THE MAGNETIC FIELD MODEL OF THE LARGE HADRON COLLIDER: OVERVIEW OF OPERATION AT 3.5 AND 4 TEV

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Abstract

The magnetic model of the LHC is based on a fit of the magnetic measurements through equations that model the field components (geometric, saturation, persistent) at different currents. In this paper we will review the main results related to the magnetic model during the run of the LHC in 2010-2011: with a top energy of 3.5 TeV, all components of the model but the saturation are visible. We first review the main results relative to the decay at injection plateau, dependence on powering history, and snapback at the beginning of the ramp for both tune and chromaticity. We discuss the precision obtained in tracking the magnets during the ramp, where the persistent current components gradually disappear. We conclude by presenting the behaviour of the quadrupoles model during the squeeze.

INTRODUCTION

The LHC relies on more than 20 different types of superconducting magnets, plus several resistive ones [1]. To ensure a proper control of the beam, the relation field versus current must be known with a relative precision of 0.01%. The FiDeL (Field Description of the LHC [2,3]) is a set of equations that describe the dependence of the field and harmonics on the current, whose parameters have been estimated thanks to an extensive campaign of magnetic measurements. LHC operation in 2011 at 3.5 TeV and first experience at 4 TeV in 2012 [4] have shown an impressive capability of the model to represent the actual magnets in the machine, with a few surprises. Here we summarize the main features and issues.

PRECYCLING

Precycling strategy has been defined on the ground of the experience of magnetic measurements. Given the several different families of magnets in the LHC, and their optical function, different rules have been established [5], to find the best trade-off between a good machine reproducibility and minimal turn-around time. Since the early phases of the beam commissioning, this strategy has been rigorously followed.

The dipole pre-cycle is used to master both reproducibility of hysteresis and powering history influence on decay and snapback components. It has a flat-top which was initially 1000 s and then has been lowered to 600 s. The pre-injection plateau at 350 A, foreseen in the design phase, has been removed in 2011 to further reduce the turn-around time. Reset has been lowered to 100 A to be avoid the necessity of a precycle after access to the LHC.

The most important feature is that this strategy allowed to pre-cycle only in exceptional cases (less than 20%), such as power abort, whereas in most cases the previous physics run was used as pre-cycle. For this reason the powering history had variability in the flat-top duration from zero to about 10 hours, as it was planned in the development of the model [2].

The initial part of the ramp, which has a parabolic dependence on time, has been also sped up after the first experience with chromaticity control of the snapback.

CHROMATICITY

Control of chromaticity in the LHC has been considered as a relevant issue since the early phases of the project, based on the Tevatron experience [6]. Chromaticity is proportional to the sextupolar component b_3 of the main dipoles, with one unit of b_3 giving 45 units of chromaticity. At 3.5 TeV one expects about 22 units of chromaticity decay: this was confirmed in early 2011. The functional shapes found on the ground of magnetic measurements (double exponential in time for the decay and exponential in current for the snapback) have been confirmed by beam operation [7].

The first surprise, still unexplained, is a relevant drift of LHC chromaticity even after one hour – corresponding to time constants of 1000 s instead of 200 s as expected from magnetic measurements [7]. This obliged us to include the decay compensation through the spool pieces from the very early stage of commissioning (April 2011) to have a stable chromaticity during injection. The coefficients were worked out on the ground of beam measurements.

Magnetic measurements were used to better understand the dependence of b_3 decay on the powering history. Operation confirmed that the relevant parameters found through magnetic measurements are (i) flat-top duration at collision energy and (ii) duration of pre-injection time. According to magnetic measurements, above 30 minutes of flat-top duration one has a saturation of the decay amplitude. One the other hand, operation showed much longer times, with decay amplitude still increasing after 1 or 2 hours of flat-top. This was the second surprise, which forced us to include the powering history since early phase of beam commissioning (May 2011). Also in this case coefficients were estimated through beam measurements.

Chromaticity is measured during routine operation only with pilot beam, and therefore when the high-intensity beam for physics is injected one is blind w.r.t. this quantity. A beautiful measurement of bare chromaticity (i.e., chromaticity without the dynamic correction of

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decay and snapback) has been performed at the beginning of the 4 TeV operation (see Fig. 1). The pilot beam managed to survive the large chromaticity sweep. The decay of about 10 units over 30 minutes, opposite in horizontal and vertical planes as expected for contribution from b_3 in the main dipoles, is clearly visible.

