Application of acoustic/electrical reflectometry for superconducting magnets

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Presentation to the SMP Technical Meeting

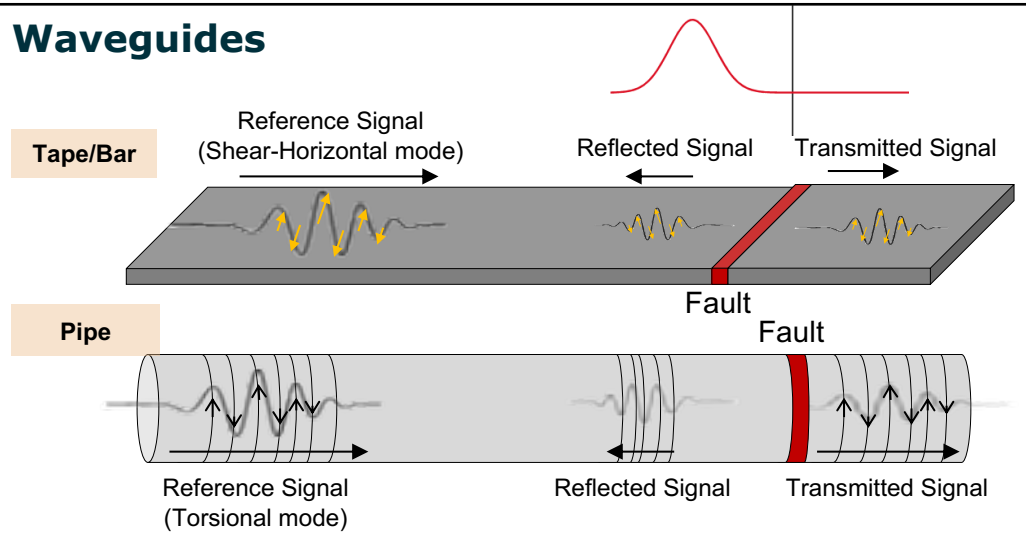
Mar 07, 2023

Outline

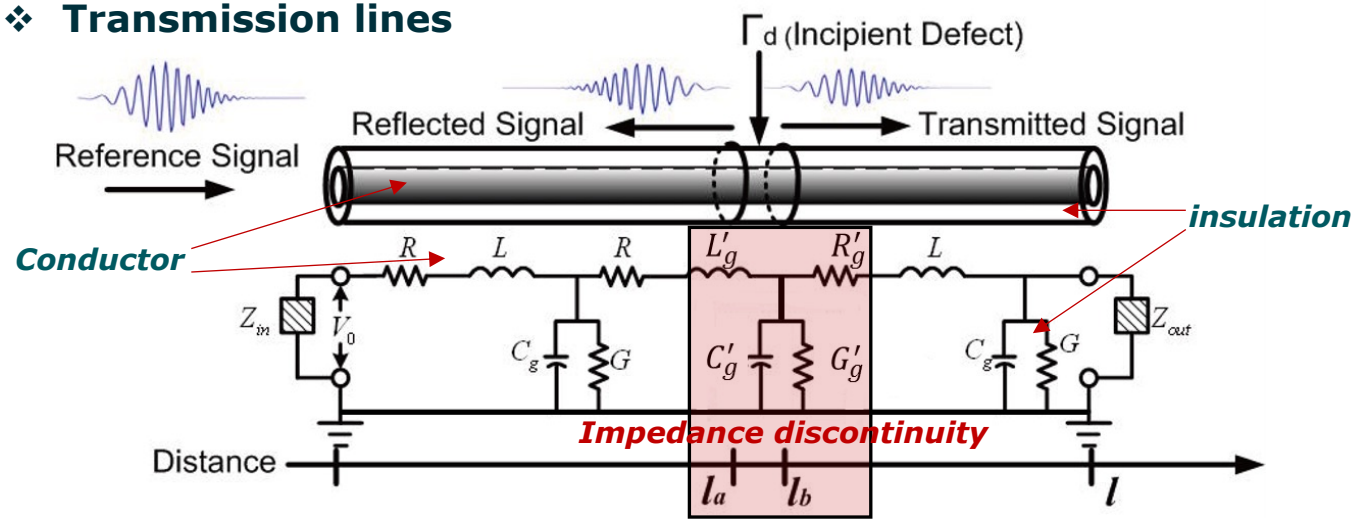
- **Motivation**
  - reflectometry is a non-invasive method to detect and localize faults
  - quench detection / localization using reflectometry for both LTS and HTS magnets
- **Acoustic reflectometry (Waveguides)**
  - fusion cable – VIPER cable (Commonwealth Fusion Systems)
  - REBCO tape – w/ time-frequency analysis for resolution improvement
- **Electrical reflectometry (Transmission lines)**
  - CCT subscale – Impregnation damage monitoring
  - distributed sensing using piezo cable (operated at 6K)

Reflected signals offer information about the properties of materials/structures

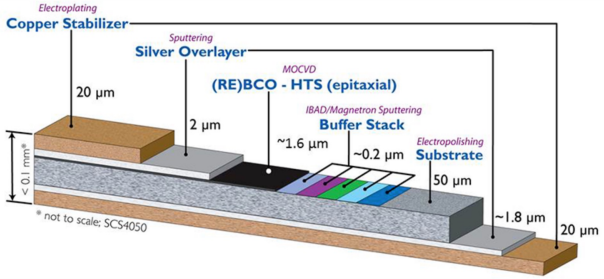
❖ Waveguides

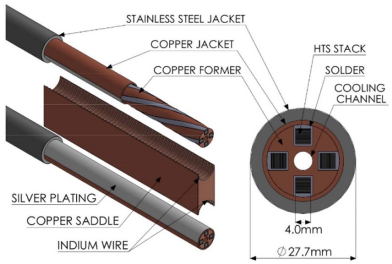


❖ Transmission lines



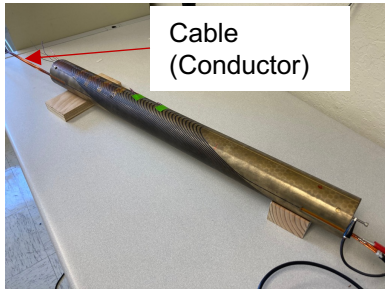
*SuperPower REBCO conductor / CFS VIPER cables**

