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To cite this article: C. Goffing *et al* 2025 *J. Phys.: Conf. Ser.* **3094** 012041

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Journal of Physics: Conference Series **3094** (2025) 012041 doi:10.1088/1742-6596/3094/1/012041

# Experimental validation of parallel quadrupole beam-based alignment at KARA

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**Abstract.** The Karlsruhe Research Accelerator (KARA), a synchrotron light source and test facility, at the Karlsruhe Institute of Technology (KIT), offers excellent conditions for testing different Beam-Based Alignment (BBA) approaches. Classical BBA approaches estimate the offset between the magnet and the closest BPM for one magnet at a time, and the required time for the BBA scales linearly with the number of magnets. Therefore, this approach is unsuitable for large storage rings like the Future electron-positron Circular Collider (FCC-ee). The time required is reduced using parallel BBA, where the magnet offset for several magnets is determined simultaneously. In this contribution, we compare new methods of parallel and individual BBA for quadrupoles at KARA. The measurement results are complemented with simulations using Xsuite and optics measurements.

## 1 Introduction

Beams passing off-centre through multipole magnets experience additional field components with lower orders than the misaligned magnets, causing additional deflections and focusing, resulting in orbit and optics deviations. Beam Based Alignment (BBA) is used to reduce the offset between the magnetic centre of quadrupoles and the beam by steering it through the magnetic centre of the magnets with orbit correctors [1–3]. Transversely misaligned quadrupoles introduce additional dipole fields due to feed-down, which lead to closed orbit and tune errors, among other effects, compared to a perfectly aligned machine. Minimizing orbit or tune errors by steering the beam through quadrupoles is the main principle of BBA studied here.

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]. Since the time required increases linearly with the number of quadrupoles in a storage ring, individual BBA is a very time-consuming procedure for machines such as the Future Circular electron-positron Collider (FCC-ee) [6]. In the past years, parallel BBA techniques have been investigated for various machines including EBS at ESRF [7] and SPEAR3 at SLAC [8], where the aim is to reduce the offset of the beam relative to the magnetic centre of several elements at the same time. Parallel BBA is also currently being explored for the FCC-ee [9].

Individual BBA of quadrupoles is performed regularly within the start-up procedure after a shutdown period at the Karlsruhe Research Accelerator (KARA) using a technique implemented in the MATLAB middle layer [10]. In this paper, we investigate a complementary technique for individual quadrupole BBA. The two techniques differ in the corrector settings, the data analysis and the additional power supply used. Furthermore, parallel quadrupole BBA techniques are applied for the first time at this synchrotron storage ring and compared with individual approaches.

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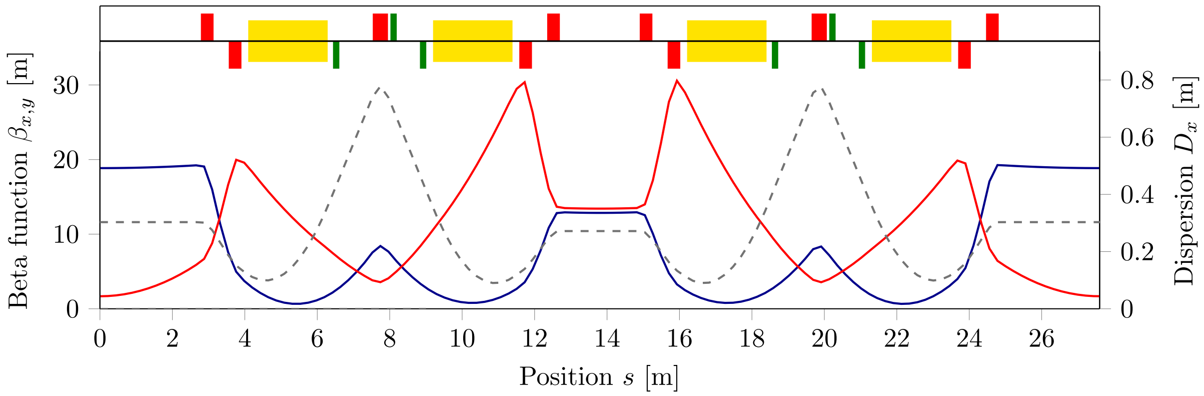


Figure 1: Lattice and optics functions for one sector. Dipoles are shown in yellow, quadrupoles in red and sextupoles in green. The lower part shows the horizontal (blue) and vertical (red) β-functions and the horizontal dispersion (grey).

