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THE MAGNETIC MODEL OF THE LHC IN THE EARLY PHASE OF BEAM COMMISSIONING

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Abstract

The relation between field and current in each family of the Large Hadron Collider magnets is modelled with a set of empirical equations (FiDeL) whose free parameters are fit on magnetic measurements. They take into account residual magnetization, persistent currents, hysteresis, saturation, decay and snapback during initial part of the ramp. Here we give a first summary of the reconstruction of the magnetic field properties based on the beam observables (orbit, tune, coupling, chromaticity) and a comparison with the expectations. The most critical issues for the machine performance in terms of knowledge of the relation magnetic field vs current are pointed out.

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INTRODUCTION

The magnetic model of the Large Hadron Collider (FiDeL) provides for each magnet the relation between the current and the field, based on the set of magnetic measurements. FiDeL includes the history of the magnet to take into account the correct hysteresis branch and the dependence of dynamic effects on the previous cycling. This is based on fits which have been presented in [1,2,3].

FiDeL is complemented by WISE [4], to create in any operational condition the sequence of the individual errors of each magnet, to be used in beam dynamics simulations [5]. WISE also includes the alignments of magnets along the ring, and can generate random errors related to the limited knowledge of fields and geometries (measuring errors, sampling strategies, etc.).

Following the experience of previous accelerators [6], pre-cycling prescriptions are needed to ensure the reproducibility of the machine [7]. Both the 2009 and 2010 run have shown the importance of the precycle. Already in this very early phase of commissioning, the LHC operation makes use of the previous ramp as a precyle to minimize the turn-around time.

Due to issues in magnet splices [8] and in the protection system, the energy of the machine has been limited to 1.2 TeV in 2009 and 3.5 TeV in 2010 [9]. At 3.5 TeV one has the best possible knowledge of the magnet since saturation effects, becoming relevant at 7 TeV, are not yet visible, whereas the magnetization, present at injection currents, has disappeared. On the other hand, the injection values are the most difficult ones to model since the magnetization component is strongly nonlinear.

In 2009, in 26 days of operations, stable beams at injection have been established, 6 ramps to 1.2 TeV have been successfully carried out, including measurements of the optics and a squeeze up to β^*=7 m. Since late February 2010, several tens of ramps to 3.5 TeV have been successfully carried out, including measurements of the optics, and collisions at 3.5 TeV with squeezed beams at β^*=2 m. To get to 3.5 TeV ramps have been performed at 2 A/s for the main quadrupoles and dipoles instead of 10 A/s to overcome problems related to the protection of the main magnets [9]. In this paper we describe the main results of the magnetic field model in terms of beam observables, and we outline the main critical 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 strength of the cell orbit correctors at 3.5 TeV is within 20% of nominal (see Fig. 1). Therefore at 7 TeV we expect to use less than half of the corrector strength.

For the vertical correctors the required strength has a pattern along the ring (see Fig. 1): half of the ring needs an average positive kick, corresponding to an average offset of the closed orbit in absence of correction of 1-2 mm. This would correspond to have a systematic tilt in the main dipoles in this region of 1 mrad; this effect is under investigation, but considered as highly improbable.

The orbit found at injection energy is stable during the ramp, barely requiring further correction at 3.5 TeV [10].
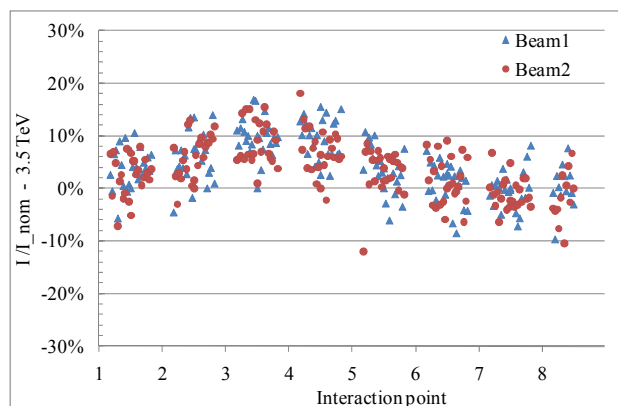

Figure 1: Used strength of vertical correctors at 3.5 TeV w. r. t. nominal strength (April 1st 2010, 18h15m).

