# BEAM-BASED ALIGNMENT OF BEAM POSITION MONITORS AT SLS 2.0

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## *Abstract*

Large initial beam position monitor (BPM) offsets have to be reduced by one order of magnitude by means of beam-based calibration (alignment) (BBA) in order to match the element-to-element magnet alignment error. At SLS 2.0 the BBA will be performed with respect to adjacent auxiliary quadrupole magnets, which are also employed for optics and tune correction. Different static and dynamic techniques can be applied to determine the offsets. The error of the individual measurements needs to be at the µm level to guarantee the necessary reproducibility of position and angle at the beamline source points on medium- and long-term time scales.

## INTRODUCTION

Initial beam position monitor (BPM) offsets with respect to the neighboring magnets are typically more than one order of magnitude larger than the element-to-element alignment of the magnet assembly. The contributions are of electronical and mechanical origin. These can be reduced by careful calibration of the electronics and surveying the BPM blocks after the installation of the vacuum system. Nevertheless the remaining offsets can be significant. Without further correction the machine performance can be significantly degraded. Especially the feed-down from beam offsets in sextupoles generates beta-beat and coupling and is thus detoriating the dynamic aperture. As a consequence beam assisted calibration (beam-based alignment, BBA) techniques need to be exploited. Typically the BPMs are calibrated with respect to the magnetic centers of adjacent quadrupoles or sextupoles by measuring difference orbit or tune changes. The quadrupole method is preferred since the precision is easily pushed to the 1 µm level. The alignment to sextupoles is then defined by the magnet alignment tolerances. It should be noted that the high precision is needed to guarantee the medium- to long-term reproducibility of reference orbit positions for beamlines. For commissioning it is sufficient to reduce the remaining BBA offsets to the element-to-element alignment error of 30 µm.

## BBA STRATEGY

The storage ring consisting of 12 identical arcs, features 10 BPMs (double arrows in Fig. 1) and 9 dipole correctors per arc. In addition there are 22 multi-purpose magnets installed, which implement an auxiliary quadrupole, skew-quadrupole and octupole function. These magnets share the same support structure with the neighboring sextupoles, as can be seen in Fig. 2. This allows for a high precision alignment / calibration of the magnetic axis of the auxiliary quadrupoles and adjacent sextupoles to better than 10 µm, which has to be compared to the envisaged element-to-element alignment tolerance of 30 µm . The BPMs will be calibrated with respect to the auxiliary quadrupoles. The sketch in Fig. 3 depicts the stack of BPMs, correctors, sextupoles and quadrupoles in the arc.

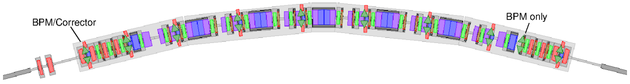

Figure 1: One of 12 arcs featuring 10 BPMs (double arrows) and 9 adjacent correctors [1].

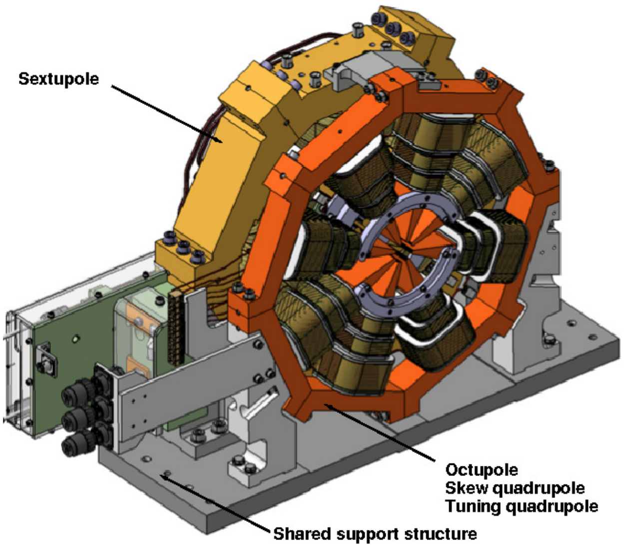

Figure 2: 3D drawing of a sextupole and an adjacent multi-purpose magnet with octupole, skew quadrupole and quadrupole function sharing the same support structure in order to decrease the relative alignment error to better than 10 µm [1].

