LHC BEAM STABILITY AND PERFORMANCE OF THE Q/Q' DIAGNOSTIC INSTRUMENTATION

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Abstract

The BBQ tune (Q) and chromaticity (Q') diagnostic systems played a crucial role during the LHC commissioning while establishing circulating beam and first ramps. Early on, they allowed to identify issues such as residual tune stability, beam spectrum interferences and beam-beam effects – all of which may impact beam life-times and thus are being addressed in view of nominal LHC operation. This contribution discusses the initial beam stability in relation to the achieved instrumentation sensitivity, corresponding tune frequency and Q' resolution.

INTRODUCTION

The LHC requires excellent control of particle loss which – with the tunes being in the vicinity of third-order resonances – implies an excellent control of tune, coupling and chromaticity effects. Relying on the Base-Band Tune meter (BBQ, [1]), the base-line Q/Q' diagnostics chain was widely considered to be a 'work-horse' from Day 1 of LHC commissioning and could since be operated with no hardware-, minimal software- and only a few beam-dynamics related issues. While the general system overview is given in [2], this contribution focuses on the system's performance and issues that arose during initial beam operation.

BBQ 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. Figure 1 shows a typical non-excited LHC beam oscillation magnitude spectrum that has been calibrated against the LHC BPM system. The spectrum is based on an acquisition of 8192 turns (corresponding bin bandwidth is about 0.72 Hz) and normalised so that the spectral amplitude has a one-to-one relation with the r.m.s. amplitudes in time-domain for single-tone frequencies. The corresponding amplitude of broad-band perturbations require an integration over the given bandwidth using this scheme. Thus, the residual tune oscillations at $q_h \approx 0.292$ and $q_v \approx 0.277$ have r.m.s. oscillation amplitudes between 0.1 and 1 μm in the time domain. The vertical tune oscillations being typically ten times stronger than the horizontal ones are typically also visible in the horizontal plane. A number of additional lines and a broad-band excitation around 0.31 f_{rev} are also visible in the spectrum.

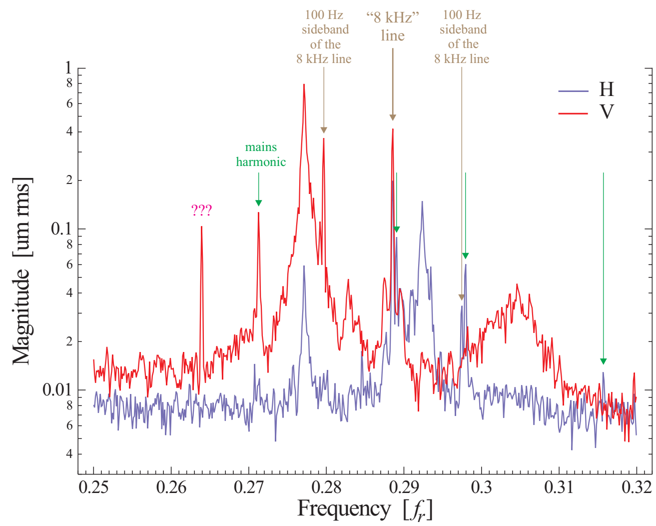


Figure 1: Typical LHC beam spectrum zoomed-in around the tune working points.

Based on this measurement, the BBQ turn-by-turn resolution is estimated to be better than 1 μm. Nevertheless, a full set of tune beam exciters (tune kickers, transverse damper exciters and an experimental strip-line based, low-amplitude and low-noise exciter) were commissioned.

FFT-based Q-Tracking

The BBQ oscillation data is typically processed using Fourier-analysis (FFT) and Phase-Locked-Loop (PLL) based systems described in [3, 4]. Figure 2 shows an exemplary FFT-based measurement of the tune and intensity evolution during the third LHC ramp with the tune feedback being switched 'off'.

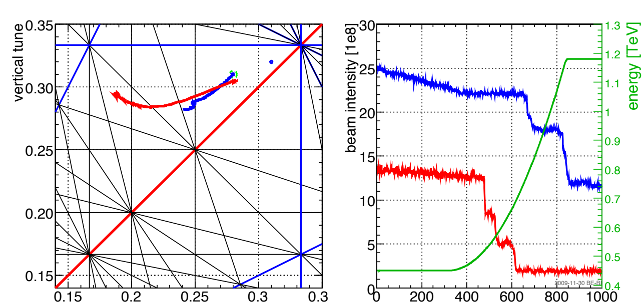


Figure 2: Tune and intensity evolution during the third ramp (2009-11-30).

