REQUIREMENTS FOR REAL TIME CORRECTION OF DECAY AND SNAPBACK IN THE LHC SUPERCONDUCTING MAGNETS

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Abstract

The Large Hadron Collider (LHC) superconducting magnets will have field errors with both static and dynamic components. These will affect the key beam parameters such as energy, tune, orbit and chromaticity. The allowed variations in these beam parameters during injection and the energy ramp are extremely small. The required compensation of certain multipole components of the field errors can probably not be performed with feed-forward correction alone. Real time control of beam parameters via appropriate correction magnets is therefore proposed. This paper outlines the requirements for such real time control

1 INTRODUCTION

The LHC aims at injecting, accelerating and then colliding beams with very well controlled beam parameters (e.g. momentum, orbit, tune and chromaticity, …) in an efficient, reliable and reproducible manner. This is a non-trivial task since the small aperture, the high stored beam energy and the sensitivity of the machine to beam loss impose very tight accelerator physics constraints. The superconducting magnets will generate field errors that have large static and dynamic components [1]. It was recognised in an early stage [2] that satisfactory operation of the machine would require real time control of beam parameters.

Static effects in the superconducting magnets are caused by, for example, the deformation from the ideal dipole geometry. These static field errors can be controlled during production and are reproducible. The idea is to account for them via feedforward corrections into the ramping tables.

Field errors that have dynamic effects are our main interest here. These field errors are mainly caused by eddy currents in the superconducting cables and by interaction between cable currents and DC magnetisation. Decay of these current is manifested as a decay of the multipole errors seen by the beam at constant current and a fast recovery ("snap-back") when the current is varied again. The contribution from the eddy currents can be difficult to control and it is difficult to account for the associated field errors using feedforward correction alone. Whether real time control of beam parameters via the power converters is feasible depends to a large extent on the time constants and the time delays introduced by the elements in the control loop. In this paper we will estimate these time constants based on the predicted evolution of the field errors during injection and the start of the energy ramp.

2 FIELD ERRORS DUE TO DYNAMIC EFFECTS

2.1 Statistic and random field errors

The standard multipole expansion for the magnetic field of a main dipole is relative to the main field B_1 of the magnet at $R_{ref} = 17$ mm from the magnet bore radius. Supposing that a_n and b_n represent the skew and normal relative field errors (with $n=1$ the dipole field), we have:

$$\vec{B}_y + i\vec{B}_x = \sum_{n=1}^{\infty} C_n \left(\frac{z}{R_{ref}}\right)^{n-1} = B_1 \sum_{n=1}^{\infty} \frac{(b_n + i a_n)}{10^4} \left(\frac{z}{R_{ref}}\right)^{n-1}$$

where $z = x + iy$. The field errors are expressed in units of 10^{-4} of the main field component $\boldsymbol{B_1}$ at a reference radius of R_{ref} = 17 mm. For the field of a main quadrupole, errors are expressed in units of 10^{-4} of the main quadrupole component $\boldsymbol{B_2}$ at a reference radius of R_{ref} = 17 mm.

We will distinguish between *systematic* and *random* components of a field error. The *systematic* component of a field error is the average error over all main dipole (quadrupole, …) magnets. The *random* component of the field error is due to the differences between the individual dipoles (quadrupoles, …).

Correction of the *systematic* errors will be achieved by feedforward and feedback control. Real time correction of the variations induced by *random* field errors is outside the scope of this paper with the exception of the correction of the closed orbit induced by $\sigma(\Delta b_1)$ the *random* error on the "normal" component Δb_1.

In terms of the notation given above, we will study the effects on the beam related to systematic errors on the "normal" field components b_1, b_2 and b_3 and the random error on the field component b_1. The effects on the beam related to the "skew" field errors will not be discussed here.

2.2 Decay and Snapback

Decay is characterised by a significant drift of the multipole errors when the current in a magnet is held constant, for example during the injection plateau. When the current in a magnet is increased again (for example, at the start of the energy ramp), the multipole errors bounce back ("snap back") to their pre-decay level following an increase of the operating current by approximately 20 A. For the energy ramp such as described in [3], the snap back takes 50-80 seconds but this can vary if, for example, the rate of change of current in the magnet is changed.

