EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 873

Performance of the Room Temperature Systems for Magnetic Field Measurements of the LHC Superconducting Magnets

J. García Pérez, J. Billan, M. Buzio, P. Galbraith, D. Giloteaux, V. Remondino

Abstract

The LHC will be composed of 1232 horizontally curved, 15-meter long, superconducting dipole assemblies and 474 Short Straight Sections containing various types of quadrupoles. These magnets are manufactured by several European companies and half of them are currently produced. The field quality at room temperature is strictly monitored to guide and validate the assembly at different stages of the production in the industry. Dipoles and quadrupoles are measured with two different rotating coil systems. These “moles” travel inside the 50 mm aperture and accurately measure the field and gradient strength integrated over the length, the field direction and high order harmonics. We describe here these two systems, their performance and the experience gained through the two first years of operation.

CERN, Accelerator Technology Department, Geneva, Switzerland

Presented at the 19th International Conference on Magnet Technology (MT19)
18-23 September 2005, Genova, Italy

CERN
CH - 1211 Geneva 23
Switzerland

Geneva, 19 May 2006

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Abstract— The LHC will be composed of 1232 horizontally curved, 15-meter long, superconducting dipole assemblies and 474 Short Straight Sections containing various types of quadrupoles. These magnets are manufactured by several European companies and half of them are currently produced. The field quality at room temperature is strictly monitored to guide and validate the assembly at different stages of the production in the industry. Dipoles and quadrupoles are measured with two different rotating coil systems. These "moles" travel inside the 50 mm aperture and accurately measure the field and gradient strength integrated over the length, the field direction and high order harmonics. We describe here these two systems, their performance and the experience gained through the two first years of operation.

***Index Terms*—Field quality, LHC dipoles, LHC quadrupoles, field angle.**

I. Introduction

The magnetic field of all 1232 dipoles of the Large Hadron Collider is being measured at room temperature at two different stages of production: after the collaring and after the welding of the cold mass shell. These measurements are holding points in the production. This is done in the three assemblers' premises, in Germany, France and Italy. The system is called Dipole Industry Magnetic Measurement (DIMM). A slightly different system called Quadrupole Industry Magnetic Measurements (QIMM) is being used in Germany, England and at CERN for the main quadrupoles of the standard arc cells, matching sections and dispersion suppressors of the LHC.

We analyse here the key elements that give the accuracy necessary to detect errors in the manufacturing process of the LHC main dipole and quadrupole magnets. We detail our experience in insuring an efficient maintenance in order to avoid delays in the production and consecutive penalties.

Manuscript received September 19, 2005.

All authors with CERN, 1211 Geneva 23, Switzerland (corresponding author: phone: 41-22-767-3762; fax: 41-22-767-6230; e-mail: juan.garcia.perez@cern.ch, except J. Billan (on retirement), Marco.Buzio@cern.ch, Peter.Galbraith@cern.ch, David.Giloteaux@cern.ch, Vittorio.Remondino@cern.ch

II. Systems description

The core of the systems (DIMM & QIMM) consists of the field measuring probes (moles) that must be carefully built and calibrated, as the final result depend on the precision of its components.

The main components of the moles (whose diameter is 50 mm) are the search coils made of 3 (DIMM) or 5 (QIMM) coils, mounted side by side, the central one being centred on the rotation axis. These coils were specifically developed for the LHC magnet measurements. The 750 mm long search coils are made of 400 turns. The coil calibration is the result of complex and delicate 3-step measurements as described in [1, 2]. The surface of each coil is 1.97 m^2 in the QIMM mole and 3.7 m^2 in the DIMM mole. The coils are sorted according to their effective surface in order to have a maximum difference of 0.1% in the same coil assembly. They are adjusted to be coplanar within 1 mrad. Therefore, the coil signals are combined to reject the main field harmonic, and electronic compensation is not required.

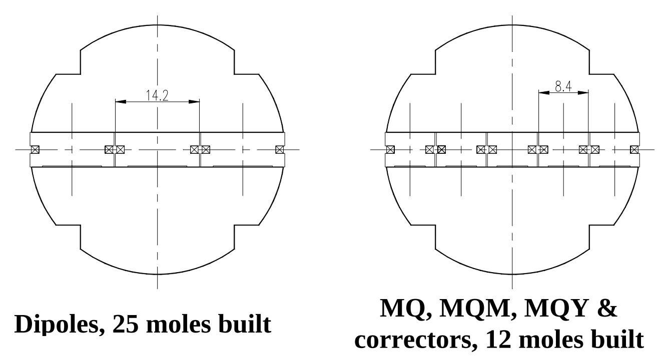

Fig. 1. Search coils cross-section of DIMM and QIMM moles.

