INFLUENCE OF MAGNETIC HYSTERESIS ON TUNE AND CHROMATICITY CORRECTIONS

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Abstract

As a follow-up of the discussions initiated at the last LHC Project Workshop, this contribution focuses on the aspects of the magnetic behaviour of tune-shift quadrupoles, as well as spool and lattice sextupoles, which may be relevant for the machine operation. The measured magnetic hysteresis and its possible influence on setting errors during operation will be presented, in particular the real-time compensation of decay and snapback in the main magnets, and the reproducibility between runs. A detailed characterization of minor hysteresis loops is presented, to explore potential effects on the stability of the feedback.

INTRODUCTION

The superconducting correctors of the LHC exhibit a significant hysteresis, with beam parameters deviations comparable or higher than the related operational tolerances [1]. In principle this poses two distinct kinds of issues: reproducibility between runs, and interactions with feed back control.

The former can be stated as follows: for each vector of currents in the corrector circuits, there exists an infinite set of possible resulting trims, corresponding to all the possible magnetic states between the upper and the lower branches of the hysteresis loops. The actual magnetic state depends on the powering history. If a given 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 in order to be able to reproduce that state of the machine on the next run. The maximum difference in the beam parameters between two such conditions corresponds to the opposite branches of the corrector major hysteresis loops. The reproducibility of settings can therefore be given an upper estimate by measuring the major hysteresis loops. The second issue of perturbations of the feed back control concerns the behavior for small increments, and calls for measurements of minor hysteresis loops. Hysteresis causes asymmetries in the effect of trims which, if too pronounced, may slow down the convergence of the feed back processes.

As long as corrections only rely on feed forward their ultimate accuracy is defined by the modeling uncertainty of the corrector transfer functions. On the other hand, once beam based feedback is available, requirements on the knowledge of TF are relaxed. However, a need to check feedback convergence speed and stability was evidenced [2], and work in this sense has started in 2005.

In the course of the year, little progress has been made on the way of a full characterization of the hysteresis effects, while all the available resources of the AT-MTM group were and are still focused on the acceptance of magnets for installation.

In the following the results of measurements carried out in 2005 are reported. The detailed return paths (minor hysteresis loops) at low currents were measured for the first time for the MQT and MCS magnets. Similar studies on the orbit corrections have been also launched, and first outcomes are reported elsewhere [3].

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 field strength is given *as the field integral* (Tm) at the standard LHC reference radius R_r of 17mm. We will refer to the *hysteresis width* defined as difference between the two branches of the hysteresis loop of the main field integral extrapolated at zero current.

VARIABILITY OF HYSTERESIS

The spread of the magnetic hysteresis in the LHC correctors is not yet known. Too few detailed magnetic measurements at cold are available. However measurements carried out in 2005 suggest that the spread could be high: figure 1 shows the hysteresis loops of two Landau octupoles belonging to the same assembly. The hysteresis widths of the two modules differ by a factor two, which cannot be attributed to measurement uncertainty.

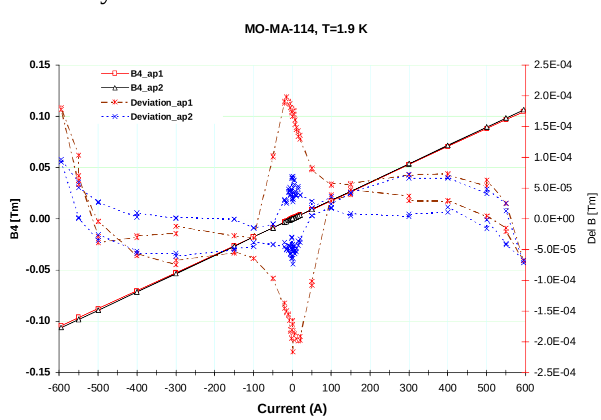

Fig. 1: Hysteresis loops of two lattice octupoles

The solution of this riddle came from inspection of the superconducting strands. The two modules had been wound with conductors issued from two different billets; micrographs showed huge deformations of the Nb-Ti filaments in one of them, and magnetization measurements finally confirmed that the persistent current effects are much larger for the strands with deformed filaments. The likely reason is the onset of proximity coupling at low field. Details on these measurements are reported in [4].

