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Mechanical Modelling of the PSI CD1 Dipole

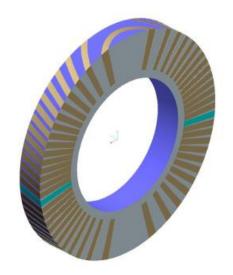
PAUL SCHERRER INSTITUT Presentation Layout

- Mechanical modelling of CCT dipoles
- PSI CD1 dipole
 - Overview
 - Mechanical model
 - Vertical bladder operation
 - Horizontal bladder operation
 - Room temperature
 - Cool down
 - Operation
 - Conductor stress & strain
 - Comparison with 2D analysis
- Full length 3D model
- Conclusions & next



Mechanical modelling of CCT dipoles

■ The conductor path in a CCT layer creates a region of symmetry that is axially periodic. By repeating the symmetry region, a complete CCT layer can be created.



A symmetry region for each layer and a mechanical outer structure of the same axial thickness can be combined to form a symmetry region for the magnet as a whole.

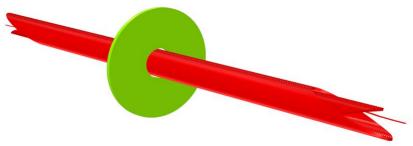






Mechanical modelling of CCT dipoles

■ We take advantage of this periodic structure to reduce the size of the mechanical model, which consists of a single CCT unit (period).



■ The periodic symmetry is enforced by relating the displacement of matching nodes on the two axial faces of the CCT unit as follows:

$$u_{x2} - u_{x1} = 0$$

$$u_{y2} - u_{y1} = 0$$

$$u_{z2} - u_{z1} = \delta_z$$

- The equations couple the transverse degrees of freedom(u_x , u_y) of matching nodes, and relate their axial displacement (u_z) to the constant length δ_z .
- lacktriangle The δ_z parameter allows for a change of axial length between nodes while still enforcing the periodic requirements of the symmetry region.



Mechanical modelling of CCT dipoles

Three different axial boundary conditions set by the choice of δ_z :

- 1. <u>Generalized Plane Strain</u> -> $\delta_z = 0$ for all nodes on the constrained axial faces. The nodes are allowed to move axially, but they displace such that the axial length between them remains unchanged.
- 2. <u>Single Strain</u> -> **single** $\delta_z \neq 0$ for all N nodes on constrained axial faces. The single value for δ_z is determined such that on the outer axial faces $\sum_{i=1}^N F_{z_i} = 0$.

This condition is the closet to the behavior of an impregnated CCT magnet where all components are bonded together.

3. <u>Generalized Plane Stress</u> -> **multiple** $\delta_z \neq 0$ for each component (i.e. coil, shell, etc...) such that net axial force on the face of each component is zero. This condition corresponds to a CCT magnet with perfect slip planes between components.

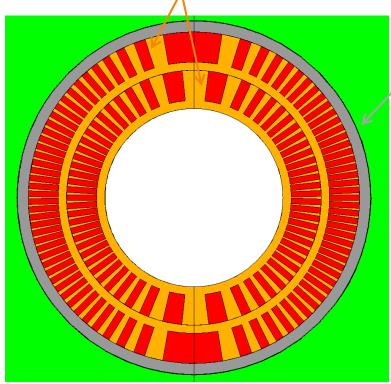


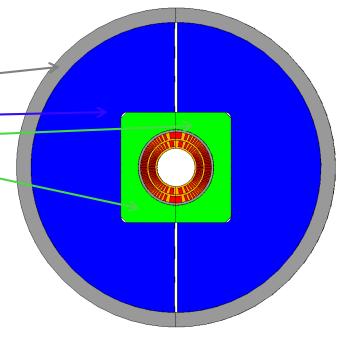
- PSI is contributing to the FCC project by studying the feasibility of a high-field accelerator dipole based on the CCT design.
- In the framework of this R&D activity, PSI is designing a model dipole with the following characteristics:
 - Single aperture
 - 2 layers
 - Inner bore: 50 mm
 - Target field: 10 T (with 20% current margin)
 - Cable: 11 T Rutherford cable for LHC Hi-Lumi
 - Although scissor laminations are envisaged to provide radial pre-stress on the mid-plane in the FCC dipole, the PSI CD1 dipole relies on a bladder &keys mechanical structure for ease of assembly and reduction of costs.



