Impregnation damage and quench monitoring using time-domain reflectometry

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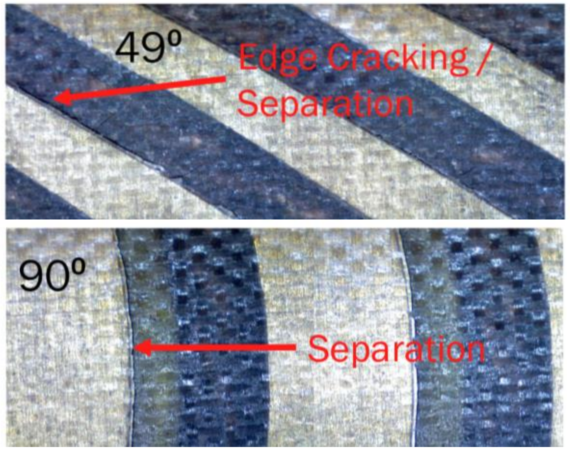
Presentation to the Instrumentation and Diagnostics for Superconducting Magnets Workshop

Apr 28, 2023

CONTENTS

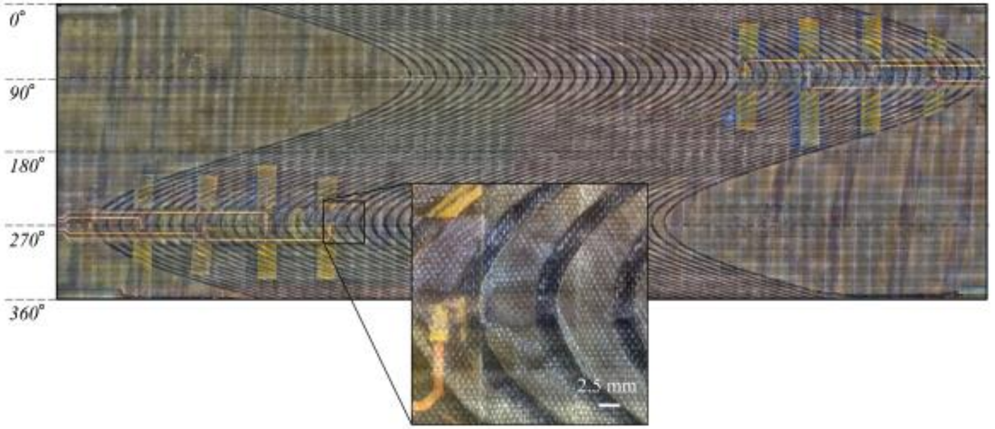
How do we localize damages when surface failure/delamination occurs?

Example of damages in CCT5 (Nb_3Sn)*



*D. Arbelaez, 2022, “Nb3Sn CCT overview,” *US-MDP Collaboration Meeting*

Microscope photos of CCT Sub2**

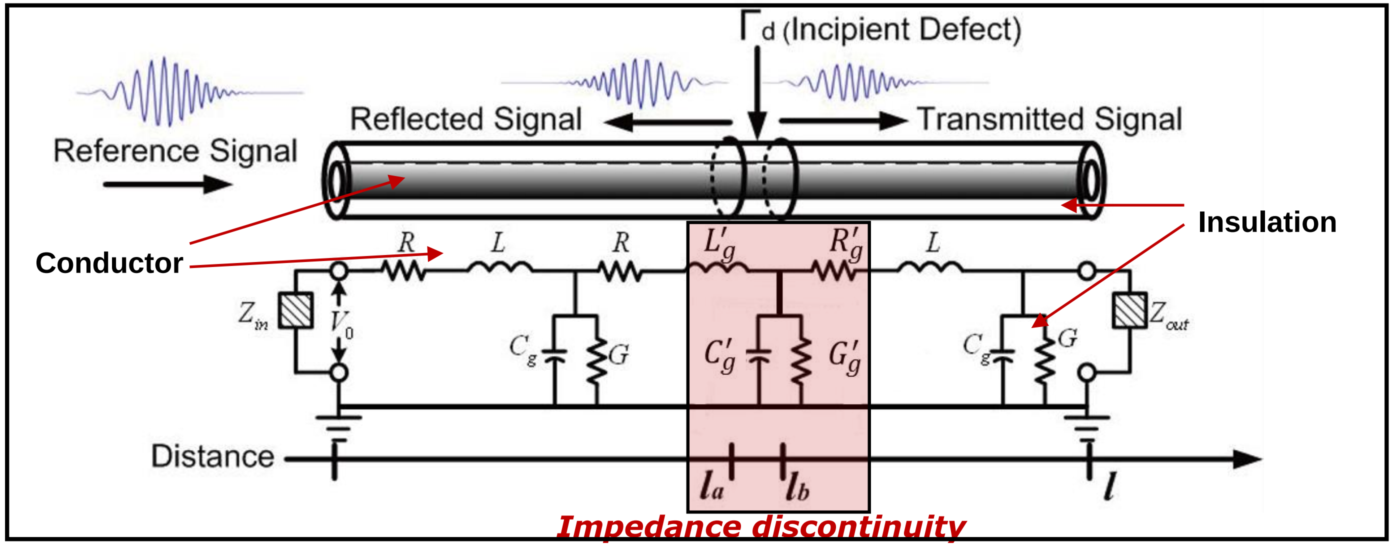


**J. L. R. Fernández *et al*., "Assembly and Mechanical Analysis of the Canted-Cosine-Theta Subscale Magnets," *IEEE Transactions on Applied Superconductivity*, vol. 32, no. 6, Sep. 2022, Art no. 4006505.

