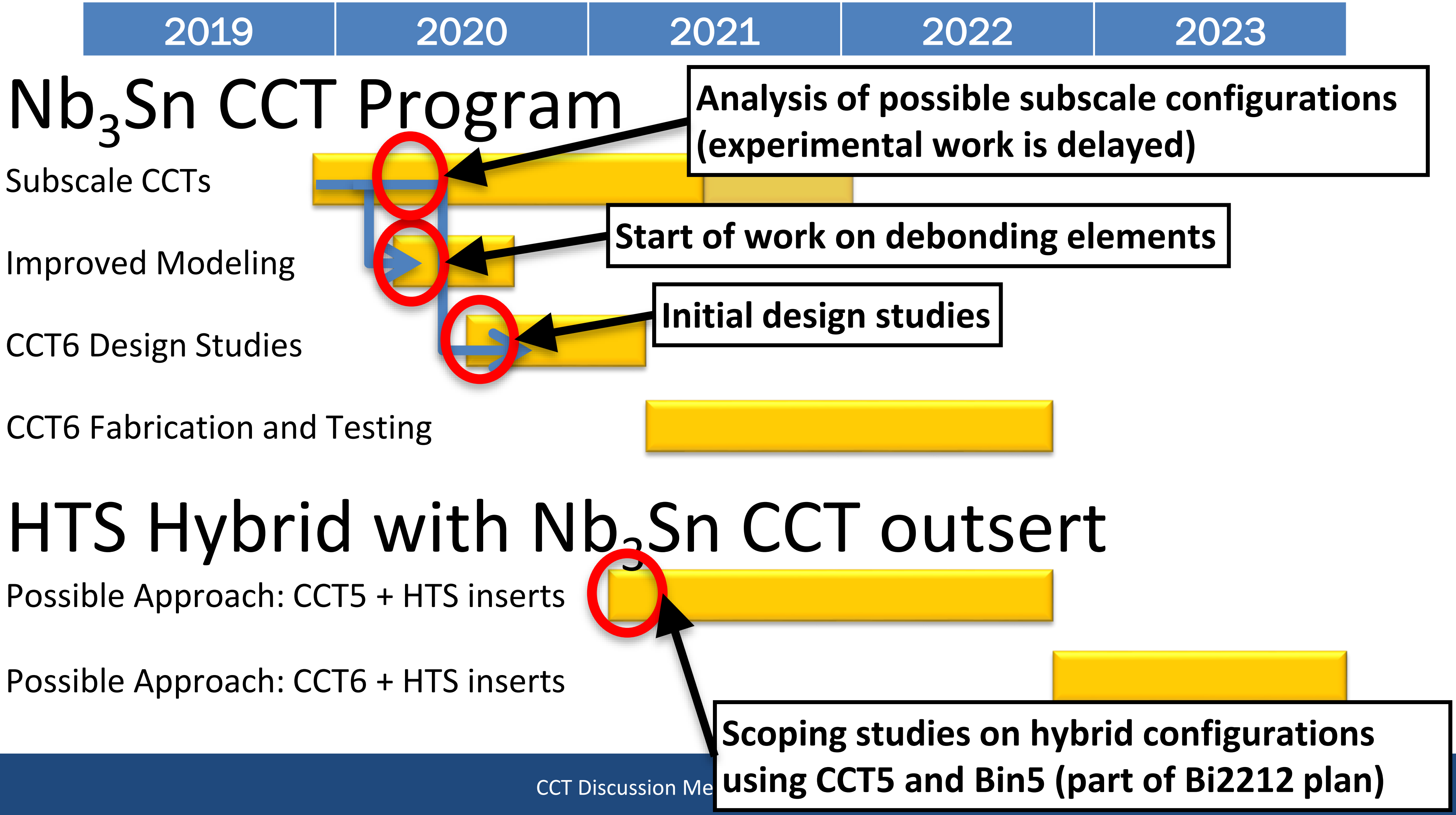
U.S. MAGNET
DEVELOPMENT
PROGRAM

Updates on Nb_3Sn CCT Program

04/29/2020

MDP Wednesday Meeting
US Magnet Development Program

Nb_3Sn CCT Roadmap (Priorities during work-from-home restriction)



Nb_3Sn CCT Program

Subscale CCTs

Improved Modeling

CCT6 Design Studies

CCT6 Fabrication and Testing

Analysis of possible subscale configurations (experimental work is delayed)

Start of work on debonding elements

Initial design studies

HTS Hybrid with Nb_3Sn CCT outsert

Possible Approach: CCT5 + HTS inserts

Possible Approach: CCT6 + HTS inserts

Scoping studies on hybrid configurations using CCT5 and Bin5 (part of Bi2212 plan)

Agenda

- Initial design studies for CCT6 (Lucas)
- Analysis of possible CCT5/Bin5 hybrid configuration (Laura and Diego)
- Updates on subscale status and plans (Diego)

CCT 6 Analysis

L. Brouwer

Introduction

1. study short-sample scaling using Nb_3Sn CCT designs with a range of:
   - 2 layers, 4 layers
   - 1.9 K, 4.5 K
   - 10 mm, 15 mm, 20 mm cable width

2. selection of first two and four layers designs for more detailed study:
   - short-sample with grading of the outer layers
   - first mechanical study leading to initial stress estimation

Initial assumptions for the short-sample study are based on CCT5

Conductor

- strand diameter = 0.85 mm (same as CCT5)
- non-cu = 1/(1.18+1) = 0.46

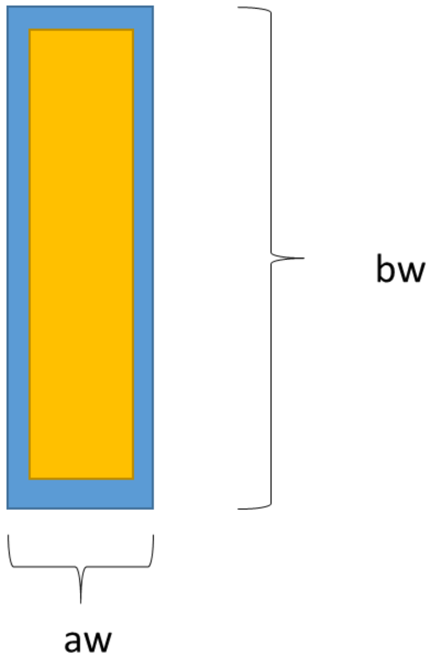
Cable/Channel

- same insulation thickness as CCT5
- channel width same as CCT5
- cable width the same as CCT5
- cable height is scaled by number of strands

Magnet

- 3 mm spar size per layer
- 120 mm clear bore

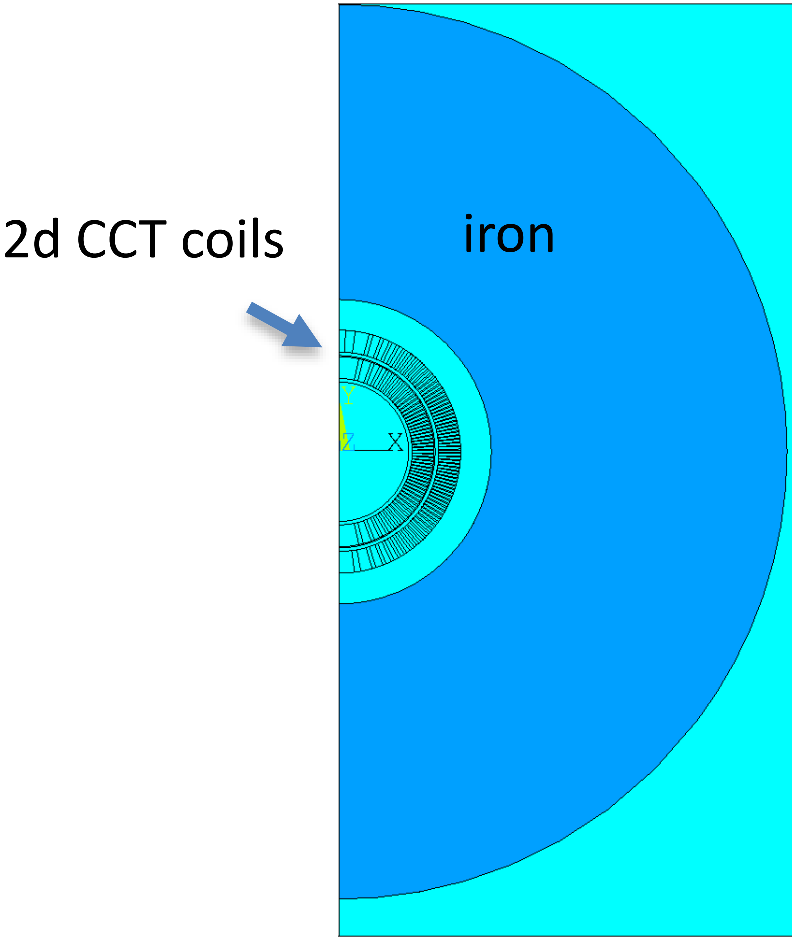
# strands	aw-cable	bw-cable	aw-channel	bw-channel
21	1.5	9.85	2.1	11.0
32	1.5	15.01	2.1	16.2
42	1.5	19.70	2.1	20.9



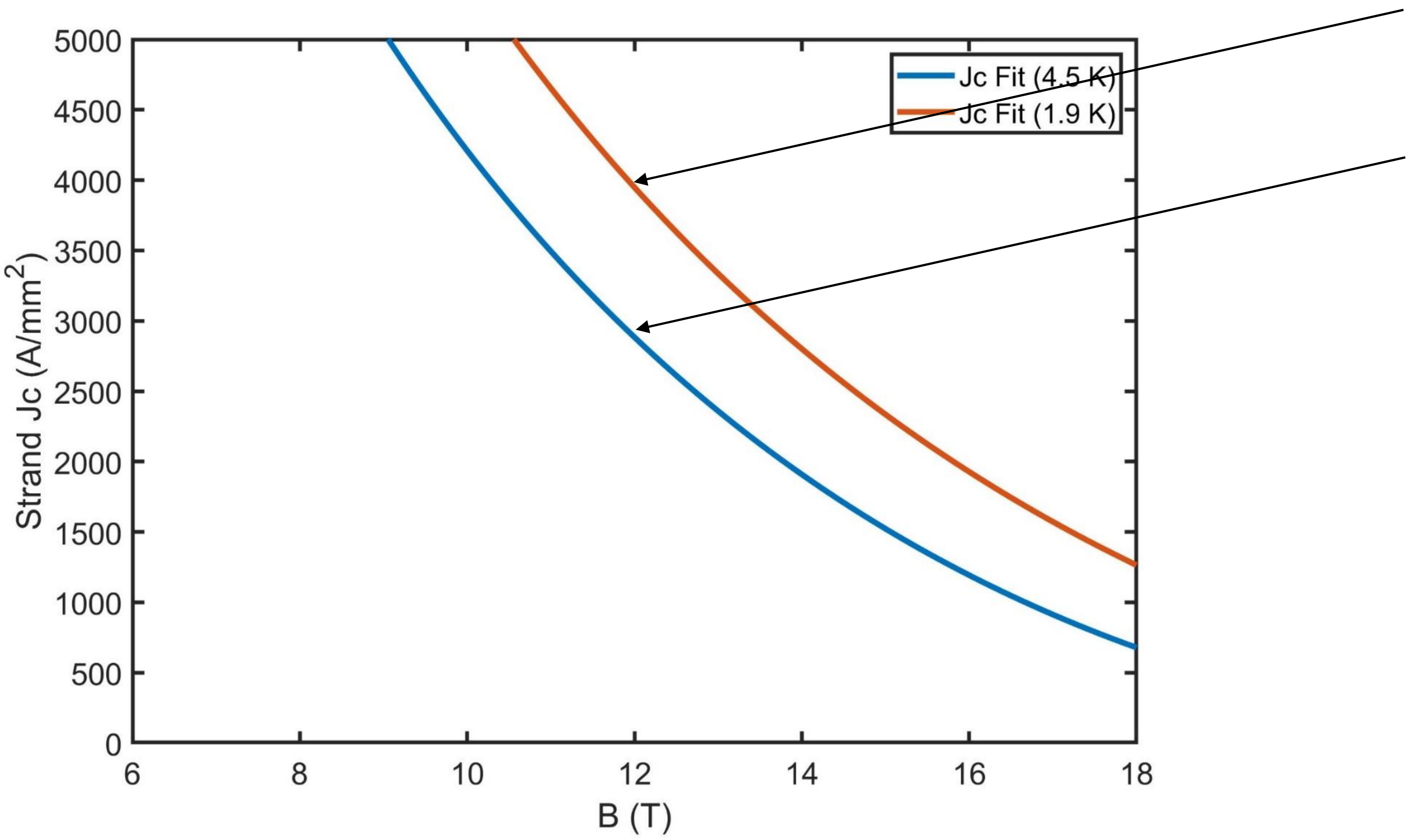
All fields come from 2D ANSYS models using 10” ring of iron

Assumptions for short-sample field at conductor

- Peak conductor field on layer 1,2: assumed to be 5% greater than aperture dipole
- Peak conductor field on layer 3,4: assumed to be peak field at layer 3 conductor ID at pole



