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Expected and measured behaviour of the tune in the LHC operation at 3.5 TeV

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The tune of the Large Hadron Collider (LHC) mainly depends on the strength of the quadrupole magnets. It is also affected by the *b2* component in the main dipoles. In case of systematic misalignments, the *b3* component due to the main dipoles and the sextupolar correctors also affect the tune due to the feed down effect. The magnetic model of the machine, based on a fit of magnetic measurements, has an intrinsic precision which can be estimated in a few units (one part over 10000). During the first years of operation of the LHC, the tune has been routinely measured and corrected through a feedback system. In this paper, we reconstruct from the beam measurements and the settings of the feedback loop, the evolution of the tune during injection and ramp. This gives the obtained precision of the magnetic model of the machine with respect to quadrupolar and sextupolar components. At the injection plateau there is an unexpected large decay whose origin is not understood: we present the data, with the time constants and the dependence on the previous cycles. Dedicated experiments aimed at excluding that this decay comes from a decay of the main dipole component were done. During the ramp the tune drifts by about 0.05: this precision is related to the precision in tracking the quadrupolar field in the machine.

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The tune of the Large Hadron Collider (LHC) mainly depends on the strength of the quadrupole magnets. It is also affected by the b_2 component in the main dipoles. In case of systematic misalignments, the b_3 component due to the main dipoles and the sextupolar correctors also affect the tune due to the feed down effect. The magnetic model of the machine, based on a fit of magnetic measurements, has an intrinsic precision which can be estimated in a few units (one part over 10000). During the first years of operation of the LHC, the tune has been routinely measured and corrected through a feedback system. In this paper, we reconstruct from the beam measurements and the settings of the feedback loop, the evolution of the tune during injection and ramp. This gives the obtained precision of the magnetic model of the machine with respect to quadrupolar and sextupolar components. At the injection plateau there is an unexpected large decay whose origin is not understood: we present the data, with the time constants and the dependence on the previous cycles. Dedicated experiments aimed at excluding that this decay comes from a decay of the main dipole component were done. During the ramp the tune drifts by about 0.05: this precision is related to the precision in tracking the quadrupolar field in the machine.

INTRODUCTION

In a particle accelerator, the betatron tune is defined as the number of transverse oscillations the particle goes through as it travels one revolution around the accelerator. In case of the LHC, this parameter has to be controlled within $\pm 3\times10^{-3}$ units [1] as it can drive particles on betatron resonances, inducing beam losses. This is achieved by measuring the tune and correcting it through a feedback system acting on the tuning quadrupoles placed close to the main arc quadrupoles [2].

The main aim of this work is to study the behaviour of the tune during injection and ramp. Data from 2011 LHC operation (measured tune and current used in the trims to lock it on the nominal value) were used to reconstruct the behaviour of the bare tune. Since the tune is always measured for every run (contrary to chromaticity [3]) a complete set of data is available. The final goal is to reduce the load on the feedback system by determining the precision of the magnetic model [4, 5] of the quadrupoles of the accelerator.

TUNE BEHAVIOUR DURING INJECTION

Figure 1 and Figure 2 show a typical behaviour of the bare tune (square data points) during the injection plateau for the horizontal and vertical plane respectively, with time zero referring to the time when the main quadrupoles reach the injection current. It can be clearly seen that the tune is decaying during the injection plateau. The amplitude of the decay is about 0.02 over a time of a few hours.

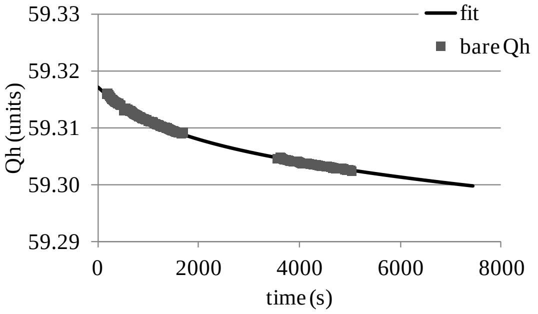

Figure 1: Horizontal tune decay as observed in Fill 1813, t = 0 s refers to the start of the injection plateau.

