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**Engineering Design and Manufacturing Challenges
for a Wide-Aperture, Superconducting Quadrupole Magnet**

G.A. Kirby¹, B. Auchmann¹, E. Bielert¹, P. Fessia¹, M. Karppinen¹, B. Lepoittevin¹, C. Lorin¹, S. Luzieux¹,
J.C. Perez¹, S. Russenschuck¹, T. Sahner¹, D. Smekens¹

M.Segreti², M.Durante²

¹ CERN, Geneva, Switzerland

², CEA, Saclay, France

Abstract

The design and construction of a wide-aperture, superconducting quadrupole magnet for the LHC insertion region is part of a study towards a luminosity upgrade of the LHC at CERN. The engineering design of components and tooling, the procurement, and the construction work presented in this paper includes innovative features such as more porous cable insulation, a new collar structure allowing horizontal assembly with a hydraulic collaring press, tuning shims for the adjustment of field quality, a fishbone like structure for the ground-plane insulation, and an improved quench-heater design. Rapid prototyping of coil-end spacers and trial-coil winding led to improved shapes, thus avoiding the need to impregnate the ends with epoxy resin, which would block the circulation of helium.

The magnet construction follows established procedures for the curing and assembly of the coils, in order to match the workflow established in CERN's "large magnet facility." This requirement led to the design and procurement of a hydraulic press allowing for both a vertical and a horizontal position of the coil-collar pack, as well as a collapsible assembly mandrel, which guarantees the pack's four-fold symmetry during collaring. The assembly process has been validated with the construction of two short models, instrumented with strain gauges and capacitive pressure transducers. This also determines the final parameters for coil curing and shim sizes.

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Abstract—The design and construction of a wide-aperture, superconducting quadrupole magnet for the LHC insertion region is part of a study towards a luminosity upgrade of the LHC at CERN. The engineering design of components and tooling, the procurement, and the construction work presented in this paper includes innovative features such as more porous cable insulation, a new collar structure allowing horizontal assembly with a hydraulic collaring press, tuning shims for the adjustment of field quality, a fishbone like structure for the ground-plane insulation, and an improved quench-heater design. Rapid prototyping of coil-end spacers and trial-coil winding led to improved shapes, thus avoiding the need to impregnate the ends with epoxy resin, which would block the circulation of helium.

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Index Terms—Superconducting accelerator magnets, Quadrupole, Manufacturing process, Tooling, Quench heaters.

I. INTRODUCTION

The goal of the Phase-1 Upgrade of LHC was to provide more flexibility for focusing of the beams in the ATLAS and CMS insertions, and to enable reliable operation of the LHC at the luminosity of $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The upgrade concerned mainly the low-beta triplets and assumed the same interface boundaries with ATLAS and CMS as at present.

The new low-beta quadrupoles feature a 120 mm aperture (as compared to 70 mm of the present ones) and use the technology of Nb-Ti superconductor cables developed for the LHC dipoles; the cross-section of the magnet is shown in Fig. 1. The separation dipoles, the absorbers, as well as other elements in the insertions would also need to be modified so as to comply with the larger beam aperture of the triplet. However, the present cooling capacity at 1.9 K of the cryogenic system and other main infrastructure would remain unchanged [1]-[3].

In view of the consolidation of the LHC machine, its

revised operational schedule, and the performance limitations imposed by a minimum β^* of 30-40 cm (if only changing the triplets and separation dipoles) [6], the project was re-scoped in 2010. The baseline is now to concentrate on one single upgrade at a later stage around 2020, which will allow studying the potential of Nb₃Sn superconductor technology and a mitigation of the above-mentioned constraints.

It is nevertheless important to summarize the work for the interaction region design not only because of the SLHC-PP framework but because it is included in a wider and longer-term program towards one single upgrade. Consequently, this report presents the interaction region design of the Phase-1 Upgrade as it was part of the original WP-6.

Fig. 1: 2D cross section of the insertion quadrupole MQXC.