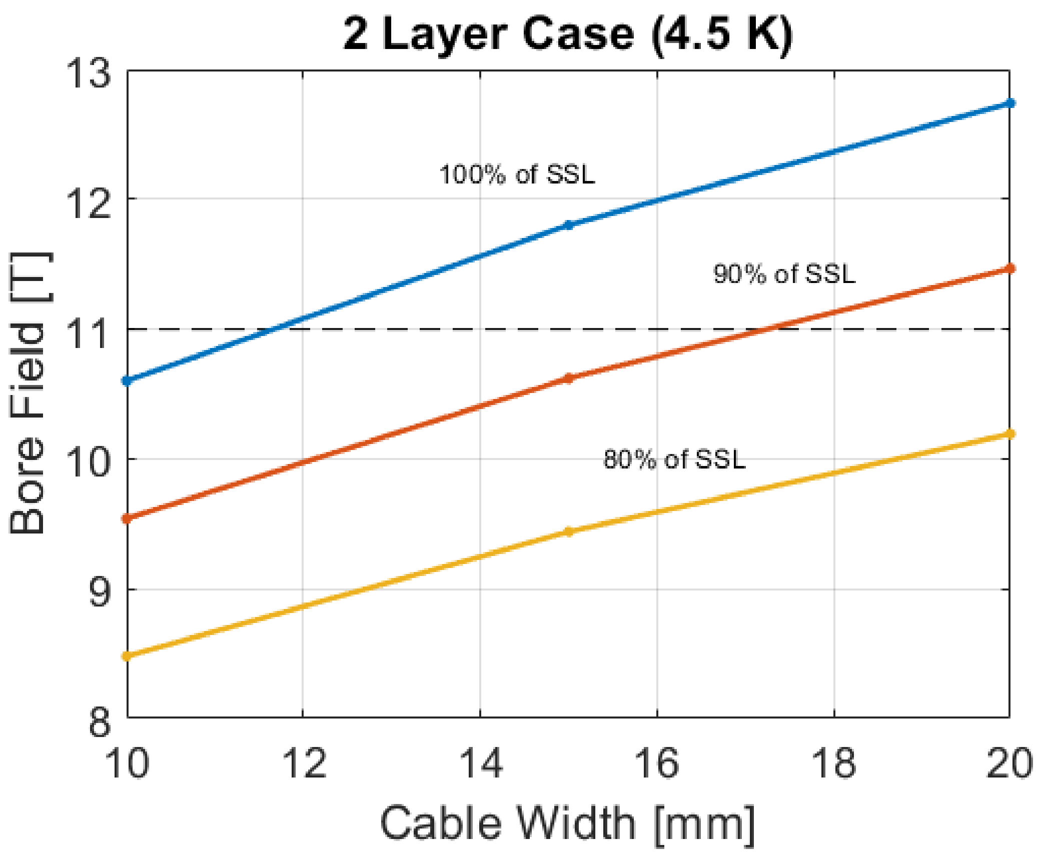
Nb_3Sn non-cu Jc fit assumed

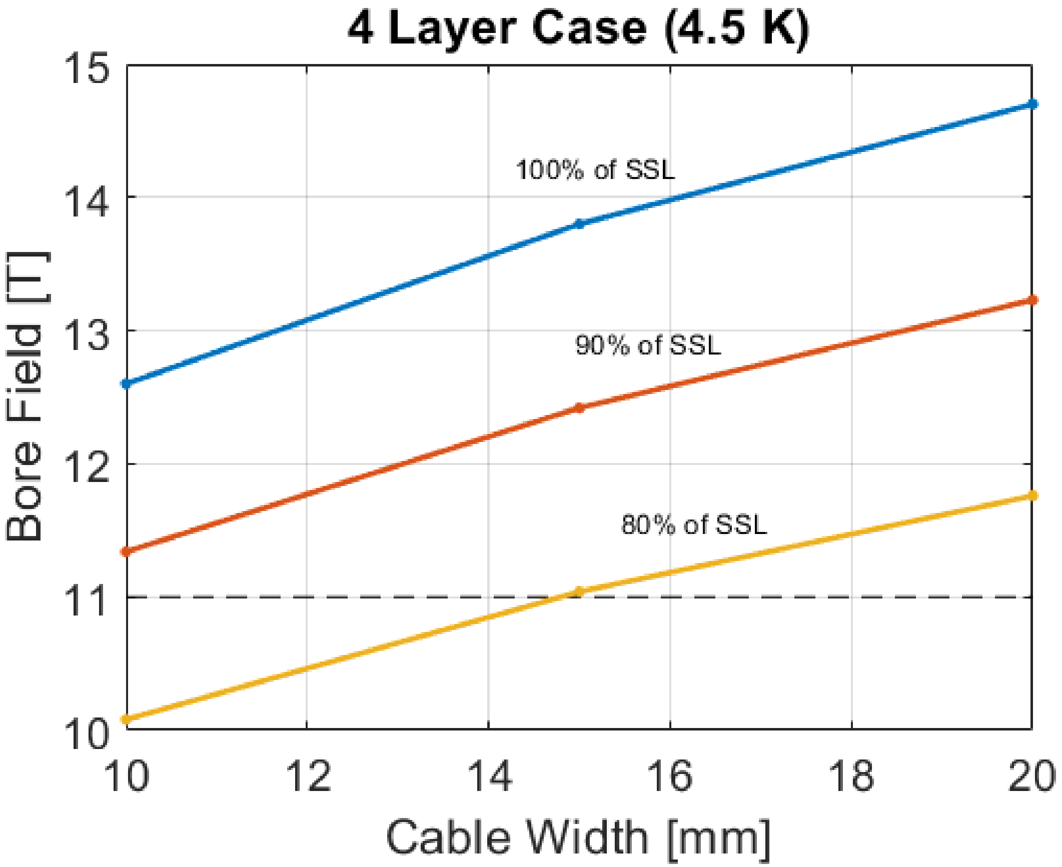


3950 A/mm^2 at 12 T, 1.9 K

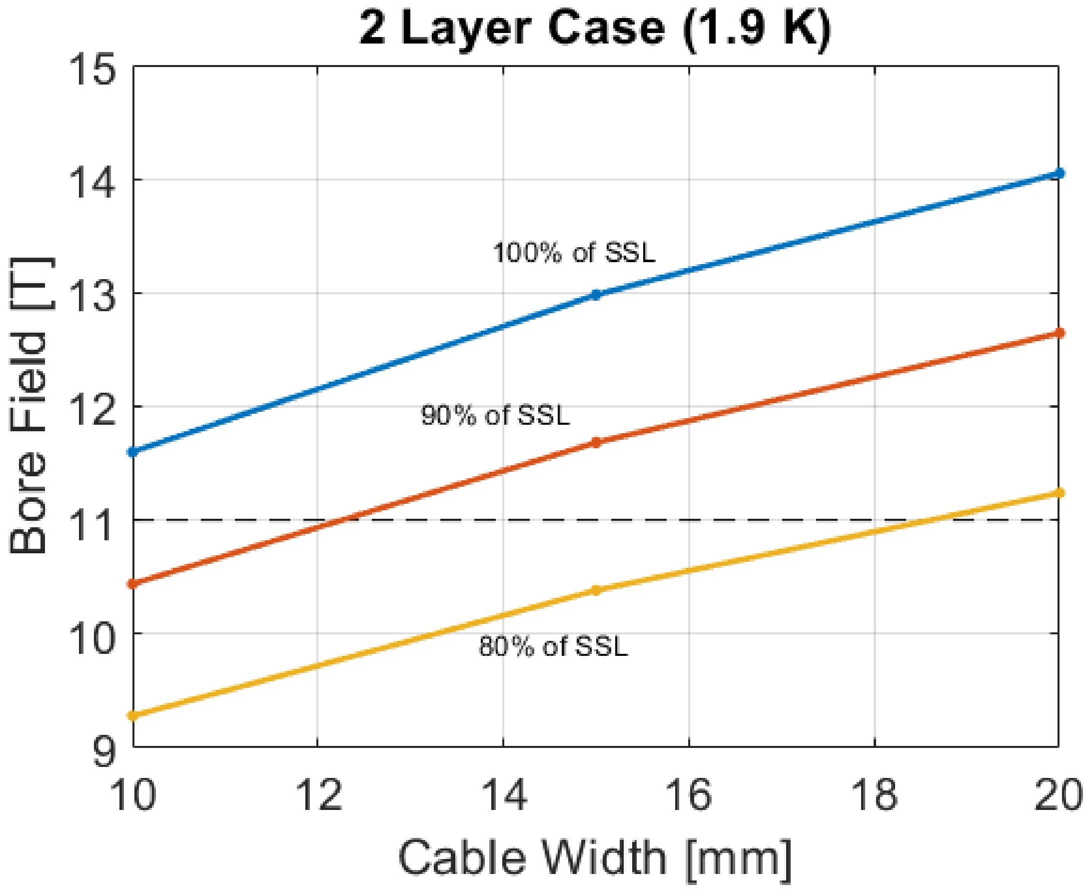
2880 A/mm^2 at 12 T, 4.5 K

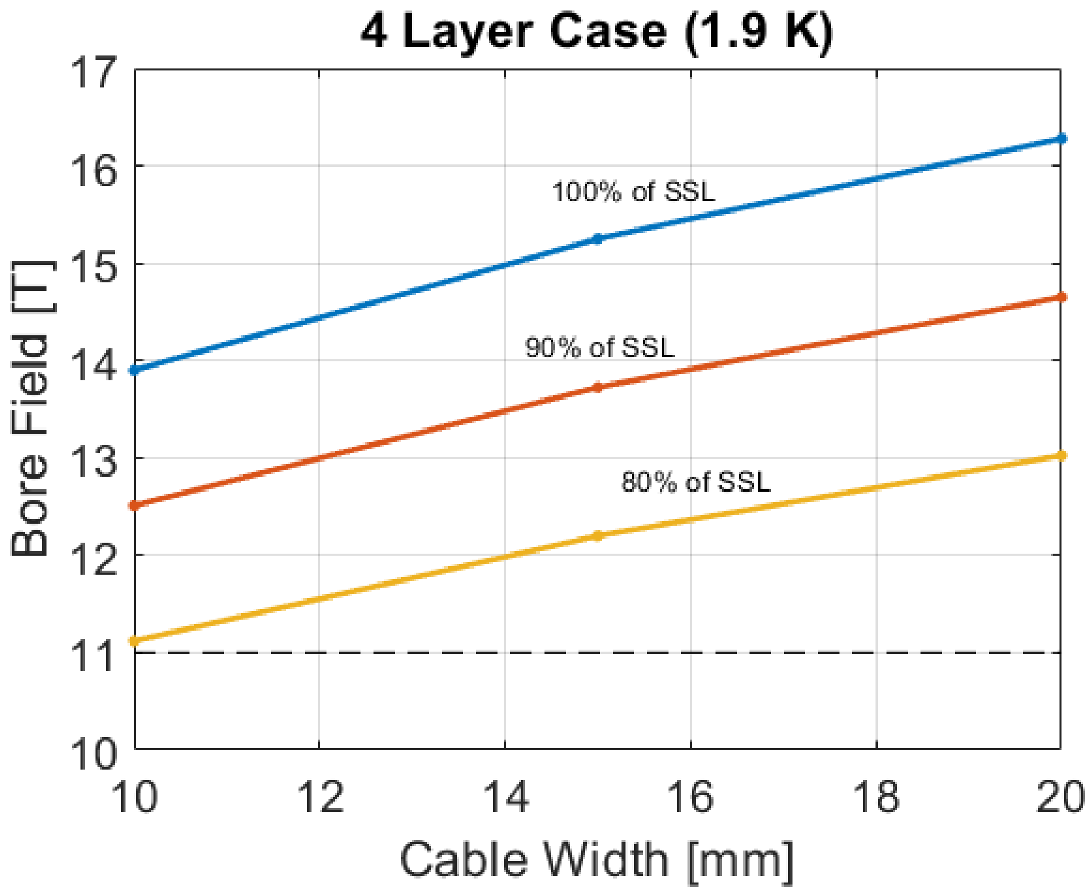
Short-Sample Results for 4.5 K



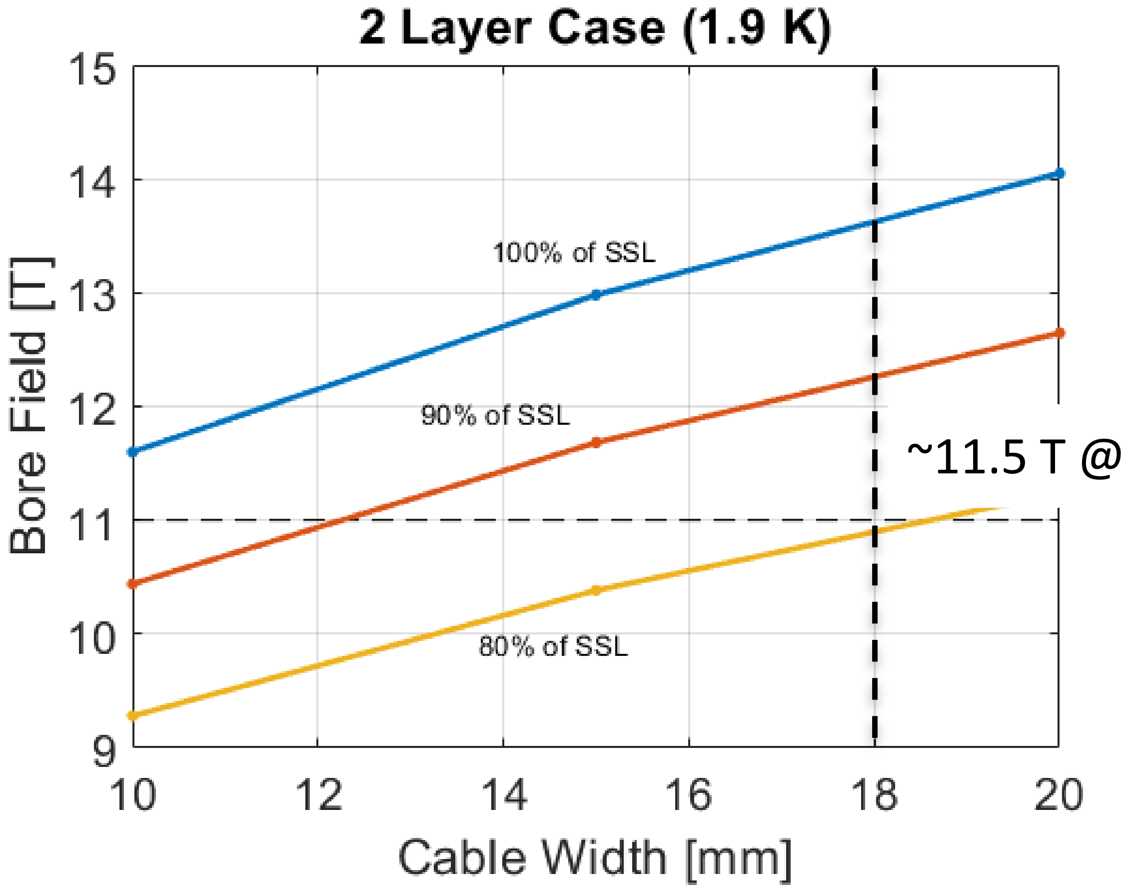


Short-Sample Results for 1.9 K

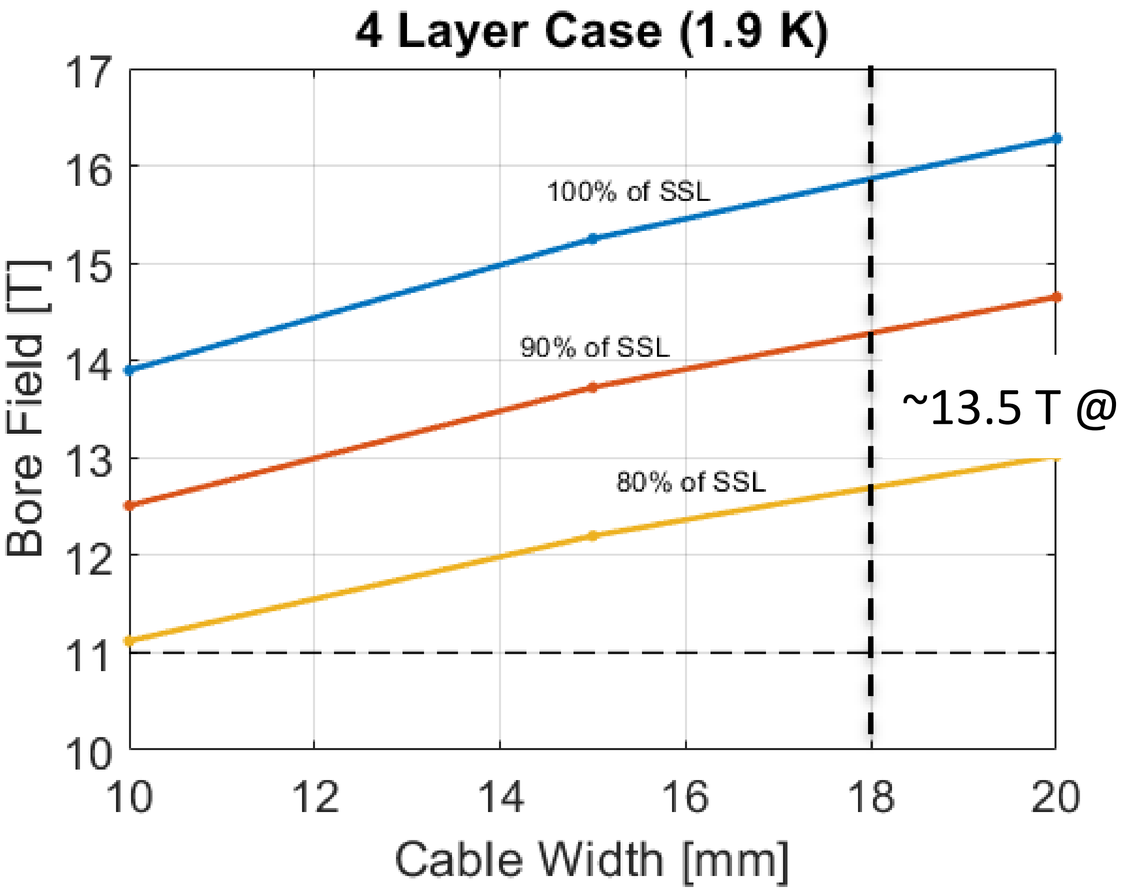




Selection of an 18 mm cable for a first, more detailed study


2 Layer Case (1.9 K)

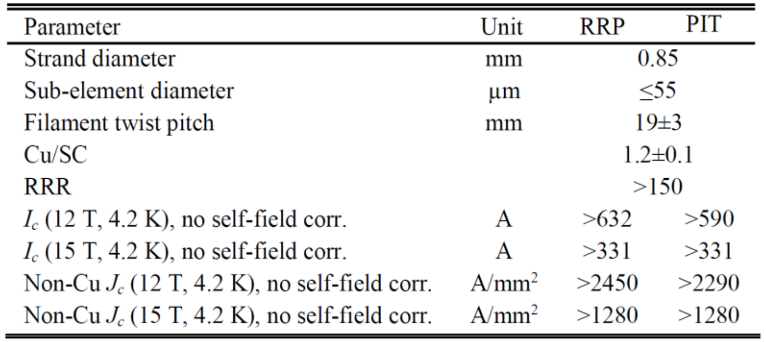
~11.5 T @ 85%


4 Layer Case (1.9 K)

~13.5 T @ 85%

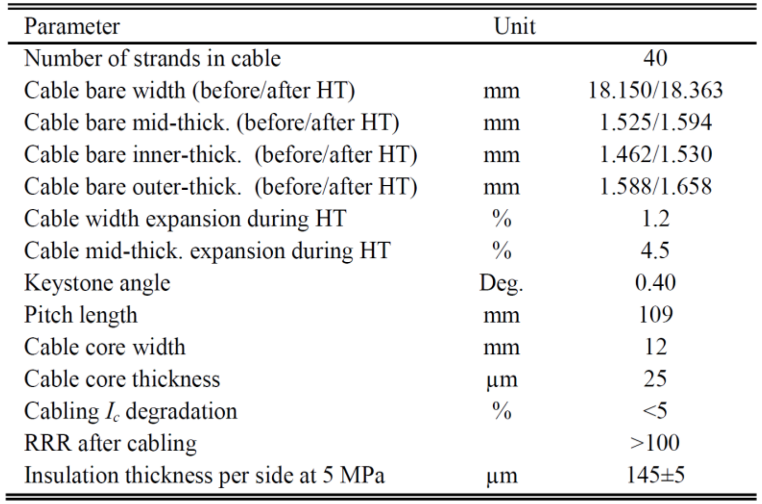
Choose the existing MQXF cable which is close to the ~18 mm width pointed to by the initial short-sample study

TABLE I
STRAND SPECIFICATIONS



Parameter	Unit	RRP	PIT
Strand diameter	mm	0.85	
Sub-element diameter	µm	≤55	
Filament twist pitch	mm	19±3	
Cu/SC		1.2±0.1	
RRR		>150	
I_c (12 T, 4.2 K), no self-field corr.	A	>632	>590
I_c (15 T, 4.2 K), no self-field corr.	A	>331	>331
Non-Cu J_c (12 T, 4.2 K), no self-field corr.	A/mm^2	>2450	>2290
Non-Cu J_c (15 T, 4.2 K), no self-field corr.	A/mm^2	>1280	>1280

TABLE II
CABLE SPECIFICATIONS

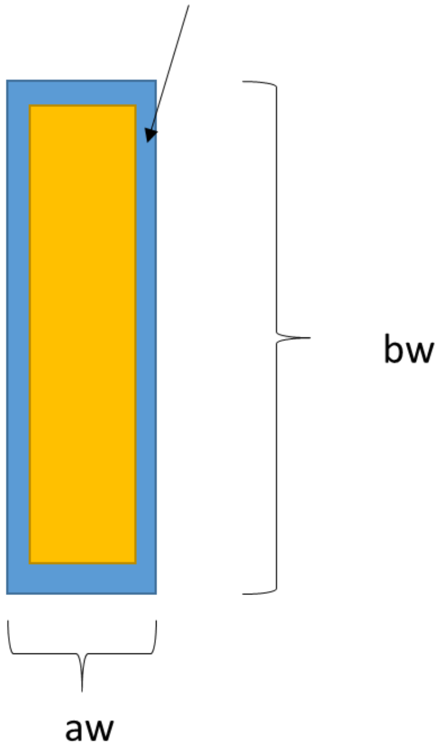


Parameter	Unit	
Number of strands in cable		40
Cable bare width (before/after HT)	mm	18.150/18.363
Cable bare mid-thick. (before/after HT)	mm	1.525/1.594
Cable bare inner-thick. (before/after HT)	mm	1.462/1.530
Cable bare outer-thick. (before/after HT)	mm	1.588/1.658
Cable width expansion during HT	%	1.2
Cable mid-thick. expansion during HT	%	4.5
Keystone angle	Deg.	0.40
Pitch length	mm	109
Cable core width	mm	12
Cable core thickness	µm	25
Cabling I_c degradation	%	<5
RRR after cabling		>100
Insulation thickness per side at 5 MPa	µm	145±5

