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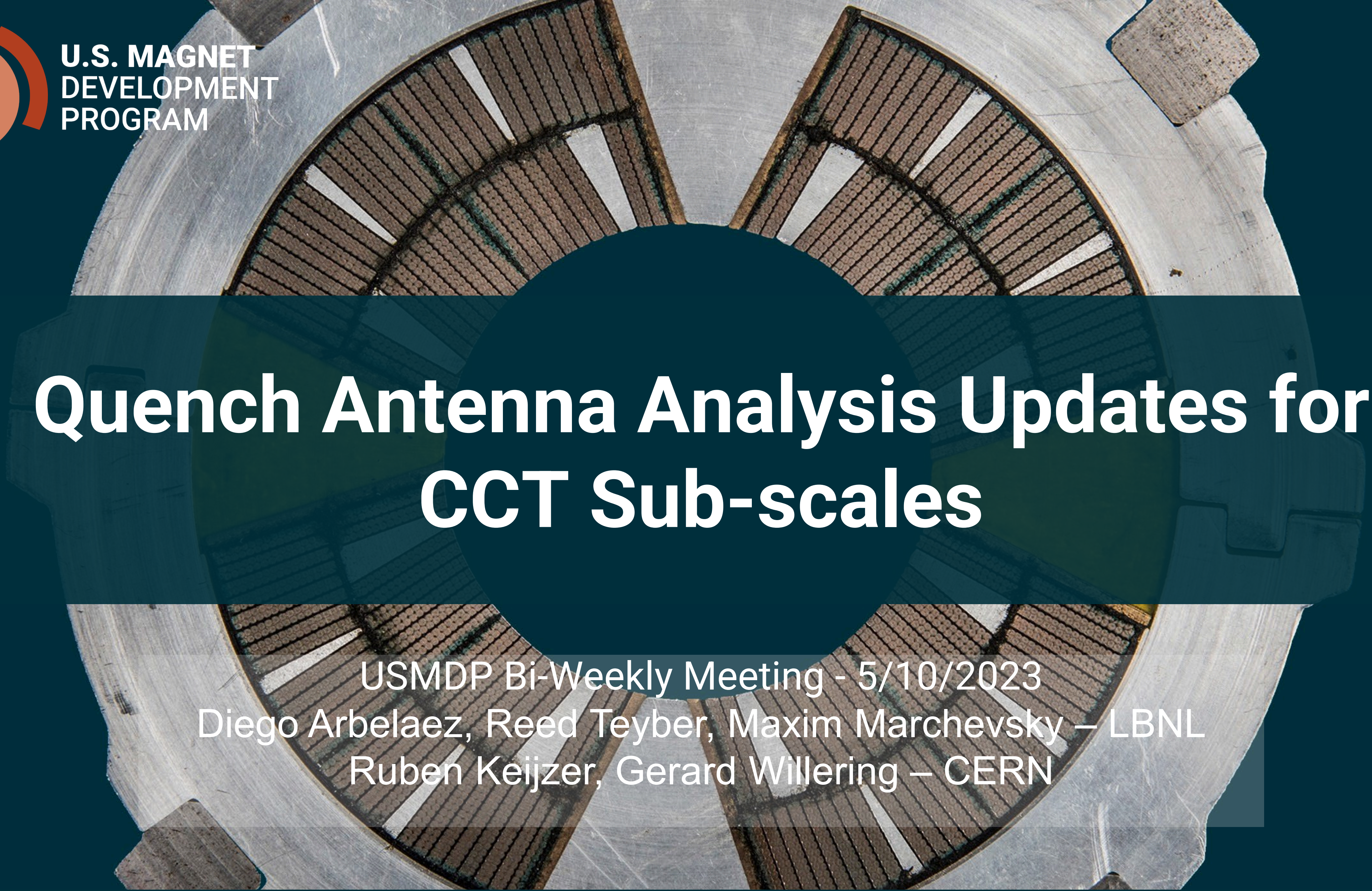

Quench Antenna Analysis Updates for CCT Sub-scales

USMDP Bi-Weekly Meeting - 5/10/2023

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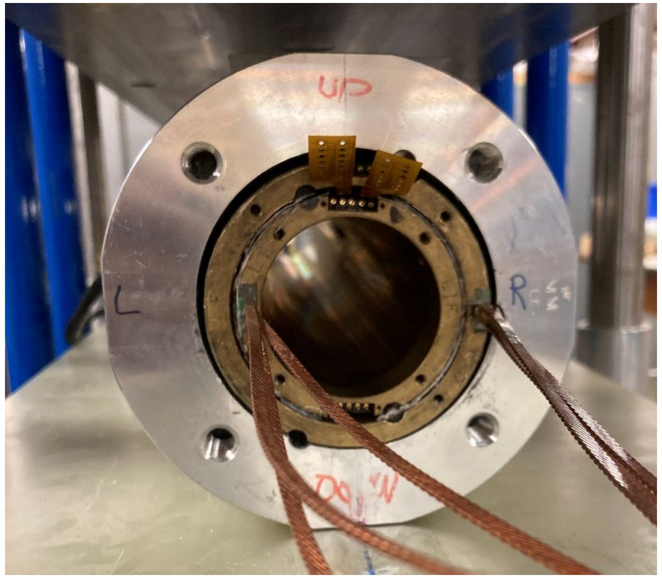
Ruben Keijzer, Gerard Willering – CERN