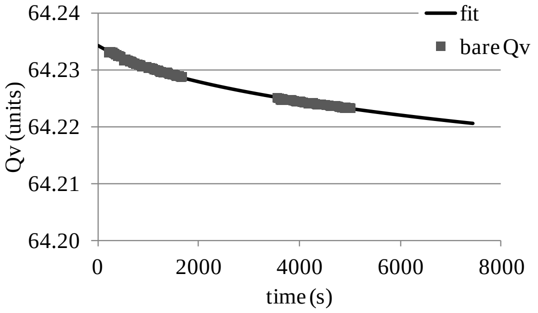

Figure 2: Vertical tune decay as observed in Fill 1813, t = 0 s refers to the start of the injection plateau.

The black continuous line is showing the fit as obtained by the model. In the literature, decay is modelled by a log *t* fit [6] or double exponentials [7]. For the LHC, we chose a double exponential given by

—— (1)
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where , , and are the fitting parameters, and we have two sets of parameters, one for the horizontal and one for the vertical tune. is the initial tune value at , the beginning of the injection plateau, is the decay amplitude as , is the weight between the fast and the slow modes and is the time constant. The fitting parameters as obtained from the 2011 beam measurements together with one standard deviation (σ) are given in Table 1. Being a four-parameter fit for a pretty smooth function, the solution is far from being unique. To have more stable fits, we fix the time constant τ at 1000 s for all cases and we varied the starting point ν, the amplitude *c* and the weight *d*.

Table 1: Fitting parameters as obtained for the tune decay

Parameter	Qh	σ	Qv	σ
v	59.317	0.004	64.239	0.007
c (units)	0.023	0.006	0.018	0.007
d	0.24	0.06	0.19	0.08
τ (s)	1000	-	1000	-

From the values in Table 1 it can be observed that the values of the bare tune (*v)* at the start of the injection are off by +0.04 in the horizontal plane and -0.07 in the vertical plane w.r.t. nominal (59.28, 64.31). This gives an estimate of ~0.1% of the absolute precision of the model of all quadrupoles transfer functions of the accelerator.

The decay during injection (as $t \to \infty$) is around 0.02 units for both planes. This corresponds to 3 units only of quadrupole transfer function, but it is one order of magnitude larger than the required tolerance, and therefore has to be corrected. Concerning the origin of this decay, both planes decay in the same direction: this suggests that the decay is due to the ratio between the main quadrupole strength and the main dipole strength, and not by feed-down of sextupolar errors coupled. A special measurement at injection showed that the decay of the main dipole transfer function is less than 0.1 unit [5]: therefore the source of the tune decay is the main field (b_2) of the main quadrupoles in the LHC. In total the accelerator has 5 different quadrupole types: one in the cell, two in the dispersion suppressor (DS) and matching section (MS), and two in the interaction region (IR). Here we do not have elements to establish which one of the five different types of magnets is the source. A decay of 3 units only in the transfer function of every quadrupole would justify the measured tune decay.

We then analysed the dependence on the powering history, namely on the flattop time t_{FT} and on the preparation time t_{prep}. These parameters vary from fill to fill in a range of zero to ten hours for t_{FT}, and 30 minutes to 3 hours for t_{prep} (refer to Figure 3). Whereas in the case of chromaticity decay a strong dependence on the precycle parameters was observed [3], for the tune the dependence is still relevant but affected by a large spread (see Figure 4 and Figure 5).

