BUNCH-BY-BUNCH CHARGE, POSITION, AND PHASE DIAGNOSTICS USING AN OSCILLOSCOPE-BASED ANALYSIS FOR ALBA

J. Bañuelos[*], U. Iriso, ALBA Synchrotron, Cerdanyola del Vallès, Spain

Abstract

The ALBA synchrotron is preparing its upgrade to ALBA II, a fourth-generation storage ring that will require improved bunch by bunch beam diagnostics in order to fully characterize the beam. To meet these requirements and based on the analysis developed using the HOTCAP code [1], we are integrating an oscilloscope-based analysis tool that processes BPM signals to extract bunch-by-bunch charge, transverse position, and relative measurement of the longitudinal phase. This report summarizes how the tool has been adapted for ALBA. We show results using this method and compare them with other techniques.

INTRODUCTION

ALBA is currently going to an upgrade called ALBA-II [2], where the beam energy is kept at 3 GeV, but the emittance is reduced to 200 pm. The machine upgrade has to comply with several constraints imposed by the decision of maintaining the same circumference (269m), The RF system will be preserved, retaining the six 500 MHz cavities and adding a new third-harmonic cavity (3HC) to lengthen the bunch and improve lifetime [3]. ALBA-II imposes certain performing challenges, which would highly benefit from a bunch-by-bunch diagnostics systems. These effects can be both in the transverse plane (like ion trapping or couple bunch instabilities) and longitudinal plane (like transient beam loading). This report shows an oscilloscope-based acquisition of BPM signals [4], providing a flexible approach for this fast diagnostics and allowing a direct digitization with high bandwidth and sampling rate without dedicated hardware. For a 500 MHz RF system, this requires GHz-class bandwidth and multi-GS s^{-1} to resolve sub-nanosecond BPM signals. We show how this method is implemented at ALBA to extract bunch-by-bunch charge, transverse position, and longitudinal phase from BPM signals. The method is first validated under nominal operating conditions and then used for beam-dynamics studies including tune measurements, beam-loading effects, and RF transients.

MEASUREMENT SYSTEM

The experimental setup relies on commercial instrumentation and is shown in Fig. 1. It consists of a BPM pickup connected through coaxial cables to a high-bandwidth scope (6 GHz, 16 GS s^{-1}), where the four button signals are directly digitized. The acquired waveforms are then transferred to a computer for offline processing and parameter extraction. In this case, the scope is the 4 channels 6 GHz Keysight scope (MXR604B). Precise matching between cables is performed in this process, so there is no need for dedicated hardware synchronization. At ALBA, the revolution period is 896 ns. Acquisitions are typically performed over time windows in the range of 2–10 ms at a sampling rate of 16 GS s^{-1}, corresponding to several thousand turns per acquisition. This results in waveform sizes of hundreds of mega-samples and therefore large datasets, for which the data processing becomes computationally demanding.

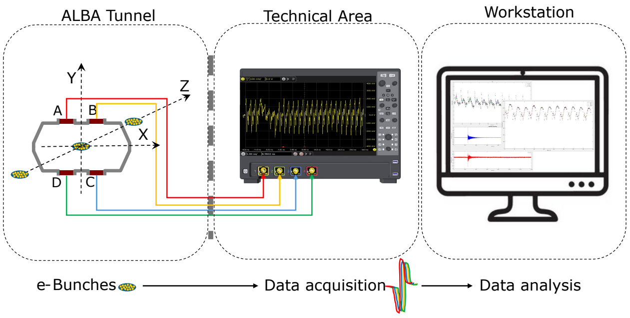

Figure 1: Schematic of the BPM-based acquisition system. The four button signals are directly digitized by the scope and processed offline.

METHOD VALIDATION

The method is thoroughly described in [4]. Briefly, the four signals from the BPM electrodes are acquired using a broadband oscilloscope during *sim*thousands of turns. From multiple turns, a response function (look-up table, LUT) is reconstructed for each bunch and electrode, achieving an equivalent resolution of 0.1 ps. Figure 2 shows a typical response function for one bunch of the LUT using this 3DBPM method, compared with the 6 GS/s raw signal obtained from the fast scope.

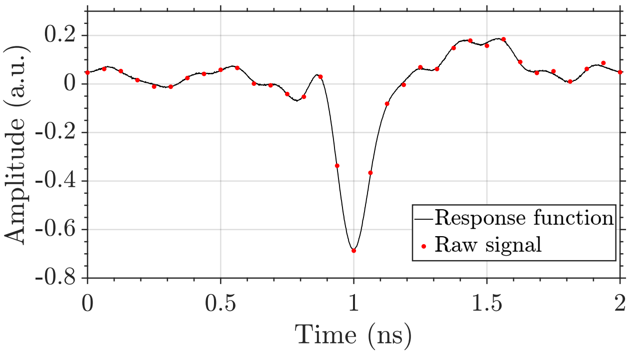

Figure 2: Response function of a bunch passing trough the electrode (bipolar pulse,2 ns duration) reconstructed from multiturn data. Compared with the raw signal (normalized) of the same bunch.