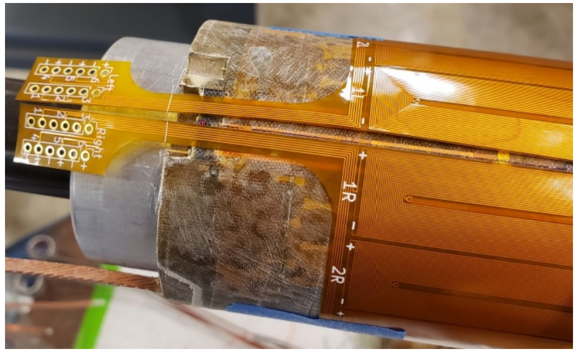
Outline

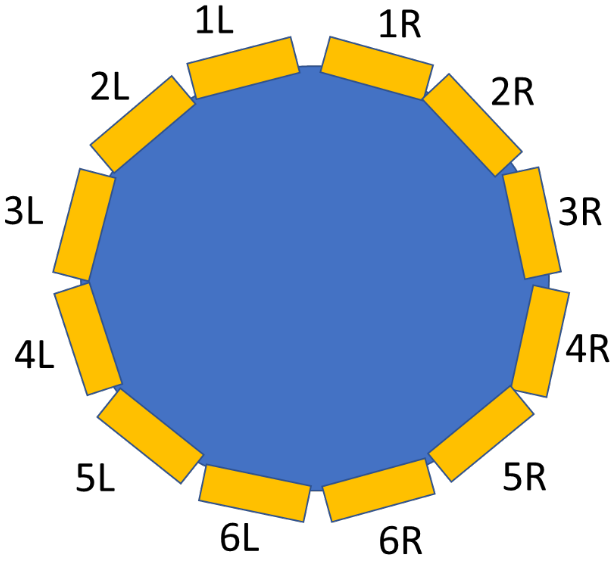
- CCT subscale quench antenna overview and previous results
- Numerical model analysis
- Improved localization method
- Spot heater results from CCT SUB5

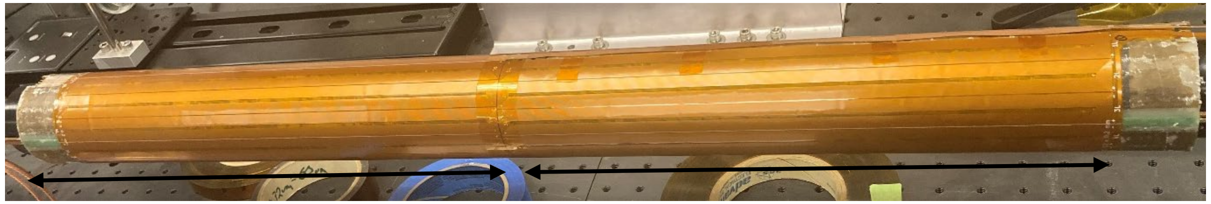
Quench Antenna Configuration

- 12 Antennas – bucked left / right
- Two Flex PCBs (lead and return end)
- Antennas are wrapped around inner layer coil and glued at the seam (further fixed in place as part of magnet assembly)



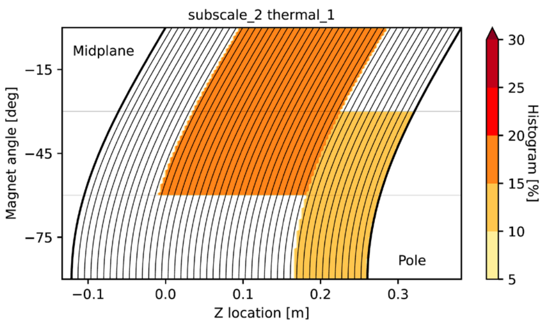


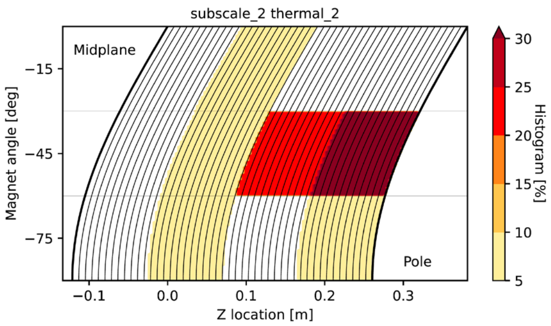


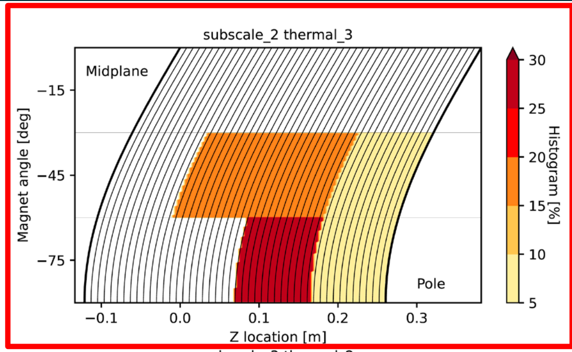


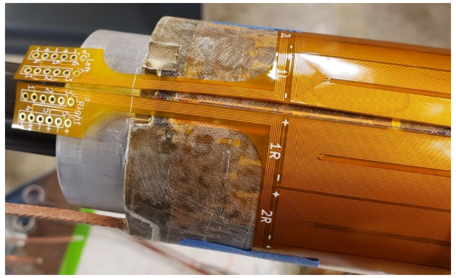
Quench Localization Analysis

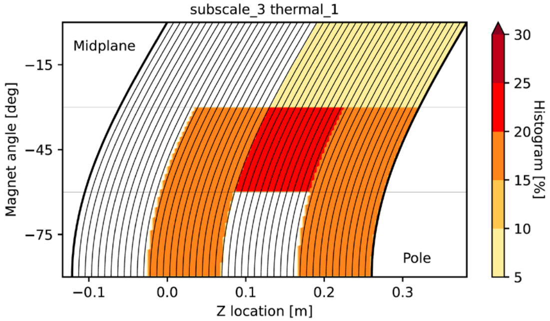
- Combine Vtap and quench antennas to localize quenches
- Histogram bins to 15, 45 or 75 degrees based on antenna element with largest measured flux
- Goal of updated analysis – develop method to use data from multiple antennas to improve azimuthal quench localization
- New tools are used to develop and validate updated analysis method
  - Cable quench simulation
  - Spot heaters in coil

