Performance of the Final Prototype of the 6-kA Matching Quadrupoles for the LHC Insertions and Status of the Industrialization Program

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Abstract—The LHC insertions will be equipped with individually powered superconducting quadrupoles, which have a coil aperture of 56 mm, and operate at a nominal gradient of 200 T/m at 1.9 K and a current of 6 kA. Three versions of the magnet are required for the LHC, with magnetic lengths of 2.4 m, 3.4 m and 4.8 m, but otherwise identical. After a prototype program which validated the design options, the contract for the fabrication of one hundred magnets was adjudicated to European industry. In this report we describe the main construction features of the magnets, present the performance of the final prototype, and give the status of the industrial fabrication program.

Index Terms—LHC, quadrupoles, superconducting magnets.

I. INTRODUCTION

THE LHC insertions will use about 100 individually powered quadrupoles. The design features and the results of the prototype development of these quadrupoles are described in [1]–[3]. The magnets have an aperture of 56 mm, and are designed for a nominal gradient of 200 T/m at 1.9 K and 160 T/m at 4.5 K. The cross section of the magnet is shown in Fig. 1

The coils are made out of two layers of an 8.8 mm height NbTi Rutherford type cable. Copper wedges are placed in the coil to position the conductors. Four coils are assembled with 2 mm thick stainless steel collars into a single collared coil structure. The collared coil is completed with one end-plate at each extremity and a series of G11 plates where the coils are spliced together. Each magnet contains two collared coils whose positions are defined by keys placed in the groove of the yoke laminations. The latter are also the return path of the magnetic circuit. The original design of the magnet was based on a 34-strand cable that had been developed for another LHC project. Two prototypes called PB1 and PB2 were made out of this cable. Although an appropriate protection of the magnet was possible with the 34 strands cable, it was decided to decrease the quench peak temperature by adding two strands to the cable.

The final prototype of the 6-kA matching quadrupole includes all modifications, in particular the cable size, introduced after the initial models. But it is identical, except for length, to the series magnets. In this report we describe the fabrication of the final prototype and present the quench training and other test

Fig. 1. Cross section of the LHC matching quadrupole.

results. Finally a short account of the industrial fabrication program is given.

II. CONSTRUCTION FEATURES OF THE PROTOTYPE

Fig. 2 shows the single aperture short prototype of the 6-kA magnet for the LHC insertions.

In this magnet a collared coil identical to the final version of the twin aperture one is placed in a single aperture yoke. Calculations and measurements on a previous twin aperture prototype, predict that the cross talk between apertures is negligible and therefore the single aperture magnet can be considered to be representative of the final twin aperture version. This single aperture structure allows a shorter design iteration cycle, as it is not required to build a twin aperture magnet to test the impact of modifications in the coil design or the way the magnet is collared.

With respect to the previous prototype, the main differences are the use of the new cable of 36 strands having a better protection behavior, and the modifications in the layer jump that was the main source of training quenches in the previous prototypes. The length of the layer jump over which the conductor

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Fig. 2. Cross section of the single aperture short prototype magnet.

TABLE I
CHARACTERISTICS OF THE 1-m PROTOTYPES. PB1 AND PB2 ARE THE TWO
PREVIOUS MODELS USING THE 34-STRAND CABLE

	PB1	PB2	Final prototype
Cable width (mm)	8.20		8.80
Mid-thickness (mm)	0.85		0.85
Keystone angle (deg.)	1.05		0.98
No of strands	34		36
Strand dia. (mm)	0.480		0.480
Cu/SC Ratio	1.3	1.7	1.75
Filament dia. (μ m)	10		40
j_c (A/mm ² , 4.2 K and 5 T)	2960	3140	-
Cable insulation	Kapton ¹		Apical ²
Operating temperature	1.9 K		1.9 K
Nominal gradient	200 T/m		200 T/m
Nominal current	5280 A		5370 A
Peak field in coil	6.16 T		6.30 T
Quench field	7.5 T	7.6 T	7.9 T
Coil inner/outer diameter	56/90 mm		56/92.24 mm
Collar outer diameter	135 mm		140.8 mm
Yoke inner diameter	138 mm		146.8 mm
Inductance	4.55 mH/m		4.40 mH/m

Kapton is a registered trademark of Du Pont de Nemours.

