HFM
High Field Magnets

WP3.1 - Nb3Sn robust performance double aperture 12T cosΘ dipole models

CERN

20.12.2023

Lucie Baudin on behalf of the 12 T project team

Content

- 12T Design Guidelines
- Conceptual Design
- Mechanical design, FEM simulations and test campaign with mock-ups

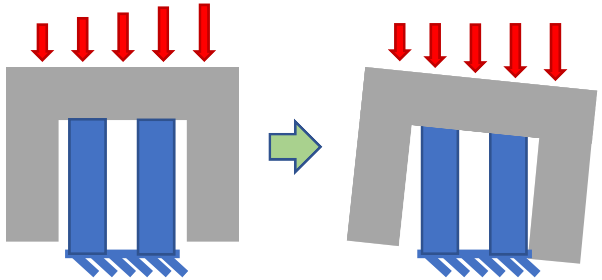
12T Design Goals and Guidelines

Minimize coil compression at all stages of magnet lifecycle

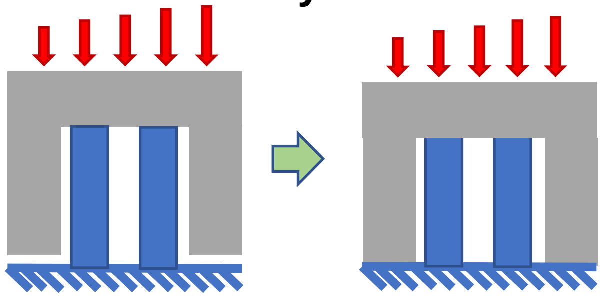
Stress at room temperature < 120 MPa
Stress at cold < 130 MPa
Pole – Coil contact closed at cold

Protect the coils against risk of overstress due to accidental loads → work with **close cavity**
A soft component deforms until the rigid cavity closes.
Once the cavity is closed, the load is handled by the cavity, the soft component do not further deform

Open cavity structure

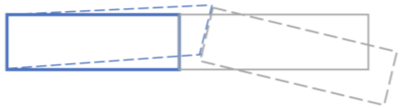


Close cavity structure



Decrease influence of manufacturing **tolerances** on magnet performances

Limit the number of components to avoid piling-up tolerances



Decrease the degree of redundancy in the structure to enable better control of contact force distribution between parts

Conceptual Design

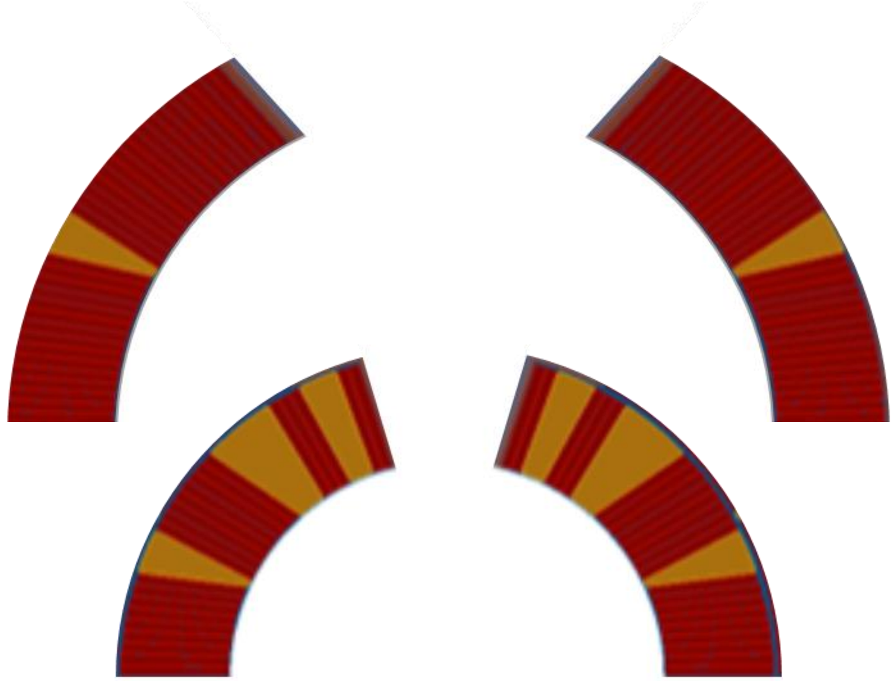
Robust, intrinsically safe mechanical structures

Presented at the Conceptual Design Review
at CERN on 5 July 2023.

12T conceptual design

Separation of inner and outer layer coils

Inner and outer layers are winded and reacted separately and placed on top of each other with an interlayer



+

Mechanical kinetics:

less statically indeterminate, the coils can slightly move with respect to each other

peaks of stresses (possibly leading to cracks, *see Diego's presentation*) **are reduced**

Cooling:

possibility of using the coil interlayer to bring helium closer to the coils

Winding:

simpler winding

no need of primer in the layers

Coil production:

inspection of outer layer of inner layer coil at each manufacturing step

in case of accident, only the concerned layer cable is discarded and not the total length of the pole

—

Winding/tolerances:

two systems of molds (for the 1^{st} and 2^{nd} layers)

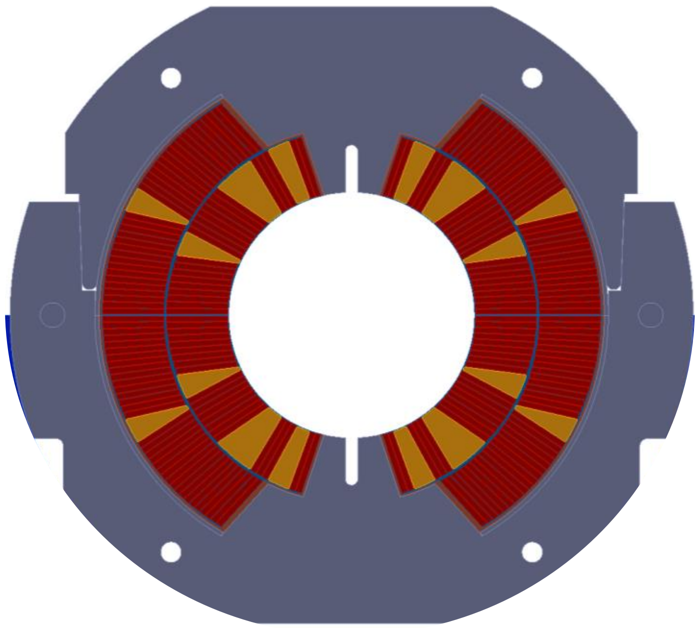
Coil production:

need of a coil splice

12T conceptual design

Collared coils

For reasons of **time and resources** we concentrate on the collared coils



Thin stainless-steel collars:

\+ Place iron close to the coils to get “free field”

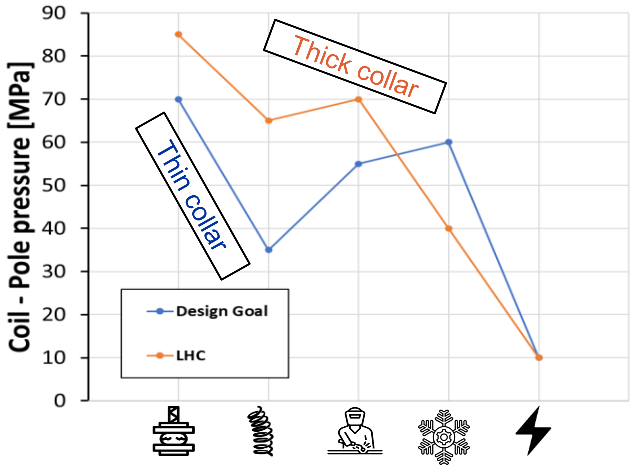
$$B = \frac{\sqrt{3}}{\pi}\mu_0 j w \to \frac{\sqrt{3}}{\pi}\mu_0 (1+\Delta_I) j w \qquad \Delta_I = \frac{r(r+w)}{R_I^2} \qquad 0 < \Delta_I < 1$$

r: aperture radius
w: coil width
R_I: iron radius

Courtesy of E. Todesco
(CERN/TE-MSC)

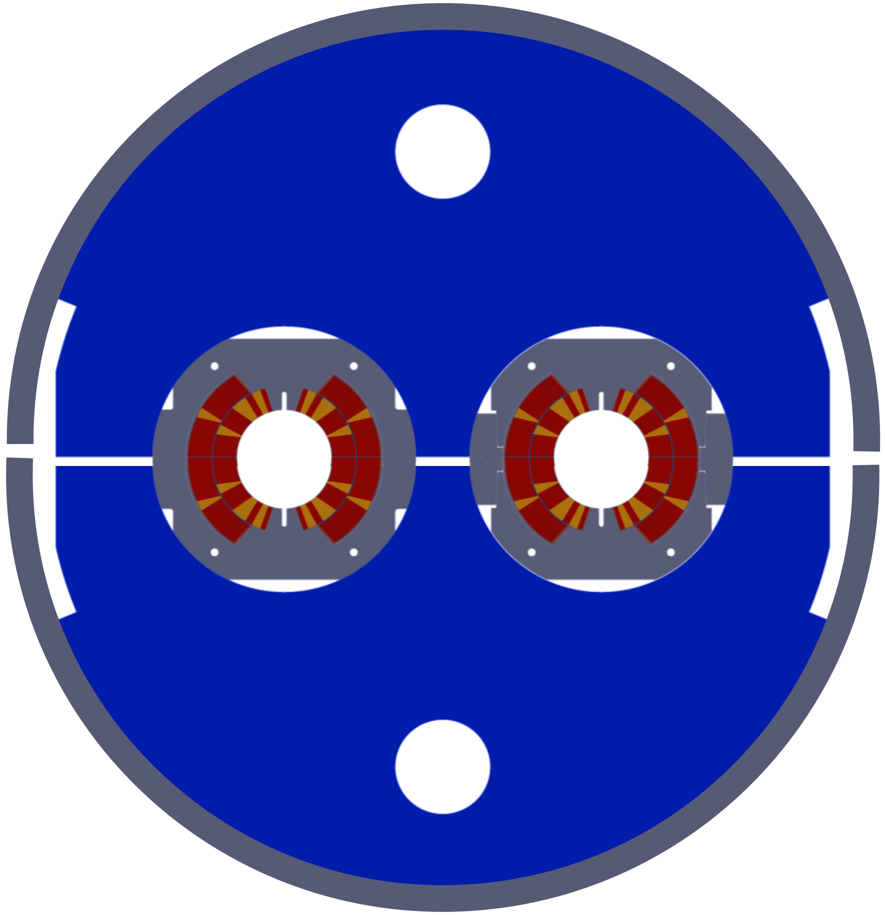
— Thin collars will result in important springback

Average coil prestress at the contact with the collar pole during the assembly and energization



We want to keep moderate coil prestress during collaring
→
We must **recover pre-stress** in the following assembly steps and during cool down

12T conceptual design



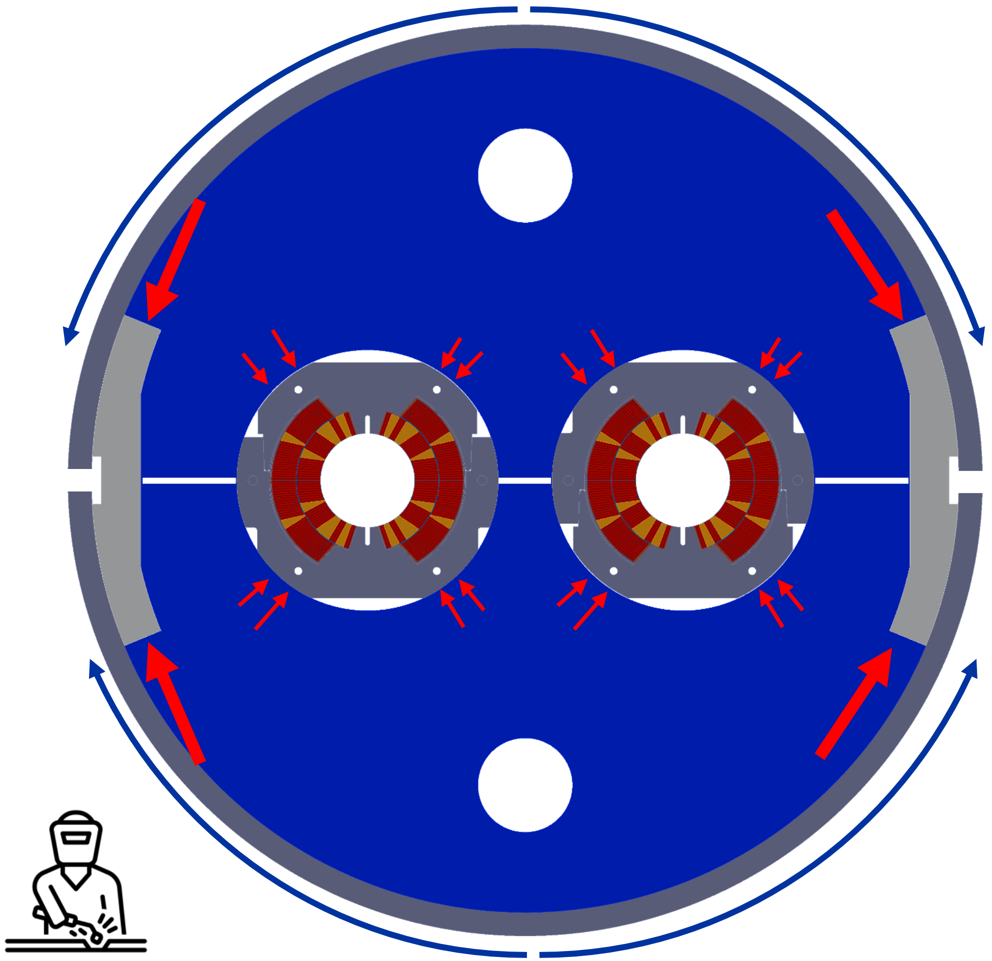
Horizontal iron yoke gap structure

Enable coil **pre-compression increase during cool down**

Stainless steel shell

Enable longitudinal preload via bullet cage

12T conceptual design



Horizontal iron yoke gap structure

Enable coil **pre-compression increase during cool down**

Stainless steel shell

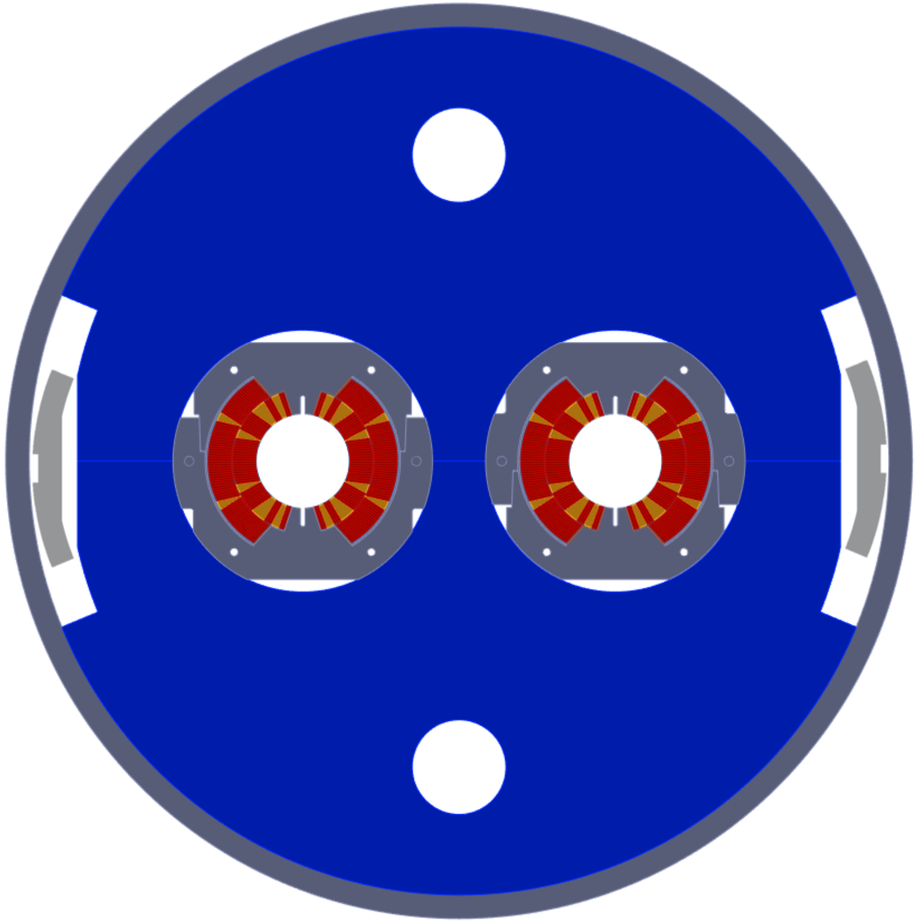
Enable longitudinal preload via bullet cage

