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FAST QUADRUPOLE BEAM BASED ALIGNMENT USING AC CORRECTOR EXCITATIONS

Z. Martí*, G. Benedetti, U. Iriso, ALBA-CELLS Synchrotron Radiation Facility,
Carrer de la Llum 2-26, 08290 Cerdanyola del Vallés, Spain

Abstract

The 10 kHz fast acquisition BPMs together with an AC excitation of the corrector magnets allow to speed up the beam based alignment process at ALBA. The former approach relies on software synchronization and tango device servers to execute a series of DC corrector magnets and quadrupoles settings designed to avoid the quadrupole hysteresis effects. The approach that we present here is simpler, gives the same level of accuracy and precision and speeds up the measurement by a factor 30. The total measurement time has changed from 5 hours to 10 minutes.

INTRODUCTION

Aligning the beam through the center of the magnetic elements is a necessary task in any accelerator in order to minimize the multipole feed down effect, through which for instance quadrupole magnets introduce beam orbit errors, and also sextupoles may produce beam linear optics and coupling errors. The Beam Based Alignment (BBA) reduces the required strength to correct these errors, and furthermore it reduces the deviations from the accelerator model in the machine. This paper presents a method to align the beam through the center of the quadrupole magnets.

Two different quadrupole BBA techniques are described in the literature. Either the position of the beam at the quadrupole is measured [1–4] or the reading of the adjacent BPM when the beam goes through the center of the quadrupole is measured [5–7]. The first technique is known as *beam-to-quad* while the second is known as *beam-to-bpm*.

The beam-to-quad technique relies on the accelerator model knowledge (tunes and optical functions) to fit the orbit distortion produced by an small quadrupole strength change. This technique does not provide the BPM offsets, but they can be interpolated between the quadrupoles whose beam-to-quad has been measured. Since the measurement relies on the accelerator model, the orbit has to be corrected and the magnet set point has to be readjusted after every measurement to avoid hysteresis effects.

The beam-to-bpm technique does not rely on the accelerator optics model but it needs to scan one or several correctors for a given quadrupole change, and so this technique requires quadrupoles with individual power supplies. This is usually much more time consuming and it may give inaccurate results if the beam has a pronounced angle at the quadrupole (for instance, when the nearby CMs have an strong effect).

The beam-to-bpm technique has been used at ALBA since its commissioning phase [8]. It is rather slow since it involves scanning one orbit corrector magnet (CM) for every magnetic element to be aligned and also changing its setting. A complete measurement of the two planes for the 120 BPMS takes 5 hours. A faster version is presented in this paper using an AC excitation of the CMs [9] and the 10 kHz BPM acquisition rate [10], which in the case of ALBA decreases the measurement time by a factor 30.

NEW ALGORITHM

When a CM is powered with a continuous excitation, the BPM readings are linearly related, and changing a quadrupole changes this linear relation. For a given BPM pair, each one of the data sets can be fitted. We show here that offsets of a BPM nearby the changed quadrupole can be determined by calculating the intersection of the two different linear fits.

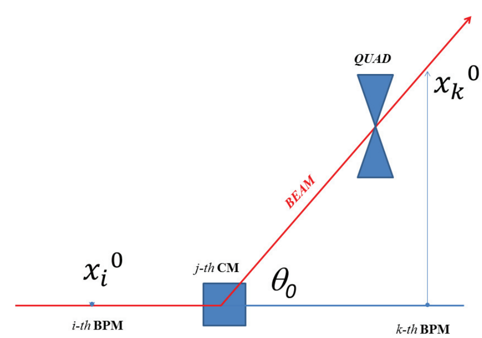

Figure 1: Sketch of the beam closed orbit when passing through the center of the quadrupole to be aligned.

