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Mechanical Modelling of the PSI CD1 Dipole

CERN - 26 June 2017

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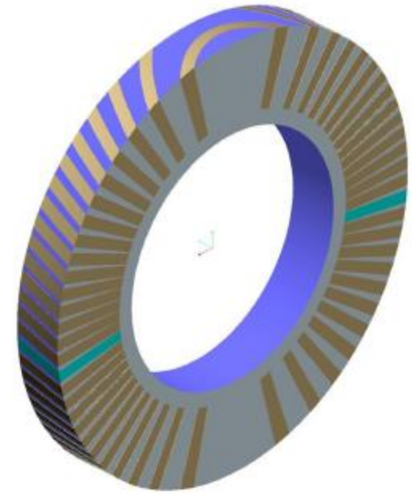
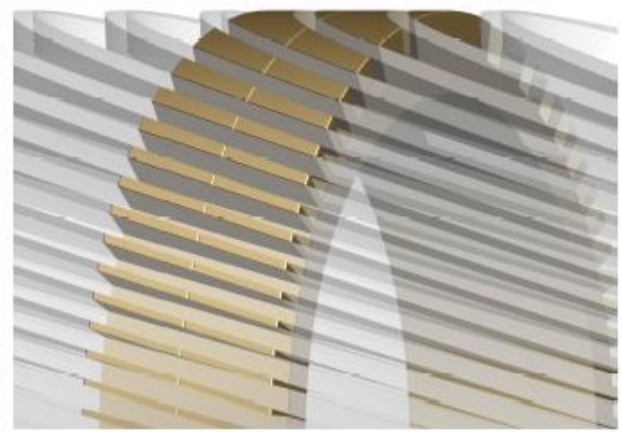
Mechanical modelling of CCT dipoles

- 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.



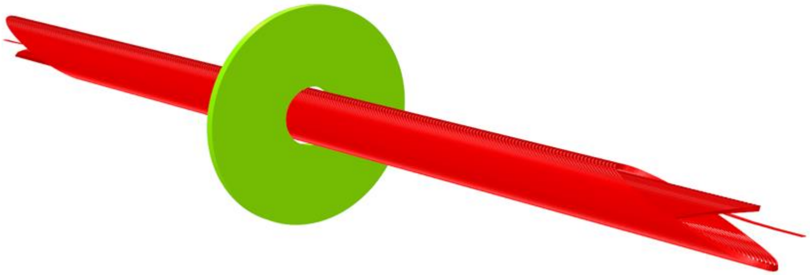
- A symmetry region for each layer and a mechanical outer structure of the same axial thickness can be combined to form a symmetry region for the magnet as a whole.



Courtesy of L. Brouwer

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.
- 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. Generalized Plane Strain -> $\boldsymbol{\delta_z = 0}$ 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. Single Strain -> **single** $\boldsymbol{\delta_z \neq 0}$ 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.

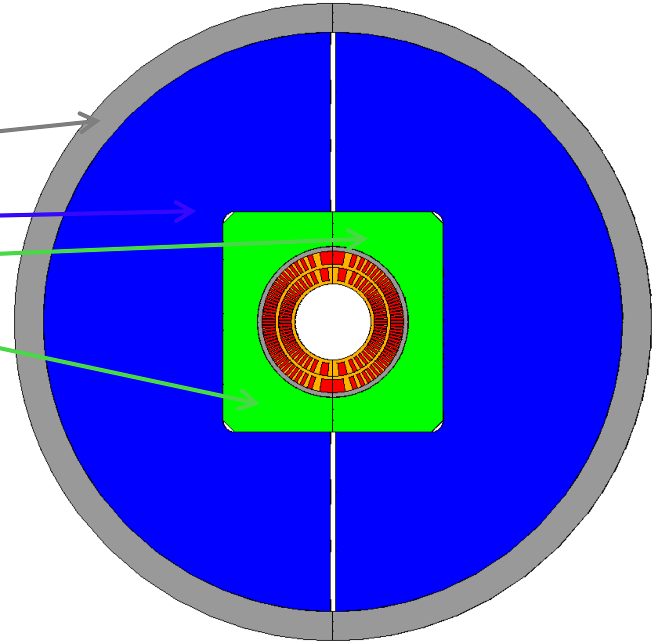
3. Generalized Plane Stress -> **multiple** $\boldsymbol{\delta_z \neq 0}$ for each component (i.e. coil, shell, etc…) such that net axial force on the face of each component is zero. This condition corresponds to a CCT magnet with perfect slip planes between components.

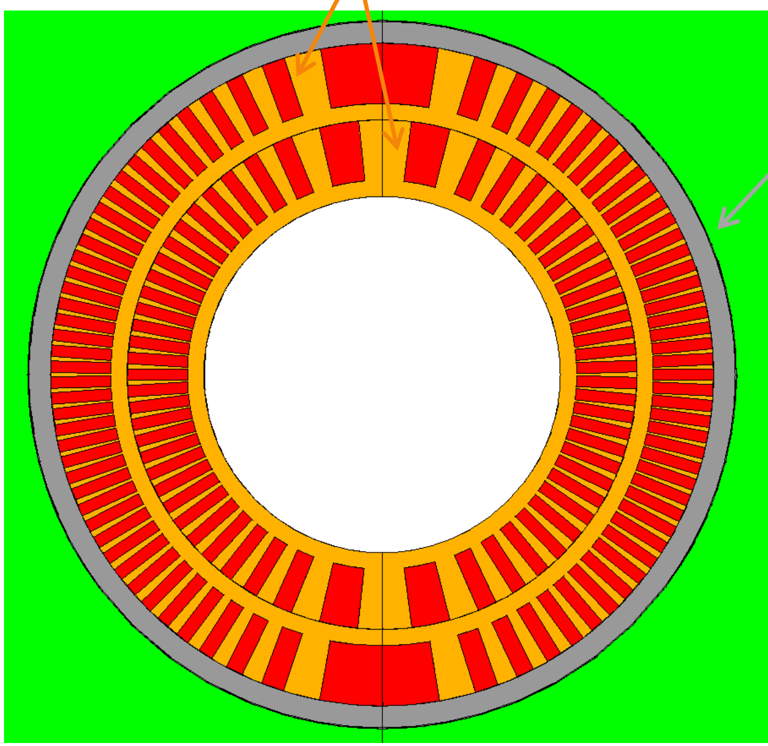
PSI CD1 dipole - Overview

- 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

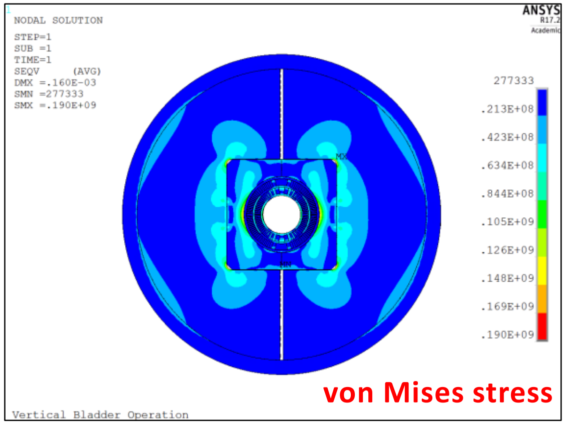
- The complete mechanical model features:
  - Aluminum outer shell
  - Split iron yoke
  - Stainless steel pads
  - Kapton layer
  - Aluminum protective shell
  - Al-bronze mandrels for the coils

