U.S. MAGNET DEVELOPMENT PROGRAM

Update on Ultrasonic Waveguide & RF TDR-based quench detection techniques

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Research progress since the collaboration meeting (2023.03)

AIIId-M3ab	Development and implementation of non-optical distributed sensing for cables and magnets - RF TDR-based techniques - Ultrasonic waveguide-based techniques

Ultrasonic waveguide-based techniques

- Conducted cryogenic waveguide measurements (77K & 6K)
- The ability to localize hot spots in a cryogenic environment

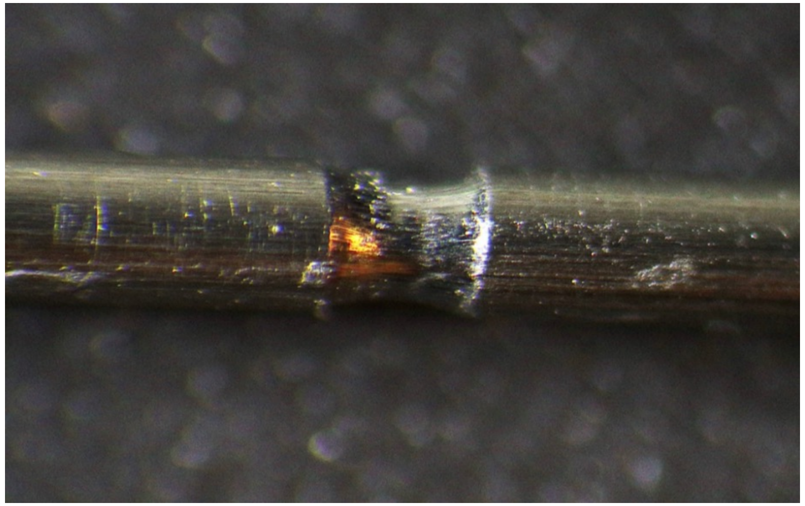
RF TDR (radio frequency time domain reflectometry)-based techniques

- Applied TDR to CCT subscale 5 (Inner layer: wax impregnated)
- Aiming for CCT subscale 6 and subscale mock-up plates (wax impregnated)

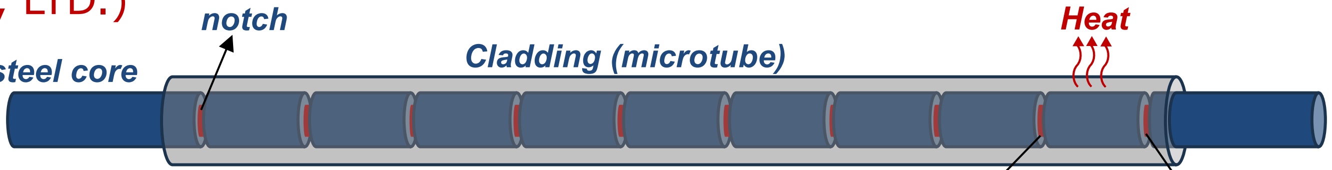
Theoretical background:

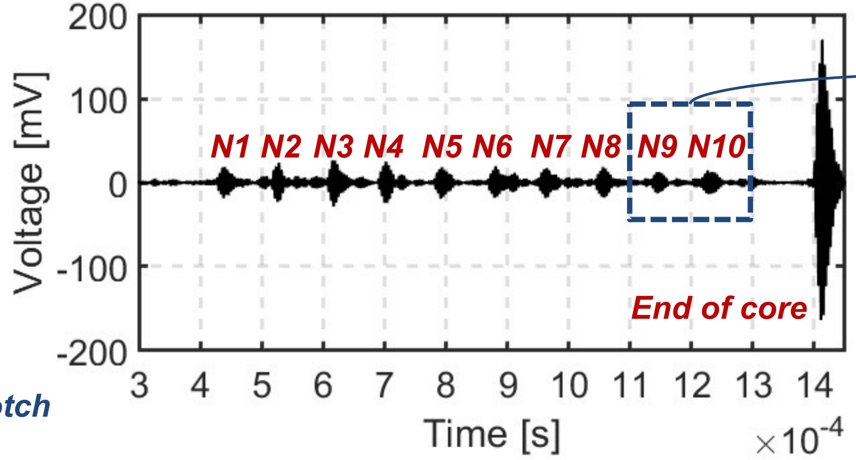
Ultrasonic waveguide temperature sensing concepts

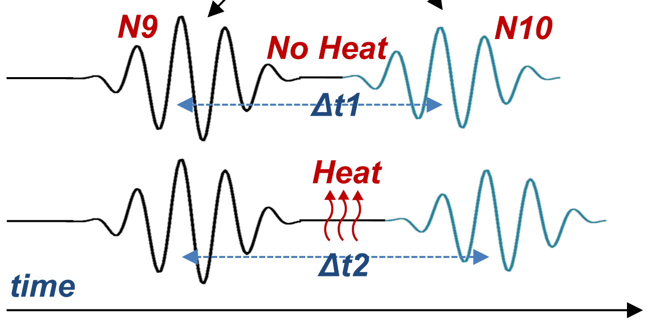
Etegent TECHNOLOGIES SBIR Phase I (ETEGENT TECHNOLOGIES, LTD.)



