ADVANCEMENTS IN THE BASE-BAND-TUNE AND CHROMATICITY INSTRUMENTATION AND DIAGNOSTICS SYSTEMS DURING LHC'S FIRST YEAR OF OPERATION

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Abstract

The Base-Band-Tune (BBQ) system is an integral part of day-to-day LHC operation, driving tune and chromaticity diagnostics and feedbacks. This contribution summarises the system's overall performance and documents the various improvements of the analogue front-end circuitry, digital post-processing and integration, necessary in response to issues arising during high-intensity physics operation since its first introduction in 2005.

INTRODUCTION

The lack of synchrotron radiation damping to maintain emittance combined with tight collimator settings at the LHC impose significant constraints on the maximum allowed beam excursions for Q and Q' measurements to below a few µm. In response, the highly sensitive BBQ system was developed, and is further exploited by a set of Fourier- (FFT) and Phase-Locked-Loop (PLL) based diagnostics systems [1, 2, 3, 4].

Schematically illustrated in Figure 1, the BBQ is – to first order – an AC-coupled peak-detection circuit, demodulating the transverse beam oscillations signals of a pick-up from the longitudinal carrier signal, whose bandwidth in the LHC can extend up to a few GHz [1].

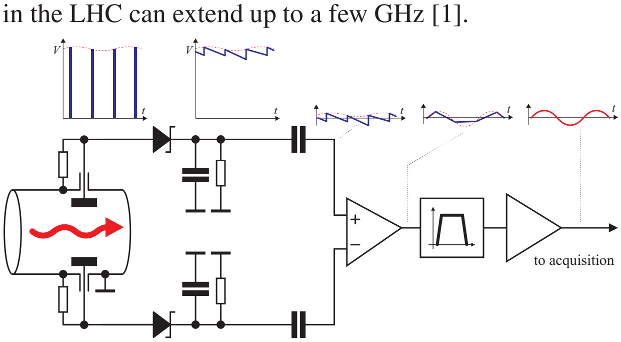
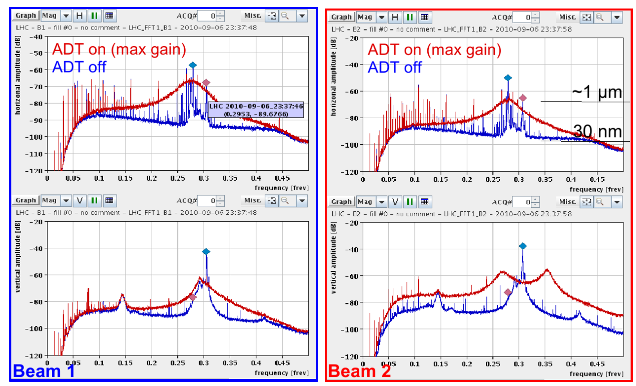


Figure 1: Schematic BBQ block diagram.

PERFORMANCE WITH BEAM

The initial tune diagnostics design assumed that there would not be sufficient residual tune signatures on the beam and thus hence periodic driving of the beam (e.g. using a 'kick', 'white noise', 'chirp' or 'PLL') was envisaged [3]. The BBQ's nm-level sensitivity was also thought to be sufficient to operate below the oscillation levels that would be detected and suppressed by the transverse damper (ADT). This seemed to be confirmed with beam during the initial prototyping at RHIC, CERN-SPS, Tevatron and initial LHC commissioning.

Cross-calibrations against the LHC BPMs indicated that the BBQ can provide a turn-by-turn resolution of better than 30 nm, more than 50 times the sensitivity of any other LHC systems (ADT: 1 µm, BPM: 50 µm[10, 8, 9]). It is also seen that there are ever-present residual tune oscillations with amplitudes in the order of 100 nm to a few micro-metres on the beam, as shown in Figure 2.



