

PERFORMANCE AND LHC BEAM STABILITY ISSUES RELATED TO Q/Q' DIAGNOSTICS AND FEEDBACK SYSTEMS

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Abstract

The baseline tune (Q) and chromaticity (Q') diagnostics and associated feedback systems played a crucial role during the LHC commissioning, in establishing circulating beam, the first ramps and their fill-to-fill feed-forward correction. Early on, they also allowed to identify issues such as the residual tune stability, beam spectrum interferences and beam-beam effects – all of which may impact beam lifetimes and thus need to be addressed in view of nominal LHC operation.

INTRODUCTION

The Q and Q' diagnostics and feedback systems – based on the Base-Band-Tune (BBQ) measurement system – were generally considered to be a 'work horse' from Day-I of LHC commissioning and could be operated with no hardware, minimal software and only a few beam related issues. While the general system overview is given in [1, 2], this contribution focuses on the system's performance and issues that arose during initial beam operation.

GENERAL Q/Q' PERFORMANCE

Due to the BBQ's nm-level sensitivity, most of the tune and corresponding chromaticity measurements could be done with residual beam excitation using one of the two Fourier analysis-based systems per beam (aka. FFT1/'Continuous-' and FFT2/'On-demand' System). Nevertheless, the full set of tune beam exciters (the MKQA tune kickers, the ADT transverse damper exciters and the experimental strip-line based, low-amplitude and low-noise BQK exciter) were commissioned without major issues relating to their primary tune-measurement function. Figure 1 shows an exemplary measurement of the tune and intensity evolution during the third LHC ramp with the tune feedback being switched 'off'. The intensity and tunes of 'Beam 1' (B1) and 'Beam 2' (B2) are indicated in blue and red respectively. The resonance lines are indicated in the tune diagram up to the sixth order, with the first and second order drawn in red, third order in blue and higher orders in black with decreasing line width and colour with increasing order. The intensity losses are correlated with the tunes crossing the fourth and fifth order resonance. The source for these drifts remains to be identified [3].

FFT-based System

After cross-calibration against the LHC BPM systems, the equivalent turn-by-turn BBQ noise has been established to about $1 \mu\text{m}$ for a single pilot bunch with about

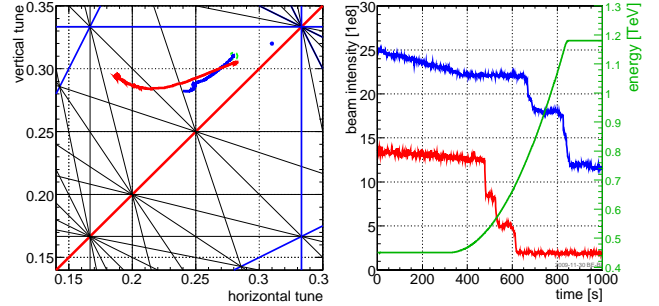


Figure 1: Tune and intensity evolution during the third ramp (2009-11-30).

$5 \cdot 10^9$ protons/bunch) compared to an equivalent turn-by-turn noise of a single LHC BPM of about $100 \mu\text{m}$. However, this estimate cannot be trivially transferred to another arbitrary beam configuration but needs re-calibration for every case. The corresponding BBQ frequency resolution was typically in the range of 10^{-4} down to 10^{-5} and essentially limited only by the available residual tune peak signal-to-noise ratio and the width of the tune signal. The system's lower resolution limit has been established to be about $3 \cdot 10^{-6}$ for a Fourier analysis based on 8192 turns and using an (assumed) constant frequency mains harmonic seen on the beam and with a signal-to-noise ratio of about 20 dB.

