U.S. MAGNET DEVELOPMENT PROGRAM

Nb_3Sn CCT General Updates

D. Arbelaez, T. Bogdanof, L. Brouwer, S. Caspi, J. L. Rudeiros Fernandez, P. Ferracin, R. Hafalia, M. Juchno, M. Krutulis, G. S. Lee, M. Marchevsky, C. Myers, S. Prestemon, M. Reynolds, T. Shen, J. Swanson, R. Teyber, G. Vallone

US Magnet Development Program

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Nb3Sn CCT Subscale Status

- CCT Subscale 2 reassembly test - determine effect of full re-assembly on training and determine if outer layers can be reused
  - Magnet is on header ready for testing
  - Test delayed due to LHe shortage
- CCT Subscale 5, wax impregnated inner layer - determine effect of using low strength impregnation material (minimal energy release) on training
  - Impregnation process development / testing is complete and coil is ready for impregnation (See slides prepared by J.L. Rudeiros Fernandez)
  - Starting work on developing wide shims to prevent radially outward motion of the cable (see analysis slides from G. Vallone)
- Developing new instrumentation / analysis methods (see talks by M. Marchevsky, G.S. Lee, and R. Teyber)

CCT5 / CCT6 Updates

- Currently reassembling CCT5 magnet using improved bend-and-shim approach (See slides prepared by J.L. Rudeiros Fernandez)
  - Will perform standalone test of magnet (depends on LHe availability) to ensure that performance has not been compromised due to disassembly / reassembly process
  - Will subsequently be used for testing of HTS inserts
- CCT6
  - Currently performing optimization of mandrel geometry and external structure (see talk by M. Juchno on structure size optimization)
  - Performing prototyping / testing of fabrication methods (see talk by L. Brouwer)

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CCT Subscale and CCT 5 *Fabrication and Assembly*

J. L. Rudeiros Fernandez*

D. Arbelaez, L. Brouwer, P. Ferracin, M. Krutulis, M. Reynolds, J. Swanson, S. Prestemon

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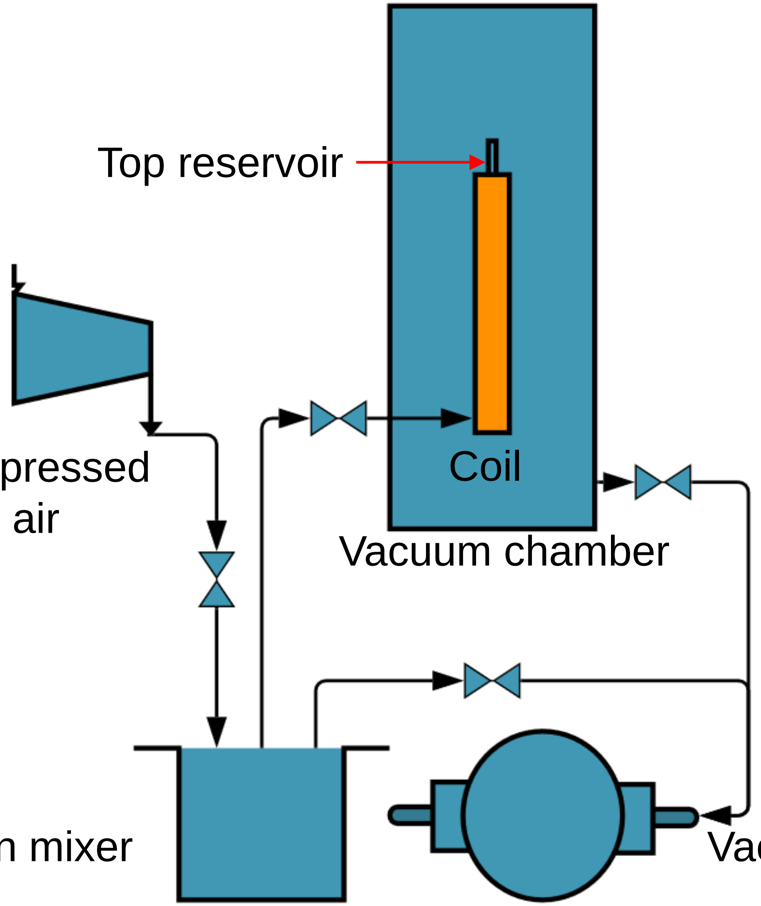
Outline

1. Wax impregnation development for CCT coils
2. Re-assembly of CCT 5
3. Conclusions

1. Wax impregnation development for CCT coils



General sequence for vacuum pressure impregnation using epoxy resins (e.g. Mix61, CTD-101K) or polyolefin-based resin (e.g. CTD-701X*)

1. Outgassing of the coil under vacuum.
2. Resin mixing and degassing.
3. Resin transfer to the coil until the reservoir is filled.
4. Vacuum open to atmospheric pressure.
5. Curing of the coils within a furnace.

Impregnation resin used for coils in the CCT subscale magnets	
Mix61	CTD-701X
CCT subscale 2	CCT subscale 4
CCT subscale 3	

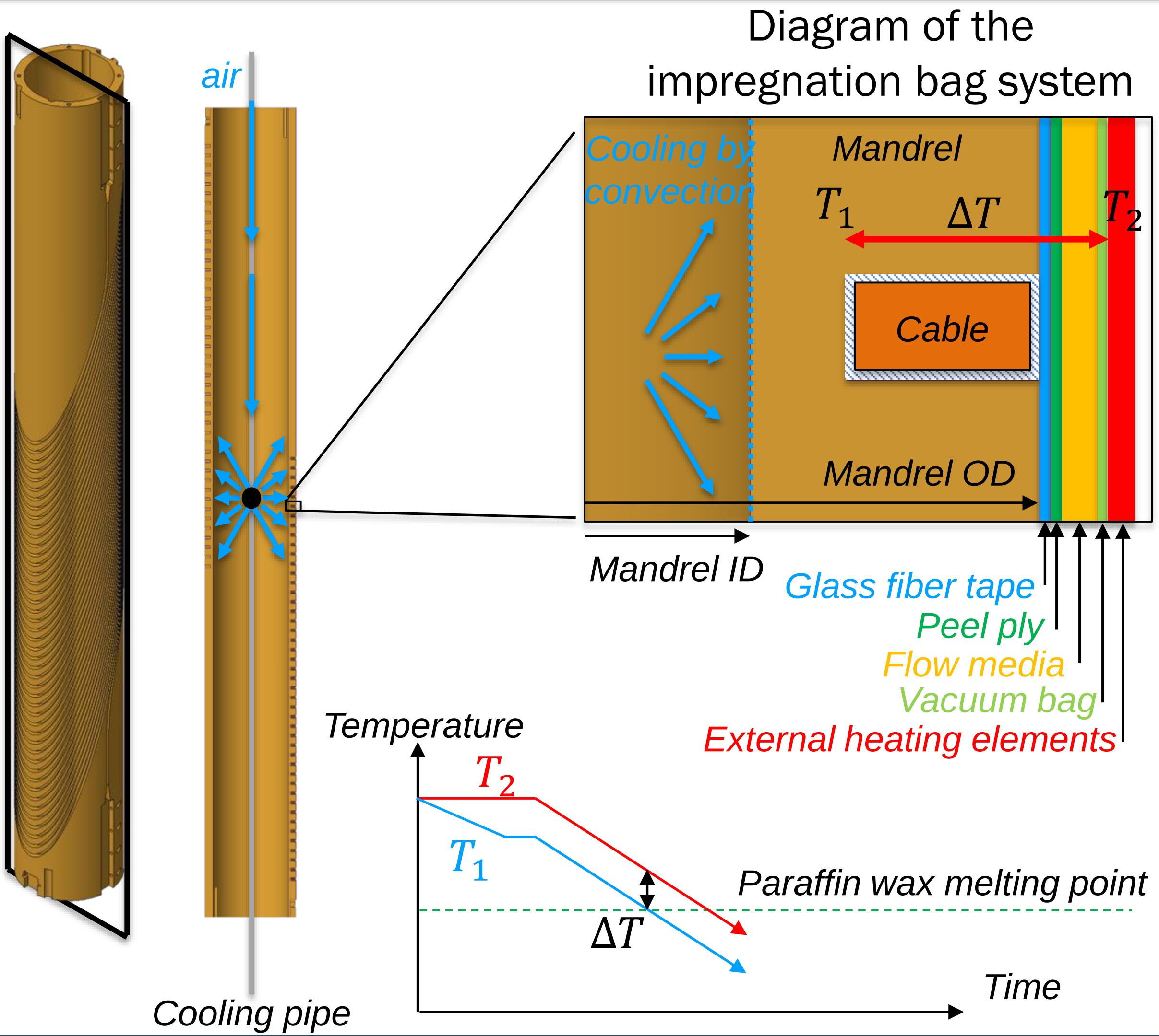
*Haight, A., Haynes, M. M., Krave, S. T., Rudeiros-Fernandez, J. L., & Shen, T. (2021). Characterization of Candidate Insulation Resins for Training Reduction in High Energy Physics Magnets. *Submitted for Publication at the CEC-ICMC*.

