NEW FINDINGS ON BPM CALIBRATION IN THE LHC

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Abstract

Accurate Beam-Position Monitor (BPM) calibration is essential for high-quality optics measurements and reliable beam-based diagnostics in the Large Hadron Collider. Recent in-depth analyses combining advanced optics-measurement techniques, including measurements of a novel 60° optics, with cross-checks from complementary beam instrumentation have revealed the presence of a previously unnoticed systematic calibration bias of approximately 3 % in arc BPMs. This correction has been implemented at the start of 2025, leading to improved consistency. Despite these improvements, not all aspects of the discrepancy have yet been fully understood. This contribution presents the investigations that enabled the identification of the bias, open questions, and implications for future operation.

INTRODUCTION

The Large Hadron Collider (LHC) [1] at CERN with approximately 27 km circumference is currently in his last year of operation for Run 3 and achieves beam energies of up to 6.8 TeV for two colliding proton beams at a maximum instantaneous luminosity above $2 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$. Its upgrade, the High Luminosity LHC (HL-LHC) [2], aims at increasing this value to at least $5 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$, which demands an improved understanding of the existing magnetic lattice and installed beam instrumentation.

Previous studies have used Turn-by-Turn (TbT) data acquired at Beam Position Monitors (BPMs) to measure the momentum compaction factor, α_c, of various optics at injection and top energy of, respectively 450 GeV and up to 6.8 TeV, taken between 2016 and 2022, with α_c, between 3.2×10^{-4} and 3.5×10^{-4} [3, 4]. Additionally, in 2022 a novel optics with a transverse phase advance of 60° in the arc FODO cells, 30 % lower compared to the nominal LHC optics which features roughly 90°, and has hence, a factor 2 larger α_c of approximately 7×10^{-4} has been carefully measured, and analysed [5]. All measurements show consistently a 3 % lower α_c, attributed to an orbit measurement calibration error. We note, that in 2022 only Beam 1 has been measured due to time constraints.

In 2024 a 60° arc cell phase advance optics has been measured for the first time for both beams with one of the goals being to verify 3 % orbit measurement error. In parallel, BPM polynomials, previously derived in 2014 have been re-analysed in early 2025. Consequently novel polynomials have been applied at the start of 2025. With these new settings optics measurements are acquired in 2025 and 2026, at various configurations. Main findings are reported here.

60° OPTICS MEASUREMENTS IN 2024

A 60° optics has been designed and measured in 2024, with one of the goals being helping to conclude on the average arc BPM calibration in both beams. Similar to first measurements of a 60° optics [5], one pilot bunch per beam with up to 5×10^9 protons each is injected and propagated sector-wise with orbit corrections in each step. After a closed-orbit is established a working point of 0.28, 0.31 is established, followed by linear chromaticity and coupling correction.

Optics measurements are performed using AC-dipoles with a $\Delta Q_{x,y}$ of −0.012, 0.010 and 6600 turns. Analysis is performed using omc3 [6]. For off-momentum optics measurements, RF-frequency shifts of ±50 Hz, ±100 Hz, and ±150 Hz are applied. Global optics corrections are based on a response matrices including horizontal and vertical tunes, phase advances and normalized horizontal dispersion, and all available quadrupole circuits [1]. Corrections are stepwise applied until the full corrector value is achieved. Linear coupling is corrected to a $|C^-|$ of 0.005 for both beams. TbT data is acquired before and after global corrections are applied. Global corrections reduce the rms β-beating from roughly 18 % to approximately 5 % in both planes and beams as shown respectively in Figs. 1 and 2.

For dispersion measurements, the relative momentum offset at each frequency shift is obtained using $\delta = \langle D_{x,i}\, CO_{x,i} \rangle / \langle D_{x,i} \rangle$ with the model horizontal dispersion D_x and the measured closed orbit CO_x at arc BPM i. After applying global corrections, the rms horizontal dispersion deviation is reduced from 64 cm to 16 cm for beam 1 and from 66 cm to 30 cm for beam 2. Vertically the rms dispersion is roughly 0.2 m. This optics is hence considered to be sufficiency well corrected to analyse α_c and hence BPM calibration.