In presence of a time t varying strength $\theta_j(t)$ of the CM "j", the closed orbit readings at the k^{th} and i^{th} BPMs $x_k(t)$ and $x_i(t)$ are related as:

$$\begin{aligned} x_k(t) - x_k^0 &= R_{k,j}\left(\theta_j(t) - \theta_0\right), \\ x_i(t) - x_i^0 &= R_{i,j}\left(\theta_j(t) - \theta_0\right), \end{aligned} \quad (1)$$

where x_k^0 and x_i^0 are the readings of the k^{th} and i^{th} BPMs when the kick produced by the j^{th} CM is θ_0, and $R_{k,j}$ represents the orbit response matrix from position of the j^{th} corrector to the k^{th} BPM. This expression is accomplished for any value θ_0 providing an appropriated value for x_k^0 and x_i^0. However, choosing θ_0 as the value that makes the orbit pass thought the quadrupole center simplifies the following calculations. Note that, as skeched in Fig. 1, x_k^0 corresponds to the BPM reading when the beam goes through the center the nearby quadrupole, which is what we want to find in this

* zeus@cells.es

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analysis. An equivalent analysis holds for both horizontal and vertical plane.

The two lines in Eq. 1 can be combined, which shows that the BPM readings $x_k(t)$ and $x_i(t)$ are linearly related:

$$x_k(t) - x_k^0 = \frac{R_{k,j}}{R_{i,j}}(x_i(t) - x_i^0). \quad (2)$$

Changing the strength of that quadrupole will only change the response matrices in Eq. 2 (at least in the thin lens approximation). Irrespectively of the quadrupole change, equations equivalent to 2 with different quadrupole strengths will only coincide when $x_k(t) = x_k^0$ and $x_i(t) = x_i^0$. For the BPM close to the changed quadrupole, x_k^0 is approximately its offset. Figure 2 shows an example of Eq. 2 with real data taken at ALBA exciting only in the horizontal plane.

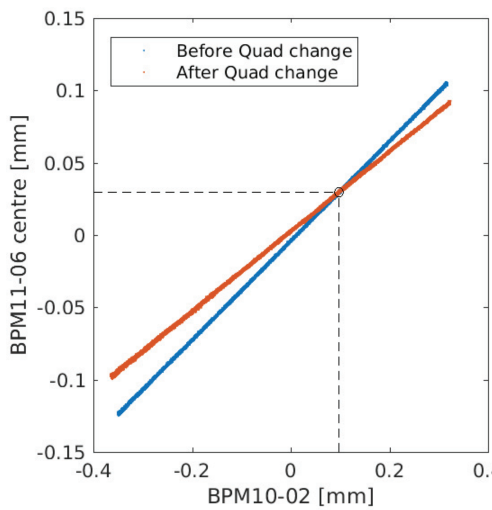

Figure 2: Correlation between the BPMs 10-02 and 11-06 readings before (blue dots) and after (red dots) a quadrupole change during the excitation of CM 01-02 at 7 Hz. The quadrupole is next to BPM 10-02 so the intersection is identified as the BPM offset.

The method speed is further improved by parallelizing the measurement for the two transverse planes. To do that, for a given quadrupole, a vertical corrector and a horizontal corrector are powered with pure sinusoidal signals of different frequencies. This ensures that the corresponding Fourier components of the BPM readings are still related by an Eq. 1 equivalent:

$$\hat{x}_k(t) - x_k^0 = R_{k,j}\left(\theta_j(t) - \theta_0\right). \quad (3)$$

In this case, $\hat{x}_k(t)$ represents the Fourier component at the horizontal corrector frequency of the horizontal readings of the k^{th} BPM (plus the zero frequency component). We have to take into account the effect of the coupled vertical frequency component on both the horizontal frequency component and on the zero frequency component. This is done with an anti aliasing treatment, or alternatively, the measurement time has to be chosen as a multiple of the two corrector periods.