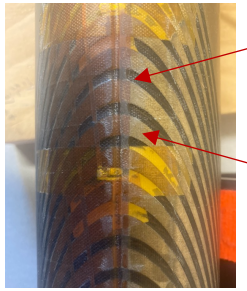




*Zachary S Hartwig *et al* 2020 *Supercond. Sci. Technol.* 33 11LT01

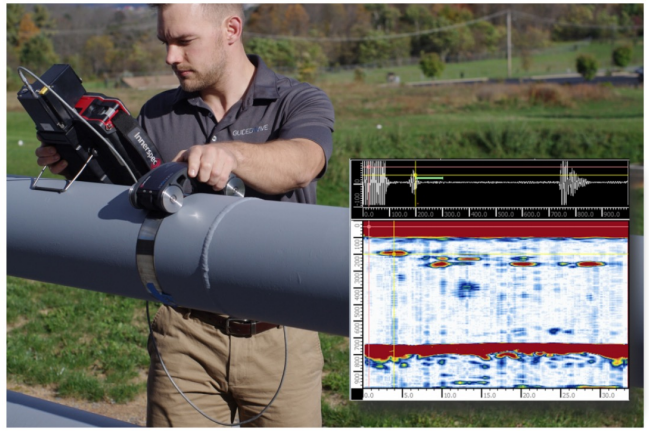
CCT subscale / Piezo coaxial cable





- Discontinuities in waveguides include mechanical damage, thermal effects (thermal load and thermal expansion)
- Distributed electrical impendence measurement for impregnation damage, thermal change, dielectric change

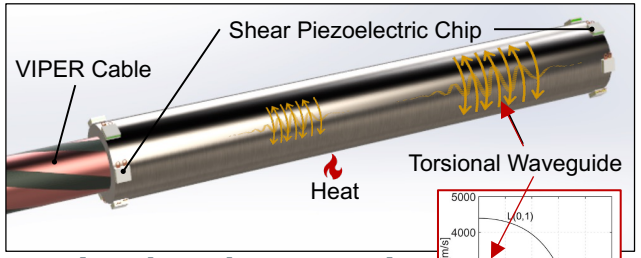
Having a good waveguide is important for obtaining accurate and reliable measurements in acoustic reflectometry

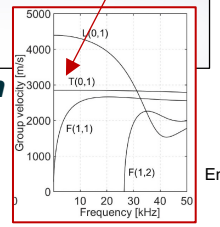


Pipe inspection (GUIDEDWAVE)

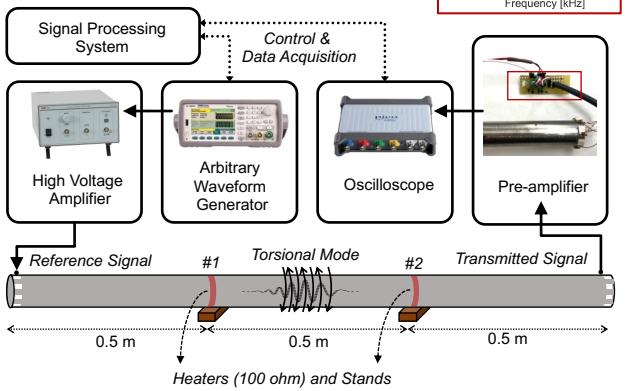
- How do we achieve a reliable quench detection and localization capability for <u>magnets that are not good waveguides</u>?
  1. The voltage tabs, clamping structures, and joints can be used as **<u>discontinuities</u>** for obtaining reflected signals in real operating conditions.
  2. Non-leaky acoustic 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.

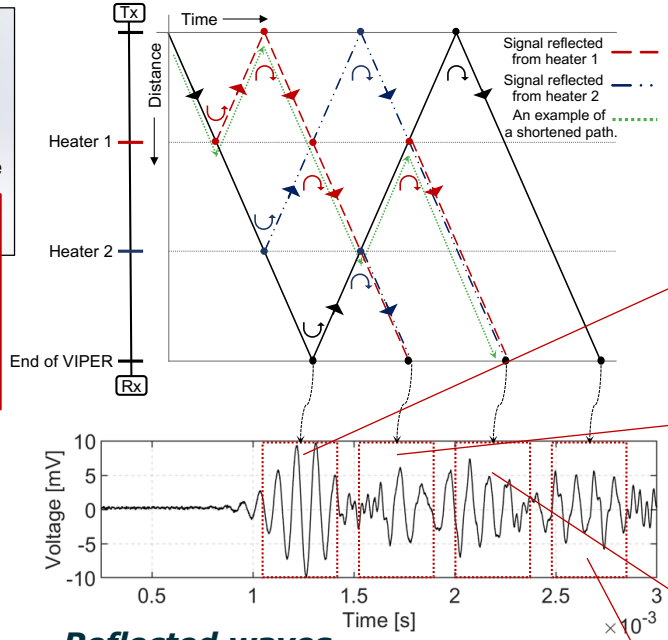
Applying acoustic reflectometry to VIPER fusion cable





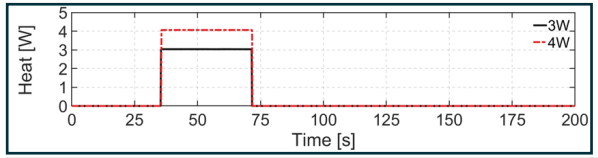
Torsional mode generation using shear piezoelectric sensors





Reflected waves from heaters and the end of the cable

Heating profile



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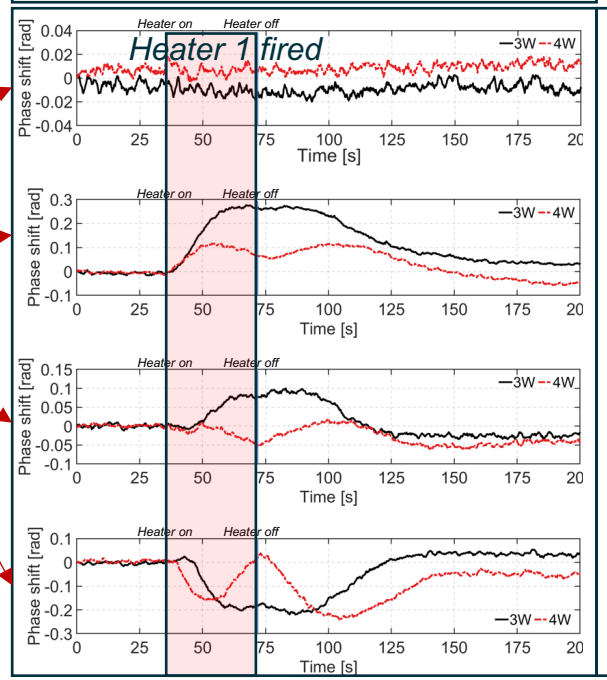
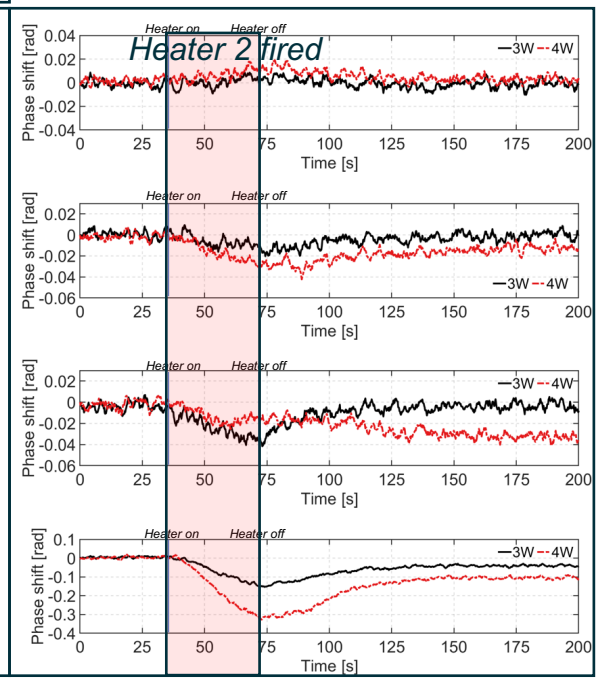
Commonwealth Fusion Systems