PSI CD1 dipole – Mechanical model

- The complete mechanical model features:
 - Aluminum outer shell –
 - Split iron yoke ——
 - Stainless steel pads =
 - Kapton layer
 - Aluminum protective shell
 - Al-bronze mandrels for the coils





- Sliding contact between:
 - CCT layers
 - CCT coil protective shell
- Bonded contact between:
 - Protective shell Kapton
- Standard contact ($\mu = 0.2$) between:
 - Pads yoke
- No friction contact ($\mu = 0$) between:
 - Kapton pads
 - Yoke outer shell



PSI CD1 dipole – Vertical bladders operation



Component	σ _r [MPa]	σ _θ [MPa]
Conductor 1	-17	-43
Former 1	36	-119
Conductor 2	-27	-29
Former 2	-41	-77

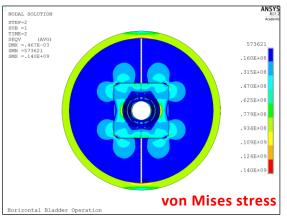
NODAL SOLUTION	ANSY
STEP=1 SUB =1 TIME=1 SX (AVG)	Acader
SX (AVG) RSYS=1 DMX =.785E-04	408E+08
SMN =408E+08 SMX =.190E+08	342E+08
	275E+08
	209E+08
	142E+08
	759E+07
	-944961
	.570E+07
	.123E+08
	.190E+08
	Acry
	Radial stress
Vertical Bladder Operation	2 211011 0 01 0 00

Component	σ _{νΜ} [MPa]	σ _{limit} [MPa]
Conductor 1	36	150
Former 1	107	250
Conductor 2	23	150
Former 2	65	250
Prot. Shell	83	480
Pads	159	350
Yoke	190	180
Outer shell	23	480

NODAL SOLUTION	ANSY:
STEP=1 SUB =1 TIME=1	Academ
SY (AVG) RSYS=1 DMX = .785E-04	119E+09
SMN =119E+09 SMX =.936E+08	952E+08
	716E+08
	480E+08
	244E+08
	-818244
	.228E+08
	.464E+08
	.700E+08
	.936E+08
	Azimuthal stress
Vertical Bladder Operation	Azimuthai Stress



PSI CD1 dipole – Horizontal bladders operation



Component	σ _r [MPa]	σ _θ [MPa]
Conductor 1	-11	-30
Former 1	-27	-113
Conductor 2	-13	-22
Former 2	-24	-73

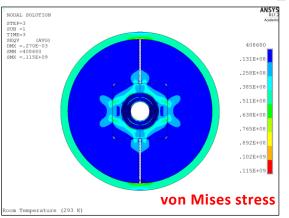
NODAL SOLUTION	ANS)
STEP=2 SUB =1 TIME=2 SX (AVG)	
RSYS=1 DMX =.457E-04	238E+08
SMN =238E+08 SMX =.764E+07	203E+08
	168E+08
	133E+08
	983E+07
	633E+07
	284E+07
	653088
	.415E+07
No.	.764E+07
	Radial stress
Horizontal Bladder Operation	maanan seness

Component	σ _{νΜ} [MPa]	σ _{limit} [MPa]
Conductor 1	23	150
Former 1	102	250
Conductor 2	16	150
Former 2	65	250
Prot. Shell	78	480
Pads	140	350
Yoke	109	180
Outer shell	129	480

NODAL SOLUTION	ANSY R17.
STEP=2 SUB =1 TIME=2	Açademi
SY (AVG) RSYS=1	113E+09
DMX = .457E-04 SMN = .113E+09 SMX = .232E+08	977E+08
	826E+08
	675E+08
	524E+08
	373E+08
	221E+08
	701E+07
X X	.811E+07
	.232E+08
	Azimuthal stress
Horizontal Bladder Operation	,a tilai 5ti C55



PSI CD1 dipole – Room temperature



Component	σ _r [MPa]	σ _θ [MPa]
Conductor 1	-8	-19
Former 1	-21	-39
Conductor 2	-10	-14
Former 2	-18	-27

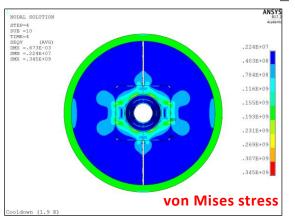
NODAL SOLUTION	ANSY
STEP=3 SUB =1 TIME=3	Acade
SX (AVG) RSYS=1 DMX = .254E-04	182E+08
DMX = .254E-04 SMN =182E+08 SMX = .511E+07	156E+08
M. M.	130E+08
	104E+08
	784E+07
	525E+07
	266E+07
	-67820.3
	.252E+07
	.511E+07
	Radial stress

