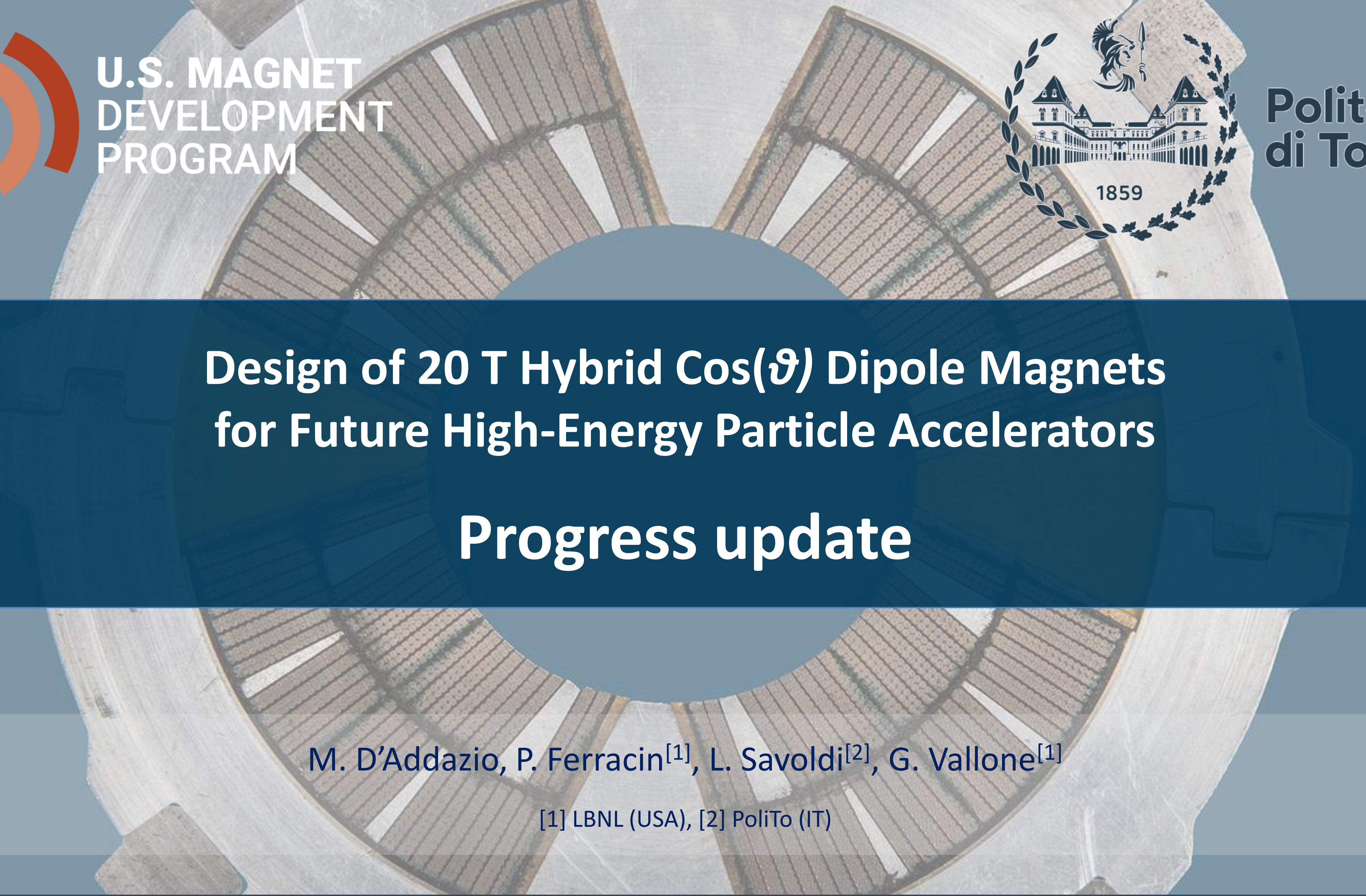
U.S. MAGNET
DEVELOPMENT
PROGRAM

Politecnico
di Torino
1859



Design of 20 T Hybrid Cos(*ϑ*) Dipole Magnets for Future High-Energy Particle Accelerators

Progress update

M. D’Addazio, P. Ferracin[1], L. Savoldi[2], G. Vallone[1]

[1] LBNL (USA), [2] PoliTo (IT)

U.S. DEPARTMENT OF ENERGY | Office of Science

12/06/2023

Acknowledgements

US MDP (in particular the “20 T working group”)

- LBNL: D. Arbelaez, E. Anderssen, L. Brouwer, M. Naus, L. Garcia Fajardo, J.L. Rudeiros Fernandez, M. Juchno, S. Prestemon, T. Shen, R. Teyber, X. Wang
- FNAL: G. Ambrosio, M. Baldini, E. Barzi, S. Gourlay, V. Kashikhin, V. Marinozzi, I. Novitski, G. Velev, A. Zlobin
- NHMFL: L. Cooley, D. Larbalestier
- BNL: K. Amm, M. Anerella, J. Cozzolino, R. Gupta, F. Kurian, B. Yahia

Contributions from

- E. Rochepault (CEA): 20 T dipole block design
- D. Martins Araujo (PSI): 20 T dipole quench protection
- B. Bordini (CERN)
- F. Niccoli (UNICAL)

Outline

- Design Criteria
- Magnetic Analysis
- Mechanical Analysis
- Results Summary
- Next Steps

Outline

- Design Criteria
- Magnetic Analysis
- Mechanical Analysis
- Results Summary
- Next Steps

Design Criteria of 20 T Hybrid Magnets

- Coil and magnet parameters
  - Free coil aperture (diameter) 50 mm
  - Operational bore field 20 T
  - Load-line fraction @ 1.9K: I_{op}/I_{ss} <= 87 %
  - 2D Geometrical harmonics b_n<3 units for n<10 (at R_{ref} = 17 mm)
- Quench protection
  - All coils powered in series
  - Maximum hot spot temperature 350 K
- Mechanics
  - Maximum Nb_3Sn coil stress <180 (<150) MPa at 1.9 (293) K
  - For the HTS <120 MPa

