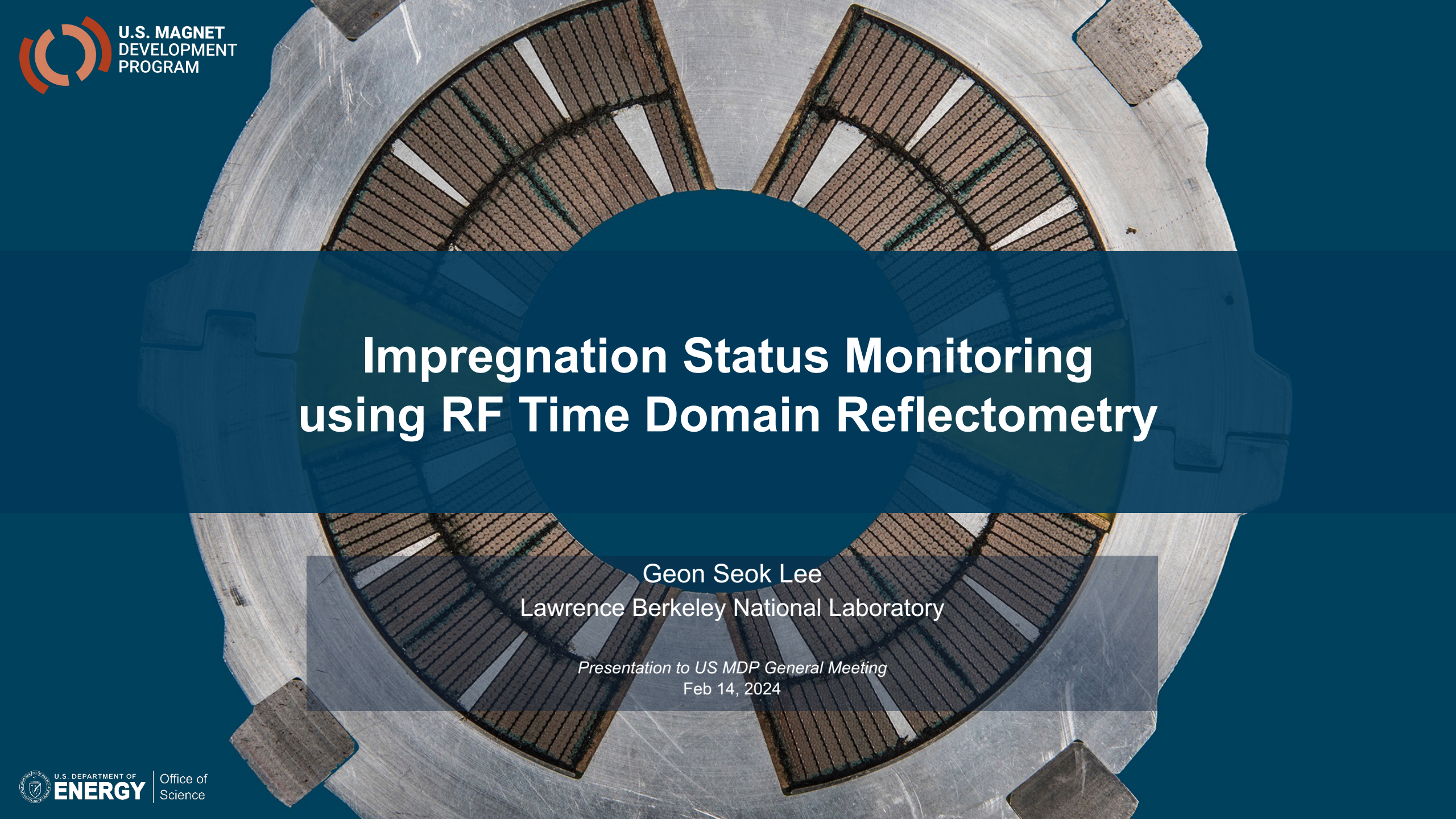

U.S. MAGNET DEVELOPMENT PROGRAM

Impregnation Status Monitoring using RF Time Domain Reflectometry

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Presentation to US MDP General Meeting
Feb 14, 2024

