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MAGNETIC FIELD TRACKING EXPERIMENTS FOR LHC

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At the Large Hadron Collider (LHC) at CERN one of the difficult requirements during the energy ramp is that the ratio between the field produced by the quadrupoles and the field in the dipoles remains constant in order to minimize the variation of the betatron tune that could induce particle loss. With a series of tracking experiments it has been demonstrated that this ratio can be maintained constant to better than 10^{-4} throughout the same current ramp as foreseen for the LHC. A technique has been developed to optimise the dipole and quadrupole current ramps to obtain the required ratio of B_2/B_1. In addition measurements performed by modulating the current with a harmonic function (so-called k-modulation) demonstrated that it is possible to modulate the strength of an individual quadrupole to determine the magnetic center through beam-based measurements.

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Abstract

At the Large Hadron Collider (LHC) at CERN one of the difficult requirements during the energy ramp is that the ratio between the field produced by the quadrupoles and the field in the dipoles remains constant in order to minimize the variation of the betatron tune that could induce particle loss. With a series of tracking experiments it has been demonstrated that this ratio can be maintained constant to better than 10^{-4} throughout the same current ramp as foreseen for the LHC. A technique has been developed to optimise the dipole and quadrupole current ramps to obtain the required ratio of B_2/B_1. In addition measurements performed by modulating the current with a harmonic function (so-called k-modulation) demonstrated that it is possible to modulate the strength of an individual quadrupole to determine the magnetic center through beam-based measurements.

INTRODUCTION

To achieve the nominal performance of the LHC accelerator, the control limits for the tune Q are extremely tight. A maximum tune excursion of 3×10^{-3} can be tolerated during the current ramp [1]. A feed-back system, the tune-loop, is eventually foreseen to maintain the tune within the above bound. The feed-back system will however be able to lock-in only when the tune excursion, due to the errors in the accelerator, is of the order of 3×10^{-2}. For the commissioning with low intensity beams acceptable bounds are up to 30 times higher (9×10^{-2}).

The above requirement can be translated in an equivalent criterion on the maximum variation of the ratio of the quadrupole to dipole field B_2/B_1 during a ramp. The tune change δQ can be derived from the normalised quadrupole error δB_2 using the natural chromaticity Q' [2].

Table 1 reports the tune limits translated to bounds for the tracking error $\delta B_2/B_1$ assuming that approximately 80 % of the machine tune is due to the main quadrupoles and taking for the nominal B_2/B_1 ratio a value of 0.45, with B_2 and B_1 expressed in T at a radius of 17 mm.

Tracking of quadrupoles and dipoles was verified during two experimental campaigns in the LHC String 2 using fluxmeters for the measurement of B_1 and B_2. Additional measurements were performed to address the feasibility of k-modulation in the LHC [3]. The aim in this case is to establish whether there would be any principle problem in modulating the quadrupole field in a frequency range 0.1 to 10 Hz, with a current amplitude of a few Amperes.

Table 1: Maximum bounds for the tracking error corresponding to achieving a tune stability as requested for nominal beam performance, for the tune-loop to lock-in and to tune tolerance during commissioning with low intensity beams.

Condition	$\delta\mathbf{B}_2/\mathbf{B}_1$
nominal performance	$\pm 2 \times 10^{-5}$
tune-loop lock-in limit	$\pm 2 \times 10^{-4}$
commissioning with low intensity beams	$\pm 6 \times 10^{-4}$

MEASUREMENT SET UP

String 2 [4, 5] was a full-size model of two consecutive LHC half-cells. Each half cell is composed of one short straight section (SSS) and three 15 m dipoles (MB). String 2 has been equipped with sets of coils mounted in vacuum inside the beam screen to measure the magnetic field of QD and QF quadrupoles (the SSS3 and SSS4 prototypes) and of the RB1 main dipole (the MBP2O1 prototype). The coils are stationary, and are used in a fluxmeter configuration to measure the magnetic field variation through the voltage induced by the change in flux linked. Three sets of coils have been used to measure the dipole and the quadrupoles fields. The coils have a total surface of 27.5 m^2 in the dipole and 46.2 m^2 in the quadrupoles.

The voltage signals from the coils are read by PDIs (Precision Digital Integrators) with a VME-bus digital interface. The PDI cards are triggered by an external trigger card that is synchronised to the 50 Hz cycle from the mains. Optimal settings for the measurements were found to be in the range of 1 to 10 Hz. Slow trigger (2 Hz) was used during all tracking measurements, while fast trigger (10 Hz) was used to resolve the field changes in k-modulation measurements.

The trigger signal is repeated to the digital Function Generator and Controller (FGC) of the power supplies. The FGC provides in response a high precision measurement of the current. This measurement, GPS time stamped, is made available through the power supply gateway and retrieved by the acquisition computers.

