Development of Superconducting Tuning Quadrupole Corrector (MQT) Prototypes for the LHC

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***Abstract*—The main quadrupoles of the Large Hadron Collider (LHC) are connected in families of focusing and defocusing magnets. In order to make tuning corrections in the machine a number of quadrupole corrector magnets (designated MQT) are necessary. These 56 mm diameter aperture magnets have to be compact, with a maximum length of 395 mm and a coil radial thickness of 5 to 7.5 mm, while generating a minimum field gradient of 110 T/m. Two design options have been explored, both using the "counter-winding" system developed at CERN for the fabrication of low cost corrector coils. The first design, with the poles composed of two double-pancake coils, each counter-wound using a single wire, superposed to create 4-layer coils, was developed and built by ACCEL Instruments GmbH. A second design where single coils were counter-wound using a 3-wire ribbon to obtain 6-layer coils was developed at CERN. This paper describes the two designs and reports on the performance of the prototypes during testing.**

***Index Terms*—Corrector magnet.**

I. INTRODUCTION

THE LARGE Hadron Collider (LHC) will incorporate 320 MQT tuning quadrupole superconducting corrector magnets. These are to be mounted in main quadrupole (MQ) cold masses, and will operate in superfluid helium at 1.9 K. They need to provide a minimum field gradient of 110 T/m, at a nominal operating current of 550 A. Space limitations in the MQ cold mass and the fact that MQT is mounted within an iron shield in order to screen it from nearby busbars (which carry currents up to 13 kA) constrain the length and diameter of the MQT module to approximately 370 mm and 150 mm, respectively. The module bore has a diameter of 56 mm. For reliability the MQT working point is specified to be at approximately 60% of the critical current. Two different designs, designated MQTA and MQTB, have been considered, and prototypes of each constructed and tested.

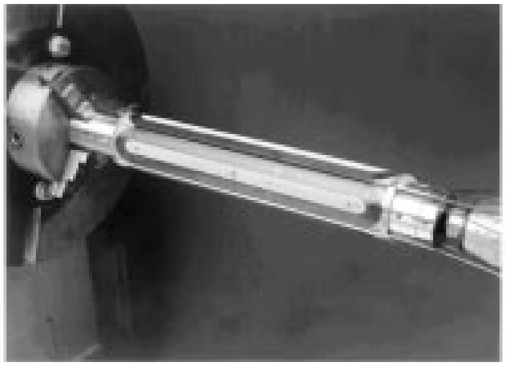

Fig. 1. Assembly of MQTA coils. The coils are doweled to a precisely machined mandrel. A glass fiber plate is mounted at the connection end to support the connections and the assembly glued together using epoxy resin.

II. MAGNET CONSTRUCTION

The construction methods used for the MQT prototypes have been developed at CERN with the aim of facilitating the industrial production of low cost, robust, superconducting corrector magnets that meet the demanding specifications of the LHC [1]. In both designs, the superconducting coils are wound using enamel insulated, copper stabilized NbTi conductor of rectangular cross-section, wet-wound around glass-fiber central posts. After curing, these coils are assembled on a mandrel and glued together using epoxy resin (Fig. 1 shows this procedure during the construction of MQTA), with a glass fiber end-plate to provide support for the electrical interconnections. An epoxy pre-preg bandage wrapped around the coils and cured forms an insulation layer, around which iron scissor laminations [2] are stacked to form the return yoke of the magnet.

An aluminum cylinder mounted around the outer diameter of the yoke by shrink fitting holds the complete assembly together and provides the necessary pre-stress, transmitted via the scissor laminations which are free to slide past each other, to the coil assembly to prevent coil movement when the magnet is energized. The amount of pre-stress is controlled by precise machining of the bandage outer diameter, thus defining the radial interference between the yoke outer diameter and the shrinking cylinder inner diameter.