In the next paragraphs, hysteresis widths will be translated into tune and chromaticity deviations: it should be kept in mind that these figures are affected by the same uncertainty as is the spread of the magnetic hysteresis.

IMPACT ON TUNE CORRECTIONS

To assess the impact of hysteresis on tune corrections, one has first to define a correction scheme. In the preferred solution, all the available MQT circuits would be used, to minimize β-beating. Sources of tune shift to be corrected in the arcs include tracking between the dipole and quadrupole power converters within a sector, and between converters of the eight sectors [5], decay of b_2 in the MQ magnets, and feed down from misaligned sextupoles. All these perturbations are in the 10^{-2} range (in units of ΔQ). Given the actual strength of the MQT magnets, their set point at injection would therefore be very close to zero. So far we have measured in detail only 6 modules. The hysteresis width (average $\pm 1\ \sigma$) was $2.3\ 10^{-4} \pm 0.6\ 10^{-4}$ Tm at 17 mm, and translates in $5.3 \cdot 10^{-3} \pm 1.4\ 10^{-3}$ tune shift, which has to be compared to the tolerance of $\pm 3 \cdot 10^{-3}$ [6]. Considering the difficulties of magnetic characterization at very low currents, and the possible onset of proximity coupling in the SC strands - which may lead to irregularities in the transfer functions - , *it is suggested to operate the MQT at some bias current to be defined*. For the first experiments we have assumed that the MQT circuits at injection are powered at 6 A, thus providing a baseline ΔQ of about 0.2.

A measurement was set up to *ascertain the required current cycle* for the MQT to compensate the decay of $\mathbf{b}_2$ in the arc quadrupoles. According to the present running average, the amplitude of main field decay in the MQ is about 2 units, which corresponds to $\Delta Q \approx 0.01$. The required trim, estimated analytically considering 8 MQT circuits/beam/plane, is $\Delta[\int \mathbf{B}_2 \mathbf{d}l]_{MQT} = 4.2 \cdot 10^{-4}$ Tm for each MQT, that gives, using a linear approximation of the TF, $\Delta I \approx 0.3$ A. This is comparable with the hysteresis loop width; and the question we wanted to address with the measurements was whether during the correction the hysteresis loop had to be crossed or not.

As shown in Fig. 2, the actual correction is only about 1 tenth of what would be needed to cross the hysteresis loop. There was nonetheless an uncorrected tune shift due to hysteresis, but it was only $1.4 \cdot 10^{-3}$. The contribution of the misalignment of the spool pieces sextupoles could be of the same order of magnitude [7], but its sign is not known. In the worst case the two contributions to the dynamic tune shift would add and the conclusion would not need to be changed: the MQT can be considered *linear* objects in the operational range defined by the above conditions.

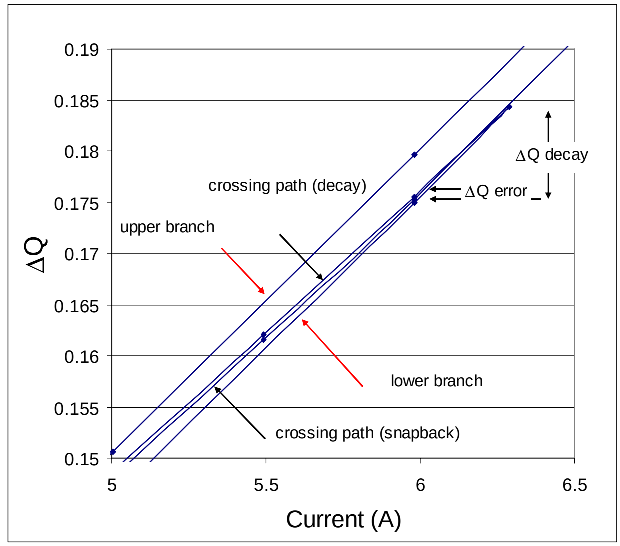

Fig. 2: Tune shift as a function of trim quadrupoles current, simulating the compensation of decay and snapback of b_2 in the main quadrupoles

