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# DETAILED CHARACTERIZATION OF ALBA QUADRUPOLES FOR BETA FUNCTION DETERMINATION

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*Abstract*

Beta function value at quadrupoles for a circular accelerator can be determined using the relationship between the machine tune and quadrupole strength variations. ALBA Storage Ring quadrupoles were measured during manufacturing, to be sure that their performance fitted the specifications. However, measurements were carried out at a limited number of current settings and do not allow an accurate determination of the beta function value. In fact, less than 1% error in the calibration of the hysteresis curve slope is required, and therefore new detailed measurements of the hysteresis cycle are needed. In order to make these magnetic measurements, the spare quadrupoles existing at ALBA have been used. In this paper we present the results of beta function values determination using this method for ALBA Storage Ring.

## INTRODUCTION

Linear optic functions like beta functions are a common figure of merit to evaluate the performance of circular accelerators. At ALBA, the beta functions are measured using both an orbit response matrix method and Turn by Turn (TbT) data analysis [1–4]. Despite they agree at the level of $1-2\%$ rms, both methods are limited by characteristic systematic measurement errors.

On one side, the orbit response matrix method, in particular the Local Optics from Closed Orbit, known as LOCO, suffers from systematic errors as it is completely model dependent. As shown in [2] the systematic contribution to the beta beating is around 1% rms.

On the other side, the unknown gains of the BPM during the TbT acquisition can introduce considerable systematic measurement errors. Recently it has been shown that the gain issue may be solved using the phase information of the TbT data, achieving agreements with LOCO around 1% rms [5].

Given the limited accuracy of these two methods, at ALBA it has been decided to measure the beta function values also by measuring the tune changes due to quadrupole change. If the quadrupole integrated strength change $\Delta\, kL$ is small, the tune change can be expressed as follows, [6]

$$\Delta Q_{x,y} = \pm \frac{\left\langle \beta_{x,y} \right\rangle}{4\pi} \Delta k L, \qquad (1)$$

where $L$ is the length of the quadrupole and $\left\langle \beta_{x,y} \right\rangle$ the corresponding plane average beta function along the quadrupole that has been varied. This allows to measure the averaged beta function at each quadrupole. Assuming that the magnet calibration $kL(I)$ as a function of the current set point $I$ is precisely known, Eq. (1) can be expressed as:

$$\left\langle \beta_{x,y} \right\rangle = \pm \frac{4\pi \Delta Q_{x,y}}{\Delta I \partial (kL)/\partial I}, \qquad (2)$$

This well known technique encounters some difficulties:

1. It requires a very good knowledge of the calibration curves of the quadrupoles as it depends on its derivative.
2. The hysteresis effects after the quadrupole change may spoil subsequent measurements.
3. The measurement is limited by the tune jitter. The present ALBA performance is $2\times10^{-4}$ rms. [4]
4. It is a very slow measurement.

As it is shown in this paper, the first three points can be greatly compensated. However, it is clearly a very slow measurement not suited for normal operation optics control. Nevertheless it could constitute a good bench mark method.

The paper is separated mainly in two sections. The first section describes the recent precise magnetic measurements of spare quadrupoles and the corresponding data processing. The second part describes the measurements done during this year dedicated machine time and how that agrees with LOCO beta functions at the quadrupoles position.

## MAGNETIC MEASUREMENTS

The ALBA Storage Ring includes 112 quadrupoles, all of them with the same iron cross section, and which can be divided into four groups depending on the length of the iron yoke: 200, 260, 280 and 500 mm. All quadrupoles were magnetically characterized by the manufacturer (BINP) during the production process [7]. The harmonic content of each magnet was determined for 5–6 current settings between the maximum one (either 200 or 225 Amp depending on the iron length) and 50 Amp. From this data an average transfer function curve $GL(I)$ providing the integrated gradient strength for each iron yoke length as a function of the current setting was obtained.

In order to increase the accuracy of the $GL(I)$ curves, four spare quadrupoles —one for each iron yoke length— have been measured in detail at ALBA magnetic measurements laboratory. Measurements have been carried out on a rotating coil bench, using a shaft based on printed circuit coils designed and manufactured at ALBA, with a diameter

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of 44 mm [8]. Prior to measurement, magnets were cycled following the same sequence which is used in the accelerator, and measurements were taken for decreasing current setpoints from maximum current down to zero. The distance between adjacent current setpoints depended on the region of the hysteresis curve that was being measured, ranging from a minimum step of 2 Amp in the region of interest which includes the working setpoints of the analyzed family, up to a maximum step of 10 Amp. A total of 60 setpoints per quadrupole type have been measured.

