U.S. MAGNET DEVELOPMENT PROGRAM

Nb_3Sn CCT Program Updates And Test Results

USMDP Bi-Weekly Meeting - 10/11/2023

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Outline

- General Updates
  - CCT subscale updates and plans
  - CCT6 updates and plans
- Application of improved quench localization method on CCT SUB2/3
- Test results from CCT SUB6 (full wax magnet)
  - *Maxim will cover acoustic data in next presentation*

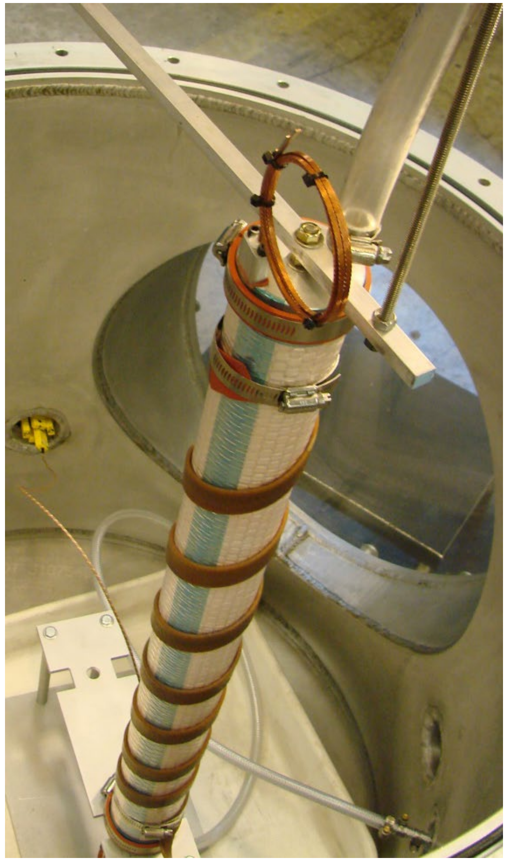
CCT Subscale

- Completed first test of CCT SUB6 (full wax magnet)
- Preparing for test of CCT SUB6 after thermal cycle
- Upcoming subscale CCT's (over next year: order not yet decided)
  - Stycast Impregnation
  - Telene Impregnation
  - Filled wax impregnation (motivated by recent PSI work)

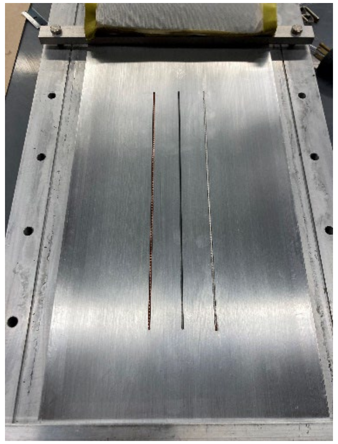
Plans for TELENE impregnated Subscale CCT at LBNL

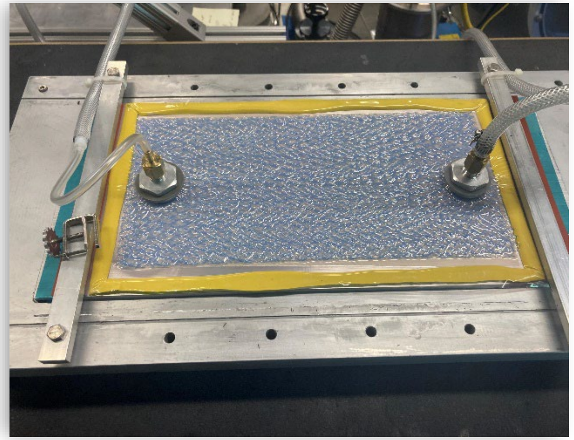
- TELENE shows promising training improvement on undulator coils (work by E. Barzi)
- Will initially perform testing of resin transfer and fill quality on flat plate setup for application to CCT impregnation
  - Same setup that is used for Stycast testing
  - Flat plate with grooves to insert cable
  - Uses consumable materials for resin transfers (vacuum bag, flow media, peel ply)
- Flat plate tests will be used to determine if same materials are compatible with TELENE impregnation (relative to resin cure temperature and pot life)

Subscale CCT Impregnation



Resin Impregnation Test Setup

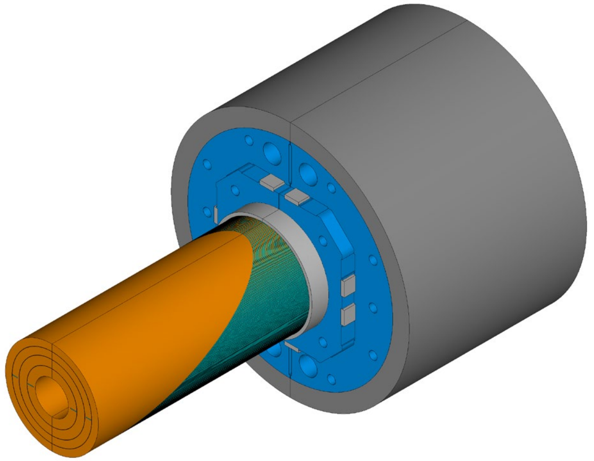




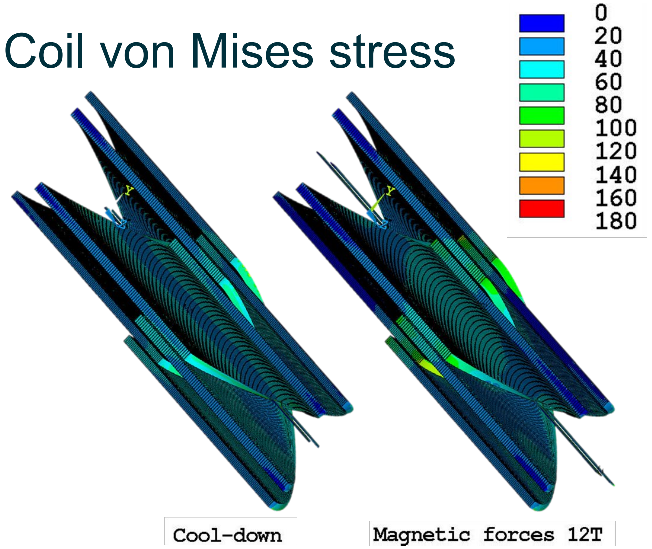
Effort led by Jose Luis Rudeiros Ferndandez

CCT6 Modeling Updates

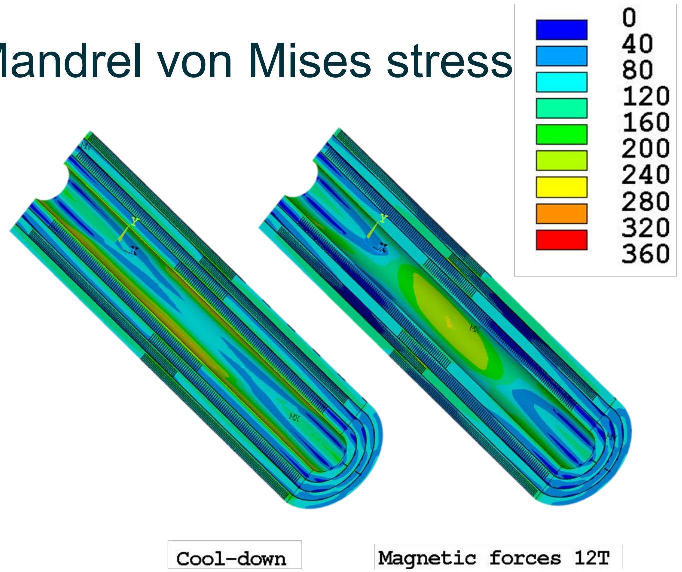
- Baseline structure design is complete
- Completed baseline 3D analysis with epoxy impregnated coils (bonded contacts)
- Working final optimization of detailed coil parameters