For each of the four BPM channels, the peak-to-peak amplitude of the reconstructed bunch response function is

---

[*] jbanuelos@cells.es

measured. The sum of these four amplitudes is a relative measurement of the bunch charge, which is then calibrated against the total beam current measured by the DCCT. Figure 3 compares the bunch current obtained with this method with the Time-Correlated Single Photon Counting system [5]. Both methods agree within 1%.

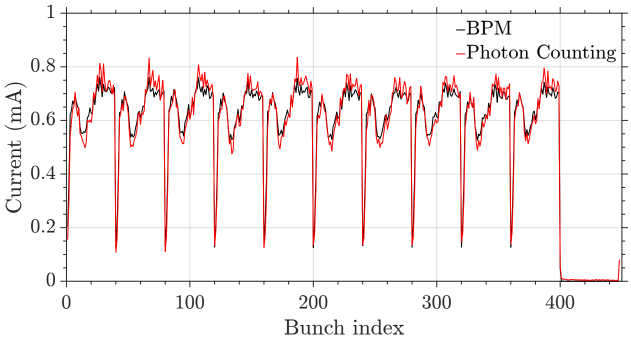

Figure 3: Bunch-by-bunch current distribution measured with the oscilloscope-based method compared with the Time-Correlated Single Photon Counting system.

Next, the reconstruction of the transverse position of all filled bunches on every turn is determined by first inferring, for each of the four buttons, the signal amplitude via correlation with the corresponding response function [4]. The four amplitudes are then combined using the well-known ”Delta over Sum” technique.

Figure 4 shows horizontal and vertical transverse positions during an injection, for all bunches and over ∼1.5 thousands turns. Note that bunches between 0-40 have a larger residual oscillations than the rest. This is a consequence of the ALBA injection system, where the bump kick drifts from 40 bunches at each injection-shot: in this case, this acquisition corresponds to an injection between bunches 0-40. Therefore, these bunches receive a larger kick and so their oscillations are larger in both hor and ver planes.

In addition to the transverse information, the same analysis method can be used to reconstruct the longitudinal coordinate from the BPM signals. This is inferred from the bunch LUT by finding the zero-crossing between the negative and positive peaks of the bipolar signal (see Fig. 2 and Ref. [4]). Due to the high sampling interpolation, the resolution is in the order of 0.1 ps. Figure 5 shows the result of the relative centroid phase, which corresponds to the relative longitudinal position (in other words, it corresponds to the bunch synchronous phase, relative to the RF reference). This completes the three-dimensional (3D) description of the beam.

The bunch-by-bunch transverse position data acquired during the injection transient enable the extraction of betatron oscillations for each individual bunch. By computing the FFT to the turn-by-turn position of each bunch, the horizontal and vertical betatron tunes Q_x and Q_y are obtained. They can be correlated with the bunch charge obtained within the same data set. This is shown in Fig. 6, showing that while the hor tune is constant, the ver tune shows a small detuning with the bunch charge (see the slight slope for the ver plane).

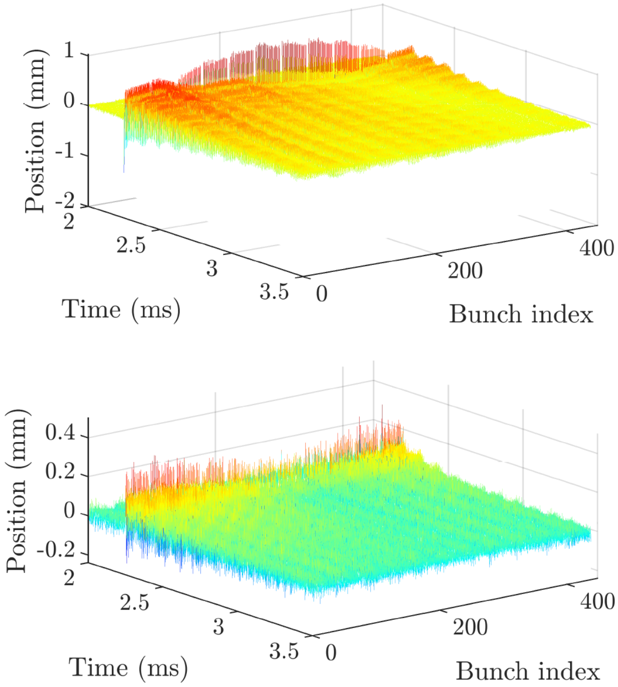

Figure 4: Transverse beam position during horizontal injection. The data correspond to the injected bunches for all turns, showing the evolution of horizontal (top) and vertical (bottom) orbits.