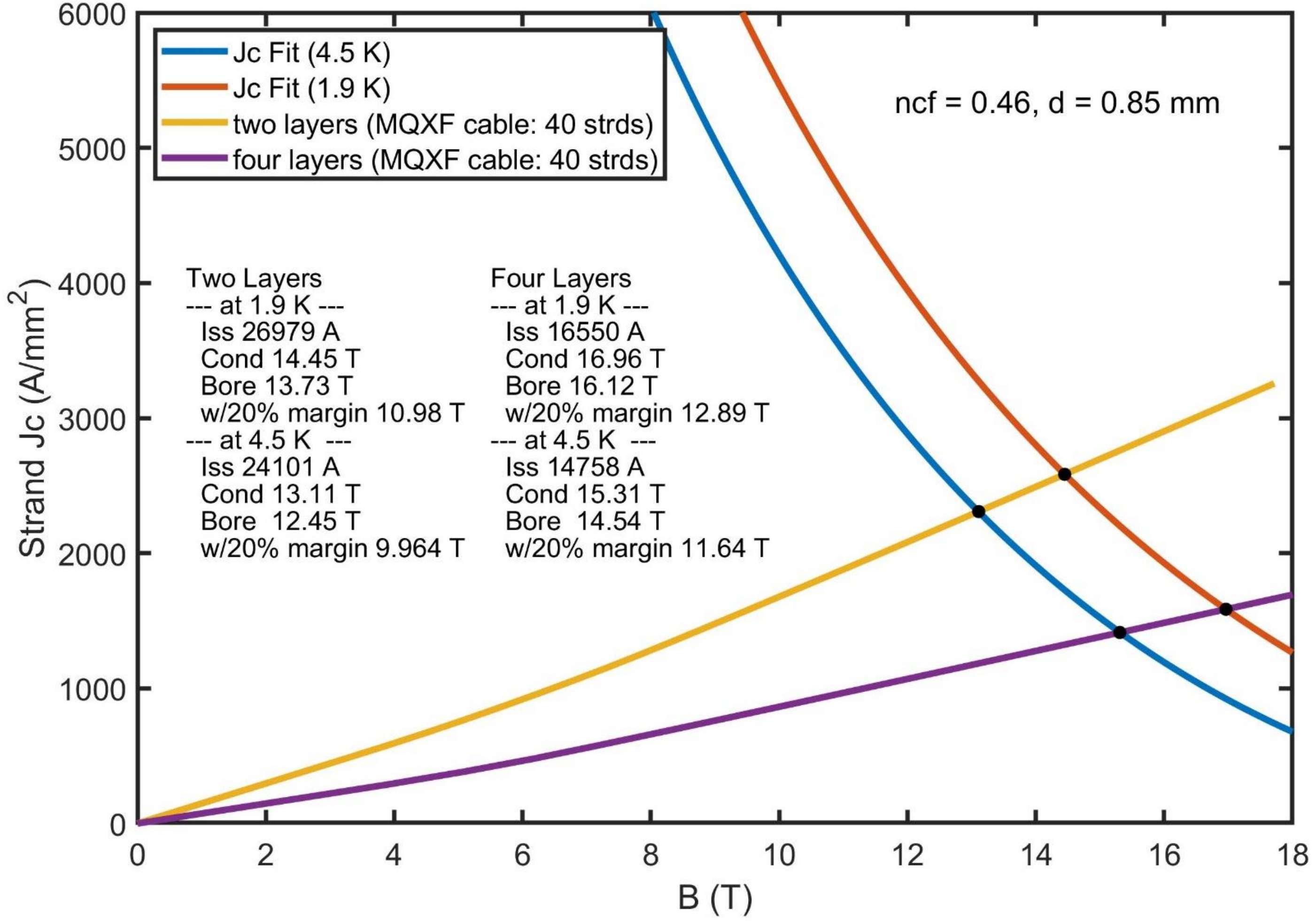
strand dia.	0.85
Cu/Sc	1.2
strands	40

bw_cable	18.2
bw_channel	18.8
aw_cable	1.5
aw_channel	2.1

Keystone removed


The large amount of insulation/space around the cable is the main source of inefficiently (0.3 mm on each side)

Short-sample using the MQXF cable



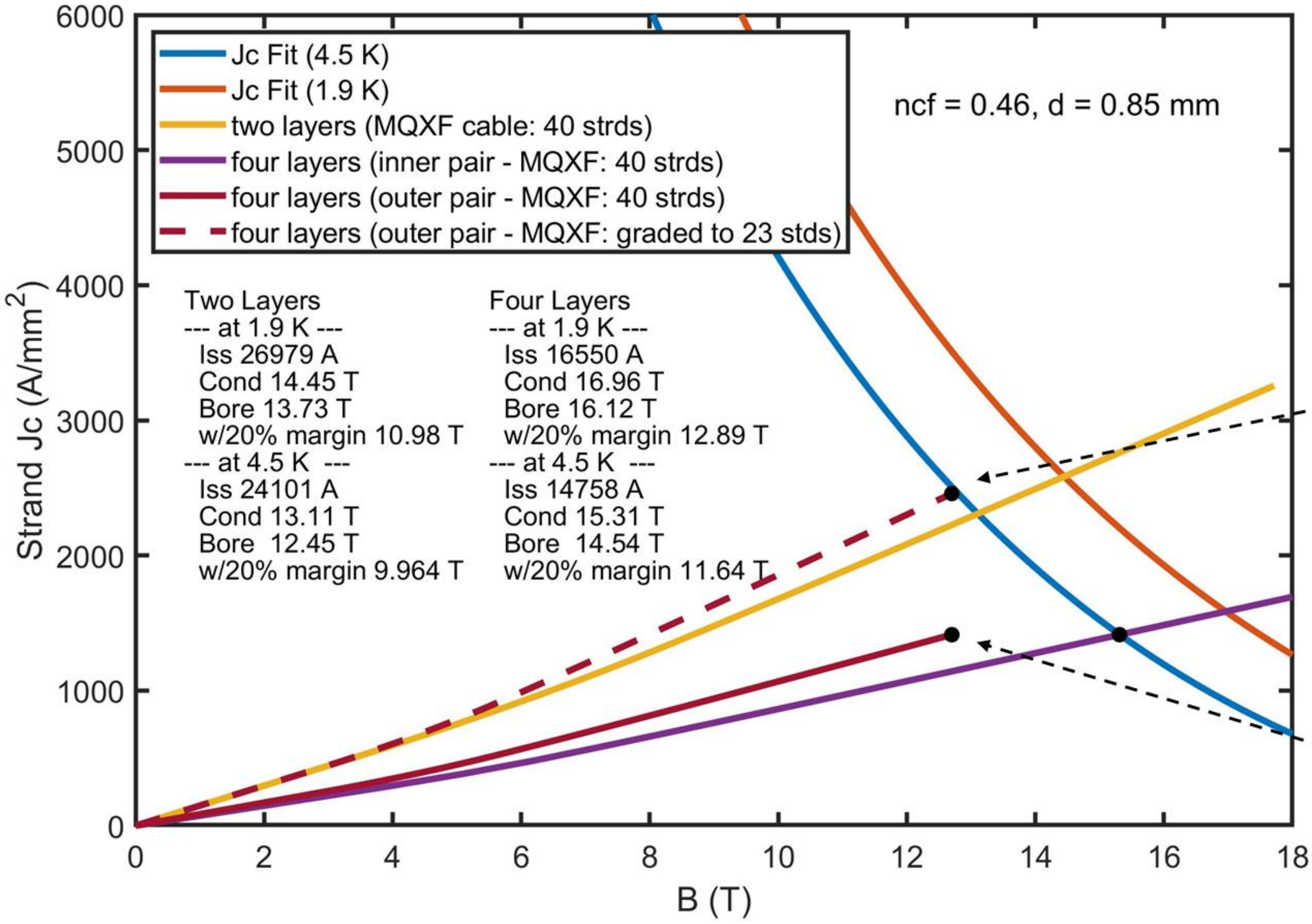
Two Layers

	4.5 K	1.9 K
Iss	24.1 kA	27.0 kA
Bss_cond	13.1 T	14.5 T

Four Layers

	4.5 K	1.9 K
Iss	14.8 kA	16.6 kA
Bss_cond	15.31 T	16.96 T

Grading the outer layer pair using number of strands



Outer layers after grading (23 strands)

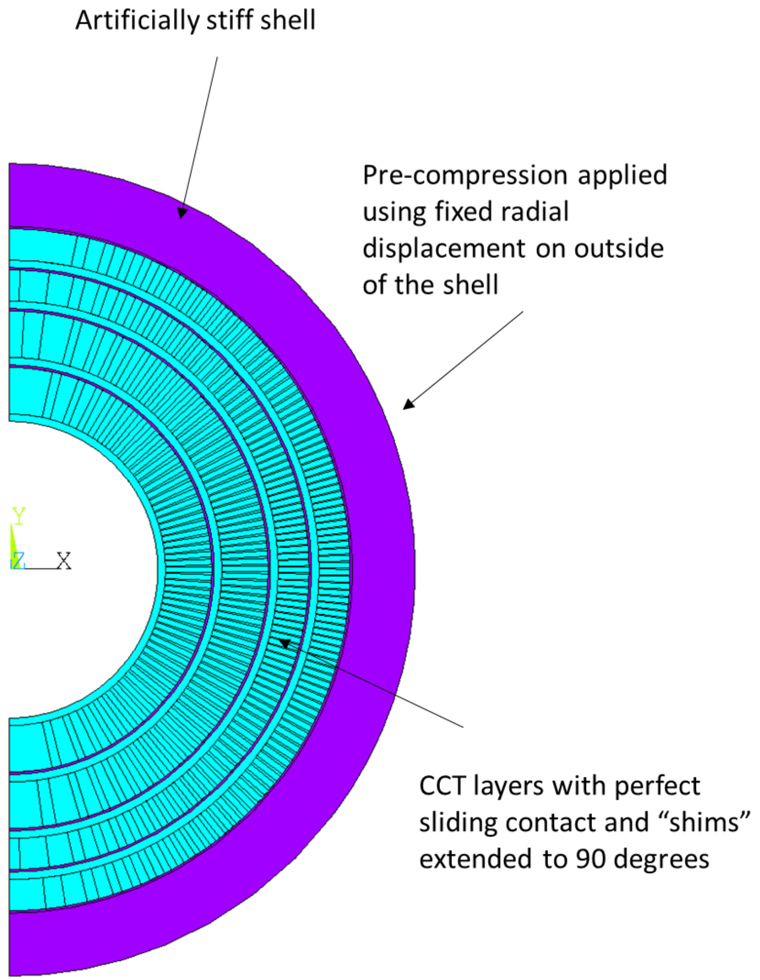
Outer layers before grading (40 strands)

First 2D mechanical models for the two and four layer MQXF cable designs explore extremes of pre-stress with a rigid boundary

- Load steps (2D - plane stress)
  1. apply fixed radial displacement on rigid shell
  2. apply Lorentz forces at ~80% of 4.5 K short-sample
     - two layers: 19.2 kA, 10.5 T bore field
     - four layer: 11.8 kA, 12.4 T bore field

- Study two extreme cases
  - no pre-compression (just rigid boundary)
  - pre-compression up to the point of no conductor azimuthal tension during powering (all Lorentz force induced tension shifted into compression)

3D models will be needed for further detailed studies (of shear etc.)

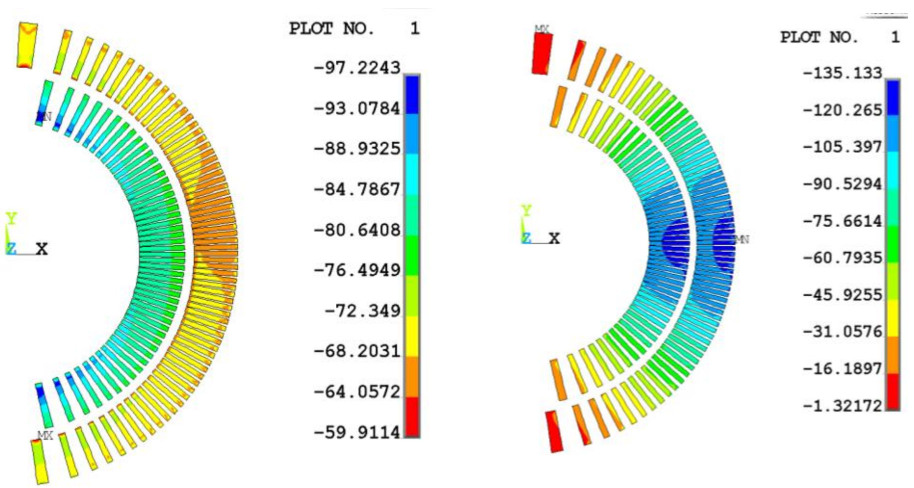


Initial 2D results for the two layer design show acceptable spar and conductor stress across the range of pre-stress

Case 1: using a precompression such that no azimuthal tension during powering

after pre-stress

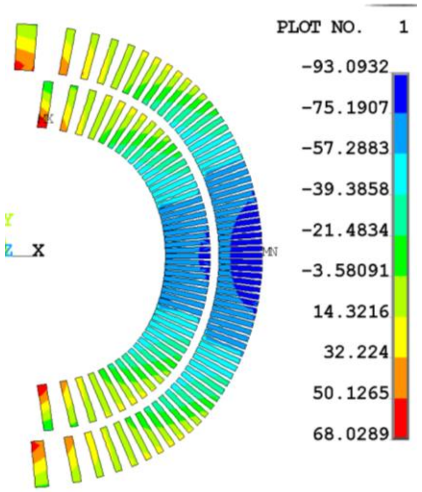
pre-stress+Lorentz force



Azimuthal stress in MPa

Case 2: no prestress

Lorentz Force



Azimuthal stress in MPa

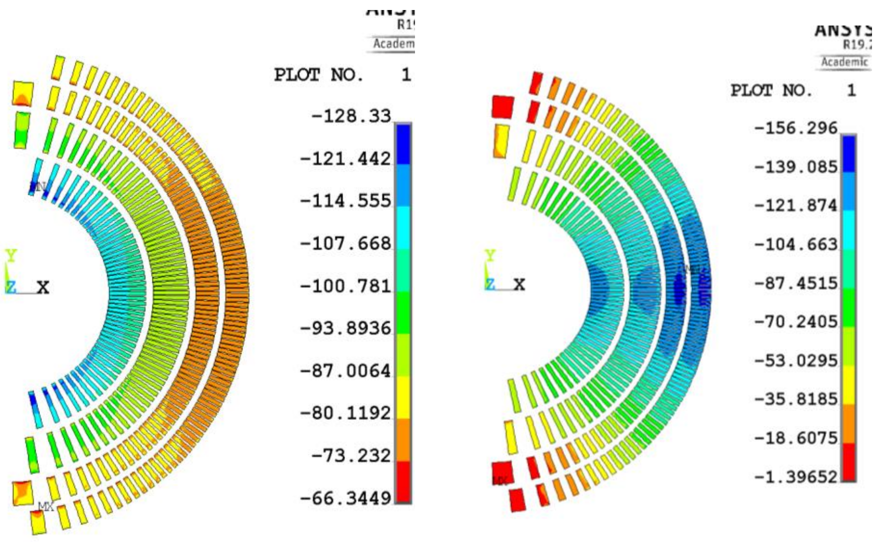
Comparing peak stress between cases

Two Layers: 19.2 kA, 10.5 T bore field

	No pre-compression	0.1 mm pre-compression
Spar	150 MPa	270 MPa
Conductor	+70/-90 MPa	+0/-135 MPa

Initial 2D results for the four layer design show acceptable spar and conductor stress across the range of pre-stress

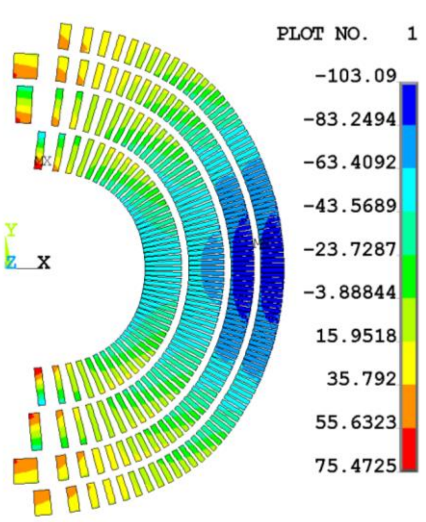
Case 1: using a precompression such that no azimuthal tension during powering


after pre-stress

pre-stress+Lorentz force

Azimuthal stress in MPa

Case 2: no prestress


Lorentz Force

Azimuthal stress in MPa

Comparing peak stress between cases

Four Layers: 11.8 kA, 12.4 T bore field

	No pre-compression	0.16 mm pre-compression
Spar	200 MPa	300 MPa
Conductor	+75/-103 MPa	+0/-156 MPa

Summary

- A first study has scoped attainable fields and provided initial feedback on stress (not a final design)

Short sample with 40 strand MQXF cable

Two Layers

	4.5 K	1.9 K
Iss	24.1 kA	27.0 kA
Bss_cond	13.1 T	14.5 T

Four Layers

	4.5 K	1.9 K
Iss	14.8 kA	16.6 kA
Bss_cond	15.31 T	16.96 T

A 23 strand cable can be used in the outer two layers for 4.5 K grading

Conductor and spar azimuthal stress from 2D with a rigid boundary

Two Layers: 19.2 kA, 10.5 T bore field

	No pre-compression	0.1 mm pre-compression
Spar	150 MPa	270 MPa
Conductor	+70/-90 MPa	+0/-135 MPa

Four Layers: 11.8 kA, 12.4 T bore field

	No pre-compression	0.16 mm pre-compression
Spar	200 MPa	300 MPa
Conductor	+75/-103 MPa	+0/-156 MPa

Next Steps

- Incorporate a real outer structure in 2D to study the level of "pre-stress" obtainable (key and bladder etc.)

