FIRST PARALLEL ARC QUADRUPOLE BEAM-BASED ALIGNMENT USING K-MODULATION AT LHC

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Abstract

The Large Hadron Collider (LHC) is a circular hadron collider for high-energy particle physics. Off-centre beam passage through quadrupoles results in additional deflection, which needs to be compensated by corrector magnets. Beam-based alignment is an option to reduce the beam offset in the quadrupoles by using an estimate for the Beam Position Monitor (BPM) to magnet offset as a reference for the orbit feedback. The in-series powered LHC arc quadrupoles do not allow the variation of the quadrupole strength of individual magnets, this requires a parallel approach for the beam-based alignment. Various approaches based on k-modulation for parallel beam-based alignment are considered.

INTRODUCTION

Beams passing multipole magnets off-centre experience additional field components with lower orders than the misaligned magnets, introducing deflections and leading to orbit and optics deviations. Beam-Based Alignment (BBA) is used to reduce the beam offset in the magnet by using orbit correctors to steer the beam towards the magnetic centre of the magnets [1–3]. Transversely misaligned quadrupoles introduce additional dipole fields due to feed-down, leading to closed orbit, dispersion and tune errors, among other effects, compared to a perfectly aligned machine.

Traditionally, a BBA is performed on individual magnets [4] using static changes of magnet strength or on multiple magnets using periodic changes with different frequencies, for example, at LEP [5]. This requires the ability to vary the strength of individual quadrupoles, which is not feasible for the in-series powered arc quadrupoles of the Large Hadron Collider (LHC) [6] at CERN. Therefore, parallel BBA techniques are required, which have already been investigated for various machines, including EBS at ESRF [7] and SPEAR3 at SLAC [8]. This aims to reduce the offset of the beam relative to the magnetic centre of several elements simultaneously.

Since the time required scales linearly with the number of quadrupoles in a storage ring, individual BBA becomes a very time-consuming procedure for large machines such as the Future Circular electron-positron Collider (FCC-ee) [9–11], a proposed successor of the High-Luminosity LHC [12], and hence, a fast and precise BBA is necessary [13,14]. With its FODO structure and high number of quadrupoles in the arcs, the LHC is well-suited to test parallel BBA experiments for FCC-ee.

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MEASUREMENT SETUP

The LHC features two separate vacuum chambers, designed for proton-proton collisions with beam energies of up to 7 TeV [6]. Measurements are performed at an injection energy of 450 GeV with a pilot bunch having a population of $\approx 10^{10}$ protons per beam. For the presented beam test, arc 56 is chosen, a decisive factor being that all BPMs are functional. For the BBA, all horizontally focusing and defocusing quadrupoles with a strength of $\pm 8.7 \times 10^{-3}$ m^{-2} and a length of 3.1 m, distributed over 23.5 FODO cells, each 106.9 m long, are used. In each circuit, 47 in-series powered magnets are varied simultaneously, 23 in beam 1 and 24 in beam 2, or vice versa, depending on the magnet family. The horizontal correctors are located next to the focusing quadrupoles, while the vertical correctors are located next to the defocusing quadrupoles. In arc 56, beam 1 misses 2 correctors, namely MCBV.26R5.B1 and MCBV.28L6.B1.

BBA TECHNIQUES

BBA methods use the orbit changes due to the dipole component of a misaligned quadrupole either directly or through the corrector strength required to keep the orbit constant.

Parallel Quadrupole Modulation Scheme

For the parallel Quadrupole Modulation Scheme (pQMS), the strength of magnets powered in series is modulated simultaneously by up to ±0.36%, while two different orbit bumps are applied with a 12 mm peak-to-peak amplitude with a periodicity of 4 FODO cells.

