TUNE AND CHROMATICITY: DECAY AND SNAPBACK

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Abstract

The drift of the magnetic field mutipoles of the superconducting magnets in the LHC during the constant current injection plateau introduces a decay of the tune and chromaticity. In the first few seconds of the ramp the original hysteresis state of the magnetic field is restored - the field *snaps back*. These fast dynamic field changes lead to strong tune excursions, inducing beam losses that potentially trigger a beam dump. This paper discusses the decay and snapback of tune and chromaticity as observed in 2015 and evaluates the quality of the applied feed-forward corrections.

INTRODUCTION

During injection the superconducting magnets are at constant current. The magnetic field multipoles drift when the magnets are on a constant current plateau, due to current redistribution on the superconducting cables. This leads to a decay of the tune (Q) and chromaticity (Q'). In the first few seconds of the ramp, when the magnetic field is increased, the original hysteresis state is restored. This initial period of the energy ramp is known as *snapback*. The field variations are reproducible.

The magnitude of the decay depends on the powering history (PH). Both, the waveform of the powering cycle as well as the waiting times (at top energy (Flat Top (FT)), t_{FT}, and at the preparation or pre-injection plateau, t_{prep}) influence the decay. Figure 1 sketches the different stages of the powering cycle of the LHC, highlighting the three constant current plateaus and the corresponding waiting times t_{FT}, t_{prep} and t_{inj} (injection plateau).

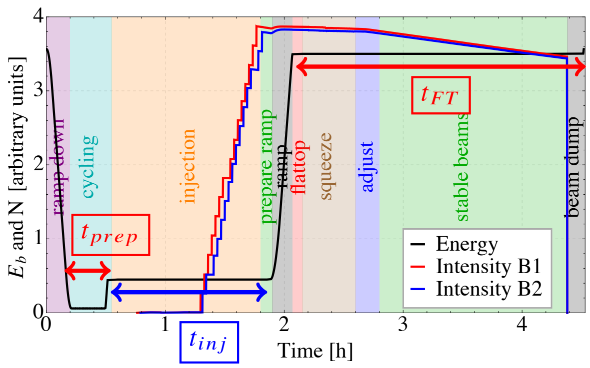

Figure 1: Sketch of LHC powering cycle.

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 and reduces the burden on the beam based tune feedback (QFB) during the first part of ramp. Dedicated measurements are necessary to measure the Q', which is done using pilot beams at the beginning of injection. Because of the absence of a continuous chromaticity measurement no Q'-feedback is available. Additionally, manual trims can be performed to correct the tune and chromaticity.

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 compensated by the FiDeL model using the following equations [2]

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

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

where Δ represents the time evolution of the decay at the constant current plateau, with t as the time spent since the beginning of the plateau. For normalization reasons, Δ_{std} is introduced as the magnitude of the decay after standardized plateau length 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 curves.

The powering history is described by Δ_{PH}, where I_{FT} is the current at top energy, t_{FT} is waiting time at top energy and t_{prep} is the waiting time at preparation plateau, 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].

Since the beam energy is proportional to the magnet current, I_{FT} (and I_{FTnom}) are equal for all fills with the same beam energy, thus the first term of Δ_{PH} does not vary from cycle to cycle. In fact, $I_{FT} = I_{FTnom}$ for the standard cycle, such that the first term of $\Delta_{PH} = 1$. On the other hand, t_{FT} and t_{prep} will be different for each individual cycle, but can easily be determined from the logged data of the previous fill.

In case of the tune decay, the powering history implementation simplifies, since (as will be discussed below) no dependence on the preparation plateau length is observed in the data, such that the last term of Δ_{PH} is set to 1. Only the second term, the dependence on t_{FT}, remains.

DECAY AT INJECTION

As mentioned above, the FiDeL model implementation requires a set of beam based parameters (mixing factor, d, decay time, τ, and the powering history scaling, δ), which are obtained by studying the bare tune and chromaticity evolutions. By *bare* evolution the natural behavior of the quantity without corrections is meant, it is obtained by removing all applied trims from the measurement:

$$q_{bare} = q_{meas} - \Delta q_{FiDeL-trim} - \Delta q_{man.-trim} - \Delta q_{QFB}, \quad (2)$$

where q is either Q or Q'.