TF-based phase (Heater #1)



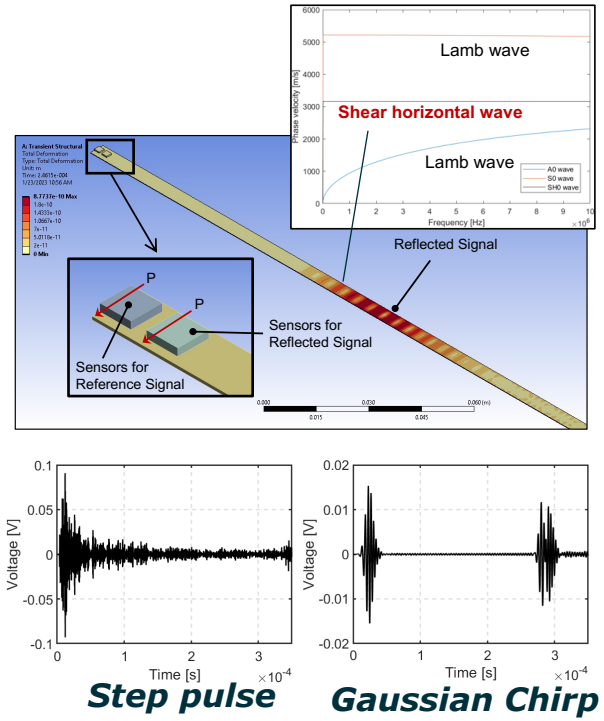
TF-based phase (Heater #2)

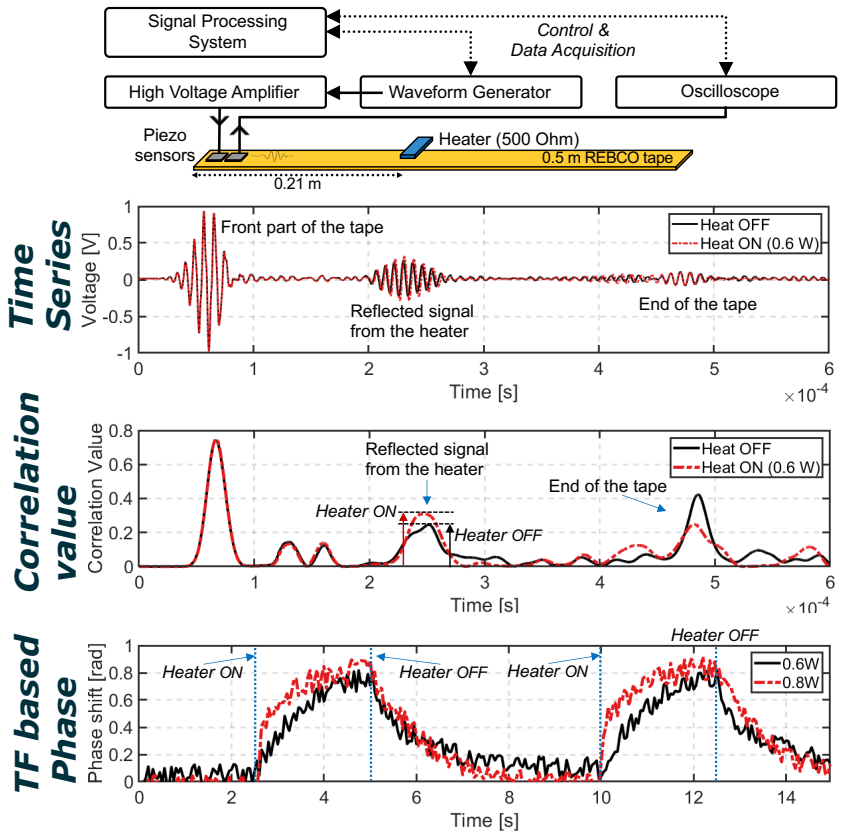
- **Torsional wave** is non-dispersive and not affected by internal fluid
- Suitable for **hollow cylinder-shaped structure**
- Acoustic reflectometry can detect **the heat location and strength**
- A time–frequency-based phase delay was extracted from the acoustic signal to monitor

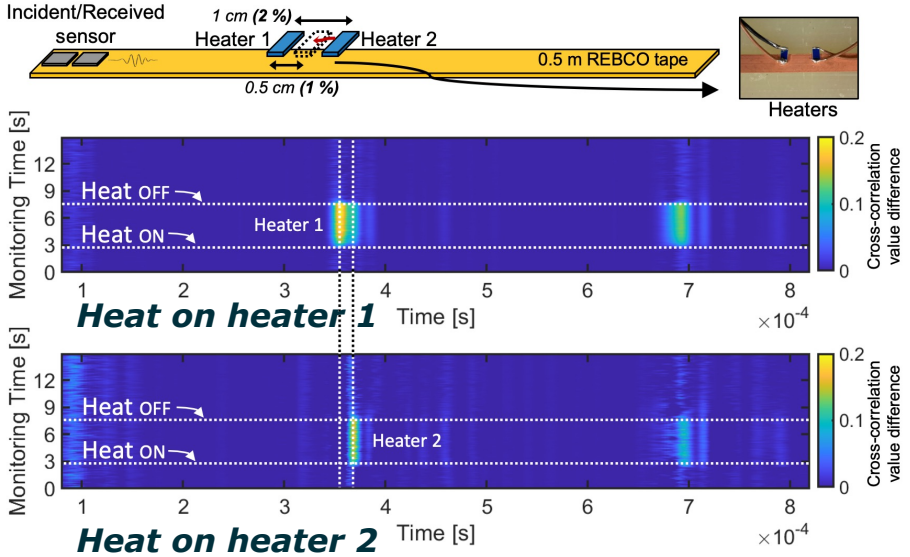
"Time–Frequency-Based Quench Detection for HTS VIPER Cable Using Torsional Acoustic Wave," *IEEE Sensors Journal*, vol. 22, no. 22, pp. 21846-21854, Nov. 2022.

