BEAM BASED ALIGNMENT OF AN X-FEL UNDULATOR SECTION UTILIZING THE CORRECTOR PATTERN

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Abstract

Beam based alignment of the undulator section is one of the delicate issues in beam commissioning and regular beam tuning of X-FEL facilities since the tolerance on the electron beam orbit straightness is tight, typically a few µm rms. A new approach to align beam position monitors based on dipole corrector strengths is under investigation for the PSI future X-FEL facility, SwissFEL. The methodology and simulations applied to the SwissFEL undulator section are presented in this paper.

INTRODUCTION

Beam based alignment (BBA) of the undulator section is one of the delicate issues in beam commissioning and regular beam tuning of X-FEL facilities since the tolerance on the orbit straightness is tight, typically a few µm rms.

A BBA method which identifies position misalignments of beam position monitors (BPMs) and quadrupoles [1] has been established at the LCLS and was successful in achieving lasing. A misalignment of a BPM changes its reading and a shift is independent of the beam momentum. In contrast, a quadrupole misalignment, which introduces a feed-down dipole component, varies the downstream beam orbit depending on the beam momentum. Therefore the beam orbit measurements for various beam momenta allow one to find these misalignments.

The procedure, however, is rather complicated. In order to find the avobe misalignments precisely, a wide variation of beam momentum is required, where one must ensure the beam transmission to the beam dump. Although an orbit measurement for two different beam momenta is minimal, one or two more measurements are performed to increase accuracy. According to the operation experiences at the LCLS, the entire procedure is usually completed within a few hours [2].

A new approach is under investigation for the PSI future X-FEL facility, SwissFEL, motivated by possible simplification of beam commissioning and machine tuning. The hard X-ray undulator section of SwissFEL is described with technical details in [3]. The BPM and quadrupole are paired on common motorized support (BPM-Quad unit). It is noted that the undulator is to be situated on an independent girder at SwissFEL while all three components are on the same girder at the LCLS. The dipole corrector is integrated into the quadrupole as additional winding coils.

The BBA procedure in this layout consists essentially of two steps: 1) aligning the BPM-Quad units onto a line as straight as possible and 2) aligning the undulators with respect to the electron beam orbit determined by the aligned BPMs. The proposed BBA algorithm, in order to find misalignments of the BPM-Quad units, requires only measuring the corrector strengths needed to steer the electron beam to the BPM centers (for the nominal beam momentum). With an orbit feedback in operation, these are available immediately, and thus the first step can be performed in a few minutes. The second step, once done, may not be always necessary since the alignment tolerance for the undulator is an order of magnitude looser than that of the BPM-Quad unit.

The methodology and simulations applied to the SwissFEL undulator section are presented in this paper.

BBA ALGORITHM

The BBA algorithm utilizes information contained in the dipole corrector strengths needed to steer the electron beam to the BPM centers. These are determined by two contributions, that is, dipolar error fields and BPM misalignments. The first contribution may contain undulator error field, stray field and feed-down dipole component from quadrupoles. The undulator error field must not be significant by definition to realize lasing. Typically the electron beam orbit through an undulator is controlled within the 1 µm level. The stray field must be also negligible or enough suppressed/shielded, and furthermore the BBA algorithm is able to filter out the influence of periodic and uniform stray field. The feed-down dipole component can be avoided by aligning quadrupoles with respect to the pair BPMs based on beam measurements. Therefore the second contribution, i.e. the BPM misalignments, mainly determines the corrector strengths and can be identified.

The BBA is performed by moving the BPM-Quad units so as to minimize the deviation of corrector strengths. By minimizing the deviation with respect to the average strength, periodic and uniform error field can be excluded as long as the initial BPM misalignments are random. Figure 1 illustrates an ideal BPM alignment under uniform dipole field.