III. MAGNETIC DESIGNS

In both cases the magnetic designs were optimized using ROXIE [2]. MQTA was also modeled using the

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TABLE I
MQT PROTOTYPES CONDUCTOR PROPERTIES

	MQTA	MQTB
Insulated dimensions	1.43 mm × 0.63 mm	1.25 mm × 0.73 mm
Insulation thickness	0.06 mm	0.06 mm
Cu/Sc ratio	1.6-1.62	1.6
Filament diameter	7 μm	7 – 10 μm
Residual resistance ratio	136-142	> 100
Critical current (5T, 4.2 K)	695 A ⊥, 799 A //	≥ 650 A ⊥, ≥ 715 A //

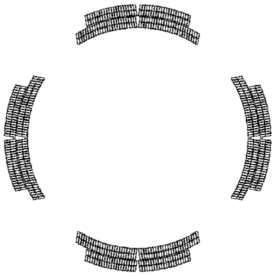

Fig. 2. MQTA coil cross section. Two-layer coils are superposed and connected in series to make four-layer coils.

OPERA/TOSCA®[1] software package to provide a cross-check with the ROXIE results. The goal of the optimization was to configure the coil block geometry so as to simultaneously maximize the integrated quadrupole field component B_2 and minimize the b_6 and b_{10} field harmonics. To keep the complexity of the construction to a minimum in order to obtain designs well suited to inexpensive production of series quantities, the use of spacers within coil blocks was not considered. This results in insufficient free parameters to allow both these harmonics to be reduced to zero at the same time. The optimizations were carried out using three–dimensional (3-D) models since the relatively short length of the coil results in a strong influence from the coil ends, in particular on the b_6 field harmonic. In both cases 2-D mechanical models were used to calculate the radial interference required between the yoke and the shrinking cylinder at room temperature in order to obtain the necessary pre-stress levels at 1.9 K.

A. MQTA

The MQTA was developed and built by Accel Instruments GmbH, under contract from CERN. The design approach concentrated on the use of "double-pancake" coils, made by counter-winding a single wire (see Table I) so that each double-pancake contains two layers wound simultaneously. Several winding tests were performed before finalizing the central post design in order to facilitate the coil winding process and maximize the precision of the conductor placement. In the resulting optimized design each pole of the quadrupole is composed of two such double-pancakes superposed and connected in series by soldering to give four-layer coils, so that the magnet in fact consists of 8 coils. The coil cross section is shown in Fig. 2.

The iron yoke increases the field gradient by 60%, and holes in the yoke control the effects of the iron saturation on the field harmonics. The dimensions and positions of these holes were included in the optimization procedure. Attempts to control b_{10} by varying the relative angular positions of the inner and outer coil blocks proved unsuccessful.

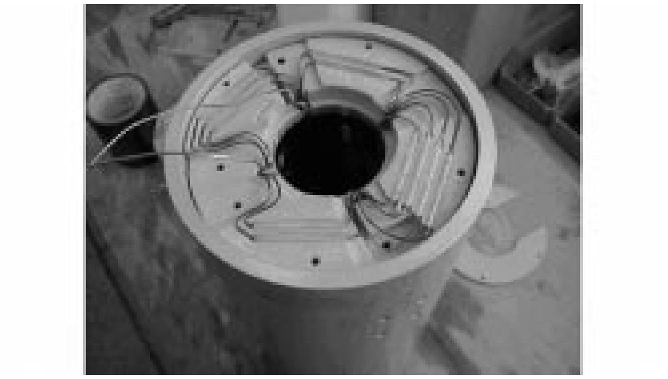

Fig. 3. MQTB electrical connections. Not only must the 4 coils be connected in series, but also the 6 layers in each coil.

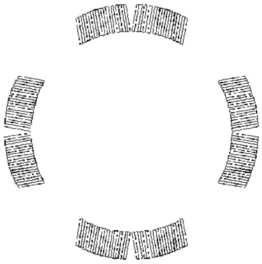

Fig. 4. MQTB coil cross-section. Coils are made by counterwinding a 3-wire ribbon to make 6-layer coils.

B. MQTB

The LHC will contain approximately 6500 corrector magnets with 18 different types of coil. To reduce conductor costs it is desirable to standardize as far as possible the conductors used in these magnets. In order for the MQT conductor to be compatible with other corrector types, a second design, MQTB, was developed at CERN using a standardized wire (see Table I). A four-layer design using this wire cannot provide the minimum required gradient of 110 T/m with an adequate safety margin, and also there is considerable interest in increasing the field gradient beyond this minimum, to at least 120 T/m. Therefore, a six-layer design was developed, with the magnet composed of four coils of six layers, each counter-wound using a ribbon of three wires. This ribbon was manufactured at CERN using a purpose-built machine that uses epoxy resin to glue single wires together and cures the resin in a continuous process. While this manufacturing method obviates the need to make series connections between superposed pancakes, it is instead necessary to make them between the conductors that make up the ribbon (see Fig. 3).