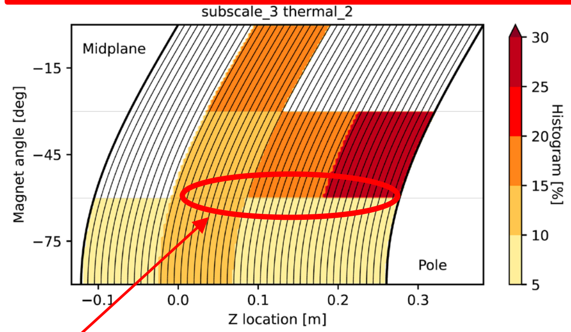


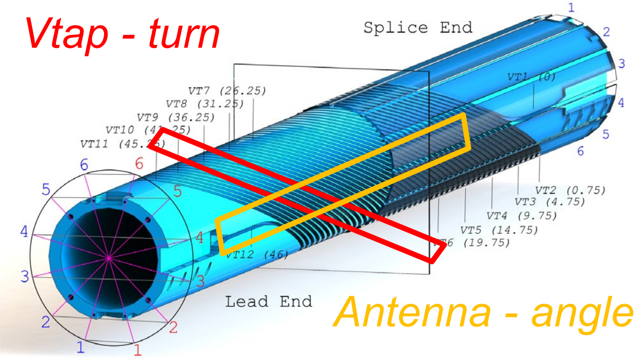


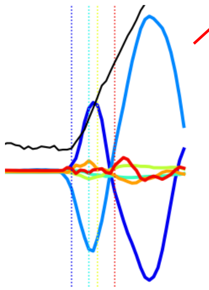








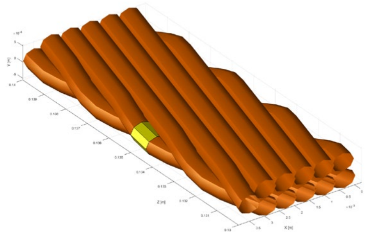


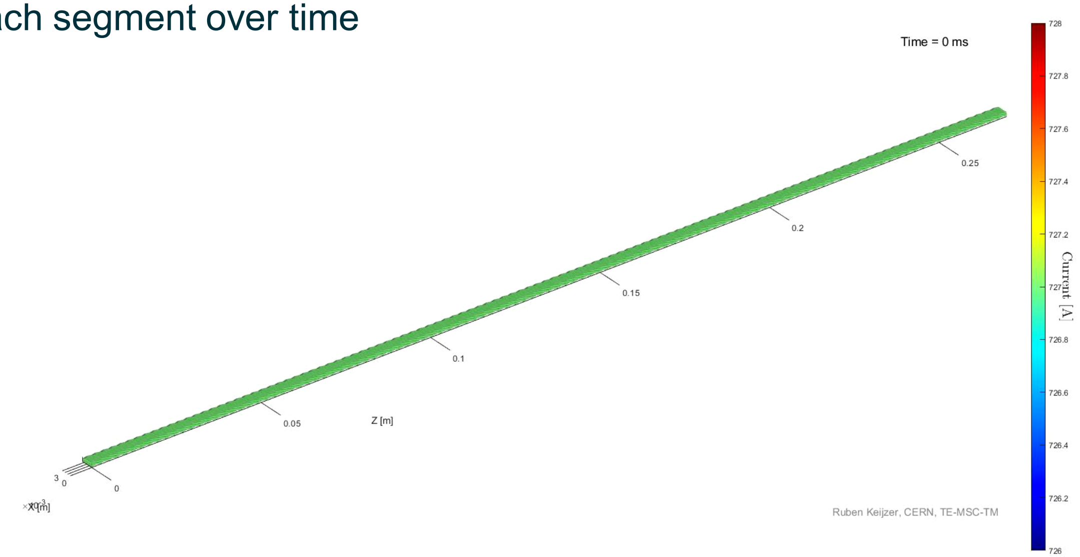


Work by R. Teyber

Cable Quench Simulation

- Ruben Keijzer & Gerard Willering (Twente / CERN) performed simulations of quench in straight subscale cable with THEA
  - Similar work can be found here: DOI 10.1109/TASC.2023.3244140
  - Simulations use provided cable parameters and conductor critical current scaling
  - Simulations performed with quench starting on the edge of the cable as well as on the broad face
  - Each strand is segmented along the length and data is provided as current in each segment over time

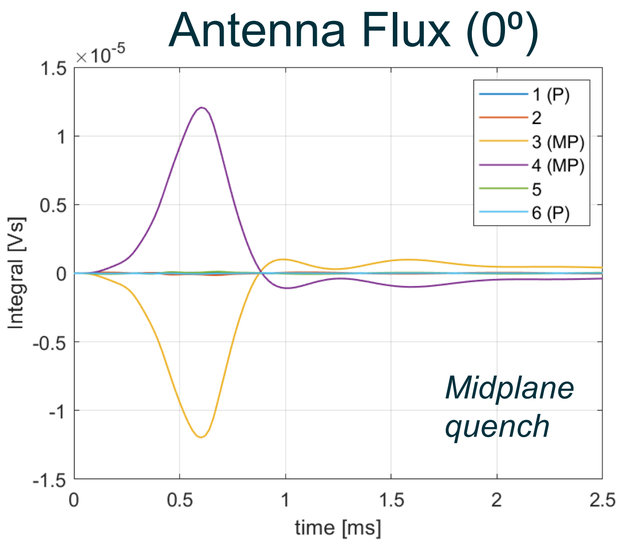


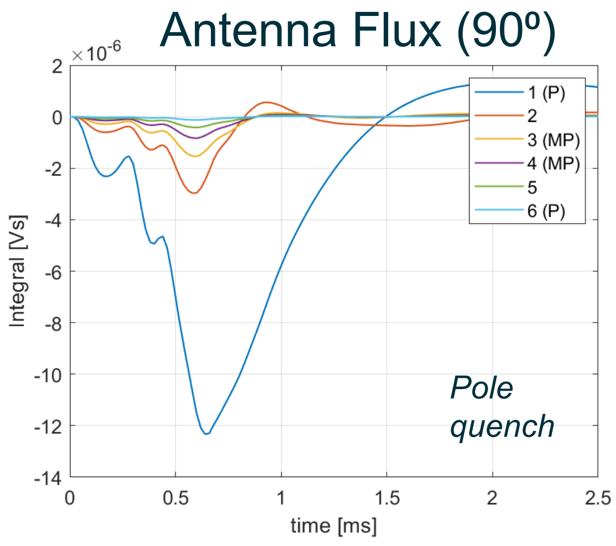


Parameter	Value
Number of strands	11
Cable width	4.0 mm
Cable thickness	1.1 mm
Strand diameter	0.6 mm
Twist pitch	27 mm
R_a	1 μΩ
R_c	20 μΩ
Temperature	4.5 K
Magnetic field	5 T
Simulated domain length	27 cm
Number of elements per strand	440