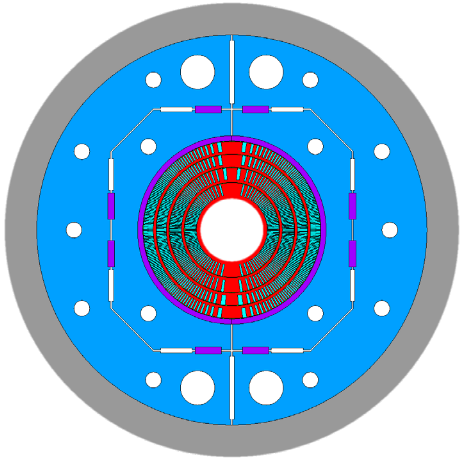


Coil von Mises stress



Mandrel von Mises stress



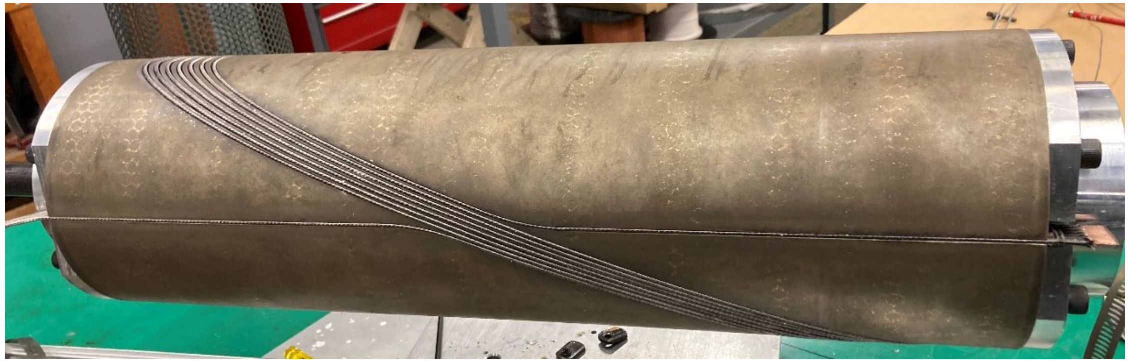


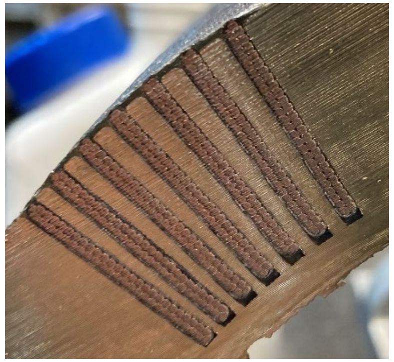
Work by M. Juchno and L. Brouwer

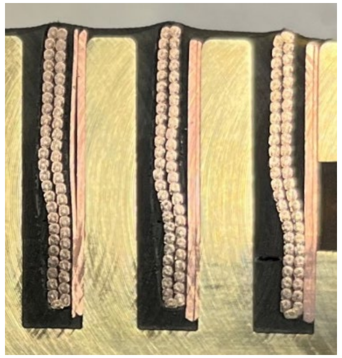
CCT6 Fabrication Updates

- Completed 7 turn test coil winding, reaction, impregnation test in early 2023 (machined by SMP machinist)
- Second test mandrel was machined by main LBNL shop with small adjustments to groove geometry
  - Loss of experience in moving work to LBNL shop (SMP machinist left LBL)
  - Machining quality was not good enough to obtain meaningful results
  - Machining time was not scalable for full length coils

First short coil after reaction







CCT6 Next Steps

- Design and Analysis
  - Investigate cases with different bonding scenarios between cable and groove
  - Analysis of segmented mandrel mechanics
  - CAD design of key-and-bladder structure

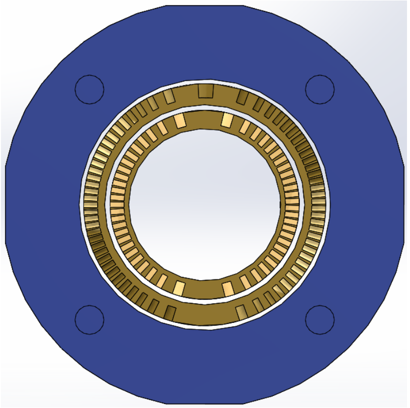
- Mandrel Fabrication
  - Main shop will gain experience and optimize process on machining of flat plates
  - Will build 20 turn inner layer test coil with four slightly different groove geometries
  - Will select best groove geometry and machine full length inner layer (mandrel with final basic dimensions has been purchased)

- Fabrication Technology
  - Investigating possible use of filled wax for CCT6
  - Investigation of options for mandrel segmentation

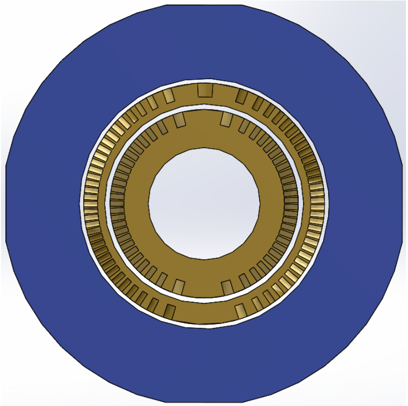
Quench localization Analysis (SUB2 and SUB3)

- Performed updated quench localization analysis in SUB2 and SUB3 quench antenna data
- Goal is to improve understanding of how stress state impacts training (stress is strongly dependent on angle)
- SUB2
  - Baseline magnet (1.5mm thin spar)
  - Three tests performed (thermal cycle 1, thermal cycle 2, disassembly / reassembly)
- SUB3
  - Inner layer has thick spar (8 mm)
  - Two tests performed (thermal cycle 1, thermal cycle 2)

Baseline Magnet (Thin Spar)

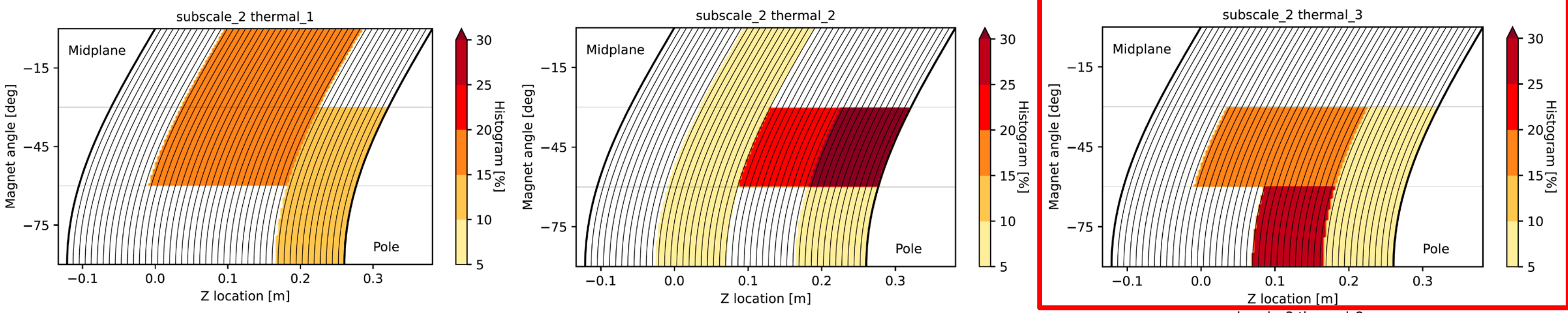


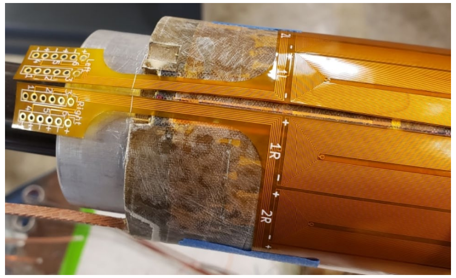
CCT Sub3: Thick Spar L1

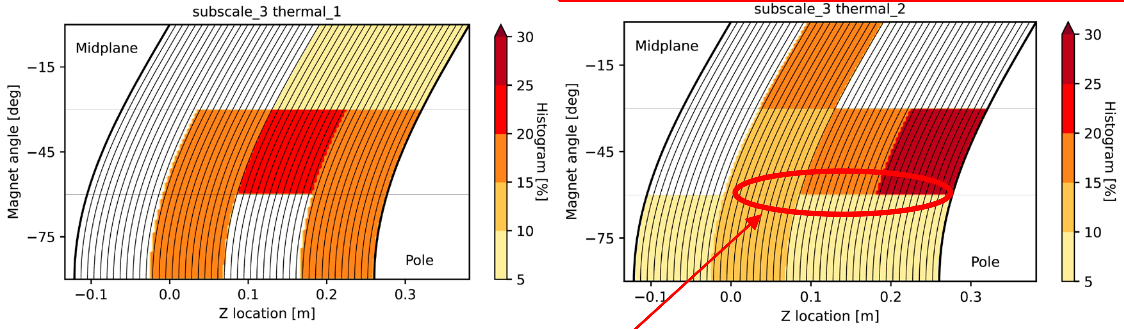


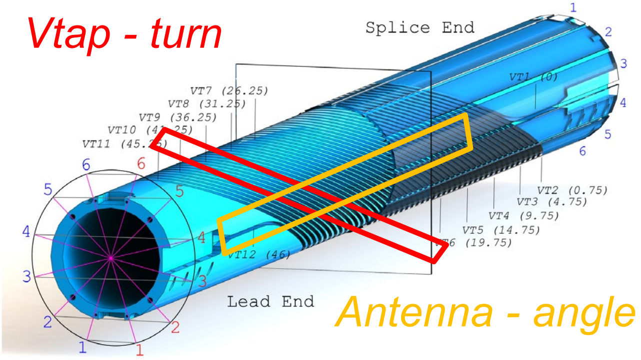
Quench Localization Analysis

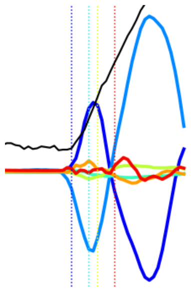
- Extensive analysis was performed by R. Teyber
  - Combine Vtap and quench antennas to localize quenches
  - Histogram bins to 15, 45 or 75 degrees based on antenna element with largest measured flux
- New method was recently introduced to improve the resolution of angle localization by using correlation between antenna segments