Aluminium stoppers

Protect the coils against **risk of overstress** due to **accidental loads during assembly process**

Decrease influence of **manufacturing tolerances** on **magnet performances**

12T conceptual design



Horizontal iron yoke gap structure

Enable coil **pre-compression increase during cool down**

Stainless steel shell

Enable longitudinal preload via bullet cage

Aluminium stoppers

Protect the coils against **risk of overstress** due to **accidental loads during assembly process**

Decrease influence of **manufacturing tolerances** on **magnet performances**

Increase pre-compression of the coil, at cold

Close horizontal gap at cold

Protect the coils against **risk of overstress** due to **accidental loads during operation**

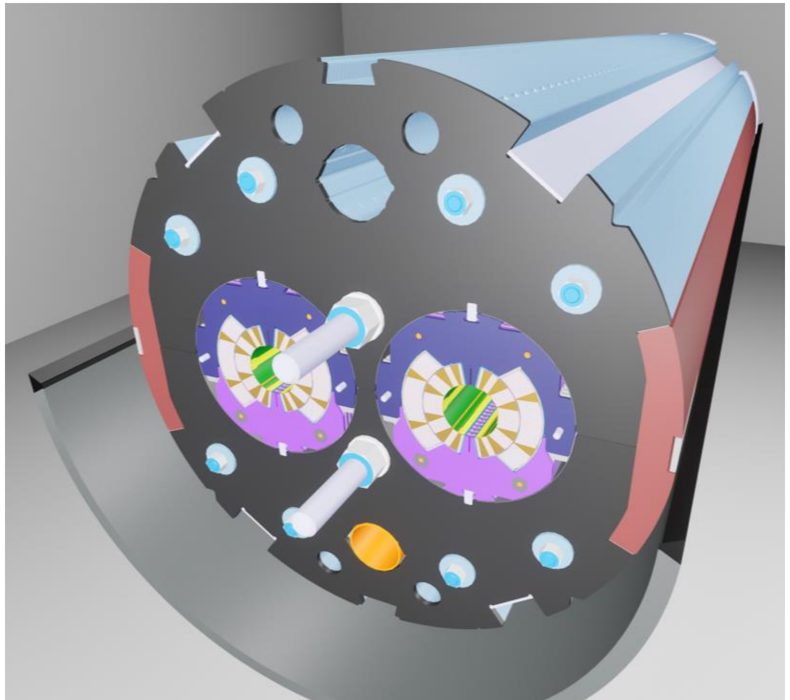
A yoke which is one piece horizontally provides stiffness against the electromagnetic forces

=

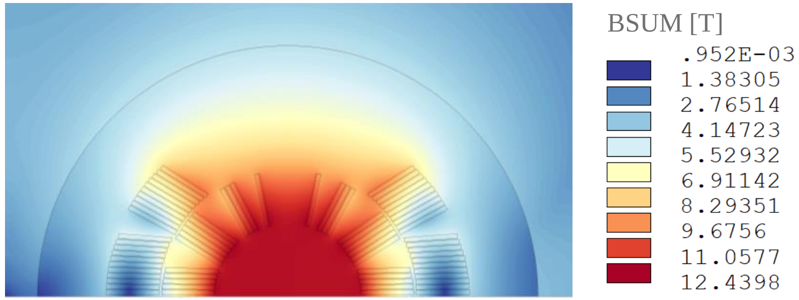
Minimize retaining structure deformations as these can generate extra coil deformations in the horizontal midplane

Mechanical design
FEM simulations
and
test campaign with mock-ups

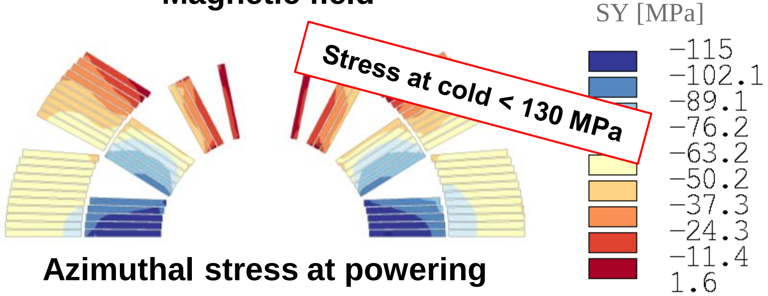
Mechanical design and simulations



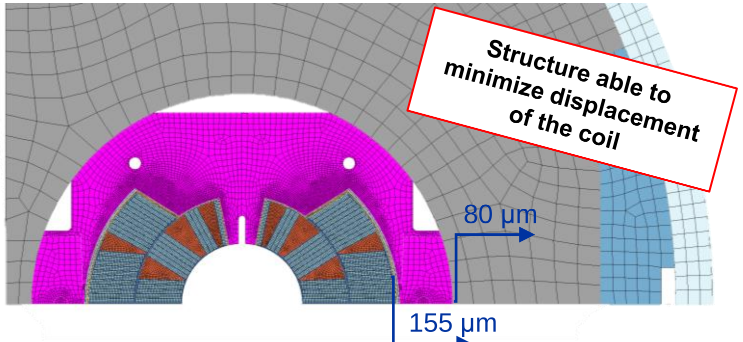
First iteration of the mechanical design



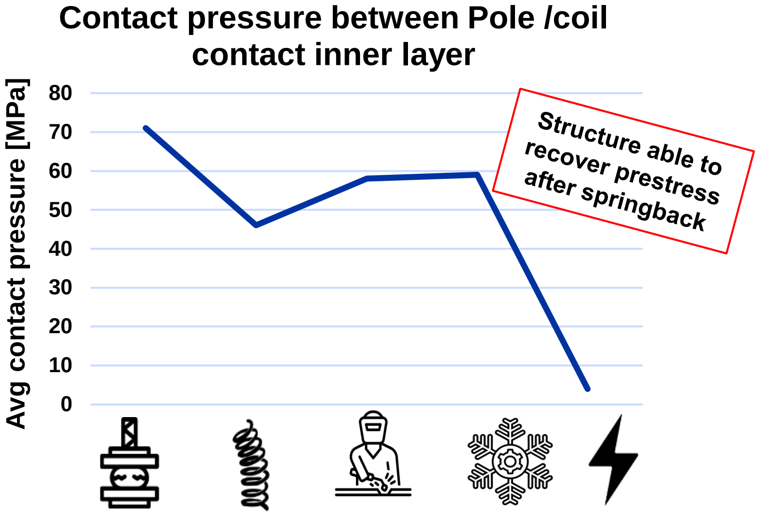
Magnetic field

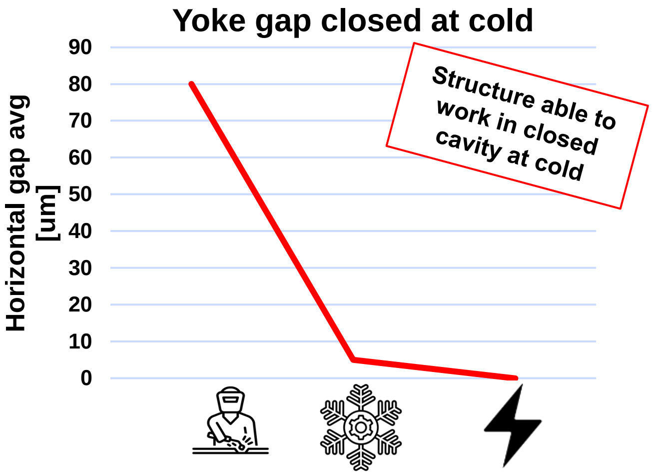


Azimuthal stress at powering



Horizontal displacement at powering





The FEM shows that, with the baseline design, the structure, is able to:

- Recover pole prestress after springback
- Minimize coil compression
- Provide rigidity against the EM forces

Test campaign with mock-ups

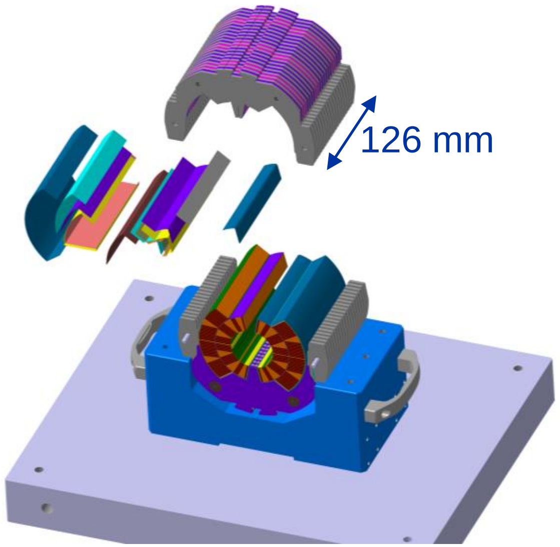
Understand and control the coil stress distribution during magnet lifecycle

Courtesy of
O. Id Bahmane
(CERN/EN-MME)

inner and outer layers reacted and impregnated **separately**

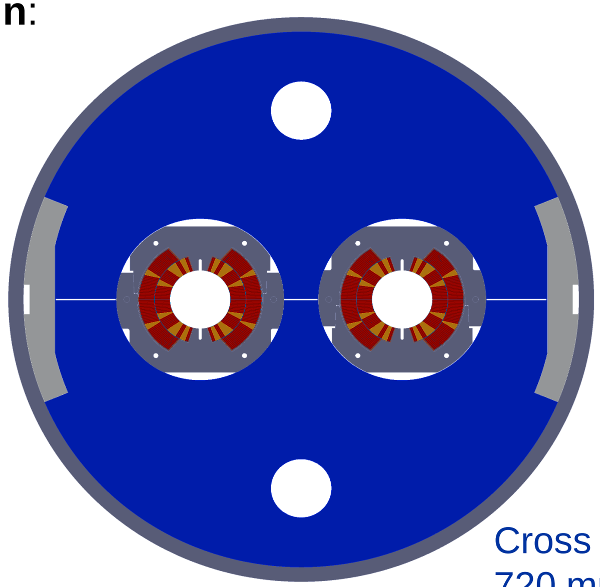
As **intermediate step**, mock-up will be done by taking advantage of the **available resources,** non-conforming straight sections of **11T's coils**. Inner and outer layers have been reacted and impregnated separately.

2 phases **test campaign**:



Collaring mock-up

+



Cross section slice
720 mm deep

Collaring, yoking, welding and cooling down mock-up

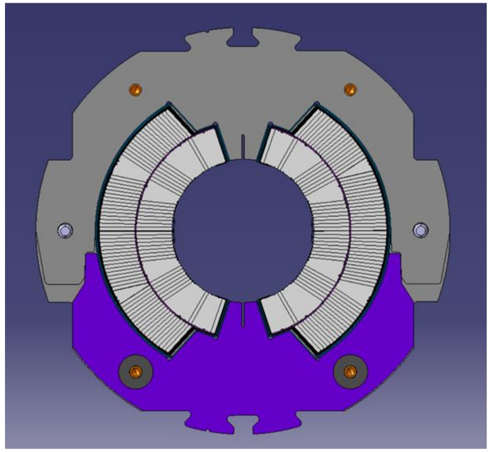
Test campaign with mock-ups

Employing the available resources :
11T coil, 11T stainless steel shell.

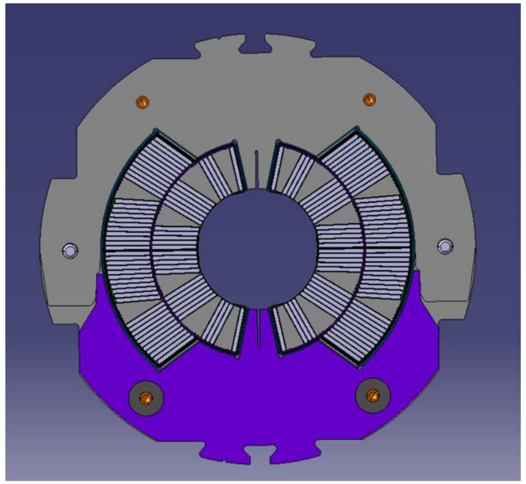
inner and outer layers
reacted and impregnated
separately

As **intermediate step**, mock-up will be done by taking advantage of the **available resources,** non-conforming straight sections of **11T's coils**. Inner and outer layers have been reacted and impregnated separately.

