MEASUREMENT AND MODELING OF MAGNETIC HYSTERESIS IN THE LHC SUPERCONDUCTING CORRECTORS*

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Abstract

The Large Hadron Collider, now under construction at CERN, relies heavily on superconducting magnets for its optics layout: besides the main magnets, almost all the correcting magnets are superconducting. Along with clear advantages, this brings about complications due to the effects of persistent currents in the superconducting filaments. Corrector magnets that trim key beam parameters or compensate field errors of the main magnets (among others those due to hysteresis), are in their turn hysteretic. In this paper we present the measured magnetic hysteresis and its possible influence on accelerator operation, with particular reference to real-time compensation of dynamic effects in the main magnets, and reproducibility issues between runs. The modeling strategy as a function of the required accuracy is discussed, and two examples are presented.

INTRODUCTION

The superconducting correctors of the LHC exhibit a significant magnetic hysteresis, corresponding to beam parameter deviations comparable or higher than the related operational tolerances [1]. Hysteresis affects the instantaneous value of the field generated by a corrector (integral transfer function, TF), and it makes it dependent on the powering history. This raises questions of reproducibility between runs, as well as on the effect on the control algorithms in the feed back loops. We have few dedicated measurements that show that the feed back loops can be designed to be robust enough so that they are only marginally perturbed by hysteresis in the corrector transfer function. It is nonetheless disturbing that, even if a suitable set of trims is reached during a run by automatic feed back control, it will not be sufficient to store the corresponding vector of currents to reproduce that state of the machine on the next run. The maximum uncertainty on the value of the magnetic field corresponds to the width of the hysteresis loops of the magnets involved. The reproducibility of settings can thereby be given an upper estimate, useful to assess the relevance of the effect.

We note here that the spread of the magnetic hysteresis in the LHC correctors has not yet been fully assessed. Data collected in 2005 suggest that the spread could be large. Differences up to a factor two have been observed [2] in the magnetization of the used strands. As long as corrections only rely on feed forward, their ultimate accuracy is defined by the modeling uncertainty of the corrector TF. On the other hand, once beam based feedback is available, requirements on the knowledge of TF are relaxed. Nonetheless feed back controllers need to incorporate suitable models of the corrector TF to achieve the desirable robustness. In the following, the definition of the appropriate level of modeling detail is discussed; a summary of the measured hysteresis is given; and examples of TF models are produced. All measurements were carried out by means of the rotating coil technique; all field quantities are given in Tm at 17 mm.

MODELING STRATEGY

Forecast based on field measurements of the main LHC magnets, beam measurements and operator requests will be combined at the level of the LHC control system to deduce field trims to be provided by the correctors. The generation of field trims requires the knowledge of the corrector transfer functions. The latter are far from being linear, due to the proximity of iron laminations to the coils; thus even the simplest useful model of the field-versus-current relationship must include the saturation of the iron. Depending on the tolerance on the beam parameter that the corrector has to control, and on the availability of beam based feedback, the model may have to take into account hysteresis effects. We plan to include models of the corrector transfer functions in the field description for the LHC (FIDEL). FIDEL will use a set of measurement-based analytical expressions for the field and field errors in the various phases of the machine cycle [3]. The decision path on the level of modeling complexity to be used for a specific corrector can be summarised as follows: if the corrector hysteresis corresponds to less than the tolerance on the beam parameter, then the model will be restricted to the geometric component plus the effect of iron saturation. If not, it must be inquired to what extent the corrector powering can be anticipated: sometimes the sequence of current ramp rate inversions is known (for example for spool pieces sextupoles and decapoles compensating decay and snapback in the main dipoles). In such cases a set of linear approximations of the transfer functions seems appropriate. Switching from one linear approximation to the next can in this case be programmed in correspondence with the sign changes of the current ramp. However, in most cases, the corrector powering cannot be foreseen. In this case, we will first verify whether the working point of the corrector can be shifted to a somewhat higher (bias) current, such to bring hysteresis effects back within tolerance. This may require adjustments of the machine optics. Finally, if this is not possible, a fully hysteretic model will have to be

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developed, requiring as an input the sequence of the last N trims to provide the (N+1)th one. Incidentally, most of this effort is not needed for the main magnets only because their current cycles are standardized, and recycling is foreseen after any deviations from the predefined powering.

MEASUREMENT RESULTS

As an example of non negligible hysteresis, the transfer functions of three lattice sextupoles (MS) at low field are shown in Fig. 1. To correct the linear chromaticity of the LHC, the setting points of these magnets at injection are at 1.1% and at 1.8% of full strength for the SF and the SD respectively. The width of the hysteresis loop is about 10^{-3} Tm at 17 mm. At injection this corresponds to 10 and 18 units of chromaticity for the horizontal and vertical planes [4], to be compared to the control target of 2 units.

