Field Quality vs Beam Based Corrections in Large Hadron Colliders

O. Brüning,
CERN, Geneva, Switzerland

Abstract

After summarising the main types of field errors in superconducting magnets the paper discusses limits for correcting the magnet field quality via dedicated correction circuits in a collider storage ring and the possibility of adjusting the powering of such correction circuits via beam based measurements.

1 INTRODUCTION

The performance of any future Large Hadron Collider depends to large extent on the field quality of the superconducting magnets. During the design phase of the magnets one has to find an acceptable compromise between the specified magnet field quality and the magnet production cost. During the magnet production the field errors can be further optimised via online magnet corrections[1].

Beam based corrections via dedicated correction circuits in the final hadron collider are the last resort for reducing the net field errors in the machine to acceptable levels during operation. This last method of controlling the non-linear field errors in the machine is limited by the number of required correction circuits, the available beam and magnet instrumentation and the 'non-locality' of the correction. In the following we will mainly discuss the last two limitations and illustrate the large number of correction circuits using the example of the LHC correction circuits.

2 FIELD ERROR TYPES IN SUPERCONDUCTING MAGNETS

Superconducting magnets have three different types of field errors. Static errors which are generated by geometric errors in the coil cross section, deformation of the coils and contributions from the magnet collars. In principle, the static field errors only need to be corrected once. However, in the following we will discuss how changing alignment errors might lead to changing feed down errors of the geometric errors.

The second type of field errors in superconducting magnets are the persistent and eddy currents. Persistent current errors originate from current loops in the superconducting filaments. Eddy current errors originate mainly from current loops over different strands of the superconducting cable. Both persistent and eddy current loops decay with time resulting in magnetic field errors that depend on the magnet cycle history and change with time. The field error decay depends on the flux creep phenomenon in hard super conductors and the electro-magnetic interplay of the eddy and persistent current loops. Two different decay processes are used to model the field error decay. The HERA magnets could be modelled by a logarithmic decay process [2]

$$b_n = b_{n,0} + b_{n,1} \cdot \log(t/\tau) \qquad (1)$$

and the RHIC magnets by a double exponential decay [24]:

$$b_n = b_{n,0} + b_{n,1} \cdot exp(t/\tau_1) + b_{n,2} \cdot exp(t/\tau_2). \qquad (2)$$

At the beginning of the ramp the persistent current field error 'snaps back' to its initial value reversing the decay process over a short time scale.

In addition to these three error classes the field errors can be characterised by error contributions that are common to all magnets (systematic field errors), error contributions that are only common to all magnets of one productions line (uncertainty field error) and purely random field error contributions. For the LHC it is planned to equip each arc of the machine with magnets from the same production line and the uncertainty error of the magnets is equivalent to the difference between the systematic field error per arc and the overall average error of all production lines. However, the installation cost and logistics could be simplified by mixing the magnets from different production lines if the uncertainty errors turn out to be small.

In the following we discuss only a correction of the systematic and uncertainty field error components.

3 DEDICATED CORRECTOR CIRCUITS IN THE STORAGE RING

There are three possible implementations for corrector elements in a storage ring:

- a true local correction of the magnetic field errors via correction coils inside the main magnet
- a quasi local correction of the magnetic field errors via dedicated corrector elements placed at the ends of the main dipole magnets
- a non-local correction of the magnetic field errors via correction elements that are not attached to the dipole magnets

The first method was implemented for the non-linear field error correction in the HERA proton storage ring. The quadrupole, sextupole and decapole correction coils (b_2, b_3 and b_5) are wound onto the vacuum chamber inside the main dipole magnets and the dodecapole correction coils (b_6) are wound onto the vacuum chamber inside the main quadrupole magnets [3]. While the above correction system offers a true local correction of the dipole field errors it also has three disadvantages which makes it difficult to be implemented in a large hadron collider:

- The system reduces the mechanical aperture of the main magnets. In the case of HERA the correction coils reduce the mechanical aperture by approximately 3mm (radius)[4].
- The critical current of the correction coils depends on the strength of the external magnetic field. If the correction coils are placed inside strong dipole magnets the critical current will be low and the correction coils require a large amount of superconducting material (→ reduced aperture and increased costs for the correction elements).
- In case of nested correction coils the field adjustments can not be done independently and a precise adjustment of the correction circuits depends on a proper sequence of magnet adjustments.