Application #2

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





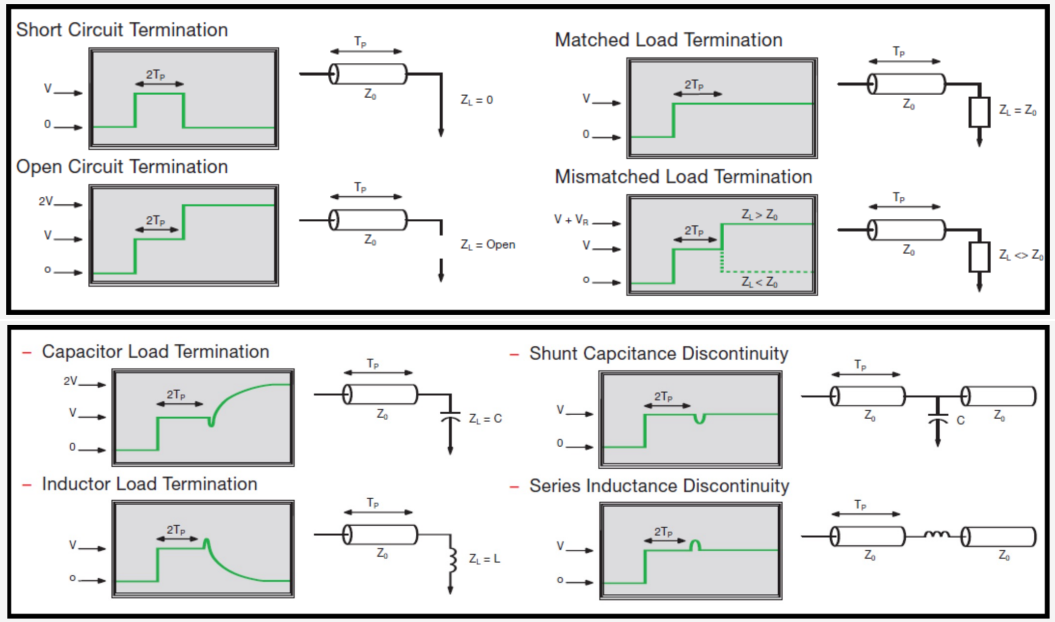


- Shear-Horizontal Acoustic wave
  - Tape type structure, Non-dispersive
- Quench detection/localization technique based on the reflection of waves at the discontinuity
- Analysis in the time-frequency domain improves the accuracy and resolution (<1%) of reflectometry

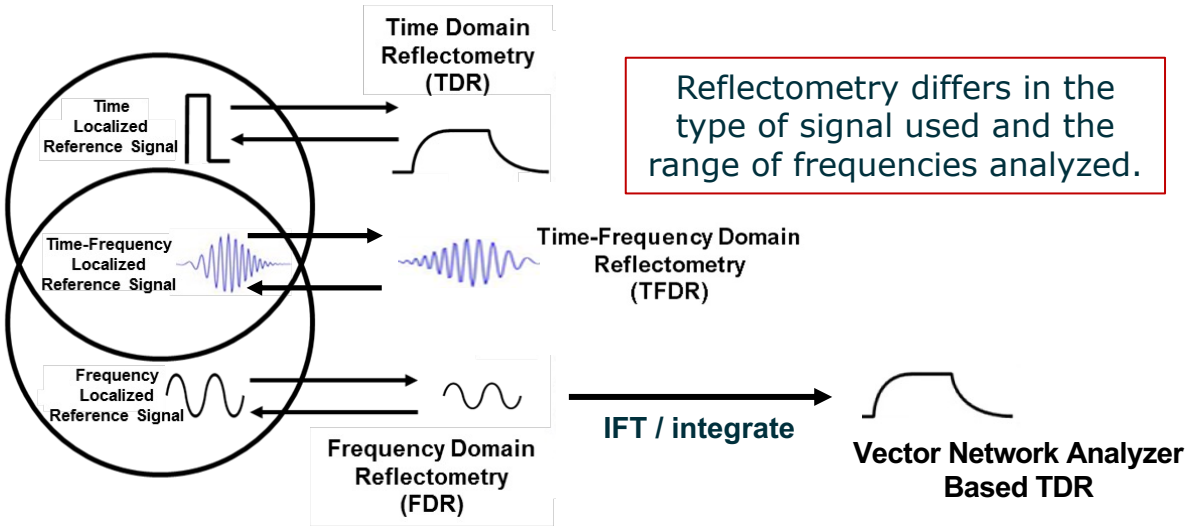
"Quench Localization for High-Temperature Superconductor 2G Tape using Acoustic Reflectometry," *IEEE Transactions on Applied Superconductivity*, vol. 33, no. 5, Aug. 2023, Art no. 9000505.

RF based reflectometry can measure the electrical properties of material

Reflections for various termination (Keysight)



Reflectometry based on the input signal



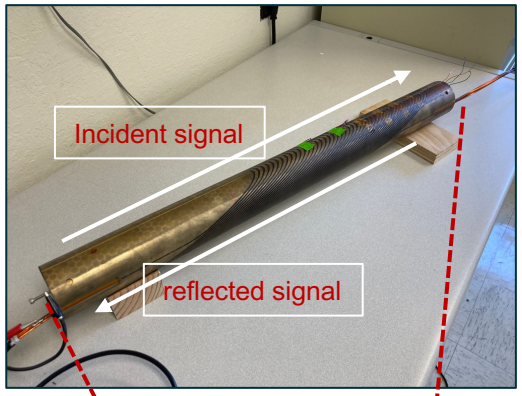
Reflectometry differs in the type of signal used and the range of frequencies analyzed.

- How do we non-invasively localize weak points and interfaces where mechanical disturbances that cause premature quenching are taking place?
  1. <u>The method of directly applying a signal to magnets</u> can evaluate and localize the impregnation damage
  2. <u>RF TDR sensors</u> can detect local variations of strain, temperature, and magnetic field.

