μV criterion)

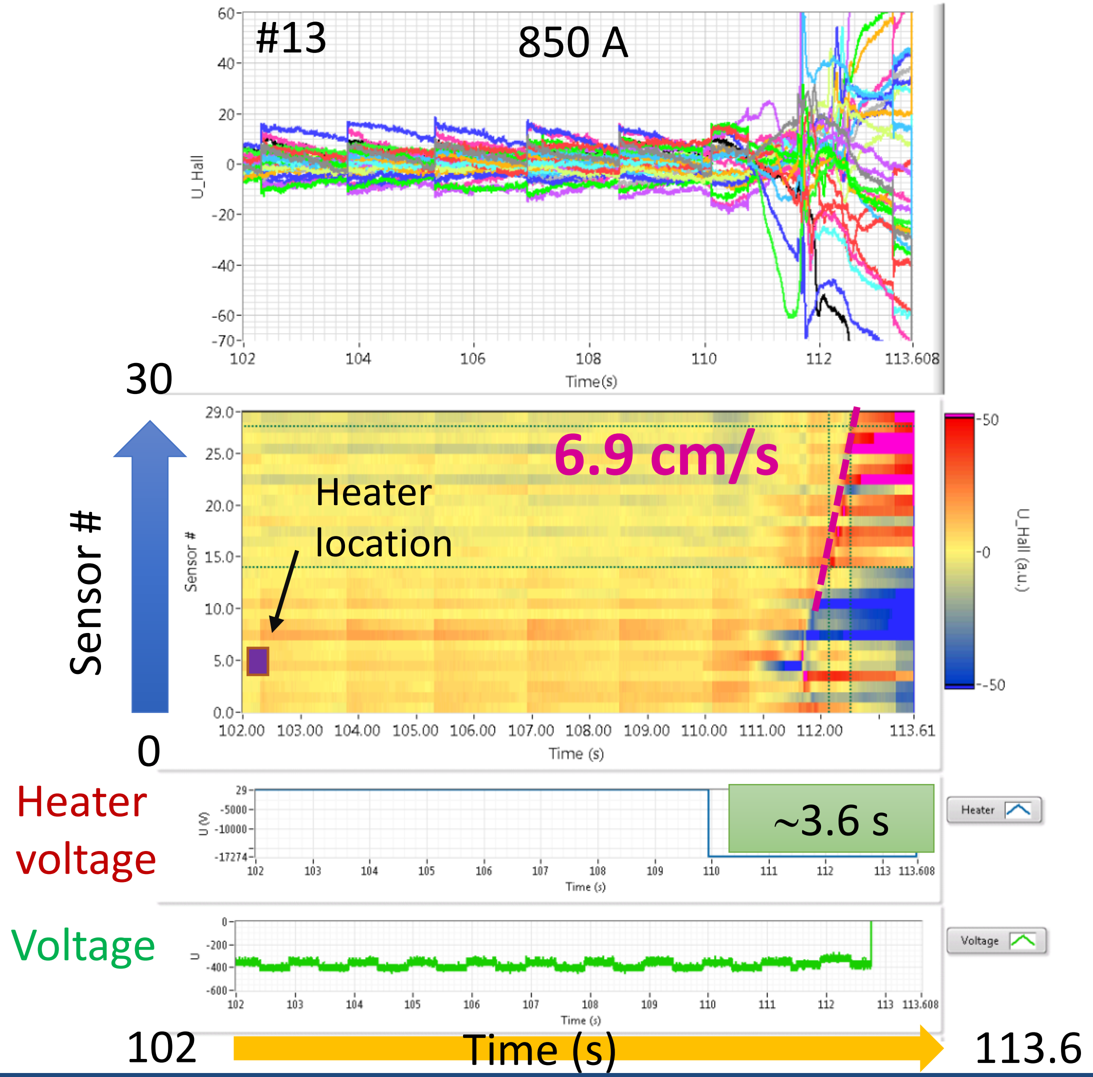


Inhomogeneous current distribution at quench

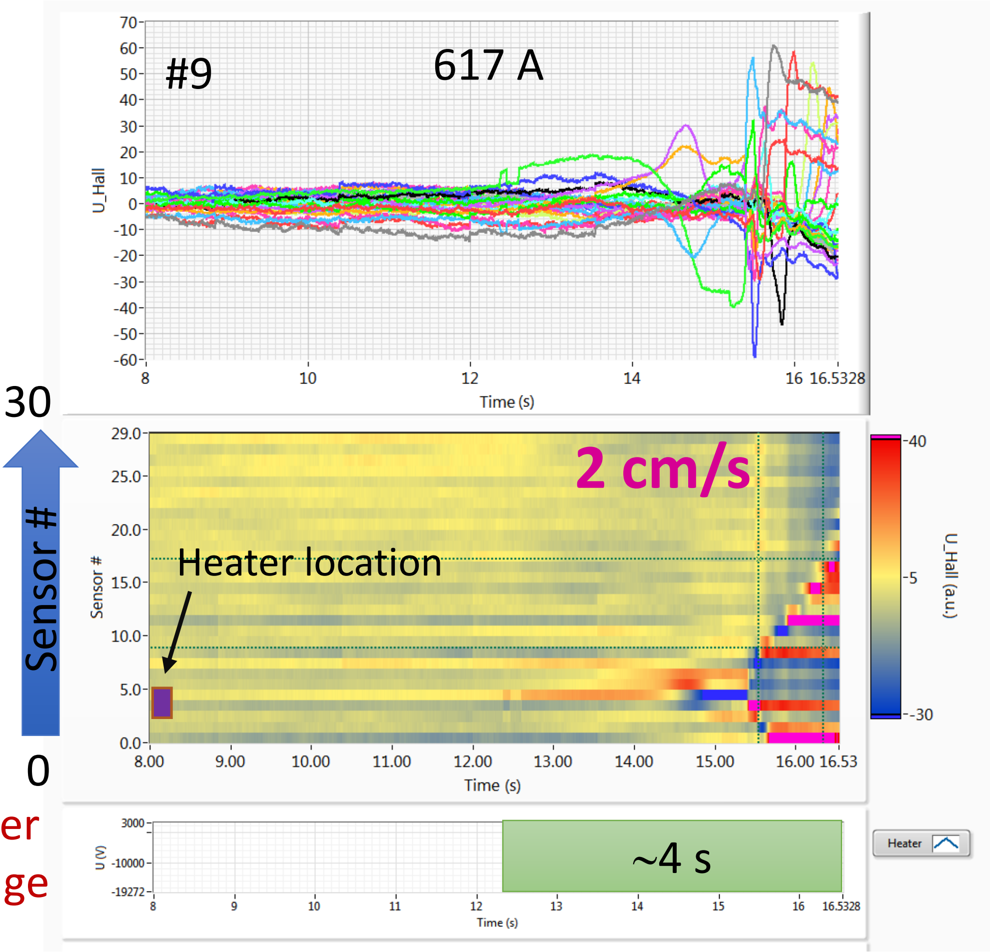
Heater-initiated quench (I)

Wire heater (~4 Ohm, bifilar chromel wire) is at sensor #4 location





Heater-initiated quench (II)