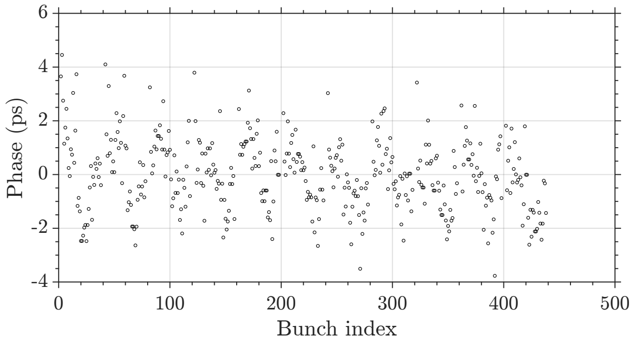

Figure 5: Longitudinal phase (relative centroid phase) of each bunch obtained from the zero-crossing of the reconstructed response function.

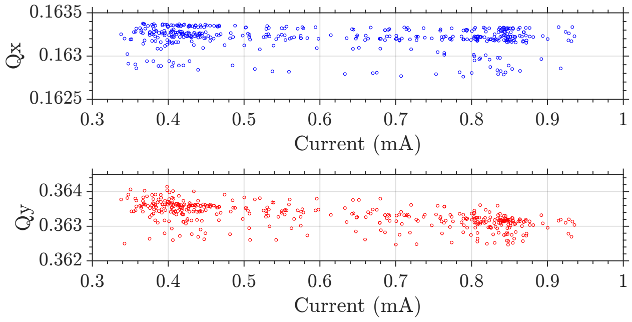

Figure 6: Dependence of transverse tunes Q_x and Q_y on bunch current.

APPLICATION EXAMPLES

The BPM-based analysis provides access to additional beam-dynamics observables. In this section, the method is

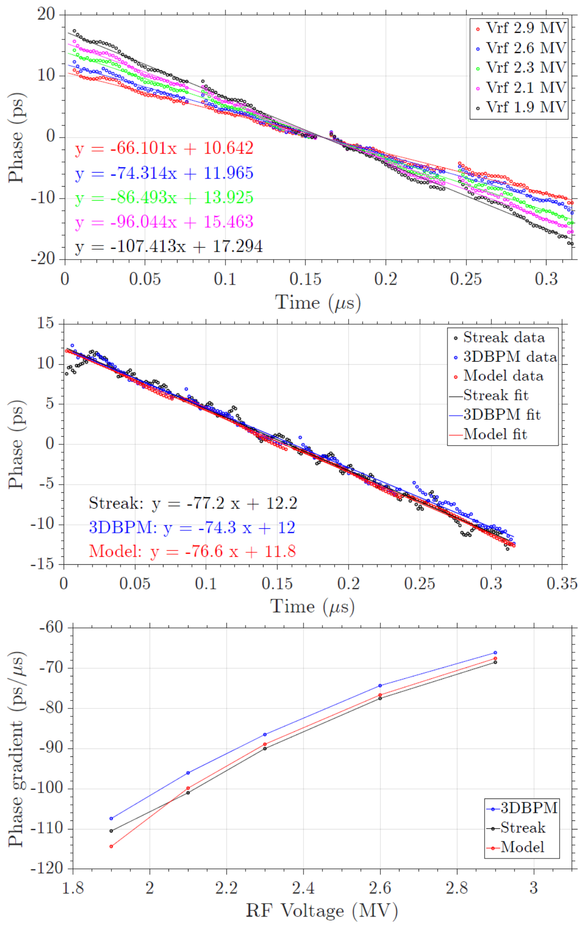

Figure 7: Bunch-by-bunch phase for different RF voltages under 1/3 filling pattern (top). Phase comparison with SC and TBL for 2.6 MV RF (middle). Phase gradients relative to the accelerating RF voltages (bottom).

applied to beam-loading and RF-transient studies. To evaluate the capability of the method to analyze transient beam loading effects (TBL), we perform measurements at 150 mA using a 1/3 filling pattern (160 consecutive bunches, i.e. a consecutive filling during 320 μs), and different RF voltages (Fig. 7, top). At ALBA, this analysis has traditionally been carried out with a streak camera (SC) by tracking the bunch centroid evolution [6, 7]. Figure 7 (middle) shows the good agreement between the scope-based method, the SC, and the TBL model for one rf voltage. This is further stressed in Fig. 7 (bottom), which compares again with the phase gradient for different rf voltages obtained with the 3DBPM, the SC, and the model, showing a good agreement between the three methods and validates the TBL studies in [8].

