PERFORMANCE OF THE SUPERCONDUCTING MATCHING QUADRUPOLES FOR THE LHC INSERTIONS

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Abstract

The optics flexibility of the LHC insertions is provided by the individually powered superconducting quadrupoles in the dispersion suppressors and matching sections. These cryo-magnets comprise special quadrupoles of the MQM and MQY type, and range in length from 5.4 m to 11.4 m. In total, 82 insertion quadrupoles will be assembled at CERN. In this paper we present the progress in fabrication and report on the performance of the first series quadrupoles. In particular, we present the quench performance of individual magnets and discuss the field quality trends and improvements based on magnet sorting.

INTRODUCTION

The LHC dispersion suppressors and matching sections comprise individually powered quadrupoles, which provide the required tuning of the insertions. Two types of quadrupole magnets are used [1]: the MQM, which features a 56 mm coil aperture and comes 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 NbTi cable, such that their nominal current is 5380 A and 3600 A, corresponding respectively to field gradients of 200 T/m at 1.9 K (MQM) and 160 T/m at 4.5 K (MQY).

The MQM magnets are produced by Tesla Engineering, England, and the MQY by ACCEL Instruments, Germany. A series of geometrical, electrical and magnetic tests are performed on the magnets during production to ensure the high performance required for the LHC. Some of these tests are repeated at CERN on delivery. In addition, a certain number of magnets are cold tested in the vertical test facility in CERN for fast feedback to production.

The assembly of the individual magnets in cold masses is performed at CERN. Apart from the MQM and MQY magnets, the cold masses contain dipole correctors, electrical buses and instrumentation, cryogenic piping and other equipment necessary for their integration in the LHC. In total, 82 insertion quadrupoles are in production at CERN.

To date 23 MQM and 7 MQY magnets have been delivered to CERN, corresponding to about 20 % of the production. Of these, eight MQM and four MQY magnets have been cold tested. In addition, five cold masses have been completed, and another five are in different stages of assembly. In this paper we discuss the performance of the individual magnets and cold masses, in particular the field quality and alignment aspects.

INDIVIDUAL MAGNETS

Quench training

The quench history of the eight tested MQM magnets is summarised in Fig. 1. The first two pre-series magnets were thoroughly tested [2]. As these magnets reached the conductor limit in a few quenches and did not retrain after a thermal cycle, all other magnets were trained in one cool-down only. Most magnets reached the ultimate current in the LHC, corresponding to the 9 T field in the main dipoles, in two training quenches or less, some of them without any training.

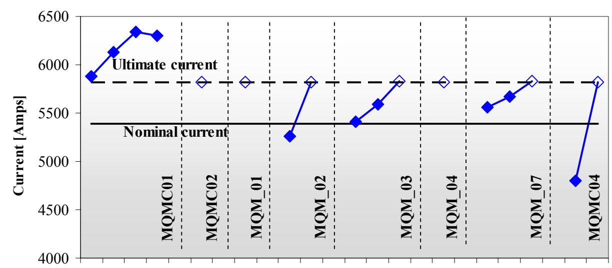

Figure 1: Quench history of the MQM magnets. Open symbols indicate that no quench occurred.

The results of quench training of the four tested MQY magnets are shown Fig. 2. Due to the large stored energy, each aperture was trained separately. In addition, several quenches were provoked in the first magnet to test the cryogenic safety system. All magnets reached the ultimate current in 2-3 quenches. After training, the apertures were powered in series for magnetic field measurements.

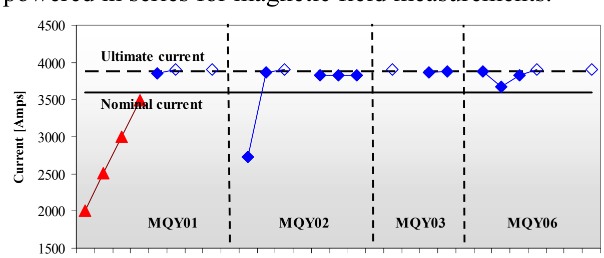

Figure 2: Quench history of the individually powered MQY apertures. Open symbols indicate that no quench occurred. Red triangles correspond to provoked quenches.

Magnetic measurements

All magnets are measured in warm conditions in the companies before delivery using the CERN supplied magnetic measuring benches. A certain number of magnets have been measured both at warm and cold at CERN. The warm-cold correlations using these measurements indicate that the offsets are small [2]. We have therefore assumed for production follow-up that the offsets can be neglected, so that the warm magnetic measurements are compared directly with the target multipoles given by beam dynamics considerations.

In the absence of dedicated MQM and MQY field quality specifications, we compare the field quality of the MQM magnets with the specification for the LHC arc quadrupoles [3]. For the MQY, comparison is made with the specification of the LHC low-β quadrupole MQXA [4], which has a similar coil design. In both cases, only geometrical errors are considered. In addition, the MQM and MQY design values of the allowed multipoles are taken as the target systematic errors.