(a) Beam 1 Spectra (b) Beam 2 Spectra

Figure 2: BBQ spectra with ADT feedback being 'off' (blue) and active with high-gain settings (red). Detected horizontal and vertical tunes are indicated with Diamonds.

These "luxurious" signal-to-noise (S/N) ratios allowed passive tune monitoring, tracking and feedbacks, proving to be sufficiently reliable for controlling tune variations during almost every LHC ramp and squeeze [4].

The competing ADT function of suppressing the very same beam oscillations required to measured the tune is compensated by the higher BBQ sensitivity. However, the higher sensitivity is nullified by the ADT pick-up noise that in high-gain operation is propagated onto the beam and which raises the effective noise floor, as visible in Figure 2. The LHC is not yet limited by instabilities, and the ADT is thus operated with reduced gains whenever precise Q/Q' diagnostics or Tune-FB are required.

While a passive detection of the tune benefits from these µm-level oscillations, they are incoherent 'noise' from a PLL diagnostics point of view which requires excitation above this 'noise' to recover the same performance as using residual oscillations only. The corresponding required absolute amplitudes of about 10-100 µm are in conflict with collimator requirements (<200 µm) and shown to cause small but measurable beam losses in the machine. Thus, driving the beam to such amplitudes seemed to be inefficient and less robust compared to the performance achieved with a passive-only system.

BBQ DATA POST-PROCESSING

The change of paradigm of using residual beam oscillations implied changes to improve the reliability of the Q and Q' fitter algorithm, specifically, adjustments to reject multiple non-tune related spectral peaks that cannot unambiguously be eliminated. Initial attempts using standard comb filters yielded unsatisfactory results due to notable changes of the synchrotron tune Q_s, and higher mains-harmonics in response to global load changes. A demanding tune spectra is shown in Figure 3, where longitudinal bunch phase and shape instabilities add a 'forest' of interference lines to the otherwise fairly clean BBQ spectrum.

Tune Fitter

A more robust, multi-stage, median-filter based algorithm has been deployed, taking advantage of the fact that the natural tune resonance width is typically larger ($\approx 10^{-3}\,\mathrm{f_{rev}}$) than those of mains harmonic ($< 10^{-4}\,\mathrm{f_{rev}}$) and longitudinal Q_s interferences. The digital post-processing performed surprisingly well and soon became the base-line mode of operation for tune the feedback. The main steps of this algorithm consists of (Figure 3):

1. calculate the raw-spectra $S_{raw}(f)$ based on the n-turn BBQ oscillations data[3],
2. compute (averaged) magnitude spectra $|S_{raw}(f)|$,
3. apply a n_{med}-wide median-filter $\rightarrow |S_{med}(f)|$,
4. apply a $\pm n_{lp}$-wide sliding average-filter $\rightarrow |S_{lp}(f)|$,
5. find highest peak $Q_{est.}$ in $|S_{lp}(f)|$ within the given boundaries $Q_{est.} \in [f_{min}, f_{max}]$,
6. find highest peak Q_{raw} in $|S_{raw}(f)|$ around the previous $Q_{est.} \cdot \frac{n}{2} \pm n_{med}/2$ estimate,
7. refine the binning-limited Q_{raw} estimate by fitting the tune resonance to a Gaussian distribution [5].
8. derive the coupling and unperturbed tunes [6].