Design Criteria – Material Properties

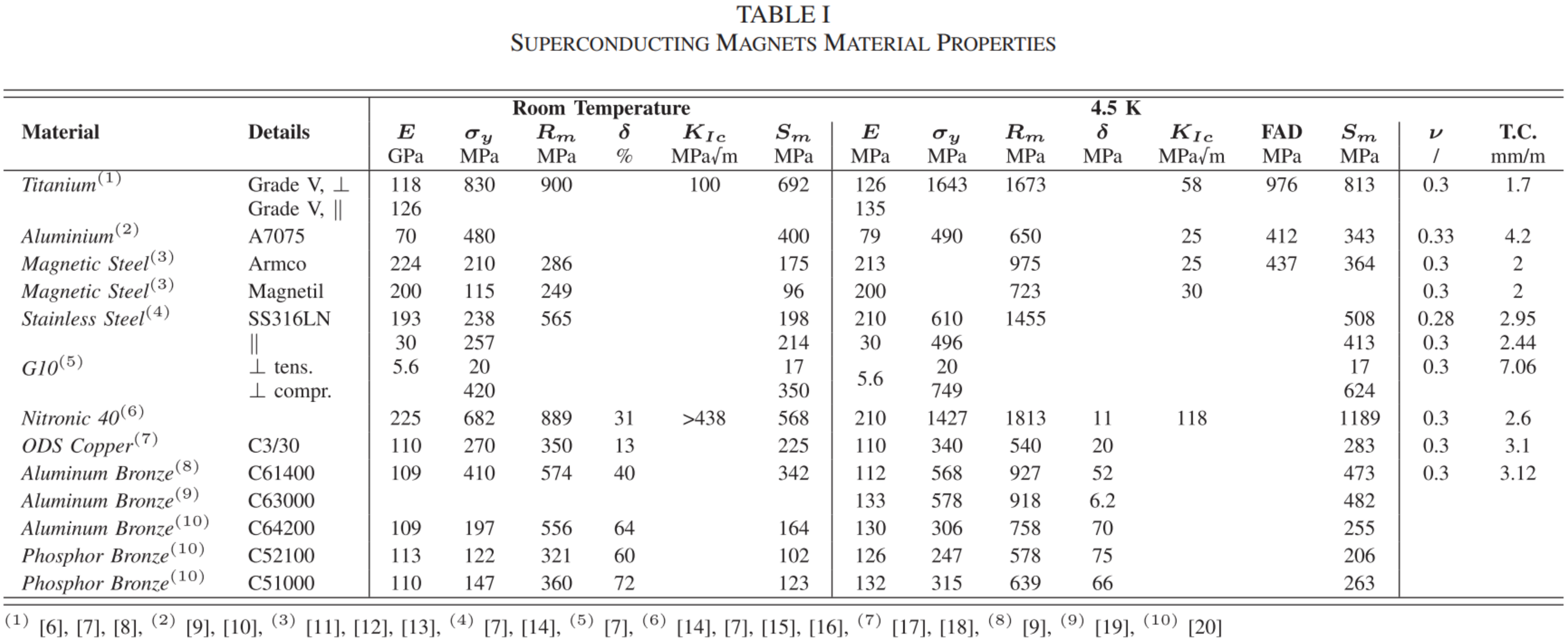


TABLE I
SUPERCONDUCTING MAGNETS MATERIAL PROPERTIES

		Room Temperature						4.5 K								
Material	**Details**	E GPa	σ_y MPa	R_m MPa	δ %	K_{Ic} MPa$\sqrt{}$m	S_m MPa	E MPa	σ_y MPa	R_m MPa	δ MPa	K_{Ic} MPa$\sqrt{}$m	**FAD** MPa	S_m MPa	ν /	**T.C.** mm/m
Titanium$^{(1)}$	Grade V, ⊥	118	830	900		100	692	126	1643	1673		58	976	813	0.3	1.7
	Grade V, ‖	126						135								
Aluminium$^{(2)}$	A7075	70	480				400	79	490	650		25	412	343	0.33	4.2
Magnetic Steel$^{(3)}$	Armco	224	210	286			175	213		975		25	437	364	0.3	2
Magnetic Steel$^{(3)}$	Magnetil	200	115	249			96	200		723		30			0.3	2
Stainless Steel$^{(4)}$	SS316LN	193	238	565			198	210	610	1455				508	0.28	2.95
	‖	30	257				214	30	496					413	0.3	2.44
G10$^{(5)}$	⊥ tens.	5.6	20				17	5.6	20					17	0.3	7.06
	⊥ compr.		420				350		749					624		
Nitronic 40$^{(6)}$		225	682	889	31	>438	568	210	1427	1813	11	118		1189	0.3	2.6
ODS Copper$^{(7)}$	C3/30	110	270	350	13		225	110	340	540	20			283	0.3	3.1
Aluminum Bronze$^{(8)}$	C61400	109	410	574	40		342	112	568	927	52			473	0.3	3.12
Aluminum Bronze$^{(9)}$	C63000							133	578	918	6.2			482		
Aluminum Bronze$^{(10)}$	C64200	109	197	556	64		164	130	306	758	70			255		
Phosphor Bronze$^{(10)}$	C52100	113	122	321	60		102	126	247	578	75			206		
Phosphor Bronze$^{(10)}$	C51000	110	147	360	72		123	132	315	639	66			263		

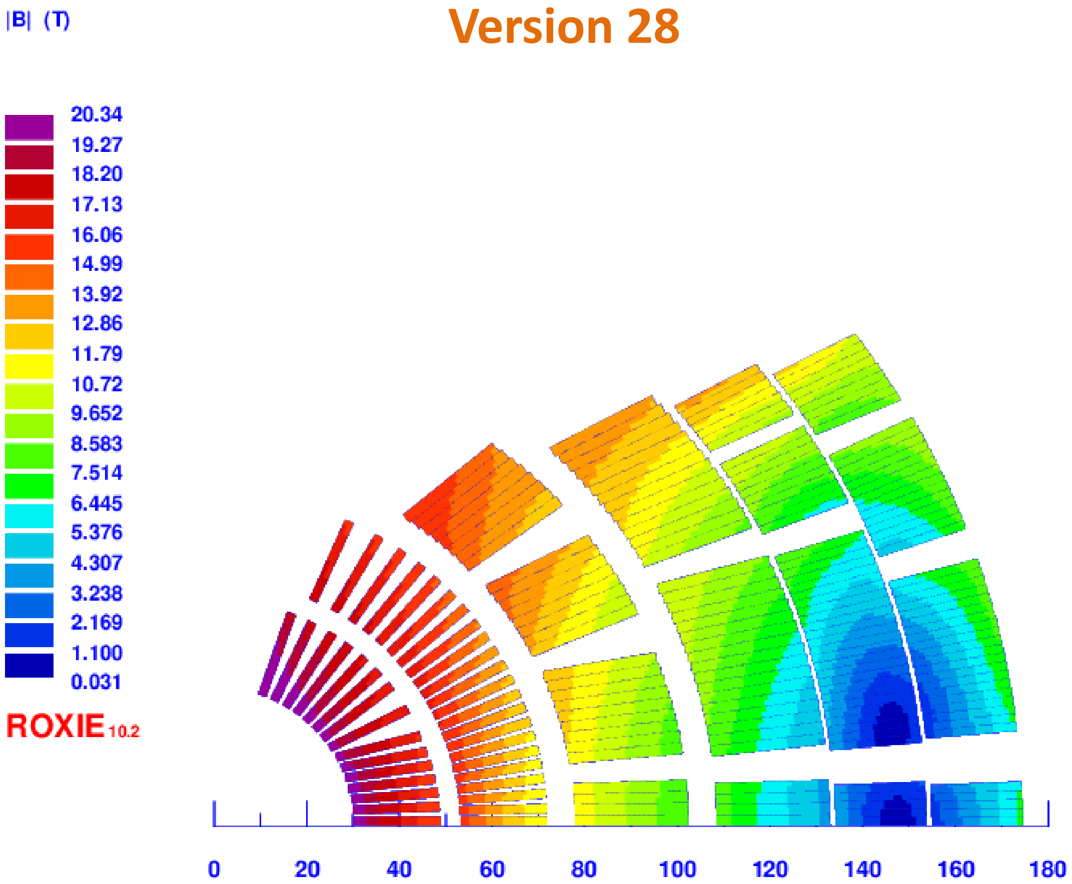
$^{(1)}$ [6], [7], [8], $^{(2)}$ [9], [10], $^{(3)}$ [11], [12], [13], $^{(4)}$ [7], [14], $^{(5)}$ [7], $^{(6)}$ [14], [7], [15], [16], $^{(7)}$ [17], [18], $^{(8)}$ [9], $^{(9)}$ [19], $^{(10)}$ [20]

G. Vallone et al., A Review of the Mechanical Properties of Materials Used in Nb3Sn Magnets for Particle Accelerators, *IEEE Transactions On Applied Superconductivity*, 2023

Outline

- Design Criteria
- Magnetic Analysis
- Mechanical Analysis
- Results Summary
- Next Steps

Magnetic Analysis - I



Version 28

- Layers 1-2: HTS (Bi2212);
  Layers 3-4: LTS1; Layers 5-6: LTS2 – Both Nb3Sn
- Strands [mm]: 0.9 – 1.1 – 0.8
  Turns[-]: 36 – 40 – 44
- Cable width [mm]: 18.59 – 24.38 – 19.50
- Stabilizer/Superconductor [-]: 3 – 1 – 1.8
- Coil width [mm]: 143
- Current [A]: 13500
- Peak field [T]: 20.45 – 15.95 – 13.6
- Margin [%]: 87 – 84 – 87

V. Marinozzi, P. Ferracin, G. Vallone, Conceptual design of a 20 T hybrid cos-theta dipole superconducting magnet for future high-energy particle accelerators, *Applied Superconductivity Conference,* 2022.