The above disadvantages of the nested correction coils motivated the choice for quasi local and non-local corrector elements for the LHC. The field error correction in the LHC is tailored towards a correction of the systematic errors per arc (uncertainty). Each arc is equipped with two types of correction elements: lattice corrector elements which are installed next to the FODO cell quadrupoles providing a non-local correction of the magnet field errors and so called spool piece corrector magnets which are directly attached to the LHC dipole magnets. The set of lattice corrector elements consists of dipole magnets (b_1 and a_1) for the closed orbit correction, quadrupole (b_2) circuits for tune adjustments, skew quadrupole (a_2) circuits for the coupling correction, sextupole elements (b_3) for a correction of the natural chromaticity, skew sextupole elements (a_3) for a correction of the chromaticity coupling and octupole magnets (b_4) for the generation of Landau damping. The spool piece circuits consist of sextupole correctors which are attached at one end of each dipole magnet and a combined package of octupole (b_4) and decapole (b_5) correctors which is attached to the other side of every other dipole magnet. Each of the eight LHC arcs has an individual powering of its correction circuits allowing a correction of the systematic error per arc. Random errors can only be globally corrected. The above system yields a total of 108 correction circuits for the LHC machine per beam (excluding the individually orbit corrector magnets). The correction circuits of the triplet assembly adds 48 additional correction circuits which are common to both beams. Verifying the proper functionality of this large number of circuits during commissioning and properly adjusting them during operation presents a quite challenging task for the operation of the LHC.

4 CORRECTOR ADJUSTMENTS DURING MACHINE OPERATION

Adjusting the correction circuits during the machine operation requires a proper beam diagnostic system and a set of measurement techniques that are compatible with the nominal machine operation. The random b_1, a_1 and b_2 field errors can be measured via beam orbit measurements [5]. The systematic b_1 field error can be measured via the longitudinal injection oscillations. The global and local coupling can be measured via tune and local bump measurements [6][7]. and chromatic measurements provide information on the systematic b_3, a_3, b_4 and b_5 field errors [8]-[10]. Expanding the chromatic tune dependence into a Taylour series up to third order in $\delta p/p_0$ one gets

$$Q = Q_0 + Q^{'} \cdot \frac{\delta p}{p_0} + \frac{1}{2} \cdot Q^{''} \cdot \left(\frac{\delta p}{p_0}\right)^2 + \frac{1}{6} \cdot Q^{'''} \cdot \left(\frac{\delta p}{p_0}\right)^3 \quad (3)$$

The b_3 error changes the linear machine chromaticity, the a_3 and b_4 errors generate a second order chromaticity ($Q^{''}$) and the b_5 error a third order chromaticity ($Q^{'''}$).

Transverse orbit displacements inside a multipole field imperfection generates feed down errors according to [11]

$$(b_{n-k} + i a_{n-k}) = \frac{(n-1)! \cdot (b_n + i a_n)}{(n-k-1)! \cdot k!} \cdot \frac{(\triangle x + i \triangle y)^k}{R_r^k} \quad (4)$$

where n is the order of the original error, $\triangle x$ and $\triangle y$ the horizontal and vertical orbit displacements inside the original multipole error, k the order of the feed down and R_r the reference radius for the field error expansion. magnets). Generating closed orbit bumps along the machine and measuring the tune changes and non-closure of the bump provides information on the local correction of all multipole field errors up to a_6 and b_6 [12]-[14].

Fourier analysis of the BPM readings with beam excitations (either single kicks or AC dipole excitations) provide information on local resonance driving terms [15]-[18].

The above beam based measurements can be complemented by online magnet measurements. For example, the HERA storage ring features two reference magnets which are powered in series with the main machine dipole magnets but are not installed in the machine. The reference magnets are equipped with NMR probes and rotating coils which provide online information on the magnetic field quality. This information on the field quality is used in operation to adjust the correction system for the systematic b_1 and b_3 field errors [19].

5 LIMITS FOR THE FIELD ERROR CORRECTION

5.1 Limits for Static errors

Mechanical Acceptance Random dipole field errors generate closed orbit perturbations and the random quadrupole field errors a β-beat and a horizontal and vertical spurious dispersion along the storage ring. Both effects reduce the available machine aperture expressed in terms of the rms beam size. The maximum acceptable limit for the random dipole and quadruple field errors depends on the available machine aperture, the number and distance of the BPMs and orbit correctors and the alignment errors of the BPMs [20].