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 orders drawn in red, the third order in blue, and higher orders in black with decreasing line width with increasing order. The intensity losses are correlated with the tunes crossing the fourth and fifth order resonances. The source for these drifts remains to be identified.

The tune data of the inital ramps was used as feed-forward corrections for the successive ramps and – for a well pre-cycled machine – reached fill-to-fill tune reproducibilities of about $\pm 3 \cdot 10^{-3}$. However, this limit was frequently exceeded due to varying magnetic pre-cycles, for instance, after an access or magnet quench that caused tune perturbations up to ± 0.02 during the following ramp that was not well described and thus not compensated for by the magnetic field description model, within the desired tolerances. Thus the tune feedback was routinely deployed during almost every ramp to compensate for these residual non-reproducibilities [6]. Figures 3 show two horizontal BBQ ramp spectra with feed-forward corrections only and with tune feedback being switched 'on'. Tune stability both without and with tune feedback around the nominal working points ($Q_h = 64.28$ & $Q_v = 59.31$) is visible. The tune stability with feedback is typically 10^{-3} during the snap-back, better than 10^{-4} during the rest of the ramp, and essentially limited by the residual tune ripple at injection and effective feedback bandwidth.

The FFT based system further facilitated the fast commissioning of the β^* squeeze within a few days. Figure 4 shows an exemplary evolution of the tune eigenmodes and corresponding unperturbed tunes taken during first squeeze attempt. The multiple crossing of the unperturbed tunes –

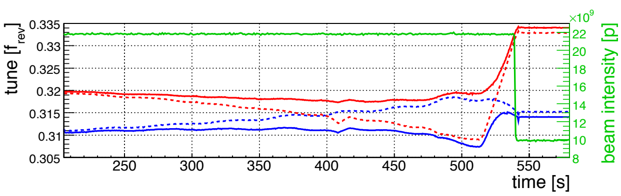


Figure 4: Tune evolution during the first squeeze to $\beta^* = 2\,\mathrm{m}$. The eigenmodes (solid lines) and tunes (dashed lines) are indicated in blue for the horizontal plane, and in red for the vertical plane.

which are the tunes in the absence of betatron coupling.– and the crossing of the third order resonance causing particle loss are visible. The same tune and coupling measurements were used as corrections, leading to the next squeeze that successfully reached a β^* of $2\,\mathrm{m}$ in all interaction points

An extraordinary tune measurement resolution of 10^{-6} has been achieved, which is illustrated in Figure 5, showing the tune evolution during the first long physics fill with colliding beams and squeezed optics at 3.5 TeV. In this particular example, the residual tune oscillation is dominated by energy fluctuations driven by tidal changes of the ma-

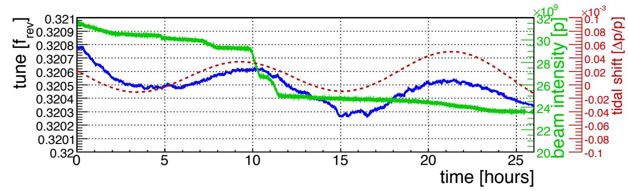


Figure 5: Vertical tune evolution and tidal-driven energy changes during the first long physics collisions.

chine circumference causing energy modulations, and in turn is propagated to the tune via chromaticity. The maximum momentum amplitude of $\Delta p/p \approx 3 \cdot 10^{-5}$ and modulation period of about 12 hours makes this measurement probably one of the the slowest high-precision chromaticity measurements achieved in any accelerator to date.

PLL-based Q-Tracking

The tune phase-locked-loop systems were 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 continuous chromaticity tracking, particularly during the ramp. A typical beam-transfer-function (BTF) measurement is shown in Figure 6. With the given

