WHAT YOU GET: ORBIT AND TUNE MEASUREMENTS AND FEEDBACK

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Abstract

The Large Hadron Collider (LHC) has now been operated successfully for 3 years relying on the good performance of its beam instrumentation, including position and tune monitors and their respective feedback systems. This contribution gives an overview of the performance and limitations of the current orbit and tune systems. The major hardware and software modifications performed in 2012 are presented as well as the developments and improvements planned during the Long Shutdown 1 (LS1). The last part of the paper discusses the expected performances of both systems with 6.5TeV beams after LS1.

INTRODUCTION

With its 1070 monitors, the LHC Beam Position Monitor (BPM) system is the largest BPM system worldwide [1]. Based on the Wide Band Time Normalizer (WBTN) [2], it provides bunch-by-bunch beam position (and intensity) over a wide dynamic range (~50dB). Despite its size (3820 electronic cards in the accelerator tunnel and 1070 digital post-processing cards in surface buildings) and complexity the performance of the system during the last three years has been excellent, with 97% availability.

The tune monitoring system is based on direct diode detection [3] allowing operation with nanometres beam oscillation. Both the BPM and the tune monitors are used for feedback [4] to stabilise the orbit and tune around their optimal values throughout whole LHC fill.

Nevertheless, after three years of operation, the performance of the existing systems has been investigated in detail and several limitations were found and partially mitigated. This paper will discuss the status of the BPM and tune related monitors with an emphasis on the planned upgrades foreseen during the long-shutdown and the expected performance of the systems with >6.5TeV beams.

BEAM POSITION MONITOR

For the BPMs, in the arcs, the position resolution was measured to be better than 150μm in bunch/bunch mode and 10μm in averaged orbit mode [5]. In 2012, an automatic configuration of the digital signal processing system was successfully tested in order to adjust the settings of an averaging filter with respect to number of bunches circulating in the machine. This functionality will be deployed after LS1 and should push the orbit resolution down to 5μm. The main limitation to the orbit stability is caused by long-term drifts due to temperature variations in VME integrator mezzanine causing position errors. The typical temperature drift behaviour is shown in Figure 1. The drift effect is known since 2010 and has shown orbit errors of millimetres over one fill. In order to mitigate this effect, an online temperature correction algorithm was established: the temperature dependence of the integrator mezzanine is measured with the BPM calibration mode, controlling the VME crate fan's speed to vary the ambient temperature. A linear, online correction of the BPM data is thus performed depending on the measured temperature. However, this technique turned out to work reliably only for small temperature drifts. An improved long-term solution was therefore initiated in 2010 investigating the use of water-cooled racks to keep the temperature of the electronics constant.

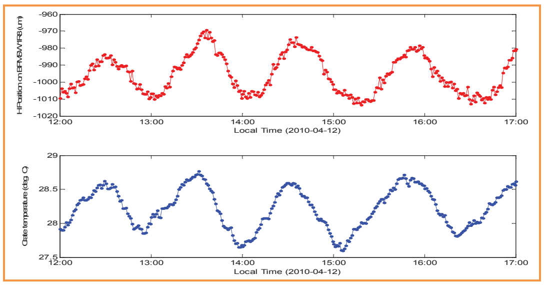

Figure 1: Time of evolution of the horizontal beam position in a selected BPMSW (top) and the temperature in the corresponding mezzanine (bottom)

Test and installation of thermalized racks

As Figure 2 shows, water-cooled racks have been evaluated for one year at LHC Point 1 on a test system, and proofed the temperature can be well controlled over long periods better than 0.05°C rms resulting in orbit drifts smaller than of 3μm.

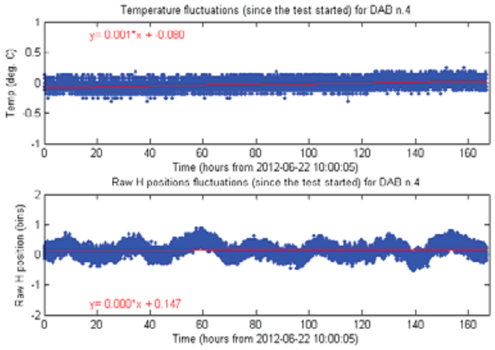

Figure 2: Temperature in water-cooled rack, (top) Corresponding horizontal position in adc's bins (bottom)

Water-cooled racks will be installed during the long-shutdown on all BPM and BLM surface racks.

