WHAT IS THE IMPACT OF HYSTERESIS ON ORBIT CORRECTION AND FEEDBACK

Ralph J. Steinhagen*, CERN, Geneva, Switzerland

Abstract

During operation the LHC corrector magnets will perform multiple field changes and are expected due to the magnet hysteresis to be in a less precisely known state at the end of each run. To return them to a predefined state, each corrector has to be pre-cycled prior injecting first beam for the next fill. First hysteresis measurement results of the MCB orbit corrector magnets are presented and compared with fill-to-fill requirements, feedback operation and stability of the power converter driving the magnets.

INTRODUCTION

During operation, the LHC corrector magnets will perform multiple field changes and are expected to be in a less precisely known state at the end of each run, due to magnet hysteresis. Earlier contributions [1, 2] estimated that these effects may have a significant impact on fill-to-fill stability, reproducibility of settings, and operation of feedbacks, assuming the maximum possible width of the hysteresis loop. As only a few magnets are expected to run at full current, it was proposed to perform a detailed cold corrector measurement campaign using more likely (small) settings and current changes to assess the effect of the hysteresis under more realistic beam steering conditions and to estimate the effect of pre-cycling the corrector magnets on fill-to-fill stability and on reproducibility of injection settings.

This contribution presents initial results of the cold orbit corrector magnet measurements performed in 2005, evaluates the impact on injection orbit reproducibility and feedback operation, and provides a comparison with the uncertainty due to the corrector power converter stability. The hysteresis of the quadrupole and sextupole circuits are discussed in [3].

MCBH(V) CORRECTOR MAGNETS

There are, in total, 1060 orbit corrector dipoles in the LHC that can be grouped into 8 families. Analysing the majority (752 out of 1060) of corrector dipole magnets (CODs), we focus exemplarily on the stability and hysteresis of the 'MCBH(V)' type COD family. The results should qualitatively apply for the other magnet types, as (except of the 'MCBX' and 'MCBW' types) they have a similar design, parameter, and location in the machine. Table 1 summarises the parameter of all COD families.

Each 'MCBH(V)' magnet has a maximum integrated dipole field strength of $BL|_{max} = 1.896\,\mathrm{Tm}$ that corresponds to maximum possible deflection of

$$\begin{aligned} \delta_{max} &= 1260\,\mu\mathrm{rad} \quad @450\,\mathrm{GeV} \\ \text{resp.}\quad \delta_{max} &= 81\,\mu\mathrm{rad} \quad @7\,\mathrm{TeV}. \end{aligned} \tag{1}$$

Using the LHC arc injection lattice and $\beta_{max} \approx 180\,\mathrm{m}$, each COD can create a maximum beam orbit excursion of about $\delta x_{max} \approx 144\,\mathrm{mm}$ and $\delta x_{max} \approx 9\,\mathrm{mm}$ for 450 GeV and 450 GeV beam, respectively. It is clear that each corrector magnet is capable of deflecting the beam into the vacuum chamber at injection. Further analysis focuses on beam stability at the injection energy (450 GeV) as the beam is more sensitive to field errors and power converter ripples at low energies.

In 2005, the hysteresis properties of an exemplary MCB orbit magnet was measured at 1.9 K [6]. This measurement series was designed to clarify the reproducibility and deviation of the hysteresis after a predefined cycle, e.g. cycling through saturation or using a 'De-Gauss'-cycle and to check whether there is a minimum required current change in order to change the magnetic field/deflection of the CODs. The purpose of the first measurement was taken to provide an estimate of the expected contribution of the MCB CODs to fill-to-fill injection stability and reproducibility of settings due to the hysteresis, whereas the second determines the expected orbit correction convergence as a possible dead-band or quantisation effect might eventually limit the correction schemes of the feedback loop.

REPRODUCIBILITY AFTER PRE-CYCLING

There are two classes of proposed current pre-cycles that are exemplarily sketched in Figure 1.

