THE MAGNETIC MODEL OF THE LHC DURING COMMISSIONING TO HIGHER BEAM INTENSITIES IN 2010-2011

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Abstract

The Field Description of the Large Hadron Collider (FiDeL) model is a set of semi-empirical equations linking the magnets behaviours established from magnetic measurements to the magnetic properties of the machine observed through beam measurements. The FiDeL model includes the parameterization of static and dynamic (time dependant) components. In the present paper, we outline the relationship between the beam observables (orbit, tune, chromaticity) and the model components during the commissioning to higher beam intensities in 2010-2011, with energy of 3.5 TeV per beam. The main relevant issues are (i) the operation at 10 A/s ramp rate and their influence on chromatic correction, (ii) the beta beating and its relation to the quadrupoles transfer functions and (iii) the origin of the observed tune decay at injection.

INTRODUCTION

The field description for the LHC (FiDeL) is a set of parametric components modelling the geometric, residual magnetization, hysteresis and saturation (static model) and the powering history, decay and snap-back (dynamic model) of the transfer function and the meaningful harmonics for each magnet family [1]-[3].

Following the experience of previous accelerators [4], pre-cycling prescriptions are needed to ensure the reproducibility of the machine [5]. The operation of the LHC since 2009 has shown the importance of the pre-cycle, which has been strictly applied in 2011. In order to minimize the turn-around time, the operation makes use of the previous ramp as a pre-cycle as much as possible.

Due to issues in magnet splices [6] and in the protection system, the energy of the machine has been limited to 3.5 TeV until the next long technical shutdown in 2013. The decision was made to focus on intensity and luminosity improvement instead [7], targeting 50 ns bunch spacing, with 1.2×10^{11} p/b. This target was reached in June, providing already more than half of the nominal beam intensity at 7 TeV, and proving the exceptional quality of the machine and the very good knowledge of the magnets.

At 3.5 TeV one has the best operational condition for the magnets since the saturation effect, becoming relevant at 7 TeV, is not yet visible, whereas the magnetization, present at injection currents, has already disappeared. On the other hand, the injection values are the most difficult ones to model since the magnetization components are strongly nonlinear at low currents.

In this paper we describe the main results of the magnetic field model in terms of beam observables.

PRE-CYCLE

In September 2010, the LHC started to use pre-cycles and cycles with ramps at 10 A/s (was 2 A/s) and top current at 6 kA (3.5 TeV) for the main dipoles and quadrupoles (Fig. 1), still in use today for safety reason [7]. The current physics cycle was reused as much as possible to pre-cycle the next run and minimize the turn-around time.

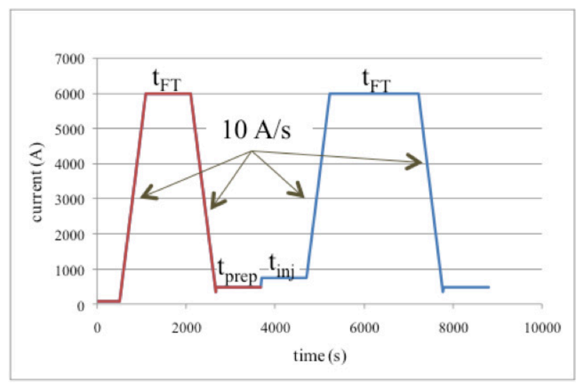

Figure 1: Current pre-cycle and cycle used for the LHC main dipoles and quadrupoles since September 2010.

Starting from 2011, few initiatives from FiDeL were proposed to improve further the situation. A new procedure was implemented [8] to limit the stored magnetic energy below 100 kJ during the preparation time (Fig. 1) and allow access to the accelerator tunnel during machine operation. This required to limit the current in the main dipoles to 100 A (was 350 A) with a negligible impact on the b_3 decay during the injection. The advantage is that the dipoles do not need a pre-cycle after each short machine stop following a ramp down.

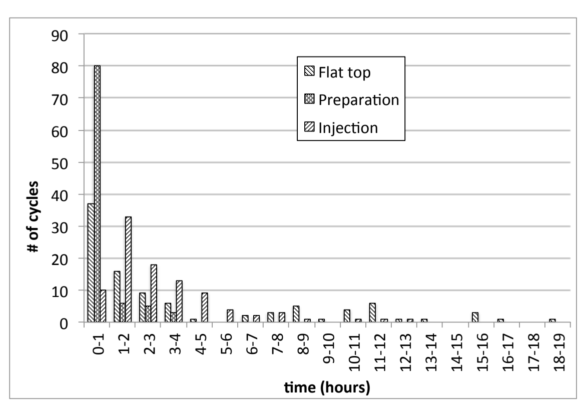

Figure 2: Histogram of time spent during the flattop, preparation and injection over 96 cycles in 2011.