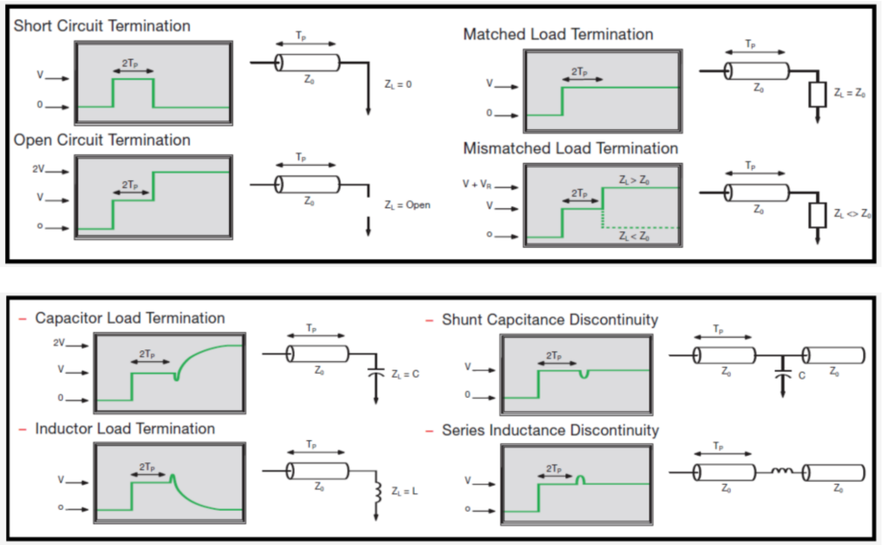
- Cracking and delamination of the impregnation materials lead to extended training and degradation of the magnet performance.
- There have been various approaches to solving interface problems such as the replacement of epoxy and the improvement of design/modeling.
- <u>Need for *In situ* evaluation of the impregnation damage</u>

RF based reflectometry can measure the electrical properties of material

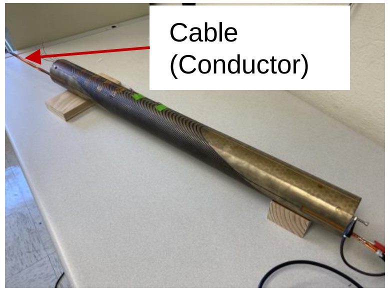
Transmission line theory

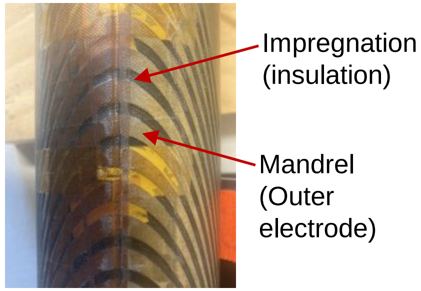


Reflections for various termination*



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





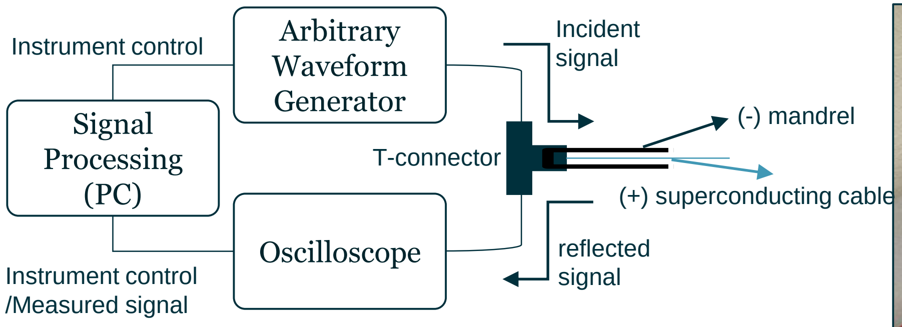
- CCT subscale can be considered as **a transmission line**
- Coil (+), Mandrel (-), Resin/Epoxy/Wax (insulation)
- We can evaluate and localize the impregnation damage by applying electrical signals to magnets

Electrical reflectometry (Transmission lines)

