U.S. MAGNET DEVELOPMENT PROGRAM

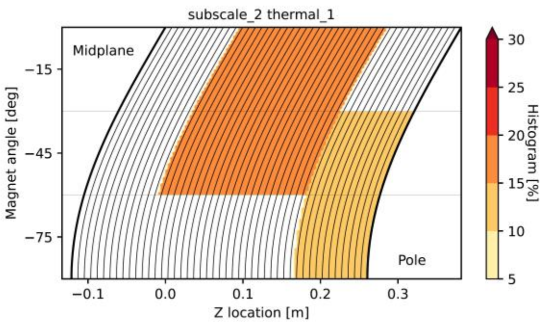
Progress in Inter-layer Flexible Quench Antenna Developments

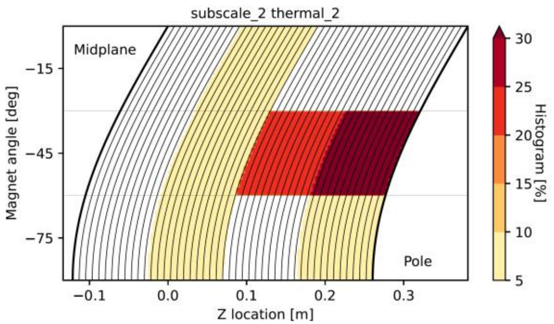
USMDP Bi-Weekly Meeting - 01/31/2023

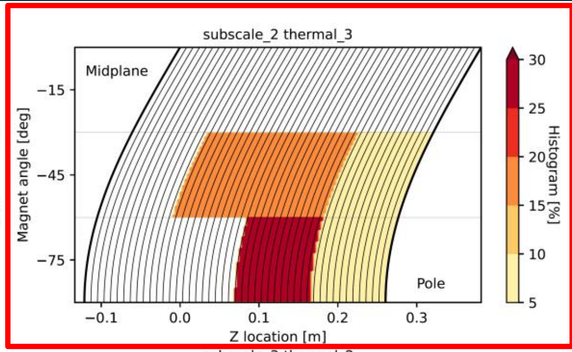
R. Teyber, D. Arbelaez, M. Marchevsky, E. Barzi, A. Plebani, E. Stabilini, R. Keijzer, G. Willering

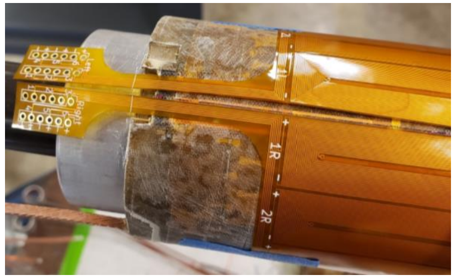
Quench Antennas and Localization

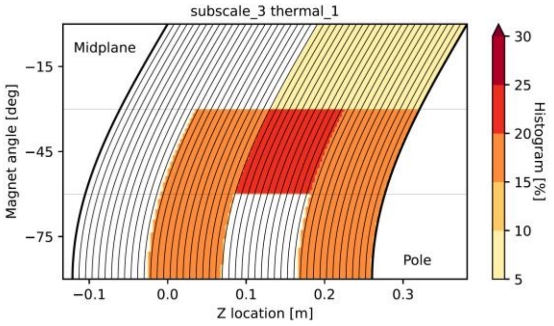
- Previously: Inter-layer flexible quench antennas implemented in all CCT subscale magnets
  - Streamed through ramp to quench
  - Rules-based binning of quench location (coarse)

