REAL-TIME CALCULATION OF SCALE FACTORS OF X-RAY BEAM POSITION MONITORS DURING USER OPERATION

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Abstract

Photoemission based X-ray Beam Position Monitors (XBPMs) are widely used at 3rd generation light sources to both monitor and stabilise the photon beam to sub-micron precision. Traditionally, finding the geometric scale factors requires either systematic stepper motor movements of the XBPM or well controlled electron beam displacements to measure the response of the XBPM. For each Insertion Device gap it is required to repeat this in order to build up a complete set of scale factors covering all possible operating conditions. Elliptically Polarising Undulators further complicate matters by having multiple operating modes which would require multi dimensional lookup tables. Presented in this paper is a method for retrieving the geometric scale factors of an XBPM in real time by making use of the intrinsic small random movements of the electron beam and finding the correlation in synchronous measurements from Electron BPMs and XBPMs at kHz sample rates.

INTRODUCTION

Diamond Light Source utilizes two photoemission X-ray Beam Position Monitors (XBPMs) on most front ends in order to monitor and improve the stability of the photon beam. XBPMs for Insertion Device (ID) beamlines are mounted on stepper motors with micron-precision encoders, and traditionally the XBPMs are calibrated by using known stepper motor offsets to emulate real X-ray beam movements. Alternatively, controlled electron beam bumps through the ID straight can also be used to calibrate the XBPMs [1, 2]. A scale factor is calculated by comparing the measured response from the four XBPM blades to the known magnitude of the controlled movements. This gives a scale factor measured for a selection of ID gaps, which is saved into an EPICS database. During user operation the scale factor database is interpolated to give a factor for the current ID gap and used to convert the dimensionless position given by the XBPM signal into a position in mm. The dimensionless response of the XBPM, Δ/Σ, is defined as follows:

$$(\Delta/\Sigma)_x = \frac{A-B-C+D}{A+B+C+D}$$

$$(\Delta/\Sigma)_y = \frac{A+B-C-D}{A+B+C+D}$$

where A,B,C,D are the four XBPM blade signal currents.

There are several limitations to both of these calibration methods. Both require dedicated beamline time, during which the beamline is not able to accommodate users: if stepper motor movements are utilised then users may see

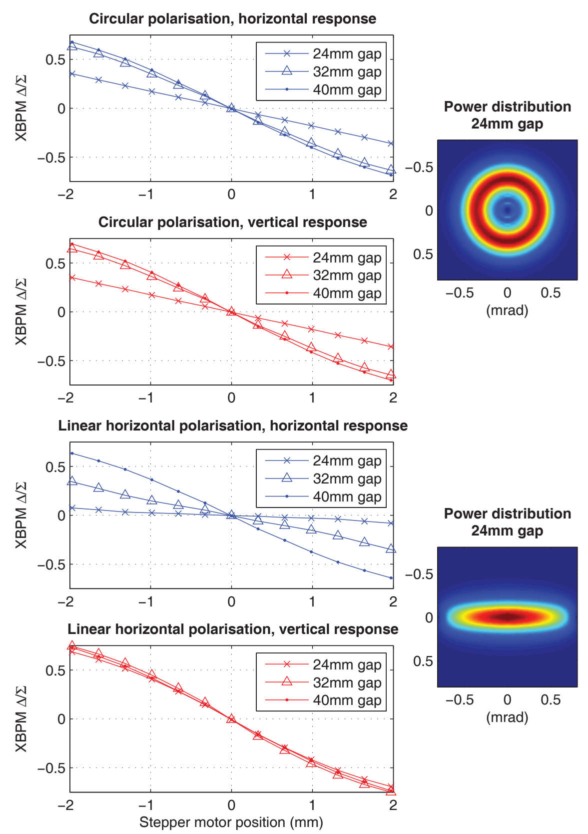

Figure 1: XBPM response to stepper motor movements for the I06 beamline at Diamond. The simulated power distribution of circular and linear horizontal polarised light are shown on the right to give an indication of the different photon distributions. Each gap and phase requires a different scale factor.