In order to extract the required parameters for the FiDeL model, a curve of the form [4]

$$q_{bare}(t) = v + c[d(1-e^{-t/\tau}) + (1-d)(1-e^{-t/(9\tau)})] \quad (3)$$

is fitted to the data obtained by Eq. (2). This functional behavior is the sum of exponential with multiples of a single time constant, τ, and is identical with Δ in Eq. (1), multiplied by a decay amplitude c and extended by an initial offset v. The initial offset v is usually adjusted by a manual trim at the beginning of each fill and therefore irrelevant for this analysis, but required for a good fit quality. The decay amplitude c is equivalent to δ in Eq. (1).

Tune

Previous studies [4,5] have found values for the parameters $d \approx 0.27$ and $\tau \approx 1000s$. Fixing these two variables, reduces the number of fit parameters in Eq. (3) to v and c, leading to a more robust fit. This will be used in the following to obtain better knowledge of the powering history dependence of the tune decay amplitude.

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

Through the injection plateau three interruptions of the continuous decay are observable:

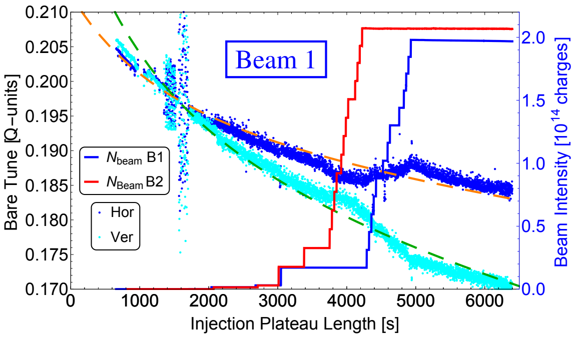

Figure 2: Bare tune evolution at the injection plateau for Beam 1 in fill 4526, overlaid with beam intensities.

- The first one around 1400 seconds arises from a chromaticity measurement, during which the tune is changed by a small variation of the RF frequency.
- Around 1600 seconds the clear tune signal is lost, because the octupoles are switched on. The signal returns with the injection of the first nominal bunch.
- As soon as the beam intensity of Beam 1 is increased quickly (~4000 s) the tune starts to drift: a positive shift is observed in the horizontal and a negative shift in the vertical plane. The tune of Beam 2 behaves similarly during the injection of Beam 2. 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 tune shift follows the same equation with opposite sign) [6]:

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

where N_b is the single bunch intensity, k_b the number of bunches per beam, r_p the classical proton radius, $\beta_{av} \approx$ 72 m the average β-function, γ the relativistic γ-factor. 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). In Ref. [6] $\epsilon_1 = 0$ for a circular or squared beam pipe and $\epsilon_2 = 0.41$ for plane magnet poles are assumed, 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. 3; in purple for the horizontal and green for the vertical plane, the original (uncorrected) curves are displayed as well for better comparison. The top plot shows Beam 1, the bottom plot Beam 2. The new fits to the intensity corrected data describe the tune decay well.

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

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

The histogram of σ_{fit} determined for Beam 1 of all fills during the 25 ns operation in 2015 is shown in Fig. 4. Black displays the horizontal and red the vertical plane. The median of these distributions lies between 3 and 4×10^{-3} with

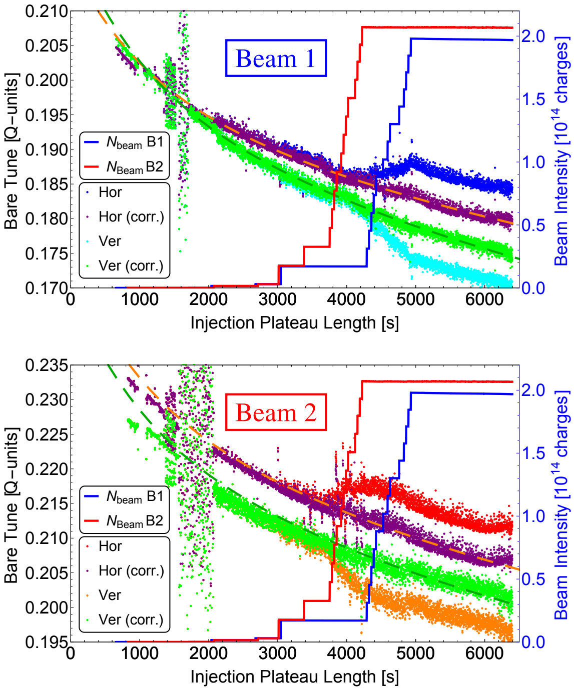

Figure 3: Bare tune evolution at injection plateau for Beam 1 (top) and Beam 2 (bottom) in fill 4526, overlaid with beam intensities and corrected for Laslett tune shift (purple and green points).

