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First field test of FiDeL
The magnetic field description for the LHC

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The start-up of the LHC has provided the first field test for the concept, functionality and accuracy of FiDeL, the Field Description for the LHC. FiDeL provides a parametric model of the transfer function of the main field integrals generated by the series of magnets in the LHC powering circuits, comprising superconducting and normal-conducting main optical elements and high-order harmonic correctors. The same framework is used to predict harmonic errors of both static and dynamic nature, and forecast appropriate corrections. In this paper we make use of beam-based measurements taken on the first LHC beams to assess the first-shot accuracy in the prediction of the current setting for the main arc magnets.

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The start-up of the LHC has provided the first field test for the concept, functionality and accuracy of FiDeL, the Field Description for the LHC. FiDeL provides a parametric model of the transfer function of the main field integrals generated by the series of magnets in the LHC powering circuits, comprising superconducting and normal-conducting main optical elements and high-order harmonic correctors. The same framework is used to predict harmonic errors of both static and dynamic nature, and forecast appropriate corrections. In this paper we make use of beam-based measurements taken on the first LHC beams to assess the first-shot accuracy in the prediction of the current setting for the main arc magnets.

INTRODUCTION

The magnetic model of the LHC (aka Field Description of the LHC, or FiDeL) is a set of semi-empirical equations that are fitted to:

- measured single magnet data at operating conditions (cryogenic for superconducting magnets), if available, or
- extrapolated single magnet data from production control data (warm for superconducting magnets), usually available, or
- average data for a given magnet family, which are always available

The semi-empirical equations are simple mathematical formulae, based on a decomposition of the magnetic field in seven physical contributions of static and dynamic nature. A complete description of the FiDeL algorithm is reported in [1]. The theoretical basis for FiDeL, the validation for the single components and conceptual tests are reported in [2] through [7]. Presently, FiDeL provides on a circuit-by-circuit basis:

- a complete transfer function model for main magnets;
- a simplified transfer function model (linear and saturation components) for correctors;
- a complete model for b3 and b5 errors (static and dynamic) and a simplified model for other relevant harmonics (linear and saturation components) in the MB's.

The above features are an integral part of the LHC controls (LSA) and were tested during the injection tests and first circulating beams of August and September 2008.

The objective of this paper is to use the result of beam measurements to derive an estimate of the accuracy of the machine settings, and compare the results to the expected accuracy derived from measurement error estimates and correlation analysis. Because of the limited beam time and measurements, we restrict our analysis to basic quantities such as momentum, tune and chromaticity estimates, which are our main indicators.

EXPECTED SETTING ACCURACY

The analysis of the magnet measurement accuracy, and correlation analysis of magnet populations partially sampled in operating conditions (e.g. requiring warm/cold extrapolation of production data) were used as the main ingredients to establish bounds for the setting errors of FiDeL in pure forecast mode [8], [9]. The result of this exercise are reported in Table 1, which gives the various contributions considered in the analysis, and the estimated uncertainty for the first injection, obtained considering all contributions as uncorrelated.

The most relevant numbers are those for the integrated dipole strength, quadrupole strength and sextupole. From the figures of Table 1, at injection (450 GeV) we expected a relative momentum uncertainty of 0.4 GeV, a tune uncertainty of 0.12 tune units, and chromaticity uncertainty of 36 units.

MOMENTUM

A verification of the momentum setting accuracy was possible already from the first shots, thanks to the excellent performance of the BPM measurement and analysis. The first injection in the LHC Sector 2-3 (August 8^{th} to 11^{th}) showed that the LHC energy was set at 450.5 ± 0.2 GeV. Subsequent evaluations for all other sectors, and for the captured beam confirmed this estimate, namely an error on the LHC momentum setting

Table 1: Evaluation of the uncertainty in the settings of the LHC for first injection based on the cumulative contribution of the various sources of errors, quoted in units of 10^{-4} of the main magnetic field of the magnet.

		Error sources					
		sampling and W/C extrapolation	measurement error	magnet stability	powering cycle	modelling	**Estimated uncertainty**
MB							
	B1	4.2	6.8	2.8	0.6	0.6	8.5
	b3	0.61	0.31	0.27	0.21	< 0.05	0.8
MQ							
	B2	10	17			1.1	19.8

of the order of +10 units of magnetic field or better, vs. the expected uncertainty of ± 8.5 units.

