THE CONSTRUCTION OF THE SUPERCONDUCTING MATCHING QUADRUPOLES FOR THE LHC INSERTIONS

R. Ostojic, P. Canard, N. Catalán Lasheras, G. Kirby, J. C. Perez, H. Prin, V. Venturini Delsolaro, CERN, Geneva, Switzerland.

Abstract

After several years of effort, the construction of the superconducting matching quadrupoles for the LHC insertions is nearing completion. We retrace the main events of the project from the initial development of the quadrupole magnets of several types to the series production of over 100 complex superconducting magnets, and report on the techniques developed for steering of the production. The main performance parameters for the full series, such as quench training, field quality and magnet geometry are presented. The experience gained in the production of these special superconducting magnets is of considerable value for further development of the LHC insertions.

INTRODUCTION

LHC dispersion suppressors and matching sections contain individually powered quadrupoles, which provide the required tuning of the insertions [1]. These superconducting magnets comprise several quadrupoles of the MQM or MQY types arranged to give the necessary focusing strength. In the dispersion suppressors the quadrupoles are part of the continuous arc cryostat and are operated at 1.9 K. They are independently powered but provide identical cryogenic and powering interfaces to the adjacent main dipoles as in the regular arc cells. Most of the quadrupoles in the matching sections are stand-alone units and are cooled in a static helium bath at 4.5 K. Although in principle simpler, their cryogenic and powering interfaces are determined by the local conditions of each insertion (e.g. slope of the tunnel, interference with injection lines etc.). This customization leads to 31 types of quadrupoles arranged in 11 families with 6 different lengths from 5.3 m up to 11.3 m, as shown in Fig. 1.

Following the completion of the comprehensive R&D programme at CERN in 2001, industrial contracts for the manufacture of the MQM and MQY superconducting magnets were awarded to European industry. The final assembly of the matching quadrupoles was performed at CERN. As of mid-2006, the production of the total number of 104 MQM and 30 MQY magnets has been finished, and the assembly of the 82 matching quadrupoles at CERN is nearing completion. In this report we present the main performance parameters of the quadrupoles and review some of the lessons learned.

MAGNET PRODUCTION

Two types of quadrupole magnets are used in the LHC insertions: the MQM, which features a 56 mm coil aperture and is produced in three magnetic lengths (2.4 m, 3.4 m and 4.8 m), and the 3.4 m long MQY which has an enlarged 70 mm coil aperture. Both types of magnets are based on an 8 mm wide Rutherford-type Nb-Ti cable, such that their nominal currents are 5390 A and 3610 A, corresponding respectively to field gradients of 200 T/m at 1.9 K (MQM) and 160 T/m at 4.5 K (MQY).

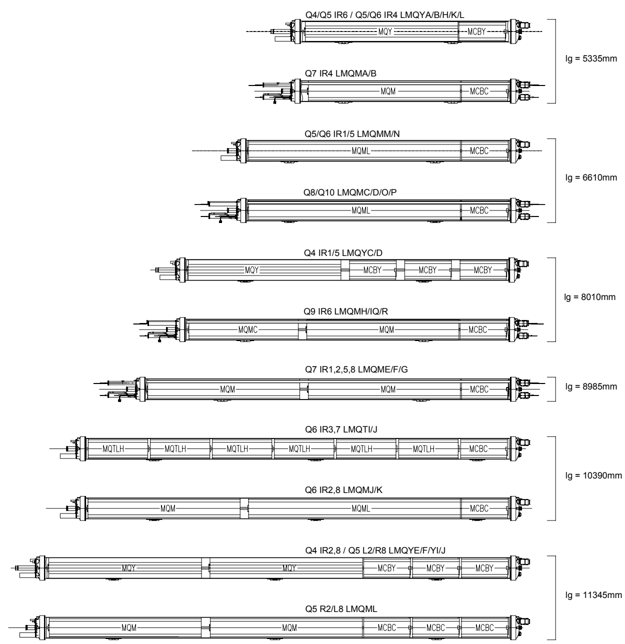

Figure 1: Types of the LHC matching quadrupoles

The MQM magnets were produced by Tesla Engineering (England) and the MQY by ACCEL Instruments (Germany). Following the transfer of technology to the firms, the pre-series magnets were extensively tested at CERN in 2003. The qualification tests showed that all requirements were fulfilled and that no further adjustments in the design were needed [2, 3]. As a result, the production of the series units could reach its full rate in early 2004. The production of the total contractual number of 104 MQM and 30 MQY magnets has been completed and the last magnets delivered to CERN in June 2006.

As part of the quality assurance, a series of mechanical, electrical and magnetic field measurements were performed in the factories and at reception at CERN. About half of the magnets were cold tested immediately after delivery. All these tests allowed quick feedback and effective steering of the production.