Work by R. Teyber

Improved Quench Localization Method

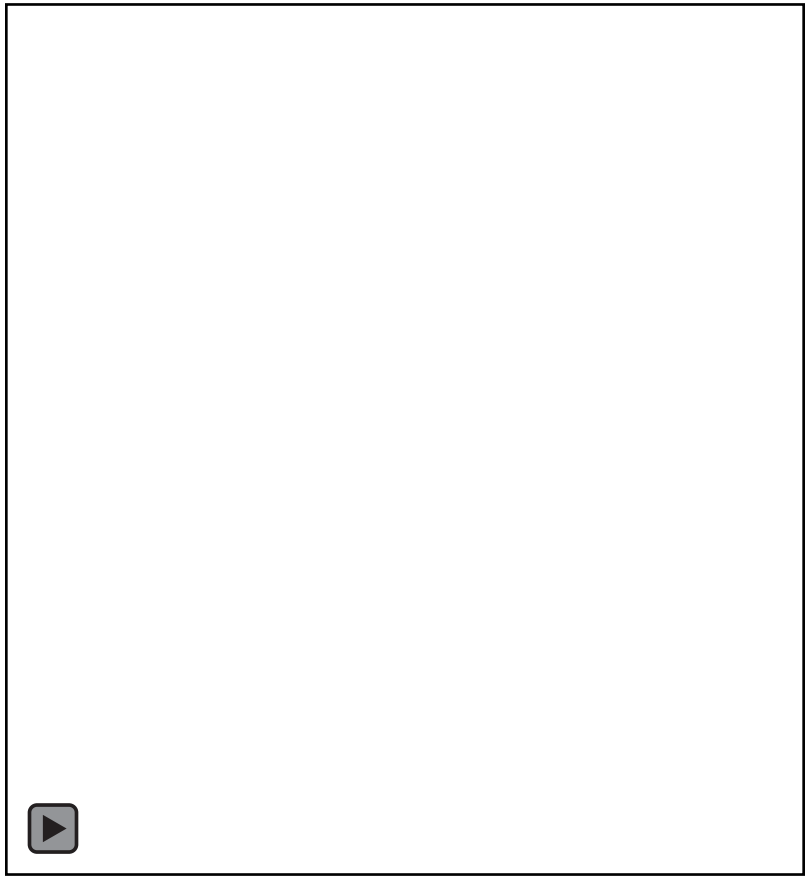
- Define Correlation parameter as $C_{ij} = \int_0^{t_0} |\varphi_i \varphi_j| dt$
- Improve localization by accounting for signals from neighboring antenna elements
  - Cross-Correlation between neighboring antennas
  - Self-Correlation of neighboring antennas
- Use Quench simulations to determine relationship between correlation parameters and quench initiation angle

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



Straight cable simulation performed by Ruben Keijzer & Gerard Willering

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: $(C_{i+1,i+1} - C_{i-1,i-1})/C_{i,i}$
  - Neighbor cross-correlation difference: $(C_{i+1,i} - C_{i,i-1})/C_{i,i}$

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

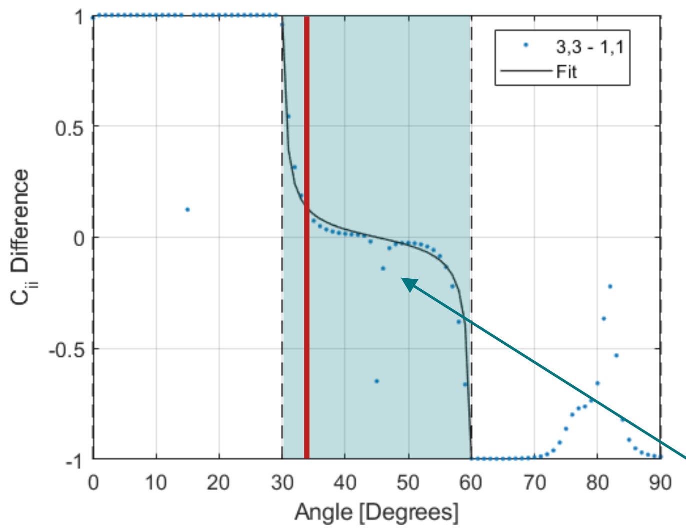
- Use fit function derived from simulations to determine angle for each case (should be consistent)

Normalized Correlation Matrix

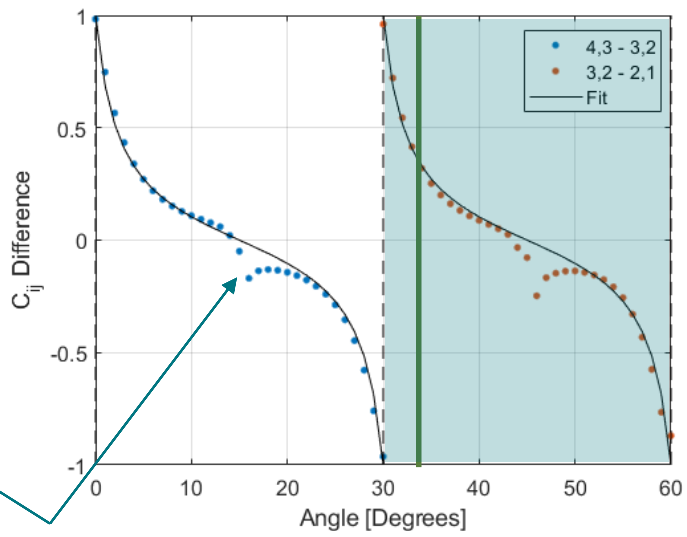
Return End

	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



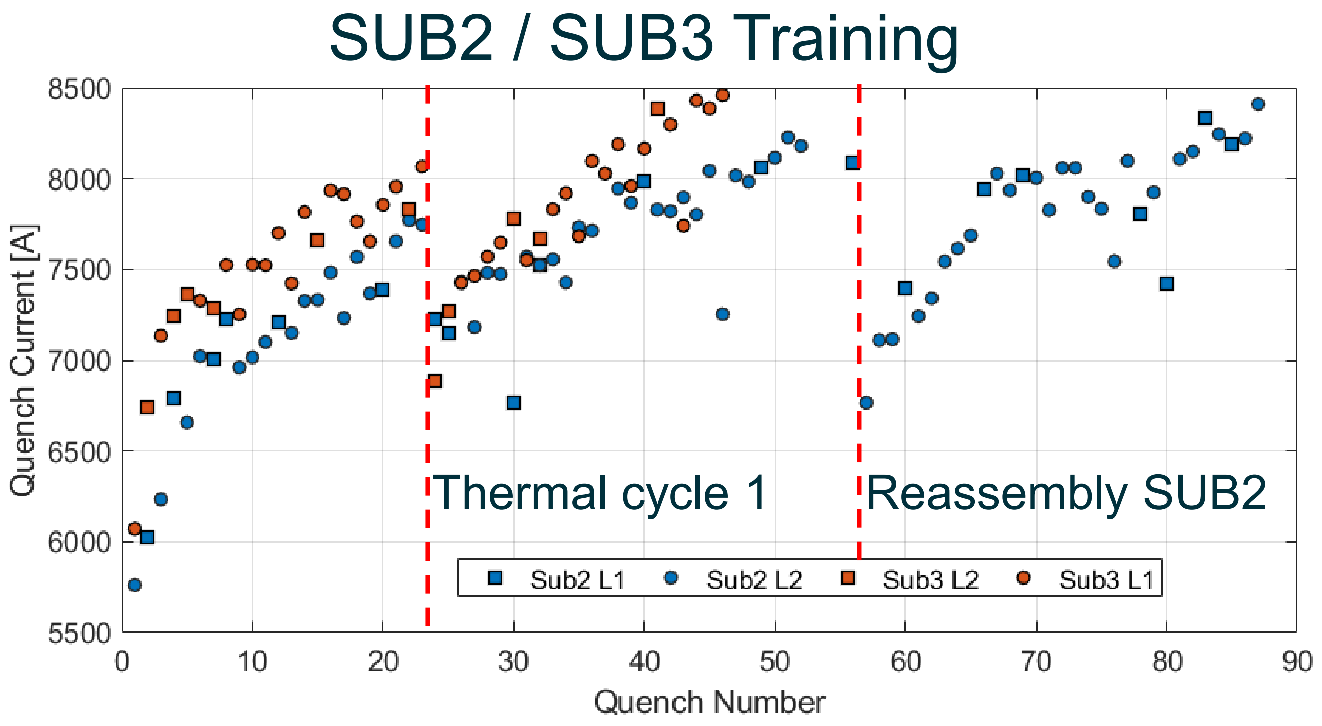
Cross-Correlation Neighbor Difference



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

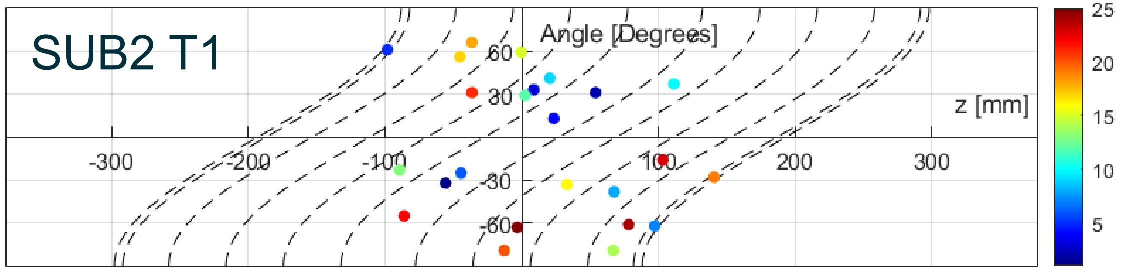
Training Results for SUB2 and SUB3

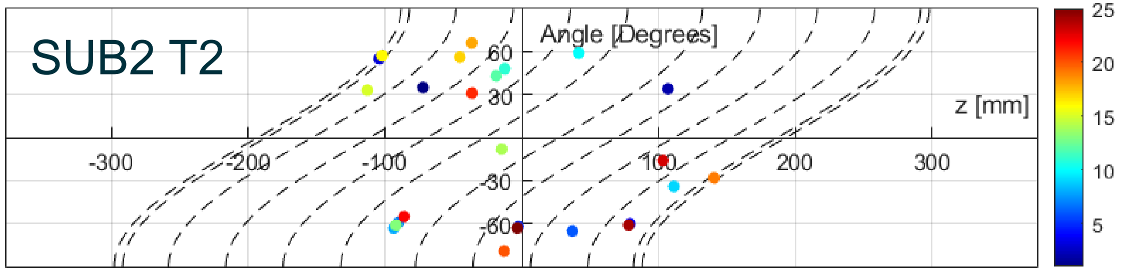
- Sub2
  - Has strong knee in training behavior for first thermal cycle and after reassembly
  - Training rate seems to decrease after each thermal cycle
- Sub3
  - Less pronounced knee in training behavior (reaches “slow” training after only 2 quenches)
  - Training rate is similar for both thermal cycles