Apical is a registered trademark of Kaneka corporation.

goes from the first to the second layer is increased from 83 mm to 130 mm, a better fit between the cable and the G11 piece that is used as a guide in the layer jump is obtained by decreasing the play between cable and groove from 1 mm to 0.2 mm, finally a cold setting epoxy resin is used to glue the conductor to the G11 piece. A further modification is the increase in the collar dimension, which produces a more rigid structure, although the iron contribution to the magnetic field decreases.

The cable that will be used for the series magnets has a filament diameter of 6 μ m. As this cable was not available for the production of the final prototype, a prototype cable of the same geometry and very similar critical current but with a filament of 40 μ m was used. The properties of the previous prototypes as well as the new one may be seen in Table I.

Fig. 3. Measurements of the azimuthal dimension of the outer layer of the test coil. The coil was cured three times with shims of increasing size.

III. FABRICATION

Five coils were wound at the CERN prototype magnet laboratory, one of them was used to test the coil size measuring tooling and the other four were used to assemble the magnet. A systematic oversize of all the coils of 0.2 mm was observed. The outer layer was larger than the inner in all coils. In order to modify the azimuthal dimension of the test coil, it was re-cured two times, increasingly larger shims were introduced in the mould cavity and the coil was subjected to a full curing cycle. The results of this process may be seen in Fig. 3. The first re-curing modified the size of the coil in about 0.06 mm, whereas the second only by about 0.03 mm.

For the final prototype, it was decided to use the coils as initially cured and compensate the oversize by decreasing the size of the collaring shim in the magnet. Therefore, field errors due to the geometry of the coil were expected.

The coils were collared around a collapsible mandrel using a quadrupole press capable of producing 500 kN on the poles and 200 kN for pushing four keys in their slots. The keys are tapered with an angle of 3° to facilitate their insertion. This angle is well below the friction angle between two stainless steel surfaces and therefore the keys will be kept in place by friction.

The coils were instrumented with capacitive gauges to measure the azimuthal pressure during assembly and operation. The measured azimuthal stress after the collaring was 80 MPa for the outer layer and 65 MPa for the inner. This difference is consistent with the size mismatch between layers. The maximum over-stress during collaring was 50%, corresponding to 120 MPa in the outer layer. Fig. 4 is the graph of the measured coil pressure during collaring. An interesting point is that the coil pressure in the different poles becomes more evenly distributed when the hydraulic system is released and the collared coil stays just held by the collaring keys.

Once the coils were collared, two end plates were welded to the full length keys. The end-plates have threaded holes that allow bolts to be used to pre-compress longitudinally the coil with a force of around 1 kN per coil and layer. This force helps to hold in place the last end-spacer of the coils. During excitation of the coil these bolts transfer the longitudinal magnetic forces

Fig. 4. Azimuthal pressure in the coil during collaring. The error bars represent the minimum and maximum reading in all four poles for any measurement. The peak occurs at the stage when the hydraulic system is still pushing while the keys are fully inserted. In points 15 to 24 the hydraulic system is pushing but the keys are not in place. In points 26 and after only the keys are keeping the collared coil together.

Fig. 5. Comparison of the training behavior of the different prototypes of the 6-kA Matching Quadrupoles. Quenches after the thermal cycle are represented starting in number 13. The first quench of the final prototype, PC1, is above 235 T/m. The conductor limit is only approximate.

in the coil heads. The collared coil is positioned in the yoke structure with four keys placed over the poles, and trapped by slots in the magnetic yoke laminations. Finally, all the structure is placed in a bolted cylinder, as may be seen in Fig. 2.

IV. COLD TEST

The coil was trained at 1.9 K liquid helium at CERN. The first quench occurred at 235 T/m, corresponding to a value more than 17% above the nominal value. The coil was then trained up to 252 T/m in three further quenches. All quenches occurred in two coils and in high field regions. These results are shown in Fig. 5, where the performance of the older short prototypes, PB1 and PB2, is also represented. As we can see the behavior has clearly improved. The magnet went through a thermal cycle to room temperature and was tested again. The first quench after the cycle was over 250 T/m showing full memory of previous training. The magnet was then tested at temperatures between 1.9 K and 2.1 K and the quench current went down from 6820 A

Fig. 6. Evolution of the azimuthal pre-stress in the coils with the current.