The field quality of the magnets and their average values are shown in Figs. 3 and 4. The full line in these figures corresponds to the limit on the mean (systematic error plus uncertainty), while the dashed line corresponds to a one-sigma deviation around the full line. As can be seen, the average value of the MQM multipoles is within the target limits and only a few magnets have multipoles outside the one-sigma boundary. In case of MQY, the averages also satisfy the target specification. However, the random b_3 and a_3 multipoles are larger than specified. It should be noted that due to the small number of measured apertures, the statistical errors for MQY standard deviation are non-negligible. The mean and standard deviations are given in Tables 1 and 2.

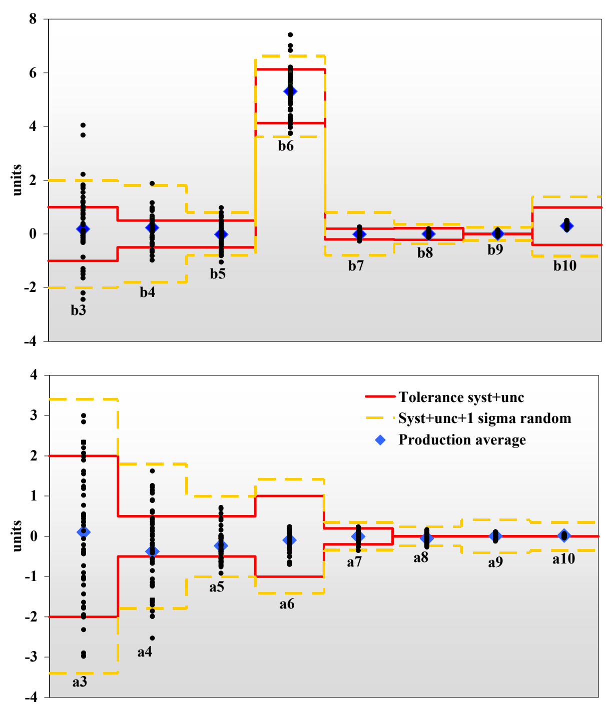

Figure 3: Field multipoles of the 23 MQM magnets (46 apertures). The shift of b_6 due to persistent currents at injection current is -7.4 units.

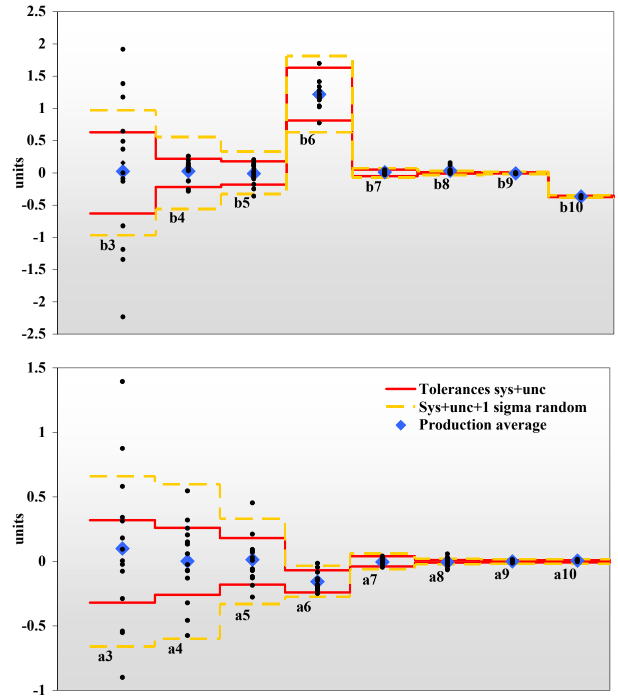

Figure 4: Field multipoles of the 7 MQY magnets (14 apertures). The shift of b_6 due to persistent currents at injection current is –1.6 units.

Table 1: Mean and standard deviation of the field multipoles of the 23 MQM magnets (46 apertures)

n	3	4	5	6	7	8	9	10
<b>	0.19	0.24	-0.02	5.31	-0.01	0.01	0.01	0.30
σ_b	1.09	0.57	0.45	0.84	0.12	0.07	0.05	0.09
<a>	0.10	-0.38	-0.25	-0.09	0.00	-0.05	0.00	0.02
σ_a	1.56	0.98	0.40	0.21	0.13	0.11	0.05	0.02

Table 2: Mean and standard deviation of the field multipoles of the 7 MQY magnets (14 apertures)

n	3	4	5	6	7	8	9	10
<b>	0.02	0.03	-0.01	1.22	0.01	0.03	-0.01	-0.37
σ_b	1.13	0.16	0.17	0.22	0.02	0.05	0.01	0.01
<a>	0.10	0.00	0.01	-0.16	0.00	-0.01	0.00	0.01
σ_a	0.60	0.31	0.18	0.07	0.02	0.04	0.01	0.01

Production follow-up

CERN has set up analysis programs and templates in the companies to control the quality of coils, collared coils and yoked magnets in all phases of production. Coil size measurements and shimming of the coil heads are done on all coils using CERN provided instrumentation. On the basis of these data the coils are sorted in every aperture so as to minimize the displacement of the mid-plane from its symmetry position. Magnetic field data are compared to target values and a system of alarms is included to detect manufacturing errors. In this way, assembly errors, incorrect polarity and electrical shorts have been detected in time for easy repair.

