FIELD QUALITY AND HYSTERESIS OF LHC SUPERCONDUCTING CORRECTOR MAGNETS

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Abstract

The Large Hadron Collider (LHC) will use some 7600 superconducting corrector magnets. The magnetic field quality is measured at room temperature by 12 magnetic measurement benches employed by the corrector manufacturers. CERN performs magnetic measurements at 4.2 K and at 1.9 K on a small subset of corrector magnets. The paper discusses the correlation between the warm and cold field measurements. The field quality is compared to the target field quality for LHC. Many corrector circuits will be powered in a way which cannot be predicted before LHC will start operation and which even then may change between physics runs. The measured magnetic hysteresis and its influence on possible setting errors during operation is discussed, in particular for the orbit correctors and the tuning/trim quadrupole magnet circuits.

INTRODUCTION

The Large Hadron Collider (LHC) will use some 7600 superconducting corrector magnets. These magnets use a cosine theta design with a cylindrical yoke [1]. There are 18 corrector types. These are assembled in 13 different types of magnets of which 4 are nested. They are being manufactured by 4 firms in Europe and 3 in India. Important corrector parameters can be found in Table 1.

In this paper the *main field strength* of a corrector is defined by the multipole coefficient B_N for a normal magnet and A_N for a skew magnet. The field is then:

$$B_y + iB_x = (B_N + iA_N) z^{N-1}$$

Here $z=x+iy$ is the complex position variable. The multipole coefficients are given in Tm^{1-N}. Sometimes however the field strength is given *as the field integral* (Tm) at the standard LHC reference radius R_r of 17mm. Similarly field multipole errors of order n in a corrector relative to the main field at R_r expressed as b_n and a_n, are given in *units* of 10^{-4}.

FIELD MEASUREMENTS

Strategy for Magnetic Measurements

In order to help assuring close follow up of the production, CERN has designed and built 12 calibrated benches for warm magnetic measurements based on rotating coils. These systems [2], now commissioned and installed at all the production sites, deliver the magnetic centres and angles, together with the harmonic content of the corrector modules. Tolerances were purposely set to

Table 1: LHC Superconducting corrector magnet assemblies and associated corrector modules

Magnet Assembly	*Nr of correctors/ assembly*	*Number of assemblies*	*Aperture (mm)*	*Corrector Module*	*Main Component*	*Nominal Strength B_N or A_N*	*Current (A)*	*Magn. Length (mm)*
MCDO	2, nested	1232	58	MCD	B_5	1.2 10^6 T/m^4	550	66
				MCO	B_4	8200 T/m^3	100	66
MCS	1	2464	58	MCS	B_3	1630 T/m^2	550	110
MO	2	168	56	MO	B_4	6.3 10^4 T/m^3	550	320
MQT	2	160	56	MQT	B_2	123 T/m	550	320
MQS	2	32	56	MQS	A_2	123 T/m	550	320
MSCB	4	376	56	MS	B_3 or A_3	4430 T/m^2	550	369
				MCB	B_1 or A_1	2.9 T	55	647
MQTL	2	60	56	MQTL	B_2	129 T/m	550	1300
MCBC	2	78	56	MCBC	B_1 or A_1	3.1 T	100	904
MCBY	2	44	70	MCBY	B_1 or A_1	2.5 T at 4.5K	72	899
MCBX	2, nested	18	90	MCBXV	A_1	3.26 T	550	480
				MCBXH	B_1	3.35 T	550	450
MCBXA	4, nested	9	70	MCBXV	A_1	3.26 T	550	480
				MCBXH	B_1	3.35 T	550	450
				MCSX	B_3	104 T/m^2	100	576
				MCTX	B_6	7.2210^{6}T/m^5	80	615
MQSX	1	9	70	MQSX	A_2	80.2 T/m	550	223
MCSOX	3, nested	9	70	MCOSX	A_4	9666 T/m^3	100	138
				MCOX	B_4	9229 T/m^3	100	137
				MCSSX	A_3	377 T/m^2	100	132