A second class of measurements was aimed at exploring minor hysteresis loops, to make sure that the transfer functions are locally regular, and that there are no "dead bands" that would harm the convergence of the feed back.

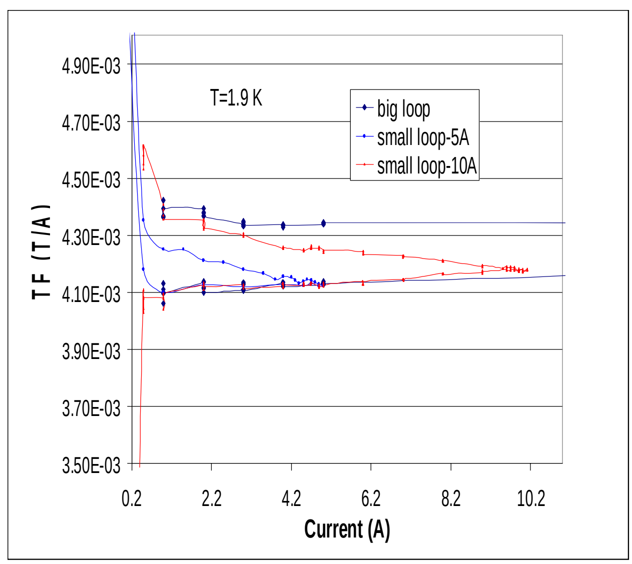

Fig. 3: Trim quadrupole transfer function as a function of current, small hysteresis loops around 5 A and 10 A

In Fig. 3 two such loops are displayed, recorded at 5 A and at 10 A. The results indicate that, in this range of currents, hysteresis would be easily absorbed by a feed back control system: a positive tune shift of $3.4 \cdot 10^{-3}$ can be reversed leaving a hysteretic error of $1.2 \cdot 10^{-4}$, only about 3% of the original trim. It appears therefore that a single iteration would already be enough to complete the requested correction within the tolerance.

IMPACT ON CHROMATICITY CORRECTIONS

In order to correct the linear chromaticity of the LHC, the setting points of the MS magnets at injection are at 1.1% and at 1.8% of full strength for the SF and the SD respectively [9]. The assumed tolerance on chromaticity is ±2 units [10]. Only 3 MS lattice sextupoles have been measured at cold so far; transfer functions are shown in Fig. 4. The maximum width of the hysteresis loop is about 10^{-3} Tm at 17 mm. This value corresponds to 10 and 18 units of chromaticity for the horizontal and vertical planes at injection [9]. Thus, if the settings are given in terms of currents (with no knowledge of the magnetic history), and taking into account that the relative measurement uncertainty on the transfer functions is of the order of a few %, magnetic hysteresis would dominate the uncertainty on Q'.

The hysteresis of the MCS is equivalent to 6 units of Q' at injection [9].