- Move to 3D modeling
  - accurate calculation for 3D rise of field at conductor
  - more accurate mechanical modeling (stiffness, forces, etc.)
  - study of 3D shear stresses between cable and channel
  - feedback on design variables such as spar thickness etc. will come from 3D modeling and subscale results

- Begin to consider insert coupling
  - protection w/strong inductive coupling
  - mechanical
  - short-sample

CCT 5 / Bin5c Hybrid Analysis

L. Garcia Fajardo, D. Arbelaez

Introduction

- Performing scoping studies to understand how to mechanically couple insert magnets in hybrid configurations
- Insert magnet under study is Bin5c (part of Bi2212 program)
- Outsert magnet under study is existing magnet CCT5 (90 mm bore, 8.5 T bore field in stand alone test)

- Possible mechanical coupling approaches
  - External support mounted at the ends on CCT5 (no mechanical coupling in bore)
  - Smart-shim approach as used for CCT5 layers

Analysis of CCT5/Bin5 hybrid configuration

- Opera 3D analysis
  - Load line analysis for insert
  - Calculate force and torque on insert/outsert including magnet leads
  - Determine how various misalignment can affect force and torque

- Ansys 2D analysis
  - Investigate options for mechanical support for hybrid test of CCT5/Bin5c (gap and no gap between insert and outsert)
  - Investigate use of aluminum or stainless steel shell outside of layer 2 of the insert
  - Investigate various “smart shim” configurations

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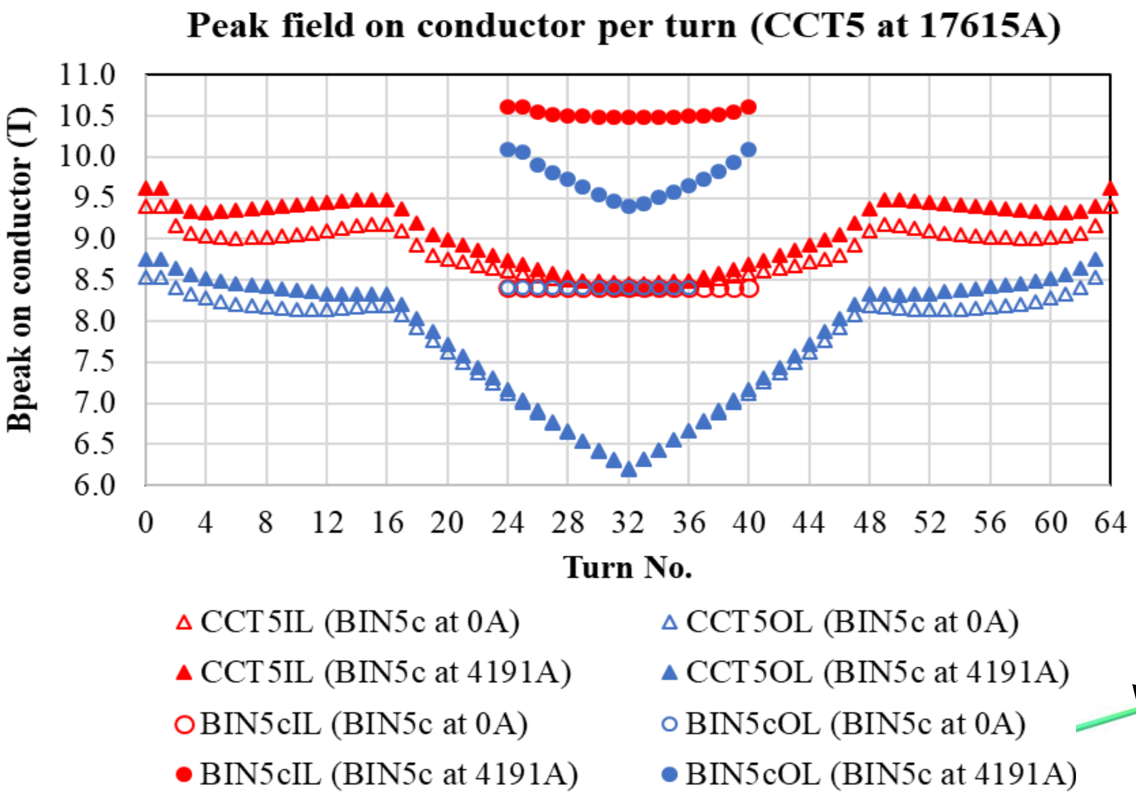
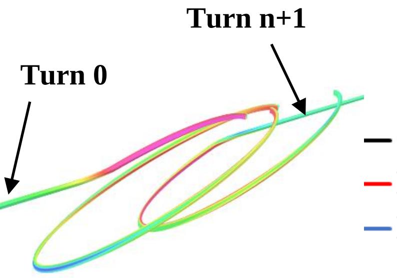
Peak field on conductor and loadlines

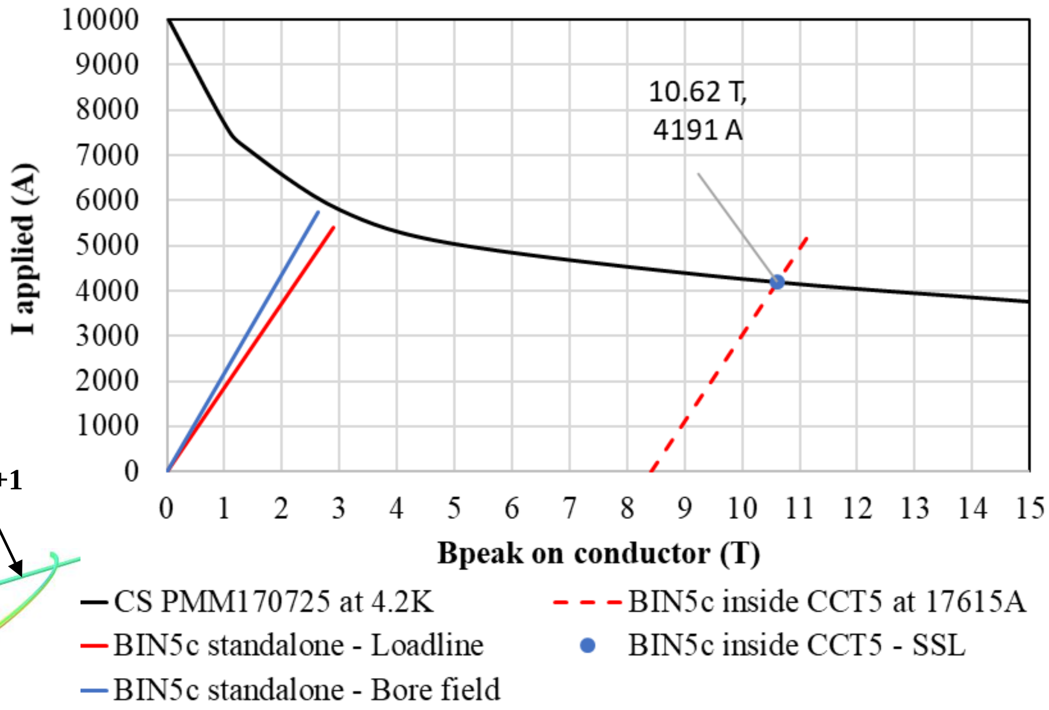
CCT5 at 17615 A*	Bore field (T)	CCT5IL Bpeak (T)	CCT5OL Bpeak (T)	BIN5cIL Bpeak (T)	BIN5cOL Bpeak (T)
BIN5c at 0 A	-8.40	9.40	8.54	8.42	8.42
BIN5c at 4191 A	-10.31	9.63	8.76	10.61	10.09

*17615 A in CCT5 produces 8.4 T in the bore without iron. 8.4 T is considered as the operation field of CCT5

Assumption:
BIN5c is powered once CCT5 reaches the operation current







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Misalignment cases (BIN5c is misaligned with respect to CCT5)

Bore diameter of CCT5: **90 mm**

Outer diameter of BIN5c-OL: **64.72 mm**

Shell of BIN5c: **10 mm** (preliminary value)

Total outer diameter of BIN5c: **85 mm**

Clearance between BIN5c and CCT5: **2.5 mm**

Displacement in X: **+2 mm**

Displacement in Y: **+2 mm**

Displacement in Z: **+2 mm** (could be larger)

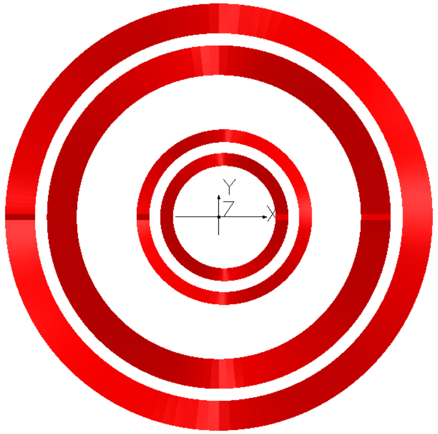
Rotation @X: **+0.6 deg***

Rotation @Y: **+0.6 deg***

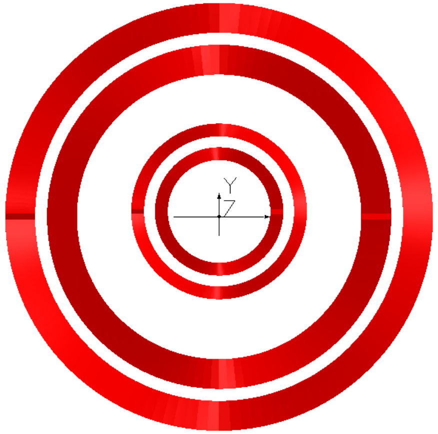
Rotation @Z: **+5 deg**

***0.6 deg corresponds to a displacement of 1 mm in 500 mm**

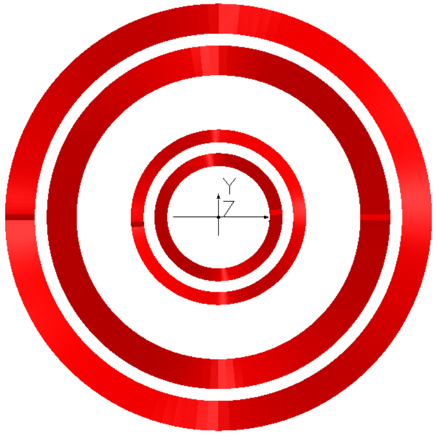
Examples



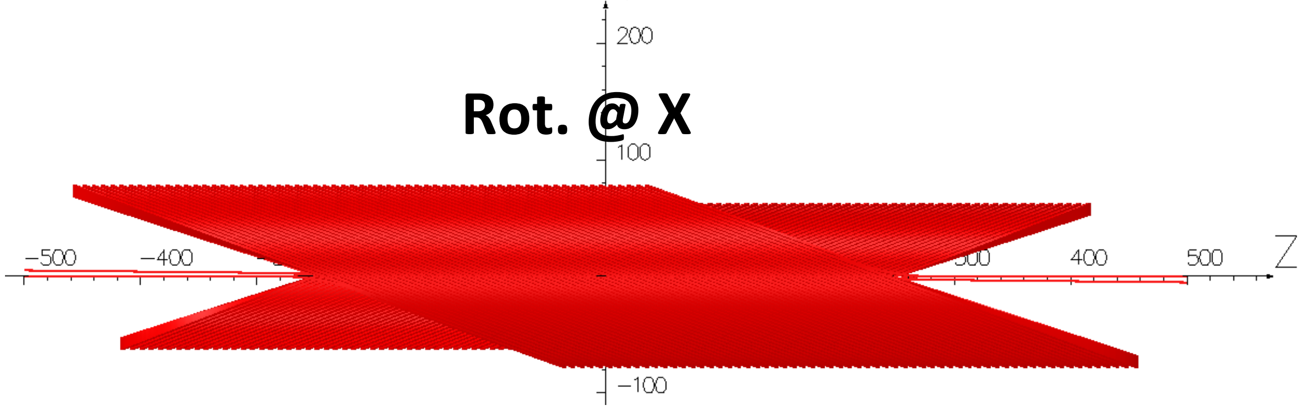
Disp. in X



Disp. in Y



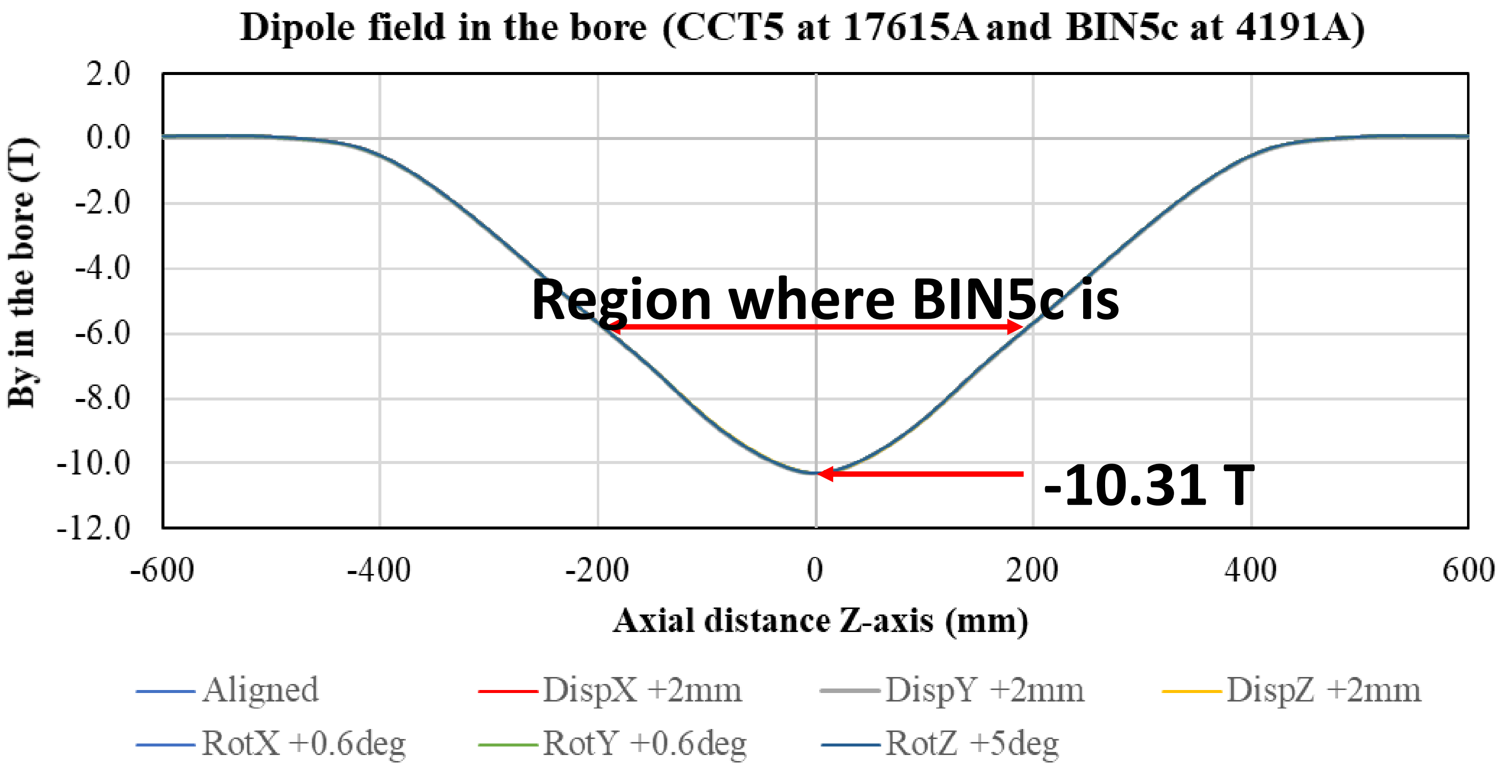
Rot. @ Z



Rot. @ X

Dipole field in the bore and peak field on coils

Peak field on conductor (T)	BIN5cIL	BIN5cOL	CCT5IL	CCT5OL
Aligned	10.61	10.09	9.63	8.76
Disp. X +2 mm	10.61	10.09	9.63	8.76
Disp. Y +2 mm	10.61	10.09	9.64	8.77
Disp. Z +2 mm	10.61		9.63	
Rot. X +0.6 deg	10.61		9.63	
Rot. Y +0.6 deg	10.61		9.63	
Rot. Z +5 deg	10.63		9.63	



Total torque when the magnets are misaligned

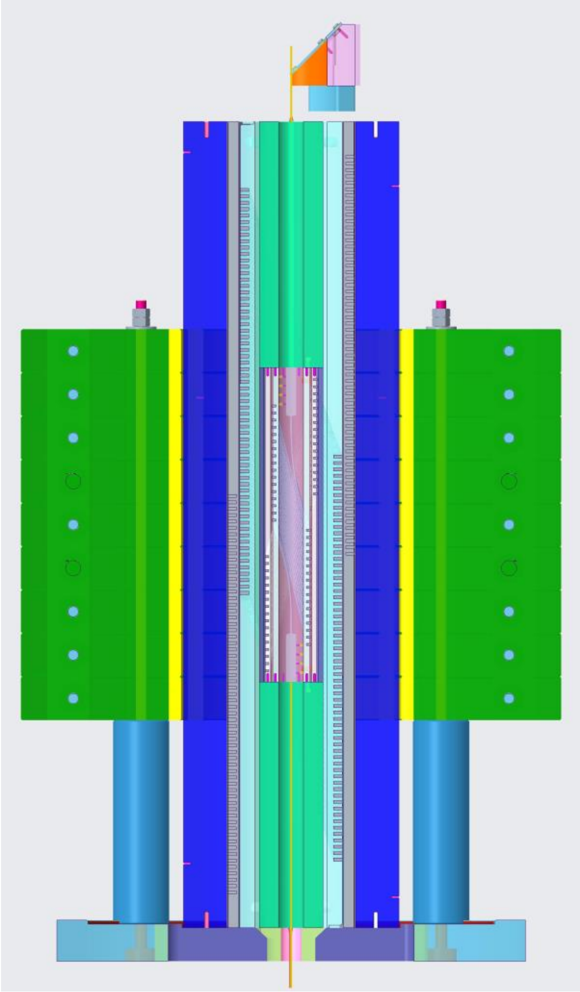
	BIN5cIL			BIN5cOL			CCT5IL			CCT5OL		
Torque (Nm)	**Tx**	**Ty**	**Tz**	**Tx**	**Ty**	**Tz**	**Tx**	**Ty**	**Tz**	**Tx**	**Ty**	**Tz**
Aligned	1034.87	-15.89	5.63	-1845.60	27.67	9.24	155218.51	-63.94	87.36	-153632.09	86.94	85.80
Disp. X +2 mm	1034.75	-10.05	5.43	-1843.56	33.11	9.31	155216.99	-63.97	88.18	-153632.62	86.63	85.27
Disp. Y +2 mm	1035.33	-15.65	5.74	-1846.30	27.80	9.46	155217.84	-65.01	87.15	-153633.74	87.62	85.19
Disp. Z +2 mm	1035.33	-15.65	5.74	-1846.30	27.80	9.46	155217.84	-65.01	87.15	-153631.78	87.24	85.76
Rot. X +0.6 deg	1019.00	-15.95	5.47	-1879.33	27.53	9.52	155239.72	-64.03	87.34	-153607.82	86.99	85.87
Rot. Y +0.6 deg	1034.92	-18.33	-7.76	-1845.58	31.98	32.05	155217.86	-66.67	64.87	-153631.39	89.03	99.42
Rot. Z +5 deg	1033.48	-9.05	-272.82	-1842.12	27.06	-531.06	155204.29	77.37	492.28	-153619.38	-60.28	500.13