Magnetic Analysis – II

Version 28			
Layer	**Bpeak**	**Jo**	**Lorentz Stress**
/	[T]	[A/mm2]	[MPa]
1	20.3	360	-110
2	18.0	360	-138
3	15.8	229	-128
4	13.7	229	-129
5	13.2	379	-175
6	12.0	379	-145

Assumed Mechanical Limits:

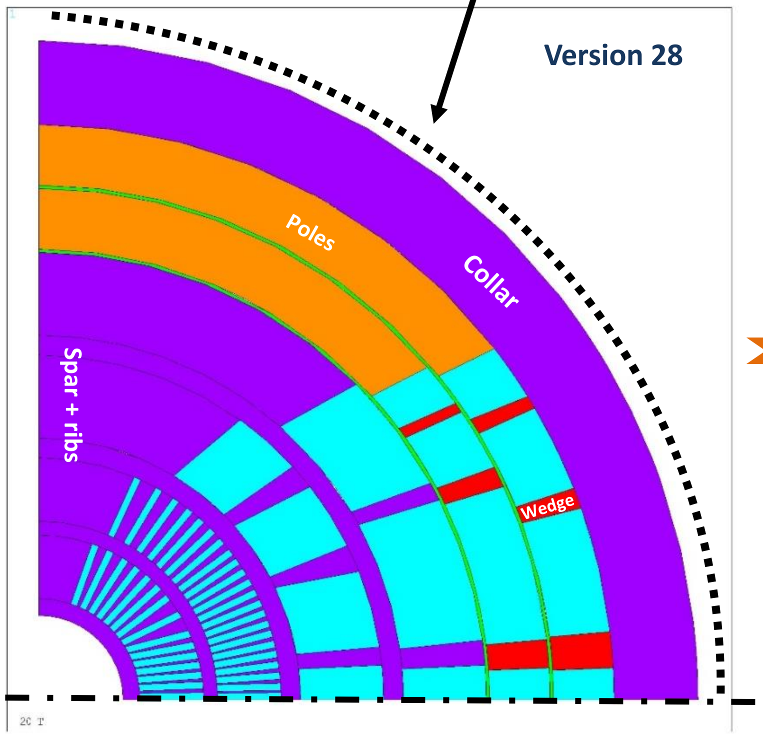
- **Bi2212** (layers 1, 2): 120 MPa
- **Nb3Sn** (layers 3 to 6): 180 MPa

Outline

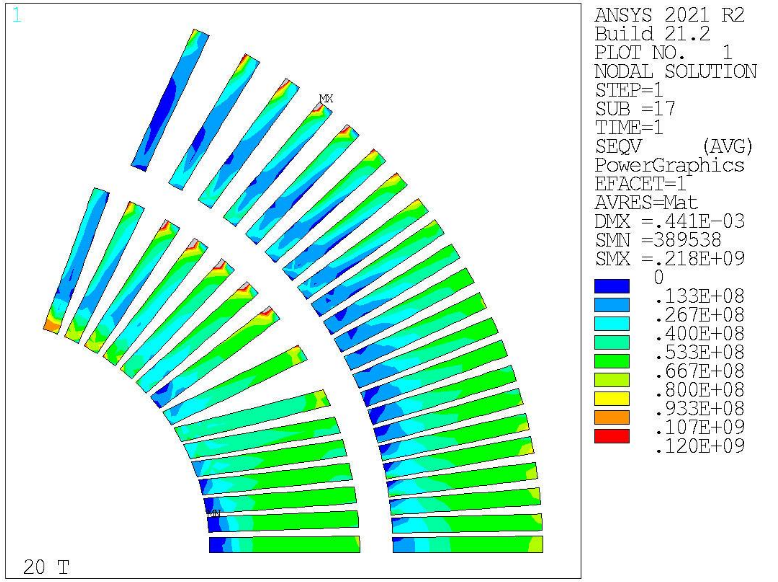
- Design Criteria
- Magnetic Analysis
- **Mechanical Analysis**
- Results Summary
- Next Steps

Mechanical Analysis – Infinitely Rigid Structure I

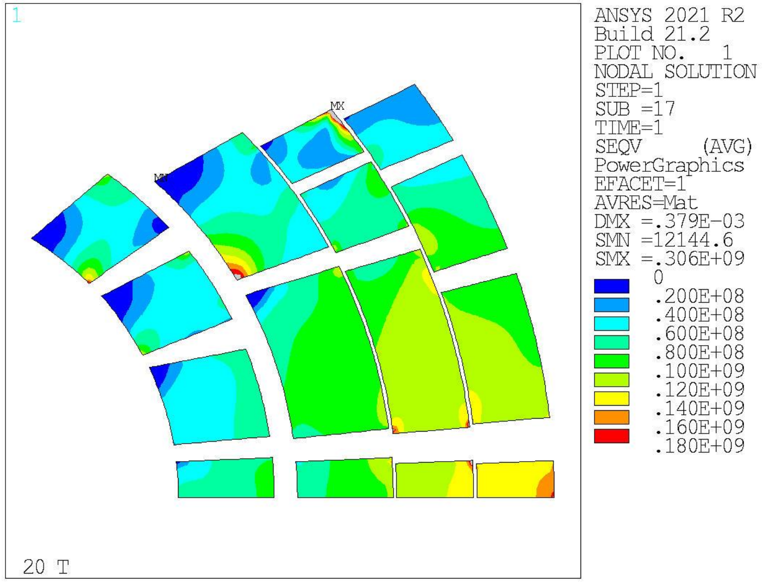
Infinitely Rigid Structure



Equivalent Stress



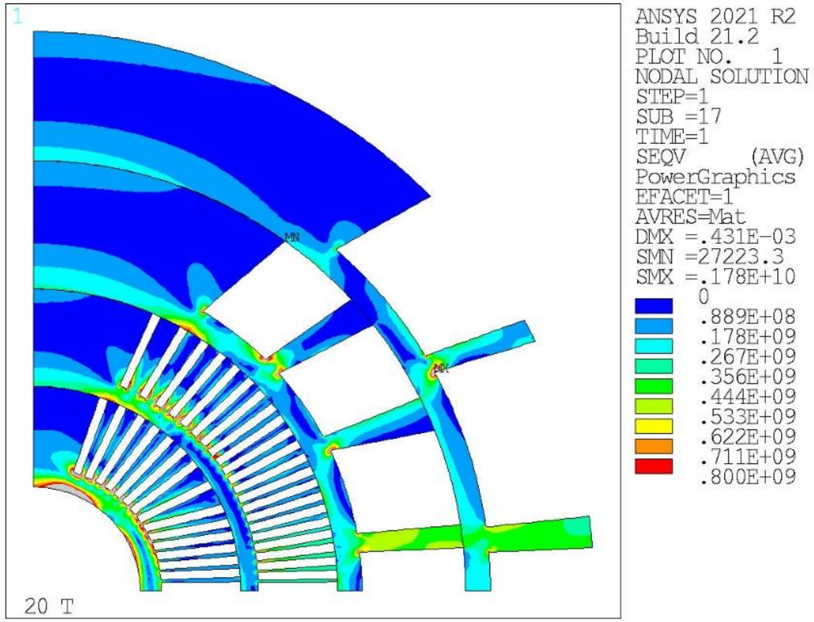
```
ANSYS 2021 R2
Build 21.2
PLOT NO.    1
NODAL SOLUTION
STEP=1
SUB =17
TIME=1
SEQV       (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.441E-03
SMN =389538
SMX =.218E+09
     0
     .133E+08
     .267E+08
     .400E+08
     .533E+08
     .667E+08
     .800E+08
     .933E+08
     .107E+09
     .120E+09
```

