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**LHC Project Report 1128**

## **A DEMONSTRATION EXPERIMENT FOR THE FORECAST OF MAGNETIC FIELD AND FIELD ERRORS IN THE LARGE HADRON COLLIDER**

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In order to reduce the burden on the beam-based feedback, the Large Hadron Collider control system is equipped with the Field Description for the LHC (FiDeL) which provides a forecast of the magnetic field and the multipole field errors. FiDeL has recently been extensively tested at CERN to determine main field tracking, multipole forecasting and compensation accuracy. This paper describes the rationale behind the tests, the procedures employed to power the main magnets and their correctors, and finally, we present the results obtained. We also give an indication of the prediction accuracy that the system can deliver during the operation of the LHC and we discuss the implications that these will have on the machine performance.

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# A DEMONSTRATION EXPERIMENT FOR THE FORECAST OF MAGNETIC FIELD AND FIELD ERRORS IN THE LARGE HADRON COLLIDER\*

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## Abstract

In order to reduce the burden on the beam-based feed-back, the Large Hadron Collider control system is equipped with the Field Description for the LHC (FiDeL) which provides a forecast of the magnetic field and the multipole field errors. FiDeL has recently been extensively tested at CERN to determine main field tracking, multipole forecasting and compensation accuracy. This paper describes the rationale behind the tests, the procedures employed to power the main magnets and their correctors, and finally, we present the results obtained. We also give an indication of the prediction accuracy that the system can deliver during the operation of the LHC and we discuss the implications that these will have on the machine performance.

## INTRODUCTION

The LHC has unprecedented demands on the control of the field and field errors during injection, acceleration, squeeze and collision. One of the most stringent requirements during the energy ramp of an accelerator like the Large Hadron Collider (LHC) at CERN is to have a constant ratio between dipole-quadrupole and dipole-dipole field so as to control the variation of the betatron tune and ensure that the beam orbit remains the same throughout the acceleration phase. This hence avoids particle losses. The sectors are powered separately and an acceptable relative error for dipole differences between sectors is of the order of  $10^{-4}$ . To achieve the expected nominal beam intensity of the LHC accelerator, a maximum tune variation of  $\pm 0.003$  tune units can be tolerated. For the commissioning with low intensity beams, acceptable bounds are up to 30 times higher [1] namely  $\pm 0.09$  tune units. For the quadrupole-dipole integrated field ratio, the above requirements can be translated in the very tight windows of 6 ppm and 180 ppm, for nominal and commissioning performance respectively [2].

It is also necessary to forecast and correct the sextupole and decapole multipoles in the LHC main dipole magnets. The tolerances of the sextupole ( $b_3$ ) and decapole ( $b_5$ ) correction are calculated from the beam requirements [3] and these hence provide a specification for the forecasting mechanism. These calculations [4] yield a tolerance of 0.35 units and 0.02 units of  $b_3$  in commissioning and in nominal operation respectively and 0.1 units of  $b_5$  at nominal operation.  $b_5$  can be ignored during the early

machine commissioning and does not need to be compensated above 2 TeV. (A unit is defined as the ratio of the harmonic and the main field multiplied by  $10^4$  as described in [5].)

To achieve these tolerances, the LHC is equipped with a hybrid control system consisting of beam based feed-back and feed-forward controls. The feed-forward control system relies on the Field Description for the LHC (FiDeL) [5, 6] which forecasts the main field and harmonics of the magnetic elements. This prediction is based on a model whose parameters are determined from magnetic measurements at warm and at cold.

FiDeL required testing before LHC starts. To this end, CERN launched a dedicated measurement campaign to verify whether based in the FiDeL models one can:

- 1) accurately generate the current ramps of the main superconducting magnets which would produce the expected magnetic fields and therefore keep the  $B_2/B_1$  and  $B_1^{S1}/B_1^{S2}$  ratios well within the limits for the machine operation. ( $B_1^{S1}$  denotes the main dipole field of a first sector and  $B_1^{S2}$  means the same thing but for a second sector).
- 2) accurately generate the corrector current ramps to compensate the sextupole and decapole field errors in the main dipoles.

So as to test the system integrity, the whole chain of systems was controlled by the LHC Software Architecture (LSA) [7].

Pick-up coils were used in static mode [8] for the  $B_2/B_1$  and  $B_1^{S1}/B_1^{S2}$  tracking and in rotating coil mode [9] for the sextupole and decapole compensation. The same electronic systems were used for both configurations. The coils were set at the standard magnetic measurement position which covered the magnetic length of the dipole magnet and that of the correctors. The magnet characterisation procedure is described in [8].

## MAIN FIELD TRACKING

The main field tracking was measured in several test runs consisting of current cycles simultaneously performed on the dipoles and on the quadrupole [8].

