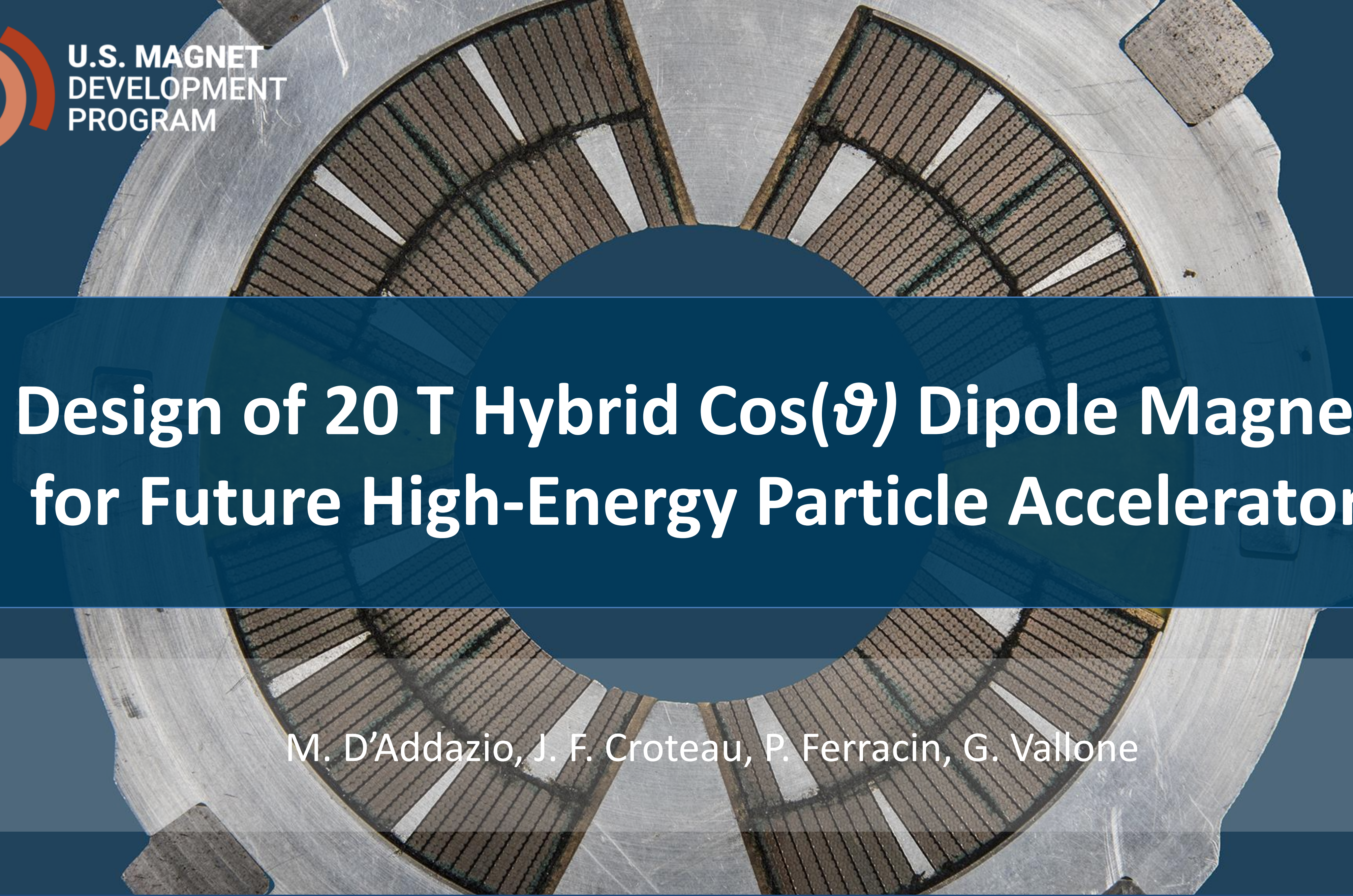

U.S. MAGNET DEVELOPMENT PROGRAM

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

M. D'Addazio, J. F. Croteau, P. Ferracin, G. Vallone

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US MDP (in particular the "20 T working group")

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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
- Measurement and Computation of Nb_3Sn Rutherford Cables Strength Under Multi-Axial Loading Conditions
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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

Material	Details	Room Temperature E GPa	Room Temperature σ_y MPa	Room Temperature R_m MPa	Room Temperature δ %	Room Temperature K_{Ic} MPa$\sqrt{\text{m}}$	Room Temperature S_m MPa	4.5 K E MPa	4.5 K σ_y MPa	4.5 K R_m MPa	4.5 K δ MPa	4.5 K K_{Ic} MPa$\sqrt{\text{m}}$	4.5 K FAD MPa	4.5 K S_m MPa	ν /	T.C. mm/m
Titanium (1)	Grade V, $\perp$	118	830	900		100	692	126	1643	1673		58	976	813	0.3	1.7
	Grade V, $\parallel$	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
	$\parallel$	30	257				214	30	496					413	0.3	2.44
G10 (5)	$\perp$ tens.	5.6	20				17	5.6	20					17	0.3	7.06
	$\perp$ 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

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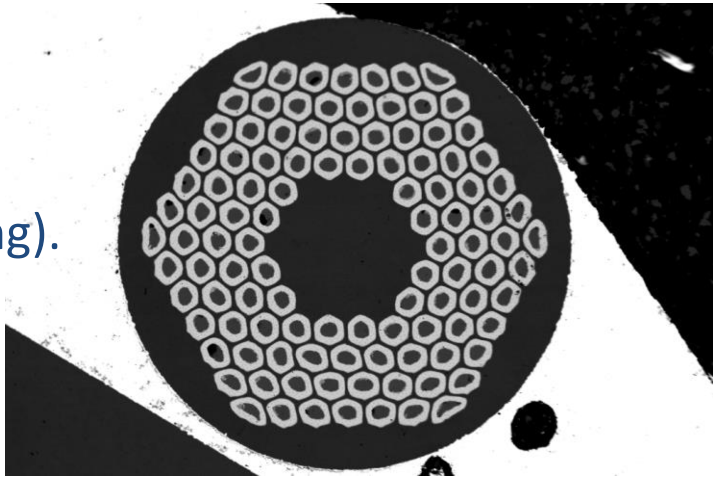
State-of-art of Failure Criteria

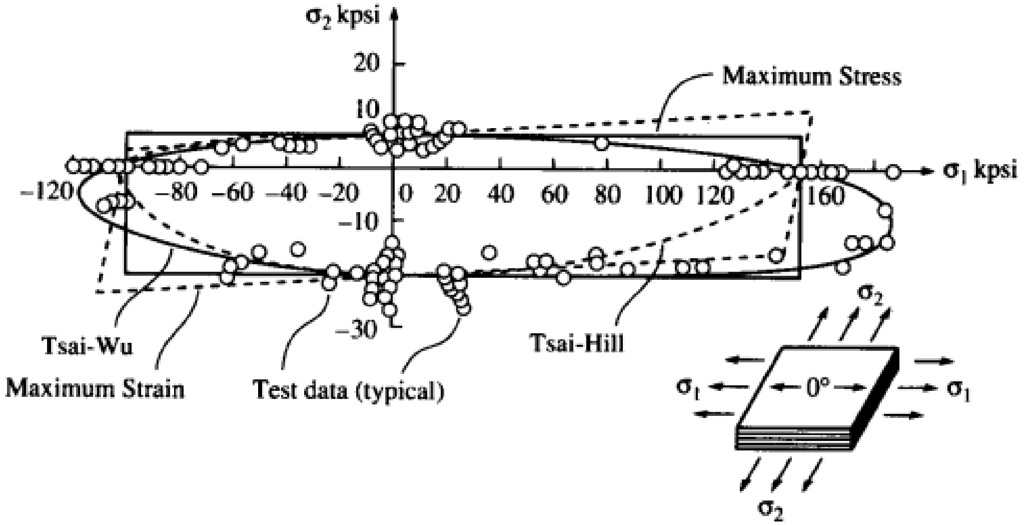
What can it be defined as **‘strength’** in superconducting coils?

- Anything that would reduce performance (e.g. critical current reduction);
- Actual failure of some part of the composite (e.g. filament cracking, debonding).



State-of-art of failure criteria:

- Non-interacting: Transverse/Azimuthal stress < 150/175 MPa
  (From measurements on transversally loaded cables)
- Interacting: Von Mises equivalent stress < 150/200 MPa
  (From comparison between models and magnet performance)



Both should **not** be applicable to composite materials.

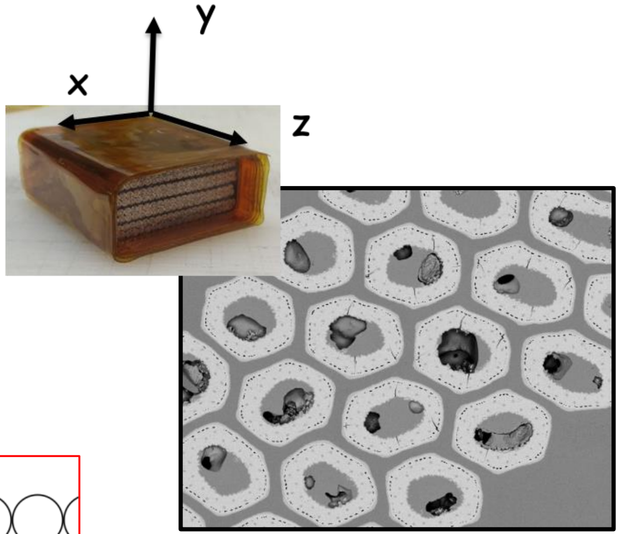
Strength Measurement – 1D Loading

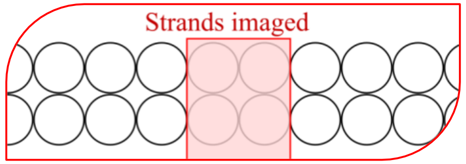
Initial run with 1D loading (*y*-direction) to verify our sample, test and imaging set-up.