*Krave, S., Shen, T., & Haight, A. (2021). Exploring New Resin Systems for Nb3Sn Accelerator Magnets. IEEE Transactions on Applied Superconductivity, 31(5), 1-4.

1. Wax impregnation development for CCT coils

Development of a vacuum pressure impregnation for paraffin wax

1. **Paraffin wax may offer some advantages over traditional resins* used in superconducting coils in terms of:**
   1. Low energy dissipation during cracking.
   2. Low bonding strength (leading to low energy debonding events).
   3. Creation of low friction interfaces between main coil constituents (i.e. mandrel, cable strands and cable).
2. **The process implies additional challenges with respect to traditional resins:**
   1. High uniform temperature is required in all parts of the system.
   2. High volumetric contraction during phase transformation.



* Daly, M., Auchmann, B., Brem, A., Hug, C., Sidorov, S., Otten, S., ... & Kate, H. T. (2022). Improved training in paraffin-wax impregnated Nb3Sn Rutherford cables demonstrated in BOX samples. *arXiv preprint arXiv:2201.11039*.

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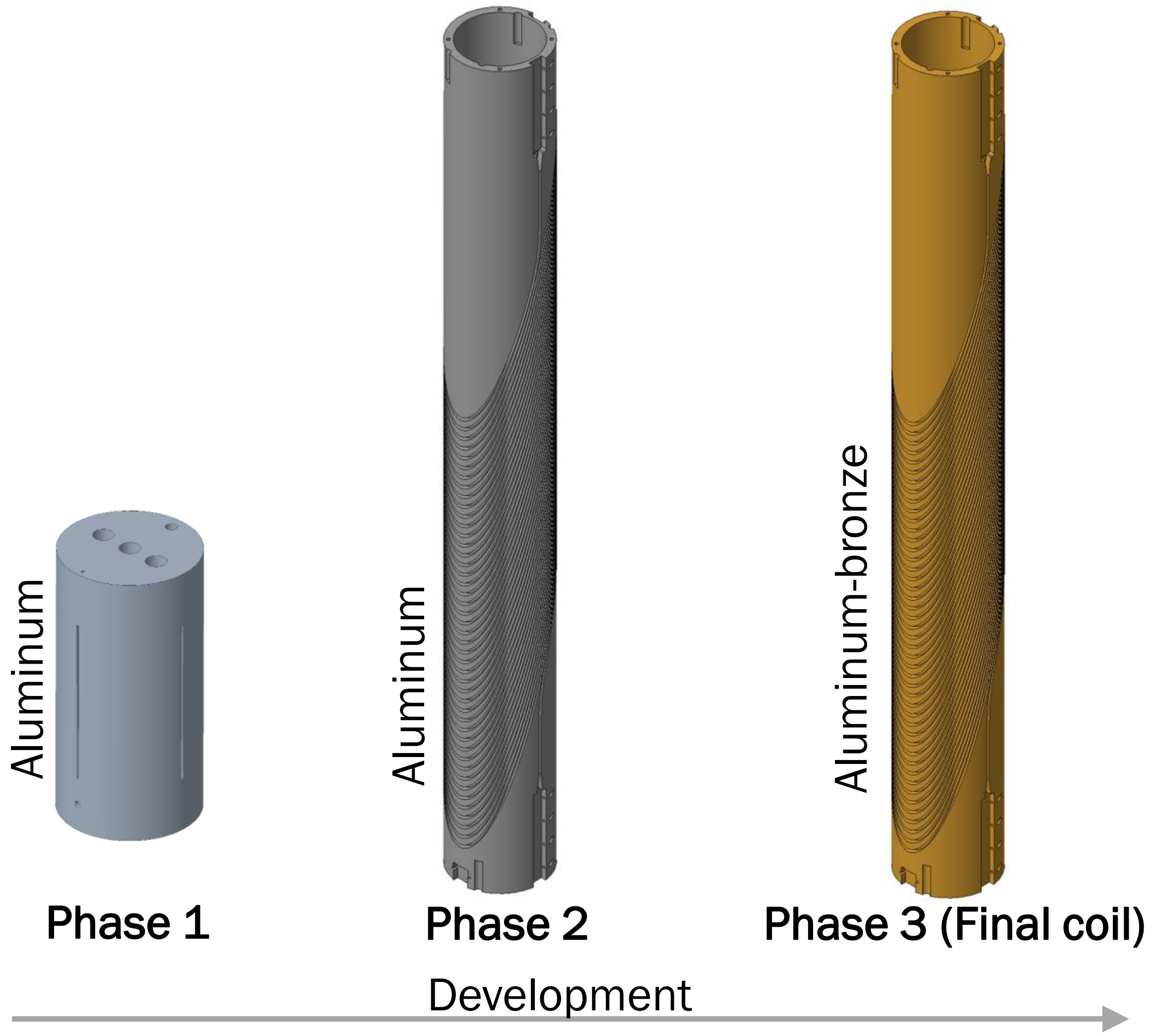
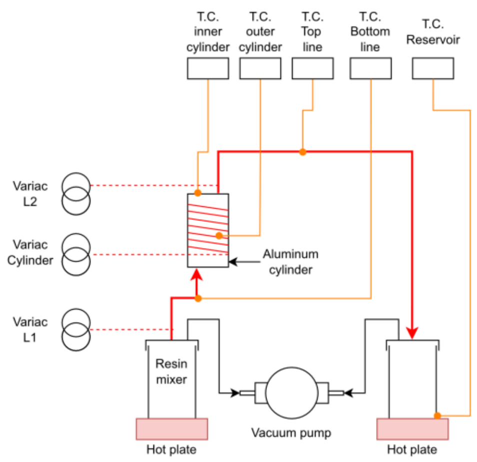
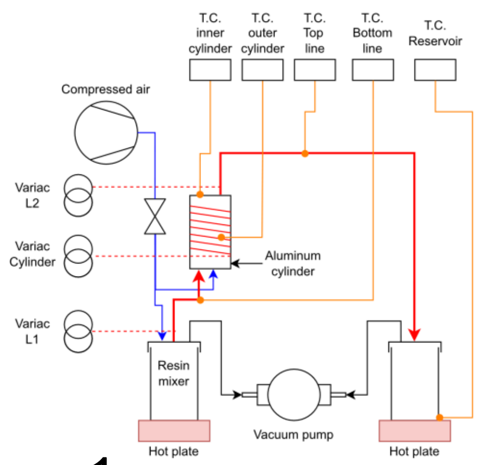