U.S. DEPARTMENT OF ENERGY | Office of Science

Research progress

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

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

- Distributed sensing for monitoring the impregnation status in Subscale magnets

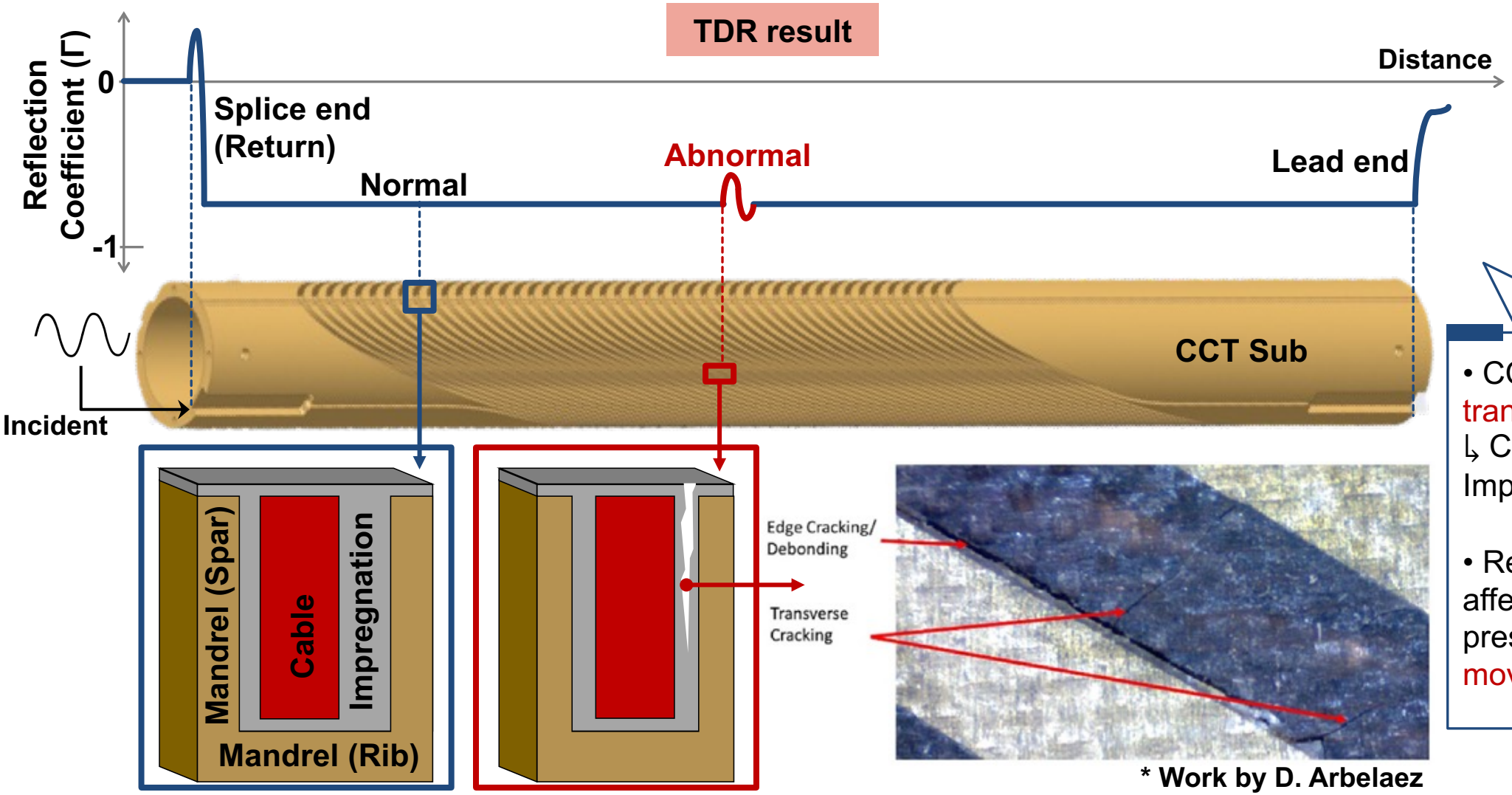
1. Completed mock-up plate test replicating a single turn in the CCT Subscale magnet's geometry
2. Completed monitoring tests for CCT Sub5, including heater study
3. Completed monitoring tests for CCT Sub6, including both pre- and post-thermal cycle test