Non-linearity correction of BPM

A potential limitation to the accuracy of buttons and strip-line BPMs arises from their non-linear response to off-centred beam position [6]. This effect comes directly from the physical geometry of the pick-up and can be precisely simulated and thus corrected. For most cases in LHC, like in the arcs, this is not an issue since the beam position remains close to the beam axis. However larger errors occur for large off-centred beams, like for example in the dump lines or for some BPMs around the interaction points where the pick-up electrodes had to be tilted by 45degrees for integration reasons.

Electro-magnetic simulations [6] have been performed using CST Particle Studio to characterise the non-linear effects for all types of LHC BPMs and determine the parameters of the polynomial fit to be used for corrections Figure 3 illustrates as example, the BPMD type, a 130mm aperture strip-line BPM located in the dump line, is presented. Based on the simulations, the difference between non-linearity corrections using either a 1D or a 2D correction scheme with cross term is considerable. The average absolute calibration error in the beam allowed area (1/3 of the BPM aperture) could be reduced from 1.1mm to 30µm and the maximum error for diagonal beam from 6mm down to 100um.

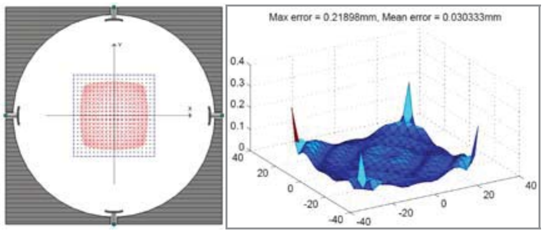

Figure 3: (left) Sketch of a BPM with the beam allowed area visible and typical errors made without correction in red (right) Residual error after 2D correction using cross-terms polynomials

In the LHC, non-linearity corrections based on single-term (1D) corrections have been implemented since the beginning of the beam operation. A more complete set of software corrections including cross-terms polynomials (2D) have been tested in machine developments and have demonstrated the potential improvements [7]. They will be put in place in the Front-end software systems during LS1 to provide better corrections for all BPMs. It is worth noting, however, that the algorithms will require testing with beam.

Orbit measurement with diodes

Originally developed to process signals from BPM buttons embedded in LHC collimator jaws [8], orbit measurement using a compensated diode detector scheme [9], named DOROS, has already demonstrated to be robust, simple and in addition providing an excellent position resolution. One prototype was tested in the SPS for two years on a LHC collimator prototype equipped with buttons BPMs. A second prototype was installed on LHC BPMs and has shown resolution in the nanometre range [9]. A comparison of the orbit measured, during a Van der Meer scan, simultaneously by WBTN and DOROS is presented in Figure 4. The resolution of DOROS is at least 50 better than for the WBTN. On this plot, there is a visible scaling error between the two systems, which is still under investigation. For this plot, the DOROS data were scaled without any non-linearity corrections of the BPM nor the electronics.

During LS1, the development of DOROS is moving from prototyping to final engineering production. This electronics will be installed on LHC collimator BPMs and on few BPMs in the LSSs region where their excellent resolution is expected to improve the LHC performance during squeeze. It is important to note that DOROS does not provide bunch-by-bunch measurements. However, if required, the electronic could be equipped with a gating circuitry, allowing the selection of single or group of bunches.

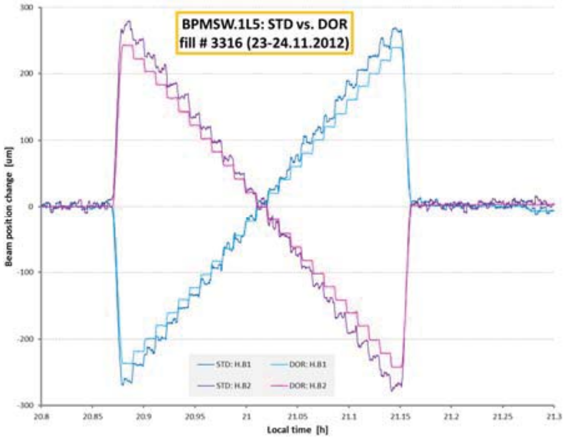

Figure 4: LHC orbits - diode system versus normaliser positions

Status of Orbit Feedback

The LHC would not have performed so remarkably well without its orbit feedback system. The current correction quality limits are not yet a real problem. In the arcs and for most of the LSS, the fill-to-fill reproducibility of the beam position is of the order of 50µm. In the common regions in points 1, 2, 5 & 8, the reproducibility is degrading with an rms value of 200 µm, mainly due to the limited directivity of strip-line BPMs.

