SENSITIVITY AND ACCURACY OF THE SYSTEMS FOR THE MAGNETIC MEASUREMENTS OF THE LHC MAGNETS AT CERN

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Abstract

Beam optics of the LHC accelerator require stringent control of the field quality of the main dipole and quadrupole magnets. The field quality measurements need challenging accuracy given the small size of the aperture (50 mm) : relative strength of the magnets within $2 \cdot 10^{-4}$, harmonics in the ppm range, axis determination within 0.1 mm, main field direction within 0.2 mrad. We present a detailed analysis of the accuracy and reproducibility obtained with the equipment presently available for the qualification tests of the first series magnets.

1 INTRODUCTION

The first superconducting magnets of the 7 TeV LHC accelerator will be delivered to CERN this year. The main MB dipole and MQ quadrupole magnets will be mounted with the relevant corrector magnets in cold mass enclosures for the superfluid helium. Detailed magnetic measurements will be performed at low current and room temperature in the manufacturing industries. The experience from previous accelerators based on superconducting magnets highlights the difficulty in controlling the beam during injection and the beginning of acceleration. Detailed magnetic measurements are therefore required in the whole current range at 1.9 K.

The experience accumulated with the measurements of the LHC prototype magnets allowed validation of the design and production of the equipment needed for the series measurements. The measurement accuracy of the main parameters is detailed in section 2. The reproducibility of the measurement of the field harmonics is analyzed in more detail in section 3.

The expansion used to express the field harmonics is relative to the main field B_1 of the magnet at R_{ref} = 17 mm. Here n=1 is a dipole field, n=2 is a quadrupole field etc. The b_n and a_n represent the normal and skew errors and are given in units of 10^{-4} relative to the main field :

$$\mathbf{B}_y + i\mathbf{B}_x = B_1 \sum_{n=1}^{\infty} \frac{c_n}{10^4} \left(\frac{z}{R_{ref}} \right)^{n-1} = B_1 \sum_{n=1}^{\infty} \frac{(b_n + i a_n)}{10^4} \left(\frac{x+iy}{R_{ref}} \right)^{n-1} \qquad (1)$$

The following illustrates some requirements for the accuracy. A standard deviation of 4 units for the integrated strength and 0.4 mrad for the field direction accuracy between the MB dipole magnets gives a similar orbit perturbation as misalignment of 0.1 mm of the MQ quadrupole magnets. This stresses the importance of precise measurement of the MQ axis.

The requirements for the control of the field quality are detailed in [1]. Among others, the contribution of the sextupole and decapole terms have to be measured to within 0.04 units to be able to steer the current in the respective corrector magnet chains.

2 PROPOSED SYSTEMS FOR THE MAIN MB AND MQ MAGNETS

We analyse here the accuracy of the three measuring systems foreseen at CERN for the main dipole and quadrupole magnets. Their magnetic field quality will be systematically measured at room and superfluid helium temperatures.

The "mole" [2] will verify the correct alignment of the "MB axis" with respect to the end correctors (sextupole MCS and decapole MCD) probably only on pre-series magnets as the main characteristics of the magnet assemblies will be fully controlled by dedicated equipment at the manufacturers' premises. Improvements to the mole to correlate axis position between room and superfluid temperatures are still under development.

The mole is a probe equipped with a 0.75 m long rotating coil and associated angular encoder and motor. It slides into the 50 mm cold bore aperture and contains a light source to transfer the transverse position of the coil rotation axis, and hence the magnetic axis, to external fiducials via a telescope located at the magnet end. The achieved accuracy at one standard deviation is:

- integrated strength including calibration 2.10^{-4}
- field direction including calibration 0.25 mrad
- magnetic axis with respect to coil axis 50 μm
- optical transfer from coil to dipole end 60 μm

Two ways are possible to measure the magnetic axis location with respect to the coil rotation axis. The use and measurement of the c_{10} = 0 line requests some 20 A of magnet excitation for sufficient resolution. This provokes a thermal gradient in the cold bore deflecting the light beam by as much as millimetres during the optical measurements rendering optical transfer impossible. The Quadrupole Configured Dipole method (feeding equal current with opposite polarity in the two dipole poles) requires current of the order of 1A. It has been shown with the 15 m long shaft [3] that both methods correlate to within ~50 μm. The measurement error is limited at the moment to 90 μm due to poor lateral stability of the probe during coil rotation. The present overall error in the measurement of the magnetic axis with respect to cryostat fiducials is 120 μm.

