FEED-FORWARD CORRECTIONS FOR TUNE AND CHROMATICITY INJECTION DECAY DURING 2015 LHC OPERATION

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Abstract

After two years of shutdown, the Large Hadron Collider (LHC) has been operated in 2015 at 6.5 TeV, close to its designed energy. When the current is stable at low field, the harmonic components of the main circuits are subject to a dynamic variation induced by current redistribution on the superconducting cables. The Field Description of the LHC (FiDel) foresaw an increase of the decay at injection of tune (quadrupolar components) and chromaticity (sextupolar components) of about 50% with respect to LHC Run1 due to the higher operational current. This paper discusses the beam-based measurements of the decay during the injection plateau and the implementation and accuracy of the feed-forward corrections as present in 2015. Moreover, the observed tune shift proportional to the circulating beam intensity and it's foreseen feed-forward correction are covered.

INTRODUCTION

The magnetic field multipoles drift when the magnets are on a constant current plateau (e.g. during injection), due to current redistribution on the superconducting cables. These field variations are reproducible and lead to a visible decay of tune (Q) and chromaticity (Q').

The magnitude of the decay depends on the powering history (PH). Both, the waveform of the powering cycle and the waiting times at constant current influence the decay. The LHC cycle features three current plateaus at different energies: for machine preparation ($prep$), injection (inj) and top energy (flat top, FT), with the corresponding waiting times t_{prep}, t_{inj} and t_{FT}, respectively.

A feed-forward system, based on the model Field Description of the LHC (FiDeL) [1,2], applies predicted corrections to keep the tunes and chromaticity constant during injection. Since dedicated measurements are necessary to estimate Q', this quantity cannot be monitored through the cycle, thus a high accuracy of the feed-forward corrections is required. The situation for the tune is less critical, because a continuous measurement is available, on which a feed-back (QFB) or manual trims can be based.

FiDeL Model Implementation

The dynamic error, σ_{dyn}, of the b_3 (chromaticity) and b_2 (tune) components of the magnetic fields of the superconducting magnets in the LHC is represented in the FiDeL model by the following equations [2]

$$\sigma_{dyn} = \frac{\Delta}{\Delta_{std}} \times \Delta_{PH}, \tag{1}$$

$$\begin{aligned}
\Delta = \quad & d \quad (1-e^{-t/\tau}) + (1-d)(1-e^{-t/(9\tau)}) \\
\Delta_{PH} = \delta \quad & \times \quad \frac{E_0 - E_1 \exp[-I_{FT}/(\tau_e \frac{dI}{dt})]}{E_0 - E_1 \exp[-I_{FTnom}/(\tau_e \frac{dI}{dt})]} \\
& \times \quad \frac{T_0 - T_1 \exp[-t_{FT}/\tau_t]}{T_0 - T_1 \exp[-t_{FTnom}/\tau_t]} \\
& \times \quad \frac{P_0 - P_1 \exp[-t_{prep}/\tau_p]}{P_0 - P_1 \exp[-t_{prepNom}/\tau_p]},
\end{aligned}$$

where Δ is the time evolution of the decay at the constant current plateau. This is best described by a double exponential, combining a fast and a slow component, which are functions of time from the beginning of injection plateau and are mixed by a factor d. For normalization reasons, $\Delta_{std} = \Delta(t = t_{inj})$ is introduced as the magnitude of the decay after a standardized plateau length of $t = t_{inj}$ (only for b_3, $\Delta_{std} = 1$ for b_2). The mixing factor, d, the decay time, τ, and the powering history scaling, δ, are obtained from fits to the measured decay.

The powering history is described by Δ_{PH}. The current at top energy (I_{FT}), t_{FT} and t_{prep} are taken from the previous cycle. Additionally, the powering history is normalized by using the values of these parameters after the standard pre-cycle ($I_{FTnom}, t_{FTnom}, t_{prepNom}$). The remaining parameters τ_e, τ_t, τ_p, $E_{0/1}$, $T_{0/1}$ and $P_{0/1}$ are obtained from magnetic measurements without beam. Further details can be found in [1–3].

GENERAL ANALYSIS STRATEGY

As mentioned above, the FiDeL model implementation requires a set of beam based parameters (d, τ and δ), which are obtained by studying the bare tune and chromaticity evolutions. The *bare* evolution is obtained by removing all applied trims from the measurement:

$$q_{bare} = q_{meas} - \Delta q_{FiDeL} - \Delta q_{manual} - \Delta q_{QFB}, \tag{2}$$

where q is either Q or Q'. In order to extract the required parameters for the FiDeL model, a curve of the form [4]

$$q_{bare}(t) = \nu + \delta \times \Delta \tag{3}$$

is fitted to the data obtained by Eq. (2). Where Δ and δ are from Eq. (1). The δ acts as decay amplitude of the sum of the exponentials and ν is an initial offset.