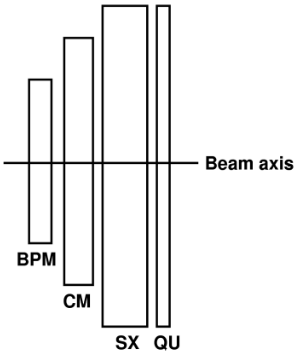

Figure 3: Sketch of adjacent BPM, corrector (CM), sextupole (SX) and auxiliary quadrupole (QU) in the arc.

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## BBA PROCEDURE

To illustrate the envisaged BBA procedure an example from the SLS is chosen, which is depicted in Fig. 4. A quadrupole strength variation leads to an rms distortion of the closed orbit (rms difference orbit) which is proportional to the beam offset within the magnet. The reading of the adjacent BPM reveals the BBA offset for a vanishing rms difference orbit. In Fig. 4 the square of the rms difference orbit is plotted as a function of the BPM reading. The precision of the measurement is significantly increased by varying the beam position in the quadrupole and BPM by exciting a closed orbit bump involving three adjacent dipole correctors. It is beneficial to have a corrector scheme that allows the variation of only one BPM reading at a time. The minimum of the parabola reveals the offset with respect to the magnetic center of the quadrupole. In this particular example the offset is found to be 79 µm with a statistical error of 0.5 µm. It becomes immediately apparent that an increase of the bump amplitude, the number of bump steps and/or the quadrupole strength variation leads to a better precision of the measurement. A good compromise needs to be found since the explorable parameter space is limited by available magnet strength and maximum possible orbital tune change. The temporal duration of the measurement (≈3 minutes in the presented example) is also influencing the precision, since orbit drifts contribute to the rms difference orbit.

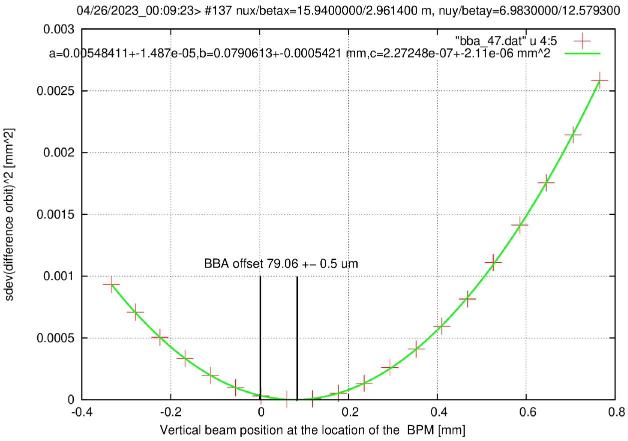

Figure 4: Example of a vertical BBA measurement at SLS. In addition to the quadrupole variation the beam position at the BPM and quadrupole is varied using an orbit bump.

The described BBA procedure can be integrated with the operation of a fast orbit feedback (FOFB). In this case the rms difference orbit measurement taken before and after the quadrupole current change is replaced by a difference kick measurement since the FOFB ideally transforms the orbit variation to a single kick change of the corrector in the vicinity of the quadrupole. The knowledge of this kick is sufficient to determine the BBA offset since the quadrupole variation is known. To increase the precision of the measurement the orbit setpoint of the BPM within the FOFB loop is altered. An example of such a measurement for the SLS is shown in Fig. 5, where the vertical difference kick (red crosses) is plotted as a function of the BPM position reading (the orbit setpoint). The BBA offset is found by linear regression (blue line) and taking the value for a vanishing kick, which corresponds to the center of the quadrupole. This technique has the advantage that it suppresses all orbit fluctuations outside of the measurement region, since the FOFB keeps the orbit constant within the bandwidth of the FOFB loop.