Measurements of MB magnets in cold conditions are performed with 15 m long shafts equipped with 13 modules of 1.2 m long measuring coil assemblies [3]. They allow to measure the field integrated along the magnet length and to quantify time and current-ramp dependent effects. The accuracy achieved is:

- integrated strength calibration 2.10^{-4}
- field direction including calibration 0.16 mrad

The bench [4] previously used to measure the early 10 m long dipole prototypes will measure in warm and cold condition the MQ mounted in the short straight section cold masses equipped with the focusing quadrupoles together with the orbit, tune and chromaticity correctors. This bench has been modified to accommodate a light source for magnetic axis measurement. The light beam travels in vacuum in order to avoid deflection due to thermal gradients in the warm finger. The figures below giving measurement accuracy are preliminary since only one magnet has been measured up to now :

- integrated strength reproducibility $1.5 \cdot 10^{-4}$
- field direction including calibration 0.5 mrad
- effective length accuracy 0.3 mm
- magnetic axis location 150 µm

The axis calibration based on the knowledge of the conventional reference quadrupoles located at each end of the MQ cold mass significantly contributes to the low precision of the magnetic axis location with respect to cryostat fiducials.

3 ACCURACY OF THE HARMONIC MEASUREMENT

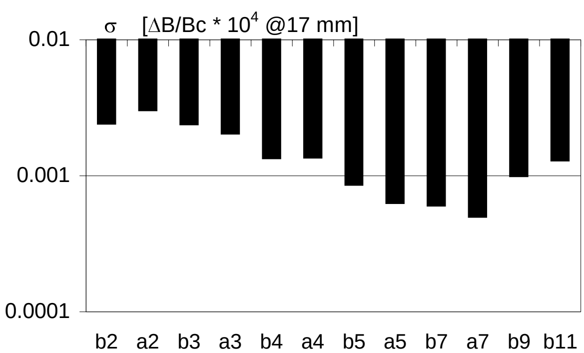

Figure 1: Reproducibility of the measurement with the 15 m shaft of the MB dipole at 3.5 T .

The most important factors limiting the accuracy of measurement of the field harmonics are analysed in this section. The overall accuracy is well within the requirements. Fig. 1 to 3 demonstrate the reproducibility obtained for the MB and MQ high field measurements and for the mole respectively. The variations of the field harmonics due to persistent currents in the magnets and their decay with time limit the reproducibility at low field.

The measurement reproducibility is expressed as random deviation: σ_r, calculated over measurements repeated in the same conditions. Fig. 3 clearly shows a reproducibility of the harmonics inversely proportional to the magnet excitation current, i.e. constant in strength since the c_n are harmonics relative to the main field strength. Our analysis will split the measurement resolution in two terms:

- the "noise limited resolution", $\sigma_{r,noise}$, seen as inversely proportional to the magnet excitation,
- the "system limited resolution", $\sigma_{r,system}$, seen constant on the c_n and due mainly to mechanical imperfections in the rotating assembly.

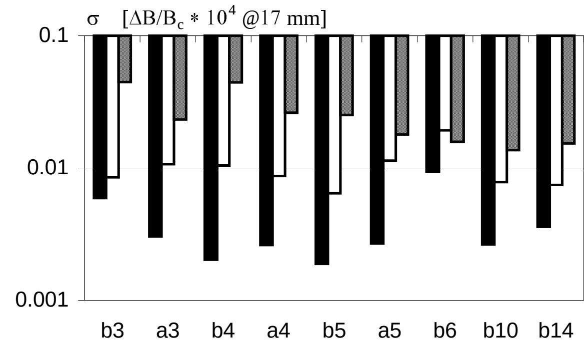

Figure 2: Harmonic measurement reproducibility of the MQ quadrupole respectively at 200, 100 & 20 Tm^{-1} .

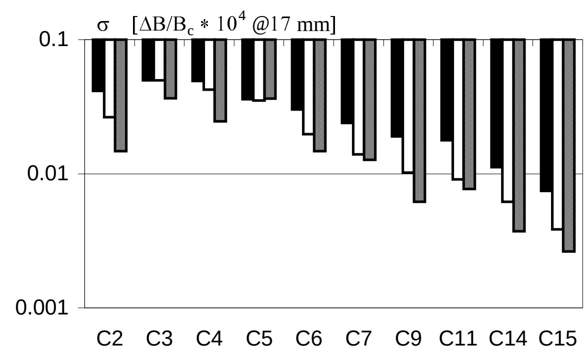

Figure 3: Reproducibility of the harmonic measurement with the mole of the MB excited at room temperature with 10, 20 & 30 A.

