Quench detection progress

M. Marchevsky, R. Teyber, G. S. Lee

LBNL

Outline

- Introduction

Quench detection techniques under development:

  - Ultrasonic techniques
  - RF techniques
  - Hall probe (magnetic) techniques – R. Teyber

- Probing cable interfaces
- Magnet protection by active control of current distributions

- Summary

Quench detection problem

Quench detection in HTS YBCO wire is a serious engineering problem. It is due to a very slow (0.1 – 1 cm/s) normal phase propagation velocity (10^3-10^4 times less than in LTS wires!), resulting in a formation of the localized hotspots.

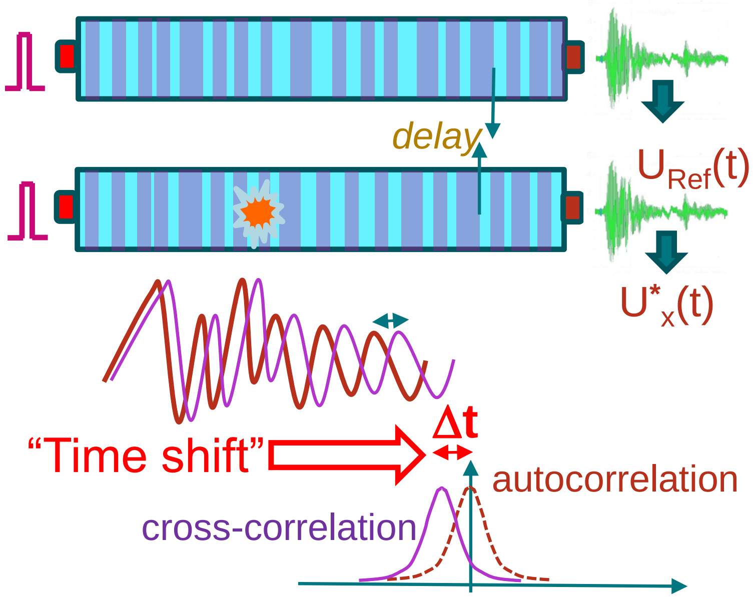
These hotspots are hard to detect, as significant local heating occurs there prior to the surrounding region transition to the normal state and onset of measurable resistance.

- Non-voltage, **non-invasive methods** are sought to replace the traditional voltage-based detection and improve redundancy

The best protection strategy appears to be **avoiding quenching altogether** (which means very first onset of dissipation. The later can be done by various means, thermal and magnetic being most promising. Using different techniques in synergy is likely required to achieve reliable detection and eliminate false positives.

Ultrasonic techniques

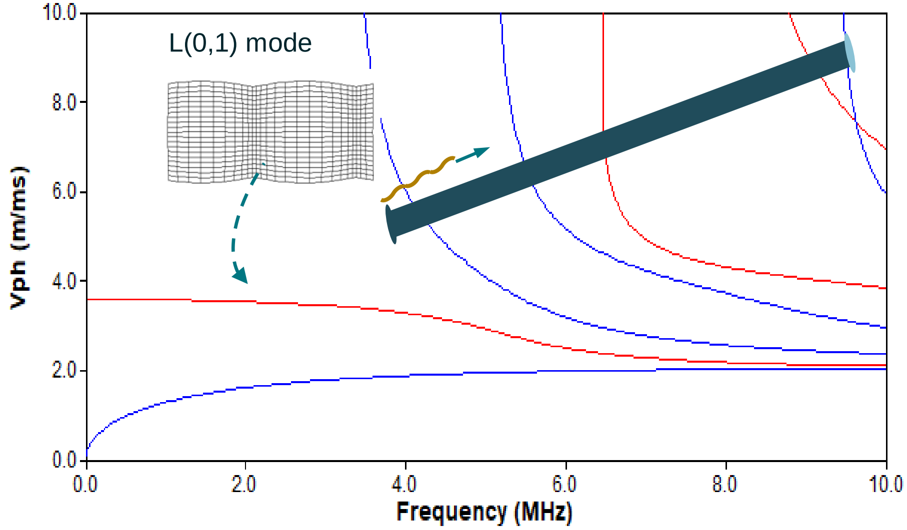
Acoustic waveguide sensors for quench detection



$$E(T) = E_0 - s/\left[e^{t/T} - 1\right]$$

(s, t – adjustable parameters)

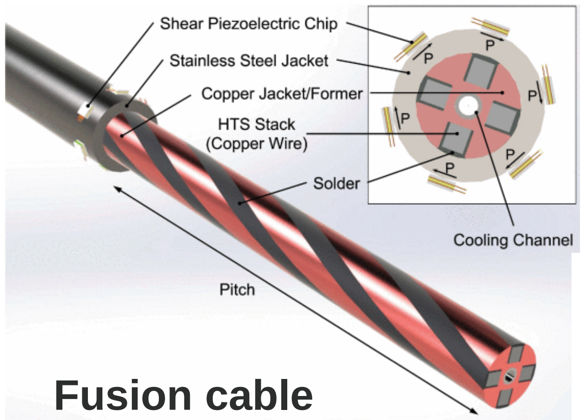
Diffuse ultrasound => guided ultrasound



Longitudinal mode in thin cylinder (wire) is very weakly dispersive and allows for the high fidelity transmission of ultrasonic signals.

- Longer probing distance
- Ability to localize the hot spot

Acoustic reflectometry for Viper cable and HTS tape (G.S. Lee)

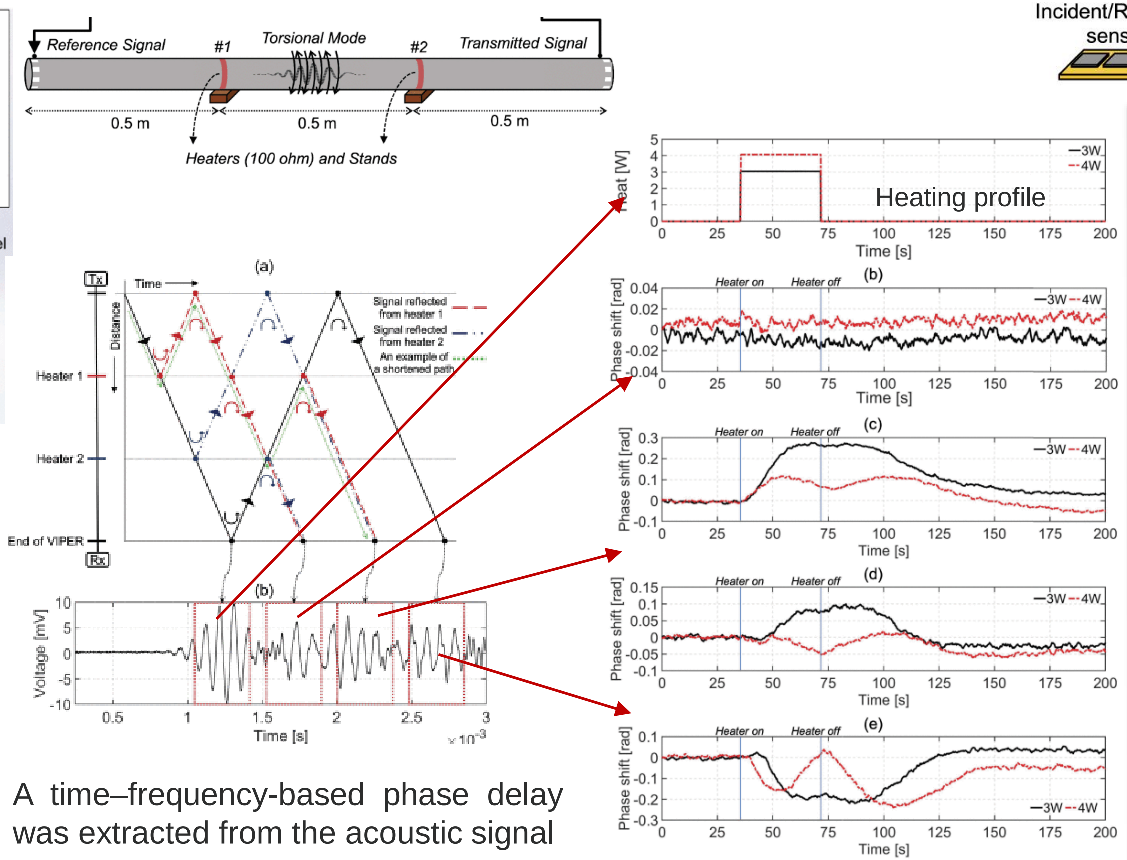


Fusion cable

- **Torsional acoustic wave** is non-dispersive and not affected by the gas or liquid in the central channel
- Method is suitable for **hollow cylinder-shaped structure**
- Acoustic reflectometry can detect **the location and magnitude of heating.**

ARPA-E “BETHE”

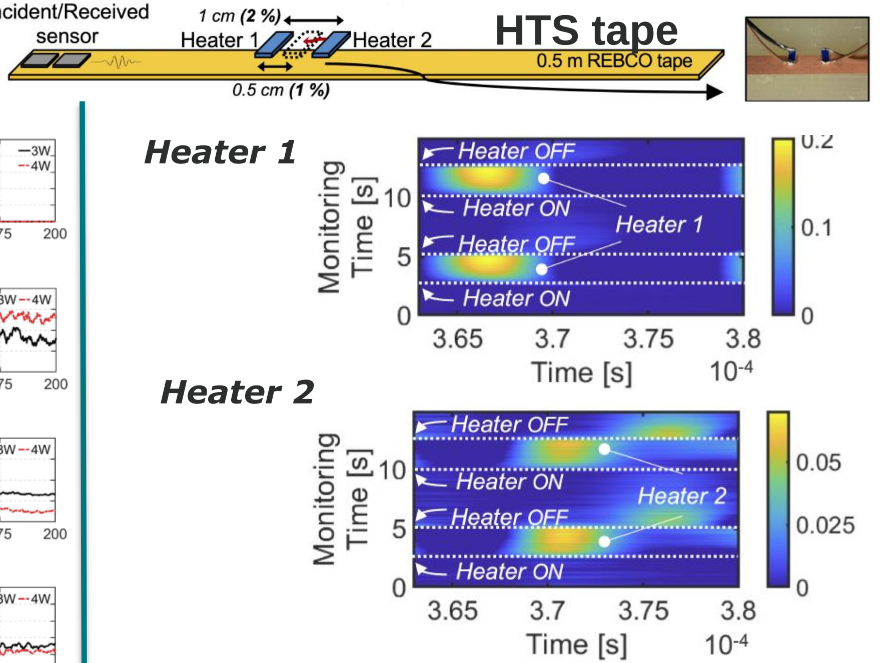
COMMONWEALTH FUSION SYSTEMS



A time–frequency-based phase delay was extracted from the acoustic signal

TF-based phase (Heater #1)

“Time–Frequency-Based Quench Detection for HTS VIPER Cable Using Torsional Acoustic Wave”, ***G.S. Lee****, M. Marchevsky, C. Sanabria, and S. Prestemon, IEEE Sensors, v. 22 (22), (2022)*

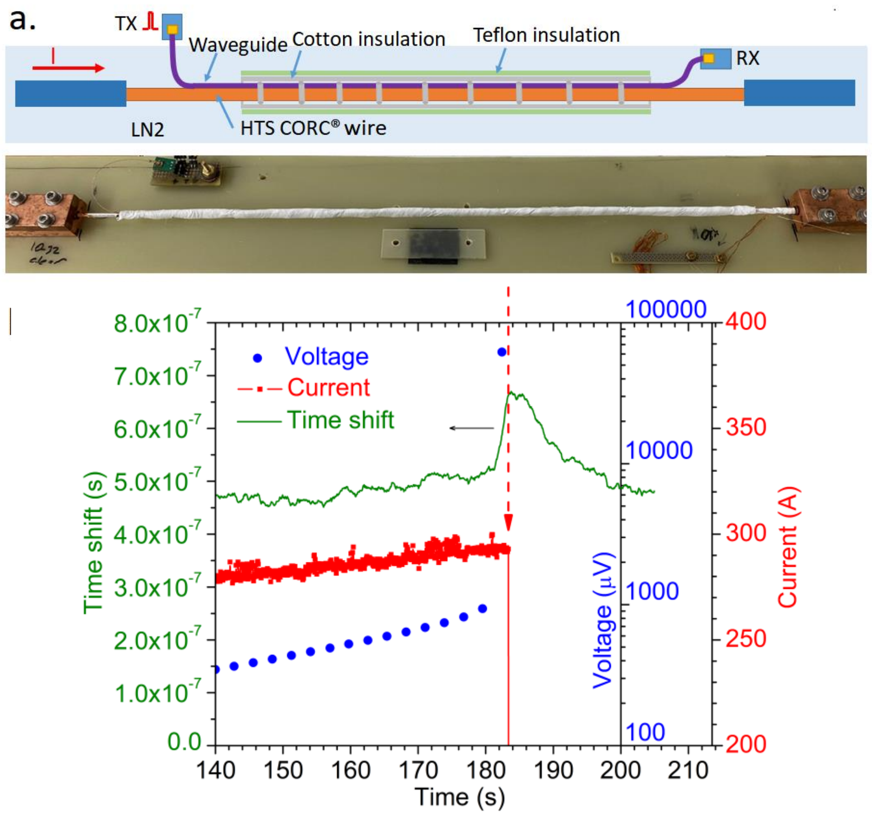


HTS tape

- **Shear Horizontal wave** is non-dispersive and suitable for **tape structure.**
- The time-frequency domain analysis yields spatial resolution to better than 1% of the sample length.