COLD MASSES

Magnet sorting

There are 82 insertion quadrupole cold masses assemblies ranging in length from 5.4 m to 11.4 m. More than half of them contain two quadrupoles connected in series, either of the MQY type, or a combination of MQM magnets of different lengths. The optics of the LHC insertions is such that most quadrupoles in the matching sections see β-functions of 600 m, significantly higher than in the arcs and dispersion suppressors (170 m). For this reason, and in view of improving the field quality of a subset of cold masses, an algorithm for assigning magnets to a particular cold mass type has been implemented.

On the basis of magnetic field data for the available magnets in CERN and those currently in production in the companies, a combination of magnets for a given cold mass is selected such that the resulting multipoles are within the restricted limits in Fig. 3. As the higher order non-allowed multipoles are all within these boundaries whatever the combination, the choice is made on the basis of low-order multipoles (b_3, a_3, b_4, a_4, b_5). The procedure is clearly limited by the available magnets at the time of cold mass assembly. If there is no satisfactory combination, a change in assembly order is envisaged, so that magnets manufactured within 2-3 months can be considered for sorting. Typically this involves a choice from a subset of 4-6 magnets. In addition, feedback is given to the companies for the best position of collared apertures in a magnet.

The result of magnet sorting is shown in Fig.5 where the random errors for the MQM magnets are compared to those of the cold masses containing two magnets. Random errors for most multipoles are reduced, in case of low order multipoles by as much as a factor of two. There is practically no change in the average values.

Alignment

Appropriate tooling and maximum care has been taken to achieve the tight alignment tolerances of the cold masses. The magnets are initially aligned after delivery using precision features on the yoke laminations and their shape locked with alignment keys. In this way every magnet is aligned to within 0.2 mm. The alignment of magnets in a cold mass is given by the full-length cradles, and their geometry verified and if necessary corrected before cold mass welding. Finally, the geometry of the cold bores is measured along their length and the mechanical reference plane so obtained used for placing the end domes. The results of the first five cold masses indicate that the alignment of individual magnets is preserved during assembly, and that their relative alignment is better than 0.2 mm. The alignment of the cold bores is better than 0.6 mm, and the end domes are within 0.5 mm from their theoretical position.

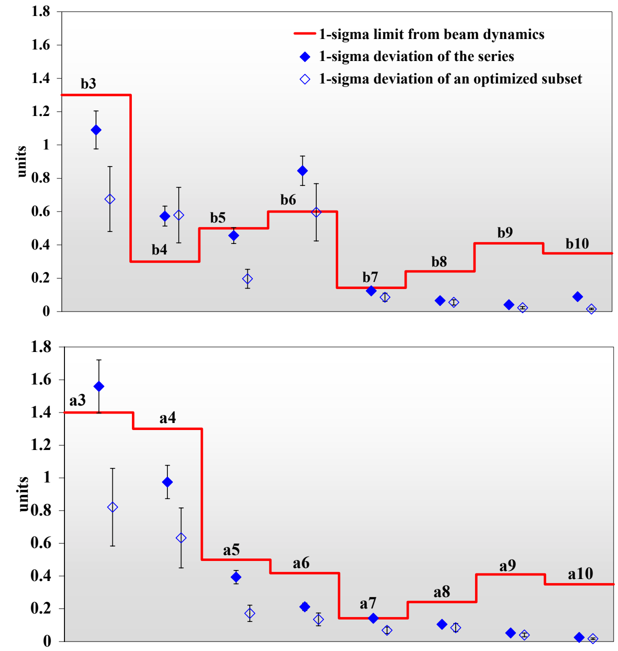

Figure 5: Random multipole errors of the 23 MQM magnets (closed symbols) and 3 cold masses containing two magnets (open symbols).

CONCLUSIONS

Following the qualification of the pre-series magnets, the production of the LHC insertion quadrupoles has reached a steady rate of 5 magnets per month, and about 20 % of the production has been delivered. Systematic warm magnetic field measurements show that the field quality of the magnets is stable and is within the targets set by the LHC beam dynamics criteria. The cold tests performed on a third of delivered magnets show that the magnets consistently reach the ultimate current in the LHC in less than two training quenches.

The production of insertion quadrupole cold masses has started at CERN. In view of improving the field quality of the quadrupoles, magnets are sorted before cold mass assembly. Tooling and procedures for precision alignment of the cold masses have been developed and have proven effective on the five completed quadrupoles.

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