#9

617 A

2 cm/s

Heater location

~4 s

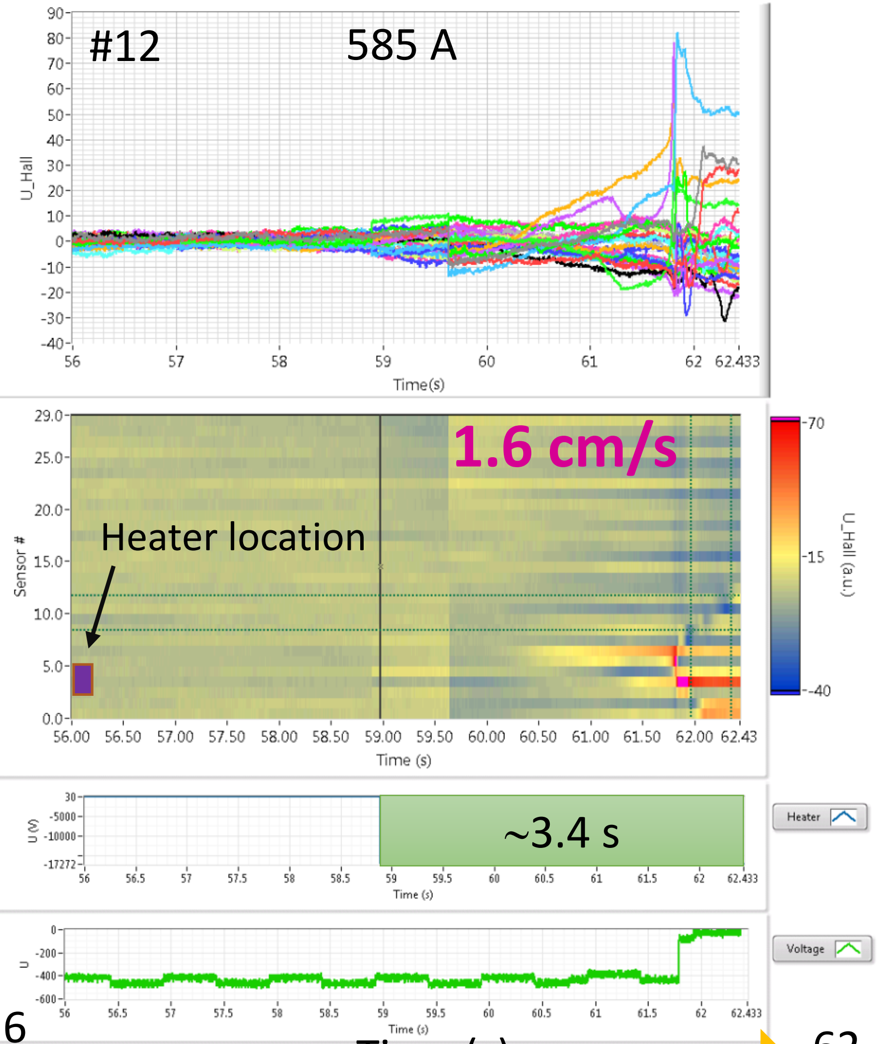
30

Sensor #

0

Heater voltage

8 Time (s) 16.5



#12

585 A

1.6 cm/s