1. Wax impregnation development for CCT coils

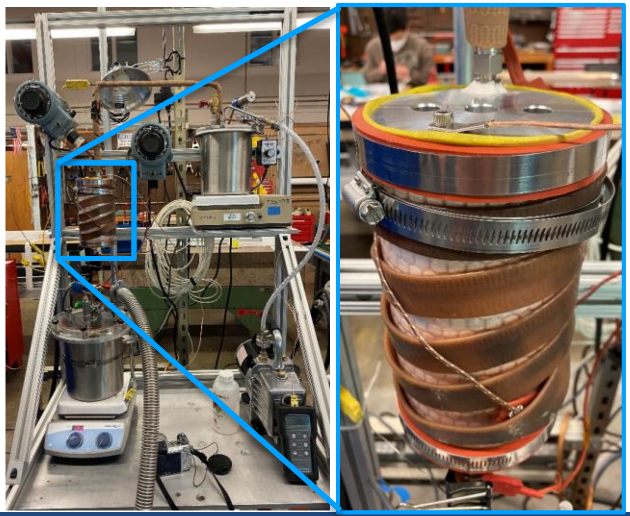
Step 1



Step 2

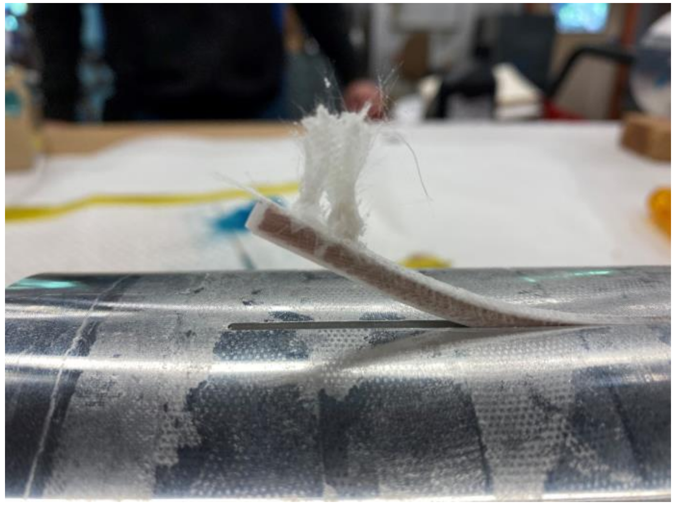


Phase 1



Results of Phase 1

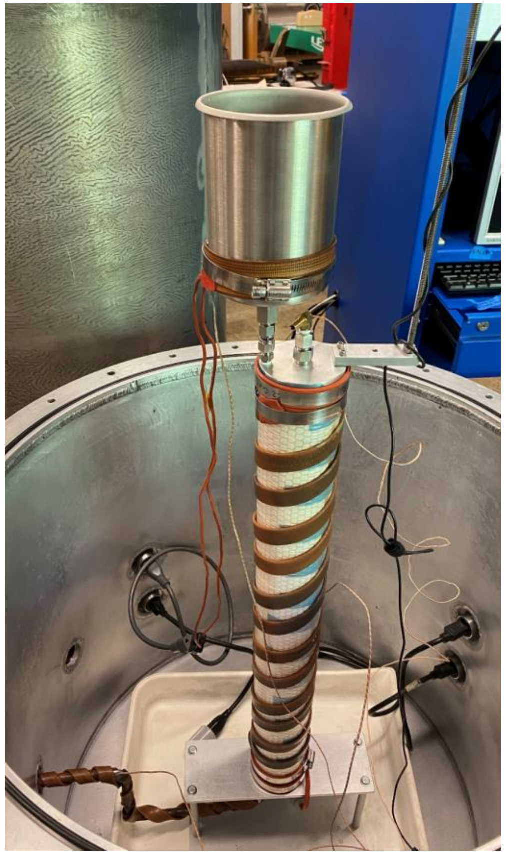
1. Filling of the grooves and cable seem successful.
2. The exhibited bonding strength between the filled cable and the aluminum mandrel was very low.



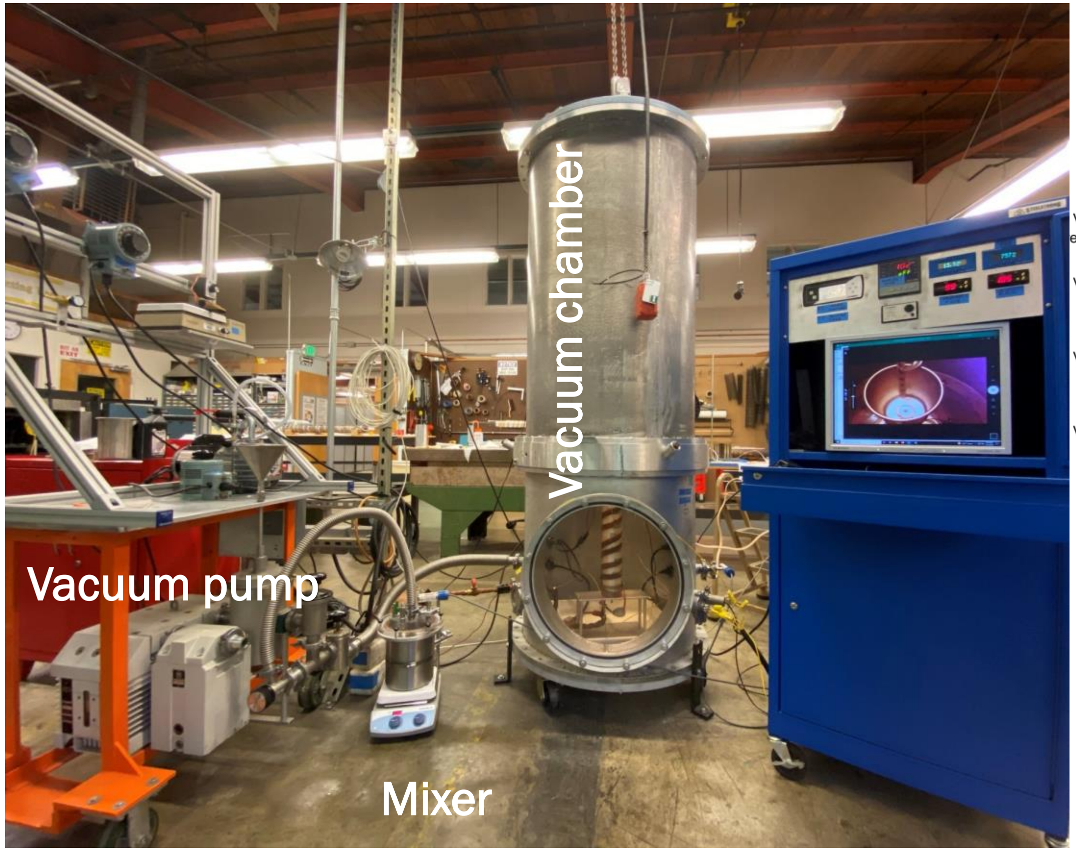
1. Wax impregnation development for CCT coils