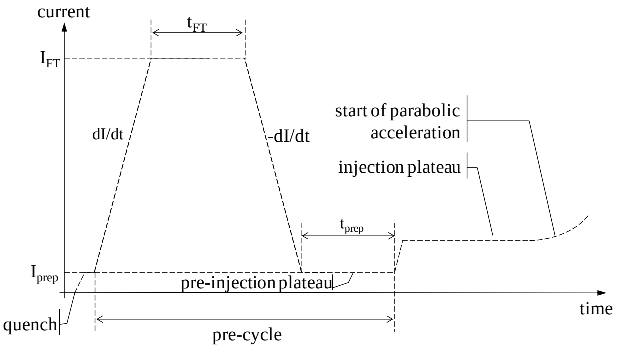

Figure 3: Definition of the parameters affecting decay during LHC injection

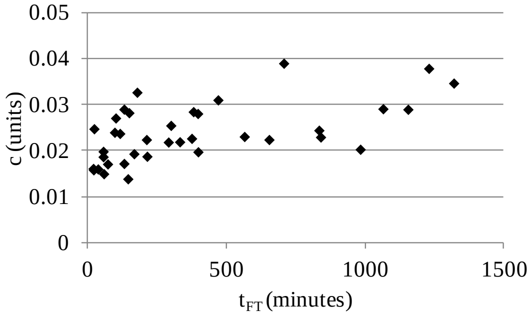

Figure 4: Decay amplitude dependence on the preparation time t_{FT} .

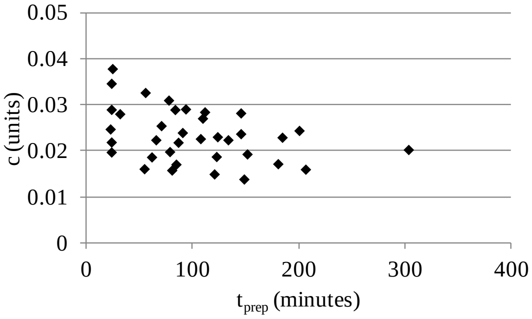

Figure 5: Decay amplitude dependence on the flattop time t_{prep}.

TUNE BEHAVIOUR DURING SNAPBACK

A typical tune behaviour in the horizontal plane during injection and ramp is shown in Figure 6. As the ramp starts, all the decay is lost during the so-called snapback [8] in 10-20 s, which are modelled as an exponential in the current

(2)

where is the decay amplitude at the end of the injection plateau, is the injection current, is the instantaneous current and is the current constant, which is a measure of how fast the snapback is. Please note that in order to use the above equation, the tune has to be converted to its equivalent . A source of error in this analysis is the fact that we do not know how to share the decay between the different types of quadrupoles. Here we work in the hypothesis that tune decay is given only by the main quadrupoles. An example of snapback fit is shown in Figure 7. The constant is of the order of 10 A, i.e. the snapback is over in ~50 A.

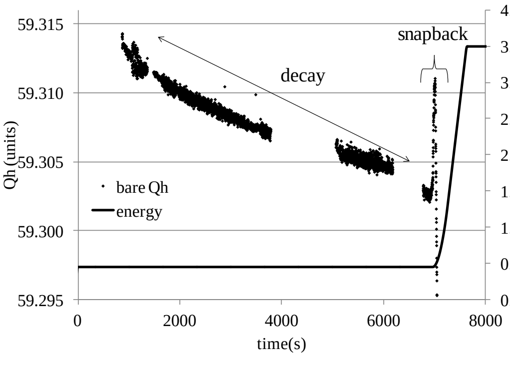

Figure 6: Bare tune behaviour in the horizontal plane during injection and ramp for Fill 2236.

According to the theory, and are also linearly correlated. In Figure 8 we give the correlation plot for several different runs. The factor

$$— \qquad (3)$$

is found to be equal to 0.07. A similar value has been found for the beam data relative to the decay of chromaticity. A two-three times larger correlation factor was found in the magnetic measurements [7] for the b_3 of the main dipoles. No data were available for the main quadrupoles since the decay of a few units was barely visible, with a large random component. For the DS and MS quadrupoles, a more significant systematic decay of ~5 units was observed during magnetic measurements.

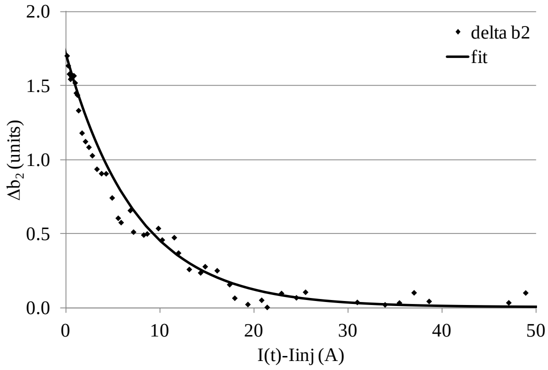

Figure 7: Snapback only and fit for Fill 2236.