Sample polished with vibratory polishing, coated with Au/Pd and then analyzed with SEM

Many cracks to count, so ML developed to help.

Only central portion of the stack investigated due to lack of time.





Result consistent with literature findings:

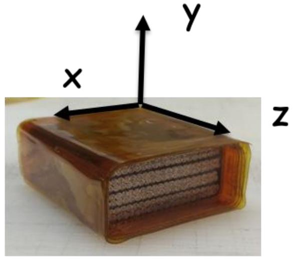
- Cracks start to appear at ~120 MPa;
- Numerical model results are not far from reality!

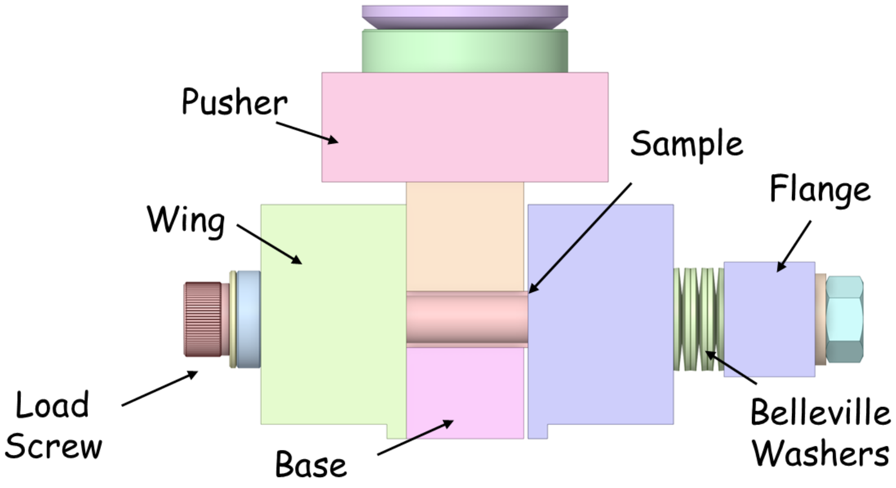
$$\begin{Bmatrix} S_x^- \\ S_y^- \\ S_z^-/S_z^+ \end{Bmatrix} = \begin{Bmatrix} 155 \\ \boxed{115} \\ 165 \end{Bmatrix} MPa$$

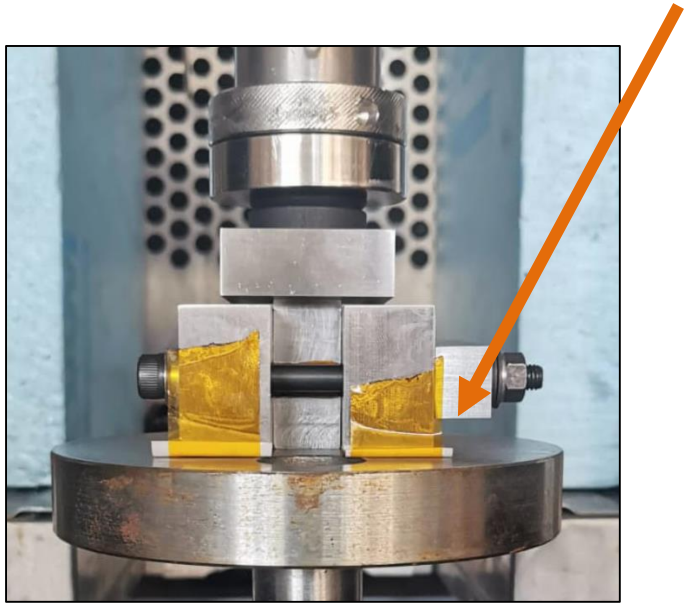
Strand Strength – Measurement Set-Up I

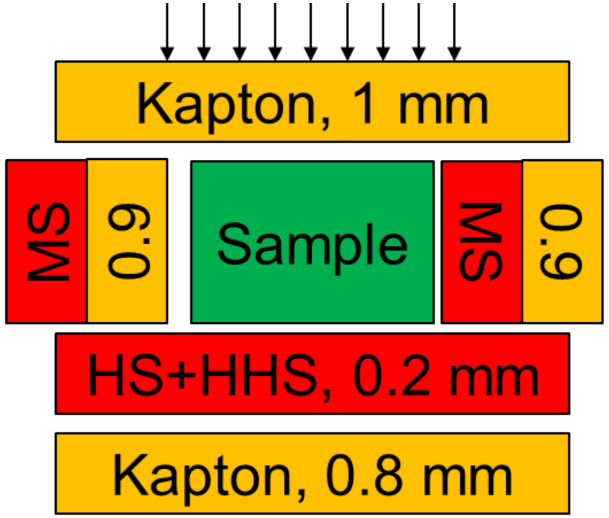
Stack holder designed to apply a bi-directional load:

- Belleville springs to control/‘measure’ the applied pre-stress;
  3 springs in parallel: 60 MPa on a 4 stack.
- Fuji films used to control the uniformity of the applied loads:
  MS on sample short edge and HS+HHS on long edge (additional Fuji below the wings of the sample holder).





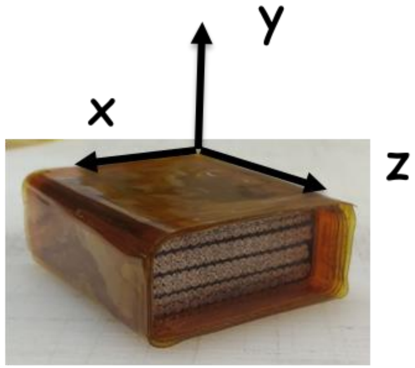




Strand Strength – Measurement Set-Up II

Vertical pre-load applied to avoid buckling:

- First test article buckled at ~ 15 MPa.

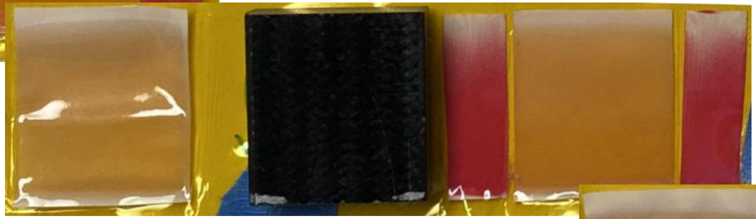


In principle, 7 samples to test under bi-axial loading conditions.

During the test, some samples slided at around 50 kN. The re-load showed sliding at the same load.

Test repeated without spherical washer → No sliding.

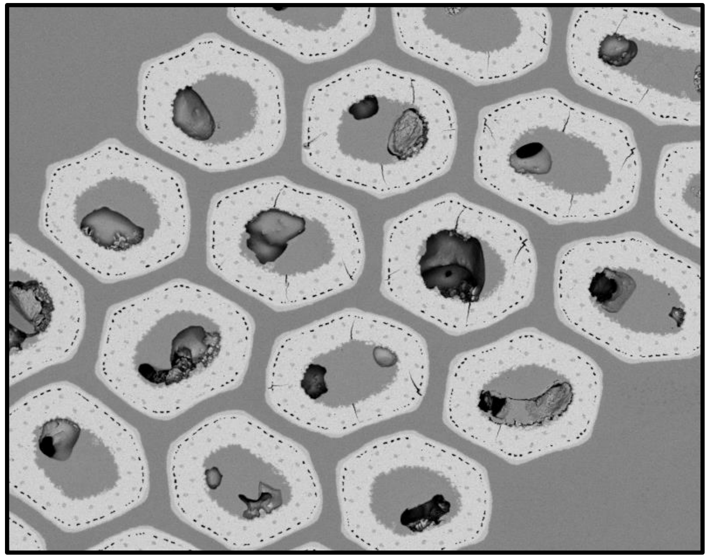
Fuji Paper – 2D Testing



The test device manages to apply a very uniform pressure on the sides:

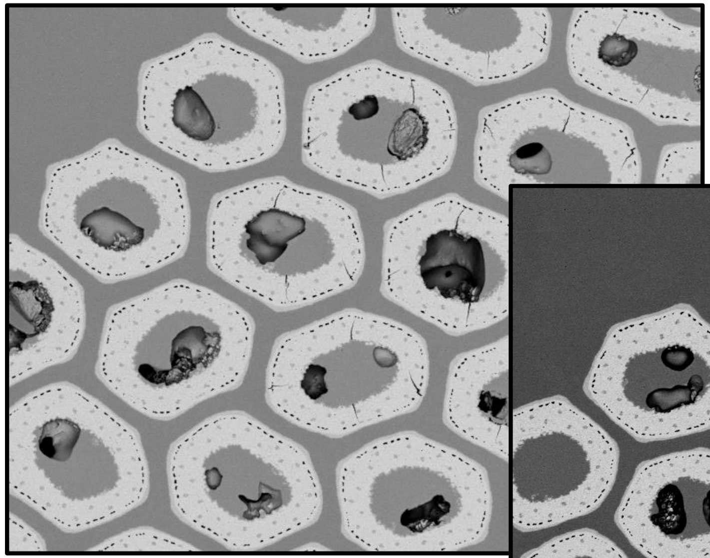
- Very good uniformity of the load applied by the wings;
- No marks on the ‘ground’ Fuji paper: ~ All the load is going through the sample.