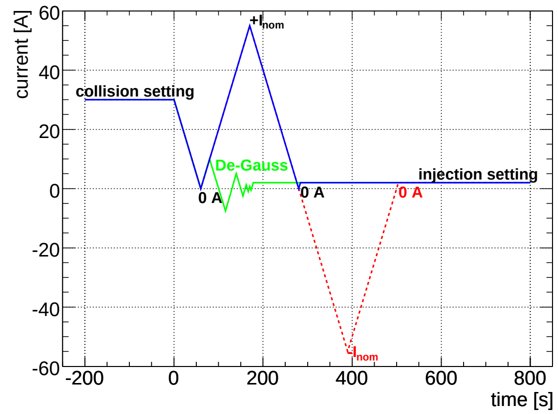

Figure 1: Schematic COD pre-cycles: cycle through positive saturation only (blue curve), through positive and negative saturation (red curve), or using a De-Gauss cycle with reducing amplitude (green curve).

* 3^{rd} Institute of Physics, RWTH Aachen University

Magnet Type	**B**	**L$_{\mathbf{mag}}$**	**BL$_{\mathbf{mag}}$**	I_{nom}	$\lvert\Delta I/\Delta t\rvert_{max}$	N_{LHC}
	[T]	**[m]**	**[Tm]**	**[A]**	**[A/s]**	
MCBH(V) @1.9K	2.93	0.647	1.90	55	0.5	752
MCBCH(V) @1.9K	3.11	0.904	2.81	100	1.0	156
MCBCH(V) @4.5K	2.33	0.904	2.11	80		
MCBYH(V) @1.9K	3.00	0.899	2.70	88	1.0	88
MCBYH(V) @4.5K	2.50	0.899	2.25	72		
MCBXH	3.35	0.45	1.51	550	5.0	48
MCBXV	3.26	0.48	1.56	550		
MCBWH(V)	1.1	1.7	1.87	500	5.0	16

Table 1: Available LHC corrector types. A complete parameter list can be found in [4, 5].

1. Cycling through saturation of the magnets (either through maximum '$+I_{nom}$' and/or minimal nominal current '$-I_{nom}$') ensuring that the magnetic history of the persistent current is erased; maximum remanent field is expected.
2. A De-Gauss cycle that applies an oscillating current with decreasing amplitude to the magnet. The initial current amplitude chosen has to be larger than the corresponding maximum expected remanent field. This cycle not only ensures that the magnetic history of the persistent current is erased, but also that the remanent field converges to zero.

In order to simplify controls, the currents are first set to zero before and after the pre-cycle prior to the new injection setting, for both pre-cycle types. The required time for both pre-cycle types is, for all orbit corrector magnets, in the order of 5- 10 minutes and at the LHC could be performed in the shadow while ramping down the main dipole magnets.

Reproducibility Measurement

We chose the first pre-cycle option to test the reproducibility and cycled the magnet through positive saturation only ('$I_0 = 0\,\mathrm{A} \leftrightarrow I_{nom} = +55\,\mathrm{A}$). After each cycle, the reproducibility of the remanent field at zero current was measured. Figure 2 shows the measurement results. Independend measurements show that the measurement reproducibility of about $2.5 \cdot 10^{-5}\,\mathrm{Tm}$, as measured at 1, 10 and 50 A. Since the cycle-to-cycle variation is larger, this excludes the contribution of the uncertainty of the measurement to the measured spread. Averaging over the measured cycles gives the following estimate for the remanent integrated dipole corrector field strength reproducibility and corresponding kicks, respectively:

$$\begin{aligned} BL_{mag} &\approx (8.4 \pm 0.8) \cdot 10^{-4}\,\mathrm{Tm} \\ \text{resp.} \quad \delta_{\mathrm{cod}} &\approx (560 \pm 53)\,\mathrm{nrad} \end{aligned} \tag{2}$$

It is important to note that these numbers are based on low statistic of only three cycles, which strictly speaking, correspond to a statistical confidence of less than one σ. The analysis revealed that the measurement may have been influenced by the power converter stability. It is known that