The difference of momentum setting between Beam 1 and Beam 2 was obtained from the evaluation of the few single turns, and is of the order of 1 to 2 units of field, which is excellent and points to a high homogeneity in the magnet construction. The homogeneity of the settings along the machine is also very good: the difference of momentum setting between sectors is of the order of 3 units of field r.m.s., compatible with the accuracy of the magnetic measurements. Finally, in steady conditions, during sequences of injections and dump with no change in the machine, the setting was highly reproducible, to the level of 1 unit of field. This allowed accurate corrections of orbit excursions well below the expected tolerances.

On the other hand, it was observed that the momentum settings had an apparent variation of the order of 5 units when undergoing long pauses (e.g. weeks between the injection tests or hours after losing the *powering permit*). We attribute these changes to variations in the magnetic state of the dipoles induced by current changes not re-set by standard re-cycling. We demonstrate the effect of pre-cycling on B-field in Fig. 1 where we reported the BPM readings for an injection of Beam 1 in point 2 through point 5. The first reading (Fig. 1, top) was taken with orbit corrected, in stable conditions. The main dipole circuit in sector 2-3 was then recycled, but injection settings were approached from higher currents, inverting the contribution of persistent currents to the main field.

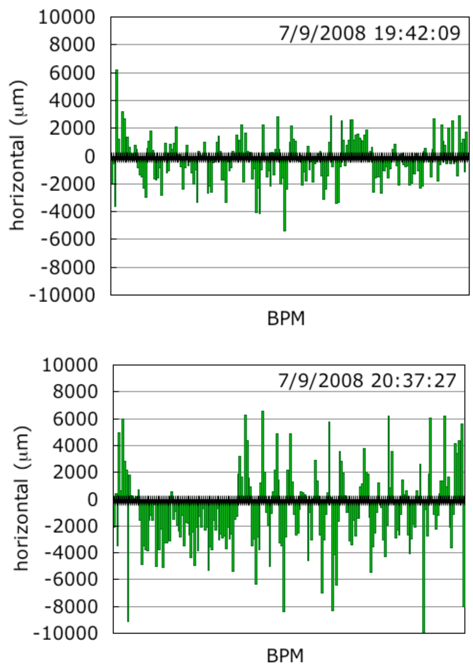

Figure 1. Shift of the horizontal BPM reading produced by an anomalous cycle performed on the main dipoles of sector 2-3. The beam travels from left to right through three sectors, from point 2 (left-most) up to point 5 (right-most). The anomalous pre-cycle in sector 2-3 inverts the magnetization, increases the integral dipole field, and shifts the orbit inwards by an average of 1.4 mm (first third of the series of BPM readings).

The effect of this anomalous cycle (Fig. 1, bottom) is to displace the orbit in sector 2-3 radially by -1.4 mm, which is consistent with a field increase of the order of 0.1 %, as expected from magnetic measurements.

Such an anomalous pre-cycle was done intentionally and is an upper estimate of the effect of sequencing ramps on the dipole circuits during the hectic days of the first injections and circulating beam events. Nonetheless, it shows the order of magnitude of the effect, and reinforces the need for strict cycling procedures at the next start-up.

TUNE

Data on tune is available only on Beam 2, but indications are that situation for Beam 1 is comparable. The integer tunes, obtained from the analysis of the beam oscillations at the BPM's were correct (64 and 59, H and V respectively). A collection of the measured fractional tunes in the horizontal and vertical plane on September 11th and 12th, from [10] and [11], is shown in Fig. 2. The fractional tunes are compared there to the nominal fractional values of Q_H = 0.28, Q_V = 0.31. We can see from there that the measured tunes are within 0.15 of the nominal ones, i.e. to ± 25 quadrupole field units setting error, vs. an expected uncertainty of ± 20 field units from Table 1. Again, we see that the ball-park estimates are holding well. We notice however that the vertical tune errors varied from day to day by 0.2, i.e. of the order of the estimate of the setting accuracy.