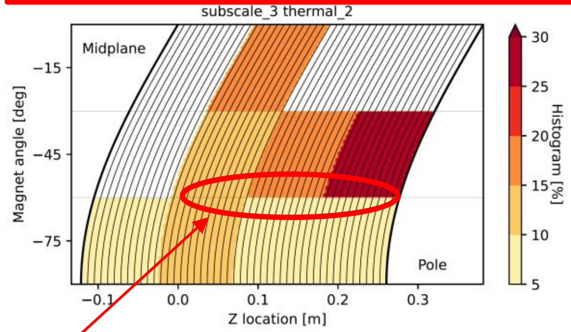


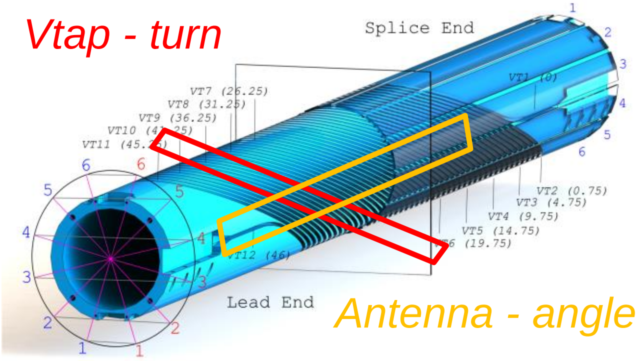


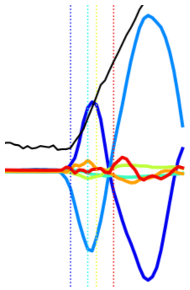






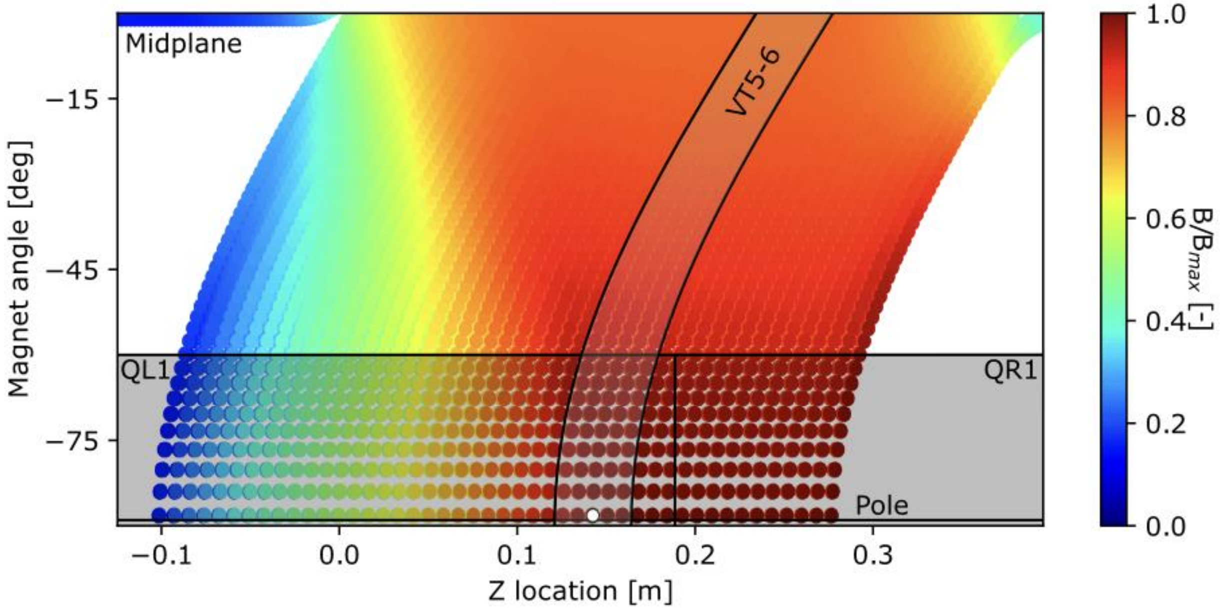


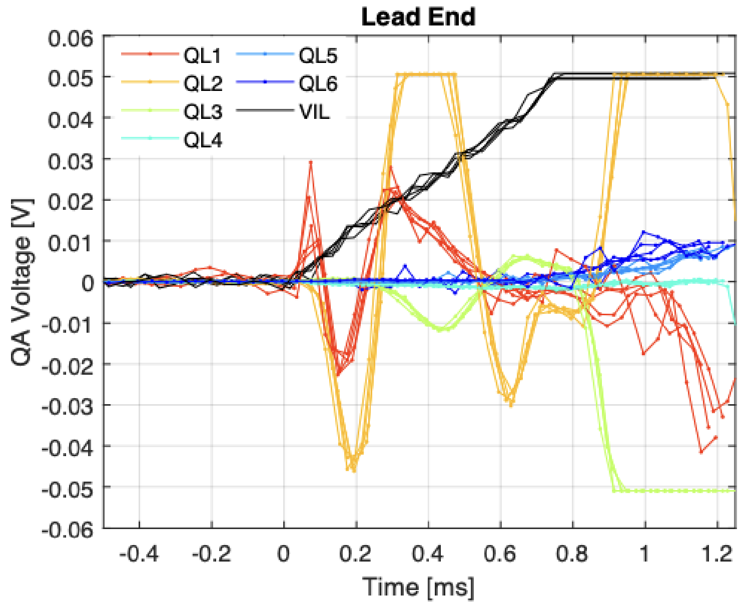




Quench Antennas

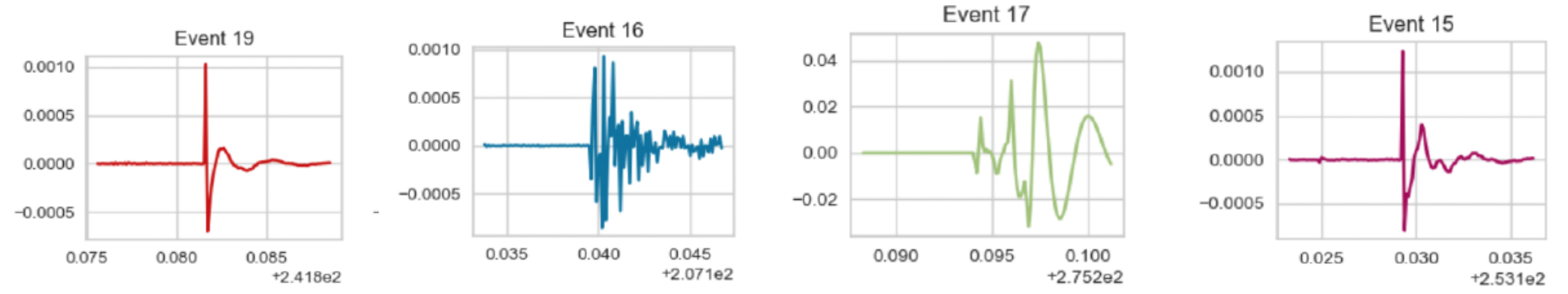
- Continuing inter-layer flexible quench antenna measurements on all magnets



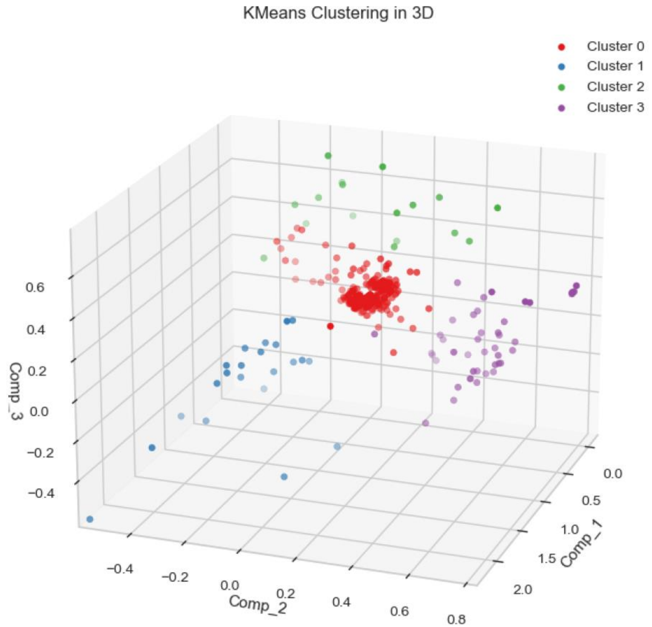


Quench Antennas

- Student (Elisa Stabilini) over summer with Emanuela Barzi (FNL) to continue clustering analysis from A. Plebani of antenna ramp data

