Experimental Test of Data Analysis Methods from Staggered Pair X-ray Beam Position Monitors at Bending Magnet Beamlines

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Abstract. Different methods have been proposed to calculate the vertical position of the photon beam centroid from the four blade currents of staggered pair X-ray beam position monitors (XBPMs) at bending magnet beamlines since they emerged about 15 years ago. The original difference-over-sum method introduced by Peatman and Holldack is still widely used, even though it has been proven to be rather inaccurate at large beam displacements. By systematically generating bumps in the electron orbit of the ANKA storage ring and comparing synchronized data from electron BPMs and XBPM blade currents, we have been able to show that the log-ratio method by S. F. Lin, B.G. Sun et al. is superior (meaning the characteristic being closer to linear) to the ratio method, which in turn is superior to the difference over sum method. These findings are supported by simulations of the XBPM response to changes of the beam centroid. The heuristic basis for each of the methods is investigated. The implications on using XBPM readings for orbit correction are discussed.

1. Introduction

When Peatman and Holldack released their staggered pair X-ray beam position monitors (see Figure 1 below) for dipole- WLS- and MPW- radiation in 1998, they proposed at the same time a method to calculate the height $z_{\text{obs}}$ of the photon beam centroid from the current readings of the four blades [1], below referred to as the $\Delta \Sigma$-method. In an algebraically simplified form it reads:

$$
\begin{align*}
  z_{\text{obs}} = o \cdot \frac{I_1 \cdot I_4 - I_2 \cdot I_3}{I_1 \cdot I_3 - I_2 \cdot I_4} \quad (1)
\end{align*}
$$

$I_1$ to $I_4$ denote the blade currents according to the scheme given below, and $o$ denotes the offset of the blade pairs. This method is still widely used at bending magnet beamlines (see e.g. [2, 3]), though alternative methods have been established [4,5,6] and simulations indicate that they are superior to the $\Delta \Sigma$-method with respect to linearity and extent of validity of the characteristic [4]. In the following we compare the $\Delta \Sigma$-method with the ratio method:

$$
\begin{align*}
  z_{\text{obs}} = o \cdot \frac{I_1 + I_4 - I_2 - I_3}{I_4 + I_2 - I_1 - I_3} \quad (2)
\end{align*}
$$

and the log-ratio method:

$$
\begin{align*}
  z_{\text{obs}} = o \cdot \frac{\log(I_1) + \log(I_4) - \log(I_2) - \log(I_3)}{\log(I_4) + \log(I_2) - \log(I_1) - \log(I_3)} \quad (3)
\end{align*}
$$
2. Heuristic approach

Though the original derivation of $z_{\text{obs}}$ according to the $\Delta/\Sigma$-method given by Peatman and Holldack [1] appears to be somewhat “handwaving” by introducing and comparing “asymmetry factors”, it can be made exact in the framework of a simple model for the vertical beam profile. Consider a “rectangular” vertical photon beam profile with a photon flux density $\Phi$ given by:

$$
\Phi = \Phi_0 \text{ for } |z - z_0| \leq \frac{h}{2} \\
\Phi = 0 \quad \text{elsewhere.}
$$

Then the individual blade currents will read:

$$
I_1(z_0) = C \cdot \left( \frac{h-g}{2} - \frac{z_0}{2} \right) \text{ for } \frac{h-g}{2} \leq z_0 \leq \frac{h+g}{2} \\
I_2(z_0) = C \cdot \left( \frac{h+g}{2} + \frac{z_0}{2} \right) \text{ for } \frac{h-g}{2} \leq z_0 \leq \frac{h+g}{2} \\
I_3(z_0) = C \cdot \left( \frac{h+g}{2} - \frac{z_0}{2} \right) \text{ for } \frac{h-g}{2} \leq z_0 \leq \frac{h+g}{2} \\
I_4(z_0) = C \cdot \left( \frac{h-g}{2} + \frac{z_0}{2} \right) \text{ for } \frac{h-g}{2} \leq z_0 \leq \frac{h+g}{2}
$$

with a common proportionality factor $C$, the blade gap $g$ and the pair offset $o$.

Substituting $I_1$ to $I_4$ in (1) and in (2) both result in

$$
z_{\text{obs}} = z_0
$$

meaning both the $\Delta\Sigma$- and the ratio methods are exact (within the framework of this model) for any $z_0$ in the intersection of the domains of definition. The same is clearly not the case for the log-ratio method. Therefore to compare the accuracy and the extent of validity of the different methods it is necessary to take a more realistic beam profile into account. A justification for the log($I_1$) ansatz of the log-ratio method is given in [6].

