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BEAM-BASED ALIGNMENT FOR LCLS-II CuS LINAC-TO-UNDULATOR QUADRUPOLES*

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Abstract

An advanced method for beam-based alignment that can simultaneously determine the quadrupole centers of multiple magnets has been applied to the LCLS-II CuS linac-to-undulator (LTU) section. The new method modulates the strengths of multiple quadrupoles and monitor the induced trajectory shift. Measurements are repeated with the beam trajectory through the quadrupoles steered with upstream correctors, from which the quadrupole centers can be obtained. Steering of the trajectory to minimize the induced trajectory shift is also done for finding the quadrupole centers.

INTRODUCTION

Steering the beam through the centers of quadrupole magnets in a linac or transport line has many benefits, for example, reducing spurious dispersion and reducing emittance dilution. While mechanic alignment and survey are a critical step to establish the beam path, it is usually necessary to perform beam-based alignment (BBA) measurements during the commissioning stage of a new accelerator. Beam-based measurements not only can identify potential alignment errors, but also determine the actual quadrupole centers as seen by nearby beam position monitors (BPM), which can be used as steering targets. The orbit target obtained by BBA automatically includes both the mechanic errors and the electronic errors.

The usual model dependent method initially proposed for rings [1–3] is applicable for one-pass systems as well. The method modulates the strength of a quadrupole magnet and observes the orbit shift on a BPM. Using the orbit response from a kick by the quadrupole to the BPM, the kick angle change due to the modulation can be obtained from the orbit shift, which can then be converted to beam orbit offset at the quadrupole with the known change of integrated gradient on the magnet. Mathematically, we have

$$\Delta x_b = R_{bq}\theta_q, \qquad \theta_q = \Delta K L x^{\rm off}, \tag{1}$$

where Δx_b is the orbit shift at the BPM, θ_q is the kick angle due to modulation, R_{bq} is the orbit response from the quadrupole to the BPM, ΔK is the change of quadrupole gradient, L is the length of the magnet, and $x^{\rm off} = x_{\rm center} - x_{\rm beam}$ is the horizontal distance of the quadrupole center measured from the beam trajectory. A similar formula applies to the vertical plane, but with the sign of integrated gradient reversed. The orbit response is calculated with a lattice model. Lattice errors and calibration errors of magnet strengths and BPM readings have an impact on the quadrupole center measurement.

One can steer the beam through the center of the quadrupole to minimize the orbit shift due to quadrupole gradient modulation [4]. As this can be done empirically, the quadrupole center can be determined without a lattice model. The quadrupole modulation system (QMS) method, also known as the "bow tie" method [5], is based on the same principle. It scans the orbit at the quadrupole to find the point with zero orbit shift with interpolation. The quadrupole centers found with these model independent methods are not affected by lattice errors or calibration errors.

The above methods target one quadrupole at a time. In reality, sometimes a number of quadrupoles are powered by a common power supply. In such a case, current shunting can be used to change the strength of one quadrupole. However, shunting a quadrupole is a slow and relatively complex process. A method to simultaneously determine the centers of multiple quadrupoles was recently proposed in Ref. [6]. It uses the response matrix method to correct the induced orbit shift with corrector magnets.

In this study, we applied a new method that can also perform BBA for a number of quadrupoles simultaneously. They not only address the challenge of BBA for quadrupoles on a serial power supply, but also can speed up the BBA process. The method is described in details in the next section and its application to the copper LTU section of the Linac Coherent Light Source (LCLS)-II in experiments is used as an illustration in the section following that. A method to scan the trajectory at the quadrupoles with combined knobs to minimize the induced orbit shift is also discussed.

METHOD

The model dependent method as described in Eq. (1) can be readily extended to multiple quadrupoles. Multiple BPMs are included to measure the trajectory shifts due to quadrupole modulations. In this case, the equations become

$$\Delta x_i = R_{ij}\theta_j, \qquad \theta_j = [\Delta K L]_j x_j^{\rm off}, \tag{2}$$

where $i = 1, 2, \cdots, M$ are indices for the BPMs, $j = 1, 2, \cdots, N$ are indices of quadrupoles. If the BPMs and quadrupole are properly chosen, the kick angles by the quadrupoles for a certain modulation pattern can be obtained by inverting the response matrix $\mathbf{R}$,

$$= (\mathbf{R}^T\mathbf{R})^{-1}\mathbf{R}^T\Delta\mathbf{x}, \tag{3}$$

where ^{T} is to take transpose of a matrix. For the scheme to work, the matrix $\mathbf{R}^T\mathbf{R}$ needs to be full rank. Therefore, one

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or more BPMs between two successive quadrupoles in the target group are necessary.

We can also adopt the same approach used in QMS to obtain model independent BBA results for multiple quadrupoles, i.e., by steering the beam at the quadrupole locations and finding the zero-crossing of orbit shift with respect to steering. For each quadrupole, the kick angle vs. beam trajectory data can be fitted to a linear curve to determine the zero-crossing position. Two or more correctors can be used, with at least one upstream of all quadrupoles. The goal is to scan a sufficiently large trajectory range, which either covers the zero-crossing position or allow it to be found by extrapolation.