Limits due to Non Local Corrections We will use the b_5 field error correction as an example for limits due to the non-local correction. A b_5 field error in the dipole magnets reduces the long term stability of the single particle motion and generates a third order chromaticity which is given by [13]

$$Q''' = \frac{6}{\pi R_r^4} \int \frac{b_5 \cdot \beta \cdot D_x^3}{\rho} ds. \qquad (5)$$

For an optimum machine operation one would like to compensate both effects, the chromatic perturbation and the perturbations on the single particle motion. The chromatic perturbation is proportional to the b_5 field error and the product $\beta \cdot D_x^3$. Figure 1 shows the β-functions and the

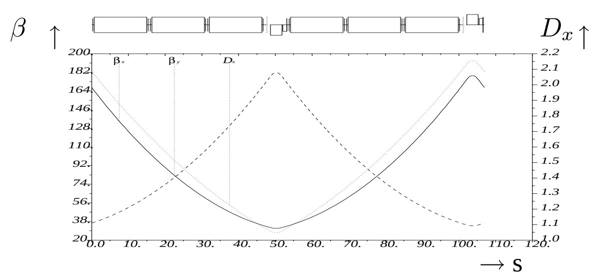

Figure 1: *The β-functions and horizontal dispersion in the LHC arc cell.*

horizontal dispersion in one LHC arc cell showing that the product $\beta \cdot D_x^3$ varies by more than 50% over the dipole length. A b_5 spool piece corrector that is attached at the end of the dipole magnets can therefore never simultaneously correct the integrated b_5 field error and the third order chromaticity Q''' [9]. The adjustments of the b_5 circuits must find a compromise between an imperfect chromatic correction (→ limited momentum acceptance of the machine) and an imperfect b_5 correction (→ limited dynamic aperture of the machine). The maximum acceptable compromise between chromatic and integrated b_5 correction imposes an upper limit to the maximum acceptable b_5 field error [20].

Feed Down Errors Alignment errors of the spool piece and lattice correction elements and orbit errors inside the lattice corrector elements generate feed down errors [21]. The feed down field error is given by Equation (4). In the case of long dipole magnets a proper alignment of the spool piece elements with respect to the design orbit requires a precise modelling of the particle trajectory inside the dipole magnet, a good correlation between the magnetic and geometric magnet axis and a tight control of the magnet shape during the magnet production, the cryostating, the magnet transport and the thermal cycling [22]. The resulting feed down errors can limit the maximum acceptable multipole field errors. For example, the maximum acceptable systematic b_3 error in the LHC dipole magnets at injection is not limited by the long term stability of the single particle motion but by the β-beat resulting from the quadrupole error feed down due to alignment tolerances. Assuming random alignment errors of 0.5mm rms for the sextupole spool piece elements one obtains for 10.7 units of b_3 dipole field error the same contribution to the β-beat as from a random b_2 field error of 0.7 units rms (one unit corresponds to a field error coefficient of 10^{-4}).

The tolerance for the spool piece alignment errors is further reduced by pitch and yaw angle errors of the magnets in the tunnel. Assuming a 14 meter long dipole magnet with spool piece elements at its extremities, a random pitch error of 0.05 mrad corresponds to an effective spool piece alignments error of 0.35 mm which represents already 50 % of the alignment error budget for the LHC spool piece elements. Therefore, controlling the effective alignment error of the spool piece elements not only requires tight manufacturing tolerances during the magnet production but also tight tolerances and survey requirements for the installation process in the tunnel.

In the triplet magnets the non-local multipole correction may limit the maximum crossing and thus the machine performance.

5.2 *Limits for Time dependent effects*

We give two examples for limits arising from the time dependent effects.

Energy error due to Systematic Dipole Field Errors A systematic b_1 error in all arcs results in an energy error and a tune change via the natural chromaticity. The energy error is given by

$$\frac{\Delta p}{p_0} = b_1 \cdot 10^{-4} \qquad (6)$$

The available bucket area determines the maximum acceptable b_1 at injection. For example, capturing the proton bunches from the SPS in the LHC RF buckets requires that the beam energy in the LHC satisfies

$$\frac{\Delta p}{p_0} \ll 10^{-4} \rightarrow b_1(S) \ll 1 \qquad (7)$$

during the injection process. The systematic b_1 error due to persistent current decays is approximately one order of magnitude larger than the above limit and requires correction during the injection process. One possibility for such a correction is a powering of the horizontal orbit correctors next to the focusing quadrupoles. This method is being used in the HERA proton storage ring. However, the non-local aspect of this correction method generates an orbit error along the machine. Fig. 2 shows the resulting orbit distortion for a systematic dipole field error of 2.6 units in the LHC machine when it is corrected using the horizontal orbit corrector elements. The orbit distortions are larger than 1 σ and require a dynamic correction of the rms orbit during the injection process. However, for larger persistent