Longitudinal wave in the wire is reflected from every notch





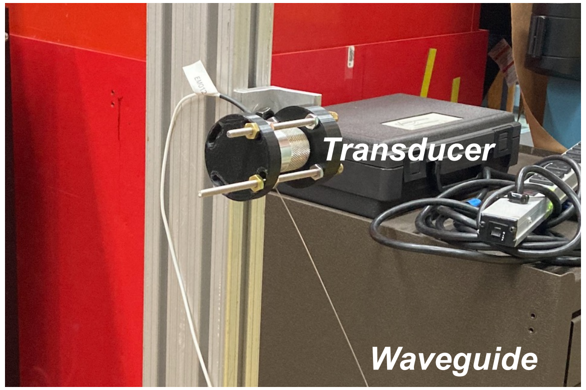


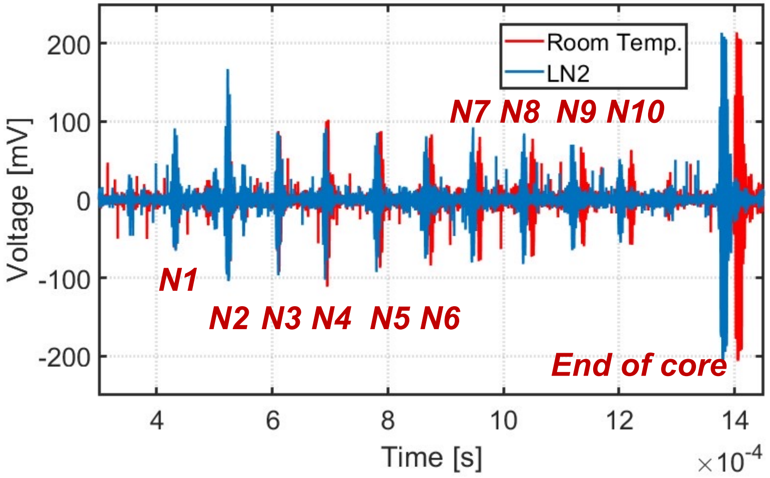
The time delay between the two reflected signals is <u>only affected by the temperature change</u> between the signals. (No change in N9)

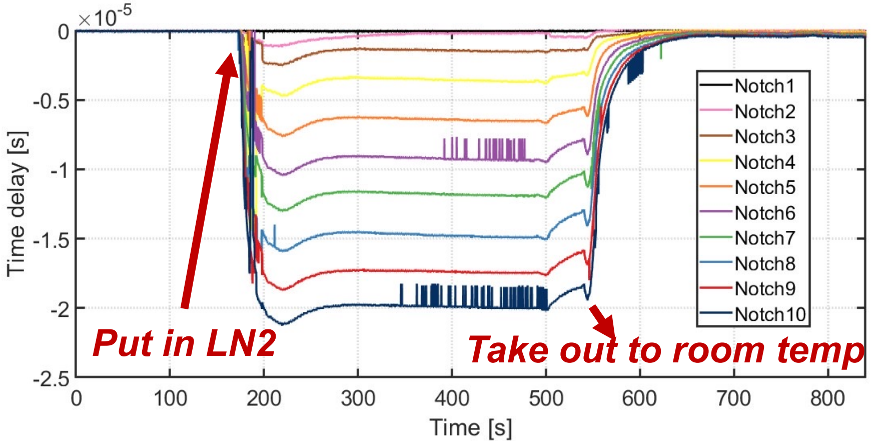
- Each of the 10 reflected signals from notches is correlated with the initially measured signals.
- **Time delay** can be calculated using a maximum point of the correlation function.
- **The correlation value** itself can be used as a monitoring index.