Table 2: Summary of warm magnetic measurements results

Module name	Number of mod. meas.	Average Xc measured	Xc sigma	Average Yc measured	Yc sigma	Main target	Average main measured	Main tolerance	Main sigma	Target angle tolerance	Average angle measured	Angle sigma
		[mm]	[mm]	[mm]	[mm]	$[10^3 Tm/A]$	$[10^3 Tm/A]$	$[10^3 Tm/A]$	$[10^3 Tm/A]$	[mrad]	[mrad]	[mrad]
MCB	50					37.8	30.68	±0.378	0.169	±3.5	-0.25	1.6
MQT	24	0.01	0.07	-0.02	0.05	1.3	1.292	±0.013	0.005	±3.5	-0.331	1.9
MS	69	-0.008	0.05	0.014	0.04	0.854	0.903	±0.0085	0.0031	±3.5	0.65	2.3
MCO(EU)	70	-0.028	0.05	-0.052	0.05	0.03	0.03	±0.0003	0.0001	±4	0.427	1.7
MCO(IN)	537	-0.012	0.09	0.022	0.06	0.03	0.03	±0.0003	0.0001	±4	-0.31	1.7
MCD (EU)	70	-0.003	0.04	-0.036	0.03	0.014	0.014	±0.0001	0.0001	±4	1.18	1.2
MCD (IN)	546	-0.011	0.05	0.003	0.05	0.014	0.014	±0.0001	0.0001	±4	0.192	1.4
MCS (EU)	1034	0.006	0.04	0.002	0.05	0.098	0.097	±0.0001	0.0004	±3	0.071	1.2
MCS (IN)	722	0.015	0.06	-0.029	0.07	0.098	0.097	±0.0001	0.0004	±3	-0.29	1.1
MO	208	-0.007	0.03	0.02	0.03	0.177	0.181	±0.0018	0.008	±2.5	0.112	1.1

permit any further positioning of the magnets to be based only on mechanical operations. A detailed procedure has been set up for measurements at the factories sites. This allows personnel at the firms to carry out standard measurements. Results are then sent to CERN to be evaluated and, if the magnet is accepted, stored in an Oracle database.

Due to the huge number of magnets involved, cold measurements are only done on a small part of the production for each type of corrector. A suitable warm cold correlation is being established and will be used to extrapolate the warm data.

Warm Measurements Results

The summary of warm magnetic measurements results is shown in Table 2. For each magnet type, the table shows the number of modules measured, the average and standard deviation of the magnetic/mechanic centre offsets (Xc /Yc), the average and standard deviation of the main field modulus (in Tm at R_r per unit current), and the average and standard deviation of the field angle with respect to the mechanical references. The measurement uncertainty on Xc, Yc and angle varies from 20% of the tolerance for the smallest magnets up to 30% of the tolerance for the biggest. The tolerance on Xc and Yc for direct acceptance of a module is 0.1 mm for the correctors (except 0.16 mm for MS and 0.3 for MCO).

According to the results obtained so far, in general the correctors are well centred in their own mechanical references. Also the measured multipole coefficients are within the targets defined by beam dynamics considerations.

Cold Measurements and Warm Cold Correlations

Magnetic measurements at cold temperature are carried out at CERN by means of the rotating coil technique in vertical cryostats. The transfer functions, the hysteresis of the main field and the multipoles at high current were measured for all the preseries magnets in their final single or twin aperture configuration. As the preseries magnets were produced before the installation of the industry benches, these measurements could not be correlated to a warm counterpart. With the ramping up of the production, it became possible to start dedicated measurement campaigns aimed at finding the correlation between the measurements done in industry, and available for almost all the magnets, and the field quality in operation conditions at different currents and at 1.9 K. So far this has been accomplished only on a very small sample of magnets, namely 4 MCB dipole correctors, 2 MQT tuning quadrupoles and 1 MS chromaticity sextupole.

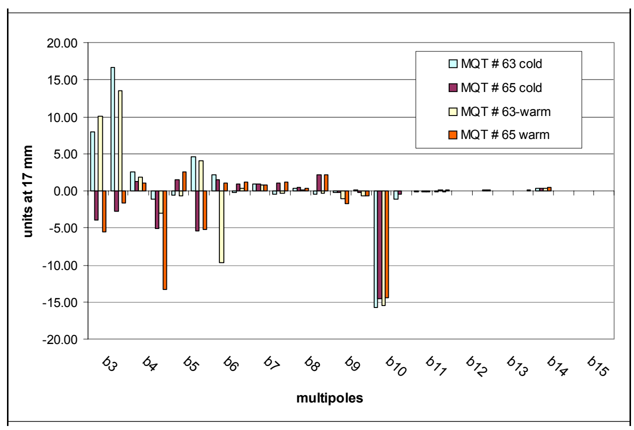

Figure 1: Warm-cold measurements of two MQT modules.

Though the statistics are insufficient to establish strict warm-cold correlations, all the data available show that the harmonic "signature" of the magnets is well visible in both sets of measurements (see Fig.1). However, care must be taken in the extrapolation of warm data, as the saturation effect is important for some multipoles such as b3 in the MCB correctors (see Fig. 2) leading to warm-cold offsets of several units.