Heater location

~3.4 s

30

Sensor #

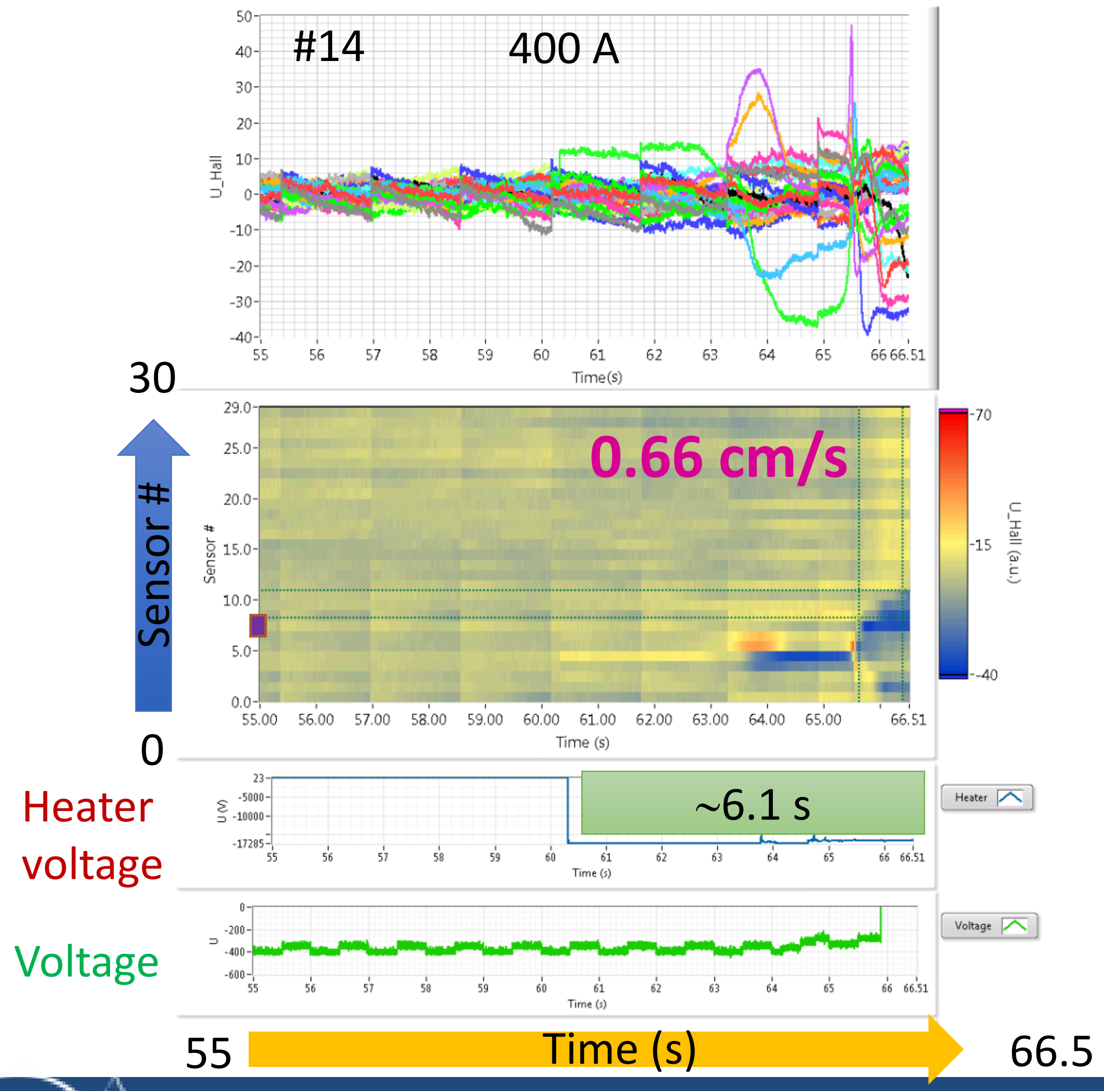
0

Heater voltage

Voltage

56 Time (s) 62.4

Heater-initiated quench (III)