"Virtual" Quench Antenna Analysis

- Quench antenna response with Ruben's cable simulation "curved" into the CCT geometry
- Antenna elements created with discretized segments
- Vector potential at antenna segments calculated using Biot-Savart and integrated to determine antenna flux

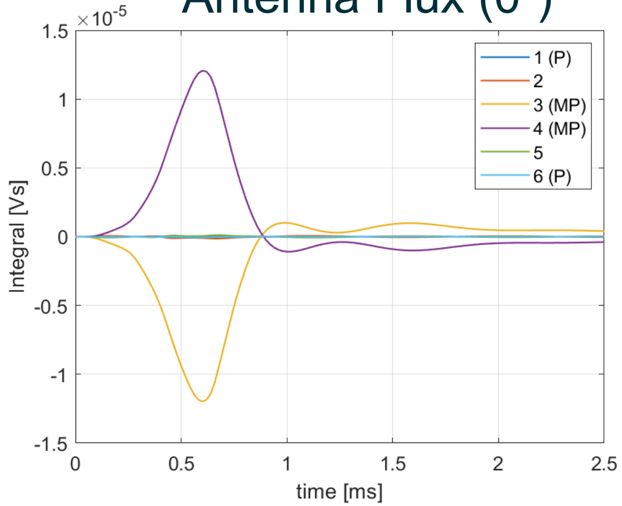




Data Reduction Using Antenna Correlations

- Need simple metric to define quench anatenna response and correlation between various antenna elements
- Define Correlation parameter as $C_{ij} = \int_0^{t_0} \left|\varphi_i \varphi_j\right| dt$

Antenna Flux (0º)

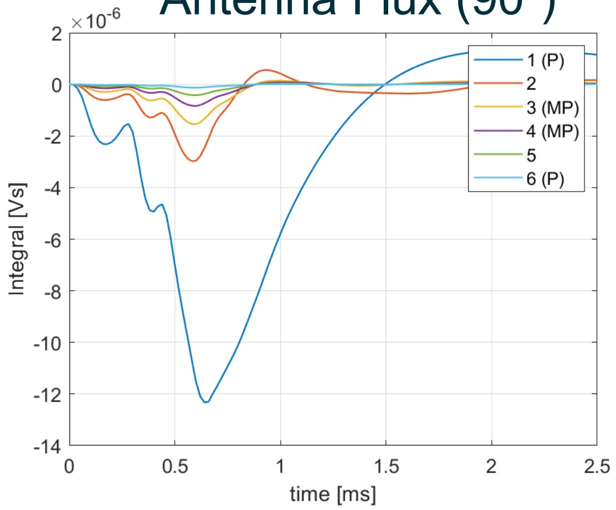


Correlation Values (0º)

	1	2	3	4	5	6
1	0.005893	0.02834	0.6047	0.6153	0.03038	0.006276
2	0.02834	0.1365	2.908	2.956	0.1462	0.03017
3	0.6047	2.908	62.67	63.84	3.12	0.6442
4	0.6153	2.956	63.84	65.09	3.173	0.6556
5	0.03038	0.1462	3.12	3.173	0.1567	0.03235
6	0.006276	0.03017	0.6442	0.6556	0.03235	0.006685

Colorbar: 10, 20, 30, 40, 50, 60

Antenna Flux (90º)



Correlation Values (90º)

	1	2	3	4	5	6
1	36.51	8.153	4.815	2.942	1.617	0.5176
2	8.153	2.123	1.229	0.7463	0.4092	0.1309
3	4.815	1.229	0.7131	0.4334	0.2377	0.07606
4	2.942	0.7463	0.4334	0.2635	0.1445	0.04624
5	1.617	0.4092	0.2377	0.1445	0.07927	0.02537
6	0.5176	0.1309	0.07606	0.04624	0.02537	0.008116

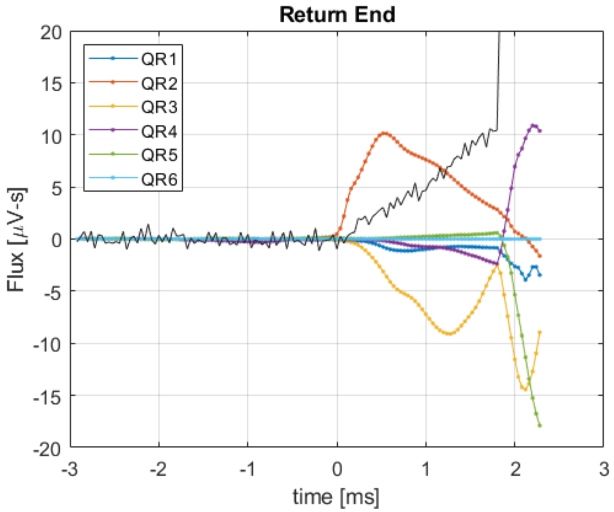
Colorbar: 5, 10, 15, 20, 25, 30, 35

Simulated Results (quench starts on cable edge)