In this case, $\hat{x}_k(t)$ represents a pure sinusoidal signal that fits $x_k(t)$ at the horizontal corrector frequency. The equivalent relation holds in the vertical plane. Following the same steps as for the single plane measurement, intersection of the Fourier components before and after the quadrupole change gives the BPM offset:

$$\hat{x}_k(t) - x_k^0 = \frac{R_{k,j}}{R_{i,j}}(\hat{x}_i(t) - x_i^0). \quad (4)$$

Since the same frequency is used to obtain both $\hat{x}_k(t)$ and $\hat{x}_i(t)$, Eq. 4 corresponds to an straight line.

OPTIMIZING THE EXPERIMENTAL SETUP

The CM waveforms are defined by a series of discrete current set points that are previously loaded in the CMs power supplies. The change between set points can be done as fast as every 80 μs. That waveform is repeated continuously so that the corrector coil current executes a continuous sinusoidal signal. However, if the current change is too steep, the output current may not be able to follow the desired waveform. For this reason, given a waveform frequency, there is a maximum on the effective waveform amplitude that can be reached. Above that maximum, the effective amplitude will stay the same and the output current will not execute a pure sinusoidal signal but a triangular like shape which induces higher harmonics of the desired frequency.

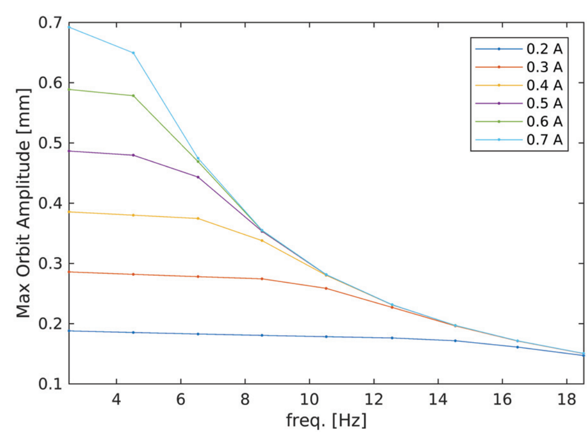

Figure 3: Maximum first harmonic amplitude as a function of the waveform amplitude and the waveform frequency. A very similar behavior is observed in both planes.

Figure 3 shows the BPMs reading average amplitude as a function of the corrector waveform amplitude and frequency. Following the standard BBA at ALBA, we aim to produce orbit excursions of around 0.5 mm. According to Fig. 3 this is only possible below 7 Hz. On the other hand, in the 0 Hz to 15 Hz range, the BPMs noise shown in Fig. 4 decreases strongly as the frequency increases. We found an amplitude of 0.5 A and frequencies 7 Hz and 6 Hz for the horizontal and vertical plane respectively to be a good compromise.

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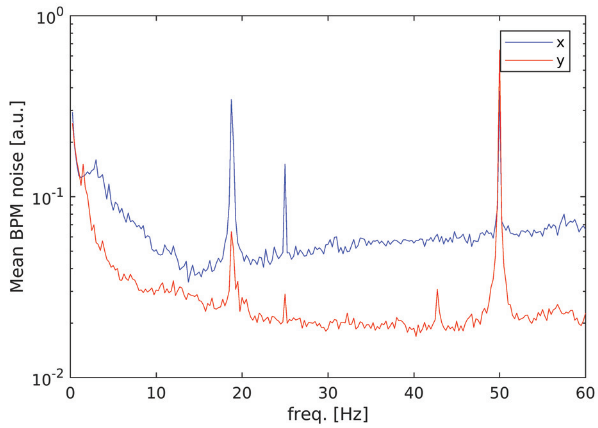

Figure 4: Average BPM noise at 18mA. This the typical beam current for a BBA measurement at ALBA. Notice the sharp noise change at frequencies between zero and 15 Hz.

Notice that some particular frequencies should be avoided in any case (i.e., 18.5 and 50 Hz).