The design and construction of a large-aperture insertion quadrupole magnet, hereafter referred to as MQXC according to the CERN naming convention, had to face a number of technical challenges: extensive heat deposit studies have revealed that the heat-load to the inner triplet magnets, is of the order of 500 W [3] as compared to the expected 100 W when LHC has reached its full potential. This heat load calls for a new, more porous coil and ground plane insulation.

The collaring of the nearly 10-m-long quadrupole magnets cannot be done with the standard presses used for the long dipole magnets. The reason is that the four-fold symmetry of the quadrupoles has to be guaranteed in order to avoid non-allowed multipole field error in the aperture field. A novel self-locking collar pack design was therefore developed in 2009. These packs require a spring-loaded and collapsible assembly mandrel.

The assembly of the 2-m-long collared coils relies on the calculation and experimental validation of the final coil size and the assembly of instrumented collar packs. All these activities have advanced successfully; the elastic modulus of

the coils was measured with dedicated tooling in order to validate the calculations of the final coil size. CERN and its partners are committed to finish the first magnet assembly by the end of 2011.

The first magnet will mainly serve to the validation of the design concepts and will therefore be tested in a vertical cryostat. The second model aims at heat extraction and good field quality and will be tested in a horizontal cryostat, so that heat transfer and quench propagation measurements can be done under realistic conditions.

II. COIL PRODUCTION

The first set of production coils was produced at CEA/Saclay, while trial coils were manufactured at CERN. These trial coils, together with the establishment of the integrated design and manufacturing process for the coil end-spacers have resulted in very compacted coil ends that need no impregnation for mechanical stability, which would hinder the circulation of superfluid helium and thus reduce the cooling capacity.

Selected from the stock of cable produced for the LHC main dipoles, all cables were insulated with the new enhanced scheme [1]. After winding trials the coil was designed so that the left-lay cables are wound in counter-clockwise direction. The internal cable joint requires that the two layers be wound in opposite directions. The less stable outer-layer cable is wound counter-clockwise while the inner-layer cable is wound clockwise. At one end of the inner layer cable, a copper strip is soldered to the cable. This strip is then hydraulically formed to produce the S-shape of the layer jump and to provide mechanical and thermal stability in this zone. In addition, a small copper block is soldered to the cable for the fixation of the cable to the winding mandrel and to withstand the winding force of 50-80 kg. Because the cable is insulated from the winding mandrel and curing mold, step-by-step electrical testing can be performed as the coil moves through the production steps.

Fig. 2 shows the coil curing at CERN. New precision-machined inserts (the so-called molds), which define the shape of the coil had to be procured. The winding mandrels and curing mould were machined from solid blocks of material and are about 2 meters long. The tolerances of the components are smaller than 0.05 mm. For use at elevated temperature, a stable material was selected for these parts (Bohler steel 1.2312).

The heating system uses a flow of heated oil. A nominally 3.0-mm-thick shim is placed between the last turn on the coil and the arched, side-pushing bars of the mold. This shim allows for fine adjustment of the curing cavity's azimuthal volume.

After a series of tests, the volume of the curing cavity was set at +0.6 mm thicker than nominal, so that when the coil is compressed to its nominal magnetic cross section it will be under the required pressure to avoid unloading after cooldown and excitation.

Coils were produced both at CERN and CEA, using identical cable, insulation, and end spacers.

In parallel, stainless steel end spacers with an insulating coating were developed, because the expected radiation dose of 150 MGy is at the limit of what epoxy glass laminates (G11) can withstand [7]. Prototype pieces were laser sintered with tolerances of ± 0.05 mm. Longitudinal slots provide for sufficient flexibility so that the curing mold is not blocked by the metallic spacers.

The curing cycle is similar to that of LHC main dipole magnets. It needs to achieve 190°C and a coil pressure of about 50 MPa. With the oil heating system the entire cycle takes no more than 3.5 hours; see Fig. 2.

Fig. 2: Coil curing cycle. Coil pressure and temperature versus time.

III. COIL SIZE MEASUREMENTS AND MODULUS

Calculations show that a pre-stress of about 80 MPa is needed in the coil at the end of the collaring process. This pre-stress takes into account the stress relaxation (from ~ 100 MPa to 66 MPa) due to collar elastic stretching, 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; we also see the increase of pressure on the poles from 66 MPa to 115 MPa; see Fig. 3.