3.1 Noise limited resolution

This noise comes mainly from electronics and wiring. Eq. (2) links the integrated voltage VS(θ) to the harmonic c_n and measuring coil sensitivity factors K_n [5]. The signal coming from the inner coil used to compensate the main harmonic is not included in these equations.

$$VS(\theta) = B_c R_{ref} \operatorname{Im}\left\{ \sum_{n=1}^{\infty} K_n \frac{c_n}{n} \exp(in\theta) \right\} \cdot \qquad (2)$$

For the mole radial coil :

$$K_n = N_t L_{eff} \left[\frac{R_e^n - R_i^n}{R_{ref}^n} \right], \qquad (3)$$

with L_{eff} = effective length of the coil
N_t = number of turns
R_e,R_i= external, internal radius of rotation
and for the tangential coils of the 15 m shaft :

$$K_n = N_t L_{eff} \frac{R_e^n}{R_{ref}^n} 2\sin\left(\frac{\sin n\varphi}{2}\right). \qquad (4)$$

The opening angle of the mole tangential coil (half width/ R_e) equals 0.25 rad.

Table I : parameters of the measuring coils

System	Mole	15m shaft	MQ bench
$\Sigma_{effective}$[m^2]	3.4	0.35	0.23
N_t	400	36	64
Coil width [mm]	11.5	8.5	6.03

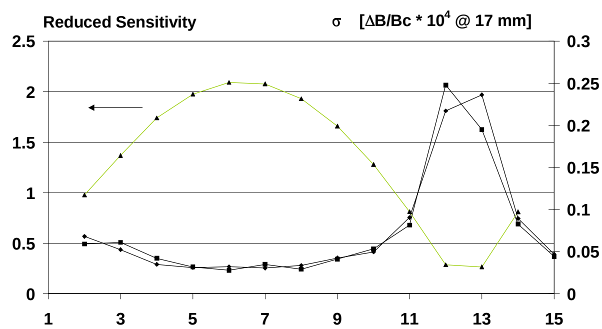

Figure 4: Reduced sensitivity [$K_n/(N_t \cdot L_{eff})$] of the tangential coil mounted in the 15 m shaft and correlation with the uncertainty of the harmonic measurement of both apertures at room temperature.

The derivative of eq. (2) with time gives the c_n as a function of the integrator input voltage, using $\theta = \omega t$:

$$V(t) = B_c R_{ref} \,\mathrm{Re}\left\{\sum_{n=1}^{\infty} K_n c_n \omega \exp(in\omega t)\right\}. \qquad (5)$$

Equation 5 demonstrates that the measured $\sigma_{r,noise}$ originates from electrical white noise. The 15 m shaft equipment has the minimum noise level, 0.35 μV, due to easily portable low noise preamplifiers allowing the shortest junction cables. Special care was taken to ensure high quality of the instrumentation wiring. In contrast, the noise level of the mole and the MQ bench are above 1 μV.

The sensitivity factors, K_n, have obviously to be maximised. Fig. 4 gives their values for the tangential coils of the 15 m long shafts. We have chosen to give a higher sensitivity to the low harmonic numbers for the 15 m shaft at the expense of having zero sensitivity between order 12 and 13. Dynamic aperture studies have shown that harmonics with order higher than 11 are in practice never detrimental for the LHC beam. Fig. 4 illustrates this electronic noise limitation. The reproducibility obtained with 30 A in a LHC dipole at room temperature and the 15 m shaft designed for low temperature correlates well with the choice of zero sensitivity between harmonics 12 and 13.

3.2 System limited resolution

The harmonic content can be measured with high accuracy by the use of bucking coils rejecting the effect of the main field signal coupled with imperfections in the rotating mechanism (encoder, bearings and motor) and noise from the current supply. We have obtained rejection ratios of 2000 and 300 for the dipole and quadrupole measurement respectively by careful sorting of the measuring coils.

Eq. 5 suggests that a higher rotation rate, ω, decreases the detrimental effect of this electrical noise. However that could degrade the reproducibility due to increased vibration in the mechanics. We found good correlation between the amplitude of the deviation from constant rotation rate and the measured low order harmonics. This shows that the rotation rate has to be chosen carefully to avoid excitation of vibration modes.

Variations in the magnet harmonics, for instance due to decay of persistent currents, explain why the $\sigma_{r,system}$ part is measured to be larger for allowed harmonics: n =3,5,7 for the dipoles and n=6,10,14 for the quadrupoles, particularly at low current.

4 CONCLUSION

The measurements at CERN of the main LHC superconducting magnets will start in 2000. Sophisticated benches with a high level of automation have been developed. The accuracy of the field quality measurements at low temperature matches the requirements for the beam with comfortable margin. A mole verifies the correct alignment of the MB cold mass and the associated correctors at room temperature.

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