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History of Changes

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The Preparatory Phase of the Large Hadron Collider upgrade (SLHC-PP) is a project co-funded by the European Commission in its 7th Framework Programme under the Grant Agreement n° 212114. SLHC-PP began in April 2008 and will run for 3 years.

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1. EXECUTIVE SUMMARY

In order to guarantee the required field quality of the magnet, the nominal size of the superconducting coil must obtain tight tolerances (on the order of 0.02 mm) under operational condition, i.e., after cool-down and excitation. Moreover, it is required that the coils are loaded with a pre-stress of about 90 MPa after collaring, resulting in a residual stress of 50 MPa after cool down, in order to avoid unloading at full excitation, which would results in so-called training quenches. To obtain the correct level of pre-stress after the coil collar pack is removed from the press, appropriate azimuthal shimming must be applied. The choice of these shims depend on the mechanical properties of the steel, and more importantly, on the mechanical properties of the superconducting coil. Although we use LHC main dipole cable for the fabrication of the MQXC insertion quadrupole magnet, the insulation was changed in order to improve the percolation of the superfluid helium.

Collaborative efforts within WP-6 have thus aimed at calculating the mechanical deformations of the collar pack, the calculation of the unloading of the coil when removed from the press and during cool-down, the design and construction of instrumented collar packs (Deliverable 6.2.1), the measurement of the coil's elastic modulus with so-called ten-stacks and the arch of a trial coil, and the design and procurement of a modulus measurement device. This work has now been completed. However, the experimental verification of the shim sizes for the production coils (Deliverable 6.3.2) is still outstanding and will be performed in the first half of 2011.

2. MECHANICAL CALCULATIONS

A mechanical 2D model, see Fig. 1, realized with the finite element software package CASTEM was set up to simulate the main loading steps applied to the coil: collaring, relaxation (due to insulation creep), cool down, and excitation. The boundary conditions for the model are prescribed at the polar plane of the front collar and polar piece, on the coil mid plane. It is furthermore imposed that the vertical displacements of the front and back collars are opposed at their mid planes.

The collaring is simulated by means of a gap angle θ between the keys and the collar keyways:

$$\text{Gap} = d_{\text{keyway}} \times \tan\theta \qquad (1)$$

where d_{keyway} is the distance from the magnet center *O* to each node at the key/keyway interface.