"Quench Localization for High-Temperature Superconductor 2G Tape using Acoustic Reflectometry,” ***G.S. Lee****, M. Marchevsky and S. Prestemon, IEEE Trans .Appl. Supercond., http://dx.doi.org/10.1109/TASC.2023.3245560*

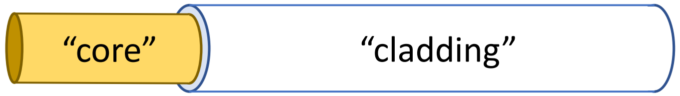
Quench detection with acoustic fibers

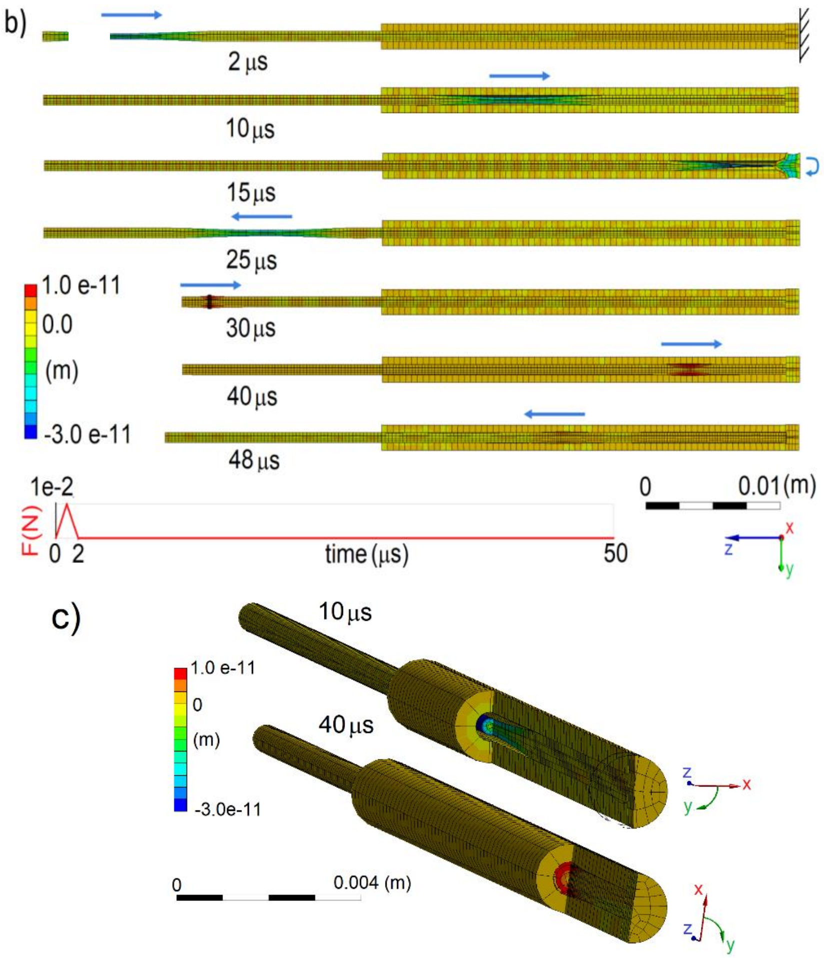


"Ultrasonic Waveguides for Quench Detection in HTS Magnets." M. Marchevsky, S. Prestemon, O. Lobkis, R. Roth, D. C. van der Laan, and J. D. Weiss, IEEE Trans. Appl. Supercond., 32, 4701705, (2022)

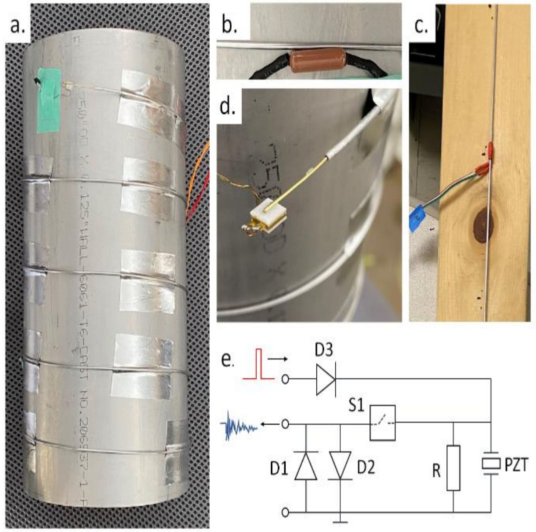
Can acoustic wave be confined inside the waveguide?

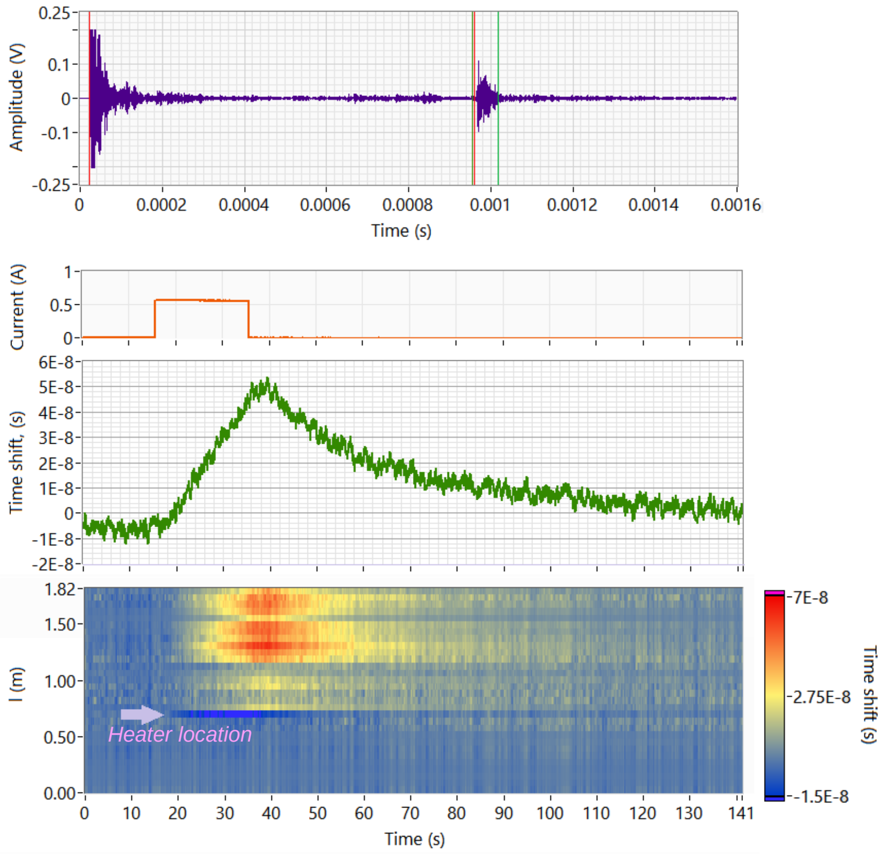
Yes!

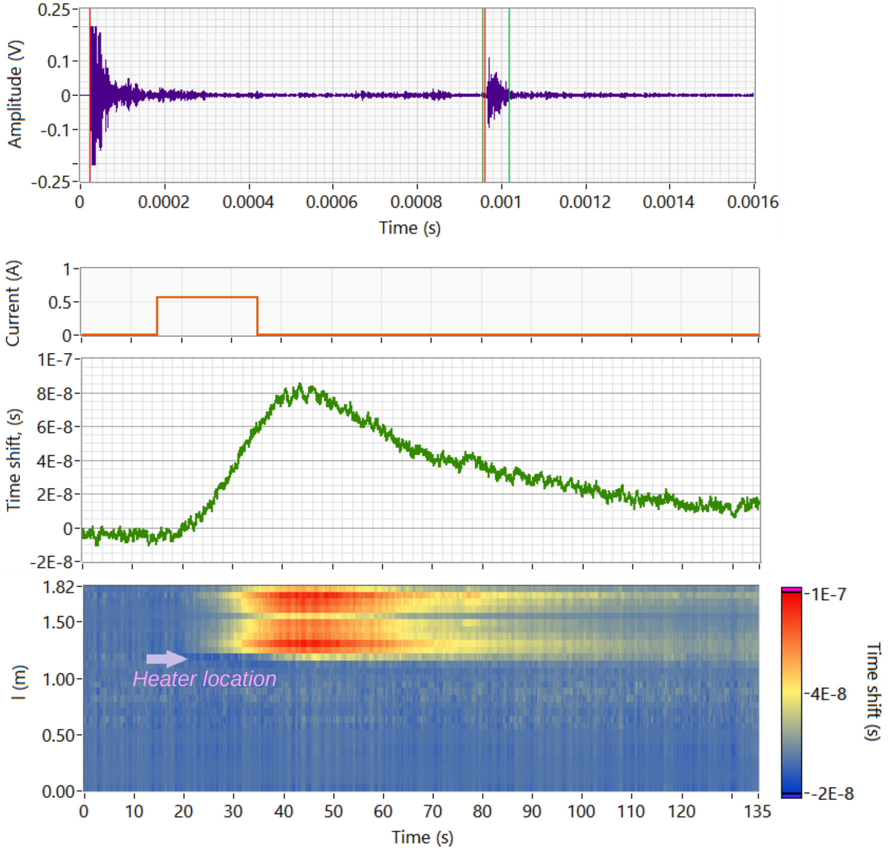




A “non-leaky” acoustic waveguide is suitable for the practical integration of distributed thermometry into HTS magnets