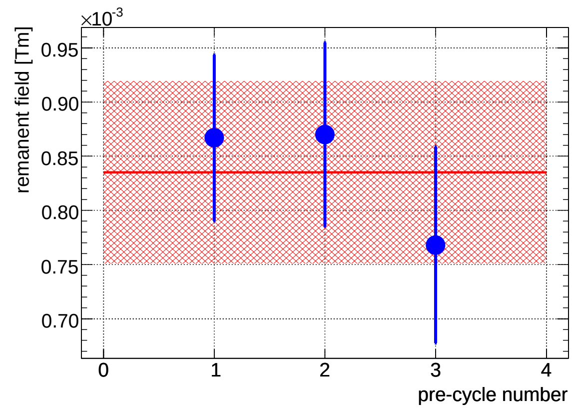

Figure 2: Field reproducibility at $0\,\mathrm{A}$ after pre-cycling the magnet through saturation. The plotted error bars (area) correspond to $1\,\sigma$ r.m.s.

converter stability around zero current is an issue. Further, these test were performed using a $\pm 600\,\mathrm{A}$ power converter that has at the nominal MCB current of $55\,\mathrm{A}$ a worse stability than the $\pm 60\,\mathrm{A}$ converter foreseen for the MCB type magnets in the LHC. In case more detailed measurements of these magnets are requested, the operational working point after cycling must be chosen to be different from zero current and if possible a nominal $\pm 60\,\mathrm{A}$ power converter be used.

Hence we believe that these numbers rather represent worst case estimates but however, are still a good estimate for fill-to-fill reproducibility of better than $10^{-4}\,\mathrm{Tm}$.

Implications for Fill-to-Fill Reproducibility

The remanent field given in equation 2 can be broken down into a systematic

$$\Delta\delta_{cod} = 560\,\mathrm{nrad} \tag{3}$$

and random

$$\sigma(\delta_{cod}) = 53\,\mathrm{nrad\ r.m.s.} \tag{4}$$

component that affect the beam in two different ways.

The pre-cycle was chosen to go always to positive saturation only. Hence the systematic kick $\Delta\delta_{cod}$ has for all correctors the same sign. In case of horizontal correctors this increases the total integrated dipole field and, as a result, the energy of the LHC. The maximum expected energy shift $\Delta E/E$ due to the horizontal MCB hysteresis is about $2 \cdot 10^{-5}$. Compared to the expected energy shifts of $1.5 \cdot 10^{-4}$ caused by the b_1 decay of the main dipole field and sun and moon tides, this contribution is negligible since this shift is reproducible from fill-to-fill and has, in principle, to be corrected only once. If required, a De-Gauss pre-cycle would minimise this contribution.

The $\sigma(\delta_{cod})$ component of about $53\,\mathrm{nrad\ r.m.s.}$ ($\sigma(\delta_{cod})/\delta_{max} \approx 4 \cdot 10^{-5}$) around the systematic part of the hysteresis causes a random orbit perturbation $\Delta x(s)$

$$\Delta x(s) = \frac{\sqrt{\beta_i \beta(s)}}{2\sin(\pi Q)} \cos(\mu(s) - \pi Q) \cdot \sigma(\delta_{cod}) \qquad (5)$$

around the ring that contributes to the total random fill-to-fill variation. Using either an analytical approach and applying an incoherent sum of the orbit corrector response (equation 5) or a numerical evaluation of the orbit response matrix due to random dipole kicks leads to the following estimate of the propagation factor between the random COD deflection $\sigma(\delta_{cod})$ and resulting orbit r.m.s. σ_H and σ_V, respectively:

$$\sigma_H \approx (966 \pm 245)\,[\mathrm{m/rad}] \cdot \sigma(\delta_{cod}) \qquad (6)$$
$$\sigma_V \approx (1004 \pm 275)\,[\mathrm{m/rad}] \cdot \sigma(\delta_{cod}) \qquad (7)$$

The simulated estimates are based on the LHC injection optics (LHC 6.5) and a seed of about 10^4 different orbits. The spread of the prediction reflects the distribution of different beta function and phase advance combinations that are sampled by the different seeds, and is not a numerical error. See [7] for details.

The expected orbit r.m.s during injection due to the hysteresis can be estimated to about $50\,\mu\mathrm{m}$ r.m.s. (0.05σ with σ being the beam size), using equation 4 and 7. This orbit excursion, solely due to the MCB hysteresis, is very small compared to the available aperture of about 11 mm, collimation requirements ($\Delta x < 0.3\sigma$) or expected ground motion contribution [7] ($0.3 - 0.5\sigma$). It is barely detectable with a LHC BPM shot-by-shot resolution of about $50 - 100\,\mu\mathrm{m}$ for a single nominal LHC bunch.

