DESIGN, PERFORMANCE AND SERIES PRODUCTION OF SUPERCONDUCTING TRIM QUADRUPOLES FOR THE LARGE HADRON COLLIDER

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Abstract

The Large Hadron Collider (LHC) will be equipped with several thousands of superconducting corrector magnets. Among the largest ones are the superconducting trim quadrupoles (MQTL). These twin-aperture magnets with a total mass of up to 1700 kg have a nominal gradient of 129 T/m at 1.9 K and a magnetic length of 1.3 m. Sixty MQTL are required for the LHC, 36 operating at 1.9 K in and 24 operating at 4.5 K. The paper describes the design features, and reports the measured quench performance and magnetic field quality of the production magnets. The MQTL magnet production is shared between CERN and industry. This sharing is simplified due to the modular construction, common to all twin-aperture correctors.

INTRODUCTION

The insertion regions of the LHC will be equipped with a total of 60 superconducting trim quadrupole magnets MQTL, the main parameters of which are given in Table 1. They feature two identical 1.4 m long independently powered magnet modules with an outer diameter of 135 mm, a bore of 56 mm in diameter, and an approximate mass of 200 kg mounted in a laminated twin-aperture support structure of two different types. The MQTL magnets are used to tune the optical parameters of a certain number of quadrupoles in the matching section and dispersion suppressors [1]. In the dispersion suppressors (DS) one or two MQTLI assemblies are integrated in the cold mass with the main quadrupole (MQ) and other corrector elements. In the matching sections of the cleaning insertions 6 MQTLH assemblies connected in series are mounted as a single cold mass.

DESIGN AND CONSTRUCTION FEATURES

Magnetic Design

The MQTL modules are designed to produce a gradient of 129 T/m at 550 A in the dispersion suppressors that operate at 1.9 K. In the cleaning insertions these modules operate at 4.5 K and are powered up to 400 A to produce a gradient of 90 T/m. In the LHC these quadrupole correctors will be connected in series in families of up to 6 magnets. Each module is equipped with a parallel resistor of 0.2 ohms made of stainless steel to safely dissipate the energy in the case of a quench.

Table 1: Main Parameters of MQTL

Magnetic		
Nominal gradient (1.9 / 4.3 K)	129 / 90	T/m
Magnetic length	1.3	m
Peak field in coil	4.1	T
Geometric		
Overall length (H- / I-type)	1403 / 1428	mm
Overall diameter (H- / I-type)	452 / 475	mm
Total mass (H- / I-type)	1700 / 1150	kg
Module mass	200	kg
Module outer diameter	135	mm
Aperture diameter	56	mm
Coil length	1354	mm
Coil inner / outer diameter	56.4 / 71.4	mm
Yoke inner / outer diameter	74.5 / 117.4	mm
Electrical		
Nominal current (1.9 / 4.3 K)	550 / 400	A
Theoretical quench current (1.9 / 4.3 K)	935 / 655	A
Turns / coil	6 x 20	
Stored energy	18.1	kJ
Self inductance	0.12	H
Parallel resistor	0.2	Ω
Conductor		
Overall section	1.25 x 0.73	mm
Metal section	1.13 x 0.67	mm
Cu:Sc-ratio	1.6	
Filament diameter	7	μm

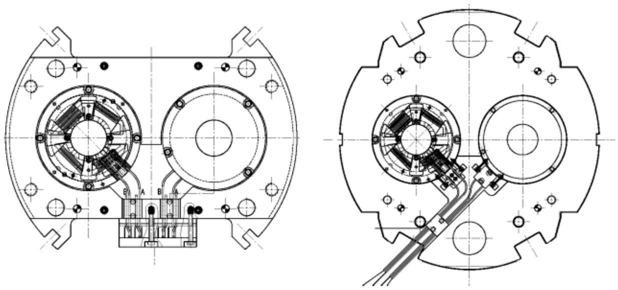

Figure 1: Cross-section of MQTLI- and MQTLH-assemblies

Mechanical Design

An MQTL magnet assembly comprises two superconducting quadrupole modules mounted in a twin-aperture support structure of two different types, H (Half shell type) for cleaning insertions and I (Inertia tube type) for the dispersion suppressors, as shown in Figure 1. The only difference between them is the external contour of the laminations and the location of the parallel resistor. The modules are each aligned through 24 keys located in precisely machined slots on the shrinking cylinders in the same way as the collared coils of the Main Quadrupoles (MQ) [1].

