CAN WE IMPROVE THE MAGNETIC CYCLE/MODEL AND THEIR EFFECTS?

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Abstract

We first recall the precycling strategy defined for operation and we give an overview of how it has been applied in the 2010 run: in how many cases the previous physics run has been used as a precycle, in how many cases we precycled the magnets, and how we did it w.r.t. specifications. We then analyse the reproducibility of tune and chromaticity, giving an estimate of the present precision of the magnetic model and discussing if it is possible to improve it. We review how the hysteresis is presently treated in the field model, and its drawbacks on the beta beating corrections during the squeeze. Possible strategies to solve the hysteresis issue are presented.

INTRODUCTION

The LHC operation in 2010 has been very successful [1]. One of the key ingredients has been the good knowledge of the relation magnetic fields versus magnet currents, and its dependence on the cycles [2]. A beta-beating close to targets for the bare machine, without corrections, both at 450 GeV and at 3.5 TeV, is the best sign of the precision of the magnetic model. Taking into account that we are in the first year of commissioning (excluding the short but nevertheless intense experience of 2008), and with some settings far from the nominal operation, the achieved reproducibility has been remarkable. In this paper we summarize the main open issues of the magnetic model and we outline the highest priority topics that have been identified to ease operation in 2011.

The precycle strategy followed in 2010, which is the main ingredient of the reproducibility, is summarized. Then, we discuss the tune decay on the injection plateau The control of chromaticity at injection and during the ramp is then analysed. Finally, we summarize the hysteresis issues, which have been considered for a long time as a critical point of the magnetic model.

PRECYCLE

The precycle of the magnets is a key element to ensure the reproducibility of the accelerator [3]. During the 2010 run at 3.5 TeV, four different combinations of precycles, ramp rates and currents have been used (see Table 1). The initial phase at 1.18 TeV is not considered here. The ramp rate has been initially limited to 2 A/s, i.e., five times slower than nominal, to cope with issues related to magnet protection. For similar reasons the flattop current has been initially lowered to 2 kA - 4 kA. The nominal condition of the main dipole operation has been recovered in the last period, with the exception of the limitation to half nominal current (6 kA) corresponding to a top energy of 3.5 TeV.

Table 1: Features of precycles and ramps in 2010.

Period	Pre-cycle			Ramp with beam		
	Flattop (A)	Ramp up (A/s)	Ramp down (A/s)	Flattop (A)	Ramp up (A/s)	Ramp down (A/s)
19.03 to 16.05	2000	2	2	6000	2	2
17.05 to 22.07	4000	2	2	6000	2	2
23.07 to 29.08	6000	10	10	6000	2	10
3.09 to 31.10	6000	10	10	6000	10	10

The precycle strategy outlined in [3], based on several studies and measurements done before and during the production [4-6], aims at ensuring identical magnetic conditions for the accelerator after a physics run and after a precycle. This allows avoiding the precycle without beam if the physics run is normally terminated, with a considerable saving in the turn-around time.

Already in this very early phase of operation, 54% of the ramps used the previous physics cycle as a precycle. Notwithstanding several difficulties which jeopardized the initial phase of the commissioning, the precycle procedure has been strictly followed: only 3% of the ramps had an anomalous precycle.

The precycle time takes about 90 minutes, and is dominated by the interaction region quadrupoles MQM and MQY, which have unipolar power converter. In future one could envisage reducing the time for these circuits through hardware changes. For the moment this is not considered as a priority since the turn-around time is not dominated by these factors.

TUNE

The LHC tune decays during injection. The order of magnitude is 0.01, i.e., enough to need a correction (see Fig. 1). Time constants are rather long, i.e., a considerable decay is observed after one hour. The fit with the double exponential [4,5] gives time constants of the order of 1000 s. The operation can be bothered by this decay: since the last trims are included in the next run, the large trims used in a previous run with long injection time can push the tune on the resonances if the successive injection occurs much faster. Then the beam is lost and one has to inject again, losing precious time.

The other critical point is that for long injection times one has to monitor the tune continuously and to trim; if the damper is on this can be difficult to measure. An easy solution for the first problem is to reset the tune trims at each injection; indeed, one can do better and implement the full correction according to measurements. This is foreseen for 2011.