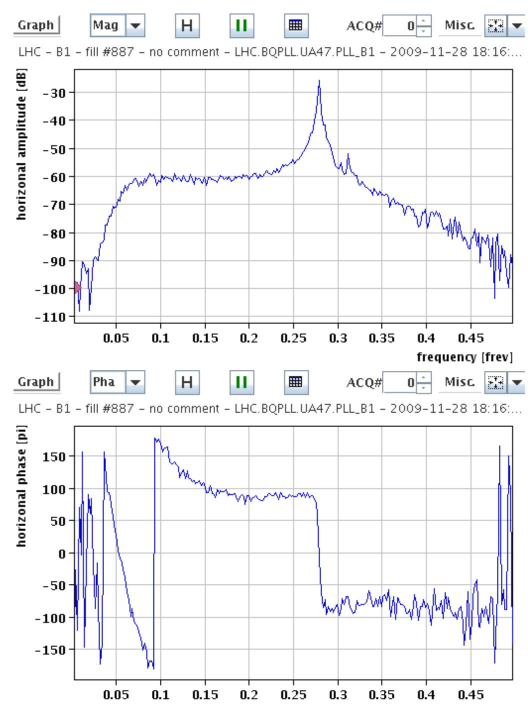
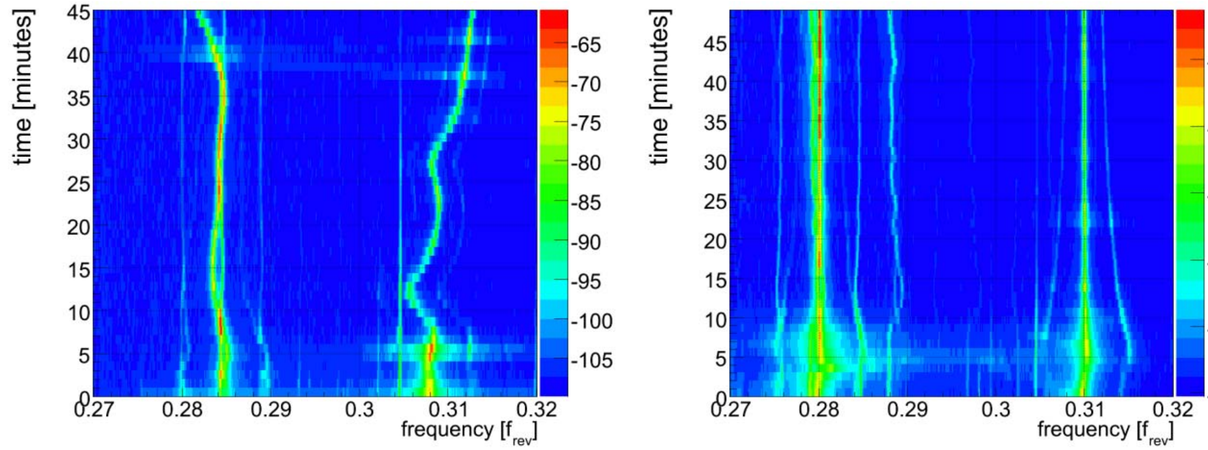


Figure 6: Full-range horizontal Q-PLL BTF example.

phase compensation, the measured BTF response is sufficiently linear and corresponds to model expectations that allow tune tracking operation within the frequency range of about 0.15 and 0.45 f_{rev}. Besides depending on the machine tune itself, the BTF is also an indicator of high-order beam physics effects. The loop gains and phase compensation established with the BTF taken during the initial commissioning may need to be re-verified for higher bunch in-



(a) Feed-forward (Q-FB 'off')

(b) Q-FB 'on'

Figure 3: Horizontal tune spectra taken during the ramps without and with tune feedback being switched 'on'. The magnitude of the residual oscillations has been colour-coded in a 'dB' scale.

tensities, other bunch configurations, and machine settings.

A Q'-Tracker measurement based on momentum modulation induced tune changes is shown in Figure 7. The induced 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 oscillations, thus resulting in a comparable frequency tracking resolution as for the FFT-based system.

CHROMATICITY TRACKING

The baseline Q' diagnostics essentially relies on the classic dependence of small $\Delta p/p$ momentum-driven tune modulations on the machine chromaticity and was prototyped at the CERN SPS [7]. The inital LHC baseline Q/Q' diagnostic chain foresaw the PLL as a tracker of these tune oscillations. However, its operation was impractical due the strong residual tune oscillations that would require larger PLL-driven beam excursions. Since the FFT-based tracking provided sufficient tune tracking, chromaticity was thus mostly measured by demodulation of the FFT-based tune tracking data. Figure 8 shows a typical chromaticity tracking example during an LHC ramp. Due to residual errors in the magnetic field description model, the chromaticity snap-back is only partially compensated, causing Q'_H to drop and Q'_V to rise by about 10 units at the start of the ramp. For the time being, these Q' transients are mitigated by raising and lowering the corresponding component at injection, and the data primarily used to re-fit and improve the magnetic field model. While the initial Q' was designed for momentum modulations of $\Delta p/p = 10^{-5}$ and modulation frequencies of 2.5 Hz, the FFT-based chromaticity tracker achieved the targeted Q' resolution of better than one unit, with the chosen momentum modulation of $\Delta p/p = 10^{-4}$ and modulation frequency of 0.2 Hz . Once accelerating higher beam intensities that require more precise chromaticity control, it is planned to use this chromaticity tracker as an input to the chromaticity feedback.