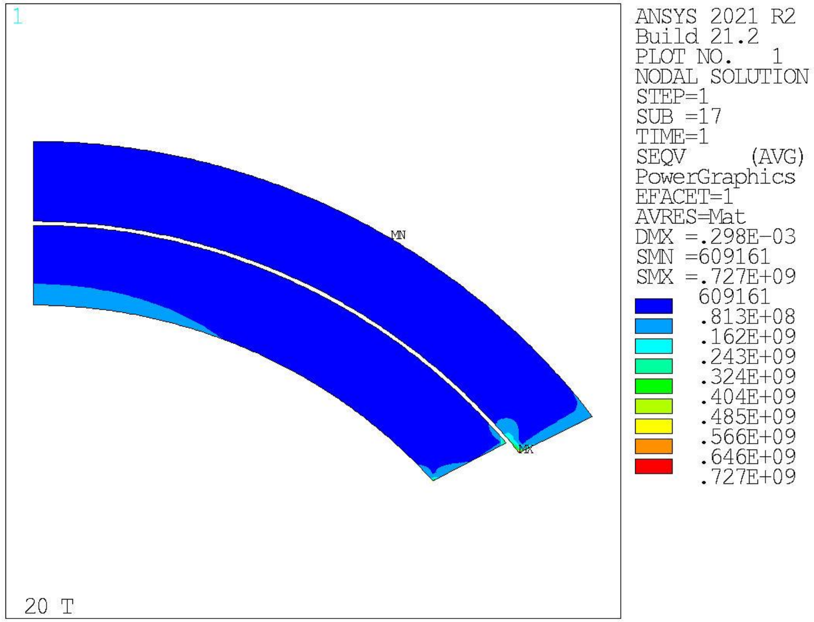


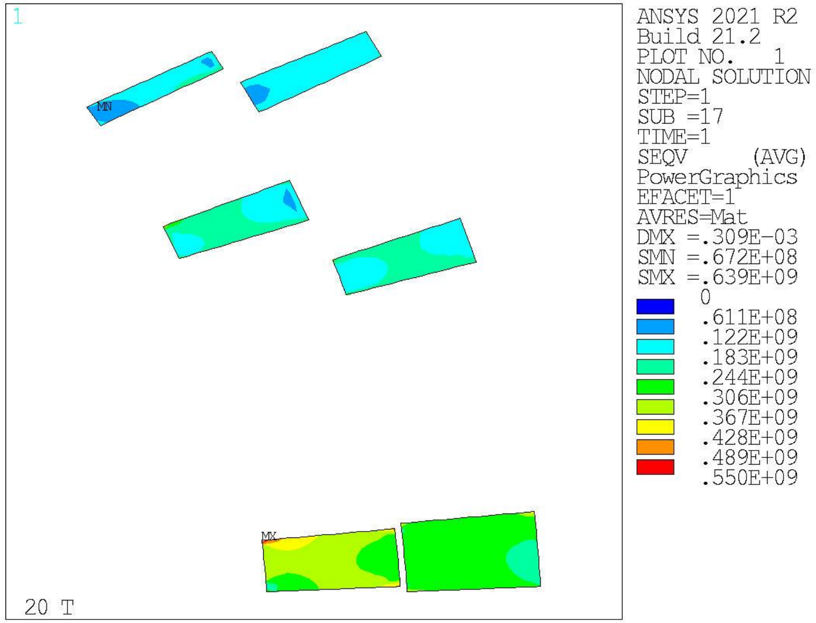
```
ANSYS 2021 R2
Build 21.2
PLOT NO.    1
NODAL SOLUTION
STEP=1
SUB =17
TIME=1
SEQV       (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.379E-03
SMN =12144.6
SMX =.306E+09
     0
     .200E+08
     .400E+08
     .600E+08
     .800E+08
     .100E+09
     .120E+09
     .140E+09
     .160E+09
     .180E+09
```

Mechanical Analysis – Infinitely Rigid Structure II

Equivalent Stress

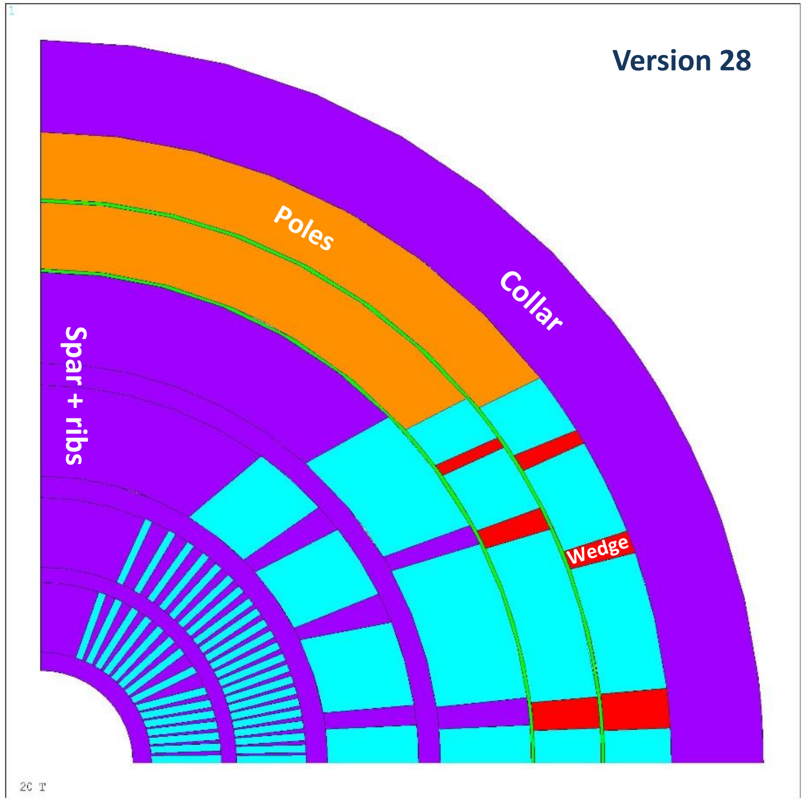




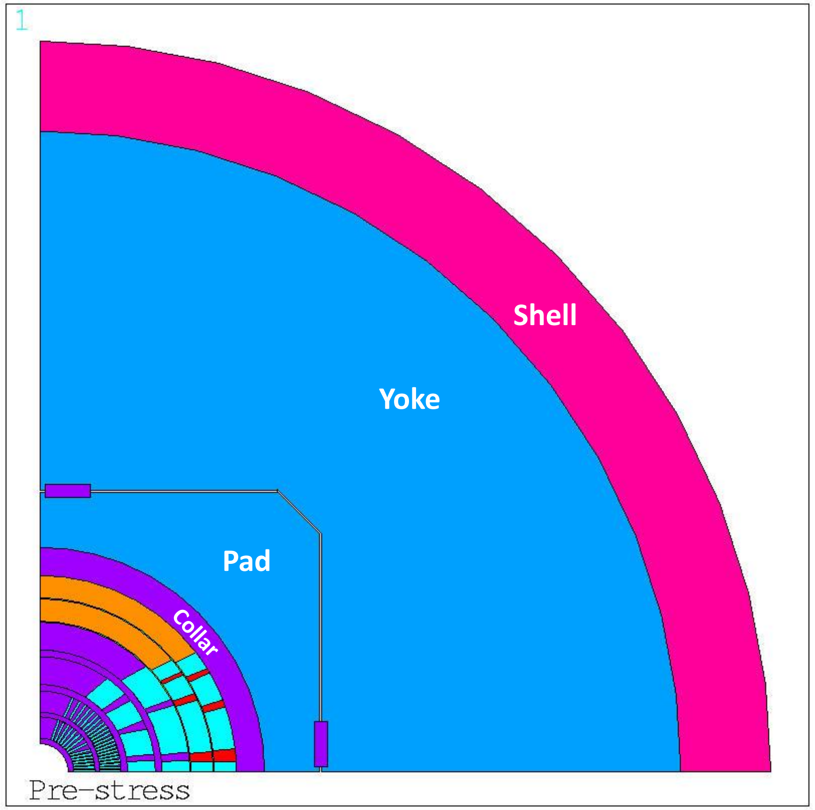


Mechanical Analysis – Real Structure

Infinitely Rigid Structure



Mechanical Structure



Thickness:

Collar – 25 mm

Pad – 50 mm

Yoke – 320 mm

Shell – 80 mm

Characteristic:

Friction: 0.2

Layers 1 – 4: Spar + ribs

Layers 5 – 6: Pole + Wedges

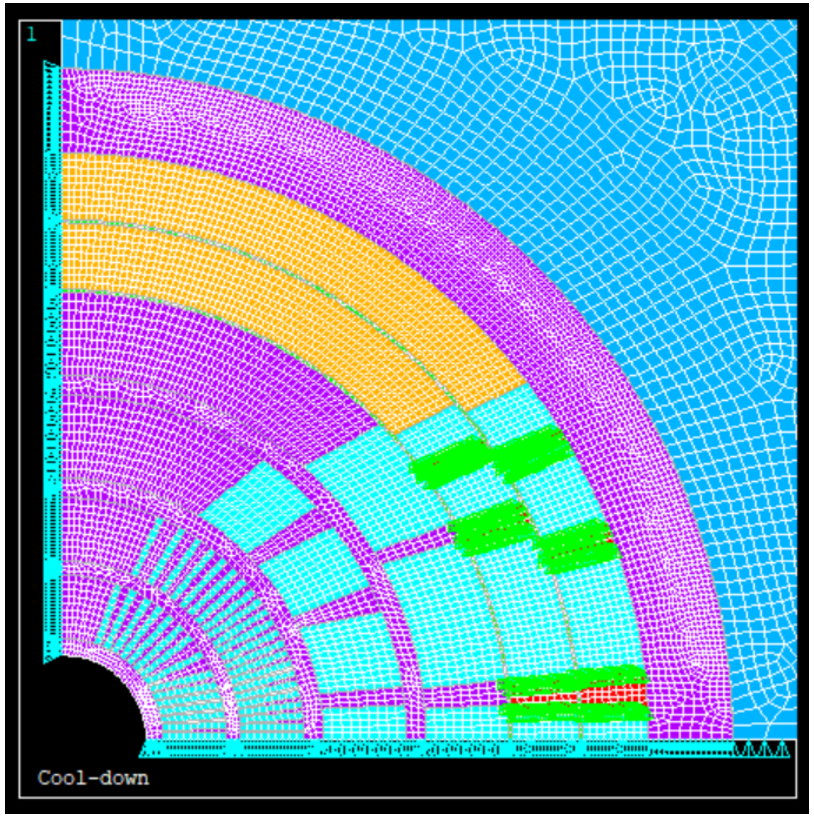
Interference: 2 mm on the horizontal key → first attempt for the max allowable stress in the shell