[REF] "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

Monitoring ultrasonic thermometry during cryogenic cooling to 77K

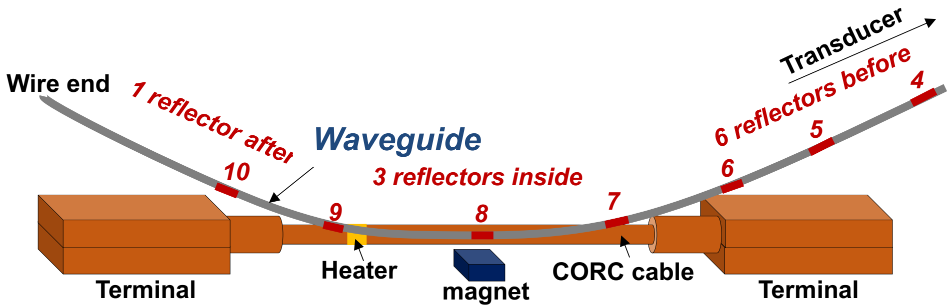




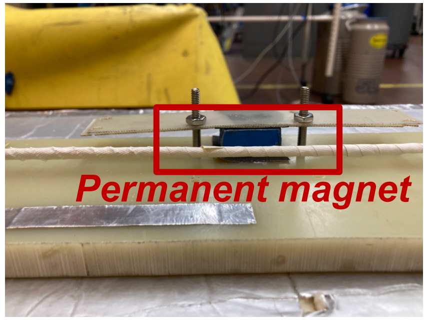


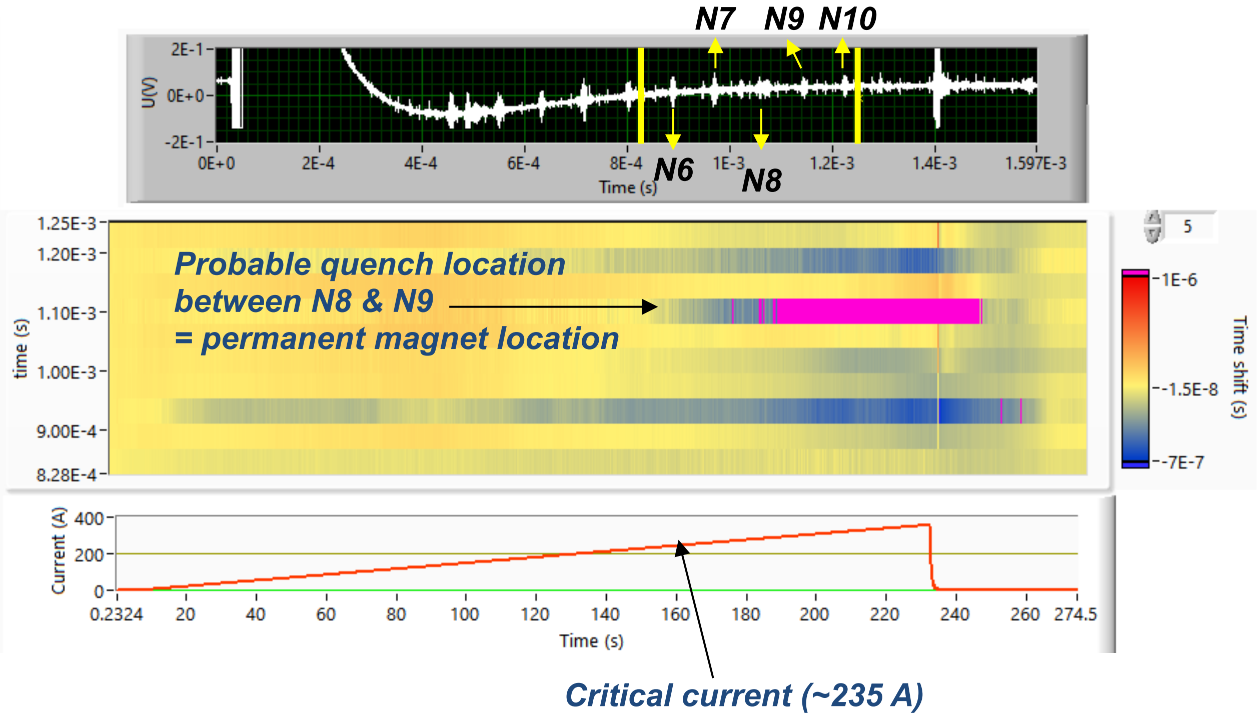
- The first 3 notches are before the LN2 box and the last 7 notches are immersed in liquid nitrogen.
- The result shows that the time shift of the 7 notches immersed in the liquid nitrogen changes more as it is placed behind.
- <u>The ultrasonic thermometry is operating in the *liquid* without the magnitude reduction of signals.</u>

Quench detection in CORC® at 77 K



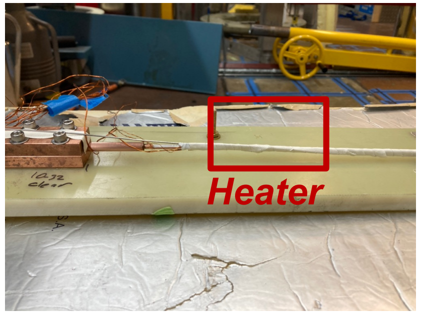
The waveguide wrapped around the CORC® cable sample. A permanent magnet is installed on the CORC® cable near notch 8.

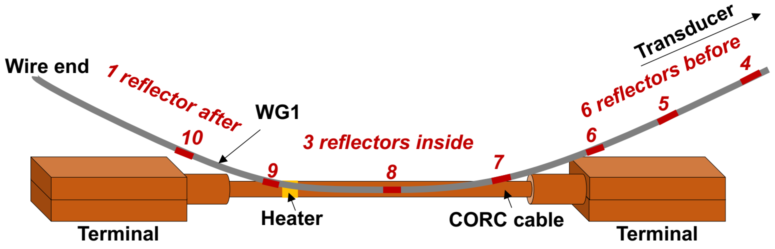




- The sample was run up to 375 A and hot spot (~29 W) was clearly detected.
- The result of calculating the time shift by selecting from notch 6 to notch 10
- Signal is only affected by the temperature change near permanent magnet