Strength Measurement – 2D Loading

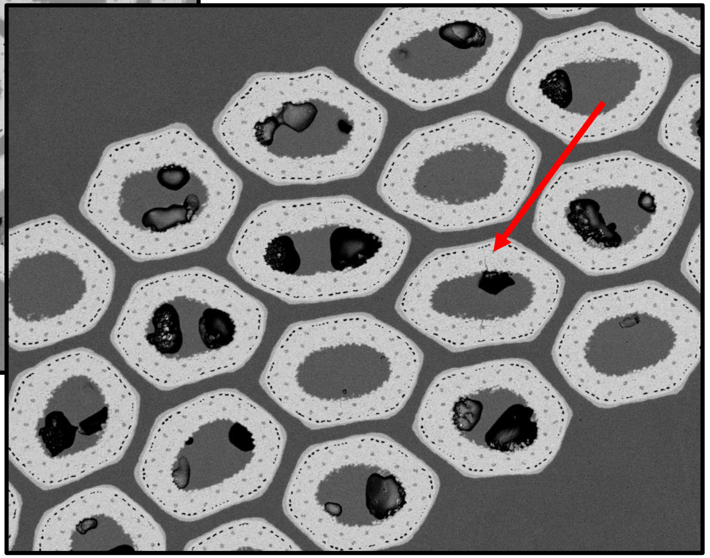


0 MPa

Strength Measurement – 2D Loading

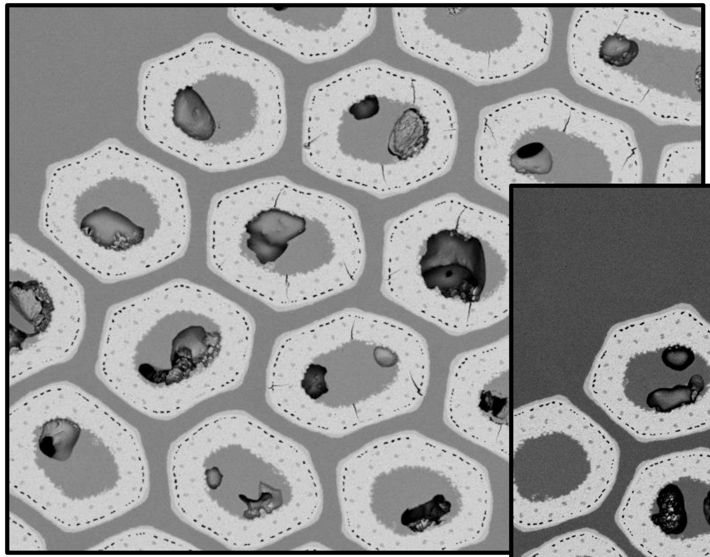


0 MPa

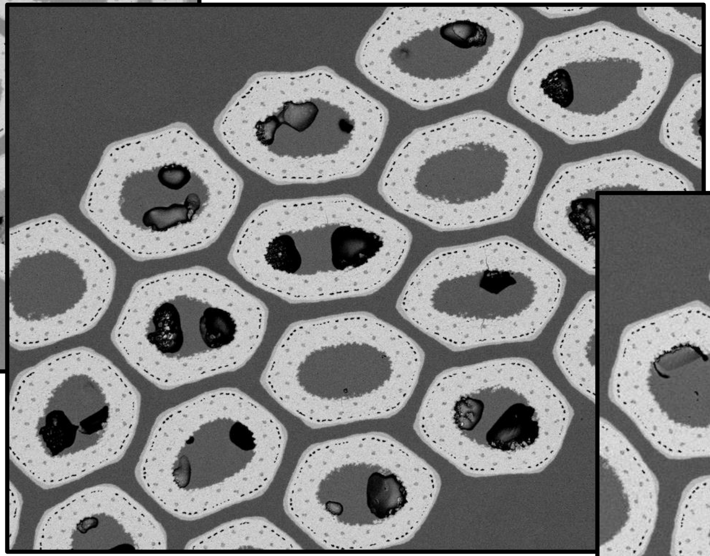


20 MPa

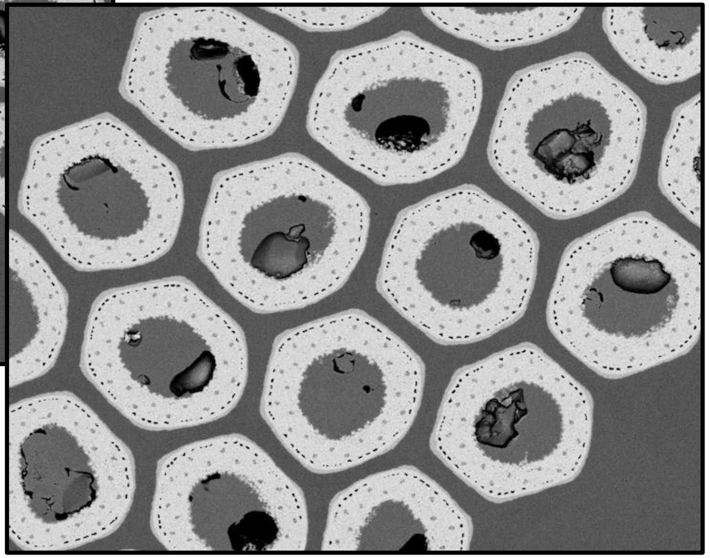
Strength Measurement – 2D Loading



0 MPa



20 MPa

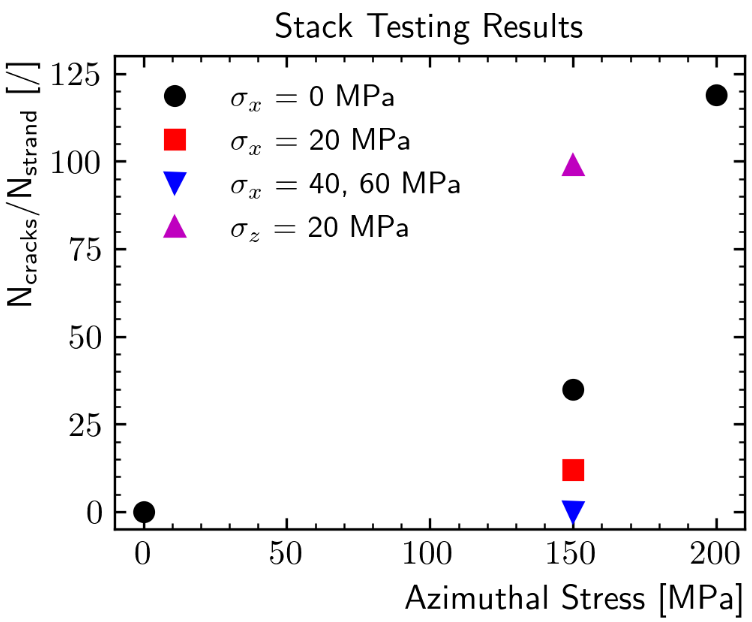


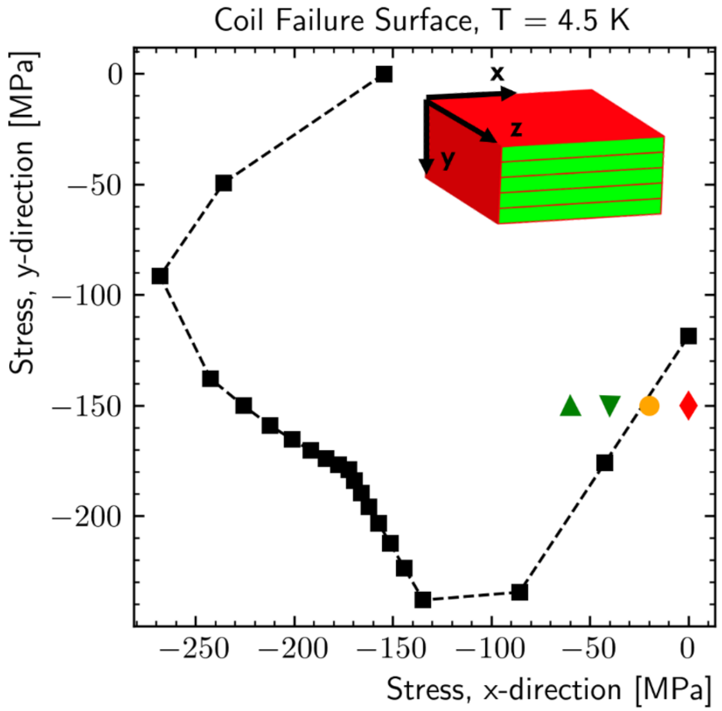
40 MPa

Strength Measurement – 2D Loading

Significant interaction between azimuthal and horizontal stress:

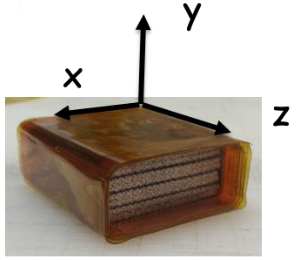
- Many cracks for no horizontal pre-stress
- Less cracks with 20 MPa
- **No cracks** with 40 and 60 MPa!





The longitudinal pre-stress (*z*-direction) increases the number of cracks:

- More data needed (just one data point)!