#14 400 A

30

Sensor #

0

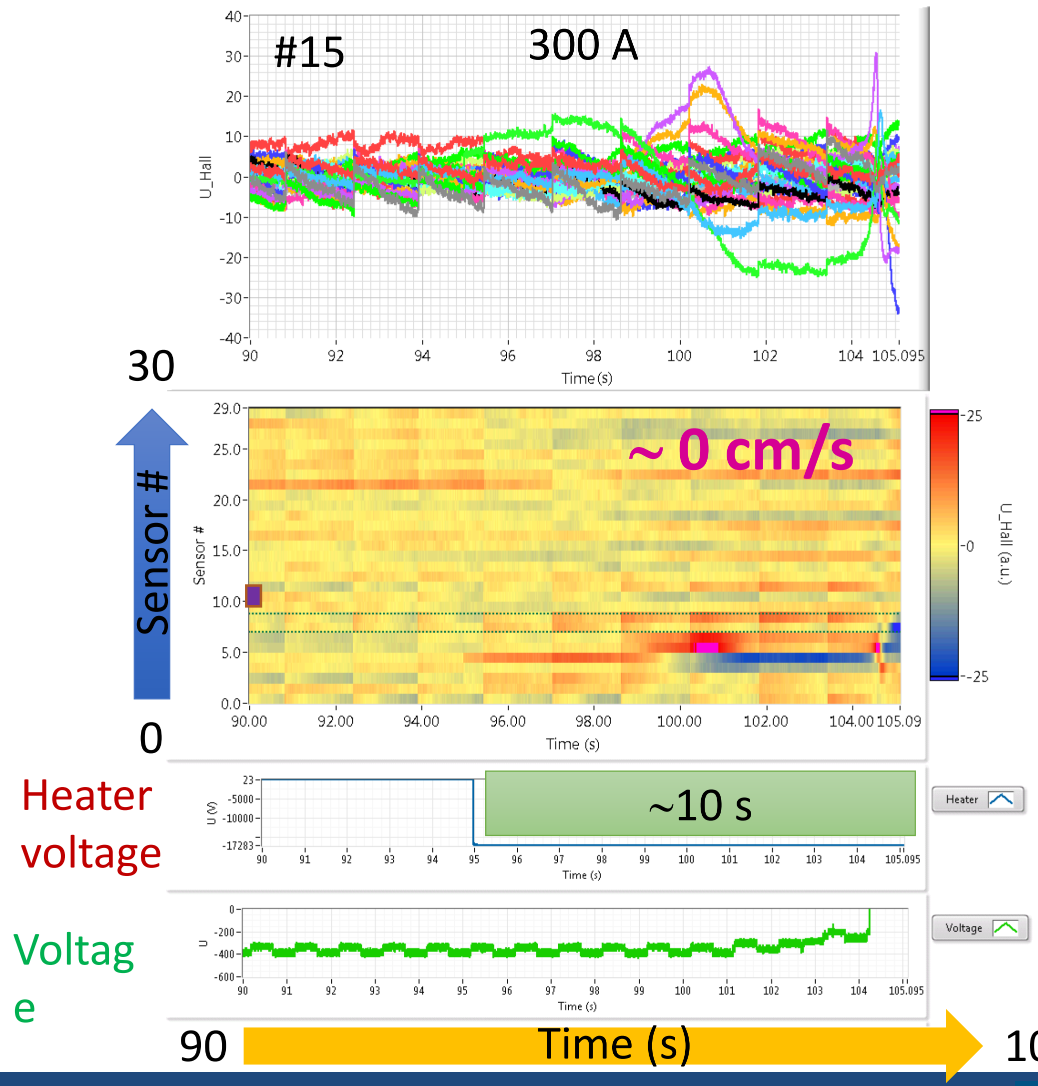
0.66 cm/s

Heater voltage

~6.1 s

Voltage

55 Time (s) 66.5



#15 300 A

30

Sensor #

0

~ 0 cm/s

Heater voltage

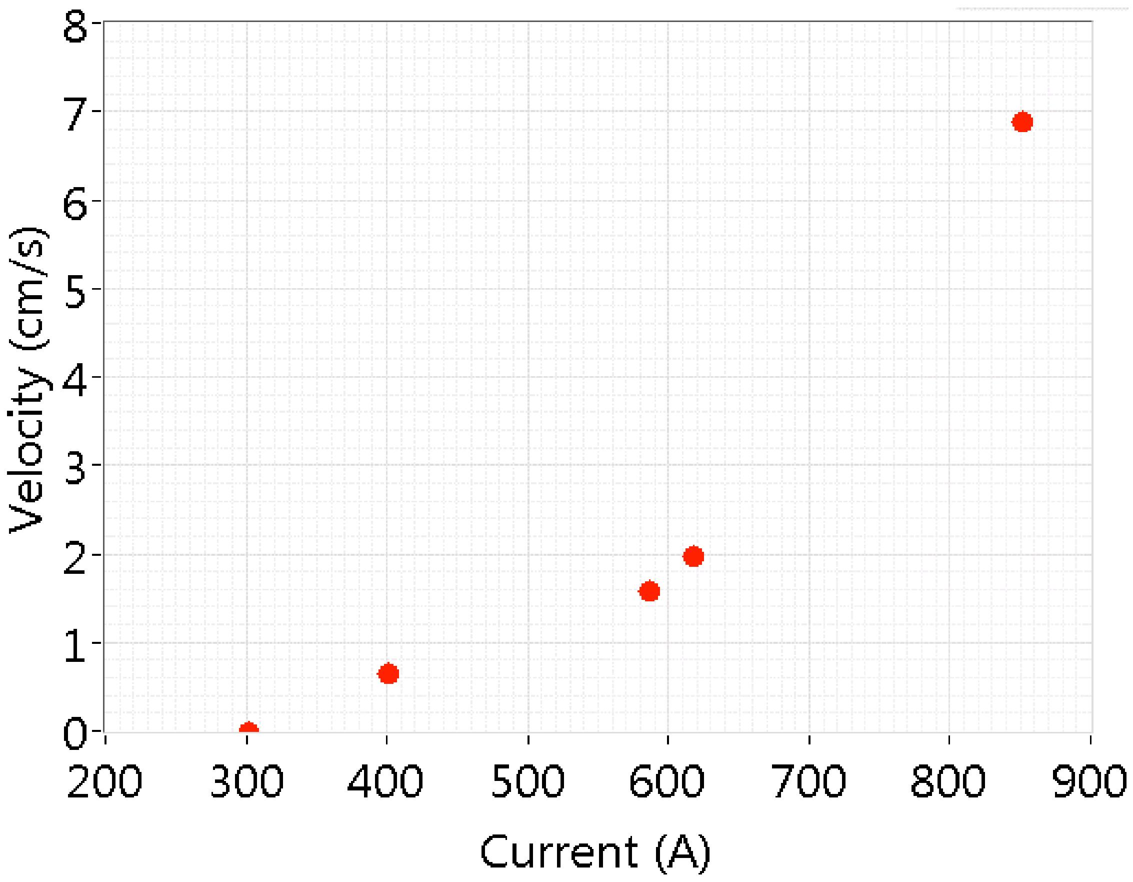
~10 s

Voltage

90 Time (s) 105.1

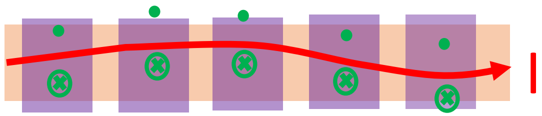
Non-propagating quench