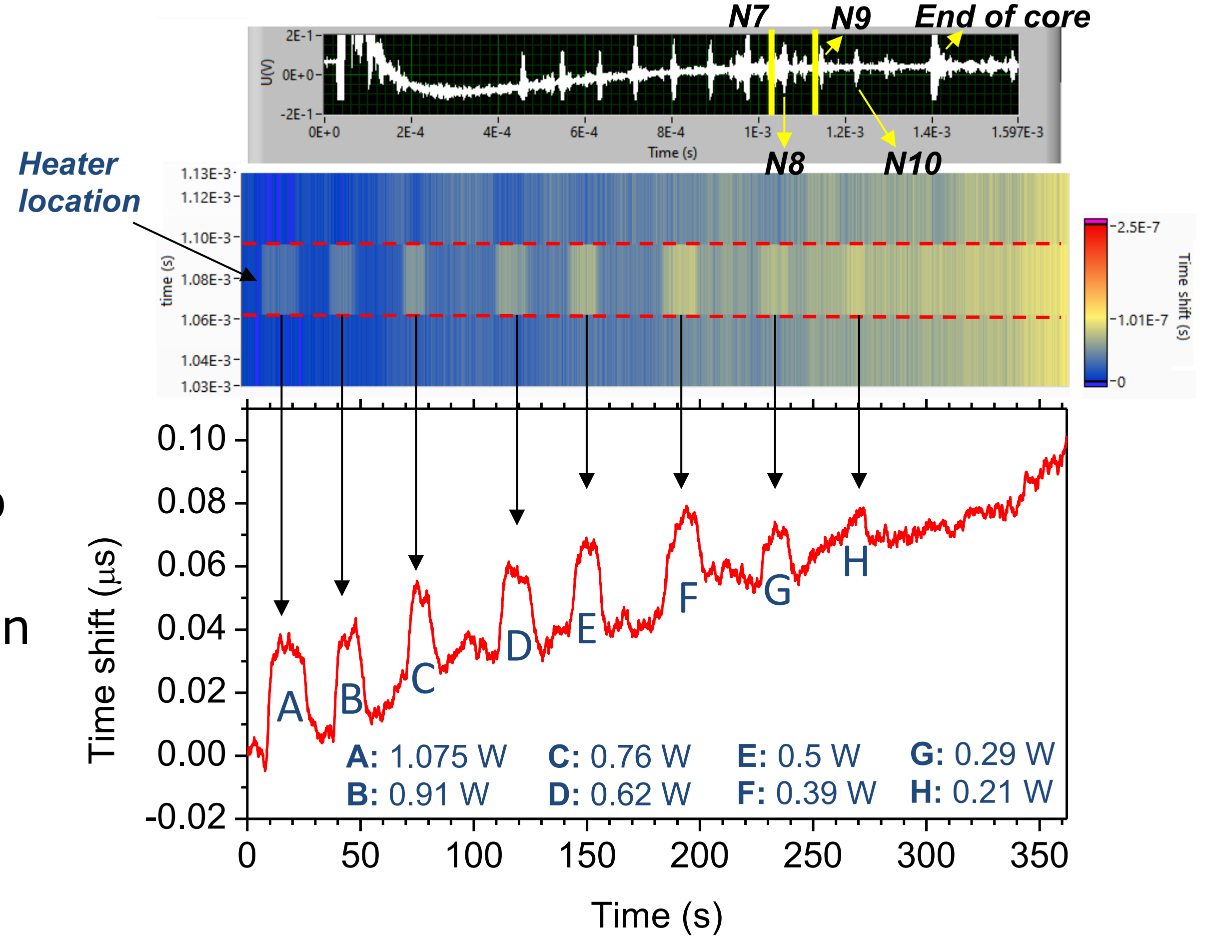
Hot spot localization in CORC® at 77 K



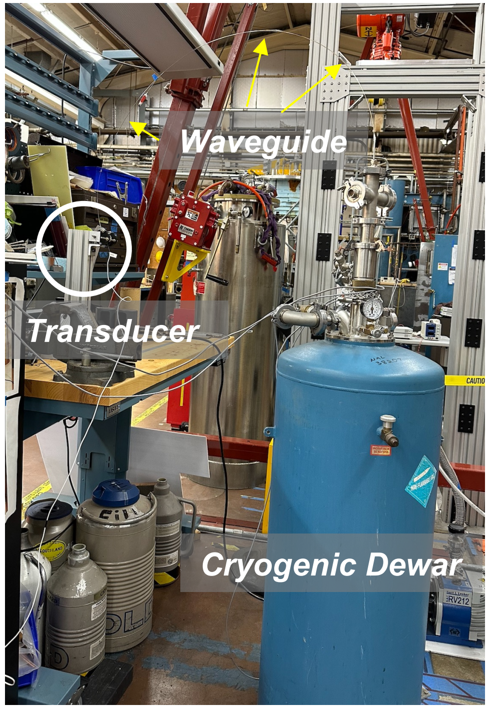


A heater (5.8 ohm) is installed near notch 8 & 9. The heater wrapped the cable and waveguide together.

