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# Requirements for real time correction of decay and snapback in the LHC superconducting magnets

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**Summary**

The 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 [1] 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 [2,3]. The superconducting magnets will generate field errors that have large static and dynamic components [4]. It was recognised in an early stage [5] that satisfactory operation of the machine would require real time control.

Static effects in the superconducting magnets are caused by the deformation from the ideal dipole geometry, the degree of saturation of the iron yoke and the DC diamagnetic contribution of the superconducting windings. These field errors can be well controlled during production, can be predicted and are reproducible. Thus, they can be accounted for by using feedforward correction into the current settings for injection and the ramp. It is assumed here that all ring magnets will be measured in a superconducting state so that one will be able to account for the resulting field errors with feedforward corrections.

Field errors that have dynamic effects are of more interest to us here. These field errors are mainly caused by eddy currents in the superconducting strands and cables and by interaction between cable currents and DC magnetisation. The latter component is visible as a decay of the field 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 predict, but they are expected to be reproducible. In contrast, the physical phenomena at the origin of the dynamic effects have not (yet) been fully understood and it is therefore difficult to account for the associated field errors using feedforward correction alone.

One proposed solution [5] is to implement real time control of beam parameters via the power converters. Whether such a control scheme for the LHC is feasible depends to a large extent on the time constants and the time delays introduced by the elements in the feedback loop. In this paper we attempt to give estimates of the delay and the time constants and summarise the requirements for a real time control scheme derived from the field errors evolution during decay and snapback.

## 2. Field errors due to dynamic effects in dipoles & quadrupole magnets

### Field errors

We will adapt the standard multipole expansion for the magnetic field of a main dipole, which 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:

$$\vec{\boldsymbol{B}}_y + \boldsymbol{i}\vec{\boldsymbol{B}}_x = \sum_{\boldsymbol{n}=1}^{\infty} \boldsymbol{C}_{\boldsymbol{n}} \left( \frac{\boldsymbol{z}}{\boldsymbol{R}_{\boldsymbol{ref}}} \right)^{\boldsymbol{n}-1} = \boldsymbol{B}_1 \sum_{\boldsymbol{n}=1}^{\infty} \frac{(\boldsymbol{b}_{\boldsymbol{n}} + \boldsymbol{i}\boldsymbol{a}_{\boldsymbol{n}})}{10^4} \left( \frac{\boldsymbol{z}}{\boldsymbol{R}_{\boldsymbol{ref}}} \right)^{\boldsymbol{n}-1} \qquad (2.1)$$

where $z = x + iy$. The field errors are expressed in units of $10^{-4}$ of the main field component $B_1$ 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.

### Systematic and random field errors

In what follows, it is important to distinguish between the 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, …).

We assume here that correction of the systematic errors will be achieved by feedforward control (using modelling, previous experience and signals from the reference magnets) and by feedback control (using measurements of beam parameters). 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 the random error on the "normal" component $b_1$.

In terms of the notation given in (2.1), 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 are outside the scope of this paper.

**Decay and Snap-back**

Decay is characterised by a significant drift of the magnetic field when the current in a magnet is held constant, for example during the injection plateau. The field decay has time constants of the order of several minutes to several hours [6].

When the current in a magnet is increased again (for example, at the start of the energy ramp), the field bounces back ("snaps back") to its pre-decay level following an increase of the operating current by 15-30 A. For the optimised ramp waveform as described in [11], this corresponds to a period of 50-80 seconds. It should be noted that the duration of the snap back phase is not a constant, but depends on, among other things, the rate of change of current in the magnet.

It should be noted that decay and snapback depend very much on the magnetic history and the characteristics of previous operating cycles. The data presented in the next sections is based on experiments described in [4,6] where a standard operation cycle has been defined.

Decay and snapback are both caused by the same phenomenon, which is the variation of so-called persistent currents in the magnets. It is difficult to predict the evolution of these currents. Recent modelling efforts indicate that the decay and snap back of a magnet can be predicted with an error ranging from 5 to 30% [6]. The present estimate is that by combining the results from modelling with real time observations from the reference magnets at a rate of 3 Hz, a feedforward correction of 80 % of the dynamic effects should be possible.

