COMMISSIONING RESULTS OF THE NARROW-BAND BEAM POSITION MONITOR SYSTEM UPGRADE IN THE APS STORAGE RING

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Abstract

When using a low emittance storage ring as a high brightness synchrotron radiation source, it is critical to maintain a very high degree of orbit stability, both for the short term and for the duration of an operational fill. A fill-to-fill reproducibility is an additional important requirement. Recent developments in orbit correction algorithms have provided tools that are capable of achieving a high degree of orbit stability. However, the performance of these feedback systems can be severely limited if there are errors in the beam position monitors (BPMs). The present orbit measurement and correction system at the APS storage ring utilizes 360 broad-band-type BPMs that provide turn-by-turn diagnostics and an ultra-stable orbit: < 1.8 microns rms vertically and 4.5 microns rms horizontally in a frequency band of 0.017 to 30 Hz. The effects of beam intensity and bunch pattern dependency on these BPMs have been significantly reduced by employing “offset compensation” correction. Recently, 40 narrow-band switching-type BPMs have been installed in the APS storage ring, two in each of 20 operational insertion device straight sections, bringing the total number of beam position monitors to 400. The use of narrow-band BPM electronics is expected to reduce sensitivity to beam intensity, bunch pattern dependence, and long-term drift. These beam position monitors are used for orbit correction/feedback and machine protection interlocks for the insertion device beamlines. The commissioning results and overall performance for orbit stability are provided.

1 INTRODUCTION

The third-generation synchrotron light sources, such as the Advanced Photon Source (APS) storage ring, must meet very tight orbit stability requirements needed for low-emittance charged particle beams. These requirements get even tighter as the beam size reduces further. The orbit stability work at APS is at the forefront in many ways; here, we will discuss results of recently commissioned narrow-band switching-type beam position monitors (NBBPMS), connected to the insertion device chambers.

This type of BPM, first developed in the late 1980s [1], was followed by several design improvements [2,3], particularly a significant increase in the input dynamic range. The bulky chassis-type package has been reduced to a single height Euro-type module with several practical built-in features. Such a unit is now commercially available. Forty of these units have been integrated together with the existing 360 broad-band-type or monopulse beam position monitors (MPBPM). Front-end upgrade work on the MPBPM system is also in progress, which will enhance the global orbit stability performance [4].

Two orbit correction systems – “fast” [5] and “slow” [6] – that correct the orbit up to about 50 Hz have been employed at the APS storage ring. Both systems make orbit correction only for the long spatial wavelength motions, taking great statistical advantage of a large number of BPMs, thus not responding to local artificial effects that may be exhibited by individual BPMs. The “offset compensations,” based upon “scrape down” fitted data [6], are made to the raw BPM data. This reduces a large number of systematic errors, such as intensity/bunch pattern dependency and thermal effect in the data, presented to the orbit correction algorithms.

The bench data for NBBPMS show that the beam intensity dependence is less than 2 microns in the upper 40 dB of the power range, but it is challenging to make similar claims in the storage ring. Uncertainty in the orbit itself and the thermally induced chamber motion are some of the culprits that contaminate the measurements. The high performance x-ray-type beam position monitors (XBPMS) [7] have been routinely used as a reliable reference, but only for the bending magnet (BM) sources. However, recent work done by modifying the lattice [8] for one insertion device may hold the key to future use of XBPMS as a reference for ID sources as well.

2 INSTALLATION/COMMISSIONING

There are ten Eurocrates installed around half the ring, each housing NBBPM modules for two sectors. The NBBPM output signals are sent to a digitizing beam position limit detector (DBPLD) for machine protection [9]. The response time requirement of 350 microseconds for a beam deflection of +/- 1 mm is easily met. A 300-Hz anti-aliasing filter module is used to provide input to a 16-bit orbit measurement digitizer that samples at the orbit feedback rate of 1.6 kHz. This sampled data is fed to the real-time feedback system and to an averager that then passes data to the “slow” correction system. The NBBPM calibrations for the 8-mm chamber are 3V/mm and 5V/mm for vertical and horizontal planes, respectively.

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For a long undulator ($\sigma_x \ll \sigma_z$) and a centered beam waist ($Z = 0$), Eq. (3) predicts that the measured effective size is smaller than the actual beam, due to the high collimation of the undulator beams. While the electrons' angular distribution is independent of their positions at the beam waist, the farther off-axis the electrons, the fewer photons they generate will pass through the pinhole. This results in a systematic error of a smaller measured effective source size, as pointed out previously [2,3,5]. This expression, based on simple geometrical optics models, applies only to the horizontal direction, where the beam size is much larger than the width of the camera point-spread-function (PSF).

2.3 Horizontal Beam Emittance

The expressions for effective divergence and beam size both show strong dependence on $\beta$ functions, as well as the location of the beam waist, thus making them susceptible to magnetic lattice fluctuations. The product of these two numbers, however, is less dependent on them,

$$\varepsilon_{\text{eff}} = \sigma_{\text{eff}} \sigma_{\text{eff}} = \sqrt{\frac{\beta_0^2 \left( S_0 - Z \right)^2 + \sigma_z^2}{\left( 1 + \beta \sigma_z^2 \right)}}$$

(4)

where $\beta_0$ is the $\beta$ function value at the beam waist.