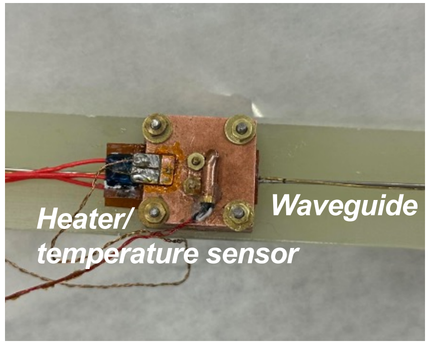
- Thermal sensitivity: the sport heater is powered up at different power levels.
- Time shifts at the heater location are detected down to **0.21 W** of heat dissipation.
- The ability to detect quenches in practical HTS conductors, even when operating at 77 K of liquid nitrogen



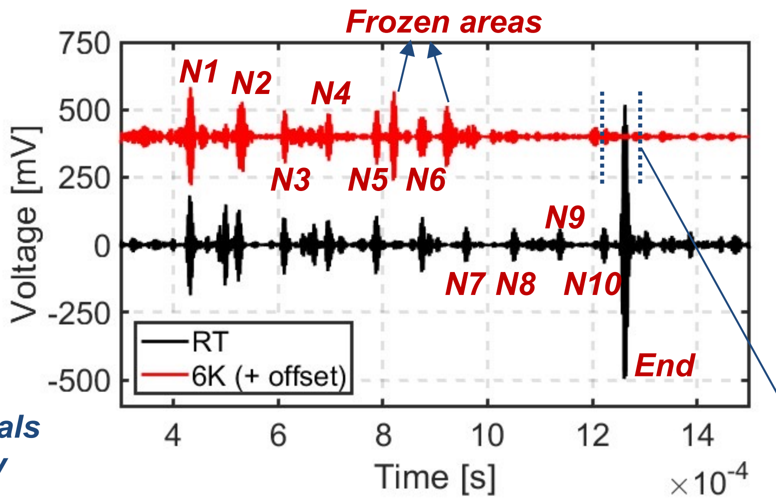
Heat sensitivity studies at 6 K



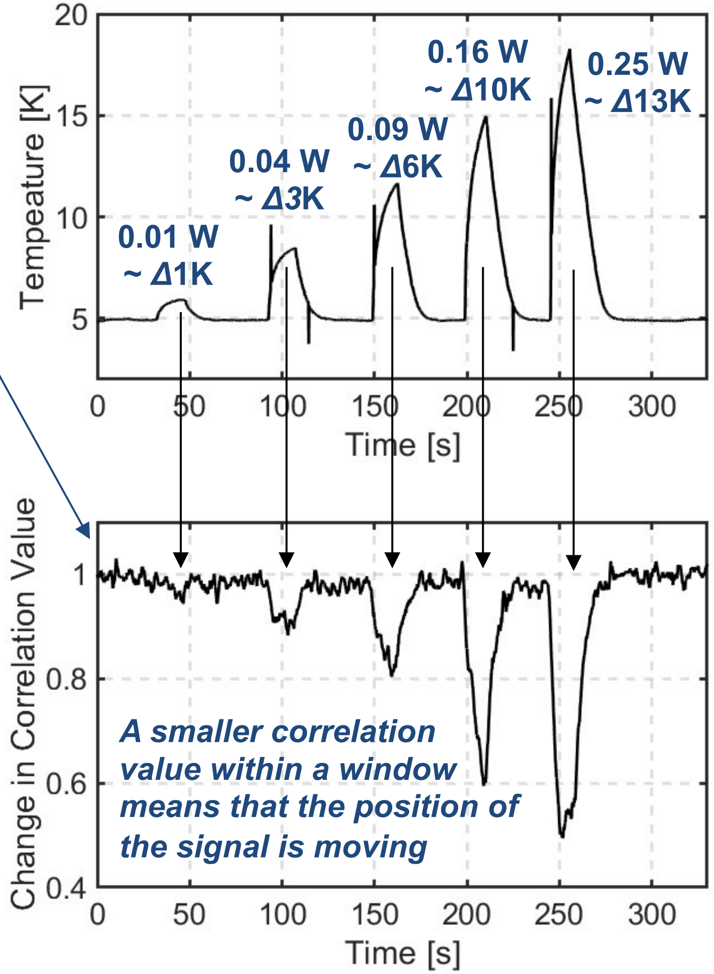
The ultrasonic transducer is located outside the cryogenic Dewar.



The spot heater is installed near N10. So, reflected signals at N1~N9 are <u>not affected</u> by the heater.



Signal loss due to frozen areas inside the tube, but still possible to analyze time delays.

