Innovative collaring concept for MQYY superconducting quadrupole magnets of HL-LHC Insertion Region

Authors: Amaury PORHIEL, Frédérick FOREST *(Sigmaphi)* / Damien SIMON, Etienne ROCHEPAULT, Simon PERRAUD *(CEA)*

Contributors: Léopold BELAINA, Morgan DELBECQ, Yannick FROIDEVAUX, Christophe LE CRENN, Vincent SIGALO, Emmanuel VOISIN *(Sigmaphi)*

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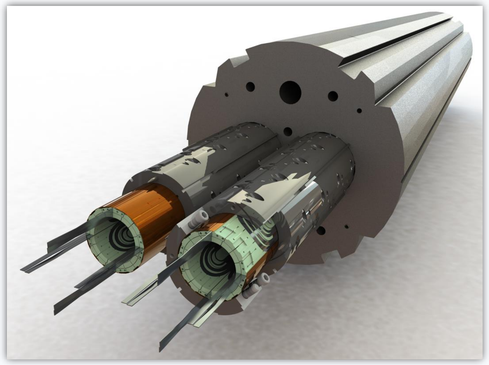
ABSTRACT

Sigmaphi participated to QUACO PCP whose objective was to propose an innovative solution for MQYY superconducting quadrupole magnets of HL-LHC Insertion Region. QUACO project was divided in three phases: a feasibility study, a detailed study including mock-ups and the manufacturing of a MQYY first-of-a-kind based on an innovative concept. The innovation proposed by Sigmaphi concerns the collaring which is based on thick half aluminum collars assembled around the coils thanks to a press. The azimuthal stress through the coils is applied by stainless steel pole parts inserted in coil poles with a second press and maintained in position thanks to the aluminum collars. This collaring concept presents the main advantage to maintain the azimuthal stress through the coils during cool-down: it makes unnecessary to apply a large azimuthal stress at room temperature. This collaring solution might be particularly interesting for superconducting magnets made of conductor much more sensitive to stress than Nb-Ti.

DESIGN & PROTOTYPING

Parameters of the MQYY first-of-a-kind

Parameter	Value	Unit
Aperture diameter	90	mm
Nominal current I_{nom}	4590	A
Integrated gradient @ I_{nom}	440	T
Magnetic length @ 1,9K	3,67	m
Peak field @ I_{nom}	6,32	T
Integrated Lorentz forces@ I_{nom}	784,5	kN
Rutherford cable dimensions:		
Bare cable width	8,8	mm
Bare cable average thickness	0,84	mm
Polyimide insulation per side	80	µm



Collaring solution

- ✓ Stress maintained after cool-down
- ✓ Unnecessary to apply large stress during collaring
- ✓ Potentially of strong interest for superconducting magnets made of conductor sensitive to stress.

Coil — *Azimuthal oversize of the coils after curing* — *Measured with a modulus press*

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316LN spacers — *Inserted in coils poles with a press*

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Aluminum collars — *Half collars assembled around the coils with a press* — *Fixation with aluminum bolts & titanium pins*

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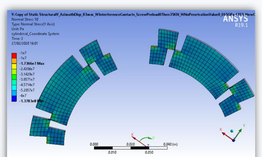
Azimuthal Stress — *After collaring = 55 MPa* — *After cool-down = 55 MPa* — *@ I_{nom} close to pole = 22 MPa*

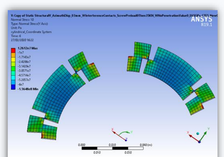
FEA Analysis

Parameter	Value	Unit
Coil modulus	6,5	GPa
Coil CTE @ 1,9K	4	mm/m
Average azimuthal stress after collaring & stress relaxation	55	MPa
Average azimuthal stress after cool-down @ 1,9K	55	MPa
Azimuthal stress close to coil pole @ 1,9K & 108% Inom	22	MPa

Left: σ_θ after collaring; Right: σ_θ @1,9K & I_{nom}



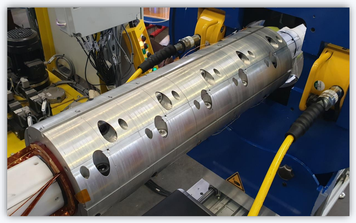
σ_{spacer} = -54.1 MPa
$\sigma_{mid\text{-}plane}$ = -51.8 MPa
$\sigma_{average}$ = -54.4 MPa

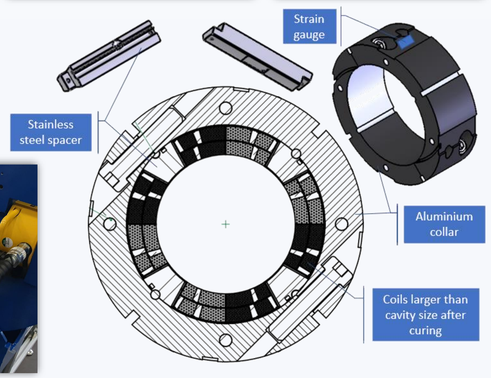


σ_{spacer} = -22.1 MPa
$\sigma_{mid\text{-}plane}$ = -60.5 MPa
$\sigma_{average}$ = -48.0 MPa

Prototyping

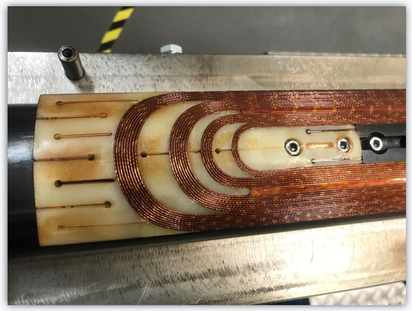
- ✓ Several collaring prototypes manufactured
- ✓ Process well defined and risks mitigated
- ✓ Target stress of 55 MPa reached after collaring
- ✓ Azimuthal stress maintained @ LN2 temperature