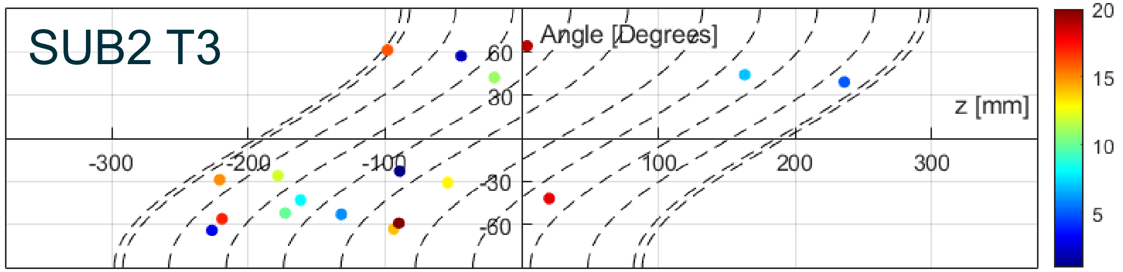


Quench Localization SUB2 and SUB3

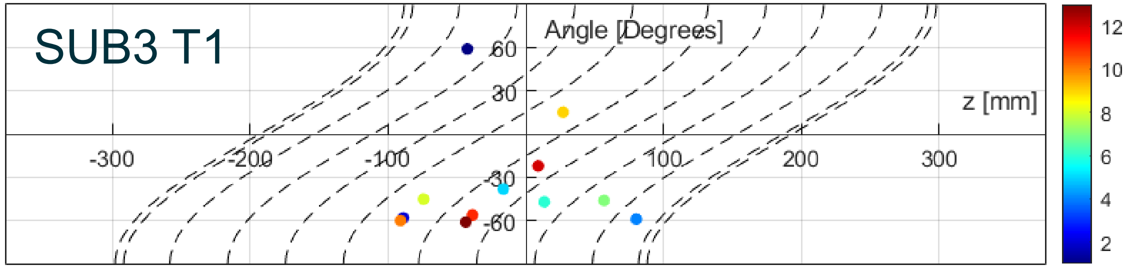
CCT Subscale 2

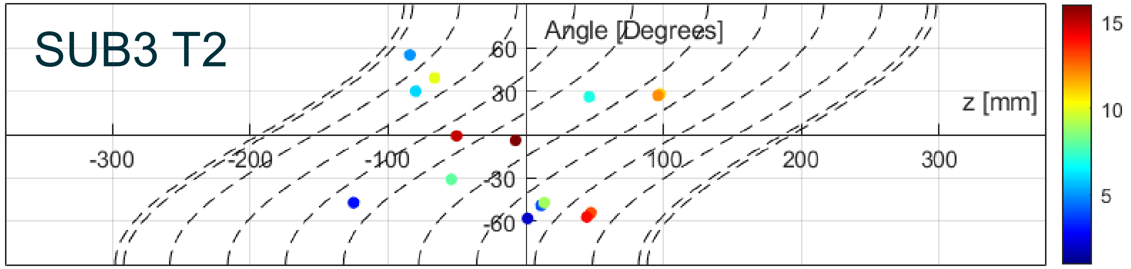






CCT Subscale 3



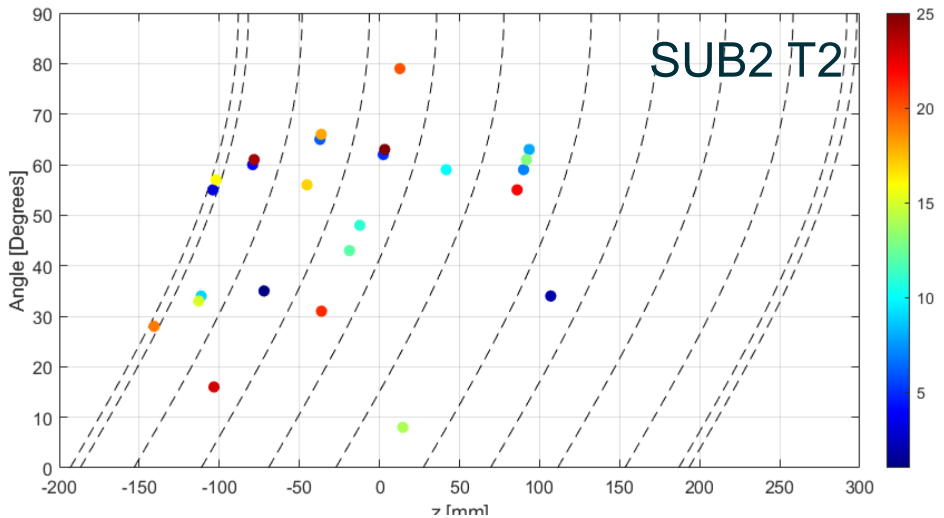


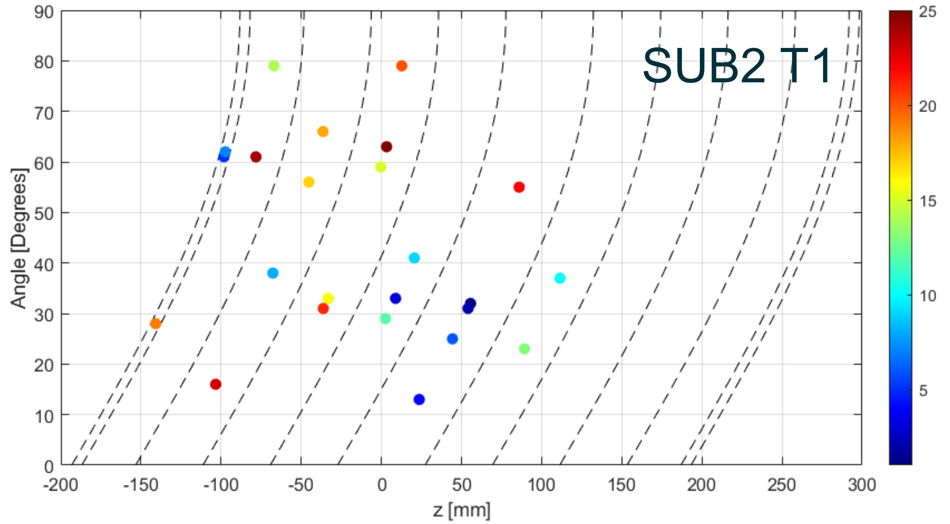
- Dashed lines represent Vtap segment
- Color represents quench number

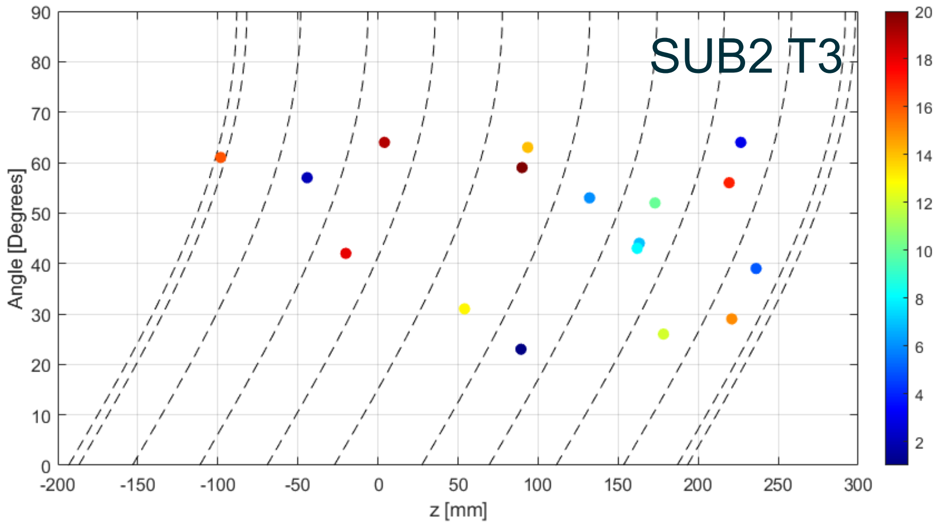
Quench Localization SUB2 (symmetric)