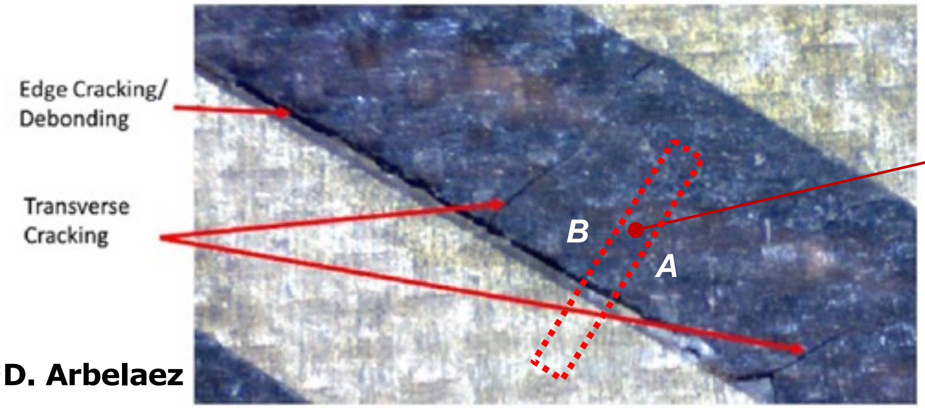


- Only signals after notch #9 have a time delay (change in correlation value)
- Time shifts at the heater location are detected down to **1 K difference (less than 0.01 W)**
- Ultrasonic thermometry operating at 6 K

[REF] "Long-length acoustic fibers for quench detection and localization in HTS accelerator and fusion magnets" will be presented **(MT28, 5OrM3)** M. Marchevsky

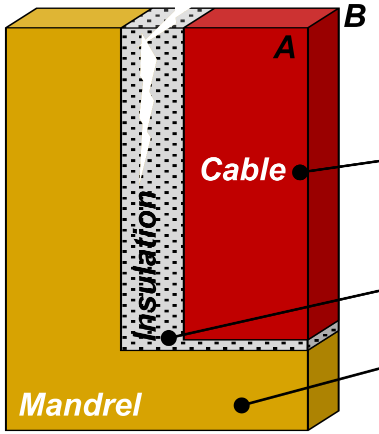
Theoretical background:
Impregnation monitoring using RF TDR

Example of damages in CCT5 (Nb_3Sn)*

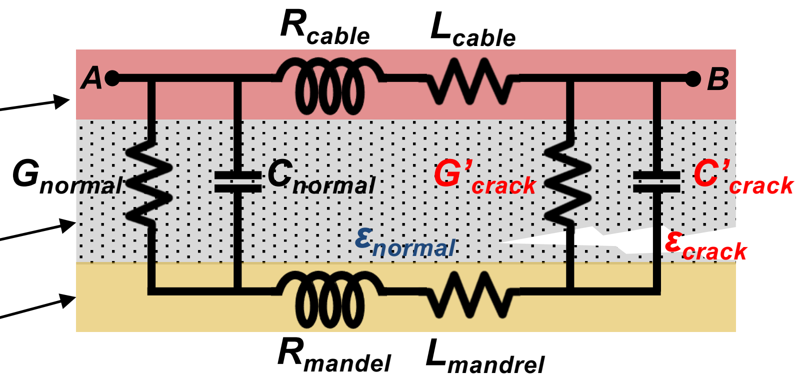


*D. Arbelaez

Cross section b/w A&B

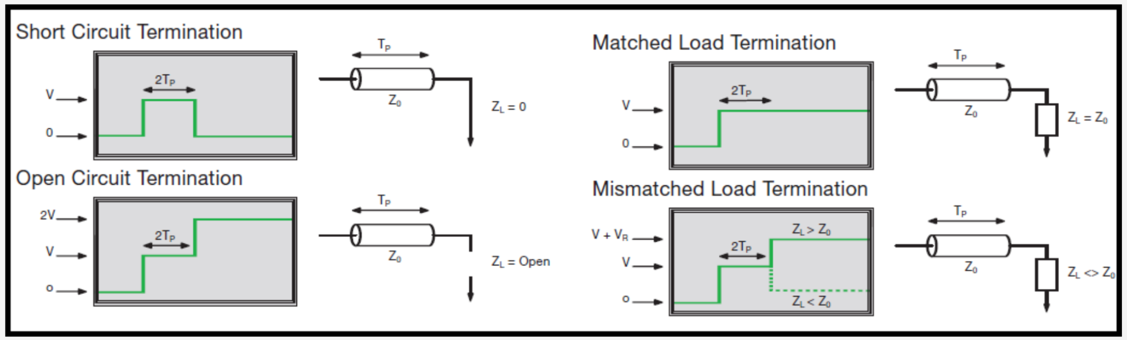


Lumped element model



The presence of cracks/debonding in impregnation layer results in changes in characteristic impedance.