Items 1~2: presented on Aug 16, 2023, MDP General Meeting

Items 1~3 (except thermal cycle): presented on Sep 13, 2023, MT28, 3OrA2

Theoretical background:

Impregnation monitoring using RF TDR



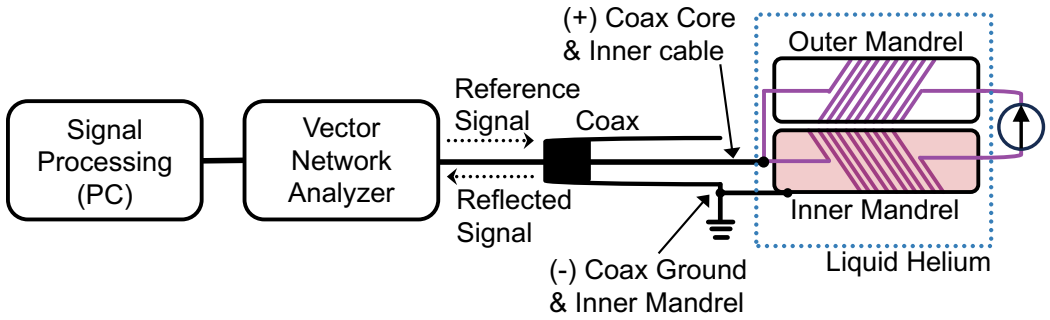
* Work by D. Arbelaez

- CCT Sub can be seen as a transmission line
  ↳ Cable (+), Mandrel (-), and Impregnation (insulation)

- Reflection coefficient (Γ) is affected by spacings and the presence of voids (conductor movements or cracks)

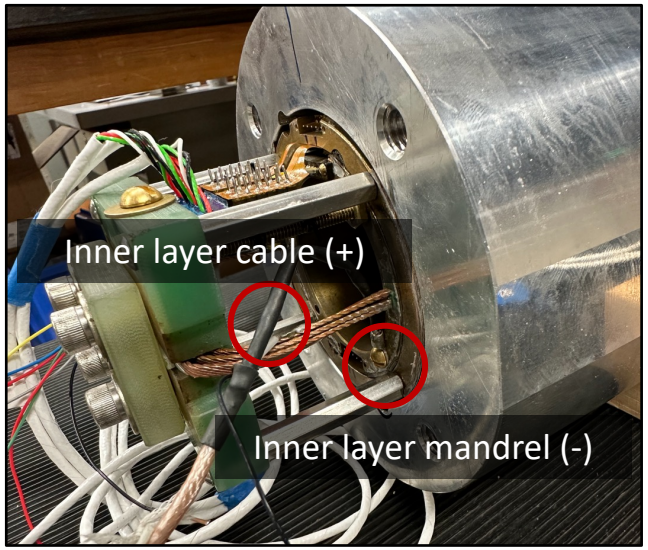
Impregnation monitoring for Subscale-5

Experimental setup (Vector network analyzer)



- Subscale-5
- Inner layer: paraffin wax impregnated (target)
- Outer layer: Mix61

Connection part (Splice)



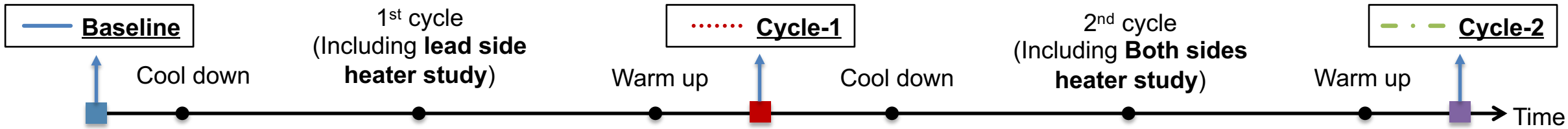
Spot heaters*

(*Work by D. Arbelaez and R. Teyber)