Fig 1 shows the cross section of the search coils assembly of the mole. When inside a magnetic field, coils rotate to produce a voltage proportional to the flux and to the speed of rotation. The signal from the outward coil (absolute signal) is used for the determination of the main component. On the other hand, the field harmonics are calculated from a combination of signals coming from different coils to reject the main harmonic, so that errors coming from imperfection of the rotation of the coils are eliminated and a higher amplification of the voltage can be applied to the field harmonics detection. The encoder, mounted on the coils rotation axis, determines their angular position during the coil assembly rotation.

The accuracy of the main field direction measurement is specified to be 0.2 mrad. The angular precision is obtained using an electronic gravity sensor to orient the mole to gravity and a pneumatic brake to hold the mole in position during measurement. A detailed description of the moles can be found in [3]. Fig 2 shows a drawing of a DIMM mole.

The main differences between the two systems are in the operation ancillary subsystems. Quadrupoles are much shorter than dipoles. Positioning of the QIMM mole inside the magnet is done manually with a set of 1.5 m shafts, and with the rotation unit outside of the magnet. Measurements are done with a single mole passing in one aperture after the other.

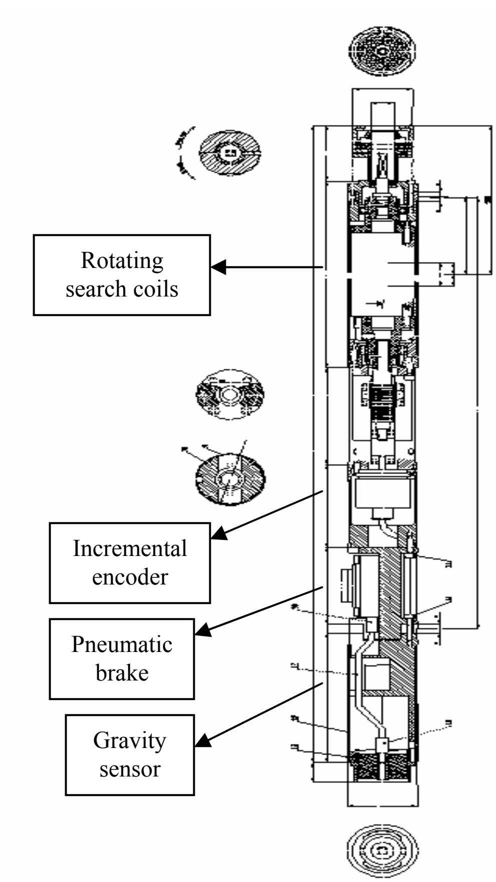

Fig. 2. DIMM system drawings of mole.

Two DIMM moles are measuring in parallel the dipoles. Longitudinal positioning is achieved by a motor and an encoder pulling two cables attached to the moles. A rotating unit is embarqued in another module called motor module. These two motor modules perform the moles orientation with respect to gravity and then make the coils rotate inside the magnetic field. Another important feature of the system is its capability to measure magnetic length. This is achieved by a Stegmann™ encoder that measures the actual position of the mole with a precision better than 1 mm over a stroke of 15 m.

The acquisition system is based on a VME industrial standard connected via a fast connection card (VME-MXI) to a SUN workstation running a LabView application. A detailed description is found in [4].

III. Measurement and Analysis Overview

A description of the data processing can be found in [5, 6]. The method used is DC excitation current and rotating search coils. To reduce noise, three sets of clockwise and anti-clockwise rotations of search coils are performed in sequence at a magnet current of 10 A giving about 7 mT in the dipoles, and 3.8 mT in the quadrupoles at 17 mm with 12.5 A. Then the set is repeated at negative current, in order to minimize iron and earth field effects. The integrated voltage signals are sampled at 360 (DIMM) or 256 (QIMM) regular intervals triggered by the encoder. The harmonic coefficients can be reconstructed applying the Discrete Fourier Transform (DFT). The analysis output file contains the integral harmonics coefficients, the magnetic length and the magnetic axis from the initial flux measurements at 20 (DIMM) or 5 (QIMM) different positions. Initially the harmonics computed at each position are normalized with respect to the main field and the gravity direction. Then the computed harmonics for the whole magnet are obtained by summing the harmonics at each longitudinal position multiplied by the length of measuring search coils. Finally, the harmonics are normalized with respect to the magnetic centre and main field direction of the magnet. A correction of feed-down effects is applied by canceling 10^{th} order harmonics (DIMM - for consistency with cold measurements) or 1 (QIMM).