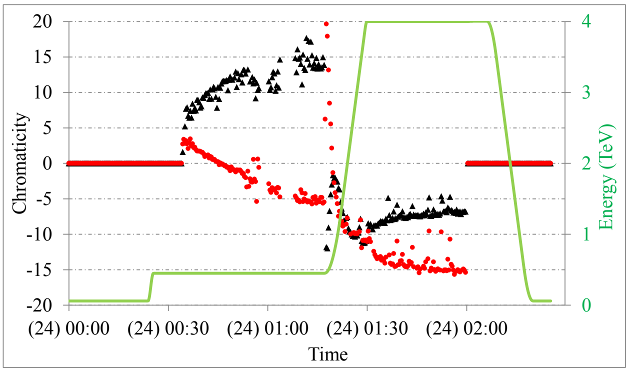

Figure 1: The bare ramp: chromaticity decay, snapback, drift during ramp and decay at 4 TeV.

The snapback is well fit by an exponential of the current [8], as predicted by the model (see Fig. 2).

$$b_3(t) = \Delta b_3 \exp\left(-\frac{I(t) - I_{inj}}{\Delta I}\right)$$

The ratio between the snapback amplitude Δb_3 and the time-like constant ΔI, foreseen to be 0.175 by magnetic measurements, has been found to be much lower, i.e., around 0.07. This corresponds to a slower snapback.

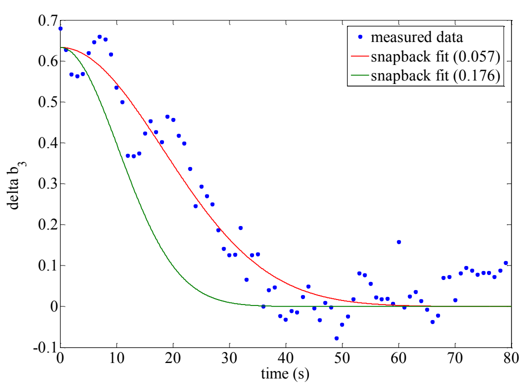

Figure 2: Snapback of b_3 at the beginning of the ramp.

After the snapback, the chromaticity changes along the ramp of a maximum of 30 units, i.e. 0.6 units of b_3. Since the change of b_3 during the ramp is 7 units, the correction with the spool pieces based on the field model works with less than a 10% error.

A non-negligible chromaticity decay of about 4 units over a few minutes is visible at 3.5 and 4 TeV (see Fig. 1). The decay in horizontal and vertical plane is in opposite directions, thus suggesting that the sextupolar component of the dipole is again at the origin of this decay. To deal with this, in the 2011 run the ramp process was made longer to wait 5 minutes at 3.5 TeV for the decay to take place. In April 2012 a correction based on beam measurements has been implemented.

TUNE

The tune is locked on the nominal value at injection and during ramp by the feedback system, which acts on the tuning quadrupoles MQT close to most of the main quadrupoles. In early phases of operation it became evident that the LHC had a tune decay of about -0.02 during the injection stage. Contrary to Tevatron, where the drift was opposite in horizontal and vertical plane, in the LHC both tunes drift in the same direction, thus suggesting that the source is the ratio between main quadrupole and main dipole strength. A negative drift of 0.02 in the tune corresponds to 4-5 units negative drift in the main quadrupole transfer function (which contribute to 40 out of 60 integer parts of the linear tune) or 3 units of positive drift in the dipole transfer function. A special measurement at injection excluded any decay of the main dipole transfer function of more than 0.1 unit (see Fig. 3). This is in agreement with the series measurements [9] that showed a main field decay in the dipoles at injection current of less than one unit.

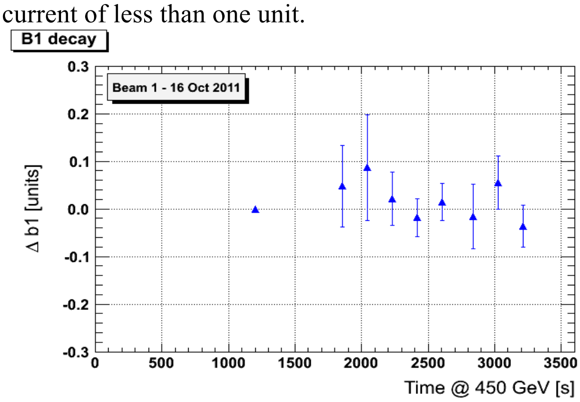

Figure 3: Estimate of decay of the dipole main field through beam measurements at injection.

The reproducibility of the tune at injection is 0.006 in both planes, corresponding to about 0.1% unit of main quadrupole transfer function. At 4 TeV the reproducibility improves, reaching about 0.003 units in both planes. A better reproducibility at higher energies is expected, as the magnetization components, present only at low field, have a non-negligible influence on the random part of the field.