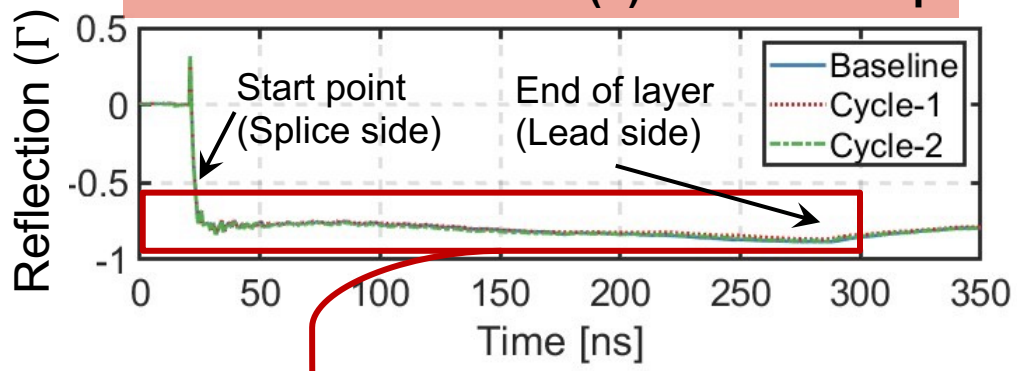
- Applied incident signal from the splice side
- Heaters installed in direct contact with the cable (both Lead and Splice sides)
- Conducted heater studies twice for CCT subscale-5 (No quench @ IL)
  - Initial study focused on heater study on the lead side (before thermal cycle)
  - The second test (after thermal cycle) included a heater study on both splice and lead sides

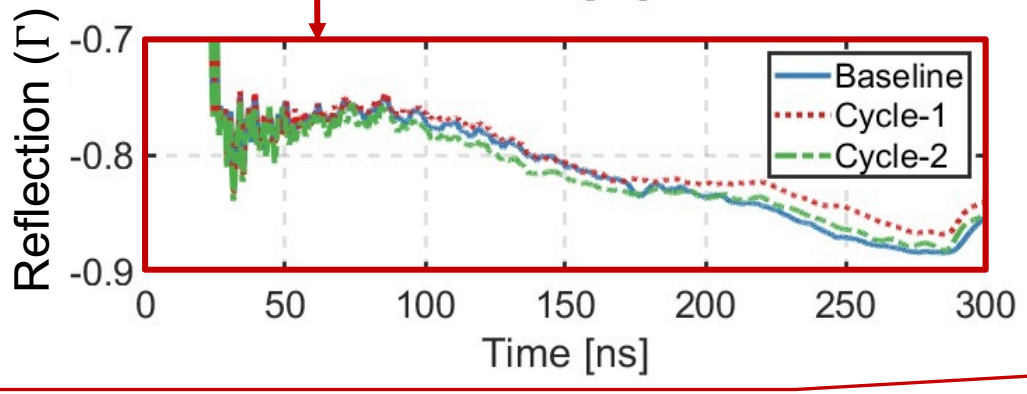
Impregnation monitoring for Subscale-5:

Localizing impregnation change points: heater study (1)