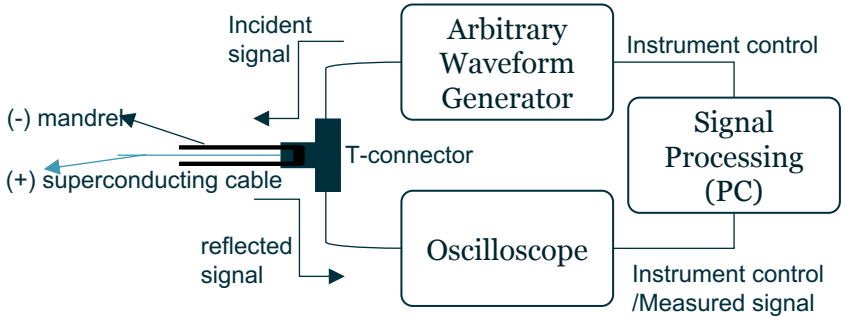
(M. Marchevsky, G. S. Lee, R. Teyber and S. Prestemon, "Radio Frequency-Based Diagnostics for Superconducting Magnets," *IEEE Transactions on Applied Superconductivity*, vol. 33, no. 5, Aug. 2023, Art no. 9000206)

Applying electrical reflectometry to CCT subscale

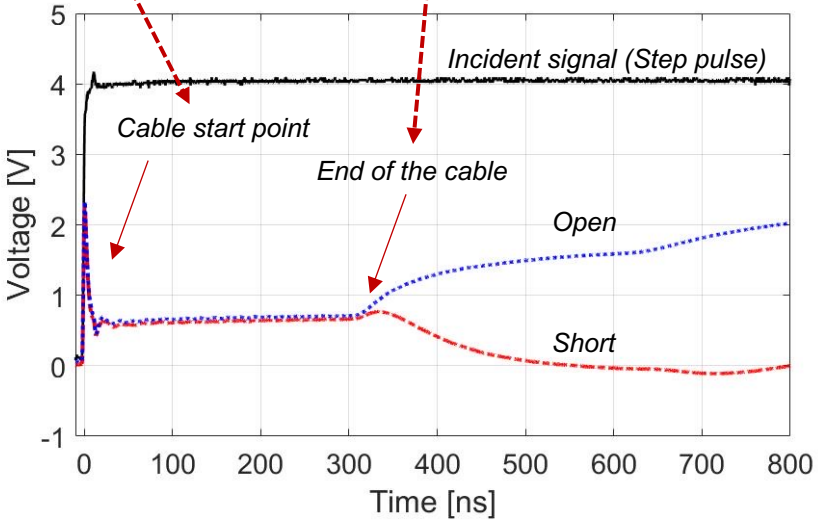
CCT subscale (Nb3Sn)



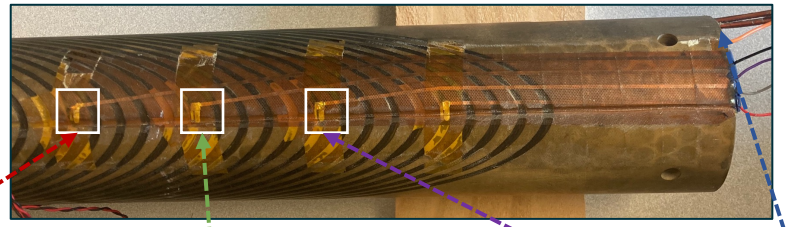
Experimental setup



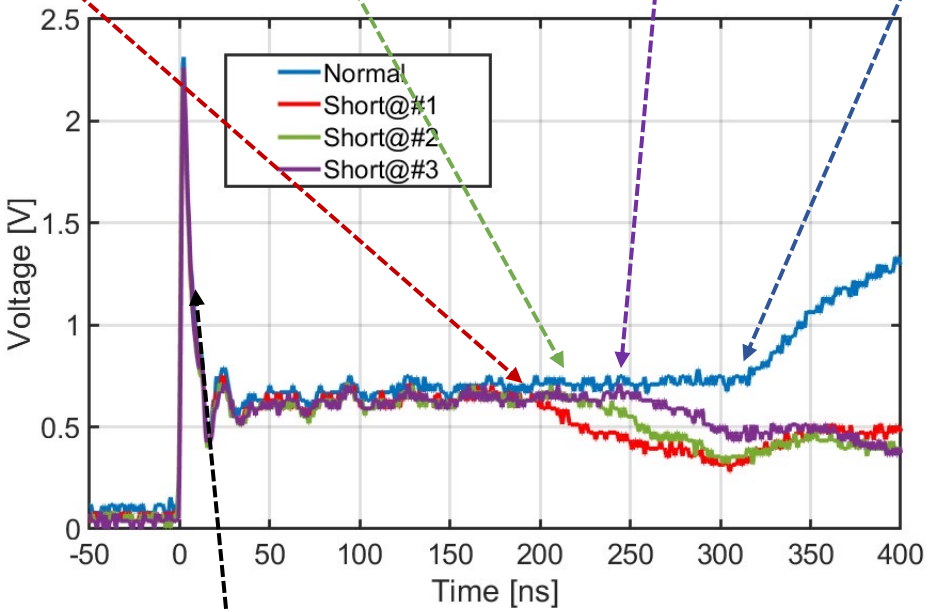
TDR results



- CCT subscale can be considered as **a transmission line!**
- Coil (+), Mandrel (-), Resin/Epoxy (insulation)
- If the voltage tap and mandrel are short-circuited, it is possible to estimate the location of the voltage tap.

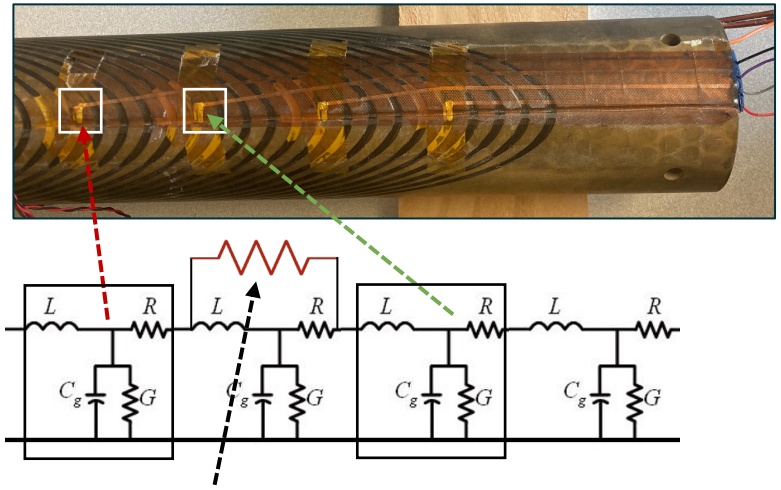


Voltage tap #1 (27/46 turns) **Voltage tap #2 (32/46 turns)** **Voltage tap #3 (37/46 turns)** **Cable End**