2

Applying electrical reflectometry to CCT subscale

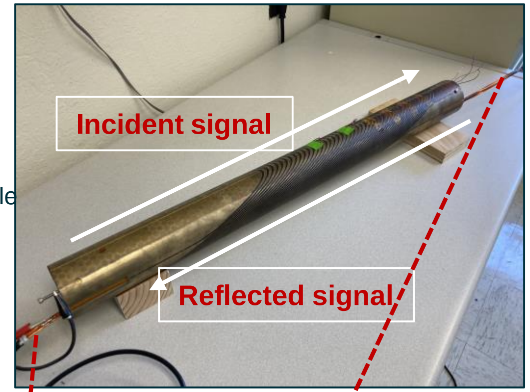
Experimental setup



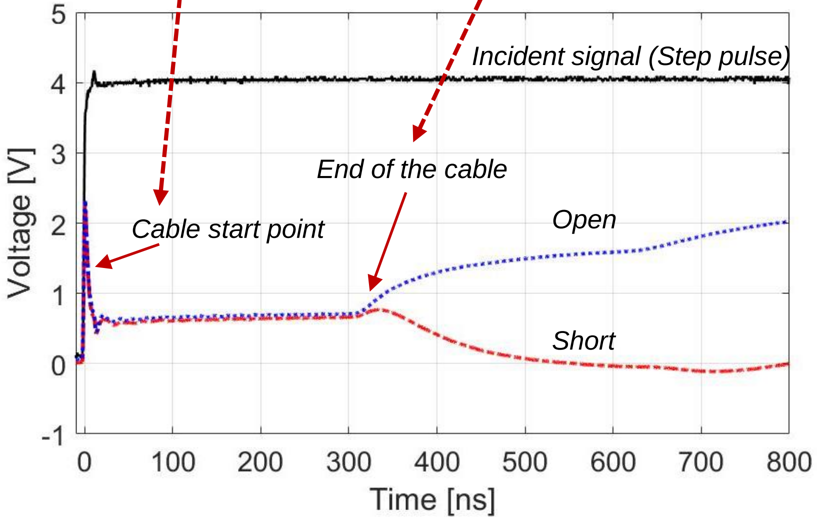
- Signal generator & scope

- (hard fault) If the voltage tap and mandrel are short-circuited, it is possible to estimate the location of the voltage tap.

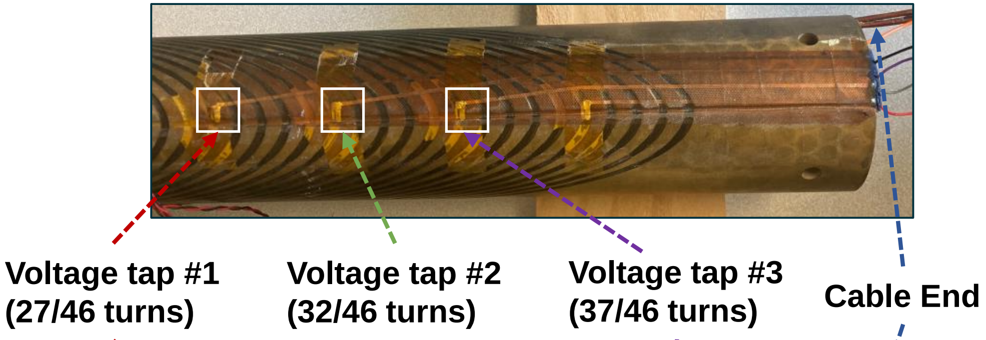
CCT subscale (Nb_3Sn)