Each magnet module consists of four epoxy impregnated coils, a laminated iron yoke, six aluminium shrinking cylinders, and an end plate that houses the electrical connections [2]. The coils are made by counter-winding three superconducting wires, pre-assembled as a flat cable, around a copper central post and G11 end-spacers. The dimensional tolerance of the 3-way cable is very tight (0.02 mm over a unit length of 120 m). During the coil production the variations in the coil dimensions were mainly caused by the variations in the cable thickness. For this reason close attention was paid on selecting coils for each assembly and on careful filling of all the voids with Nomex*.

Pre-compression is applied to the coils by the shrink fitting of aluminium cylinders over the eccentric steel laminations that make up the yoke [4]. The laminations are sequentially stacked around the coils in 8 different azimuthal orientations. The radial pressure from the outer shell induces the compressive azimuthal stress in the coils that is needed to prevent tensile strain when the magnet is powered. The magnitude of the pre-compression, determined by the interference fit between the aluminium outer shell and the yoke laminations around the coils, is chosen to produce pre-compression of about 80 to 100 MPa in the coils at room temperature. This pre-compression is increased by approximately 15 MPa at the operating temperature due to different thermal contraction coefficients of the aluminium shrinking cylinders and the iron laminations.

To keep the ohmic heat load into the helium bath down to an acceptable level, the contact resistance of each connection will be less than 2 nΩ at 1.9 K. The wires in the flat cable of each coil were connected in series by ultrasonic welding. The coils were then connected in series in the same way and all the connections were filled with charged epoxy resin.

*Nomex is a trademark of DuPont de Nemours & Co

MAGNET PRODUCTION STATUS

Due to delays in starting up the production the magnet fabrication was shared between CERN and industry such that CERN has made 130 of the 144 magnet modules that are required, including the spare magnets. The final assembly in the twin-aperture structure was carried out in industry.

All 144 magnet modules have been completed and successfully tested. The 36 series MQTLI assemblies have been delivered to the cold assembler of the DS cold masses. We expect to have remaining 6 of the 24 MQTLH assemblies delivered by the end of June 2006.

TEST RESULTS

All magnet modules were trained at 4.5 K after which the field quality was measured at warm prior to assembling them in the twin-aperture support structures. Most of the cold and warm testing was carried out at CERN

Quench Performance

Figure 2 illustrates the number of quenches to reach the ultimate current for all the modules made at CERN and in industry. After the first prototype module the eccentricity of the laminations was increased from 0.3 mm to 0.5 mm to make sure that there was no loss of pre-compression due to the laminations lining up during the cool-down. The radial interference fit between the laminations and the shrinking cylinders was increased from 0.12 mm to 0.23 mm. It was also decided to change the central post material from G11 to copper. The copper central post sustains better the winding tension and there is less residual stress in the winding after potting. At a later stage the winding tension was increased from 32 to 42 MPa. The variation in the coil azimuthal size was reduced to less than 0.1 mm after it was decided to produce all the cable at CERN. These measures improved significantly the training performance such that the modules reached the ultimate operating current of 600 A after 2 to 5 training quenches. To make use of the modules that did not reach the nominal operating current, 15 slots were identified in the LHC, where the expected operating current is in the range of 150 to 500 A

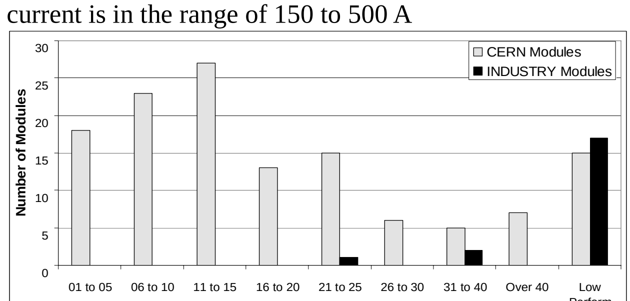

Figure 2: Number of training quenches to reach 600 A.