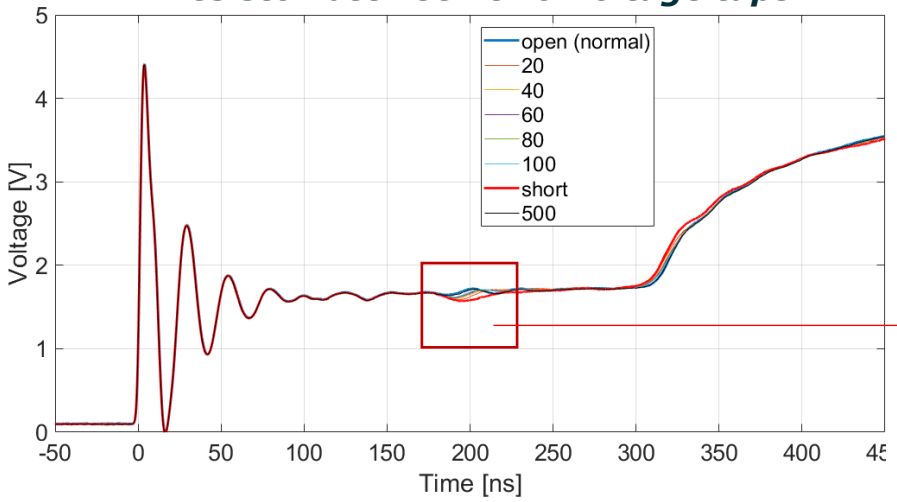


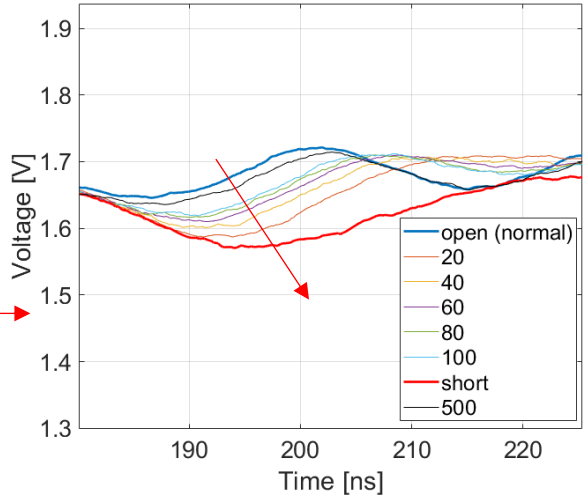
Large voltage drop at cable start point

Series inductance/resistance discontinuity in CCT subscale



Resistor between two Voltage taps



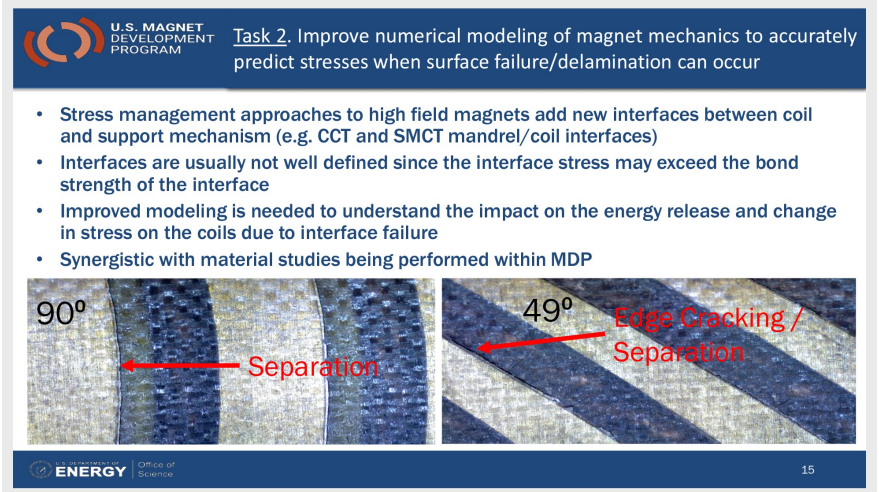


TDR can detect the impedance variations of CCT subscale

09:00 **Nb3Sn CCT overview**

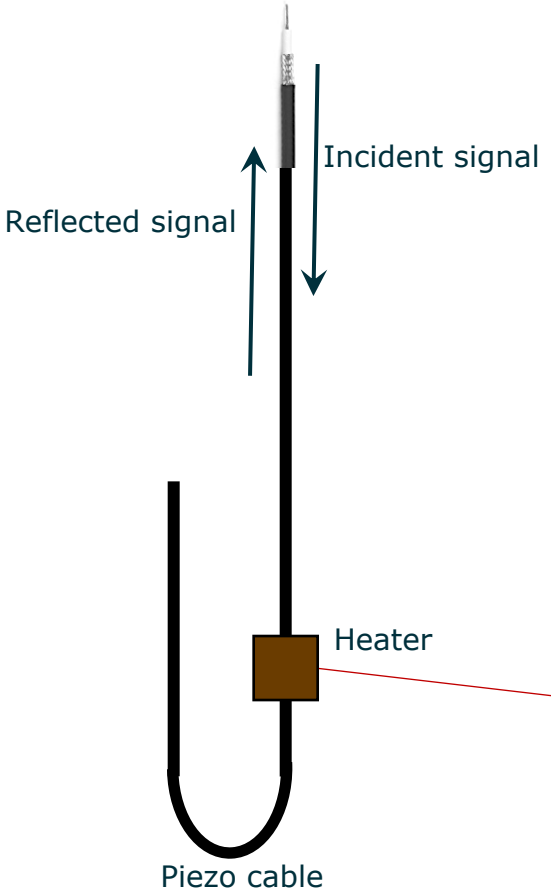
Speaker: Diego Arbelaez (Lawrence Berkeley National Lab)

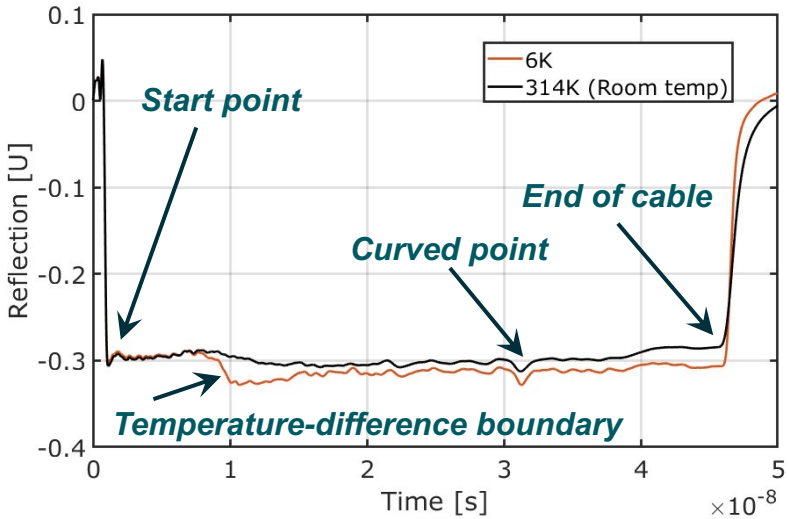
Arbelaez_MDP2022...