The discrepancy between nominal and bare tune is 0.04 units in the horizontal plane and -0.07 in the vertical one, i.e., the bare tune at injection is around (64.32, 59.24) rather than (64.28, 59.31) see [10] for details. This corresponds to about 10 units precision (0.1%) in the absolute values of the average strength of the machine quadrupoles, which is close to what is expected from magnetic measurements. Indeed, part of this discrepancy is explained by a model accounting for all imperfections of the machine. In particular, the b_2 systematic component of the dipoles (given by the two-in-one magnetic design) and the local correction through the tuning quadrupoles can be a critical issue which needs further investigation.

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During the ramp the bare tunes drift from 64.32, 59.24 (but the real tune is locked on the nominal values 64.28, 59.31), to 64.24 and 59.27 at 4 TeV. This means that the discrepancy between nominal and real tune is reduced by a factor two during the ramp, i.e. from 10 to 6 units. This effect is systematic, and it is interesting to note that most of the drift in the tune plane takes place from 450 GeV to 1-2 TeV. This suggests that the missing part in the model at injection could be a magnetization component active only at low energies. A detailed analysis is given in [10].

BETA-BEATING

Whereas the tune is a global indicator of the modelling capabilities of the quadrupole transfer function, beta-beating gives a direct measurement of the local optics, i.e., the local precision of the quadrupole model. The tune is corrected by feedback system or by global trims acting on the MQT; beta-beating is corrected through an offline procedure, where the optics is once measured locally, and corrections to the transfer functions of the individual quadrupoles are estimated with an optimization algorithm.

Two types of corrections are done: first a local one, where the beta-beating is corrected with the quadrupoles close to its source. Then, the residual beta-beating can be corrected globally with quadrupolar knobs through an optimization algorithm involving several degrees of freedom. In both cases the solution is not unique, and must be taken as an indication of the precision of the model rather than a direct evidence of a wrong transfer function in one single quadrupole.

At injection the beta-beating of the bare machine is around 30-40%, and is reduced to 5-10% through the above mentioned techniques [11]. The correction corresponds to about 10 units in some IR quadrupoles. There is a rather good reproducibility of a few percent during the 2012 run. Some non-negligible differences, under investigation, have been noted w.r.t. the 2011 run.

At the end of the ramp, at 4 TeV and before the squeeze, beta-beating is within specifications (10%) without need of corrections (see Fig. 4). This is a strong indication that the geometrical part of the model, which gives the full behaviour at 4 TeV for most magnets, is correct in all families within a few units.

As expected, beta-beating grows during the squeeze, where the optic becomes very sensitive to the IR magnets, especially to the triplets. It reaches 60% at β^*=1 m, and 100% at β^*=0.60 m (see Fig. 4). It has been reduced to 10% with the local and global correction strategy, acting on the transfer functions of the triplet and of the matching sections around IP1, 5, 6 and 8. Corrections are of the order of 10-20 units in the triplets around IP1 and IP5, plus a large 100 units correction in one Q4. Around IP8 one has 1-3% corrections in the MS quadrupoles Q4, Q5 and Q6. These corrections have the good feature of being constant during the squeeze.

An error of 10 units in the transfer function of the inner triplet can be possible, even though it should be applied uniformly to all magnets of the same type and not only to some of them. On the other hand, it looks extremely unlikely, if not impossible, to have large errors of 1-3% in the MS quadrupoles.

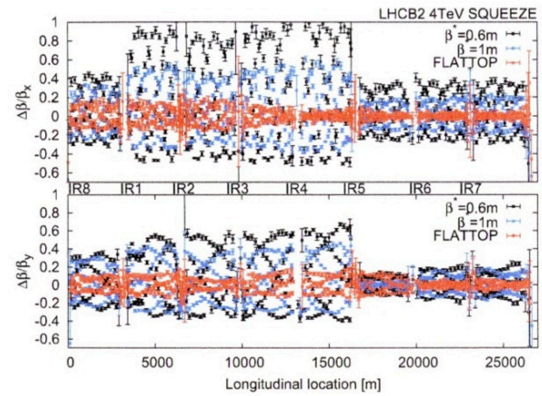

Figure 4: Beta-beating without corrections at 4 TeV.

CONCLUSIONS

The LHC magnetic field model has guaranteed a smooth and fast commissioning of the accelerator up to 3.5 TeV in 2011 and up to 4 TeV in 2012. The pre-cycling strategy has ensured a very good reproducibility of the magnets, of the order of 10^{-4} relative to the main field. The efforts spent in an intensive campaign of measurements during the magnet production and the analysis effort to translate this knowledge in the LHC control system did pay back, with a large saving of commissioning time. The mastering of the LHC is particularly impressive when new optics have been commissioned in a few hours [12] (or even less). For the 6-7 TeV run in 2014 the expected unknowns are (i) the modelling of the saturation in most of the main magnets and (ii) the nonlinearities in the triplets at very low β^*.

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