Fig. 3: Estimated coil pressure during collaring, spring-back, creep, cool down and powering.

E-modulus testing establishes 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 80 MPa. The aim is thus to obtain nominal coil size (as determined by magnetic field calculations) when the azimuthal stress is about 80 MPa on the unloading curve (down-ramp part of hysteretic pressure versus deformation graph); see Fig. 4.

A precision-machined press has been procured from European industry. This press can be configured to measure

both sides of the coil at the same time and to measure both layers individually or together. Position transducers record the vertical movement. An array of strain gauges records the pressure over five 2-cm-long pads on each coil layer. A set of precision machined, steel dummy coils are used to gauge the device at 80 MPa. Several pressure cycles are applied to bed the coil in place without damaging the fragile insulation. This is followed by a cycle that matches the pressures exerted during collaring. The size of the coil is recorded on the unloading curve as it passes through zero. This process is also used in the coil ends, to check the layer jump box and to determine the shim-size the coil ends.

Fig. 4 shows that the MQXC insulation is softer than the one chosen for the LHC main dipole. At lower pressure there is a difference between MQXC 10-stack and arch measurements. This difference vanishes at high pressure. The gain in pressure versus the size of the shims was measured to be 155 MPa/mm. The knowledge of this value is crucial to adjust the coil pressure during the assembly. At the coil ends, shims will be added to the mid-plain to gradually reduce the pressure. The coil end will not be potted with any resin, because we need to leave the structure open to maximize heat extra

Fig. 4: Coil pressure versus deflection for the steel reference coil, 10-stacks from LHC dipole and MQXC, scaled to be compared with MQXC coil arch.

IV. INSTRUMENTED COLLAR PACKS

The main reasons for the construction of an "instrumented collar pack," are: the measurement of the resulting coil stress under realistic assembly conditions, conformation of the collaring procedure, to check that no damage occurs to the coil-insulation-collar-key components.

The instrumented collar pack requires special collars for the routing of the instrumentation. Both strain gauges and capacitive pressure transducers are used for measuring the residual pre-stress during collaring, after the removing from the collaring press and cooldown to cryogenic temperatures. This type of transducers is produced at CERN and each gauge is calibrated at both ambient and cryogenic (77 K) temperatures. A special setup has been developed for the calibration at cryogenic temperature on the tensile machine delivering 0.1 to 200 kN of force. The capacitance of the transducer changes during cooldown (so-called apparent capacitance). So the output signal of unloaded transducer (zero balancing value) changes as well.

The instrumented collar pack can also be cooled to cryogenic temperatures in order to study the loss of pre-stress.

The results of these tests are crucial for the production of magnet coils, because both the coil size prior to the collaring and the elastic modulus must be known in order to calculate the required coil shimming. This shimming will guarantee the appropriate pre-stress in the coil after cooldown and excitation.

A second instrumented collar pack will serve for heat-transfer measurements. The bath temperature of the coolant in the MQXC magnets is estimated to be 1.96 K, which is at the maximum of the thermal conductivity of superfluid helium. Because the thermal conductivity drops sharply above 1.96 K, the additional temperature gradient to the heat exchanger has to be kept at a minimum.

The more porous cable insulation will therefore be complemented with more porous ground-plane insulation shown schematically in Fig. 6. The ground-plane insulation of the LHC main magnets consists of 4 layers of 0.125 mm polyimide sheets pressed onto the coil and making a near perfect hydraulic seal. Therefore the energy must be extracted by solid conduction through this layer. Another possible path for heat extraction is via the helium channels towards the inner layer coil, via the annulus and then outward via the collar nose.

When the new ground insulation is used, heat can flow radially outward from the outer layer through the helium channels in the fishbone and through the holes in the stainless steel protection sheet (collaring shoe). The electrical insulation is provided by the channel length, which exceeds 12 mm.

Fig. 6: Open ground insulation scheme.

Moreover, the collars are separated by a set of small dimples, 0.2 mm high, providing a lower stacking factor, i.e., 6% open channels for the heat conduction toward the bayonet heat exchange.