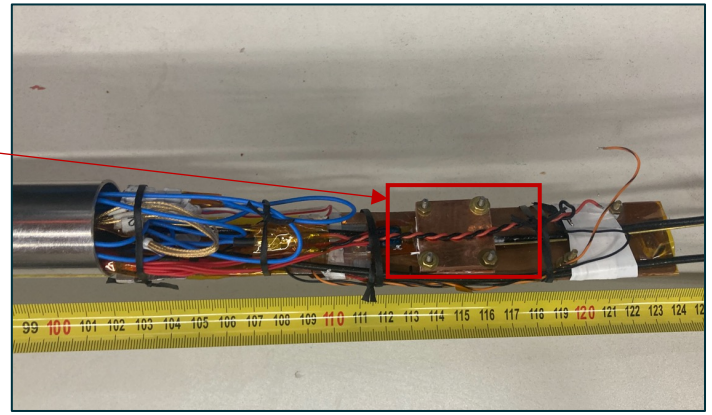


Cracks and separations are expected to yield local impedance variations along that line through induced changes in the effective dielectric permittivity of the impregnation layer

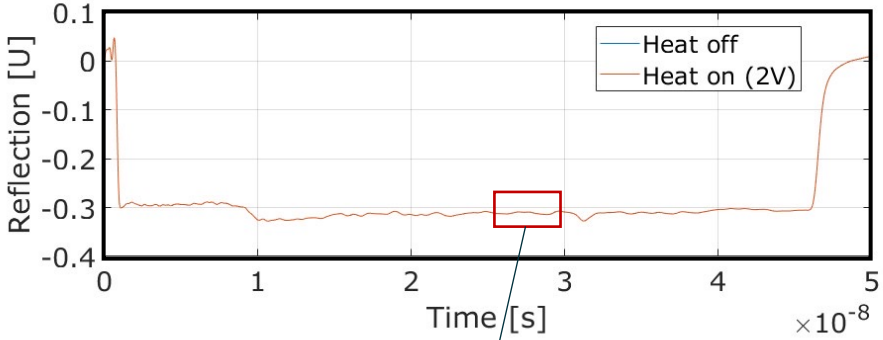
Insulations responding to changes in temperature and strain

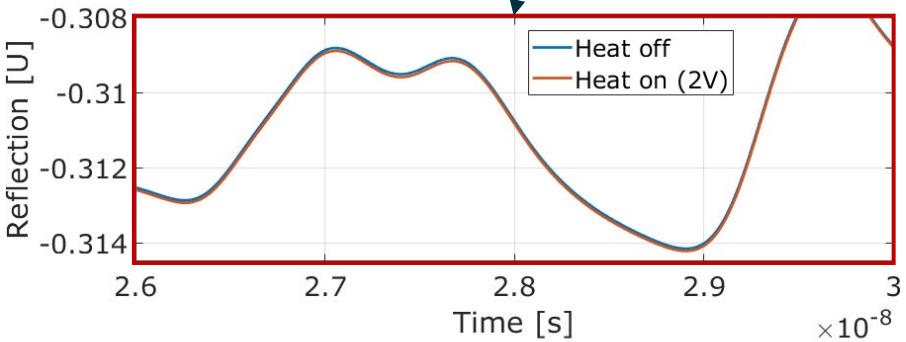






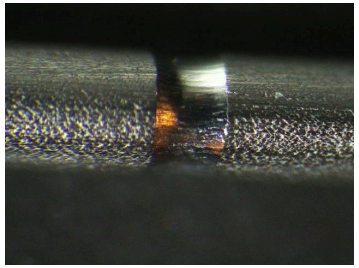
- Heat 2V (100 ohm): 6K->6.82K





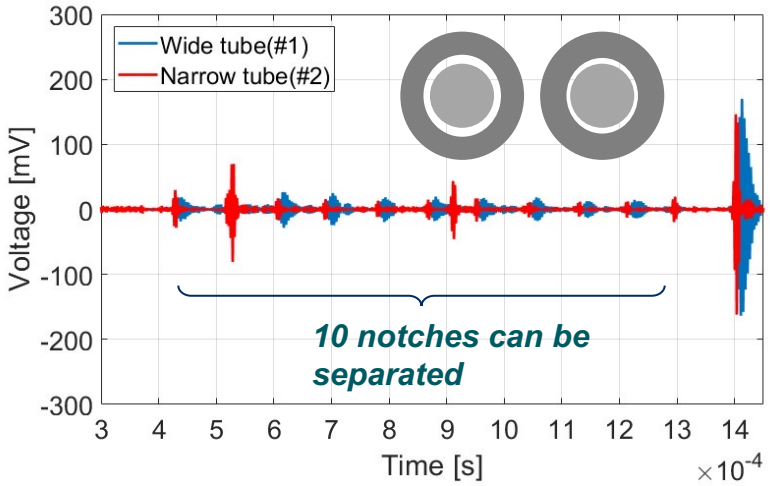
Summary

- The reflectometry method can provide information on the quench detection of the magnet; temperature and mechanical defects
- Acoustic reflectometry can detect and localize heating points on superconducting cables.
- RF reflectometry has potential to identify locations of the gradual impedance variation in the training process
- Analysis in the time-frequency domain improves the accuracy and spatial resolution of reflectometry.
- A SBIR project is underway to find good waveguide and good insulation for distributed sensing.