The operation enforced systematically proper pre-cycling, following the recommendation of FiDeL, thus leading to a machine behaviour much more reproducible comparing to 2010. The average time spent during preparation and injection (Fig. 2) has been shorter compared to 2010 [9] and 61 cycles used the previous physics run as pre-cycle.

Some wrong magnet pre-cycle settings were detected and corrected. In particular, bipolar magnets with wrong pre-cycle current sign (some MQT and MQTLI) or magnets with current above injection current during the preparation were adjusted to avoid hysteresis issues.

ORBIT

The needed strength of the orbit correctors mainly reflects the homogeneity of the dipole field, its direction, and the alignment of the quadrupoles. The used strengths of the cell orbit correctors at 0.45 TeV and 3.5 TeV are within 2.5% and 20% respectively of their nominal strength for both the horizontal and vertical planes since 2010, with no change for 2011. The linear dependency of the strength versus energy is very well respected and therefore we expect to use less than half of the corrector strength at 7 TeV. The stability of the corrected orbit is about ±0.4 mm from fill to fill (±4 mm without correction) and ±0.1 mm during the same fill. These excellent results are inline with the very good reference orbit used, which led to an aperture gain of about 2 mm [10].

Some hysteresis has been observed when large orbit bumps are applied and then cancelled out by the online feedback loop running at 25 Hz. Also, some degradation of the uncorrected orbit was observed between 450 GeV and 1.2 TeV and vanished at higher energy. These two phenomena are possibly due to hysteresis in some orbit corrector magnets MCBH/V, MCBCH/V, MCBXH/V (nested), MCBWH/V (resistive) and should be investigated in future.

In 2011, the orbit is pretty stable and reproducible over months and the accuracy of the correction is mainly limited by the performance of the beam position monitors. Effects on the uncorrected orbit are dominated by uncertainties on the machine alignment and not by the field errors, with no specific issue for the operation [11].

TUNE

The number of betatron oscillations Q is related to the ratio between the integrated strength of the quadrupoles and the main dipoles, as well as closed orbit offset and misaligned sextupoles giving a quadrupolar term (feed down). The tune of the bare machine agrees with the nominal tunes ($Q_h = 64.28$, $Q_v = 59.31$) since 2010, with a drift of −0.08 in the horizontal plane and +0.05 in the vertical plane during the ramp. This ratio B_2/B_1 confirms the good knowledge within 0.1% of B_1 and B_2 assuming that the different contributions are uncorrelated.

In 2011 the propagation of the tune trims settings from fill to fill has been removed [12] because large trims due to long injection time (large decay) from previous run could push the tune on resonances if the next injection is fast (small decay). Furthermore the changes in pre-cycle parameters and the systematic application of pre-cycling policy had a significant impact on the tune decay correction compared to 2010, with an average amplitude reduced by 40% to 0.02 and a time constant increased by a factor 2 (Fig. 3).

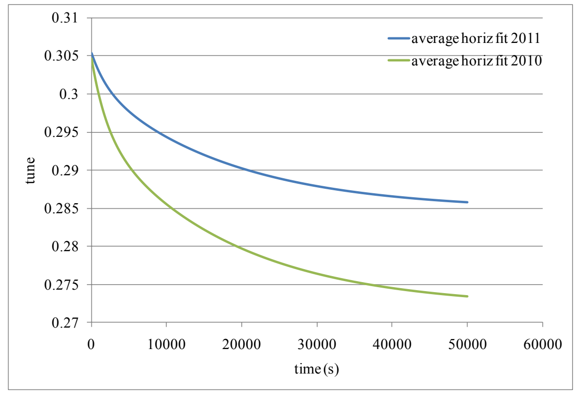

Figure 3: Difference between 2010 and 2011 of the average horizontal tune decay during injection.

In April 2011, the tune decay during injection was fully implemented using the double exponential FiDeL model [2] and the correction applied through quadrupole trim magnets (MQT). The model parameters were extracted from beam measurements since the time constant in the machine (~4000 s) is much longer than what was measured on individual magnets (~200 s). No dependency on powering history is yet implemented and the forecast correction from fill to fill is always the same.

In order to disentangle the contribution of the B_2 versus B_1 to the tune decay at injection, some simulations were carried out with MAD-X. The variation of the tune per unit of change of the transfer function was studied for magnets with Rutherford cable (i.e. MB, MQ, MQM, MQX, MQY) since other cable types do not decay, and taking into account the ramp rates used during magnetic measurements (10 A/s to 50 A/s). Only the dipoles (MB) could have a sufficient decay ($\Delta b_1 = 1.5$ unit @ 50 A/s) compared to the average tune decay observed in the machine ($\Delta b_1 = 0.6$ unit @ 10 A/s). Moreover the ratio 1.07 of the average tunes decay for the horizontal and vertical planes measured in the machine (i.e. $\Delta Q_h/\Delta Q_v$), is consistent with the way MB decay should affect the tune of the machine. Other magnet types have either insufficient decay or wrong decay direction (negative sign) like the main quadrupoles (MQ) that have a purely random decay component for the transfer function.

