FIELD QUALITY AND ALIGNMENT OF THE SERIES PRODUCED SUPERCONDUCTING MATCHING QUADRUPOLES FOR THE LHC INSERTIONS

N. Catalan Lasheras, G. Kirby, R. Ostojic, J.C. Perez, H. Prin, W. Venturini Delsolaro , CERN,
Geneva, Switzerland.

Abstract

The production of the superconducting quadrupoles for the LHC insertions is advancing well and about half of the magnets have been produced. The coil size and field measurements performed on individual magnets both in warm and cold conditions are yielding significant results. In this paper we present the procedures and results of steering the series production at the magnet manufacturers and the assembly of cold masses at CERN. In particular, we present the correlation between coil sizes and geometrical field errors, the effect of permeability of magnet collars, and the analysis of warm-cold correlations and hysteresis of the main field multipoles. The results are compared with the target values for field multipoles and quadrupole alignment.

INTRODUCTION

Superconducting quadrupoles for the LHC insertion regions are assembled at CERN using quadrupole magnets and dipole correctors manufactured in industry. To satisfy the specific optics requirements of the dispersion suppressors and matching sections, quadrupole cold masses are assembled using one or two magnets of the MQM or MQY type, and one to three MCBC or MCBY dipole correctors. MQM and MQY are superconducting quadrupoles developed specifically for the LHC insertions [1]. MQM magnets have a coil aperture of 56 mm, a nominal gradient of 200 T/m at 1.9 K and 160 T/m at 4.5 K. Three lengths of MQM magnets are required with a magnetic length of 2.4 m, 3.4 m and 4.8 m. MQY have an aperture of 70 mm, a nominal gradient of 160 T/m at 4.5 K and a magnetic length of 3.4 m. MCBC and MCBY dipole correctors have a 56 mm and 70 mm apertures, a magnetic length of 0.90 m and field of 3.1 T at 1.9 K and 2.5 T at 4.5 K [2]. So far, about half of the production of the quadrupoles and correctors has been delivered.

The mechanical, electrical and magnetic quality of the MQM and MQY quadrupoles is closely monitored during manufacturing in industry. After magnet delivery to CERN, acceptance tests and checks are performed. Before further assembly, a large fraction of magnets are cold tested in the vertical test facility at CERN, which can accept magnets up to 3.6 m long. The results of these tests, and when applicable of the warm field measurements made in industry, are used to select the magnets for a particular insertion quadrupole. In total, 82 cold masses will be built in 31 variants ranging in length from 5 to 12 m. The production has reached a steady rate of one quadrupole per week and 28 quadrupoles have been completed by April 2005. In this report we present the results of steering the magnet and cold mass production.

INDIVIDUAL MAGNETS

Coil size and magnet quality

To keep the multiple errors at the level of 10^{-4} of the main field, coil size has to be tightly controlled. MQM and MQY coils are wound and cured to their nominal size and are all measured by the manufacturer with an E-modulus tester supplied by CERN that measures the size of the coil as a function of stress. The azimuthal tolerance from 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 are 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 cumulated is 20 μm.

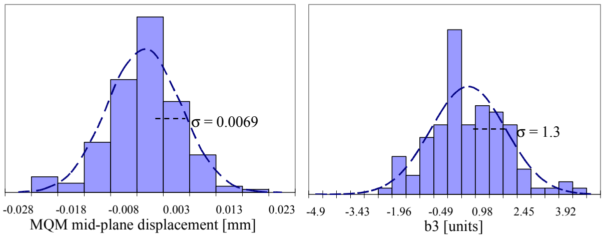

Figure 2: Distribution of the mid-plane displacement (left) and of the b_3 multipole (right) in MQM magnets.

The most sensitive multipole in the MQM quadrupole is the b_3 which changes by 0.16 units 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 random multipole errors.

Effect of the permeability of the collars

Half way in the series production of the MQY magnets their field quality seemed to degrade. A trend of an increase of the transfer function and a decrease in b_6 indicated a systematic effect that was traced to the high magnetic permeability of stainless steel used for the collars. A similar effect had been observed at the same time in the LHC main quadrupoles.

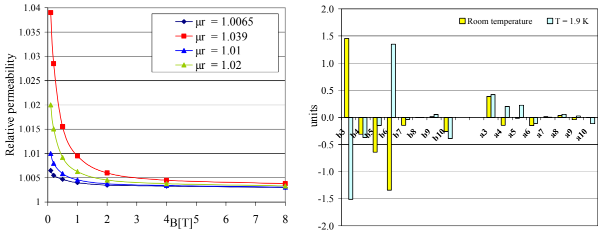

Figure 3: Magnetic permeability of stainless steel vs. magnetic field (left). Measured multipoles at low and high field for a high permeability collared magnet (right).