G. Vallone *et al.*, Measurement and Computation of Nb3Sn Rutherford Cables Strength Under Multi-Axial Loading Conditions, *IEEE Transactions On Applied Superconductivity*, 2023

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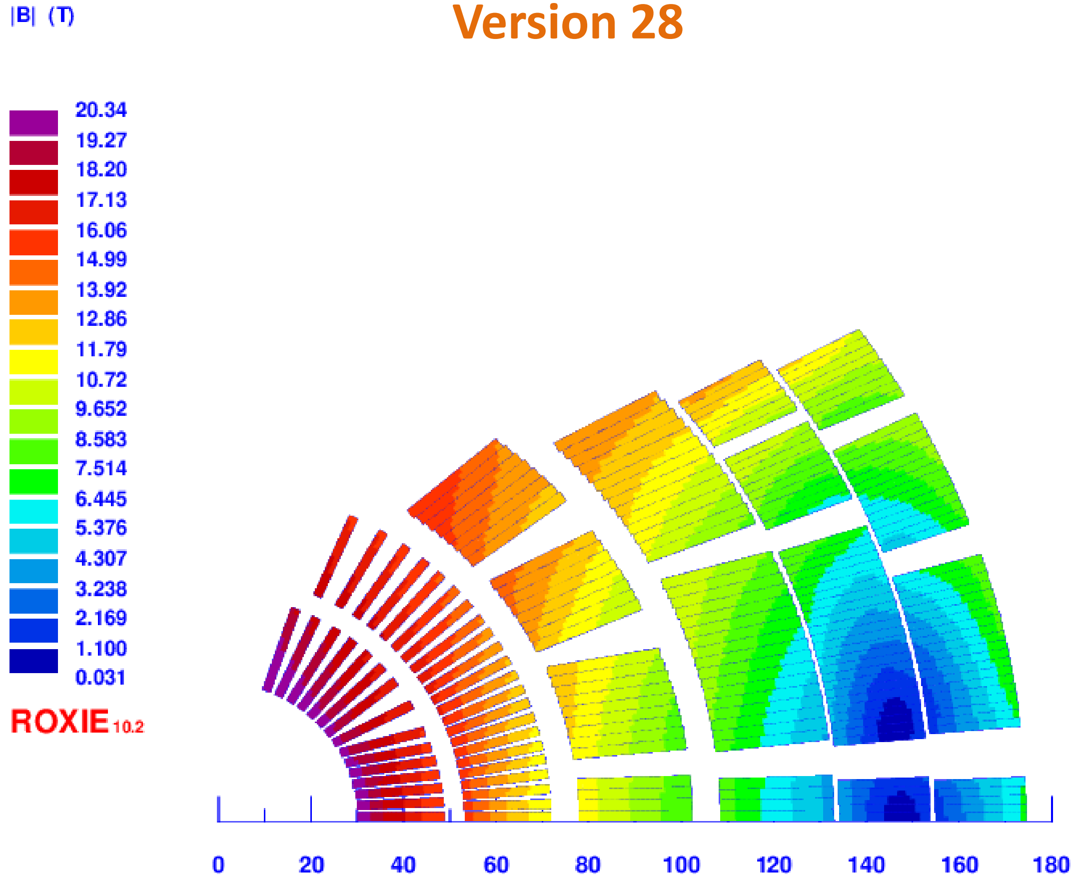
Magnetic Analysis - I

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

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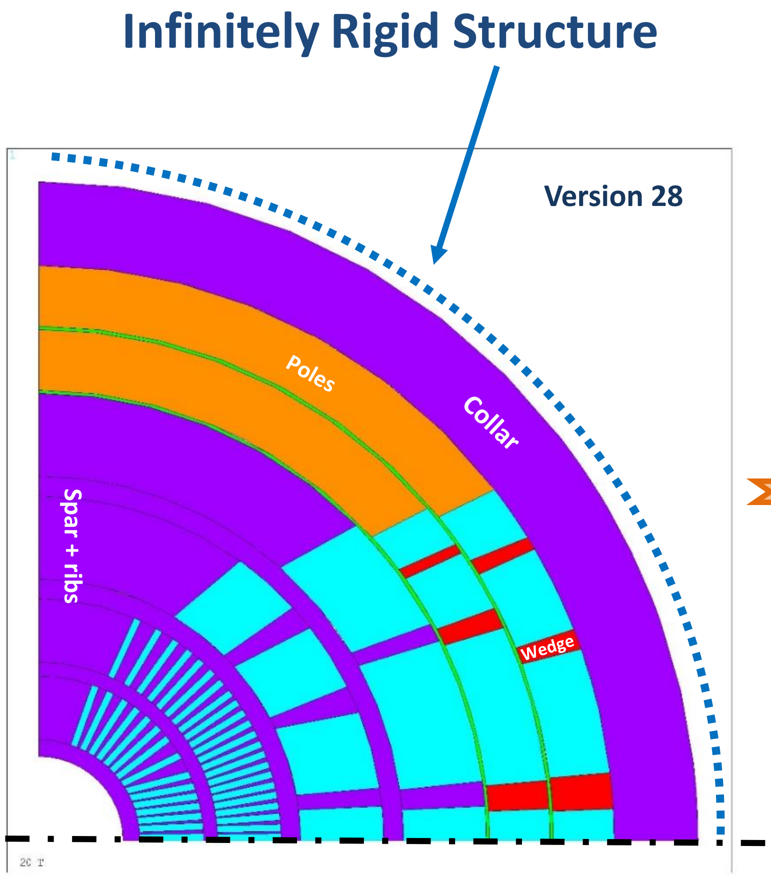
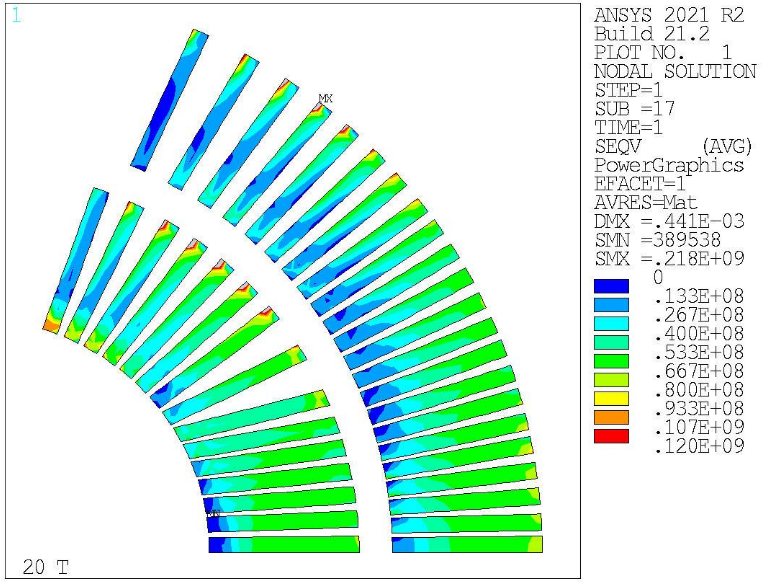
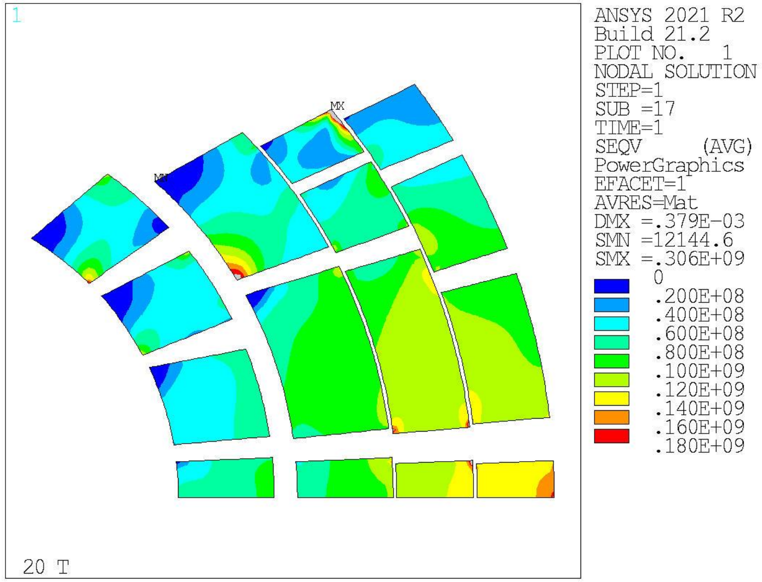
Mechanical Analysis – Infinitely Rigid Structure I