Coil size and magnetic field quality

An important element of the quality assurance was the control of the coil sizes. The MQM and MQY coils were wound and cured to their nominal sizes and were all measured by the manufacturer using E-modulus measuring systems supplied by CERN. The azimuthal tolerance for the nominal coil size at 70 MPa is ± 50 µm in the body and ± 100 µm in the coil ends. Before assembly of a quadrupole aperture, the coils were selected to minimize the average displacements of the four mid-planes in the straight part of the magnet. The standard deviation of the individual displacement of each mid-plane in the MQM quadrupoles, shown in Fig. 2, is estimated from the coil size data as 7 µm, while the standard deviation of the four mid-plane displacements is 20 µm.

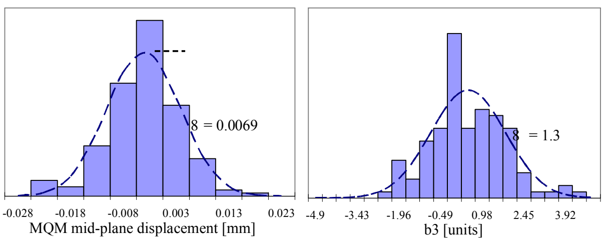

Figure 2: Distribution of the mid-plane displacement (left) and of the b_3 multipole (right) in MQM magnets.

The most sensitive multipole in the MQM quadrupole is b_3 which changes by 0.16 units (10^{-4} at 17 mm) for a 10 µm shift of one mid-plane. As shown in Fig. 2, the measured b_3 distribution has a standard deviation of 1.3 units. Taking into account the shift of the four mid-planes, the coil size variations contribute to about a third of the random b_3 error. Other factors such as tolerances of components (ground plane insulation, collars, etc.) and of the assembly tooling, contribute to the remainder of the random multipole errors.

Training and quench performance

About half of MQM and MQY magnets were individually tested in the vertical cryostat at 1.9 K and 4.3 K before further assembly. All MQM and MQY magnets exhibited very fast training with an average of 0.3 and 0.4 quenches respectively to reach the nominal current in the LHC. No detraining after thermal cycles was observed. All insertion quadrupoles were tested in the horizontal test facility as part of the final qualification. In these tests, the quadrupoles confirmed the excellent performance at 1.9 K, but the stand-alone quadrupoles (tested at around 4.6 K) showed retraining related to the higher bath temperature than in the vertical cryostat.

ASSEMBLY OF THE QUADRUPOLES

The assembly of the matching quadrupoles follows the same principle whatever their length. The main structural elements of the assembly are two half-shells which serve for positioning of the various magnets (quadrupoles and orbit correctors), provide the rigidity for their alignment and serve as a helium pressure vessel. The vessel is closed with end-domes, which also support the elements required for interconnecting the string of LHC superconducting magnets. In particular, the main 13 kA electrical bus-bars and 1.9 K header are guided by the end-domes, and the beam position monitors (BPM) and beam vacuum interconnection elements are precisely positioned on them. These operations were performed on the precision assembly benches, shown in Fig. 3, using the laser tracker for geometrical controls.

Figure 3: Closure and geometrical verification of the quadrupoles are performed on two alignment benches.

Sorting of magnets

In order to optimize the field quality of the magnets the two apertures inside a magnet were matched on the basis of field measurements of each collared aperture, and the magnets with best field quality were assigned to the most critical locations in the LHC insertions. In addition, as more than half of assemblies contain two quadrupole magnets, it was possible to reduce the integral errors, in particular their random component, by sorting the magnets [4]. The random errors of the individual MQM magnets and of the completed quadrupoles with sorted magnets are presented in Fig. 4. The random b_3 of the subset of quadrupoles containing two magnets is reduced by half a unit. This optimization was limited by the number of magnets available at the time of assembly.

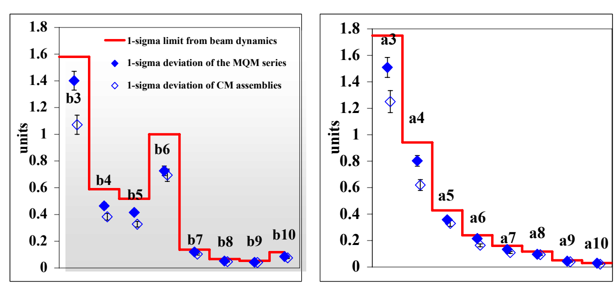

Figure 4: Standard deviation of the field multipoles, given in units of 10^{-4} at 17 mm, for the individual MQM magnets and completed matching quadrupoles. The solid line corresponds to the allowed random errors.