	BIN5c			CCT5		
Torque (Nm)	**Tx**	**Ty**	**Tz**	**Tx**	**Ty**	**Tz**
Aligned	-810.73	11.79	14.87	1586.42	22.99	173.16
Disp. X +2 mm	-808.81	23.06	14.73	1584.37	22.66	173.45
Disp. Y +2 mm	-810.97	12.15	15.19	1584.10	22.61	172.35
Disp. Z +2 mm	-810.97	12.15	15.19	1586.06	22.23	172.92
Rot. X +0.6 deg	-860.33	11.58	14.99	1631.90	22.96	173.21
Rot. Y +0.6 deg	-810.66	13.65	24.28	1586.47	22.35	164.29
Rot. Z +5 deg	-808.64	18.02	-803.88	1584.91	17.09	992.41

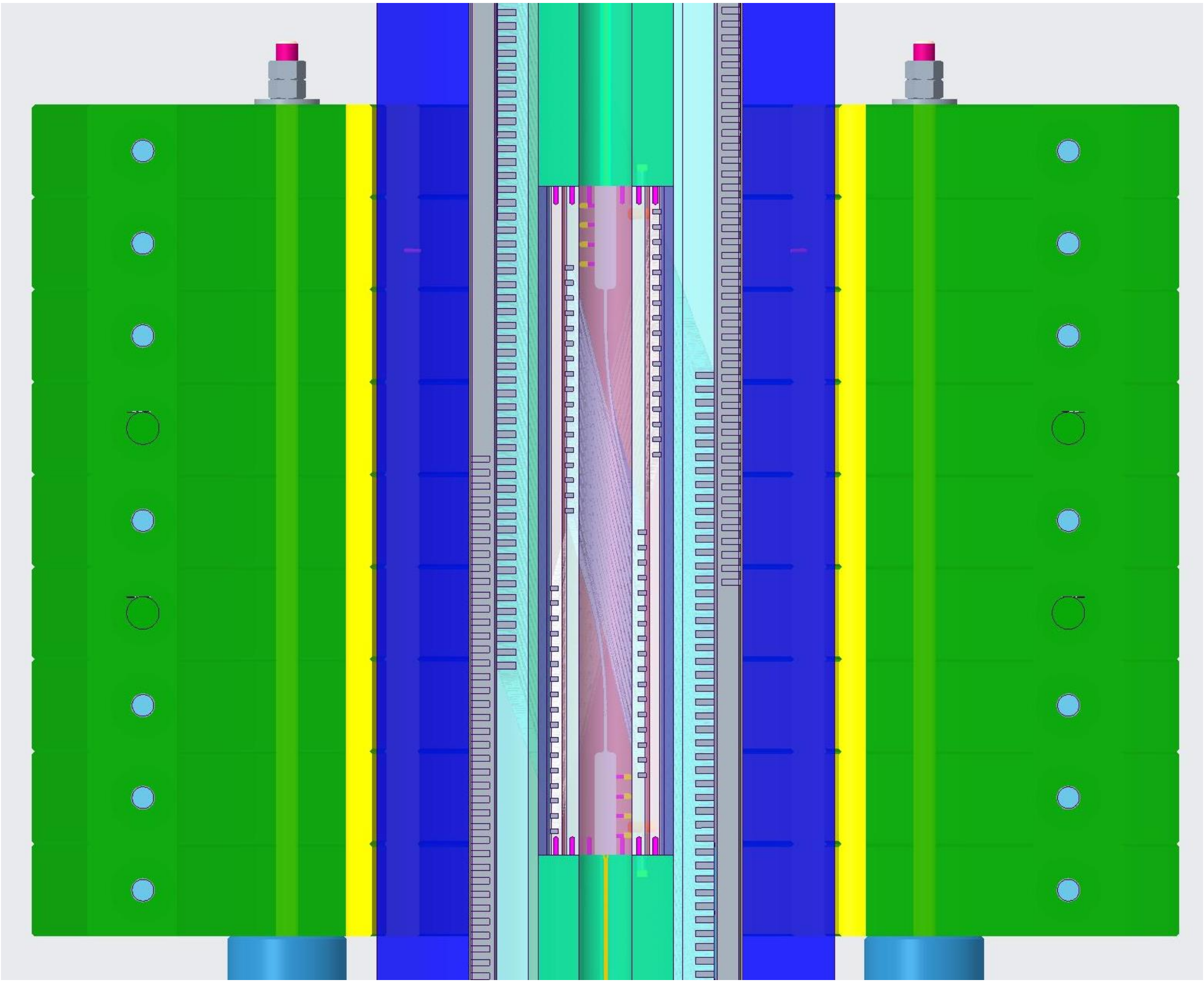
$$\vec{\tau} = \sum_{i=1}^{nBRICK8} \vec{r_i} \times \vec{F_i} \cdot V_i$$

BIN5c in CCT5

The leads of BIN5c need to be extended

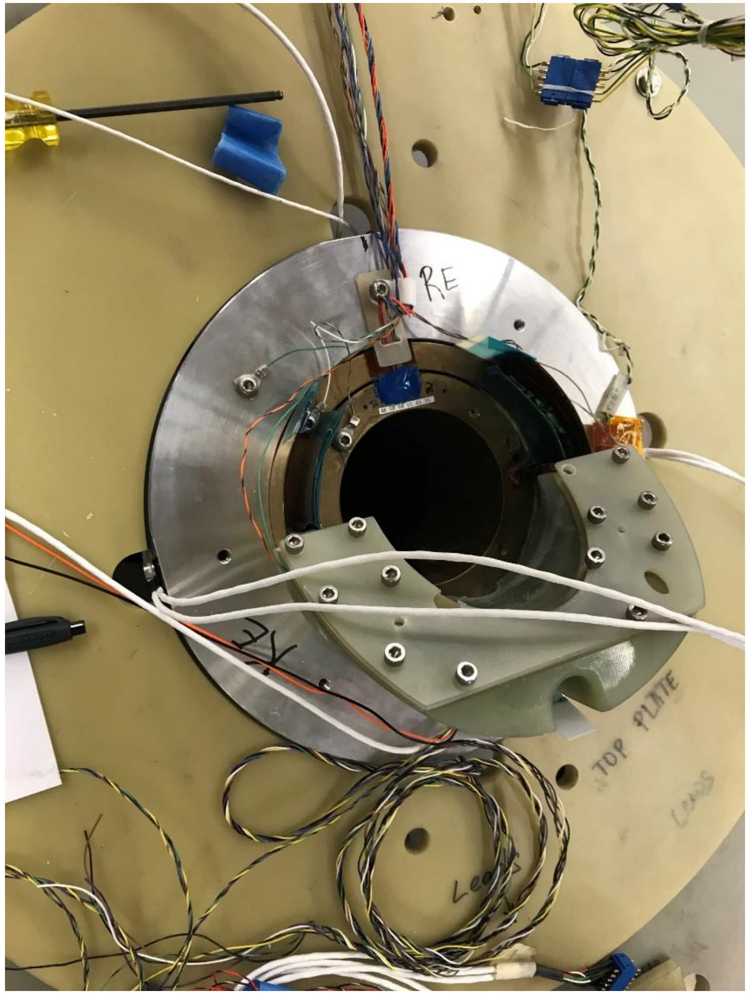


BIN5c has no straight section



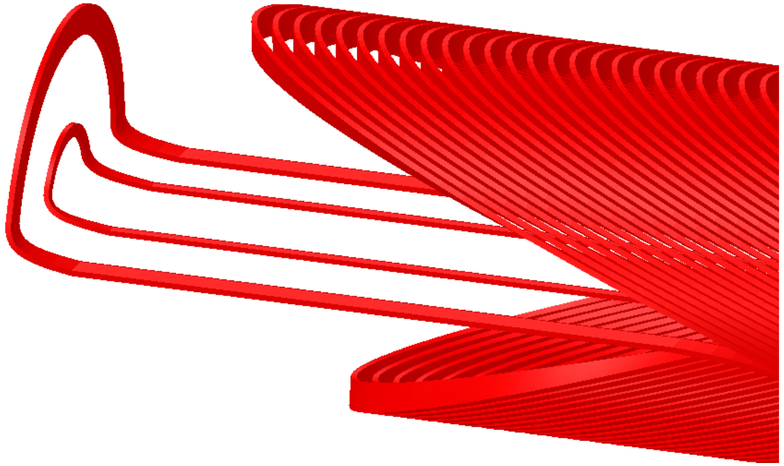
2nd Part: Add splice connection between layers

CCT5 inter-layer splice structure

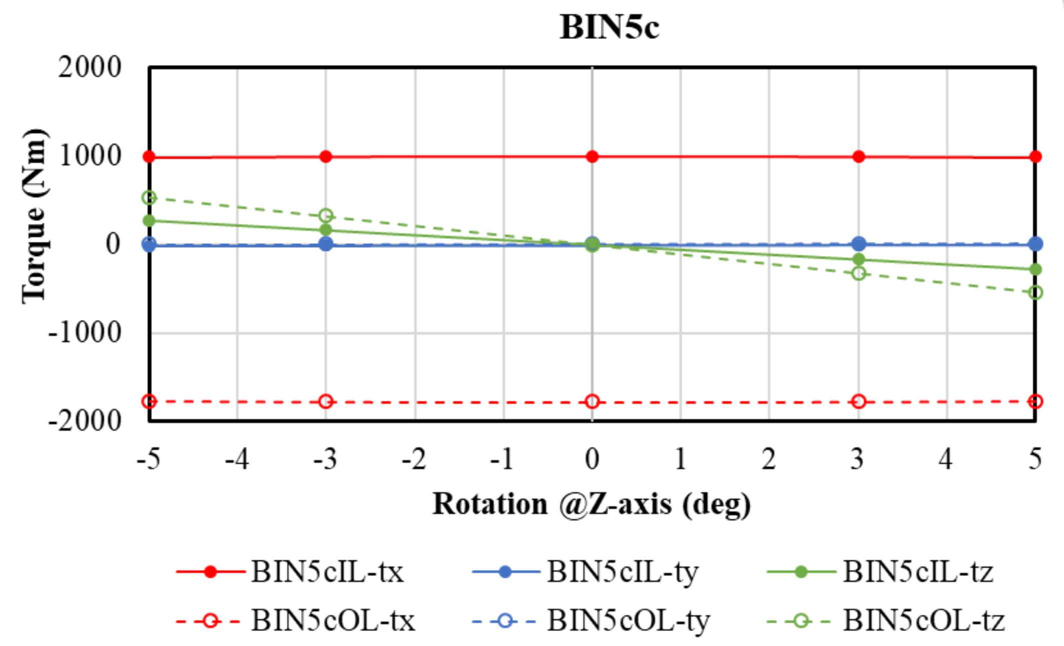


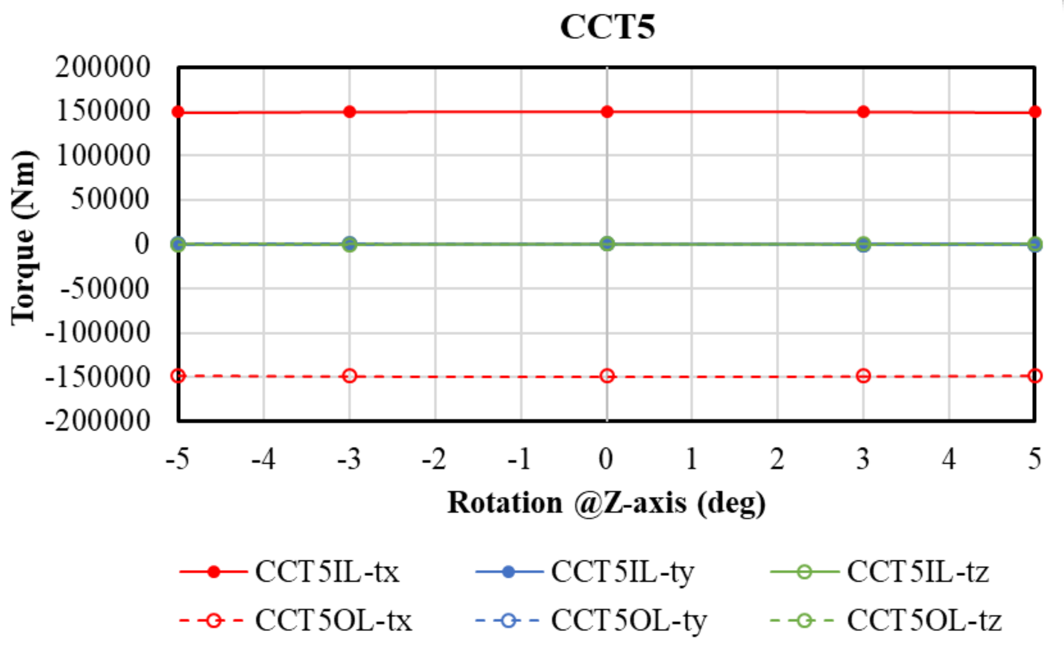
We'll do a similar inter-layer splice for BIN5c

The G10 structure of the inter-layer splice in BIN5c will be placed on the same side as in CCT5 in order to have space for additional hardware to support the two magnets together at the ends



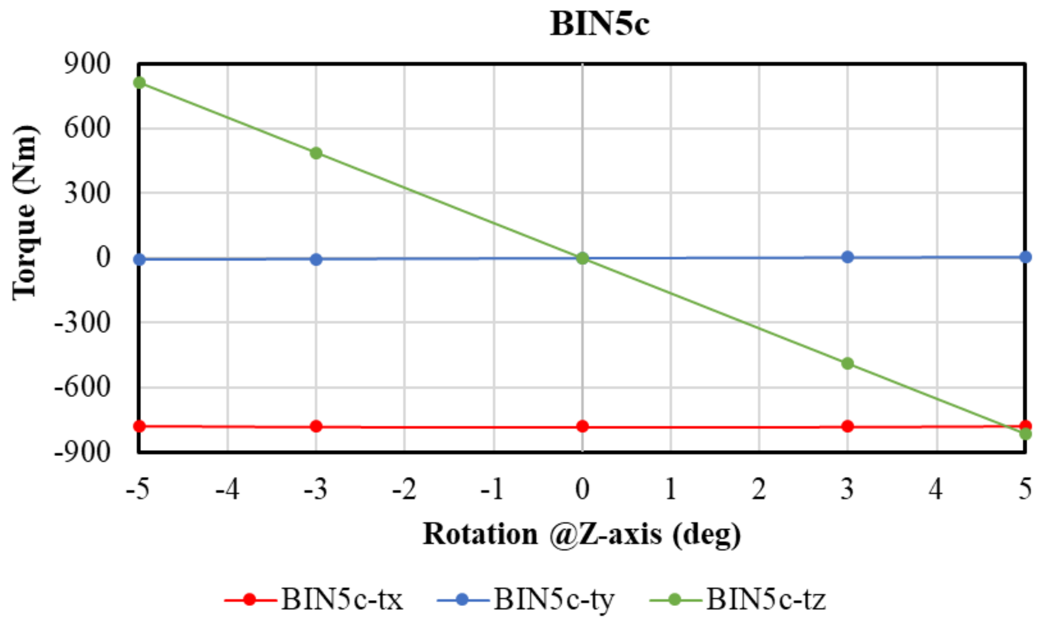
Effect of the rotation @Z-axis on the total torque per coil

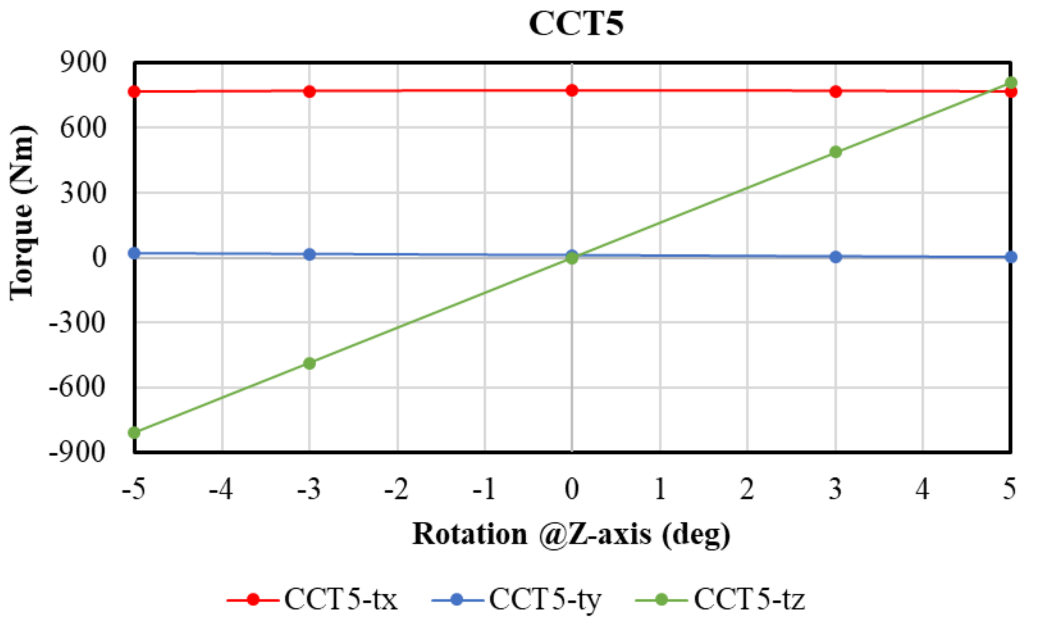

BIN5c


CCT5

Torque (Nm)	BIN5cIL			BIN5cOL			CCT5IL			CCT5OL		
Rotation @Z (deg)	Tx	Ty	Tz	Tx	Ty	Tz	Tx	Ty	Tz	Tx	Ty	Tz
-5	996.10	-12.00	275.54	-1772.59	2.87	536.29	149688.47	-154.78	-403.07	-148918.84	173.85	-408.12
-3	996.91	-10.26	165.41	-1774.70	4.42	321.99	149697.65	-99.57	-243.10	-148926.72	115.10	-244.04
0 (Aligned)	997.35	-7.68	-0.11	-1775.91	6.93	-0.06	149702.93	-16.74	-2.70	-148931.22	26.79	2.57
3	996.87	-5.10	-165.62	-1774.76	9.44	-322.11	149697.99	66.10	237.69	-148926.93	-61.53	249.18
5	996.03	-3.35	-275.75	-1772.69	10.96	-536.40	149689.03	121.31	397.67	-148919.20	-120.26	413.25