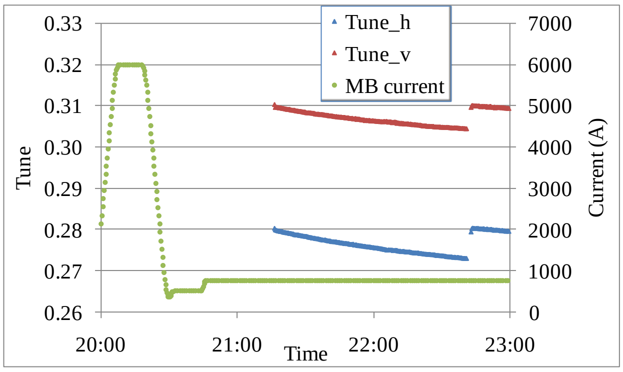

Figure 1: Measured decay of horizontal and vertical tune in different injection plateau.

CHROMATICITY

Decay at injection

In 2010 the magnets stayed at injection energy 1-2 hours [7] (see Fig. 2). We define this time from the point of view of the magnets, i.e., the time covering the span from dipoles reaching injection current to the beginning of the energy ramp. The minimal time has been 30 minutes, and the average time, including all ramps, of 5 h. During the injection plateau, the sextupolar component (b_3) in the dipole decays. The experience gathered through the magnetic measurements is that 80-90% of the decay takes place during the first 30 minutes (see Fig. 3). Since during the first year of operation we did not expect to inject in the first 30 minutes, the correction of the b_3 decay implemented in the control system has not been activated [8].

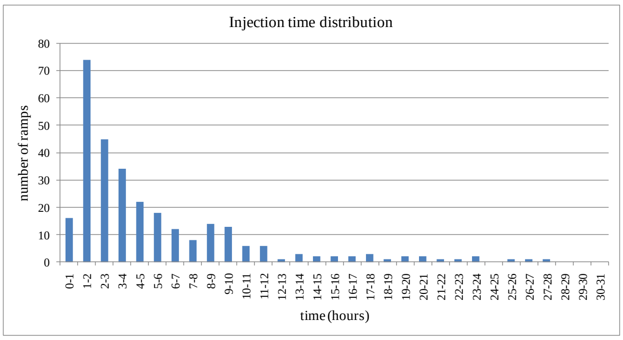

Figure 2: Time spent on the injection plateau by the main dipoles in 2010.

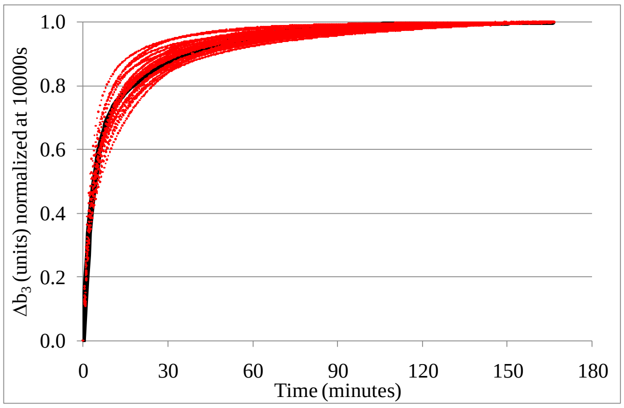

Figure 3: Measured decay in the main dipoles, normalized after 10000 s, versus time. Precycle at 50 A/s, flattop at 11.85 kA.

The expected amplitude of the decay with a 6 kA operation is 0.5 units, corresponding to 20 units of chromaticity [2]. The experience gathered during 2010 operation confirms this order of magnitude (see Figs. 4-5), even though a direct estimate is imprecise since no measurements are available from the time zero, where the decay is very steep. Indeed, the constant time is much longer, and 10 units of chromatic decay are observed from 2 to 10 h. A fit of the double exponential used for modeling the decay gives time constants of the order of 2000-4000 s, i.e., at least 10 times larger than what measured on the dipoles [5,6].

The large chromatic decay forced the operators to trim chromaticity before the injection, trying to guess the correct values and to avoid negative chromaticity based on personal experience and look-up tables. The implementation of the decay based on beam measurements is recommended for the 2011 run. From the point of view of the magnet builder, more investigation is needed to understand the discrepancy between the measurements of individual dipoles and the behaviour of the accelerator.