Figure 1 a) shows the ratio of the quadrupole to dipole integral field  $B_2/B_1$  with and without FiDeL. It can be noted that without the use of FiDeL, the ratio deviated uncontrollably after 6000 A, due to the difference in iron saturation between the dipole and quadrupole. Figure 1 b) shows the ratio of the quadrupole to dipole (MB2598)

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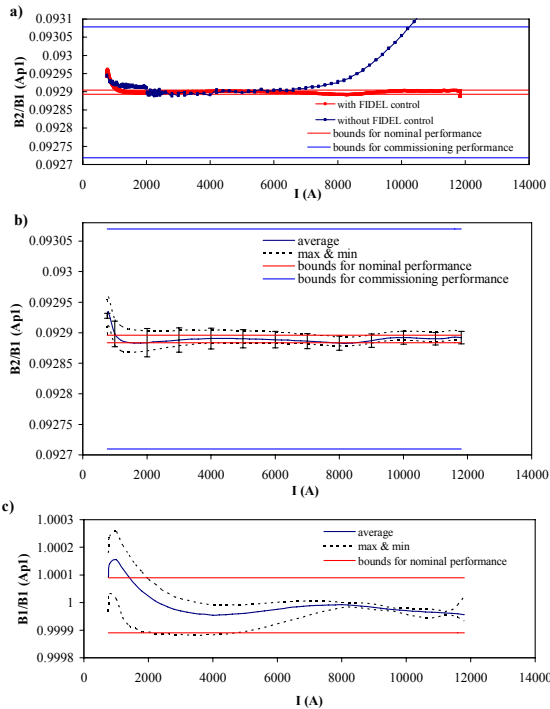


Figure 1: (a)  $B_2/B_1$  with and without FiDeL (b)  $B_2/B_1$  (MB2598) measurements with FiDeL implemented (c)  $B_1^{S1} / B_1^{S2}$  with FiDeL implemented

integral field  $B_2/B_1$  with FiDeL implemented. Figure 1 (c) shows the ratio of the dipole to dipole integral field  $B_1^{S1} / B_1^{S2}$  with FiDeL implemented. In the last two cases the blue curve shows the average of the measurements performed whilst the dotted lines show the maximum and minimum measurement values obtained during the campaign.

Figure 1(b) shows that the  $B_2/B_1$  ratio is definitely within the range to be achieved for commissioning operation. It is also quite close to the range necessary to maintain the maximum allowable tune variation to within  $3 \cdot 10^{-3}$  as dictated for the nominal LHC performance. The quadrupole-dipole ratio is constant to approximately  $\pm 0.36$  units when tracking MB2624 with SSS064 and constant to  $\pm 0.29$  units when tracking MB2598 with SSS064. However in both cases the reproducibility from cycle to cycle is  $\pm 0.1$  units which is very close to bounds for nominal performance. The dipole-dipole field (Figure 1 (c)) is constant to approximately  $\pm 1.23$  units with a reproducibility of  $\pm 0.5$  units which is well within the maximum allowable variation for nominal performance.

## HARMONICS COMPENSATION

Harmonic correction was performed in LSA by using FiDeL to generate the harmonic curve that needs to be compensated (e.g.  $b_3$  or  $b_5$  of the dipole). The magnetic strength of the corrector was then obtained by using the harmonic curve and the ratio of the magnetic lengths between the dipole and the corrector. The corrector current was hence obtained from the corrector magnetic strength by using the transfer function of the corrector as

defined in FiDeL.

The compensation of the sextupole and decapole in the main magnets was performed by powering the sextupole (MCS) and decapole correctors separately in two dipole cold masses with the standard LHC cycle.

### *b3 Compensation*

Figure 2 (top) shows the dependence of the integral sextupole on time before and after correction. The red curves show the uncorrected harmonics whilst the blue curves show the harmonic component after compensation with the corrector. The latter are integral measurements of the harmonic over the length of the dipole and the corrector. From the plot it is evident that at this scale, the correction works to a high degree.

Zooming in on the scale to examine the compensated sextupole further, some remnant features of the multipole variation can still be observed. Figure 2 (bottom) shows the measured integral sextupole of MB2598 aperture 1 in two subsequent cycles. The sextupole variation is of  $\pm 0.25$  units corresponding to a variation of about  $\pm 10$  units of chromaticity. The reproducibility is better than 0.1 units of sextupole corresponding to a chromaticity range of 5 units.

The origin of these features is as yet unclear. The range of variation of integral sextupole is comparable to the measurement uncertainty. Systematic errors in the measurement of  $b_3$  in the dipole, or of the MCS corrector, could explain some of the features observed. To verify this possibility, we have tested the effect of a reduction of 2% of the parameter that sets the gain for the MCS corrector transfer function (Figure 2 (bottom)).

The hardware effect is to increase the field generated by the MCS. The integral sextupole, including compensation, is centred around zero, and has a reduced range of  $\pm 0.15$  units.