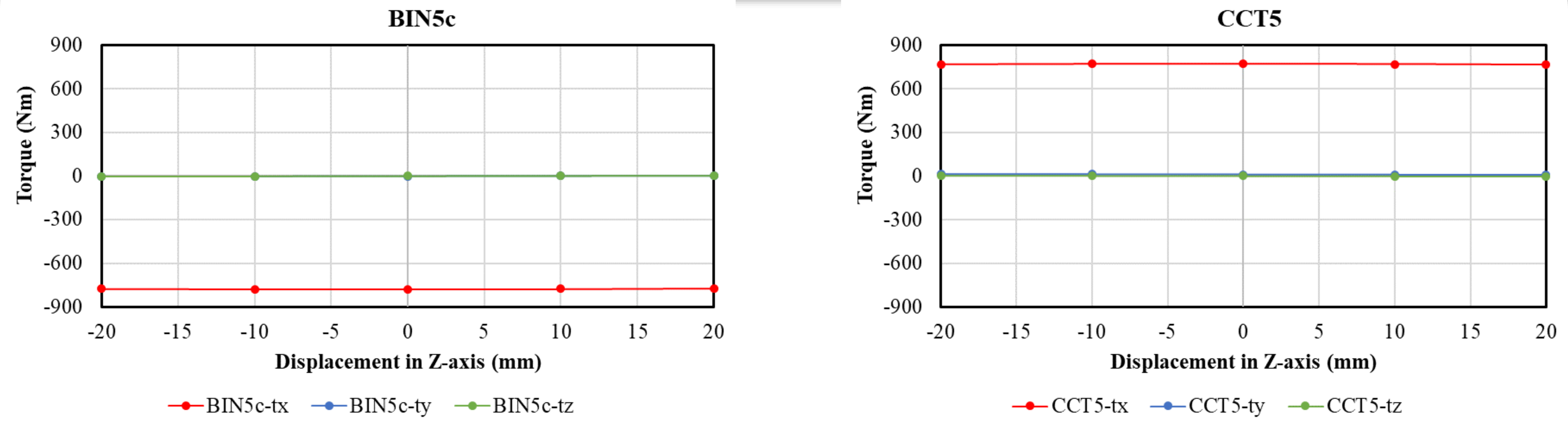
Effect of the rotation @Z-axis on the total torque per magnet





Torque (Nm)	BIN5c			CCT5		
Rotation @Z (deg)	Tx	Ty	Tz	Tx	Ty	Tz
-5	-776.49	-9.13	811.83	769.63	19.06	-811.19
-3	-777.79	-5.84	487.40	770.93	15.53	-487.14
0 (Aligned)	-778.56	-0.75	-0.16	771.71	10.05	-0.13
3	-777.89	4.34	-487.73	771.06	4.56	486.87
5	-776.66	7.61	-812.15	769.83	1.05	810.92

Effect of the displacement in Z-axis on the total torque per magnet



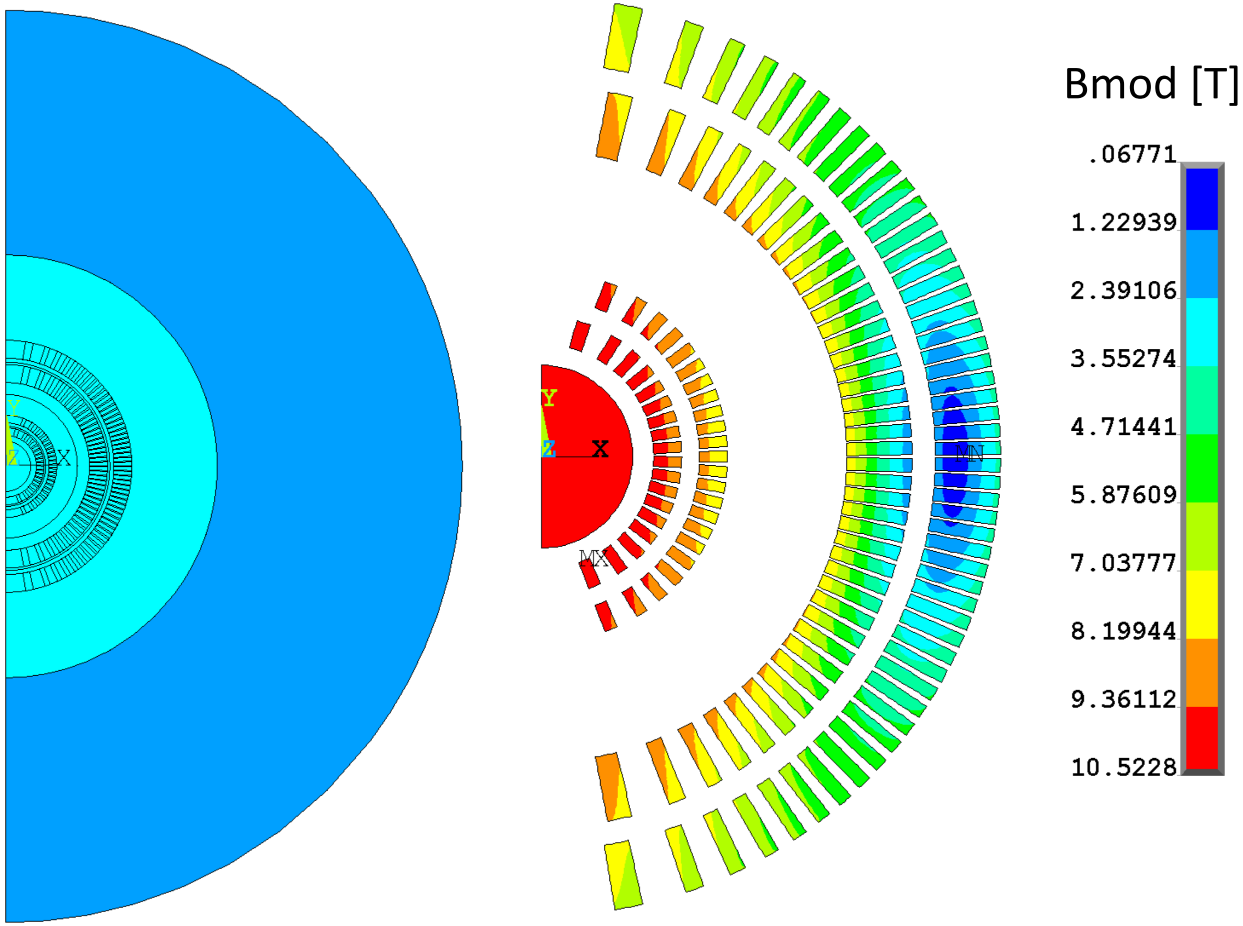
Torque (Nm)	BIN5c			CCT5		
Displacement in Z (mm)	Tx	Ty	Tz	Tx	Ty	Tz
-20	-775.20	-4.04	-3.35	767.73	13.57	3.06
-10	-778.14	-2.40	-1.76	771.01	11.80	1.46
0 (Aligned)	-778.56	-0.75	-0.16	771.71	10.05	-0.13
10	-776.70	0.97	1.44	770.10	8.22	-1.74
20	-771.72	2.72	3.07	765.33	6.39	-3.36

Summary of key points about the torque calculations

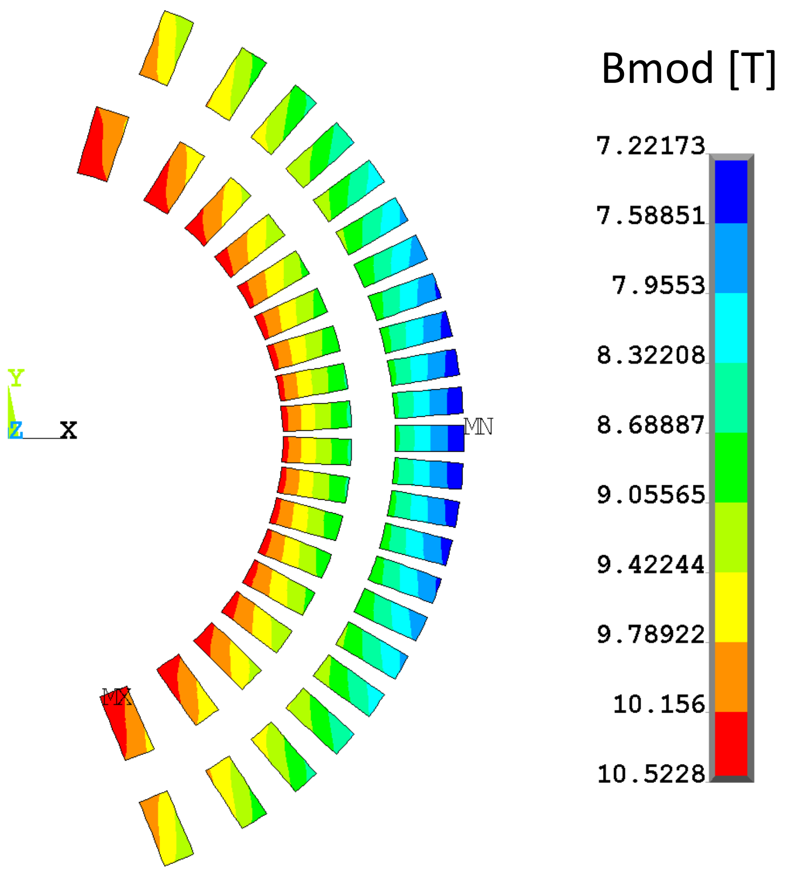
- There is a toque @X axis (tx) between the layers of BIN5c and between the layers of CCT5
- The 2 mm displacement of BIN5c with respect to CCT5 along X, Y and Z axes, do not affect the torque
- The 0.6 deg rotation of BIN5c with respect to CCT5 @X and Y axes do not affect the torque
- The rotation @Z axis affects the torque @Z axis (tz) between the layers of each magnet and between the magnets
- Overall, the torque is small

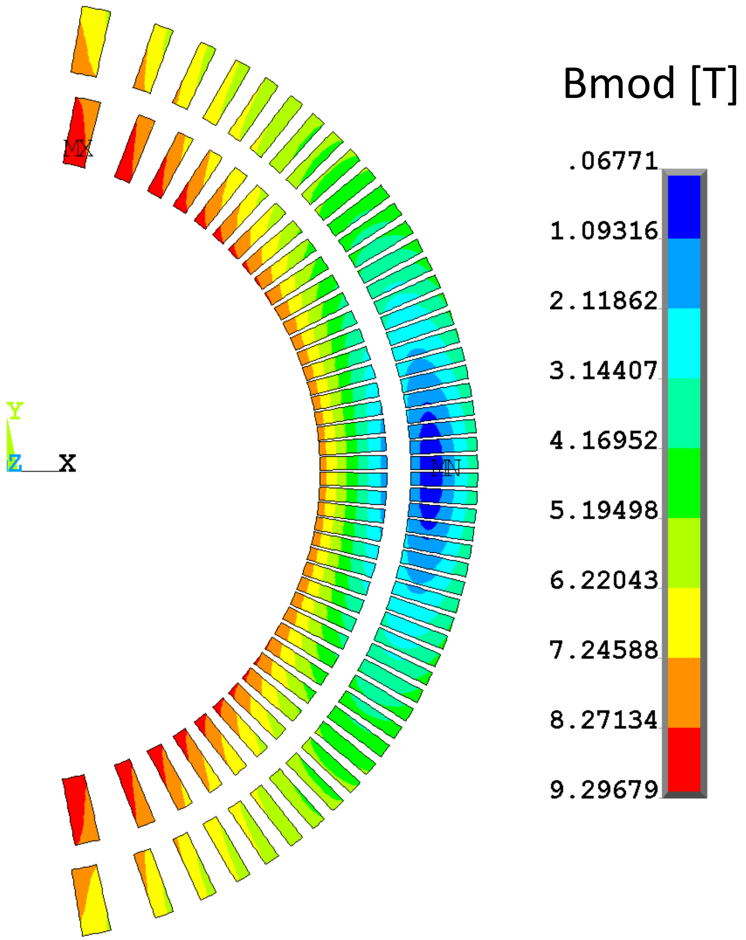
2D Magnetic Analysis

- Insert/Outsert Current
  - CCT5 – (15,500 A, 8.4 T) (highest current achieved in standalone test)
  - Bin5c – (3,500 A, 1.9 T)
- Bore field is 10.3 T



Peak Field on Each Layer

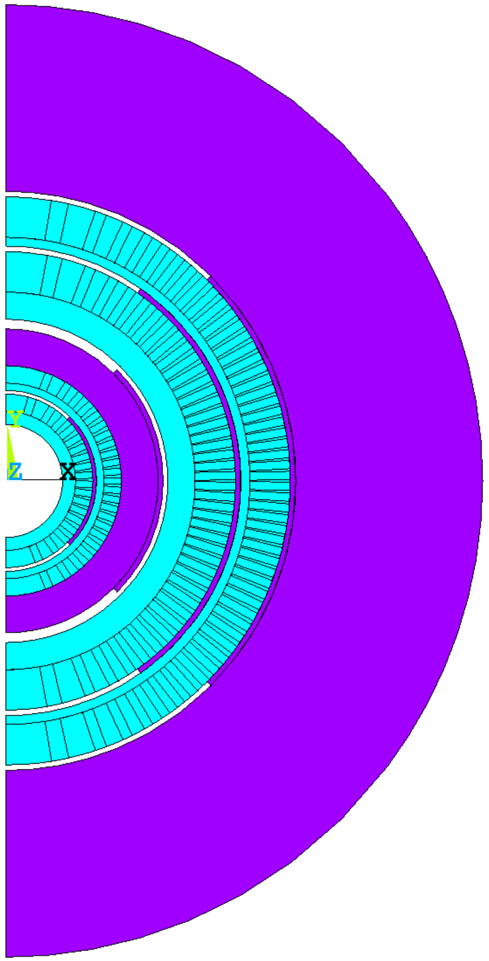


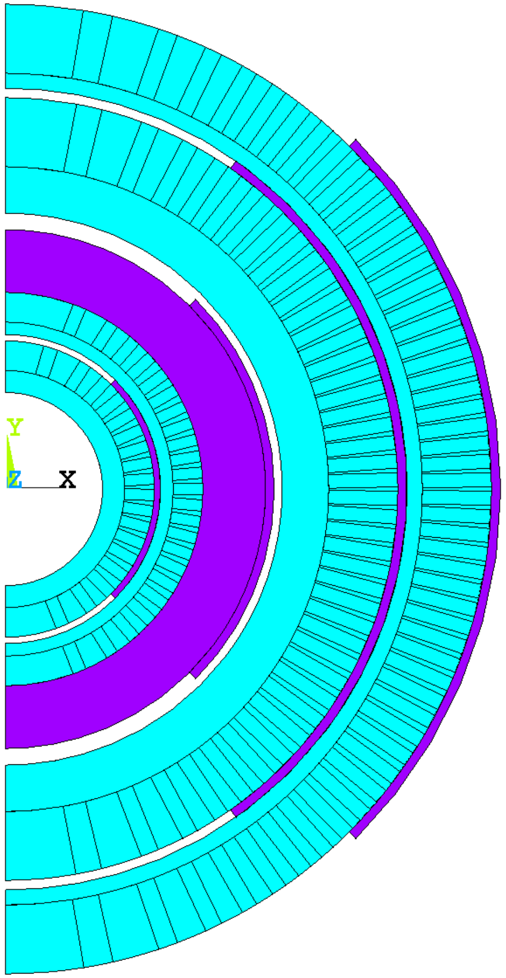


2D Mechanical Analysis

- Shell is included around the insert
- Optional gap can be included between insert and outsert

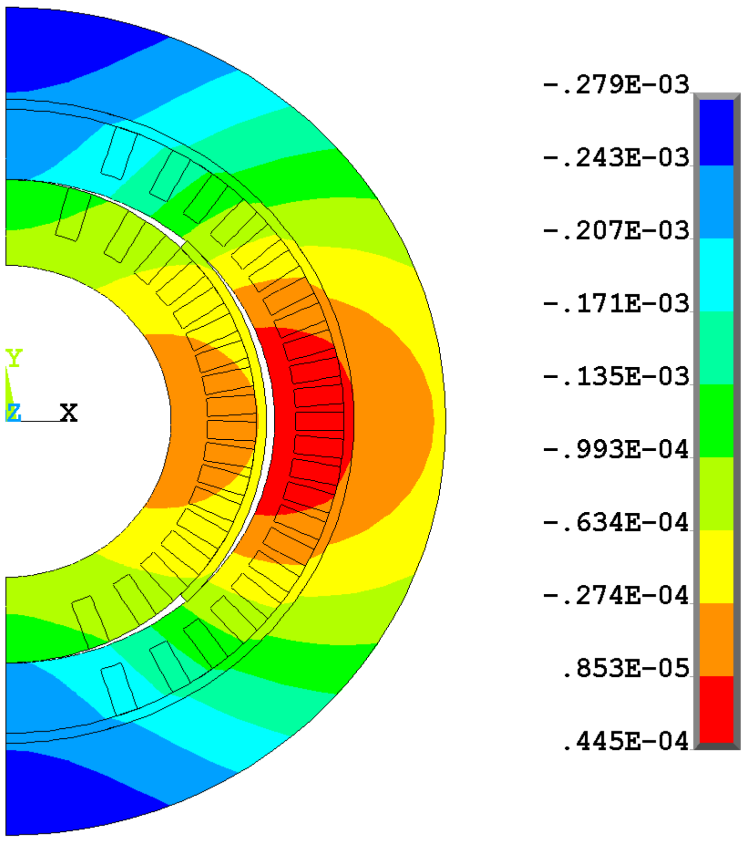
- Contact Assumptions
  - Frictional contact between shims and neighboring layer
  - Conductor is bonded to spar and ribs