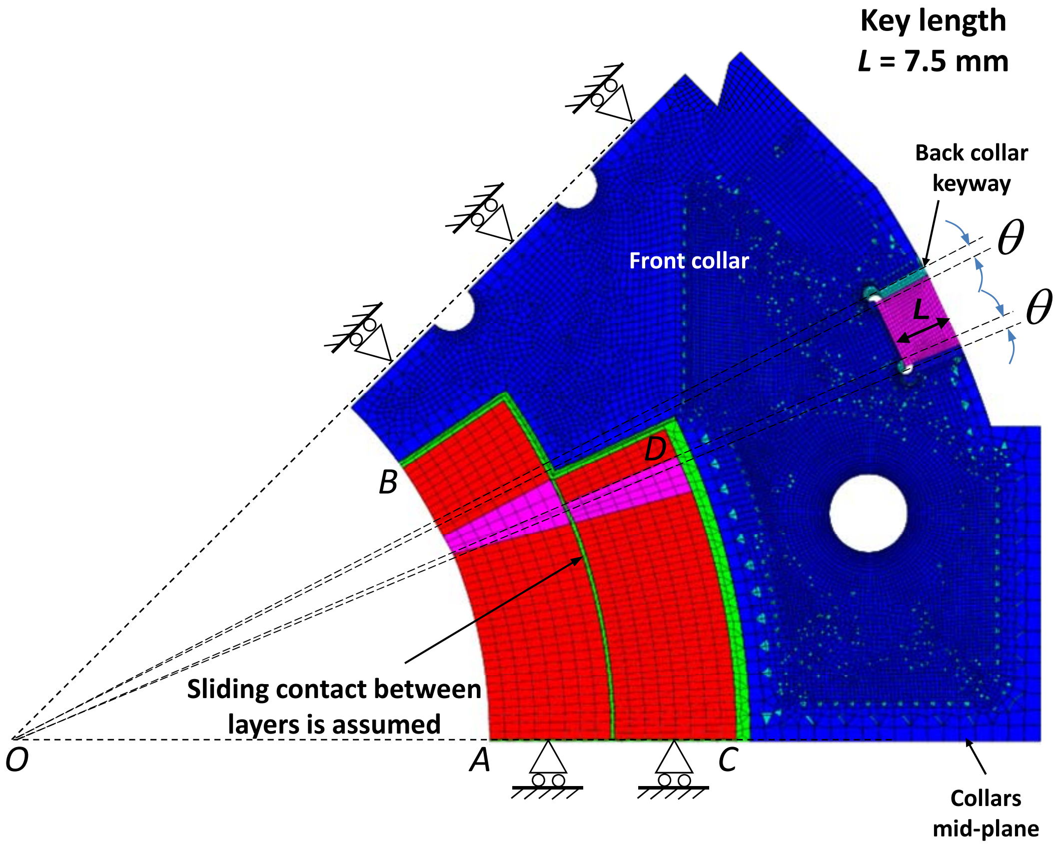

Fig. 1: Mechanical model

The gap angle θ introduces an average azimuthal stress in the coil, denoted σ_θ and referred to as “pre-stress”. The gap angle θ also determines the coil azimuthal oversize (OL) required before collaring in order to obtain the pre-stress after the coil collar pack is released from the press:

$$OL_{IL} = R_{IL} \times \tan\theta \quad (2)$$

$$OL_{OL} = R_{OL} \times \tan\theta \quad (3)$$

where R_{IL} and R_{OL} are the average radius of inner and outer layers. The cool down is modeled by an applied thermal body force over the entire structure by the use of integrated thermal shrinkages. Magnet excitation is simulated with the magnetic forces calculated at each coil node.

Table 1 gives the thermo mechanical properties of the materials used for calculations. A high integrated thermal shrinkage of the coil blocks from 300 K to 2 K was taken into account for the calculation (a = 7 mm/m).

Table 2 and Fig. 1 summarize the main results obtained at the end of each loading step.

Materials *Componants*	**Temp. (K)**	**Elastic Modulus** ***E* (GPa)**	**Yield Strength (MPa)**	**Ultimate Strength (MPa)**	**Integrated Thermal Shrinkage** **α (mm/m)**
yus 130 S Nippon Steel	300	190	445	795	
Collars	2	210	1023	1595	2.4
316L Stainless Steel	300	205	275	596	
Keys	2	210	666	1570	2.9
Copper	300	136			
Angular wedges	2	136			3.3
Kapton Foils	300	2.5			
inter-layer & inter-pole insulations	2	4			6
Mix Kapton-G11 (50%-50%)	300	4.45			
Ground insulation	2	5.2			7
∗ **insulated NbTi conductor blocks**	300	5.5/4.5			
Coil inner/outer layers	2	**7.7/6.3**			**7**

Table 1: Thermo mechanical properties of materials used for the finite element calculations

	Collaring with keys	**After 30 % relaxation**	**Cool down 300 K to 2 K**	**Nominal current 12803 A**
Gap angle (Deg)	0.455			
Azimuthal stress σ_θ in coil blocks (MPa)				
Max	-146	-102	-89	-81
Average inner layer	-97			
Average outer layer	-90			
Average	**-93**	-65	-53	-53
Minimum on polar plane				**-10**
Average on polar plane				-21
Average on mid plane				-72
Coil oversize (mm)				
Inner layer	**-0.54**			
Outer layer	**-0.66**			
Coil radial displacement due to Lorentz forces $\Delta_{r\ \mathrm{Lorentz}}$ (µm)				
Point A				103
Point B				20
Point C				28
Point D				5