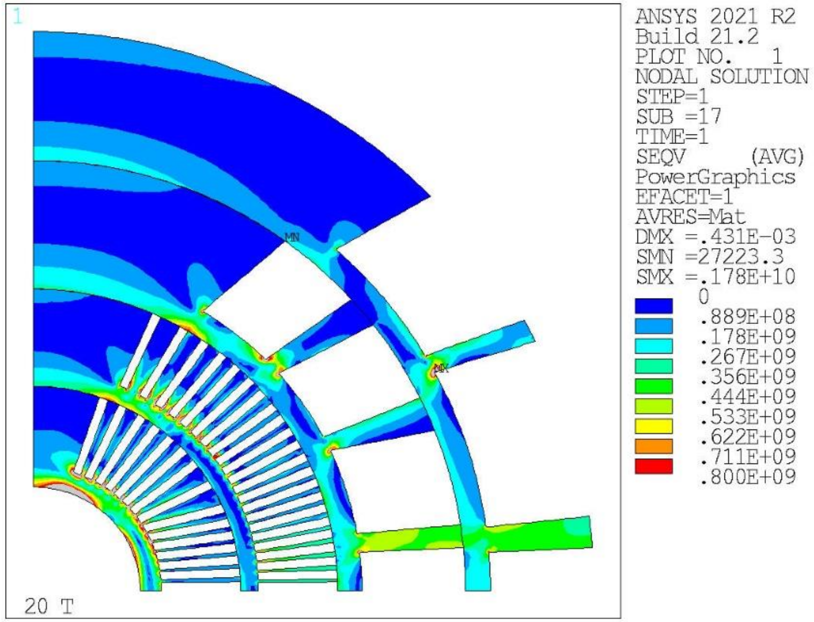
Equivalent Stress

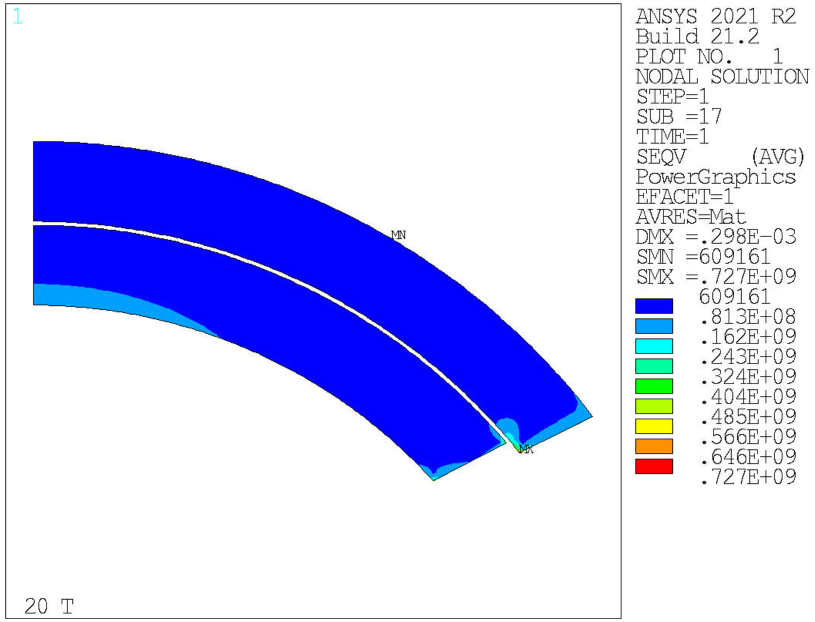


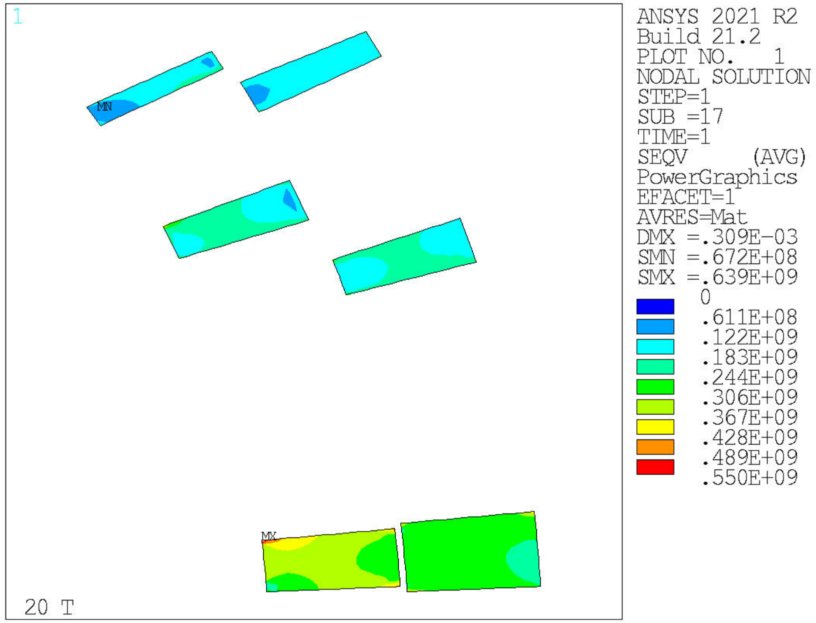


Mechanical Analysis – Infinitely Rigid Structure II

Equivalent Stress

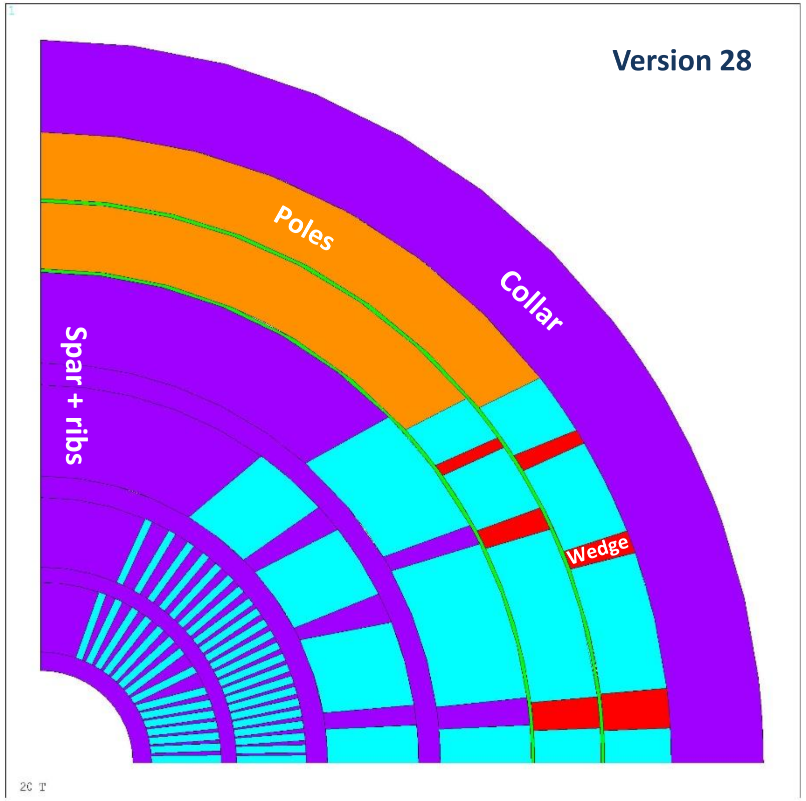




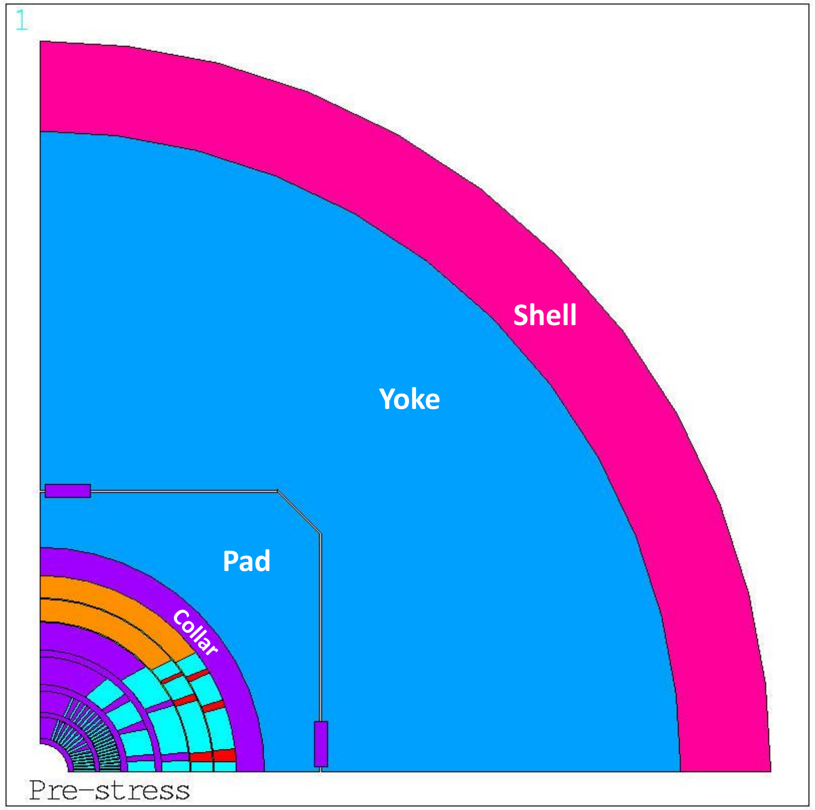


Mechanical Analysis – Real Structure

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

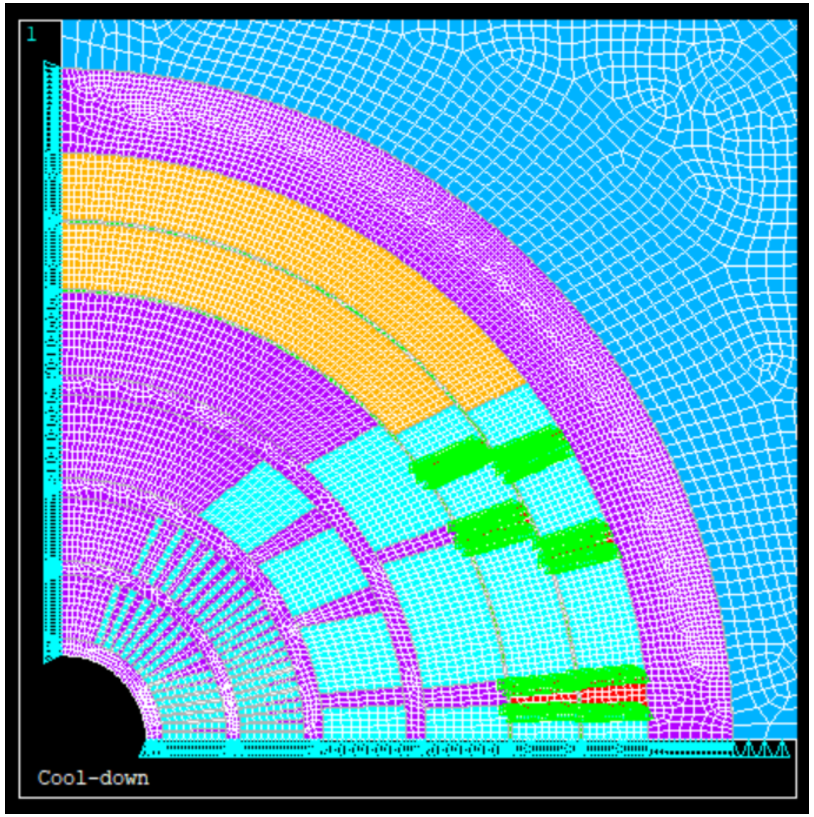
Interference: 2 mm on the horizontal key → first attempt for the max allowable stress in the shell