Component	σ _{νм} [MPa]	σ _{limit} [MPa]
Conductor 1	15	150
Former 1	37	250
Conductor 2	10	150
Former 2	28	250
Prot. Shell	115	480
Pads	85	350
Yoke	62	180
Outer shell	73	480

NODAL SOLUTION	ANSYS R17.
STEP=3 SUB =1 TIME=3	Academi
SY (AVG) RSYS=1	391E+08
DMX = .254E-04 SMN =391E+08 SMX = .134E+08	332E+08
	274E+08
	216E+08
	158E+08
	994E+07
	411E+07
	.172E+07
	.754E+07
	.134E+08
	Azimuthal stress
oom Temperature (293 K)	Azimuthai stress



PSI CD1 dipole – Cool down



Component	σ _r [MPa]	σ _θ [MPa]
Conductor 1	-21	-73
Former 1	-61	-172
Conductor 2	-23	-49
Former 2	-81	-199

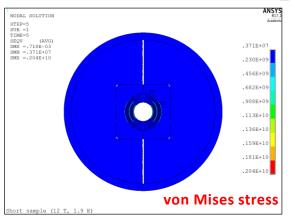
NODAL SOLUTION			ANS
STEP=4 SUB =10 TIME=4 SX (AVG)			Acade
RSYS=1 DMX =.301E-03		A Che	509E+08
SMN =509E+08 SMX =.287E+08			421E+08
	March 1		332E+08
			-,244E+08
			155E+08
		EEV	668E+07
			.216E+07
			.110E+08
		Dead	.199E+08
			.287E+08
		HILL	
		Rad	ial stress
ooldown (1.9 K)			

Component	σ _{νΜ} [MPa]	σ _{limit} [MPa]
Conductor 1	59	200
Former 1	184	400
Conductor 2	44	200
Former 2	181	400
Prot. Shell	162	690
Pads	345	1050
Yoke	242	720
Outer shell	189	690

NODAL SOLUTION	ANSY:
STEP=4 SUB =10 TIME=4	Academ
SY (AVG) RSYS=1 DMX =,301E-03	161E+09
SMN =161E+09 SMX =.138E+09	128E+09
	-,947E+08
	615E+08
	282E+08
	.502E+07
	.383E+08
	.715E+08
	.105E+09
	.138E+09
	Azimuthal stress
cooldown (1.9 K)	Aziiiiutiiai Sti ess



PSI CD1 dipole – Operation



Component	σ _r [MPa]	σ _θ [MPa]
Conductor 1	-113	-101
Former 1	-383	284
Conductor 2	-135	-120
Former 2	-315	-255

ANSY: R17 Academ
383E+09_
333E+09
282E+09
231E+09
180E+09
-,129E+09
787E+08
279E+08
.229E+08
.737E+08
Radial stress

Component	σ _{νм} [MPa]	σ _{limit} [MPa]
Conductor 1	123	200
Former 1	380	400
Conductor 2	156	200
Former 2	437	400
Prot. Shell	2040	690
Pads	281	1050
Yoke	320	720
Outer shell	207	690

NODAL SOLUTION	ANSYS R17.3
STEP=5 SUB =1 TIME=5 SY (AVG)	Azademir
RSYS=1 DMX =, 371E-03	227E+09
SMN =227E+09 SMX =.284E+09	170E+09
	113E+09
	567E+08
	32190.2
	.568E+08
	.114E+09
223	.170E+09
	.227E+09
	.284E+09
	A missouth of stages
hort sample (12 T, 1.9 K)	Azimuthal stress



PSI CD1 dipole – Conductor stress & strain

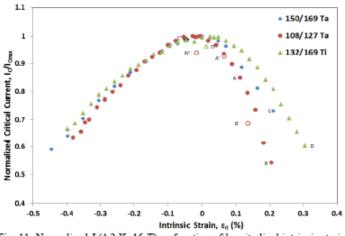
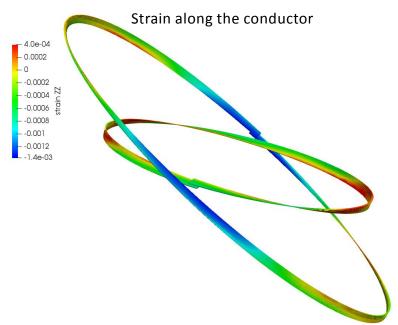
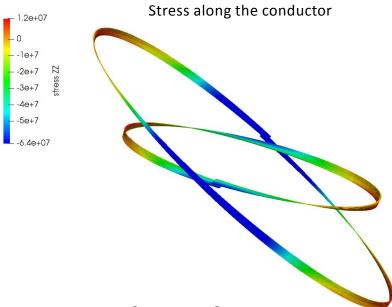