Phase-Locked-Loop System

The tune phase-locked-loop systems have been also commissioned for both beams. The Q-PLL was designed for beam scenarios when the residual tune oscillations do not allow sufficient diagnostics with the FFT-based system and is a prerequisite for a continuous chromaticity tracking, particularly during the ramp. Its function and performance remains to be verified. A typical beam-transfer-function (BTF) measurement is shown in Figure 2. With the given phase compensation, the measured BTF response is sufficiently linear and corresponds to model expectations to allow tune tracking operation within the frequency range of about 0.15 and $0.45 f_{rev}$. Beside depending on the machine tune itself, the BTF is also an indicator of high-order beam physics effects. The gain relations and phase compensation established with the BTF taken during the initial commissioning may need to be re-verified for higher bunch intensities, other bunch configurations and machine settings. While most of the ramp diagnostics has been relying on the FFT-based system, the Q-PLL was used during the initial Q'-Tracker commissioning. The Q'-Tracker is based on the measurement of slow momentum modulation induced tune changes as exemplarily shown in Figure 3. The in-

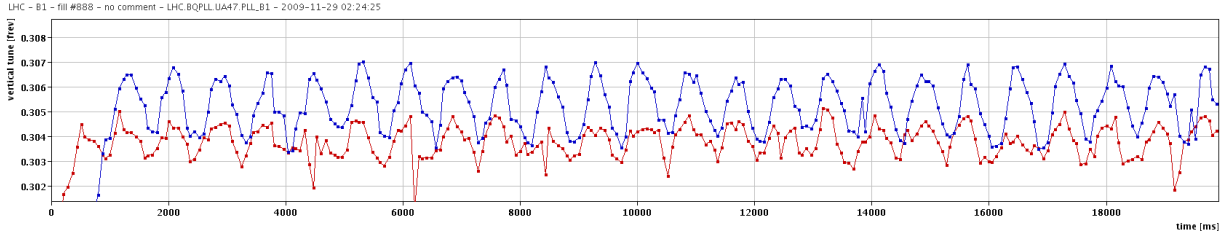


Figure 3: PLL tracking of momentum-induced tune modulation before (blue) and after a $\Delta Q' = 10$ trim (red).

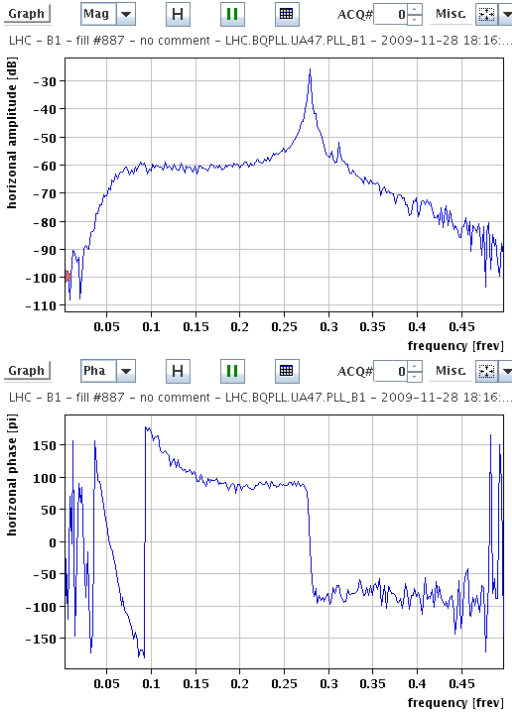


Figure 2: Full-range horizontal Q-PLL BTF example.

duced tune modulation and amplitude reduction before and after the chromaticity trim of 10 units is visible. The momentum has been modulated with an amplitude of about $\Delta p/p = 10^{-4}$ and a frequency of 1.0 Hz. The measured loop-gain-response relation agree to first order with the underlying theoretic model assumptions and the loop was thus able to track these fast tune changes. For the initial tracking tests, the driven excitation amplitudes were comparable or only slightly larger than the residual tune oscillation, thus resulting in a comparable frequency tracking resolution as for the FFT.