Observations

- Relatively high number of quenches on first turn
- Quenches start at lower angles on thermal cycle 1 and move towards higher angles as training progresses
- Quenches are more concentrated at higher angles in thermal cycles 2 and 3 with almost no quenches near the mid-plane in thermal cycle 3
- High concentration of quenches at ~60º on thermal cycle 3





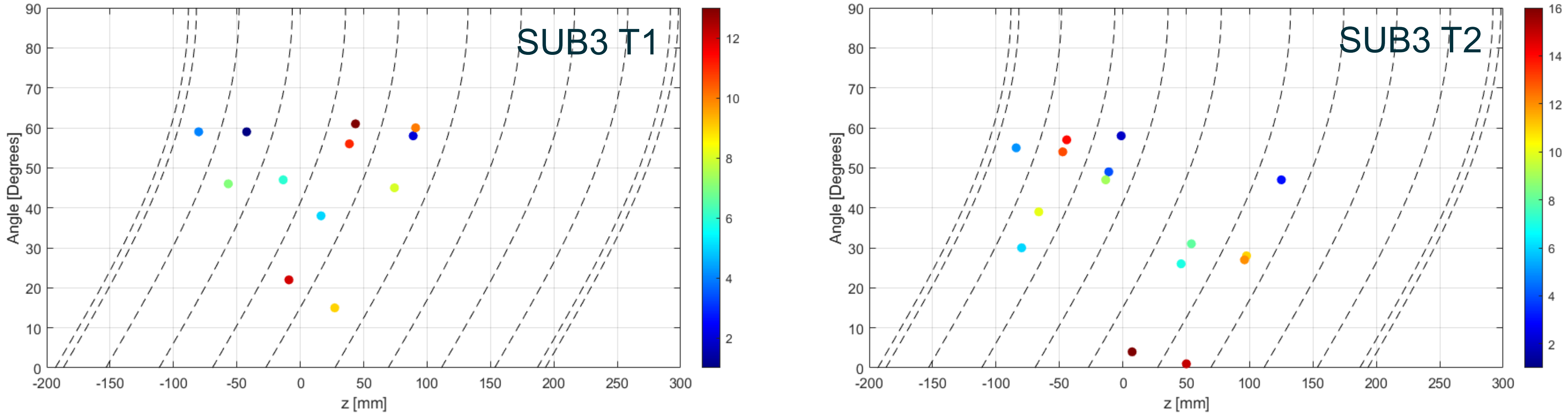


Quench Localization SUB3 (symmetric)

Observations

- No quenches on first turn
- Most early quenches are at an angle near ~60º
- Some later quenches near the midplane

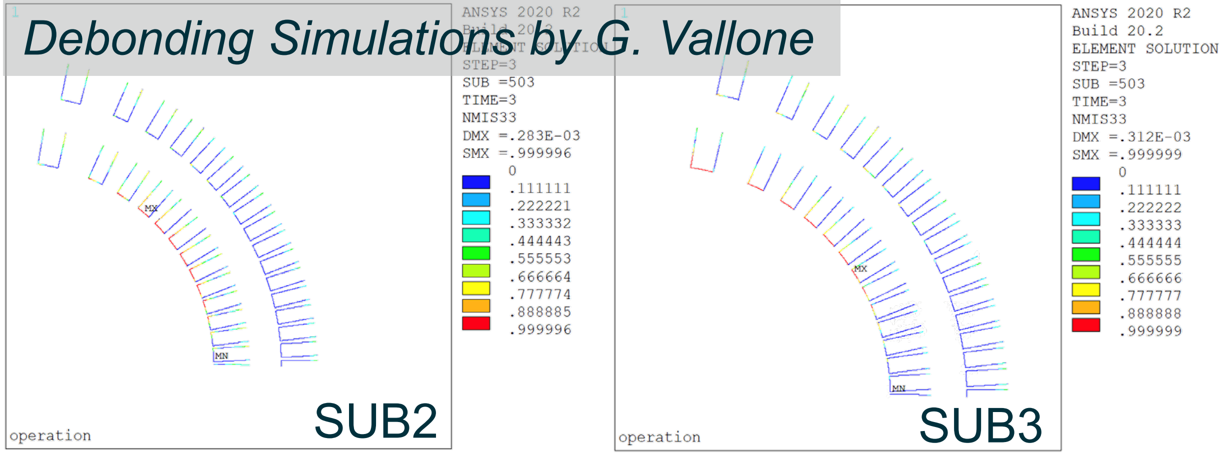
Quench localization for SUB3 Thermal Cycles 1 and 2

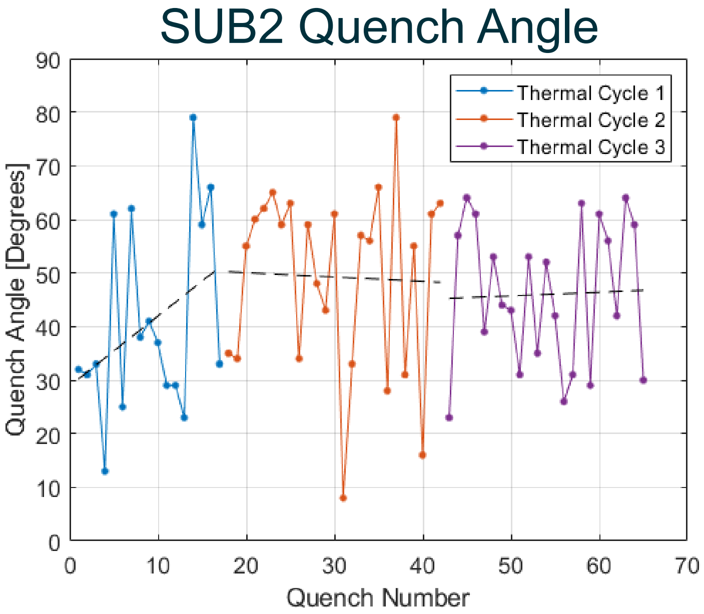


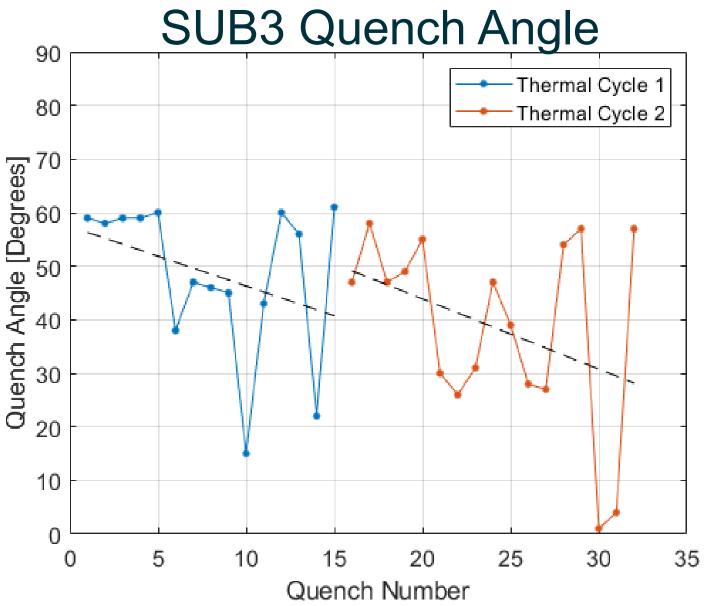
Quench Angle Localization Summary and Next Steps

