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# OPTICS-MEASUREMENT-BASED BPM CALIBRATION

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## *Abstract*

Beam position monitors (BPMs) are key elements in accelerator operation, providing essential information about different beam parameters that are directly related to the accelerator performance. In order to obtain an accurate conversion from an induced voltage to the position of the centre of mass of the charge distribution, the BPMs have to be calibrated prior to its installation in the accelerator. This calibration procedure can only be performed when the accelerator is in a period of non-activity and does not completely reproduce the exact conditions that occur during the machine operation. Discrepancies observed during the optics measurements at the Large Hadron Collider show that the impact of the BPM calibration factors on the optics functions was greater than expected from the design values and tolerances. Measurement of the optics functions allows obtaining extra information on BPM calibration together with its associated uncertainty and resolution. The optics measurement based calibration allows computing optics functions that are biased by a possible calibration error such as beta function, dispersion function and beam action.

## INTRODUCTION

Accurate optics measurements are an essential step performed during the commissioning of present and future colliders such as LHC [1–4], its upgrades HL-LHC [5] and HE-LHC [6] or the FCC [7, 8]. The requirements of increasing the luminosity moves the LHC into more challenging operational regimes with lower $\beta^*$. Optics measurements and corrections will play an important role in this scenario, aiming to correct strong localized magnetic errors to achieve the design value of the $\beta$ function at the interaction point (IP), called $\beta^*$, to provide the design high luminosity within the 5% tolerance limits to the experiments: ATLAS, located in the Interaction Region 1 in the LHC (IR1) [9] and CMS [10], located in the Interaction Region 5 in the LHC (IR5). These corrections rely on the accuracy that can be achieved in the $\beta^*$ measurements and it has been the primary motivation for further developing $\beta$-function reconstruction methods.

Most common optics reconstruction approaches are based on driven turn-by-turn measurements recorded at each BPM location [11–15]. The excitation induced by an external source moves the beam in phase space, allowing to record larger betatron oscillations, improving the resolution of the $\beta$ reconstruction. The motion of the beam, when subjected to an external periodic force, is denoted as driven oscillation. In driven turn-by-turn measurement mode, BPMs record the centre-of-charge position of a given bunch excited by an external source every time it passes throught the BPM [16].

Advanced Fourier analysis tools allow transforming turn-by-turn data from the time domain to the frequency domain [17]. Information contained in the frequency spectra: frequency, phase and amplitude, is used for optics functions reconstruction around the ring.

On the one hand, relative phase advances between a reference BPM and at least two other BPMs allow reconstructing the values of the $\beta$ functions at the reference BPM. This method, known as $\beta$ from phase ($\beta^{\phi}$), was first used in LEP [18] and has been further developed in LHC, ALBA and ESRF [19–22]. This approach is very sensitive to errors for values of the BPMs phase advance close to n$\pi$. Those values match the phase advance between consecutive BPMs for certain BPMs in the LHC and the entire BPM range in the Proton Synchrotron Booster (PSB).

On the other hand, the amplitude of the transverse motion at a given position is proportional to $\sqrt{\beta}$, and this can be used for $\beta$ measurements. This approach is known as $\beta$ from amplitude ($\beta^{\mathrm{A}}$). Nonetheless, a possible calibration error of each BPM will directly propagate to the measured amplitude. This $\beta$-function reconstruction does not allow to separate the contribution of BPM calibration errors from the real driven amplitude. The $\beta^{\mathrm{A}}$ approach has been used in the past [18, 22–24], it is currently implemented as part of the OMC software [25], but it has not been as widely used as $\beta^{\phi}$. The lack of resolution in the $\beta$-function calculation when using $\beta^{\phi}$ for specific values of the phase advance triggered further development of an alternative method for computing the calibration factors.

Knowledge of BPM calibration factors would allow to accurately measure $\beta$ function using $\beta^{\mathrm{A}}$ approach where the performance of $\beta^{\phi}$ is limited.

This paper introduces an optics-based-BPM calibration measurement method based on $\beta$ function measurements using the ratio $\sqrt{\beta^{\phi}/\beta^{\mathrm{A}}}$. Calibration factors are calculated in an optics configuration where the systematic lattice errors affect as less as possible $\beta^{\phi}$ and dispersion measurements. In case of LHC, an optics that is suitable for this method is the Ballistic or Alignment optics, characterised by having the triplets switched off [26].

## CALIBRATION PROCEDURE

### *$\beta$-function Measurements Based on Amplitude Analysis*

The parameters obtained after applying Fourier transformation to turn-by-turn data- frequency, phase and amplitude- are the base of optics functions reconstructions: $\beta^{\phi}, \beta^{\mathrm{A}}$.