## 2 KARA

KARA is a synchrotron light source and test facility with a Double Bend Achromat (DBA) lattice [11], operating with an electron energy in the range 0.5 GeV to 2.5 GeV. The storage ring is made up of 4 sectors, each consisting of a DBA and a mirrored DBA cell. The lattice and optics used for the study presented here are shown in Fig. 1. The 40 quadrupoles are divided into 5 families of 8 elements each. In total, 39 Beam Position Monitors (BPM) [12] and 28 horizontal and 16 vertical orbit correctors are installed [13, 14]. The flexible optics allows operation with non-dispersive straight sections, short bunches with positive and negative momentum compaction factor, as well as theoretical minimum emittance optics [15]. The latter is used for the BBA measurements with a horizontal and vertical betatron tune of 6.761 and 2.802, respectively. An additional power supply can be connected via a switching matrix to each quadrupole individually. The KARA lattice, therefore, allows applying both parallel and individual quadrupole BBA.

## 3 BBA techniques

### *3.1 Individual quadrupole BBA*

For each individual quadrupole an orbit corrector located at the opposite side of the ring is used to generate orbit-offsets at this quadrupole. By changing the corrector's strength, different orbits at the quadrupole are generated. For each of these settings the quadrupole gradient is varied and the induced orbit-shift caused by that modulation is measured at the BPM closest to that quadrupole. Furthermore, the induced orbit shifts at all BPMs are measured and plotted over the measured orbit at the modulated quadrupole, as shown in Fig. 2. The orbit at the modulated quadrupole, where the induced orbit shift

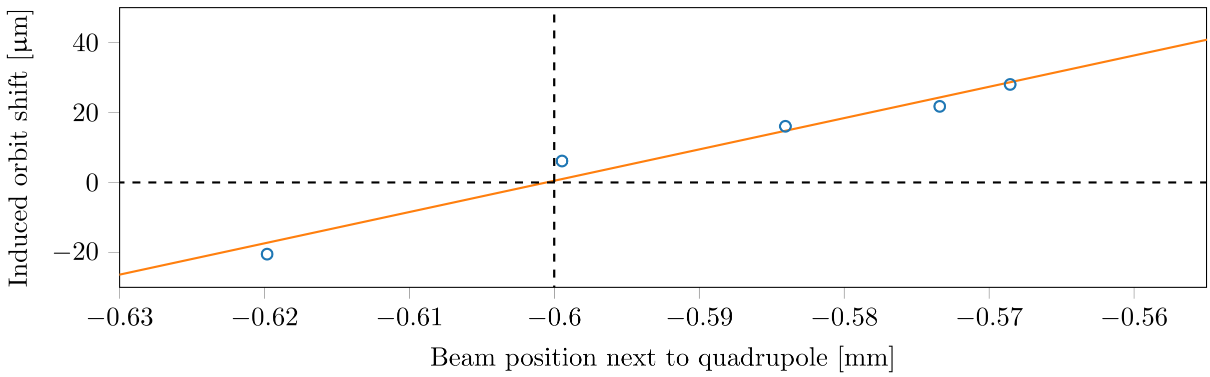


Figure 2: Dependence of measured induced orbit shift on beam position close to quadrupole.

Journal of Physics: Conference Series **3094** (2025) 012041 doi:10.1088/1742-6596/3094/1/012041

vanishes for all BPMs corresponds to the transverse offset of the magnet with respect to the closest BPM which, in the example shown, is −0.6 mm. While the already implemented individual BBA technique (rms BBA) uses the rms orbit shifts over all BPMs, the new technique (linear BBA) is based on measuring the induced orbit shift individually for all 39 BPMs. These 39 individual results are combined using an error-weighted mean value with the inverse error square of the fit uncertainty as weight. We note that the already implemented rms BBA uses individual trims for all correctors, whereas the linear BBA technique investigated here varies all correctors by the same amount. Another difference between the two individual BBA measurements is that for the already implemented rms BBA a unipolar power supply is used, allowing only an increase of the quadrupole gradient, while with the alternative linear BBA a bi-polar power supply unit is used and larger modulations are applied. Precycling the quadrupoles with a bi-polar power supply has also shown to reduce magnet hysteresis effects.