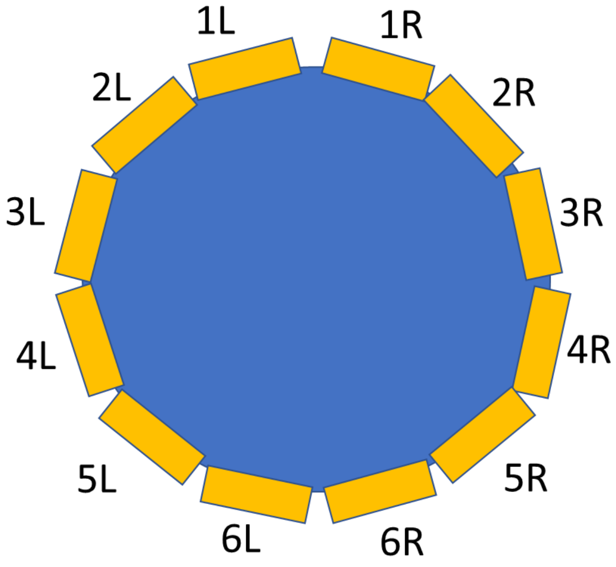


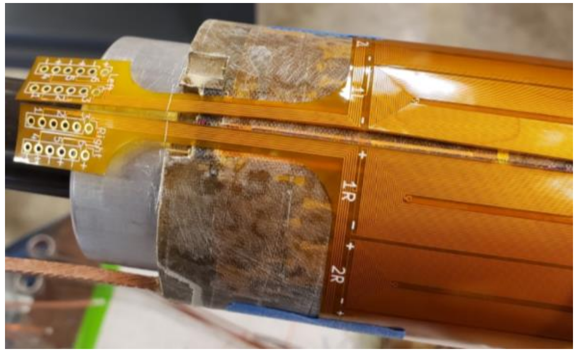
(a) Example from cluster 0 (b) Example from cluster 1 (c) Example from cluster 2 (d) Example from cluster 3

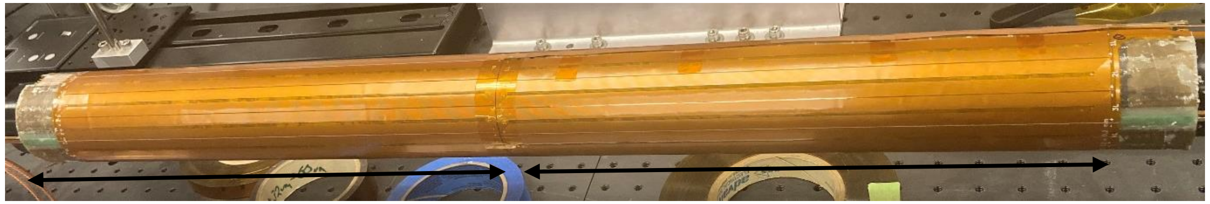


Improved Quench Localization Method

- Define simplified metrics for data reduction
- Use cross-correlations between antenna segments to improve localization
  - Use computational tools to understand quench antenna array response for a given quench location
  - Define improved localization function base on cross-correlation metrics