11 T modified
ST1685289_01



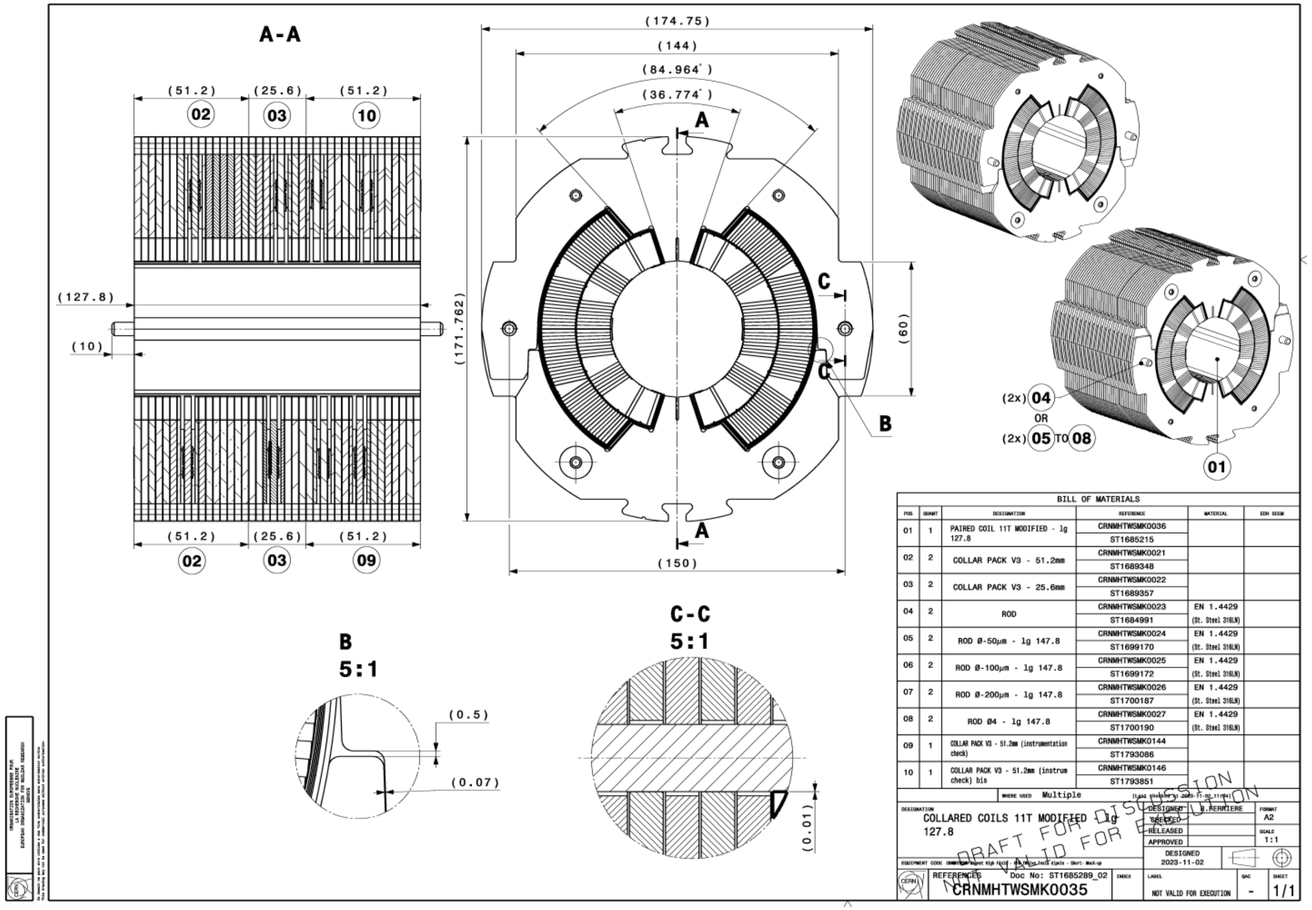
12 T
ST1757039_01



Coil	11T modified	12T baseline	12T backup
Ø Internal Coil [mm]	60	50	60
R int collar [mm]	62.375	64.675	(69.675)
R ext collar [mm]	87.375	89.675	(94.675)
Collaring tool distance between teeth [mm]	144	148	(158)

Test campaign with mock-ups

Evaluate the influence of the two layers separation and interlayer characteristics



Dummy coil aluminum:

- 1 block
- 2 separated layers

11T coil:

- 1 block (section of 11T coil with the two layers impregnated together)
- 2 separated layers

Interlayer characteristics:

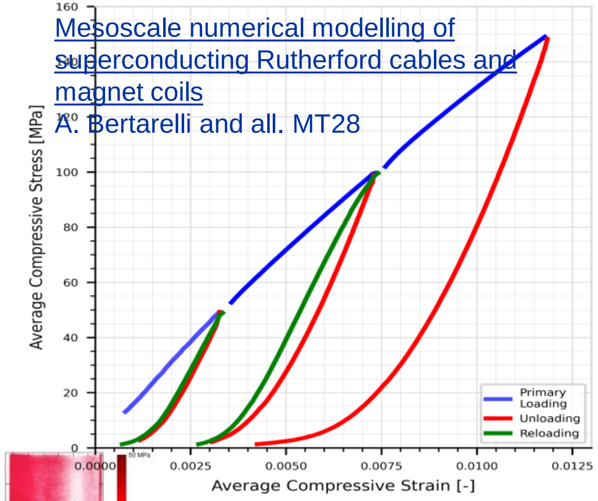
- thickness
- materials : mica, fiberglass, wax impregnated fiberglass, fishbone…

Experimental measurement
and benchmark of FEM parameters

CTE, Interlayer frictional coefficient, E-modulus…

Test campaign with mock-ups

[Mesoscale numerical modelling of superconducting Rutherford cables and magnet coils](#)
A. Bertarelli and all. MT28

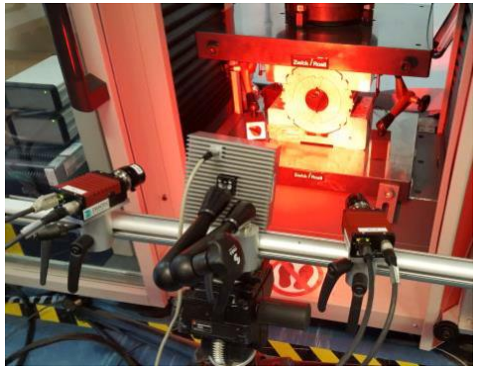


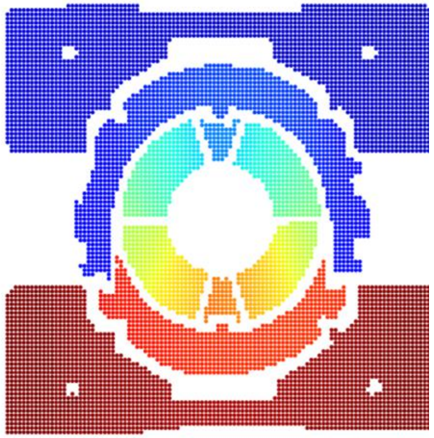
Knowledge of coil material properties

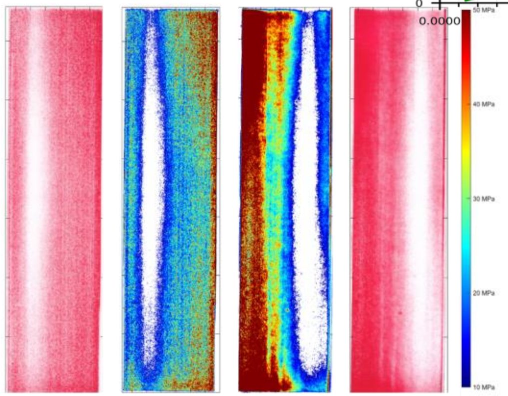
[Mock-up Based Testing Methodology for the Mechanics of High-Field Superconducting Magnets](#). A. Bertarelli and all. MT28

Nb3Sn coil characteristics – Non-linear Young Modulus
Tests and measurement done on 11T coil
FEM mechanical simulations are now carried out using this curve (or bi-linear approximation).

measurement

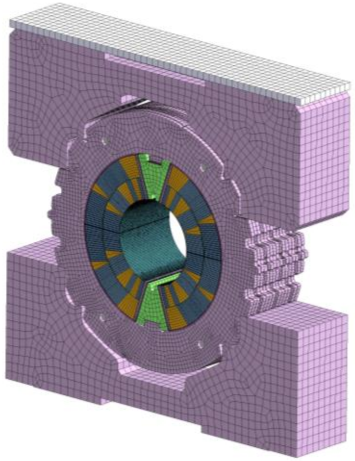


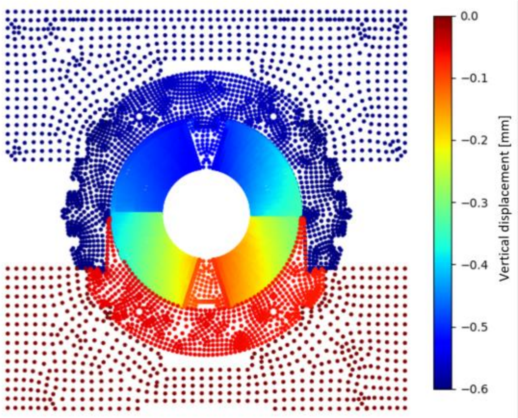


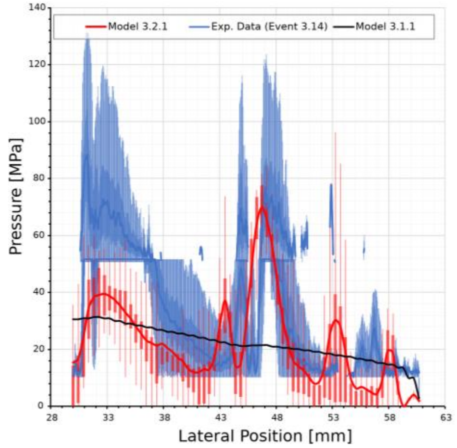


vs

FEM computations





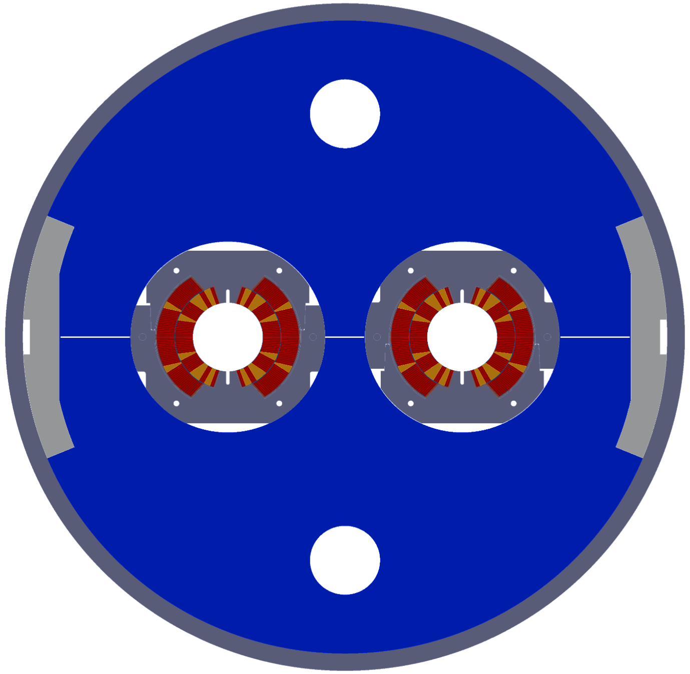


Test campaign with mock-ups

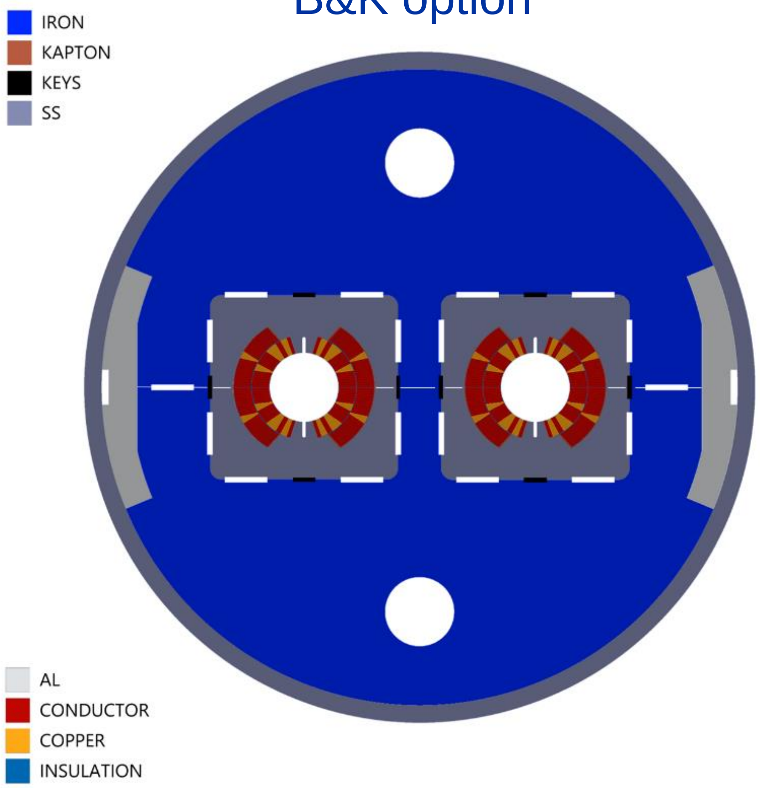
Experimental verification of the assembly parameters in the pre-compression of the coils during magnet lifecycle

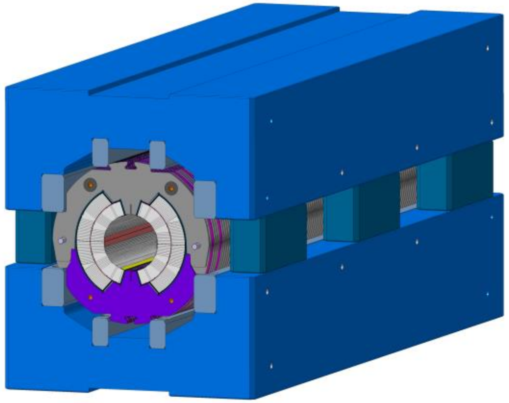
720 mm cross section slice
Reusing 11T stainless steel shell

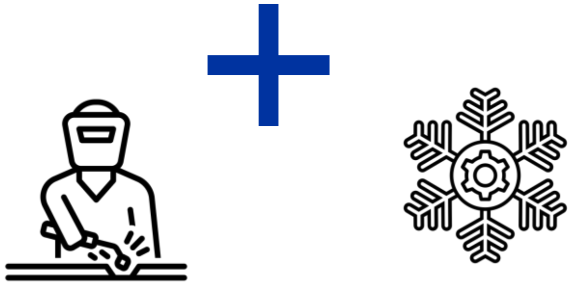
Collared option



B&K option



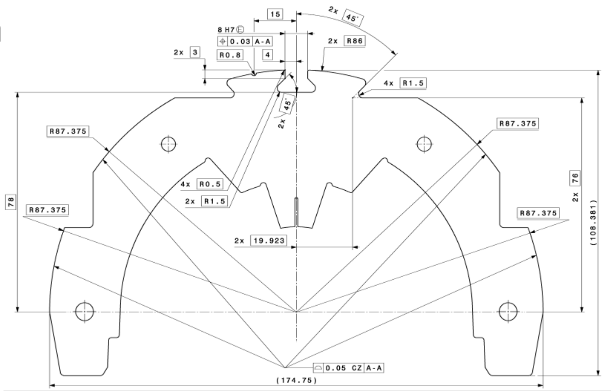




Test campaign with mock-ups

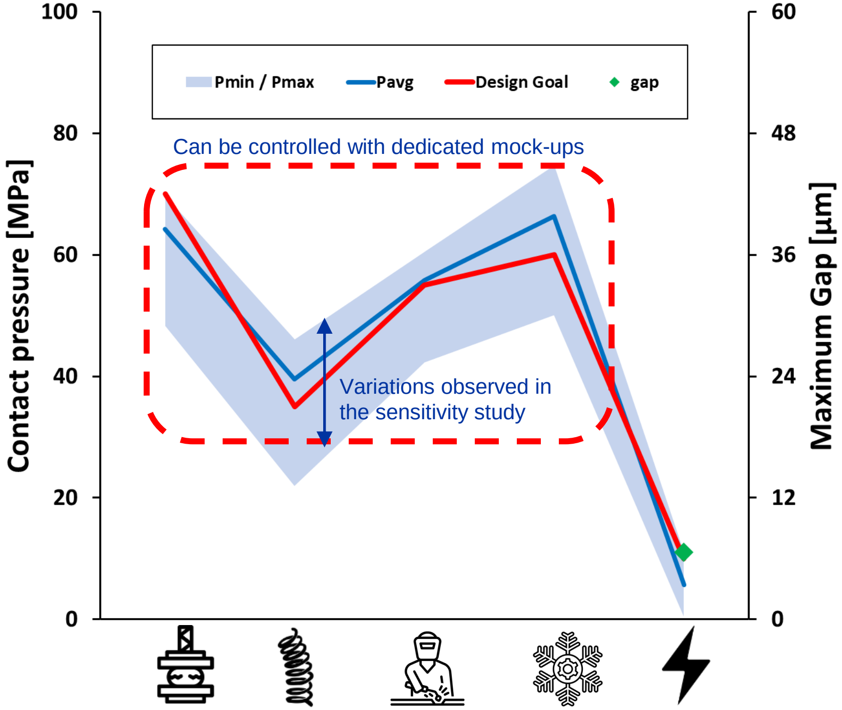
Evaluate the influence of manufacturing tolerances and assembly parameters in the pre-compression of the coils