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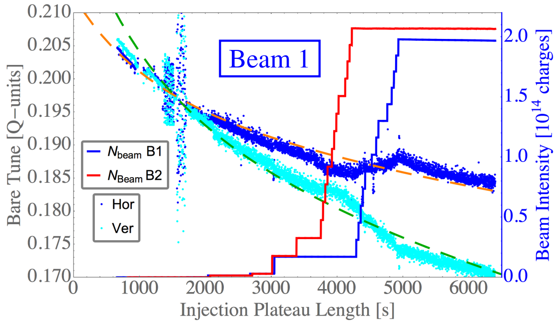

Figure 1: Bare tune evolution at the injection plateau for Beam 1 in fill 4526, overlaid with beam intensities.

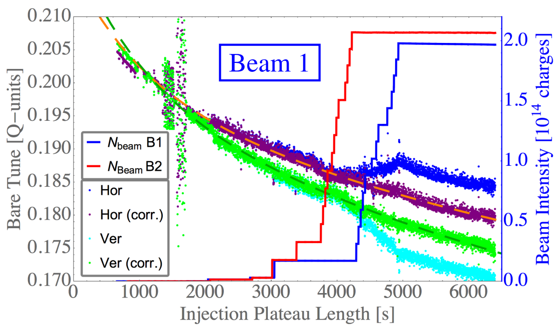

Figure 2: Fig. 1 overlaid with the tune evolution corrected for intensity effect. Orange and green dashed lines show fits to purple (hor.) and green (ver.) points.

TUNE DECAY AT INJECTION

Previous studies [4, 5] have found values for the parameters $d \approx 0.27$ and $\tau \approx 1000$ s. In the following these two variables will be fixed to the given values, reducing the number of fit parameters in Eq. (3) to v and δ, leading to a more robust fit.

An example of the bare tune evolution of Beam 1 over an injection plateau of a bit less than 2 h is displayed in Fig. 1. The dark blue points show the horizontal and the cyan points the vertical plane. The orange and green dashed lines display the corresponding fits according to Eq. (3). The blue and red lines indicate the beam intensity of Beam 1 and 2, respectively. The moment the magnet current reached the injection value corresponds to $t = 0$.

Through the injection plateau three interruptions of the continuous decay are observable. The first two around $t = 1500$ s arise from a chromaticity measurement and switching on the octupoles. As soon as the beam intensity of Beam 1 is increased ($t \sim 4000$ s) the tune starts to drift: a positive shift is observed in the horizontal and a negative shift in the vertical plane. This tune shift biases the fit and the obtained parameter values.

Laslett Tune Shift

The observed intensity related tune shift has the same order of magnitude and direction as the so-called *Laslett tune shift*, which arises from image currents on the beam screen introduced by the beam itself. The vertical Laslett tune shift can be calculated with the following equation (the horizontal shift has the same magnitude but opposite sign) [6]:

$$\Delta Q_{Laslett} = -\frac{N_b k_b r_p \beta_{av}}{\pi\gamma}\left(\frac{\epsilon_1}{h^2} + \frac{\epsilon_2}{g^2}\right), \tag{4}$$

where N_b is the single bunch intensity, k_b the number of bunches per beam, r_p the classical proton radius, γ the relativistic γ-factor and $\beta_{av} \approx 72$ m the average β-function. The Laslett coefficients ϵ_1 and ϵ_2 depend on the geometry of the beam pipe (half-height h) and of the ferromagnetic magnet poles (with radius $g \simeq 2.8$ cm for the LHC). Ref. [6] assumes $\epsilon_1 = 0$ for a circular or squared beam pipe and $\epsilon_2 = 0.41$ for plane magnet poles, knowing that these values are not well suited for the geometry of the LHC magnets, but a more realistic estimate is missing.

Correcting for the instantaneous Laslett tune shift by taking into account the beam intensity ($= N_b k_b$) evolution and the Laslett parameters given in Ref. [6], overcompensates the effect. Empirically choosing a value of $\epsilon_2 = 0.25$, yields the corrected tune evolutions shown in Fig. 2; in purple for the horizontal and green for the vertical plane, the original (uncorrected) curves are displayed as well for better comparison. The new fits to the intensity corrected data describe the tune decay well.

Quality of Fit to Bare Decay

In order to quantify how good the fits describe the data, the RMS of the residuals between each data point (x_i) and the fit ($f(x_i)$) is determined:

$$\sigma_{fit} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - f(x_i))^2}. \tag{5}$$

Equation (5) was calculated for all fills during the 25 ns operation in 2015. The median and standard deviation of the resulting distribution over all fills is about $(4 \pm 2) \times 10^{-3}$. This is in the order of the measurement accuracy and thus mainly introduced due to the spread of the measurement points around the fitted curves.

However, the fit parameters show a large spread between fills with a standard deviation in the order of 10^{-2}. This is partially introduced by the dependence on the powering history, but could also be influenced by octupole and chromaticity settings, which were frequently changed during the run.