In conclusion, the expected systematic and random component of the hysteresis after pre-cycling the magnet should not pose a problem for reproducibility of the injection orbit or for threading the first circulating beam as it is within the shadow of much larger effects such as b_1 decay of the main dipole magnets, ground motion and other effects.

SMALL HYSTERESIS LOOPS

The orbit perturbations on the injection plateau, which are corrected by the orbit feedback, are expected to be in the order of about 0.5 mm as described in [7]. Assuming an arc COD at $\beta = 180\,\mathrm{m}$, this amplitude corresponds to an average current modulation around the initial COD working point of about 0.2 A at 450 GeV, which is small compared to the nominal current (55 A). 1 and 10 A are likely working points of the CODs, assuming a static random misalignment of the quadrupole magnets of 0.5 mm r.m.s. during injection and collision, respectively.

Small Hysteresis Loop Measurement

The small hysteresis loop of 0.2 A was measured around 1 and 10 A. Figure 3 shows the result of the 1 A measurement

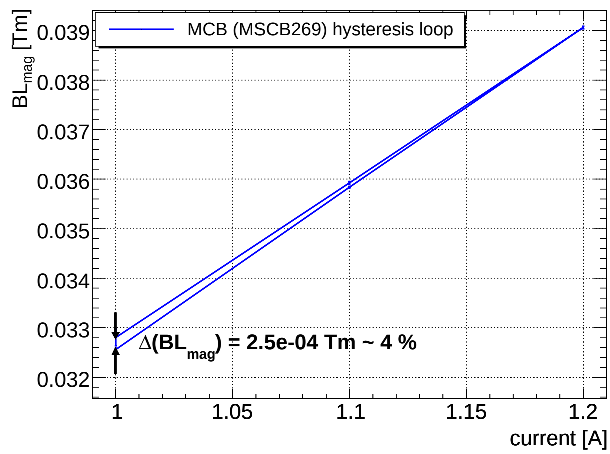

Figure 3: Exemplary small MCB hysteresis loop around 1 A.

The width of the small hysteresis loops are $2.4 \cdot 10^{-4}\,\mathrm{Tm}$ and $1.1 \cdot 10^{-4}\,\mathrm{Tm}$ at 1 A and 10 A, which correspond to deflections of about $\Delta\delta_{cod} = 167\,\mathrm{nrad}$ and $\Delta\delta_{cod} = 73\,\mathrm{nrad}$, respectively. This additional deflection due to the hysteresis can be translated into a scale error ϵ_{scale} of about $4\,\%$. In a feed-forward-only environment, this scale error would translate directly into a 4 % error with respect to the given reference orbit. It is important to note that, though the requested field change is less due to hysteresis, neither quantisation nor a dead-band effect has been observed. This shows that even a small current change yields an immediate change of the field, and hence deflection of the magnet. This hysteresis effect can be measured with the beam and corrected by beam-based alignment procedures such as the LHC Orbit Feedback.

Implication for Orbit Feedback Operation

The LHC Orbit Feedback relies on a Singular Value Decomposition (SVD) based global correction scheme with local constraints in space-domain and a Proportional-Integral-Derivative (PID) controller in time-domain as used in all modern light sources.

Space Domain The SVD algorithm is a eigenvalue-based method (see [8]) used to create the pseudo-inverse of the orbit response matrix. The strength of this algorithm is that near-singular solutions can be easily eliminated by the choices of numbers of eigenvalues $\#\lambda_{SVD}$ used for inverting the orbit response matrix. Singular solutions may arise, for example, due to optics errors, COD and BPM errors, and other effects that may potentially make the feedback loop instable. As an intrinsic property, the correction uses all (selected) CODs with rather small correction strengths compatible with the results from the small hysteresis measurements. Generally, a large number of used eigenvalues correspond to a more precise orbit correction, but which is more prone to BPM/COD failures and errors than if a small number of eigenvalues is used as shown in [10, 11].