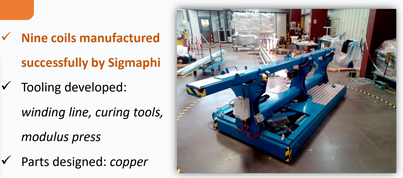


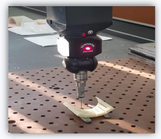
MANUFACTURING

Coils manufacturing & testing



- ✓ **Nine coils manufactured successfully by Sigmaphi**
- ✓ Tooling developed: *winding line, curing tools, modulus press*
- ✓ Parts designed: *copper wedges, end spacers, interlayer insulation*





Coils assembly & collaring

- ✓ Coil measured with modulus press in order to define the shims thickness at coils mid-planes.
- ✓ 316LN spacers and 7075-T6 collars cut by EDM - quench heaters provided by CERN.
- ✓ Collaring line composed of a press for spacers insertion and a press for collars tightening.
- ✓ Azimuthal stress indirectly measured thanks to strain gauges on aluminum collars.
- ✓ Targets: σ = 55 MPa; ε = 1030 µm/m
- ✓ **Two apertures collared successfully**
- ✓ Easy modification of the azimuthal stress by disassembling the aluminum collars.

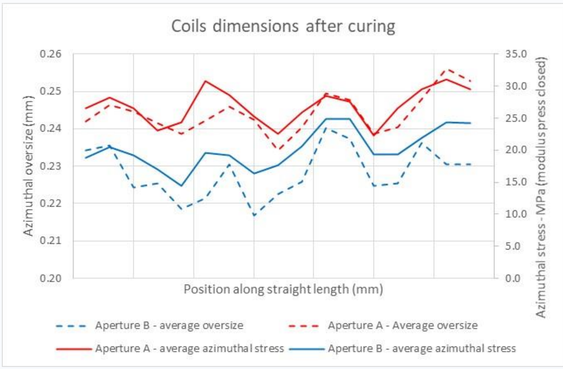
Magnet assembly

- ✓ Yoking of 653 laminations: packing factor = 99,7%.
- ✓ Splices after compression of coil ends.
- ✓ Tooling developed by Sigmaphi: *yoking tool, shipping frame, splicing tool*
- ✓ Magnetic measurements at CERN

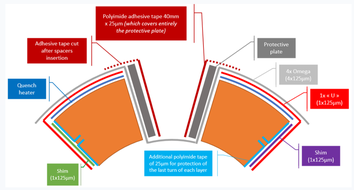
VALIDATION

Measurement of the coil dimensions after curing

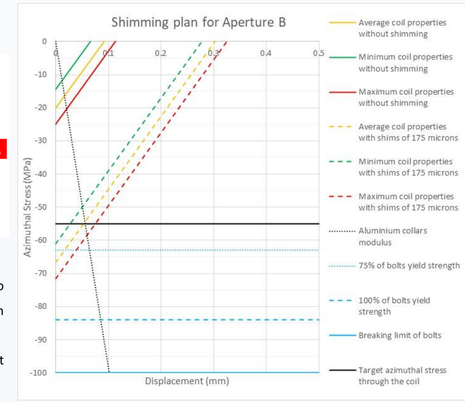
- ✓ Modulus press designed by Sigmaphi
- ✓ Coils modulus & size measured every 200mm with 4 LVDT & one force cell.



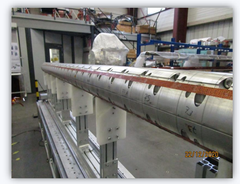
Definition of shims to insert at mid-plane



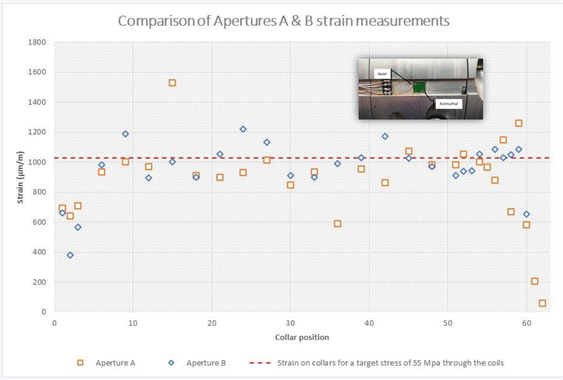
- ✓ Coils smaller than required after curing.
- ✓ Polyimide shims inserted at coils mid-planes in order to increase the azimuthal stress through the coil and reach the target stress of 55 MPa.
- ✓ Stress relaxation of the coil material is taken into account in the shimming plan.



Strain measurements on aluminum collars



- ✓ 120 cryogenic strain gauges installed.
- ✓ Target stress of 55 MPa reached on both Apertures after optimization of the shimming plan.
- ✓ This collaring solution works well and is promising for future magnets.



CONCLUSIONS

Sigmaphi manufactured successfully nine superconducting coils and performed modulus measurements on these coils. Two quadrupole apertures have then been collared according to the process defined by Sigmaphi thanks to an intensive mock-up program. The azimuthal stress through the coils is measured with 120 cryogenic strain gauges and the target of 55 MPa is reached on both apertures. The two apertures have finally been surrounded by iron yoke laminations and the MQYY magnet has been delivered at CERN in mid-June 2021. The magnetic performances at warm and low current have been checked by CERN. The next step consists in cooling down and energizing at nominal current this MQYY prototype in CEA's test station. This success story has been possible thanks to Sigmaphi's strong investment in design and prototyping and thanks to the intensive and pertinent implication of QUACO's technical experts at Sigmaphi's side.