Design



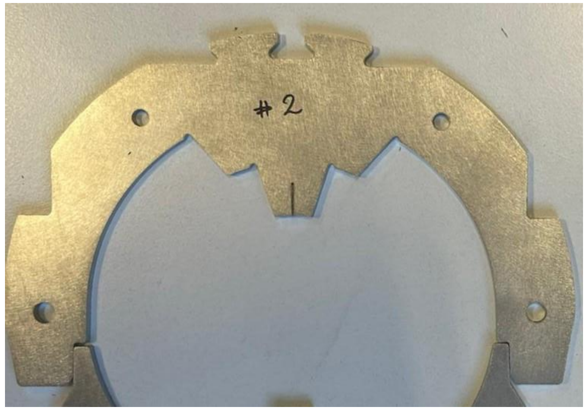
Sensitivity study
on design and assembly parameters
- Pole stress relief slit size
- Excess size
- Yoke gap

on manufacturing tolerances

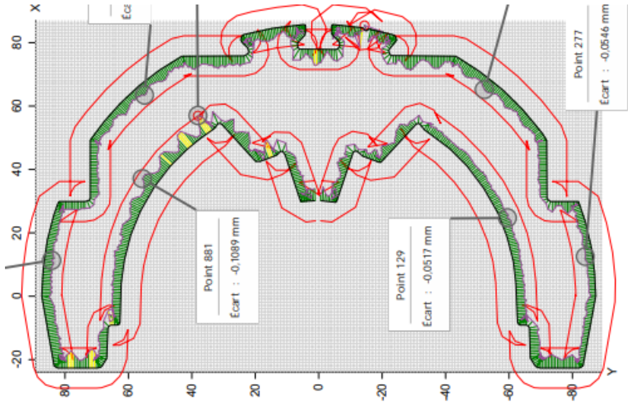


The measurement gather during this sensitivity study will be benchmarked against FEM

Manufacturing



Quality control



Thanks for your attention

Thanks to

CERN/TE-MSC-SMT section
and
12T project team members

D.Perini, C. Abad Cabrera, L.Baudin, T. Boutboul, L.Fiscarelli, A.Foussat, A.Haziot, S.Hopkins, V.Ilardi, K.Lazaridou, N.Lusa, R.Piccin, P.Wachal, F.Mangiarotti, M.Masci, D.Paudel, S.Russenschuck, M.Wozniak

home.cern

Test campaign with mock-ups

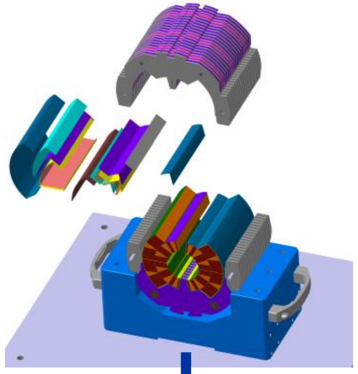
Understand and control the coil stress distribution during magnet lifecycle

inner and outer layers reacted and impregnated **separately**

As **intermediate step**, mock-up will be done by taking advantage of the **available resources,** non-conforming straight sections of **11T's coils**. Inner and outer layers have been reacted and impregnated separately.

Courtesy of O. Id Bahmane (CERN/EN-MME)

2 phases **test campaign**:
Collaring mock-up



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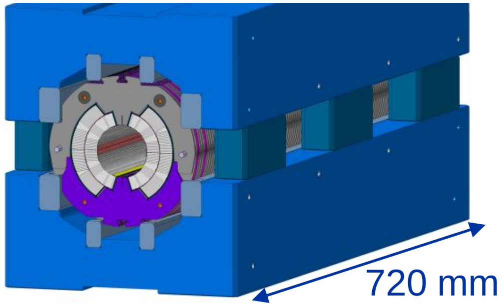
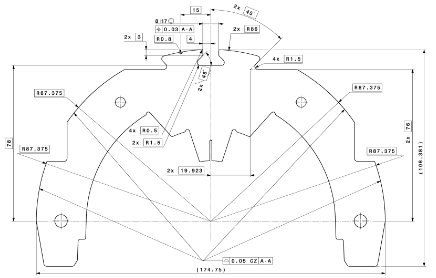
Collaring, yoking, welding and cooling down mock-up



Design



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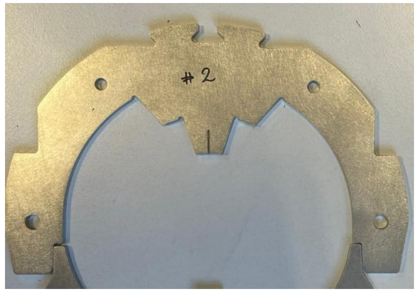
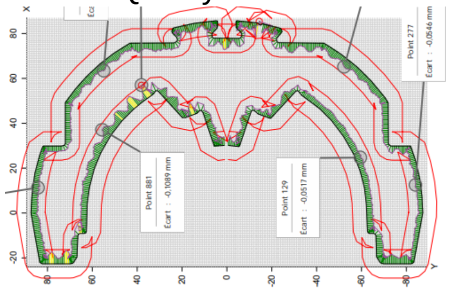
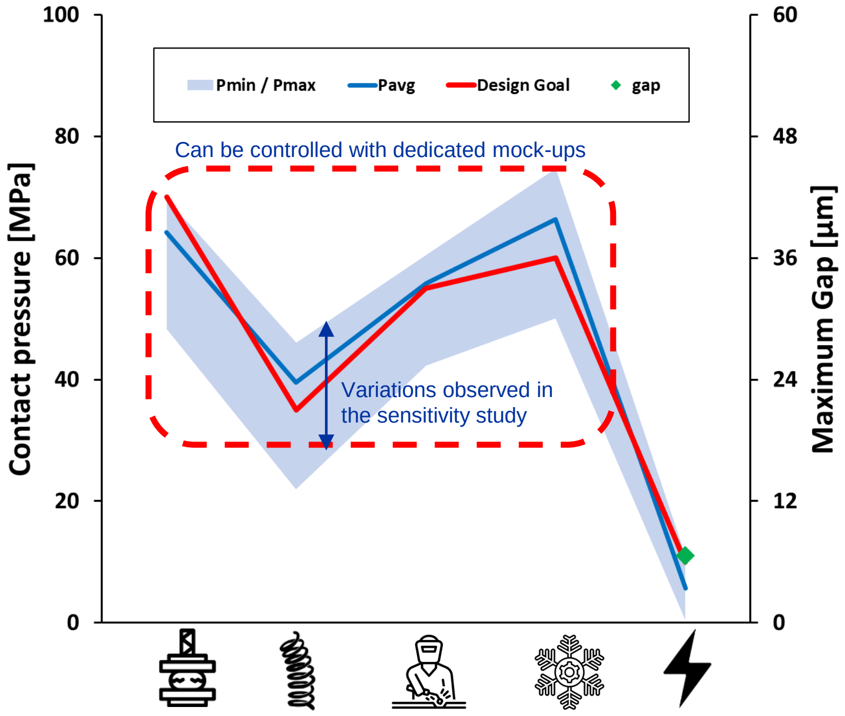


Quality control

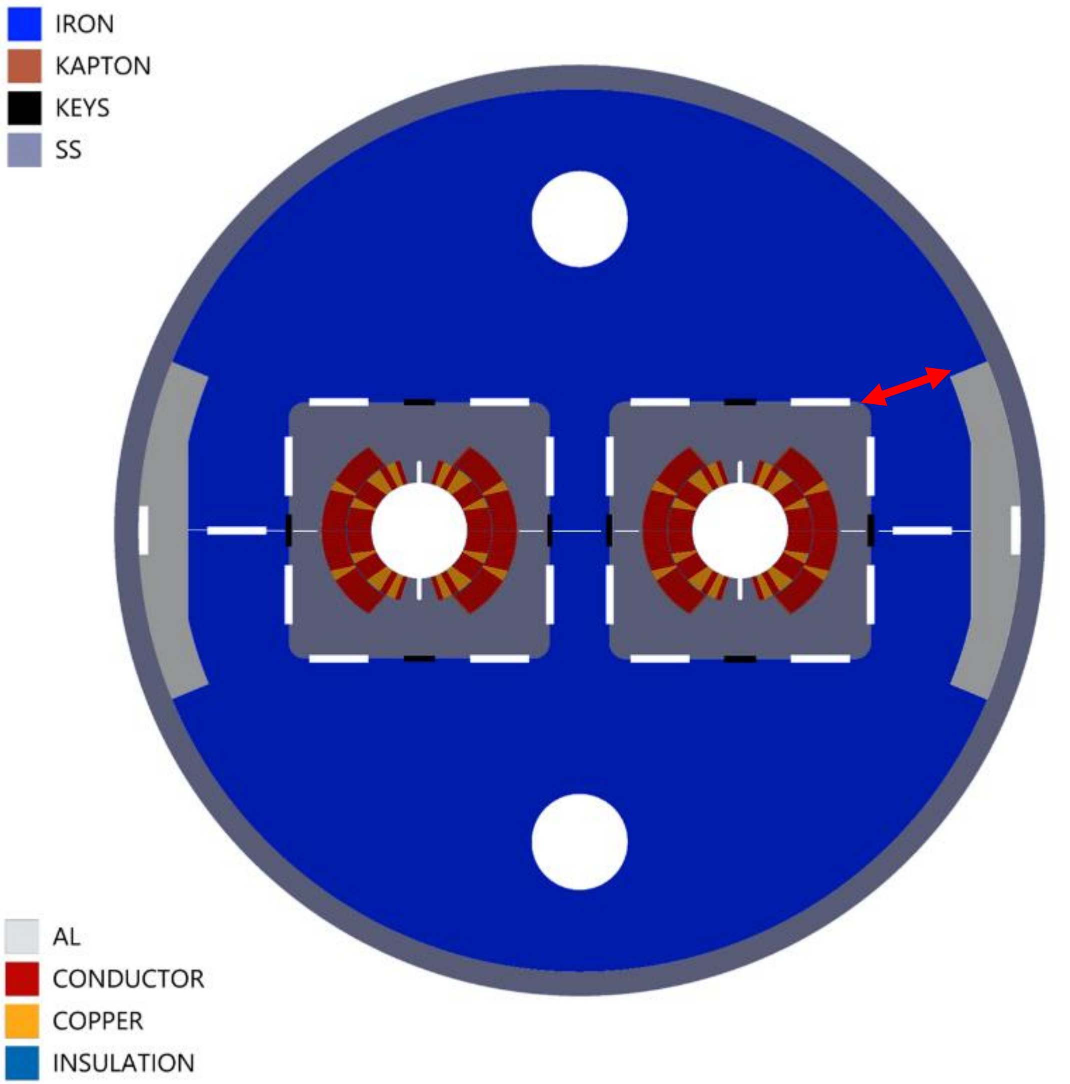


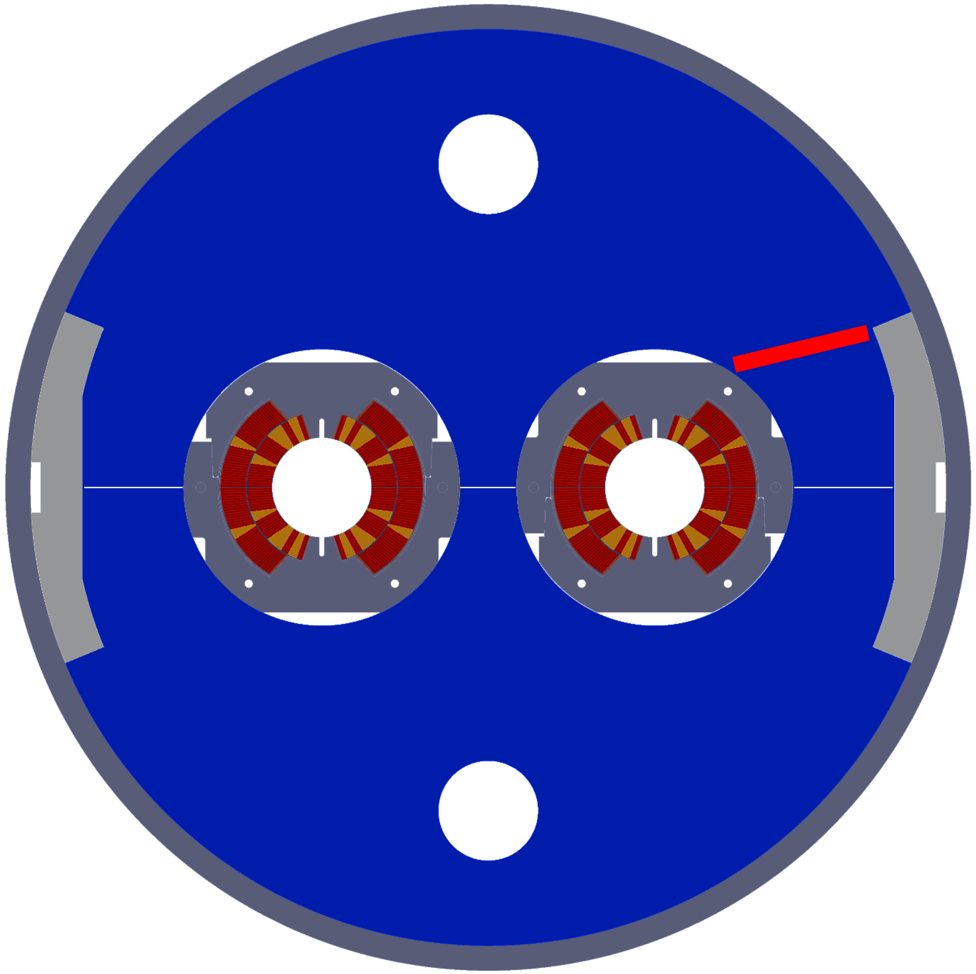
Evaluate the influence of manufacturing tolerances in the pre-compression of the coils