The stability of the feedback in space domain has, among other errors, been studied for scale errors of the beam transfer function. The hysteresis has a similar impact on the beam transfer function as a quadrupole induced beta-beat for which the stability of the correction algorithm has been simulated for various LHC optics. The stability of the correction algorithm in space domain is given by the attenuation of the correction defined as:

$$\mathrm{attenuation} = 20 \cdot \log \left. \frac{\mathrm{orbit\ r.m.s.\ after}}{\mathrm{orbit\ r.m.s.\ before}} \right|_{\mathrm{ref}} \qquad (8)$$

For a good loop convergence in space domain, it is required that the attenuation be less than -3 dB. An exemplary result for the sensitivity to beta-beat of the SVD-based orbit correction using LHC injection optics and correcting the orbits for beam 1 and 2 is shown in Figure 4. It is visible that the

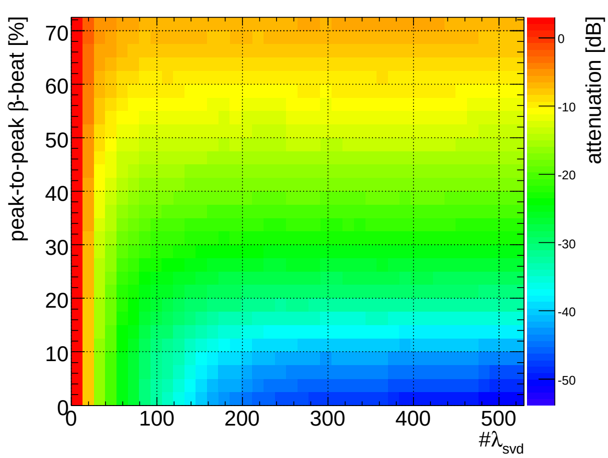

Figure 4: Orbit Feedback sensitivity to optics failures: The colour-coded attenuation of the orbit correction is plotted as a function of peak-to-peak beta-beat and for the inversion of the orbit response matrix used number of eigenvalues $\#\lambda_{SVD}$. It is visible that the $-3dB$ line is for $\#\lambda_{SVD} > 20$ above about 100% peak-to-peak beta-beat.

correction algorithm can cope with beta-beat up to about 100 % once $\#\lambda_{SVD} > 20$. Compared to the expected beta-beat, the small loop hysteresis effect will have a negligible effect on the spacial correction.

Time Domain In time domain, the feedback uses a standard PID controller to optimise the transition from the actual COD setting to the required steady-state deflection given by the space domain algorithm. The PID function and optimisation is well understood and does not require an accurate process model in order to get good parameter stabilisation [9]. The integral part of the PID is essentially responsible for the minimisation of model uncertainties (steady-state errors), non-linearities of magnet and beam transfer functions. It uses the integrated measured error signal which, in case of the orbit feedback, is the difference between reference and the measurement orbit. In contrast to feed-forward only, a continuous running feedback will measure the orbit error and minimise the effect of the hysteresis within a few iterations and will converge if underlying perturbations are slow compared to the feedback bandwidth. The MCB hysteresis, other uncertainties, as well as scale errors of transfer function thus rather affect the convergence speed (feedback bandwidth) than maximum achievable stability, which is determined by the noise floor of the beam position measurement and of the actuators (CODs).

POWER CONVERTER STABILITY

In 2005, a $\pm 8\,\mathrm{V}/\pm 60\,\mathrm{A}$ power converter that is foreseen for the LHC MCBH(V) magnets has been tested with a MCB cryogenic load attached[12]. The stability of the power converter was measured to $\frac{\Delta I}{I_{nom}} = 5 \cdot 10^{-6}$ with respect to its nominal current $I_{nom} = 55\,\mathrm{A}$. The stability corresponds to a random r.m.s. deflection of each MCB magnet in the LHC of

$$\sigma(\delta_{cod}) = 6.3\,\mathrm{nrad} r.m.s. \qquad (9)$$

Using equations 9 and 7, the noise floor due to the COD power converter can hence be estimated to

$$\Delta x \approx (6 \pm 2)\,\mu\mathrm{m r.m.s} \qquad (10)$$

corresponding to a stability of about $0.01\,\sigma$ (σ being the beam size), which is about the noise floor of LHC BPM system measuring with single nominal bunch ($100\,\mu\mathrm{m}$ shot-to-shot, 255 turn average).