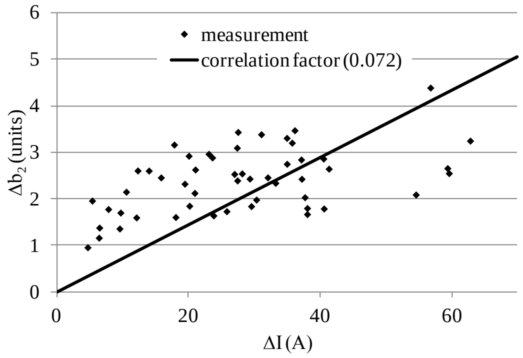

Figure 8: vs as obtained from 2011 beam measurements.

TUNE BEHAVIOUR DURING RAMP

The evolution of the bare tune during the ramp is shown in Figure 9 and Figure 10. From these two figures, it can be observed that the tune is moving “up” in the same direction in both planes during the snapback. Following this, the tune moves in opposite direction with the horizontal tune reaching a stable behaviour at an energy of 1 TeV and the vertical tune reaching a stable behaviour at an energy of 2 TeV. This movement corresponds to imprecision of the field model at injection energy. After 2 TeV the tracking becomes more precise (the magnets behaving in a more linear way) and stays around (59.25, 64.28). The spread in the bare tune from injection energy to 3.5 TeV reduces by 30-50%, from ~0.01 to ~0.007 (see Table 2).

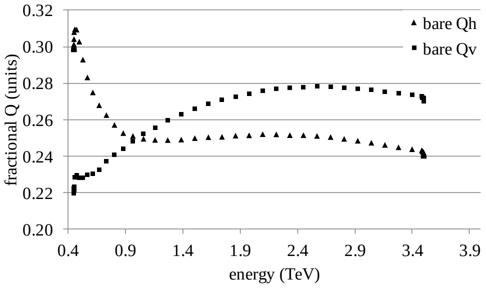

Figure 9: Tune evolution during ramp against energy.

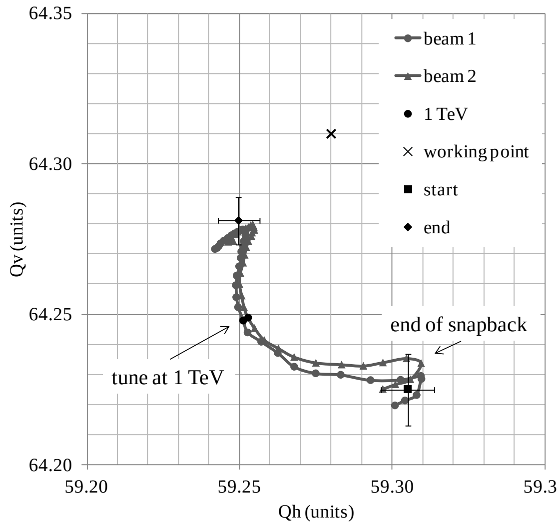

Figure 10: Tune evolution during ramp.

Table 2: Tune values at the start and end of the ramp.

Energy	Qh	σ	Qv	σ
working point	59.280	-	64.310	-
0.45 TeV	59.305	0.009	64.225	0.012
3.5 TeV	59.250	0.007	64.281	0.008

CONCLUSIONS

A tune decay of -0.02 is observed in both planes; it corresponds to 3 units of decay in the transfer function of all LHC quadrupoles. Time constants are of the order of 1000 s, and some dependence on powering history is visible, with a large spread. At the beginning of the ramp a snapback is clearly visible, with an exponential behaviour in the current, as expected. The absolute precision of the quadrupole transfer function model is around 0.1% at injection, and is reduced by a factor two at 3.5 TeV. Corrections are implemented today with a tune feed-forward based on average behaviours, plus the feedback system.

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