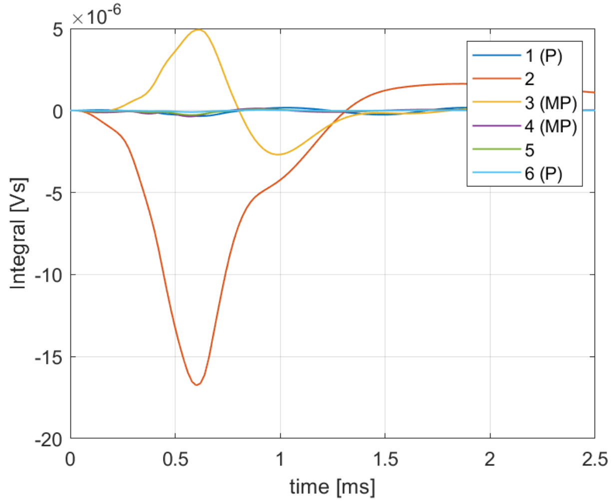
Simulation Result Observations

- Comparison between simulation and test results shows similar time scales for quench antenna response
- Simulation results show that amplitude of signal is highly dependent on details of the quench
  - Quench location (azimuthal angle)
  - Location on cable (i.e. inner vs outer edge or broadface)
- Low sensitivity zones may be present and depend on quench location on cable
- Behavior from ~ 70º – 90º deviates from behavior elsewhere (cable orientation, no neighbor due to bucking)

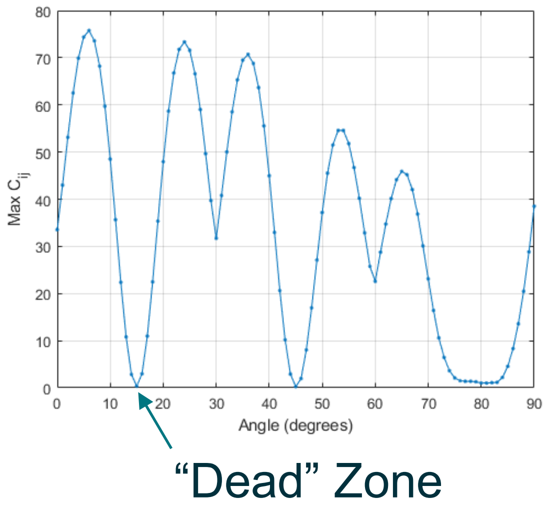
Quench Antenna (Test Result)



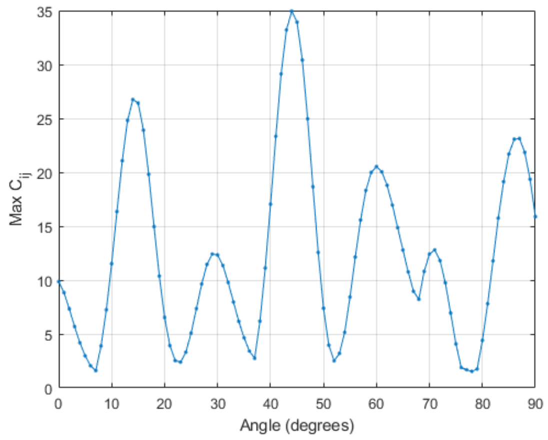
Quench Antenna (Simulation)



Edge Quench



Broad Face Quench



Improved Quench Localization Method

- Use normalized correlation matrix to improve quench localization (normalize by largest value)
- Dominant diagonal component corresponds to 30º quench segment location (as was done with previous analysis)
- Improve localization by accounting for signals from neighboring antenna elements
  - Cross-Correlation between neighboring antennas
  - Self-Correlation of neighboring antennas

0º Simulation

	1	2	3	4	5	6
1	0.00032	0.0009468	0.09322	0.09332	0.0006833	0.0003939
2	0.0009468	0.003964	0.336	0.3393	0.002955	0.001192
3	0.09322	0.336	33.1	33.29	0.2314	0.1175
4	0.09332	0.3393	33.29	33.52	0.2337	0.1177
5	0.0006833	0.002955	0.2314	0.2337	0.002383	0.0008524
6	0.0003939	0.001192	0.1175	0.1177	0.0008524	0.0004862

5º Simulation

	1	2	3	4	5	6
1	0.0001387	0.001305	0.07979	0.02255	0.0004082	0.0002941
2	0.001305	0.02232	1.264	0.3669	0.003343	0.003645
3	0.07979	1.264	74.39	21.4	0.2083	0.2177
4	0.02255	0.3669	21.4	6.227	0.05771	0.0627
5	0.0004082	0.003343	0.2083	0.05771	0.001296	0.0008122
6	0.0002941	0.003645	0.2177	0.0627	0.0008122	0.0007119

Improved Quench Localization Method (cont.)

- Find quench location segment by identifying maximum C_{ii}
- Within this segment compare the normalized values of the two neighboring self and cross-correlation values
  - Neighbor self-correlation difference: $\left(C_{i+1,i+1} - C_{i-1,i-1}\right)/C_{i,i}$
  - Neighbor cross-correlation difference: $\left(C_{i+1,i} - C_{i,i-1}\right)/C_{i,i}$
- Use fit function derived from simulations to determine angle for each case (should be consistent)

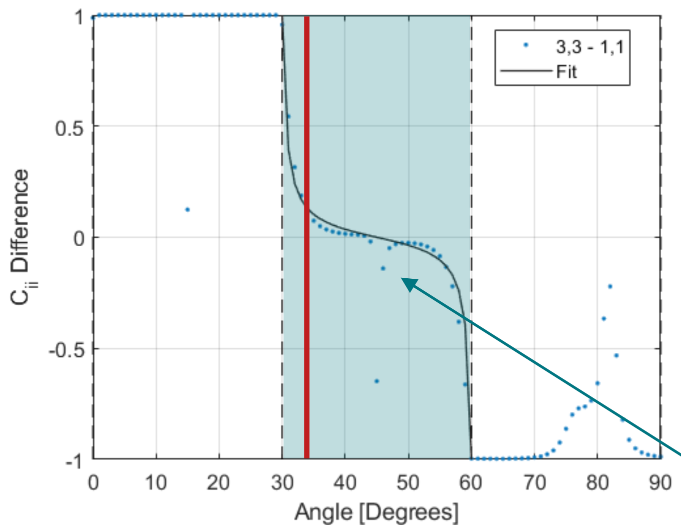
$$f(\theta) = -\frac{\tan(b\theta)}{\tan(b\pi/12)}$$