This method is applicable to storage rings. It has been successfully tested on the SPEAR3 ring.

APPLICATION TO LCLS-II COPPER LTU-SXR

The LCLS-II cu LTU-SXR is a 300-m long transport line that connects the copper linac to the soft X-ray undulator. There are a few groups of quadrupoles that are on serial power supplies.

For example, in the dog-leg section, the four quadrupoles, QDL12, 15, 16, and 19 are on a common power supply. The two middle magnets in the group are next to each other. However, since each quadrupole is co-located with a BPM, it is still possible to resolve the contributions of the individual quadrupoles. Figure 1 shows the calculated trajectory response matrix observed by BPMs due to kicks at the quadrupoles (marked by vertical bars). It is worth noting that in both planes, the QDL 12 and 16 trajectory responses are opposite in phase downstream of the latter magnet, and likewise for QDL15 and 19. Consequently, if the two magnets apply an identical kick to the beam, the downstream BPMs will not detect an trajectory shift. Nonetheless, the BPMs between the two can reveal the contribution of the upstream magnet.

The four quadrupole magnets in the group have equal magnitudes for the integrated gradients, but with alternate signs. The induced orbit shifts are measured by changing the strengths of the magnets by an equal percentage. Figure 2 shows an example of the induced orbit shifts for 5 modulation levels. The design dispersion is finite on some BPMs in this area and there is also residual dispersion on other BPMs. The energy jitter causes distortion to the induced orbit shifts. To miminize the jitter effect, we measure the orbit 30 times and use the average trajectory. In addition, the jitter effect is eliminated by removing the dispersion like component from the induced orbit shifts, using the following formula to obtain the energy deviation,

$$\delta = \frac{\Delta\mathbf{r}\cdot\mathbf{D}}{\mathbf{D}\cdot\mathbf{D}}, \tag{4}$$

where $\mathbf{D} = (\mathbf{D_x}, \mathbf{D_y})$ and $\Delta\mathbf{r} = (\Delta\mathbf{x}, \Delta\mathbf{y})$ are vectors that combine the functions on both planes on selected BPMs.

The corresponding kick angles by the quadrupoles due to the modulation are obtained with Eq. (3). Figure 3 shows

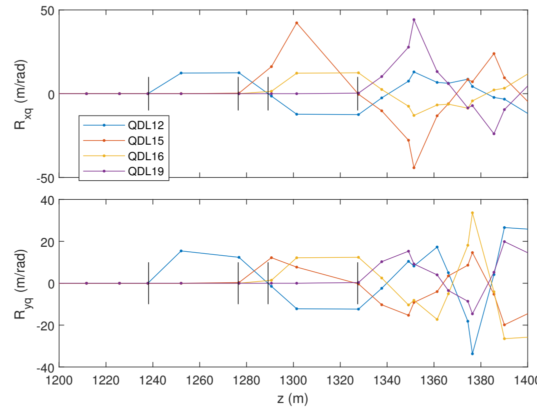

Figure 1: Calculated quadrupole-to-BPM trajectory response matrix for the QDL12 group. Top: horizontal; bottom: vertical.

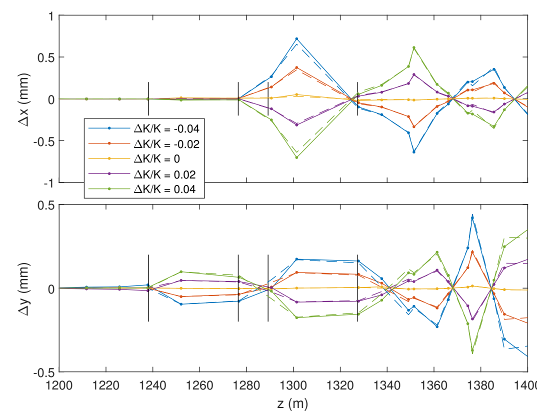

Figure 2: An example of measured induced orbit shifts for the QDL12 group. Solid lines are measured; dashed lines are calculated with the kick angles and the response matrix. Top: horizontal; bottom: vertical.

the kick angle vs. the modulation levels for each quadrupole. From the slope of the line and the change of integrated gradient, the offset of the quadrupole center can be calculated. For example, for the example data shown in Fig. 3, the θ_x vs. $\frac{\Delta K}{K}$ slope for QDL15 is -0.435 ± 0.059 mrad and the integrated gradient was $KL = 0.1104$ m^{-1}, hence the quadrupole center offset is $x^{\rm off} = -3.94 \pm 0.53$ mm. Knowing the initial trajectory at the quadrupole is $x_0 = 1.69$ mm from the co-located BPM, the horizontal coordinate for the magnet center is found to be $x_{\rm center} = -2.25 \pm 0.53$ mm. The large error bar comes mostly from the under-constrained pattern for QDL15 and QDL19 to apply equal kicks. The error sigma can be reduced by using a stronger gradient modulation. The quadrupole center position obtained this way depends on the magnet calibration.