TUNE

The tune is mainly related to the ratio between the strength of the quadrupoles and of the main dipoles, and to the closed orbit in the sextupoles. The tune of the bare

machine agrees with the nominal tunes (64.28, 59.31) within 0.1. This ratio B_2/B_1 is therefore known to 0.16%, corresponding to a 0.1% in B_1 and B_2, if different contributions are uncorrelated and neglecting the sextupoles. This good result agrees with specifications.

At the beginning of the ramp, a variation of tune of less the 0.005 is measured. This corresponds to a very small snapback of B_2/B_1 of 0.01%, in agreement with the results of magnetic measurements: both dipoles and quadrupoles have a main component decay <0.01% [2,3,11].

During the ramp, tunes drift of the order of 0.05-0.1 have been observed [12] (see Fig. 2). The drift of the 1.2 TeV run of 2009 can be decomposed in a negative drift of 0.05 in both tunes (parallel to the diagonal), plus a drift of 0.05, negative for Q_H and positive for Q_V. Errors producing drifts of the same sign in horizontal and vertical are related to errors in B2/B1 tracking. In early 2010 it has been found that a wrong precycle of the resistive quadrupoles MQW and of the inner triplet MQXA and MQXB, having a reset current above the injection current, placed these magnets on the wrong hysteresis branch at injection. The error disappears in the early phase of the ramp, producing a tune drift. The effect was estimated through magnetic measurements [13] and beam dynamics simulations [14] to about 0.04, in agreement with the measured tune drift.
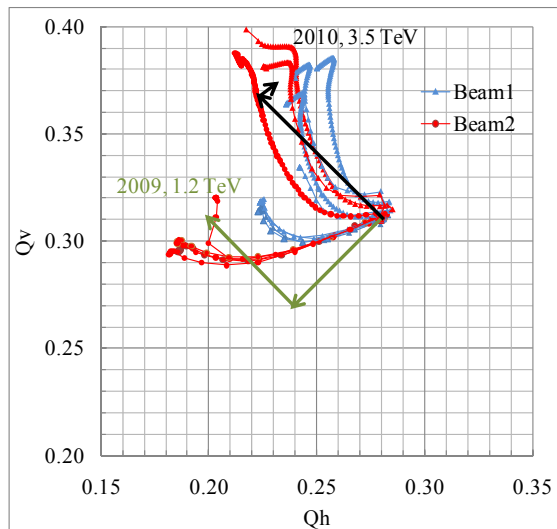

Figure 2: Reconstructed tune drift during 3 ramps to 1.2 TeV in 2009 and 3 ramps to 3.5 TeV in 2010, and decomposition along diagonals (arrows).

In 2010 the precycle has been corrected and the drift parallel to the diagonal disappeared (less than 0.003), leaving a drift of about -0.07 in horizontal and +0.07 in vertical. One possible explanation is a misalignment of sextupole correctors, giving a feed-down of the sextupole on quadrupolar terms. The systematic misalignment needed to produce 0.08 tune with a Δb_3=7 units span along the 3.5 TeV ramp is 0.5 mm, which looks large (specification is 0.3 mm). This drift still needs to be understood. A rather strong systematic difference between beams observed in 2009 disappeared in 2010 (see Fig. 2).