TRACKING MEASUREMENTS

The tracking measurements were performed in several runs. Every run consisted of current cycles sent simultaneously to the dipoles and both quadrupoles. The current cycles were always preceded by a pre-cycle made to magnetise the magnets on the ramp-up hysteresis branch of the

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persistent currents (a ramp to high current followed by a ramp to a current of 350 A and ramp-up to injection level). The result of each measurement was processed to produce synchronised time-stamped values of the dipole and quadrupole strength, B_1 and B_2 respectively. The tracking error $\delta B_2/B_1$ was determined as the difference between the instantaneous value of the ratio B_2/B_1 and a reference value B_{20}/B_{10} established, for convenience, as the average ratio during the first run. The tracking error was used to derive a corrected current waveform for the quadrupoles to be used for the following run.

For all the runs performed, the current ramp for the MB is a waveform between injection (760 A) and flat-top (11850 A) calculated on the basis of the optimisation made in [6], with a combination of several mathematical functions (Parabolic-Exponential-Linear-Parabolic, PELP). The time duration of the ramp is 25 minutes.

Throughout the experiments the MB ramp was left unchanged in order to avoid additional, unnecessary variability.

During the measurements the current in the QD was limited to 6 kA because the QD powering circuit was used to test a prototype of the LHC 6 kA bus-bars connected in series with the QD bus-bars.

Current ramps and feed-forward correction

The quadrupoles current ramps were shaped performing an iterative correction of the current waveform.

A first measurement was made using the same current ramp as for the dipole. From this measurement the reference value of B_{20}/B_{10} was established to be 0.4511.

The result of this measurement is plotted in Fig. 1 (for the QD) and 2 (for the QF) and is marked as “no correction”. We have plotted there the instantaneous value of the ratio B_2/B_1. The horizontal lines correspond to the bounds given in Table 1. The region between the two innermost corresponds to the tighter tune range of 3×10^{-3} followed by the tracking error for the tune feed-back system to lock-in (dashed lines) and the tracking error for the commissioning.

As expected, because of the difference in the iron yoke saturation at high field (see QF in Fig. 2), the result of this first measurement is a large and unacceptable deviation from the desired constant at large current.

A second quadrupole current ramp was computed to compensate the difference in the quadrupole vs. dipole transfer functions. The “corrected” quadrupole current was calculated using a fit of the transfer functions of the dipole and quadrupoles measured on the test benches. The fit was made in order to reduce the effect of measurement noise:

$$T_1 = \frac{B_1}{I_1} = a_1 + \frac{b_1}{I_1} + c_1 \left(\frac{I_1}{I_0}\right)^{n_1} \qquad (1)$$

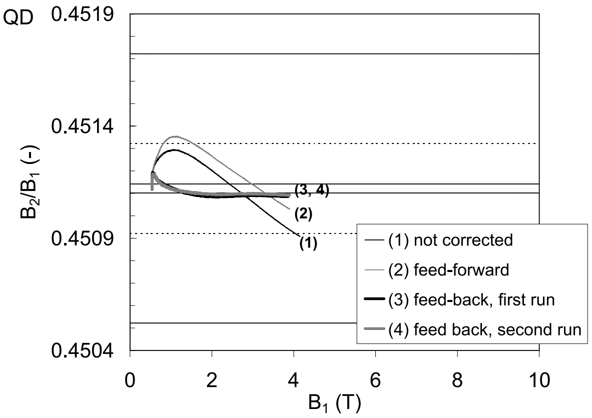

Figure 1: Ratio B_2/B_1 for the QD quadrupole, plotted as a function of the dipole field along the reference current ramp.

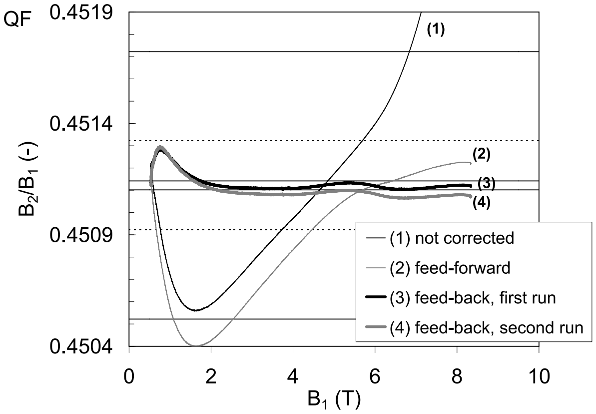

Figure 2: Ratio B_2/B_1 for the QF quadrupole, plotted as a function of the dipole field along the reference current ramp.

I_1 is the dipole current, I_0 is the nominal maximum current value (approximately 11850 A) and a_1, b_1, c_1 and n_1 are fit constants. B_1 is computed using the known PELP current in the dipole and the expected dipole transfer function T_1. The corresponding quadrupole field B_2 was calculated from the reference value of B_{20}/B_{10}. Finally, the current in the quadrupole I_2 was computed inverting the implicit Eq. 1 with the quadrupole fit constants.