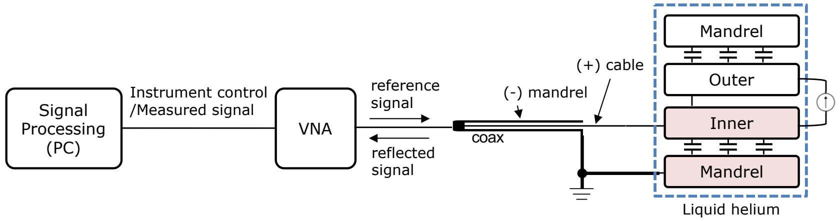
- CCT subscale can be considered as **a transmission line**
- Coil (+), Mandrel (-), Resin/Epoxy (insulation)
- We can evaluate and localize the impregnation damage by applying electrical signals to magnets

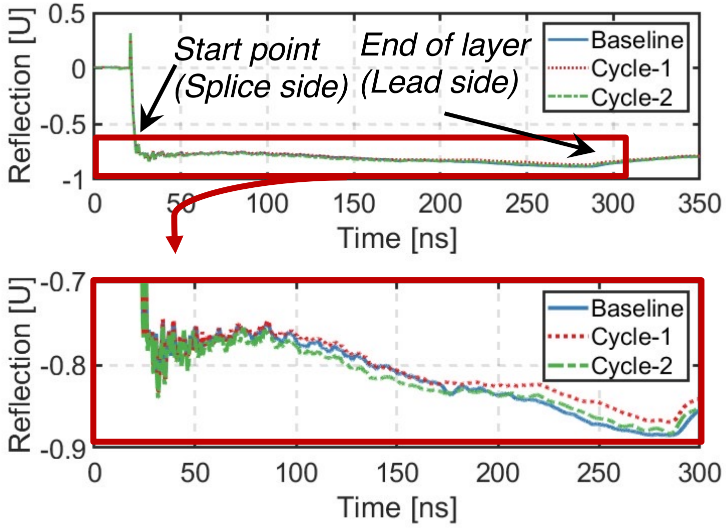


Tektronix application notes, "TDR Impedance Measurements: A Foundation for Signal Integrity."

Impregnation damage monitoring for subscale 5

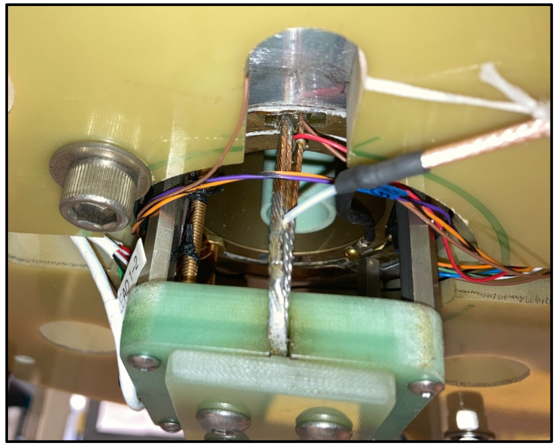
Experimental setup (VNA)





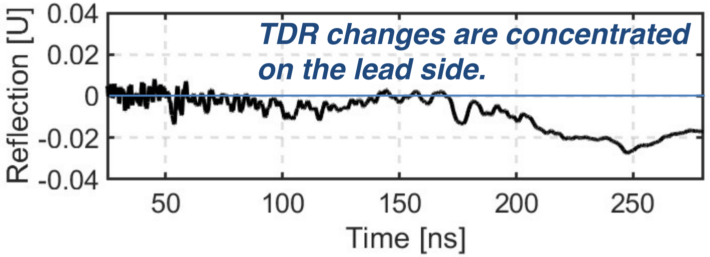
TDR results (inner layer) measured at room temp. before and after training/thermal cycle (disconnected from current source)

Connection part (Splice side)

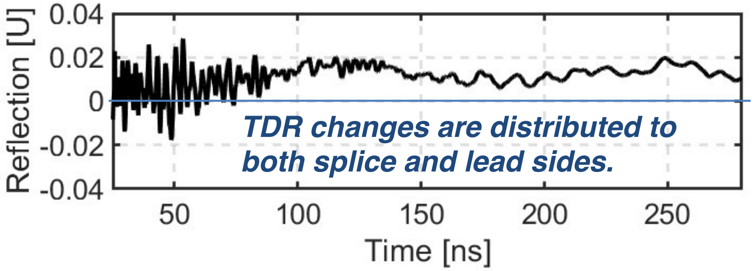


- LBNL have conducted three CCT subscale-5 test (No quench @ IL)
- Cycle-1: Quench training and <u>heat study on the lead side</u>
- Cycle-2: <u>Heat study on both lead and splice sides</u>

Difference Between <u>Baseline and Cycle-1</u>



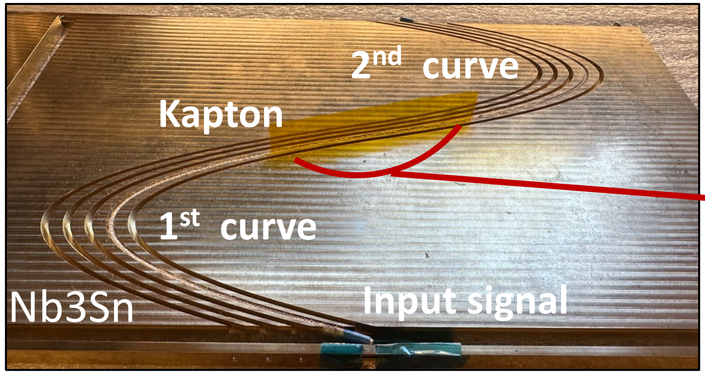
Difference Between <u>Cycle-1 and Cycle-2</u>