Tune-Feedback

As illustrated in Figure 1, a large portion or the entire beam was lost due to tune drifts during the first ramps. In response, the tune feedback has been commissioned, tested prior and used during the fourth ramp, initially for B2 only and during later ramps for both beams. The feedback control of orbit, tune, chromaticity, coupling and the radial loop are combined in one single feedback controller. In order to isolate potential problems, the initial commissioning planning foresaw a thorough test of each of the individual

feedback sub-components and associated system responses and was eventually limited to checks of the tune and orbit corrector circuits and open-loop feedback polarities. Nevertheless, the open- and closed-loop responses proved to be stable and well in agreement with the model transfer function. Figures 4 and 5 show the corresponding tune and orbit feedback responses to external perturbation sources. The

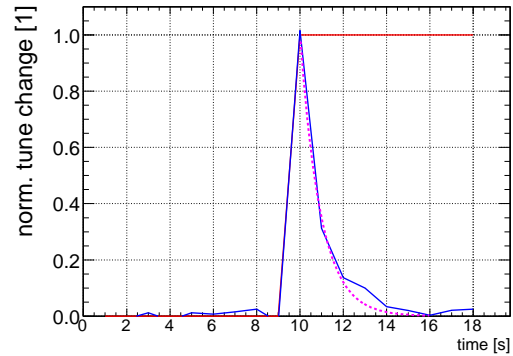


Figure 4: Tune feedback response (blue) to an external $\Delta Q = 0.003$ perturbation (red) and model response (dashed, magenta).

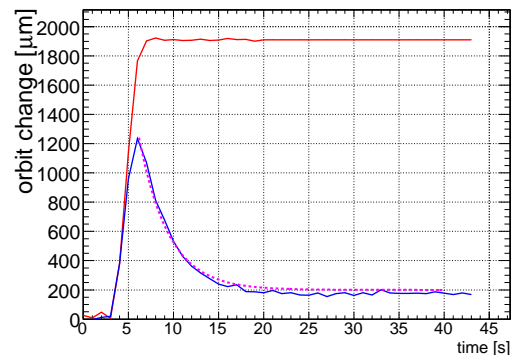


Figure 5: Orbit feedback response (blue) to an external $\Delta x = 2$ mm perturbation (red) and model response (dashed, magenta).

tune and orbit feedback response have been tested using an independent input to the tune and orbit corrector circuits, in case of the orbit using a single three-corrector bump. The residual error in the orbit feedback response is a result of the chosen locality of the correction algorithm that prevented the correction of local bumps but can easily be ad-

justed. While the tune and orbit feedback have been tested, only the tune feedback has been routinely used during the fourth and later ramps. The residual tune stability was in the order of or better than 10^{-4} and the bare tunes were reconstructed using the feedback-driven tune trims. Since the closed-loop responses of both tested feedbacks were stable, essentially limited only by the quality of the associated beam instrumentation and in very good agreement with the model assumption (indicated as dashed magenta lines), this confirms the absence of polarity and large calibration errors. While the initial closed-loop response was configured to be 0.1 Hz, due to the absence of larger transfer function errors an equivalent closed loop bandwidth of 1 Hz seems feasible. Higher closed-loop bandwidth requires a more detailed assessment of all involved corrector and beam transfer functions.

Q/Q' DIAGNOSTICS OPERATION AND BEAM STABILITY ISSUES

The feedback performance is tightly linked to the underlying model and instrumentation performance. Thus, much time was spent on verifying beam instrumentation performance and residual beam stability. During the early commissioning, some effects that could impact beam performance and affect tune and chromaticity diagnostics operation could be identified:

- residual amplitude tune oscillations,
- residual tune jitter, and
- various spectra perturbations

that deteriorate beam life time and reduce beam diagnostics performance.

Residual Tune Oscillations

While the LHC tune diagnostics chain is supported by a set of various type beam exciters, most tune measurements could be performed without any explicit beam excitations due to the high BBQ sensitivity and the residual um-level tune oscillations seen on the beam. Figure 6 shows a typical non-excited LHC beam oscillation magnitude spectrum whose magnitude has been calibrated against the LHC BPM system. A number of beam signals are visible:

- two large residual tune peaks ($q_h \approx 0.28$ and $q_h \approx 0.29$),
- a broad-band excitation signal around the nominal vertical tune working point (0.31), colloquially referred to by the operational crew in the CCC as 'The Hump',
- a narrow-band excitation at a constant frequency of 8 kHz or $Q = 0.2886$, and
- various smaller-amplitude discrete interference lines mostly believed to be related to mains harmonics.