To obtain model independent results of the quadrupole centers, we repeat the BBA measurements with changes to

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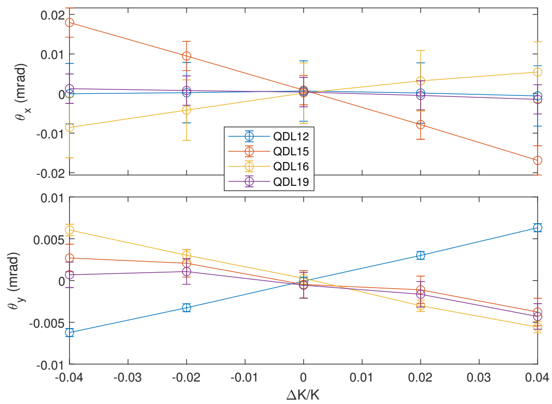

Figure 3: The kick angles derived from the induced orbit shifts for the QDL12 group example. Top: horizontal; bottom: vertical.

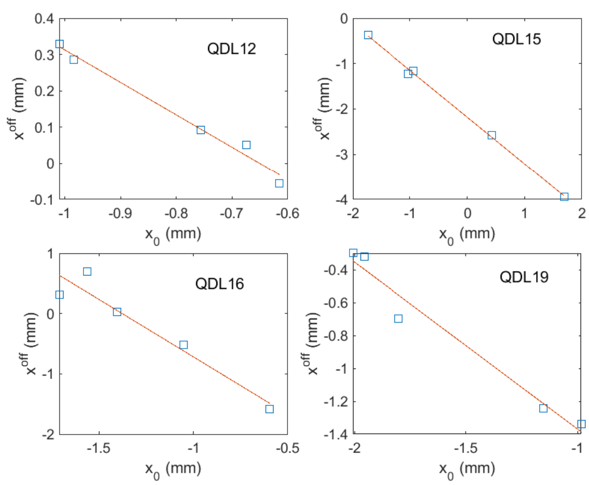

Figure 4: Horizontal quadrupole offsets vs. beam trajectory at the magnets for the QDL12 group. The quadrupole center corresponds to the zero crossing position.

the trajectories at the quadrupole locations. A scheme may be implemented to steer the trajectory with upstream and local correctors and to correct the trajectory at a short distance downstream so that the trajectory variations are kept local. Figure 4 shows the horizontal quadrupole center offsets for the QDL12 group quadrupoles for 5 different trajectories. The quadrupole center corresponds to the horizontal intercept of the x_{off}-vs-x_0 line. The QDL15 horizontal center position is found to be -2.11 mm, which is close to the model dependent value (the average of the 5 measurements is -2.17 mm).

The method of grouping quadrupoles in BBA measurements can be used to expedite the BBA process. In such a case, the quadrupoles can be chosen to have more BPMs between the magnets within the same modulation group. This helps reduce the error bars.

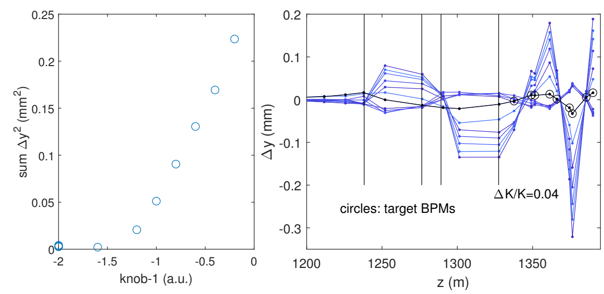

Figure 5: Minimization of the induced orbit shift for the vertical plane for the QDL12 group using a combined knob. Left: objective function vs. knob; right: the induced orbit shifts. The black curve corresponds to the minimal induced orbit.

MINIMIZING INDUCED ORBIT SHIFT

The method of correcting the induced orbit shift by quadrupole modulation with corrector magnets as proposed in Ref. [6] can be implemented as a minimization problem, using properly arranged corrector knobs as optimization variables. For example, the SVD patterns of the orbit response matrix of trajectory at the quadrupoles with respect to correctors upstream and between the magnets can be used as combined steering knobs. Additional downstream correctors can be used to cancel the steering effects. The sum of squares of the induced orbit on selected BPMs can be used as the minimization objective. Figure 5 shows an example of scanning one such combined knob for the vertical plane for the QDL12 group. The trajectory with minimal induced orbit shift is found to agree with the BBA results with the method described in the previous section.

The minimization method can be extended to include all quadrupoles in a section, in which case, a trajectory with minimal impact from quadrupole misalignment can be found. This is useful as in many cases there are not enough correctors to steer the beam onto the target trajectory as determined by BBA. If the modulation pattern is by equal percentage for all magnets, it becomes similar to the dispersion free correction scheme [7].

SUMMARY

We propose a new method to perform beam based alignment (BBA) which can determine the centers of multiple quadrupoles simultaneously. The method uses the orbit response matrix from kicks at quadrupole locations to BPMs to determine the kick angles due to quadrupole gradient modulations and in turn the distances between the current trajectory and the magnet centers. By repeating the measurements with trajectories varied and finding the position with zero kicks, the quadrupole centers can be obtained in a model independent manner. We have applied the method to the LCLS-II transport line LTU-SXR.

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