The variation of the relative magnetic permeability of the collar material is shown in Fig. 3. It decreases rapidly with field and reduces to the specified value at B > 2 T. Warm magnetic measurements used for acceptance of the magnets are done at low current and fields of the order of a few mT. Comparison with measurements in magnet operating conditions, Fig. 3, shows that low order multipoles are significantly different. Although the effect of collar permeability disappears at high fields, it prevents using warm-cold correlations for production follow-up and performance analysis. As a result, all MQY magnets will be measured cold before further assembly, and a new error table will be established. This problem was not observed in the MQM production.

Training and quench performance

In total 22 MQM type magnets and 12 MQY magnets have been tested individually in the vertical test cryostat. The first MQML units including the pre-series have been tested as completed cryo-magnets in the CERN magnet test facility. Both MQM and MQY magnets exhibit a very fast training with an average of 0.3 and 0.4 quenches respectively to reach nominal current and 1.0 and 2.5 quenches to reach ultimate current in the LHC. No detraining after provoked quenches or thermal cycles was observed.

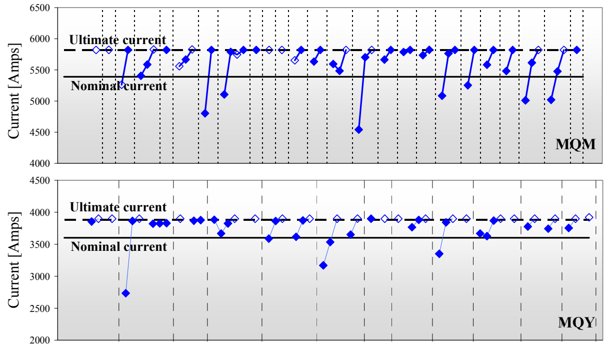

Figure 4: Training history of MQM and MQY magnets

COLD MAGNETIC MEASUREMENTS

Warm cold correlations

First tests of completed insertion quadrupoles at 1.9 K were performed at the beginning of 2005. Two 5 m long MQML quadrupoles underwent a full programme of magnetic field measurements. These measurements, together with those obtained for the individual magnets corroborate the magnetic field error tables established from warm measurements on the MQM series magnets [3]. The warm-cold correlations of low order field multipoles measured on MQM type magnets are shown in Fig. 5. To improve statistics, local as well as integral measurements were included. This introduces noise in the correlation as the integration length for warm and cold magnetic measurements is slightly different. Nevertheless, the warm measurements correlate very well with the cold ones and validate the use of the present error table for tracking and other studies.

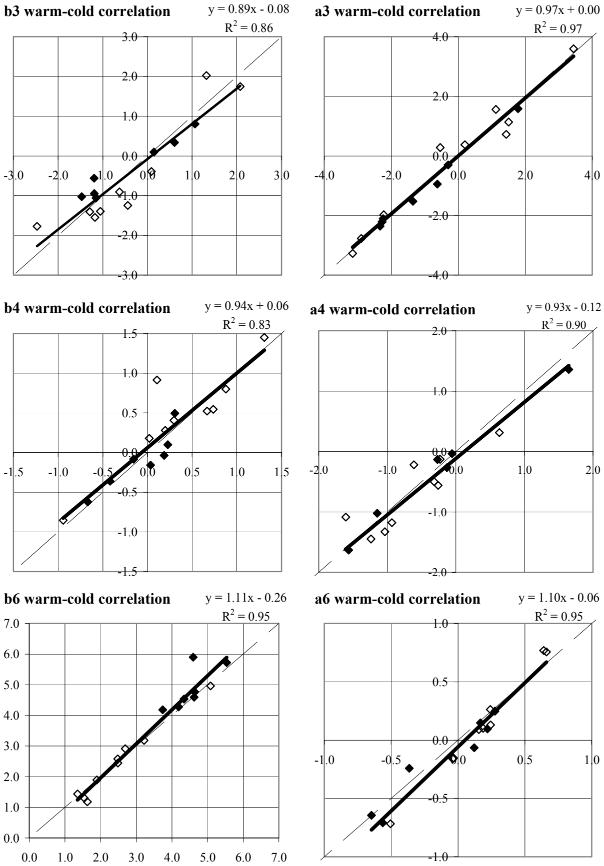

Figure 5: Warm-cold correlations for the low order field multipoles based on 17 measurements. Local (open symbols) and integral measurements (full symbols) are taken into account.