X-ray beam shadowing as the XBPM moves across the beam; if electron beam bumps are used then the changing X-ray beam position and angle causes changes to the measured intensity and photon energy at the sample-point.

A second limitation is that a scale factor must be measured for each ID setting that a beamline could use, as different ID gaps produce different spatial distributions of radiation and thus require different scale factors. Elliptically polarising undulators, such as APPLE II devices, also require a different scale factor value for each different polarisation, as seen in Fig. 1. It is possible to create a look-up table for each individual ID setting, but populating such a table is a time consuming process. Typically at Diamond, a single XBPM stepper motor scan in one axis would take

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some minutes, and would be performed for 10 different ID gaps. Performing such a scan for two axes, horizontal and vertical, and for three different polarisations for an APPLE II device would take two hours of dedicated beamline time.

On top of this, a typical scale factor is linear only on a small range, typically $\pm 100\mu m$. Beyond this, a new scaling factor needs to be produced or non-linear correction needs to be used.

Previous efforts to calculate the XBPM scale factors automatically using self-learning and artificial intelligence methods have still relied on performing physical stepper motor movements, and generating scale factor tables for a range of gaps [3, 4]. Presented in this paper is a method for acquiring the XBPM scale factor, K, in real-time by making use of the intrinsic electron beam movements, and fast electronics that are capable of recording the Electron Beam Position Monitor (EBPM) and XBPM measurements synchronously.

SYSTEM CONFIGURATION

A Fast Acquisition (FA) communications network has been developed at Diamond [5] to capture and distribute position data from EBPMs and XBPMs at an update rate of 10kHz. This stream allows for a real-time comparison of the electron beam trajectory through the ID straight as measured on the EBPMs, and the photon beam position at 12.25m from the ID, as measured on an XBPM.

Using the FA network the last 10s of data from the BPMs is pulled into a rolling buffer. The data is then low-pass filtered in order to remove high frequency (kHz) noise. The projected X-ray beam position, P_x, at XBPM-01 can be calculated from the EBPMs as follows:

$$P_x = (P_{e2} - P_{e1})\frac{d_x}{d_e} + \frac{P_{e1} + P_{e2}}{2}$$

where P_{e1} and P_{e2} are the upstream and downstream EBPM beam positions respectively, d_x is the distance from the ID to XBPM-01 (12.25m), and d_e is the separation between the two EBPMs (5.76m), as shown in Fig. 2.

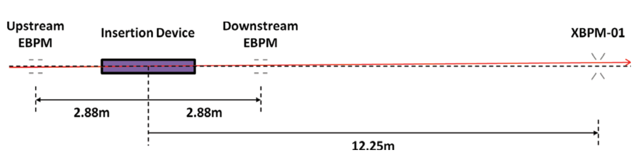

Figure 2: Schematic of the EBPM and XBPM locations for a typical ID straight at Diamond.

The two sets of data (measured XBPM response and projected EBPM data) are stored in a matrix for analysis. Calculating the Singular Value Decomposition (SVD) of this matrix to find the major axis between the two sets of data then returns the required information: the scale factor between the XBPM response and the EBPM projections (Fig. 4).

The SVD is a factorisation of the form:

$$M = USV^T$$

where M is an $m \times 2$ matrix. The two columns contain the measured XBPM response and projected EBPM data, and m is the length of the buffer used. U and V are unitary matricies of size $m \times m$ and 2×2 respectively. S is a 2×2 diagonal matrix whose elements are the singular values of the original matrix.

The scale factor between the XBPM response and the EBPM projections is found by taking the ratio of the first two elements of V^T, the rotational component of the SVD:

$$K = \frac{V^T(2,1)}{V^T(1,1)}$$

Because the residual movements of the electron beam are so small, the resulting scale factor computed from the SVD can be noisy. A longer buffer of data can be used in order to reduce the noise. However, a longer buffer requires more computing power to calculate the SVD, and also brings a slower response after a change to the system (such as an ID gap or polarisation change). With our system, the noise on a 10s buffer is an acceptable compromise between computing time, stability, and system response.