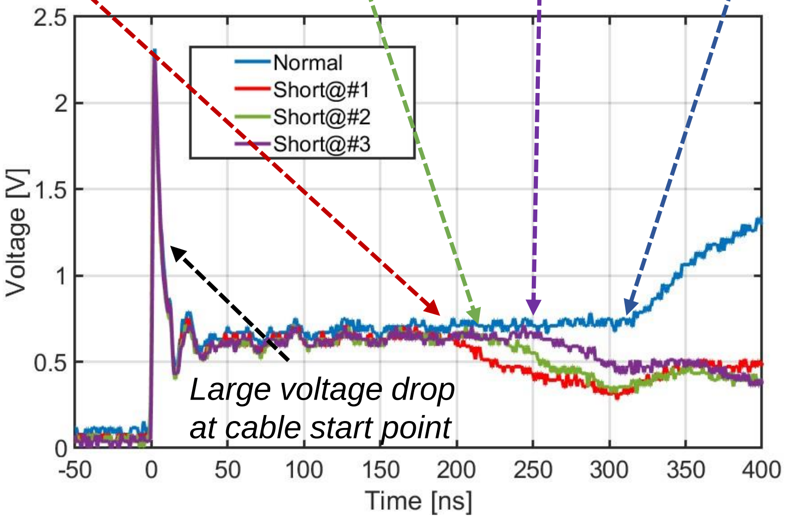


TDR results



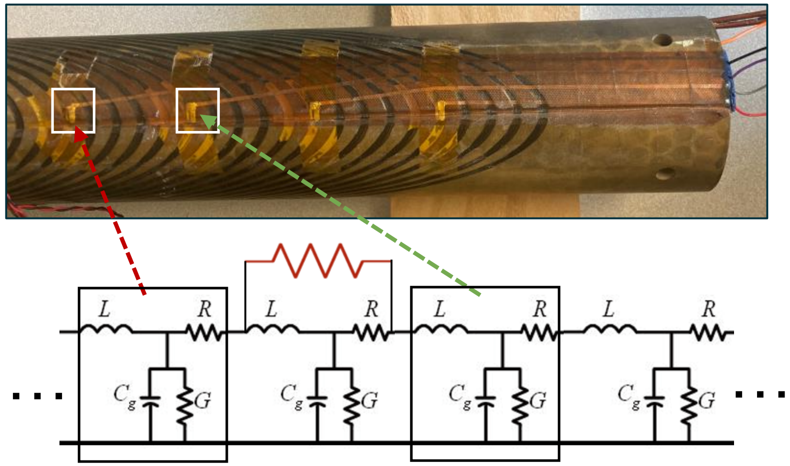
TDR results: voltage tab short



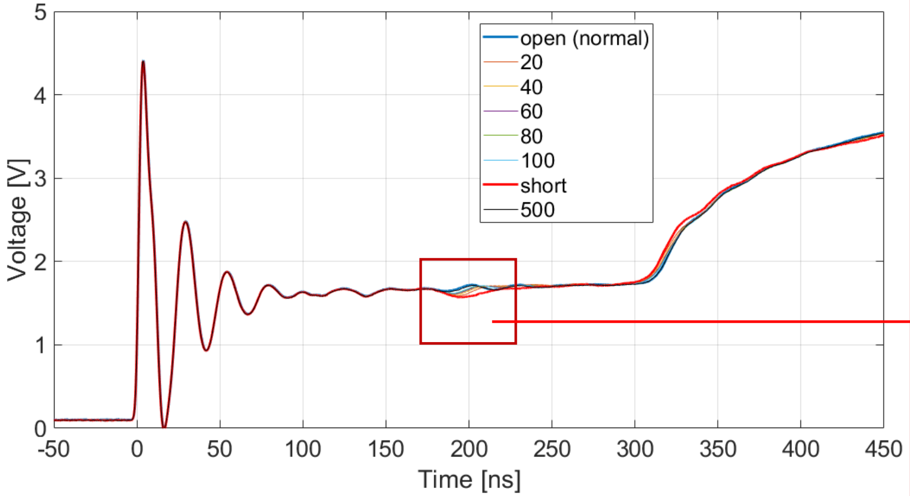


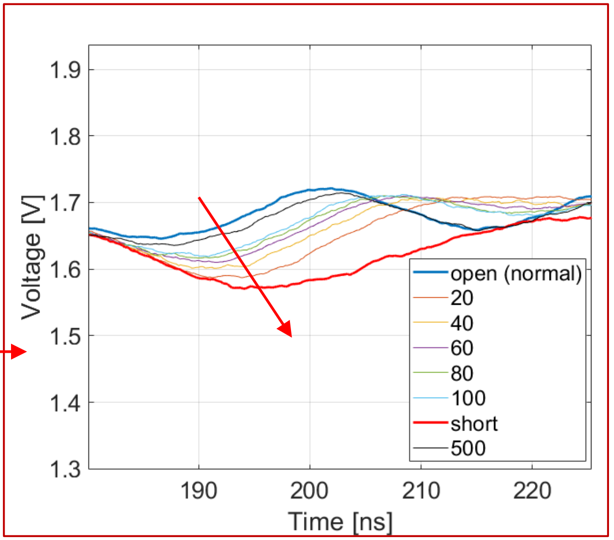
Why TDR can be useful for magnet diagnostics, although SC magnet is not a good transmission lines?

Series inductance/resistance discontinuity between two Voltage taps



TDR results

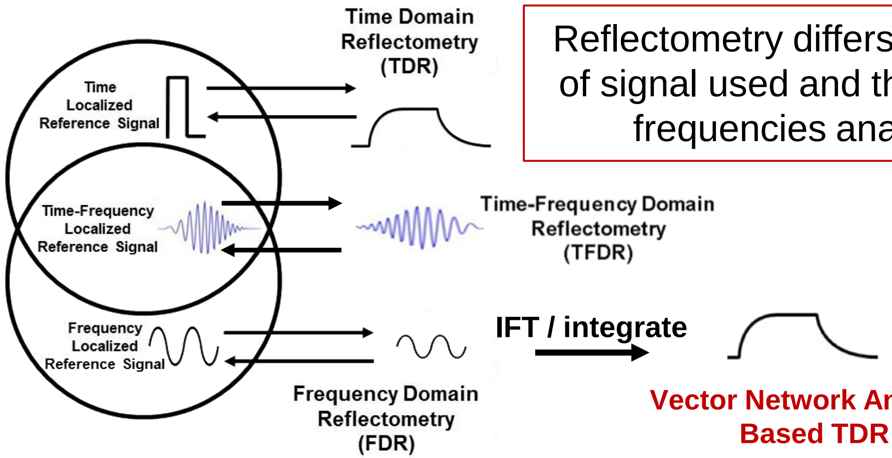




- TDR can detect and localize the impedance variations of CCT subscale
- Magnets are not good transmission lines, but we can still apply RF-based reflectometry methods
  - Need to improve impedance mismatch & connectors
  - Need to improve resolution and sensitivity

Impregnation damage monitoring for subscale 5

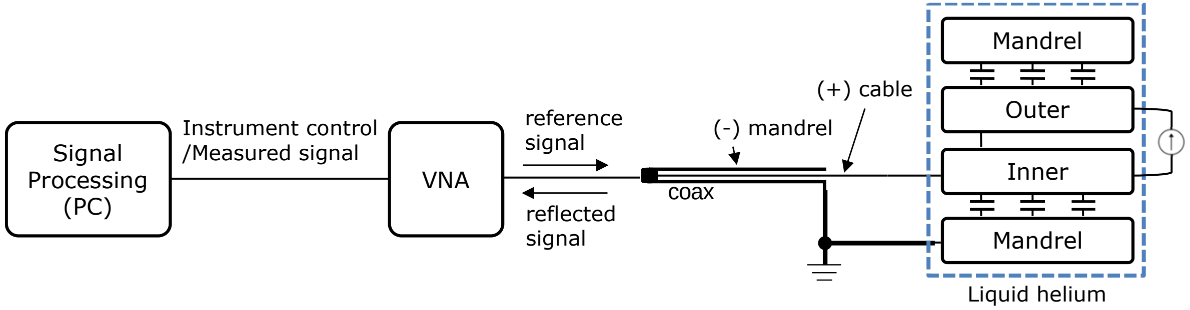
Type of reflectometry signal



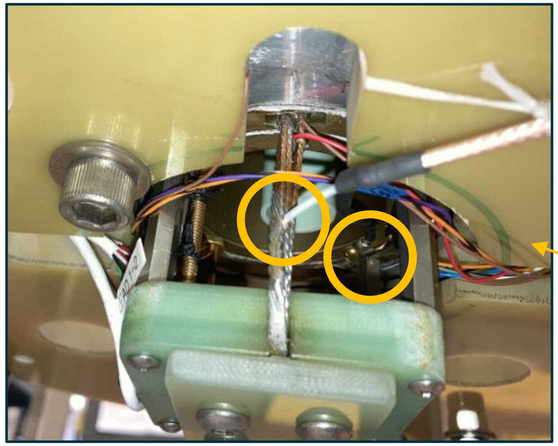
Reflectometry differs in the type of signal used and the range of frequencies analyzed.