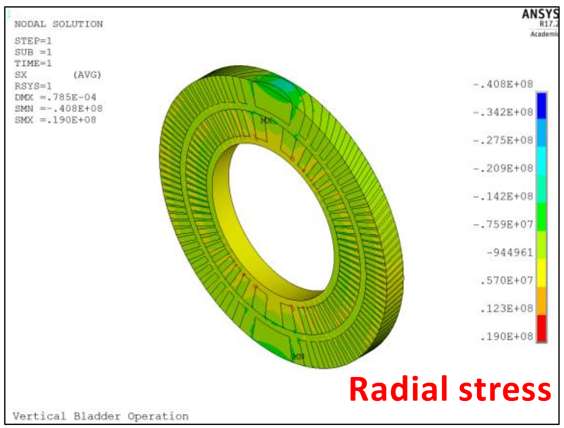


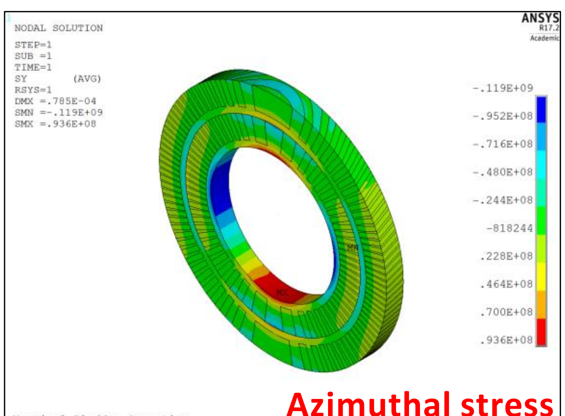


- Sliding contact between:
  - CCT layers
  - CCT coil – protective shell
- Bonded contact between:
  - Protective shell - Kapton
- Standard contact (μ = 0.2) between:
  - Pads – yoke
- No friction contact (μ = 0) between:
  - Kapton - pads
  - Yoke – outer shell

PSI CD1 dipole – Vertical bladders operation



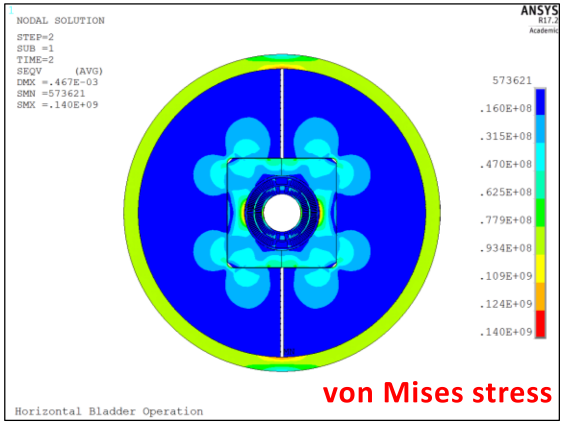


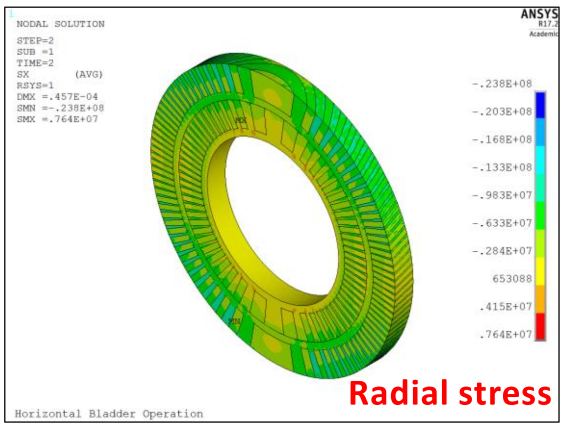


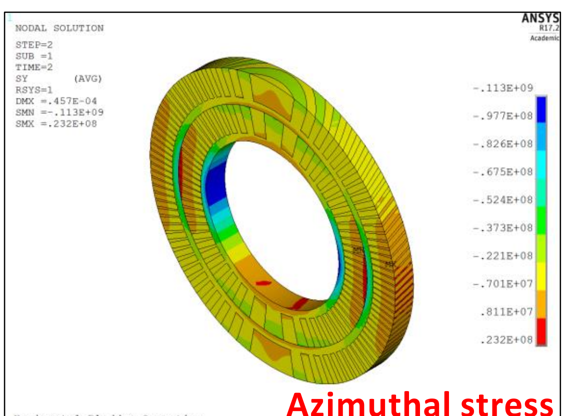
Component	σ_r [MPa]	σ_θ [MPa]
Conductor 1	-17	-43
Former 1	36	-119
Conductor 2	-27	-29
Former 2	-41	-77

