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Local Impedance Measurements at ALBA from Turn-by-Turn Acquisition

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INTRODUCTION

Transverse coupling impedance plays a steadily growing role in the landscape of synchrotron light sources, where new designs require small sized beam pipes, complex geometrical transitions, as required by in-vacuum insertion devices, and the use of multilayer materials as in the case of metal coated ceramic beam pipes or non-evaporable getter coating (NEG) [1–3]. All such elements contribute to the machine impedance budget and participate in defining the transverse stability region of the beam. The ability to directly measure the contribution of different impedance sources provides a valuable tool not only to verify the results of the design process, but also make it possible to directly characterize the behavior of such structures.

In order to discern the contribution of different impedance sources, a transverse optics measurement techniques can been exploited. In fact a transverse impedance source manifests itself by affecting the beam with a transverse defocusing kick, whose strength depends among the other things on the bunch charge and results in a small optical function distortion. Measurement techniques can exploit two main approaches: closed orbit measurements and turn-by-turn measurements. While the first one has been the choice of reference in the light sources world, e.g. Diamond and APS [4, 5], the turn-by-turn approach has been mostly applied to larger machines, as in the case of SPS or LEP [6–8]. The reason being mainly related to the intrinsic difficulties to carry out turn-by-turn measurements with an adequate degree of accuracy to observe the faint optics distortion produced by smaller impedance sources as those one found in a light source.

Turn-by-turn beam position data are especially well suitable for fast non-intrusive linear optics measurement, providing a direct assessment of optical functions at the beam position monitor (BPM) with no need for manipulation of any magnetic element.

Taking advantage of the turn-by-turn capabilities of the last generation BPMs, we applied successfully the turn-by-turn technique to estimate the major contributors to the impedance budget in the ALBA synchrotron light source. Furthermore we found how smaller impedance sources can still be precisely characterized recurring to a lattice manipulation in order to boost on purpose the effect of such faint kicks.

TRANSVERSE COUPLING IMPEDANCE AND BETATRON MOTION

The electromagnetic interaction between a charged beam and the surrounding environment produces a small linear optics distortion of the lattice. The linear dependency of such an optic distortion on the bunch charge provides the key to disentangle the impedance induced effects from the overall machine optics.

The equivalent defocusing kick per unit length, produced by a transverse coupling impedance source $Z^{eff}_{\mathrm{H,V}}$ on a ultra relativistic bunch of particles with Gaussian longitudinal profile, is given by:

$$\Delta K_{\mathrm{H,V}} = -\frac{N_p q^2}{E_0} Im(Z^{eff}_{\mathrm{H,V}}) \frac{1}{2\sqrt{\pi}\sigma_\tau}, \quad (1)$$

where N_p is the number of particles in the bunch, q the charge of each particle, σ_z is the Gaussian bunch length and the subscripts H, V stand for horizontal or vertical plane.

Note that for asymmetric structures, the quadrupolar-like kick has different strength on the vertical and horizontal planes. This is the case of synchrotron light sources, where an extensive use of flat beam pipes and the presence of many insertion devices can easily lead to a rather significant overall effect on the vertical plane, while on the horizontal plane it is usually negligible. For this reason only the effect on the vertical plane has been covered in this paper.

The coherent betatron oscillation of a particle beam excited in a storage ring by means of a fast transverse dipole kick can be expressed in terms of two position dependent functions: the betatron amplitude $\beta_{\mathrm{H,V}}(s)$, and the betatron phase $\psi_{\mathrm{H,V}}(s)$. An expression for the transverse beam motion is given by:

$$X_{H,V} = \sqrt{\beta_{\mathrm{H,V}}(s) J_{\mathrm{H,V}}} \cos(\psi_{\mathrm{H,V}}(s) + \phi_{\mathrm{H,V}}), \quad (2)$$

where $J_{H,V}$ is the Courant-Snyder invariant and $\phi_{H,V}$ is an initial phase. The betatron amplitude and phase are both determined by the overall machine optics, therefore they are good candidates to probe the linear focusing distortion due to the transverse coupling impedance. On the other hand since only the measurement of the betatron phase provided satisfactory results, the betatron amplitude measurements has been discarded in the following analyis.