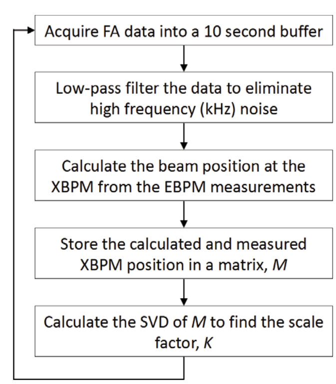

Figure 3: Block diagram of the on-line calibration system.

Figure 4 shows the correlation between the projected measurement and the XBPM measurement. Once the calculated scale factor has been applied the standard deviation of the residual error between the two measurements is $0.81\mu m$ horizontally, and $0.61\mu m$ vertically. If the calculations are still noisy, then further averaging is performed. A rolling average of the scale factor from the last 60 seconds generally provides very stable results.

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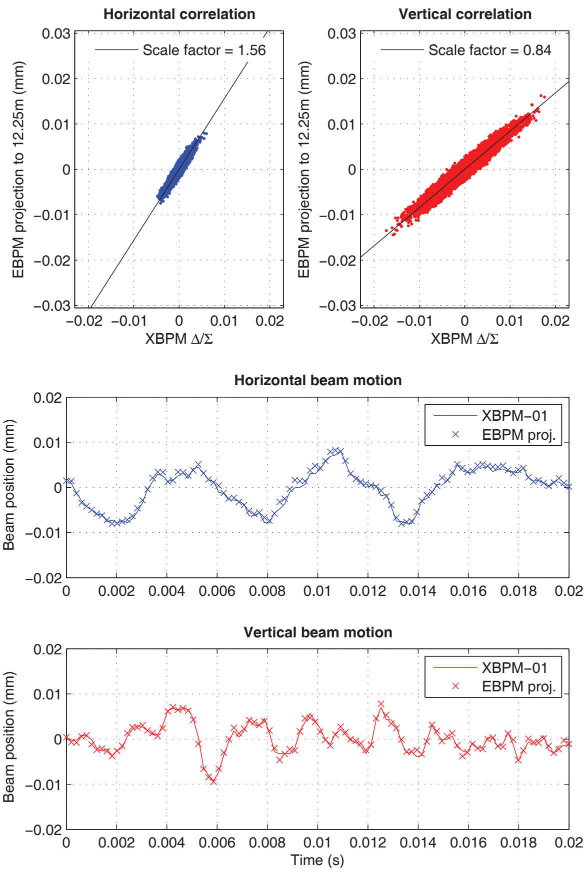

Figure 4: Beam position measurements from the I19 ID straight. The geometric projection of the EBPM measurements to a distance of 12.25 m is in excellent agreement with the XBPM measurements. The scale factor shown here is calculated from the SVD of the correlation. The photon beam size at the XBPM is $\sigma_x = 296\,\mu\text{m}$, $\sigma_y = 51\,\mu\text{m}$ (calculated from electron beam divergence).

FIRST RESULTS

The initial results show that the system can indeed provide an on-line scale factor measurement, over a range of ID gaps (Fig. 5). However, there are some discrepancies between the on-line measurement and the stepper motor measurement, particularly in the vertical axis. The on-line calibration shown in Fig. 5 has been averaged over a long period of time to reduce the effects of random variations, and the stepper motor calibrations were calculated from $\pm 10\mu\text{m}$ movements.

More work is required to understand these differences, but this method could conceivably make a good replacement for the large, multi-dimensional look-up tables that are required in order to fully utilise the XBPM measurement for every possible ID gap and polarisation.

