TUNE AND CHROMATICITY CONTROL DURING SNAPBACK AND RAMP IN 2015 LHC OPERATION

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Abstract

Because of current redistribution on the superconducting cables, the harmonic components of the magnetic fields of the superconducting magnets in the Large Hadron Collider (LHC) show decay during the low field injection plateau. This results in tune and chromaticity variations for the beams. 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 and chromaticity excursions that, if not properly controlled, induce beam losses and potentially trigger a beam dump. A feed-forward system applies predicted corrections during the injection plateau and to the first part of the ramp to avoid violent changes of beam conditions. This paper discusses the snapback of tune and chromaticity as observed in 2015, as well as the control of beam parameters during the ramp. It also evaluates the quality of the applied feed-forward corrections and their reproducibility.

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. These field changes are reproducible and lead to a decay of the tune (Q) and chromaticity (Q'). The observation and correction of this decay at the injection plateau are discussed in Ref. [1].

When a current change occurs (e.g. in the first few seconds of the energy ramp, when the magnetic field is increased), the original hysteresis state is restored. This initial period of the energy ramp is known as *snapback*.

A feed-forward system, based on the model Field Description of the LHC (FiDeL) [2,3], applies predicted corrections to keep the tunes and chromaticity constant during injection and incorporate them into the ramp; in this way, the chromaticity swing and the burden on the beam based tune feedback (QFB) is reduced during the snapback.

On the example of the b_3 magnetic component, Fig. 1 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 $I = 760$ A of the main 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) in Ref. [1], 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

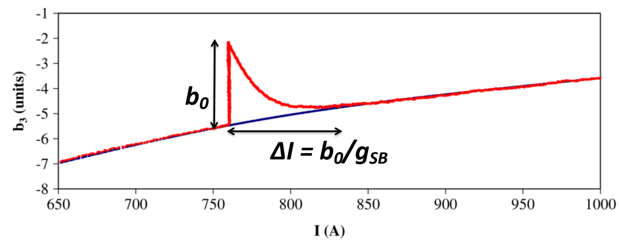

Figure 1: b_3 evolution and snapback as a function of magnet current [4].

plateau length and the powering history. The snapback of the multipole components follows [4]

$$b_{SB}(t) = b_0 \exp\left[\frac{(I_{inj} - I(t))g_{SB}}{b_0}\right]. \quad (1)$$

TUNE

Equation (1) can be applied to the bare tune measurement (measured tune from which all applied corrections have been removed) by setting $b_{SB}(t) \to Q_{SB}(t)$ and $b_0 \to \delta$, with δ 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. (1), which is kept variable for fitting.

Figure 2 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 using Eq. (1) 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. 3, which shows that the RMS

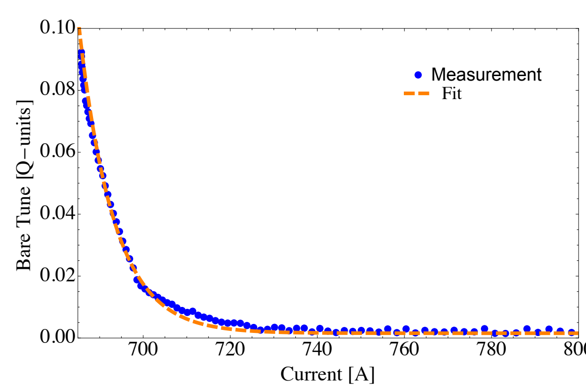

Figure 2: Example of bare snapback decay for Beam 1 horizontal of fill 4526. The plot range covers about the first 88 s of the ramp.

