FIRST FIELD TEST OF FIDEL THE MAGNETIC FIELD DESCRIPTION FOR THE LHC*

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Abstract

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 the parametric model of the transfer function of the main field integrals generated by the series of magnets in the LHC powering circuits, from main optical elements to high-order harmonic correctors, both superconducting and normal-conducting magnets. The same framework is used to predict harmonic errors of both static and dynamic nature, and forecast appropriate corrections. In this paper we use beam-based measurements 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 various (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].

At the time of this writing (March 2009), FiDeL provides on a circuit-by-circuit basis:

- A full-blown transfer function model for main magnets (optical elements);
- A simplified TF model for correctors (linear + saturation);
- A full-blown b3, b5 errors for the MB's (static + dynamic).

The above features were implemented as an integral part of the LHC controls (LSA) and tested in the settings of the injection tests and first beam of August and September 2008. For reference, it should be noted that in the present form, the FiDeL settings and model do not (yet) provide:

- An accurate persistent current description for magnets operated at currents much below nominal (e.g. MQM, MQY, MQT(L);
- Hysteresis crossing of transfer functions (or harmonics);
- Data on a magnet-by-magnet basis (or finer granularity) unless a magnet is a circuit.

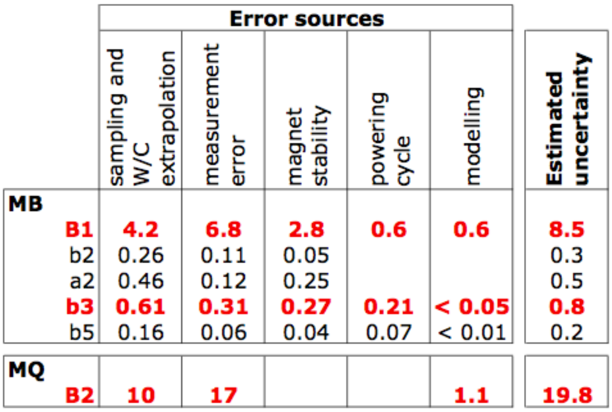
In spite of these known limitations, and to the best of our knowledge, FiDeL is presently the most advanced model of the magnetic field in an accelerator magnet, based on recent advances in the physical understanding and the largest measurement database ever available.

The main objective of this paper is to establish ballpark accuracy for the machine settings observed from beam-based measurements, and compare the results to the expected setting accuracy derived from measurement error estimates and correlation analysis. Because of the limited beam time, a sensible analysis can only be performed on basic quantities such as momentum, tune and chromaticity estimates, which are our main indicators in this paper.

EXPECTED SETTING ACCURACY

The analysis of the magnet measurement accuracy, and correlation analysis of magnet populations partially

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.



	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**
b2	0.26	0.11	0.05			0.3
a2	0.46	0.12	0.25			0.5
b3	**0.61**	**0.31**	**0.27**	**0.21**	**< 0.05**	**0.8**
b5	0.16	0.06	0.04	0.07	< 0.01	0.2
MQ						
B2	**10**	**17**			**1.1**	**19.8**

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 I, 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 analysis of Table I, 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 accuracy was possible already from the first shots thanks to the excellent performance of the BPM measurement and analysis. Figures provided by J. Wenninger (CERN-BE) on the first injection in the LHC Sector 23 (August 8th to 11th) showed that the LHC momentum 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 energy setting of the LHC of the order of +10 units or better, vs. ± 8.5 units expected uncertainty

The difference of energy 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, 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 energy between sectors is of the order of 3 units r.m.s., compatible with the accuracy of the magnetic measurements. Finally, the orbit in steady conditions, during sequences of injections and dump with no change in machine settings, was highly reproducible, to the level of 1 unit. This allowed accurate corrections of orbit excursions well below the expected tolerances.