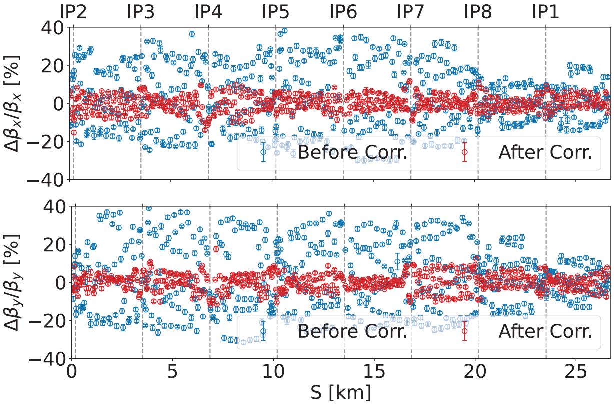

Figure 1: Beam 1 horizontal (top) and vertical (bottom) β-beating before and after applying global corrections.

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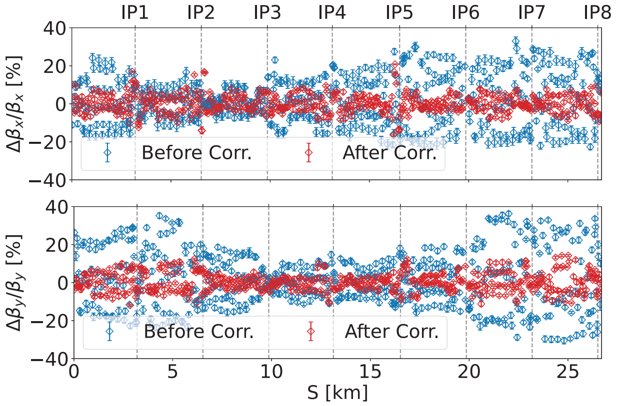

Figure 2: Beam 1 horizontal (top) and vertical (bottom) β-beating before and after applying global corrections.

Similar to [3] it is aimed to measure α_c by comparing the relative momentum offset obtained from the orbit data in combination with the model dispersion, with the relative momentum offset obtained using the RF-frequency shift, namely $\delta = -(\gamma_{\rm rel}^{-2} + \alpha_C)^{-1}(\Delta f/f)$. At 450 GeV the Lorentz-factor, $\gamma_{\rm rel}$, $\gamma_{\rm rel}^{-2}$ is 4.33×10^{-6}. For the here presented 60° optics measurements a 4.53 % and 4.17 % lower α_c is measured, respectively for beam 1 and beam 2, with respect to the model expectations, which is consistent with previous findings.

Over all analysed measurements at injection and top energy for various optics configurations, including 60° phase advance, from 2016 to 2024 a systematically lower value is measured of, respectively, -3.3 ± 0.3 % and -3.1 ± 0.4 %. It is shown in Fig. 3. The error bar reflects the fitting error using a least square fit technique. Since the same systematic error is measured for optics measurements at various machine configurations for both beams it is attributed to an average arc BPM calibration error.

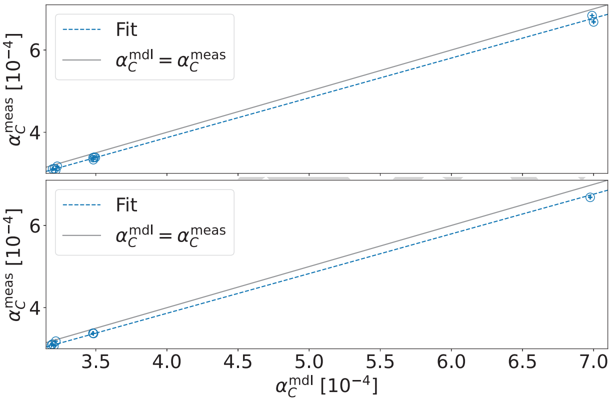

Figure 3: Measured compared to model α_c for beam 1 (top) and beam 2 (bottom).