Table 2: Main results obtained at end of each loading step

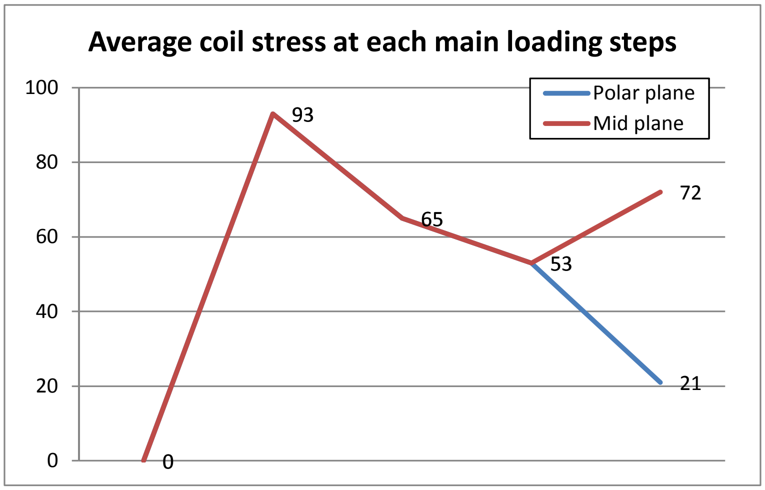

Fig. 1: Main results obtained at end of each loading step

The calculations show that a pre-stress of 93 MPa is needed in the coil at the end of the collaring process (with a gap angle θ = 0.455 deg), see Fig. 2. This pre-stress takes into account of a 30% stress relaxation (from 93 MPa to 65 MPa) due to insulation creep after collaring [1,2], pre-stress reduction due to differential thermal shrinkage between coil and collars during cool down, and a minimum azimuthal compression stress of 10 MPa on the coil polar plane at nominal current. This value is required to avoid separation at coil/collar interface due to magnetic forces; see Fig. 3.