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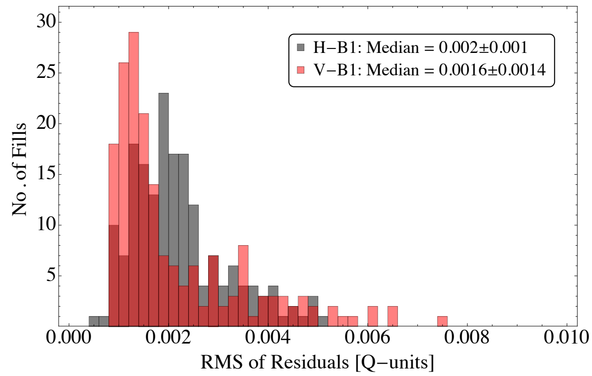

Figure 3: RMS of bare tune snapback with respect to fit according to Eq. (1) for fills of the 25 ns run in 2015.

of the residuals between measurement and fit are around 2×10^{-3} (data over the first 40 s of the ramp was taken into account). Nevertheless, similarly to what was found in [1] for the injection decay, also here a large spread of the fit parameters between fills is observed.

Dependence on Intensity

Looking at the evolution of the fit parameters as a function of fill number, reveals a drift over the year; see Fig. 4 where g_{SB} is displayed on top and 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 [5], following the procedure described in [1] and 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 on the example of Beam 1 in Fig. 5, the horizontal plane is shown in black, the vertical plane in red. Compared to the best correction, with individual time constants and corrected intensity effect, shown in Fig. 3, the actually applied

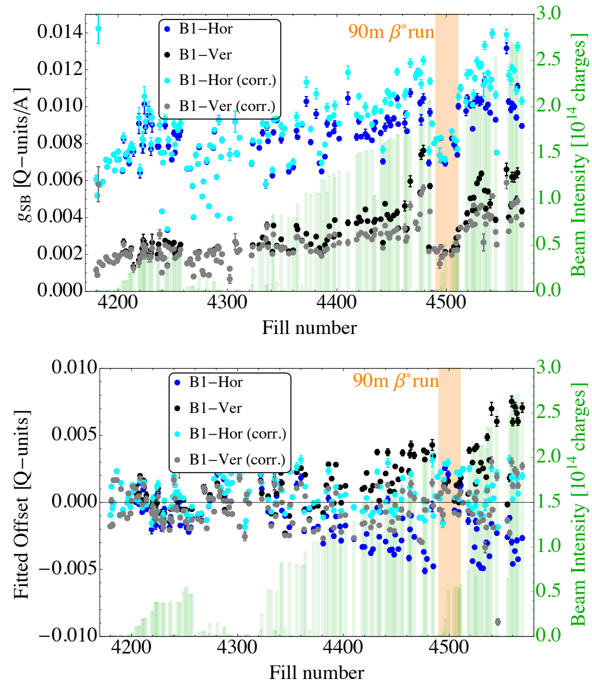

Figure 4: Intensity dependence of the snapback fit parameters through the 25 ns run.

corrections were significantly worse. The drift of g_{SB} and the uncorrected intensity dependence degrade the quality of the correction.

However, taking into account as well the work of the 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).

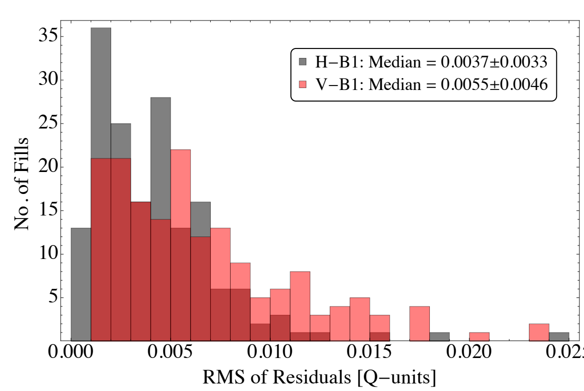

Figure 5: Quality of actual snapback feed-forward corrections applied in 2015.

CHROMATICITY

Dedicated measurements have been done to verify the snapback behavior of the b_3 of the main superconducting dipoles. The precision of the measurements is strongly affected by the short time (less than 60 s) and the high dynamic range. The hardware limitation of the radio-frequency system, does not allow a very fast frequency modulation. This results in a very low number of periods during the first seconds of the ramp, making the snapback measurement not precise. In addition, the combined effect of tune and chromaticity increases the complexity of the measurements. In order to disentangle at least one effect, the lattice sextupole knob was made constant for the measurements.