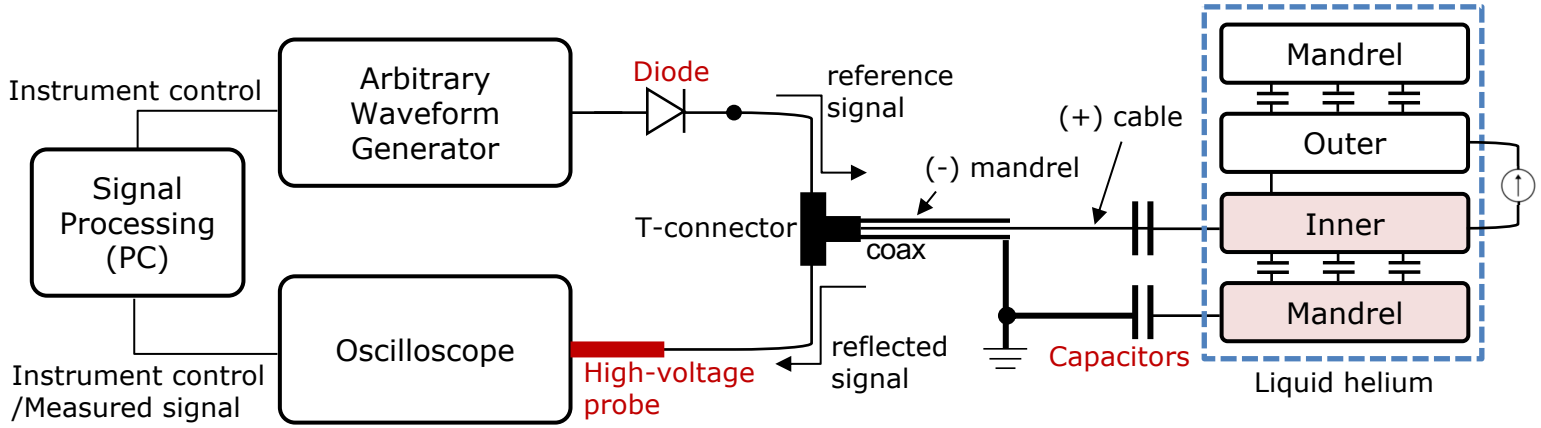
SBIR

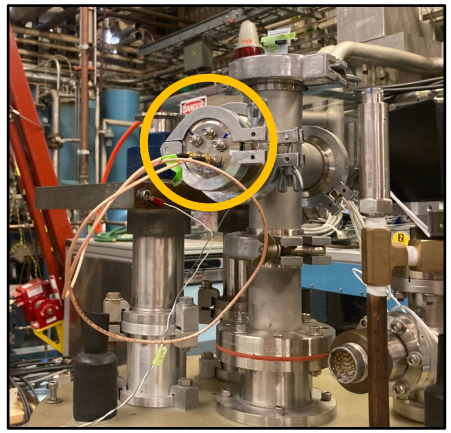
Etegent TECHNOLOGIES ltd

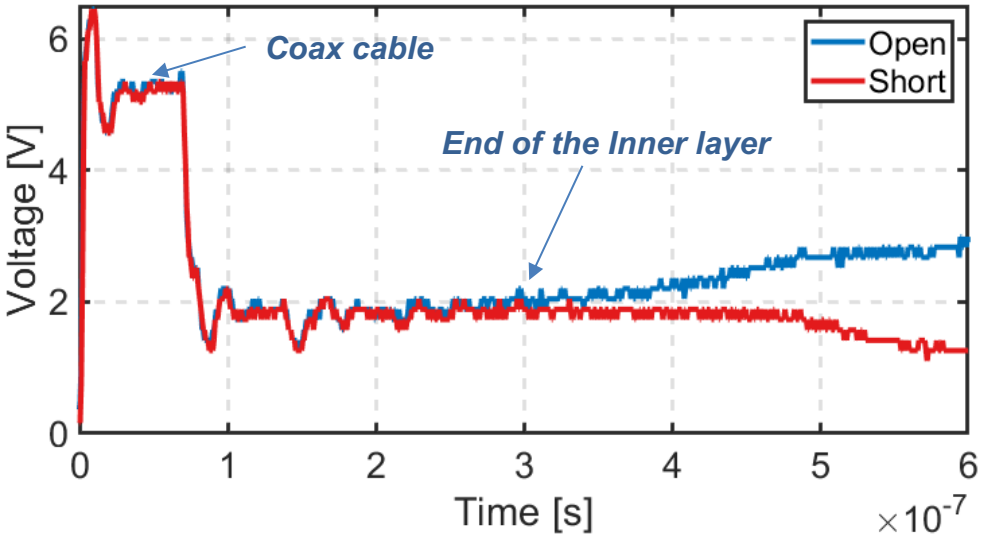


Subscale 2

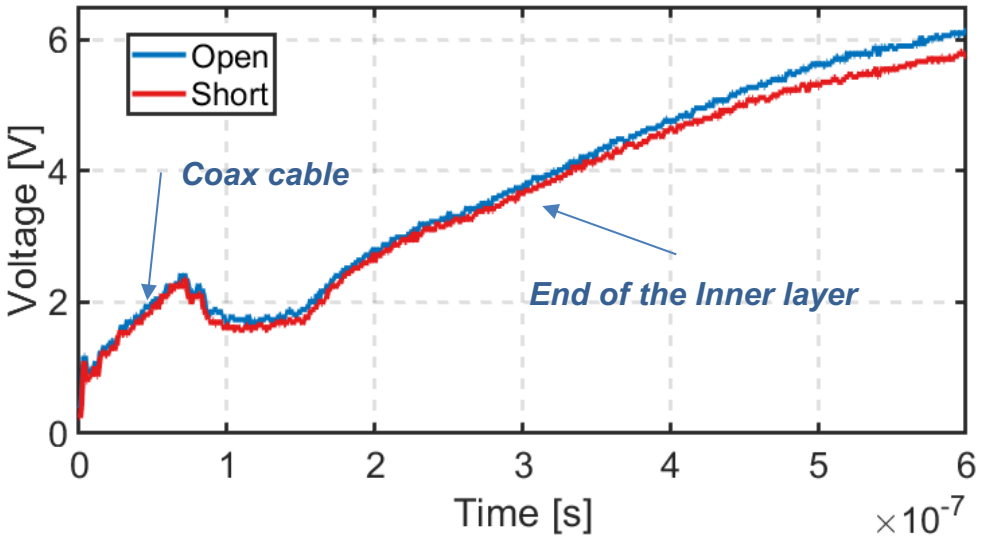
Input: 4 V Step, **High voltage Probe:** 10:1, **Sampling rate:** 1.25 GS/s, **Inner layer:** ~300 points,







w/o capacitors and diode



w/ capacitors and diode

- Allows measurement of the beginning and end of the cable (Step Pulse)
- The insulation change affects the shape of the reflected signal.
- But, resolution degradation due to protection devices (diode, capacitors, and HV probe)