BPM POLYNOMIAL CORRECTION

Complementary investigations from beam instrumentation perspective in 2025 have re-evaluated scaling factors applied to the arc BPM readings. We note, that the LHC BPM system measures normalised beam positions in the scale of [-1, 1], which is then translated to physical position in SI units by software using 5th-order cross-term polynomials with 6 non-zero coefficients. The polynomial used for the arc BPMs up to 2025 has been derived in 2014 from quasi-2D electrostatic simulations with CST Microwave Studio [7]. Upon verification of the 2014 CST model it is discovered that some of its dimensions do not correspond to the true arc BPM design, most notably the BPM button electrode was modelled 14 % too large. In the typical arc BPM measurement range of up to ±5mm, this would result in an overestimation of the beam orbit reading by up to 3 %.

In 2025 a new CST model, using the true arc BPM dimensions, has been developed, including deriving a novel polynomial based on full 3D electrostatic simulations. Compared to the 2014 polynomial, the newly calculated coefficients varied by up to 170 %, and notably, the linear term, decreased by 2.5 %. More information is available in [8]. Overall, the residual measurement error of the the polynomial correction has been reduced to below 10 µm as shown in Fig. 4.

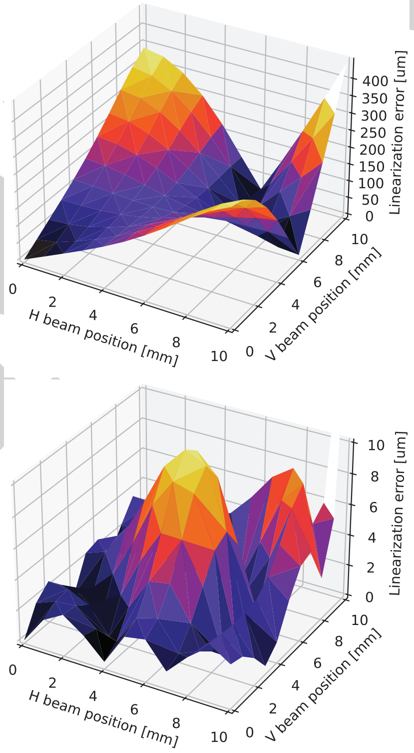

Figure 4: Residual beam position measurement errors of arc BPMs introduced by the 2014 (top) and 2025 (bottom) polynomial.

MEASUREMENTS IN 2025 AND 2026

Since both independent analyses, based either on optics or on CST have found a systematic average arc BPM calibration error of roughly 2.5 – 3 %, the newly derived polynomials, see also [8], have been applied in the LHC before the start of the run in 2025. Optics measurements based on TbT

Table 1: Relative Deviation Of α_c For Beam 1, Given In %

Date	**Optics**	D_x	D_x **and** $D_x^{(2)}$
11/04/25	11 m	-3.36 ± 0.40	-3.35 ± 0.87
20/04/25	11 m	-3.91 ± 0.23	-3.62 ± 0.17
26/02/26	11 m	-3.40 ± 0.38	-3.17 ± 0.35
12/04/25	2 m	-0.57 ± 0.25	-0.48 ± 0.21
13/04/25	60 cm	-0.71 ± 0.71	-0.09 ± 0.88
13/04/25	1.2 m	-0.45 ± 0.30	-1.75 ± 0.11
26/02/26	1.2 m	-0.47 ± 0.78	-1.05 ± 1.09

data are acquired at injection and top energy of, respectively, 450 GeV and 6.8 TeV for both beams and the relative error on the α_c is evaluated as before. While at top energy optics measurements with β^* of 2 m, 1.2 m or 60 cm show a clear improved for both beams and planes, a comparable discrepancy as found from 2016 to 2024 is measured at injection in 2025 and 2026. Details are summarized in Tables 1 and 2.

Table 2: Relative Deviation Of α_c For Beam 2, Given In %

Date	**Optics**	D_x	D_x **and** $D_x^{(2)}$
11/04/25	11 m	-3.08 ± 0.68	-2.08 ± 0.74
20/04/25	11 m	-3.47 ± 0.33	-2.58 ± 0.11
26/02/26	11 m	-3.33 ± 0.46	-2.11 ± 0.74
12/04/25	2 m	-0.43 ± 0.16	-0.11 ± 0.22
13/04/25	60 cm	-0.64 ± 0.63	-1.43 ± 0.85
13/04/25	1.2 m	-0.35 ± 0.37	-0.34 ± 0.49
26/02/26	1.2 m	-0.31 ± 0.74	0.10 ± 0.47

DISCUSSION

While measurements at top energy clearly reflect the expectations from applied novel BPM polynomials, resulting to an average error of -0.5 ± 0.2 % and -0.4 ± 0.1 % respectively for beam 1 and beam 2, at injection energy it remains at -3.7 ± 0.2 % and -3.4 ± 0.3 %. Possible sources are investigated in the following.