Since the snapback can be described by an exponential decay in current (Eq. (1)) and the current variation during the first part of the energy ramp follows a quadratic function, the snapback has a Gaussian shape in time. The results of a clean measurement are reported in Fig. 6; the snapback effect disappears in about 30 s, as expected. If the model was perfectly under control the chromaticity would have been constant. Instead there is a jump of about 10 units during the snapback and a second one just after. The first effect is due to a non-perfect compensation of the injection decay and the second one arises from an error in the b_3 model during the ramp, described in the next section. Nonetheless, this data allowed to fit the parameter g_{SB} used for the automatic corrections. The fitted value perfectly corresponds to the one measured during Run1. This parameter was not expected to change, as it is independent from the magnet history.

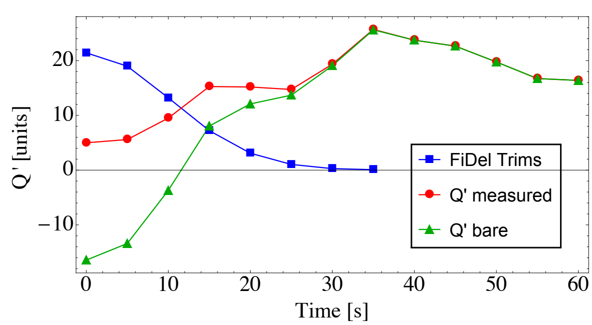

Figure 6: Example of vertical chromaticity snapback.

Chromaticity During the Ramp

Because of superconductor magnetization, the b_3 component of the main dipoles changes during the ramp by about 7 units [6, 7], which correspond to a chromaticity swing of about 250 to 300 units. A high level of control is essential to ensure stability of the beams. The chromaticity has to be maintained in within 2 units from the target all along the ramp. Several measurements and feed-forward have been done to guarantee stable chromaticity. Chromaticity control is ensured by two sets of correctors. The so-called spool pieces are used to compensate the b_3 changes and the lattice sextupoles are used to correct the residual effect. In ideal conditions the spool pieces would compensate the 7 units of b_3 change and the lattice sextupole would not be used.

The bare chromaticity during the ramp, calculated by removing the contribution of the lattice sextupole correctors is shown in Fig 7. As discussed in [8], the precision of the field model is very good above 3 kA, but there is an error reaching 30 to 60 units of chromaticity at low current ($t < 5000$s), which indicates about 1 unit of uncorrected b_3 of persistent current in the dipoles. Nevertheless, once the b_3 unit removed (43 chromaticity units on the H plane and -35 in the V plane), there is still and error of about 15 chromaticity units, positive in both planes, which is not due to error in the dipole b_3 model. The bare vertical chromaticity evolution shown in Fig. 7 also explain the last part of the graph in Fig. 6, when a clear increase of chromaticity is visible after the snapback has ended ($t \geq 25$ s).

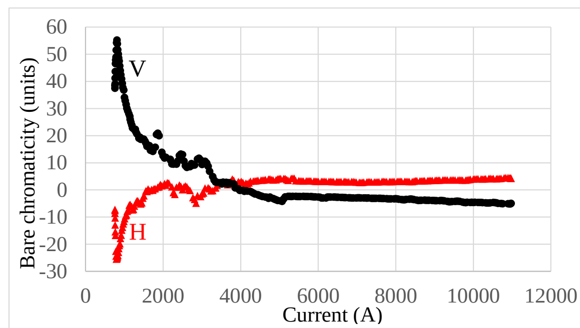

Figure 7: Bare chromaticity during the ramp.

The good quality of the data will be used to correct the persistent current model, integrating the b_3 unit error in the model for 2016 run. This will help to reduce the load present in the lattice sextupole corrections.

CONCLUSION

The tunes and chromaticity are in general well controlled along the cycle to the required accuracy. The characterization of the chromaticity snapback done in 2015 confirmed the values measured in Run1. The FiDeL trims are incorporated into the ramp according to the expected exponential shape of the snapback now 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 tune snapback corrections. 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, which is foreseen for 2016, the feed-forward corrections during the tune snapback could further be improved.

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