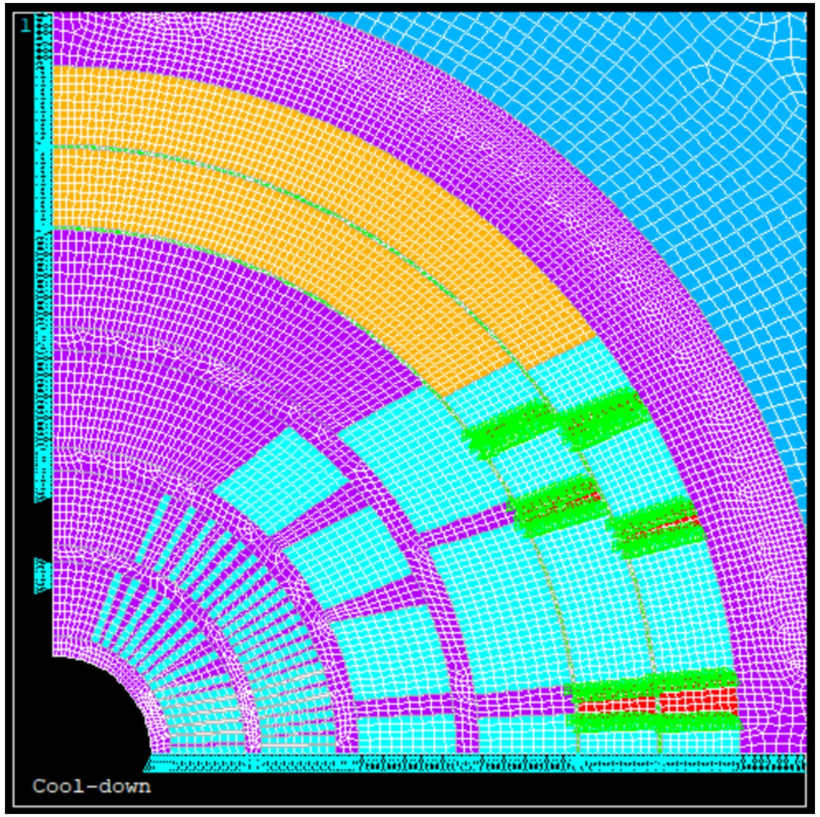
Mechanical Analysis – Cases Comparison

Case 1) Free coils in layers 1 – 4
Coils bonded to wedges in layers 5 – 6

Case 2) Free coils in layers 1 – 4
Coils bonded to wedges in layers 5 – 6

No constraints in layers 1 – 2 (by D. M. Araujo)





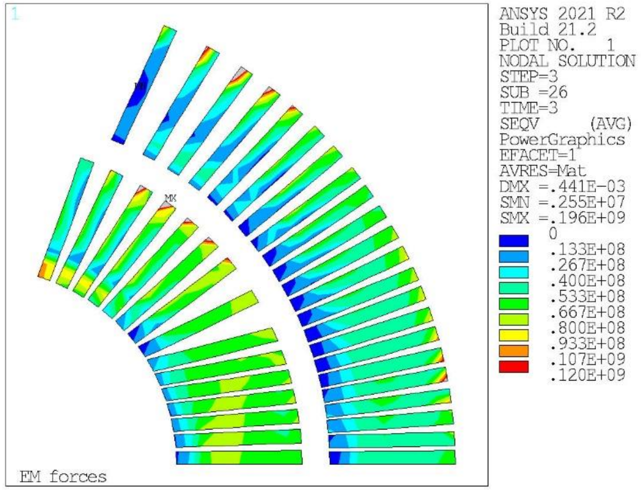
Mechanical Analysis – Coils

Case 1

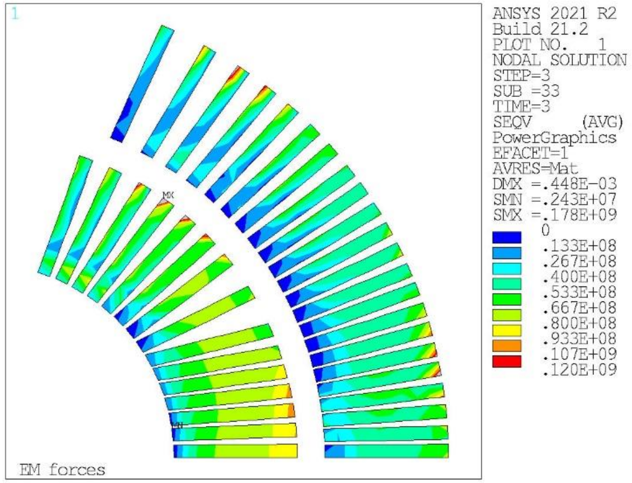
Case 2

Equivalent Stress

HTS



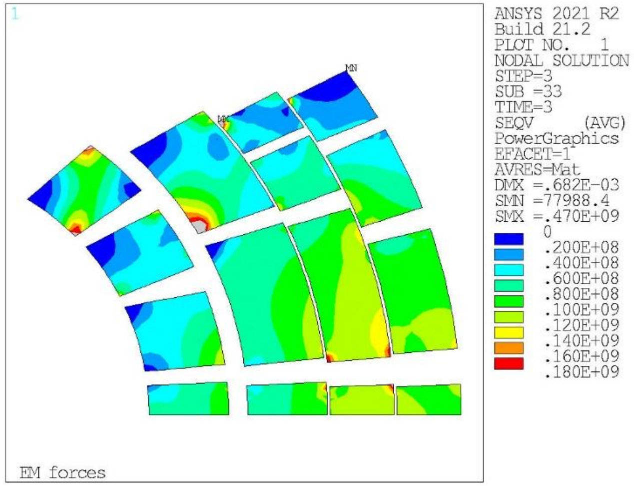
```
ANSYS 2021 R2
Build 21.2
PLOT NO.    1
NODAL SOLUTION
STEP=3
SUB =26
TIME=3
SEQV       (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.441E-03
SMN =.255E+07
SMX =.196E+09
      0
      .133E+08
      .267E+08
      .400E+08
      .533E+08
      .667E+08
      .800E+08
      .933E+08
      .107E+09
      .120E+09
```



```
ANSYS 2021 R2
Build 21.2
PLOT NO.    1
NODAL SOLUTION
STEP=3
SUB =33
TIME=3
SEQV       (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.448E-03
SMN =.243E+07
SMX =.178E+09
      0
      .133E+08
      .267E+08
      .400E+08
      .533E+08
      .667E+08
      .800E+08
      .933E+08
      .107E+09
      .120E+09
```

LTS

```
ANSYS 2021 R2
Build 21.2
PLOT NO.    1
NODAL SOLUTION
STEP=3
SUB =26
TIME=3
SEQV       (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.701E-03
SMN =107094
SMX =.434E+09
      0
      .200E+08
      .400E+08
      .600E+08
      .800E+08
      .100E+09
      .120E+09
      .140E+09
      .160E+09
      .180E+09
```