Normalized Correlation Matrix

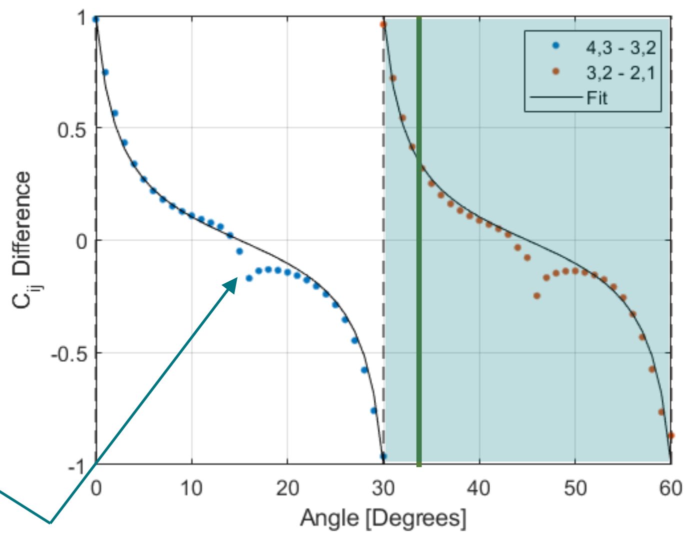
Return End

	1	2	3	4	5	6
1	0.00725	0.07719	0.03182	0.00242	0.0008946	0
2	0.07719	1	0.3347	0.02413	0.009743	0
3	0.03182	0.3347	0.1403	0.01075	0.00395	0
4	0.00242	0.02413	0.01075	0.0008708	0.0003189	0
5	0.0008946	0.009743	0.00395	0.0003189	0.0001373	0
6	0	0	0	0	0	0

Self-Correlation Neighbor Difference



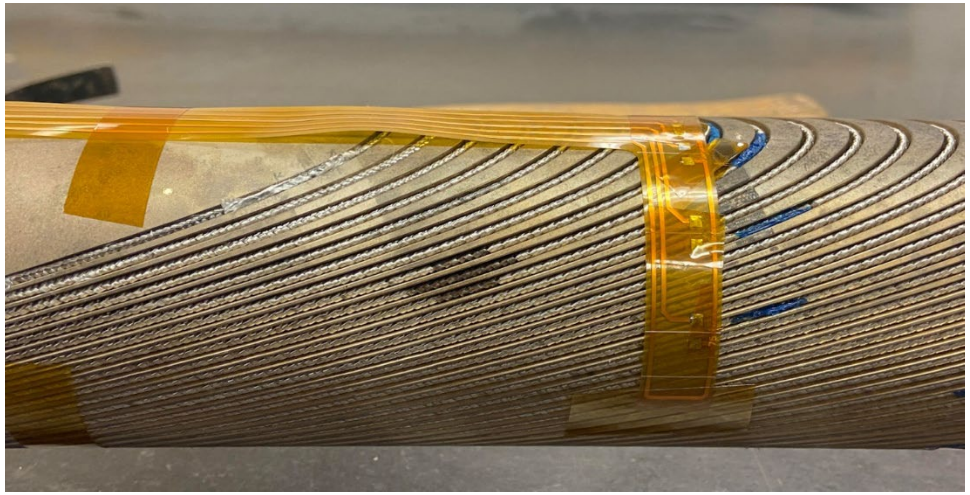
Cross-Correlation Neighbor Difference

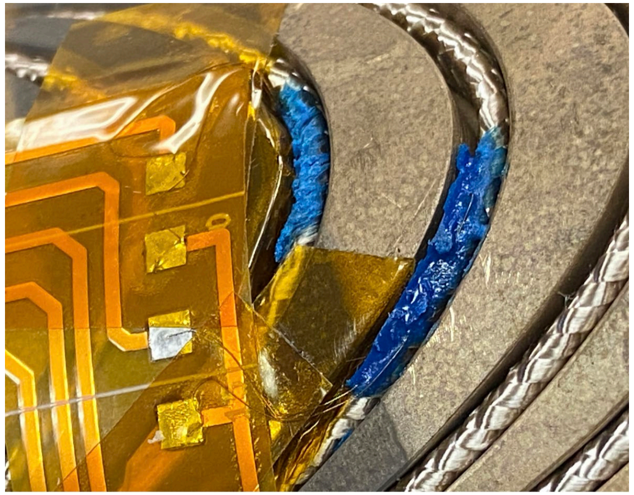


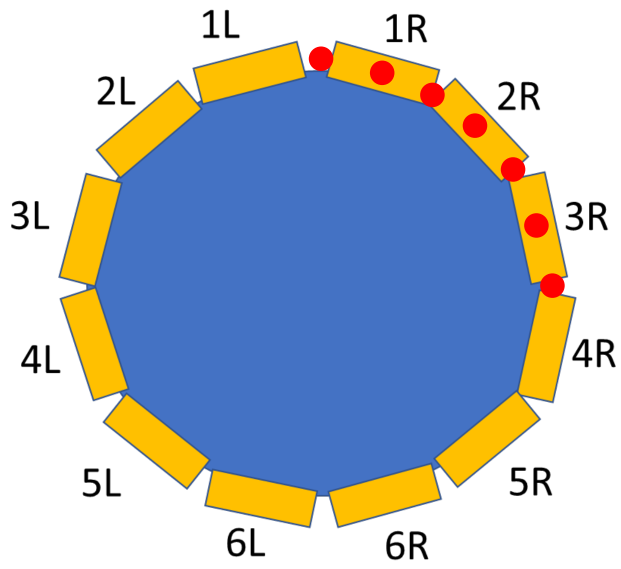
Points are simulation results (deviations near "dead" zones)