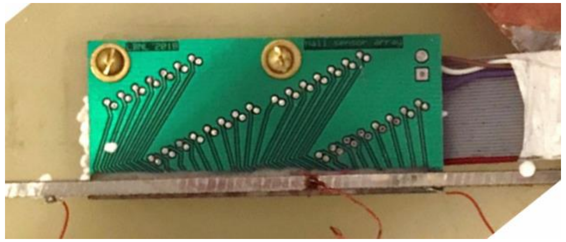
Quench propagation velocity summary

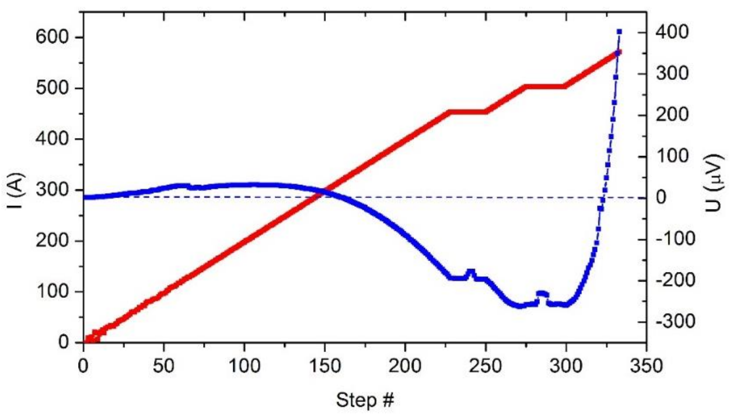


QPV appears to be somewhat higher than in bare HTS tape at similar conditions. Potentially, current sharing and reduced cooling capacity within the CORC® wire play a role here; we will investigate it further.