BPM Sensitivities For arc BPMs settings, it is verified that the same BPM polynomials are applied between injection and top energy. Although the bunch length at top energy could vary by about almost factor 2 in analysed measurements, compared to injection energy, e.g. 1 ns compared to up 1.7 ns on measurements at 26/02/26, this is not expected to introduce a significant scaling error in the arc BPM readings. Detailed analysis is still ongoing, however, first results indicate that the scaling error due to the bunch length variation is expected to be below 0.3 %. It is, hence, excluded that the overall error source stems from beam instrumentation.

Orbit Correctors Another possibility which is studied is an energy offset with respect to the nominal energy, leading to an orbit shift corrected by orbit correctors. Complementary studies, see [9], measure the relative momentum offset by using DNLM by fitting the best relative momentum offset to the orbit corrector settings and the measured horizontal linear dispersion. This technique has been tested for beam 1 at injection optics measurements of 26/02/26, which, however, reproduced the findings on α_c.

Second-order Dispersion The relative momentum offset from orbit is re-calculated by a least-square fit including model horizontal linear and second-order dispersion and the measured horizontal closed-orbit. Results are also given in Tables 1 and 2. The mean values are, respectively for beam 1 and beam 2, at top energy -1.6 ± 0.1 % and -0.2 ± 0.2 %, and at injection energy -3.5 ± 0.2 % and -2.6 ± 0.1 %. It is found that by including second-order dispersion the relative error shifts by up to 1 %.

Action Dependence Larger errors at injection energy could stem from non-linear optics contributions, driven by AC-dipole kicks. The action is obtained for on-momentum measurements using the peak-to-peak amplitude, $p2p$, and the model β-function, $\beta_{x,y}^{\mathrm{mdl}}$, $2J_{x,y} = \langle (p2p/2)^2/\beta_{x,y}^{\mathrm{mdl}} \rangle$. For analysed measurements at top-energy the horizontal action is smaller by up to roughly one order-of-magnitude as seen in Fig. 5. However, obtaining α_c directly from orbit readings do not show a clear dependence on the action, shown in the same figure at $\sqrt{2J_x} = 0$, nevertheless, this analysis suggests that the deviation without kicks could be roughly 1 % lower.

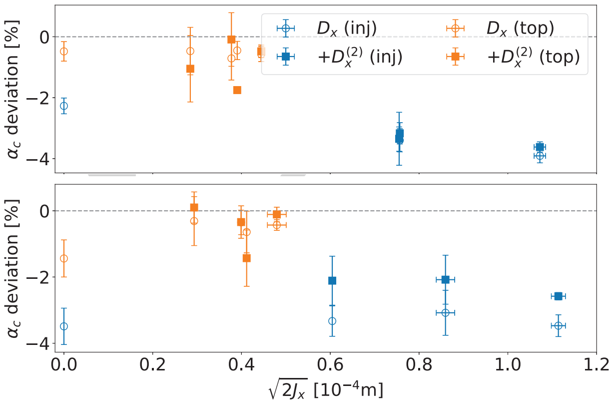

Figure 5: α_c Deviation over horizontal action.

SUMMARY

Optics measurements between 2016 and 2024 consistently revealed a systematic error of approximately 3 % between measured and model α_c. Complementary investigations by beam instrumentation identified a comparable scale error for the arc BPM calibration. New BPM polynomials have been applied at the start of 2025. Measurements in 2025 and 2026 show that this correction significantly improves measurements at top energy, however, injection optics measurements remain unchanged. A range of possible sources has been investigated from both beam dynamics and beam instrumentation perspectives. However, currently no clear source of this discrepancy has been identified.

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