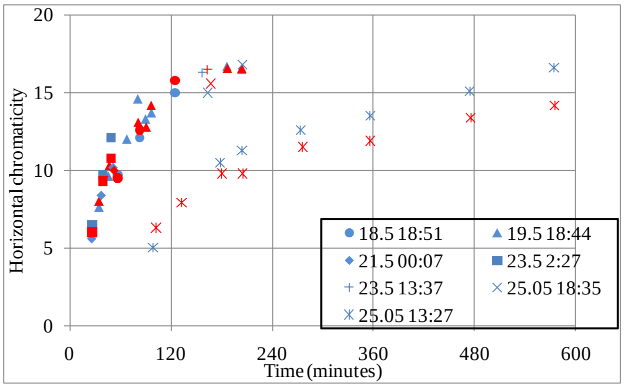

Figure 4: Measured decay of horizontal chromaticity in seven different injection plateaus [9].

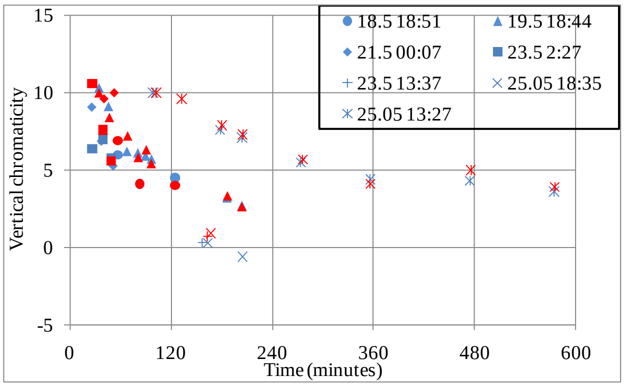

Figure 5: Measured decay of vertical chromaticity in seven different injection plateaus [9].

Behaviour during ramp

If the chromaticity decay is 20 units, as expected from magnetic measurements, during the snapback the model manages to keep track of two third of it, leaving about ±7 uncorrected units (see Fig. 6). This 30% error in the tracking precision has to be compared to the expected 20% error [10]: we are not yet there, but not so far.

The first possible source of error is the time constant of the snapback, which is given by the model and is related to the decay amplitude: a larger decay would imply a larger time constant [11], thus creating the pyramidal shape shown in the first 200 s of Fig. 6. Another source is the removal of the trims, which linearly decrease with time in 120 s: this could be too fast. We believe that there is space for improvement in 2011.

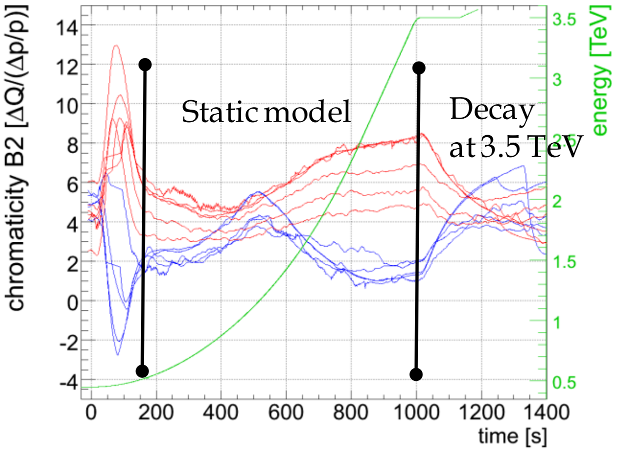

Figure 6: Chromaticity measurements [12] during the ramp in five different runs (red: horizontal, blue: vertical).

During the ramp, the model (with trims) tracks the chromaticity within ±3 units. The total change of b_3 in the dipoles from 450 GeV to 3.5 TeV is ~7 units, corresponding to about 300 units of chromaticity: this means that we manage to track chromaticity during ramp with an astonishing 1% error. Honestly, it looks difficult to make it better.

Surprise: the decay at 3.5 TeV is clearly visible (see Fig. 6) and corresponds to 5-10 units. For the moment, the strategy is to reach 3.5 TeV with a positive horizontal chromaticity of about 10 units to avoid ending up in the negative range when the squeeze is started. Moreover, a waiting time of a few minutes has been implemented to avoid setting the machine during the decay. This has not been shown to be critical for operation.

