MAGNETIC BEHAVIOR OF LHC SUPERCONDUCTING CORRECTORS: ISSUES FOR MACHINE OPERATION

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Abstract

This contribution concentrates on the aspects of the magnetic behaviour of correctors which could be relevant for the machine operation. Warm measurements, measured excitation curves at cold, correlation between the warm and cold field measurements and comparisons of the field quality to the targets for LHC are reviewed. The measured magnetic hysteresis and its possible influence on setting errors during operation are discussed, as well as estimations of the order of magnitude of cross talks. Finally the strategy for the field measurements of correctors is reviewed.

INTRODUCTION

In the Large Hadron Collider (LHC) the corrector magnets come in 13 different types of assemblies, of which 4 are nested. Important corrector parameters can be found in Table 1. The LHC correctors can be classified in several ways. For instance, according to their function, one can distinguish **Orbit correctors**: (MCB, MCBC, MCBY, MCBX); **Lattice correctors** (MQT, MQS, MS, MSS, MO; MQTL, MQSX); and **Multipole correctors** (MCS, MCO, MCD, MSSX, and MCSOX). Each corrector type is directly acting on one (or more) beam parameter, such as the closed orbit or the tune. In addition, all corrector fields have higher order harmonics which in principle may affect the dynamic aperture.

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 $\boldsymbol{z}=x+iy$ 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}.

ISSUES FOR MACHINE OPERATION

The magnetic characteristics of correctors which are relevant for the machine operation are, in order of importance: the transfer functions of the main fields, the field quality, and the possible cross talks in nested magnets. Alignement issues are not treated here: in principle, the warm measurement benches installed in industry are designed to assure that the magnetic centre and field angle of the correctors stay within tolerances which allow their further positioning in the cold assemblies to be based only on mechanical operations. In the following, we discuss the above topics for the correctors in the arcs, starting from the impact of transfer function uncertainties, notably due to magnetic hysteresis,

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	$1.2\ 10^6\ \mathrm{T/m^4}$	550	66
				MCO	B_4	$8200\ \mathrm{T/m^3}$	100	66
MCS	1	2464	58	MCS	B_3	$1630\ \mathrm{T/m^2}$	550	110
MO	2	168	56	MO	B_4	$6.3\ 10^4\ \mathrm{T/m^3}$	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	$4430\ \mathrm{T/m^2}$	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	$104\ \mathrm{T/m^2}$	100	576
				MCTX	B_6	$7.2210^6\mathrm{T/m^5}$	80	615
MQSX	1	9	70	MQSX	A_2	80.2 T/m	550	223
MCSOX	3, nested	9	70	MCOSX	A_4	$9666\ \mathrm{T/m^3}$	100	138
				MCOX	B_4	$9229\ \mathrm{T/m^3}$	100	137
				MCSSX	A_3	$377\ \mathrm{T/m^2}$	100	132

on the related optics parameters.

TRANSFER FUNCTION OF MAIN COMPONENTS

The knowledge of the transfer function of the main field is needed in order to set the corrector values. Transfer functions are subject to: warm-cold offsets (the vast majority of correctors are only measured at warm); saturation of the iron yoke at high field (particularly high in LHC correctors because of the closeness of iron laminations to the superconducting coils), and hysteresis at low field, due to the iron and superconductor magnetization. The first two can be extrapolated from warm cold correlations with defined statistical uncertainty. The problem of assessing the tolerable uncertainty on the transfer functions can be tackled starting from the available tolerances on the optics parameters that the corrector has to control. On the other hand, some correctors will be powered in a way which can be only in part foreseen: for instance, orbit or tuning corrections could require reversing the current ramps, thus crossing hysteresis loops. In this sense, the hysteresis will contribute a random component to the main field in settings reached by the feed back systems, which would make it difficult to reproduce a given working point from run to run. In addition, the non-univocal character of the transfer functions might affect the convergence of the correction algorithms, either slowing it or, possibly, even triggering instabilities. The latter may arise in case the effect of reversing the current ramp is, because of the hysteresis, so small that it cannot be properly resolved by the beam instrumentation [1].