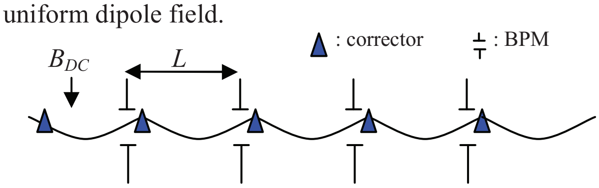

Figure 1: BPMs are ideally aligned on a straight line by minimizing the deviation of corrector strengths under uniform dipole field, B_{DC}. The layout is periodic as in a general undulator section. The corrector strength in units of radian is constant, $B_{DC}L/B\rho$, where L is the unit length and $B\rho$ is the magnetic rigidity of the electron beam, and thereby the deviation is zero.

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A sensitivity matrix to compute possible corrections of BPM-Quad unit positions may be taken from an optics model. A matrix taken from the machine, however, may remove possible systematic errors, for example an error in the transfer function of a corrector. The matrix once measured may be reusable in regular beam tuning and is in principle scalable with the beam momentum.

The matrix measurement is performed as follows: The electron beam is first steered to go through the BPM centers. One of BPM-Quad units is then shifted, and the corresponding changes in corrector strengths, which are needed to follow the center of the shifted BPM and the ones in downstream, are then recorded. The BPM-Quad unit position is finally restored, again steering the beam to the center of BPMs. Running an orbit feedback eases the measurement tremendously. This is repeated for all the BPM-Quad units in the undulator section in the horizontal and vertical plane, respectively. The matrix measurement error due to BPM noise is negligible when the shift of BPM-Quad unit is much larger, ~100 µm, than the noise level. The response of corrector strengths appears to be fairly linear to the BPM-Quad unit position.

Once this preparation work (quadrupole alignment, commissioning of an orbit feedback and sensitivity matrix measurement) are completed, the corrections of BPM-Quad unit positions are computed by applying an SVD matrix inversion and successively applied. Two or three iterations may be necessary to achieve a convergence of the corrector strength deviation.

The preparation work may be carried out with the undulator gaps open in order to minimize the possibility of beam loss at the undulators. On the other hand, once an orbit feedback is configured properly, the alignment can be performed with the nominal undulator gaps, where the undulator field is tuned to minimize dipolar field errors, since the beam orbit may be confined to the BPM centers.

An experience of magnet girder realignment with stored beam and an orbit feedback [4] running has been established at the SLS [5]. Although the realignment is performed in the storage ring, the layout of components is quite similar to the undulator line. The BPMs are aligned with respect to the adjacent quadrupole, and the dipole correctors are close to the BPMs. Therefore the corrector strengths were closely correlated to the girder misalignments. In fact, the corrector strengths were significantly reduced after the realignment.

The performance of this BBA method can be analytically estimated. An arbitrary vertical dipole error, $B_y(s)$, between two BPMs in the undulator section is represented by a Fourier expansion.

$$\frac{B_y(s)}{B\rho} = a_0 + \sum a_i \cos\left(\frac{2\pi i}{L}s\right) + \sum b_i \sin\left(\frac{2\pi i}{L}s\right), \qquad (1)$$

where s is the longitudinal distance from the upstream BPM, a and b are the expansion coefficients normalized by the magnetic rigidity. The horizontal electron beam orbit under the dipolar error is expressed as:

$$x(s) = \int_0^s x'(s')ds' + x(0), \qquad (2)$$

$$x'(s) = \int_0^s \frac{B_y(s')}{B\rho}ds' + x'(0), \qquad (3)$$

where $x(0)$ and $x'(0)$ are the position and angle of the electron beam orbit at the upstream BPM.

The impact of the dipole error can be derived term-wise when an error field is situated in the middle of the undulator section for an even number of BPMs to be aligned as shown in Fig. 2. The correctors are assumed to be situated right after the adjacent BPMs as it is the case in the SwissFEL design.