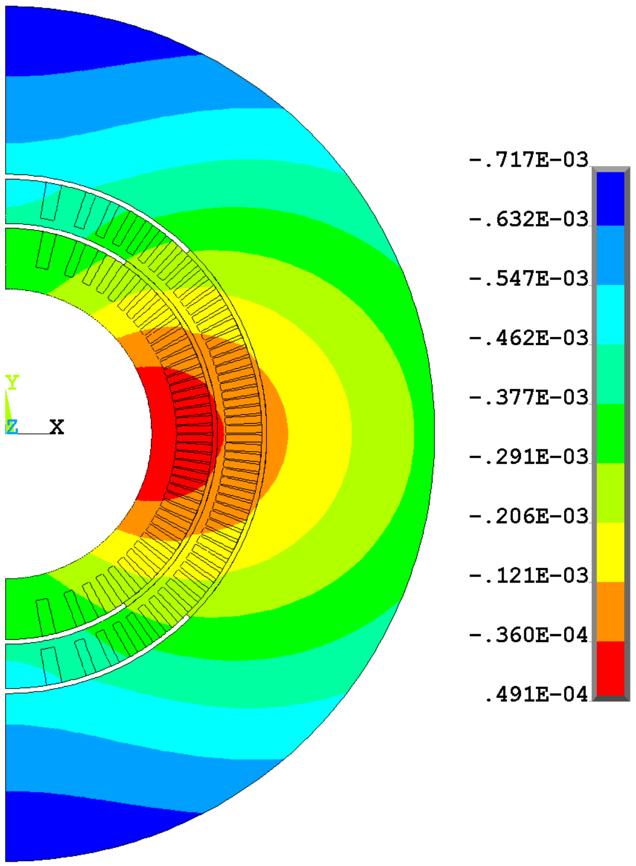


Contact is not maintained between the insert and outsert with and without gap

Radial Displacement Insert [m]



Radial Displacement Outsert [m]

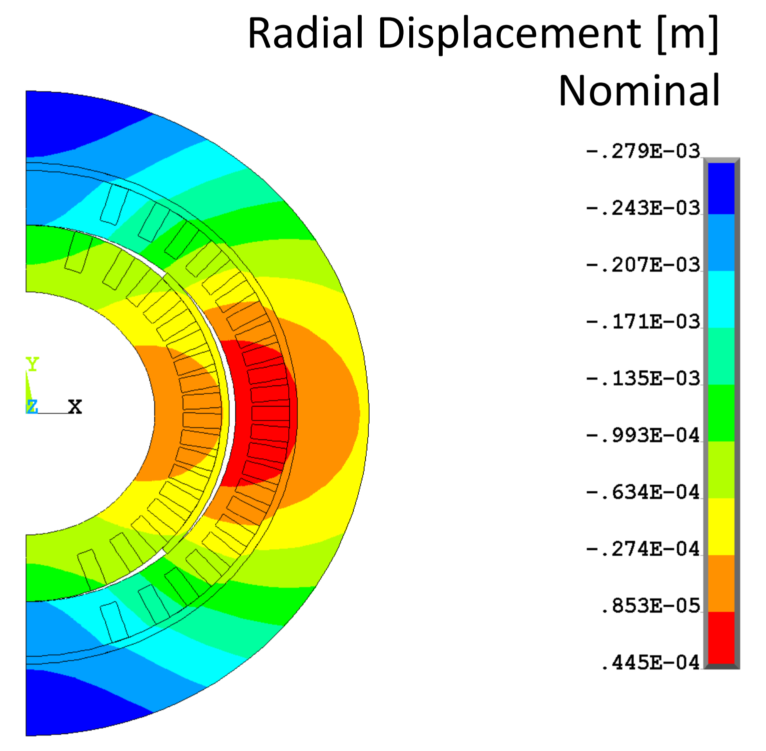


Contact between insert and outsert will not help reduce insert radial displacement at the midplane

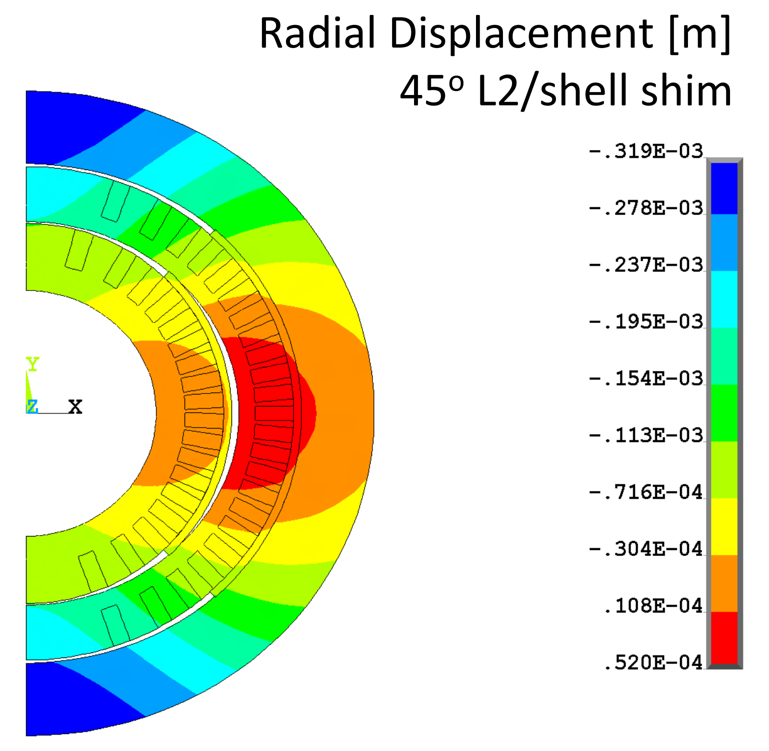
Shim Configuration and Shell Material Analysis

- Insert baseline
  - 45^0 L1/L2 shim
  - 90^0 L2/shell shim
  - Al shell
- Different scenarios
  - 45^0 L1/L2 shim, 45^0 L2/shell shim, Al shell
  - 45^0 L1/L2 shim, 90^0 L2/shell shim, SST shell
  - 90^0 L1/L2 shim, 90^0 L2/shell shim, Al shell
  - 90^0 L1/L2 shim, 90^0 L2/shell shim, SST shell

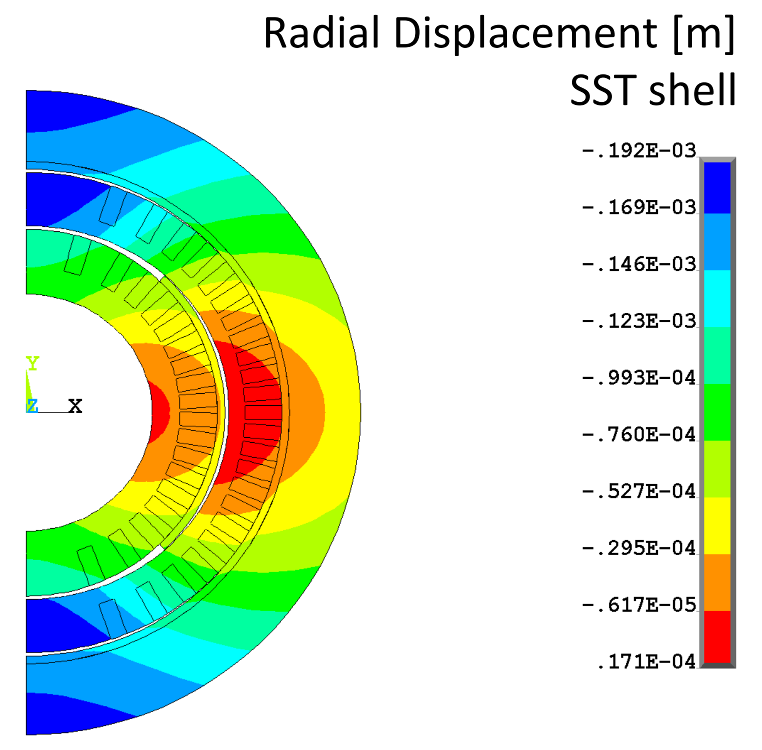
Effect of shell material and shell shim configuration on coil displacement (after cooldown and Lorentz force)



Radial Displacement [m]
Nominal

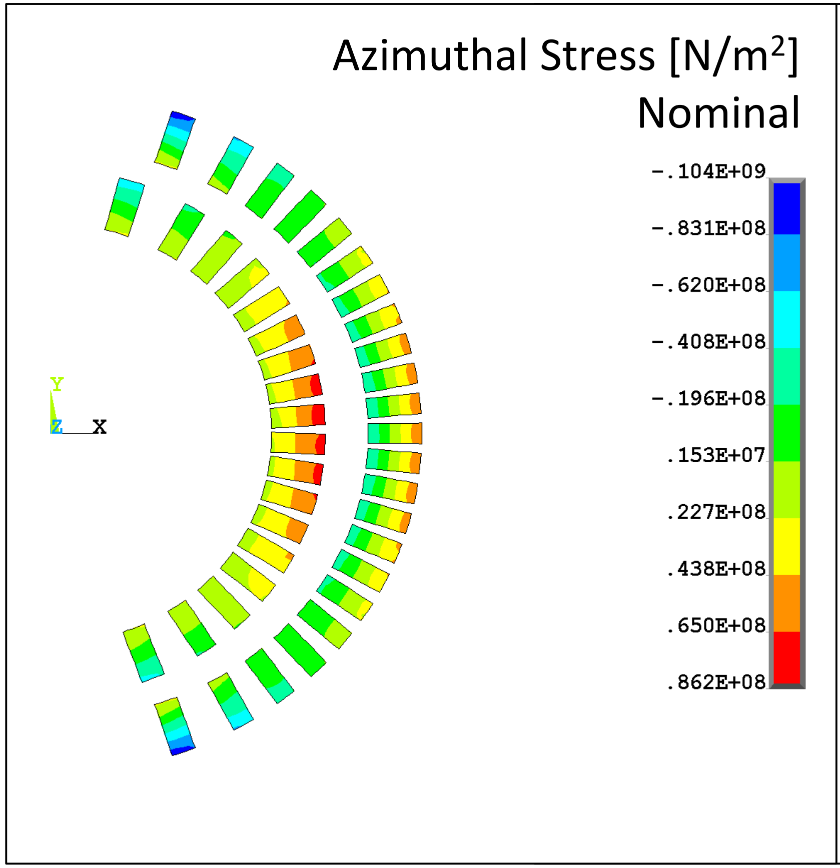


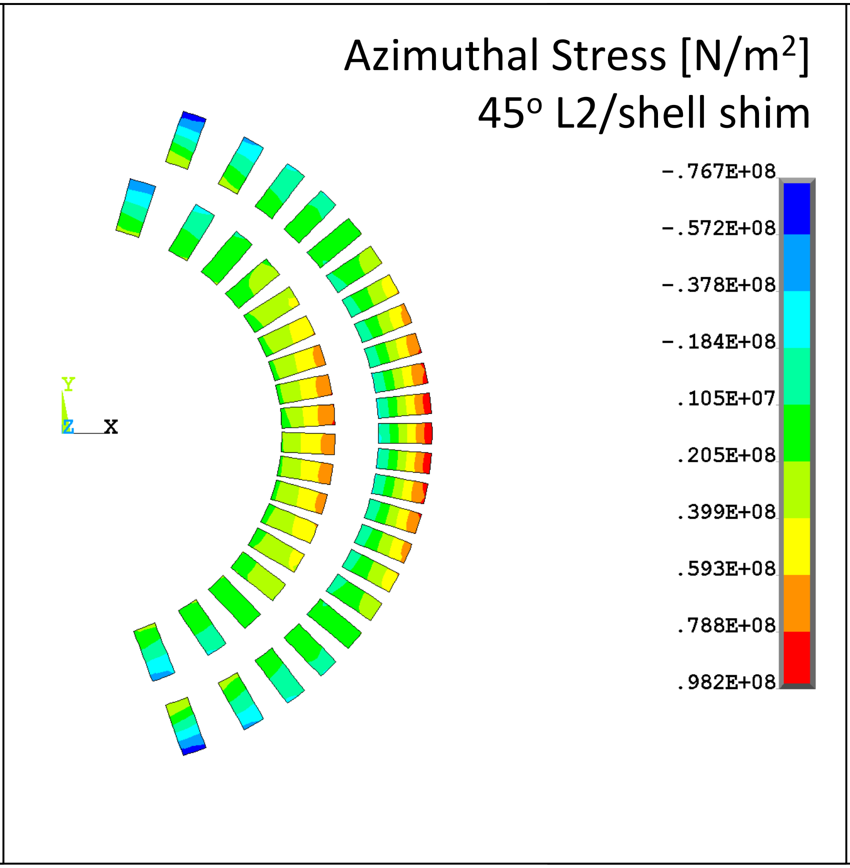
Radial Displacement [m]
45° L2/shell shim

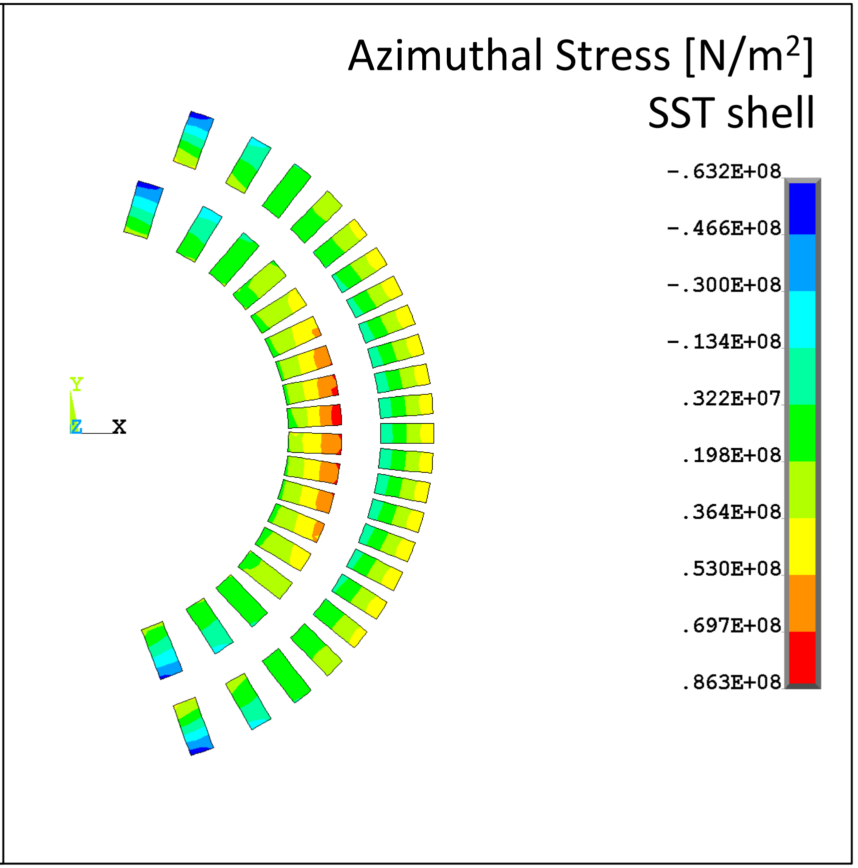


Radial Displacement [m]
SST shell

Effect of shell material and shell shim configuration on azimuthal coil stress (after cooldown and Lorentz force)

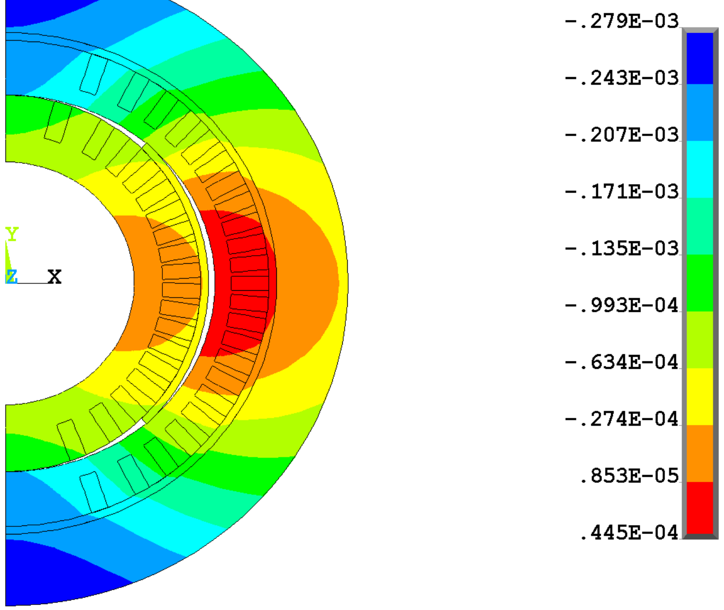




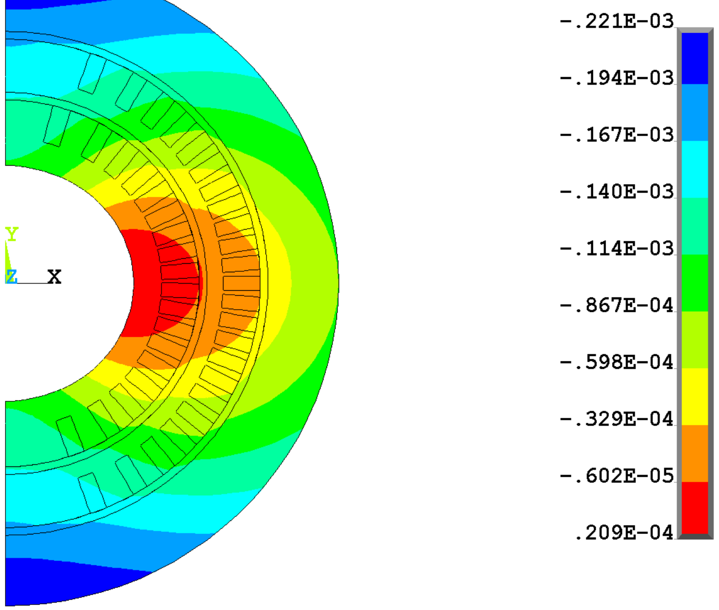


Effect of shell material and L1/L2 shim configuration on coil displacement (after cooldown and Lorentz force)