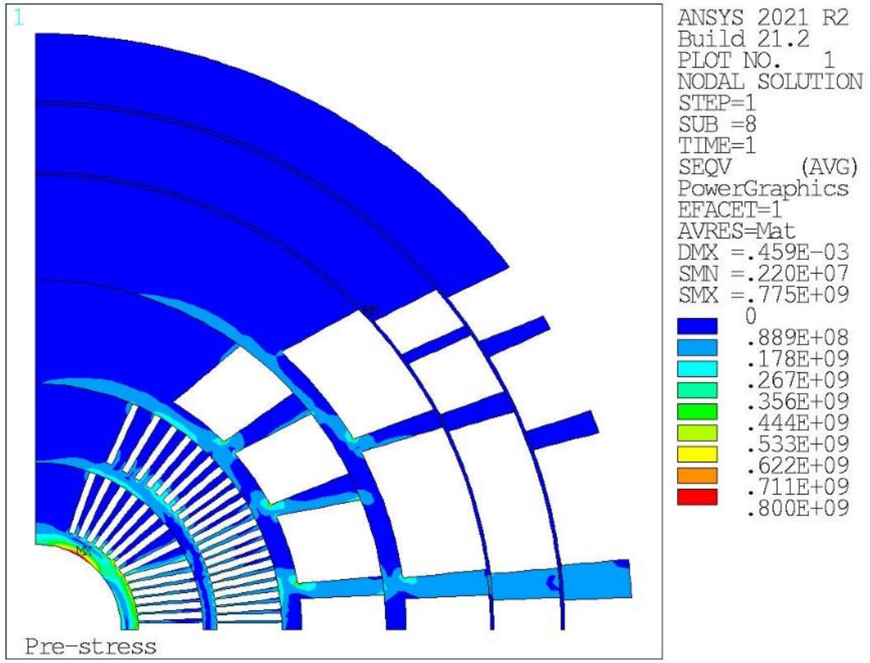
```
ANSYS 2021 R2
Build 21.2
PLOT NO.    1
NODAL SOLUTION
STEP=3
SUB =33
TIME=3
SEQV       (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.682E-03
SMN =77988.4
SMX =.470E+09
      0
      .200E+08
      .400E+08
      .600E+08
      .800E+08
      .100E+09
      .120E+09
      .140E+09
      .160E+09
      .180E+09
```

Mechanical Analysis – Mandrel I

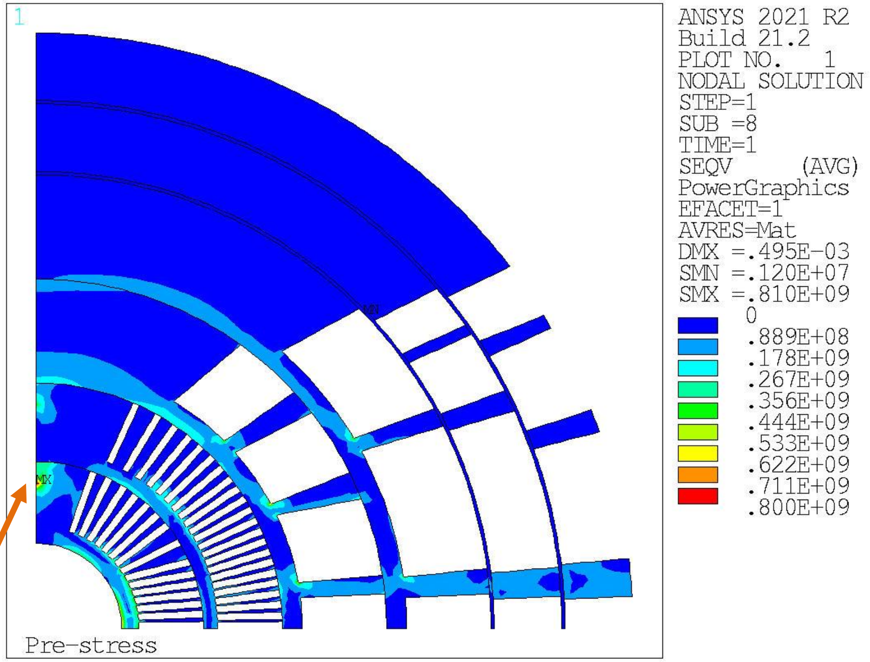
Pre-stress

Equivalent Stress

Case 1



Case 2



All cases) On the mandrel, starting from the midplane and moving along the circumference at the same radius r_0, there is first tension and then compression.

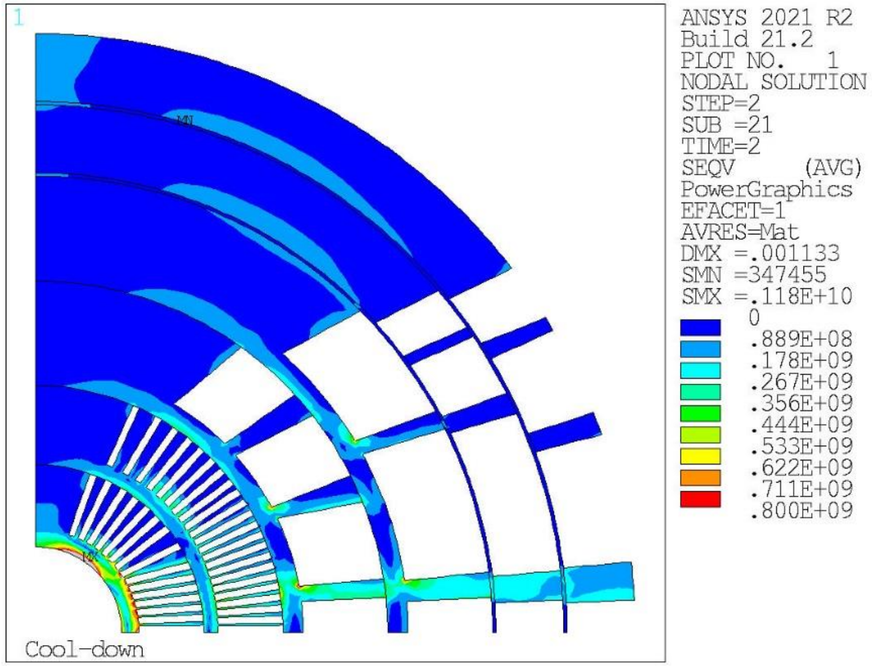
Case 2) Peak stress concentrated in the area where the constraints are removed.

Mechanical Analysis – Mandrel II

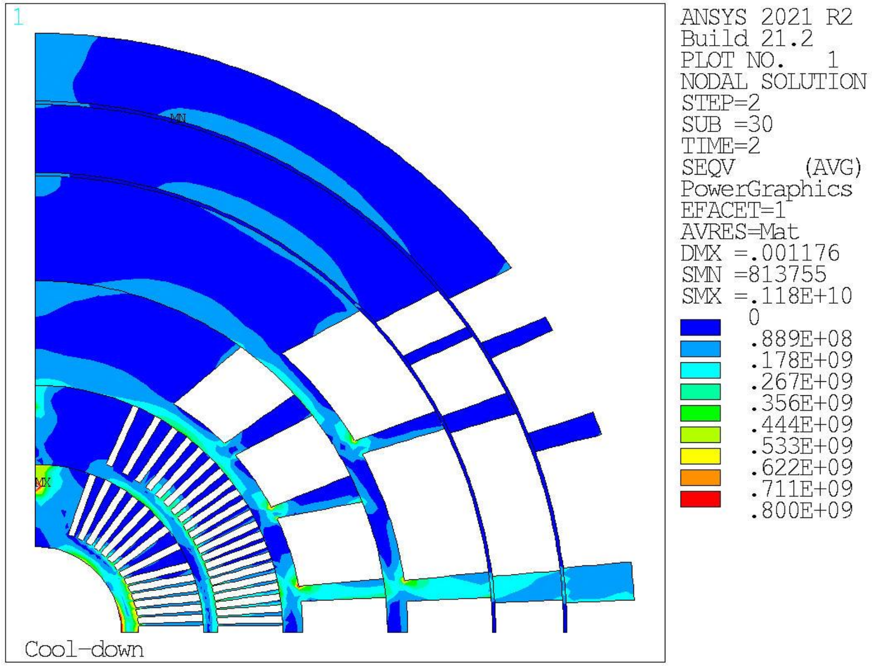
Cooldown

Equivalent Stress

Case 1



Case 2



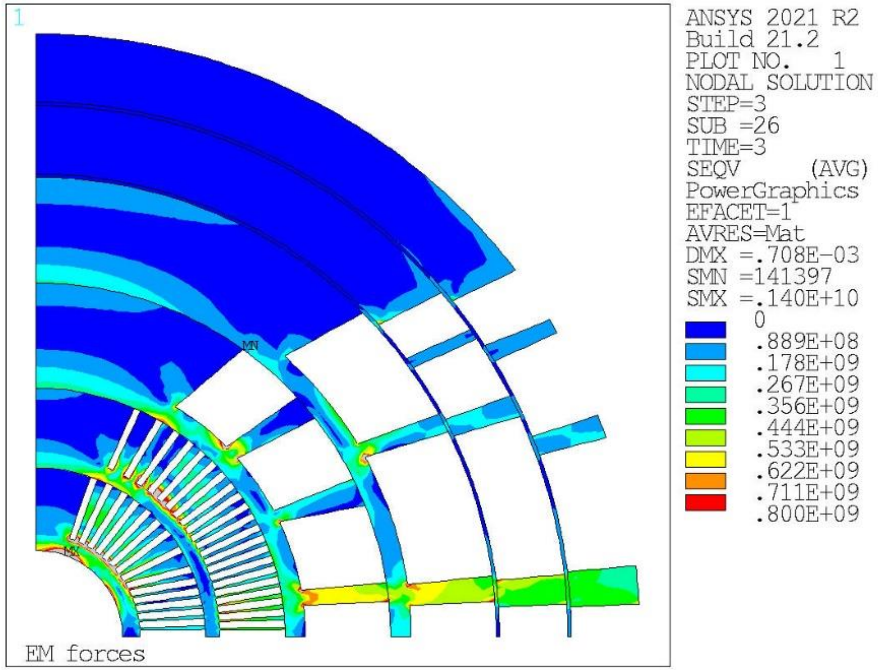
Case 2) The peak stress is concentraced where the constraints are removed. The stress distribution on the layer 1 is better than the one encountered in the case 1.