REACHING NOMINAL STABILITY

In order to meet the tight requirements on energy, orbit, tune, chromaticity and other parameters, the following two-stage approach will be used in the LHC:

1. The first injected low-intensity beam, which (for machine protection reasons) is required prior to a nominal beam in the machine, is used to perform beam-based alignment and to minimise the fill-to-fill uncertainties due to hysteresis, b_1 decay random ground motion, and other effects.

2. Once the beam parameters have been optimised, the nominal beam may be injected and will be further stabilised by the feedbacks.

This procedure guarantees that the nominal beam will find similar beam parameter conditions as the low-intensity beam, since the beam physics does not change significantly from low to high intensities at the LHC energies. Even though the expected perturbations may be smaller than the tolerance, a continuously running orbit feedback is required to guarantee the stability in the event of unexpected effects that may perturb the orbit.

CONCLUSION

The hysteresis of the MCB type orbit correctors mainly affects the closed orbit of the first injected low-intensity beam and does not significantly affect feedback operation with circulating beam due to the integral part of their PID controller and intrinsically minimises unknown effects and errors due to wrong transfer function scale and hysteresis. For a good fill-to-fill reproducibility, each correction magnet should be cycled after the end of each run to return it to a more defined state for the next injection, for instance by cycling the magnets through positive saturation or a de-gauss pre-cycle. Both pre-cycle types require about 5 to 10 minutes and could be performed in the shadow while ramping down the main dipole magnets. The 2005 measurements of cold MCB corrector dipole hysteresis shows a reproducibility of the remanent field after precycling through saturation better than $10^{-4}\,\mathrm{Tm}$, which is small and compatible with requirements on the injection orbit. However, the estimate is based on very low statistic and confirms rather the qualitative low order of magnitude than the absolute precision. The stability of the MCB power supplies are likely to define the minimum achievable stability of the orbit after feedback correction to about $(6 \pm 2)\,\mu\mathrm{m\ r.m.s}\ (0.01\sigma)$. In order to ensure the required orbit stability, a continuous operation of the orbit feedback from the first low-intensity beam till the end of the fill is foreseen.

ACKNOWLEDGEMENTS

The numerous discussions and MCB magnet and power converter measurements of W. Venturini, A. Cantone, V. Montabonnet and J. Wenninger are gratefully achnowledged.

REFERENCES

[1] W. Venturini, “Magnetic Behaviour of LHC correctors: Issues for Machine Operation”, Proceedings of Chamonix XIV, 2005

[2] J. P. Koutchouk, S. Sanfilippo, “Magnetic Issues affecting Beam Commissioning, Session Summary”, Proceedings of Chamonix XIV, 2005

[3] W. Venturini, “Hysteresis in magnet correctors versus tune and chromatic correction”, Proceedings of Chamonix XV, 2006

[4] F. Bodry, “LHC Power Converters - Performance Requirements”, Proceedings of Chamonix XI, 2001

[5] CERN, “LHC - The Large Hadron Collider”, http://lhc.web.cern.ch/lhc/ and references therein

[6] W. Venturini et al., “Hysteresis measurement of a twin aperture MCB orbit corrector”, AT-MTM internal Memo, 2005-10-19

[7] R. J. Steinhagen, “Analysis of Ground Motion at SPS and LEP, Implications for the LHC”, CERN-AB-2005-087, 2005

[8] G. Golub and C. Reinsch, “Handbook for automatic computation II, Linear Algebra”, Springer, NY, 1971

[9] G. Ziegler and N. B. Nichols, “Optimum settings for automatic controllers”, Trans. A.S.M.E., Vol. 64, pp. 759-765, 1942

[10] R. J. Steinhagen, “Can the LHC Orbit Feedback save the beam in case of a closed orbit dipole failure?”, MPWG #46, 2005-06-01

[11] R. J. Steinhagen, “Closed Orbit and Protection”, MPWG #53, 2005-12-16

[12] A. Cantone, V. Montabonnet, “60A Converter Testing in SM18”, private communications, 2005