### *3.2 Parallel quadrupole BBA*

For parallel BBA, quadrupoles belonging to the same family are powered in series and therefore modulated simultaneously by up to ±0.5%. In contrast to the individual BBA, the beam position must be varied not only at the position of a single quadrupole but at all modulated magnets. This is achieved using two orbit correctors separated by $9.3\pi$ in the horizontal and $2.7\pi$ in the vertical plane.

The orbit response matrix $R_{i,j}$ describes the relationship between a change of the strength $\triangle k_j$ of quadrupole $j$ with offset $\triangle x_{mag,j}$. The closed-orbit change $\triangle x_{\mathrm{beam},i}$ at BPM $i$. $R_{i,j}$ is obtained from simulations using

$$R_{i,j} = \frac{\triangle x_{\mathrm{beam},i}}{\triangle k_j \cdot l_{\mathrm{quad},j} \cdot \triangle x_{\mathrm{mag},j}}, \tag{1}$$

with the deflection at the position of $j$-th quad given by $\theta_j = \triangle k_j \cdot l_{\mathrm{quad},j} \cdot \triangle x_{\mathrm{mag},j}$. The dipolar kick $\vec{\theta}$ from each of the eight modulated quadrupoles is obtained by [8]:

$$\vec{\theta} = (R^T R)^{-1} R^T \cdot \vec{x}_{\mathrm{mag}}, \tag{2}$$

or the Moore-Penrose inverse or pseudo-inverse [16]

$$\vec{\theta} = R^{+} \cdot \vec{x}_{\mathrm{mag}}. \tag{3}$$

We find that the differences of the two methods is negligible in practice. For the different orbits achieved by varying the strength of the two orbit correctors in each plane, the induced orbit shift caused by the change in quadrupole strength of the entire magnet family is measured. The kick angle in the respective quadrupoles is determined from these orbit changes. Similar to the individual BBA, the offset corresponds to the beam position at which the reconstructed kick strength vanishes and is determined using a linear fit.

## 4 Results

The measurements are supplemented by previous simulations using Xsuite [17], confirming the feasibility of individual and parallel BBA at KARA, while assuming a rms misalignment of 100 µm. Additionally, BPM noise of up to 1 µm is included and sextupoles deactivated, which show an rms accuracy below 10 µm for individual, and 50 µm for parallel BBA [18]. In addition, the distance between the BPM and the quadrupole limits the achievable accuracy of the offset determination. With KARA, it is up to 1.2 m.

Several beam tests have been performed with beam currents between 50 mA and 60 mA distributed equally over approximately 135 bunches and a beam energy of 2.5 GeV. All quadrupoles are pre-cycled to reduce magnet hysteresis. For the individual quadrupole BBA, the current is changed by ±5 A at each quadrupole individually. For the parallel BBA, the current is changed by ±1 A to ±1.5 A for all 8 quadrupoles in a family. The relative changes of the quadrupole currents, and hence, gradients are summarized in Table 1. We note, that the set and read-back values for the quadrupole currents could differ by up to a few tens of mA, which is not considered further here.

Both beam tests and complementary optics measurements based on turn-by-turn BPM data have been performed with and without sextupoles. The measured natural chromaticity is $-12.94 \pm 0.16$ in the horizontal and $-7.50 \pm 0.07$ in the vertical plane. Using the sextupoles, the chromaticity is trimmed to $-0.18 \pm 0.05$ in the horizontal and $0.76 \pm 0.11$ in the vertical plane. The β-beating is in the range of ±12 % in the horizontal and ±20 % for 90 % of BPMs in the vertical plane. A significantly larger β-beating of ±40 % and ±30 %, respectively, occurs during operation with natural chromaticity. Since the accelerator

Table 1: Relative changes of the quadrupole currents during the BBA for the five quadrupole families.