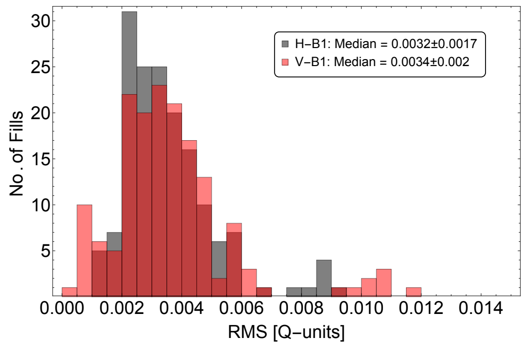

Figure 4: RMS of bare tune decay with respect to fit of the form Eq. (3).

a standard deviation of 2×10^{-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 Figure 5 shows the fitted amplitude c as a function of the waiting time at top energy (top) and at the preparation plateau (bottom) for fills of the

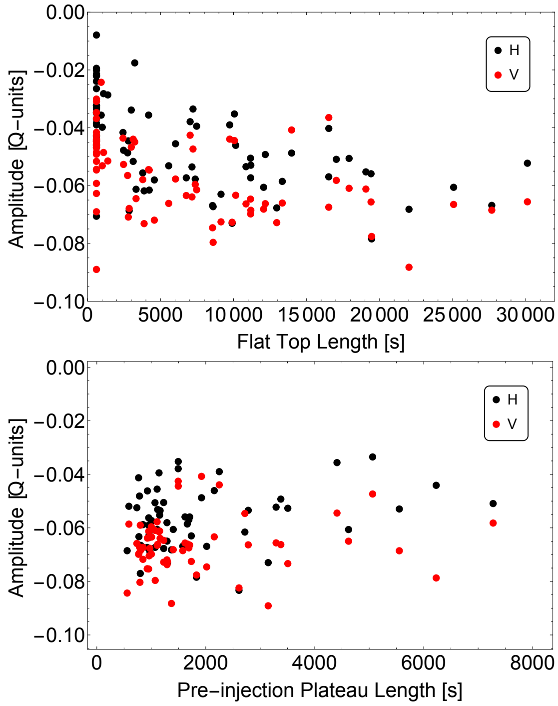

Figure 5: Powering history dependence.

25 ns operation in 2015. Only fills with $t_{prep} > 1000\,s$ and $t_{FT} > 4000\,s$ were selected to investigate the dependence on t_{FT} and t_{prep} respectively.

As mentioned earlier the reproducibility between fills is bad, but the decay amplitude tends to decrease with flat top length, while no clear dependence is visible for the preparation plateau. A dependence of the decay amplitude on the time spent at top energy has been implemented in the online correction system in 2015, following Eq. (1).

Applied Corrections The optimal goal is for the FiDeL corrections to be able to keep the tunes at the constant reference value, with no need for manual trims or the QFB to be active. The histograms in Fig. 6 show 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. The applied corrections are 30% worse compared to Fig. 4, which would be the best result, if we could correct for the intensity effect and apply individual correction parameters in each fill. Nevertheless, the implementation uses average decay and powering history parameters, such that a somewhat worse situation is intrinsically expected.

Chromaticity

As mentioned, in the LHC Q' is computed with dedicated measurements performed by small periodic modification of the RF signal. The amplitude of the induced tune shift is a measure of the chromaticity. These (dedicated) measurements are time consuming and as consequence, the minimum number of measurements has been performed to measure the dynamic decay of the b_3 component of the dipole and