Component	σ_{VM} [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

PSI CD1 dipole – Horizontal bladders operation



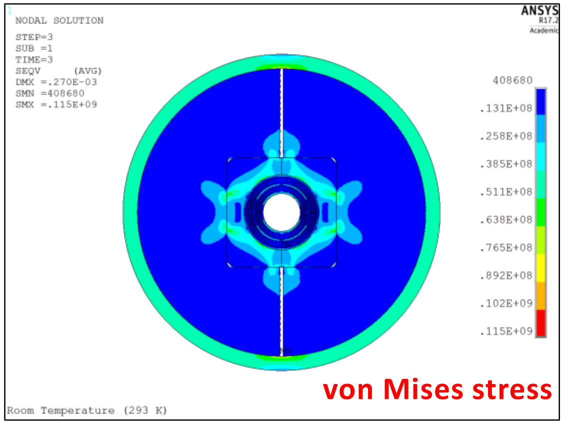


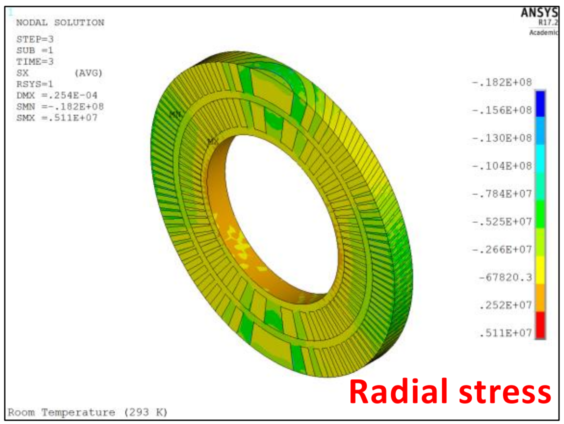


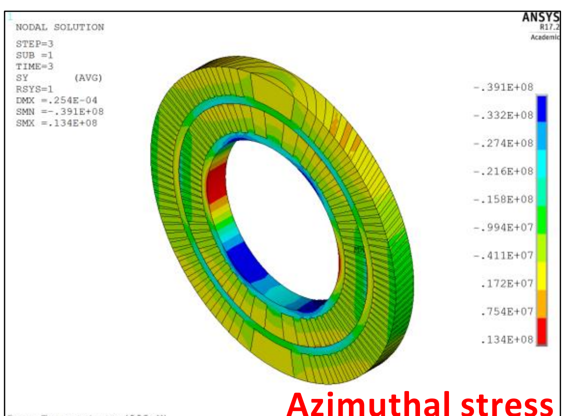
Component	σ_r [MPa]	σ_θ [MPa]
Conductor 1	-11	-30
Former 1	-27	-113
Conductor 2	-13	-22
Former 2	-24	-73

Component	σ_{VM} [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

PSI CD1 dipole – Room temperature



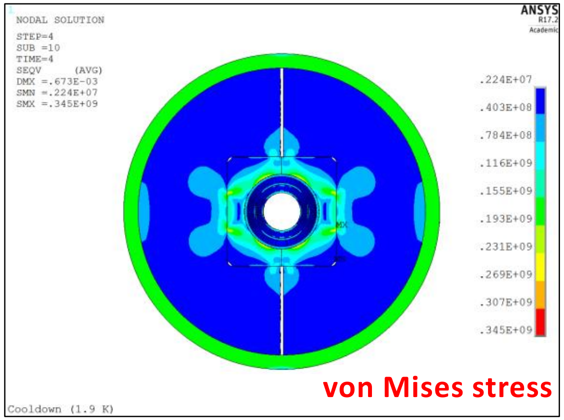


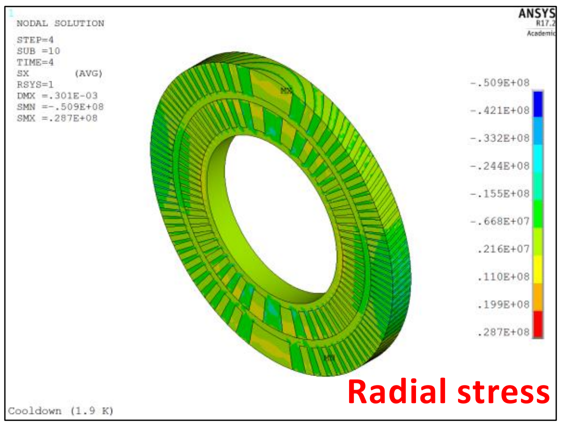


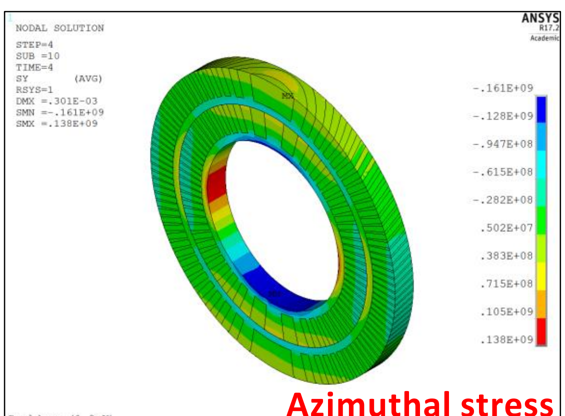
Component	σ_r [MPa]	σ_θ [MPa]
Conductor 1	-8	-19
Former 1	-21	-39
Conductor 2	-10	-14
Former 2	-18	-27

Component	σ_{VM} [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

PSI CD1 dipole – Cool down



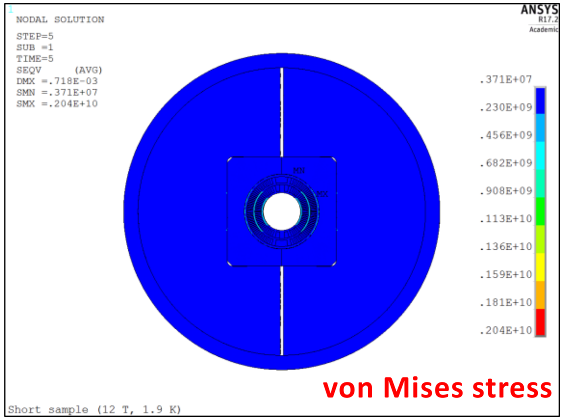


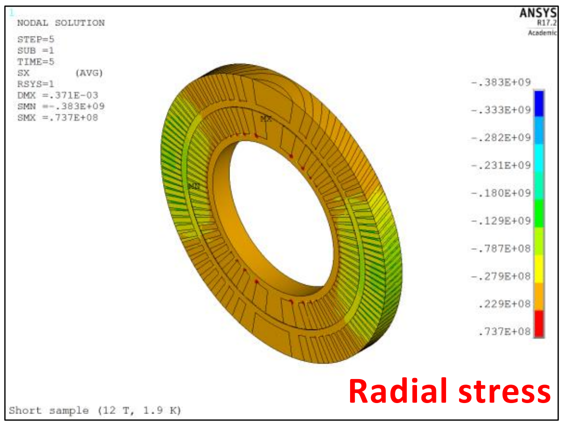


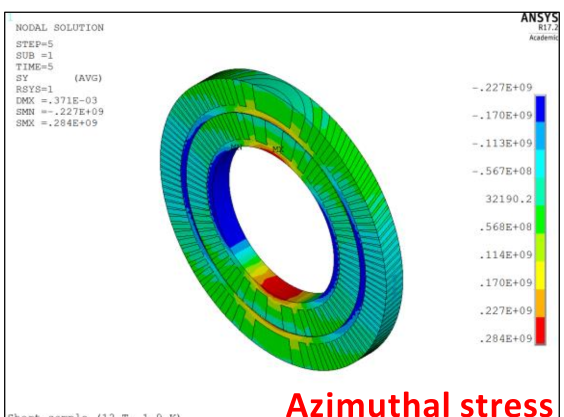
Component	σ_r [MPa]	σ_θ [MPa]
Conductor 1	-21	-73
Former 1	-61	-172
Conductor 2	-23	-49
Former 2	-81	-199