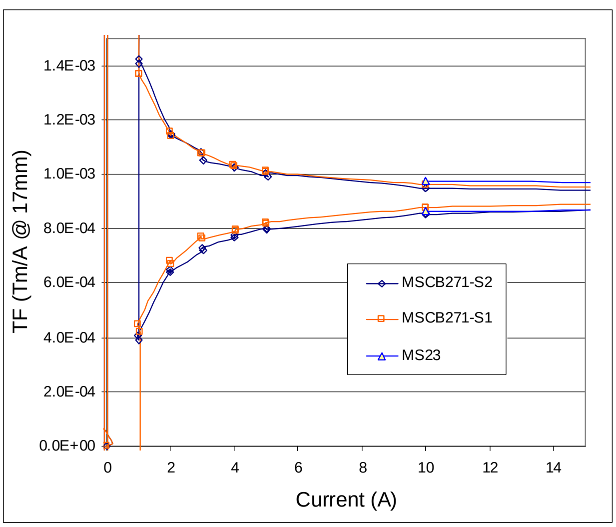

Fig. 4: Lattice Sextupoles transfer functions as a function of current

As done for the MQT, also for the MCS we have carried out measurements to asses the impact of hysteresis during decay and snapback compensation. The assumption made on the correction scheme was that the MCS would locally compensate the $\mathbf{b}_3(t)$ of the main dipole: this can of course only be done in average over one sector. We thus started from the expected average $\mathbf{b}_3(t)$ of the dipoles in sector 7-8, and used a first order approximation of the MCS transfer function to generate a current cycle for the corrections: the assumed transfer function TF_{MCS} was just a real number and the current-field relationship was therefore a straight line passing through the origin. The current function for the corrector is then: $I(t)_{MCS} = -\mathbf{b}_3(t)/TF_{MCS}$. The resulting MCS field was measured and its difference with respect to $\mathbf{b}_3(t)$ was translated in a residual (uncorrected) chromaticity.

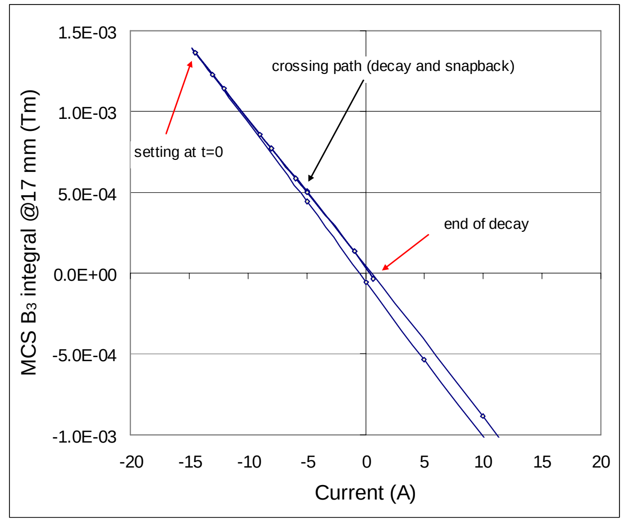

Fig. 5: Spool pieces sextupoles integrated strength as a function of current, simulating the compensation of decay and snapback of b_3 in the main dipoles of sector 7-8

In Fig. 5 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 is fairly linear; nevertheless the 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. 6. As already arguable by the fact that the hysteresis width corresponds to 6 units of Q', the error never exceeds 3 units.

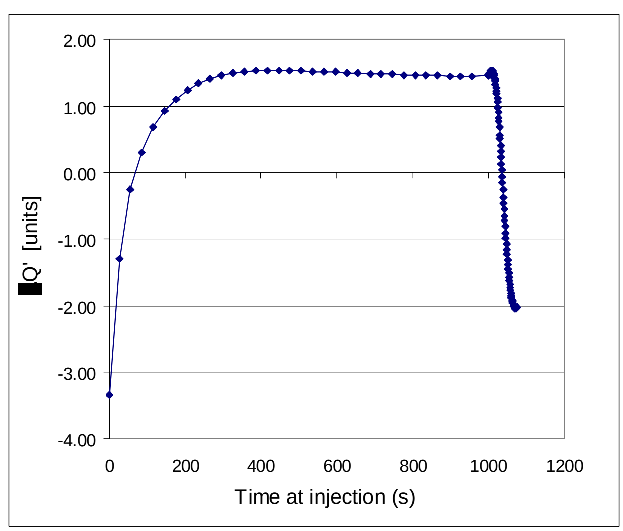

Fig. 6: Uncorrected chromaticity as a function of time during decay and snapback, resulting from non taking into account the corrector hysteresis

Landau Octupoles

At injection, the tolerance for the residual field of the Landau octupoles is of ±7.4 10^{-5} Tm at 17 mm per magnet [11]. As the actual residuals are in the order of a few 10^{-4} Tm, it is necessary to devise a pre cycle to suppress as much as possible the remnant fields at zero current.