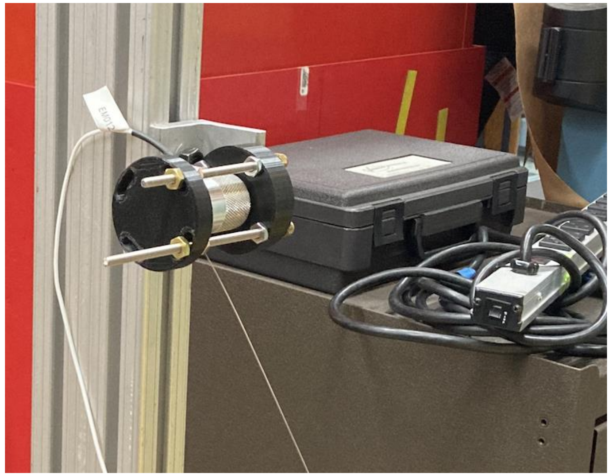


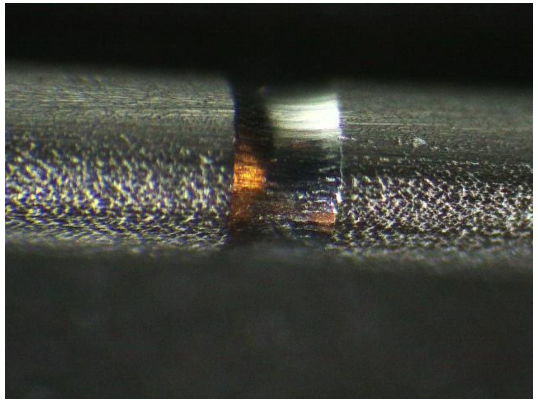


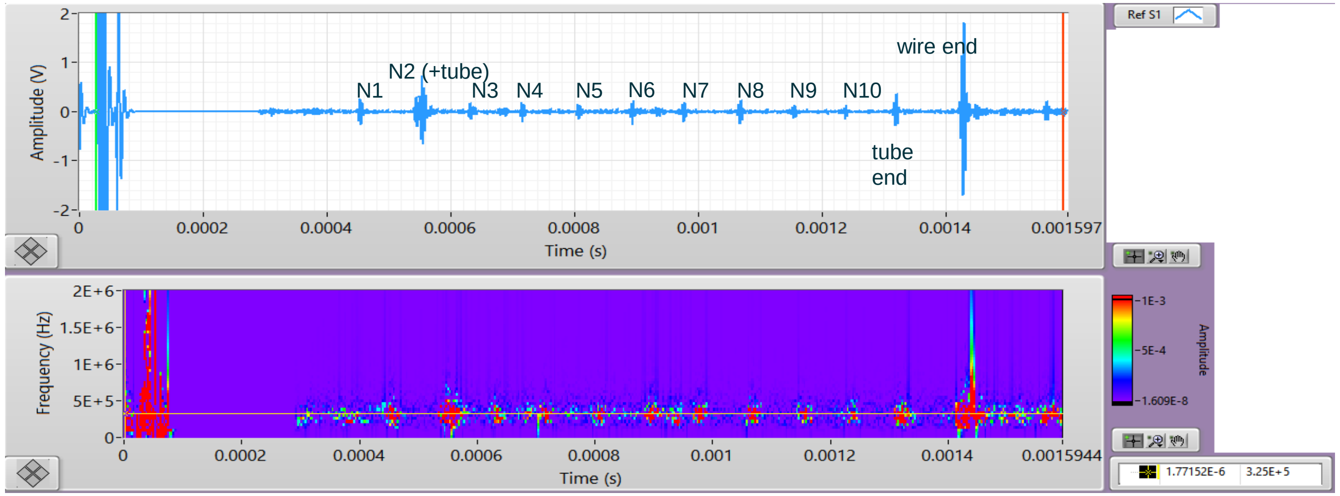
“Distributed thermometry for superconducting magnets using non-leaky acoustic waveguides”,
M. Marchevsky and S. Prestemon, Supercond. Sci. Technol. 36 045005, doi:10.1088/1361-6668/acb23a

Tests of a 3.4 m-long acoustic fiber sensor

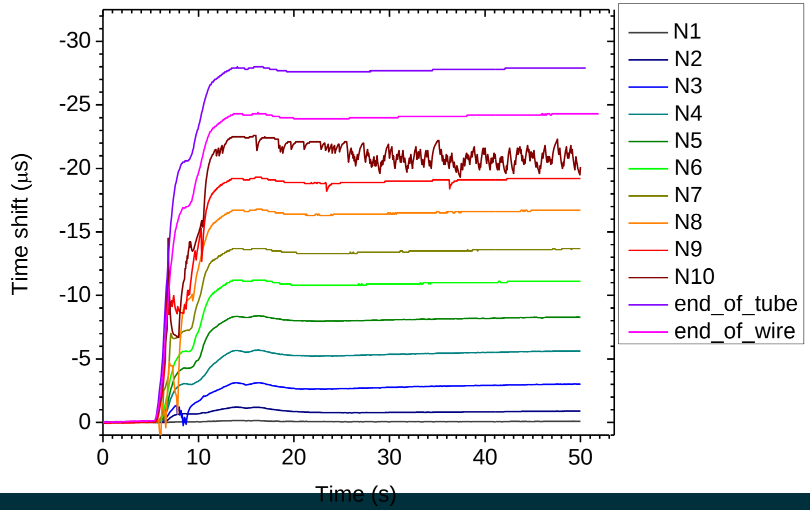
- **SBIR Phase I project with Etegent Technologies**



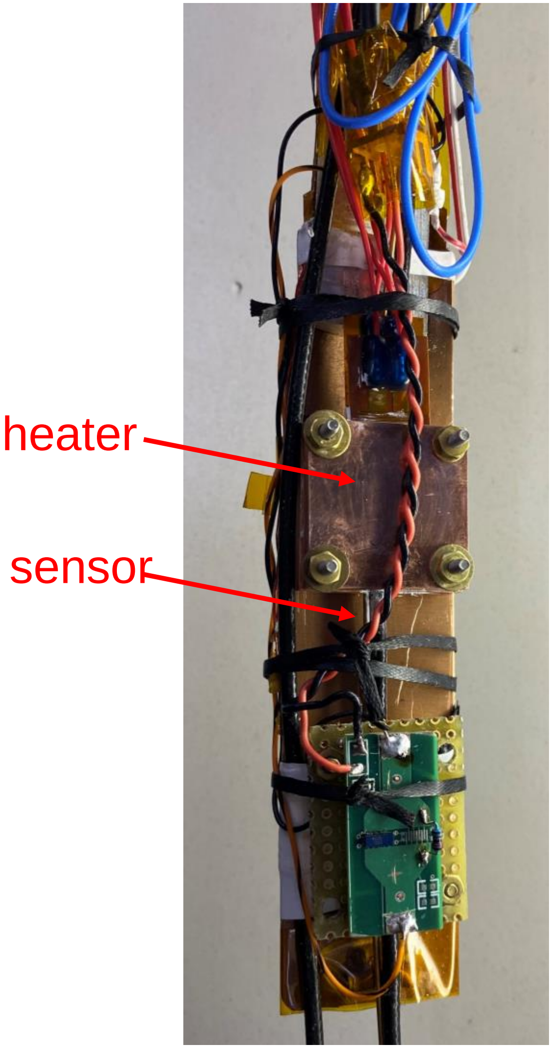




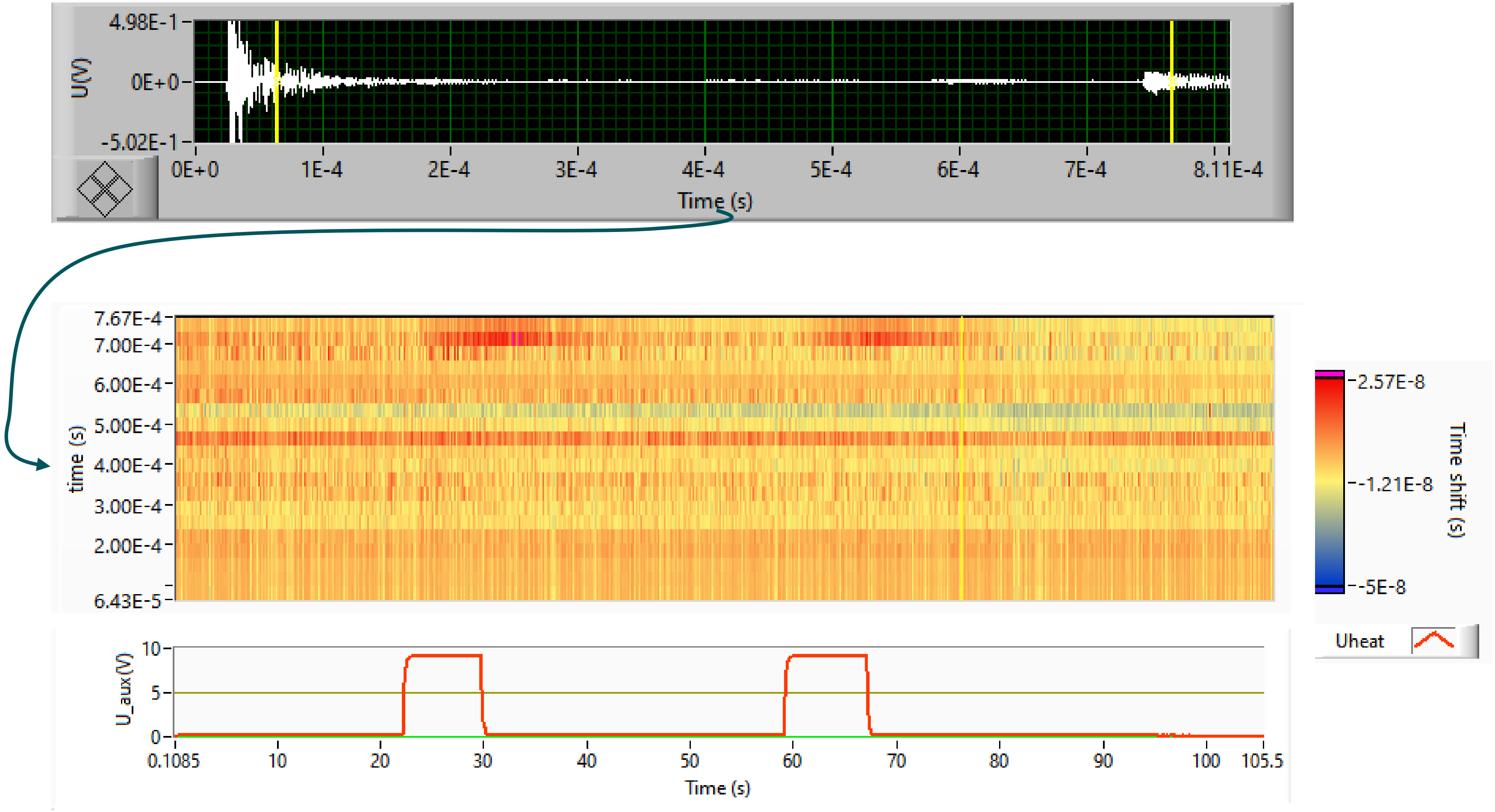
Time shift over cooldown to 77 K



Test at 6 K

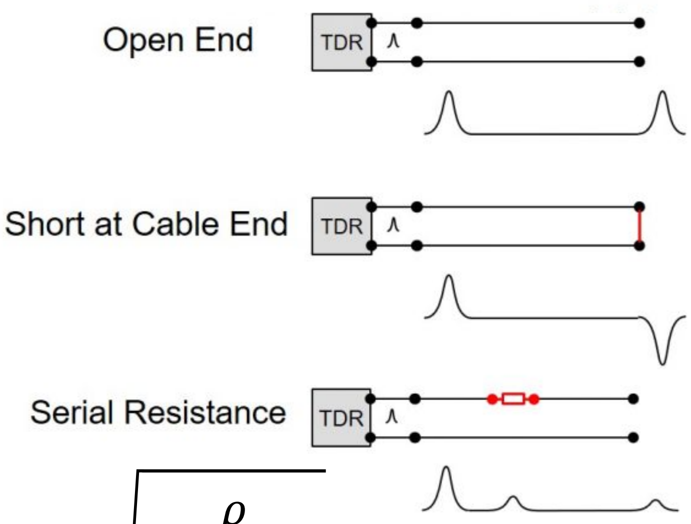


ΔT ~ 4 K (from 6 K to 10 K)