Fig. 11. Normalized $I_c(4.2 \text{ K}, 15 \text{ T})$ as function of longitudinal intrinsic strain over channel CH1 for 0.7 mm samples of Ta-alloyed 108/127 RRP® (RRP1), Ta-alloyed 150/169 RRP® (RRP2) and Ti-doped 132/169 RRP® (RRP4).





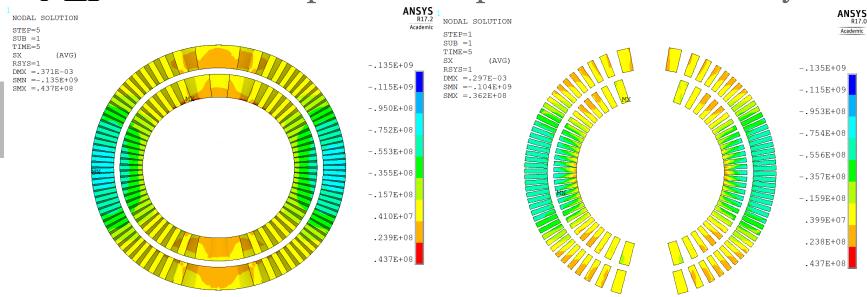
Strain reference from:

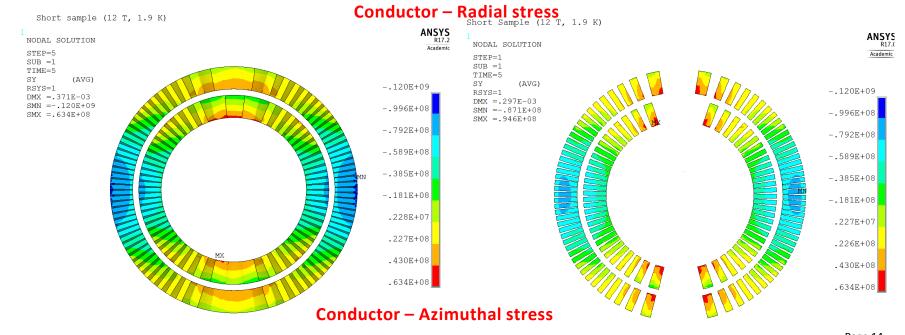
"Progress in Nb3Sn RRP strand studies and Rutherford cable development at FNAL, Barzi E. et al., FERMILAB-CONF-13-298-TD

 Peak strain along the conductor resulting in minimal current degradation based on measured reference values



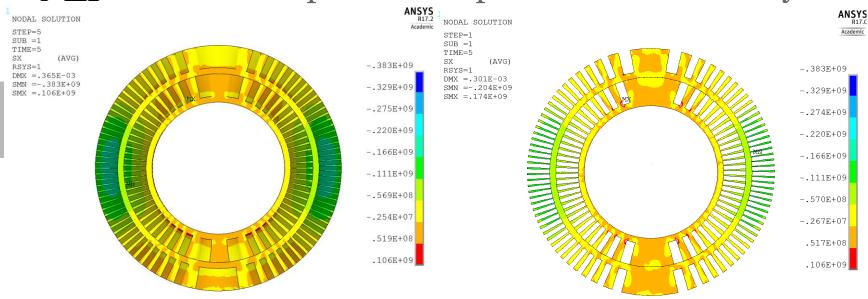
PSI CD1 dipole - Comparison with 2D analysis