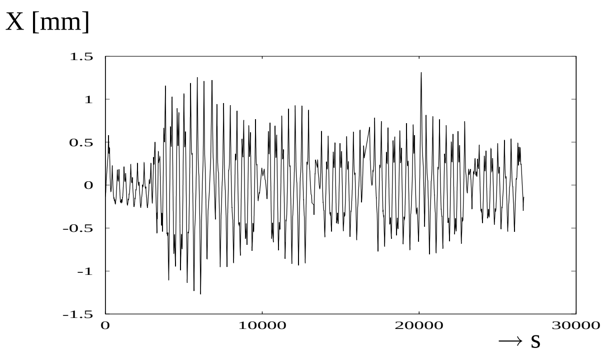

Figure 2: *Orbit distortion in mm along the LHC for $b_1(S) = 2.6$ and a b_1 compensation using the horizontal orbit correctors next to the focusing quadrupoles.*

current dipole field errors the dynamic orbit correction during the injection process might impose tight constraints to the online orbit correction.

Change in Chromaticity due to Systematic Sextupole Errors The systematic b_3 persistent error decay in the main dipole magnets changes the chromaticity of the machine by

$$\triangle\xi = \frac{2N_{MB}}{4\pi} \cdot \frac{<\beta_x> \cdot L \cdot <D_x>}{R_{ref}^2 \cdot \rho} \cdot b_3 \cdot 10^{-4}, \quad (8)$$

where N_{MB} is the number of dipole magnets, $<\beta_x>$ the average horizontal β-function, $<D_x>$ the average horizontal dispersion, R_{ref} the reference radius for the multipole errors, ρ the radius of curvature inside the dipole magnets, L the dipole magnet length and $\delta p/p_0$ the relative momentum error. Inserting, for example, the LHC parameters $N_{MB} = 1232$, $<\beta_x> \approx 85$ meter, $<D_x> \approx 1.4$ meter, $R_{ref} = 17$ mm and $L/\rho = 2\pi/1232$ into Equation (8) one gets for the chromaticity $\triangle\xi \approx 41 \cdot b_3$. Figures 3 and 4 show the sextupole persistent current decay in the LHC and RHIC dipole magnets respectively [23] [24]. The maximum sextupole persistent current variation of the LHC dipole magnets covers approximately 2.5 units of b_3 corresponding to a maximum chromaticity decay of 100 units. The maximum sextupole field error variation of the RHIC magnets is approximately 1.5 units corresponding to a maximum chromaticity variation of 2 units [24].

While the change in chromaticity might still be acceptable in RHIC it definitely requires a dynamic correction in the case of the LHC. Figure 5 shows a comparison between the expected chromaticity change based on magnet field error measurements and the measured changes during operation for RHIC [24]. The left hand side shows the expected values for the chromaticity change based on a double exponential fit of the b_3 decay and the right hand side to a logarithmic fit. The upper and lower two solid curves correspond to the expected chromaticity change for the average b_3 decay. The estimates for the maximum change in chromaticity differ by approximately 40 %. The two

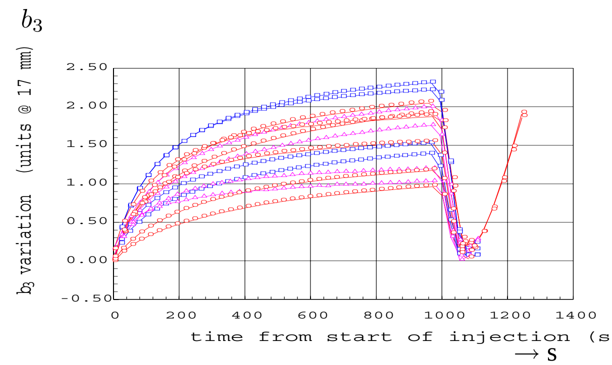

Figure 3: *Sextupole field error decay in the LHC dipole magnets versus time (including snap back).*