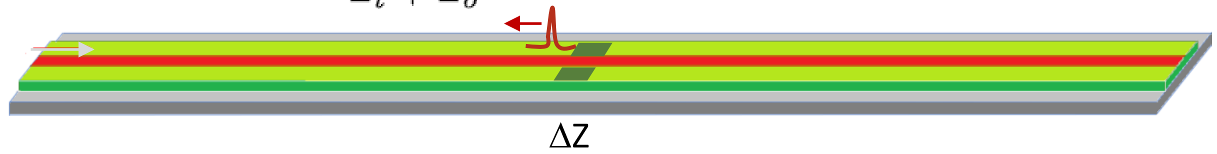


RF-based techniques

Radio-frequency TDR sensors

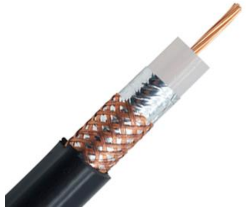


$$\rho = \frac{Z_t - Z_o}{Z_t + Z_o}$$



Coaxial cable

The typical characteristic impedance is 50 Ω

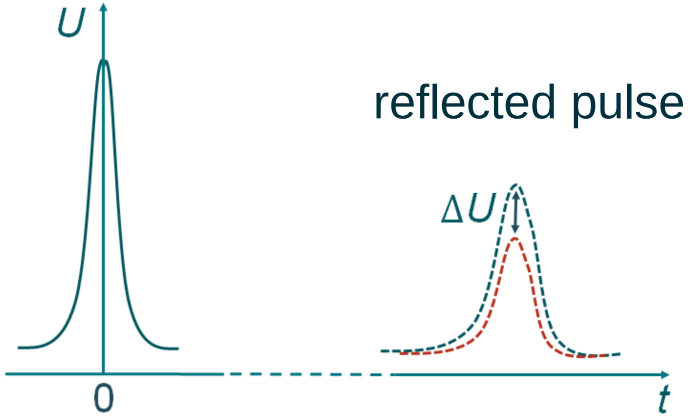


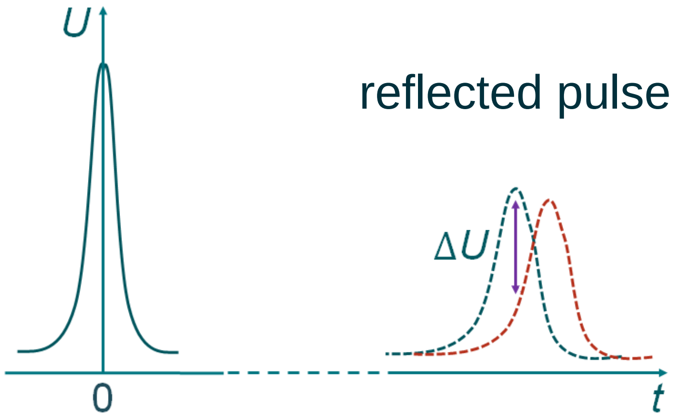
$$Z = \sqrt{\frac{L}{C}} = \frac{1}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0 \varepsilon_r}} \ln\left(\frac{b}{a}\right)$$

$$\delta = \sqrt{\frac{\rho}{2\pi f \mu_R \mu_0}}$$ - skin depth

Change in amplitude

(variation of impedance)

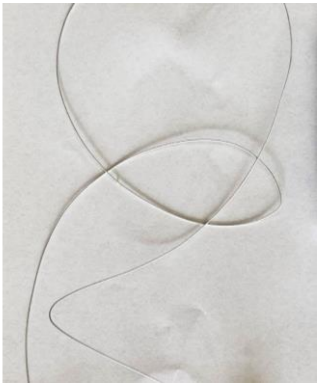




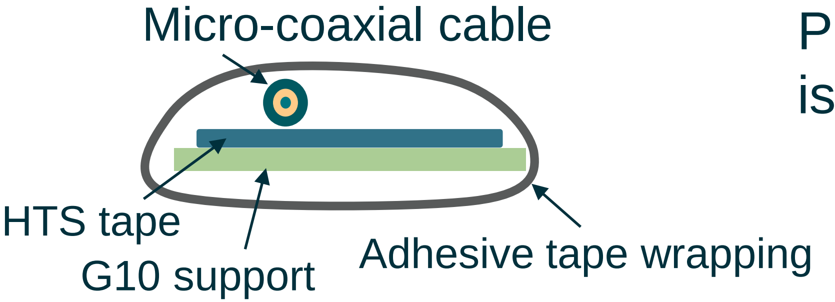
Change in position

(variation of length)

Thermal quench sensing using micro-coaxial cable



- 32 AWG (0.2 mm central conductor, 1.1 mm diameter) micro-coaxial cable, PFA insulation)



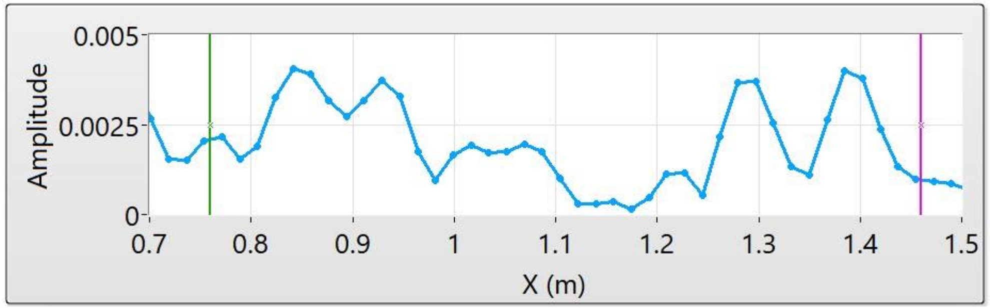
Micro-coaxial cable

HTS tape

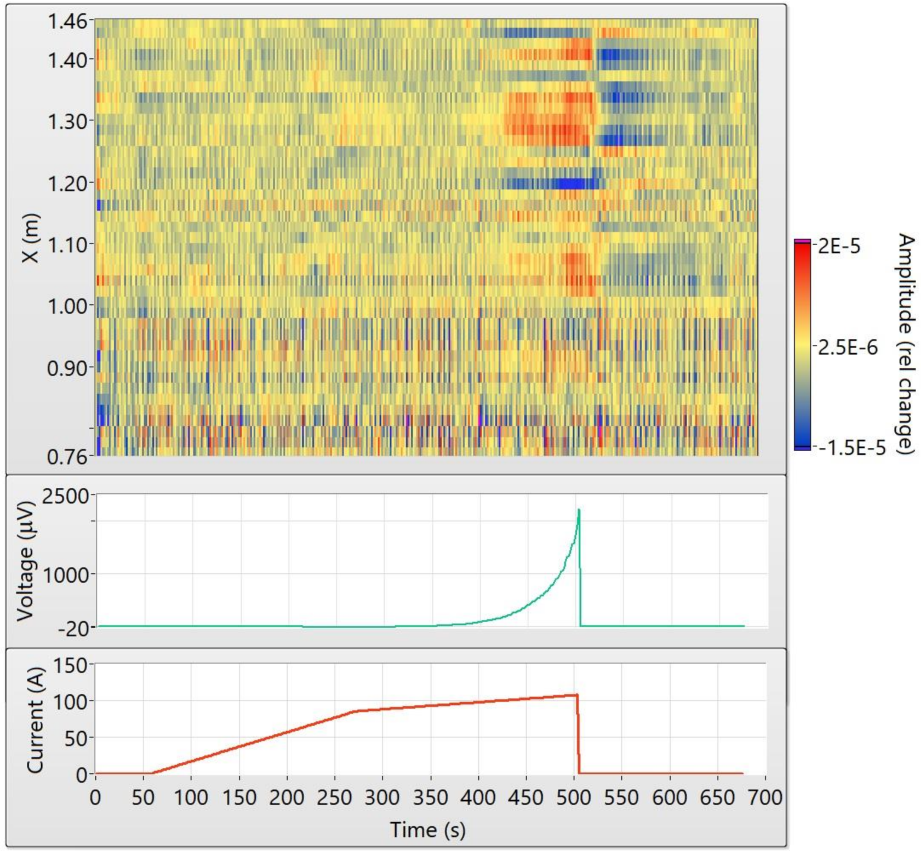
G10 support

Adhesive tape wrapping

Peak power is 0.24 W



Plotting a derivative of the change allows to better separate local variations from the background.



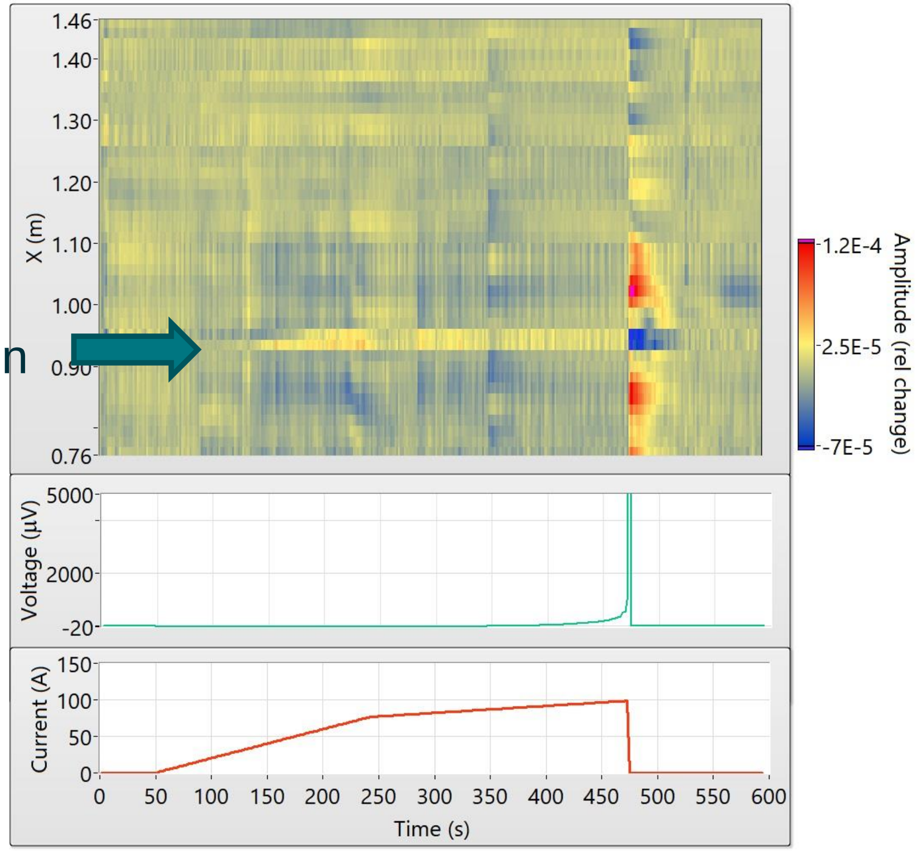
Thermal quench sensing using micro-coaxial cable

Permanent magnet (~ 0.1 T surface field)

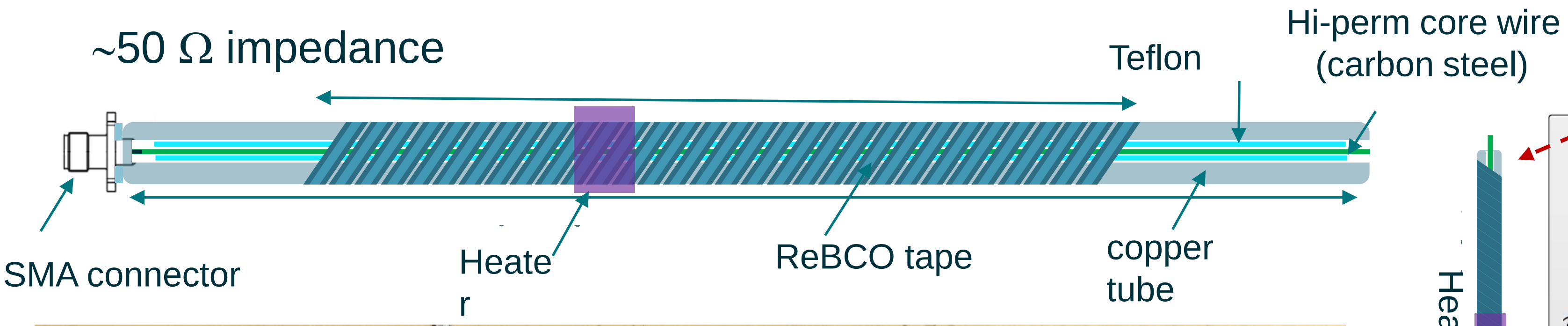
Placing a permanent magnet next to the tape reduced critical current locally, leading to a quench development at ~100 A

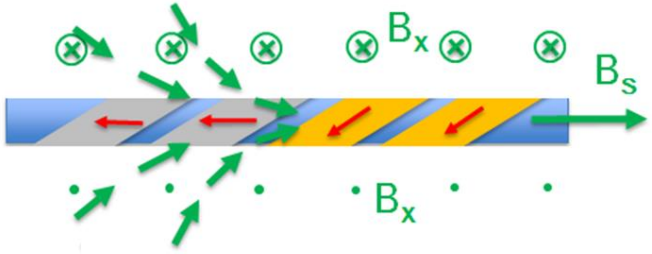
Heat distribution along the tape has changed, and a large heated area has been observed centered at the magnet position.