Heater firing experiments: generating non-propagating hot spots



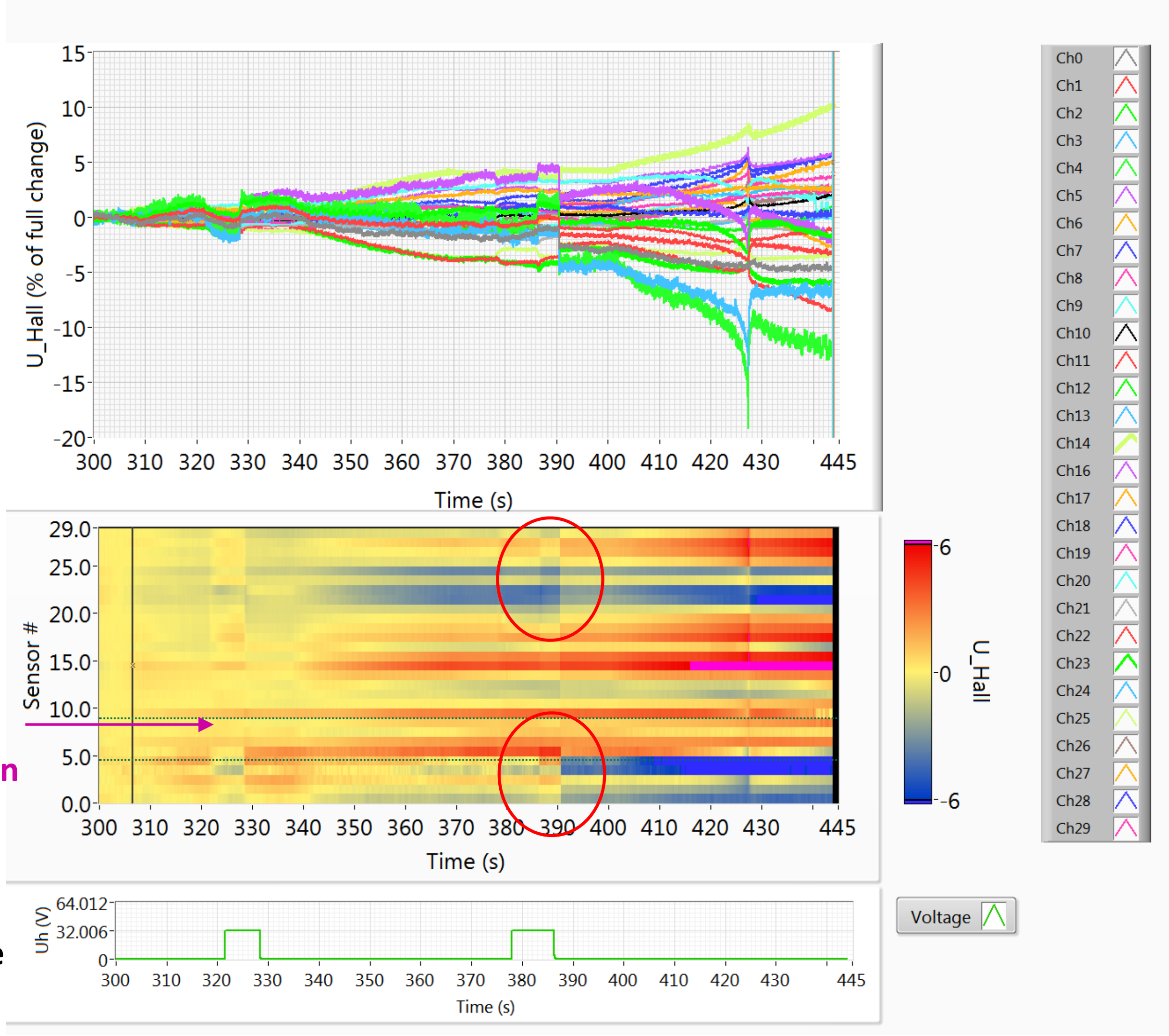




Brookhaven Technology Group

Heater location

Heater voltage

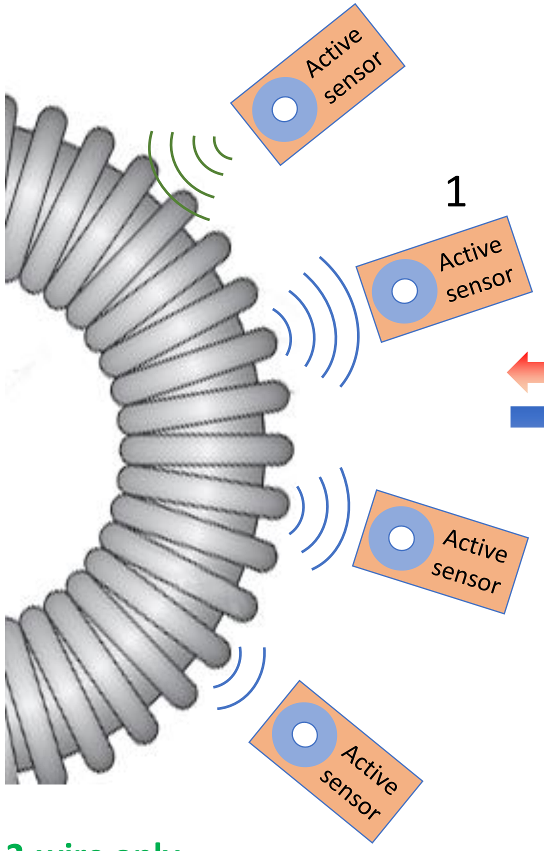


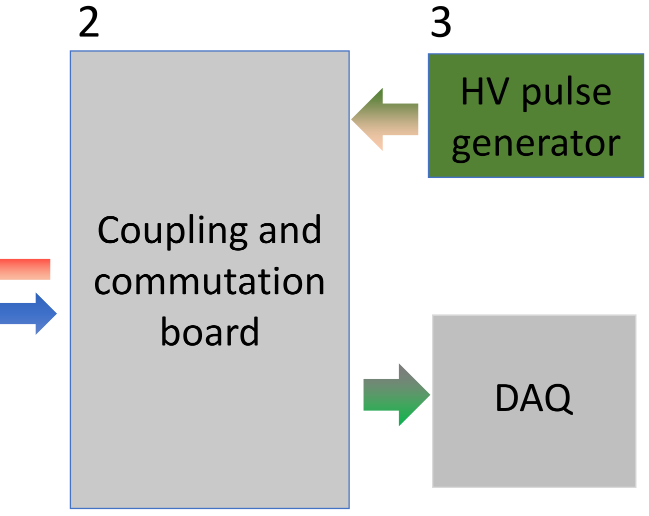
Current path changes irreversibly upon firing the heater (and not just at the heater location!)

Re-distributed current pattern is stable after heater is off

Future development highlights

Active acoustic diagnostics system for hot spot localization




2

Coupling and commutation board

3

HV pulse generator

DAQ