The variation is so far not explained. The suspicion, however, is that some of the variations could be attributed again to magnets cycling. Especially the tune trim circuits (MQT) are the possible cause of a significant hysteretic response. This is shown in Fig. 3, reporting the horizontal tune variation during a trim study. Different horizontal tunes are measured for the same trim settings (and the same current in the MQT circuits). If we ignore the large variations in the vicinity of fractional tune 0.5, where measurements may be affected by a larger uncertainty, the typical amplitude of the tune hysteresis is of the order of 0.05. This is compatible with magnetic measurements on single MQT magnets powered in the range of few A and arbitrary current waveform.

Additional information that confirms the overall *sanity* of the settings is finally provided by the coupling and

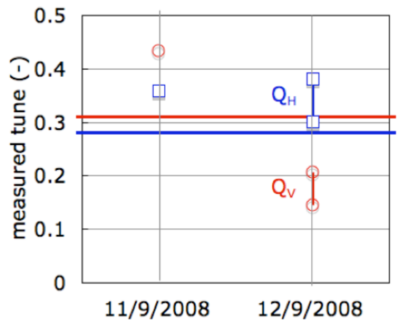

Figure 2. Measured horizontal (blue) and vertical (red) tunes (symbols) compared to the nominal settings (horizontal lines) based on circulating beam data.

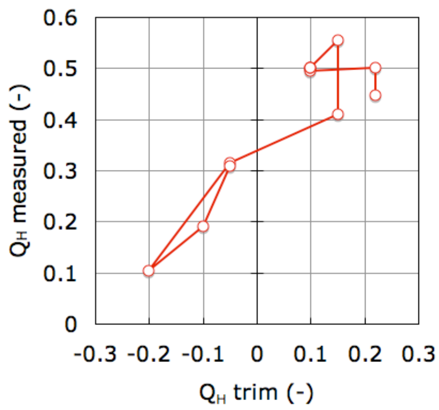

Figure 3. Variation of the horizontal tune as a function of the tune trim applied during a trim study.

beta-beating results. Coupling (not corrected) was measured on Beam 2 in the range of 0.07 [10], compatible with the expected value of 0.04 [12]. Measured beta-beating in the two planes was Δβx/βx ≈ 20 to 30 % and Δβy/βy ≈ 100 % [11], to be compared to the best expected values from simulations based on field and alignment errors of the order of Δβ/β ≈ 15 % [13]. It is worth mentioning that a deeper analysis of the optics measurement revealed a hardware issue with one quadrupole (swap between the two apertures), which, when added to the nominal optics [14], is already responsible for 17% and 54% beta-beating in the two planes.

CHROMATICITY

Preliminary studies [10] show that Beam 2 had a chromaticity of approximately 30 chromaticity units, equivalent to an uncorrected 0.7 units of sextupole field in the main dipole circuits. This value should be compared to ± 0.8 units of field expected uncertainty from Table 1, again within the expected ball-park. In this case, however, we must note that the b3 decay correction (estimated at 0.2 units of field) was deliberately ignored to simplify operation procedure. This brings the estimated residual chromaticity error to approximately 20 chromaticity units (or 0.5 units of equivalent sextupole field in the main dipoles). Although promising, these estimates are only a first taste of the LHC chromaticity settings at injection and during ramp, which will require our full attention during the next start-up.

CONCLUSIONS

The first indications collected from the short beam time at the LHC point to the fact that the overall strategy for modelling through FiDeL and setting in LSA is remarkably successful. All indicators discussed in the paper show that the concept is working as expected, and so far we could not find any real showstoppers.

Looking forward, we have identified a few critical items to be resolved before the start-up in 2009, namely (i) having a model of field harmonics of all main magnets, (ii) define a tight control of cycling during operation, compatible with minimizing the turn-around time, (iii) modifications in the nominal optics to avoid current settings at very low currents, where the magnet transfer function is highly non-linear and hysteretic, (iv) improved modelling for the magnets involved in the squeeze at low currents, and taking into account the actual pre-cycle.

Much still needs to be done before the LHC beam reaches nominal energy and luminosity (especially the control of the energy ramp and squeeze). Nonetheless, the results presented here show that the many years of magnet measurements and dedicated R&D that are built in FiDeL are now paying back.

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