Abstract

During installation of Front-ends in sections 4th (XMCD beamline frontend) and 6th (PHELIX beamline frontend) at National Synchrotron Radiation Centre Solaris (NSRC Solaris), two units (one for each front end) of X-ray Beam Position Monitors (XBPM) have been installed as a diagnostic tool enabling for measurement of photon beam position. Hardware units of XBPM were manufactured, delivered and eventually installed in Solaris by FMB Berlin [1]. In order to get readouts of beam position from XBPM units, Libera Photon 2016 [2] controller has been used as a complementary electronic device. Since XBPM units are supposed to be used along with insertion device, an on-site Libera calibration was necessary. Libera’s calibration required few iterations of scans involving gap and phase movement of insertion devices at 4th and 6th section of Solaris ring. Main focus was put onto derivation of \( K_x \) and \( K_y \) coefficients. The content of this document describes step by step the procedure of Libera’s \( K_x \), \( K_y \) coefficients value derivation at NSRC Solaris.

GOAL OF XBPM’S CALIBRATION

Purpose of xbpm calibration is the determination of such two values of \( K_x \) and \( K_y \) coefficients so that physical shift of the photon beam in a given plane (horizontal \( X \) or vertical \( Y \)) by a certain amount (µm) will be reflected by the beam position controller in the ratio 1:1.

DETERMINATION OF \( K_x, K_y \) COEFFICIENTS VALUES THROUGH LONG TERM SCANS

At Solaris, to perform scans, which we determined \( K_x, K_y \) values from, we used data from: undulators, High Voltage power supply and motor positions of xbpm. For each gap and phase setting we made a long scan of xbpm motors to collect data from all 4 photo-blades. Then, based on the scan results we determined \( K_x, K_y \) values for X and Y planes. In Fig. 1, double bending achromat (DBA), xbpm, its photoblades and beam are shown schematically. Since the scans are time consuming, eventually we had to develop a fast method allowing for online calibration of \( K_x, K_y \) values using \( K_x, K_y \) values calculated from long run scans.

Scan Results

In Fig. 2 is shown an exemplary result of the motors scan, showing data from each photoblade. Map on the left is not normalized and map on the right shows normalized values. This is to show how incoming light evenly distribute each of the photo blade. Before we got this result, we had to make an effort to mechanically shift xbpm unit at the very beginning of its calibration. Based on these maps, we have the possibility to calculate \( K_x, K_y \) values. It is also worth noting that positive and negative values of the photo blades counts indicate different direction of the photo-current flow.

\[
\begin{align*}
  x_{ij} &= K_x M_x S_x - x_{ij}^0 \\
  y_{ij} &= K_y M_y S_y - y_{ij}^0,
\end{align*}
\]

where

\( K_x, K_y \) Calculation Method

The primary equation used for \( K_x, K_y \) calculation can be found in Libera Photon 2016 user’s manual [2]. These equations cover calculation of single values of \( K_x, K_y \). At Solaris, we made scans so we needed to adapt user’s manual formulas to its iterative versions. Below are the equations for calculating the photon beam position in both planes:

\[
\begin{align*}
  x_{ij} &= K_x M_x S_x - x_{ij}^0 \\
  y_{ij} &= K_y M_y S_y - y_{ij}^0,
\end{align*}
\]
\[
M_{ij}^x = (V_{ij}^a + V_{ij}^b) - (V_{ij}^c + V_{ij}^d), \quad M_{ij}^y = (V_{ij}^a + V_{ij}^d) - (V_{ij}^b + V_{ij}^c), \quad S_{ij}^x = V_{ij}^a + V_{ij}^b + V_{ij}^c + V_{ij}^d, \quad V_{ij}^x, V_{ij}^y, V_{ij}^a, V_{ij}^b, V_{ij}^c, V_{ij}^d
\]
- matrices of raw signals from A, B, C, D XBPM channels - directly from scans. Since in equations for beam position calculation Eqs. (1) and (2) we already use initial \( K_x, K_y \) coefficients, it is not straightforward how to get correct \( K_x, K_y \) using possibly inaccurate predefined \( K_x, K_y \) values. However, from scans there are known two things:

1. relative X and Y position of XBPM

2. Difference in millimeters between two consecutive positions of XBPM motors

Based on 2., we can calculate \( K_x, K_y \) for given pair of points, e.g. pair: \([\{(i,j), (i-1,j+1)\}]\). We know how much XBPM was moved, either in X or Y plane, so we can use this XBPM position difference in beam position Eqs. (1) and (2) to determine correct \( K_x, K_y \) values. For convenient matrices indexing and iterating over their elements, we constructed the meshgrids of X and Y XBPM motor positions. The meshgrids \( X_{\text{mesh}}, Y_{\text{mesh}} \) are given as:

\[
X_{\text{mesh}} = \begin{pmatrix} X_1 & \cdots & X_n \\ \vdots & \ddots & \vdots \\ X_1 & \cdots & X_n \end{pmatrix}, \quad Y_{\text{mesh}} = \begin{pmatrix} Y_1 & \cdots & Y_1 \\ \vdots & \ddots & \vdots \\ Y_1 & \cdots & Y_n \end{pmatrix}.
\]

Then, we can put difference of XBPM position movement as beam position difference and calculate correct \( K_x, K_y \) values for X, Y planes, as follows:

\[
K^x_\beta = \frac{\left( X_{\text{mesh}}^x - X_{\text{mesh}}^{ij} \right) \left( S^\beta_x S^{ij}_x \right)}{\left( M^\beta_x S^\beta_x - M_x S^{ij}_x \right)}, \quad (3)
\]
\[
K^y_\beta = \frac{\left( Y_{\text{mesh}}^y - Y_{\text{mesh}}^{ij} \right) \left( S^\beta_y S^{ij}_y \right)}{\left( M^\beta_y S^\beta_y - M_y S^{ij}_y \right)}, \quad (4)
\]

where

\[
\beta \in \{(i-1,j-1), (i-1,j), (i-1,j+1), (i,j-1), (i,j+1), (i+1,j-1), (i+1,j), (i+1,j+1)\}.
\]

Equations (3) and (4) provide a compact way of writing 8 points in the neighbor of point \((i,j)\) of the motors scan. This is being done to enable calculation of mean \( K_{ij} \) out of 8 neighboring \( K_p \). It can be rewritten in a form, independent of plane which we are currently calculating \( K_{ij} \) for:

\[
\bar{K}_{ij} = \frac{1}{8} \sum_{p} \left( \frac{p_{\text{mesh}} - p_{\text{mesh}}^{ij}}{P^\beta_x P^\beta_y} \right) \left( S^\beta_x S_{ij}^\beta_x \right), \quad (5)
\]

where \( p_{\text{mesh}} \in \{X_{\text{mesh}}, Y_{\text{mesh}}\}, P \in \{x,y\} \). - plane that we are currently calculating \( K_{ij} \) for. Equation (5) assumes that the mean \( K_{ij}^p \) is calculated at specific point \((i,j)\) of the x bpm motors scan. General algorithm calculating \( K_{ij}^p \) from Eq. (5) was shown schematically in Fig. 3.

**Guidelines to Optimally Choose \( K^x_{ij}, K^y_{ij} \) Values**

Since we know how to create a map of means \( K^x_{ij}, K^y_{ij} \) for each scanned point, we are now facing an issue how to choose the \( K^x_{ij}, K^y_{ij} \) values optimally. To do that, we defined four main guidelines which we should follow while determining optimal \( K^x_{ij}, K^y_{ij} \) values:

- Preferably, \( K^x_{ij}, K^y_{ij} \) values should be chosen in the middle point of the scan.
- The ratio of the \( \delta K^x_{ij} \) to \( \delta K^y_{ij} \) should not exceed 20%.
- \( \delta K^y_{ij} \) - standard deviation of mean \( K^y_{ij} \) at point \((i,j)\) of the x bpm motors scan.
- XBPM motors position should be selected in a way so that \( K^x_{ij}, K^y_{ij} \) values are as close to each other, as possible - independently of the \([\text{gap, phase}]\) pair, which \( K^x_{ij}, K^y_{ij} \) values were calculated for.
- Xbpm motors positions are kept at fixed positions, regardless of the current undulator setting.