Vector Network Analyzer Based TDR

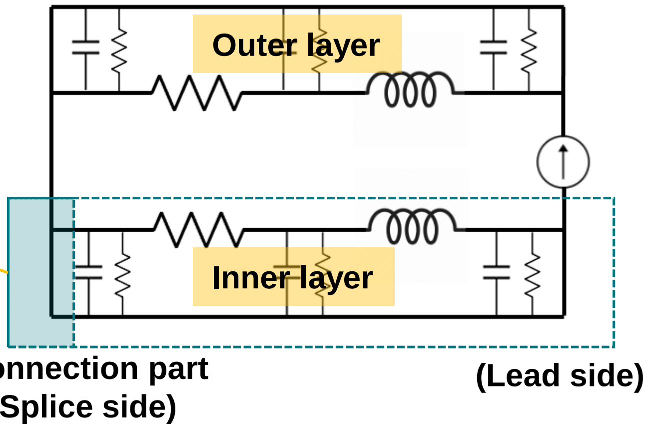
Experimental setup (VNA)



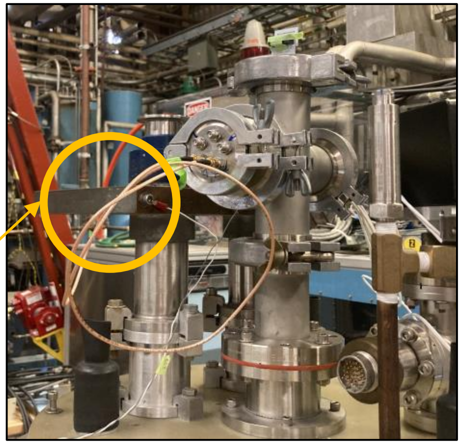
Connection part (Splice side)



Equivalent circuit of Inner layer



Lead side

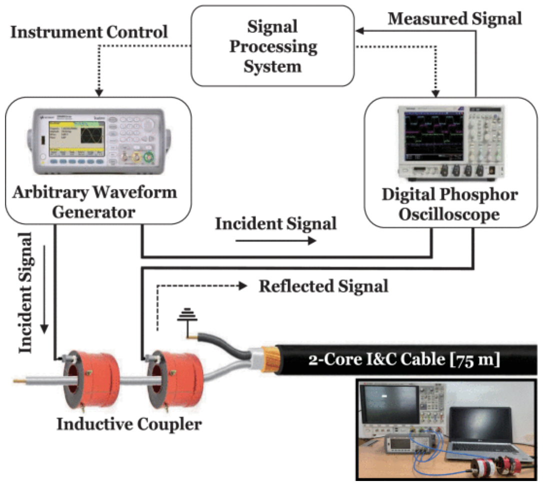


How can we improve the TDR application to monitor SC magnets with high accuracy & resolution in a real-time manner?

- Contactless monitoring technique via inductive coupler can be used for the real-time monitoring.
- Signal Processing (time-frequency analysis, ML, etc.) can improve the accuracy and resolution.
- SC magnets with no insulation/transmission line: RF TDR sensors* and waveguides can be alternatives.

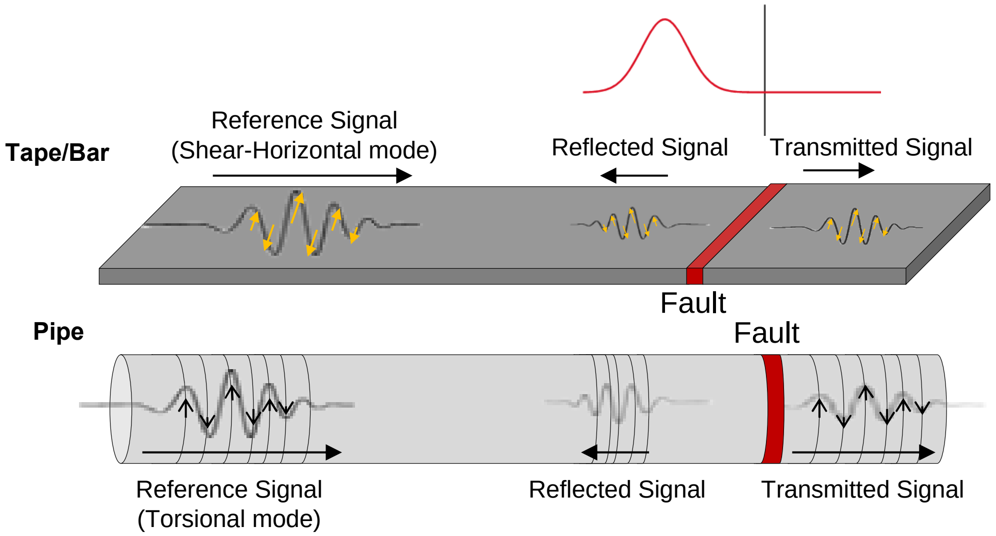
*M. Marchevsky, G. S. Lee, R. Teyber and S. Prestemon, "Radio Frequency-Based Diagnostics for Superconducting Magnets," *IEEE Transactions on Applied Superconductivity*, vol. 33, no. 5, Aug. 2023, Art no. 9000206