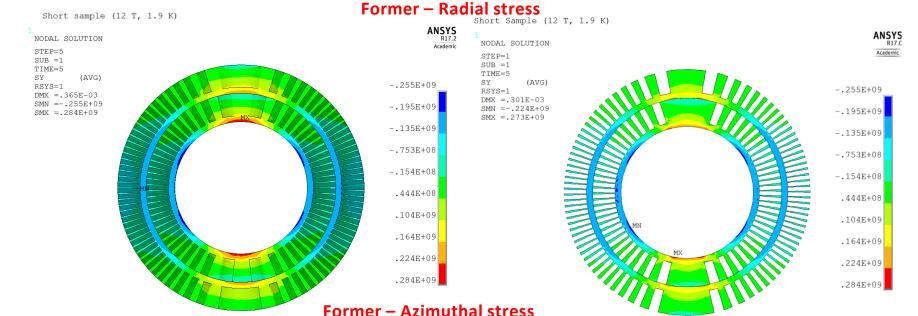






PSI CD1 dipole - Comparison with 2D analysis

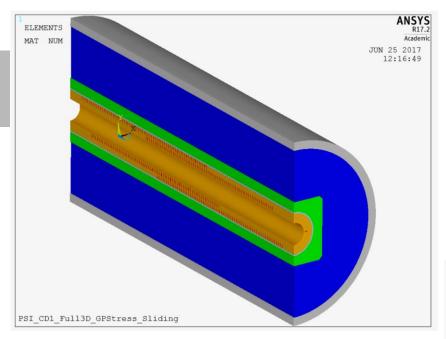




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Short sample (12 T, 1.9 K)

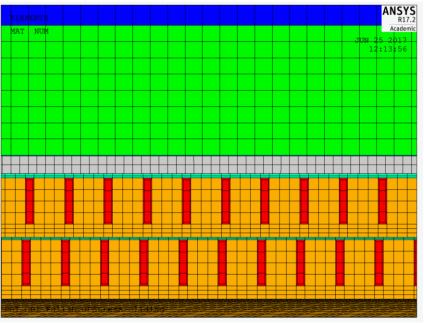


Full length 3D model



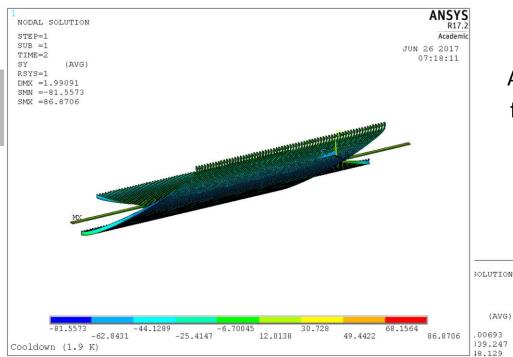
- Future developments:
 - Epoxy layer around conductor
 - Anisotropic epoxy properties

- Development of the full length 3D model of the PSI CD1 is ongoing
- Full coil geometry and mechanical structure already generated in ANSYS
- Definition of contacts and solution steps in progress

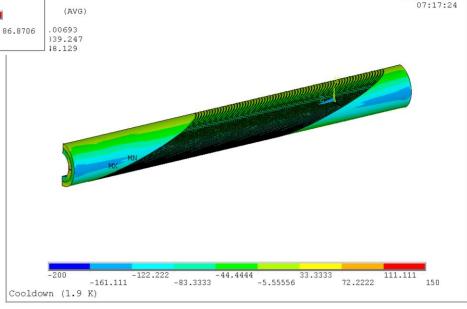




Full length 3D model



Azimuthal stress in conductor and former in the PSI CD1 dipole with bonded layers



ANSYS

Academic JUN 26 2017

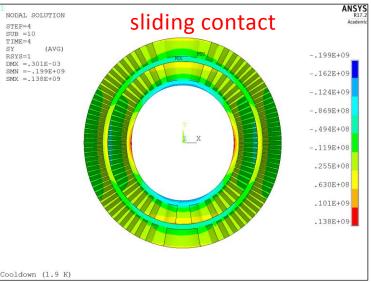


Full length 3D model

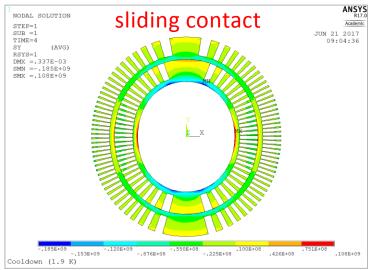
Comparison of stress in the former at the center of the coil after cool down



3D slice model -



2D model -





Conclusions & next

- Developed a 3D CCT slice model with sliding interface between CCT layers and Generalized Plane Stress boundary conditions
- Other boundary and layer-to-layer interface conditions tested as well (results not presented)
- Good comparison between 2D and 3D analysis: fast 2D model can be used for preliminary mechanical analysis
- Radial and azimuthal stress in conductor and former below max allowed values at each assembly and operation step
- Excessive vonMises stress in protective shell during operation likely related to BCs. To be further analyzed with full 3D model
- Full length 3D model of the CD1 dipole under development to understand stress distribution along the magnet