Component	σ_{VM} [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

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

Component	σ_{VM} [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

PSI CD1 dipole – Conductor stress & strain

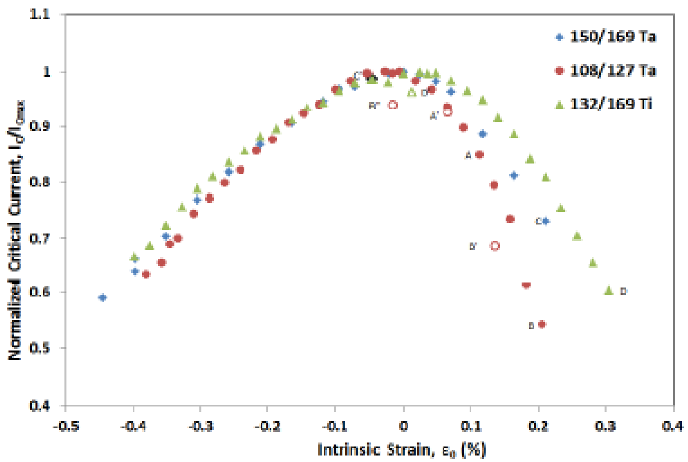
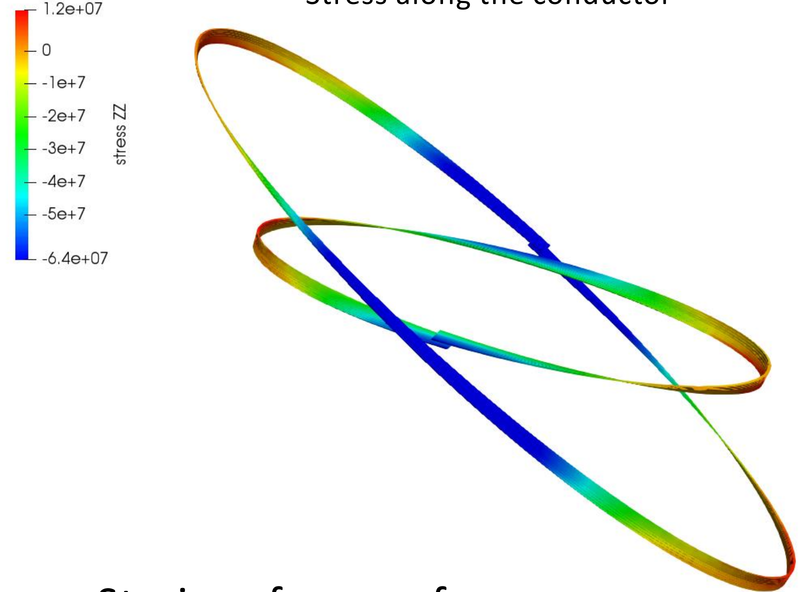
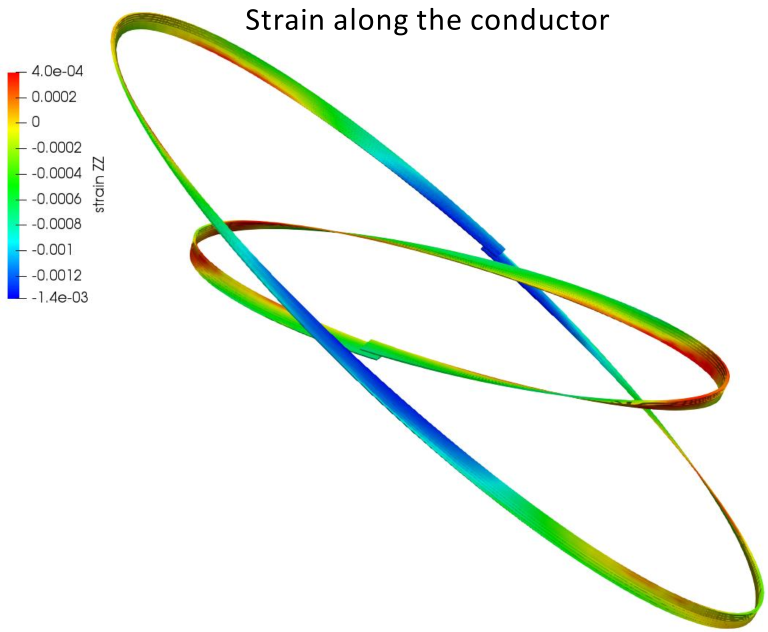


Fig. 11. Normalized I_c(4.2 K, 15 T) as function of longitudinal intrinsic strain over channel CH1 for 0.7 mm samples of Ta-alloyed 108/127 RRP® (RRP1), Ta-alloyed 150/169 RRP® (RRP2) and Ti-doped 132/169 RRP® (RRP4).