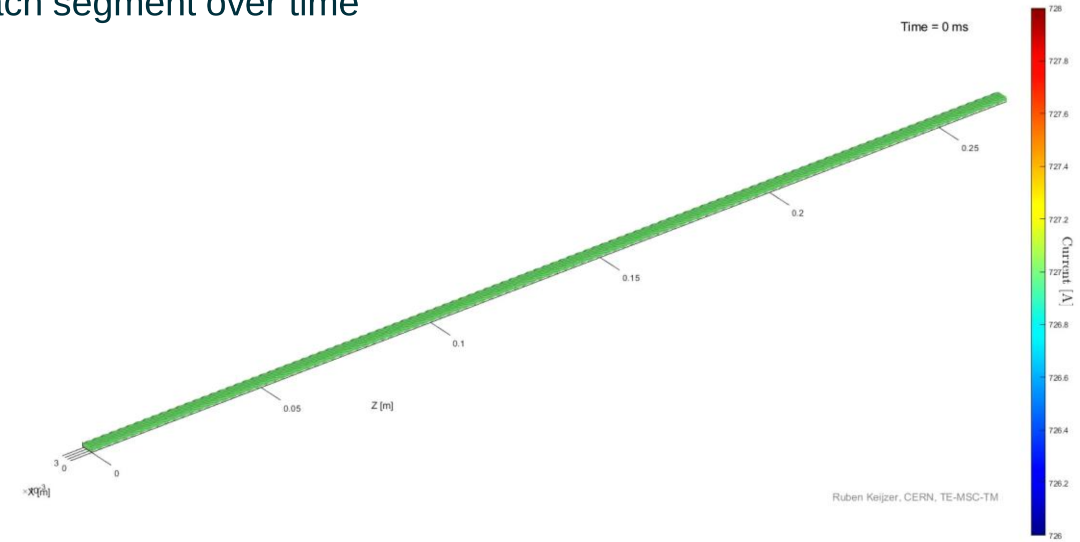


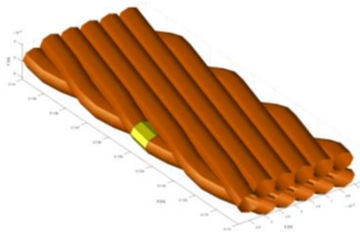




Cable Quench Simulation

- 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

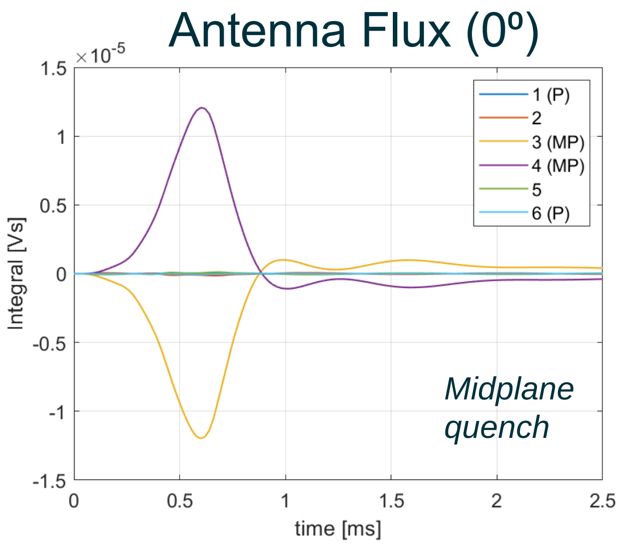


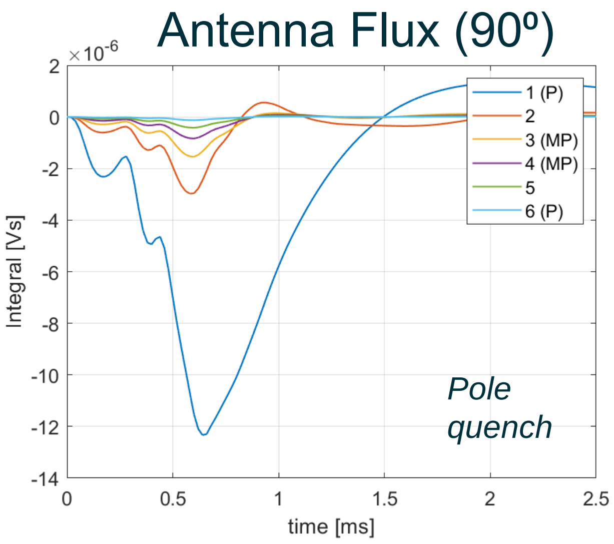


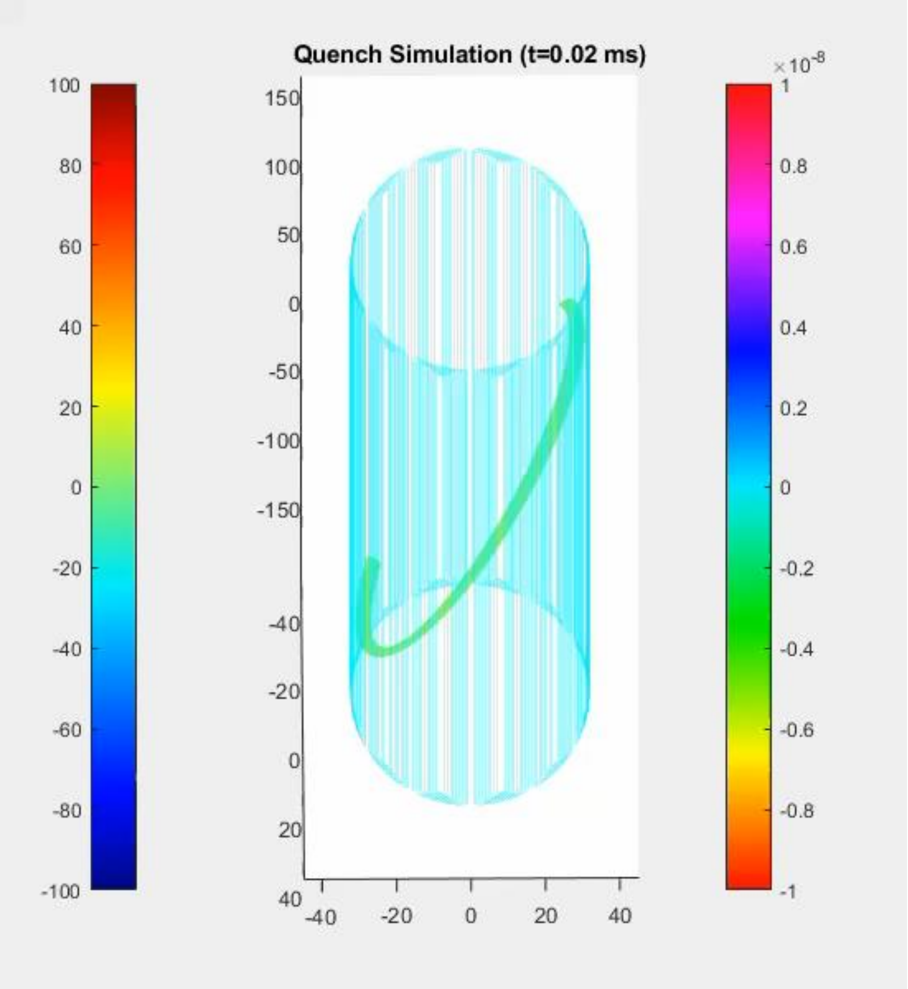
Parameter	Value
Number of strands	11
Cable width	4.0 mm
Cable thickness	1.1 mm
Strand diameter	0.6 mm
Twist pitch	27 mm
R_a	1 μΩ
R_c	20 μΩ
Temperature	4.5 K
Magnetic field	5 T
Simulated domain length	27 cm
Number of elements per strand	440