- 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

Debonding Simulations by G. Vallone

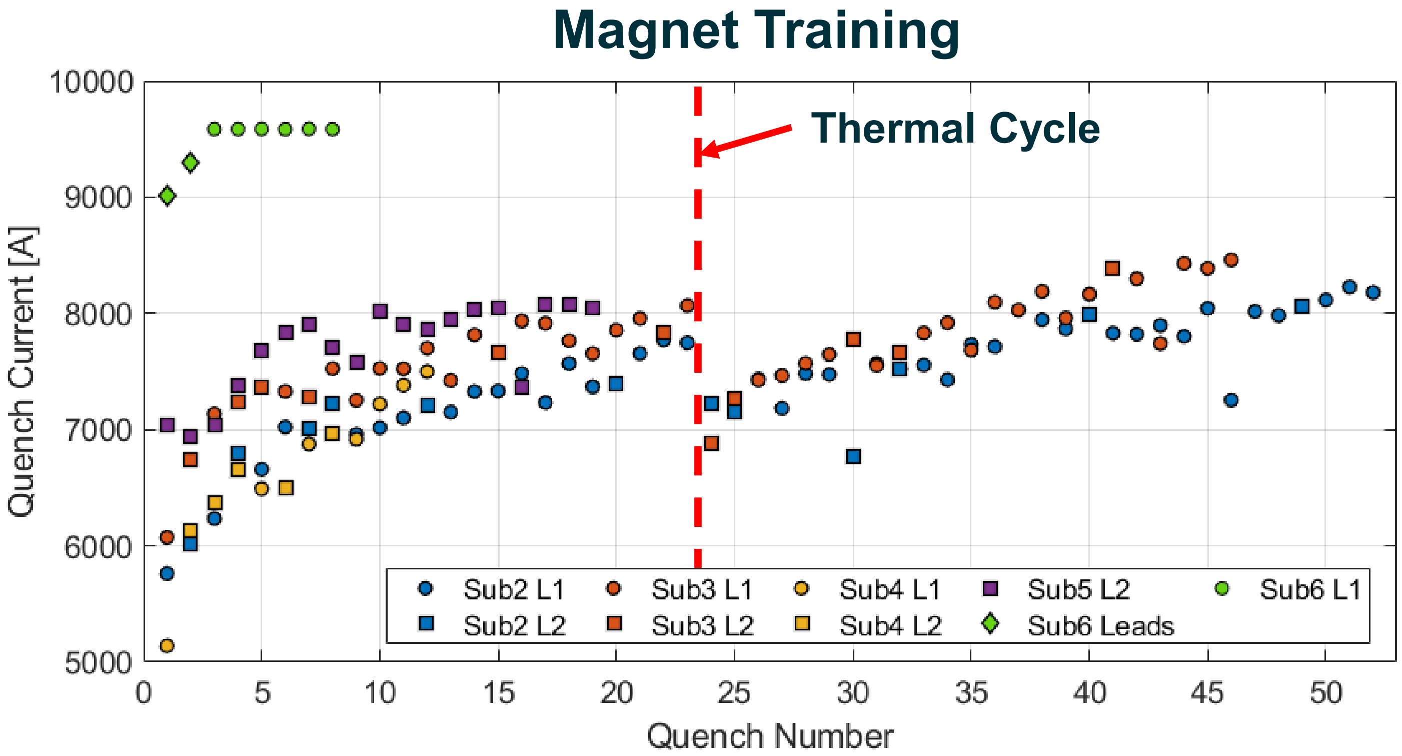






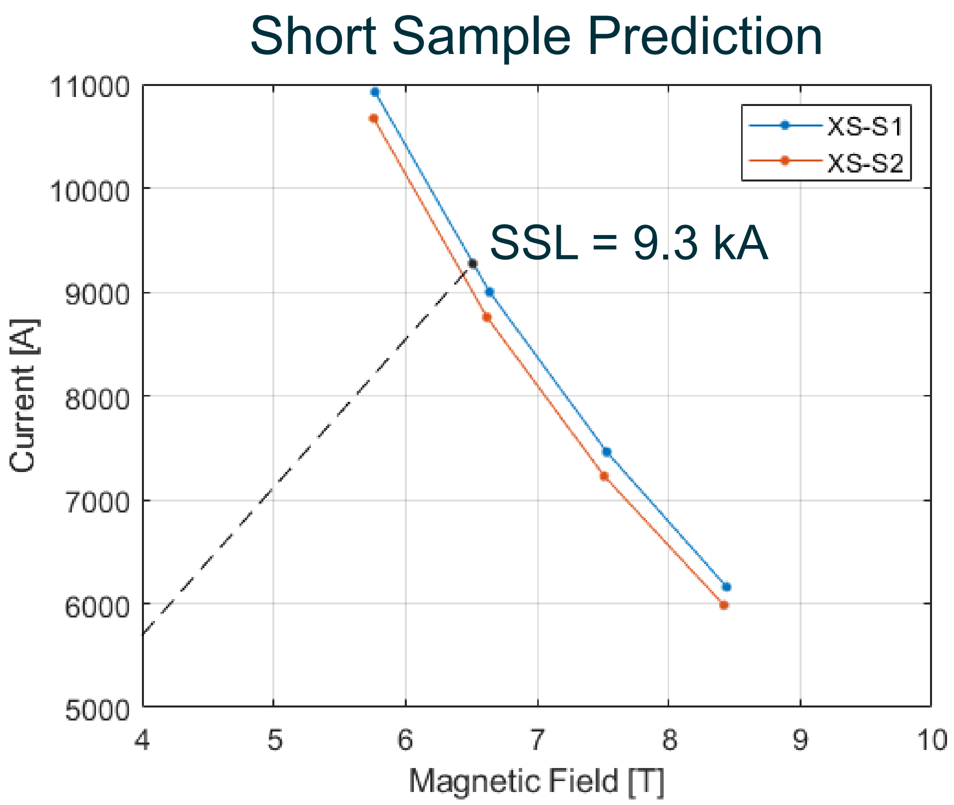
Wax Impregnated Magnet Reaches Plateau On First Quench Inside the Coils

- First two quenches are outside of the coils
- Reach plateau on first quench inside the inner layer coil
- All quenches in same inner layer segment
- Quench current is the same to within 3 A on subsequent ramps
- Held current at 50 A below plateau for 5 minutes without quench

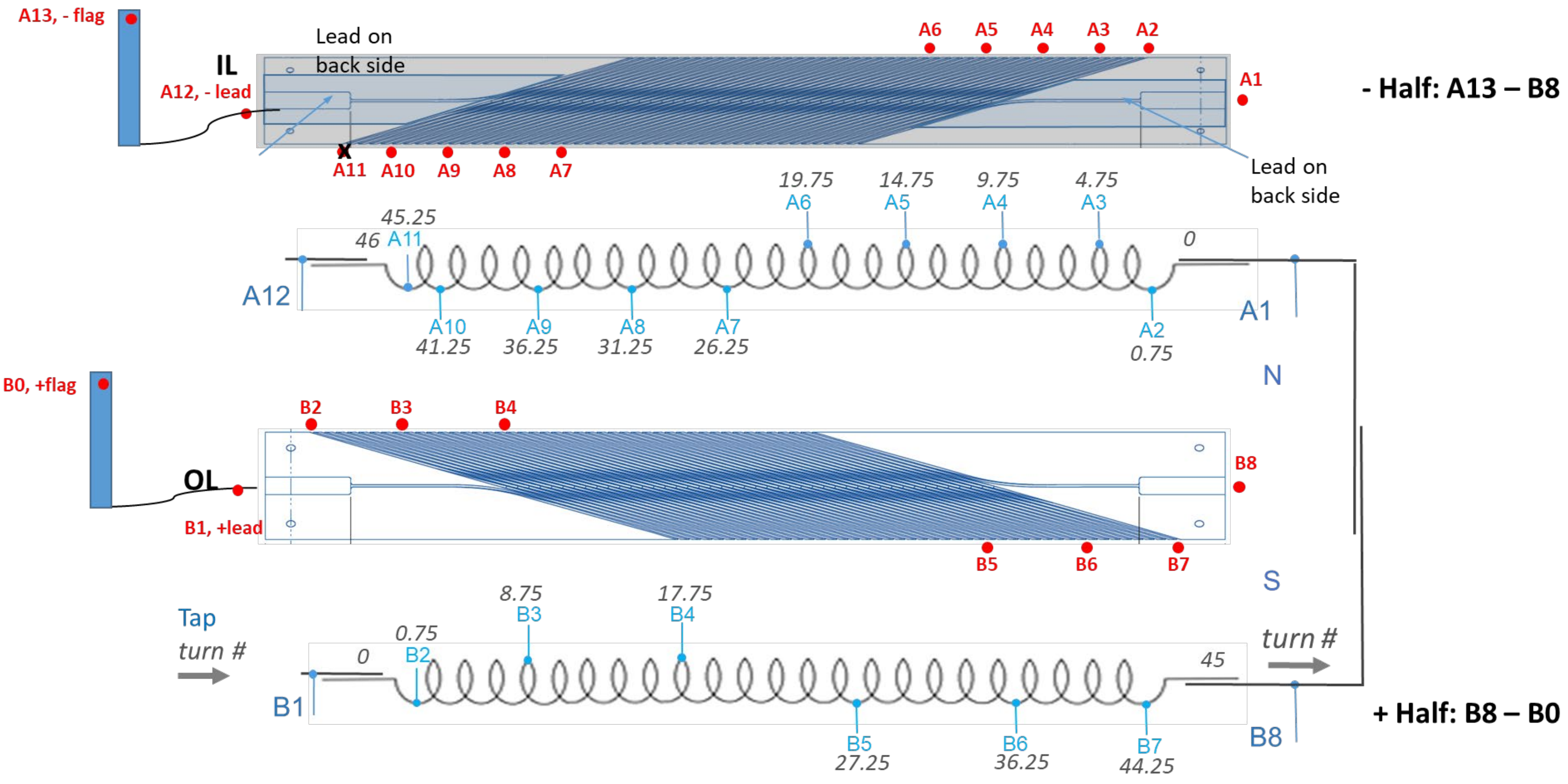


Short Sample Current Analysis

- Short sample measurements performed on extracted strands at NHMFL (Jun Lu)
- Predicted SSL based on extracted strand measurements is 9.3 kA
- Magnet plateau reached at approximately 3% above predicted SSL
- Reason for this is not yet clear
- Witness samples from coil heat treatment are available but have not yet been tested due to current upgrade of short sample test facility