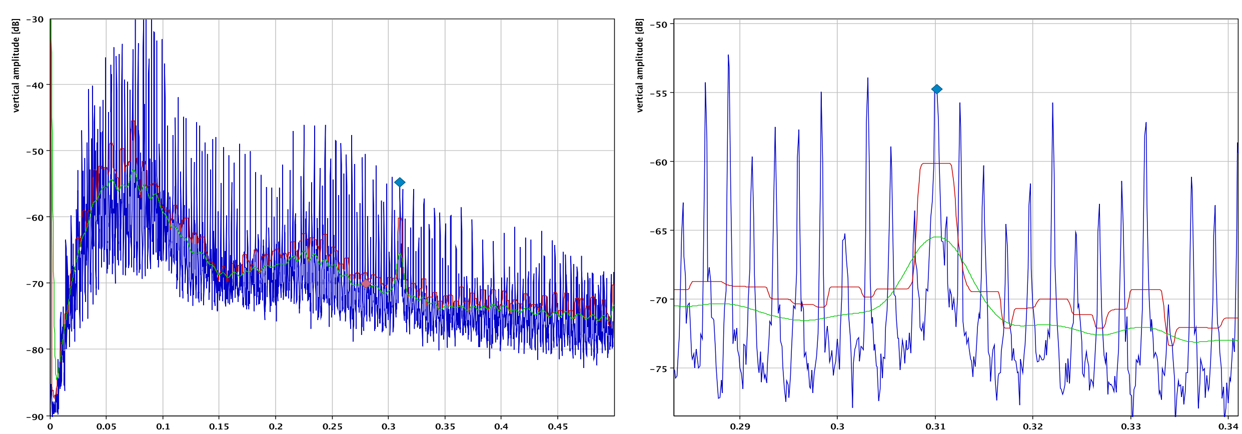
The averaging described in step 2 is optional and only executed when a fast tune time response is not required. The parameter n_{med} and n_{lp} are chosen to be larger than the width of the mains and Q_s harmonics but smaller than the tune resonance itself. Step 3 removes the artifacts created by the median-filter (plateaus) and step 5 is needed since the true tune peak and estimates of the coupling parameter $|C^-|$ are often distorted by the median- and low-pass filter, especially in cases of asymmetric synchrotron side-bands. The fitter ranges in step 5 are typically only roughly adjusted to reject the larger Q_s forest around $0.1 f_{rev}$ and to distinguish between Q_H and Q_V.

This algorithm usually works quite well for the vast majority of spectra observed during regular operation, and once setup requires little or no adjustments, even for demanding cases such as that shown in Figure 3. The remaining known limitations of the algorithm are due to fairly special cases related to vanishing tune oscillation signals, seen so far only for very low intensity proton beams and too large ADT gains discussed above, and small but undesired jumps of the tune estimate between the actual tune and its synchrotron sidebands in case of larger chromaticities.

The lower limit on the revolution line and its synchrotron side-band width is essentially given by the beam momentum spread, which can be easily accounted for by adjusting n_{med} appropriately. However, the widths of the tune synchrotron side-bands are typically slightly larger than their longitudinal counter parts since they are affected by the same non-linear effects as the tune resonance itself. In addition, these tune synchrotron side-bands may become even larger than the main tune peak that may for higher chromaticities.

Chromaticity Fitter

The standard chromaticity (Q') demodulation algorithm required minor modifications, mainly related to intercepting non-physical outlier of the tune estimate. The algorithm could be kept very simple since the RF modulation is generated by the same controller that also performs the chromaticity detection and feedback. Detailed results are described in [7, 2, 4].



(a) LHC BBQ spectra

(b) Zoom around betatron tune

Figure 3: Raw ($|S_{raw}(f)|$, blue), intermediate median- ($|S_{med}(f)|$, red) and low-pass filtered magnitude spectra ($|S_{lp}(f)|$, green) as used in the revised tune fitter algorithm.

SECOND-ORDER BBQ EFFECTS

The driving sources of the discussed tune signals remain unknown but appear independent of the stored bunch intensity, energy, collimator settings and chromaticity. On the turn-by-turn scale, visualised in Figure 4, these oscillations do not appear to be long coherent wave-trains which can be correlated with a single excitation source but seem to consist of small bursts of instabilities that start and stop on the time scale of tens to a few hundreds of turns. Two noteworthy effects have been observed which led to improving a better understanding of the BBQ's second order effects:

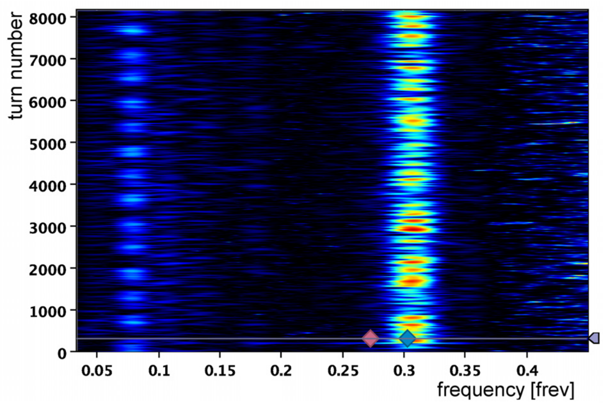


Figure 4: BBQ Wavelet spectrum. The burst-type character of the tune oscillations at $Q_y = 0.31$ is visible.

Peak-Detection

While operating with only a few bunches, it was seen that the BBQ spectrum contained tune peaks for colliding as well as non-colliding bunches, indicating that the BBQ is not a perfect peak detector but measures the average tune of all bunches. This effect becomes less prominent once operating with a large number of bunches.

This can be explained by the fact that the storage capacitor charging time cannot be neglected for the very short LHC bunch length of about 0.25 ns r.m.s. compared to the revolution period of 89 µs. Assuming a very simple linear model of the BBQ detector, modelling the diode as an ideal switch (neglecting the forward voltage which is much smaller than the input and output voltages of $\approx 100\,\mathrm{V}$) with a series resistance r, storage capacitor C and discharge resistor R, the steady-state detector output voltage V_0 can be calculated from the charge balance equation

$$\Delta Q_{in} = \frac{V_0 - V_I}{r} \cdot n \cdot \tau \stackrel{!}{=} \Delta Q_{out} = \frac{V_0}{R} \cdot T_{rev} \qquad (1)$$

with T_{rev} being the revolution period, τ the length of the rectangular bunch approximation, V_I the detector input voltage and n the number of bunches. Solving the equation for the normalised output voltage V_0/V_I one gets:

$$\frac{V_0}{V_I} = \left(1 + \frac{r}{R} \cdot \frac{T_{rev}}{\tau} \cdot \frac{1}{n}\right)^{-1} \qquad (2)$$

The steady-state detector voltage depends on the time and resistance ratios of charging and discharging and approaches the true peak voltage with increasing number of bunches n. As the intensity spread between bunches is finite (LHC: $< \pm 10\%$), the detector can be considered a true peak-detector, once $1 - V_0/V_I$ is smaller than relative peak voltage difference of the largest to second largest bunch. For the real diode detector, the series resistance depends increases strongly for small $V_I - V_0$, causing an ever slower increase of the output voltage than given in Eq. 2.

Intra-Bunch Oscillations

The ADT relies on average bunch position measurements and in high-gain operation typically suppresses coherent bunch oscillations down to the um-level. Nevertheless, operating with a large number of bunches, narrow bandwidth tune signals similar to those with the ADT being 'off' often remain visible on top of the damped tune spectra. In addition, earlier BBQ modifications deploying low-pass filters to remove dependencies on bunch shape oscillations that typically are more pronounced for GHz-range frequencies showed to have in some cases smaller tune S/N ratios than their full bandwidth counterparts. The observed remaining tune oscillations are thus indicative that the BBQ is also sensitive to intra-bunch head-tail oscillations that cannot be damped by the ADT.

CONCLUSIONS

The BBQ system facilitated a fast and reliable LHC commissioning, and with its nm-level sensitivity and ever-present um-level tune allowed passive tune monitoring. In response, a multi-stage tracker algorithm has been implemented, efficiently suppressing non-tune related components in the beam spectrum. Second order effects such as the BBQ measuring the average tune for a low number of bunches and becoming increasingly sensitive to intra-bunch head-tail oscillations for a larger number of bunches could be traced back to finite BBQ charging time constants.

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