Alignment

The alignment of the matching quadrupoles is very important for the installation in the LHC tunnel and for achieving the largest possible clear aperture for the circulating beam. The straightness of the individual magnets, of the shells and of the assembled units was carefully monitored during production and geometry checks were done at every assembly step. The final quadrupole geometry was checked by 3D measurements of the beam tubes using a laser tracker. The statistics of the measurements performed on 74 quadrupoles is shown in Fig. 5. The standard deviation is 0.22 mm in the horizontal plane and 0.31 mm in the vertical plane. The difference between the two planes comes from the general tendency of the beam tube to sag inside the correctors as the supports of the quadrupoles are placed such to minimize the deviations inside the main magnets. The alignment of the extremities of the beam tubes, shown in Fig. 6, is better than ± 0.2 mm on the BPM side and ± 0.4 mm on the non-connection side, and fulfils the very tight specifications.

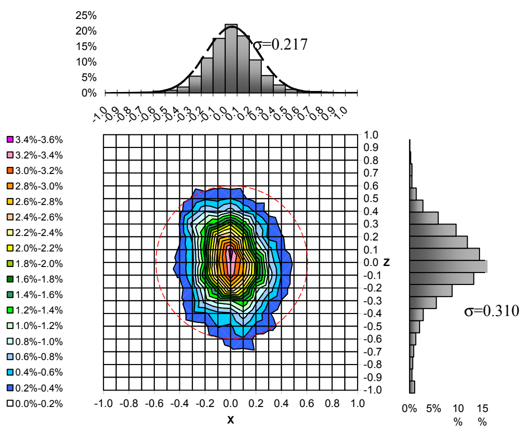

Figure 5: Distribution of the beam tube straightness in the horizontal and vertical planes.

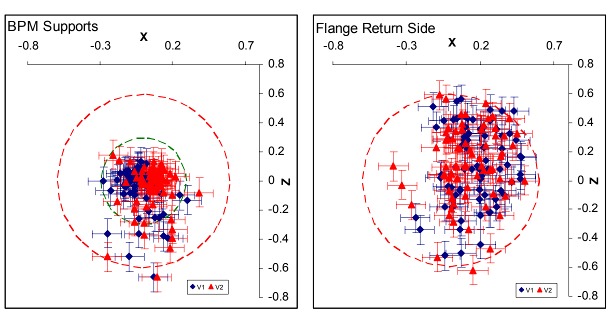

Figure 6: Deviation of the beam tube extremities. Error bars of 0.1 mm correspond to the observed reproducibility of the measurements.

Production experience

The assembly of the matching quadrupoles involves several steps. Following the qualification of the manufacturing procedures and tooling, the main effort in the initial phase was focused on streamlining of the production and improving critical operations. Electrical connections and instrumentation, although fully mastered, remained a delicate operation and a number of intermediate checks were introduced to avoid time consuming rework. The longitudinal welding, based on the semi-automatic MIG process has proven to be very reliable. Tooling for placing the top half-shell was developed, so that even the longest shells could be optimally placed for the root pass.

The closure of the quadrupoles was found to be the most labour intensive and delicate operation, requiring several special tools and procedures. In order to increase the throughput, two assembly benches that could accept any length (Fig. 3) were put in operation. All geometrical controls were performed using a laser tracker. Although this precision instrument is adapted to industrial environment, the measurements remained delicate, and frequent checks and calibrations were necessary. All techniques developed for this production remain available for assembly of the spare quadrupoles, and for future developments that will be required for the upgrades of the LHC insertions.

As a result of the improvements in the assembly techniques the initially planned production rate of two quadrupoles per month was achieved in mid-2004, after three months of production. With further streamlining, in particular with the better supply of critical components, the production rate increased to four magnets per month in 2005. As of mid-2006, 78 out of 82 LHC matching quadrupoles were completed.

CONCLUSIONS

After three years of production, all MQM and MQY matching quadrupoles have been delivered. All magnets that were cold tested reached the nominal field in less than two training quenches, half of them without any training at all. The field quality of the magnets remained stable and within specifications. The assembly of the different types of matching quadrupoles was performed at CERN. A number of specific techniques were developed, and a high production rate and high quality of manufacture were achieved.

ACKNOWLEDGMENT

The authors would like to thank the assembly team involved in the quadrupole production and the technicians of the LHC vertical test facility for their excellent work.

REFERENCES

[1] LHC Design Report, Vol. 1. The LHC Main Ring, CERN-2004-003.

[2] R. Ostojic et al., "Construction and Qualification of the Pre-Series MQM Superconducting Quadrupoles for the LHC Insertions", IEEE Trans. Appl. Superconductivity, Vol. 14 (2004), No. 2, p. 199.

[3] G. Kirby et al., "Fabrication of the Pre-Series Wide Aperture Superconducting Quadrupoles for the LHC Insertions", IEEE Trans. Appl. Superconductivity, Vol. 14, (2004), No. 2, p. 207.

[4] N. Catalan Lasheras et al., "Field Quality and Alignment of the Series Produced Superconducting Matching Quadrupoles for the LHC Insertions" PAC'05, Knoxville, TN, May 2005, p. 2738.