Calculating the scale factor over a long period of time shows that there significantly more variation in the horizontal measurement than the vertical (Fig. 6). The exact reasons for this are not fully understood, but one could hypothesize that this is down to simple geometry: the electron beam is around 10 times larger horizontally than vertically, leading to the horizontal position measurement on the EBPMs being less sensitive, and thus containing more noise. Compounding this, the XBPM blades are located 25% closer together horizontally than they are vertically, also resulting in slightly reduced sensitivity to horizontal motion.

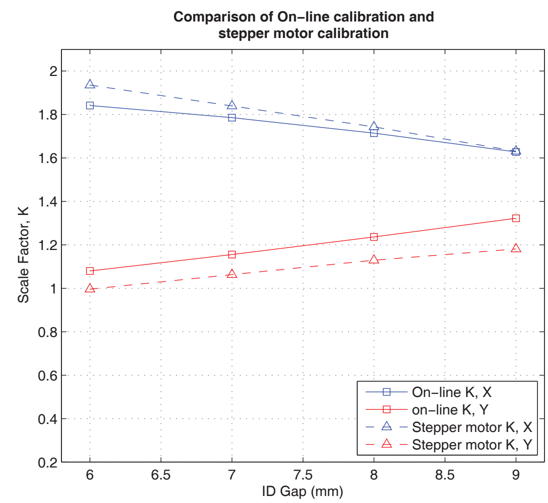

Figure 5: Calibration results during a scan of the I18 ID. An averaging time of 60 seconds is used for the on-line calibration.

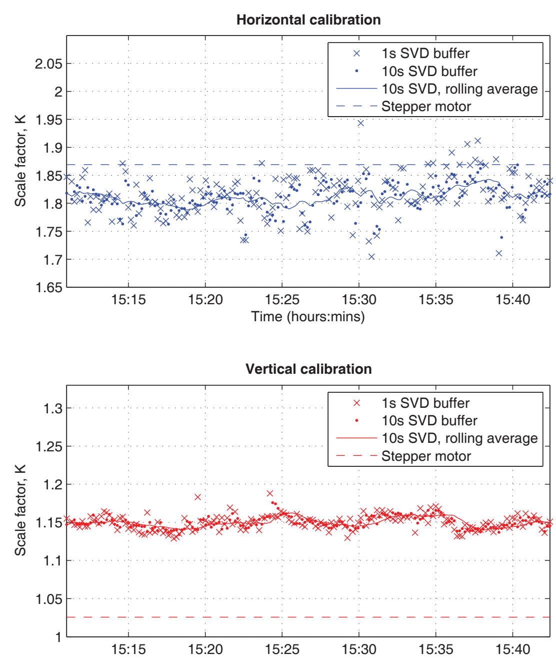

Figure 6: The calculated scale factor over a 20 minute period, for a constant gap on the I18 beamline. There is a clear discrepancy between the on-line measurement and the stepper motor measurement in the vertical axis.

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CONCLUSIONS

This method of utilising the residual movements of the electron beam shows promise, but the small size and random nature of the movements is the limiting factor. These movements are of $\ll$10% of beamsize horizontally and $\sim$10% of beamsize vertically, however they are of sufficiently high frequency to be negligible to the beamline users. One could consider deliberately introducing a known modulation onto the electron beam at $>$200Hz that could be detected by the XBPMs, but this introduces the risk of disturbing the beam unnecessarily. Further work is required to optimise the system in order to reduce the fluctuation seen in the calculated scale factor.

The final limitation on the system is that the calculation relies on the accuracy of the EBPM measurements. Whilst this has been simulated to a high degree of precision [6] and experimentally verified using LOCO [7], the EBPMs experience the same non-linearity as the XBPMs. Over time it is possible that we may drift from the physical centre of the EBPMs, which may introduce errors into the results. It is possible that this is the cause of the discrepancy between the vertical stepper motor results and the on-line measurement. Fortunately, the on-line calibration method presented here can always be verified by using the XBPM stepper motors.

Currently the system runs as a MatLab script, and will shortly be ported to a more robust system suitable for long-term deployment.

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