The MQTB coil cross section is shown in Fig. 4. In this design, variation of the b_6 harmonic with yoke saturation is controlled by optimizing the dimensions of the yoke and the air gap between the yoke and the surrounding iron shield, rather than by the use of holes in the yoke.

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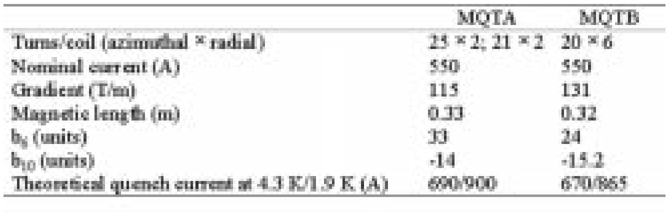
[1] Registered trademark of Vector Fields Ltd., Oxford, England.

TABLE II
COMPARISON OF MQT PROTOTYPES MAGNETIC DESIGN



	MQTA	MQTB
Turns/coil (azimuthal × radial)	25 × 2; 21 × 2	20 × 6
Nominal current (A)	550	550
Gradient (T/m)	115	131
Magnetic length (m)	0.33	0.32
b_6 (units)	33	24
b_{10} (units)	-14	-15.2
Theoretical quench current at 4.3 K/1.9 K (A)	690/900	670/865

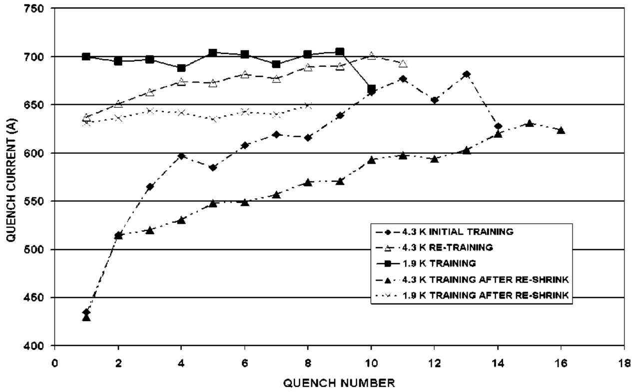


Fig. 5. MQTA training. No increase in the critical current is observed at 1.9 K, indicating a mechanical limitation to the magnets' performance.

The 2-D design values of the magnetic parameters of MQTA and MQTB are summarized in Table II. The relatively high b_6 is required to cancel the contribution from the coil ends in both designs.

IV. TEST RESULTS

A. Training Tests

The MQTA was initially trained at Accel Instruments at 4.3 K. Re-training at 4.3 K and further training at 1.9 K were then carried out at CERN. The results are shown in Fig. 5. During the initial training at 4.3 K the nominal operating current was exceeded at the third quench, and the magnet trained steadily to a value approaching the theoretical estimate of the critical current. At the final quench of this test program some de-training was seen. On re-training at CERN, the first quench agreed well with the final training quench at Accel Instruments and once again the magnet trained steadily to about 700 A. On cooling the magnet to 1.9 K no increase in the critical current was visible. Combined with the slow training at 4.3 K, this implies the presence of some mechanical limitation to the performance of the magnet.

To investigate the possibility that the lack of improvement in critical current at 1.9 K was due to insufficient pre-stress, the radial interference between the shrinking cylinder and the yoke was increased, changing the pre-stress of the coils at 1.9 K from an estimated 60 MPa to approximately 80 MPa. More training tests were then carried out. It is apparent that the increased pre-stress had a detrimental effect on the performance of the magnet, with the first 4.3 K quench occurring at 430 A and being followed by slow training up to about 620 A. Cooling to 1.9 K produced only a further 30 A increase in the critical current.