A **next-generation** acoustic system **will enable all advantages of acoustic diagnostics in a single package.** Pulse will be applied to the piezoelectric element of one sensor while the rest of the sensor array is listening. This allows for:

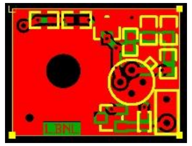
- ***Real-time monitoring and localization of hot spots and thermal gradients***

as well as:

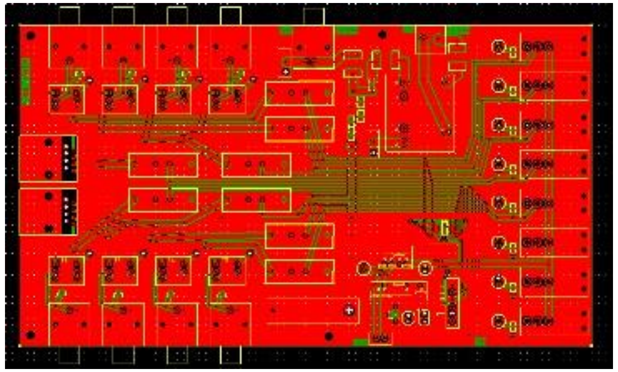
- ***Real-time monitoring of mechanical interfaces and fault development***
- *Precise mapping of sound speed across the magnet for* ***accurate triangulation of mechanical disturbances****.*