Stress along the conductor



Strain along the conductor

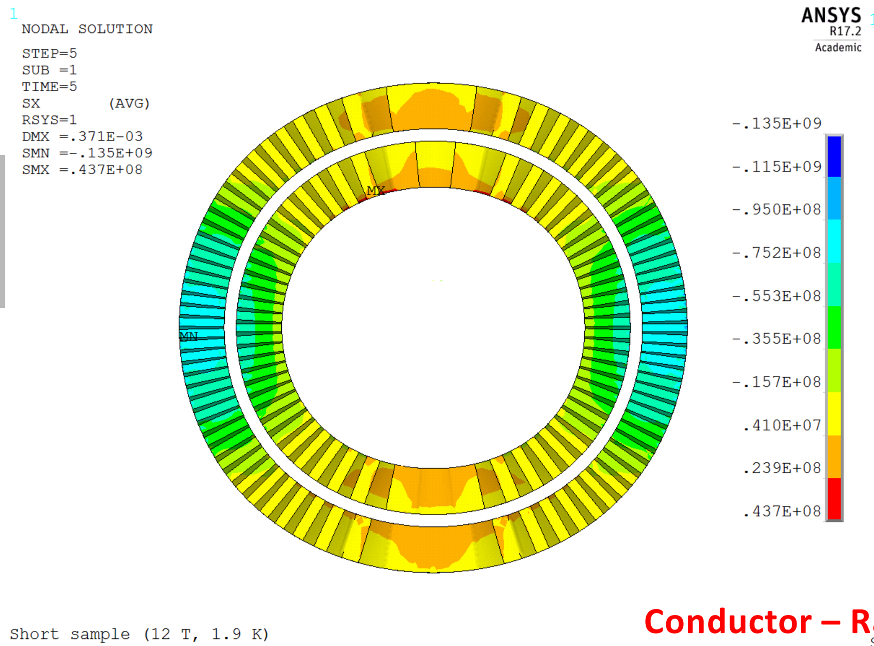


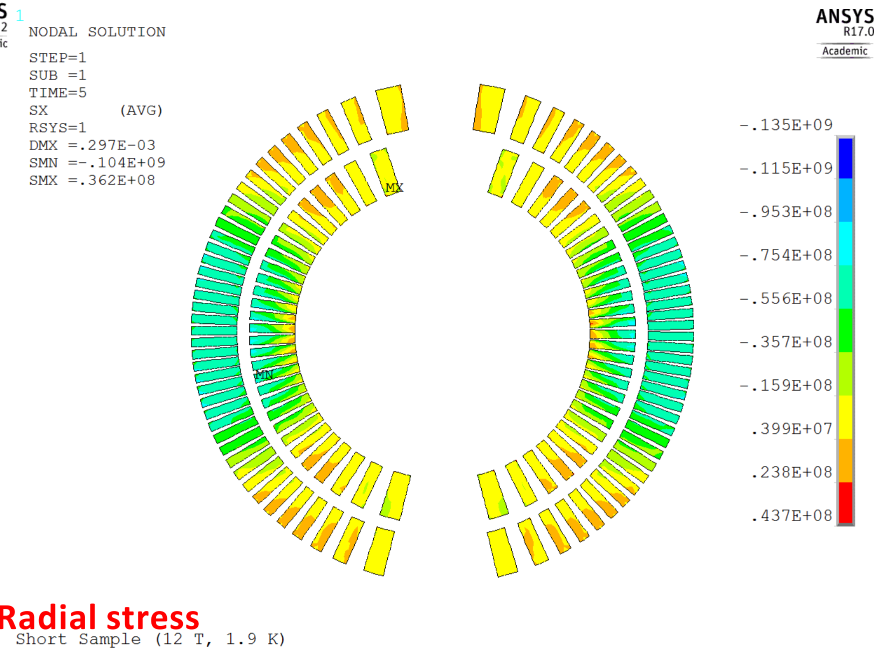
- Strain reference from:

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

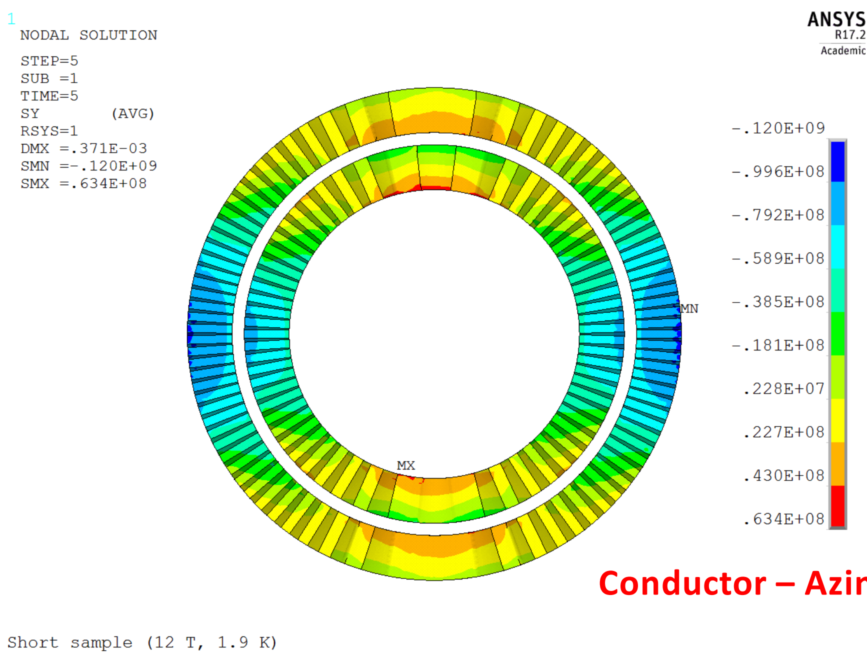
- Peak strain along the conductor resulting in minimal current degradation based on measured reference values

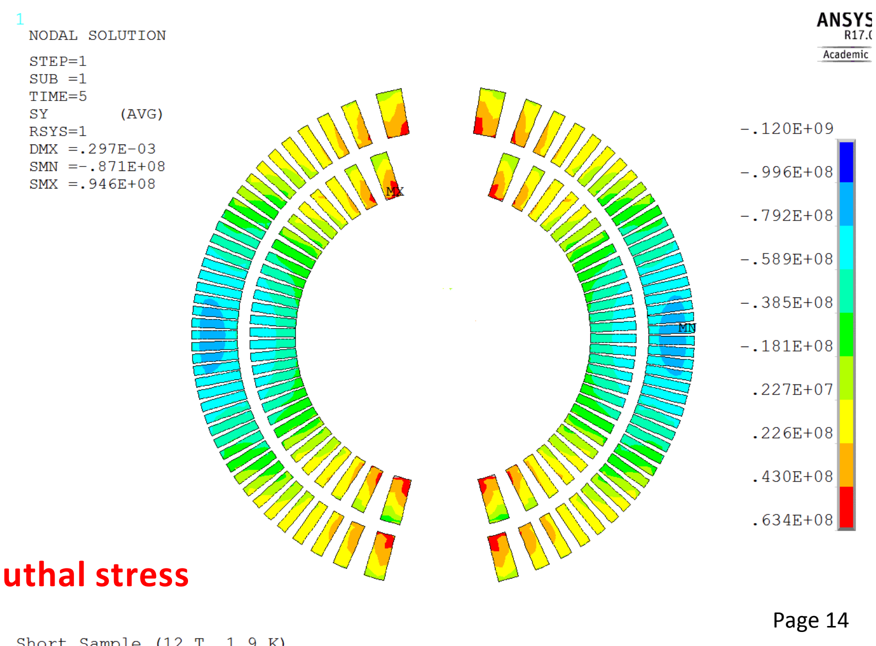
PSI CD1 dipole – Comparison with 2D analysis