In figure 1 the measured width of the hysteresis loop in a lattice sextupole is displayed as an example. As the hysteresis is higher at low current, the measured width of the main field hysteresis loop at 0 A can be assumed as the maximum setting error.

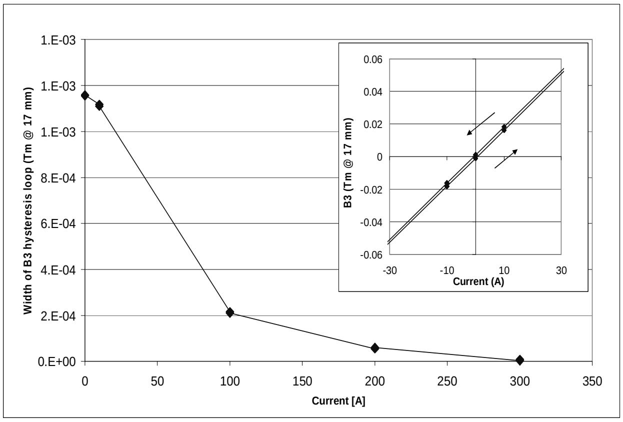

Fig. 1: Hysteresis amplitude of a lattice sextupole

In Table 2 we report measured hysteresis widths at 0 A from the available measurements at 1.9 K. In the next paragraphs the effects of crossing the hysteresis loop are evaluated and compared to the operational tolerances for some optics parameters.

Orbit		Lattice		Multipole	
	Tm @17 mm		Tm @17 mm		Tm @ 17mm
MCB	10^{-3}	MQT	$2\ 10^{-4}$	MCS	$6\ 10^{-5}$
MCBC	$1.3\ 10^{-3}$	MQTL	$8\ 10^{-4}$	MCD	10^{-5}
MCBY	Not yet measured	MS	10^{-3}	MCO	10^{-4}
MCBX	$6\ 10^{-3}$	MO	$4.6\ 10^{-5}$		

Table 2: Hysteresis amplitudes of corrector main fields (from pre-series measurements)

Maximum influence of hysteresis on the orbit

The orbit corrector dipoles are powered individually. In the arcs, insofar as the main quadrupoles are “well” aligned, their current level, at injection, will be very low [2]. Furthermore, to correct the decay of b1 in the MB at injection (1 unit), the required current change in the MCB lies in the sub ampere range.

In order to compare kicks due to wrong settings of the orbit correctors with tolerances on the orbit, the formula for the orbit perturbation from N randomly distributed kicks has been used [3]. For a tolerance of 100 μm rms [4], and N=200 correctors, the formula yields 1.3 10^{-4} Tm tolerable absolute error at injection. From Table 2, the uncertainty related to the hysteresis is a few times higher, assuming a uniform distribution of the magnetic state of the correctors between the two branches of the loop.

Maximum influence of hysteresis on tune

From the simplest formula relating gradient errors to the tune shift [5], at injection, 1 Tm at 17 mm of change in focusing strength translates in a tune shift of about 0.56.

We assume a tolerance on tune shifts of $\pm 3\cdot 10^{-3}$ [6]. From the above data, the hysteresis width relative to one MQT corresponds to a tune shift of $1.1\cdot 10^{-4}$. Ideally tune corrections would have to be carried out by using all the available circuits, for the LHC this means 8 circuits of 8 magnets each powered in series. Having these magnets sitting on the “wrong” branch of the hysteresis loop, would then result in a tune shift of $7\cdot 10^{-3}$, which is more than 2 times the allowed value. Fig 2 displays the tune correction of the 8 tuning quadrupole circuits, as a function of current, as deduced from the magnetic measurement of one magnet at 1.9 K. The straight lines are interpolations of the measured ramp-up and ramp-down branches of the hysteresis loop, while the curved line is a qualitative sketch of the path followed when the current ramp is reversed. The current sweep required to cross the loop is related to the field change needed to reverse the magnetization of the superconducting filaments. For the MQT it is estimated around 1 A. However, with respect to the feed back systems, the behaviour for small increments is particularly important. As in Fig. 2 only the upper and lower branches are deduced from real measurements, the actual crossing path will have to be measured in detail in order to assess the impact on the correction algorithms.