A puzzle is still remaining on the side of these very good results. 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 loosing 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 momentum in Fig. X1 where we reported the BPM readings for an injection of beam 1 in point 2 through point 5. The first reading was taken with orbit corrected, in stable conditions. The main dipole circuit in sector 23 was then recycled, but injection settings were approached from higher currents, inverting the contribution of persistent currents to the main field. The effect of this anomalous cycle is to displace the orbit in sector 23 radially by -1.4 mm, which is consistent with a field increase of the order of 0.1 %, as expected from magnetic

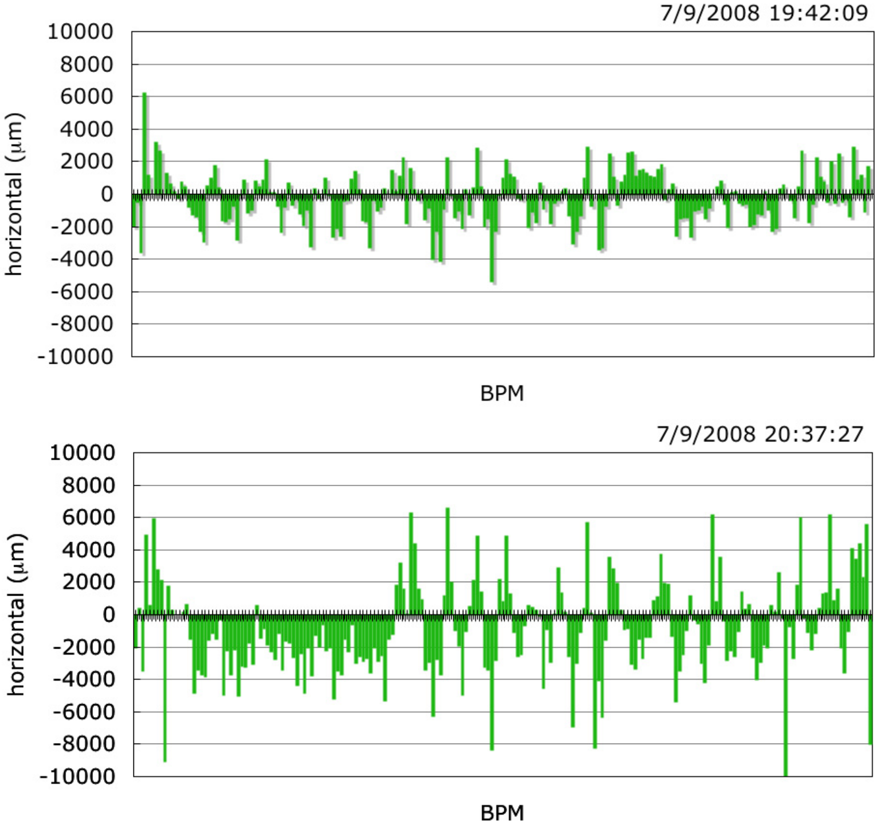


Figure 1. Shift of the horizontal BPM reading produced by an anomalous cycle performed on the dipoles of sector 23. The beam travels from left to right through three sectors, from point 2 (left-most) up to point 5 (right-most).

measurements.

Such an anomalous pre-cycle was done intentionally and is definitely an upper estimate of the effect of sequencing ramps on the dipole circuits during the hectic days of the first injections and circulating beam days. 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 analyses were performed by R. Steinhagen (CERN-BE) and R. Tomás (CERN-BE) A collection of the measured 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 $Q_H = 0.28$, $Q_V = 0.31$ (the integer tunes were correct, as far as it could be obtained from the analysis of the beam oscillations at the BPM's). We can see from there that the measured tunes are within 0.15 of the nominal ones, i.e. to ± 25 quadrupole units setting error, vs. an expected uncertainty of ± 20 units from Tab. I. 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 units, i.e. of the order of the estimate of the setting accuracy.

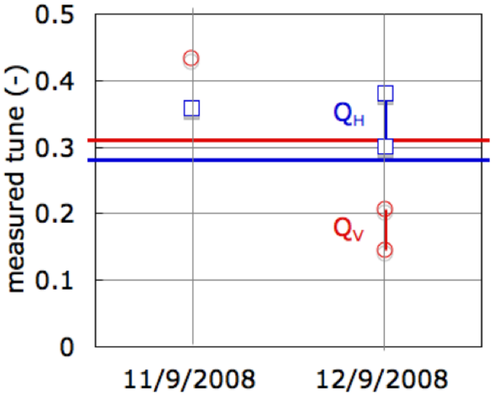


Figure 2. Measured horizontal (blue) and vertical (red) tunes (symbols) compared to the nominal settings (horizontal lines).