In the case of real time control, we are interested in the dynamics of these effects. During injection, the persistent currents decay over a period of approximately 1000 seconds. At the start of the ramp, magnetisation is recovered (or "snap-back") over a period of only 80 seconds. Consequently, the correction of the disturbances of the beam parameters should be carried out much more frequently at the start of the ramp then during the injection and it is this phase that motivates the possible use of feedback control loops.

***Physics operations requirements***

The beam physics requirements have been summarised in [5]. One should:

- control the energy to within $\Delta E/E < 3\text{x}10^{-4}$,
- keep the peak orbit excursion inferior to 0.4 $\sigma$ in the arcs and inferior to 0.2 $\sigma$ in the IPs and in the cleaning sections ($\sigma$ is the beam size).
- keep the RMS orbit excursion inferior to 1 mm
- keep the tune excursions small ( $\Delta \boldsymbol{Q} < 3 \times 10^{-3}$ )
- keep the variation of the chromaticity $\xi$ inferior 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 $\Delta E/E < 1x10^{-4}$. 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 orbit, tune and chromaticity

The effect of the multipole variation on the beam during the decay and snapback has been computed with the MAD code and version 6 of the LHC optics.

### Injection plateau

***$b_1$* decay**

We first consider the effect of a *systematic* error in $b_1$. Variation of the integral dipole field will lead to a variation in beam energy during the injection plateau and this will create two main problems:

1. An energy mismatch between the SPS and the LHC since the momentum of the injected beam will not lie within the acceptance window of the LHC RF system.

2. Variation in beam parameters arising from a mismatch between the energy of the beam given by the main bends and the other lattice elements.

The expected total decay of the integral dipole field over a 1000-second injection plateau is around 2.6 units [9]. The LHC RF system demands that the energy of the beam stays constant to within $10^{-4}$. Clearly correction of the $b_1$ error is required.

The mismatch between the energy of the beam given by the main bends and the quadrupole gradients will lead to a tune shift. At the end of the injection plateau, the tune shift due to this effect is $\Delta Q = \xi_N \Delta E/E = 0.03$ (where $\xi_N$, the natural chromaticity, is around 100). Correction of the source of error, or the resulting effect, is clearly required.

The *random* error in $b_1$ will disturb the orbit (ignoring higher order effects). The error in $b_1$ is estimated to be around 0.5 units after 1000 s [5,7]. This estimate is based on the experience at HERA [14] where the total spread in the magnet distribution is 30%. Assigning such a random error in MAD, this generates a RMS horizontal closed orbit distortion of around 0.4 mm with a maximum excursion of around 1.6 mm. This will require a certain number of orbit corrections.

***$b_2$* decay**

The *systematic* error on $b_2$ induced by the main quadrupoles is estimated to be 1.7 units over a 1000-second injection coast [9]. This will generate a tune shift of 0.011 units and will need to be corrected.

It should be mentioned that the main dipoles contribute a *systematic* field error on $b_2$ as well. However, this error is very small (i.e. 0.001 units) compared to the contribution of the quadrupoles. Moreover, the error changes sign from the inner to the outer bore and thus cancels for a beam that traverses the same number of dipoles in the inner and outer channel. In good approximation, we can therefore ignore the contribution of the main dipoles to the systematic error on $b_2$.

***$b_3$ decay***

The *systematic* error on $b_3$ due to persistent current decay in the dipoles is estimated at 3.3 units [9] over 1000 s. Uncorrected this will cause something like 170 units of chromaticity swing, which clearly needs to be corrected.

**Start of the ramp**

***$b_1$ snap back***

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 around 0.03.

The *random* error in $b_1$ during the snapback will affect the closed orbit. If one assumes 0.5 unit random error on $b_1$ that is evolving smoothly during the snapback, this will generate a RMS orbit distortion of about 0.4 mm with a maximum excursion of 1.6 mm.

***$b_2$ snap back***

As for the decay, we assume that the systematic error on $b_2$ from the dipoles will generate a negligible tune shift compared to that induced by the systematic error on $b_2$ from the quadrupoles. From MAD it can be estimated that a snapback of 1.7 units of $b_2$ on the main quadrupoles gives a tune shift of about 0.011.

***$b_3$ snap back***

We assume a snapback of 3.3 units of $b_3$ from the main dipoles which, if uncorrected, generates a chromaticity shift of around 170 units.