Sub 5 - Quench Heaters

- Installed quench heaters on CCT Sub5 inner layer
  - Heater are made of fine manganin wire
  - Heaters are attached with stycast to the edge of the cable (outside of the glass insulation)
- Two heater traces installed (4 heaters each)
  - Heaters aligned with antenna edges (90º, 60º, 30º, 0º (failed))
  - Heaters aligned (mostly) with antenna centers (90º, 75º, 45º, 15º)



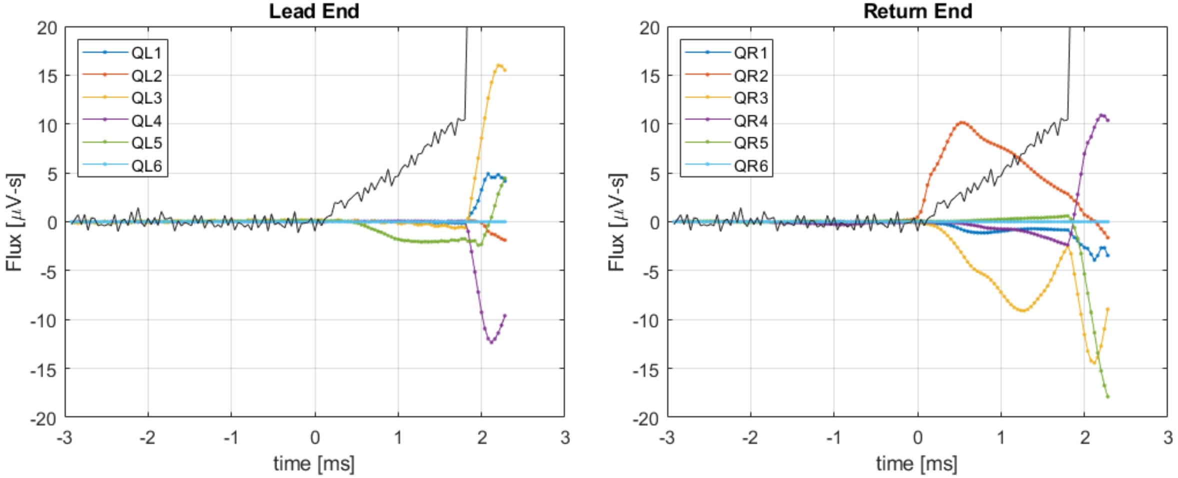




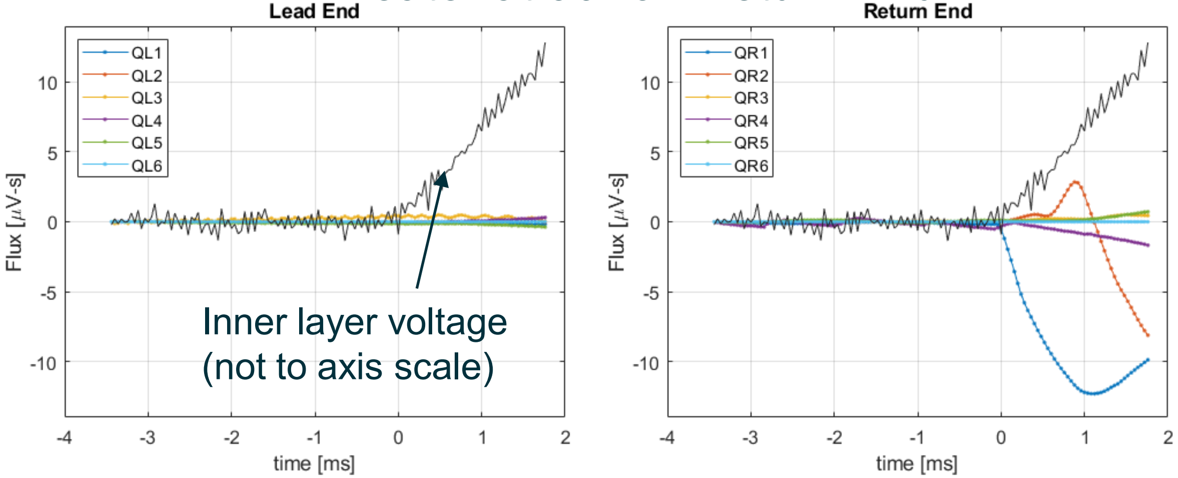
Sub 5 - Quench Heater Signal Examples

- Heater studies validate previous assumptions for quench antenna localization
- Did not have “dead” zone at center of antennas

