OPTICS-MEASUREMENT-BASED BPM CALIBRATION

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Abstract

The LHC beta function (β) can be obtained using the phase or the amplitude of betatron oscillations measured with beam position monitors (BPMs). Using the amplitude information results in a β measurement affected by BPM calibration. This work aims at calibrating BPMs using optics measurements. For this, βs from both amplitude and phase obtained from many different measurements in 2015 and 2016 with different optics and corrections are analyzed. Simulations are also performed to support the analysis.

INTRODUCTION

In Run II, LHC is foreseen to operate with a β^* of 40 cm at the interaction points 1 and 5. Aiming for lower values of β^* brings many challenges. One of these challenges is to measure and perform optics corrections at the interaction regions (IRs) [1,2]. Figure 1 shows a schematic layout of one IR, including quadrupoles, dipoles and BPMs. β^* cannot be directly measured and, in order to compute it, the βs from the BPMs closer to the triplets (BPMSW.1L1 and BPMSW.1R1 in case of the ATLAS experiment and BPMSW.1L5 and BPMSW.1R5 in case of CMS experiment) are used. A low value of the β^* corresponds with a high value of the beta function at the triplets (Q1, Q2, Q3) which implies a very small phase advance in the triplet area.

Currently, the β function is measured using the N-BPM method (β_{phase}), which uses the phase advance between different sets of BPMs [3]. As a consequence, the very small values of the phase advance between triplet BPMs leads to a poor beta function measurement in this region.

Two alternative methods exist to calculate β^*: K-modulation and β from amplitude. A deeper analysis of the K-modulation can be found in [2,4,5]. The β from amplitude method consists in using the amplitude of the signal measured at each BPM. This method relies on the individual BPM calibration, C, which affects directly the β function calculated. Traditionally, in the LHC, β from amplitude is only used for the measurement of normalized dispersion to remove the dependence on the BPM calibration [6]. This paper proposes a method to calibrate the BPMs closer to the IP 1 and 5 which correspond to ATLAS and CMS experiments respectively. This calibration method relies on using an optics where the triplets are switched off. This configuration, called "ballistic" or "alignment" optics [7], has two main advantages: the convenient phase advance between BPMs and the absence of possible magnetic errors due to the quadrupoles Q1, Q2 and Q3. These advantages can be translated into a more accurate computation of the β from

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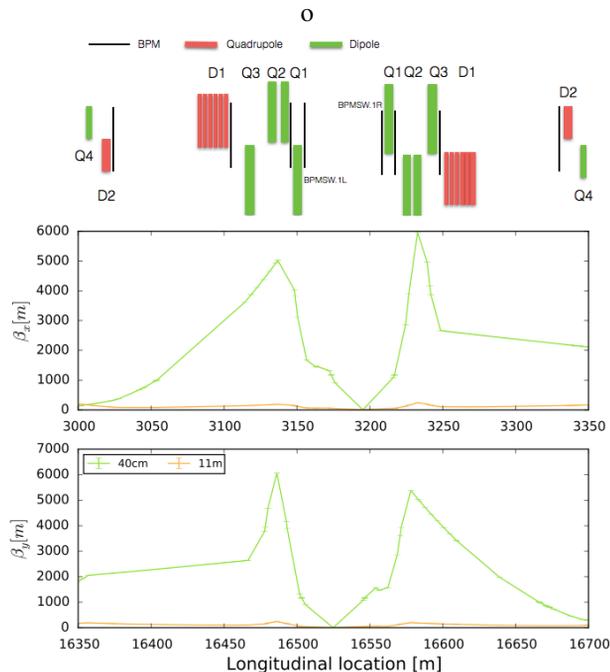
Figure 1: IR1 horizontal and vertical β from model: 40 cm β^* vs 11m β^*

phase, which will allow us to have more reliable reference values to compare to the β from amplitude.

BETA FROM AMPLITUDE METHOD

The transverse oscillations of beam particles around the equilibrium orbit (closed orbit) due to the focusing effect of the magnetic fields in a storage ring are called betatron oscillations. The equation describing the turn-by-turn (TbT) motion at the i$^{\text{th}}$ BPM is given by:

$$x_i(N) = \sqrt{\beta_{x,i} 2J_x} \cos[2\pi Q_x N + \mu_{x,i} + \phi] \qquad (1)$$

where β_x and μ_x are the beta and the phase functions, $2J_x$ is the action, ϕ is initial phase and Q_x is the tune, and N is the turn number. The amplitude observed at each BPM is modified according to the its calibration factor C_i as it is shown in Eq. (2)

$$A_i = C_i \sqrt{\beta_{x,i} 2J_x} \qquad (2)$$

The beta from amplitude method is based on the analysis of the amplitude of the spectrum lines of the Fourier Transformation (FT) of the TbT (several successive turns) unlike the N-BPM phase advance method where the phase is being used.

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The advantages of using the amplitude of the FT line corresponding to the main tune rather than the peak-to-peak amplitude are the lack of coupling dependence and the better signal-to-noise ratio.