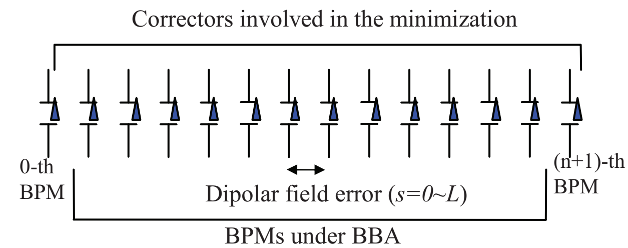

Figure 2: Schematic layout for the performance analysis. The number n of BPMs to be aligned is 12. The undulators are omitted in the figure but they are situated between the BPMs.

The 0-th and (n+1)-th BPMs are chosen as the BPMs to determine a reference straight line. These n+2 BPMs and a few more upstream and downstream ones are included in the orbit feedback loop.

A full derivation of the following equations is found in [6]. Here, only the results are presented with simple descriptions:

DC term

The sum of corrector strengths will be $-a_0L$ in order to compensate a DC field error of a_0L at the end of BBA. It is uniformly distributed into all the correctors to realize a zero deviation. DC term will then result in an orbit bump over the section with the amplitude at the n/2-th and n/2+1-th BPMs of

$$x(0) = x(L) = -\frac{a_0 L^2}{n+2}\sum_{j=1}^{n/2} j \qquad (4)$$

as illustrated in Fig. 3.

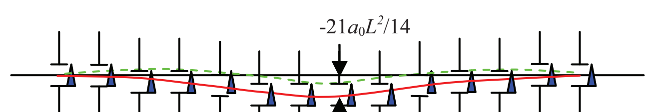

Figure 3: Orbit bumps due to DC dipolar error situated in the middle of the undulator section for n=12. The solid (red) line indicates the orbit bump without clipping and the dashed (green) line with clipping. (See text for clipping).

Although the amplitude of the orbit bump due to DC term is rather large the bump is spread over the entire section, and thus the electron beam orbit is still locally smooth. Moreover it can be clipped to ~20% by applying

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an SVD matrix inversion with an Eigen-value cut-off (>3% of the maximum) because this prevents the BPMs from shifting by a large amount.

Cosine term

It is easily found that cosine terms have no impact for any harmonics. From Equations 1-3,

$$x(L) = x(0), \tag{5}$$

$$x'(L) = x'(0). \tag{6}$$

Thus the strength will be zero in all correctors.

Sine term

A sine term introduces an orbit shift as found from Equations 1 and 2:

$$x(0) = -x(L). \tag{7}$$

when the symmetry is imposed.

The amount of the shift is found to be

$$x(0) \sim -\frac{b_i L^2 \sum_{j=1}^{n/2} j^2}{2\pi i \left[\sum_{j=1}^{n/2} (j + j^2)\right]}. \tag{8}$$

The orbit distorted due to a sine term of i=1 is schematically shown in Fig. 4.

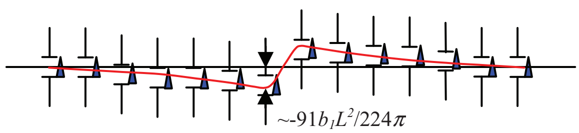

Figure 4: Orbit distortion due to a sine term dipolar error situated in the middle of the undulator section (n=12).

To summarize, DC term may lead to a rather large orbit bump, of which the amplitude can be regulated by applying an Eigen-value cut-off in SVD matrix inversion. Sine terms introduce a limited orbit deviation, and cosine terms have no impact.

The simulations described in the next section show (see Fig. 5) that an error located off centre of the section results in a larger orbit deviation by up to a factor of ~2 depending on the location. The orbit distortions from all terms are summed up, and therefore the orbit straightness achieved with this BBA algorithm depends on the distribution and amount of dipolar errors. The undulator tends to introduce field errors at the entrance and exit. It is expected to be ~20 µTm at most, corresponding to a kick of ~1 µrad at the nominal beam energy of 5.8 GeV. A sine like term, i.e. ±1 µrad at the entrance and exit of the undulator, results in an orbit distortion of 2~3 µm for n=12. A DC like term, i.e. +1 µrad at both ends results in an orbit bump of 3~6 µm (clipping with Eigen-value cut-off). These numbers are compatible with the tolerance. Note that n=11 at the SwissFEL hard X-ray line.