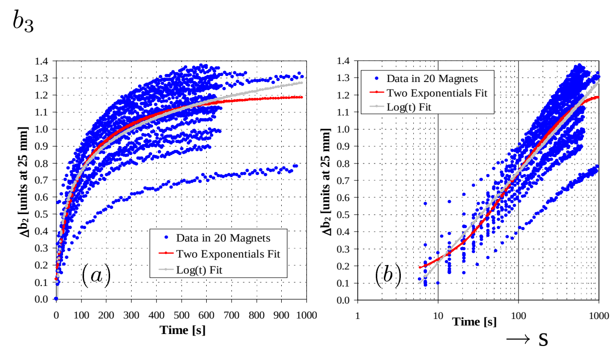

Figure 4: *Sextupole field error decay in the RHIC dipole magnets versus time.*

central dashed curves correspond to a fit based on one single magnet measurement which was chosen such that the estimates reproduce the final value for the change in chromaticity. However, while the final values of the estimates agree with the machine measurements the estimates still differ by approximately 50 % at the beginning of the decay precess. While these discrepancies are still acceptable for

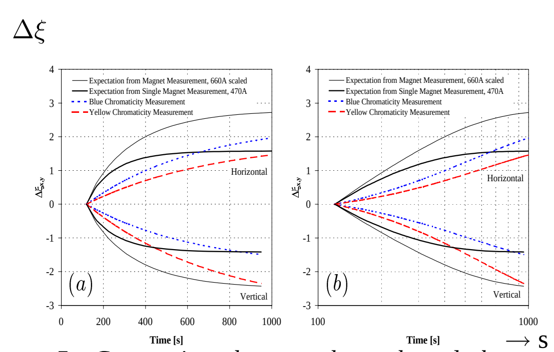

Figure 5: *Comparison between beam based chromaticity measurements and the predictions from magnet measurements in RHIC.*

RHIC they are approximately two order of magnitudes too large for the LHC and the correction of the dynamic sextupole field error decay in the LHC can not rely on magnet measurements only. In order to control the chromaticity during the persistent current decay and snap back within one unit, the machine operation requires beam based feed back from online chromaticity measurements.

Apart from the classical chromaticity measurement via RF frequency shifts, there are currently several new techniques for the chromaticity measurement under study[25]-[27]. Table 1 summarises the pro and cons for the different measurement options. There is not one single chromaticity measurement technique which covers all the applications for the LHC operation. The first two methods can generate a large $\delta p/p_0$ and, thus, allow the measurement of the nonlinear chromaticity. The third method, the head tail measurement, is the only fast chromaticity measurement that has been demonstrated to work in existing storage rings. Unfortunately, it requires large beam excitations and is destructive. The LHC requires at least measurements with the first and third method. The last measurement options is a new proposal for fast, non-destructive measurements of the linear chromaticity [27].

Technique	Limit	Advantage
RF frequency shift	slow	large $\delta p/p_0$
off momentum ramps	several ramps	large $\delta p/p_0$
head tail oscillations	beam blow up	fast
RF phase modulation	small $\delta p/p_0$	fast

Table 1: *Potential measurements techniques for the chromaticity measurement.*

The maximum acceptable tolerance for the dynamic sextupole field error changes depends on the performance of the online chromaticity measurements during operation and the level of understanding the connection between magnetic sextupole field error measurements and the resulting machine chromaticity during operation.

6 SUMMARY

Estimates for the maximum acceptable field errors for a future large hadron collider require a combined analysis of the multipole field errors and alignment errors and any future magnet design should aim at a robust design that facilitates control of the magnet shape during the magnet production, the cryostating, the magnet transport and the thermal cycling.

In the case of long dipole magnets the feed down errors have significant contributions from the pitch and yaw alignment errors in the tunnel. Therefore, controlling the effective alignment error of the corrector elements not only requires tight manufacturing tolerances during the magnet production but also tight tolerances and survey requirements for the installation process in the tunnel.

The operation of a large hadron collider requires a global correction of the sextupole errors so that the machine chromaticity changes by less than one unit during the machine operation. Modelling the changes of the machine chromaticity via magnet measurement data (off line or online) without additional feedback from beam based measurements still produces errors of up to 50 % of the uncorrected chromaticity changes. Relaxing the tolerances for the persistent current sextupole field errors for a future large hadron collider requires the development of fast, nondestructive online chromaticity measurements that can be used during routine machine operation.

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