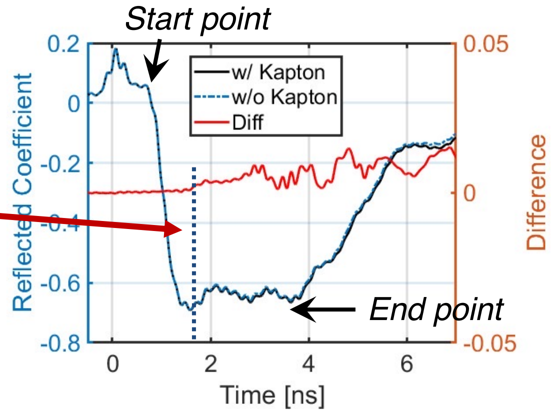


- Variations observed in the TDR measurement results indicate an impedance change that has occurred at that specific location.

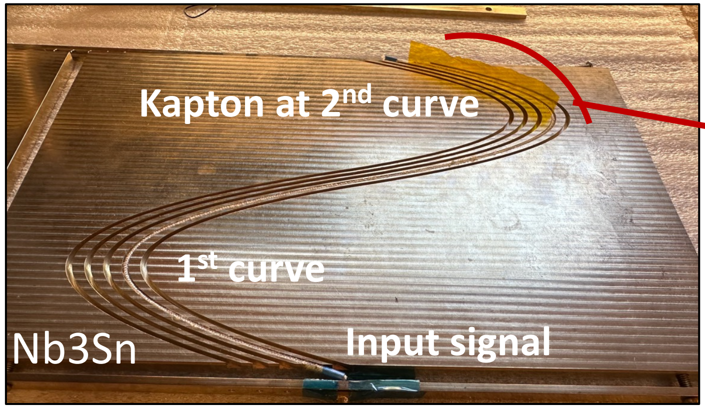
Analyzing how changes in impregnation affect TDR – mockup plate

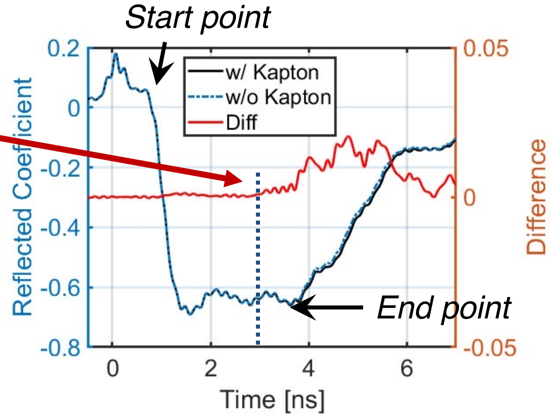
Kapton at middle





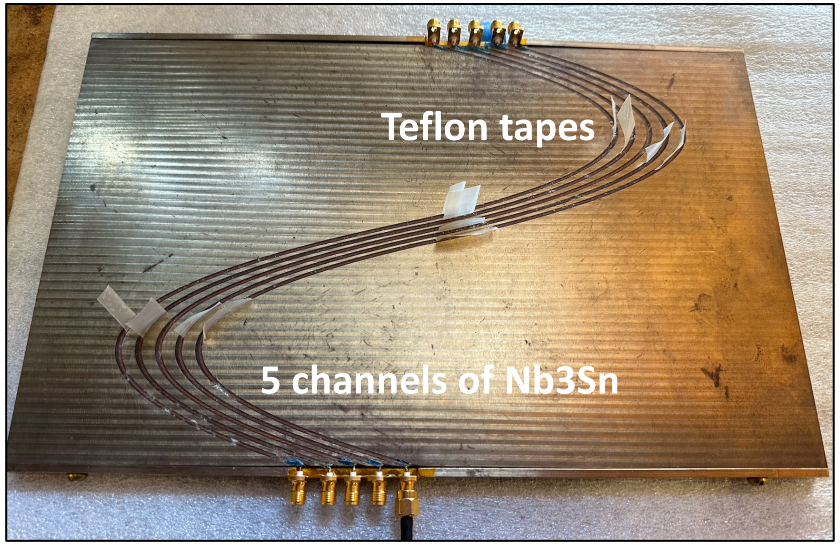
Kapton at second curve





Not impregnated plate (air + glass fiber (ε_r = 6~7)):
Impedance changes occur based on the presence or absence of Kapton tape (ε_r = 3~4). TDR can localize the Kapton's position.

Wax impregnated subscale mock-up



- Paraffin wax has a similar dielectric constant with Teflon tape. (*ε_r = 2~2.5*)
- The tape placement – TDR accuracy
- The length of the tape - TDR resolution

[REF] "Impregnation damage monitoring for the Nb3Sn Canted-Cosine-Theta magnets using time-domain reflectometry" will be presented (MT28, **3OrA2**) G.S. Lee