V. QUENCH HEATER DESIGN AND PRODUCTION

Quench simulation has shown that for 10-m-long magnets, quench heaters are mandatory for magnet protection [6]. In order to quench as many conductors as possible, the quench heater strips were moved to the space between the inner and the outer coils, thus making contact to both coils. This protection scheme has to be tested with a magnet model in a horizontal cryostat. This is due to the fact that the multi-physics simulation problem of quenching superconducting magnets involves a large number of empirical parameters, for example, the residual resistivity ration (RRR) of the cables,

the amount of confined superfluid helium in the cables and the thermal conductivity of the insulation.

The cross section of the heating element was optimized to give a faster time constant and higher maximum temperature compared to the standard LHC quench heaters.

Fig. 7: Section of quench heater with S-shaped heating elements and heat flux holes, 2 mm wide, visible through the 0.5 mm thick foil assembly.

Two layers of 316-LN steel strips, 0.025 mm thick and 14 mm wide are used, electrically connected at one end of the heater. Polyimide insulation is placed between the strips and on the outer surfaces. The heaters are assembled in a 0.5-mm-thick curved foil, see Fig. 7. The heat density and shear strength are both doubled in comparison to LHC heaters. A power supply was built to be able to scale, from the 1.8-m-long model magnet, to the full-length production magnet. The S-shaped heater leaves space for channels to extract heat from the magnet during normal operation. In 0.01 seconds the heater has achieved 80 K temperature rise and reaches a maximum of about 200 K in 0.1 seconds as shown in Fig. 8. The heater has been tested at 850 V both at room temperature and 77 K.

Fig. 8: Simulation of quench heater temperature, current, and voltage versus time. Semi-adiabatic (fixed heat sink temperature) simulation.

VI. COLLARING

During the initial compression, each coil will be squeezed by approximately 2.5 mm azimuthally. After the keys have been pushed into the collars, the mandrel radius must be further reduced to allow it to be extracted from the assembly. The roller bearings allow the extraction of the central port and therefore the extraction of the entire mandrel without damaging the coil insulation. This is an important development, which was previously not required because the movement with the LHC style insulation and coil dimensions were considerably smaller.

A 150-mm-long model mandrel was built and tested, the full length, 1.8-m-long mandrel, is being procured from European industry.

The collars are made from CERN stock, 3-mm-thick Nippon stainless steel that was used for the main LHC dipoles. To

reduce cost, the parts of lower tolerance (± 0.07 mm) are laser cut, while for the tighter tolerance (± 0.02 mm) parts wire erosion was chosen. For model magnets, this is a cost effective alternative to fine blanking or complete wire erosion. The 0.2-mm-high dimples, which reduce the stacking factor in the collar packs, were added to the collars in a separate pressing operation that was proven not to change the overall dimensions on the collar.

The collars are pre-assembled in 26-mm-long packs held with aluminum pins. The four poles of collars can only be slid together simultaneously. This technique will allow the horizontal assembly of the collars and stop collars falling apart during assembly, collar “massaging,” and key insertion. A special tool was developed to insert and retract the collars simultaneously.

A new magnet collaring press was built, capable of collaring sequentially 20-cm-long section. The press has eight 1000 kN hydraulic cylinders for the collars and eight 250 kN key pushing hydraulic cylinders. The press is compatible with other LHC magnet collaring systems such as MQ and MQY. This collaring press is controlled by a touch screen and has synchronized position controlled and independent movement of the high power rams. For long magnets, it can be configured horizontally.

VII. CONCLUSION

We present new features (open ground insulation, fast quench heaters, locking collar system) and manufacturing challenges for a large-aperture insertion quadrupole that is compatible with the high radiation doses expected after the next major LHC upgrade. A new set of tooling for coil winding and curing, coil size measurements, aperture assembly, and collaring has been designed and commissioned. CERN, in collaboration with CEA, Saclay has so far wound and cured coils to build two magnets. All components for three 1.8-m-long magnets have been produced. The cold test of the first model magnet is expected by mid 2012.

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