1. When the pinhole camera and the divergence measurement are using x-rays of the same energy, we may choose the location of monochromator and x-ray slits to be at the same distance from the undulator, $S = S_0$. Equation (4) can be further simplified to

$$\varepsilon \equiv \sigma_{\text{eff}} \sigma_{\text{eff}}$$

(5)

with a small correction term (less than 1% for the APS diagnostics undulator, $\sigma_x \approx 2.6 \mu\text{rad}$ and $\sigma_z \approx 20 \mu\text{rad}$).

2. When the pinhole camera is operating with a broad-band x-ray beam, $\sigma_z$ increases somewhat, but the correction to Eq. (5) is still expected to be small.

2.4 Fresnel Diffraction Broadening in y-Direction

The diffraction broadening of the pinhole image has been discussed by several authors [2,3], based on the hybrid model in which the geometric shadow of the pinhole and the Fraunhofer diffraction pattern were both approximated by Gaussian function, and the total broadening was assumed to be their convolution. Borland [5] appeared to be the first to point out the inadequacy of Fraunhofer diffraction and briefly discussed the effect of Fresnel diffraction. We have performed a detailed analysis of the PSF based on Fresnel diffraction. The PSF for monochromatic radiation for a pinhole aperture (width $= d$) can be written as the square of a Fresnel integral. It can be represented by an integral to allow analytical convolution with a Gaussian source function and a Gaussian spectrum function (polychromatic PSF). The result can then be compared directly with experimentally measured profiles.

3 EXPERIMENT

The experiment was performed at the diagnostics beam line of the Advanced Photon Source. The setup is shown in Figure 1 with relevant parameters given in Table 1.

![Figure 1: APS diagnostics undulator beamline](image)

Table 1: Parameters for the APS undulator experiment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undulator, period length, $\lambda$</td>
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</tr>
<tr>
<td>Undulator length, $L$</td>
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</tr>
<tr>
<td>Undulator, fundamental photon energy</td>
<td>25.9 keV</td>
</tr>
<tr>
<td>Monochromator to undulator distance, $S_m$</td>
<td>27.47 m</td>
</tr>
<tr>
<td>Monochromator crystal</td>
<td>Si(400)</td>
</tr>
<tr>
<td>Monochromator crystal thickness</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Pinhole to undulator distance, $S$</td>
<td>28.56 m</td>
</tr>
<tr>
<td>Pinhole to x-ray camera distance, $S'$</td>
<td>9.13 m</td>
</tr>
</tbody>
</table>

3.1 Divergence Measurement

The Bragg reflection of a 300-μm Si(400) monochromator crystal was used for the divergence measurement. The crystal angle is chosen to be slightly lower than that for the resonance (10.13°). Integrated intensity profiles were obtained from digitized video images and fitted to Gaussian functions at video frequency (30 Hz). The data are logged at one-minute interval during user runs. Figure 2 shows such a log in a 12-hour run during December 1998. At high current in the fill, the horizontal beam size and divergence were high due to a subtle transverse instability [8]. As current decays, the divergences settle to values independent of the current,

$$\sigma_x = 22 \pm 1(\mu\text{rad}) \quad \text{and} \quad \sigma_y = 3.2 \pm 0.2(\mu\text{rad})$$

(7)

after correction for resolution (3 μrad).

3.2 Source Size from Pinhole Camera

The pinhole camera operates with a broad-band x-ray spectrum. The upstream 300-μm monochromator crystal at 10° grazing incidence angle is effectively a 1.73-mm thick silicon filter, which only allows photons above 15 keV to pass. The calculated angular distribution of the transmitted photons fits well to a Gaussian function ($\sigma_x = 20.3 \mu\text{rad}$). We also found that the measured horizontal intensity profile from the pinhole camera has...
a nearly perfect Gaussian shape, giving an effective beam size \( \sigma_{x,\text{eff}} = 360 \, \mu\text{m} \). Correction for instrument resolution is insignificant in this case.

### 3.4 Fresnel Diffraction in the Vertical Direction

Figure 3 shows the vertical intensity profile obtained from the pinhole image. Attempts to fit the profile with either a Gaussian function or a hybrid profile function failed due to the pronounced center peak and sidelobes. The polychromatic Fresnel model appears to improve the fit with an effective beam size of \( \sigma_{y,\text{eff}} = 34 \pm 7 \, \mu\text{m} \). The vertical emittance is thus \( \varepsilon_y = 0.11 \, (\text{nm rad}) \). This represents a vertical coupling of 1.4%, larger than that deduced from the measured beam size at the bending magnet source and measured beta functions.

### 4 SUMMARY

We reach the following conclusions from this work.

1. By combining a thin monochromator crystal and a pinhole camera with a suitable undulator source, we have demonstrated experimentally that both electron beam divergence and size can be measured simultaneously. The current rate of measurement is limited by the speed of the camera/digitizer at about 30 Hz.

2. While the lattice function and the properties of the undulator radiation can significantly affect either measured effective beam divergence or size, their product remains a good measure of emittance, robust against fluctuations of lattice \( \alpha - \beta \)-functions.

3. We have presented experimental evidence showing that the Fresnel diffraction is valid and important in understanding x-ray pinhole camera data. Its introduction also pushes the fundamental resolution limit below that of the current, hybrid model by \( \sim 30\% \).

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### 5 REFERENCES