Linear optics studies are especially focused on the analysis of amplitude and phase corresponding to the main line of the spectrum, associated to the driven tune. For the $i^{\mathrm{th}}$ BPM,

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ideal amplitude and phase are related to the beam position through:

$$x_i, y_i(N)^{\mathrm{D}} = A^{\mathrm{D}}_{x,y,i} \sin(\mu^{\mathrm{D}}_{x,y,i} + 2\pi Q^{\mathrm{D}}_{x,y} N), \qquad (1)$$

where $A^{\mathrm{D}}_{x,y,i}$, $\mu^{\mathrm{D}}_{x,y,i}$ and $Q^{D}_{x,y}$ are the amplitude, the phase and the tune of the driven motion respectively. The amplitude, $A^{\mathrm{D}}_{x,y,i}$, can also be expressed in terms of the driven $\beta$ function, $\beta^{\mathrm{D}}_{x,y,i}$, and a common observable for all BPMs, the driven action, $2J^{\mathrm{D}}_{x,y}$,

$$A^{\mathrm{D}}_{x,y,i} = \sqrt{2J^{\mathrm{D}}_{x,y}\beta^{\mathrm{D}}_{x,y,i}} \qquad (2)$$

.

To simplify the equations, the subindexes, $x$ and $y$ are omitted in the following. Since measurement of the oscillation amplitude is biased by the individual BPM calibration factors, $\mathrm{C}_i$, the measured amplitude, $\mathrm{A}_i^{\mathrm{D,meas}}$, deviates from Eq. (2) as:

$$A_i^{D,\mathrm{meas}} = C_i^{\mathrm{A}}\sqrt{2J^{\mathrm{D}}\beta_i^{\mathrm{D}}}. \qquad (3)$$

$\mathrm{A}_i^{\mathrm{D,meas}}$, is a direct measurement obtained from the Fourier analysis of the transverse oscillations, and is the basis for the $\beta^{\mathrm{A}}$ analysis.

In order to obtain the value of the action corresponding to the external excitation source, it is necessary to normalize the square of the amplitude of the transversal excitations, $(\mathrm{A}_i^{\mathrm{D,meas}})^2$, by the $\beta_i^{\mathrm{D}}$ function. This value can be obtained in two ways, using either the measured $\beta_i^{\phi,\mathrm{D}}$ or the model $\beta_i^{\mathrm{model,D}}$ given by MADX [27]. The average of the product of the action times the square of the individual calibration factors can be expressed regrouping the terms in Eq. (2) as:

$$\frac{1}{\mathrm{N}}\sum_{i=1}^{\mathrm{N}}\left(C_i^{\mathrm{A}}\right)^2 2J^{\mathrm{D}} = \frac{1}{\mathrm{N}}\sum_{i=1}^{\mathrm{N}}\frac{\left(A_i^{\mathrm{D,meas}}\right)^2}{\beta_i^{\mathrm{D}}}, \qquad (4)$$

where N is the number of BPMs.

In order to simplify the notation, the average of the product of the action times the individual calibration factors square will be denoted as calibration-weighted action given by:

$$2J_C^{\mathrm{D}} = \overline{(C_i^{\mathrm{A}})^2}2J^{\mathrm{D}} = \frac{1}{\mathrm{N}}\sum_{i=1}^{\mathrm{N}}\frac{\left(\mathrm{A}_i^{\mathrm{D,meas.}}\right)^2}{\beta_i^{D}}. \qquad (5)$$

Once the calibration weighted action is calculated, the driven $\beta$-function at a given BPM, $\beta_i^{\mathrm{A,D}}$, can be computed by normalizing the amplitude by the driven action

$$\beta_i^{\mathrm{A,D}} = \frac{(A_i^{\mathrm{D,meas}})^2}{\overline{(C_i^{\mathrm{A}})^2}2J^{\mathrm{D}}} = \frac{(A_i^{\mathrm{D,meas}})^2}{2J_C^{\mathrm{D}}}. \qquad (6)$$

Equation (6) can be expressed in terms of the ideal unknown $\beta_i^{\mathrm{D}}$ function as:

$$\beta_i^{\mathrm{A,D}} = \frac{(C_i^{\mathrm{A}})^2\beta_i^{\mathrm{D}}}{\overline{(C^{\mathrm{A}})^2}} \qquad (7)$$

which shows that the $\beta_i^{\mathrm{A,D}}$ calculation is affected by a factor $(C_i^{\mathrm{A}})^2/\overline{(C^{\mathrm{A}})^2}$, i.e, the arc calibration factors also have an impact on the $\beta_i^{\mathrm{A,D}}$ function calculation.