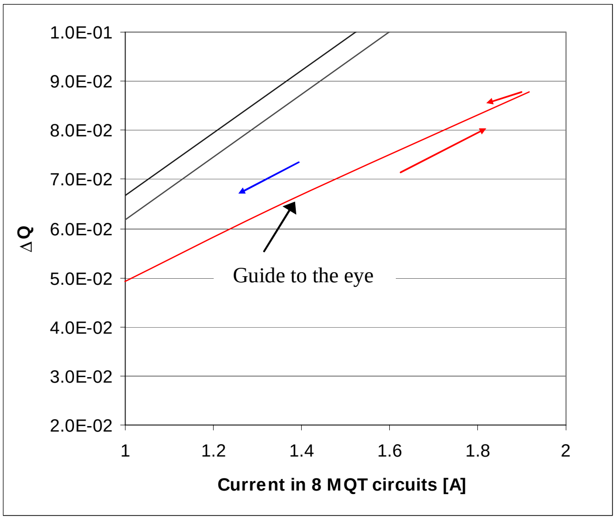

Fig. 2: Tune shift as a function of tuning quadrupoles powering (8 circuits)

Maximum influence on Chromaticity

To set the chromaticity at 2 units, the lattice sextupoles at injection have to be powered at about 4% (focusing) and 2% (defocusing) of their maximum strength. At this level of current the width of the hysteresis loop is about 10% of the total field.

From MAD simulations [7], the hysteresis in the MS corresponds to a Chromaticity jump of more than 10 units at injection. As discussed for the case of the tune, a possible impact on the convergence of the feed back systems is envisaged depending on the behaviour for small increments.

The spool piece sextupoles have to compensate the decay and snapback of b3 in the main dipole at injection. Their powering cycle is therefore somewhat more predictable. Their hysteresis corresponds to a chromaticity jump of 3.5 units.

Landau Octupoles

The requirement that the contribution to the amplitude detuning at injection due to the residual hysteresis of the Landau octupoles be lower 10-20% of the specified budget of 2 10^{-3} [8], translates in a tolerance per magnet of ±7.4 10^{-5} Tm at 17 mm [9]. Comparing this figure with the value in Table 2, one can see that a set up cycle to minimize the effective integrated octupolar field at injection would be useful, as the residual field at zero amperes is about the tolerance.

FIELD QUALITY

The field quality of all the LHC correctors is measured a room temperature at the manufacturers' premises, by means of 12 benches for warm magnetic measurements. For the sake of production monitoring, the benches compare automatically the harmonic content with values derived from the mechanical tolerances on magnet assembly. In parallel, the Field Quality Working Group issues target values with respect to the requirements of beam dynamics. In general, the field quality of all correctors is found to be within the tolerances of the FQWG [10]. In a few cases the tolerances had to be reconsidered in order to avoid unnecessary reject of too many magnets. For the MCDO the limit for certain multipoles was raised with an engineering change request in 2002 [11].

The MQT and MQTL display b6 and b10 of the order of 10 and 15 units respectively. The MCBC has got a b3 of 40 units. The FQWG has evaluated these cases, judging them acceptable, although at the limit of tolerance [12].

Warm cold correlations

The transfer functions are highly non-linear. Besides, warm data are relative to modules, whereas the modules are eventually assembled in twin aperture structures. Therefore cold measurements at high field are needed in order to determine the current-to-field relationship in the operational regime.