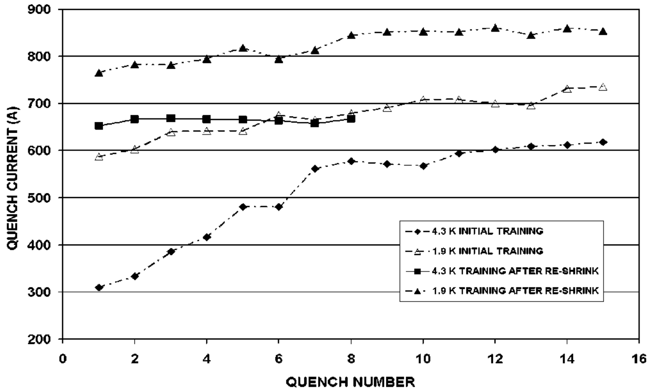


Fig. 6. MQTB training. After increasing the pre-stress the magnet reached the theoretical critical current at both 4.3 K and 1.9 K.

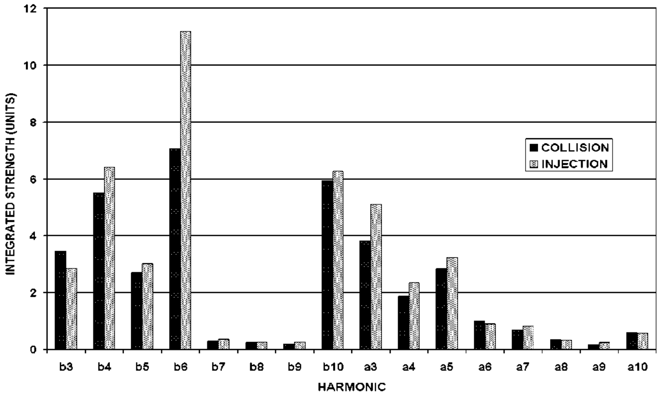


Fig. 7. Magnitudes of the measured integrated field harmonics of MQTA, at a reference radius of 17 mm, in units of $B_2/10^4$.

MQTB underwent training tests at 4.3 K and 1.9 K at CERN. In the first series of tests, training was slow and the magnet remained well below the theoretical critical current, as shown in Fig. 6.

To see the effect of increasing the pre-stress in MQTB, a 0.05 mm stainless steel foil was then fitted between the shrinking cylinder bore and the yoke outer diameter to increase the radial interference to 0.12 mm and the pre-stress to an estimated 80 MPa at 1.9 K. The magnet was then re-tested. In this instance this procedure significantly improved the performance of the magnet. At 4.3 K the magnet began training at 650 A, although it should be noted that it is common for an impregnated magnet to retain memory of previous training tests after the pre-stress has been modified. The theoretical critical current, 670 A, was reached at the second quench. Cooling to 1.9 K then brought an immediate improvement to over 760 A, following which the magnet trained to a limit of 860 A, again in good agreement with the calculated critical current.

B. Magnetic Field Quality

The magnetic field was measured as a function of excitation current at CERN at 1.9 K for both MQTA and MQTB. In the LHC, the collison and injection energies are 7 Tev and 0.45 TeV,

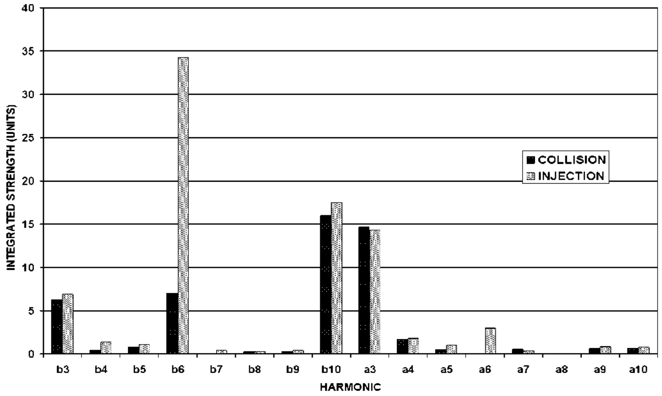


Fig. 8. Magnitudes of the measured integrated field harmonics of MQTB, at a reference radius of 17 mm, in units of $B_2/10^4$.