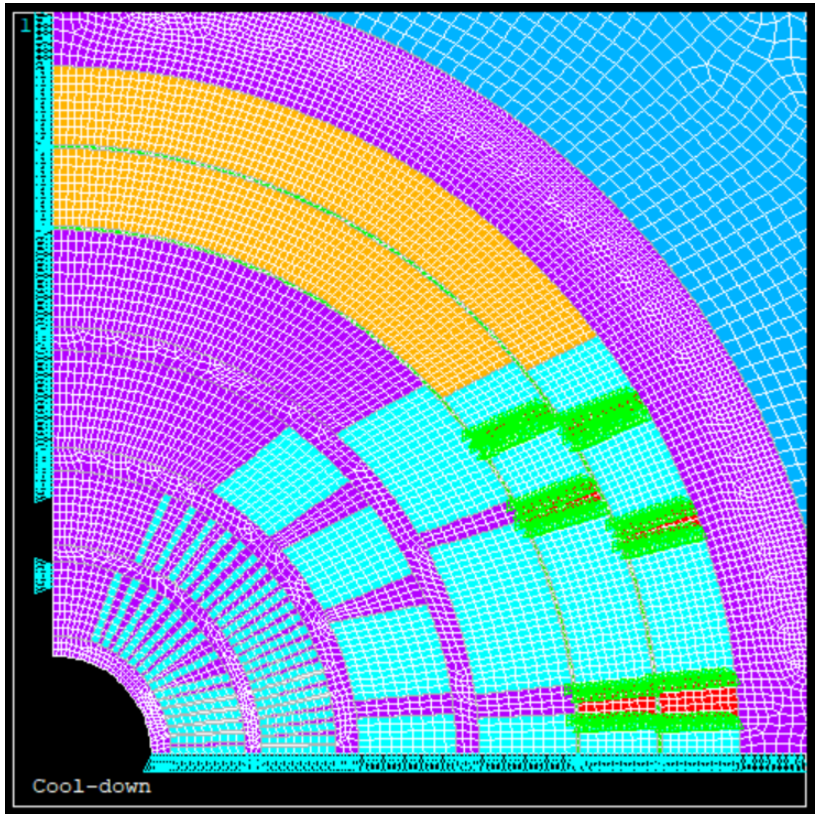
Mechanical Analysis – Cases Comparison

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)





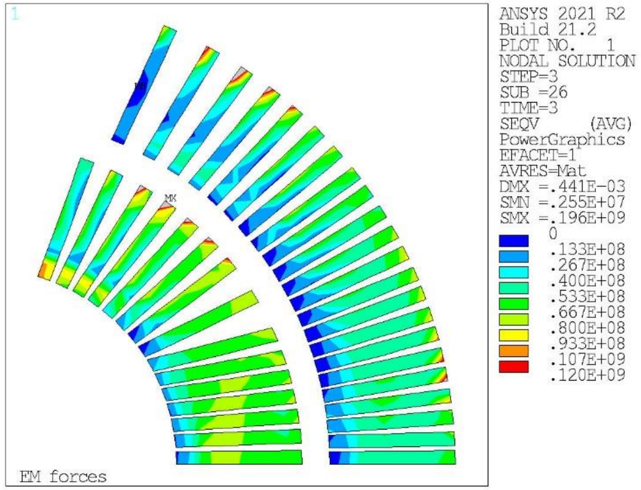
Mechanical Analysis – Coils

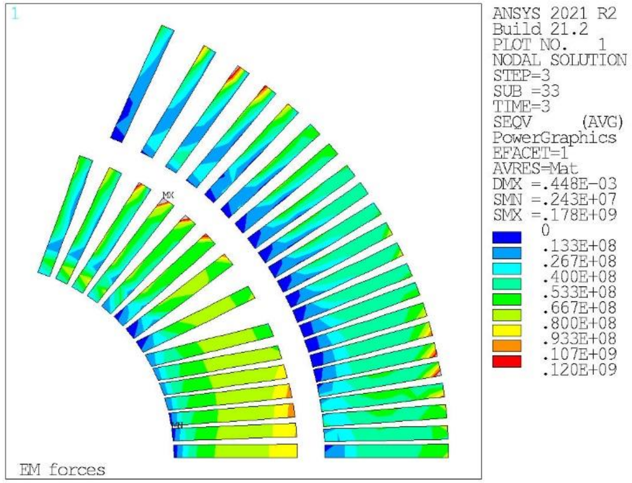
Equivalent Stress

Case 1

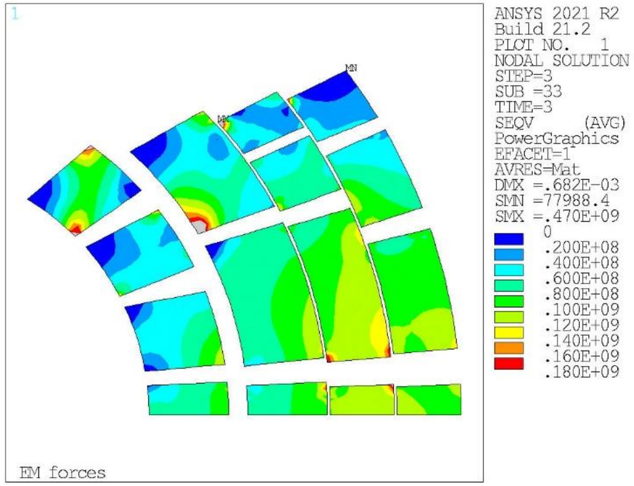
Case 2

HTS





LTS

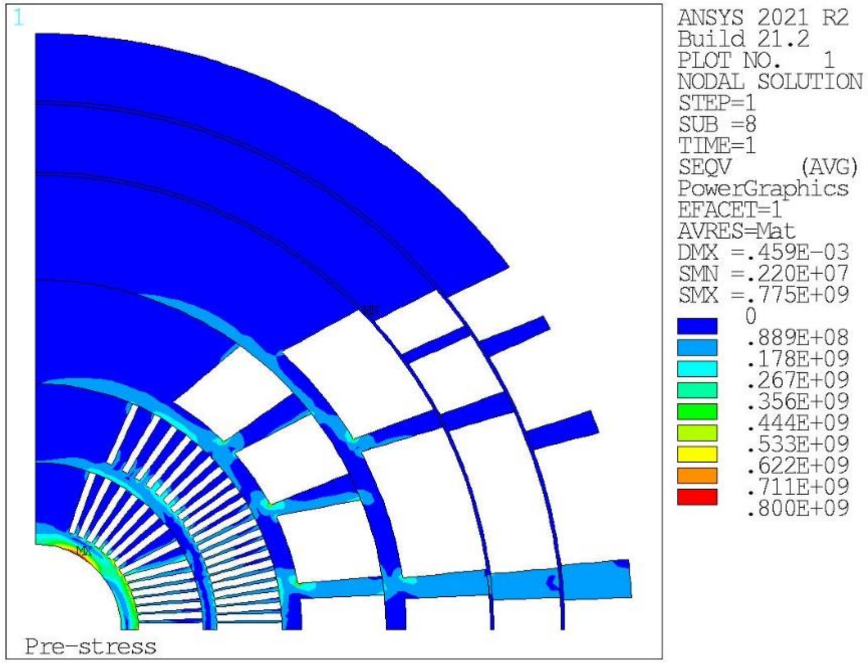


Mechanical Analysis – Mandrel I

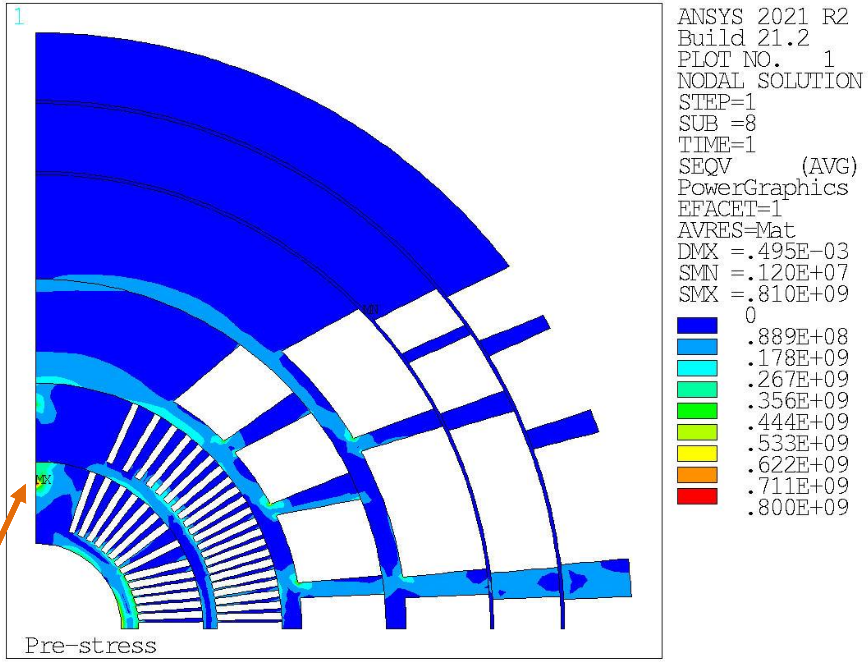
Pre-stress

Equivalent Stress

Case 1



Case 2



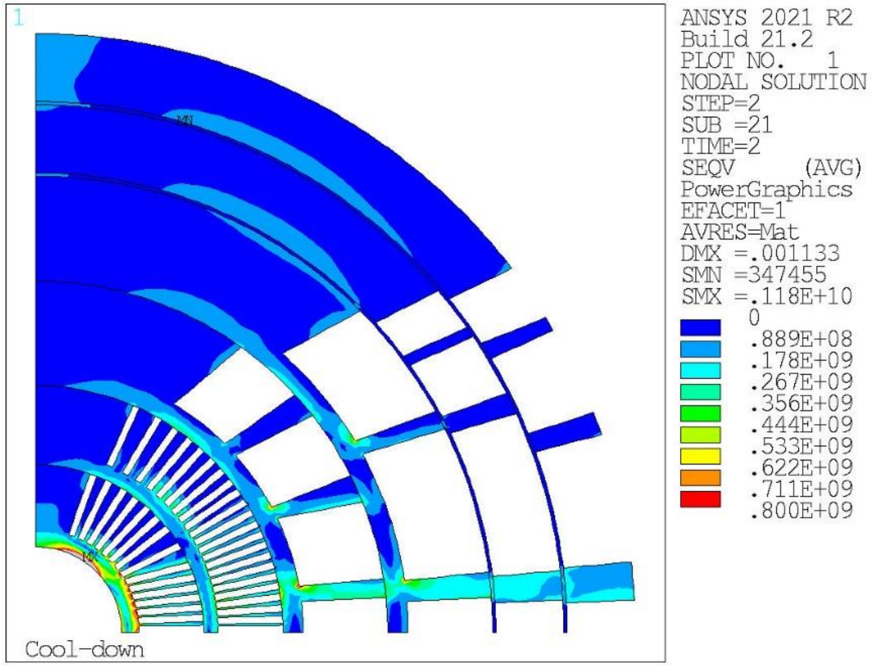
All cases) On the mandrel, starting from the midplane and moving along the circumference at the same radius r_0, there is first tension and then compression.