2-wire only sensor interface for power, signal out and pulse-in

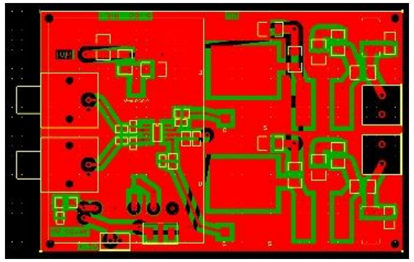
1



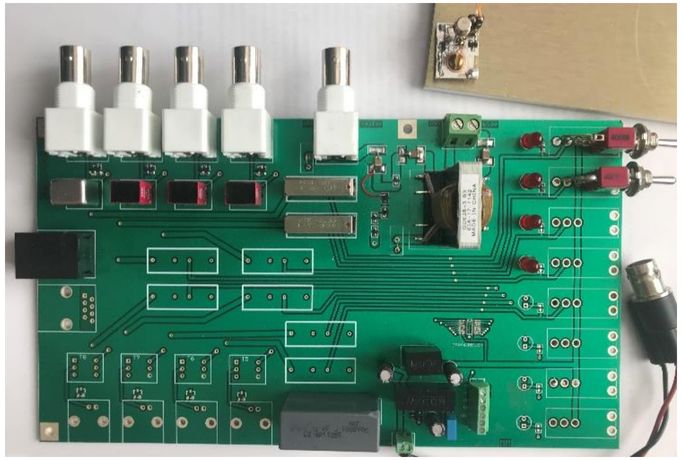
2 PCB designs



3

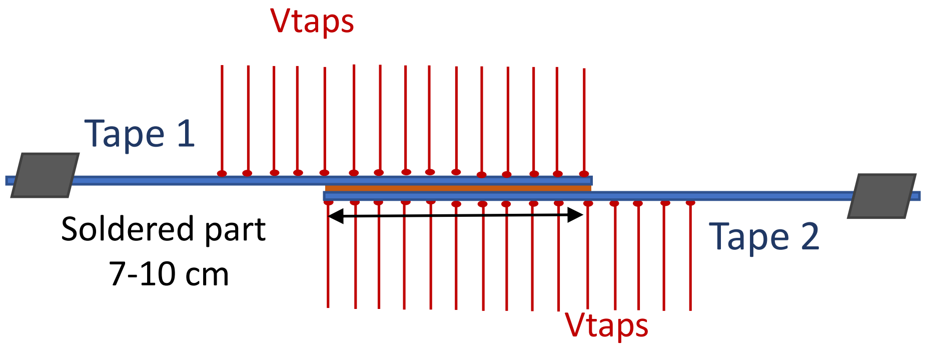


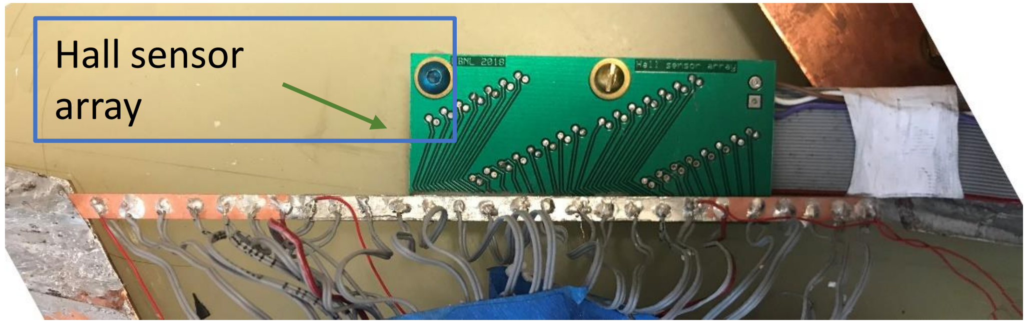
The boards are being assembled and tested



Understanding current distribution in stacked tape arrays and developing new QD approaches based on Hal array sensing

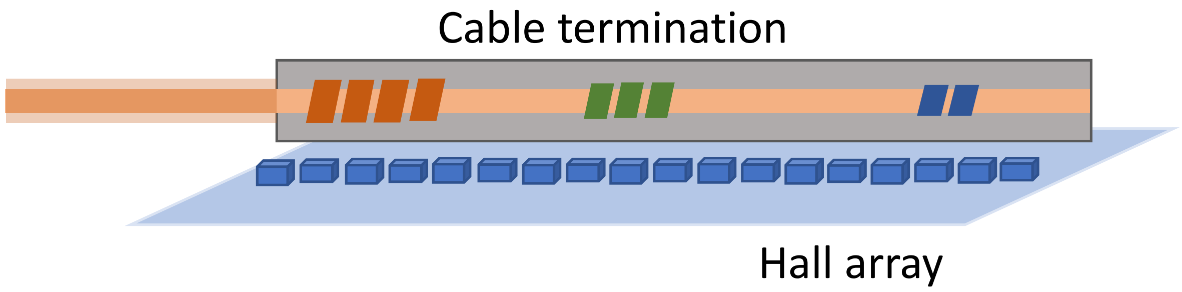
- **New experiments are underway on stacked/soldered ReBCO tapes where current sharing is monitored simultaneously using Hall sensor and voltage tap arrays**





Stacked and soldered ReBCO tapes and ExoCable stacks; the joint area is monitored with a 30-sensor Hall array while voltage distribution is measured with an array of voltage taps at both sides of the stack.

- **Using Hall sensors to detect current re-distribution around the terminals of the CORC© wire caused by formation of a normal zone**



M. Marchevsky et al., "Quench detection method for 2G HTS wire", Supercond. Sci. Technol. ***23*** *034016 (2010)*

Ongoing projects related to HTS / fusion

- Advanced Conductor Technologies
  - SBIR (DOW FES, Phase 1) on Smart Terminals for CORC© cable ($60K)
  - STTR (Phase 1) on developing active acoustic QD system for US NAVY ($90K)
- Commonwealth Fusion Systems
  - Sponsored project on developing acoustic QD for fusion cables ($69K)
- Brookhaven Technology Group
  - Collaboration on styling current sharing in ExoCable© tape stacks
- Technology Commercialization Fund (DOE)
  - Localization of hot spots in solids using acoustic waves ($150K)