A measurement of the quadrupoles field was performed with the so-calculated current ramps. We refer to this measurement as the 1st correction measurement yielding a new value of the instantaneous ratio B_2/B_1.

The adapted current ramps (1st correction), marked in the plots as “feed-forward”, show that this correction compensates well the difference in the high field saturation, but leaves a substantial deviation at low and intermediate field. We believe now that this deviation is mostly due to an uncorrected systematic effect the origin of which is still not understood.

Irrespective of the nature of this systematic effect, a second corrective iteration was performed using a procedure similar to the one outlined above. In this case the experimental value of the tracking error $\delta B_2/B_1$ was fitted with a polynomial function of the dipole current to remove this systematic effect. The $\delta B_2/B_1$ fit function was then translated in a current excess (or defect), added algebraically to the quadrupole ramps established in the 1st correction process. The result of this 2nd correction are shown by the curves marked as “feed-back” in Fig. 1 and Fig. 2. In this case the tracking error on the B_2/B_1 ratio is definitely inside the range to be achieved for the tune feed-back system to lock, and in fact quite close to the range necessary to maintain the maximum allowed tune variation to within 3×10^{-3} as dictated for the nominal LHC performance.

We remark that the 2nd correction contains a compensation for all effects in the measured field, including physical deviations between measured and expected field, but also random and systematic measurement errors.

The 2nd correction current ramp was sent unchanged in a second cycle, with the aim to verify the reproducibility of the measurement. For the QD quadrupole, the change in field from one measurement to the other is less than ±10 ppm, and for the QF it is less than ±50 ppm. These values compare very favorably with the specification on the tracking error for nominal performance (±20 ppm from Tab. 1), especially considering that the values of reproducibility quoted above include both powering and magnetic effects, as well as measurement reproducibility.

K-MODULATION MEASUREMENTS

The K-modulation is a technique that can be used to find and correct for magnetic center offsets among quadrupoles and the beam orbit [3].

The current in QD and QF was modulated by a sine function superimposed on the DC excitation current. The amplitude of the modulation was varied in the range 0.5 A to 5 A, while the frequency was varied between 0.1 Hz and 1 Hz. The transfer function values are practically the same for different amplitudes of the modulation, while they increased with frequency in the frequency range 0.1 to 1 Hz by approximately 6 %. The observed frequency dependence could be a measurement artifact due to the not very high sampling frequency (10 Hz) compared to the modulation frequency. The value of the transfer function, extrapolated at zero frequency (i.e. in steady state conditions) is consistent with the measurement of 0.319 (T @ 17 mm)/kA at 5 kA performed on the test bench.

The results show that from the point of view of magnet excitation and response the K-modulation is feasible and produces field changes that are broadly consistent with the expected values. Assuming that the frequency effect has a physical origin, a modulation with a maximum 1 % deviation from the steady state value is possible up to a frequency of approximately 0.3 Hz.

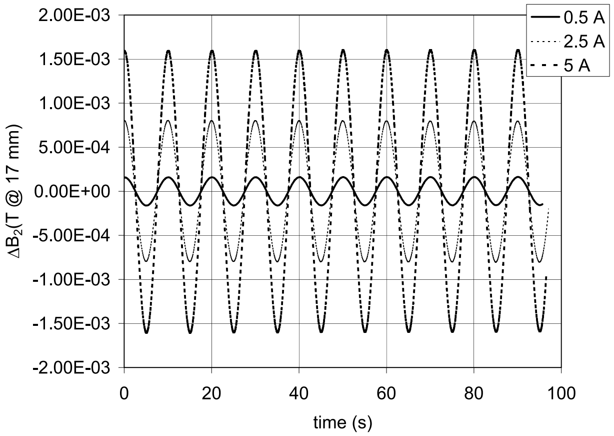

Figure 3: Quadrupole field change generated by current modulation of amplitude 0.5, 2.5 and 5 A at 0.1 Hz frequency.

CONCLUSIONS

In this paper we presented the results of tracking measurements performed on the String 2. The tracking error $\delta B_2/B_1$ obtained was within the range to be achieved for commissioning (tracking error below 6×10^{-4}). Iterative correction of the current waveform was used to reduce the tracking error to the range necessary for the tune-loop to lock-in (tracking error below 2×10^{-4}). Furthermore, the reproducibility of the tracking, including all effects, was better than 5×10^{-5}. The implication is that once a machine setting and cycling procedure will be established for the LHC, the tracking errors should stay comfortably within a range that allows the tune feed-back loop to act.

K-modulation measurements showed that it is possible to modulate the magnetic field of quadrupoles and dipole with periodic current functions within a useful range for the use of this procedure in the LHC. Based on the results collected so far, the quadrupole transfer function will change by less than 1 % at modulation frequencies below 0.3 Hz, which is a feasible range for this measurement in the LHC.

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