Mechanical Analysis – Mandrel III

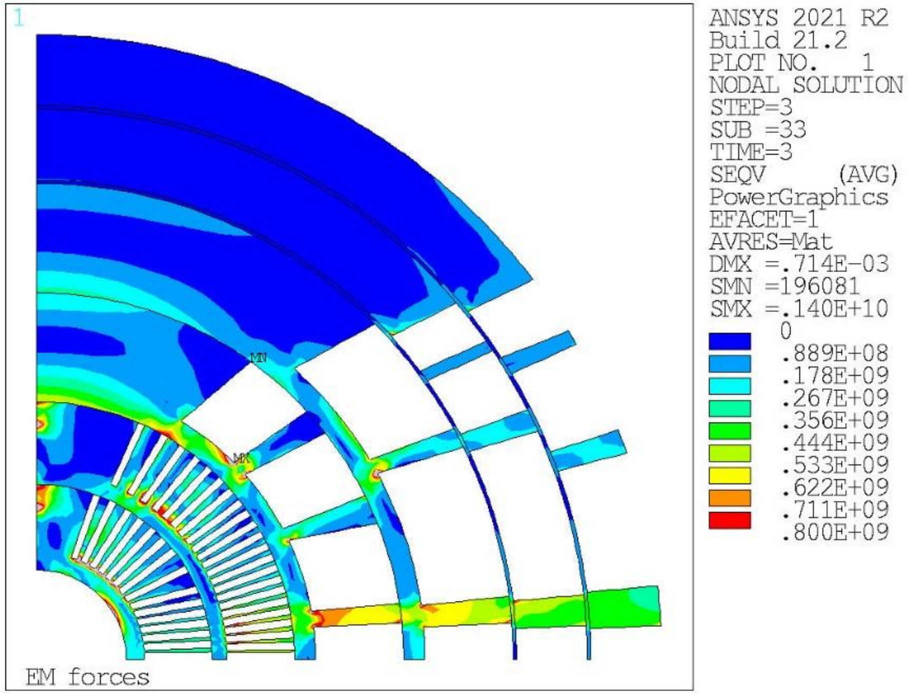
EM forces

Equivalent Stress

Case 1



Case 2



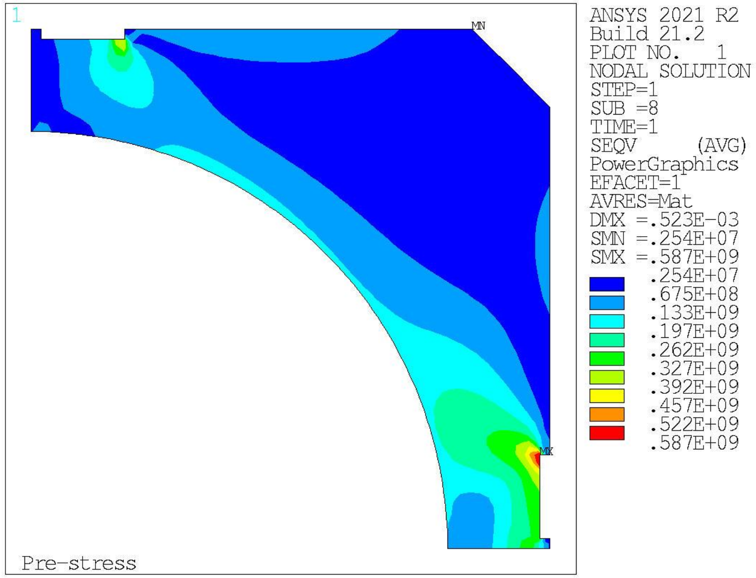
Case 2) Stresses on the mandrel are significantly improved.

Mechanical Analysis – Pad

Case 2

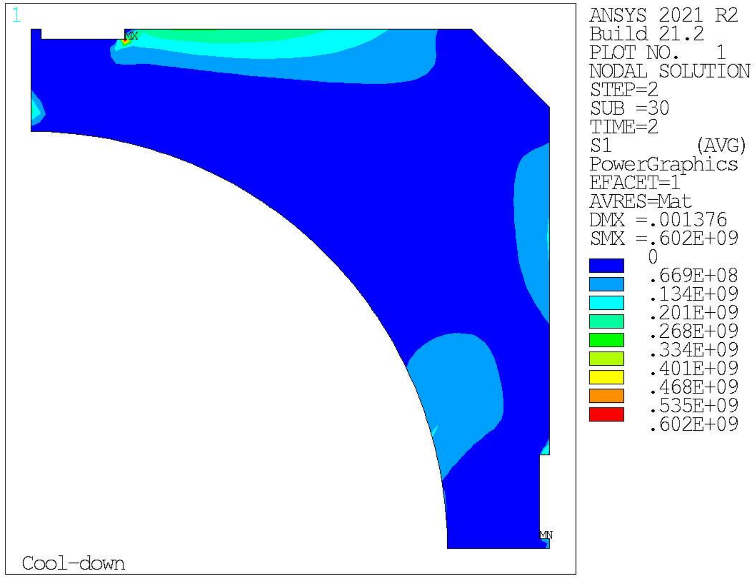
Pre-stress

Equivalent Stress



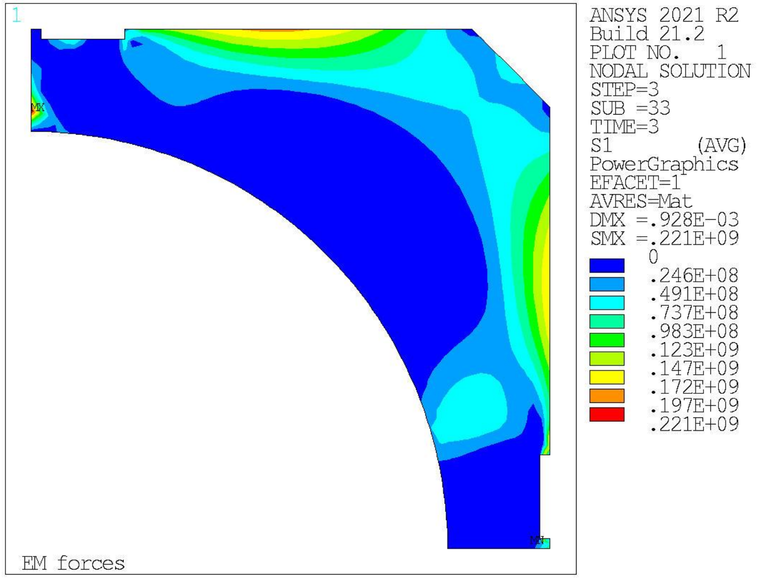
Cooldown

First Principal Stress



EM forces

First Principal Stress



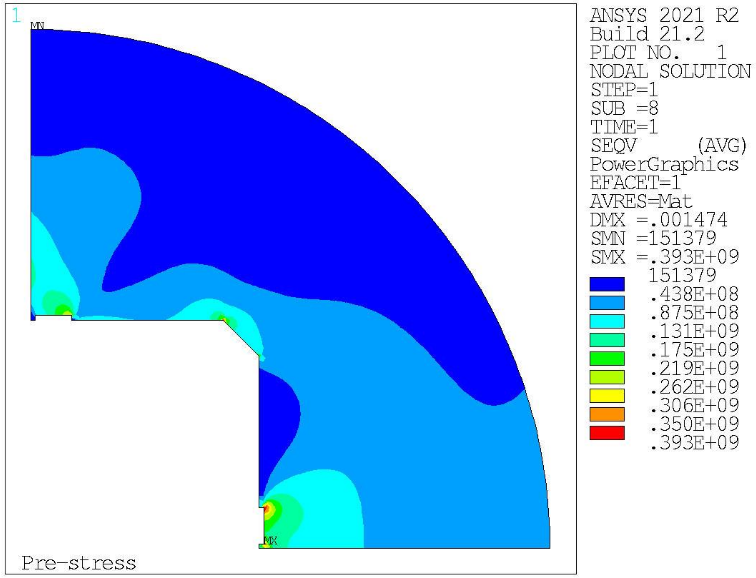
Both case 1 and case 2 show similar results.
It is not clear the reason of the location of the maximum tensile stresses.
Overall, the retrieved results do not present critical issues compared with the limits imposed in the material properties table.