The measurement gather during this sensitivity study will be benchmarked against FEM

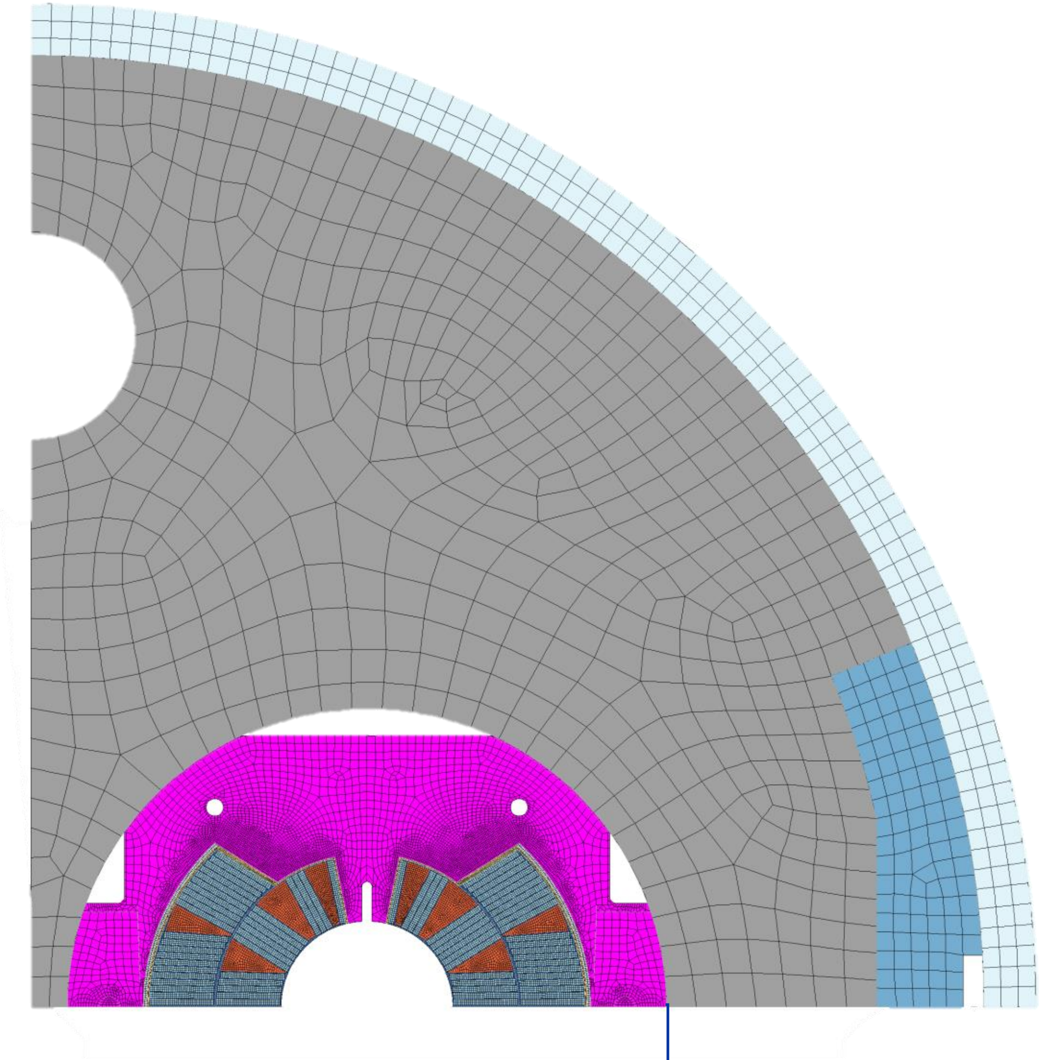


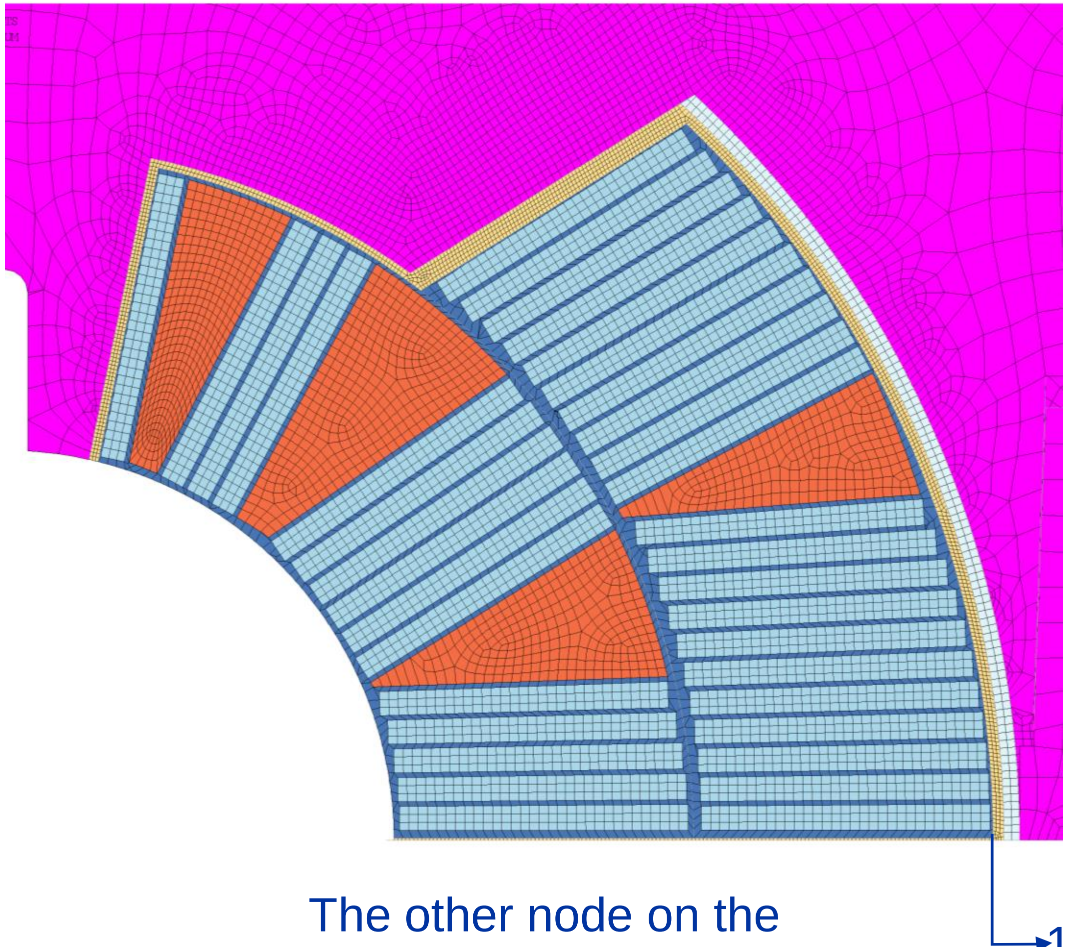
Iron yoke stiffness with the b&k version





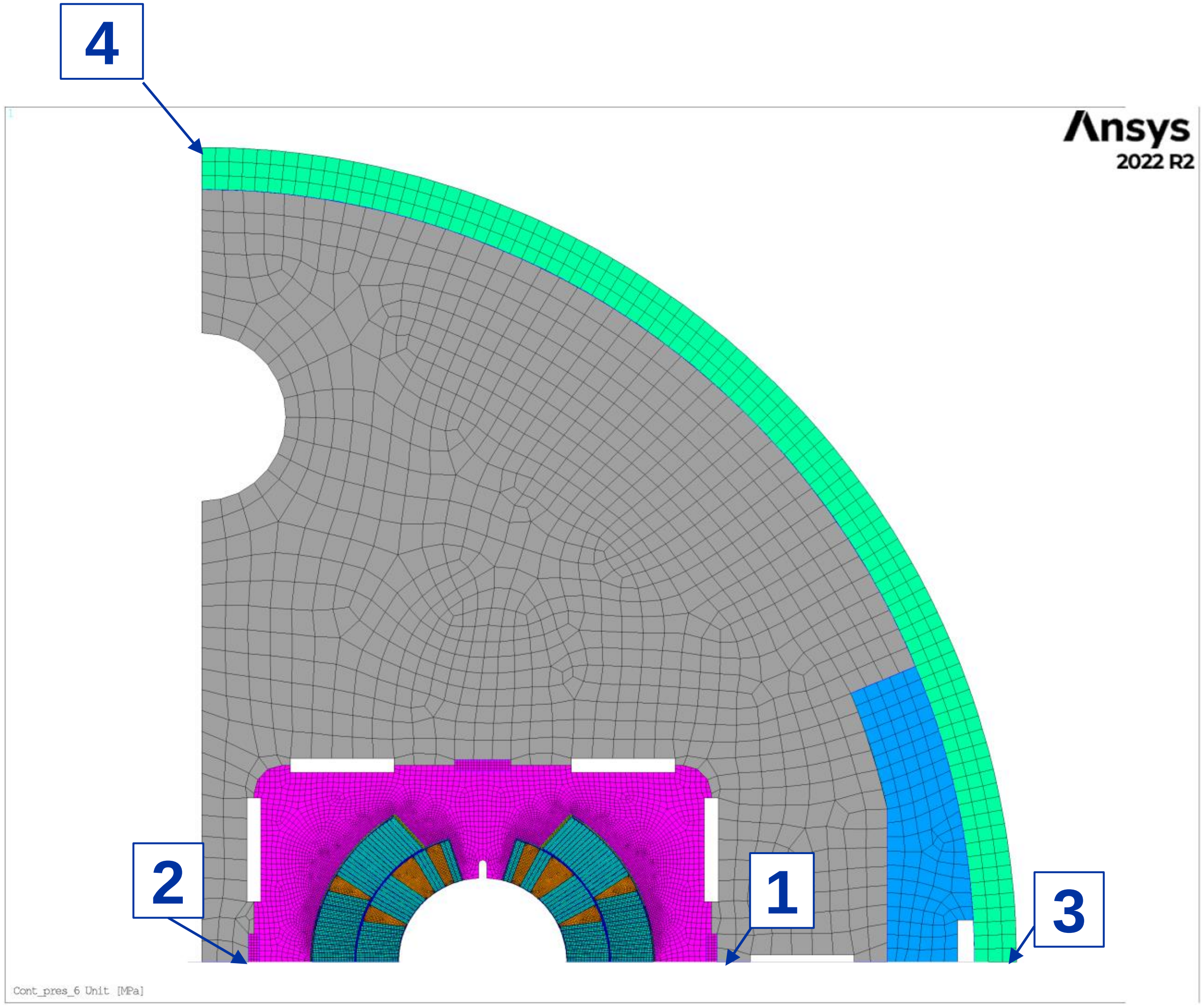
Displacement 12T





The other node on the left moves by 80 μm

Displacements – closed gap



	1		2		3		4	
	Ux	Uy	Ux	Uy	Ux	Uy	Ux	Uy
	64	76.4	-6.2	-106.3	30.4	0	0	-104.8
	-392	-29.2	-33.1	-22.8	-689.2	0	0	-636.2
	**127.9**	-26.9	-7.6	-73.6	109.6	0	0	-79.6

Magnetic design

Choice of conductor motivated by the availability of strands and cable

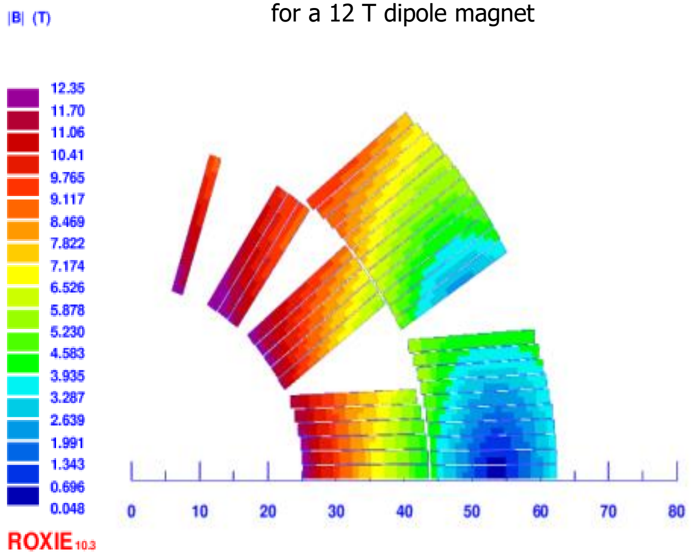
Parameter	Unit	Value
Strand		
Strand type		MQXF
Strand layout		RRP 108/127
Strand diameter	mm	0.85
Non-Cu Jc	A/mm^2	2087 at 4.4 K and 13.54 T
Cable		
Number of strands		40
Pitch direction		Left
Cable mid thickness	mm	1.525 ± 0.010
Cable width	mm	18.15 ± 0.05
Cable Keystone	°	0.40 ± 0.1
Pitch	mm	109 ± 3
Core material		316L
Core thickness	µm	25
Core width	mm	12
Cabling Ic degradation		< 5%
RRR		150

Cable characteristics for a 12 T dipole magnet

Design of the 2D cross section geometry

Aperture	mm	50	56
Cable	#str x mm	40x0.85	40x0.85
Number of blocks		6	6
Number of turns		37	41
Coil outer radius	mm	62.5	65.5
Current	kA	17.750	17.110
Bore field	T	12.01	12.00
Peak field	T	12.42	12.33
Load line	%	83.62	82.48
Temp. margin	K	4.1	4.3
b3	units	-0.4	-0.1
b5	units	0.0	0.0
b7	units	15.8	5.6
b9	units	2.5	0.3
Diff. inductance	mH/m	2.641	3.128
Stored energy	MJ/m	0.451	0.508

Conceptual cosθ coil design for a 12 T dipole magnet



Protection must be evaluated

Baseline to start working on mock-ups, tooling: 50 mm diameter aperture
Winding tests are required

Winding tests

Extensive winding tests to optimize the geometry of the end spacers, tooling and the winding parameters

First trials with a 50 mm aperture

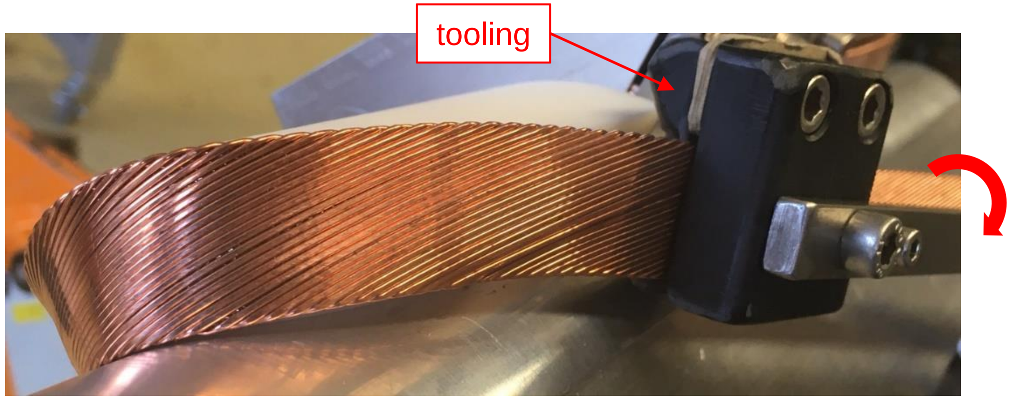
3D rapid prototyping allows us a quick and low-cost way to compute, manufacture and test end spacers, **fast feedback loop**