It is again emphasised that a DC field error over the entire section such as the geomagnetism has no impact on the straightness of BPMs while the electron beam orbit may remain unknown and bumped between BPMs as in Fig. 1. However, the undulator is to be tuned taking into account the geomagnetism.

It is noted that this analytical evaluation of residual orbit straightness can be directly connected to a result of undulator field measurements providing an estimation of position and angle orbit error (x, x') at the exit of undulator. A DC term results in both position and angle error while a sine term only position with the initial condition of x(0)=0 and x'(0)=0. Therefore an orbit error from field measurement can be converted to a combination of DC and sine term, and it allows us to evaluate the achievable orbit straightness with this method.

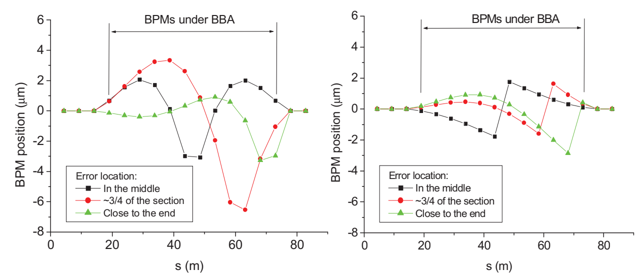

Figure 5: BPM positions after BBA disturbed with an error field situated in various locations, (a) DC like term with +1 µrad at both undulator ends and (b) sine like term with ±1 µrad at the entrance and exit.

SIMULATION

In the following, the described BBA algorithm is examined with numerical simulations. The layout of the hard X-ray undulator section of SwissFEL is employed. The number of undulator is 12 and the number of BPMs to be aligned is 11, which are situated between the undulators. The sensitivity matrix of this layout is shown in Fig. 6.

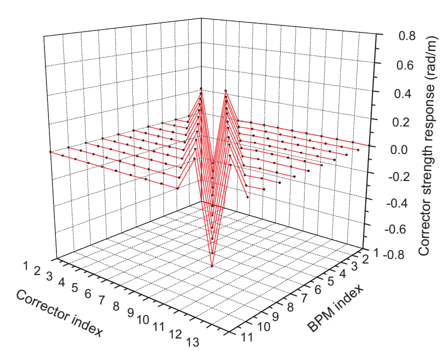

Figure 6: Sensitivity matrix of the SwissFEL hard X-ray undulator section. Since the BPM and the corrector are close to each other, almost only three correctors respond to the shift of one BPM.

Figure 7 shows typical BPM positions during BBA together with the variation of the corrector strengths. It is seen that the corrector strengths are correlated with the BPM misalignments and that the deviation is largely reduced at the end of iteration.

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The strength of the corrector just before the first undulator section is not considered in the minimization. It includes additional bending necessary to match the launch orbit to the reference straight line, and thus an unwanted change in the average corrector strength is introduced. This is also true for the last corrector when some downstream BPMs are included into the orbit feedback loop. Therefore the number of correctors involved in the minimization is 11 instead of 13.

Figure 8 shows a statistics of the BBA performance. The BPM straightness is computed at the end of iteration for many random seeds. It is defined as the deviation from a reference curve fitted by a parabolic function to the BPM positions. The BBA method of [1] is also simulated for comparison. It turned out that the performances of the two methods are comparable. At the same time, in a worst case, the BPM/orbit straightness may not be good enough to realize a full saturation of FEL. An empirical tuning based on a random optimization [5] would be useful to complement the BBA and to maintain the FEL power during the operation. The BPM-Quad positions can be adjusted as increasing the FEL power once a lasing is realized.