Given a nominal model for the machine optics, a quadrupolar kick of integrated strength ΔK produces a distortion of the phase of the form [6, 9]:

$$\Delta\psi_{H,V}(s) = \begin{cases} \dfrac{\beta_{H,V}(s_k)\Delta K}{2}\left(1 + \dfrac{\cos(2\psi_{H,V}(s_k) - \psi_{H,V}(s))\sin(\psi_{H,V}(s) - 2\pi Q_{H,V})}{\sin(2\pi Q_{H,V})}\right) & \text{if } s \geq s_k \\ \dfrac{\beta_{H,V}(s_k)\Delta K}{2}\dfrac{\sin(\psi_{H,V}(s))\cos(\psi_{H,V} - 2\psi_{H,V}(s_k) + 2\pi Q_{H,V})}{\sin(2\pi Q_{H,V})} & \text{if } s \leq s_k. \end{cases} \quad (3)$$

In this case, s_k is the quadrupolar kick position and $Q_{H,V}$ are the machine tunes. The phase beating produced by the defocusing kick are proportional to $\beta_{H,V}(s)$ at the kick location (Eq. 3), therefore the contribution to the optics distortion of impedance sources located at small $\beta_{H,V}$, as in the case of the insertion device vacuum chambers in the light sources, is strongly suppressed. On the other hand a larger weight is given to impedance sources located at high $\beta_{H,V}(s)$ values, like in the case of the injection kickers. Figure 1 shows the location of the main contributors to the ALBA impedance budget along with the nominal betatron functions. Note that due to the difference β_y values, a similar impedance produces a larger effect in the injection section (i.e., s=0) than in the locations designed for insertion devices (i.e., s=15, 32, 50 m).

Once the phase beat has been measured a simple linear regression is adequate to disentangle the effect of multiple and distributed impedance sources. For this purpose we proceeded by creating a simulated response matrix M containing the expected phase beat resulting from a defocusing kick located at each one of the different impedance source. The inverted matrix M^{-1} has been obtained from M by means of singular value decomposition. Given a set of measured phase variations $\Delta\vec{V}$ the strength of each impedance source $\vec{Z}$ is reconstructed as:

$$\vec{Z} = M^{-1}\Delta\vec{V}. \quad (4)$$

EXPERIMENTAL SETUP

ALBA is a third generation synchrotron light source equipped with several insertion devices, some of which make use of flat NEG coated beam pipe, and a four kickers injection system using titanium coated ceramic beam pipe among other elements. Along with the standard beam pipe, these devices account for most of the total transverse impedance budget.

A fast magnetic kicker along with 120 BPMs equipped with "Libera Brilliance" electronics [10] made it possible to carry out good quality turn-by-turn observations. The setup of the BPMs resulted to be one of the most critical

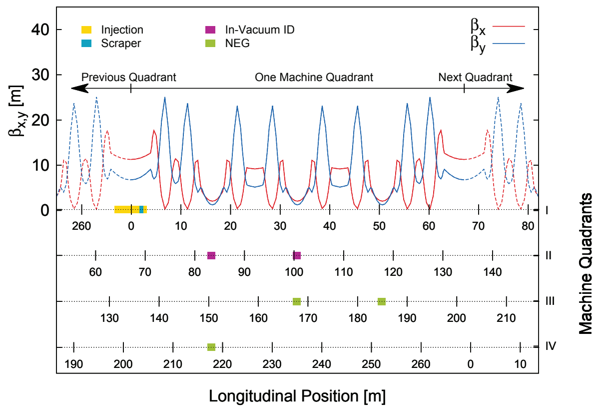

Figure 1: Beta functions and location of the major transverse impedance sources in the ALBA storage ring. The ring nominal lattice has a four fold symmetry, where each quadrant is composed by two Chasman-Green cells surrounded by two matching cells. The injection section is sandwiched in between two matching cells where the vertical beta function reach higher values.

steps, requiring a great deal of work before it was possible to collect proper turn-by-turn measurements. In fact in order to reach the temporal resolution required to discriminate the beam position on a turn-by-turn basis it was necessary to replace the slow time constant used in the default firmware provided by the BPM manufacturer with a new one [11, 12] where a finite impulse response filter of the moving average window type is used.