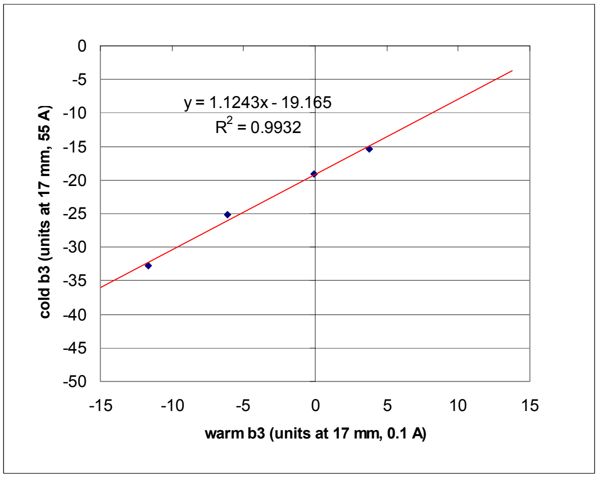

Figure 2: Warm cold correlation of sextupole in 4 MCB.

HYSTERESIS OF MAIN COMPONENT

The magnetic hysteresis due to the iron yoke and to the persistent currents in the superconducting strands will influence the setting precision of the corrector main fields, and consequently also the fine tuning of beam parameters such as orbit and tune. In particular, the hysteresis will contribute a random component to the main field in settings reached by feed back loops, which would render problematic to reproduce a given working point from run to run. In figure 3 the measured width of the hysteresis loops of the dipole field versus current in 4 MCB correctors is displayed as an example. As it might be expected, the effect is higher at low current. We can therefore take the measured width of the main field hysteresis loop at 0 A as the maximum setting error. The measured value of the latter is about $1{\cdot}10^{-3}$ Tm for the MCB and $4{\cdot}10^{-4}$ Tm at 17 mm for the MQT. The dipole hysteresis is highest for the MCBX dipoles, up to $6{\cdot}10^{-3}$ Tm at 0 A.

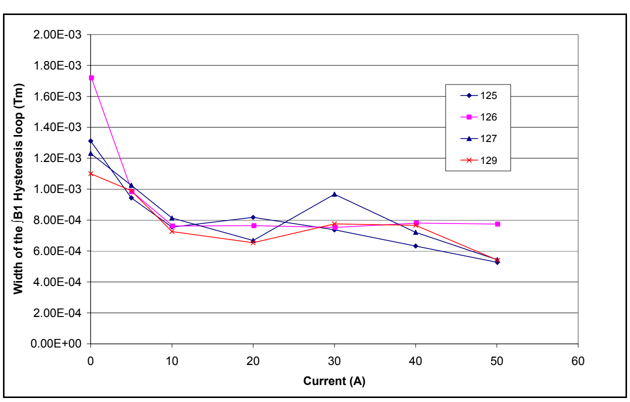

Figure 3: Hysteresis width in MCB dipoles.

The situation is most pronounced at injection energy, where an MQT would have to work at very low current to correct 1 unit of b2 of one main quadrupole (MQ). Due to the hysteresis, the uncertainty at low field on the MQT corrector strength corresponds to 5 units of b2 in one MQ at injection. For one MCB, at injection, the uncertainty due to the hysteresis corresponds to 1.3 units of b1 in one main dipole.

Maximum Influence on Orbit Kick Angle

The orbit corrector dipoles are powered individually. In the case of the MCB, the hysteresis width corresponds to a maximum kick angle of a 0.7 µrad at injection, which is equivalent to about 0.3 units of b1 in the main dipoles (integrated over a cell). The worst case is the MCBX, where the hysteresis corresponds to a maximum kick angle of a 4.1 µrad at injection.

Maximum Influence on Tune

From tracking simulations, a change of 1 unit of b2 in one MQ provokes a tune shift ΔQ of $1.66{\cdot}10^{-5}$. At injection this translates in a tune shift of about 0.22 for 1 Tm at 17 mm of change in focusing strength.

We assume a tolerance on tune shifts of $\pm 3{\cdot}10^{-3}$ [3]. From the above data, the hysteresis width relative to one MQT corresponds to a tune shift of $8{\cdot}10^{-5}$. In the unfavourable case that all the 20 MQT circuits have their magnets sitting on the wrong branch of the hysteresis loop, the resulting tune shift would then be $1.3 \cdot 10^{-2}$, which is 4 times the allowed value.

The corrector magnet powering and control will have to be adapted to compensate for the effects described in the above examples.

CONCLUSION

Warm field measurements of the LHC correctors are systematically done in industry and used to monitor the production. Measurement results allow timely reaction to assure that the magnetic centre, the field angle, and the field quality of the magnets produced stay within the limits defined from the beam optics requirements. Cold measurements campaigns have started for all types of correctors, the warm cold correlation are not yet fully established.

The possible effect of the hysteresis in orbit correctors and trim quadrupoles on the setting precision of orbit and tune has been evaluated. It was shown that the hysteresis in the trim quadrupoles could potentially lead to tune shifts of excessive amplitude between runs.

Appropriate operation of the correctors will be implemented to maintain the above effects within acceptable limits.

REFERENCES

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[3]https://edms.cern.ch/file/463763/0.2/LHC-B-ES-0009-00-20.pdf