Powering History Dependence

To investigate the dependence of the fitted decay amplitude δ on t_{FT}, only fills with $t_{prep} > 1000\,s$ were selected. For the dependence on t_{prep}, $t_{FT} > 4000\,s$ was used. The reproducibility between fills is bad, but the decay amplitude tends to decrease with flat top length (see Fig. 3), while no clear dependence is visible for the preparation plateau. A dependence of the decay amplitude on the time spent at top energy (only) has been implemented in the online correction system for the tune in 2015, following Eq. (1).

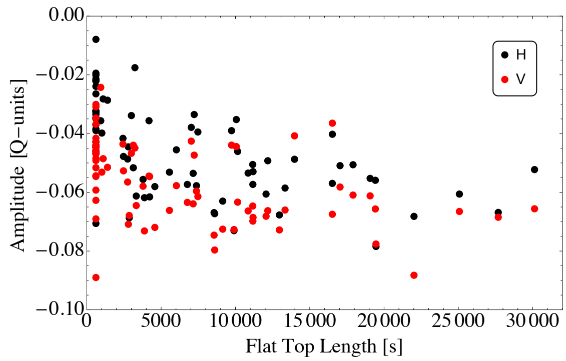

Figure 3: Powering history dependence for fills of the 25 ns operation in 2015.

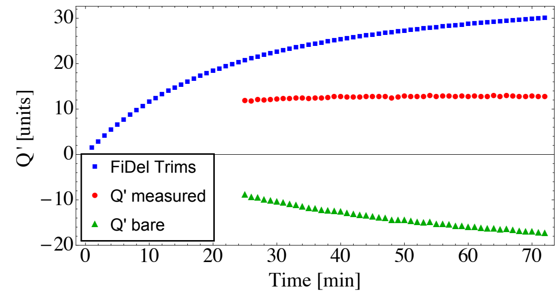

Figure 4: Example of Q' decay during the injection plateau.

Applied Corrections

The goal is to keep the tune at a constant reference value only by applying feed-forward corrections, with no need for manual trims or the QFB to be active. The RMS of the residuals according to Eq. (5) with $f(x)$ as the corresponding reference value (usually 0.28 (H) or 0.31 (V)) and x as the measured tune value including all corrections indicates that the achieved correction was about 30% worse compared to best correction possible, as noted in the text below Eq. (5).

The optimum result could only be achieved if the intensity effect would be corrected and if individual correction parameters could be applied in each fill. In reality, the implementation uses average decay and powering history parameters, such that a somewhat worse situation is intrinsically expected. Moreover, in 2015 no systematic correction of the intensity related tune shift was performed. Only occasionally manual trims were applied, which as well reduced the ability to reach the optimal situation.

CHROMATICITY DECAY AT INJECTION

In the LHC, Q' can only be determined by dedicated measurements, performed by small periodic modification of the RF frequency (f_{RF}), which produces a tune shift (ΔQ). The chromaticity of the beam can be computed from the amplitude of the tune oscillation, following the formula

$$Q' = \alpha \Delta Q \left(\frac{\Delta f_{RF}}{f_{RF}} \right)^{-1} \tag{6}$$

where α is the momentum compaction factor. These measurements, beyond being time consuming, cannot be performed with high intensity beam. Consequently, a minimum number of measurements was performed to parameterize the dynamic decay of the b_3 component of the dipoles and to obtain the required parameters for the FiDel model. As the amplitude of the decay depends on the powering history, a complete re-parameterization was needed due to the operational energy change; the amplitude of the decay was supposed to increase by about 15%. An example of Q' decay and its corrections is presented in Fig. 4 for the vertical plane. The red curve shows the measured chromaticity evolution over 90 min, once corrected by the automatic system.

For technical reasons it is often difficult to inject during the first 20 min of the injection plateau, which produces an uncertainty on the fit, since the first part of the decay cannot be measured. As a consequence, a part of the b_3 decay is corrected by the lattice sextupole (offset from zero) and not properly integrated into the ramp, producing a non-perfect correction of the snapback effect [7]. As visible in Fig. 4, there is a residual of about half a unit of chromaticity decay (slope of red line) in the present parameterization, but this is inside the uncertainty of the powering history model and it is fully acceptable for LHC operation.

The parameter value used for operational corrections of b_3 decay during Run1 and Run2 are shown in Table 1. Several dedicated measurements have been done to verify the chromaticity. They confirmed a good control of Q' within 2 units. Moreover, measurements carried out more than one month apart showed a high level of reproducibility.

Table 1: FiDel parameters of b_3 Decay at Injection

LHC Run	d	δ	τ
Run1	0.44	0.174	600
Run2	0.32	0.26	850

CONCLUSION

Tunes and chromaticity are in general controlled to the required accuracy for operation. More details about the presented analysis can be found in [8, 9]. Moreover, some improvements are expected for 2016. Optimization of the injection process will make it possible to measure the first part of the decay, guaranteeing a better fit and more accurate corrections. Additionally, a feed-forwarding of the Laslett tune shift based on calculations with Eq. (4) and the measured instantaneous beam intensity will be implemented. This would not only increase stability of the injection process, but also diminish the transient effects at the beginning of the ramp.

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