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Figure 1: Scheme of a staggered pair XBPM with the numbering pattern of the blades and the simplified model beam profile

Figure 2: Simulation of the staggered pair XBPM response to a Gaussian beam profile according to different methods (see section 3)
3. Simulation of the staggered pair XBPM characteristic

We have approximated the true vertical photon beam profile of the bending magnet radiation by a Gaussian profile. A mean effective photon energy of 1 keV was assumed in calculating the vertical photon beam divergence, corresponding to the Copper L edges where the XBPM blades are most sensitive to the incoming radiation. The height of the vertical beam profile at the XBPM position was calculated by taking the vertical electron beam size $\sigma_e$, the vertical electron beam divergence $\sigma'_e$ and the vertical photon divergence into account. Semi-infinite blades were used for the calculation. In this model the photocurrent of each individual blade is proportional to the Gaussian error integral with the actual blade length intersecting the beam, normalized to $2$ times the vertical RMS beam height at the XBPM position, as the argument. The simulation is based on the parameters of the ANKA SCD beamline: source to XBPM distance = 4165 mm, $\sigma_e = 0.1$ mm, $\sigma'_e = 0.01$ mrad, $E_c = 6.2$ keV, $\gamma_e = 4892.4$, $g = 4.4$ mm, $o = 1.0$ mm. The result is shown in figure 2: for large vertical beam displacements the $\Delta \Sigma$-method becomes arbitrarily inaccurate, whereas the characteristic of the log-ratio method always lies close to the bisecting line. What a large beam displacement means in this context will of course depend on the actual instrumental parameters, in the given situation the limit is $\sim 1$ mm.

4. Experimental

While generating bumps in the electron beam orbit of the ANKA storage ring during a machine shift, both eBPM readings and XBPM blade currents were sampled at discrete time stamps $t_i$. In the absence of electron beam focusing elements the electron “$z$” coordinate can be assumed to change linearly along the particle trajectory, thus the “true” vertical coordinate $z_0$ of the photon beam centroid will depend linearly on the readings of the eBPMs before and behind the photon beam exit port:

$$z_0(t_i) = a_0 + a_1 \cdot z_{eBPM1}(t_i) + a_2 \cdot z_{eBPM2}(t_i) \quad (4)$$

For an ideal XBPM $z_{obs}(t_i)$ would be identical to $z_0(t_i)$, thus the standard deviation resulting from a linear least squares (LLSQ) fit for the parameters $a_0$, $a_1$, $a_2$ of $z_{obs}(t_i)$ versus $z_{eBPM1}(t_i)$ and $z_{eBPM2}(t_i)$, calculated with the different models, allows a quality assessment of the respective model. We performed two runs, one providing bumps in the electron orbit with amplitudes of the order of 1 mm (Run 1) and one with amplitudes in the order of 0.1 mm (Run 2). The standard deviations resulting from the LLSQ fits are summarized in table 1. It should be noted that due to the geometry of the actual distorted electron orbit, by coincidence the absolute displacements of the photon beam arriving at XAS were comparatively small, just of the order of 0.1 mm in run 1, so that we are always in the linear range of the XBPM response here, irrespective of the model. Inserting the fitted parameters $a_0$, $a_1$, $a_2$ in equation (4) allows to compare the “observed” vertical beam displacement with the displacement “predicted” from the eBPM readings during one run. The result for the most extreme case, run 1 at the SCD beamline, is shown in figure 3. It is clearly to be seen that the ratio method and the log-ratio method provide a much better approximation in this case.

| Table 1. Standard deviations (in mm) of the LLSQ fits of vertical beam displacements according to the different methods versus readings of the eBPMs before and behind the exit port. |
|----------------|----------|----------|----------|
| Beamline | Run | $\Delta \Sigma$-method | Ratio method | Log-ratio method |
|----------|-----|-----------------|--------------|-----------------|
| XAS | 1 | 0.0148 | 0.0159 | 0.0168 |
| PDiff | 1 | 0.409 | 0.166 | 0.144 |
| SCD | 1 | 1.365 | 0.0562 | 0.0533 |
| XAS | 2 | 0.00370 | 0.00420 | 0.00407 |
| PDiff | 2 | n/o | n/o | n/o |
| SCD | 2 | 0.0219 | 0.0269 | 0.0238 |
5. Conclusions
For large beam displacements the log-ratio method approximates the true vertical beam centroid position better than the ratio method, which in turn is much better than the widely used \( \Delta/\Sigma \)-method. In routine storage ring operation vertical beam displacements are so small that the difference between the data analysis methods is negligible. It should however be considered from a “fail safe” point of view when XBPM readings are used as complementary information for the orbital feedback system.

References
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