The good side of the story is that one could use the 3.5 TeV decay, measured with very good precision and not affected by the issue of the 'zero time', to guess the decay at 450 GeV. The higher the energy, the lower the decay: we will not see this at 7 TeV! But there are still a few years to go...

THE HYSTERESIS ISSUE

Hysteresis is a ghost that has periodically hunted the nights of the magnet modeller. Some years ago the hysteresis of the MQT, used for the tune trim, was considered to be too large, endangering the capability of setting the trim. Indeed, operation showed that this is not the case and that we have a full capability of controlling the tune. The same concern was expressed for orbit correctors, which today are not an issue for operation. More recently, a problem with the matching sections and dispersion suppressor quadrupoles has been identified: during squeeze, some magnets have decreasing current and reach very low values, where the persistent current component is large. Since the current is descending, the magnet is walking on the other branch of the hysteresis. Since the model considers only the upper branch, an error of several tens of units can be done on some cases [13].

The implemented strategy has been to change branch in the magnetic model, i.e., to change the sign of the persistent current component, when dI/dt changes sign. Unfortunately, this has shown some drawbacks [14]: during squeeze, some magnets have to perform small changes of currents, both positive and negative, and the current jumps on the other branch of the hysteresis, whilst the magnet stays close to the original branch (see Fig. 7). The same unwanted effect appears when trims are done to correct beta-beating during the squeeze. This reduces the efficiency of trimming.

The proposed solution is to remove the change of the hysteresis branch. This is inducing an error in some quadrupoles only for small β^* (below 1 m). These are deterministic, well-known errors that can be cured by a separate additional trim without jeopardizing the correction strategies. So for 2011 the change of hysteresis branch will not be in the model. A more refined approach would imply the complete modelling of hysteresis, i.e., including the path between the two branches. This is not considered to be a priority for the moment and could be treated after the first long shutdown.

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. Notwithstanding these conditions, the precycling strategy has been strictly followed and has ensured remarkable machine reproducibility. More than half of the runs used the previous physics run as a precycle, reducing the turn-around time.

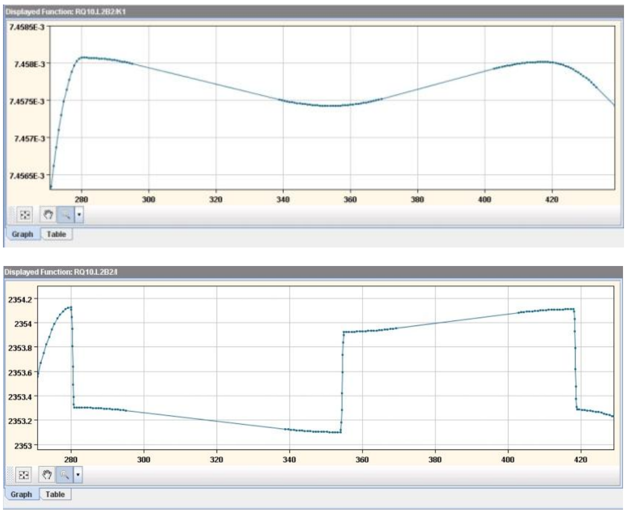

Figure 7: Quadrupole gradient during squeeze required by optics (upper part) and related current with the change of hysteresis branch.

Chromaticity control during ramp is done within 1%, i.e., a few units of b_3: this amazingly good result will be difficult to improve. On the other hand, some more work is needed to understand decay over times which are much longer than expected. At the beginning of the ramp, the snapback has proved not to be a major source of beam losses. Nevertheless, the model works with a 30% error, and additional work should be done to reach the 20% target that has been established many years ago.

The inclusion of the change of the hysteresis branch has shown to cause more problems (reduce the trimming capability) than what it had to solve. Since this change is only needed for a few magnets and for β^* below 1 m, we propose to remove it and to treat these magnets separately with ad hoc trims.

The magnetic model in the next years will be constantly improved through beam and magnetic measurements to ease operation and increase the integrated luminosity. The copious data coming from beam commissioning are also a fundamental tool to better understand the magnet behaviour, and to improve our knowledge needed for the future upgrades.

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