The simplest conceivable "degaussing" cycle is just one saw tooth at a small negative current after a positive cycle at nominal current. We tried -10 A and -5 A, with encouraging results, as visible in Fig. 7.

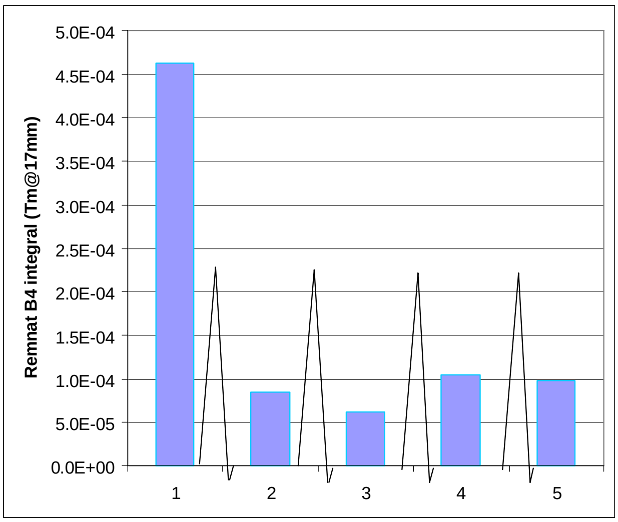

Fig. 7: Remnant octupole strength at zero current after a cycle at nominal, after 2 "degaussing" swings at -10 A, and at -5 A.

SUMMARY AND CONCLUSION

A precise assessment on the reproducibility of magnetic settings between runs is not yet possible. On one hand, the upper estimates that it is possible to give considering the major hysteresis loops are likely to be pessimistic, as it seems reasonable to expect some degree of averaging among the various circuits. On the other hand, the knowledge of the hysteresis, especially at low fields, is not yet satisfactory and more statistics is needed.

It is however clear that pre cycles will have to be implemented for all the corrector circuits to bring the magnets in a known magnetic state before each run.

The MQT magnets operate at very low currents at injection: the proposal was made to bias them at a few A, to stay out of operating points that are more difficult to measure and to model, and where the spread of the transfer functions could be enhanced by the proximity coupling of the superconducting filaments.

The correction cycle needed to compensate decay and snapback of $\mathbf{b}_2$ in the arc quadrupoles with the MQT was reproduced and it was shown that the correction, within the required tolerance for the tune shift, does not need to take hysteresis into account.

The lattice Sextupoles have hysteresis corresponding to chromaticity shifts much larger than tolerable.

The spool pieces sextupoles MCS need modelling of the hysteresis only if it is wished to keep the dynamic chromaticity error below 3 units during decay and snapback.

An important outcome of these measurements is the observation that it is possible to adapt the pre cycles in order to avoid to change the slope of the field to current relationships at the beginning of the snapback phase.

Concerning the possible perturbations of feed back controls, we provisionally conclude from the available measurements that hysteresis is not going to endanger the convergence of feed back loops.

The Field Quality Working Group held two meetings on correctors in 2005, and recommendations were issued [12], specifying the number and type of cold magnetic measurements to be executed for each type of corrector before LHC commissioning with beam. Subsequently, this test program was endorsed by the LHC Main Ring Committee. The work has begun and will be pursued after the end of the series tests, with the objective of providing a complete set of information on the corrector transfer functions in view of LHC commissioning.

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