## 4. Real Time control

The present idea is to correct the perturbing effects of the persistent current decay on the beam in two different ways:

1. *Feedforward correction* together with real time signals from the reference magnets. Feedforward correction consists in sending corrections to the power converters that anticipate the effects of persistent current changes. The present estimate is that 80% reduction of the *systematic* errors can be achieved. How the correction schemes will be implemented and how signals from the reference magnets will be incorporated is yet to be defined. It is not yet clear to what extend the *random* errors can be reduced by feedforward control. Only measurements on the serie-produced magnets can make this issue more precise.

2. *Feedback control* will reduce any remaining effects so that the beam parameters will not exceed the given limits. The maximum error reduction (i.e. the maximum gain) that can be achieved depends on the closed loop bandwidth of the feedback control loop. The minimum bandwidth will just keep the excursion of the beam parameters within the limits defined in section 3. Higher closed loop bandwidths will allow further error reduction. The maximum closed loop bandwidth that can be achieved is determined by the filtering effect of power converters and associated magnets.

**Feedforward control**

We assume that feedforward correction will be applied to the horizontal orbit correctors ($b_1$ error), the tuning quadrupoles ($b_2$ error) and to the sextupole and decapole spool pieces (respectively, $b_3$ and $b_5$ errors) (other correction elements are not considered here).

The proposed solution to compensate the $b_1$ error is to use the horizontal correctors to balance the drift in the field of the main bends.

The tuning quadrupoles will eliminate the major part of the $b_2$ field error. There are 64 trim quadrupoles around the ring, electrically connected into 16 circuits.

The $b_3$ error will be partially compensated with appropriate feedforward on the sextupole spool pieces using the $b_3$ measurements from the reference magnets. There are 16 lattice circuits each with 154 sextupole and decapole spool pieces (2208 magnets in the arc, 256 magnets for the dispersion suppressors which gives 2464/16 = 154 magnets per circuit).

Table I a and I b summarise on the variation of the field harmonics due to persistent current decay and the associated variation of the beam parameters before and after feedforward correction.

| ***Field Harmonic*** | ***$\Delta b_1$ [units] (MB)*** | ***$\Delta b$ [units] (MB)*** | ***$\Delta b$ [units] (MB)*** | ***$\Delta b$ [units] (MQ)*** | ***$\sigma(\Delta b)$ [units] (MB)*** |
|---|---|---|---|---|---|
| ***Total Decay*** | 2.6 | 3.3 | -0.4 | 1.7 | 0.5 |
| ***After feedforward*** | 0.52 | 0.66 | -0.08 | 0.34 | 0.5 |

*Table I a : Total variation of the field harmonics due to persistent current decay in the LHC superconducting main bends and main quadrupoles.*

| *parameter* | *Field harmonic* | *Before feedforward* | *After Feedforward* | *Within limits ?* | *Control loop ?* |
|---|---|---|---|---|---|
| *momentum* | $\Delta b$ | $\Delta E = 2.5 \times 10^{-4}$ | $\Delta E = 5 \times 10^{-5}$ | yes | not required |
| *Peak orbit* | $\sigma(\Delta b_1)$ | 1.6 mm | 1.6 mm | no | in critical sections |
| *RMS orbit* | $\sigma(\Delta b_1)$ | 0.40 mm | 0.08 mm | yes | not required |
| *Tune* | $\Delta b_1 \, \Delta b_2$ | $35 \times 10^{-3}$ | $7 \times 10^{-3}$ | no | yes |
| *Chromaticity* | $\Delta b_3$ | 170 | 34 | no | yes |

*Table I b : Variation of beam parameters due to persistent current decay before and after feedforward correction.*

It is clear that 80 % reduction of the persistent current decay with feedforward control is sufficient to keep the excursion of momentum and the RMS orbit within the physics operations limits as defined in section 2.

Until measurements on the series-produced magnets will become available, we will assume that no feedforward reduction of the peak orbit distortion due to $\sigma(\Delta b1)$ will be possible. The peak orbit excursion of 1.6 mm quoted in Table I b has to be compared to the requirements (see section 2) expressed in terms of millimetres. Taking the nominal emittance, we estimate maximum excursions of 0.5 mm in the arcs, 0.25 mm in the cleaning sections and 0.4 mm in the IPs. Feedback control of local orbit will thus be necessary and local orbit control in the cleaning sections probably requires the highest closed loop bandwidth.