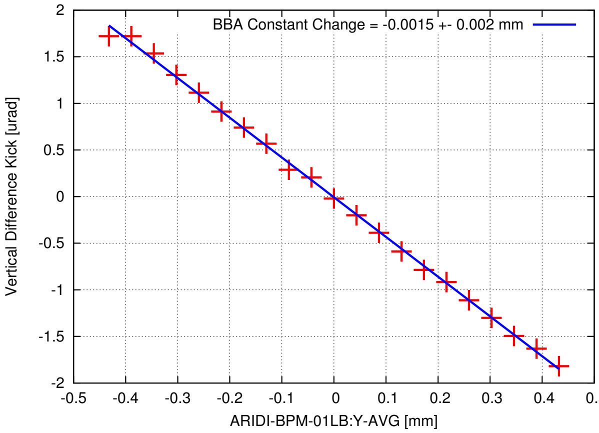

Figure 5: Vertical difference kick (red crosses) as a function of the BPM position reading. A linear fit (blue line) determines the BBA offset.

## BBA SIMULATIONS

A full simulation of the BBA procedure has been performed for SLS 2.0 using TRACY-3.5 [2] to find the optimum position in BBA parameter space aiming for maximum precision at minimum distortion. The simulation includes the expected residual BPM noise of 50 nm up to 1 kHz and a finite corrector resolution of 20 bit for the strength range of ±400 µrad . The horizontal correctors will feature a 50% larger maximum strength at commissioning time. But this range will be reduced for early operation to restore the best corrector resolution within the FOFB loop. We scanned closed orbit bump amplitudes from 50 to 150 µm. The integrated quadrupole strength was varied from 6 to 18 1/km which corresponds to 20–60% of the maximum strength of 30 1/km. The 40% margin is needed since the auxiliary quadrupoles have static settings for optics and tune correction. Figure 6 depicts the horizontal and vertical BBA simulation for one arc BPM varying the quadrupole strength by 60%. The bump scan covered ±100 µm . In this example the precision of the simulated measurement is well below 1 µm in both planes.

Figure 7 shows how the BBA error (mean, rms and max. for all 120 arc BPMs) evolves with changing quadrupole variation $dq$ and with changing bump amplitude for $dq$ = 12 1/km. In this case a $dq$ of 12 1/km and a bump amplitude of 100 µm allows obtaining a maximum BBA error below 2 µm .

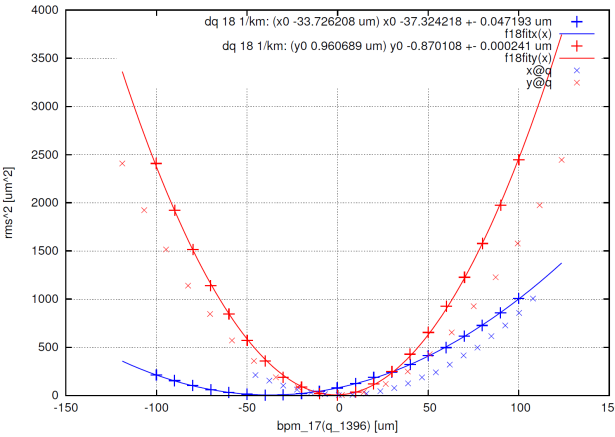

Figure 6: Horizontal (blue) and vertical (red) BBA simulation for one arc BPM varying the quadrupole strength by 60% (18 1/km). The bump scan covered ±100 µm . The estimated precision of the BBA offsets ($x_0$, $y_0$) is well below 1 µm in both planes for the chosen parameters. The crosses without parabola fit visualize the position changes in the quadrupole.