In order to obtain the lattice $\beta$ function, $\beta_i^{\mathrm{A}}$, the effect induced by the AC-dipole in the measured amplitude has to be compensated. This compensation is based on the phase advance, $\phi_{i\Rightarrow\text{AC-dipole}}$, between the AC-dipole and the $i^{\text{th}}$ BPM as:

$$\beta_i^{\mathrm{A}} = \frac{(C_i^{\mathrm{A}}A_i^{\mathrm{D}})^2}{2J_C^{\mathrm{D}}}\frac{1+\lambda^2+2\lambda\cos(\phi_{i\Rightarrow\text{AC-dipole}})}{1-\lambda^2} \qquad (8)$$

where $\lambda$ is given by the tune separation between the natural tune and the driven tune, $\lambda = \frac{\sin[\pi(\mathrm{Q_d}-\mathrm{Q})]}{\sin[\pi(\mathrm{Q_d}+\mathrm{Q}))]}$ and $\phi_{i\Rightarrow\text{AC-dipole}}$ is the phase advance between the BPM $i$ and the AC-dipole [16].

### *Optics-based Calibration Factors*

Optics-based calibration factors are computed as the ratio between two different optics measurements: $\beta_i^{\phi}$ that is not affected by the calibration factors and $\beta_i^{\mathrm{A}}$,

$$C_{\beta,i}^{\mathrm{A}} = \sqrt{\frac{\beta_i^{\mathrm{A}}}{\beta_i^{\phi}}} = \frac{C_i^{\mathrm{A}}}{\sqrt{\overline{(C^{\mathrm{A}})^2}}}. \qquad (9)$$

## CALCULATION OF LHC BPMS CALIBRATION FACTORS

Different types of BPMs are installed in LHC with different geometries. They have been grouped according to the geometry of the pick-ups in the following categories: standard, enlarged aperture and stripline as shown in Table 1 [28]. Standard or cold BPMs are button BPMs, and they are the most widely used type of pick-ups installed in the LHC arcs. Enlarged aperture monitors are also button BPMs with a larger aperture, placed close to the recombination dipoles. Stripline or directional BPMs, able to measure the beam direction, are placed in the IRs where both beams circulate in one vacuum pipe.

The calibration analysis focuses on the IRs because during the annual LHC commissioning [29, 30] a systematic difference between the results obtained using $\beta^{\phi}$ and $\beta^{\mathrm{A}}$ was observed in those regions.

The average $\beta$-beating, $\left\langle(\beta^{\mathrm{A}}-\beta^{\phi})/\beta^{\phi}\right\rangle$ between the two techniques, illustrates that a systematic lower value is obtained in the $\beta^{\mathrm{A}}$ with respect to the $\beta^{\phi}$ only in the case of stripline and enlarged aperture BPMs.

Figure 1 shows the histogram of the ratio $\sqrt{\beta^{\mathrm{A}}/\beta^{\phi}}$ for stripline BPMS, proportional to the calibration factors, measured for several optics: Injection, Flattop, Ballistic and High-$\beta^*$. The main parameters of this distribution, average and standard deviation, show the impact of the calibration factor in the $\beta$-function measurement.

Table 1: Summary of BPM characteristics.

| Name | Stripline | | Enlarged Aperture | Standard |
|---|---|---|---|---|
| Geometry | Strip-line | | Button | Button |
| LHC prefix | BPMS | BPMSX | BPMW | BPM |
| Aperture | 61 mm | 81 mm | 61 mm | 49 mm |

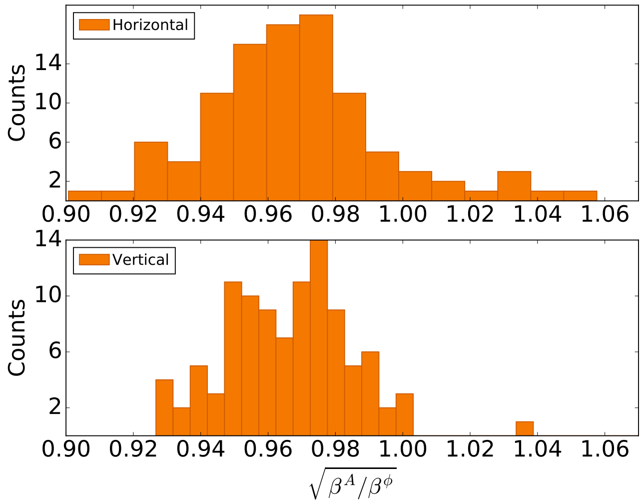

Figure 1: Histogram of the ratio $\sqrt{\beta^{\mathrm{A}}/\beta^{\phi}}$ in the stripline BPMs measured in 2017 using different optics configurations: Injection, Flattop, High-$\beta^*$ and Ballistic.