Application of inductive coupler**



**Y. H. Lee, *et al.*, *IEEE Transactions on Industrial Electronics*, vol. 69, no. 9, pp. 9494-9503, Sep. 2022.

Waveguides

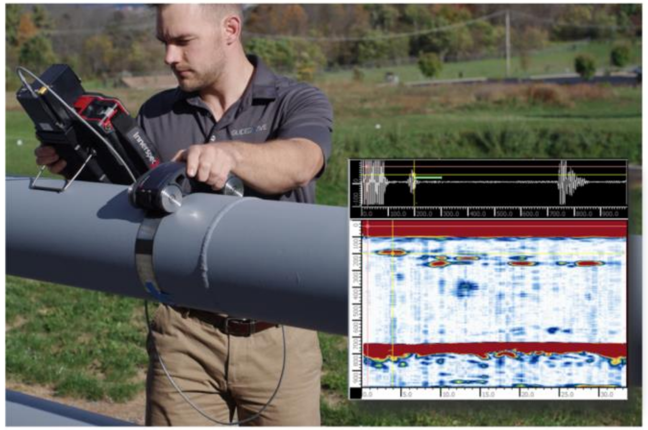


Acoustic reflectometry (Waveguides)

3

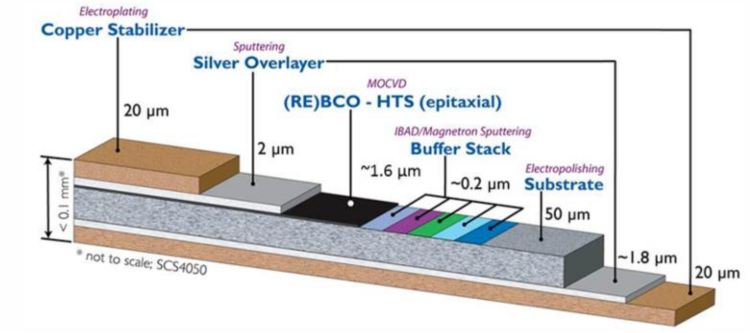
Having a good waveguide is important for obtaining accurate and reliable measurements in acoustic reflectometry

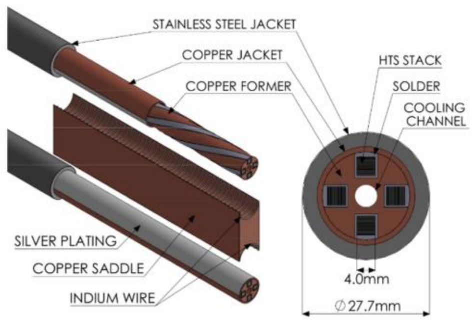
Pipe inspection*



* Guidedwave (FBS, Inc.)

SuperPower REBCO conductor / CFS VIPER cables**



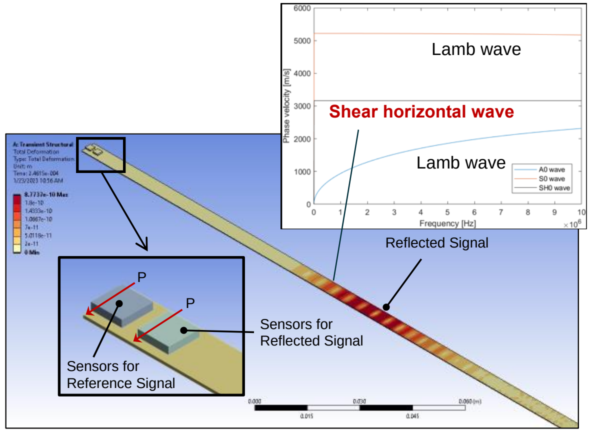


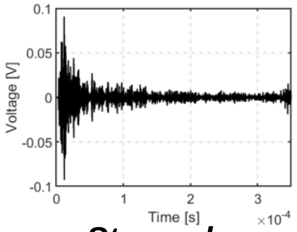
** Zachary S Hartwig *et al* 2020 *Supercond. Sci. Technol.* 33 11LT01,
"Time–Frequency-Based Quench Detection for HTS VIPER Cable Using Torsional Acoustic Wave," IEEE Sensors Journal, vol. 22, no. 22, pp. 21846-21854, Nov. 2022.

- Discontinuities in waveguides include mechanical damage, thermal effects (thermal load and thermal expansion)

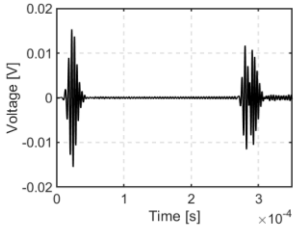
- How do we achieve a reliable quench detection and localization capability for magnets that are not good waveguides?
  1. The voltage tabs, clamping structures, and joints can be used as **discontinuities** for obtaining reflected signals in real operating conditions.
  2. Non-leaky acoustic waveguides
     - ✓ M. Marchevsky and S. Prestemon, "Distributed thermometry for superconducting magnets using non-leaky acoustic waveguides", *Supercond. Sci. Technol*., vol. 36, no. 4, Feb. 2023.