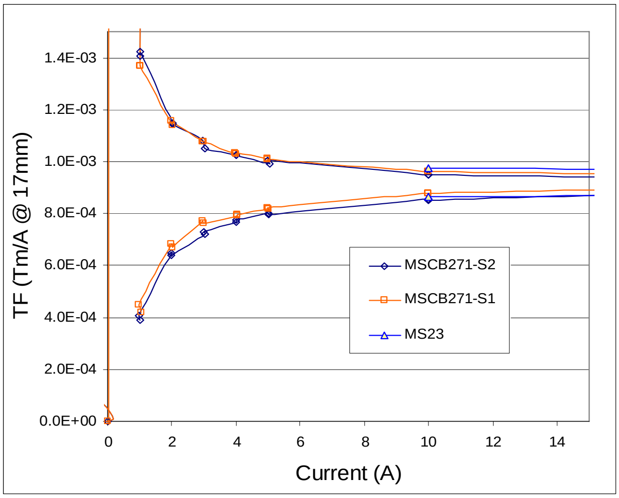

Figure 1: Lattice Sextupoles transfer functions as a function of current.

Table 1: Summary table of hysteresis data and relevance thresholds.

Corrector type	Beam parameter	Hysteresis [10^{-3} Tm]	Relevance threshold [10^{-3} Tm]	Possible forecast
MCB	closed orbit	1.2	0.193	no
MCBC	closed orbit	1.2	0.27	no
MQT	tune	0.4	0.032	no
MQS	coupling	0.4	0.128	no
MS	chromaticity	1	0.074	no
MCS	chromaticity	0.1	0.011	yes
MO	amplitude detuning	0.12-0.4	0.096	yes

A summary of the available data for some corrector types is given in table 1, where the hysteresis is defined as the width of the major loops at zero current, which maximizes the effect. The thresholds [5] are derived from the resolution of the beam instrumentation. In the last column the possibility to anticipate the powering cycles of the corrector is evaluated

MODEL EXAMPLES

Chromaticity Correction During Decay and Snapback

The hysteresis of the MCS, in charge of correcting the sextupole error b3(t) of the main dipoles, corresponds to about 6 units of chromaticity; therefore it cannot be simply ignored. The time dependence of the normal sextupole in the main dipoles during injection and the ramp can be anticipated, so we could use a set of linear approximations of the corrector transfer function. However, supposing that the tolerance can be relaxed at the start of operations, we have carried out measurements to better asses the impact of hysteresis during decay and snapback compensation. Due to the powering scheme, the MCS correct the average over one sector of the machine. We thus started from the expected average b3(t) of the LHC dipoles in sector 7-8, and used a linear approximation of the MCS transfer function to generate a current cycle for the corrections: the assumed transfer function TFMCS was a constant (geometric component) and the current-field relationship was therefore a straight line passing through the origin. The current function of the corrector power supply was then: I(t)MCS=-b3(t)/TFMCS. The resulting MCS field was measured and its difference with respect to b3(t) was translated in a residual (uncorrected) chromaticity.

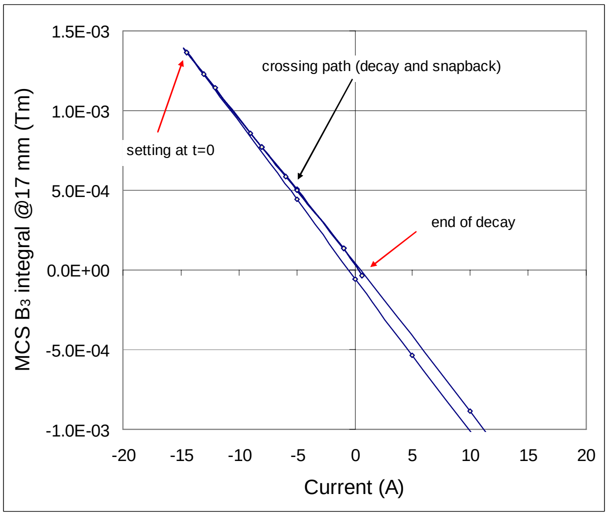

Figure 2: Spool pieces sextupoles integrated strength as a function of current, simulating the compensation of decay and snapback of b3 in the main dipoles of sector 7-8.

In Fig. 2 the measured MCS field integral is shown as a function of current. The setting current at t=0 for the MCS is -14.5 A; and at the end of the decay it is of +0.6 A. As visible in the plot, with the pre cycle adopted in the experiment, the current to field relationship of the corrector during the decay and the snapback phases remains linear; nevertheless its slope is different from that of the linear best fit of the whole hysteresis loop. The uncorrected chromaticity, as defined above, is shown in Fig. 3.