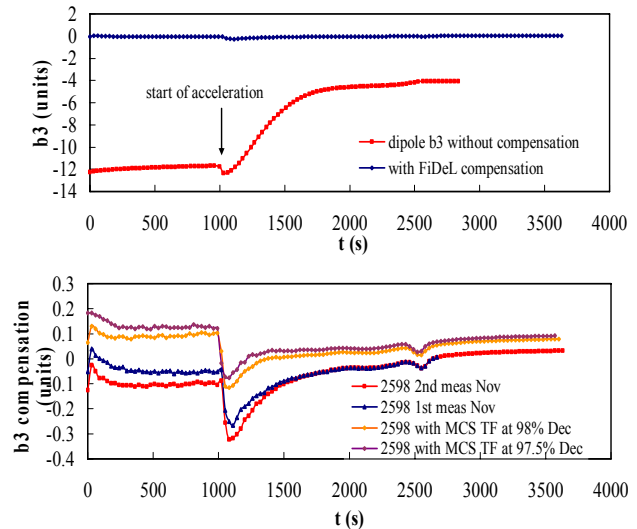


Figure 2: (top) integral sextupole of MB2598 ap1 before and after correction; (bottom) remnant integrated sextupole during two machine cycles (red and blue curve) compared to the effect of arbitrarily changing the transfer function of the corrector magnet by 2% (green curve).

In the case of aperture 1, the corrector transfer function was reduced further to 2.5%.

The sextupole remnant variation in this case is very similar to what is obtained with a reduction of 2% except that the average error shifts upwards by 0.05 units. Another idea is that the residual  $b_3$  at the beginning of the ramp partly occurs because the snapback correlation [6] varies slightly from magnet to magnet. However this does not explain why the residual  $b_3$  persists for 500 s.

Another cause of the remnant field could be due to the instrumentation. Whilst the magnet characterisation is performed with the rotating coil amplifier gains in automatic range mode, during compensation tests the amplifiers are placed in fixed gain mode. The difference in the amplifier sensitivity of the two modes may contribute to the remnant field error.

Another issue is that there seems to be a difference of about 0.2 units between different loadlines performed at different times. The origin of this difference is unknown but the effect may be the source of the remnant sextupole field.

### *b5 Compensation*

Figure 3 (top) shows the dependence of the integral decapole on time before and after correction. The red curves show the uncorrected harmonics whilst the blue curves show the harmonic component after compensation with the corrector. Zooming in on Figure 3 (top) to examine the compensated decapole further, some remnant features of the multipole variation can still be observed. Figure 3 (bottom) shows the measured integral decapole in the two apertures of the two magnets. The decapole variation is  $\pm 0.02$  units with a reproducibility of 0.01 units. However, during the cycle, the maximum strength of the decapole magnets is reached and the harmonic is not corrected further. For magnet 2598 this occurs at 2000 s for aperture 1 and does not occur in aperture 2. In the case of magnet 2624, this occurs at about 2500 s for both apertures.

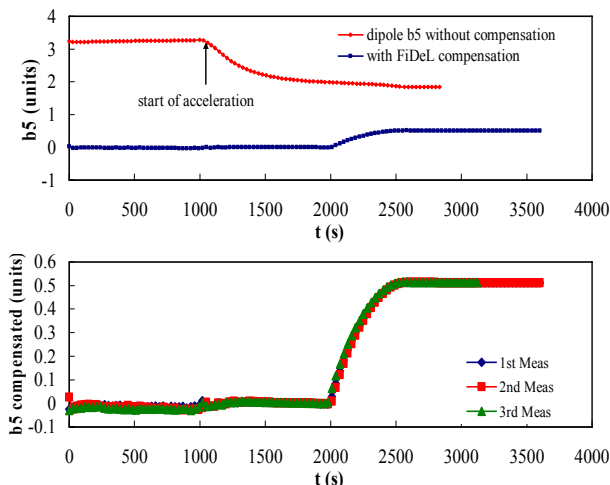


Figure 3: (top) integral decapole of MB2598 ap1 before and after correction; (bottom) remnant integrated decapole during three machine cycles.

From series measurements performed at warm [10], it is known that the  $b_5$  component, for the whole dipole population, on average, is just at the specification limit.

Therefore it is expected to have individual magnets reaching their field strength. However, for  $b_5$  compensation over the whole machine, the corrector strength should be enough on average. This could however mean that a more complex control algorithm would be required for this harmonic to compensate for the variation of the average  $b_5$  in each sector.

## CONCLUSIONS

The tracking experiments have demonstrated that the principle of FiDeL as well as its implementation in LSA works well. Some effects are not yet understood but these are systematic and seem to be within the tolerances.

The results for the main field tracking show that dipole-dipole and dipole-quadrupole ratios can be kept constant within the range to be achieved for beam commissioning and quite close to the range necessary to maintain the maximum allowable tune variation for the nominal LHC performance. Furthermore, the cycle-to-cycle reproducibility is very close to the tight targets needed.

The harmonic compensation tests works well with a maximum error swing of 0.3 units for  $b_3$ . The origin of remnant sextupole field after correction is still unknown. LSA timing issues were studied and solved so that each part of the model is suitably matched and launched precisely at the right time. The contribution of the corrector hysteresis is also calculated to be 0.05 units hence not being the cause of the remnant field. More tracking tests are planned at CERN to understand the origin of the residual  $b_3$  further and hence correct it.

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