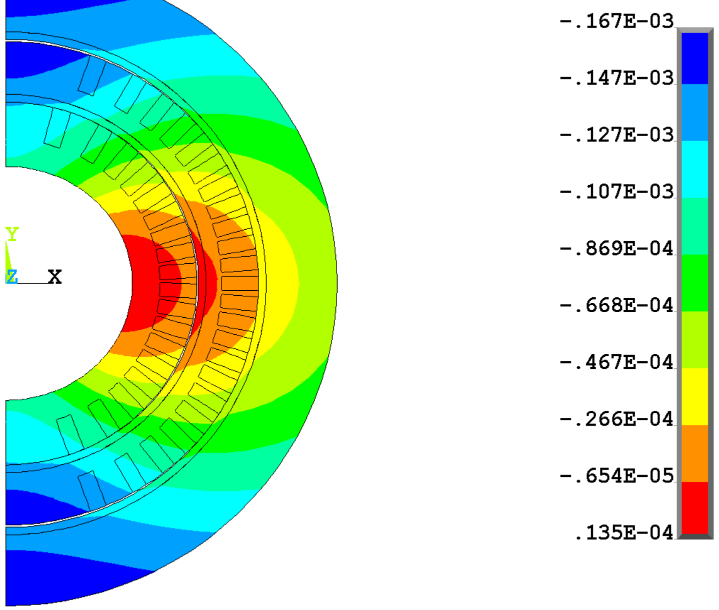
Radial Displacement [m]
Nominal



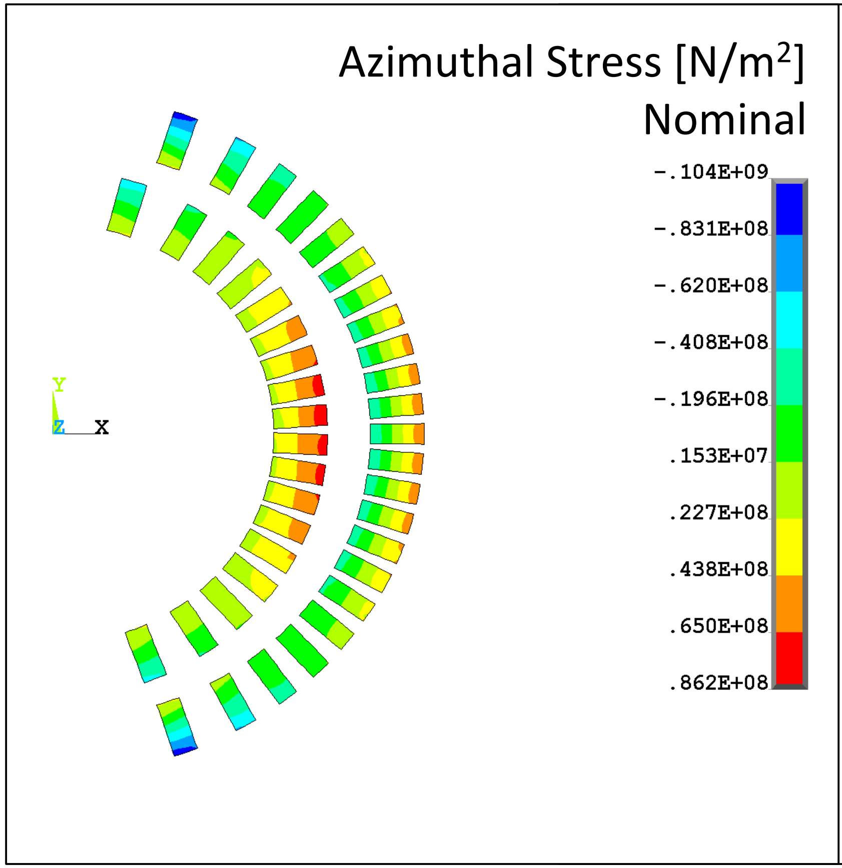
Radial Displacement [m]
90^o L1/L2 shim



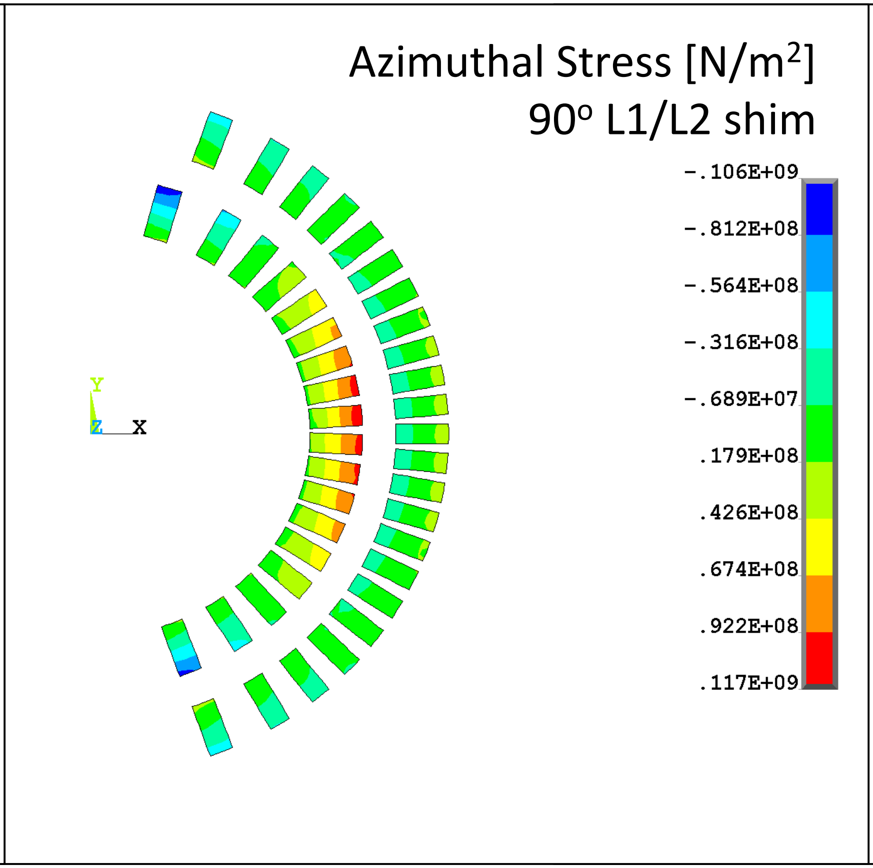
Radial Displacement [m]
90^o L1/L2 shim + SST shell



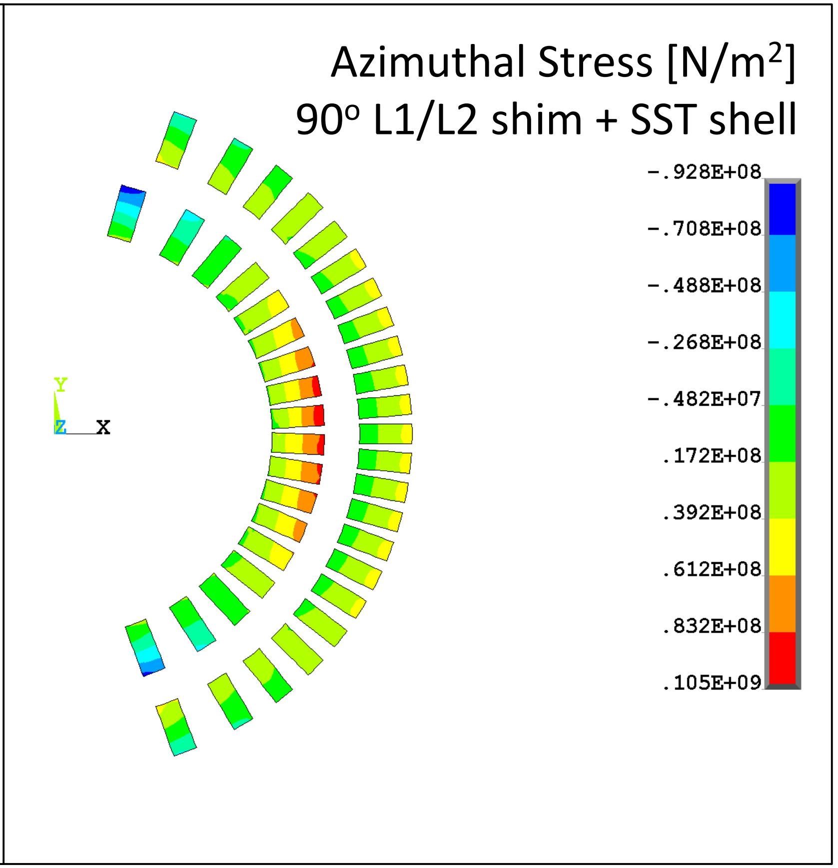
Effect of shell material and L1/L2 shim configuration on azimuthal coil stress (after cooldown and Lorentz force)



Azimuthal Stress [N/m^2]
Nominal



Azimuthal Stress [N/m^2]
90° L1/L2 shim



Azimuthal Stress [N/m^2]
90° L1/L2 shim + SST shell

Conclusions and Next Steps

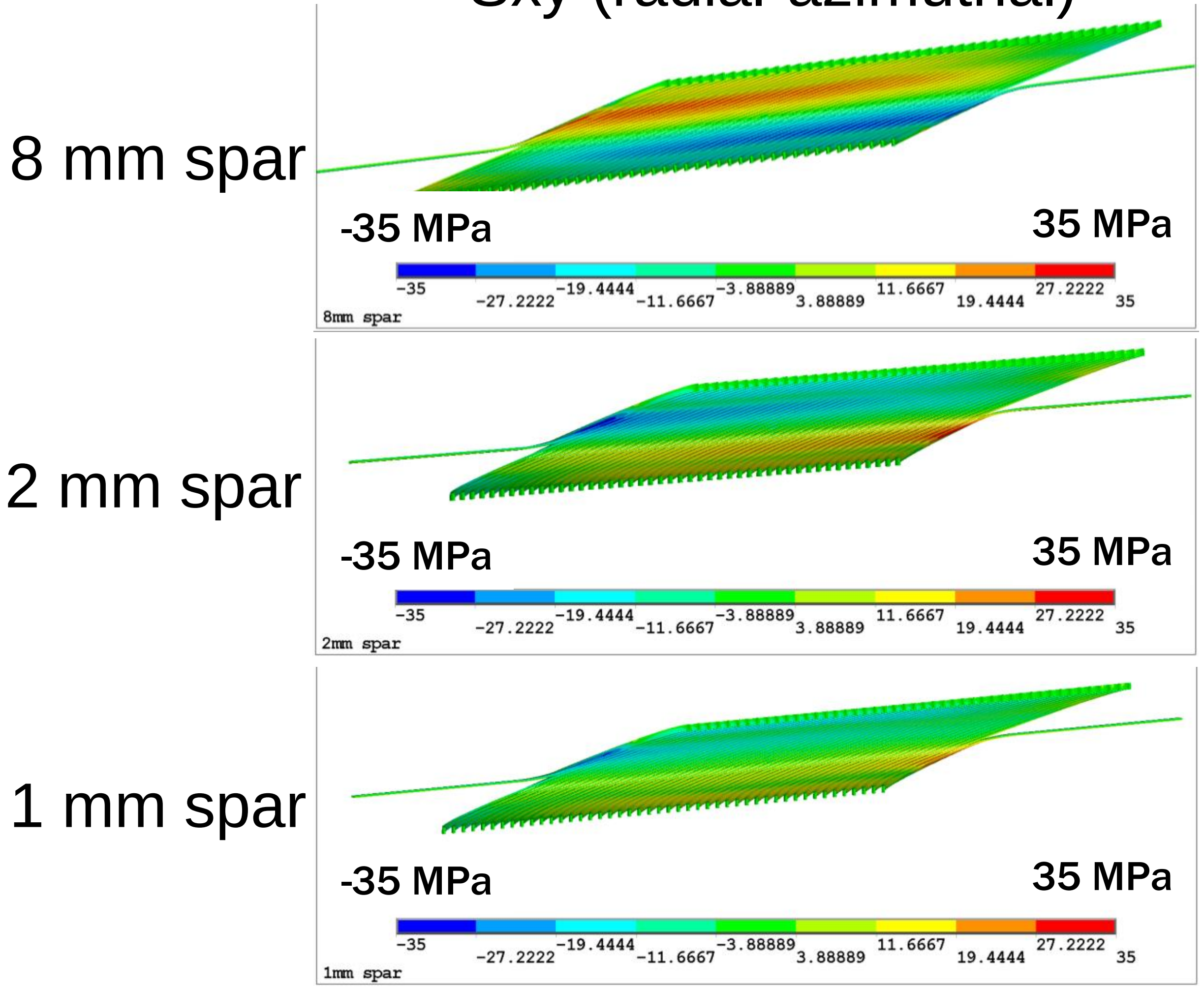
- Based on 2D results SST shell with ~45^o L1/L2 shim might be best option, but not so much difference from other cases
- 2D analysis overestimates bending
  - For short magnet with no straight section the mandrel stiffness is underestimated and total force is overestimated
  - Force direction near pole is not accurate
- 3D analysis is needed for more accurate representation of the insert mechanics
- 2D model could be a good place to start with simulation of debonding interfaces

CCT Subscale Update

D. Arbelaez

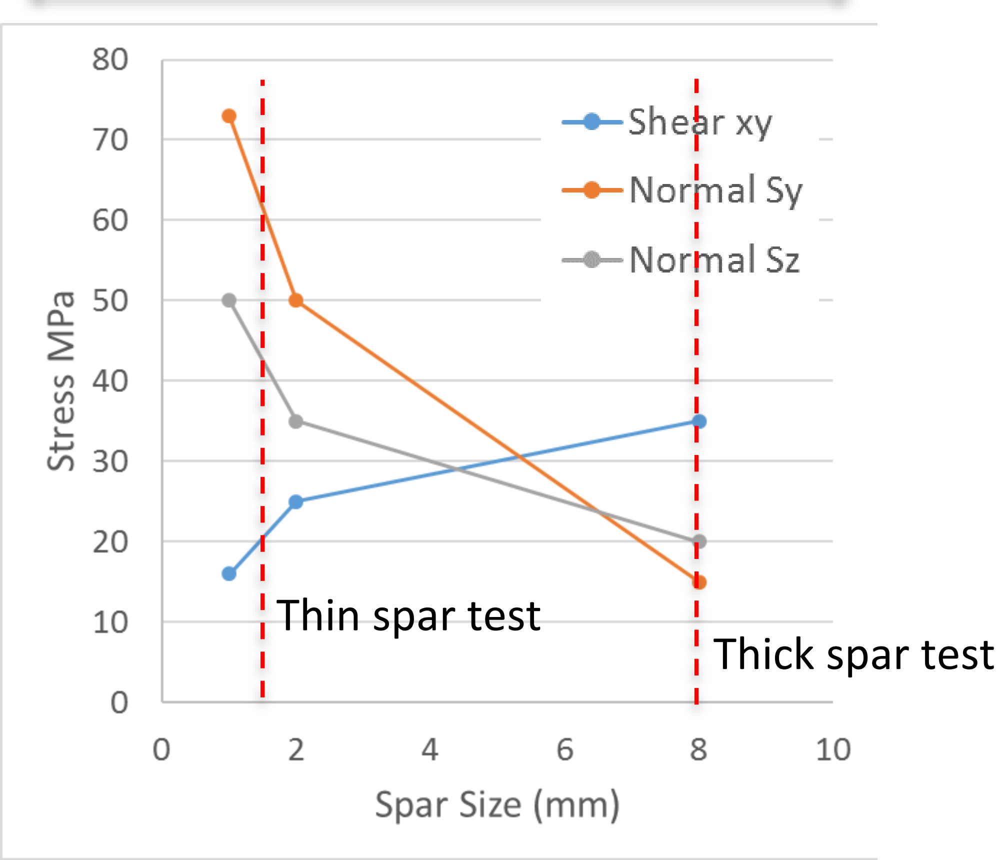
First set of Subscale Magnets will Probe Different Stress States by Adjusting the Spar Thickness of Layer 1

Sxy (radial-azimuthal)



<u>Thin spars</u>
Low shear
High normal

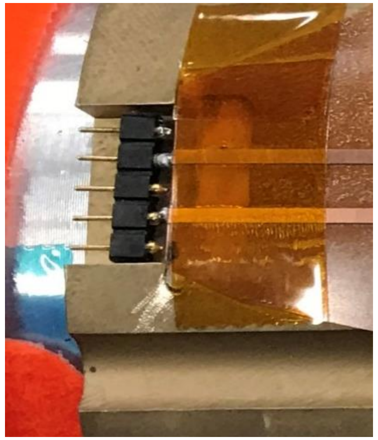
<u>Thick spars</u>
High shear
Low normal

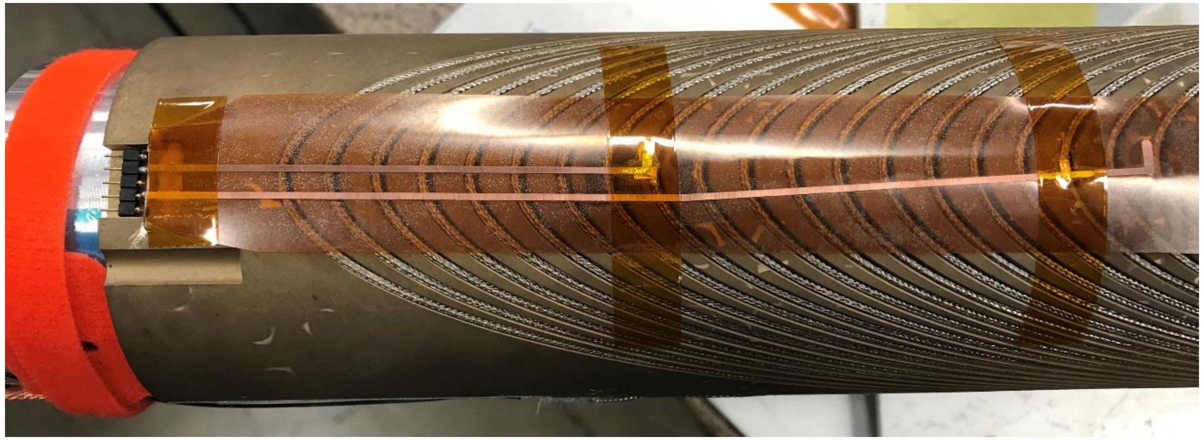


After Lab Shutdown End Fabrication of Thin/Thick Spar Magnets will Continue

- Both outer layer mandrels have been heat treated
- First outer layer mandrel was being prepared for epoxy impregnation
- Thin and Thick spar mandrels were being machined in the LBL main shop

New Mandrels Include Features to Allow for Faster Assembly and Test Setup





Analysis Topics for CCT Subscale

- Thin and thick spar tests exchange normal stress for shear stress
- Want to probe case where both shear and tensile normal stress is low for comparison (may be an optimal situation for CCT)
  - Need thin spar for low shear
  - Need stiff external structure to reduce bending (reduce tensile stress)
- Work on this analysis is planned to take place over the next several weeks