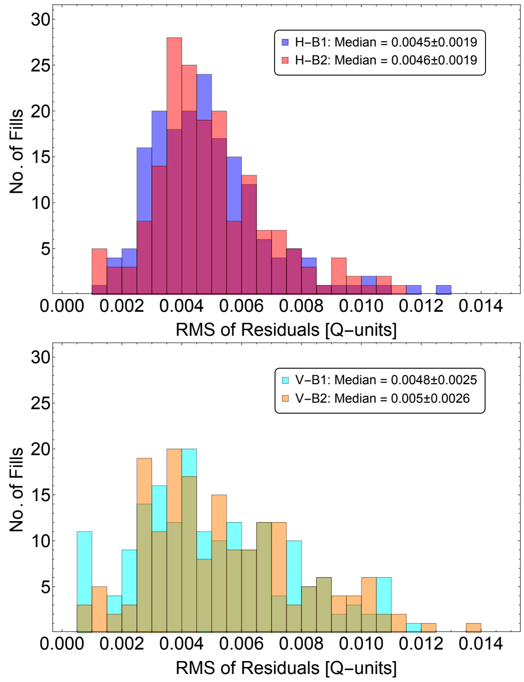

Figure 6: Quality of actual corrections applied in 2015.

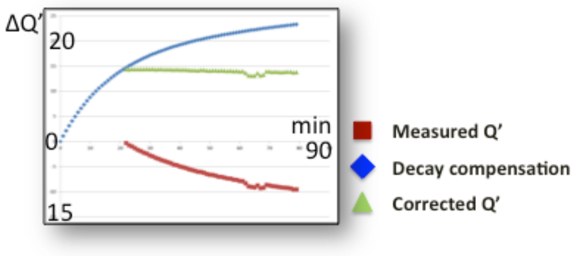

Figure 7: Example of chromaticity decay.

parameterize the automatic system in order to keep it under control. An example of Q' decay and its corrections is presented in Fig. 7 for the vertical plane. The green curve shows the chromaticity evolution over 90 minutes, once corrected by the automatic system. A residual of about half a unit of chromaticity decay is present, but this is fully acceptable for LHC operation.

Several dedicated measurements have also been done to verify the chromaticity all along the cycle; they highlighted a good control of Q' in within 2 units. Moreover, measurements carried out more than one month apart showed a high level of reproducibility. A small imperfection on the persistent current model has been identified during the ramp in the region below 3 TeV [7].

SNAPBACK

On the example of the b_3 magnetic component, Fig. 8 shows the evolution of this multipole component as a function of magnet current. The vertical red line visualizes the drift during a constant current plateau at 760 A of the main

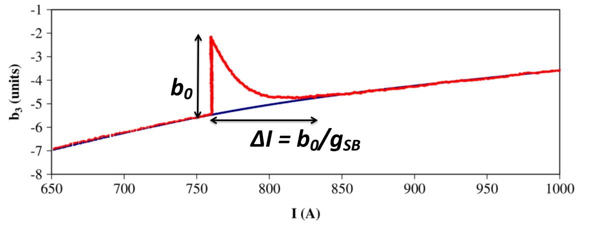

Figure 8: b_3 evolution and snapback as a function of magnet current [3].

dipoles and the following exponential decay, once the current starts to increase again.

The amplitude, b_0, of the drift, is equivalent to the decay amplitude of Eq. (3), but has different units. The time or current difference, ΔI, it takes for the decay to die out, is proportional to b_0, hence depends on the injection plateau length and the powering history. The snapback of the multipole components is described by the following formula [3]

$$b_{SB}(t) = b_0 \exp\left[\frac{(I_{inj} - I(t))g_{SB}}{b_0}\right]. \qquad (6)$$

Tune

Equation (6) can be applied to the bare tune measurement by setting $b_{SB}(t) \rightarrow Q_{SB}(t)$ and $b_0 \rightarrow c$, with c as the decay amplitude at the end of the injection plateau. The time constant g_{SB} acts as fit parameter. In order to achieve a better accuracy on g_{SB}, an offset is added to Eq. (6), which is kept variable for fitting.

Figure 9 gives an example of the tune decay (blue points) during the snapback phase in the first ~88 s of the ramp. The orange line is a fit of form in Eq. (6) plus offset. The snapback lasts between 30 and 60 s depending on the initial amplitude at the end of the injection plateau. Because the measurement accuracy is more than an order of magnitude below the tune swing during this phase, the agreement between data and fit is very good. See also Fig. 10, which shows that the RMS of the residuals between measurement and fit are around 2×10^{-3} (data over the first 40 s of the ramp was taken into

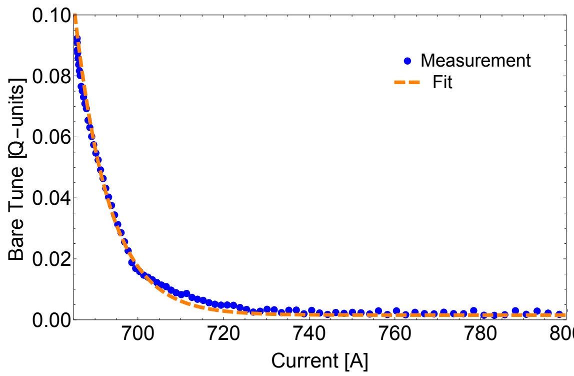

Figure 9: Example of bare snapback decay for Beam 1 horizontal of fill 4526. The plot range covers about the first 88 s of the ramp.