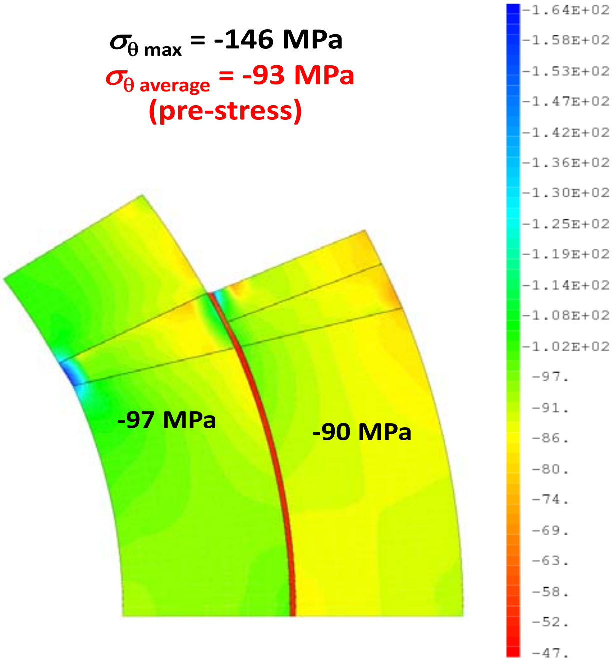

Fig. 2: Azimuthal stress distribution (pre-stress) in the coil after collaring

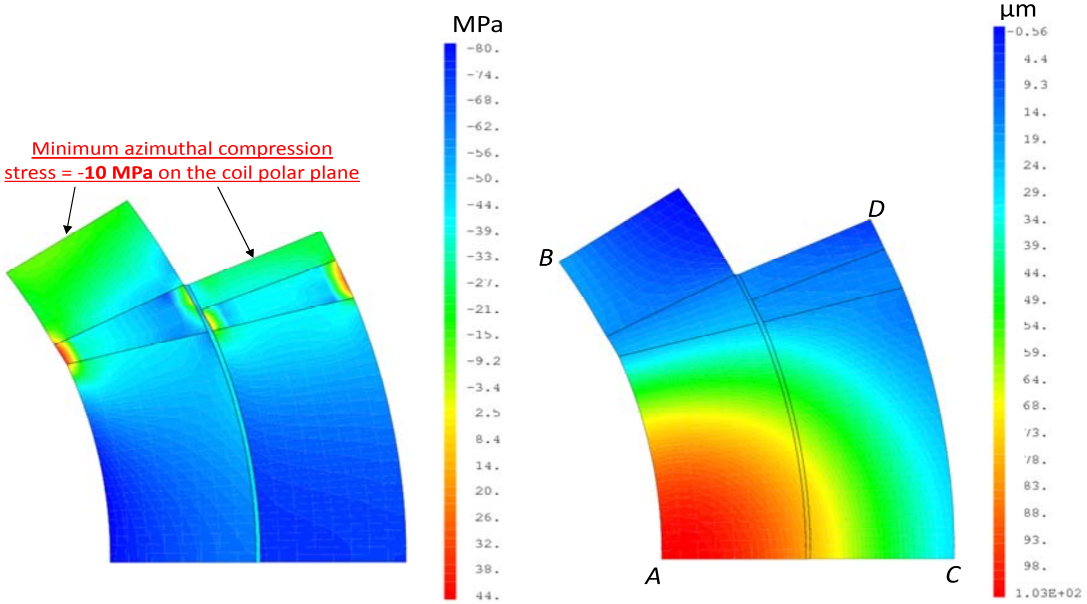

Fig. 3: Left: Azimuthal stress distribution in coil at nominal current. Right: Displacement in coil due to magnetic forces during excitation

To obtain this residual pre-stress, the inner and outer layers oversize should be 0.54 mm and 0.66 mm before the collaring. The radial displacement at points *C* and D due to magnetic forces remains below 60 µm, see Fig. 3 (right). If we consider fully elastic collars in the calculation, the pre-stress σ_θ linearly increases with the gap angle θ, see Fig. 4. If we consider plastic deformations, the pre-stress σ_θ quasi-linearly increases with θ up to a maximum of about σ_θ = 100 MPa: severe plastically deformed zones occurring in the collars prevent coil pre-stress to exceed this value, see Fig. 5. Nevertheless, this result is pessimist because work hardening is not taken into account.

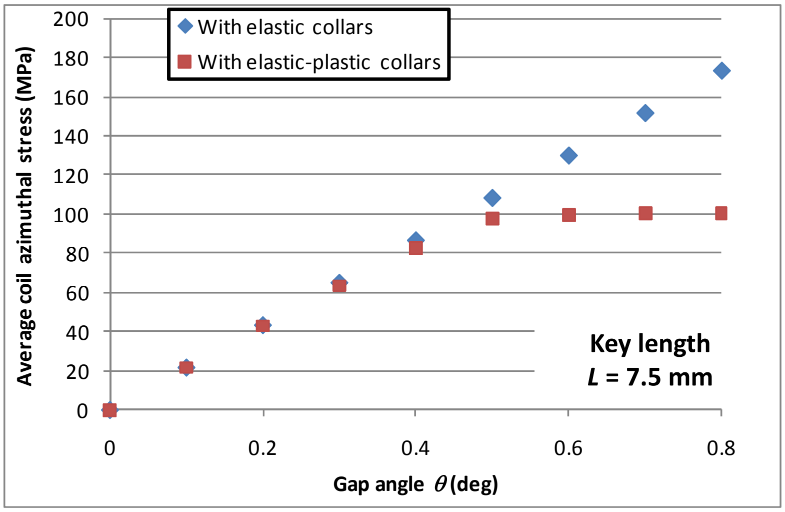

Fig. 4: Coil pre-stress evolution versus gap angle θ with elastic and elastic-plastic collars.