Phase 2 – Iteration 1

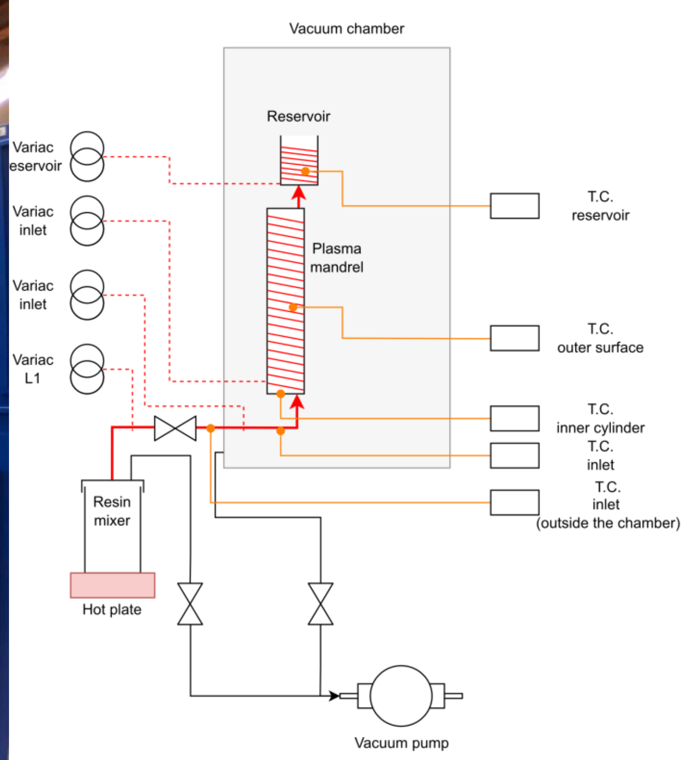
Aluminum (subscale outer-layer)



Main set-up



Step 1



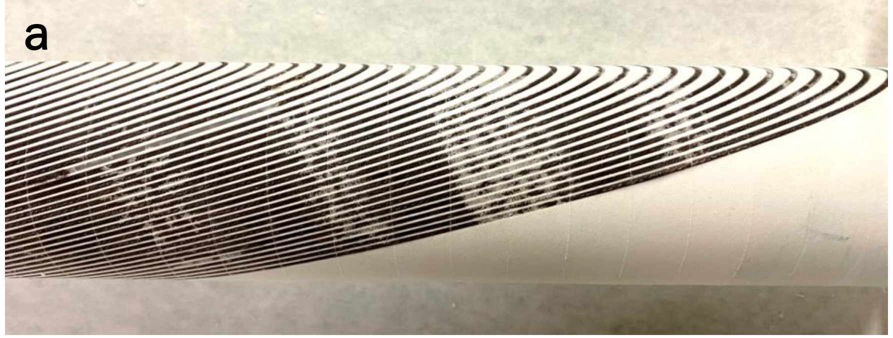
1. Wax impregnation development for CCT coils

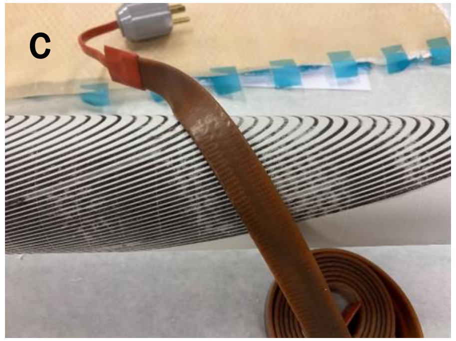
Phase 2 – Iteration 1

Step 2 - pressurization

Results of Phase 2 – Iteration 1

a. Overall filling of the grooves and cable seem successful.
b. Voids detected in the region of the connection to the reservoir.
c. There seems to be a non-uniform flow and solidification pattern along with the coil due to the non-homogenous temperature on the coil's outer surface.





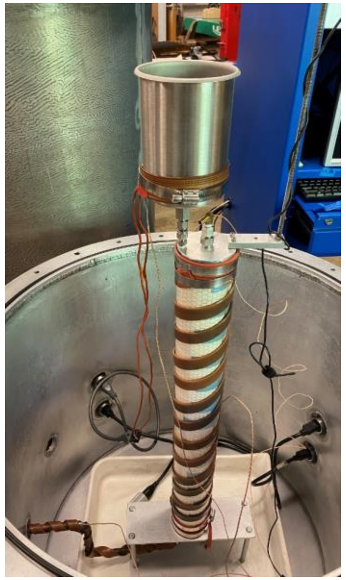
1. Wax impregnation development for CCT coils

Phase 2 – Iteration 2 and 3

Additional developments

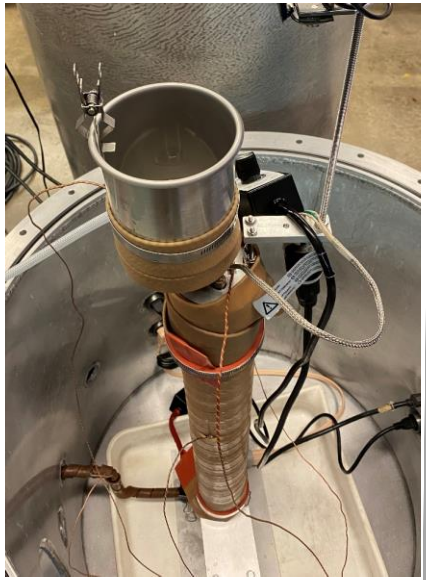
Improved heating system for higher temperature uniformity

Iteration 1



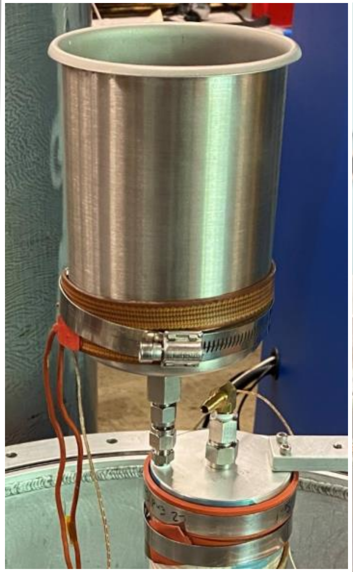
Iteration 2

Iteration 3

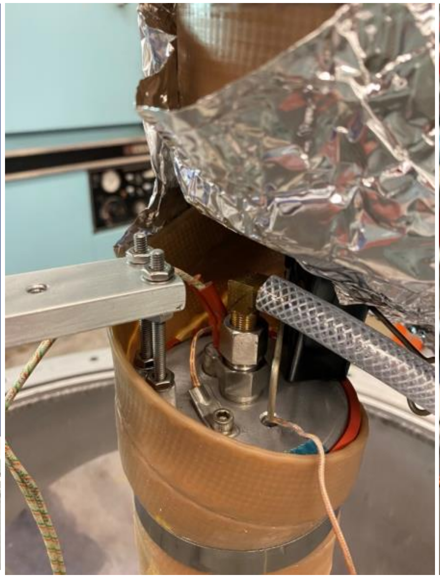


Additional TC, new heating elements, guided air flow and new design of connection from the coil to reservoir