Finally, to study the longitudinal beam dynamics under an RF perturbation, a transient experiment was performed by switching off one of the six ALBA RF cavities. The evolution of the bunch phase oscillations is compared with Low-Level RF (LLRF) signal [9]. Following the cavity switch-off, a transient response is observed with an initial phase overshoot followed by damped synchrotron oscillations that evolves toward a new equilibrium phase defined by the reduced RF voltage (Fig. 8). The agreement between both the LLRF and the data with the 3DBPM is very good.

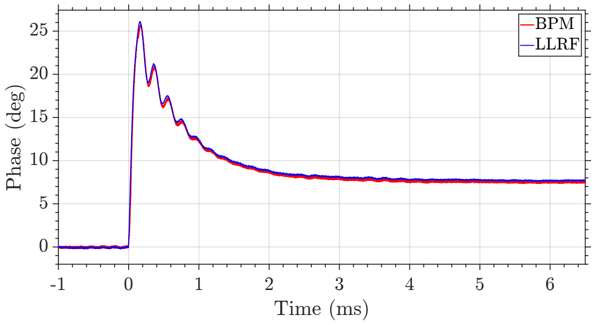

Figure 8: Transient longitudinal phase evolution after RF cavity switch-off, compared with ALBA LLRF.

SUMMARY

An oscilloscope-based bunch-by-bunch diagnostic system has been implemented at ALBA for beam characterization. The method processes BPM signals acquired with an oscilloscope to extract bunch-resolved charge, transverse position, and longitudinal phase without a dedicated synchronization hardware. Under nominal conditions (440 bunches, 250 mA), it reproduces the bunch charge distribution and enables turn-by-turn transverse analysis, from which normalized betatron tunes Q_x and Q_y are obtained on a bunch-by-bunch basis. The synchronous phase reconstruction extends the analysis to longitudinal dynamics, providing a three-dimensional description of the beam motion. Beam loading measurements using a 1/3 filling pattern and different RF voltages show clear phase gradients along the bunch train. Finally, the evolution of the transient longitudinal phase during an RF trip has been captured showing a very good agreement with the LLRF data. These results demonstrate a flexible BPM-based tool using a fast high sampling oscilloscope for bunch-by-bunch diagnostics in both the longitudinal and transverse plane.

ACKNOWLEDGMENTS

Authors warmly thank the ALBA RF group, in particular I. Bellafont, for support with the TBL analysis, and thank Y. Leng for providing the HOTCAP code and his help.

REFERENCES

[1] X.-Y. Xu *et al.*, “HOTCAP: a new software package for high-speed oscilloscope-based three-dimensional bunch charge and position measurement”, *Nucl. Sci. Tech.*, vol. 32, no. 11, p. 119, 2021. `doi:10.1007/s41365-021-00966-z`

[2] F. Pérez *et al.*, “ALBA II accelerator upgrade project status”, in *Proc. IPAC’24*, pp. 1220–1223, 2024. `doi:10.18429/JACoW-IPAC2024-TUPG02`

[3] F. Pérez *et al.*, “3HC: third harmonic normal conducting active cavity collaboration between HZB, DESY and ALBA”, in *Proc. IPAC’22*, pp. 1471–1474, 2022. `doi:10.18429/JACoW-IPAC2022-TUPOMS028`

[4] X. Xu, Y. Leng, Y. Zhou, B. Gao, J. Chen, and S. Cao, “Bunch-by-bunch three-dimensional position and charge measurement in a storage ring”, *Phys. Rev. Accel. Beams*, vol. 24, no. 3, p. 032802, 2021. `doi:10.1103/PhysRevAccelBeams.24.032802`

[5] L. Torino and U. Iriso, “Time correlated single photon counting using different photon detectors”, in *Proc. IBIC'16*, 2017. `doi:10.18429/JACoW-IBIC2016-MOPG59`

[6] U. Iriso, “Streak camera measurements at ALBA: bunch length and energy matching”, in *Proc. IBIC'12*, paper TUPA46, 2012. `https://proceedings.jacow.org/IBIC2012/papers/tupa46.pdf`

[7] A. A. Nosych, B. Bravo, and U. Iriso, “Energy loss measurements with streak camera at ALBA”, in *Proc. IBIC'18*, pp. 548–551, 2019. `doi:10.18429/JACoW-IBIC2018-THOB02`

[8] I. Bellafont, “Study and mitigation of transient beam loading in the double RF system of ALBA II”, unpublished.

[9] A. Salom and F. Pérez, “Digital LLRF for ALBA storage ring”, in *Proc. EPAC'08*, paper TUPC148, 2008.