In order to reconstruct the average transfer function for each group of quadrupoles from measurements of an individual member of the group, obtained data has been rescaled so as to minimize the integrated gradient difference at the setpoint values of the original average transfer curves. After doing so, differences for the common setpoints are smaller than $5 \times 10^{-4}$. The obtained $GL(I)$ curves are shown in Fig. 1.

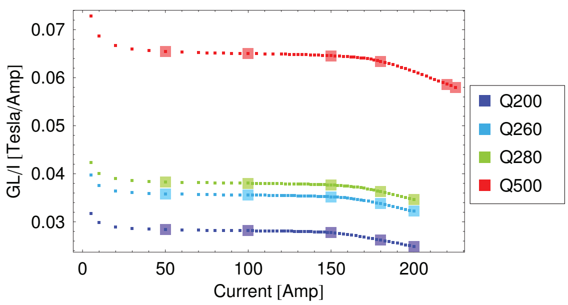


Figure 1: Integrated gradient normalized to the excitation current as a function of the current setpoint for each type of ALBA SR quadrupole. Large symbols stand for the original data provided by the manufacturer, and small symbols correspond to the detailed measurements carried out at ALBA.

The integrated gradient $GL$ is related with the quadrupole integrated strength as $kL = GL/(B\rho)$, where $B\rho = 10.007\,\mathrm{T \cdot m}$ for ALBA. Therefore from the data in Fig. 1 we can calculate the term $\partial(kL)/\partial I$ in Eq. (2). Results are shown in Fig. 2, normalized to the effective length of each group of quadrupoles.

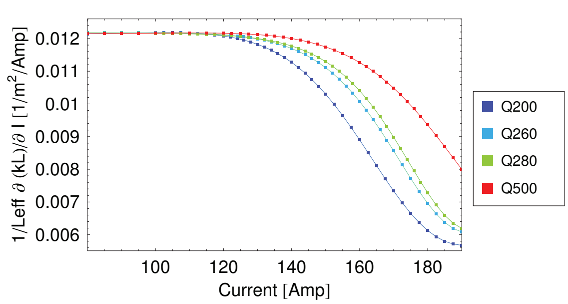


Figure 2: Slope of the quadrupole integrated strength when changing the current setting for each type of ALBA SR quadrupole. Results have been normalized by the magnet's effective length for ease of comparison.

## BETA FUNCTION MEASUREMENTS

In order to cancel the effect of the tune jitter, the tune measure is repeated 20 times. During the measurement the orbit correction feedback is active, 88 out of 120 BPMs are employed for this task, while the remaining 32 BPMs are used to monitor the tune. A dedicated pinger magnet [9] is used to excite the TbT tune measurement. The pinger was installed in summer 2014. Before that, the tune measurements were done using a white noise from an AFG and a stripline kicker. That system was giving a resolution not better than $1 \times 10^{-3}$. With the pinger, resolutions down to $1 \times 10^{-6}$ are achieved, however, the tune jitter $2 \times 10^{-4}$ partially spoils this resolution.

Before doing the beta function measurement, the hysteresis effect for each quadrupole family is calibrated. During the beta function measurement the current setting of each quadrupole is decreased by an small amount (2 A in our case). Along this change the quadrupole strength follows the calibration curve determined in previous section. However, when the current setting is increased back to the starting value, the original values of the tune are not recovered due to hysteresis: an additional current increment is required in order to restore the initial situation. It is called the recovery current $I_{rec}$.

The tune variation after such small cycle is also small; for this reason, the 8 quadrupoles belonging to each one of the 14 families are varied together. The results are shown in Fig. 3.