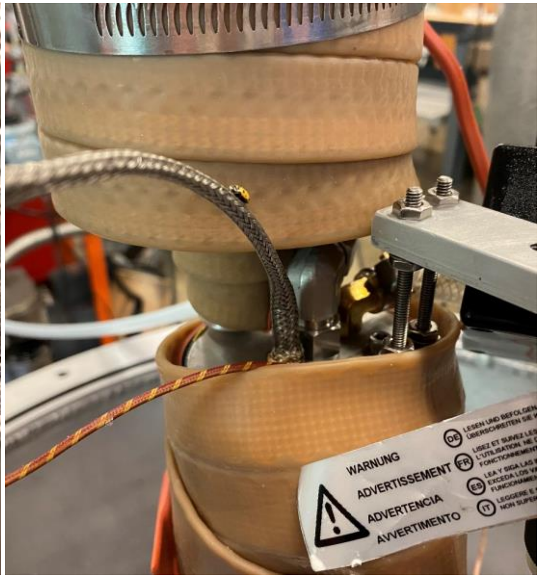
Iteration 1



Iteration 2



Iteration 3



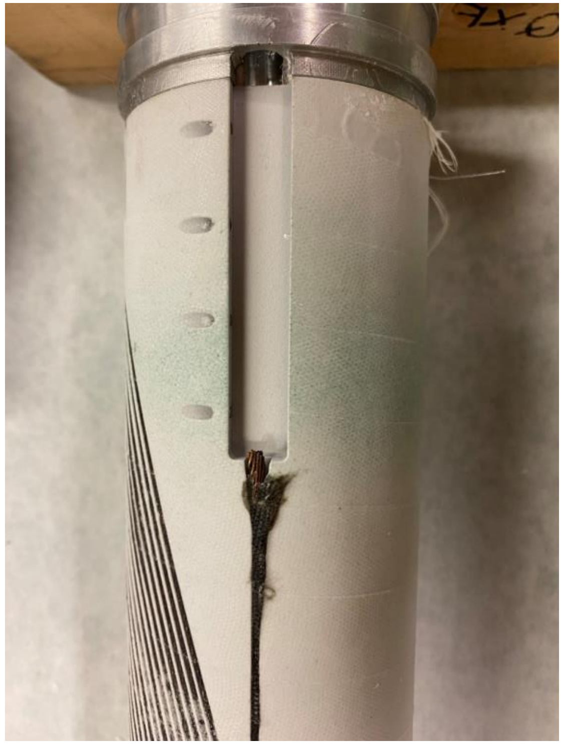
1. Wax impregnation development for CCT coils

Phase 2 – Iteration 2 and 3

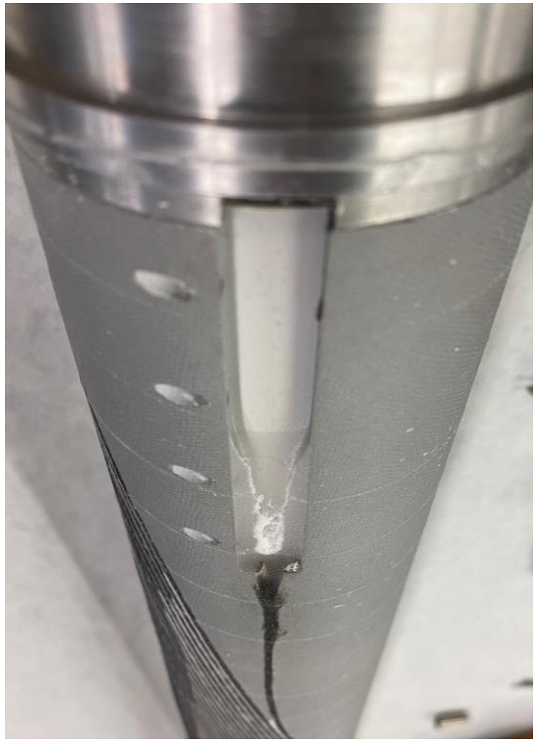
Results

1. The overall filling of the grooves and cable seem to be improved.
2. The incremental improvements in the set-up lead to the complete filling of all the main cavities.
3. The higher temperature uniformity led to a uniform flow of wax along the outer surface of the mandrel.