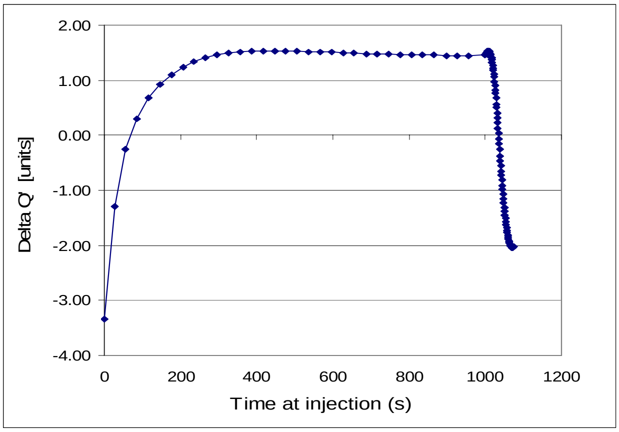

Figure 3: Uncorrected chromaticity as a function of time during decay and snapback, using a linear approximation of the MCS transfer function.

Modeling of the MQTL Major Hysteresis Loop

The measured transfer function of a long trim quadrupole magnet (MQTL) has been fitted with the following equation:

$$TF^{DC\_up}_{down} = \gamma_m \pm \mu_m \left(\frac{I_{inj}}{I}\right)\left(\frac{I}{I_{inj}}\right)^{p_m}\left(\frac{I_c - I}{I_c - I_{inj}}\right)^{q_m}\left(\frac{T_{co}^{1.7} - T^{1.7}}{T_{co}^{1.7} - T_{meas}^{1.7}}\right)^{m_m}$$

$$+ \sum_{i=1}^{N} \sigma_m^i \Sigma\left(\frac{1}{\pi}\operatorname{atan}\left(S_m^i\left(\frac{I - I_{0,m}^i}{I_{nom}}\right)\right) + \frac{1}{2}\right) + \rho_m\left(\frac{I_{inj}}{I}\right)^{\gamma_m}$$

Definitions and the values of the parameters are given in table 2. The result is shown in Fig. 4. It appears that the model works satisfactorily for the major hysteresis loop as well as for the high field saturation. However, it is slightly limited at low currents where the superconductor is not fully penetrated.

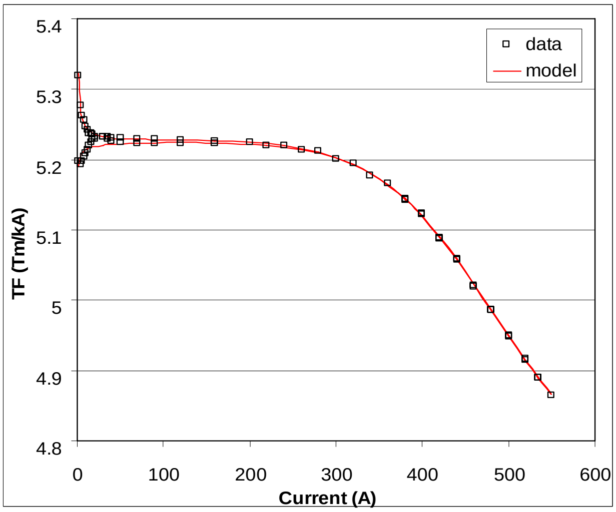

Figure 4: Measured transfer function of a MQTL magnet and FIDEL model.

CONCLUSION

Hysteresis can cause significant uncertainties in the knowledge of the transfer functions of the LHC correctors at injection. We have sketched a roadmap to the solution of the issue for LHC start-up. We need to complete a dedicated campaign of magnetic measurements, to fix the required level of modeling accuracy for all corrector families. As reported here, we already started this work for some LHC corrector types. In particular, we have taken two examples (spool pieces sextupoles MCS and long trim quadrupoles MQTL) to demonstrate modeling accuracy and implications for operations. A practical result is that MCS only need modeling of the hysteresis if the dynamic chromaticity error is to be kept below 3 units during decay and snapback. Models are presently limited to the major branches of the hysteresis loop. The next step is a parameterization of the crossing paths as a function of current, which is a necessary ingredient for a fully hysteretic model.

Table 2: Definition and values used for the MQTL TF fit

Symbol	**Meaning**	**Units TF**	**Value TF**
γ	geometric field error	(Tm/kA)	5.2252
μ	DC magnetization strength	(Tm/kA)	-0.1211
p	DC magnetization pinning exponent	(-)	0.1242
q	DC magnetization pinning exponent	(-)	0.0132
m	DC magnetization pinning exponent	(-)	2
T	temperature	(K)	1.89
T_{co}	critical temperature	(K)	9.5
T_{meas}	temperature during measurement	(K)	1.89
σ^1	iron saturation strength	(Tm/kA)	-35.8972
I_0^1	iron saturation current	(A)	442.2576
S^1	iron saturation current range	(-)	2.7004
σ^2	iron saturation strength	(Tm/kA)	35.2885
I_0^2	iron saturation current	(A)	439.8142
S^2	iron saturation current range	(-)	2.6632
N	number of smooth step functions	(-)	2
ρ	residual magnetization strength	(Tm/kA)	0.066
r	residual magnetization exponent	(-)	1.0962
I	current	(A)	-550 <I< 550
I_{inj}	current at injection	(A)	1
I_{nom}	nominal current	(A)	550
I_c	critical current	(A)	930

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