COUPLING

Coupling generated by field errors, alignments and experimental solenoids is corrected via 24 families of skew quadrupoles (following the 2008 incident, 3 circuits in sector 3-4 are not in operation). They operate in the range ±5 A at 450 GeV. Even though their nominal current is 550 A, the magnets feature a very low magnetization and a negligible hysteresis, as the tune correctors (in fact, they are tune correctors rotated by 45º). At 3.5 TeV they typically operate with currents in the range of ±50 A. The used strength is about 5% of the maximum available power, with peaks up to 15% in a few cases (see Fig. 3).
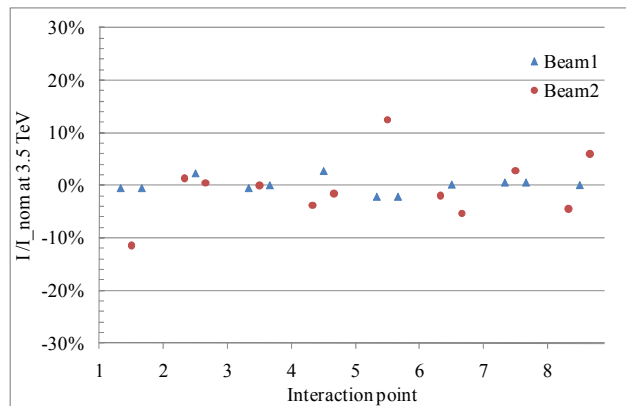

Figure 3: Used strength of skew quadrupoles at 3.5 TeV, w. r. t. nominal strength (April 1st 2010, 18h15m).

BETA BEATING

Beta-beating gives the precision of the optics; it is extensively discussed in [15]. Here we shortly report on the aspects related to the magnetic field model. Beta-beating measured both at 1.2 TeV in 2009 and at 3.5 TeV in 2010 is within 20% in the unsqueezed optics, without the need of correction. Previous simulations have shown that this accuracy could be achieved if all transfer function of the LHC quadrupoles zoo (6 different families, including one resistive!) were known within specifications [4]. This rather amazing result reflects a very good knowledge of the geometric part of the transfer function of all quadrupoles of the machine.

At injection the beta beating without correction is 30%-50%. Early measurements and inverse simulations have located the main sources of errors in the resistive quadrupoles MQWA and MQWB in the interaction regions 3 and 7, and to the triplet quadrupoles MQXB. In 2009 beta beating has been corrected through a 3% trim on the MQWA transfer function. The MQWB resistive trim quadrupoles are a special case, since they are powered with very low currents (1 to 10 A), in a region where the residual magnetization is overwhelmingly large. Beta beating has been brought back to 20% by using strong corrections on these magnets (up to a factor 2). Trims of 0.5% of the interaction region quadrupoles MQXB transfer functions were also used.

In early 2010, it has been found that both MQWA and MQXB had a precycle with a minimum current higher that the injection current [13,16]. This means that at injection these magnets were on the wrong hysteresis branch. Magnetic measurements confirmed that the effect was as high as 4% for the MQWA, and 0.5% for the MQXB. In 2010 the precyle strategy has been corrected. A trim at injection was still needed to correct beta beating, but it went down from 3% to 1.8%. Additional measurements of MQWA have been done to fits the exact precyle used during operation: work is in progress, the final aim being to avoid all trims.

CHROMATICITY

The natural chromaticity (85) from the quadrupoles is corrected through the lattice sextupoles. Another large contribution comes from the sextupolar field error in the dipoles (45 per 1 unit of b_3), and is controlled through the lattice sextupoles, including the snapback component at the beginning of the ramp.

At injection the lattice sextupole are powered with about 5 or 10 A (focusing and defocusing family respectively) to set the chromaticity to the target. In this very low range of currents (nominal current is 550 A) the lattice sextupole operate in a region where the magnetization contribution is 5 to 7% of the main field (with a total value to correct of 85, and a required granularity of a few units). Nevertheless, chromaticity trims were effective.

At injection chromaticity is in general trimmed by 10-15 units to reach the nominal values. This corresponds to an error of the b_3 in the dipoles of 0.2-0.3 units. This also includes the decay of b_3, since the beam is injected when the decay is fully established (typically a few hours after reaching the injection currents).