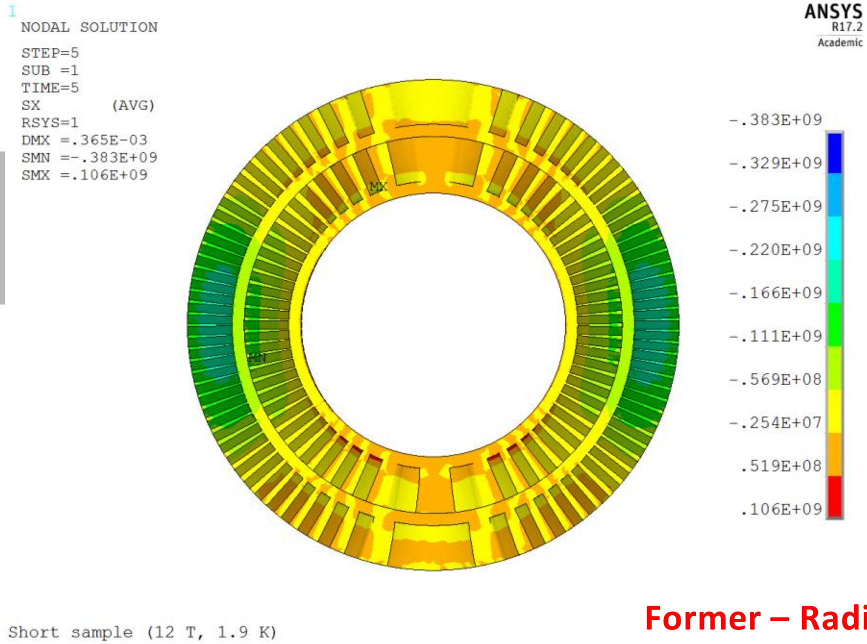
Conductor – Radial stress

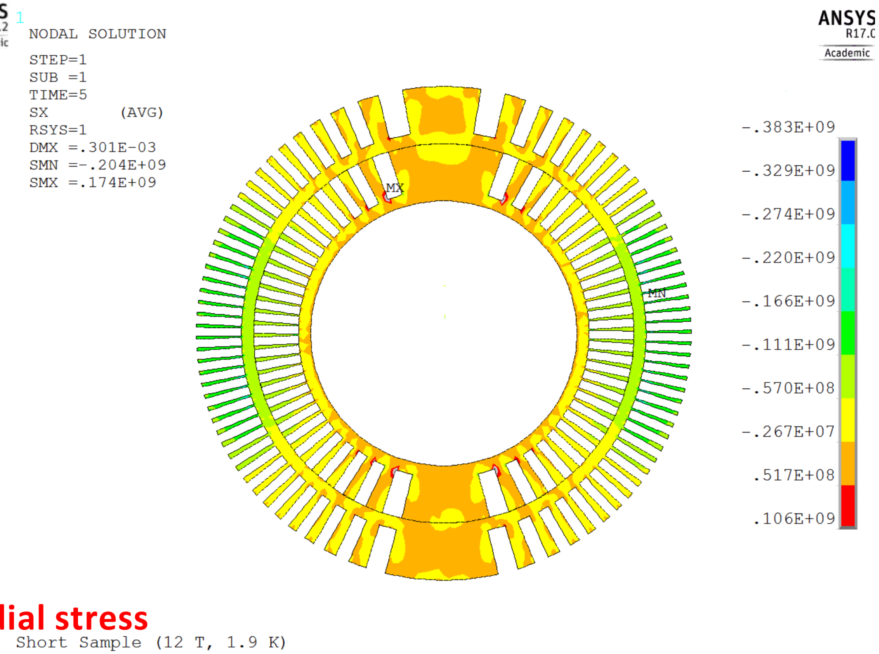




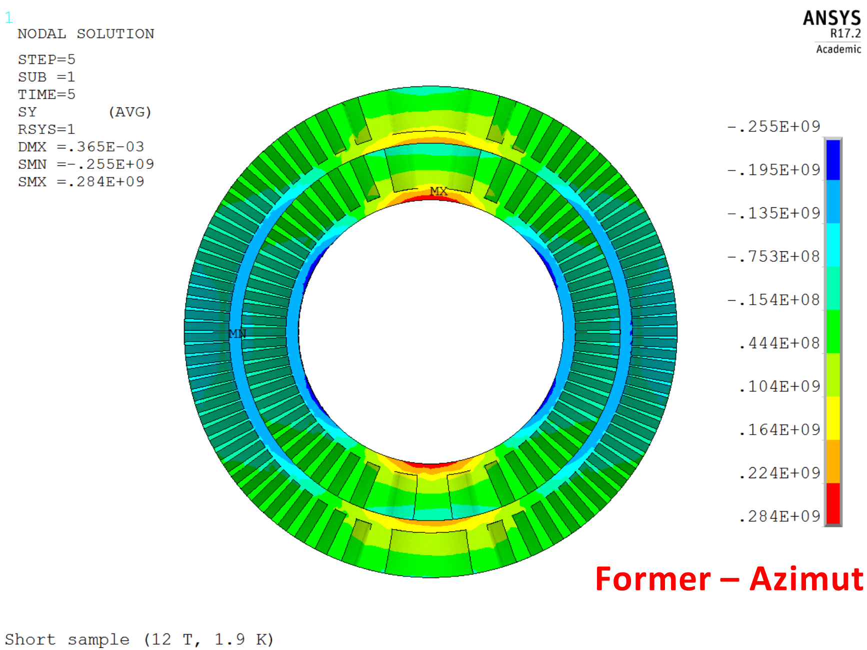
Conductor – Azimuthal stress

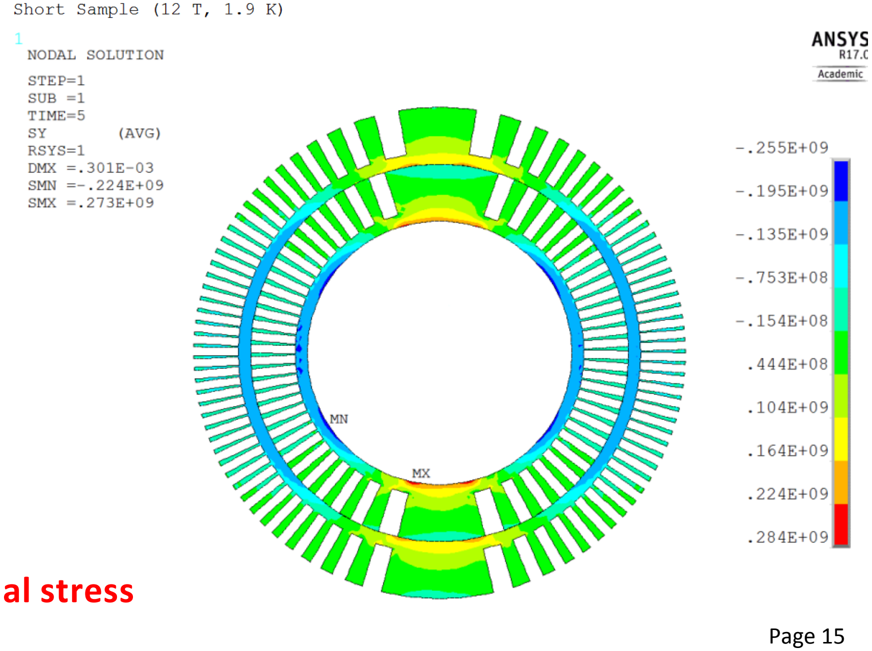
PSI CD1 dipole – Comparison with 2D analysis