CHROMATICITY

The measured chromaticity of the machine is mainly coming from the natural chromaticity (85 units) induced by the main quadrupoles and from the sextupolar field error in the main dipoles (45 units per unit of b_3). The dominating effects for its stability occur during the injection decay and the beginning of the ramp (snapback).

In 2010, the chromaticity at injection was trimmed manually by 10-15 units (0.2-0.3 units of b_3) using only the lattice sextupoles to reach the target values. This corresponds to a current of about 5 A (focusing) and 10 A (defocusing) in the MS for a nominal current of 550 A. The magnets were working in an operational region where the magnetization contribution is 5 to 7% of the main field. Hence, the machine reproducibility at that time was around 20 units.

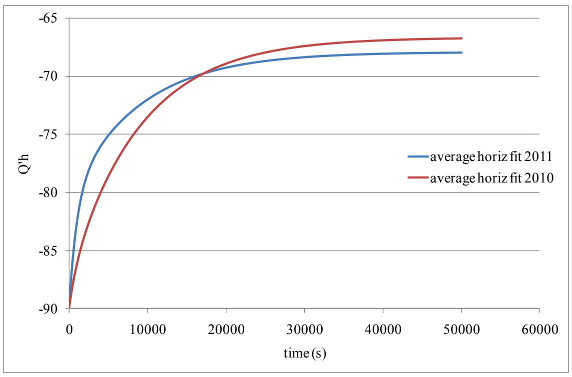

Figure 4: Difference between 2010 and 2011 of the average horizontal chromaticity decay during injection.

In 2011, the better reproducibility of the machine (because of the systematic pre-cycling) allowed to further study the machine chromaticity. The static model of the b_3 decay correction during injection was transferred from the MS to the sextupole spool pieces (MCS) and the residual magnetization of the lattice sextupoles (MS) was implemented in the FiDeL model. As for the tune, the b_3 model parameters were extracted several times from the beam measurements as the statistic was growing. While the decay amplitude has always been consistent with the model (Fig. 4), the time constant in the machine (~1000 s) is also much larger than the one measured on the magnets (~200 s). The full decay model has been implemented since May 2011, including the powering history correction, with moderate success. The model parameters were recently updated and showed an unexpected much larger decay dependence on the powering history, which is actually under investigation.

All these actions led to a machine reproducibility of 5 units, and 1-2 units (~0.03 units of b_3) for stable powering history, an excellent result beyond the initial expectations.

BETA BEATING

Beta beating reflects the good quality of the optics. Beta beating measured at 3.5 TeV in 2011 is within 20% for the unsqueezed optics and in 10% for the squeezed optics at $\beta^* = 1.5$ m after correction [13], which represents a 10% improvement with respect to 2010.

Figure 5 summarizes the relative errors due to wrong branching in the hysteresis model of the various quadrupole magnets used during the optics squeeze. Therefore, the change of the branch of the transfer function when dI/dt changes sign has been disabled in the FiDeL model since January 2011, considering only the branch with positive dI/dt. The case of the few magnets working on the negative branch of the hysteresis will be treated with deterministic trims for β^* below 1 m.

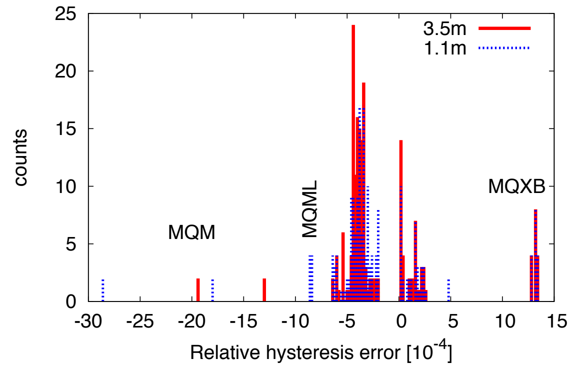

Figure 5: Hysteresis errors seen from quadrupoles used during optics squeeze at $\beta^* = 3.5$ m and 1.1 m.

CONCLUSIONS

Operation in 2010 started with conditions pretty far from the nominal ones, i.e. slower ramp and reduced energy. At the end of 2010, the nominal ramp rate has been reached. In 2011, the pre-cycling strategy has been strictly followed and has ensured remarkable machine reproducibility. Two-third of the runs used the previous physics run as their pre-cycle.

The orbit reproducibility is within specs, and its correction poses no issues. The tune reproducibility agrees with specifications, and tune feedback loop through trim correctors is very effective. The chromaticity control during injection is now done within 1-2 units, an amazing result. On the other hand, some more work is needed to understand tune and chromaticity decay over time as this effect is much longer than expected. The selection of the hysteresis branch has shown to cause problems and was removed early in 2011.

The magnetic model will be constantly improved in the next years through beam and magnetic measurements to ease operation and increase the integrated luminosity.

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