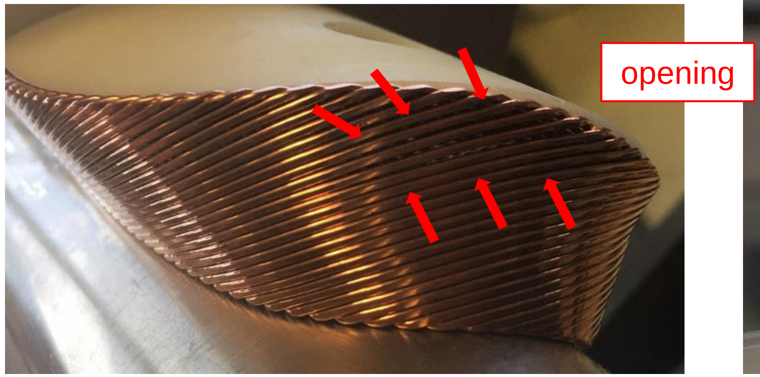
Variants characterized by quantifiable parameters:
torque, soft bending, hard bending

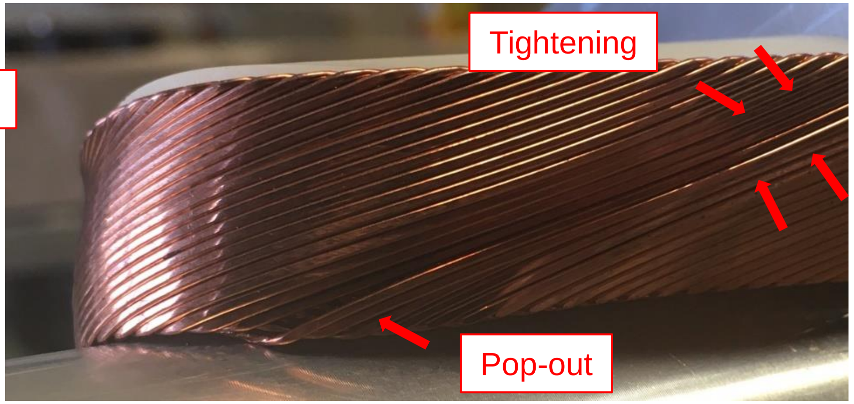
Benchmarked against Roxie computations

The parameters to be optimized:

- cable tension
- angle and external torque
- tooling
- geometry of the spacer head







Design of suitable production tools

Objectives for a robust design (tooling and process) :

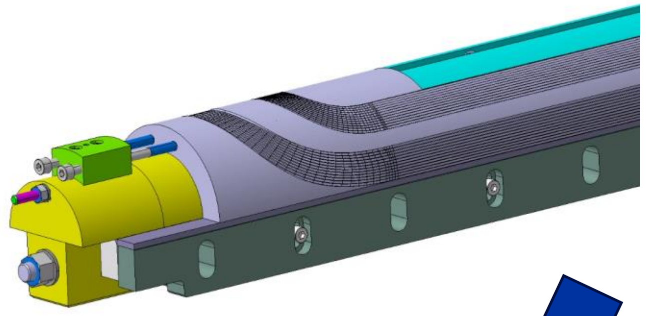
- **minimize of coil handling** during fabrication (minimize human errors)
- remove of the ceramic binder *(see Roland's presentation)*
- strong attention to the scaling up in length

Design baseline:
CERN contribution on FalconD Project *(see Stefania's presentation)*

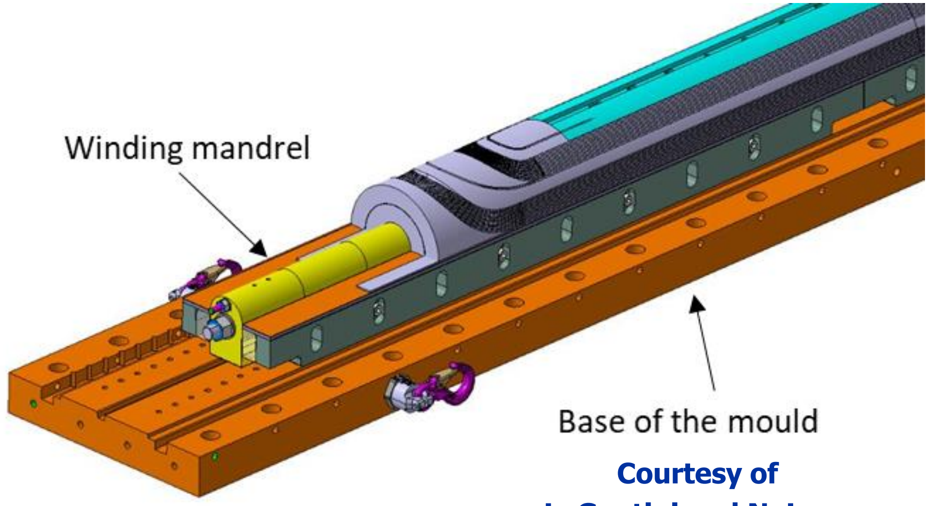
Main idea:
The **winding mandrel** becomes **part of heat treatment mould** no need to move the stand-alone coil from the winding machine to the heat treatment mould

Coil production steps tooling final design for 12 T VE :

- winding & press cycle
- reaction heat treatment
- impregnation



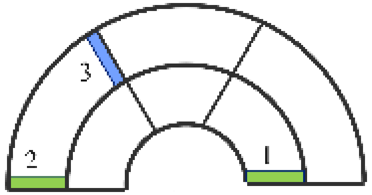
The assembly coil/winding mandrel is moved in the reaction fixture



Courtesy of
L. Gentini and N. Lusa
(CERN/EN-MME & CERN/TE-MSC)

Splice designs

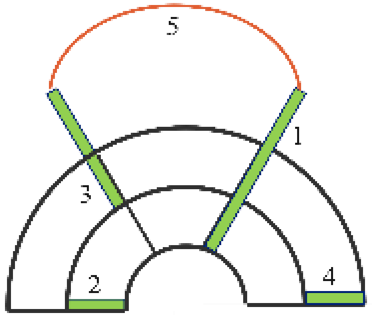
Internal Splice



- Nb$_3$Sn – Nb$_3$Sn splice
- Nb$_3$Sn – Nb-Ti splice

Challenges:
- **Support the brittle Nb3Sn cable**
- Splicing in the **limited space** of the pole region
- Splice in the **high field** region

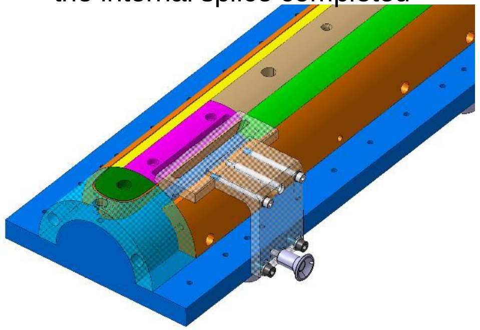
External Splice



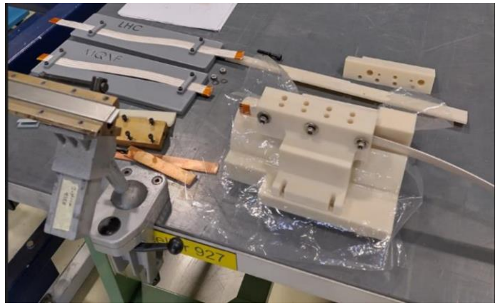
- Nb$_3$Sn – Nb-Ti splice
- Nb-Ti – Nb-Ti splice

Challenges:
- **Support the brittle Nb3Sn cable**
- **Two layer-jumps** to be accommodated into the coil pack
- **Double-layer jump** for the inner layer cable

Mechanical design for the mould for the internal splice completed

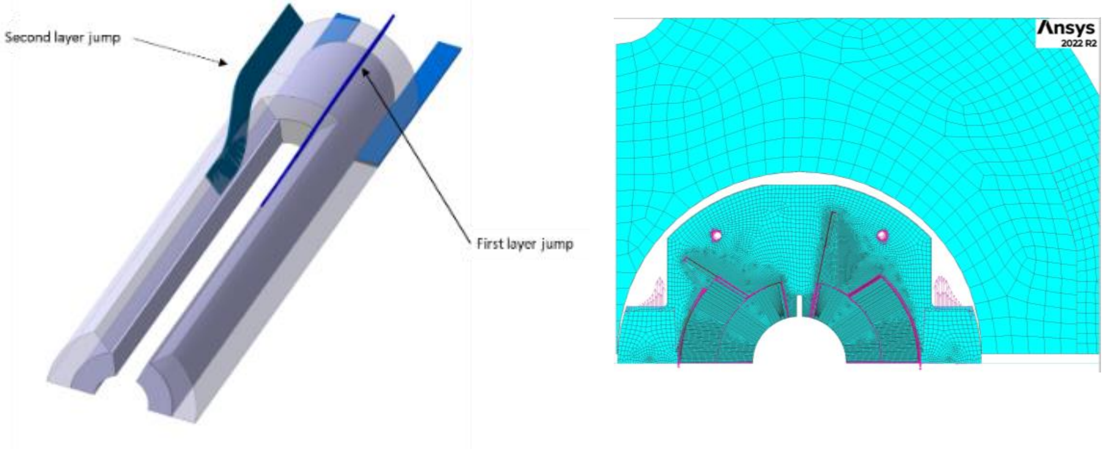


First iteration with 3D printed plastic parts



First soldering tests done. Results under analysis

FEM computations to assess the special collars in the splice area



Modular coil molds and assembly tooling are designed to realize the two different splices

Control the reproducibility of coil fabrication procedures

Size and rigidity measurements of the coils

Refurbishment of the E-modulus press in 927
Measured data used to define procedure for the **pre-compression** assembly on the coil **during collaring**

Test coil structure under production

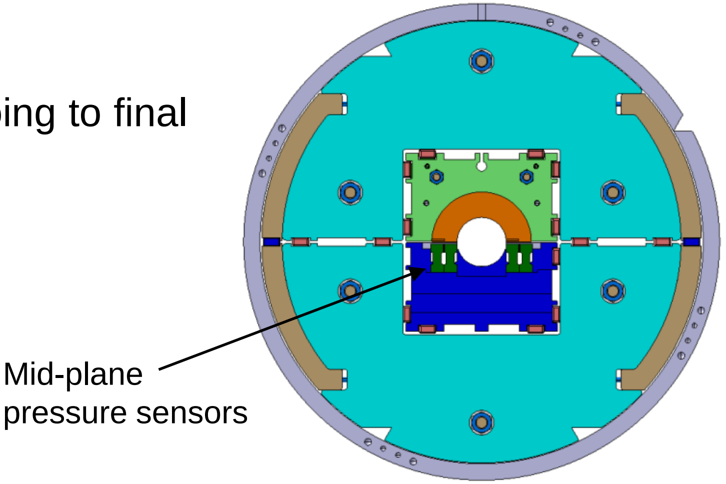
Construction of a coil test device to validate single coils in a ‘mirror’ configuration

Step by step approach:
Validation of coil design and manufacture before going to final dipole configuration and production

Fast feedback loop on the coil fabrication

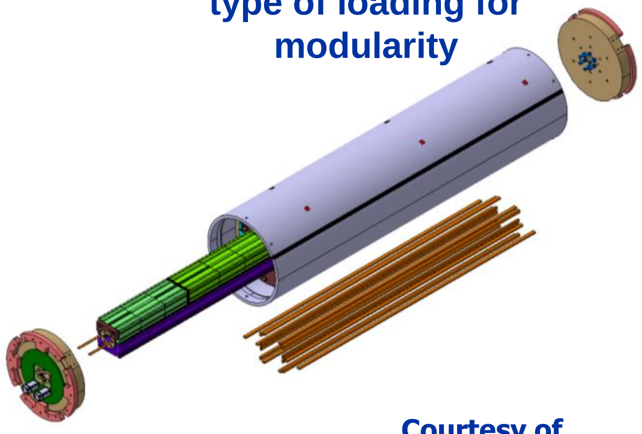
Part of the technology development program as between a test structure *(see Diego’s presentation)*

Some of the concepts apply for 12T :
Aluminum stoppers
Horizontal close gap



Single aperture half (mirrored)

‘bladders and keys’ type of loading for modularity

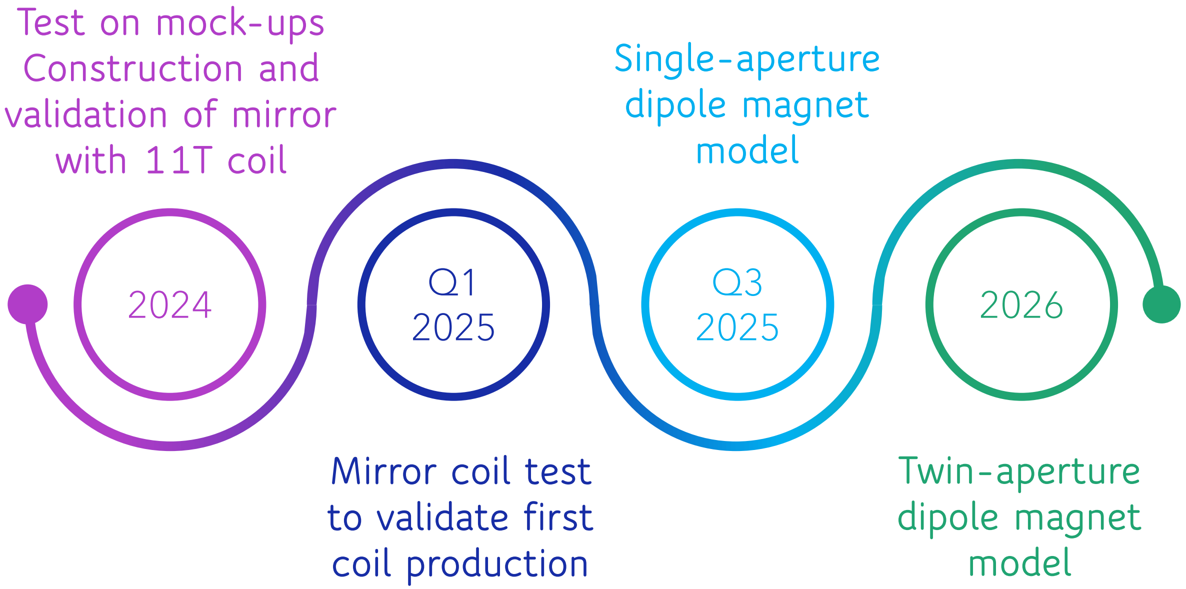


Courtesy of L.Dassa, N.Vejnovic
(CERN/EN-MME)

Conclusions and perspectives

Scope of the 12 T VE program is the design, manufacture, and qualification of a value-engineered, accelerator-fit, 12-T, Nb3Sn dipole magnet model, by 2026.