To illustrate the performance of the orbit feedback, Figure 5 shows the evolution of the orbit correction at

IP1 to bring beams into head-on collisions (here B1H correction) over one year. There is a clear slow drift developing over the year, which is not corrected but the fill-to-fill difference is very small and sufficiently good.

At 7TeV, with tighter collimator settings and the lowest achievable β*, the orbit stability must be improved. During the long shutdown, several actions highly beneficial for OFB are foreseen to overcome the known limitation. Most of them are directly related to improvements in hardware, like the installation of water-cooled racks and the deployment of DOROS wherever possible. In parallel, software improvements are also under investigation. This includes a better handling of response matrix, better filtering of bad elements and improvements in the data transfer. A lot of modifications and improvements were made already since 2010 and the long shutdown will give the occasion to review in details the system architecture and improve the in-depth knowledge.

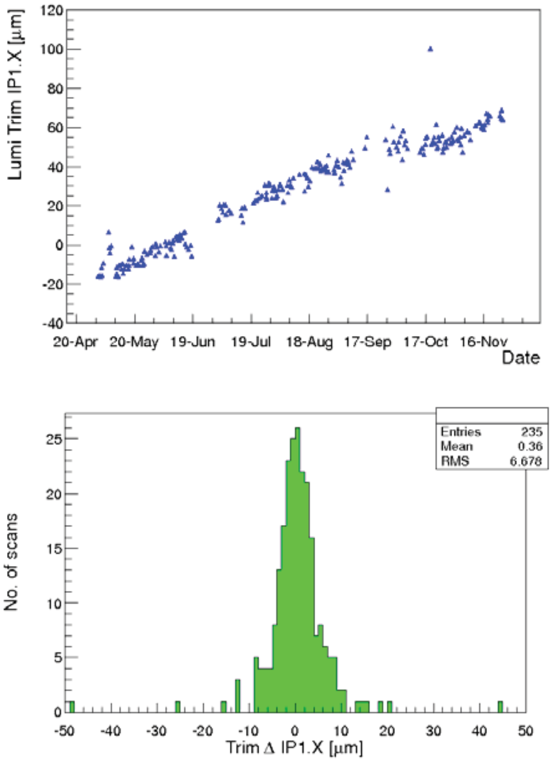

Figure 5: (top) Horizontal orbit stability in IP1 along the year (bottom) Corresponding fill to fill orbit shift in um over the year

Status of interlock BPMs

In order to ensure a safe extraction trajectory into the dump lines, the beam orbit around the extraction septum must stay within ±4mm. A set of 4 BPMs per beam was installed on both sides of the septum, 2 redundant BPMs near TCDQ and 2 near preceding quadrupole, Q4. Their positions have a 90° phase advance to minimise the possibility of a sudden unforeseen orbit bump. The system must be capable of reacting on a bunch-by-bunch basis since a single high intensity bunch at high-energy can cause damages to the septum. The read-out electronic is based on standard LHC BPM analogue electronics (WBTN), however a dedicated FPGA firmware is used and counts the number of bunches with off-centred positions outside the pre-set limits. The system will trigger a beam dump interlock if the beam conditions match the following scenarios working on two different time scales: a single bunch instability defined as 70 readings outside limits over 100 turns and a fast full beam instability with 250 readings outside limits over 10 consecutive turns. The beam abort is automatically triggered once one of the BPM channels has detected either of these errors.

Unfortunately, the WBTN electronics has a limited dynamic range in terms of bunch intensity as illustrated in Figure 6. As for the standard LHC BPMs, the system operates with 2 sensitivity ranges: High and low sensitivity modes covering respectively the corresponding bunch intensity ranges [2×10^9 - 5×10^{10}] and [4×10^{10} to 3×10^{11}]. The system shows signal quality issues when single bunch have intensity close to either end of the dynamic range. For too low intensity, the WBTN diverges rapidly and provides false BPM readings. For high bunch intensity, the system becomes sensitive to signal reflections and a false bunch count occurs. In both cases the interlocked BPM triggers a dump.