| Quadrupole family | $\lvert\frac{\Delta I}{I}\rvert$ individual BBA | $\lvert\frac{\Delta I}{I}\rvert$ parallel BBA |
|---|---|---|
| 1 | 1.46 % | 0.29 % - 0.44 % |
| 2 | 1.34 % | 0.27 % - 0.40 % |
| 3 | 1.73 % | 0.35 % - 0.52 % |
| 4 | 1.61 % | 0.33 % - 0.49 % |
| 5 | 1.65 % | 0.33 % - 0.49 % |

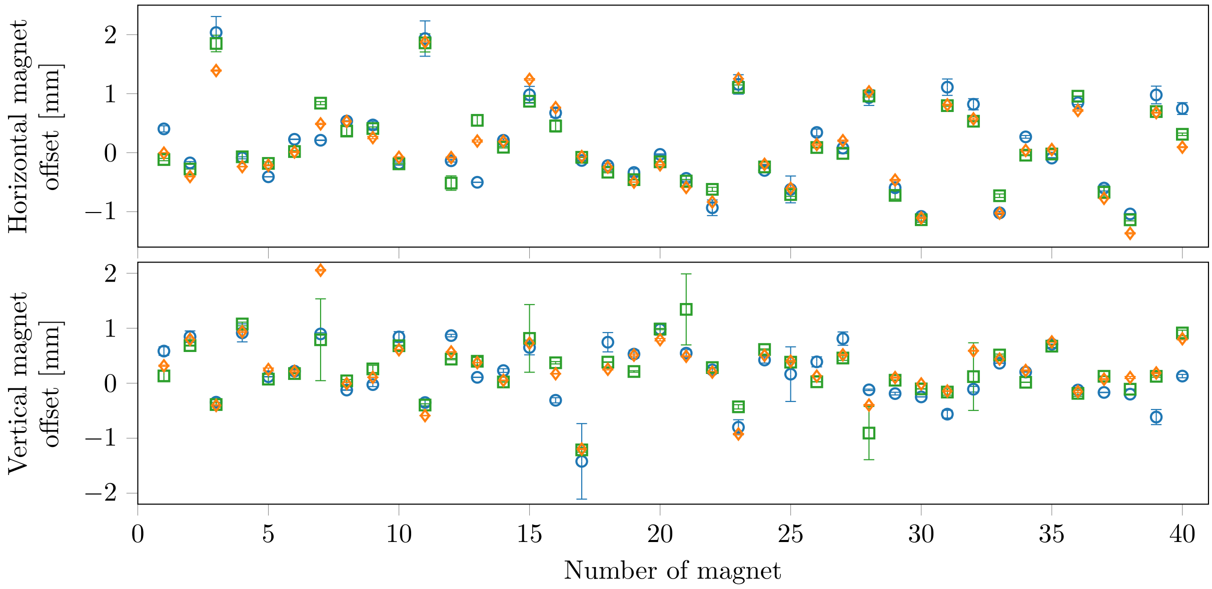


Figure 3: Estimated magnet offsets with respect to closest BPM using linear (blue), rms (orange) and parallel BBA (green).

model is adapted to the optics with activated sextupoles, the deviations are attributed to the reduced feed-down effects from the sextupoles. Changes in the chromaticity and tune are observed during the BBA tests, but it is not fully understood whether these are caused by the BBA, as significant tune drifts are also observed during operation without changing settings. The measurement results obtained are comparable with earlier measurements [19].

Sextupoles are switched off for the linear BBA with the aim of reducing non-linear effects in the optics, while the sextupoles are switched on for the rms BBA. The reproducibility of rms BBA, is in the range from 30 µm to 40 µm for the vertical and horizontal planes, respectively, and is calculated based on earlier offset estimates measured after the shut-down in summer 2024. The offsets determined with the two individual and the parallel BBA approaches are shown in Fig. 3 and show an rms deviation of 242 µm and 351 µm.