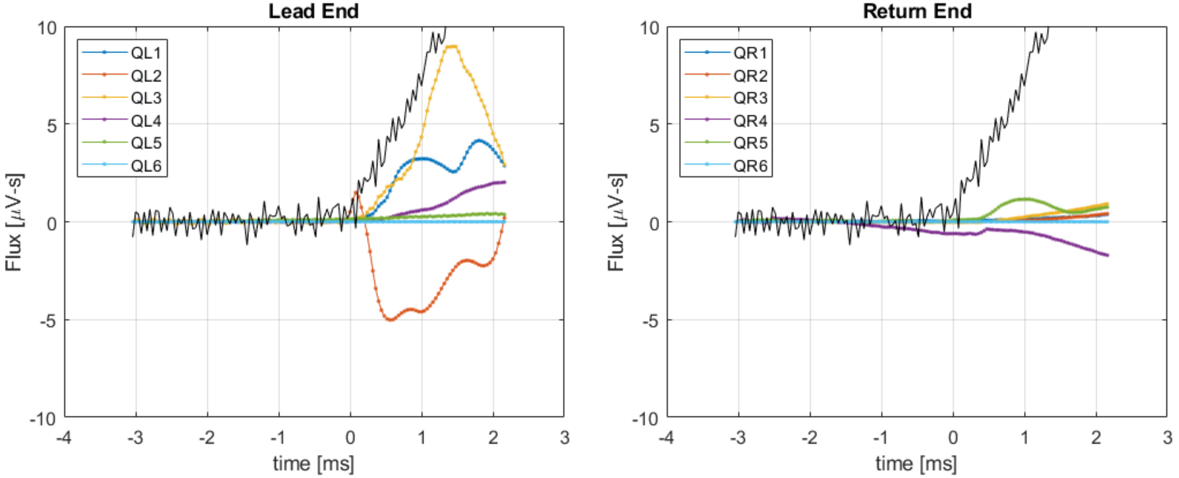
Heater at 30º on Return End



Heater at 90º on Return End



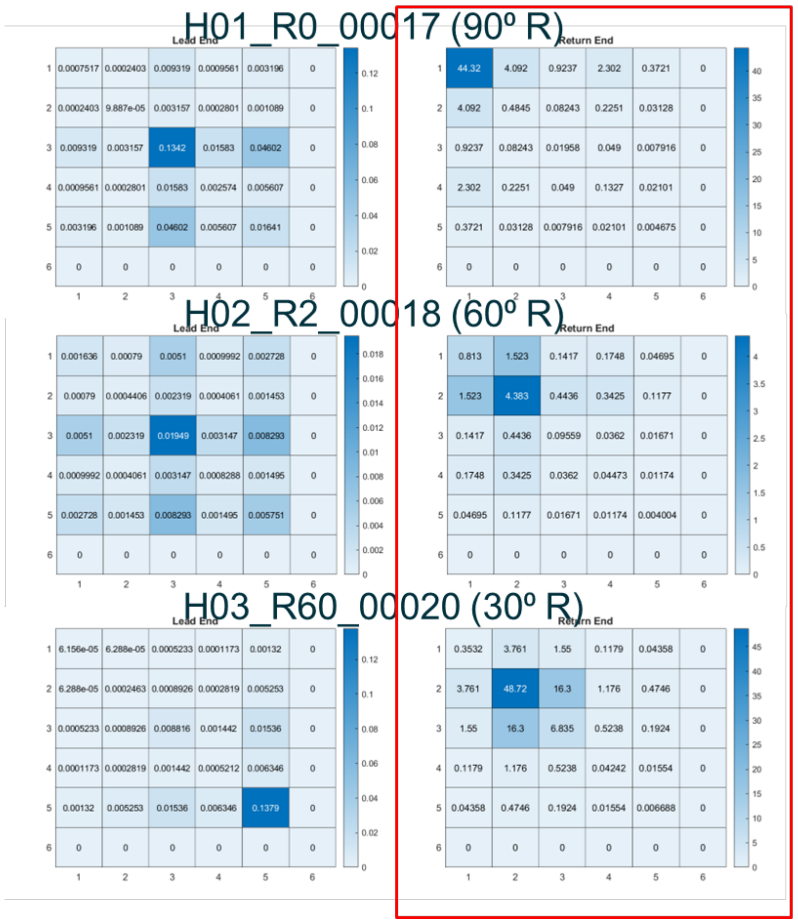
Heater at 45º on Lead End



Sub 5 - Quench Heater Localization Results

- Improved localization method gives results consistent with the heater location

L R



70º-90º

56º

35º

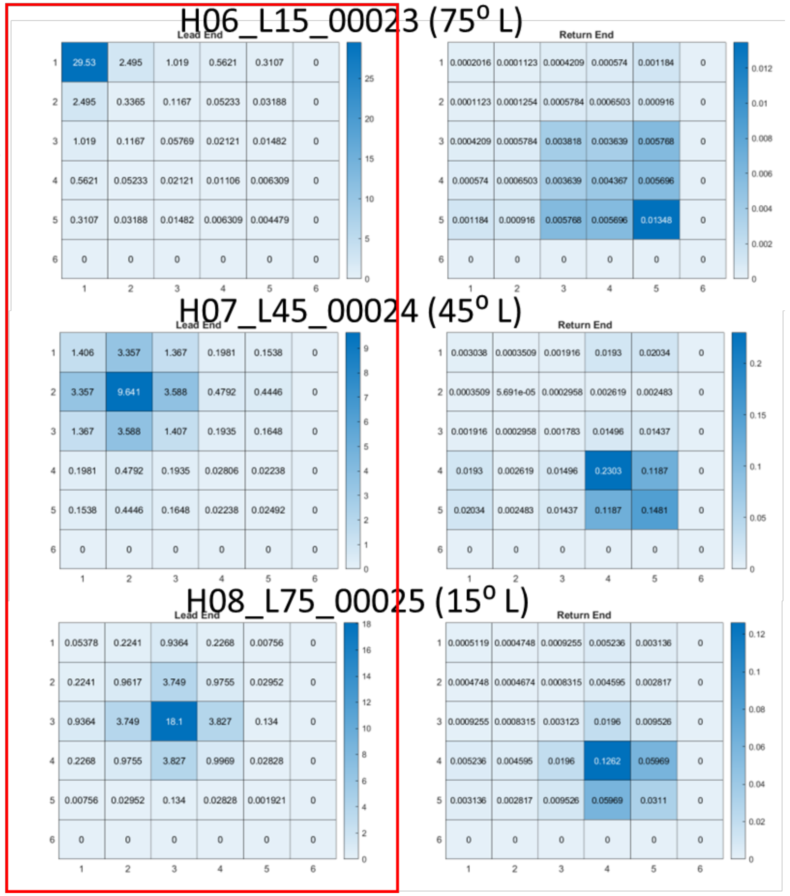
Results from improved localization method

70º-90º

44º

15º

L R



Conclusions and Next Steps

- Quench simulation provided by Ruben Keijzer was very useful for understanding and interpreting quench antenna signals
- Heater test validates previous analysis of quench locations
- Improved localization method has been developed and validated with heater studies

- Next steps
  - Investigate if it’s possible to improve localization near the poles
  - Run updated analysis on all previous tests