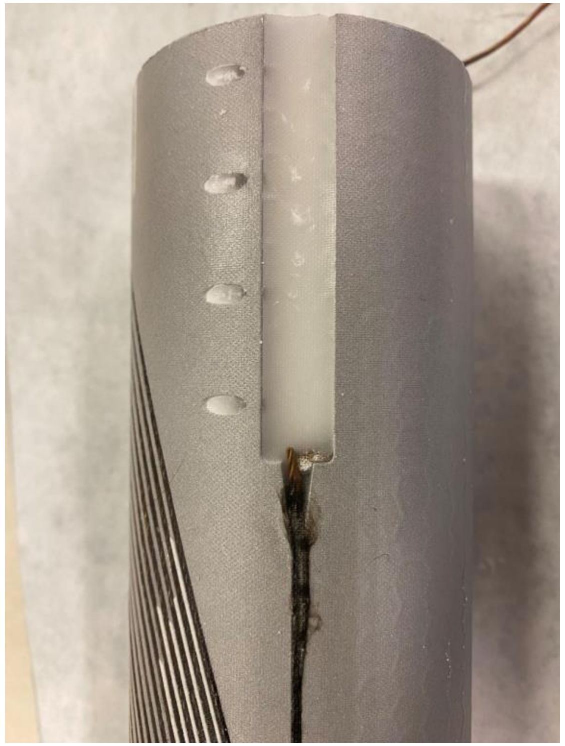
Iteration 1



Iteration 2



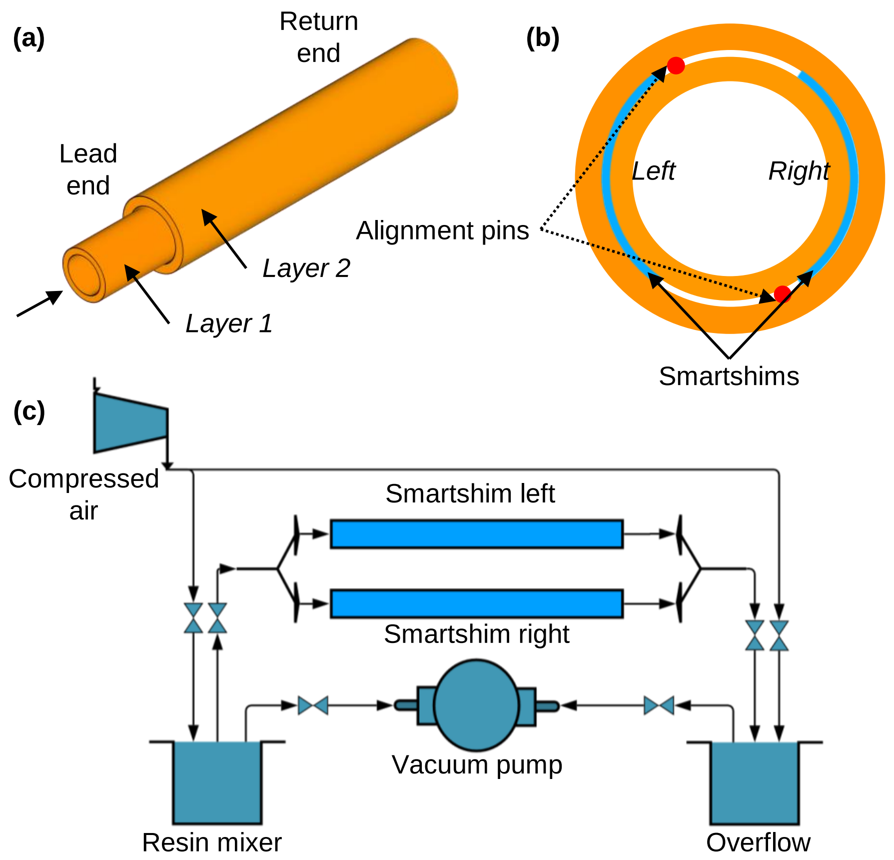
Iteration 3

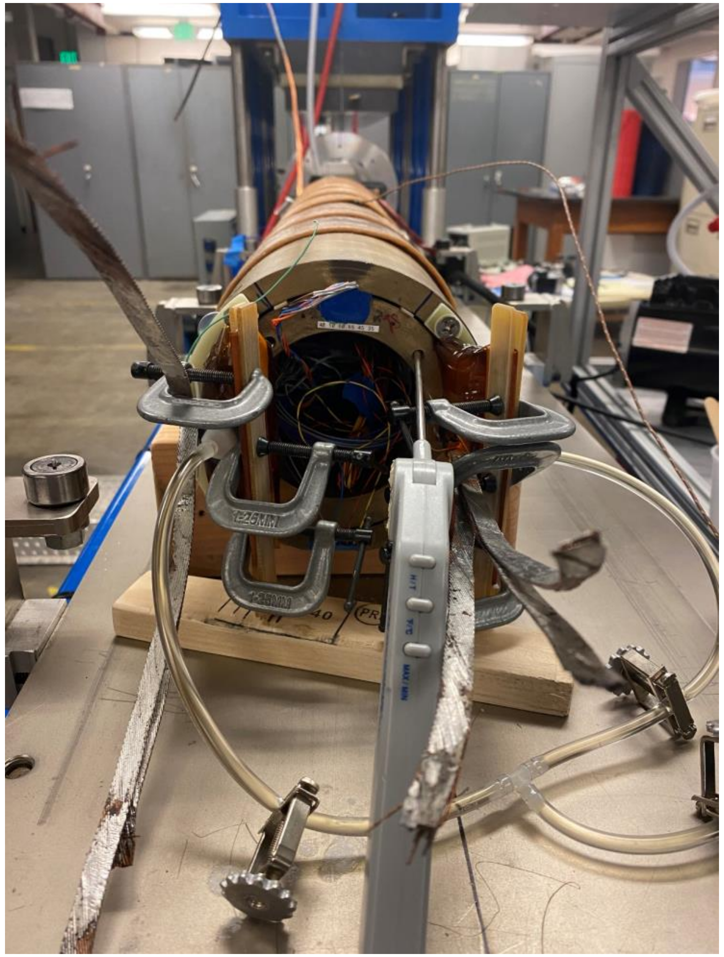


2. Re-assembly of CCT 5

New VPI system for smartshims used in CCT 5

Smartshims layer 1 to layer 2

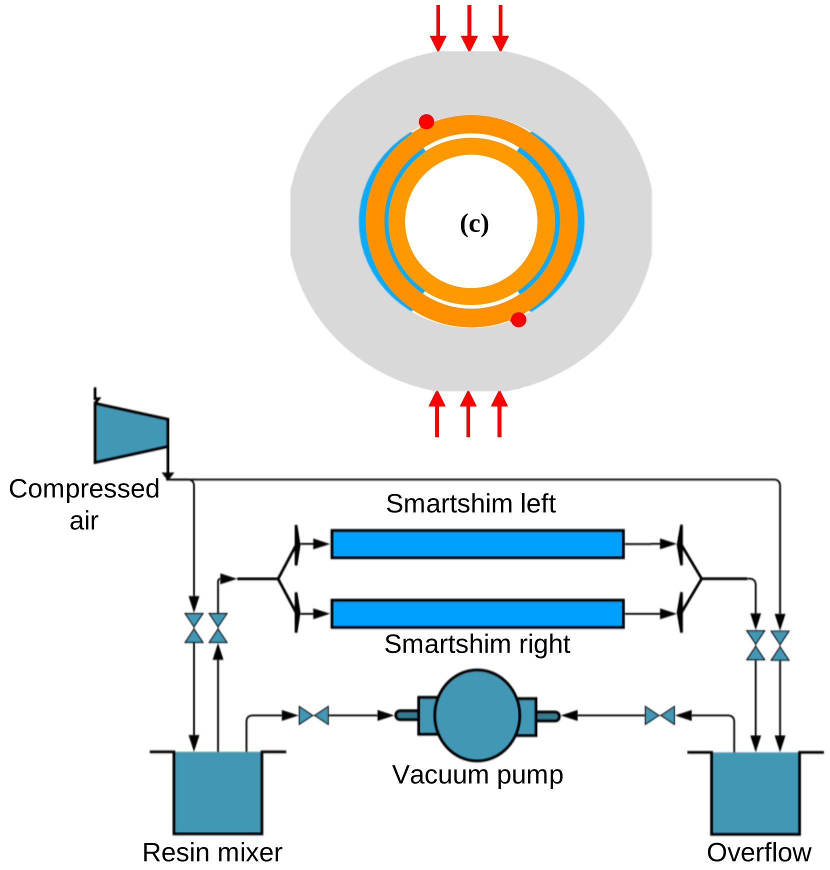


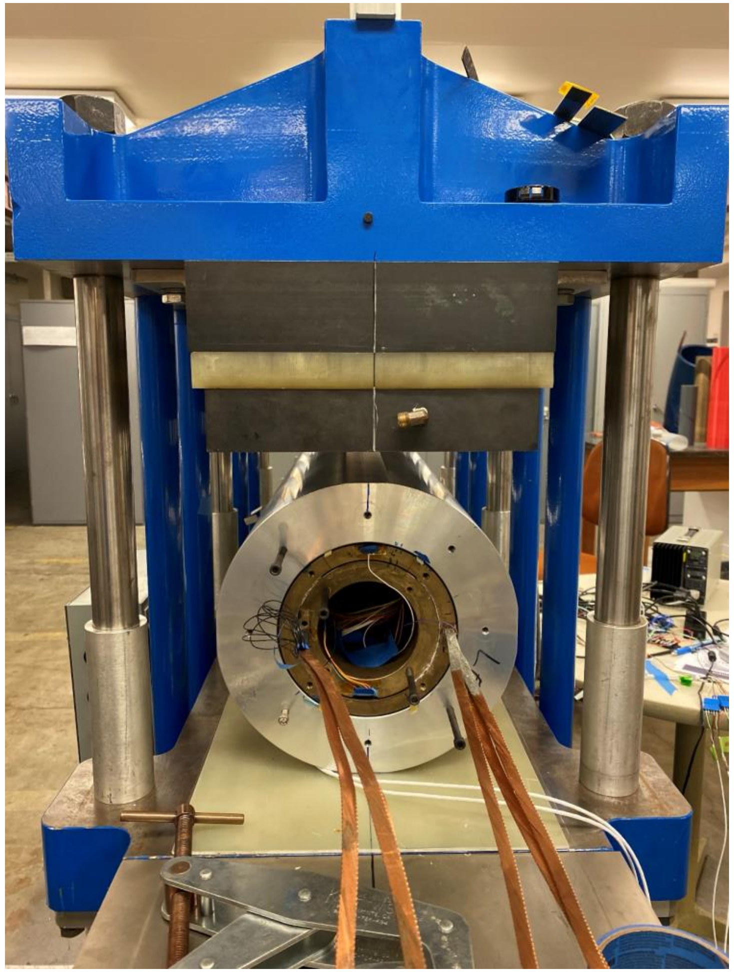


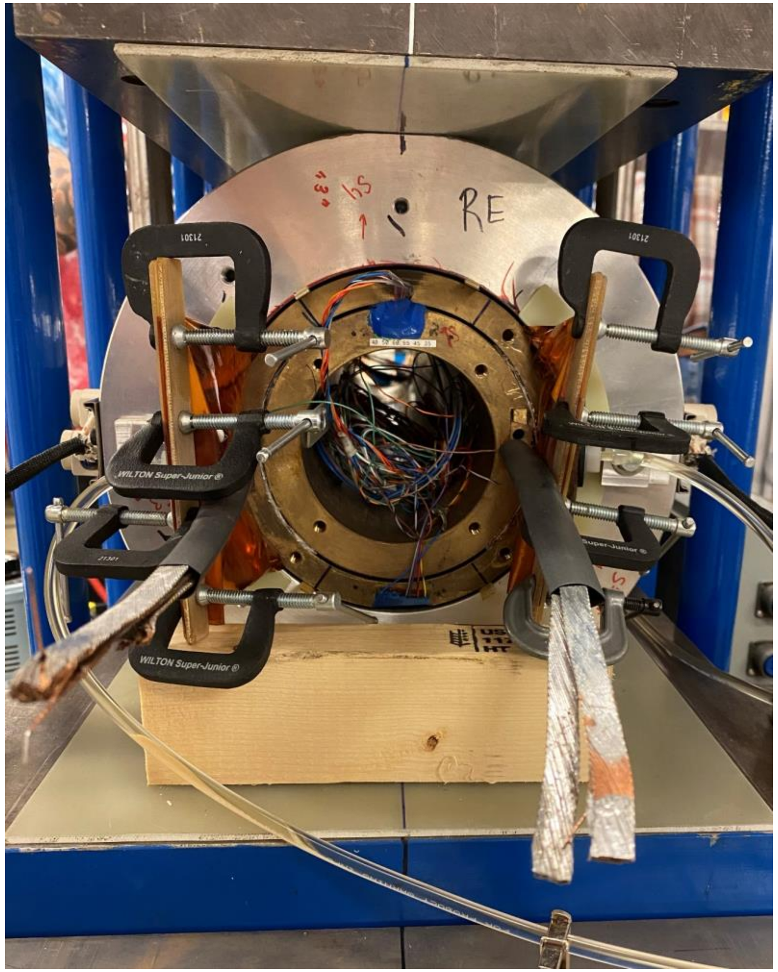
2. Re-assembly of CCT 5

New VPI system for smartshims used in CCT 5

Smartshims layer 2 to shell







3. Conclusions

- The new VPI system developed for paraffin wax, has successfully impregnated a test subscale mandrel after iterative improvements of the process.