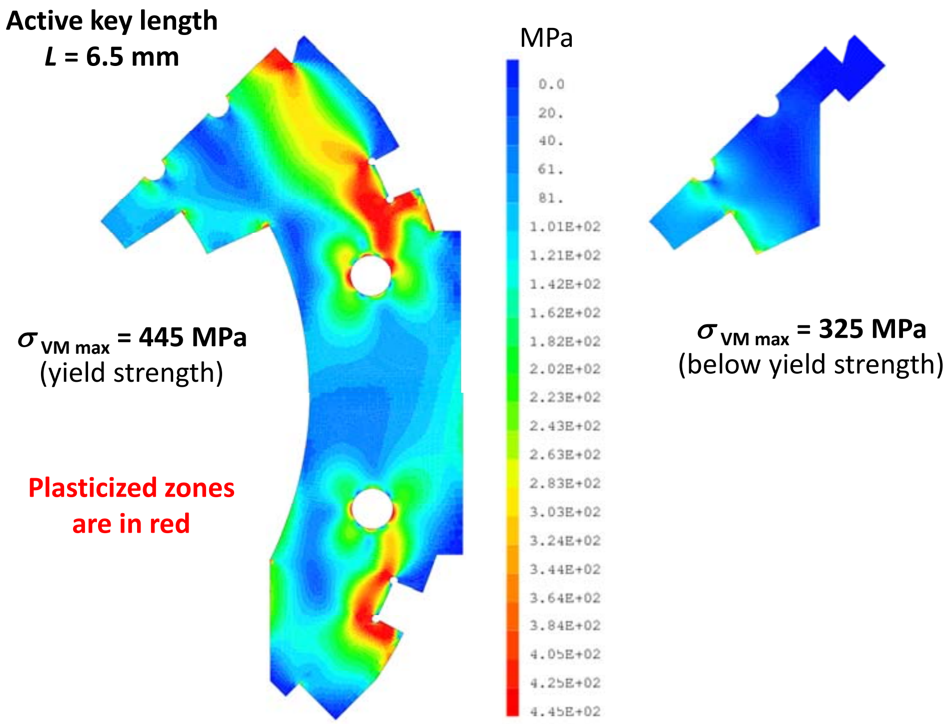

Fig. 5: Von Mises stress distribution in collars after collaring.

3. AZIMUTHAL COMPRESSION TEST ON THE TRIAL COIL

A 700-mm-long coil mockup was realized at CEA/Saclay using LHC inner layer dipole cable 01, with the new porous insulation; see Fig. 6 [3]. The coil was made of 12 turns corresponding to the inner layer external block conductor of 4-block magnetic design.

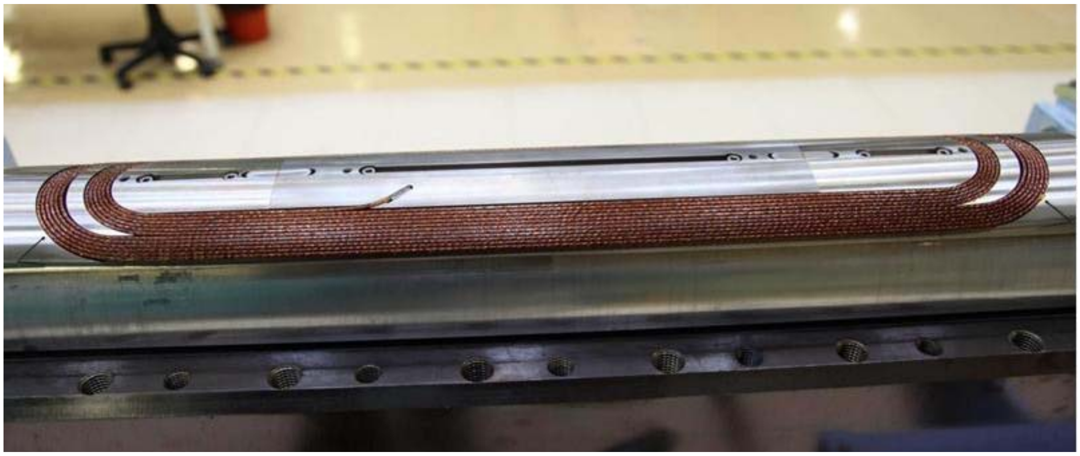

Fig. 6: 700 mm long mockup realized at CEA/Saclay

The required size of the compacted, insulated coil at cold conditions is given by numerical field computation (CERN's field computation program ROXIE), assuming an average insulated cable width of 2.17 mm and a compacted insulation thickness of 0.135 mm. A first curing cycle was realized at constant volume (with the mould closed at 135 °C) and the conductor stack less compacted (by 0.2 mm) than at nominal. After this first curing cycle, compression tests were made in the coil's straight part to identify its mechanical behaviour in the azimuthal direction [4].

A second curing cycle of the mockup was then performed with the conductor stack compacted to the nominal size. To compare with CERN results obtained on straight ten-stacks, all results obtained with the mockup were converted from a 12-stack to an equivalent 10-stack of conductors. The following conclusions can be drawn:

- The stress versus stack-height curves have a very close form compared to those measured at CERN, see Figs. 7 and 8.
- For a stress of 50 MPa the E-modulus of the conductor stack reaches about 5 GPa and remains constant, see Fig. 8. These results confirmed those of CERN.
- Compaction of the coil during the curing process does not significantly affect the E-modulus of the conductor stack. It only displaces the stress versus stack-height curve; see Figs. 7 and 8.