Magnet position

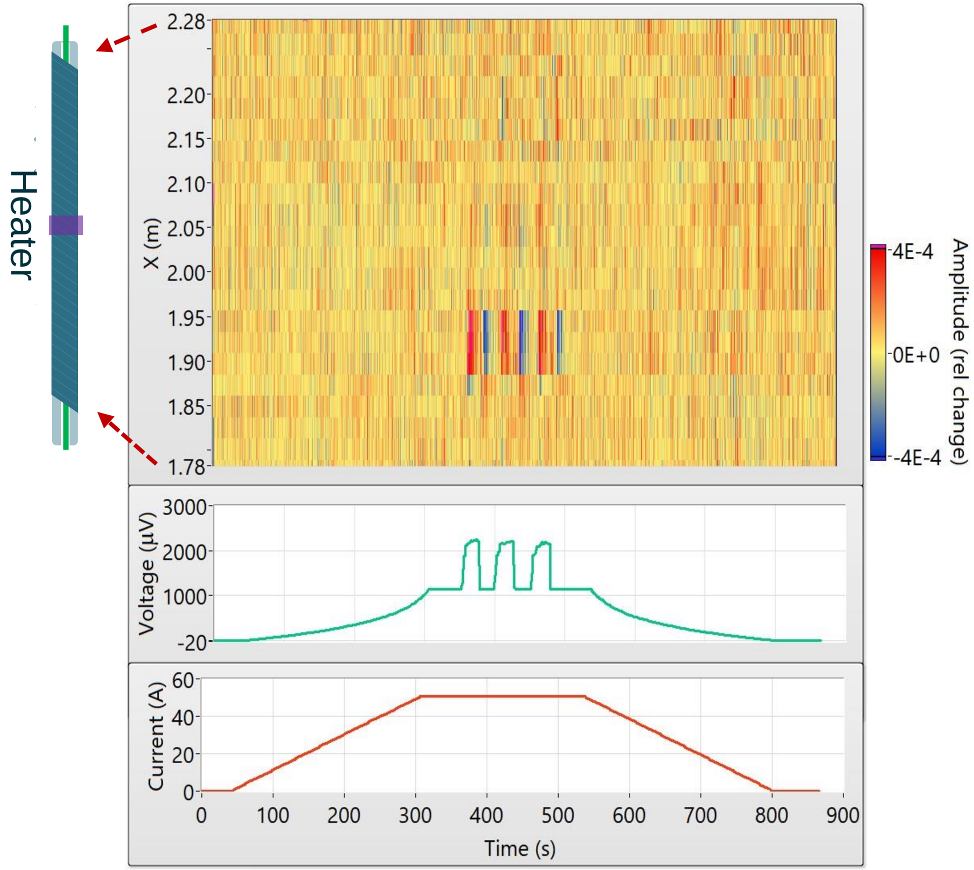


Magnetic TDR sensor



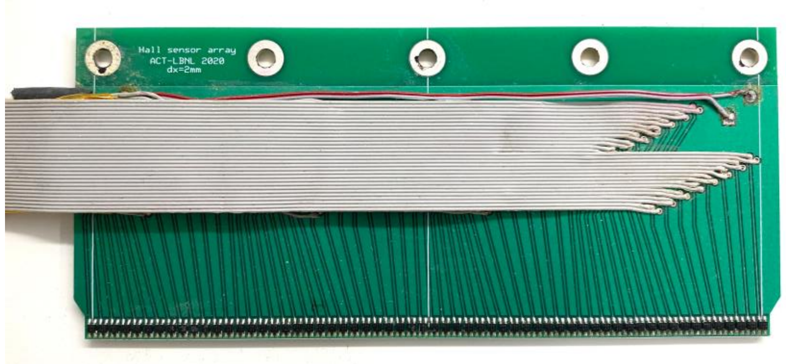


- The giant magnetoimpedance effect present in soft magnetic materials, causes significant changes in ac impedance through μ(B) dependence of the skin depth. Local variation of magnetic inductance, caused by current re-distribution around the normal zone can therefore be detected

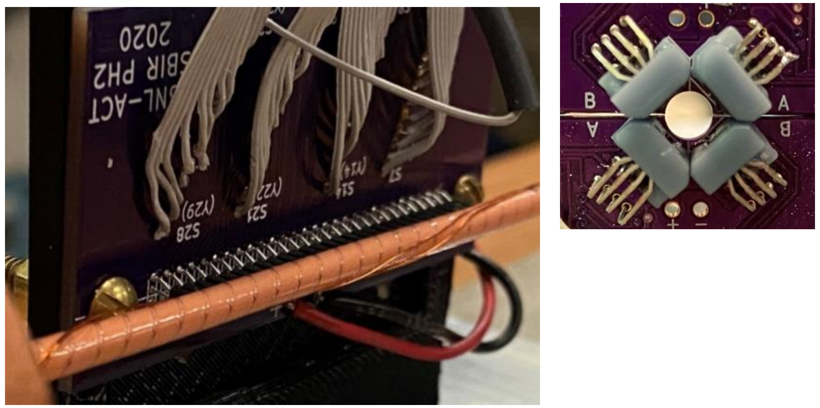


Magnetic techniques

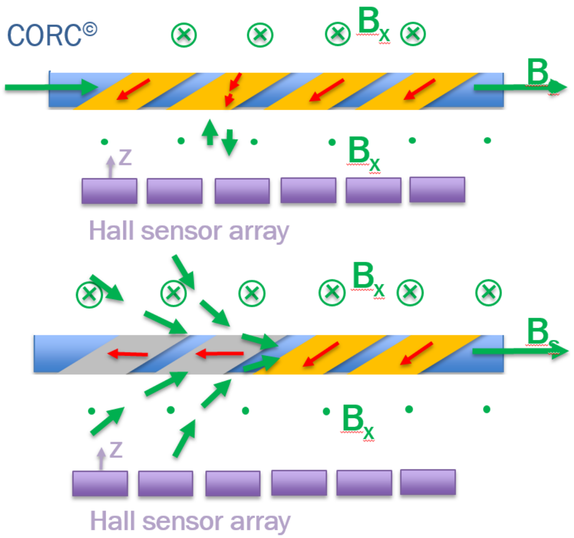
HTS cable diagnostics using Hall sensor arrays



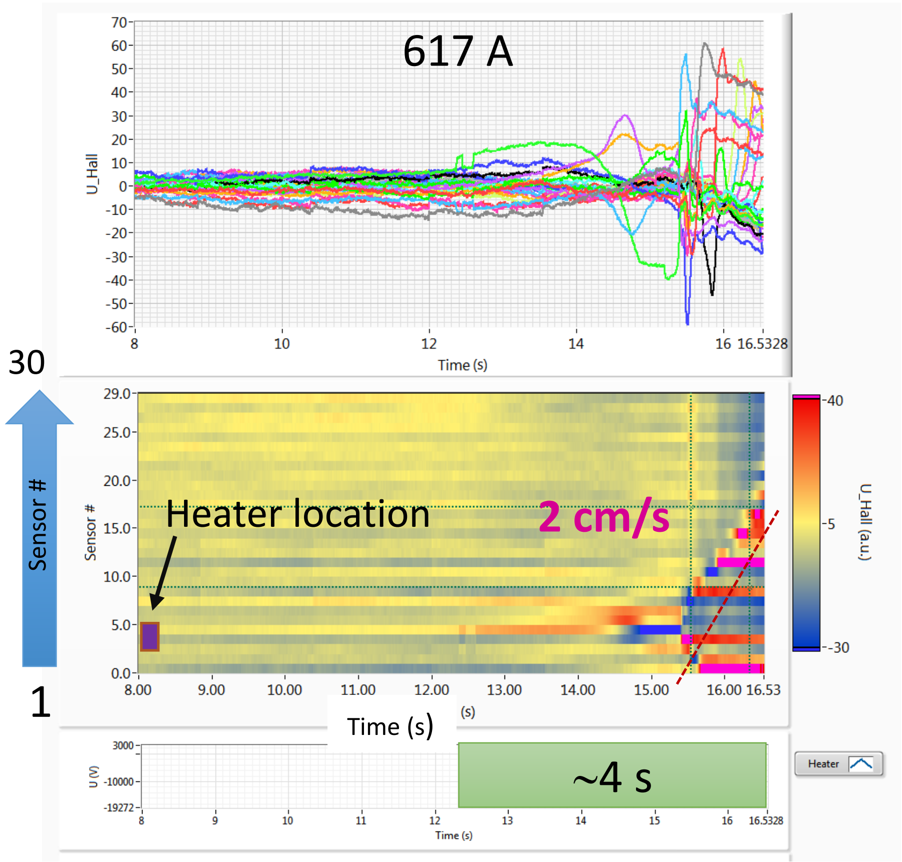
A linear array of 60 Hall sensors for quench detection / quench propagation studies



Hall sensors and arrays to probe axial field along the CORC® conductor



- Re-distribution of current flow away from its solenoidal path can be near the normal zone boundary



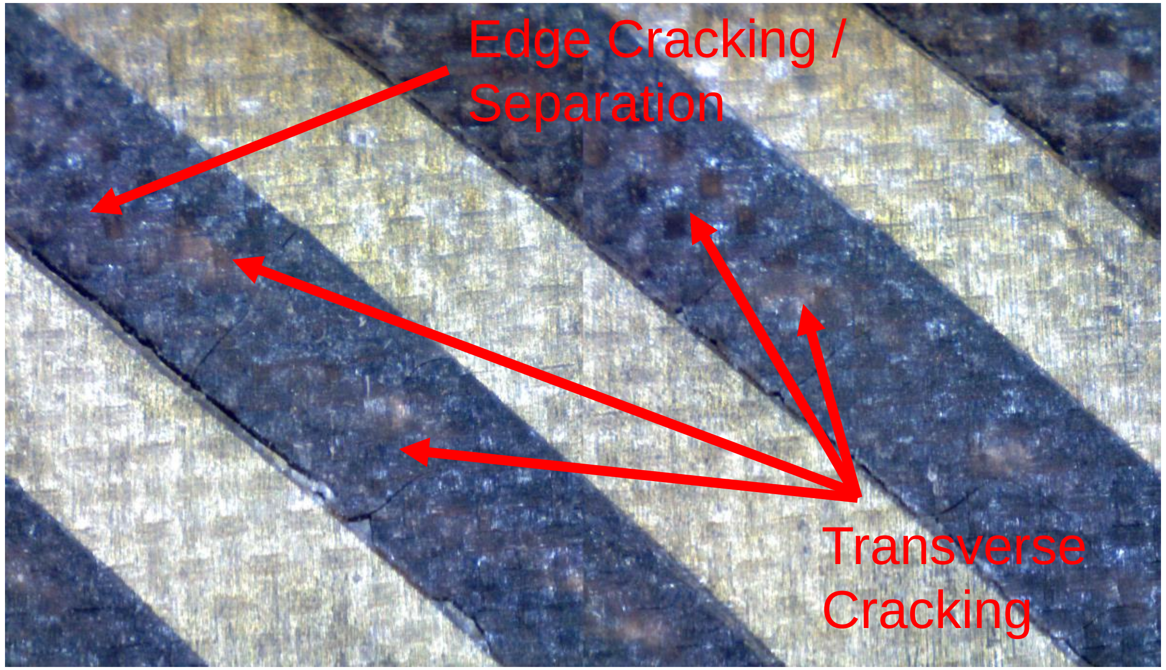
➢ **Cable QD and QC with Hall sensors: Reed's talk**