Special magnetic measurements

The effects of the persistent currents were measured on a few MQM magnets. The transfer function and the first allowed multipole b_6 are shown in Fig. 6. The hysteresis

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of the transfer function has a special interest as some of the magnets in the matching sections will have their current reduced during β-squeeze. The same type of measurements done in four different apertures show that the average difference between up and down ramps is about 40 units at 260 A.

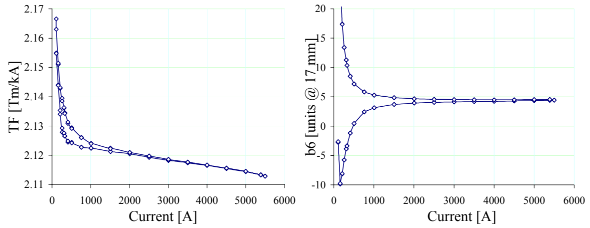

Figure 6: Transfer function (left) and b6 multipole (right) measured on a full up and down ramp cycle.

COLD MASS PRODUCTION

Cold mass sorting and optimization

As mentioned, insertion quadrupoles have one or two quadrupole magnets. By sorting the magnets it is possible to reduce the integral multipole errors, in particular their random component. In Fig. 7, the random errors of the MQM production and of the sorted cold masses are presented. The random b_3 of the subset of cold masses containing two quadrupoles is reduced by half a unit. This optimization is limited by the number of magnets available at the time of assembly. In addition, sorting of two apertures inside a magnet has also be done based on the intermediate measurements of collared apertures. Finally, the magnets with best field quality are assigned to the most critical quadrupoles in the matching sections where the β-function is large.

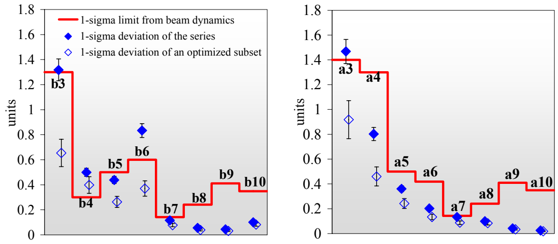

Figure 7: Standard deviation of the field multipoles for the MQM production. The solid line corresponds to the maximum allowed values given by beam dynamics.

Alignment

The precision of the alignment of the insertion quadrupoles is a very important requirement for correct installation of the cryo-magnets and for achieving magnet aperture in operation. The straightness of the individual magnets and of the cold mass assemblies is carefully monitored during the production and geometry measurements are done at every assembly step. Finally, a complete check of the cold mass is performed at the end of production. As an example of the obtained results, a histogram of all measurements taken for the beam tube position along the length for the first 18 cold masses is shown in Fig. 8. The tolerance of the position of the tube along the quadrupole is 0.6 mm.

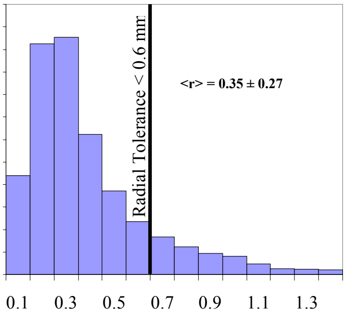

Figure 8: Histogram of the beam tube radial measurements for all cold masses.

The position of the beam tube at the extremities of the cold mass shown in Fig. 9 has a radial tolerance of 0.3 mm for the beam position monitor (BPM) supports and 0.6 mm for the return end. In some cases the position of the BPM support is outside the tolerance. However, it is possible to bring them inside the 0.3 mm tolerance in both apertures by re-aligning the magnet during installation.

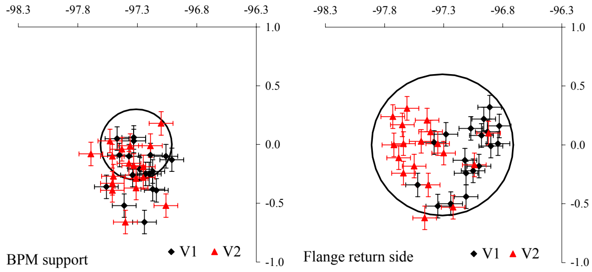

Figure 9: Deviation of the beam tube at the extremities of the cold mass. Error bars of 0.1 mm correspond to the observed reproducibility of the measurements.

CONCLUSIONS

The production of magnets and cold masses for the insertions of LHC is now at it maximum rate. Cold magnetic measurements of MQM show a good correlation to warm data and confirm the expected multipole errors. The first data on cold mass alignment are compatible with the tolerances.

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