The excursions of tune and, especially, chromaticity are clearly too large and require feedback control.

### Feedback control

The frequency bandwidth that is required to control the excursion of the beam parameters 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. For a given snap back, $f_{sb}$ will increase with the ramp speed, i.e. the decay as quoted in table I a will occur on a shorter timescale.

One way to obtain $f_{sb}$ for a particular ramp is via a spectral analysis of the measurements on the prototype short dipoles (see also error tables no. MB09902 in [8] for the dipoles and no. MQ0497 in [9] for the main quadrupoles). One obtains a frequency of approximately $f_{sb}$ = 4 mHz for a linear ramp at 0.5 A/s, $f_{sb}$ = 2 mHz for a linear ramp at 0.25 A/s and so on. There are no such measurements available (yet) for the nominal ramp as defined in [11][†]. Therefore, the theoretical model as quoted in [12] was used in this case to estimate the snap back frequency of the ramp at $f_{sb}$ = 4.3 mHz.

Table II summarises the required closed loop frequency bandwidths for dealing with the snap back. These rates can easily be obtained from standard control theory assuming 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.

| ***parameter*** | ***After Feedforward*** | ***Operational margin*** | ***Required Gain*** | ***Closed loop bandwidth*** | ***Sampling rate*** |
|---|---|---|---|---|---|
| ***momentum*** | $\Delta p/p = 5x10^{-5}$ | $\Delta p/p < 1x10^{-4}$ | - | – | - |
| ***Peak orbit*** | 1.6 mm | 0.25 mm | 6.4 | 0.03 | 0.3 Hz |
| ***RMS orbit*** | 0.12 mm | 1.0 mm | - | – | - |
| ***Tune*** | $7x10^{-3}$ | $3x10^{-3}$ | 3 | 0.013 Hz | 0.13 Hz |
| ***Chromaticity*** | 34 | 1 | 34 | 0.14 Hz | 1.4 Hz |

*Table II : Required closed loop bandwidths after feedforward correction during the snap back phase of a nominal current ramp as defined in [11].*

For the peak orbit distortion for example, a gain of about 6 is required to keep the peak orbit distortions below their the short-term stability limits. The minimum sampling rate is thus $f_{sb}$ x 10 x 6.4 = 0.3 Hz. For the tune, a gain of at least 3 is required. The minimum sampling rate is now $f_{sb}$ x 10 x 3 = 0.13 Hz. In a similar fashion, we obtain a minimum sampling rate for the chromaticity at 1.4 Hz.

## 5. Discussion

A number of issues that have been raised here are subject to debate :

- No measurements of the field harmonics during the snap back phase of an optimised ramp as defined in [11] are available at present. The data quoted in table II have been deduced by assuming a third order transfer function as given in [12] and a current span during the snap back of 32 Amps.

- The rms spread of the *random* errors in $b_1$ of the main dipoles was estimated using experience of other machines (e.g. HERA), where the total spread of the *random* errors in $b_1$ is roughly ±30 % of the total decay. A statistical analysis of measurements on all series-production magnets has to make this value more precise.

- In section 2, we quoted the maximum peak orbit distortion that can be tolerated in various sections of the machine. These tolerances are based on the assumption that the

[†] The nominal ramp has a parabolic-exponential-linear start of the energy ramp and was designed to anticipate on the effects of the snapback.

RMS orbit is about 1 mm which, with a Gaussian distribution, gives a peak orbit distortion of about 3.5 mm (see [7]). Whether this is an optimistic or pessimistic estimate remains an open question.

The feedforward corrections will develop over time. It remains an open question as to what extent feedforward control will balance the persistent current decay. It is clear that the benefit from feedforward control will increase as we learn more about operating the LHC.

## 6. 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 as was initially thought. 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 a feedback control loop 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 $b_1$ 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.

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. There exists an "emittance budget" which limits the number of measurements that can be done on a beam destined for physics production [13].

Finally, we note that slowing down the energy ramp remains an efficient method to reduce the snap back frequency.

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