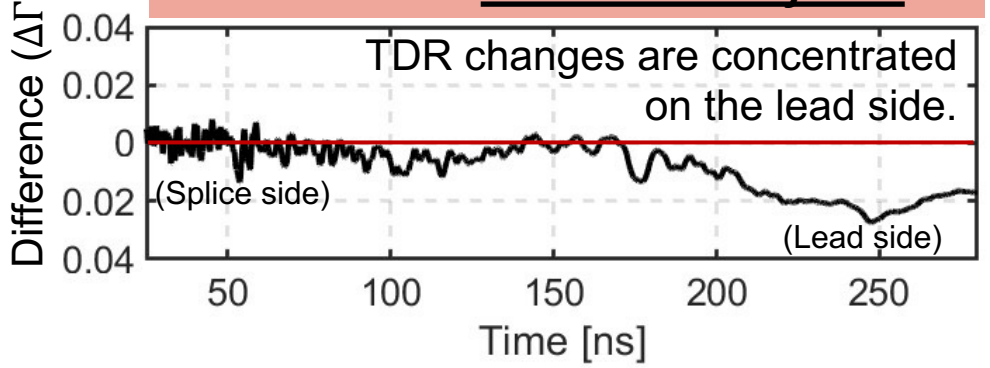


Reflection coefficient (Γ) at Room temp

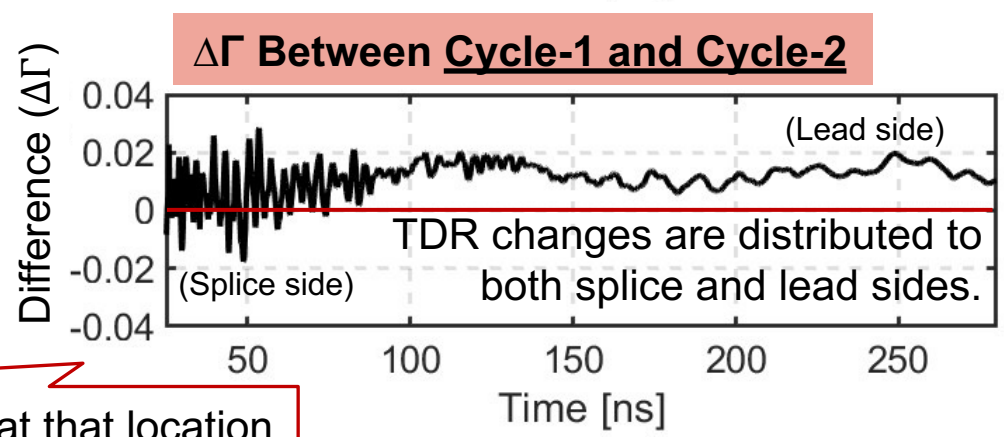




ΔΓ Between baseline and Cycle-1



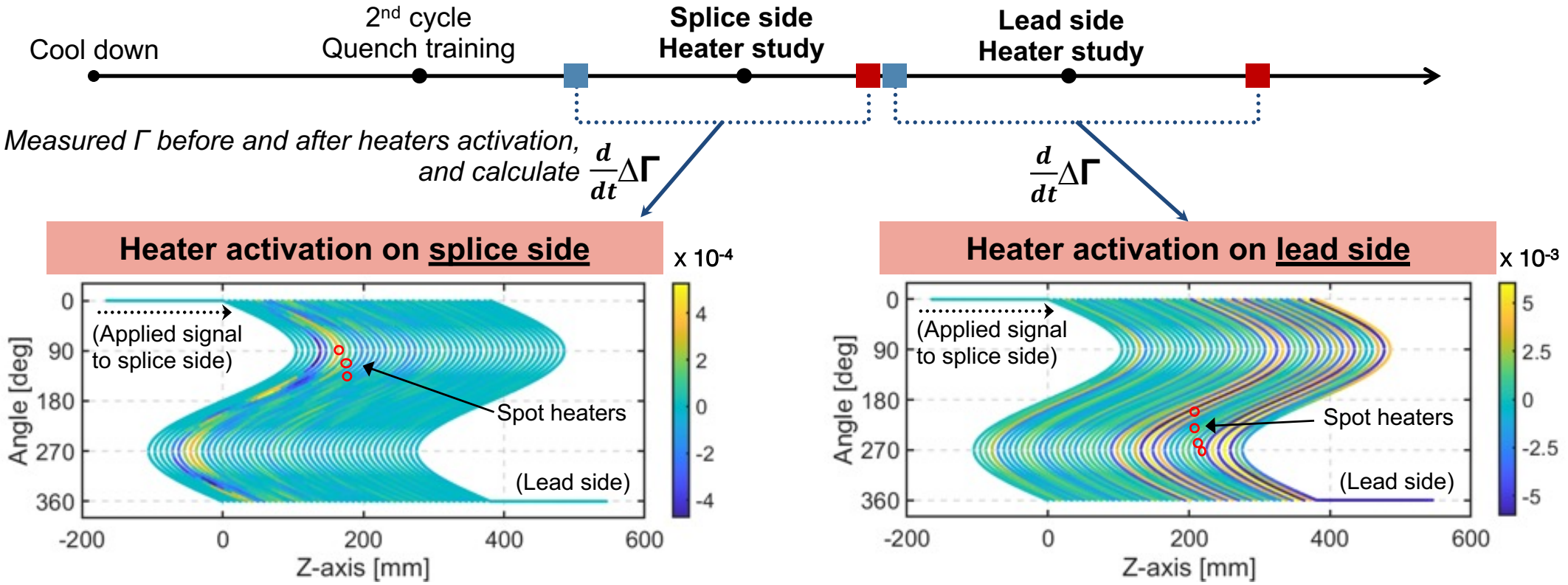
ΔΓ Between Cycle-1 and Cycle-2



TDR measurement variations indicate impedance change at that location

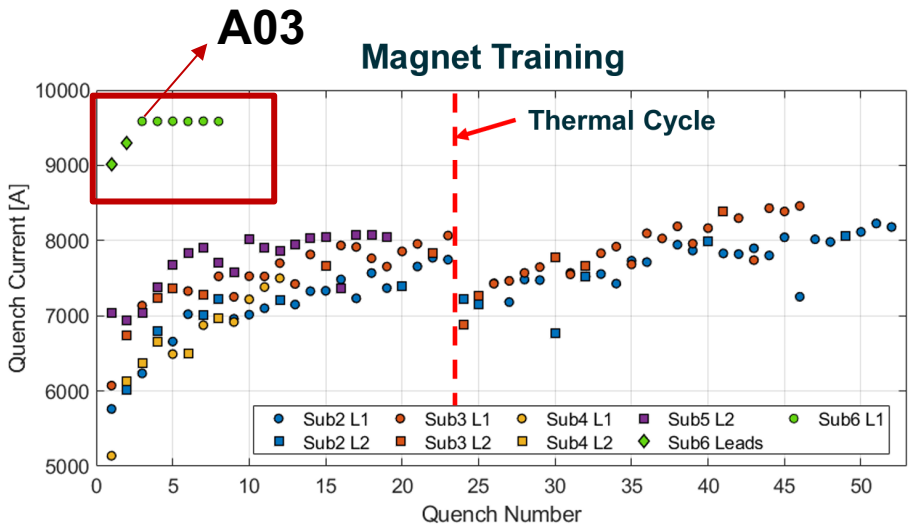
Impregnation monitoring for Subscale-5:

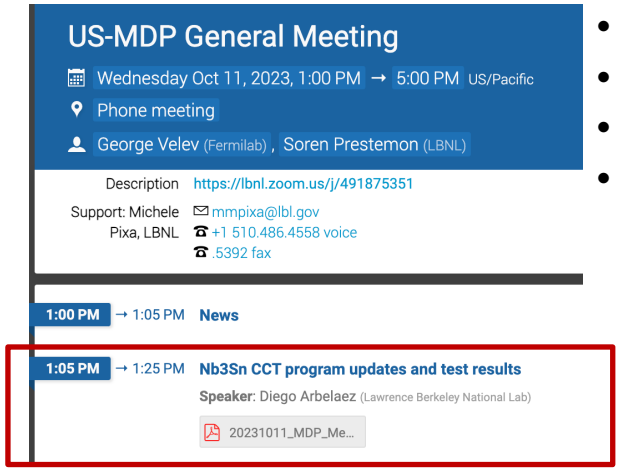
Derivative analysis of the TDR difference (ΔΓ)



- The color indicates $\frac{d}{dt}\Delta\Gamma$, the derivative of TDR difference between two signals (measured at 4.2 K)
- $\frac{d}{dt}\Delta\Gamma$ indicates the point where the change in impregnation begins
- Impregnation change areas are localized near the installed heaters