Two different filling patterns are required for the measurement process, one containing only low charge bunches and one containing only high charge bunches. We decided to keep the overall amount of charge equal for both configurations, in order to reduce the effects related to the non perfectly flat charge response of the BPMs. Bunches have to be organized in a short train in order to fit the kicker pulse length and ensure an equal excitation amplitude along the

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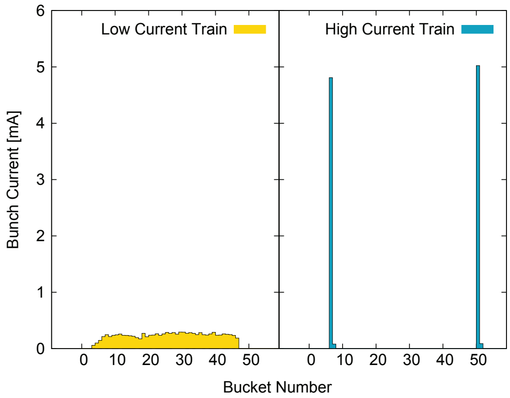

Figure 2: The two filling patterns required for the measurements. A low current filling pattern (left) composed by a train of 45 buckets, each one filled with 0.10 nC on average. A high current filling pattern (right) composed by only two bunches carrying around 4.4 nC each. Only the first 50 buckets out of the total 448 are shown.

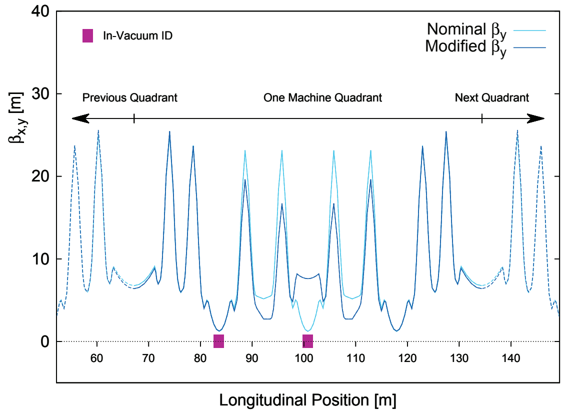

Figure 3: Vertical beta functions for the nominal and modified ALBA lattices. The vertical beta function has been increased from 1.2 m to 6.4 m at the location of one in-vacuum insertion device.

train itself. While in the low charge case, it is possible to employ a short train where all the buckets are filled with a small amount of charge, the same does not apply for the high charge case where wake field interaction can cause instabilities in the trailing bunches. Figure 2 shows an example of the two employed filling patterns, the low charge one made of a train of 45 bunches ~0.10 nC on average and the high charge one made of only two bunches around ~4.4 nC each, 90 ns apart.

LOCAL IMPEDANCE MEASUREMENT

Phase advance measurements have been acquired alternating the high and the low charge filling patterns (Fig. 2). Phase beat is extracted and the intensity of the kick due to each different impedance source reconstructed by means of a linear regression as explained before.

Since the impedance kicks provided by the insertion devices are strongly suppressed by the small values of the vertical beta function at their location, the nominal lattice has been detuned by increasing the vertical beta function by a factor 5.2 at the location of one of the insertion devices (Fig. 3) [13]. The increased value of the beta function simplifies strongly the characterization of the insertion device impedance.

Figure 4 shows the results of the measurements for the two different lattices under examination. In the case of the nominal lattice only the beam pipe and the injection section were fitted since all the other sources did not provided a significant contribution, while in the case of the high vertical beta lattice also the insertion device corresponding to the high beta location was added.

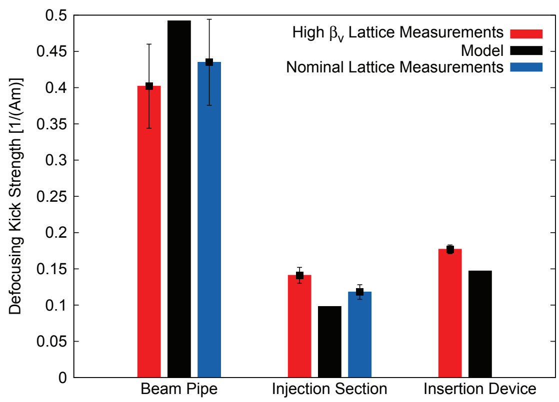

Figure 4: In blue the defocusing kick strength measured with the nominal lattice including: the beam pipe and the injection section. In red the results for the modified lattice including: the beam pipe, the injection section and the in-vacuum insertion device located at the high vertical beta straight section. Error bars represent the shot to shot fluctuation of the measurement expressed as one standard deviation. In black the predicted value from theoretical simulation.

CONCLUSIONS

A satisfactory agreement was found between the two different sets of measurements and the theoretical values obtained from Gdfidl electromagnetic simulations and analytical calculation [14, 15]. proving the reliability of turn-by-turn measurements as a tool to investigate small optical distortion and in particular to the assessment of small impedance induced defocusing kicks.

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