Probing cable interfaces

Diagnostics of interfaces in high-field LTS accelerator magnets

Optical image of the inner layer in the Canted Cosine Theta magnet disassembled after test

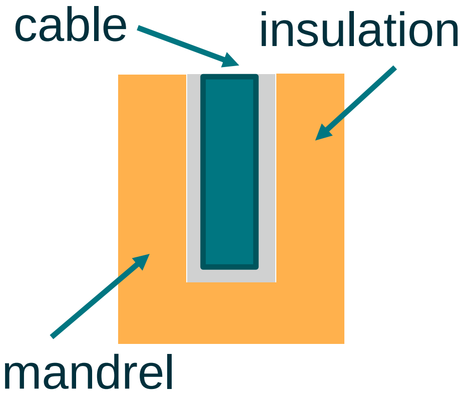
(Diego Arbelaez)



- ➢ We aim at using TDR methods to try to localize areas of interfacial de-bonding

Interfaces are critical in defining the training performance of high-field superconducting magnets. De-bonding along interfaces is one of the key contributors to the magnet disturbance spectrum.

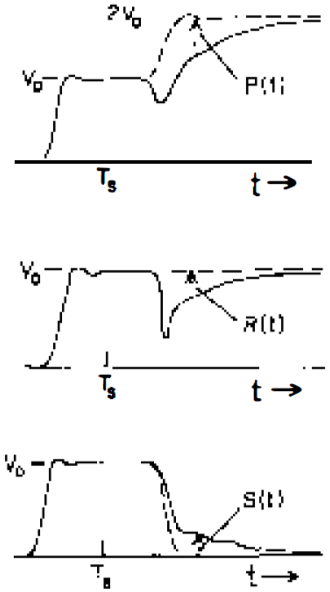
No direct diagnostic tools are available at the moment to perform in-situ characterization of debonding during the magnet training process



CCT coil winding has in fact a “transmission line” geometry that can be potentially exploited for performing TDR measurements

Instrumenting a CCT coil for TDR monitoring during quench training (G. S. Lee)

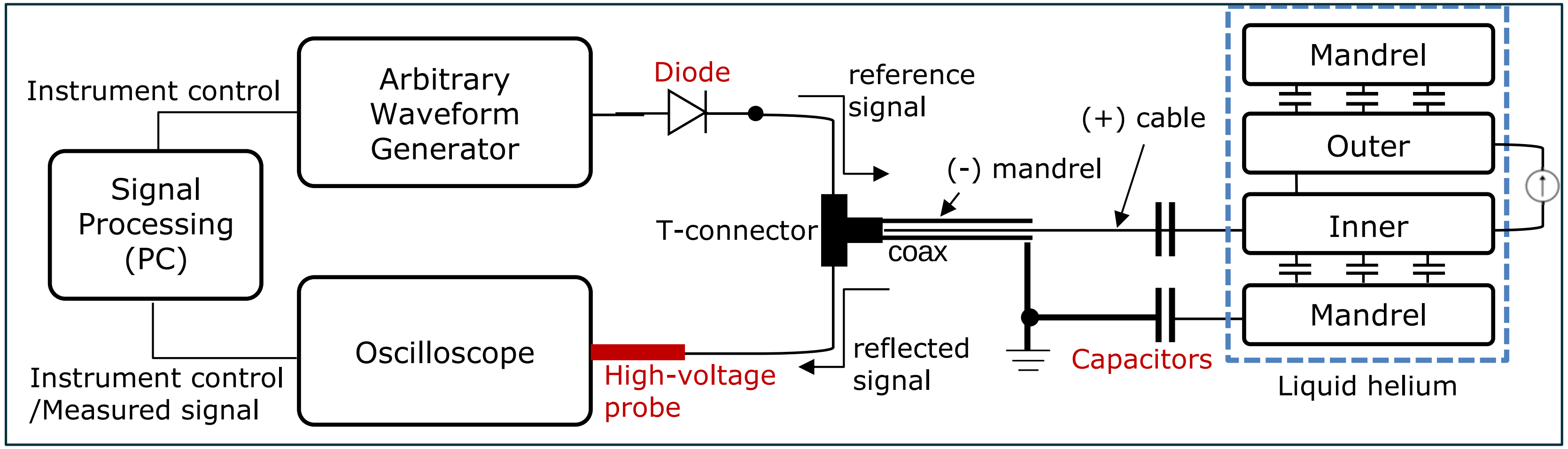
TDR step responses

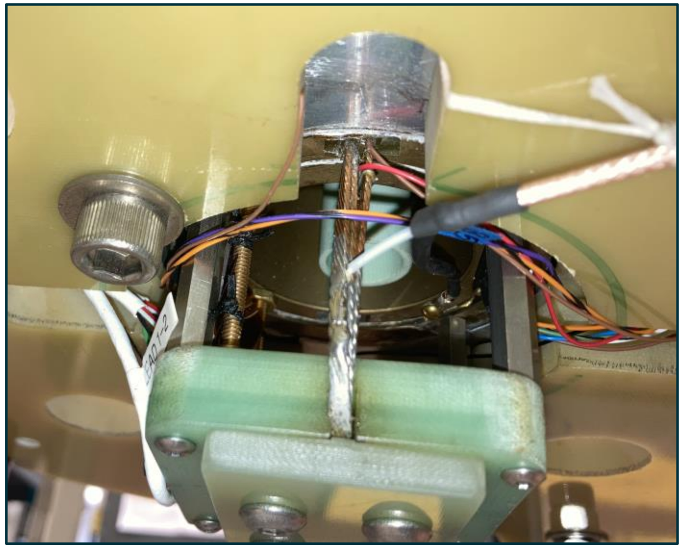


Open circuit

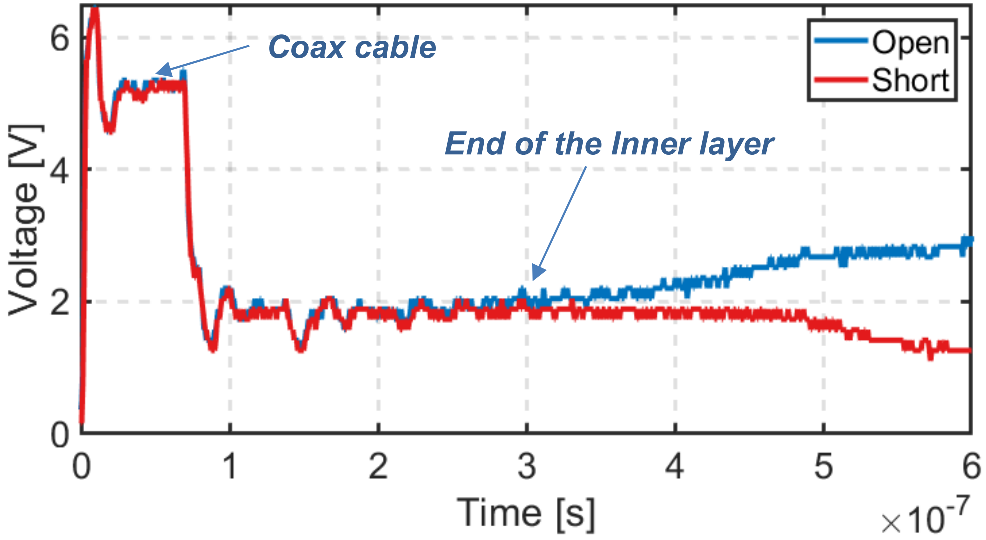
Matched line

Short circuit



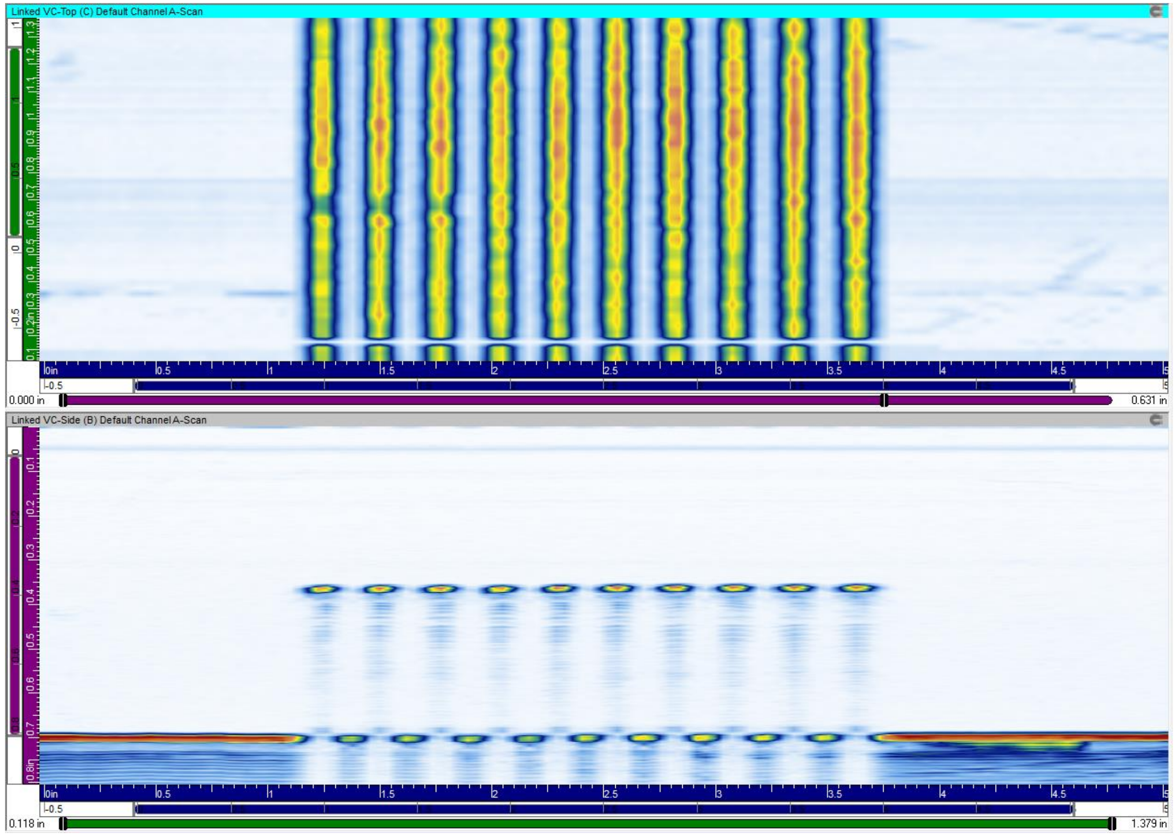


TDR connection to the CCT subscale magnet



Direct ultrasonic imaging of cable delamination

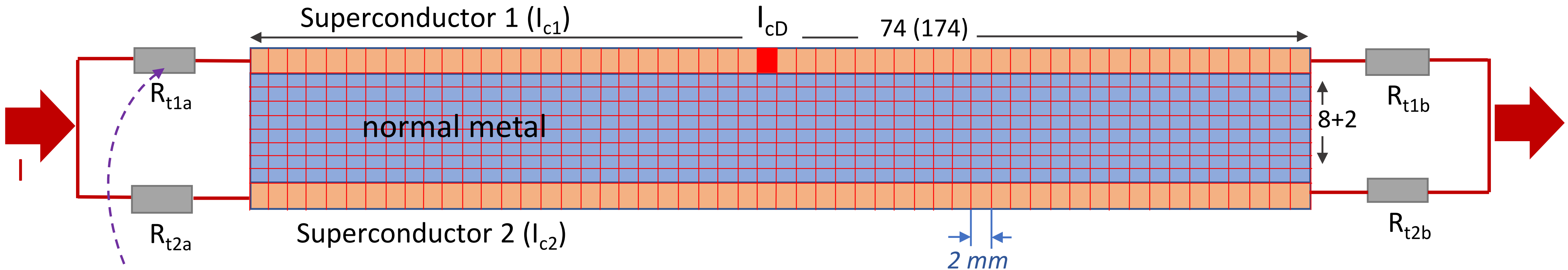
- **SBIR Phase I with GudedWave (FBS, Inc.)**