The measurement error for each BPM couple is determined as the distance from the correlation intersection to the point when the separation equals the BPM reading noise previously measured. The final error is the average among the used BPM couples. The BPM couples showing large measurement errors are discarded. The acquisition time is optimized according to that statistical error. A test for a single BPM was done with an acquisition time of 5.5 s. Taking the result with all the 5.5 s as a reference, we can calculate the systematic error induced by reducing the acquisition time. Figure 5 presents such analysis for both the horizontal and vertical plane compared with the statistical error. For acquisition times of around 1 s, the systematic error is already several times smaller than the statistical error.

RESULTS

Following the studies in the previous section, the measurements in Fig. 6 correspond to CMs excited with a frequency of 7 Hz and 6 Hz for the horizontal and vertical plane respectively, with an amplitude of 0.5 A during an acquisition time of ≈1.5 s (for a better data analysis, the measurement time has been chosen as a multiple of the two frequencies, and also an anti-aliasing treatment has been carried out).

Figure 6 shows comparison of the standard BBA and the fast BBA measurements. The error bars correspond to the statistical error measured for each case and technique. The 120 BPMs were measured in both cases, but due to some electronic modifications between the two measurements, only half of them can be compared. The agreement between the standard and FBBA measurements is very good, and it is always within the measurement error bars.

CONCLUSIONS

Using an AC excitation of the CMs and the 10 kHz BPM data acquisition, a new method to align the beam through the center of the quadrupoles around the machine has been developed. The technique speeds up the standard BBA at ALBA by about a factor 30 (10 minutes vs of 5 hours). The results show a very good agreement with the standard method.

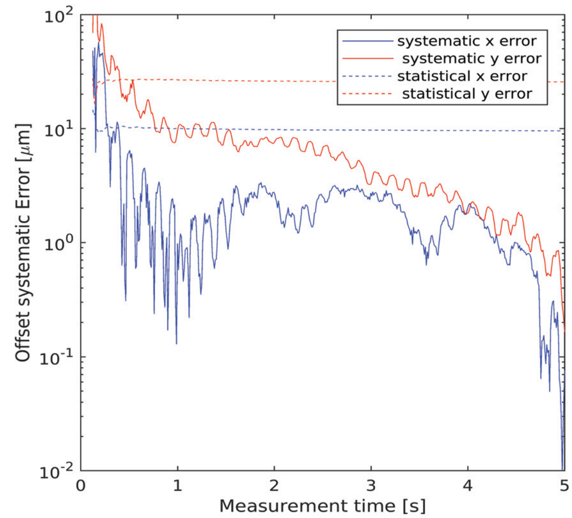

Figure 5: BPM offset noise as a function of the acquisition time. Above 1.5 s, the systematic error (solid lines) due to the acquisition time is several times smaller than the statistical error (dashed lines).

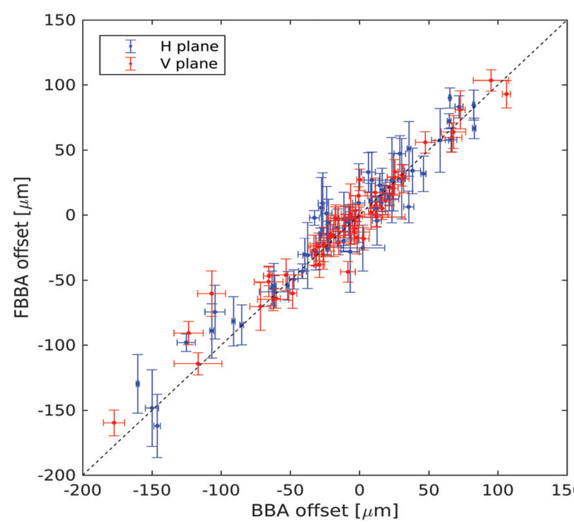

Figure 6: Standard BBA and and FBBA measurements correlation for 60 of the 120 ALBA BPMs. Data of the horizontal plane is represented by blue dots while the data of the vertical plane is represented by red dots. An identity dashed black line has been included as a reference.

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