"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



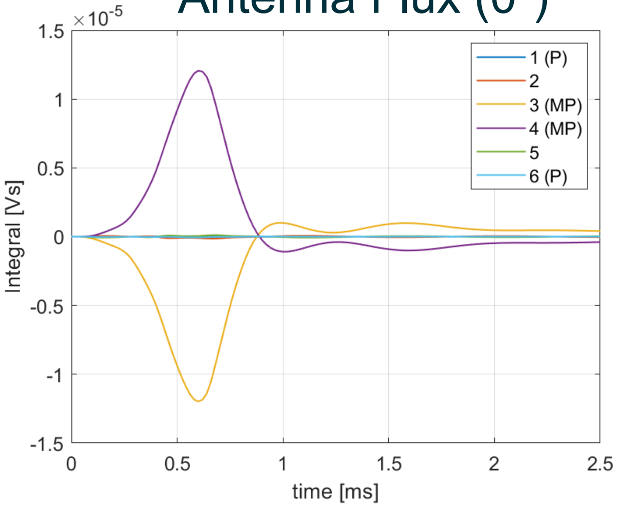




Data Reduction Using Antenna Correlations

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

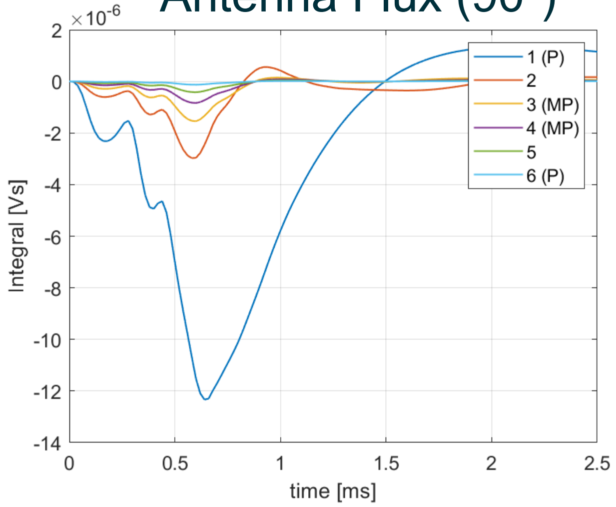
Antenna Flux (0º)



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

Antenna Flux (90º)



Correlation Values (90º)

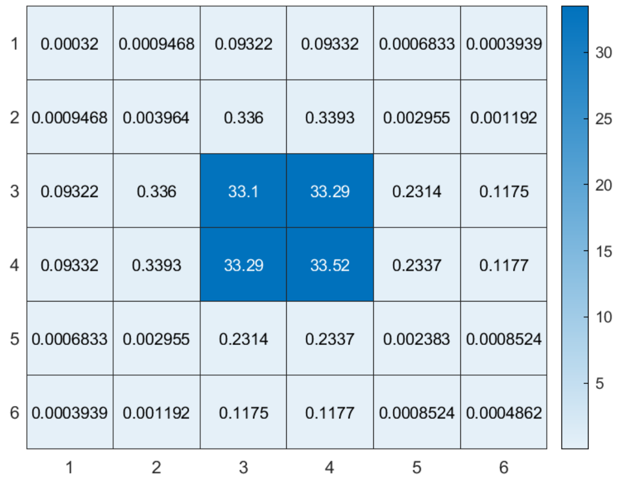
	1	2	3	4	5	6
1	36.51	8.153	4.815	2.942	1.617	0.5176
2	8.153	2.123	1.229	0.7463	0.4092	0.1309
3	4.815	1.229	0.7131	0.4334	0.2377	0.07606
4	2.942	0.7463	0.4334	0.2635	0.1445	0.04624
5	1.617	0.4092	0.2377	0.1445	0.07927	0.02537
6	0.5176	0.1309	0.07606	0.04624	0.02537	0.008116

Simulated Results (quench starts on cable edge)

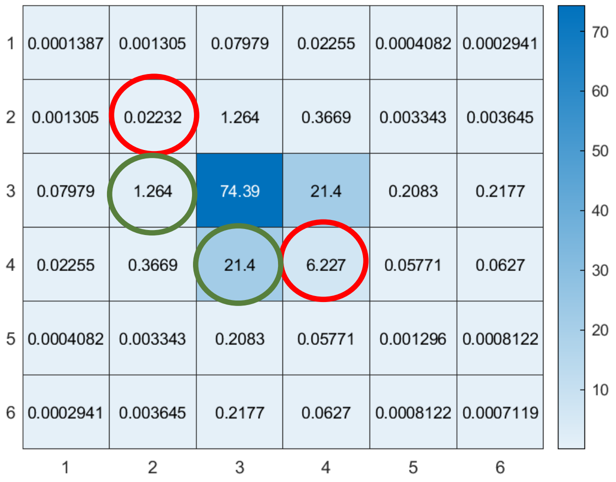
Improved Quench Localization Method

- 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



5º Simulation

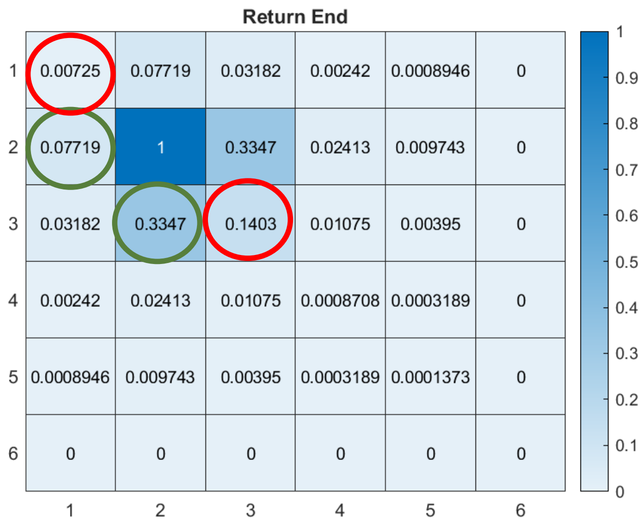


Improved Quench Localization Method (cont.)