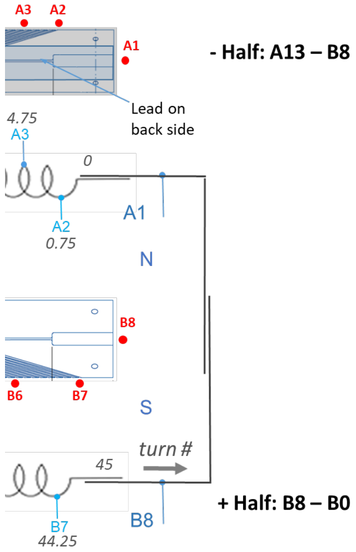


Voltage Tap Layout

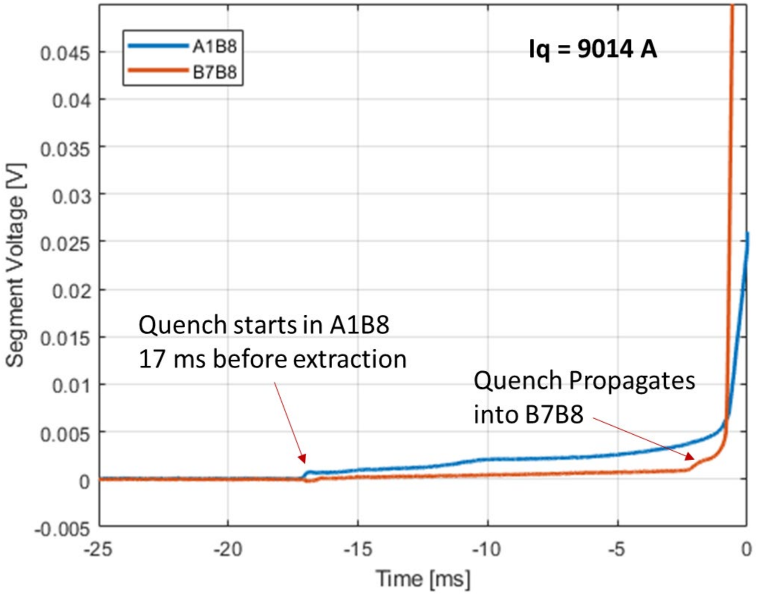


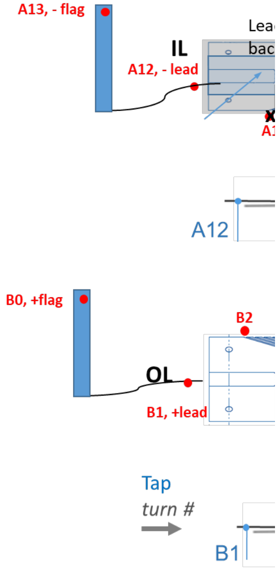
First Quenches Start at the Leads

- First two quenches likely due to lead motion
  - Ramp A02: near return splice
  - Ramp A03: at negative NbTi lead

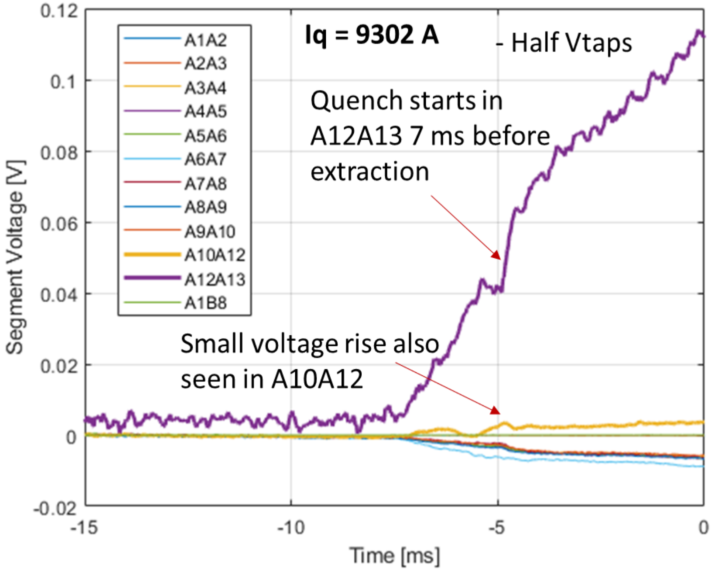


Voltage Signals: Ramp A02





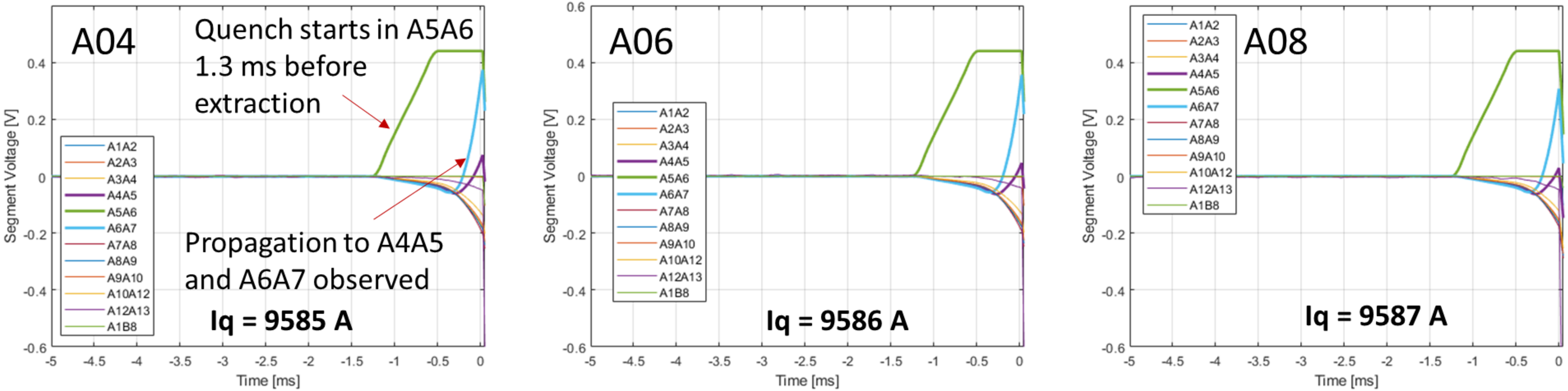
Voltage Signals: Ramp A03



Voltage Signals from Inner Layer Quenches

- All quenches start in segment A5A6
- Propagation to segments A4A5 and A6A7 is observed (usually not observed in previous magnets where quench occurs with more margin)
- All quenches almost identical voltage signals

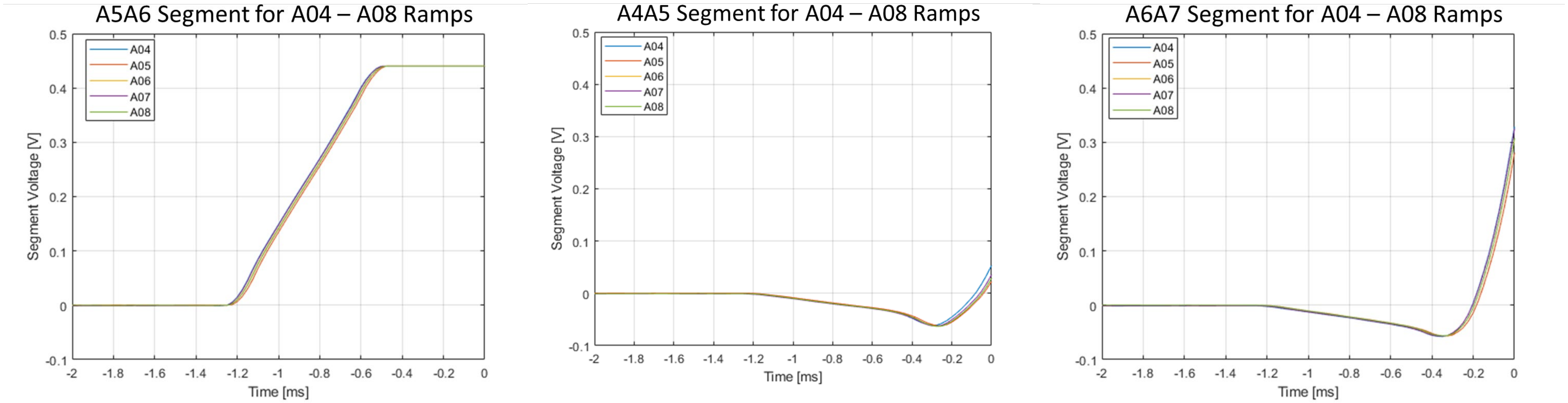
Inner Layer Segment Voltages for Three Different Quenches



Comparison of Voltage Signals for All Quenches

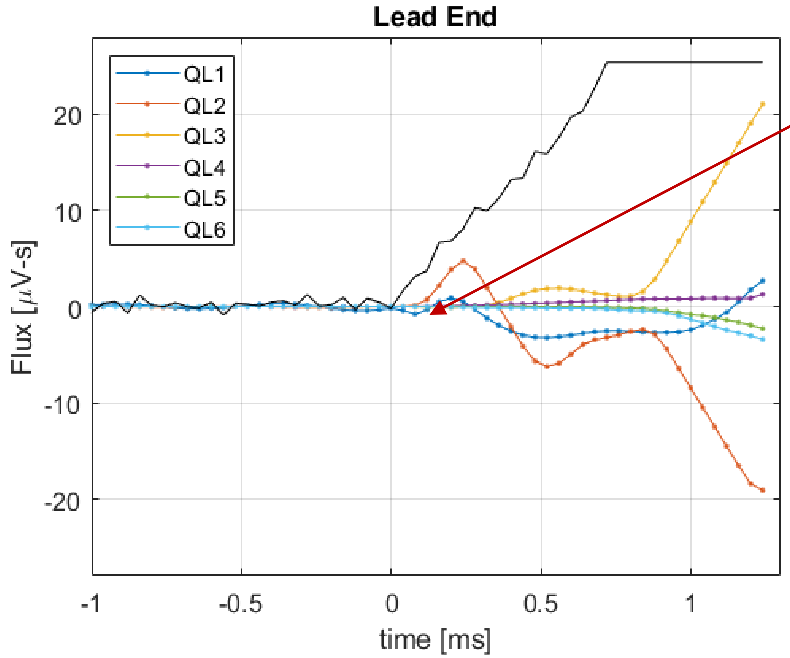
- Voltage signal are nearly identical for all coil quenches
- Quench is occurring in the same location