Robust, intrinsically safe structures
Knowledge of coil material properties
Rigorous procedures and suitable assembly tools



Requirements

Scope of the 12 T VE program is the design, manufacture, and qualification of a value-engineered, accelerator-fit, 12-T, Nb3Sn dipole magnet model, by 2026.

Coils made from Nb3Sn Rutherford cables with a cosΘ layout and two layers

The **solutions** for a short dipole must be **scalable to a long one**
Magnetic length of ~1.2 m for short models, ~5 m and 15 m for the long versions

Step by Step approach:

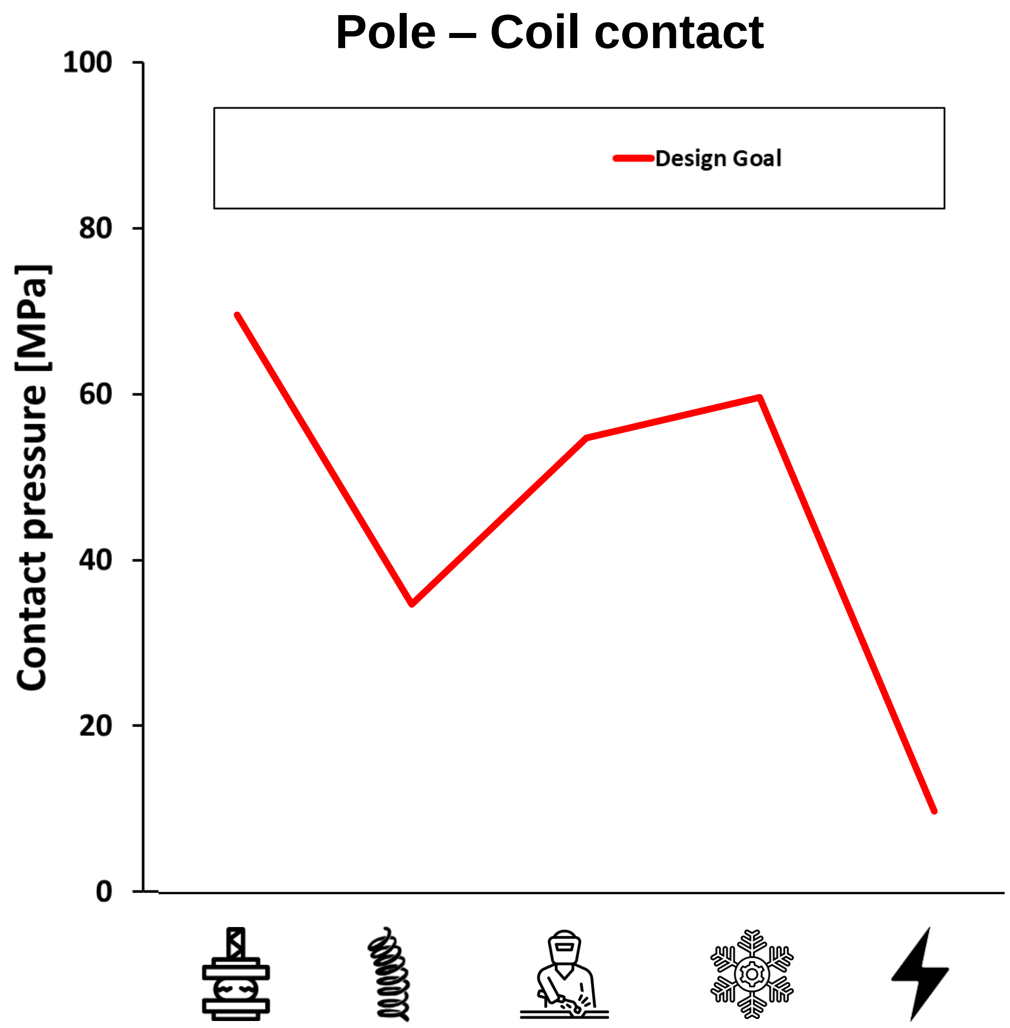
Evaluation of possible diverse solutions. Choice of most promising options and final analysis.

Test campaign with **mock-ups** to understand and control the coil stress distribution during the magnet lifecycle.
Confirmation of the **FEM computation**.

Construction of a **coil test device** to validate single coils in a ‘mirror’ configuration and two coils in a single aperture structure.

Only when we obtain satisfactory coils, we can go to a double aperture dipole

Design goals:

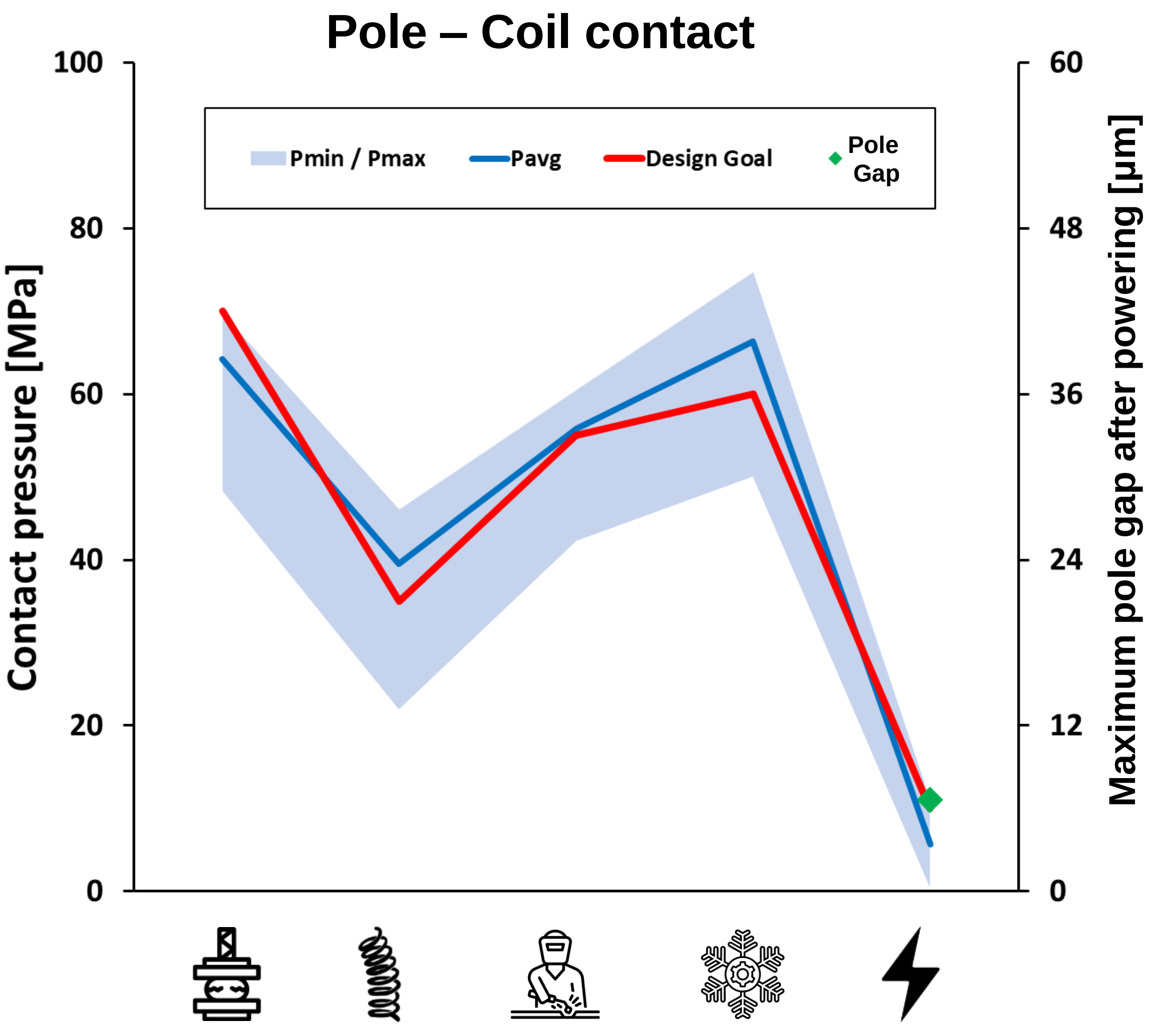


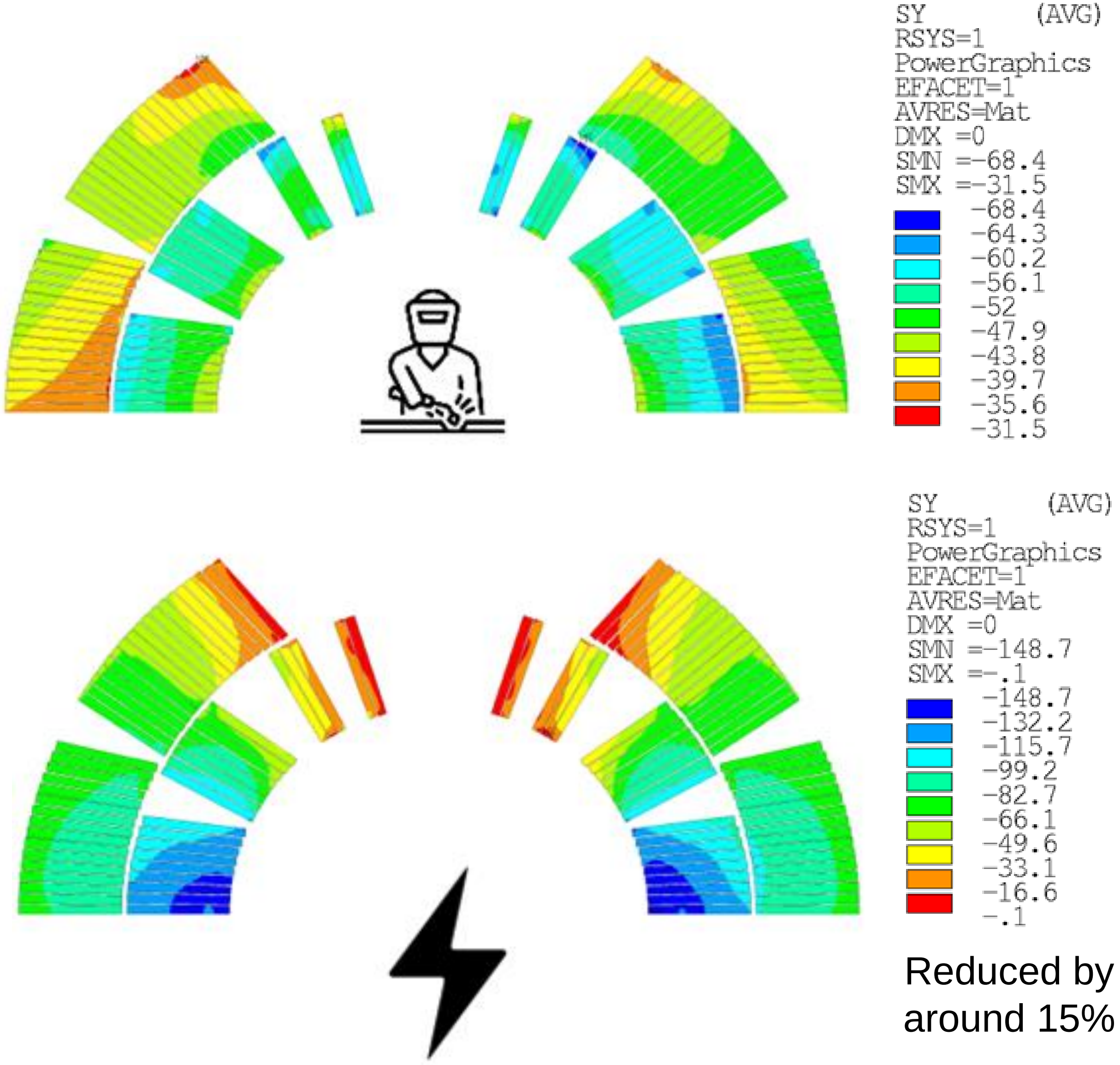
Stress at room temperature < 120 MPa

Stress at cold < 130 MPa

Pole – Coil contact closed at cold

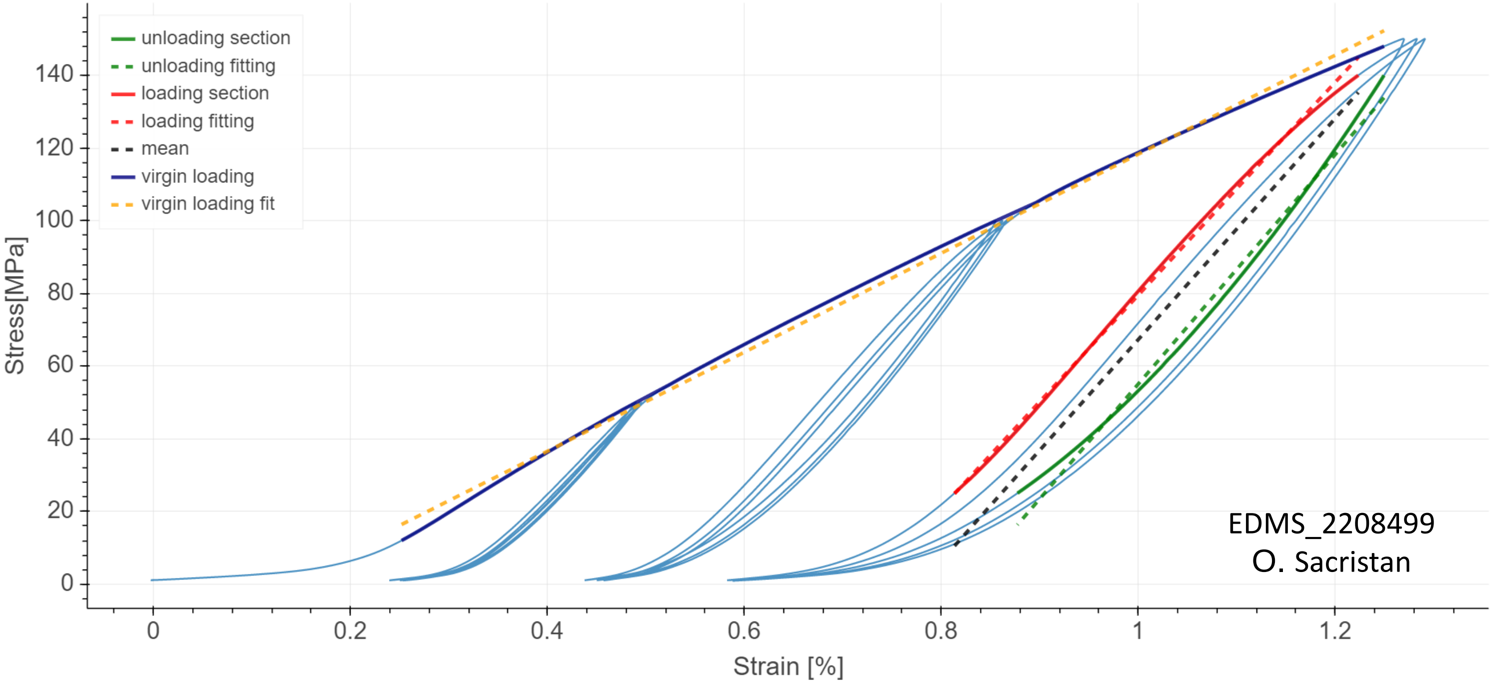
Design goal: Achieved





Reduced by around 15%

Material models



Material	Young's modulus [GPa]	Poisson's ratio [-]	CTE [mm/m/ΔT]
Copper	100/110	0.3	3.37
Kapton	1.9/2.7	0.3	4.37
Stainless Steel	191/210	0.28	2.8
Kawasaki	186/204	0.28	1.8
Iron	203/225	0.28	2.0
Aluminium	72/79	0.3	4.2