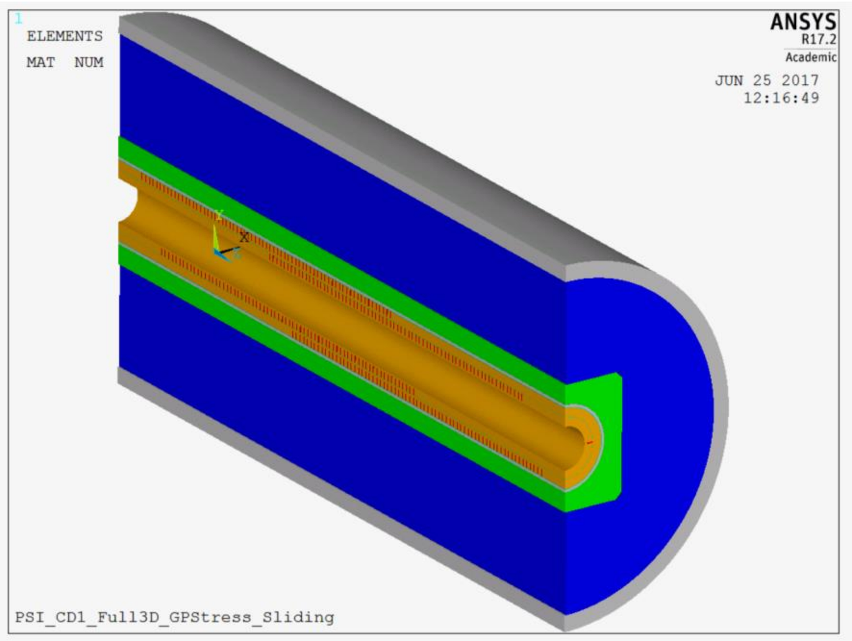
Former – Radial stress



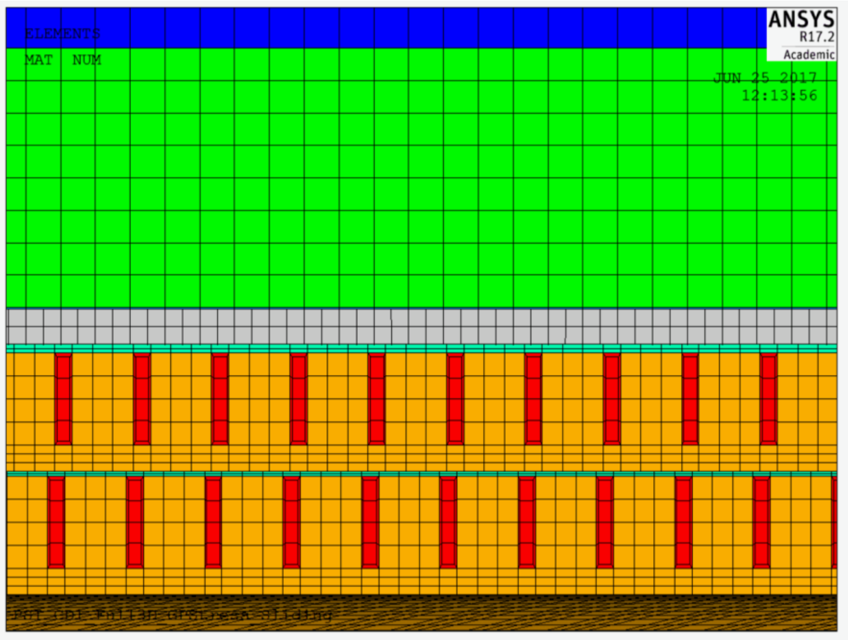


Former – Azimuthal stress

Full length 3D model

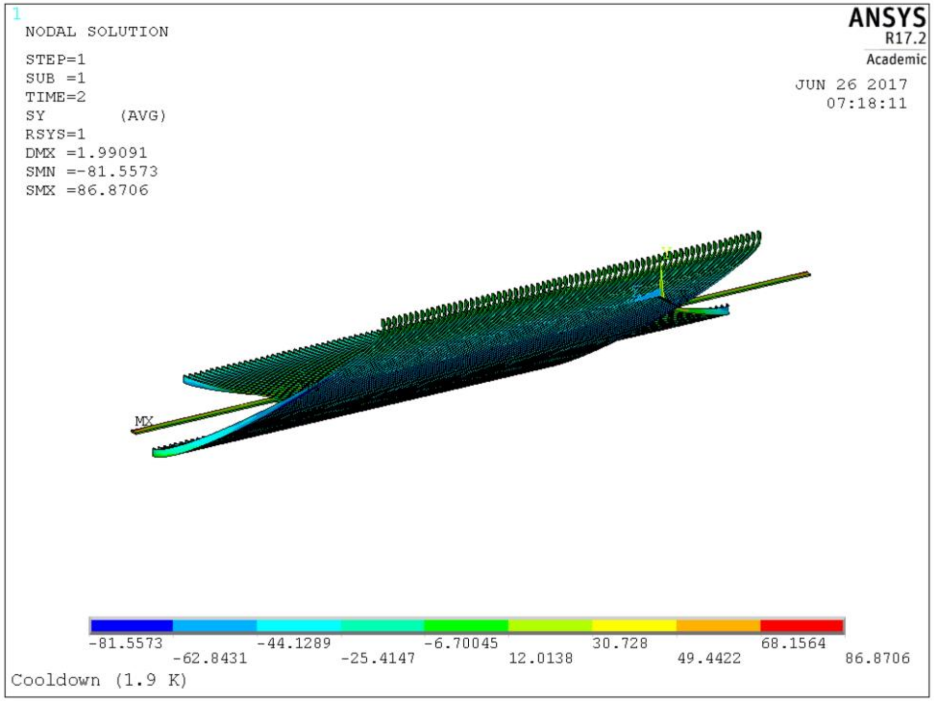


- Development of the full length 3D model of the PSI CD1 is ongoing
- Full coil geometry and mechanical structure already generated in ANSYS
- Definition of contacts and solution steps in progress

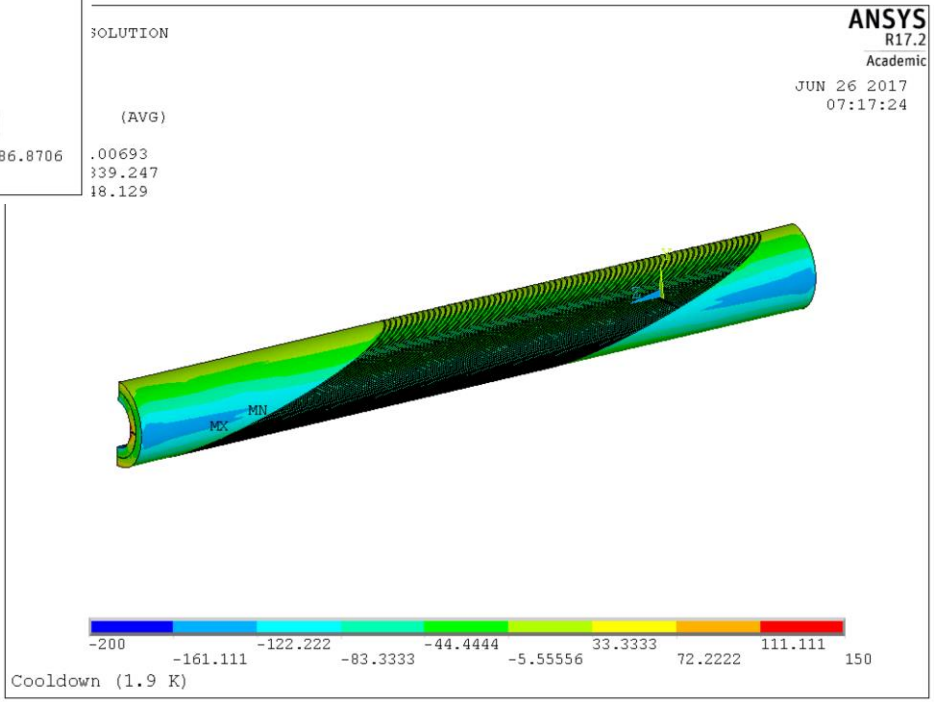


- Future developments:
  - Epoxy layer around conductor
  - Anisotropic epoxy properties