The orbit response matrix $R_{i,j}$ describes at first order the relationship between a change of the strength $\triangle k_j$ of quadrupole j with beam to magnet offset $\triangle x_{\mathrm{mag},j}$ and the closed-orbit change $\triangle x_{\mathrm{beam},i}$ at BPM i [15, 16]. $R_{i,j}$ is obtained from simulations performed in Xsuite [17] using

$$R_{i,j} = \frac{\triangle x_{\mathrm{beam},i}}{\triangle k_j \cdot l_{\mathrm{quad},j} \cdot \triangle x_{\mathrm{mag},j}}.$$

The dipolar kick from the modulated off-centre quadrupole with beam offset $\vec{x}_{\mathrm{beam}}$ is obtained by inverting the matrix using the Moore-Penrose inverse or pseudo-inverse [18]

$$\vec{\theta} = R^{+} \cdot \vec{x}_{\mathrm{beam}}.$$

The BPM to quadrupole offset corresponds to the BPM reading at which the reconstructed kick strength vanishes. The beam position at which the kick strength disappears is again determined from the beam positions in the quadrupole

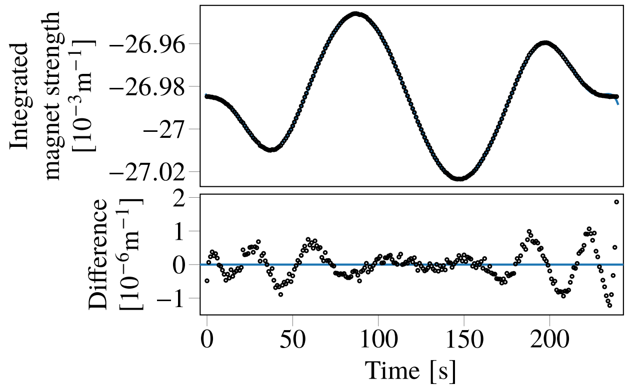

Figure 1: Modulation of the quadrupole strength and fit of an eleventh-order polynomial.

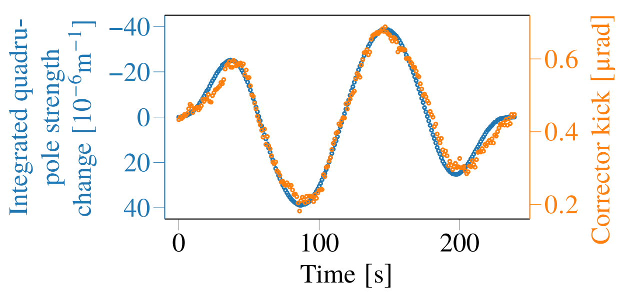

Figure 2: Modulation of the quadrupole current and change of the corrector strength by the orbit feedback.

and the reconstructed kick strengths. The calculation is performed for two orbit bumps, each shifted by one FODO cell, and the error-weighted average of the values is used as the final result.

K-Modulation

For this BBA approach, the strength of a group of quadrupoles is modulated in the range of ±0.15 %. The change of the integrated quadrupole strength and a fit of an eleventh-order polynomial to the data are shown in Fig. 1. The resulting variable kick strength of the quadrupoles is compensated by the orbit feedback that adjusts the corrector strengths to keep a constant beam position. Figure 2 clearly shows the modulation over time and the simultaneous change in correction strength due to orbit feedback. The ratio of the measured corrector and quadrupole strength variations yields the beam offset with respect to the magnetic centre of the quadrupole. A polynomial describing the temporal change in quadrupole strength is fitted to the corresponding change in corrector strength, and the offset is derived from the resulting fit parameters. Subsequently, the BPM offset is calculated from the quadrupole offset using the measured beam position at the nearest BPM and the previously determined beam–quadrupole misalignment.

RESULTS

The measurement of the BPM to quadrupole offsets using pQMS is performed twice for the horizontally defocusing quadrupoles (circuit kqd.a56) in the vertical plane and once for the horizontally focusing quadrupoles (circuit kqf.a56) in the horizontal plane. The vertical BBA is also performed using the technique of modulation, whereby only the horizontally defocusing quadrupoles (circuit kqd.a56) are used, since only vertical correctors are required for this method, which are located next to them. The modulation technique and pQMS are executed once for two propagating orbit bumps. Whilst the amplitude is varied for the pQMS BBA, the k-modulation is performed once for each bump with a peak-to-peak amplitude of ±4 mm. The results of the vertical BBA for one execution of the modulation-based and two executions of the pQMS BBA are shown in Fig. 3. The rms differences for beam 1 and 2 between the two pQMS BBA are 290 µm and 213 µm, respectively, and between pQMS and modulation in the range from 300 µm to 400 µm. The results for the horizontal BBA are shown in Fig. 4.