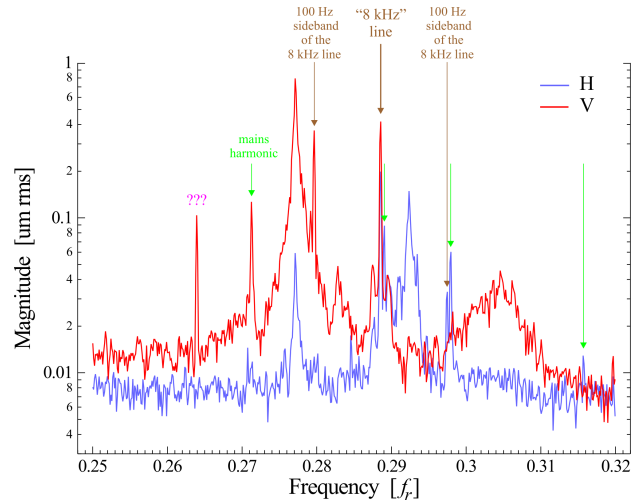


Figure 6: Typical LHC beam spectrum zoomed-in around the tune working points.

In this particular example, the vertical tune was deliberately set below the horizontal tune working point to investigate and mitigate the effect of the broad-band excitation source discussed in the further sections.

While these tune oscillations are beneficial with respect to the FFT-based tune diagnostics, these contribute to an increase in beam size, reduction of beam lifetime and reduced performance of the Q-PLL system. The latter implicitly relies on the assumption that the main excitation and amplitude contribution to the tune resonance is driven by the PLL. Since the observed residual oscillations are not (systematically) correlated to the PLL excitation, they de-facto translate to an effective raise of the beam noise floor as seen by the PLL, and thus cause either a reduced PLL measurement resolution or the necessity of increased excitation amplitudes. While the transverse damper operation will likely damp the base-band oscillations, this damping will make a reliable tune diagnostic also more challenging as the PLL's closed-loop response depends not only on the beam but also the entire transverse damper closed-loop response.

Tune Stability

The baseline Q' diagnostics is essentially based on the classic dependence of small $\Delta p/p$ momentum driven tune modulations on the machine chromaticity. In order to be transparent for regular operation, momentum modulations in the order of 10^{-5} were envisaged. In combination with the desired Q' resolution of one unit this corresponds to a required tune measurement resolution of also about 10^{-5} . While the given BBQ signal-to-noise ratio supported tune resolutions down to 10^{-6} , the residual measured tune stability was order of magnitudes larger as illustrated for example in Figure 7 showing the relative tune changes during the third LHC ramp. The residual stability was typically about $\pm 5 \cdot 10^{-4}$. This tune frequency noise proved to have little or not no particular frequency or chromaticity depen-

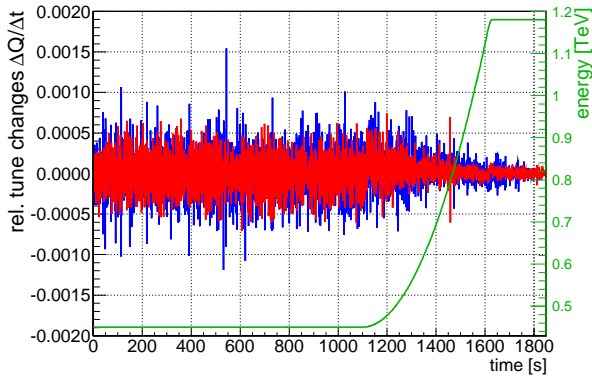


Figure 7: Residual tune noise during injection and third LHC ramp.

dence but rather 'white noise'-like. While this random tune modulation is believed to have less impact on life-time or beam-beam effects, it implies larger required $\Delta p/p$ modulations in the order of 10^{-4} for the Q'-tracker operation which may be impractical for every-day operation and limit its usage to ramp diagnostics and boot-strapping of selected ramps. Though the tune frequency stability improves significantly as the beams are accelerated, the Q'-tracker is most needed at injection energies to allow b3-snapback diagnostics during the ramp start. The tune trim quadrupoles may be one of the perturbation sources as they are usually used with very small milli-Ampere-level currents during their nominal operation while their maximum current rating is 600 A. The corresponding current to tune trim relation is given by equation 1 for the nominal injection optics:

$$\begin{pmatrix} \Delta I_{QTD} [\text{A}] \\ \Delta I_{QTF} [\text{A}] \end{pmatrix} \approx \frac{p [\text{GeV}]}{450 \text{ GeV}} \cdot \begin{pmatrix} +4.3 & +22.2 \\ +22.7 & +3.9 \end{pmatrix} \cdot \begin{pmatrix} \Delta Q_H \\ \Delta Q_V \end{pmatrix} \quad (1)$$