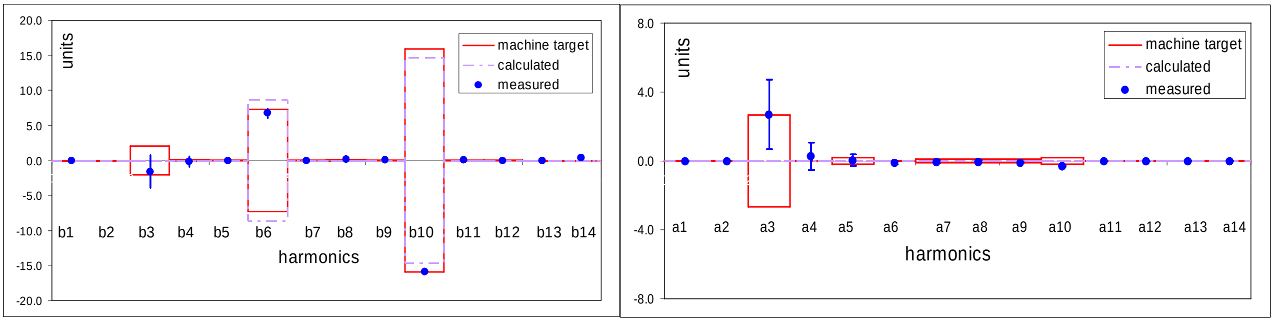

Figure 3: Measured normal (b_n) and skew (a_n) harmonics in units of all MQTL modules compared to the calculated values and to the machine targets at a reference radius of 17 mm [4].

Field Quality and Alignment

Figure 3 shows the multipole components for the 144 MQTL modules measured at warm. The systematic normal and skew components are compared to the calculated field errors and the machine targets. The systematic b_{10} of -15.9 units (multipole field at a reference radius of 17 mm divided by the main field and multiplied by 10000) is slightly outside the tolerance of -14.6 units, which is due to the single block design. Systematic normal and skew sextupole are -1.6 and -2.7 units being close to the machine targets of -2.07 and 2.63, respectively.

The alignment of the magnetic centre relative to the mechanical reference is listed in Table 2. The tolerance for offset was 0.1 mm and, if the measured roll angle was greater than 2.5 mrad, special offset keys were used to correct for it.

Table 2: Measured alignment of MQTL modules

	dx (mm)	dy (mm)	roll (mrad)
Mean	-0.01	0.01	-0.08
Stdev	0.07	0.07	1.18

So far only two twin aperture assemblies have been magnetically measured at cold. The most prominent feature of the current to field relationship is the effect of iron saturation that reduces the transfer function by about 7% between 100 and 550 A. Based on the available results, the projected field quality offsets between warm and cold should be less than a few units at nominal current, (larger on b_6, about 2 units, as visible in Figure 4).

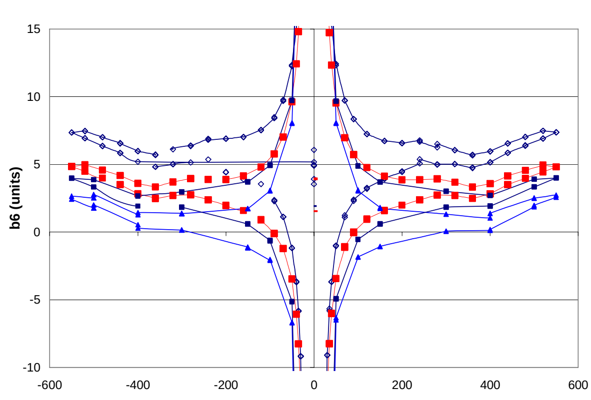

Figure 4: Normal dodecapole as a function of current.

However, magnetization effects contribute 11 units offset in b_6 and of 1 unit on b_{10} at 35 A, a current corresponding to the injection energy in the LHC for these magnets (at least for those replacing MQ).

CONCLUSIONS

The MQTL production is now almost completed after delays in the starting up. The last deliveries of the series magnets are expected in June 2006. After some design modifications and the optimization of the assembly parameters the quench performance was improved significantly. The field quality, as evaluated from the warm measurements, just meets the criteria for the machine optics and the module alignment is within the specified limits.

ACKNOWLEDGEMENTS

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