Voltage Signals for All Quenches in Relevant Voltage Tap Segments

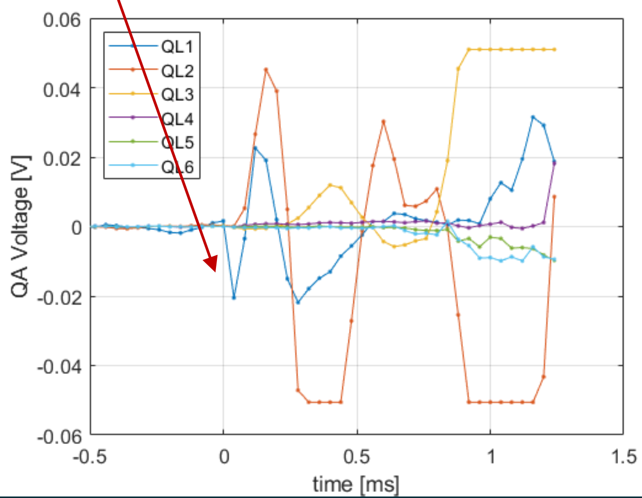


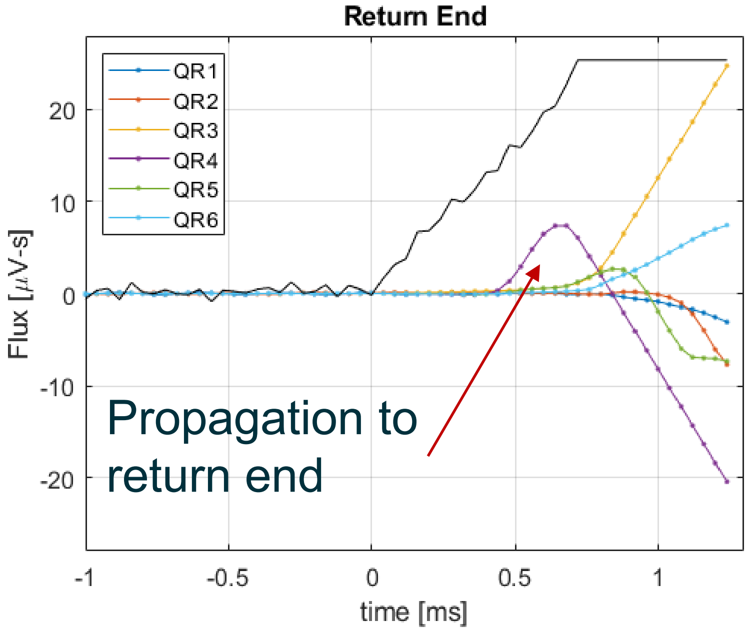
Quench Antenna Analysis

- Correlation integral method was not used for the analysis due to the much higher propagation velocity when compared to previous magnets (can likely be used with smaller integration time)
- Pole antenna is first to respond followed by neighboring antennas
- Quench is likely initiated at / near the pole region



Initial voltage rise seen on Pole Antenna

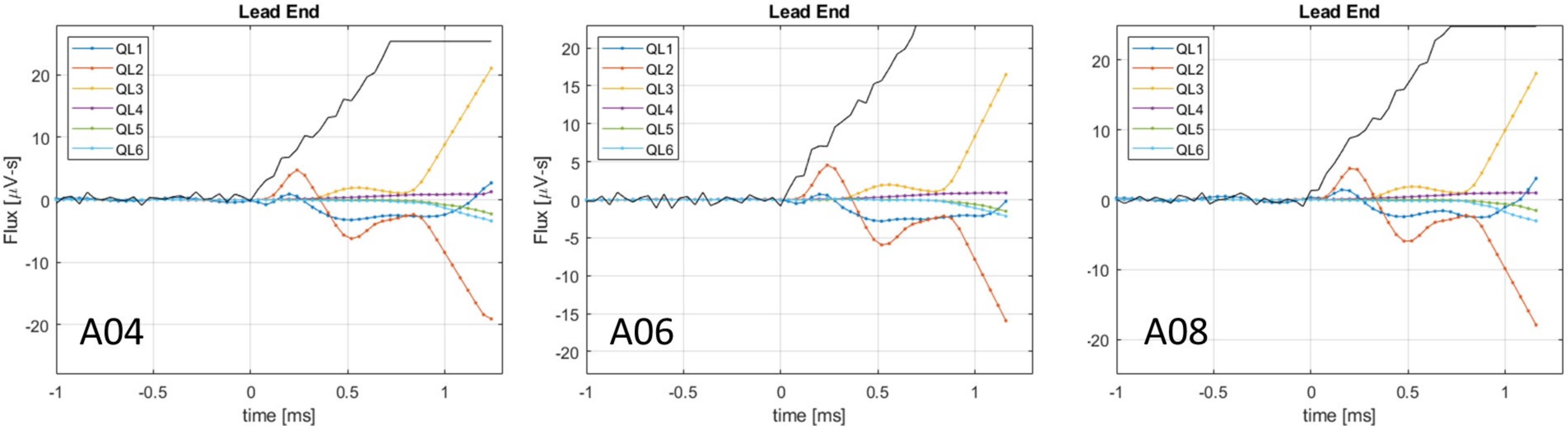




Propagation to return end

Comparison of Quench Antenna Signals for Various Quenches

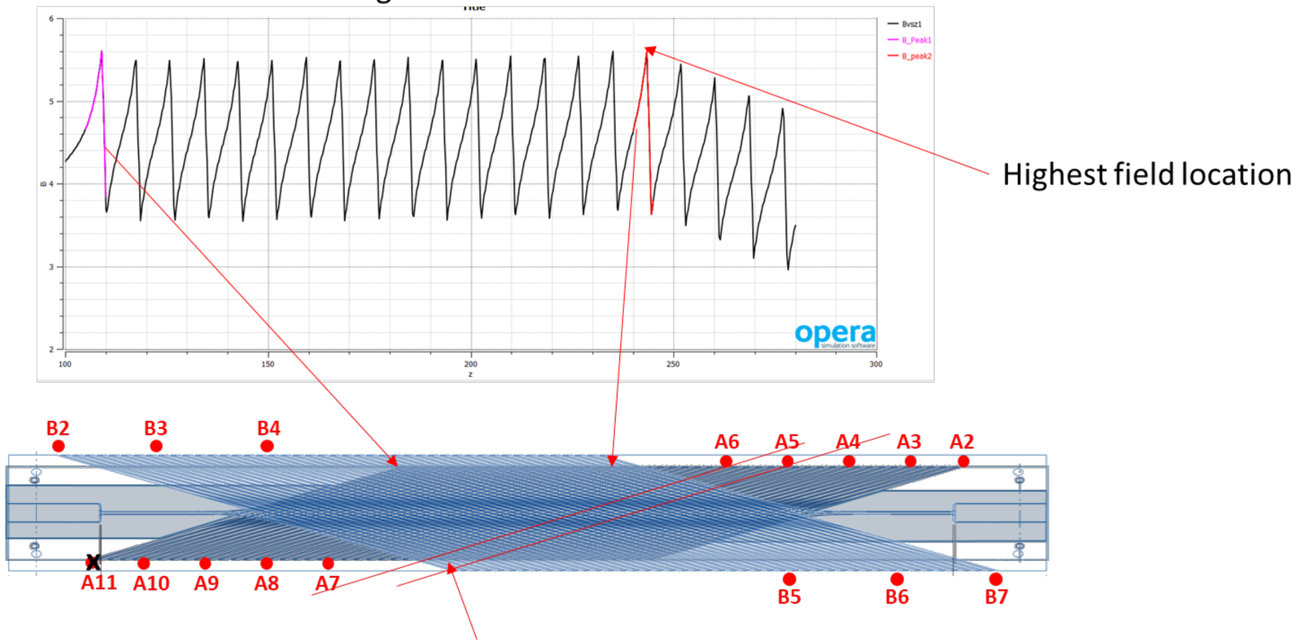
- As with voltage tap signals, quench antenna signals are nearly identical for all quenches
- Quench is occurring in the same location



Quench Location is Likely at the Peak Field Region

- Peak field occurs in layer 1 at the overlap with the first / last turn of the outer layer
- Slightly lower field in first / last turn of layer 1
- Intersection of voltage tap segment and pole quench antenna coincides with peak field region in the magnet

Magnetic Field Peaks



Quench likely occurs here in layer 1

Summary

- Demonstrated training free feasibility in subscale Nb_3Sn CCT with wax impregnated magnet
- Continue to increase understanding of CCT mechanics and training through
  - Diagnostic methods, for example quench localization (quench antennas, Vtaps), acoustic methods (next talk by Maxim), and other novel techniques
  - Advance modeling methods (for example debonding / training model by G. Vallone)
- Continue to explore novel impregnation materials on subscale CCT magnets
- Subscale results are influencing design of CCT6 (exploring possibility of wax impregnation)
- CCT6 design progressing but fabrication progress has been slowed by machining issues