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

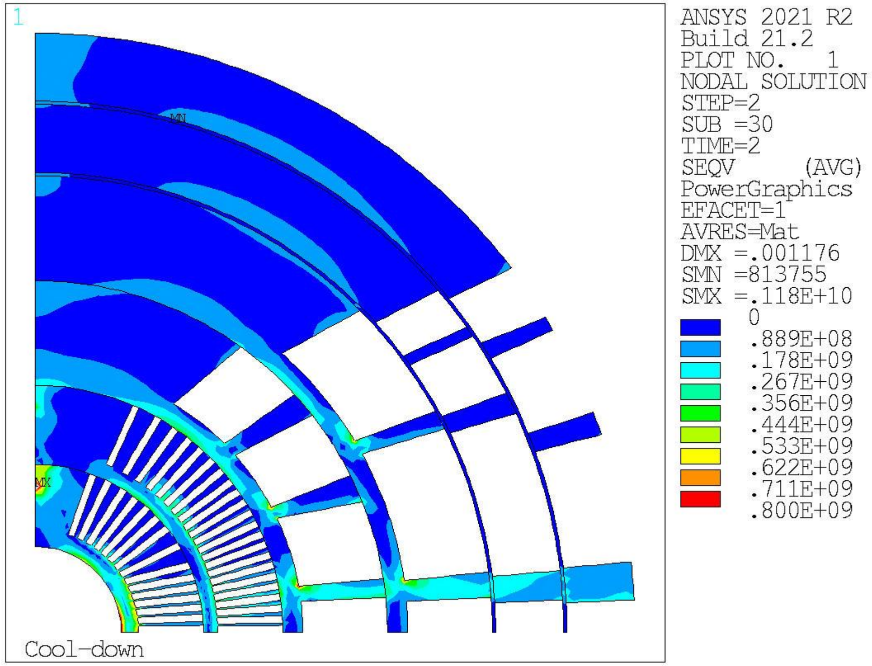
Mechanical Analysis – Mandrel II

Cooldown

Case 1



Case 2



Equivalent Stress

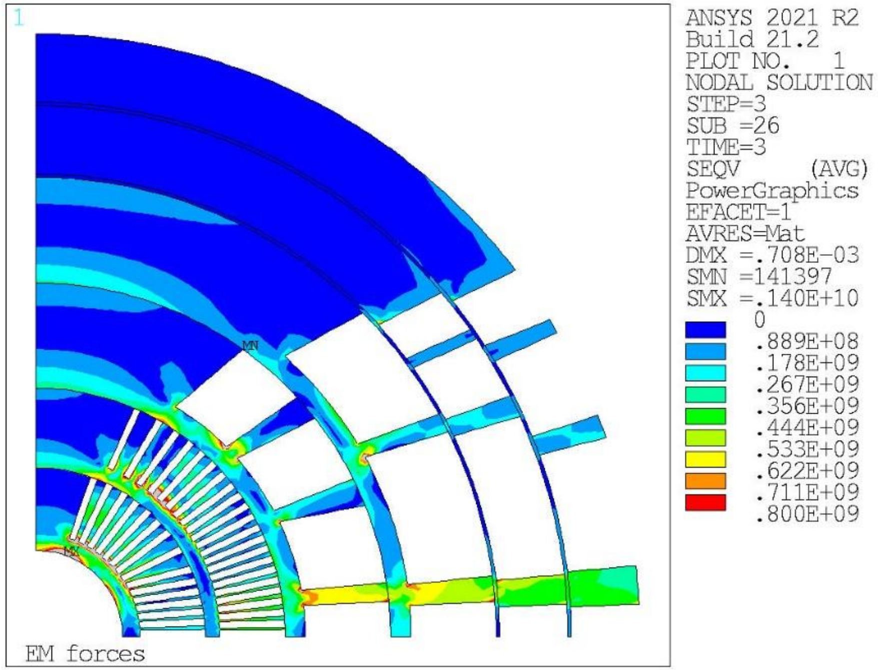
Case 2) The peak stress is concentraced where the constraints are removed. The stress distribution on the layer 1 is better than the one encountered in the case 1.

Mechanical Analysis – Mandrel III

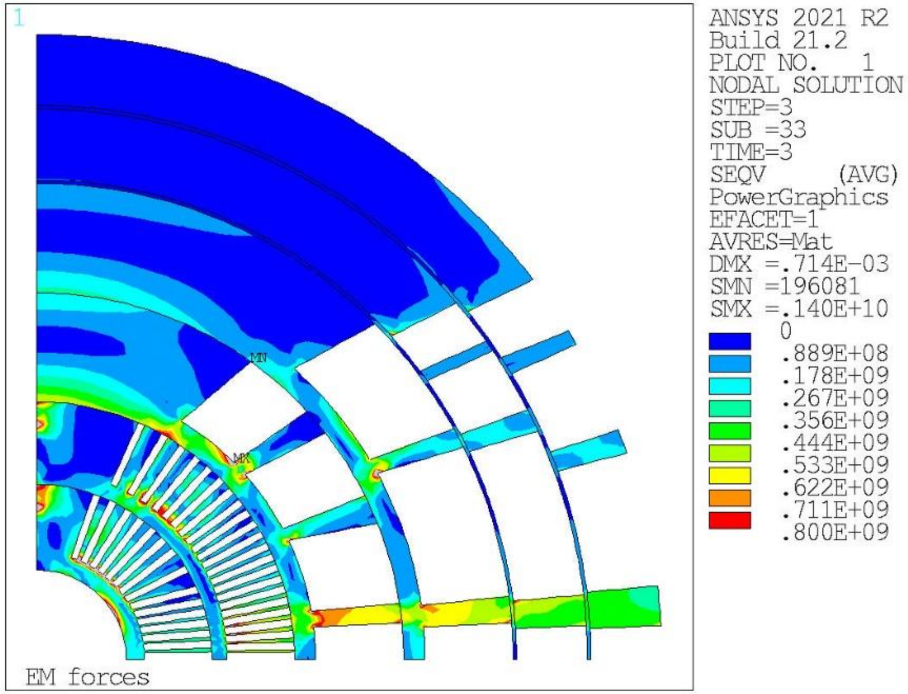
EM forces

Equivalent Stress

Case 1



Case 2

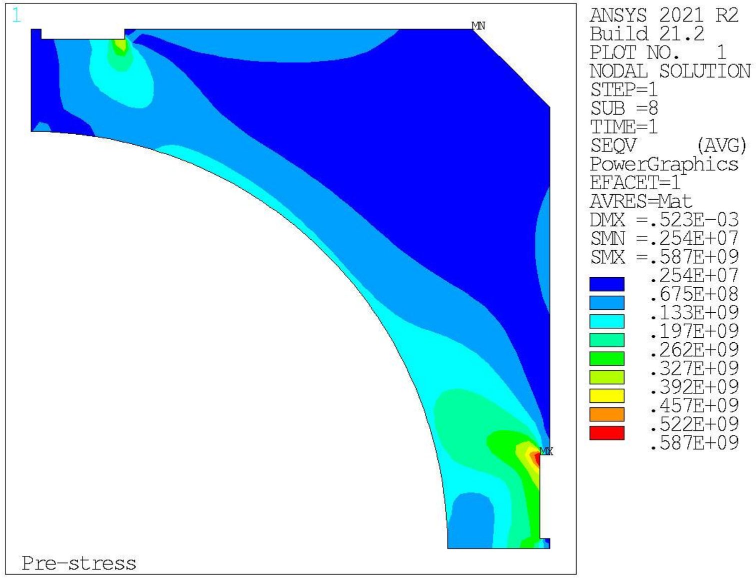


Case 2) Stresses on the mandrel are significantly improved.