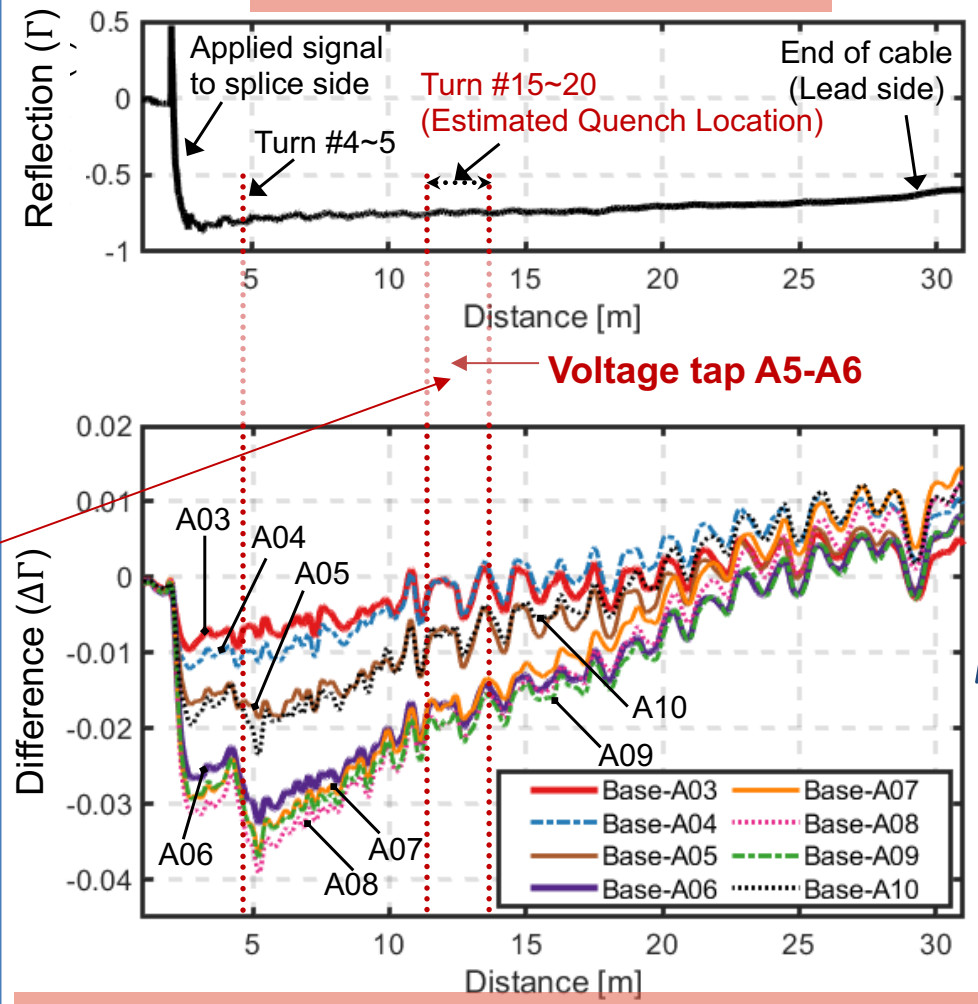
Impregnation monitoring for Subscale-6 (fully waxed)





- A01-A02: Lead
- A03~A08: IL
- A9-A10: Hold
- No training

Baseline Γ at 4.2 K



ΔΓ between the baseline and after each ramping

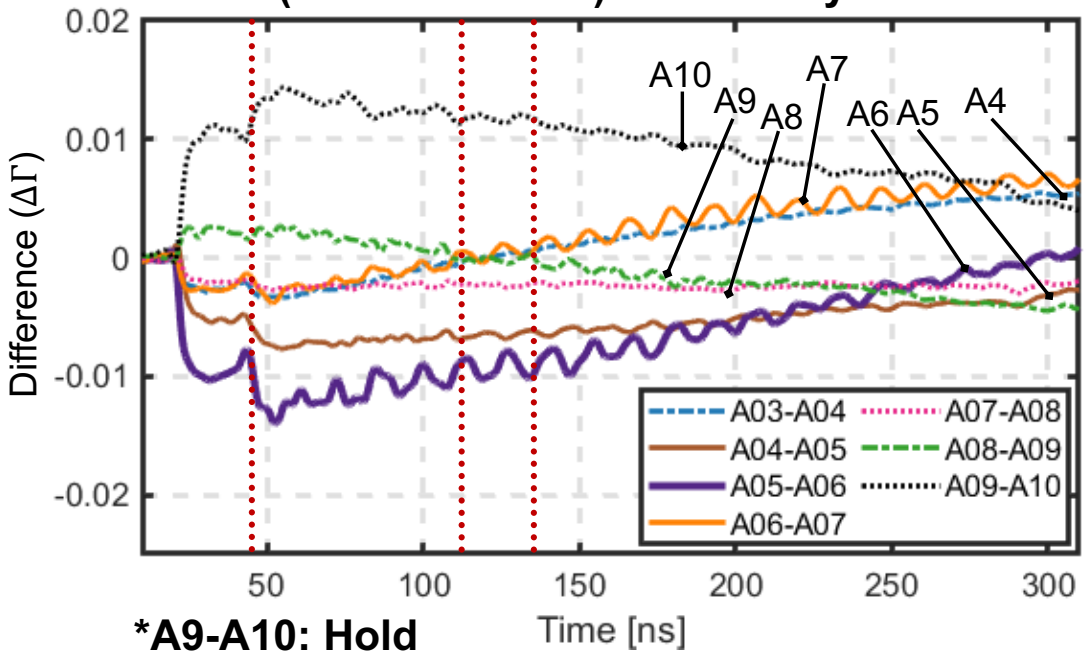
- A03 exhibits peaks near the quench location
- A sharp decline at 20ns/40ns: a change at the boundary between the impregnated and non-impregnated cable, accompanied by multiple reflections (No impact for magnet performance)