During the measurements, the AC-dipole was used with different amplitudes in order to see larger betatronic oscillations. Equation (3) describes how the kick amplitude is being calculated:

$$2J_{x,i} = \sum_i^n \frac{(A_{x,i})^2}{\beta_{\mathrm{model}x,i}} \frac{1}{n} \qquad (3)$$

where the β_{model} is the β obtained using the MAD-X model and the summation is restricted to the arc BPMs to avoid the effects of the different BPM types in the IRs.

Once the action has been calculated, the β_{amp} can be obtained by using Eq. (4),

$$\beta_{\mathrm{amp},i} = \frac{A_{x,i}^2}{2J_{x,i}} \frac{1 + r^2 + 2r \cos(2\pi\mu)}{1 - r^2} \qquad (4)$$

whit r equal to:

$$r = \frac{\sin[\pi(Q_{\mathrm{d}} - Q)]}{\sin[\pi(Q_{\mathrm{d}} + Q)]} \qquad (5)$$

where Q_{d} is the AC-dipole tune and Q is the natural beam tune [9]. The AC-dipole effects are taken into account in the second term of the Eq. (4).

As can be observed from previous equations, the method that is being used at CERN uses the β from MAD-X model in order to normalize the amplitude. In this way, an error is being introduced in the calculation of the action caused by the beta-beating present in the LHC. A deeper study of this effect can be found in [6, 8].

BALLISTIC OPTICS

In the ballistic configuration, the β function over the IR follows a parabola given by:

$$\beta(s) = \beta^* + \frac{(s - \omega)^2}{\beta^*} \qquad (6)$$

where β^* is the β function at the waist ω. This behavior can be used to obtain an accurate value of the β function via ffitting to the beta from phase measurements. The IR dipoles, however, produce weak focusing that might distort the parabola. An estimation of the impact of this focusing effect on the beam has been made in [10] by fitting the β from the model to the Eq. (6) and it was concluded that the MBXW dipoles have a negligible effect on the β function.

The calibration factors using ballistic optics were first calculated in November 2015 [10]. Due to technical problems, only measurements for Beam 2 at injection energy (450 GeV) were made. The promising results obtained in this analysis led to redo the calibration factors at top energy (6.5 TeV) for Beam 1 and Beam 2 in 2016.

Figures 2 and 3 show, respectively, the horizontal β_{amp}, β_{phase} and β_{fit} for IR1and IR5 with Ballistic optics measured
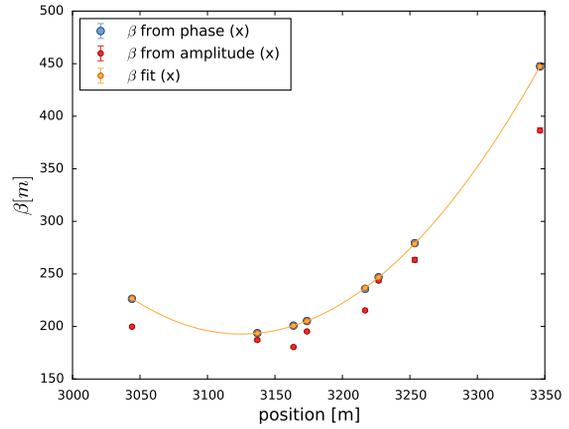
Figure 2: IR1 Beam 2 measured horizontal β from amplitude and β from phase including the fit to Eq. (6). β from amplitude is consistently below β from phase.
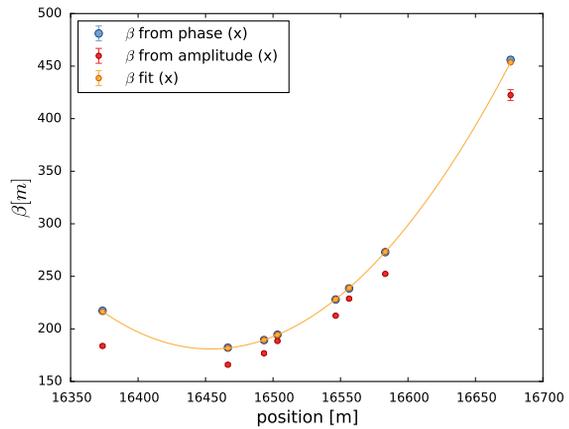
Figure 3: IR5 Beam 2 measured horizontal β from amplitude and β from phase including the fit to Eq. (6). β from amplitude is consistently below β from phase.

in 2016. In these plots the parabolic behavior of the β can be observed, as well as the systematic difference between the β_{amp} and β_{phase}.

The BPM calibration factor is computed using the Eq. (7),

$$C_i^2 = \frac{\beta_{\mathrm{fit},i}}{\beta_{\mathrm{amp},i}} \qquad (7)$$

where β_{fit} are the values obtained when replacing the position (s) by the BPM position in the previous fit of Eq. 6

For Beam 1, a comparison of the calibration error for vertical and horizontal plane, that has been computed using 2016 results, is shown in Fig. 4.