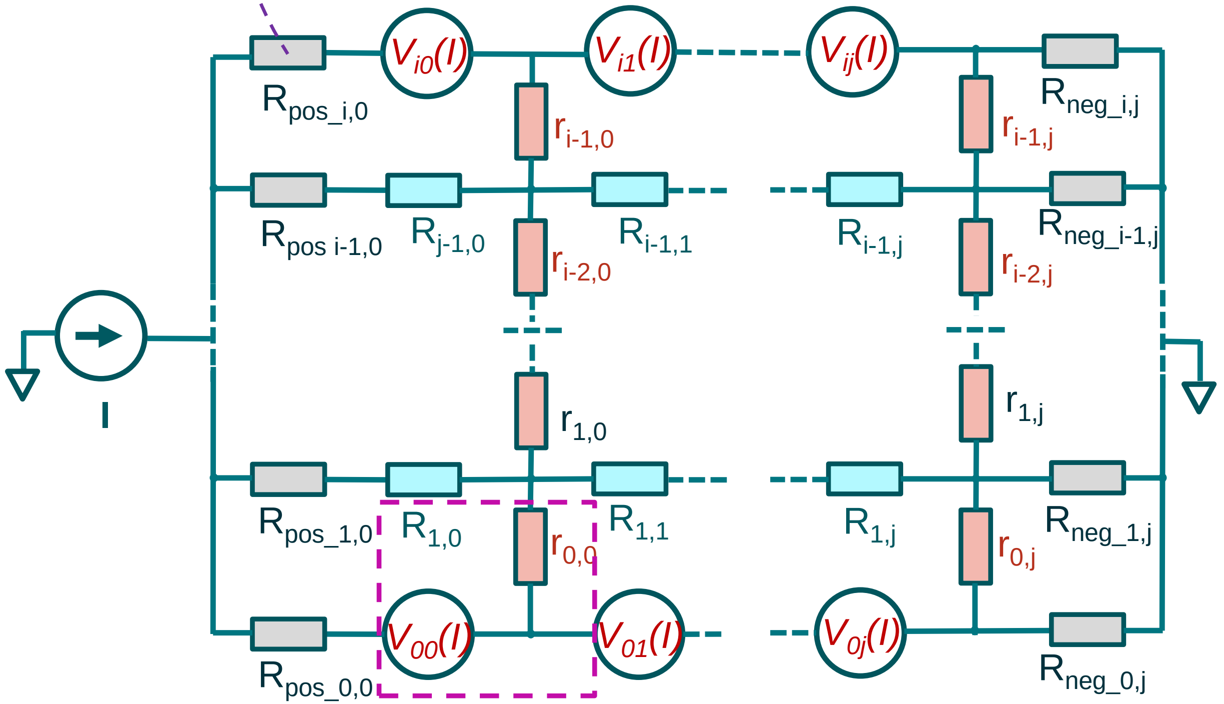


GUIDEDWAVE
THE GUIDED WAVE INNOVATIONS COMPANY

Active control of current distribution

Understanding current sharing: a network model





$$V_{ij}(I_{ij}) = U_0\ exp\left(\frac{I_{ij}}{I_{c\ ij}}\right)^n$$

$U_0 = 2\ x\ 10^{-7}$ V - represents 2 mm of HTS conductor

$n = 20$

Assuming the normal metal is brass with $\rho = 6x10^{-3}\ \Omega$ m

Inter-tape distance is taken at 6.35 mm, then each resistive element is 2 mm long and 0.794 mm wide

$R_{ij} = 4.76\ x\ 10^{-5}\ \Omega$

$r_{ij} = 7.8\ x\ 10^{-6}\ \Omega$

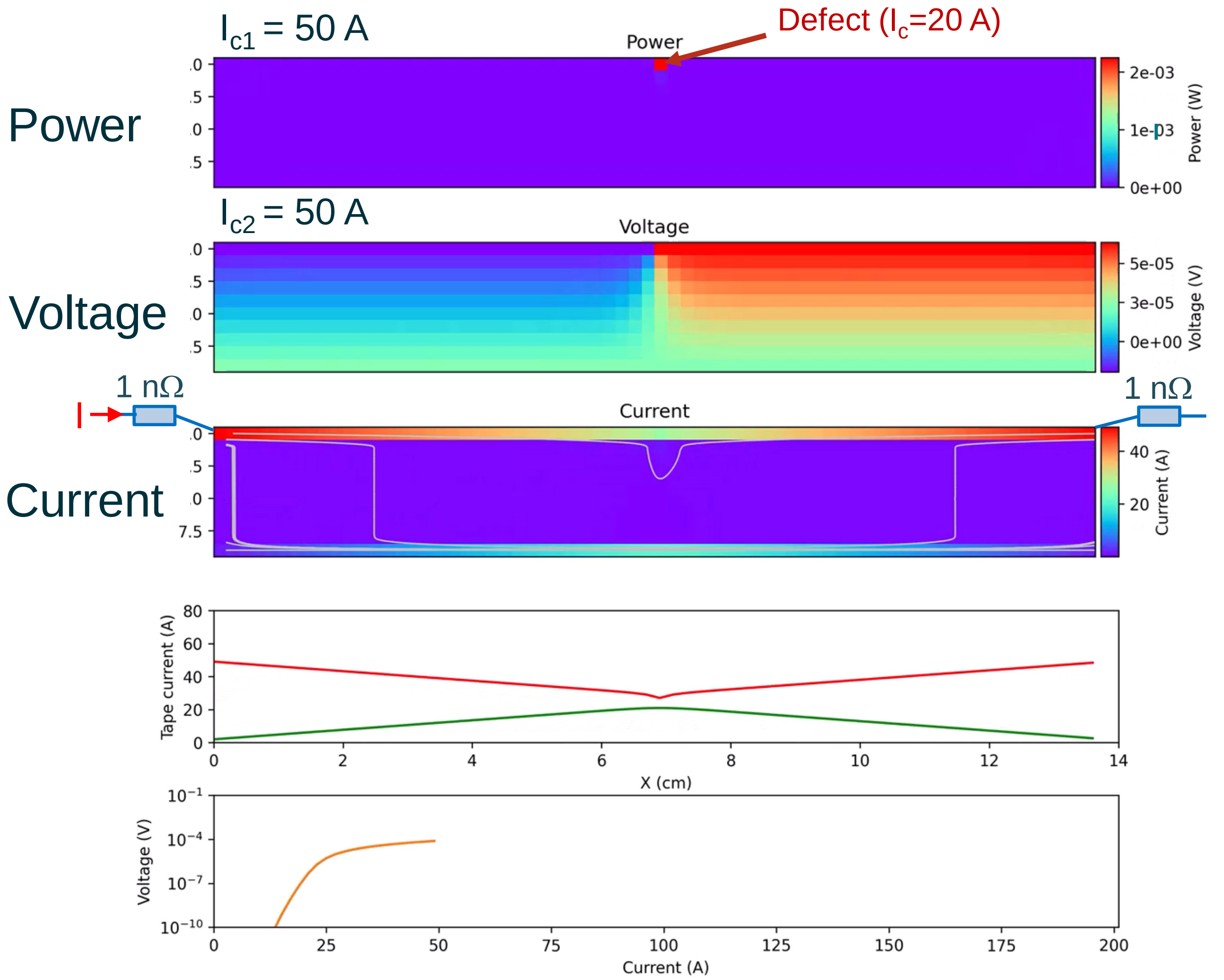
$R_{pos}, R_{neg} = 10^{-9}\Omega$ (SC joint), $10^{-3}\ \Omega$ (resistive shunt/switch) or 1 Ω (~open)

74x10 elements: “short model”
174x10 elements: “long model”

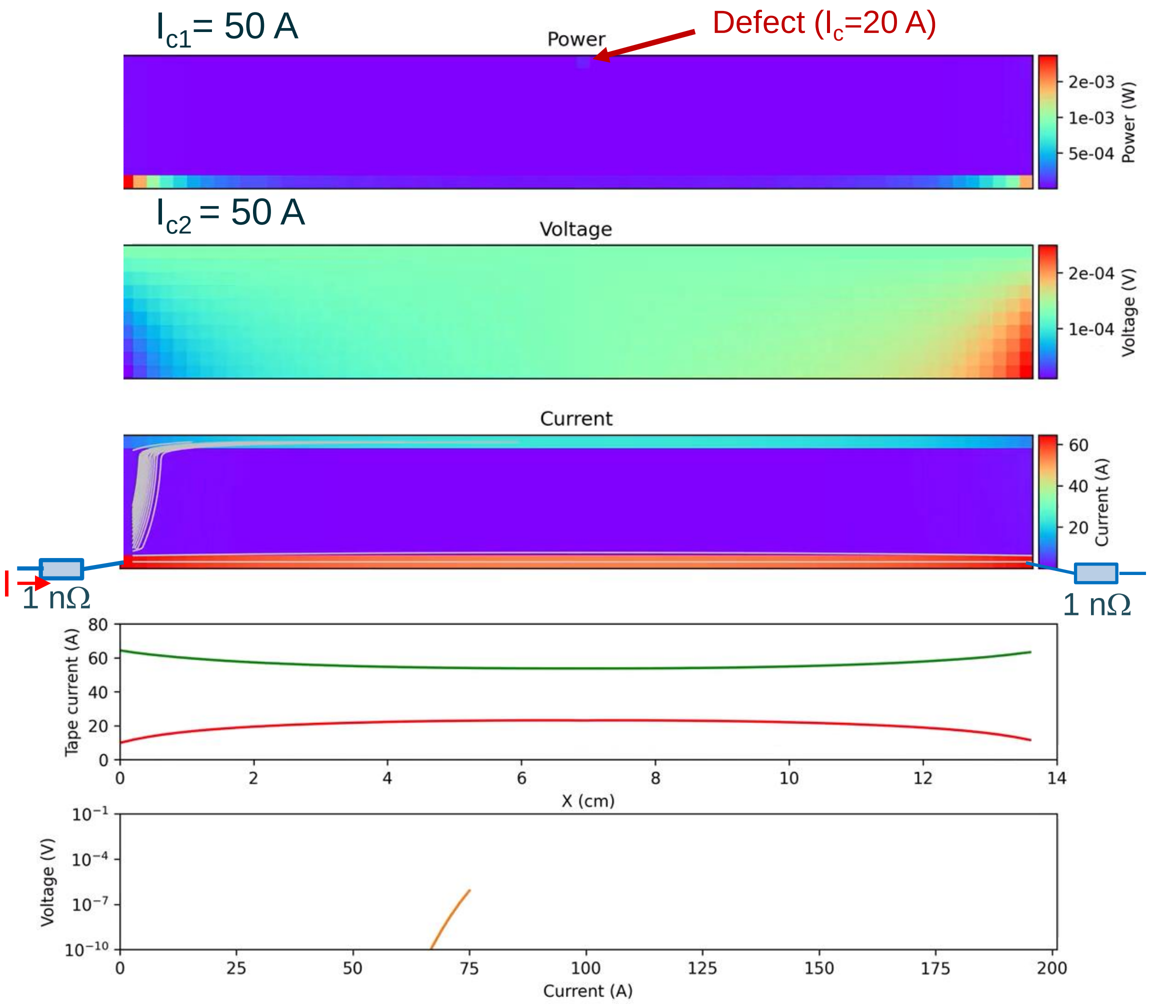
Schematics are generated in Python => solved in LTSpice® circuit simulator => results are plotted using Python.