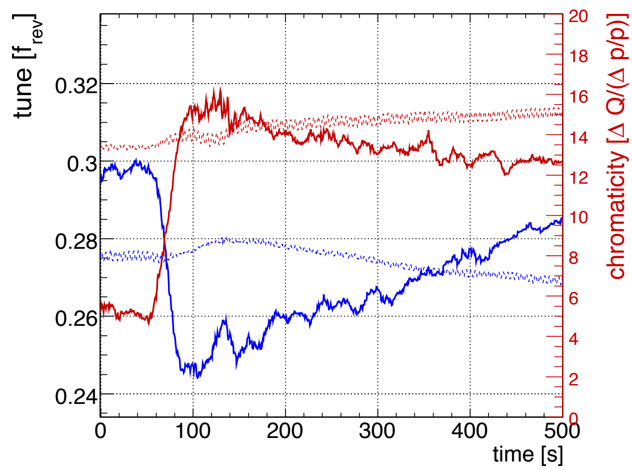


Figure 8: Chromaticity tracking during the energy ramp. The chromaticities (solid lines) and modulated tune signals (dashed lines) are indicated in blue for the horizontal and in red for the vertical plane.

Q/Q' DIAGNOSTICS OPERATION AND BEAM STABILITY ISSUES

Since any feedback performance is tightly linked to the underlying model and instrumentation performance, much time was spent on verifying the Q/Q' beam instrumentation systematics and residual beam stability. During early commissioning, some effects that could impact beam performance and that affect tune and chromaticity diagnostics operation were identified:

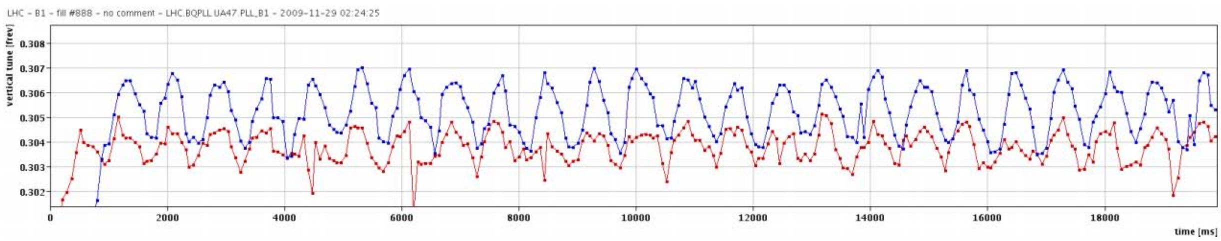


Figure 7: PLL tracking of momentum-induced tune modulation before (blue) and after a $\Delta Q' = 10$ trim (red).

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

deteriorating beam emittances and life-time.

Residual Tune Oscillations

Most tune measurements could be performed without any explicit beam excitations due to the residual um-level tune oscillations by the beam. In addition to the tunes, a number of non-tune beam signals are visible in Figure 1: a broad-band excitation signal around the nominal vertical tune working point (0.31), colloquially referred to by the operational crew 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. 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 subsequent sections.

While these tune oscillations are beneficial with respect to the FFT-based tune diagnostics, they contribute to an increase in beam size, reduction of beam life-time 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 defacto translate to an effective rise of the beam noise floor as seen by the PLL, and thus causes either a reduced PLL measurement resolution or necessitates increased excitation amplitudes. While the transverse damper operation would likely attenuate the base-band oscillations, this will also make a reliable tune diagnostic more challenging, as the PLL’s closed-loop response would, in this case, not only depend on the beam but also on the entire transverse damper closed-loop transfer function.

Tune Stability

In order to be transparent for regular operation, momentum modulations in the order of 10^{-5} were initially envisaged. 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 several orders of magnitude larger at injection, as illustrated in Figure 9, which shows the relative tune changes during the third LHC ramp. Filtering

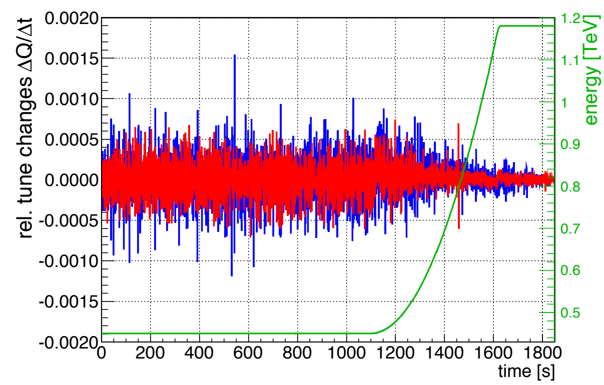


Figure 9: Residual tune noise during injection and ramp.