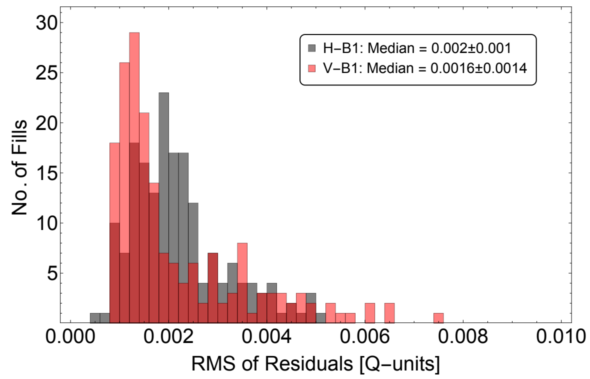

Figure 10: RMS of bare tune snapback with respect to fit according to Eq. (6).

account). Nevertheless, also here a large spread of the fit parameters between fills is observed.

Dependence on Intensity Looking at the evolution of the fit parameters (g_{SB} and the offset) as a function of fill number, reveals a drift over the year. See Fig. 11, g_{SB} is displayed on top, the fitted offset on the bottom. The dark blue and black points indicate the horizontal and vertical plane, respectively. The time constant increases along the year, while the offset shows opposite slopes in the horizontal and vertical plane.

A correlation with the beam intensity is present, which can be confirmed by comparing with the green bars in the background indicating the maximum beam intensities for each fill. Especially during the 90 m-β^* run, when the beam intensity was relatively low, a drop of the decay parameters back to their original values at the beginning of the 25 ns operation is visible.

Correction of the Laslett tune shift (taking into account the correct energy for each point) removes the intensity dependence of the fitted offset, but not of the time constant. The Laslett tune shift corrected data points are shown in light blue and gray. The source of the time constant drift remains unknown, but seems to be related to the intensity.

Applied Corrections Similarly to the decay at injection, the snapback can only be corrected based on average parameters, such that the same g_{SB} was used for all fills in 2015. However, the initial amplitude is taken individually for each fill from the magnitude of the FiDeL trims applied during injection. No offset is fed-forward in the current implementation. The histogram of the RMS of the residuals between data and tune reference value is plotted in Fig. 12, for the horizontal plane on top and for the vertical plane on the bottom. The two colors show Beam 1 and 2. Compared to the best correction, with individual time constants and corrected intensity effect, shown in Fig. 10, the actually applied corrections were significantly worse. The drift of g_{SB} and the uncorrected intensity dependence degrade the quality of the correction.

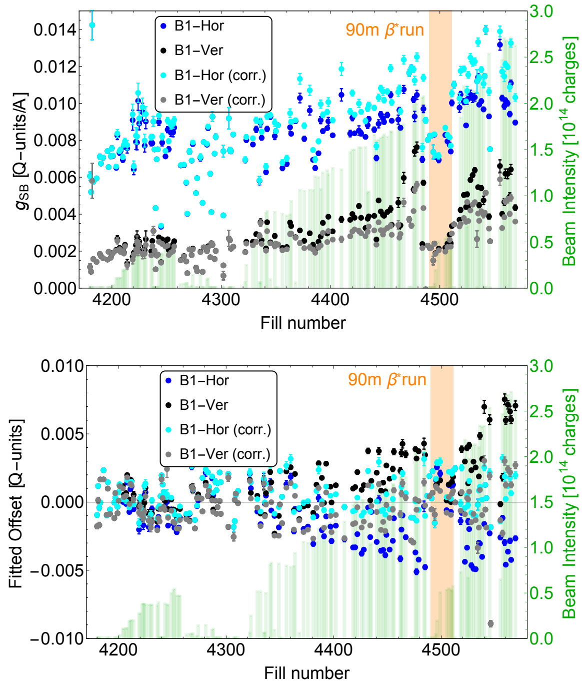

Figure 11: Intensity dependence of the snapback fit parameters through the 25 ns run.