Impregnation monitoring for Subscale-6:

Comparison of TDR results before and after thermal cycle

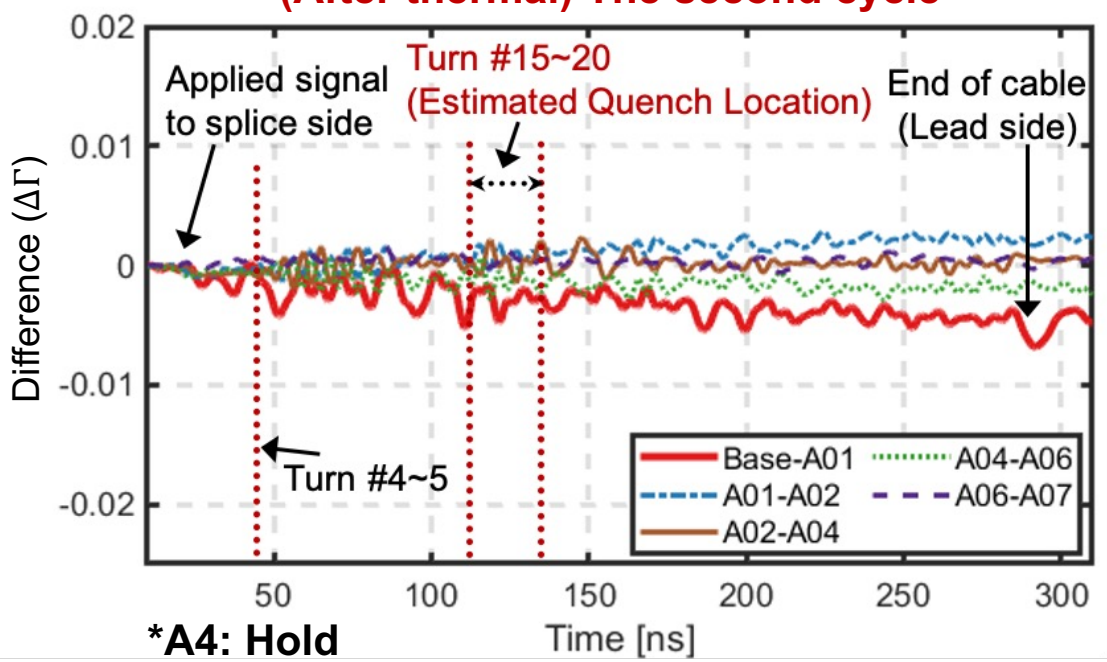
ΔΓ between sequential measurements

(Before thermal) The first cycle



***A9-A10: Hold**

(After thermal) The second cycle



***A4: Hold**

- No training after thermal cycle
- All quenches exhibit ΔΓ values of less than 0.005.
- A10 (first) vs A4 (second): hold and ramp to quench, ~1/10 of magnitude
- The variations in impregnation status are much smaller than those observed in the first cycle

Summary and next steps

- RF reflectometry has potential to identify locations of the gradual impedance variation during the training process.
- The impedance is potentially influenced by conductor displacement or impregnation damages.
- This method can be extended to other types of superconducting magnets, provided they form a transmission line.
- Additionally, we will conduct research to improve the accuracy of damage location estimation.