slow tune drifts below 0.1 Hz, the residual short-term stability was typically about $\pm 5 \cdot 10^{-4}$. This tune frequency noise proved to have little or no particular frequency or chromaticity dependence, but was 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 everyday operation and limits its usage to ramp diagnostics and boot-strapping of selected ramps. Though the tune frequency stability improved significantly as the beams are accelerated, the Q’-tracker is most needed at injection energies to allow snapback diagnostics during the start of the ramp. The tune trim quadrupoles may be one of the perturbation sources as they are usually used with very small milli-Ampere-level currents, while their maximum current rating is 600 A. The corresponding typical current to tune trim relation is given by Equation 1:

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

While a small, horizontal tune shift 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 measured effect. Individually powered strong quadrupoles such as 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

Besides the residual tune oscillations, the beam spectrum also contains other strong non-tune excitation lines, as visible in Figure 1. In case the beam tune is close or on these excitations, it gets resonantly excited, leading to emittance blow-up and reduced beam life-times. These additional lines are particularly 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. However, in this case, the Q-PLL is less affected by these lines as these are not strictly phase coherent with the PLL excitation.

The narrow-band 8 kHz line was caused by the UPS switching power-supplies and, among other systems, was propagated by the transverse damper exciter (ADT) via its input to the beam. Yet, even with the ADT being switched 'off' and these perturbations being filtered within the ADT, a small portion of the 8 kHz component prevailed, which is being further investigated. In any case, their effect is expected to pose less problems as the 8 kHz and other mains harmonics are fixed in frequency and not in the vicinity of the nominal tune working points.

The source of the broad-band excitation signal around the nominal vertical tune working point (0.31) visible in Figure 1 remains elusive. Similar to the 8 kHz lines, once this perturbation is in the vicinity of the tune, the beam gets resonantly excited, subsequently decreasing beam lifetime. While the effect has been observed on both beams, it is more dominant in the vertical plane of B2. 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 shown in Figure 10. The central frequency of the hump shifted typically between 0.15 and 0.45 f_{rev} over a duration of a few minutes to hours. The B1 to B2 hump

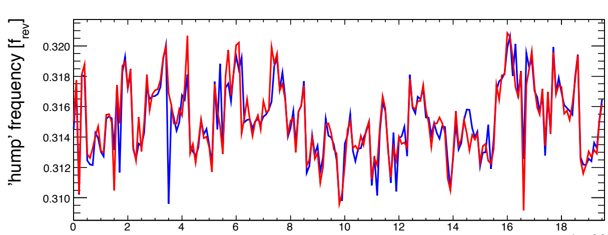


Figure 10: Beam 1 (blue) and Beam 2 (red) 'hump' frequency change.

frequency correlation factor is about 0.896. Nevertheless, the 'hump' is visible independent of whether there are one or two beams circulating in the machine. The magnitude spectrum of the hump frequency shift as a function of time revealed a $1/f$ dependence. As visible in Figure 1, the amplitude of the 'hump' corresponding to a few hundred nano-metre is extremely small and – provided it is caused by a single dipolar-type kick – corresponds to a deflection angle in the order of a few nano-rads. Due to the huge number of elements in the machine that a priori could potentially create these minuscule deflections, the identification and location of the true perturbation source proved to be extremely difficult. Based on switching 'off' given accelerator elements, the orbit correctors, transverse damper exciter, injection septa, transfer lines, pre-injector accelerators, experimental magnets and higher-order magnets could be ruled out as the cause for the 'hump'. Despite a series of investigations, the true source of the 'hump' remains unknown, and its investigation and mitigation is a priority of the ongoing LHC commissioning.

CONCLUSIONS

The commissioning of the tune and chromaticity diagnostic chain advanced well, and facilitated a fast and reliable establishing of ramps, β^* squeeze, and the identification of potential beam stability issues early on such as residual tune oscillations, tune frequency ripples, and spectral interferences. Due to the BBQ's high sensitivity for small beam oscillations, the FFT- and PLL-based tune systems system could achieve measurement resolutions between 10^{-4} and 10^{-6} depending on energy and mainly limited by the available signal-to-noise ratio of the tune peaks. Derived from the tune trackers, the chromaticity tracker achieved a chromaticity resolution of about 1 units on a regular basis facilitating. While the initial performance is sufficient for present operation, some effects such as the residual un-explained tune oscillations, the large tune jitter during injection and the 'hump' will need to be addressed in view of nominal LHC operation.

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