For Beam 2, a comparison of the calibration ratio together with the corresponding uncertainty from 2015 and 2016 is shown in Figs. 5 and 6 for IR1 and IR5 BPMs. From Fig. 6 it can be seen that the calibration corresponding to the BPMSW.1L5.B2 (2015) in the horizontal plane had a significantly smaller value than the rest of IR BPMs.

Moreover, during the measurements made in 2015, this BPM was just recording data in the horizontal plane while
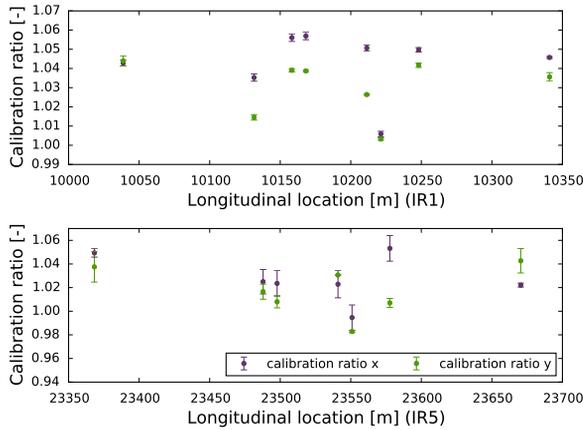
Figure 4: C^2 for horizontal and vertical BPMs in IR1 (top) and IR5 (bottom) : horizontal and vertical Beam 1
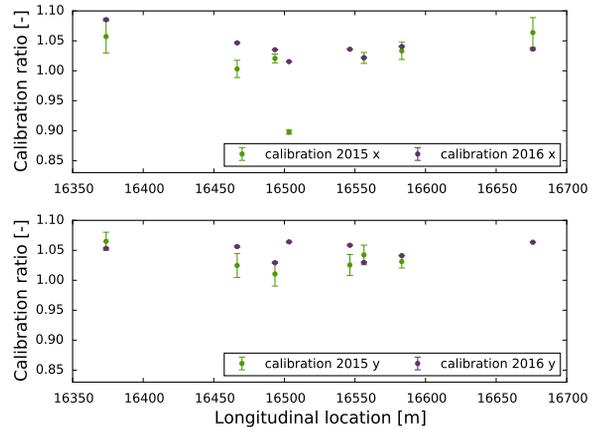
Figure 6: C^2 for horizontal and vertical BPMs in IR5: 2015 (Injection energy) vs 2016 (Flat top energy)
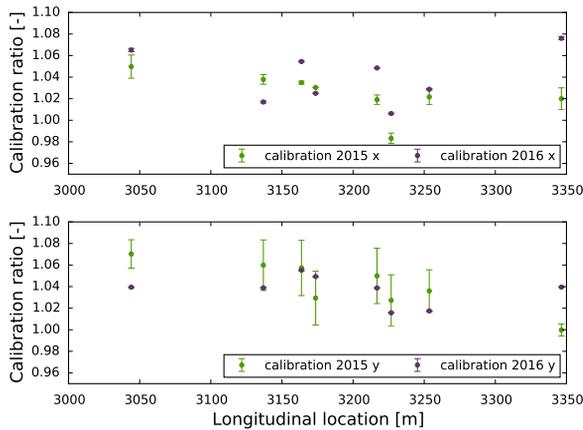
Figure 5: C^2 for horizontal and vertical BPMs in IR1: 2015 (Injection energy) vs 2016 (Flat top energy)

Values of the β_{amp} are closer to the K-modulation results when the calibration factors are applied than when these factors are not used. Even though, the agreement of β_{amp} with K-modulation is not yet satisfactory, and therefore, a review of the algorithms is being developed.

The possible algorithm upgrades follow:

- Equation (3) uses β from model, which might introduce an error in the computed action. A possible alternative could be to use the β from phase in Eq. (3).

- One of the strongest assumptions that has been made in order to do these studies is the fact that the calibration factor is independent of amplitude. Otherwise, this should be considered when extrapolating from ballistic to collision optics.

ACKNOWLEDGEMENT

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its symmetric BPM (BPMSW.1R5.B2) was just working in the vertical plane. The BPM improvements, that have been implemented by BE-BI group during the technical stop [11], are specially remarkable in those BPMs. The calibration ratios measured in 2016 do not show any outliers. Also, the problem with missing data in one plane, horizontal for left and vertical for right, has been resolved.

SUMMARY AND OUTLOOK

A new method to compute the BPM calibration with optics measurements is being investigated. A considerable decrease in the calibration error bars corresponding to the measurements of 2016 at 6.5 TeV, with respect to the 2015 injection errorbars, has been observed. Besides that, the quality of the BPM signal has improved from 2015 [11]. This improvement is specially significant for the BPSW.1L5.B2 in the horizontal plane, one of the key BPMs used to compute the β^*.

The calibration factors for the BPMs placed in IR 1 and IR 5 have been used in the 40 cm β^* measurements (2016).

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