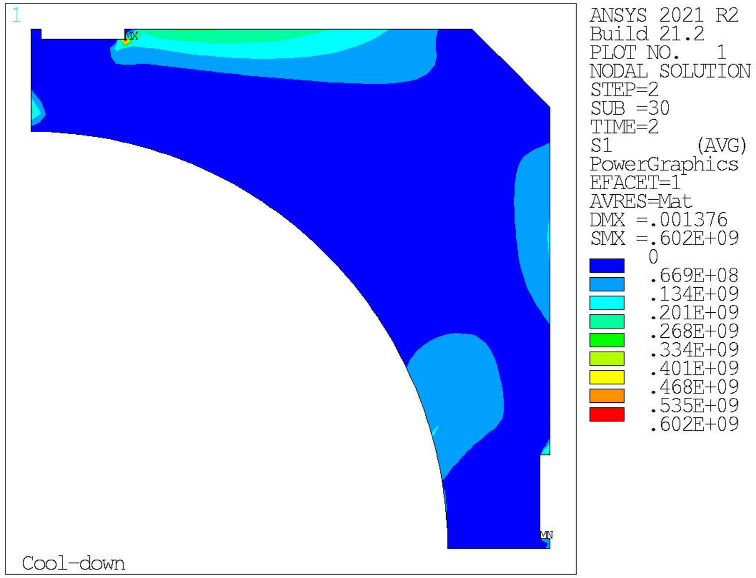
Mechanical Analysis – Pad

Case 2

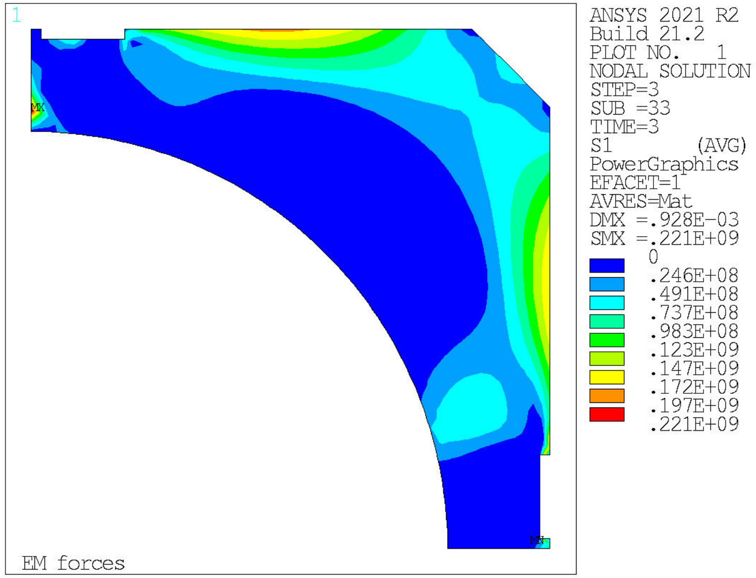
Pre-stress
Equivalent Stress



Cooldown
First Principal Stress



EM forces
First Principal Stress

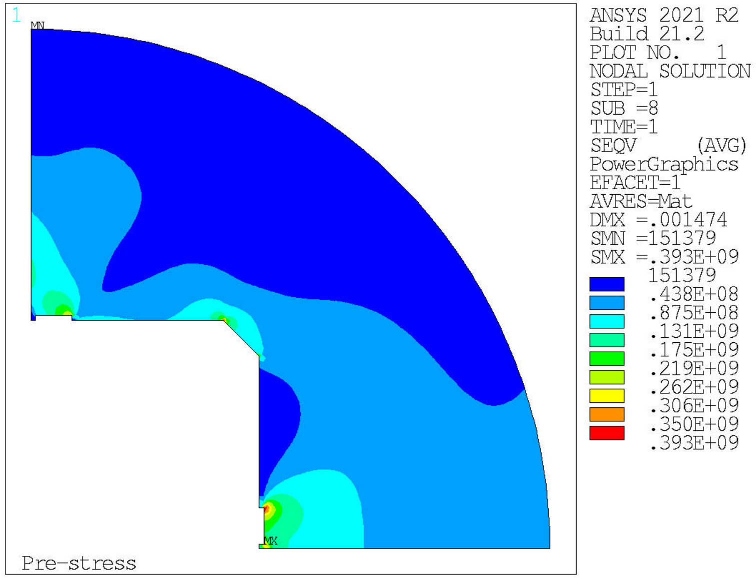


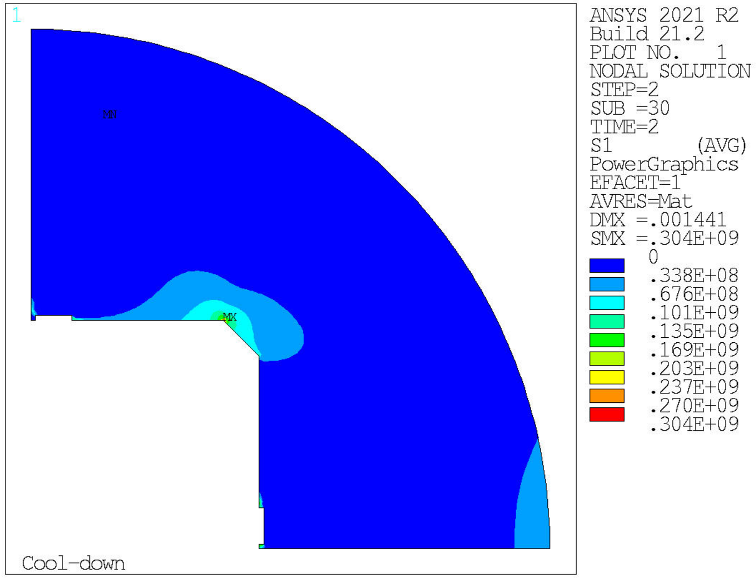
Both case 1 and case 2 show similar results.
It is not clear the reason of the location of the maximum tensile stresses.
Overall, the retrieved results do not present critical issues compared with the limits imposed in the material properties table.

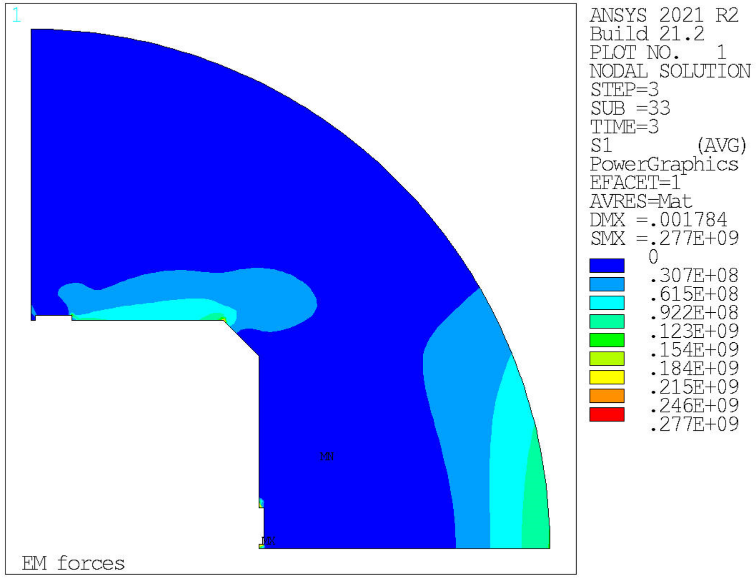
Mechanical Analysis – Yoke

Case 2

Pre-stress	Cooldown	EM forces
Equivalent Stress	First Principal Stress	First Principal Stress







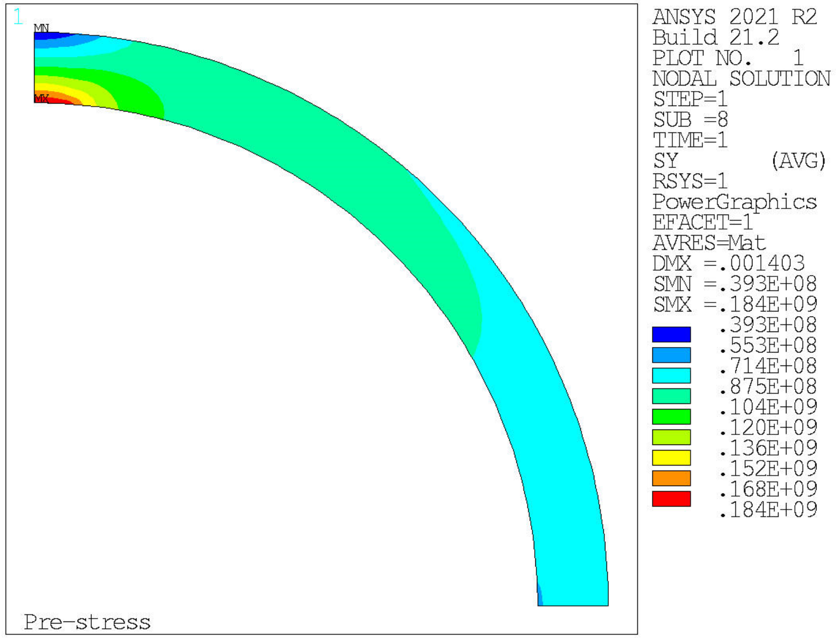
Also the yoke does not have major issues, so we are currently focusing on other parts of the mechanical structure.

Mechanical Analysis – Shell

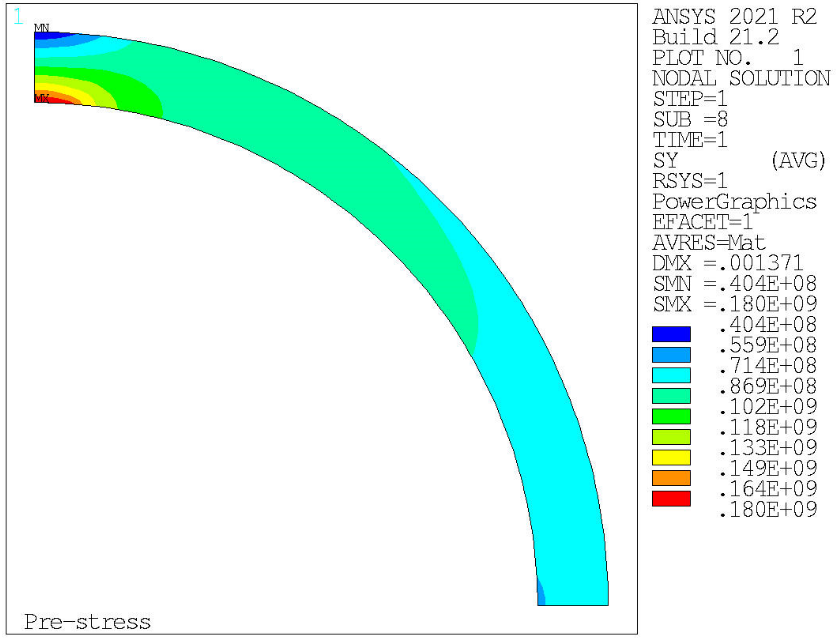
Pre-stress

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
- Measurement and Computation of Nb_3Sn Rutherford Cables Strength Under Multi-Axial Loading Conditions
- Magnetic Analysis
- Mechanical Analysis
- Results Summary

Results summary

Measurements of cable stacks under transversal pressure:

- Cracks appear at around 120 MPa under 1D loading;
- Cracks disappear when the horizontal pre-stress is increased;
- Investigate the failure surfaces $S(\sigma_x, \sigma_y, \sigma_z)$ at room temperature and at cold condition.

Comments on the mechanical structure model:

- Limits are exceeded in the mandrel (bending);
- Peak stress localized in the corner of the coils;
- Mechanical structure optimization.