Fig. 3. QIMM system measuring a Short Straight Section Quadrupole.

IV. Overall Performance

The DIMM detects most of the magnet imperfections during measurement of the Collared Coils (CC) before their assembly in the iron yoke. Field quality and magnetic length (or integrated field value) measurements aim at detection of misalignments and short circuits. Most corrective actions end in decollaring and repair. Results found at Collared Coils (CC) are usually confirmed when measuring the Cold Mass (CM); moreover at this stage the final field angle is used to qualify the magnet.

Table I shows the number of measurements done with DIMM and QIMM, with the number of magnets assembled

(CC or CM). Most of the repeated measurements are intended to confirm magnet assembly errors. The number of faulty measurements due to system failure is below 3%: as far as the QIMM is concerned, only a few measurements were ever repeated and all confirmed the first one. This proves that both measuring systems are reliable and well suited to work in the industrial environment with high production rate. Since the

TABLE I
PERFORMANCE OF WARM MAGNETIC SYSTEMS

Result	DIMM	QIMM
Number of Collared Coil measured	919	314
Number of measurements on Collared Coil	1057	325
Number of Cold Mass measured	850	239
Number of measurements on Cold Mass	919	239
Number of magnets with problems found in CC	67	11
Number of magnets with problems found in CM	6	0

magnetic measurements are a holding point of the assembly process, a careful follow-up of the measuring system during all the production is required. Details of the production follow-up strategy and online algorithms implemented in the holding point control can be found in [7].

MQ imperfections detected include an initial design error (cross section with mid-plane), as well as austenitic steel collars with too high μ_r.

V. DETAILED PERFORMANCE

As mentioned above, the systems are able to measure accurately the field and gradient strength integrated over the length, the field direction and high order harmonics. In the following we discuss their performance in more detail.

- LOCAL AND INTEGRATED DIPOLE FIELD

Dipole field measurements are very sensitive to local assembly errors, e.g. double protection sheet placed in the middle of one collared coil. Fig 4 shows the agreement between two measurements of the main field performed on the same magnet with two different moles.

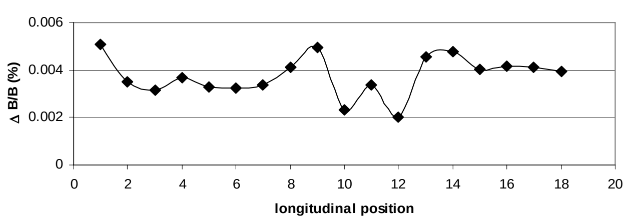

Fig. 4. Difference between two measurements of the main field for the same magnet performed with two different moles.

For the dipole strength, in addition to the main field the magnet length must be known with a precision better than 1 mm. For this purpose DIMM is equipped with a subsystem (Stegmann™) consisting of a stretched wire and an encoder to measure the mole longitudinal displacement. Stegmann™ has been calibrated with a Laser Tracker interferometer and its precision is better than 0.5 mm. Magnetic length can be adjusted by adding or removing iron yoke laminations.

- HIGH-ORDER HARMONICS

The DIMM has been used to optimize the design of the dipole cross section to respect the tight requests of LHC beam dynamics and to monitor the production quality by setting holding points in the assembly for CC and CM.

The search coils surface matching and their respective alignment is a key issue in order to obtain precise measurements. In Fig 5, that contains the plot of the difference between two different moles measurements of the same magnet for the most important high order harmonics, shows that the precision of DIMM is constantly better than few tenths of unit.

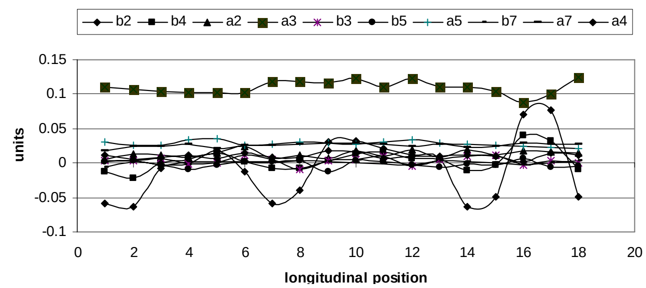

Fig. 5. Difference between two measurements of the high order harmonics for the same magnet performed with two different moles.