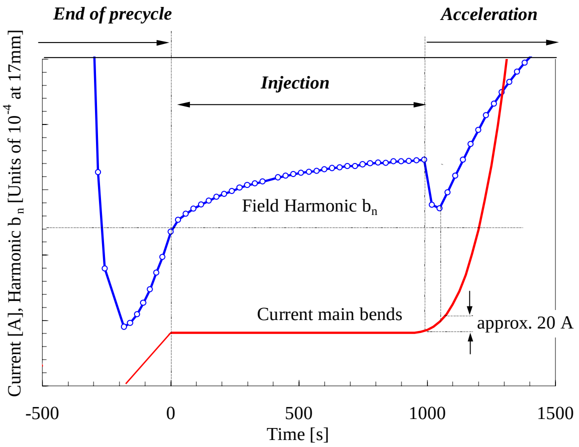

Figure 1: Example of the decay of a field error in a LHC dipole showing the current in the dipole and the evolution of the field error b_n as a function of time.

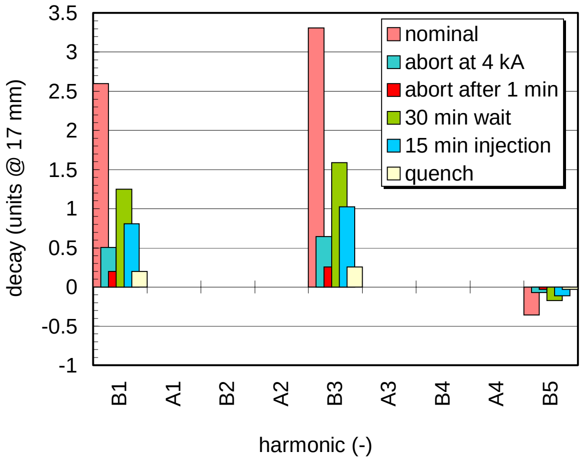

Figure 2: The magnitude of the decay of field errors in the main bends (in units of 10^{-4} of the main dipole field) for various operational scenarios.

The magnitude of the decay depends very much on the magnetic history and the characteristics of previous operating cycles (see figure 2). The decay of the field errors is caused by the variation of so-called persistent currents in the magnets and is difficult to predict. Recent modelling efforts indicate that a prediction will have an error between 5 to 30%. More accurate mdels and measurements from the reference magnets are expected to compensate around 80 % of the decay and snap back.

2.3 Physics Operation margins

The beam physics requirements are described in detail in [4] and can be summarised as follows :

- control the energy to within $\Delta p/p < 3\times10^{-4}$
- keep the peak orbit excursion inferior to 0.4 σ in the arcs and less than 0.2 σ in the IPs and in the cleaning sections (σ is the beam size).
- keep the RMS orbit excursion less than 1 mm
- keep the tune excursions small ($\boldsymbol{\Delta Q}<3\times10^{-3}$)
- keep the variation of the chromaticity ξ less than or equal to 1 unit.

We assume that these requirements are also valid during the injection plateau with the exception of the energy error : here the RF capture system demands that the energy remains constant to within $\Delta p/p < 1\times10^{-4}$. In order to remain within this limit, the integral dipole field should remain constant for the duration of injection to within $\Delta|b_1| < 0.5$ units.

3 VARIATION OF BEAM PARAMETERS

The effect of the multipole variation on the beam during the injection plateau has been computed with the MAD code and summarised in table I.

parameter	Field Harmonic	Magnet	Total Variation
$\Delta p/p$	$\Delta b1$	MB	2.6×10^{-4}
peak orbit	$\sigma(\Delta b1)$	MB	1.6 mm
RMS orbit	$\sigma(\Delta b1)$	MB	0.4 mm
Q	$\Delta b1$, $\Delta b2$	MB,MQ	35×10^{-3}
ξ	$\Delta b3$	MB	170

Table I: Variation of beam parameters due to persistent current decay in the LHC Main Bends (MB) and Main Quadrupoles (MQ)