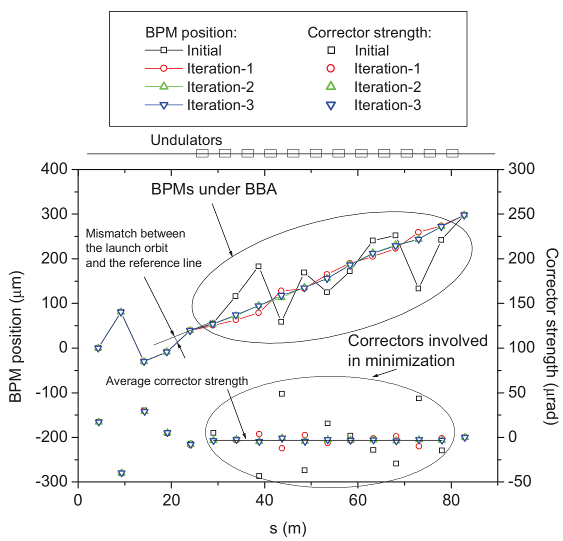

Figure 7: Typical BPM positions and corrector strengths during the BBA. Initial BPM misalignments of 50 μm rms in addition to a long range misalignment of 250 μm over 85 m are assumed. After 3 iterations, an orbit straightness of 3.6 μm rms is achieved.

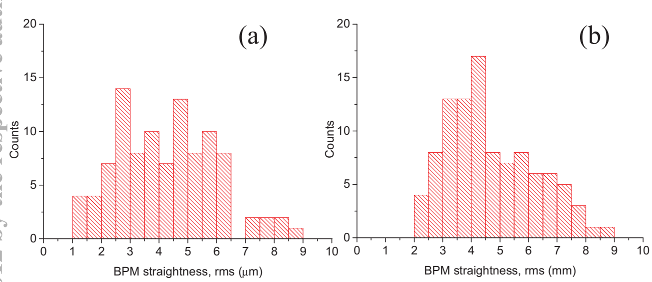

Figure 8: BBA performance of (a) the proposed method and (b) the method of [1].

In these simulations, the dipolar field error and other adverse effects are introduced as summarized in Table 1. Since the initial beam jitter (error in the launch angle and position) does not affect the BPM straightness considerably in both methods, it is not included. It can be included in the sensitivity matrix in the method of [1]. In the proposed method, a few upstream correctors not involved in the BBA but used by the orbit feedback must be able to correct the launch error. Also a feedback gain <1 may reduce the effect of shot-to-shot initial beam jitter on the corrector strengths used in the minimization.

Table 1: Error Sources Assumed in Simulation

The errors are generated by random numbers with uniform (U) or Gaussian distribution (G).

Error source	Value	Remarks
DC dipolar kick	~3 μrad/unit	~1/3 of the geomagnetism
Random dipolar kick	±1 μrad (U)	At both ends of undulator
BPM noise	1 μm rms (G)	
BPM-Quad misalignment	±5 μm (U)	Only for the proposed method
Corrector str. error	50 nrad rms (G)	Only for the proposed method
BPM calibration error	±2% (U)	Only for the method of [1]
Beam momentum error	±0.25 % (U)	Only for the method of [1]
Quad. gradient error	0.3% rms (G)	Only for the method of [1]

SUMMARY

A new approach to align BPMs in the undulator section based on dipole corrector strengths is under investigation for the PSI future X-FEL facility, SwissFEL. The proposed method, which allows us to find the BPM-Quad unit misalignments, requires only measuring the corrector strengths needed to steer the electron beam to the BPM centers. These are immediately available when an orbit feedback is in operation, and therefore the main part of the BBA can be performed within a few minutes. The proposed method is able to align the BPMs under the condition that the dipolar field errors are suppressed to values required for lasing. It performs comparably well to the method employed at the LCLS. An empirical tuning may be useful to complement the BBA and to maintain the FEL power during the operation.

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