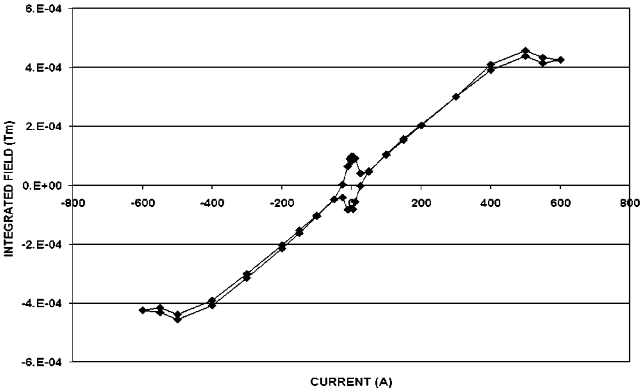


Fig. 9. Integrated B_6 harmonic of MQTA, at a reference radius of 17 mm, measured passing through zero current from opposite directions.

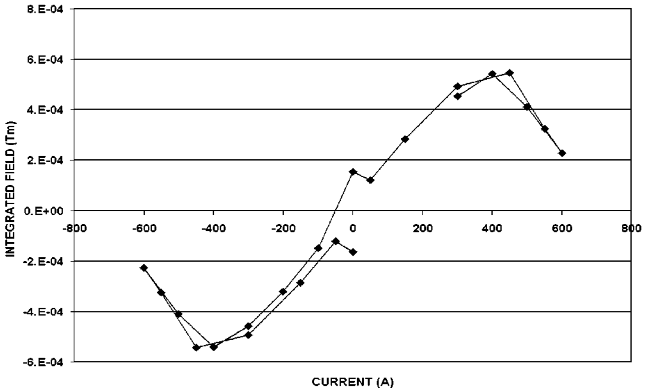


Fig. 10. Integrated B_6 harmonic of MQTB, at a reference radius of 17 mm, measured passing through zero current from opposite directions.

respectively. With a target gradient at collision of 110 T/m ($B_2 = 1.87$ T at a radius of 17 mm) and therefore at injection of $110 \times 0.45/7 = 7$ T/m, the loadline measurements of MQTA give an excitation of 541.2 A at collision and 33.9 A at injection. For MQTB, taking the target gradient at collision to be 120 T/m ($B_2 = 2.04$ T at 17 mm), the currents at collision and injection were found to be 493.4 A and 33.1 A, respectively. The integrated strength of the magnetic field multipoles at collision and injection strengths are shown in Fig. 7 for MQTA and Fig. 8 for MQTB.

Nonlinear effects from iron saturation are evident in both magnets. At collision, the observed magnetic field components of both prototypes were found to lie within the range of variation to be expected, taking into account the random field errors introduced by the use of general tolerances of ±0.1 mm during their fabrication. MQTB has a higher residual integrated b_{10} than MQTA by about 10 units, b_6 is similar for the two magnets at approximately seven units.

However, at injection MQTB was found to have a higher than expected b_6 of 34 units (1.4×10^{-4} Tm), compared to MQTA with a b_6 of 11 units (4.5×10^{-5} Tm). Further investigation of the multipoles by making measurements when passing through zero current from opposite directions (see Figs. 9 and 10), shows that hysteresis due to persistent currents in the superconducting filaments makes a significant contribution at low excitations to the b_6 harmonics of both magnets.

V. CONCLUSION

Two different designs of MQT tuning quadrupole corrector magnet have been developed and tested. The MQTA, with four-layer coils designed to meet the original 110 T/m gradient requirement of the LHC, provided this nominal gradient at 78% of the loadline at 4.3 K, but the critical current did not improve at 1.9 K. Increasing the pre-stress in the coils caused a deterioration in the performance of the magnet. The MQTB with six-layer coils designed to produce a gradient of 120 T/m trained to theoretical critical current at both 4.3 K and 1.9 K, and provided the nominal gradient at 57% (73%) of the loadline at 1.9 K (4.3 K). For both prototypes magnetic field multipoles at collision energy were within the expected ranges considering the manufacturing tolerances. At injection energy hysteresis effects make a significant contribution to the b_6 field component.

Following the satisfactory performance of the prototype, the MQTB design has been selected as the design to be used for the MQT correctors in the LHC, since it generates a greater field gradient and is expected to be the least expensive of the two designs to fabricate in series quantities.

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