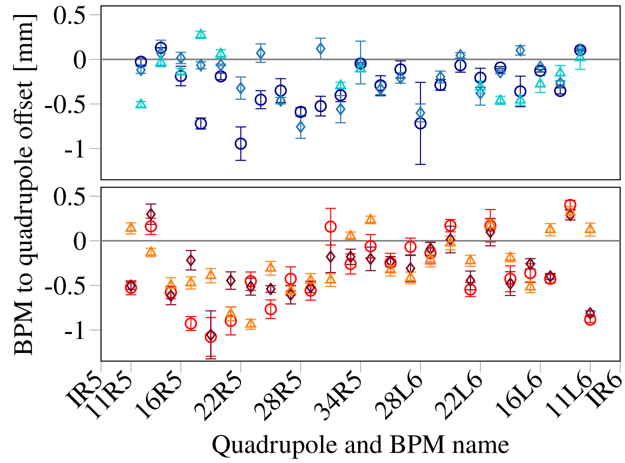

Figure 3: The results for beam 1 (upper plot) and beam 2 (lower plot) are shown for the vertical BPM to quadrupole offset determined using two runs of pQMS (circle, diamond) and modulation (triangle) for the defocusing quadrupoles using orbit bumps.

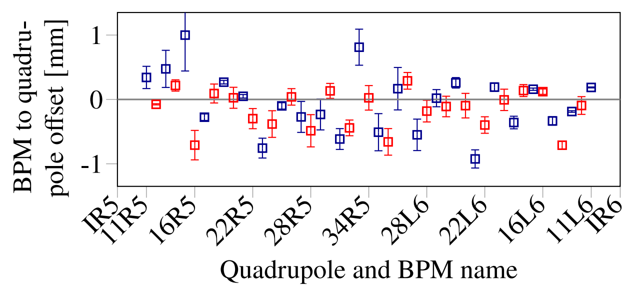

Figure 4: The results for beam 1 (blue) and beam 2 (red) are shown for the horizontal BPM to quadrupole offset determined using pQMS for the focusing quadrupoles.

A clear linear relationship between beam position and reconstructed quadrupole kick strength is observed for magnets at the extremities of the arc in beam 1 (left Fig. 5). However, significant deviations from linearity occur between MQD.20R5.B1 and MQD.20L6.B1, where a parabola provides a better description of the data (right Fig. 5). These non-linearities, which impact the BBA result by up to 1 mm,

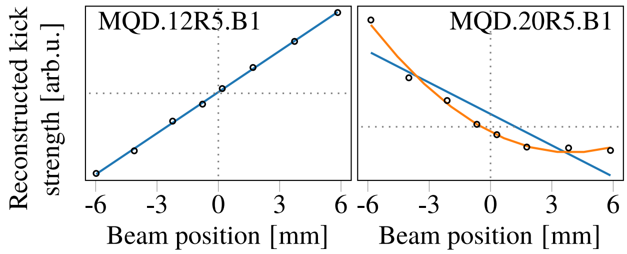

Figure 5: Data and fit functions for two single measurements in the vertical plane for beam 1, with the horizontal line indicating vanishing kick strength.

are confined to the centre of the arc for beam 1. Sextupole and octupole fields are ruled out by simulations as causes, leaving the origin of the non-linearity under further investigation.

K-modulation BBA requires correctors at the modulated magnets. With two missing corrector magnets in beam 1, the quadrupole-induced kicks are not corrected locally during modulation. The orbit feedback compensates by using two additional correctors positioned before and after the missing ones. Therefore, the observed changes in corrector strength during BBA are not solely attributable to the kicks from the neighbouring quadrupole and are excluded.

Additional uncertainties arise from the beam angles. For this test, large orbit bumps are deliberately introduced to enhance the induced orbit shifts. However, this results in significant beam angles between the BPM and the quadrupole centre. The resulting uncertainty scales with the bump amplitude, yielding 150 µm for an amplitude of 6 mm and 100 µm for an amplitude of 4 mm. Therefore, this constitutes a relevant source of uncertainty for the offset measurement.