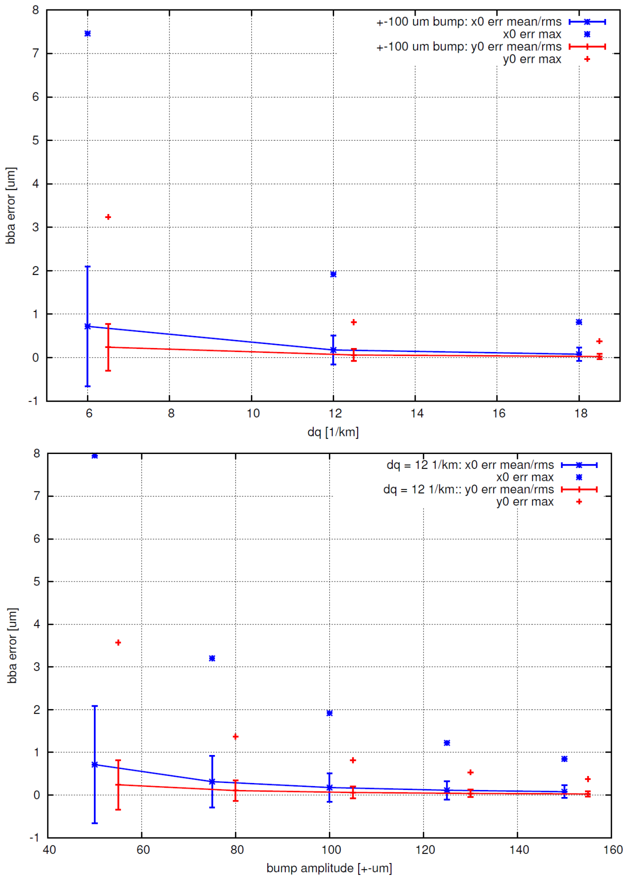

Figure 7: BBA error (mean, rms and max. for all 120 arc BPMs) as a function of quadrupole variation $dq$ for a bump amplitude of 100 µm (top) and as function of bump amplitude for $dq$ = 12 1/km (bottom).

Figure 8 summarizes all results in a 2D representation. The combination of a ±100 µm bump and 40% variation of the quadrupole strength turns out to provide the necessary resolution of the BBA measurement for commissioning and early user operation. The first option would be a slow scan, which takes less than a minute per BPM. Since correctors and quadrupoles can be triggered by the timing system, much faster scans can be realized as a next step. Once the FOFB is running, scans can be realized within the FOFB loop, making BBA nearly transparent even during beamline operation. The ultimate speed limit is defined by the maximum modulation frequency of 8 Hz for the quadrupole strength limit of 30 1/km.

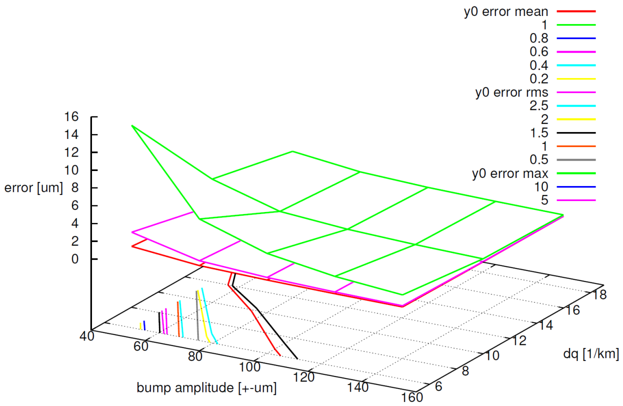

Figure 8: BBA error (mean, rms and max. for all 120 arc BPMs) as a function of quadrupole variation $dq$ and bump amplitude.

## SUMMARY

The concept for the envisaged BBA procedure for SLS 2.0 has been outlined. It has been shown by simulation studies that BBA can be performed with the necessary precision for commissioning and user operation guaranteeing µm reproducibility.

## REFERENCES

[1] H. Braun *et al.*, "SLS 2.0 Storage Ring. Technical Design Report", PSI Report No. 21-02, 2021, `https://www.dora.lib4ri.ch/psi/islandora/object/psi:39635`

[2] J. Bengtsson, "TRACY-3.5 Source Code", `https://github.com/jbengtsson/tracy-3.5`