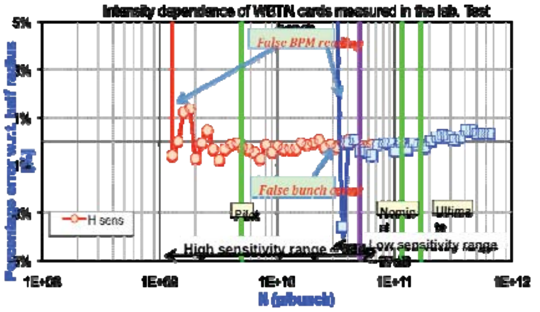

Figure 6 : Bunch intensity dependency of the WBTN

In 2012, the system suffered from several false dumps. Removing cable attenuation has allowed the system to reach 2×10^{10} in low sensitivity, which was an acceptable scenario to optimize for the proton-proton physics fill integrated luminosity. However, for heavy ions, the current settings were not adequate and required modifications. Finally non-linearity effects systematically dumped the ion fills once a single bunch reached ~3×10^9.

During the long shutdown, several actions have been initiated to address these issues. We are studying the possibility to cover an extended dynamic range by reducing spurious reflections. To improve the tuning of the two sensitivity modes and provide the best flexibility for operational reasons, a DAC would be implemented to remotely control the threshold of the comparators.

Alternative acquisition electronics are also under investigation (e.g. analog divider scheme for normalization). An improved version of the firmware will be commissioned to provide more diagnostics for the system.

TUNE AND TUNE FEEDBACK

Since the very early beams in 2010, the tune monitor and feedback have been fully operational. They have however encountered several limitations due to their interaction with other systems like the transverse damper operating at very high gain and the sensitivity of the quench protection system to (too) large trim request [4]. The latter one was partially addressed by reducing the speed and the gain of the tune feedback.

Gated tune monitor

The incompatibility between the transverse damper operating at high gain and the tune monitor has been a serious limitation for the beam operation. During the fill, one has to choose between high damper gain to control beam instabilities or reliable tune signals.

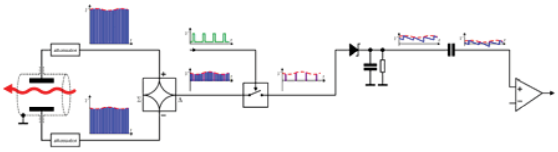

Figure 7: Schematic of the Gated BBQ system

A solution was found during summer 2012 based on the development of a new tune front-end, which enables gating on bunches for which the damper operates at lower gain. The system, as depicted in Figure 7, processes the electrodes signals using a hybrid to reduce the signal amplitude, an RF switch for gating and a normal BBQ front end [3] as a peak detector. After the success of the first prototype, the system was quickly made operational as shown in Figure 8.

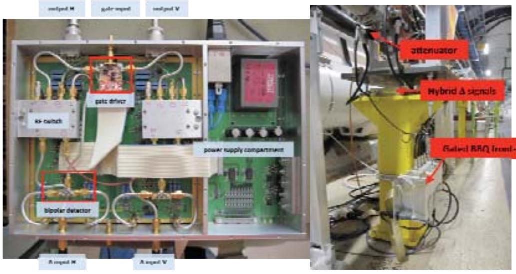

Figure 8: Picture of the Gated BBQ and its implementation in LHC Tunnel

During the long shutdown, two additional strip-lines will be installed to extend the current operational system, providing measurements in parallel in order to fulfil the different functionalities as required by operation: like pilot and high intensity bunches, the gated BBQ and coupling measurement. Some operational software development is required to exploit the full functionality of nominal and gated BBQ, with a GUI for bunch selection and bunch scans display.

Status of Schottky monitor

During the last 3 years, the LHC Schottky monitors [10] were able to provide high-level Schottky signals on all ion fills, for B1H, B1V and B2H, providing reliable single bunch measurements for the tune [11] and with some limitations also for the chromaticity measurements as visible on Figure 9.

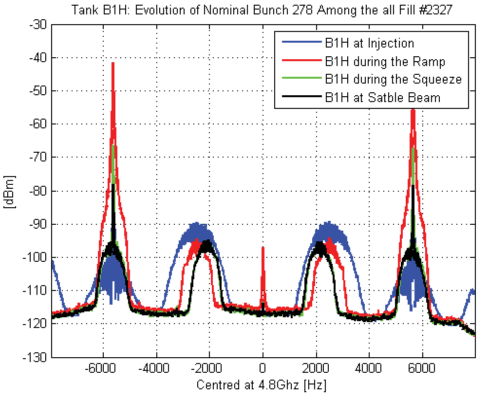

Figure 9: Schottky signals with ions

With Protons, the Schottky transverse signals are still acceptable on the B1H system, for single and multi-bunch measurements at injection and at stable beam. However, the too large coherent signals saturate the pre-amplifiers on the other systems. On one monitor, (B2H), the pre-amplifiers was damaged. A modification on the gating scheme of the B2V pick-up has led to a significant reduction of the coherent signal peaks, but no improvement of the transverse Schottky signal bumps was observed.