Current sharing details revealed by network modeling

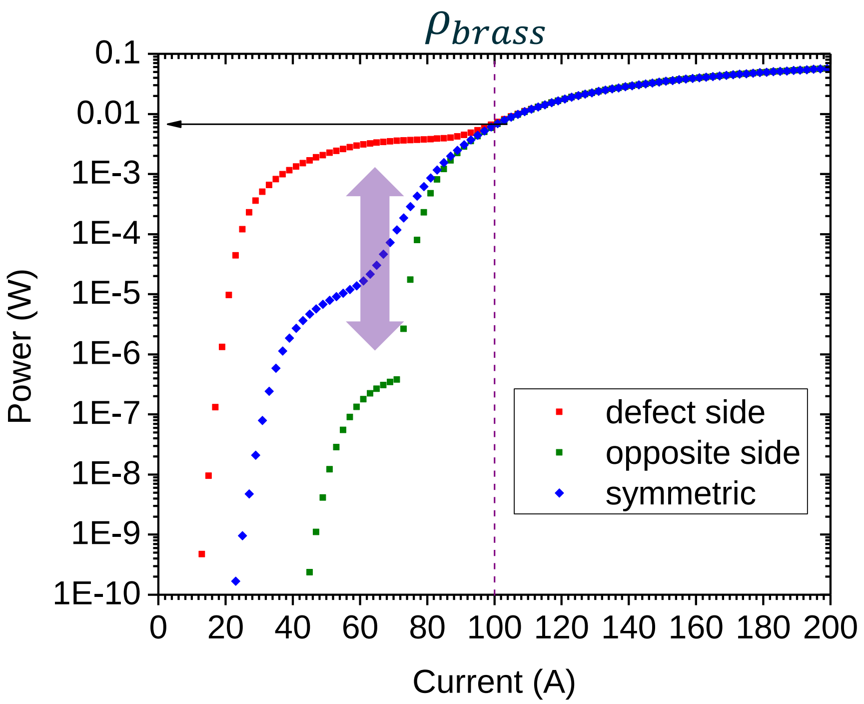
Current injected and removed at the defect side

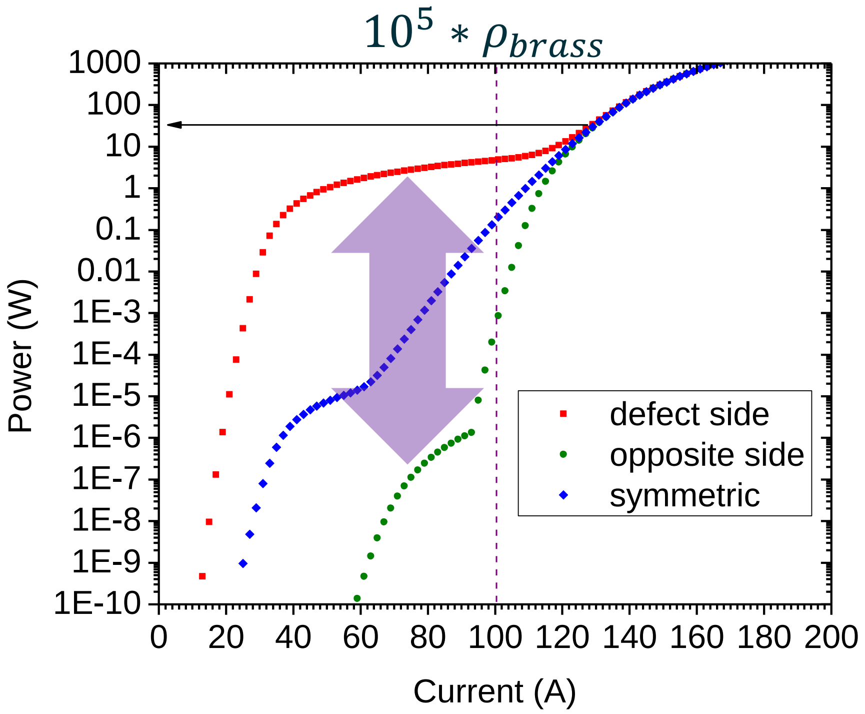


Current injected and removed at the opposite side



When current sharing is poor, power dissipated in the hotspot strongly depends on the distribution of termination resistances

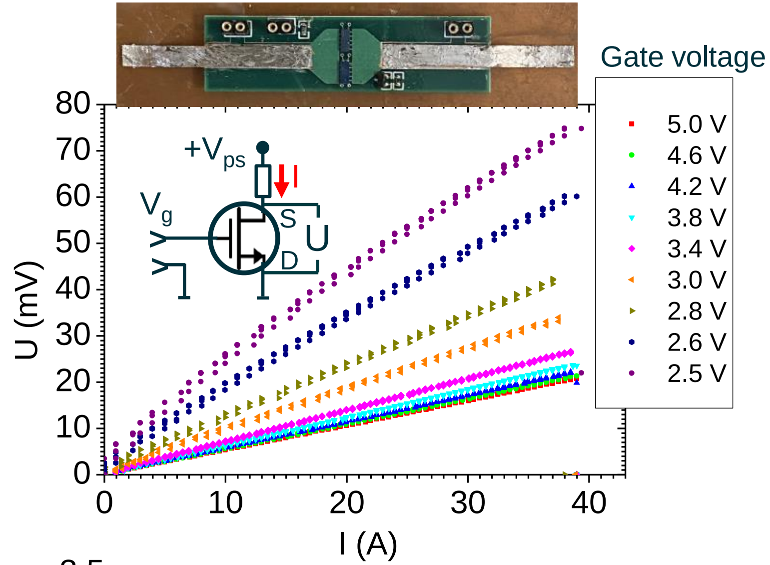




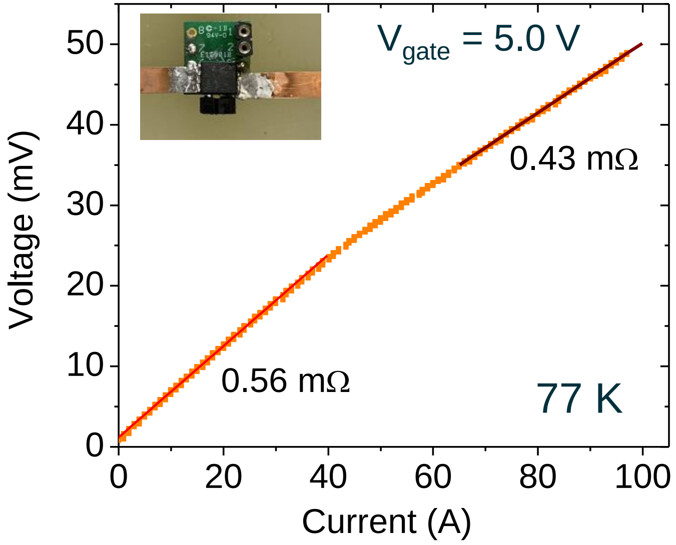
- If current sharing is strong, termination resistances do not play much of a role in defining power dissipated in the hotspot. But as the degree of current sharing is reduced, the role of terminations increases and becomes dominant at a progressively lower fraction of the critical current. Active controls can be effective in reducing hot spot power dissipation in this regime.

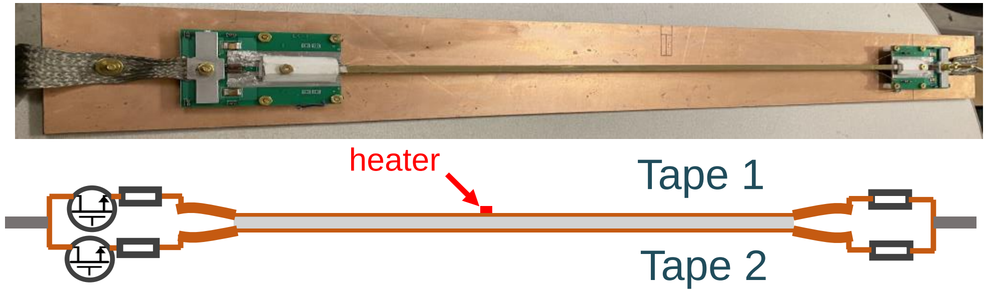
MOSFETs for cryogenic current control in HTS cables

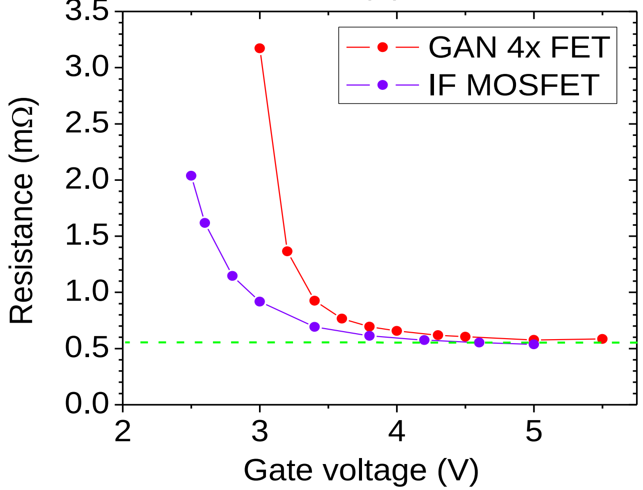
GAN 4xFET, 77K



IF MOSFET, 77 K







- MOSFET assemblies can be used as efficient cryogenic current regulators with closed-state resistance in tens of micro-Ohms. A pathway to “active terminations” for HTS cables!
- MOSFET resistance at a given gate voltage is only weakly independent of the magnitude of the regulated current. This allows pre-calibrating MOSFETs at a fixed current value and using them simultaneously to <u>regulate and measure</u> the current.

Prospective uses of MOSFET controls

- **Improved quench detection => active protection**

Integrated detection/protection: controls will be activated as needed to improve protection margins

- **AC modulation of current paths**

MOSFETs allow for fast switching of the current path. The time constant defined by the mutual inductance of cable sub-elements can be substantially smaller than the inductance of the cable especially when it is wound as a magnet coil. Therefore current path modulation can be used for:

- Ac-voltage based quench detection
- Protection involving hysteretic and eddy current losses (similar to CLIQ)
- Removal of remnant magnetization

- **Distributed powering of hybrid magnets from a single power supply**

We are working on designing and multi-MOSFET boards capable of controlling currents of several kA to enable such testing in the future.

Summary

- We have developed a comprehensive array of diagnostic techniques for quench detection and monitoring based on ultrasonic, RF and magnetic principles.
- We are working with partners on SBIR programs and FES to implement some of these diagnostics on a large scale suitable for implementing in large-scale magnets
- New ideas about implementing current control distribution and distributed protection of HTS and hybrid magnets are being tested

We always look for opportunities to test our instrumentation in magnets tested by the MDP, propagate the techniques across the labs and provide useful feedback to magnet designers. Coordination and advance planning are essential for success.