- The coil L1F is currently being prepared for wax impregnation, which will form CCT sub5.
- The re-assembly of CCT 5 magnet is being finalized.

Rudeiros-Fernandez, J. L., Arbelaez, D., Brouwer, L., Caspi, S., Ferracin, P., Hafalia, R., Krutulis, M., Prestemon, S., Reynolds, M., Shen, T., Swanson, J., & Vallone, G. (2021). Assembly and Mechanical Analysis of the Canted-Cosine-Theta Subscale Magnets. *Submitted for Publication at the MT27*.

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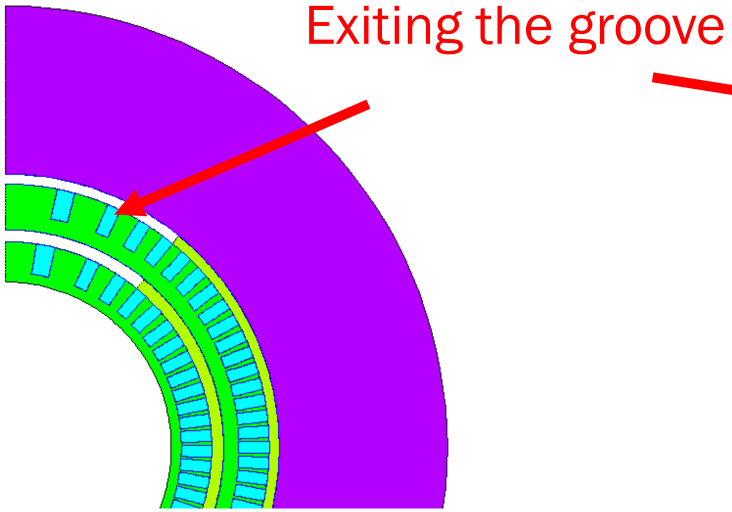
CCT Wax Subscale Shim Analysis