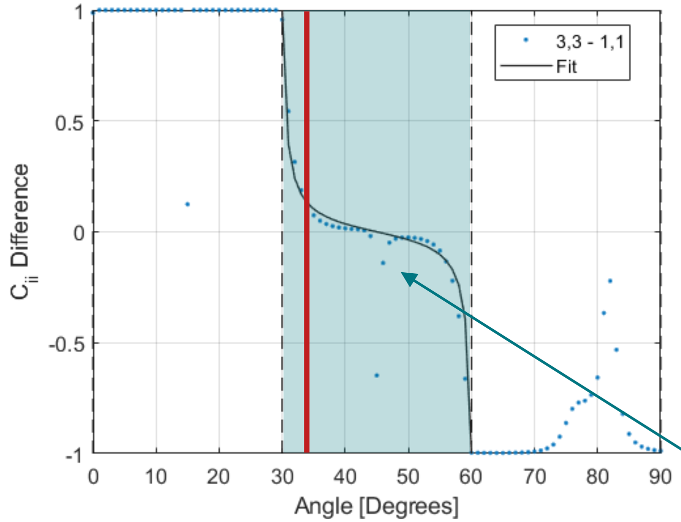
- Find quench location segment by identifying maximum C_{ii}
- Within this segment compare the normalized values of the two neighboring self and cross-correlation values
  - Neighbor self-correlation difference: $\left(C_{i+1,i+1} - C_{i-1,i-1}\right)/C_{i,i}$
  - Neighbor cross-correlation difference: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

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

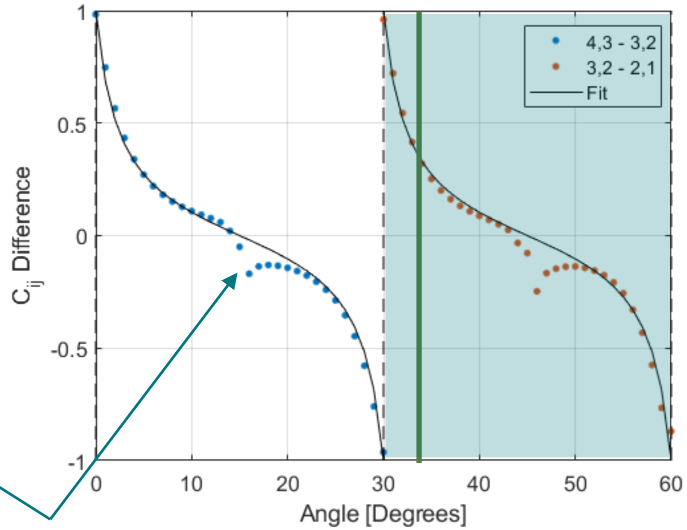
Normalized Correlation Matrix



Self-Correlation Neighbor Difference



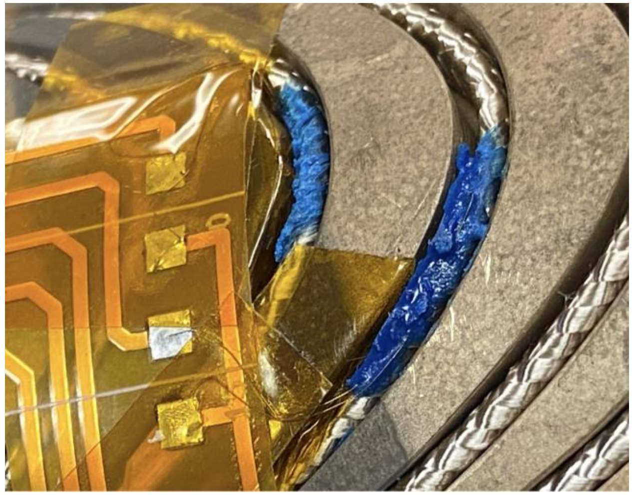
Cross-Correlation Neighbor Difference

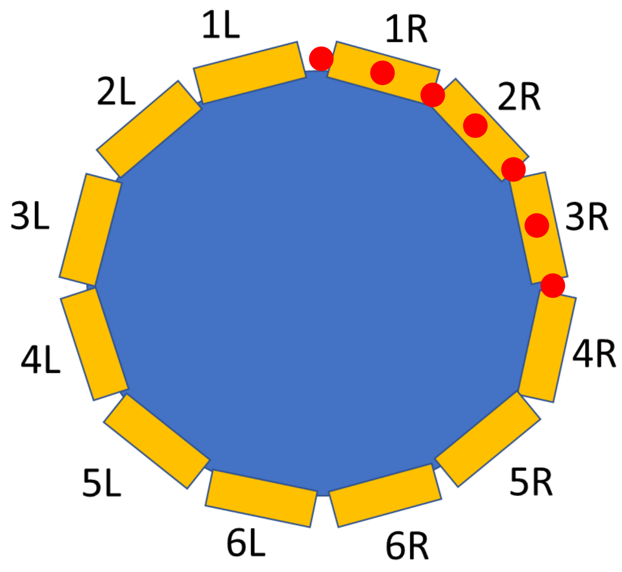


Points are simulation results (deviations near “dead” zones)