The calculation \( K^p_{ij} \) was done for all measured \([\text{gap, phase}]\) pairs. Measured pairs \([\text{gap[mm], phase[mm]}]\) are:

\[
[14, -29], [30, -29], [50, -29], [14, -16.77], [30, -16.77], [50, -16.77], [14, 0], [20, 0], [30, 0], [40, 0],[50, 0],[14, 16.77],[30, 16.77],[30, 16.77],[50, 16.77],[14, 29],[30, 29],[50, 29]
\]

Figure 3: Schematic presentation of algorithm calculating \( K_{ij} \) from Eq. (5).
pairs which haven’t been measured. The calibration procedure is using lookup table as a reference for starting/defaults $K_{ij}$ values in order to apply $\Delta K_{ij}$ correction at unknown/unmeasured [gap, phase] pairs. The characteristics of $K_{ix, ij}$, $K_{iy, ij}$ as a function of gap and phase were shown in Fig. 4.

**Figure 4:** characteristics of $K_{ix, ij}$ (left), $K_{iy, ij}$ (right) as a function of gap and phase.

**ONLINE CALIBRATION ALGORITHM**

The online calibration algorithm can be broken down into three main steps:

- At unmeasured undulator pairs, the default $K_{ij}$ value is used at the beginning of calibration
- Using default $K_{ij}$ values at unmeasured pair, algorithm performs 10s cross scan with X BPM motors in both planes
- If linear response on default $K_{ij}$ value does not give a slope close to 1 between xbpms motors and libera controller readouts, then the correction factor $\Delta K_{ij}$ is being calculated and recalibrated $K_{ij}^p, \Delta K_{ij}$ value is implemented into beam position controller.

**Beam Position Controller Response after the Calculation of Correction Factors at Unmeasured [gap, phase] Settings**

Once we know how to determine $\Delta K_{ij}$, we can check how the response between X BPM motors position and beam position controller look like, now using the corrected $K_{ij}^p, \Delta K_{ij}$ value. In both planes, it is clear that online calibration works well, since the slope from linear fit is close to one and squared correlation coefficient also shows a high-quality match between data points and the fit. The response between beam position controller and xbpms motors positions is shown in Fig. 5. Still, we need to keep in mind that default values already provide linear response between physical beam shift and libera output, however, this shift is not always characterized by the slope close to 1.

**Corrected $K_{ix, ij}$ and $K_{iy, ij}$ Characteristics as a Function of Undulator’s Gap**

Since at specific [gap, phase] setting the online calibration takes roughly 10 s and involves both default $K_{ij}$ values from long term scans and xbpms motors movement, it enables quicker scans of yet unmeasured gap and phases resulting in more accurate than defaults $K_{ij}$ values. Additionally, it adapts $K_{ij}$ values to the actual value of the beam current in storage ring. Below, in Fig. 6 are shown two $K_{ix, ij}$ and $K_{iy, ij}$ characteristics as a function of the gap values, ranging from 200 to 14 mm at phase 0. Time of the scan of gap values takes around 2 hours. In Solaris, we measured similar characteristics for 5 mostly used undulator’s phases. In order not to use online calibration each time and save X BPMs motors lifetime, we decided to implement these characteristics as a lookup table for X BPM calibration and keep X BPM motors position constant. Nevertheless, whenever needed, online calibration can be run as a verification tool or for any other reasons.

The asymptotic blow up in $K_{ix}$ characteristics in Fig. 6 is probably due to very wide horizontal beam profile above 100 mm gap value. In opened undulator’s gap, the beam profile is filling the whole horizontal range of xbpms motors scan. It begins to be more compressed below 75 mm gap values. Based on the observations, the asymptotic blow up can shift a bit depending on the beam current in the ring and on the undulator’s phase which scan is being done at.

**SUMMARY**

Based on shown methods and results, calibration of X BPM was completed. It consisted of two main parts: long scans and online calibration. To save xbpms motor’s lifetime a trade off between calibration accuracy and utility must have been made. The linear response between beam position controller and xbpms motor positions was ensured in the total range of 200 µm in horizontal and vertical planes.
REFERENCES