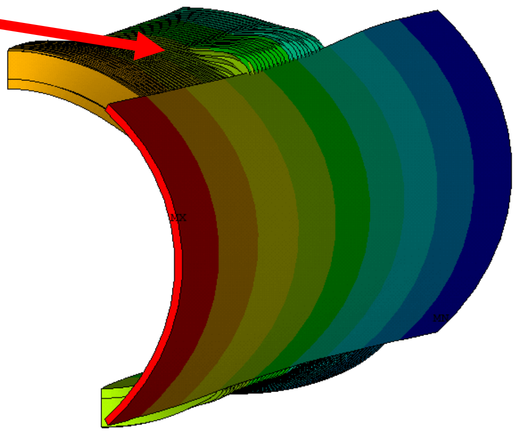
G. Vallone

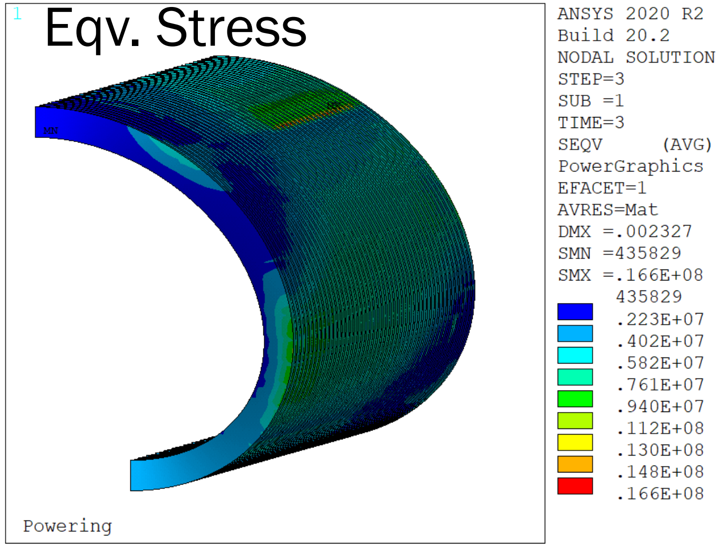
Lawrence Berkeley National Laboratory

Subscale 3D Model - Debonded Coil Motion

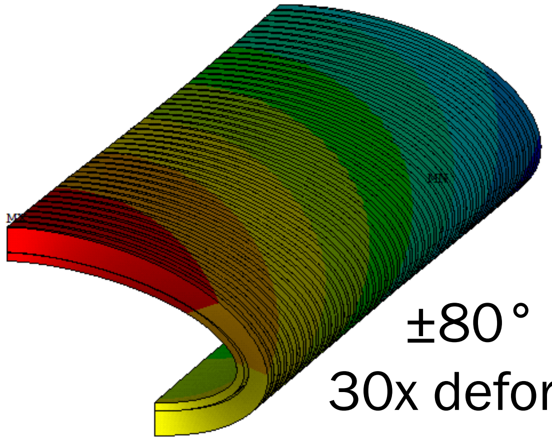


±60° Shim
30x deformations





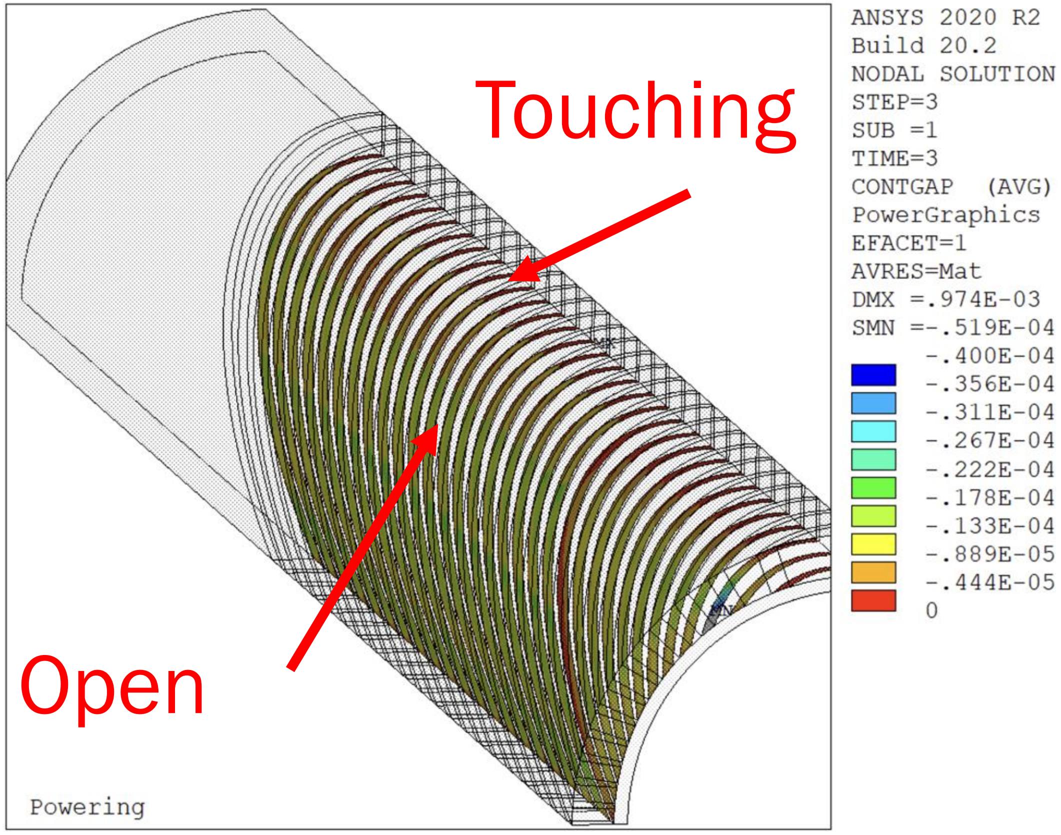
- 2D FE model show that the cables not covered by the interlayer shim fly away unless constrained.
  - However, this model does not include the 3D cable mechanics
- 3D model result shows that the cable does not fly away
  - It does move out a bit, getting some local shear stresses
  - The effect disappears when increasing the shim angle to 80°
  - Larger shim important for wax impregnation: strands might see large motions and even break under the shear load

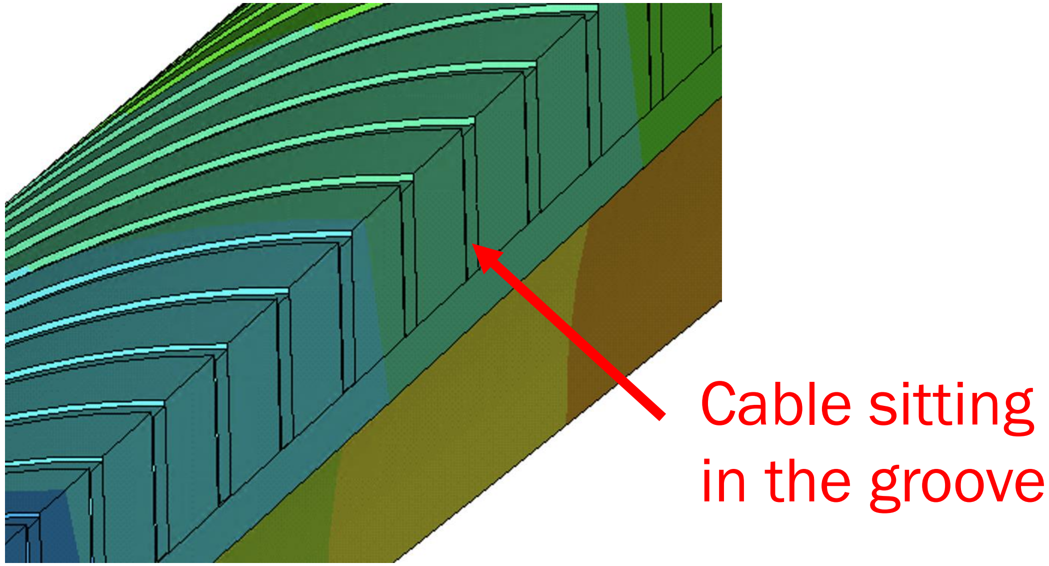


±80° Shim
30x deformations

Wax - 3D Modeling with Contact Elements

Cable/Spar Contact (@5 T)





- The coil is modeled with a 1 GPa modulus
  - An attempt to introduce the low cable rigidity due to internal (strand/strand) debonding.
- Only in a very small region of the magnet (90°) the cable sits on the spar during powering.
  - However, since the cable contracts more after cooldown, it is still not 'coming out' of the groove
  - Not flying away with the 80° shim