Full length 3D model



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



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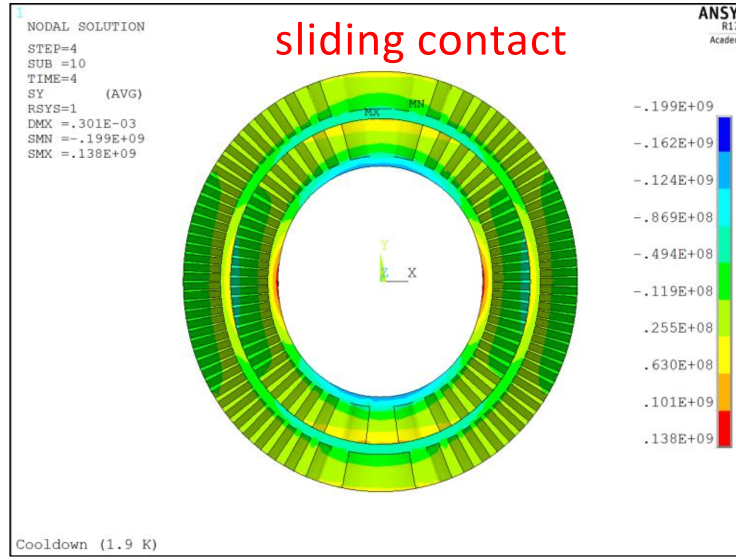
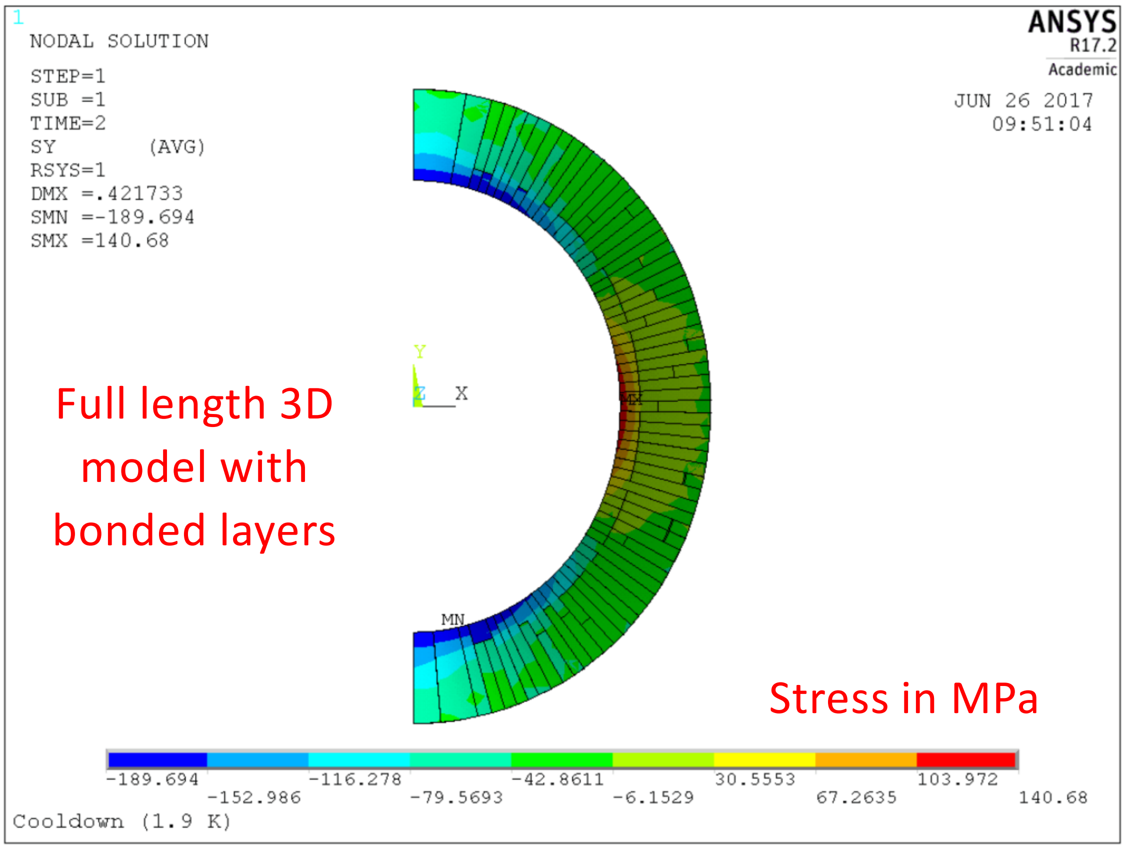
Full length 3D model

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

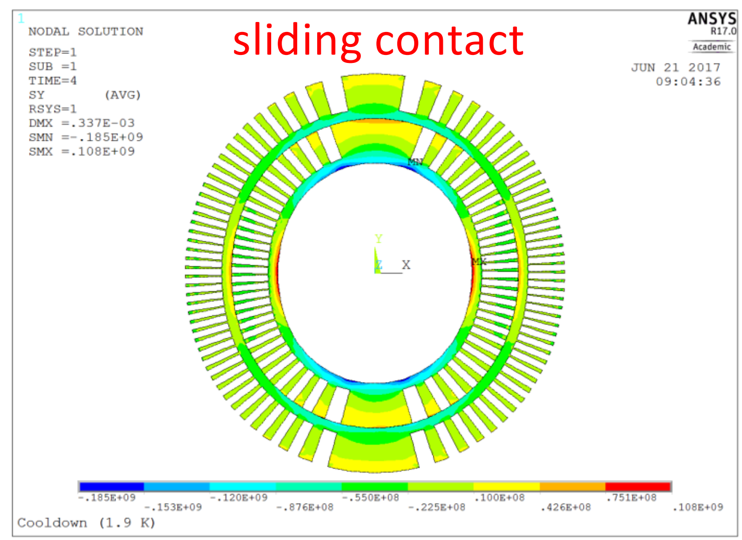
3D slice model - sliding contact



Full length 3D model with bonded layers



2D model - sliding contact



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