### *Ballistic Optics*

In Ballistic optics configuration, the optics used for calibration calculation, the triplet quadrupoles are switched off. This set of magnets located in IR1 and IR5 are common to both beams. This optics configuration was first designed for alignment of the magnets placed in the triplet area, the Q1, Q2 and Q3 quadrupoles. An extended version of this optics, designed in 2017 specifically for these BPM calibration studies, has Q4 quadrupoles also switched off [31]. Switching off the focusing system presents some challenges for the machine operation that have to be taken into account. The main limitation comes from the significant drift generated in the segment between the active quadrupoles, leading to large values of the $\beta$ function in the interaction regions (IR1 and IR5).

By switching off the quadrupole Q4, the drift region is extended and so the region of calibration. These extra BPMs that have been calibrated using the latest Ballistic configuration will be useful for the future measurements in HL-LHC. Those monitors will be placed close to the crab cavities, which also require tight optics control.

Figure 2 shows the designed $\beta$ function in the horizontal and the vertical planes as well as the dispersion in the horizontal plane used in 2016 (top) and 2017 (bottom) in IR1 and IR5.

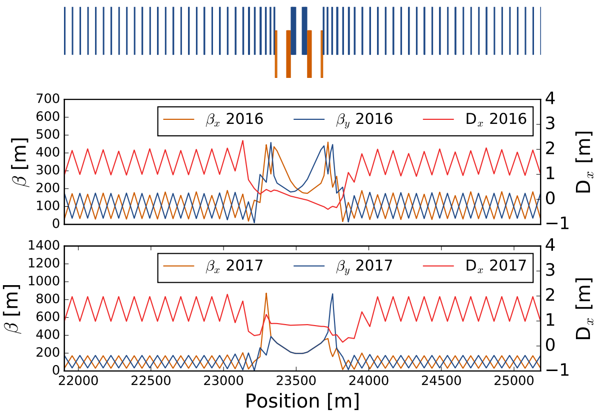

Figure 2: Comparison of the horizontal model $\beta$, vertical model $\beta$ function and dispersion for IR1: top 2016 and bottom 2017.

Ballistic optics measurements have been performed in three consecutive years: 2015, 2016, 2017. In 2015, due to technical issues, measurements were only performed at injection energy (450 GeV) [32]. Thanks to the promising results obtained in 2015, optics measurements were repeated in 2016 using the same Ballistic configuration, this time at flattop energy (6.5 TeV).

The main reason for measuring the BPM calibration factors in consecutive years was to evaluate the improvements performed in the BPMs during the yearly shutdown and to have the most recent value of the calibration factors. During the extended end of year stop 2016-2017, several improvements were performed in the BPM electronics regarding minor software and several hardware problems, such as comparator thresholds [33]. Studies presented in this article focus on the calibration factors measured at high-energy in 2016 and 2017 and their application of the 2017 calibration factors to several different optics measurements performed during 2017 and 2018.

### *Calibration Factors 2016 vs 2017*

A comparison between the calibration factors calculated in 2016 and 2017 is introduced in this section. Figure 3 shows a comparison of calibration factors measured in consecutive years, separated by IR and by plane. This comparison is merely illustrative since the improvements performed in the BPMs involving both software and hardware do not allow to have a direct comparison of both sets of calibration factors.

## METHOD VALIDATION

This novel optics-based method has been validated using different optics configurations. In the case of LHC, the optics configurations used have been chosen according to the $\beta^\phi$ resolution. Optics with large $\beta^*$ ($\beta^* > 1$ m), where $\beta^\phi$ can be accurately measured, are being used as reference values. These optics are: Flattop, Injection and High-$\beta^*$.