β-FUNCTION MEASUREMENT

Measuring the average β-function $\overline{\beta}$ by modulation of the strength k of a quadrupole with length l is a standard technique, known as k-modulation, using the induced tune change $\triangle Q$ [19]. Here, instead of the thin element approximation, more terms based on [20, Eq. (10)] are used, assuming N identical quadrupoles:

$$\overline{\beta} = \frac{4\pi\triangle Q}{Nl\triangle k}\left[1 + \pi\cot(2\pi Q)\triangle Q - \frac{2\pi^2}{3}\triangle Q^2 + O\left(\triangle Q^3\right)\right].$$

The parametrised change in quadrupole strength is fitted to the horizontal and vertical tunes. The measurement results, their mean value and standard deviation, as well as the simulation result, are presented in Fig. 6. The first measurement is performed without a bump, the second with a bump amplitude of 2 mm, and all subsequent ones with 4 mm. Simulations showed a reduction of the average β-function due to the beam offset in the sextupoles. The measured values are therefore corrected upwards by up to 2.2 ‰ (0.55 ‰) for the 4 mm (2 mm) bump.

The reconstructed average β-function in the modulated quadrupoles is comparable to the simulated values and deviates from them by a maximum of 6.0 % for the horizontal

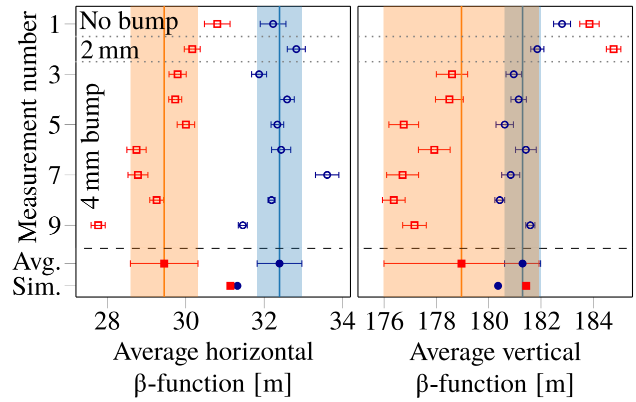

Figure 6: Measured and simulated average β-function in modulated quadrupoles for beam 1 (blue) and beam 2 (red).

and by up to 1.36 % for the vertical beta function in the defocusing quadrupoles. Overall, the simulated values are within the range of twice the standard deviation of the individual measurement results and are therefore compatible.

SUMMARY AND OUTLOOK

A parallel BBA beam test has been performed for arc quadrupole strings in the LHC for the first time. Two different approaches, pQMS and k-modulation, were tested, showing rms differences from 200 µm to 400 µm. In the middle region of the arc for beam 1, the reconstructed kick strength exhibits unexpected and significant deviations from a linear position dependence. These deviations could not be reproduced in simulations and require further investigations. Dominant sources of error arise from beam angles; further error sources include BPM noise and optics changes due to large orbits. The exact 90° phase advance per FODO cell in this arc constitutes a systematic source of degeneracy in the orbit response matrix. The resulting harmonic correlation between the corrector response vectors reduces the effective matrix rank and deteriorates its conditioning, thereby limiting the robustness of the orbit correction and the optics reconstruction, affecting both BBA approaches.

As a complementary measurement, the average β-function has also been measured using k-modulation. Results agree with simulations to within a few percent.

In future BBA studies, the use of smaller bump amplitudes reduces the beam angles and therefore the transverse position difference between BPM and quadrupole centre. For k-modulation BBA, the bumps could also be omitted, requiring slow modulation, sensitive orbit feedback, and increased modulation amplitude. Using a continuous modulation instead of two discrete strengths could improve the induced orbit shift measurements for the pQMS. Additionally, BBA measurements in arcs with not exactly 90° could be performed.

Considering the target of 10 µm to 20 µm BBA accuracy for FCC-ee, the BBA requires very precise position measurement and correction. The phase advance between the BPMs and correctors must also be taken into account in order to minimise systematic sources of error.

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