- FIELD ANGLE

Field angle measurement in the dipole controls the ***vertical*** bending component of 15 m long dipole magnets. Tolerance of this bending field angle is ±1 mrad. For this measurement the inclinometer is used. Its precision is better than 50 µrad. Its offset is calibrated in a reference magnet by measuring from the two sides. The DIMM first rotate the mole with respect to gravity. This alignment must stay stable inside tens of µrad during the rotations of the search coils. In the first year of operation we faced some difficulties related to the friction between cold bore and mole feet that were metallic and need long time to get oriented. Feet material was changed to DELRIN™, which solved the problems.

The second difficulty is to have a mechanical reference of the cold mass angular position. The field angle we are looking for should be referred to the geometrical mean plane defined by the cold bore axis lines. Mean plane is determined during geometrical survey at an earlier step of the assembly with a dedicated mechanical measurement. An intermediate measurement of the cold mass orientation is needed in order to express the field angle in this coordinate system. To solve this problem a jig has been built. It measures the cold mass angular position through two pins located on the end covers. In the geometrical bench this angle is measured with the Laser Tracker with respect to gravity. So we can correct for eventual angular change between benches. Precision of field angle with DIMM is within 0.2 mrad. Fig 6 shows the good agreement between two measurements of the same magnet performed with two different moles.

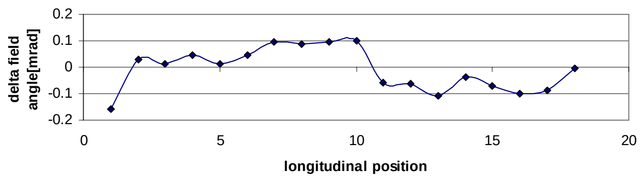

Fig. 6. Difference between two measurements of the field angle for the same magnet performed with two different moles.

For the QIMM, only the parallelism between apertures can be verified, as there is no geometrical measurement of the mean plane during the assembly. This parallelism measurement is easier than in DIMM, due to the fact that only one mole is used for both apertures, so absolute calibration is less important.

VI. EXPERIENCE GAINED

The DIMM systems are being used at the 3 dipole firms with success. More than half of the magnets have been produced and one dipole manufacturer has completed the collared coils needed. 8 systems have been produced, 6 of them are in industry and two spare are at CERN, where they are regularly used to perform special measurements or for testing and improving associated equipment. Maintenance interventions are done regularly every 4-5 months or less, in case of faults. Particular care is taken in having the best possible feedback from the firm's staff in order to help them solving most of the problems autonomously. 24 moles (every firm has 2 moles per system and two spares) and 24 motor modules have been built. To localize with more spatial resolution CC defects one special, shorter mole (125 mm long search coils) is used. Moles and motor modules have sometimes small problems that require them to be shipped back to CERN for repair and then spare units in the firms are used. When at CERN, moles area usually recalibrated. Coil calibration values are very stable, surface (few ‰), parallelism (tenths of mrad) and radial position (few µm) into the coil assembly. The mole angular offset are systematically calibrated after any maintenance. DELRIN™ feet are consumables but they are easy to change, and indeed done by the firms staff. Electronics has had very few problems, and spare units for the most critical parts are in the firms.

For the QIMM no maintenance is regularly organized and we repair moles at CERN when there are problems. Spares moles are on site.

VII. CONCLUSION

The room temperature magnetic measurement systems, DIMM and QIMM, have been able to detect and confirm at an early stage many defects in the industrial assembly of the LHC dipole and quadrupole magnets. This saved more money than the whole investment in the warm magnetic measurements. Furthermore, because of the good correlation found between warm and cold measurements, only a fraction of the dipoles are now magnetically measured at cryogenic temperature. Two hours are needed for a complete dipole measurement, and the failure rate and maintenance given are compatible with the availability requested for the magnet production.

ACKNOWLEDGMENT

We would like to acknowledge D. Cote for his important contribution to the system design and follow-up; C. Vollinger, P. Hagen and E. Todesco for the analysis of the huge quantity of data produced by the systems and A. Rijllart and his team for the acquisition software development and maintenance. We also thank all the CERN and firm personnel involved in the magnetic measurements.

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