Parallel BBA is performed with sextupoles turned off and on. A total of 5 measurements are carried out with the sextupoles switched off. All measurements agree with a rms error of $(13.2 \pm 1.9)$ µm in the horizontal and $(137 \pm 12)$ µm in the vertical plane. We note that increasing the amplitude of the corrector strength and the associated position changes reduces the deviations and measurement uncertainties in the vertical plane for the subsequent measurements. To validate the reproducibility, parallel BBA is performed with activated sextupoles in different fills. While the reproducibility with activated sextupoles is within 35 µm to 50 µm in the horizontal and vertical planes respectively, local outliers up to 0.7 mm in horizontal and 1.3 mm in vertical are observed, as shown in Fig. 4. To find the best settings for parallel BBA parameter scans are performed. It is found that the amplitude of the quadrupole current change has little impact on the accuracy of the BBA. However, large effects are observed with variations of the orbit changes using the amplitude and the relative signs of the corrector strength changes. The

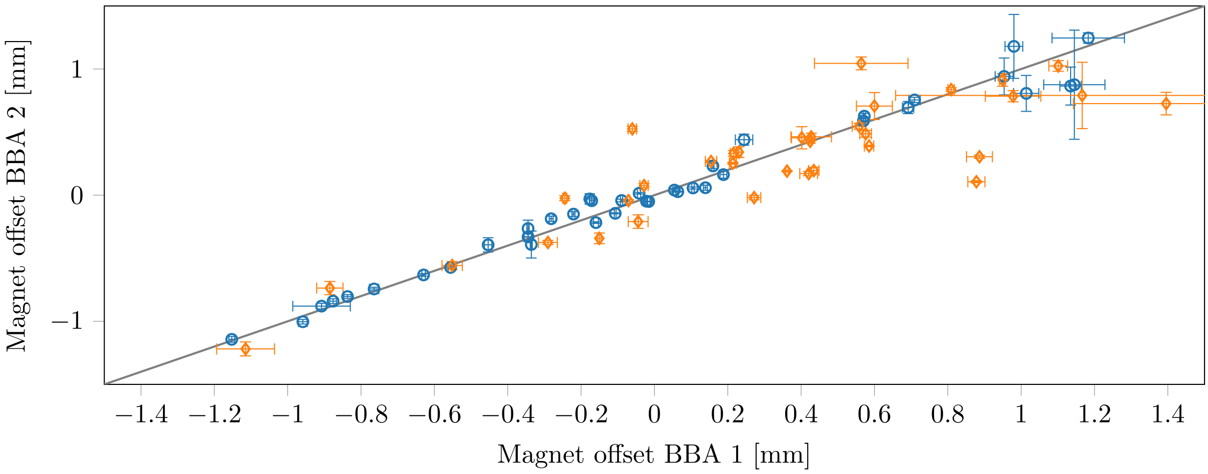


Figure 4: Reproducibility of estimated horizontal (blue) and vertical (orange) offsets with two parallel BBA measurements with activated sextupoles (BBA 2) and deactivated sextupoles (BBA 1).

same selection of orbit correctors, two for the horizontal and two for the vertical plane, was used for all offset measurements with the parallel BBA. For further optimisations, different orbit correctors could be selected, as large offset deviations and uncertainties occur with the same magnets, regardless of the choice of the parameter values mentioned. Comparing parallel BBA results with and without sextupoles, the rms error is 57.3 µm horizontally and 263 µm vertically.

Comparing individual with parallel techniques shows an rms deviation of 174 µm and 334 µm for rms BBA (with sextupoles) or 281 µm and 358 µm for the newly implemented linear BBA (without sextupoles). However, local outliers, showing deviations of up to 1.3 mm occur, the origin of which remains to be investigated. One reason for the different results could stem from using simulated orbit response matrices based on an accelerator model. Future studies could aim to reduce discrepancies between the machine and the model using measurements. The improved model could also improve the parallel BBA technique by providing a response matrix which fits better to the accelerator.

## 5 Summary and outlook

For the first time, a parallel BBA was implemented and used for offset determination in KARA. This BBA reduces the time required from around 90 min to less than 10 min. The reproducibility is only slightly worse despite a significant reduction in the amplitude of the quadrupole strength change. Deviations of the model and different optics could explain the deviating results of the 3 methods. Further potential for improvements in accuracy lies in the selection and variation of the strength of the orbit correctors, as well as in the adaptation of the orbit response matrix to the machine using an improved accelerator model or measurements.

## 6 Acknowledgements

This project has received funding from the European Union's Horizon Europe Research and Innovation programme under Grant Agreement No 101057511 (EURO-LABS). We would like to thank X. Huang (SLAC) for inspiring discussions.

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