Sub 5 - Quench Heaters

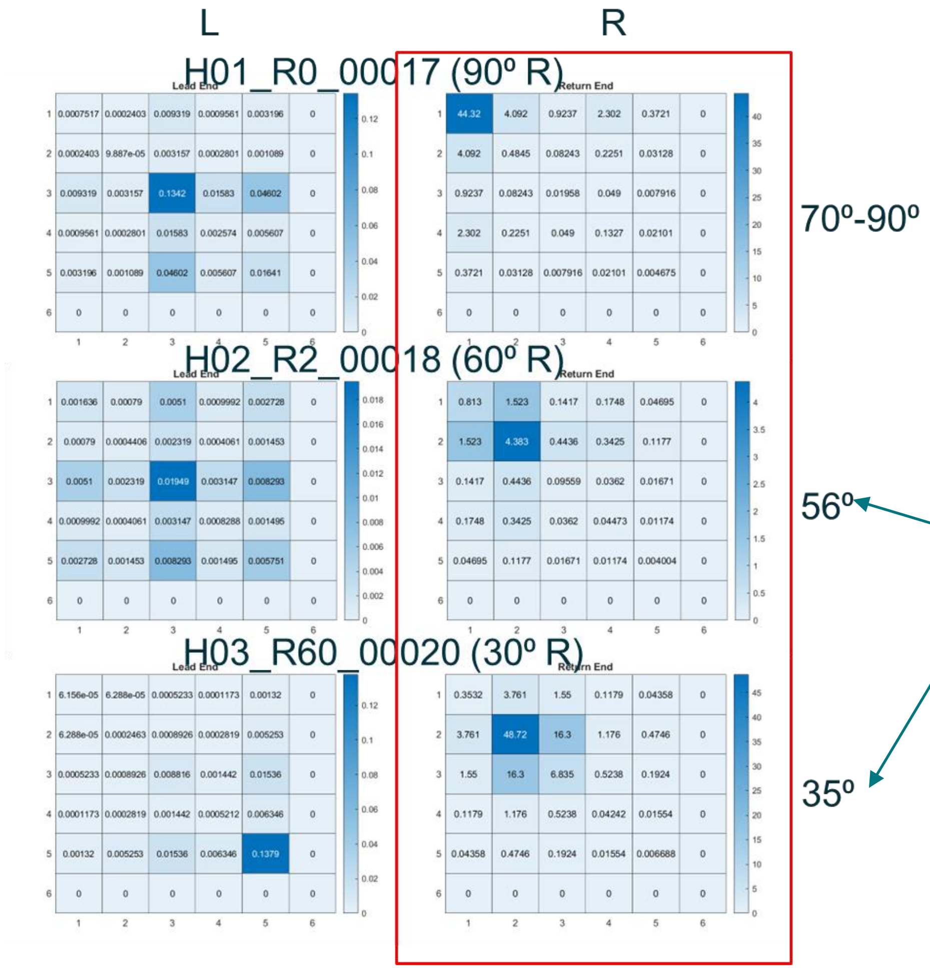
- Installed quench heaters on CCT Sub5 inner layer
  - Heater are made of fine manganin wire
  - Heaters are attached with stycast to the edge of the cable (outside of the glass insulation)
- Two heater traces installed (4 heaters each)
  - Heaters aligned with antenna edges (90º, 60º, 30º, 0º (failed))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