During the long shutdown, an overhaul of the pick-ups has been organised and all Schottky tanks will be removed from the beam line. Preliminary RF simulations demonstrate a reduction of the signal reflections with the pick-up system is necessary. This includes a better matching between the slotted and un-slotted waveguide, as well as for the waveguide-to-coaxial transition. New RF mechanics have to be manufactured and mounted on the monitors. Systematic RF measurements on a test bench with stretched wire measurements will be performed with the aim of controlling and improving the symmetry of opposite electrodes, e.g. lowering the tolerances. All internal SiO2 coaxial cables will all be replaced as some are found to be not vacuum-tight.

The RF signal processing will also be redesigned with modifications of the gating and a new RF input filter to better cope with 25 ns bunch spacing, while improving the S/N ratio.

The control and software requires some development as well. The RF attenuators and phase shifters must become remotely controllable. Requirements for the operational java GUI, which requires a complete redesign, is being specified.

DETECTION OF TRANSVERSE INSTABILITIES

Observation of instabilities in 2012 relied mainly on BBQ spectra and transverse damper (ADT) activity.

The LHC head tail monitors using fast sampling oscilloscopes (8-bits ADC) are limited to the detection of 100um oscillation amplitudes and limited in on-board memory. During summer 2012 a Multi-band Instability Monitor (MIM) was developed. It is using a set of RF band-pass filters and high sensitivity diodes, similar to the one used in BBQ. A prototype, as presented in Figure 10, was realized and tested successfully on the SPS and LHC. The monitor is processing the position signals coming from a Δ-hybrid mounted on a strip-line BPM. The signal is split into 5 frequency bands, each measured simultaneously by diode detectors: no filter and respectively 0.4GHz, 0.8GHz, 1.2GHz and 1.6GHz filters.

Figure 10: MIM tested in 2012 on SPS and LHC

When a beam instability occurs, the MIM provides the relative amplitude of the beam position oscillations in the different frequency bands, which then can be related to a specific instability mode. In Figure 11, data acquired with MIM clearly shows a strong activity at 400MHz, not visible in the unfiltered channel, which would indicate the presence of a head-tail instability mode with m≥1.

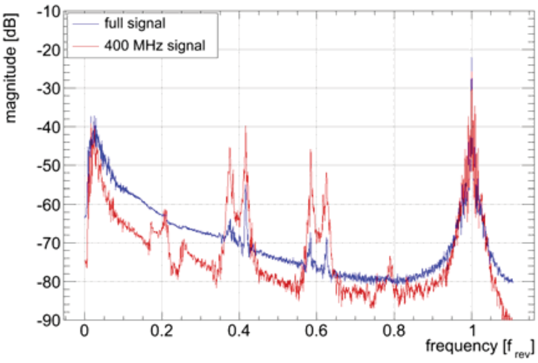

Figure 11: RF signals measured by the MIM in two frequency bands: full bandwidth and using a 400MHz band-pass filter

CONCLUSION AND PERSPECTIVES

The LHC BPM system has operated very reliably over the last 3 years. Several modifications are however under implementation to improve the performance of the system. Water-cooled racks will be installed to control the temperature in the VME crate and to provide a better long–term stability of the resulting position data. A new non-linearity correction algorithm will be implemented to minimize the errors caused by for off-centred beams. The interlocked BPM system will be revisited with the aim of increasing its dynamic range. Finally, the high-resolution diode orbit observation system will be deployed for some critical BPMs in the LSSs.

The orbit and tune feedback system will be reviewed during the long shutdown with the aim of improving its reliability and knowledge base.

The recently developed tune monitors based on gated BBQ have overcome most of the operational limitations of the previous system. After the long shutdown the tune system (hardware and software) will be made fully operational with multiple tune monitors adapted to the operational needs (pilot bunch, gated tune for feedback, coupling measurement and single bunch tune scan).

The Schottky monitors will undergo a complete system overhaul with improvements planned on pick-ups, front-end electronics and software. The goal is to make them operational with protons after the long shutdown.

The observation of beam instabilities in the LHC is crucial and clearly requires new hardware/software developments. A discussion is currently on-going to define the needs in terms of beam instruments and look into what is technically achievable (BBQ, HT monitor, MIM, ADT monitor). A coherent plan will be proposed ensuring that, when operation resumes, adequate monitors are made available.

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