Time-frequency based acoustic reflectometry for localizing the quench and improving spatial resolution

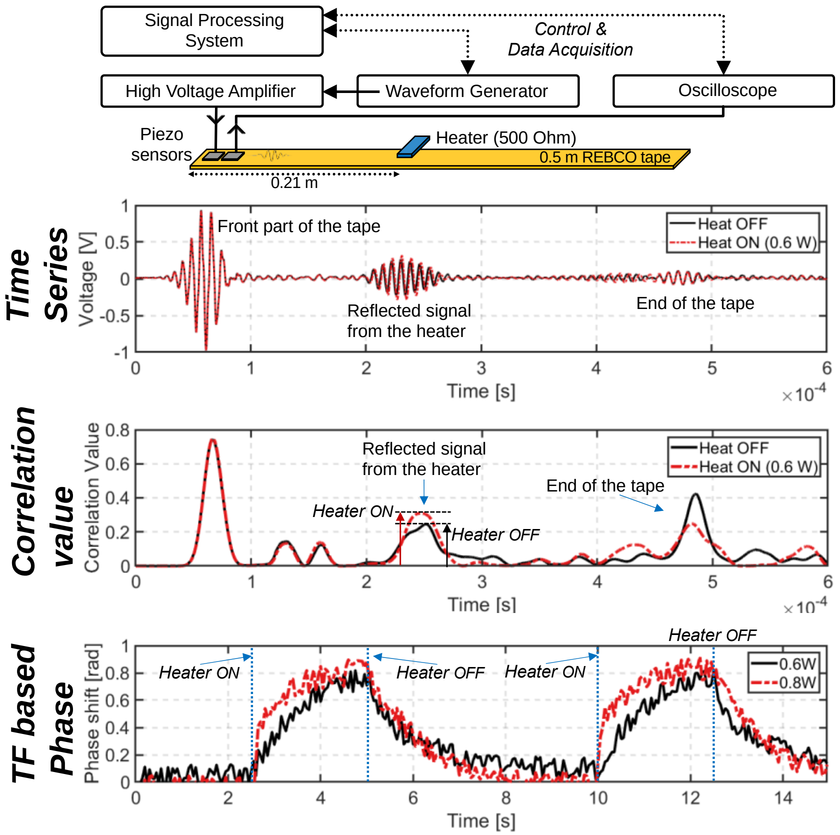


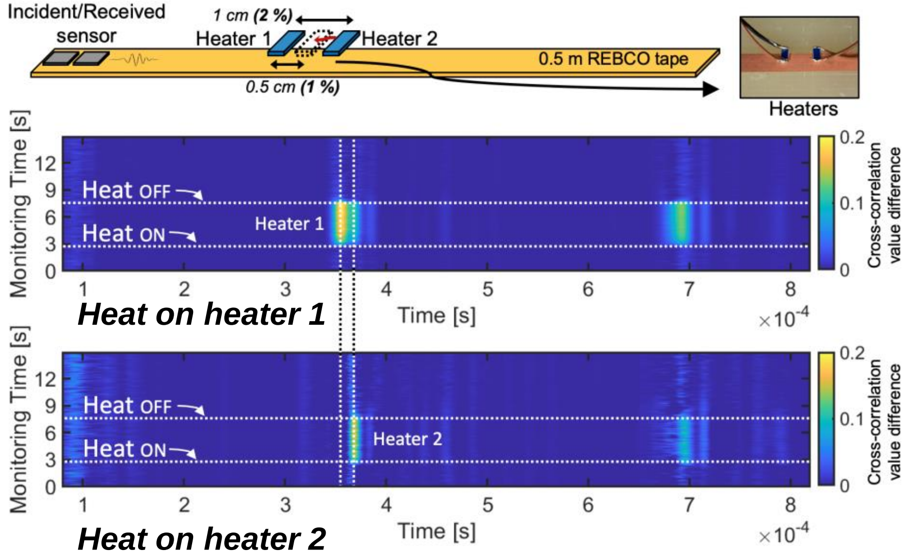


Step pulse



Gaussian Chirp



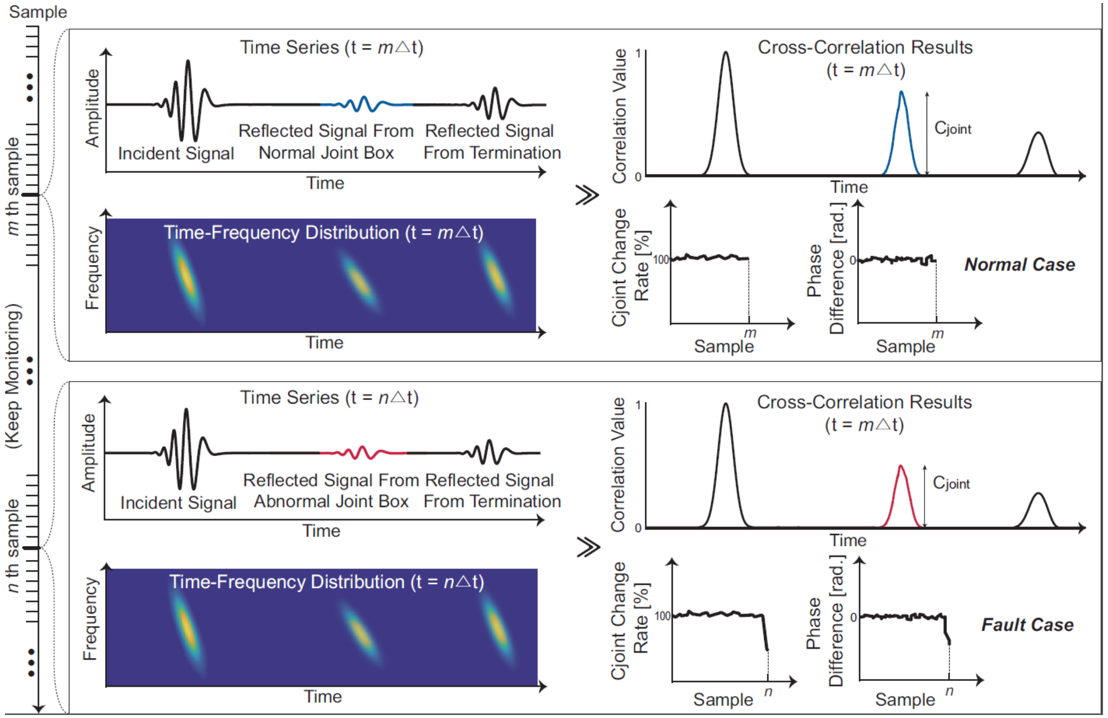


"Quench Localization for High-Temperature Superconductor 2G Tape using Acoustic Reflectometry," *IEEE Transactions on Applied Superconductivity*, vol. 33, no. 5, Aug. 2023, Art no. 9000505.

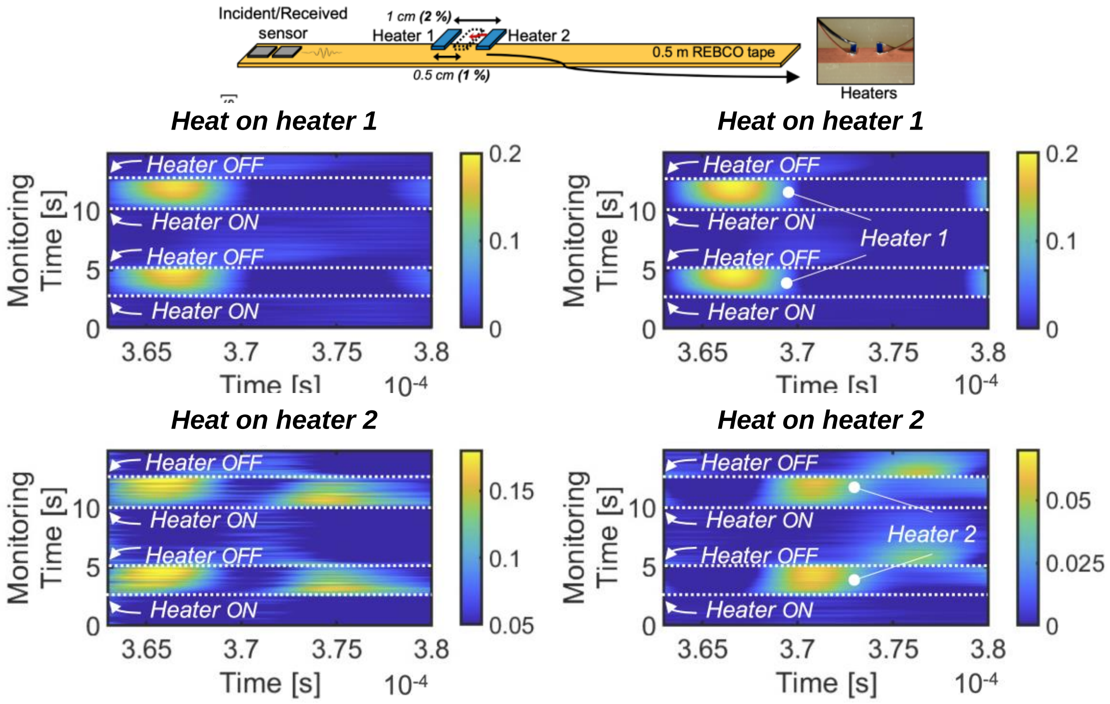
- Shear-Horizontal Acoustic wave: Tape type structure, Non-dispersive
- Quench detection/localization technique based on the reflection of waves at the discontinuity
- Acoustic reflectometry can detect **the heat location and strength**
- A time–frequency-based phase delay was extracted from the acoustic signal to monitor

The performance of quench detection/localization depends on which time-frequency distribution is used

Time-frequency distribution-based monitoring method



Wigner-Ville distribution vs Chirp-let transform



- The reliability of the monitoring index derived from the Wigner-Ville distribution can be reduced owing to cross-terms
- Chirp-let transform: TF analysis method with a relatively low impact on cross-terms
- Analysis in time-frequency domain improves the accuracy and resolution (better than 1% of the sample length) of reflectometry

Conclusions

- The reflectometry method can provide information on the quench detection of the SC magnet; impregnation damage/change

- RF reflectometry has potential to identify locations of the gradual impedance variation during the training process.

- Analysis in the time-frequency domain improves the accuracy and spatial resolution of reflectometry.

- “Impregnation damage monitoring for the Nb_3Sn Canted-Cosine-Theta magnets using time-domain reflectometry” will be presented (oral) – MT28

Acknowledgments

- ✓ Jose Luis Rudeiros Fernandez, Marcos Turqueti, Robert Memmo, Pardeep Chahal, Chet Spencer, Derek Hochvert, James Swanson, Matthew Reynolds, and Hugh Higley.
- ✓ The work was supported by the U.S. Magnet Development Program (MDP), sponsored by DOE Office of High Energy Physics.

Thanks!