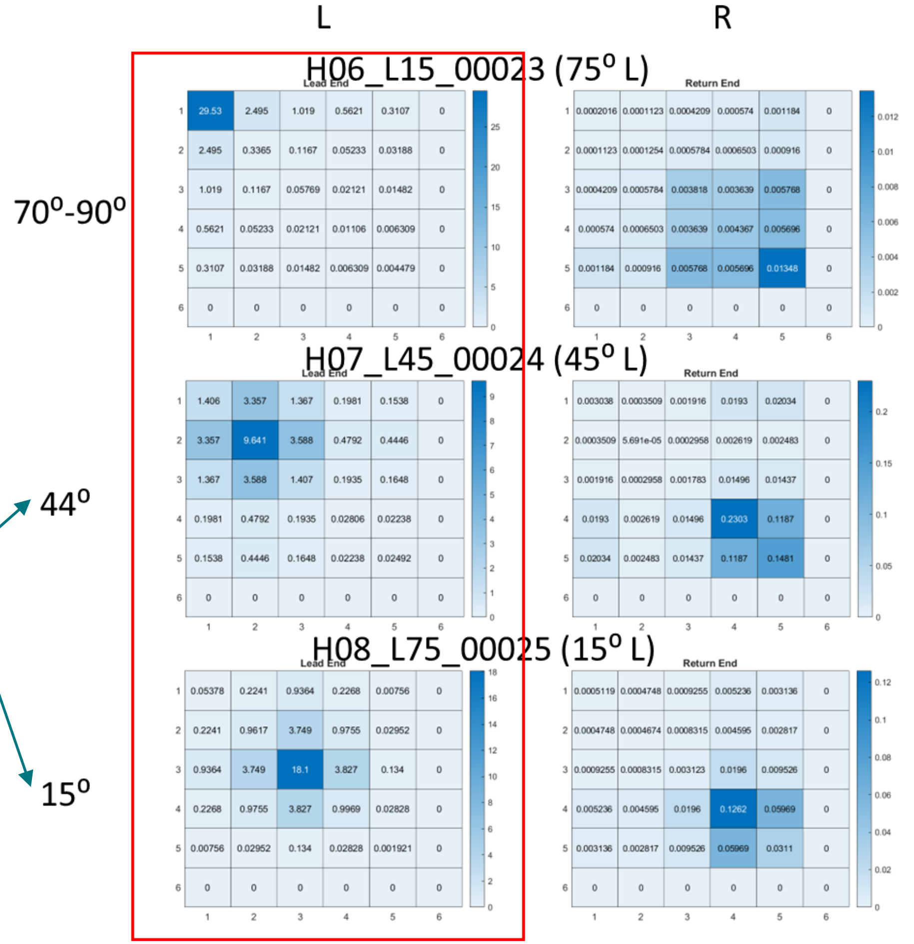


Sub 5 - Quench Heater Localization Results

- Improved localization method gives results consistent with the heater location

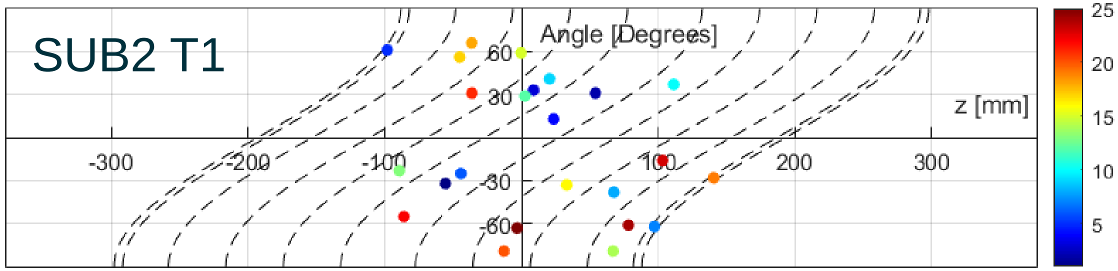


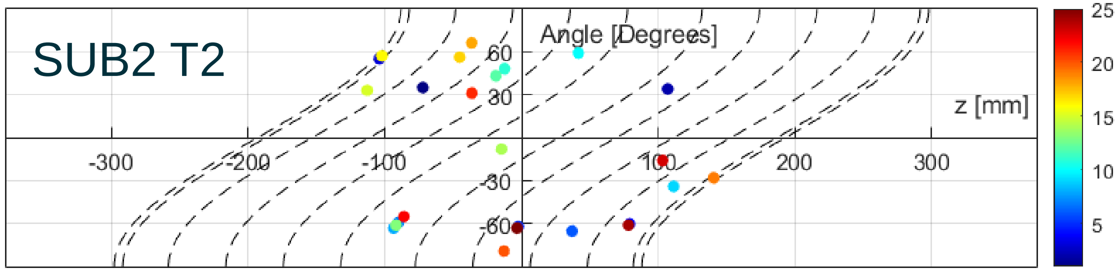
Results from improved localization method

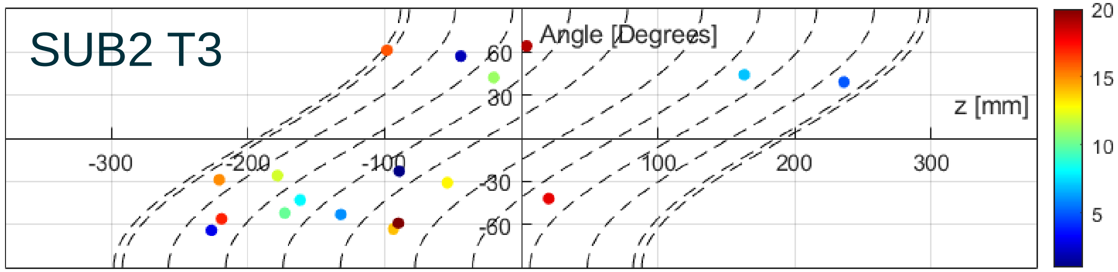


Quench Localization SUB2 and SUB3

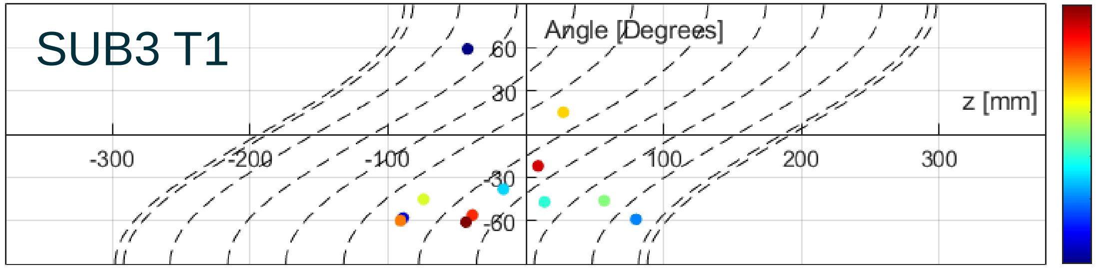
CCT Subscale 2

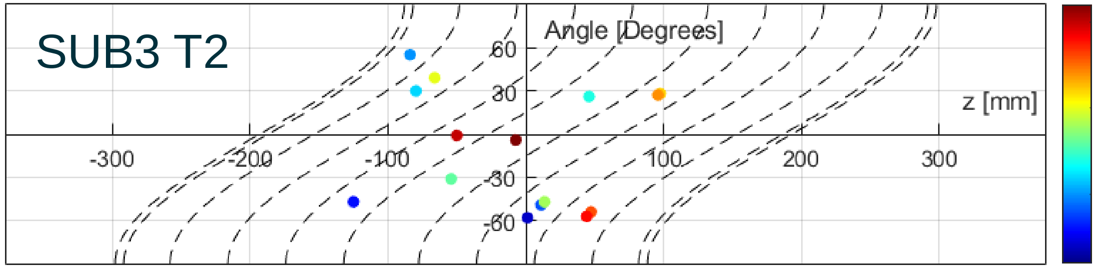






CCT Subscale 3





- Dashed lines represent Vtap segment
- Color represents quench number

Quench Angle Localization Summary and Next Steps

- General trends for quench angle on thin and thick spar magnets have been established
- Simulations of debonding and training in CCT magnets are being performed by G. Vallone
- Will continue to use available information and tools to improve understanding of training mechanisms in these magnets
- Continue statistics / clustering analysis of ramp data with focus on wax magnet