Calculated Stiffness

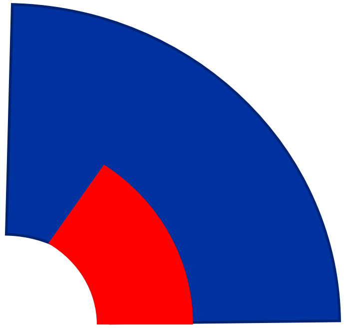
- Virgin Loading (RT and 77K): 14 ±2 GPa
- RT Loading/unloading phase: 31 ±3 GPa
- 77K Loading/unloading phase: 39 ±3 GPa

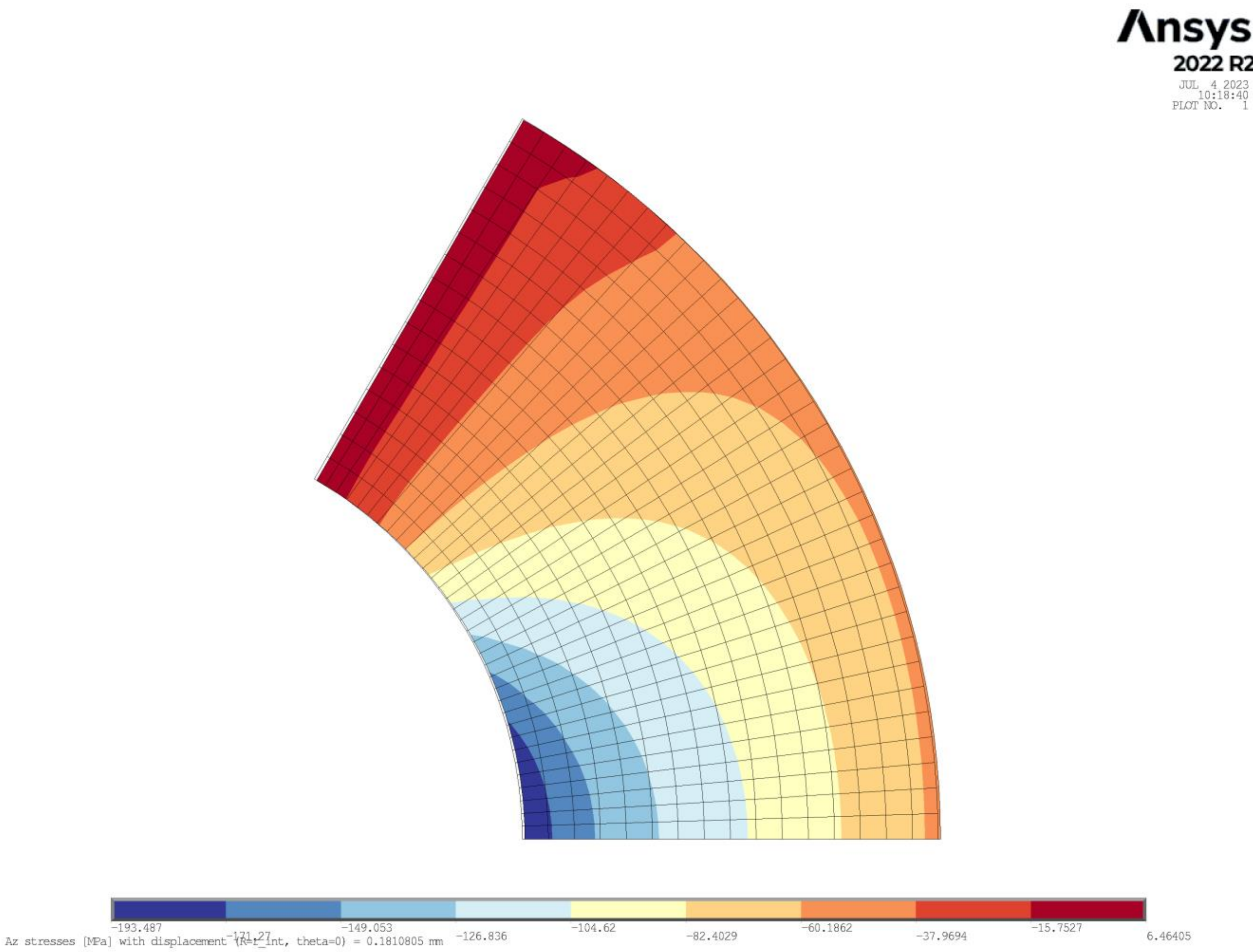
Orthotropic CTE

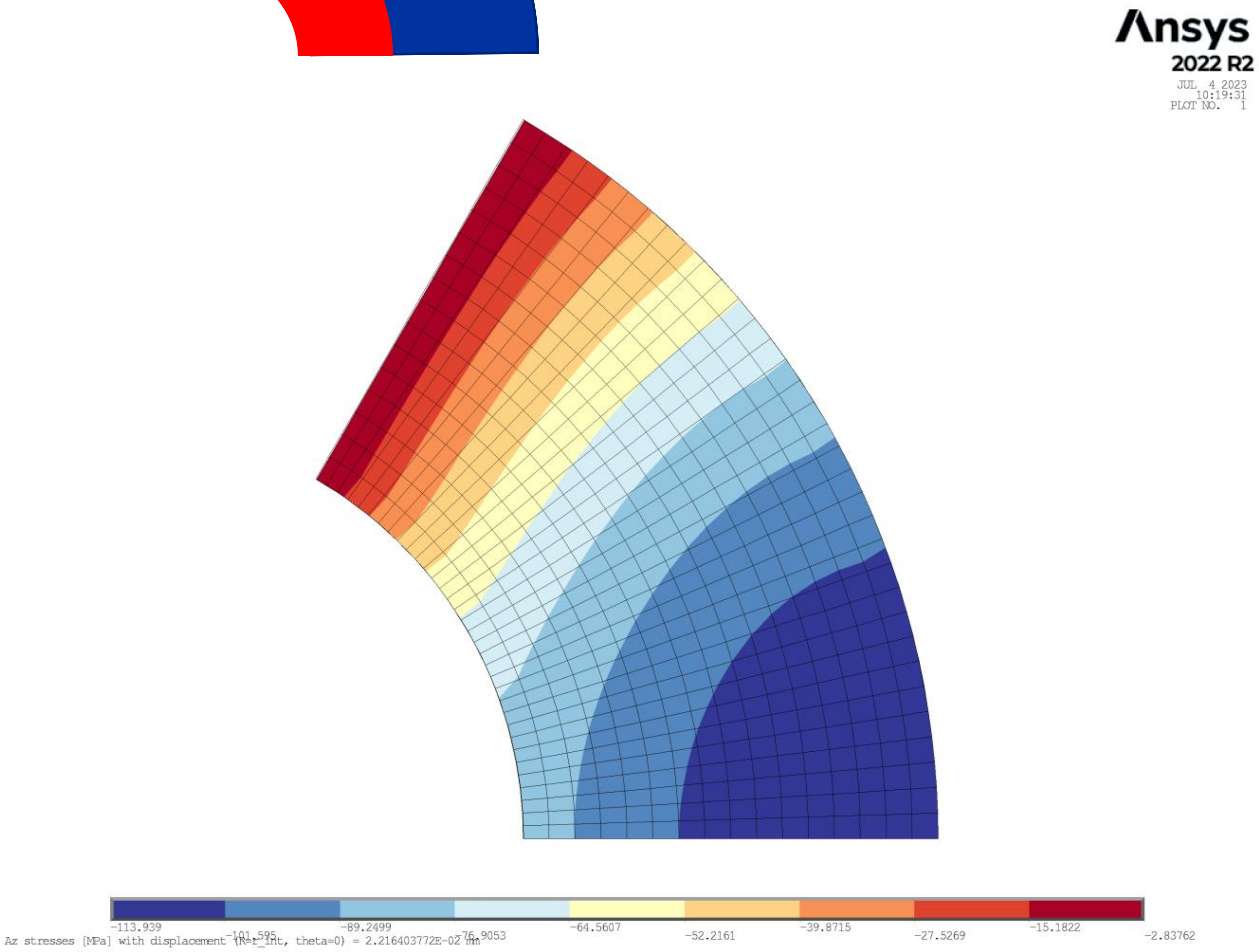
Direction	$\Delta L/L_0$ at 1.9 K * 1000 Inner/outer layer	$\sigma(\Delta L/L_0)$ at 1.9 K * 1000 Inner/outer layer
Longitudinal	-2.98	0.06
Radial	-1.61 / -1.75	0.04 / 0.03
Azimuthal	-2.55 / $-\mathbf{3.77}$	0.38 / 0.47

CERN-THESIS-2022-274 (Stefan Höll)

Rigid vs flexible collars-pads

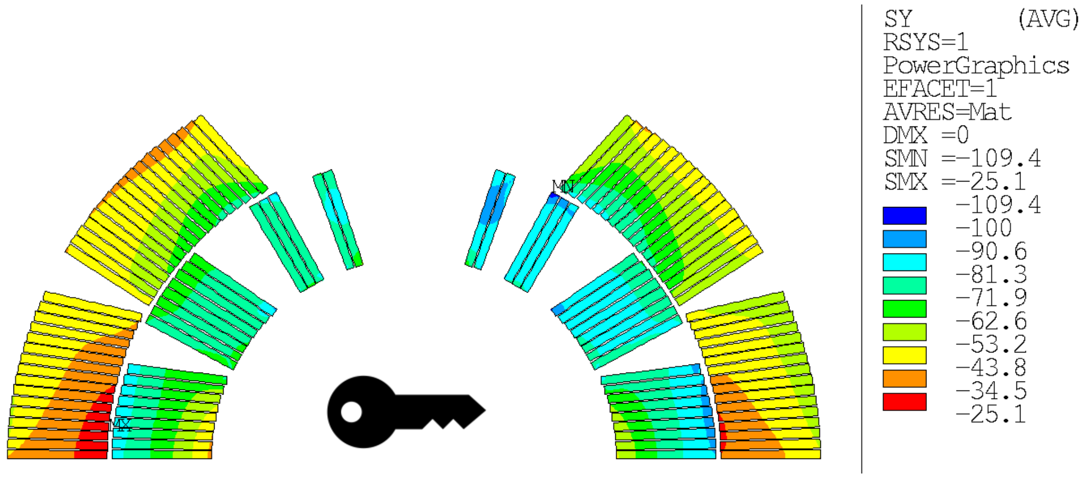






Curtesy of G.Vernassa

Stress – AZ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EFACET=1
AVRES=Mat
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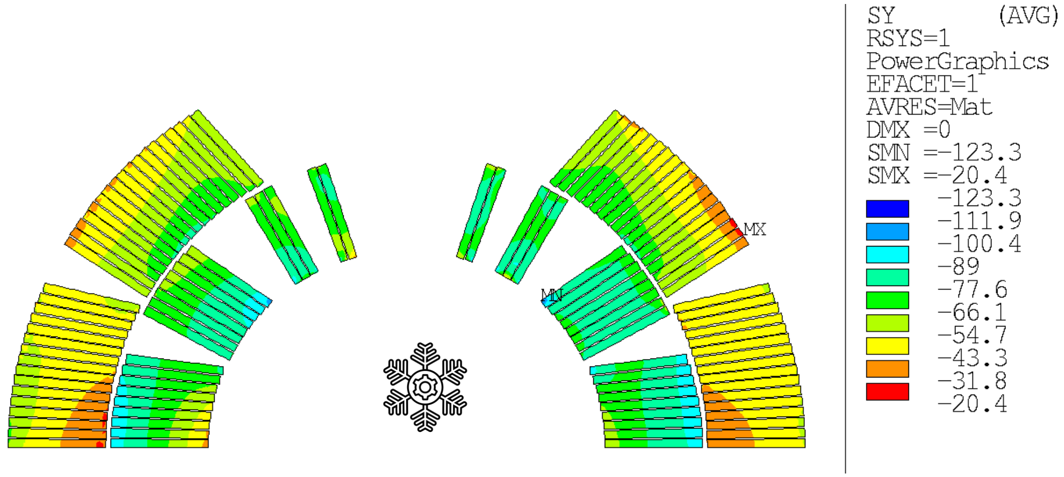
SMN =-109.4
SMX =-25.1
-109.4
-100
-90.6
-81.3
-71.9
-62.6
-53.2
-43.8
-34.5
-25.1
MN
MX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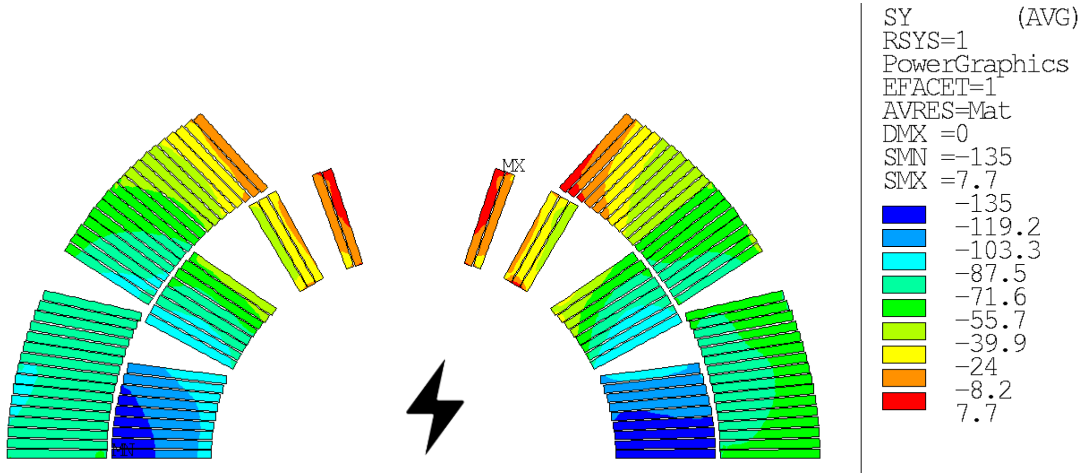
-20.4
MN
MX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AVRES=Mat
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-71.6
-55.7
-39.9
-24
-8.2
7.7
MX

Pole pressure