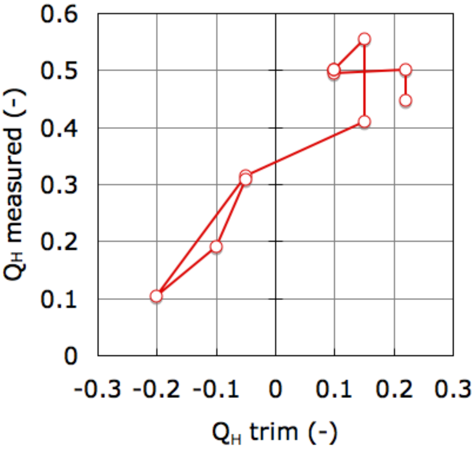


Figure 3. Variation of the horizontal tune as a function of the tune trim applied during a tune trim study.

The variation is so far not explained, better machine conditions are required to pinpoint the cause. An indication however is that some of the variations could be attributed again to magnets cycling. Especially the MQT circuits were found during the trim studies to cause a hysteretic response. This is shown in Fig. 3 for the horizontal tune during a trim study. Different horizontal tunes are measured for the same trim settings (and the same current in the MQT circuits). The typical amplitude of the tune hysteresis is of the order of 0.05 tune units (NOTE that we prefer to ignore the large variations in the vicinity of 0.5 tune units), which is compatible with magnetic measurements on single magnets powered in the range of few A and arbitrary current waveform. This is a topic that definitely deserves more analysis and attention.

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 $\Delta\beta x/\beta x \approx$ 20 to 30 % and $\Delta\beta y/\beta y \approx 100$ % [11], to be compared to expected values from simulations based on field and alignment errors of the order of $\Delta\beta/\beta \approx 15$ % [13].

Both coupling and beat-beating values are satisfactory, and point to the overall *sanity* of the settings.

CHROMATICITY

Preliminary studies [10] show that beam 2 had a chromaticity of approximately 30 units, equivalent to an uncorrected 0.7 units of sextupole in the man dipole circuits. This value should be compared to vs. ± 0.8 units expected uncertainty from Tab. I, again within the expected ballpark. In this case, however, we must note that the b3 decay correction (estimated at 0.2 units) was deliberately ignored to simplify operation procedure. This brings the estimate residual chromaticity error to approximately 20 units (or 0.5 units of equivalent sextupole in the main dipoles).

It is fair to say that 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.

DISCUSSION AND PERSPECTIVE

The first indications that we could collect 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, beam measurements have given us a wealth of data that we are presently exploiting. Thanks to this precise tool, we have already identified a few critical items to be resolved before the start-up in 2009, namely:

- Non-nominal cycles are most likely the reason for the day-to-day reproducibility issues observed on momentum, tune, and chromaticity. Objectively, in the frenzy of the first injection tests, and given the limited system availability, it was simply impossible to proceed differently. This should be considered, possibly with more rigorous cycling, for the next start-up;
- Several circuits in the injection optics are set to a very small fraction of the nominal current (i.e. below 1 %, of the order of 1 A and smaller). Most critical examples are the arc RQT (minimum current 48 mA), the warm RQT (minimum current 0.9 A), the RQTL (minimum current 37 mA). The optics should be modified where possible to attain a range of current suitable for precise control, e.g. shifting the working points (introduce an injection offset), and eliminating magnets from the optics if not critical (degaussing before injection);
- A hysteresis model may be needed for trim magnets working around zero current. This will require dedicated theoretical and measurement work over a period of several months, followed by testing in the LHC.

We are conscious that much still needs to be done before the LHC beam reaches nominal energy and luminosity (control of the ramp, squeeze). Nonetheless, we also feel that the many years of magnet measurements and dedicated R&D that are built in FiDeL are now paying back, and were (only) one of the (many) key contributions to the success of the first beam on September 10th 2008.

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