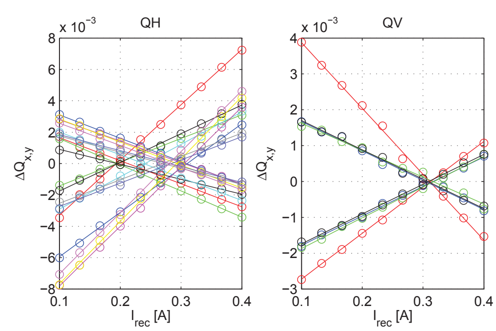


Figure 3: Tune difference with respect to the nominal as a function of the recovery current. Each family is represented in a different color. Horizontally focusing magnet families are shown in the left hand side plot while the vertical focusing ones are in the right hand side plot. The horizontal tune is represented by positive slope lines in the left hand side plot and by negative slope lines in the right hand side plot, the other way around for the vertical tune.

The measurement is done lowering the quadrupole current by 2 A. Within this range, the tune is measured at 10 equidistant points. The average betas are measured at every quadrupole by fitting the tune change using Eq. (2). Figure 4 shows the last results obtained on March 2015. The beta function values have been compared with the model and with respect to LOCO. It can be appreciated a better agreement with the LOCO fit, specially in the vertical plane.

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In the best case, the agreement goes down to 1.8%. We believe that the *not-so-good* behavior of the horizontal plane is related with the residual horizontal tune variation during the measurements. Such tune variation, which is shown in Fig. 5, indicates that the optic functions are changing along the measurement. Using the fitted slopes when measuring the recovery current for each family and the change of tune after each quadrupole measurement, the extra recovery current after each quadrupole measurement can be extrapolated. Figure 5 shows a reasonably good agreement between the extra recovery currents calculated with the vertical and horizontal tune changes. Possibly, the different settings of the individual quadrupoles may explain the difference in recovery currents. However, a new measurement with better tune variation in the horizontal plane is needed to confirm that.

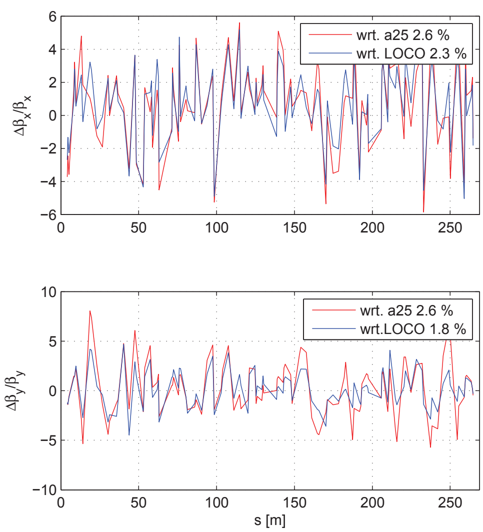


Figure 4: Beta beat measurement at the quadrupoles respect to the bare model (red lines) and respect to the model reconstructed by LOCO (blue lines). The upper plot shows the horizontal values while the lower one shows the vertical ones.

## CONCLUSION

In this paper we show that thanks to a combination of a dedicated pinger magnet with a new set of detailed calibration curves measured on spare quadrupoles, it has been possible to perform beta function measurements at the ALBA storage ring quadrupoles that agree with LOCO at the level of 2% rms. In order to reach this agreement it has been necessary to take into account and compensate for hysteresis effects, as well as averaging over several tune readings to minimize the tune jitter. The results indicate that there is still room from improvement, specially in the horizontal plane, and we foresee to reach a better agreement in future measurements.

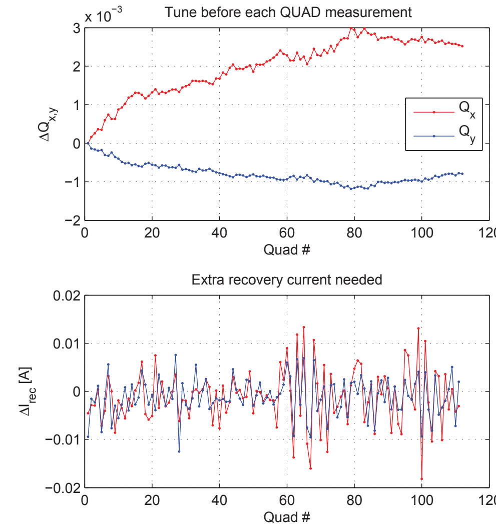


Figure 5: The upper plot shows the tune change after each magnet measurement and having applied the corresponding recovery current. The lower plot shows the corresponding additional recovery current to compensate each tune change.

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