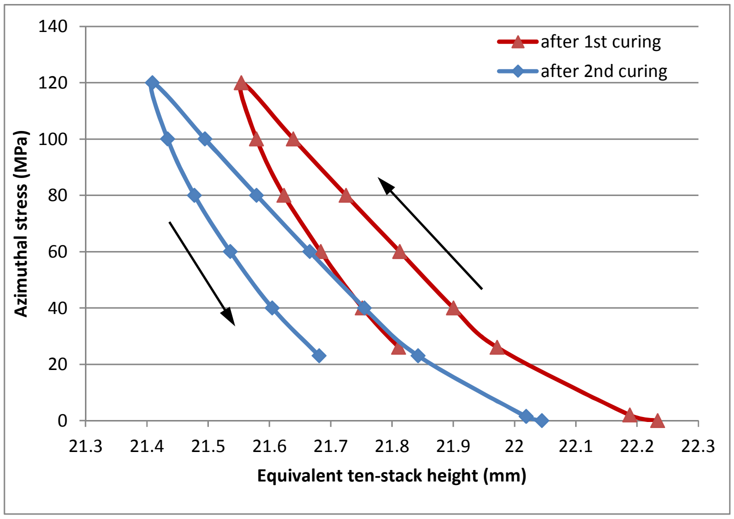

Fig. 7: Stress versus stack-height curves obtained for the coil (renormalized to equivalent ten-stack)

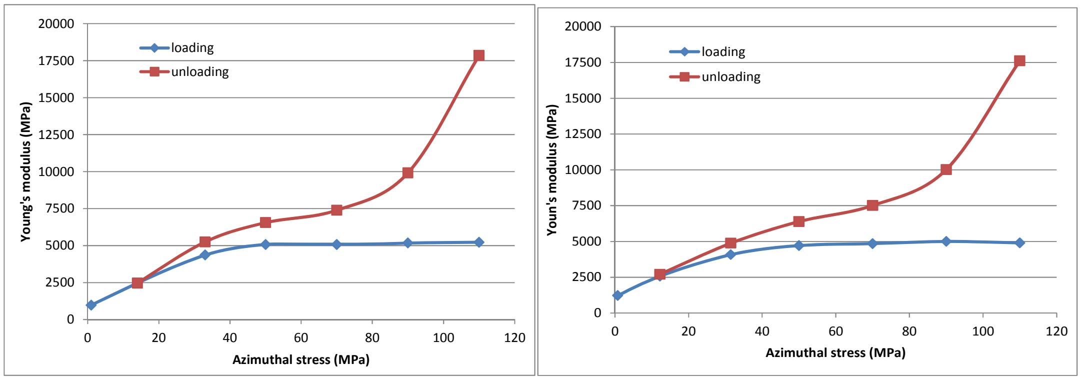

Fig. 8: Left: Evolution of E-modulus versus azimuthal stress (after 1st curing). Right: Evolution of E-modulus versus azimuthal stress (after 2nd curing)

E-modulus testing will establish the azimuthal oversize of each coil layer under a chosen pressure and will thus help to optimize the size of the compacted stack during curing, in order to make sure that the cable insulation thickness will be nominal under operational conditions of the magnet. Mechanical calculations show that this residual stress should be about 53 MPa. The aim is thus to obtain nominal coil size (as determined by magnetic field calculations) when the azimuthal stress is about 53 MPa on the unloading curve (down-ramp part of hysteretic stress versus stack-height graph).

For this purpose, a new press-insert tool was procured from European industry. It is shown in Fig. 9.

Fig. 9: Press inserts for measuring the coil size under the required azimuthal pressure.

Now, after the series manufacturing of the coils has started (see Deliverable 6.3.2), the experimental verification of the shim sizes is the next important step towards the final assembly of the magnet cold mass. CERN and its partner CEA/Saclay are committed to the assembly of up to three 2-m-long magnet cold masses during 2011 and early 2012, well exceeding the goal stipulated in the second year report of SLHC-PP (WP-6).

4. REFERENCES

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[2] Pier Paolo Granieri *et al.:* Heat Transfer in an Enhanced Cable Insulation Scheme for the Superconducting Magnets of the LHC Luminosity Upgrade.
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