The integrated effect of the persistent current decay on the beam is identical during injection plateau and at the start of the ramp (but with opposite sign, see figure 1). During injection, the decay of the integral dipole field is expected to generate a momentum variation of $\Delta p/p = 2.6\times10^{-4}$. The resulting mismatch between the energy of the beam given by the main bends and the quadrupole gradients will lead to a tune shift of $\Delta Q = \xi_N \Delta p/p = 0.03$ (where ξ_N, the natural chromaticity, is around 100). The *random* error in b_1 will disturb the orbit (ignoring higher order effects) and we expect a RMS horizontal closed orbit distortion of around 0.4 mm with a maximum excursion of around 1.6 mm. The *systematic* error on b_2

induced by the main quadrupoles is expected to give a tune shift of ΔQ=1.1x10^{-5}. The *systematic* error on b_3 due to persistent current decay in the dipoles is estimated at 3.3x10^{-4} that will cause nearly 170 units of chromaticity swing (!).

At the end of the injection plateau, the entire beam has been injected so there is no longer any concern about injection energy offsets. The *systematic* error on b_1 will affect the energy of the beam but not the orbit since this is defined by the central RF frequency. If uncorrected the variation of the energy results in a tune shift via the natural chromaticity (see above) of ΔQ= 0.03. The closed orbit and the chromaticity are expected to vary the same amount as during the injection plateau.

4 REAL TIME CONTROL

The present idea is to correct the perturbing effects on the beam with feedforward and feedback control. Feedforward control consists in using the experience from previous fills and on-line measurements from the reference magnets. Feedback control will reduce any remaining effects.

The frequency bandwidth that is required for feedback control during the snap back phase has been the subject of many debates. The key issue is to determine the frequency of the field harmonics induced by the snap back (f_{sb}) for a given energy ramp. Once this is known, the required sampling rates can be obtained by combining the physics requirements and data from table I and including 80 % error reduction due to feedforward control. One has to remember here that a control loop which samples at 1 Hz will have a closed loop bandwidth of 0.1 Hz and will reduce errors with a gain of 2 at 0.05 Hz, a gain of 4 at 0.025 Hz and so on.

We used a theoretical model [6] to estimate the snap back frequency of the ramp as described in [3] at f_{sb} = 4.3 mHz.

Table 2: Required correction and associated closed loop bandwidths for feedback control loops during a nominal ramp (feedforward error reduction of 80 % included).

Beam Parameter	Required correction	Required Gain loop	Frequency loop
Momentum	5x10^{-5}	–	–
Peak Orbit	1.6 mm	6.4	0.03 Hz
RMS Orbit	0.12 mm	-	-
Tune	7x10^{-3}	3	0.013 Hz
Chromaticity	34	34	0.14 Hz

Although it is expected that the benefit from feedforward control will increase as we learn more about operating the LHC, it remains an open question as to what extent feedforward control will be able balance the persistent current decay.

5 CONCLUSIONS

If the LHC is ramped in a smooth and slow mode from the injection plateau, snapback effects will not have such a big impact on the beam parameters. Based on the figures that have been present here, it seems that the snap back has a characteristic frequency of the order of 10^{-3} Hz. The amplitude of the beam perturbations due to persistent current decay are such that the short term stability limits will be reached, even when the overall effect due to systematic errors has been reduced by 80% using feedforward correction (i.e. tables, modelling and reference magnets). This concerns the tune and the chromaticty in particular but also applies to control of the peak orbit in critical sections of the machine.

It has been proposed here to implement feedback control loops for the tune and the chromaticity operating with sampling rates of at least 0.13 Hz and 1.4 Hz respectively. If random errors in b1 during the snap back are not reproducible, local orbit feedback control with a sampling rate of at least 0.3 Hz is required to reduce the peak orbit distortions. Higher sampling rates can reduce the errors further. The maximum closed loop bandwidth that can be achieved is determined by the filtering effect of power converters and associated magnets. However, it has become clear that on line measurements of beam parameters are the most critical part of real time control. It is yet to be demonstrated that tune and chromaticity can be measured on a physics beam at a sufficiently high rate. One of the complications here is that both the tune and chromaticity measurements require transverse kicks that blow up the transverse beam size. The "emittance budget" which limits the number of measurements that can be done on a beam destined for physics production. Finally, we note that slowing down the energy ramp remains an efficient method to reduce the snap back frequency.

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