As can be seen, while a small e.g. horizontal tune shifts of $\Delta Q_H = 10^{-4}$ at 450 GeV causes current changes in the order of 2.2 and 0.4 mA for the focusing (RQTF) and defocusing (RQTD) trim quadrupoles, the measured current stability ranged between 1 and 10 mA for some corrector circuits which could possibly explain the given effect. Individually powered strong quadrupoles e.g. the warm insertion or triplet quadrupoles could be also sources for these tune perturbations. Further studies are required to fully assess these effects.

Spectral Perturbations

Beside the residual tune oscillations, the beam spectrum contained also other strong non-tune excitation lines as visible in Figure 6. In case the beam tune was close or on these excitations, it got resonantly excited leading to reduced beam life-times and emittance blow-up. These additional lines are problematic for the FFT-based tune diagnostics that relies on the fact that the tune line is the strongest spectral component within the given search window. The Q-PLL is less affected by these lines since these

are not strictly coherent or in phase with the PLL excitation.

The narrow-band 8 kHz line has been identified to be caused by the UPS switching power-supplies and among other systems is propagated by the transverse damper exciter (ADT) via its input to the beam. Still, even with the ADT being switched 'off' a small portion of the 8 kHz component prevailed which is further being investigated. In any case, their effect should pose less problems since the 8 kHz and other mains harmonics are fixed in frequency and not in the near vicinity of the tune working points.

The source of the broad-band excitation signal around the nominal vertical tune working point (0.31) visible in Figure 6 remains elusive. Similar to the 8 kHz lines, once this perturbation frequency is in the vicinity of the tune the beam gets resonantly excited, significantly reducing the beam life-time and increasing reduces. The 'hump' became more prominent after the 28th November 2009 as the cause of the deteriorating beam life-times. Its amplitude scales linearly with energy and the effect has been seen on both beams and in 2009 predominantly in the vertical plane. A higher temporal analysis revealed that the broad-frequency distribution is actually caused by a narrow-band single frequency with the same shifting mean frequency for both beams as exemplarily shown in Figure 8. The central frequency of the hump shifted typically between 0.15 and 0.35 over a duration of a few hours. The B1 to B2 hump

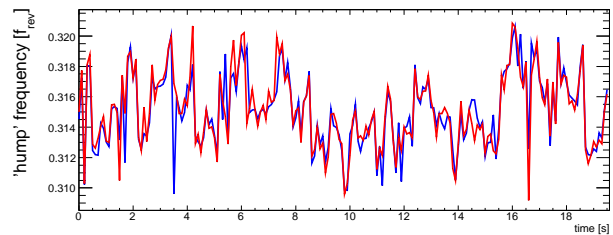


Figure 8: Beam 1 (blue) and Beam 2 (red) 'hump' frequency change.

frequency correlation factor is about 0.895207. The magnitude spectrum of the hump frequency shift as a function of time revealed a $1/f$ dependence. Based on switching 'off' given accelerator components the orbit correctors, the damper exciter and injection septa could be ruled out as being the potential source for this effect. Despite multiple investigation its true source remains elusive and its investigation and mitigation a priority for the upcoming 2010 LHC start-up.

CONCLUSIONS

The commissioning of the tune and chromaticity diagnostic chain advanced well during the first days with LHC beam and allowed early-on the establishing of ramps and the identification of potential beam stability issues such as the residual tune oscillations, tune frequency ripples and spectral interferences. Latter effects, in particular the 8 kHz

line and broad frequency hump, will be further investigated during the upcoming 2010 LHC restart.

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