Mechanical Analysis – Yoke

Case 2

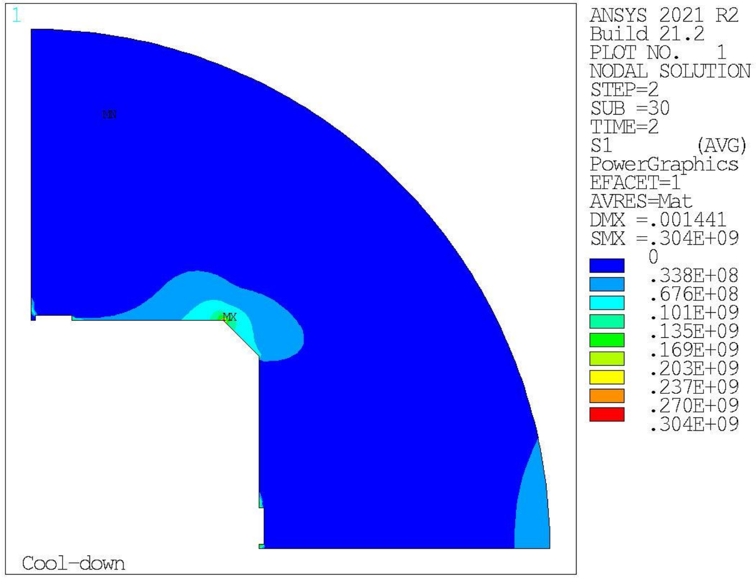
Pre-stress

Equivalent Stress



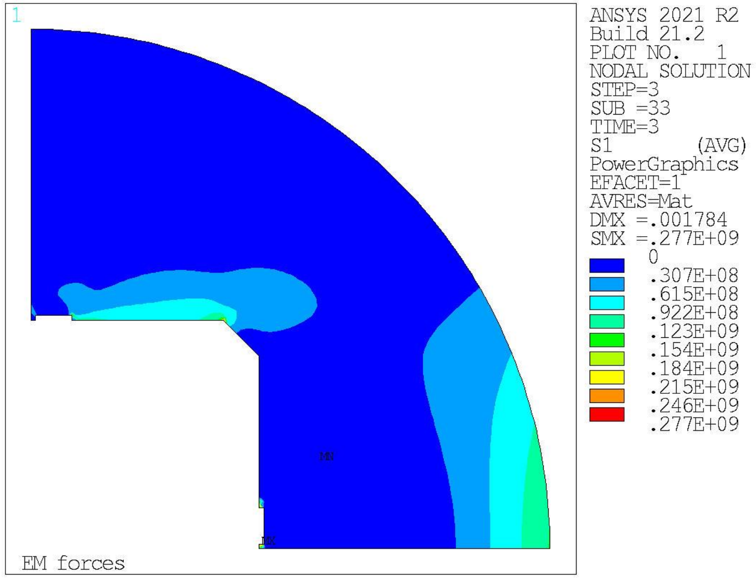
Cooldown

First Principal Stress



EM forces

First Principal Stress



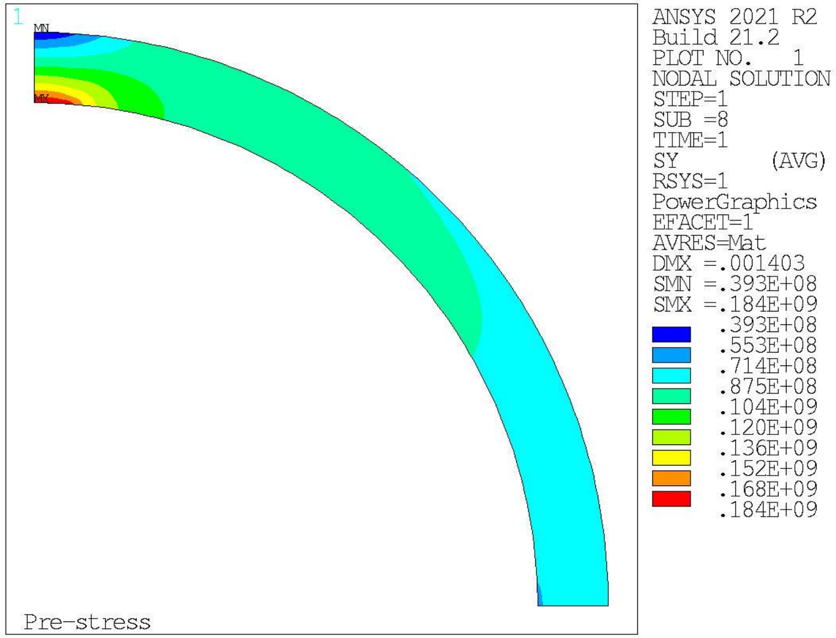
Also the yoke does not have major issues, so we are currently focusing on other parts of the mechanical structure.

Mechanical Analysis – Shell

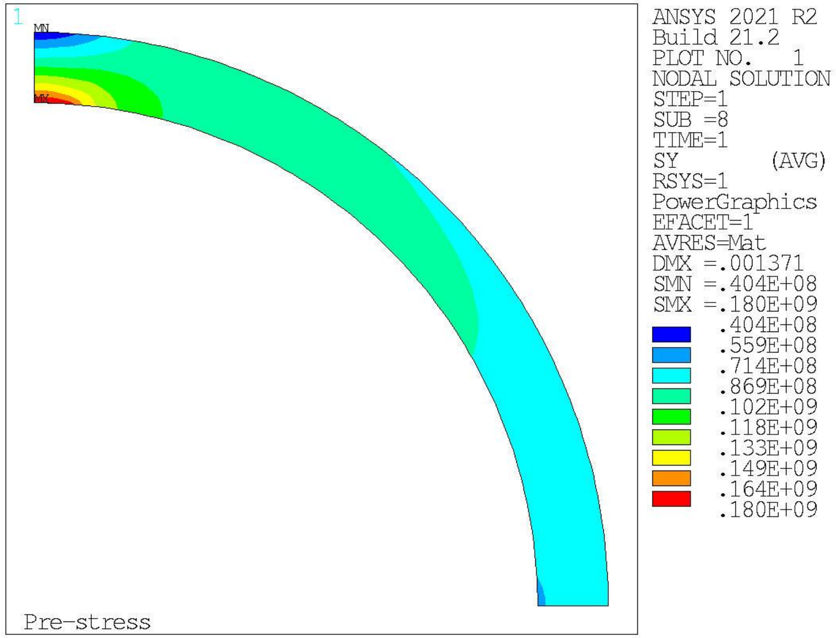
Pre-stress

Azimuthal Stress

Case 1



Case 2



The peak azimuthal stress is roughly 180 MPa.

As a first attempt, we set the limit roughly equal to 150 MPa at room temperature.

Outline

- Design Criteria
- Magnetic Analysis
- Mechanical Analysis
- **Results Summary**
- Next Steps

Results summary

Comments on the mechanical structure model:

- *Bending* in the innermost radius of the mandrel and stress limits are also exceeded in the area where the rib and the spar are in contact;
- *Stresses exceed the limits* in the conductors (the peak stresses are localized in the corner of the conductors);

- Solution attempt with the optimization of the structure → attempt to change the azimuthal stiffness of the structure to solve the mandrel issues.

More investigation on the mechanical structure optimization are needed.

Outline

- Design Criteria
- Magnetic Analysis
- Mechanical Analysis
- Results Summary
- Next Steps

Next Steps

Mechanical structure optimization:

- Influence of the interference and the key position → We are trying to find the optimized values of these parameters;
- Dimensions of the mechanical structure.

HTS superconducting materials for the conductors in layers 1 and 2:

- The *current option* is **Bi2212** as Rutherford cables;

- *Another option* could be **REBCO** coated conductors → Magnetic analysis.