However, taking into account as well the work of QFB, the total corrections are close to the optimum. It should be mentioned that, even if the QFB is able to smooth out relatively large tune excursions, the FiDeL feed-forward corrections are necessary. The beam has been lost due to too large tune changes in the snapback phase in the beginning of the year when the FiDeL corrections were not yet running. As well there are occasions when the QFB has to stay off during the ramp (e.g. during Q' measurements).

Chromaticity

Dedicated measurements have also been done to verify the snapback behavior of the b_3 of the main superconducting dipoles. Unfortunately, the precision of the measurements is strongly affected by the short time (less than 60 seconds) and the high dynamic range. The hardware limitation of the RF, in fact, does not allow a very fast modulation thus a precise measurement of the snapback is not possible. Besides, the combined effect of tune and chromaticity snapback makes things even more complicated. Nevertheless, the data reported in Fig. 13 for the vertical case clearly shows the b_3 snapback. As mentioned before, the snapback can be described by an exponential decay in current (Eq. (6)). As in this phase of the ramp the current follows a quadratic function, the snapback shape in Fig. 13 is a Gaussian in time. As for the tune, this data allows to fit the parameter g_{SB} used for the automatic corrections.

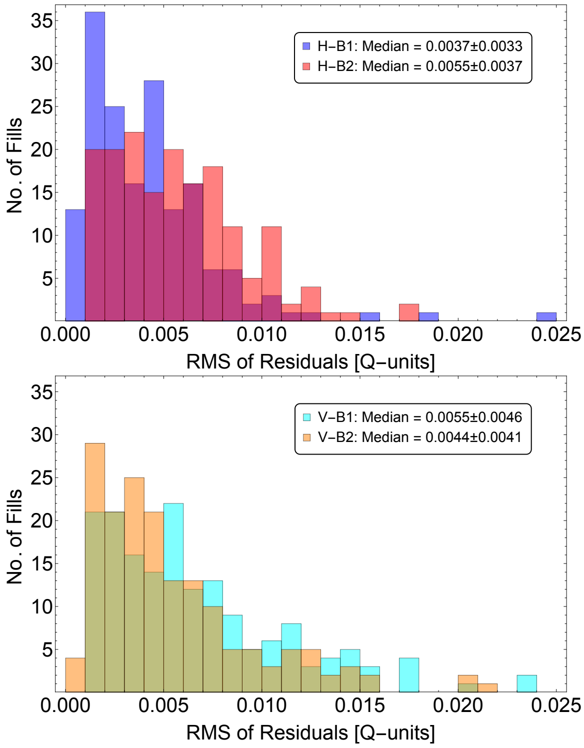

Figure 12: Quality of actual snapback corrections applied in 2015.

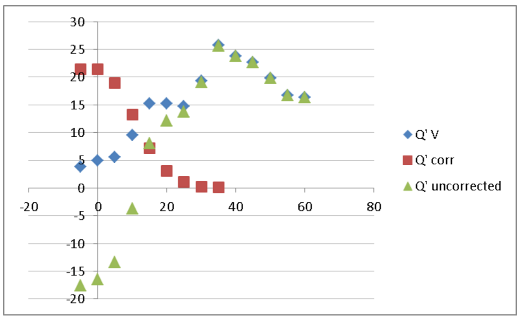

Figure 13: Example of chromaticity snapback.

CONCLUSION

The tunes and chromaticity are in general well controlled along the cycle to the required accuracy. Since mid 2015 the FiDeL trims are incorporated into the ramp according to the expected exponential shape of the snapback also for the tune. Note that the manual trims are still linearly incorporated, but contain leakage of the FiDeL model, which should as well be treated exponentially. During 25 ns operation (high statistics) it was observed that the increasing beam intensity degrades the snapback corrections, and even after correction of the Laslett tune shift, an unexplained drift of the snapback time constant remains. Only a combination of feed-forward corrections and QFB controls the tunes sufficiently during the snapback.

With a better incorporation of the manual trims and feed-forwarding of the Laslett tune shift, the feed-forward corrections during injection and snapback could further be improved.

ACKNOWLEDGMENT

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