TABLE II

FIELD QUALITY. THE VALUES ARE IN UNITS OF 10^{-4} OF B_2 AT A REFERENCE RADIUS OF 17 mm. THE VALUES FOR B_2 IN THE FIRST ROW ARE IN T

n	Current level					
	350 A		3500 A		6500 A	
	b_n	a_n	b_n	a_n	b_n	a_n
2	0.20	0.00	2.21	0.00	4.10	0.00
3	-1.07	0.90	-1.04	0.84	-0.97	0.97
4	-0.19	0.42	0.02	0.34	-0.06	0.35
5	-0.59	0.83	-0.56	0.91	-0.50	0.91
6	-14.30	-1.97	-0.70	-0.78	-0.85	-0.80
7	0.54	0.08	0.46	0.04	0.46	0.03
8	-0.09	-0.07	-0.08	0.02	-0.07	0.03
9	-0.27	-0.01	-0.19	-0.02	-0.19	0.00
10	2.68	-0.05	1.42	-0.17	1.40	-0.18

to 6750 A, pointing to an operation near the conductor limit. The magnet was also tested at 4.4 K and had a first quench at 5140 A. Again a temperature sweep between 4.33 K and 4.53 K showed the magnet to operate at a conductor limited condition.

The evolution of the coil pre-stress during cool down and powering of the magnet is shown in Fig. 6. More than 40 MPa of pre-stress is lost during cool down due to the differential thermal contraction of the coil and the stainless steel collars. The coils unload at about 6 kA, although the magnet trained above 6.6 kA. The slope of the loss of pre-stress is about 0.77 MPa/kA^2 , in very good agreement with the calculated value.

The field quality was measured after training as a function of the current between 100 A and 6500 A. Table II gives the measured harmonics for three current conditions. The target value for b_6 , without taking into account saturation or magnetization effects, is 2.5 units, and the smaller measured value is thought to be due to the nonnominal shim compensating the coil over-size. The large b_6 at injection current is due to the large filament diameter and should be drastically reduced once the production quality cable is used. Some nonallowed harmonics have similar values to the allowed ones, indicating the presence of construction errors in the fabrication of the magnet. The change in the field quality after the thermal cycle was negligible.

Fig. 7 is the quadrupole transfer function at the magnet center in the range 100 A to 6.7 kA. The large hysteresis cycle at low current may again be attributed to the large filament diameter.

Fig. 7. Measured transfer function of the prototype magnet.

The saturation effect is relatively small, with a variation in the transfer function of -0.3% between 2 kA and 6 kA. The value of the transfer function in the nominal current region, 5.4 kA, is $37.14 \text{ T}/(\text{m} \cdot \text{kA})$.

V. STATUS OF THE INDUSTRIAL FABRICATION PROGRAM

The contract for the fabrication of the 96 6-kA matching quadrupoles for the LHC insertions was awarded to Tesla Engineering (UK) in 2000. The fabrication takes place in Lancing (UK). The contracts for the supply of most components are already adjudicated. Cable, quench heaters, polyimide insulation and steel for collar and yoke laminations are supplied by CERN. All the other components are purchased by Tesla Engineering. Most of the tooling, designed by Tesla Eng. in agreement with CERN, is in the final stages of assembly or being commissioned with the pre-series magnets. Five coils of 2.5 m length using LHC-quality cable have been wound. A detail of the coil windings in the ends is shown in in Fig. 8.

The trial coils have been measured at CERN and have an azimuthal stress in the range of 70 to 110 MPa when compressed to their nominal size as expected. The collaring press was commissioned with a 250 mm mechanical model. The average value of the azimuthal stress in the mechanical model was 65 MPa for the outer layer and 60 MPa for the inner. The first pre-series magnet is expected by October 2002, and it will be tested in the vertical test station at CERN which has been upgraded to accept up to 3.3 m long magnets.

Fig. 8. Heads of one of the prototype coils made at Tesla Engineering. The lead end of the first layer is the upper one and the return end is the lower. The photograph was taken previous to the curing of the coil.

VI. CONCLUSIONS

A 1-m long final prototype of the 6-kA quadrupole for the matching sections of the LHC was built and tested at CERN. The prototype fully confirmed the correctness of the final design both from the magnetic and training point of view. The magnet had a first quench at 1.9 K at a gradient of 235 T/m, well above the nominal value of 200 T/m and quickly trained to the conductor limit. The field quality was good in spite of using a nonnominal shim for coil size adjustment.

The program to produce in industry the 96 units that are required for the LHC is well under way. Five trial coils have been wound and the completion and testing of the first pre series magnet is expected in October 2002.

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