This section summarizes a comparison of the values obtained using the $\beta$ from amplitude method before and after re-

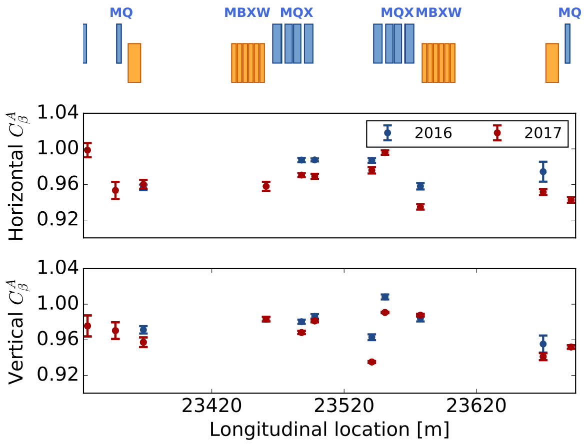

Figure 3: Comparison of calibration factors measured at 6.5 TeV in 2016 and 2017 (IR 1, Beam 1).

calibrating the BPMs, using the optics-measurement-based calibration factors.

Figure 4 shows a comparison of the beating of the measured $\beta^{\mathrm{A}}$ with respect to the $\beta^{\phi}$ measured at the stripline BPMs placed in the IRs 1 and 5, using the optics previously described, before and after applying the calibration factors. A summary of the properties of these distributions, that combines the results obtained both in the horizontal and in the vertical plane, is presented in Table 2 average $(\beta^{\mathrm{A}}-\beta^{\phi})/\beta^{\phi}$ and its associated spread. Figure 4 and Table 2 show that the difference between the values of $\beta^{A}$ and $\beta^{\phi}$ is reduced significantly. The minimum spread associated with the ratio $(\beta^{A}-\beta^{\phi})/\beta^{\phi}$ is given by the combination of error-bars associated to the $\beta^{\phi}$ and $\beta^{\mathrm{A}}$ and therefore cannot be significantly decreased.

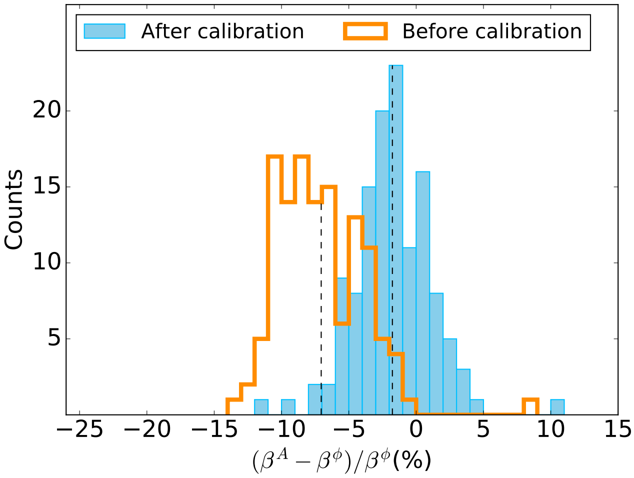

Figure 4: Histogram of the relative difference between $\beta^A$ and $\beta^{\phi}$ before and after calibration in horizontal and vertical planes measured in several optics: Injection and Flattop during 2017 and 2018 (Horizontal and vertical plane, IR1 and IR5).

Table 2: Average and standard deviation of the distributions $\left(\beta^{\mathrm{A}}-\beta^{\phi}\right)/\beta^{\phi}$ before and after applying the calibration factors.

| | Not calibrated | | Calibrated | |
|---|---|---|---|---|
| | Beam 1 | Beam 2 | Beam 1 | Beam 2 |
| $\overline{\left(\beta^{\mathrm{A}}-\beta^{\phi}\right)/\beta^{\phi}}$ (%) | -6.9 | -7.1 | -0.2 | -1.8 |
| $\sigma\left(\beta^{\mathrm{A}}-\beta^{\phi}\right)/\beta^{\phi}$ (%) | 4.0 | 3.1 | 2.9 | 2.9 |

## CONCLUSIONS

BPM calibration factors have been computed for the first time in LHC using optics functions. This method, denoted as optics-measurement-based BPM calibration, is based on the analysis of $\beta$-functions. A dedicated optics configuration, known as Ballistic optics, has been developed for these studies. A drift space is generated in the vicinity of the IP, allowing to measure $\beta$-function using phase with a precision of about 0.5%. The achieved precision on $\beta$-function has allowed computing the BPM calibration factors by comparing $\beta^{\mathrm{A}}$ to $\beta^{\phi}$, with an average uncertainty in the sub per cent level as shown in Figs. 3. It has been observed that the relative difference of the $\beta^{\mathrm{A}}$ with respect to the phase, $(\beta^{\mathrm{A}}-\beta^{\phi})/\beta^{\mathrm{A}}$, is reduced on average by “6%" when BPMs are re-calibrated using the optics-measurement-based approach.

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