At the end of the ramp the chromaticity decreases by up to 15 units. This is equivalent to track the b_3 in the main dipole within 0.3 units. Since the b_3 change during ramp is 7 units, this corresponds to a correction error of 5%.
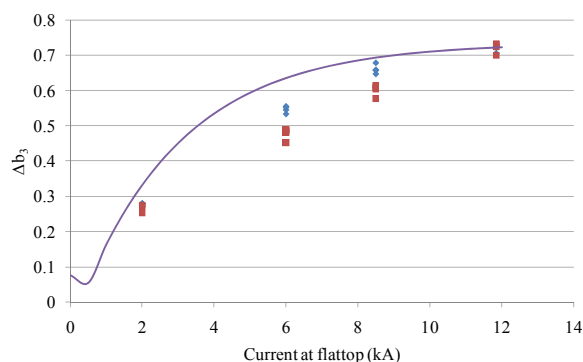

Figure 4: Snapback amplitude of b_3 versus flattop current measured on one dipole (markers) and field model given in [3].

Values at injection include the decay, since the beam is usually injected after at least one hour. Operation in 2009 involved a dipole precycle at 2 kA at 10 A/s: the expected decay (and snapback) of b_3 is 0.25 units. At 6 kA precycle one expects 0.5 units decay (see Fig. 4), but the 2 A/s ramp rate should reduce it to 0.1 units. In the machine a larger snapback has been observed, and the correction has been set to 0.4 units. Unfortunately, no measurements of the dipoles have been done in these conditions: a new campaign will start in June 2010.

CONCLUSIONS

The early phase of commissioning has shown a good knowledge of the magnetic model of the LHC. Orbit is within specs, and its correction poses no issues. In three octants of the machine it is about 1-2 mm below zero: this does not pose problem for operation but its origin is not understood. Tune reproducibility agrees with specifications, and tune trimming through correctors is effective. A tune drift during the ramp of about 0.07 units is well managed by the feedback system, but its origin still needs to be understood. Chromaticity reproducibility is within 0.3 unit of dipole b_3. The snapback at the beginning of the ramp provokes very limited beam losses, or no losses at all. The change of chromaticity during the ramp corresponds to the capability of tracking b_3 with a precision of 0.3 units over a total 7 unit span, i.e. 5%.

The precycle procedure has proven to be crucial to ensure both a good reproducibility of the machine and stable nominal conditions. A bug in the strategy has been found, giving a relevant impact on beta beating. The situation has improved after correction, but further work is needed. The un-squeezed optics at 3.5 TeV is almost within specifications without the need of any trim.

REFERENCES

[1] N. Sammut, et al., Phys. Rev. STAB 9 012402, 2006.
[2] N. Sammut, et al., Phys. Rev. STAB 10 082802, 2007.
[3] N. Sammut, et al., Phys. Rev. STAB 12 102401, 2009.
[4] P. Hagen, et al., European Particle Accelerator Conference, 2006, 2248, and European Particle Accelerator Conference, 2008, 1744.
[5] M. Giovannozzi, these proceedings.
[6] G. Ambrosio, et al., IEEE Trans. Appl. Supercond. 15 (2005) 1217.
[7] E. Todesco, et al., 'Precycle strategy for the LHC operation', LHC Project Report, in press.
[8] F. Bertinelli, these proceedings.
[9] S. Myers, these proceedings.
[10] J. Wenninger, private communication, and K. Fuchsberger, Evian workshop, 2010.
[11] L. Deniau, 'Magnetic model of the LHC main quadrupoles', LHC Project Note, in press.
[12] W. Venturini Delsolaro, Evian Workshop, 2010.
[13] P. Hagen, private communication, January 2010.
[14] R. Tomas, private communication, January 2010.
[15] R. Tomas Garcia, these proceedings.
[16] E. Todesco, et al., Evian Workshop, 2010.