The status of cold measurements at the end of 2004 is shown in Table 3. Generally speaking, proper cold warm correlations are not available as the preseries magnets have been measured at cold before the commissioning of the industry benches. Cold measurements of the series magnets have only started in 2004 [13]. For the corrector types that show multipoles at the limit of tolerance, the cold measurements confirmed the warm results, in some cases the cold harmonics are greater because of the saturation of the iron. As an example, Fig. 3 shows the field quality of an MCBC module.

Corrector type	Pre series	Series	Cold/warm
MCS	10+10	none	good
MCDO	10+10	none	poor
MO	3 assemblies	none	1 mod., fair
MQT/S	3 assemblies	8 modules	poor, improving
MCB	1 assembly	2 ass. + 4 mod.	good
MS	1 assembly	1 ass. + 3 mod.	1 mod., fair
MCBC	1 assembly	1 module	1 mod., fair
MCBY	none	none	-
MQTL	2 modules	-	-
MCBX+MCBXA	2	17/25	fair
MQSX+MCSOX	1	8/9	to check

Table 3: Status of available cold measurements

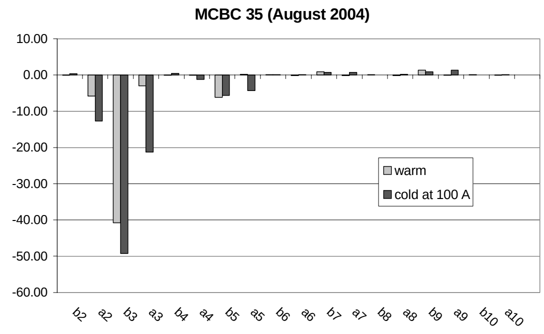

Fig. 3: Cold and warm field quality of an MCBC module

CROSS TALKS

Cross talk can take place between twin apertures of magnet assemblies, and between the different windings of nested magnets such as the correctors for the inner triplets

Cross talks between apertures was investigated in MSCB and MO and found negligible (of the order of 10^{-4} Tm at 17 mm and at high field).

Significant effects are foreseen for the MQTL, and measurements are planned on one of the first assemblies.

In the nested perpendicular windings of the MCBX the persistent currents limit the setting precision of the field angle.

MAGNETIC MEASUREMENTS PLAN

The required accuracy of the corrector transfer functions deduced from the warm and cold data could not yet be fully assessed, as it will also depend on the correction schemes and on the actual accuracy of the beam instrumentation. However, the cold measurements available so far do not allow the estimations of standard errors on the warm cold correlations to be comparable with likely values of the tolerances, which range between a few 10^{-3} and the percent level.

In addition the local behaviour of the hysteresis curves will have to be determined with dedicated measurement cycles, to be defined in collaboration with the designers of the feed back systems. The same is true for the setting up cycles at injection, and for the cross talks. In Table 4 we propose a minimal set of measurements aimed at looking for a correlation with the warm data.

Corrector type	TF	Hysteresis measurement setting up cycle
MCS	10+10 (1%)	10
MCDO	10+10 (1%)	10
MO	9	4
MQT/S	9	4
MSCB	12	6
MCBC	9	4
MCBY	9	4
MQTL	4	1
MCBX+MCBXA	-	3
MQSX+MCSOX	-	1

Table 4: Proposed minimal set of magnetic measurements

CONCLUSIONS

Further cold measurements and modelling work are still necessary before the current to field relationships needed to operate the correctors can be provided with a reasonable accuracy (between 10^{-3} and 10^{-2}).

We have shown that the effects of the hysteresis of corrector fields on the closed orbit, on the tune, and on the chromaticity potentially exceed the operational tolerances.

The field quality of the correctors measured at warm is under control, although a few cases need close follow up.

Set up cycles at injection are needed, notably for the Landau octupoles and the nested magnets.

Cross talk at high field between apertures and between neighbouring magnets in the same cold masses is probably negligible, but will be further checked.

The absence of field decay and snapback remains to be verified for the 4 different strand types used in correctors.

The definition of the remaining cold measurements (test programs and share between SM18 and Block 4) is urgent in order to set priorities and focus on the most critical issues.

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