

Performance evaluation of BPM system in SSRF using PCA method^{*}

CHEN Zhi-Chu(陈之初)^{1,2;1)} LENG Yong-Bin(冷用斌)^{1,2;2)} YAN Ying-Bing(阎映炳)^{1,2}
YUAN Ren-Xian(袁任贤)^{1,2} LAI Long-Wei(赖龙伟)^{1,2}

¹ Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China

² Shanghai Synchrotron Radiation Facility, Chinese Academy of Sciences, Shanghai 201203, China

Abstract: The beam position monitor (BPM) system is of most importance in a light source. The capability of the BPM depends on the resolution of the system. The traditional standard deviation on the raw data method merely gives the upper limit of the resolution. Principal component analysis (PCA) had been introduced in the accelerator physics and it could be used to get rid of the actual signals. Beam related information was extracted before the evaluation of the BPM performance. A series of studies had been made in the Shanghai Synchrotron Radiation Facility (SSRF) and PCA was proved to be an effective and robust method in the performance evaluations of our BPM system.

Key words: PCA, MIA, SVD, storage ring, SSRF

PACS: 29.20.db, 29.27.Fh, 29.85.Fj **DOI:** 10.1088/1674-1137/38/7/077004

1 Introduction

As the key beam diagnostics tool, BPM systems are widely equipped in all kinds of accelerators and are being used in daily operation and machine study. The BPM system could not detect beam dynamics that have smaller amplitudes than its resolution. The resolution of the BPM system should, therefore, determine the boundary of all measurable beam dynamics during machine study or daily operation. Demands for the precise measurement of the resolution of the BPM system arose when fine beam dynamics studies were proposed.

The performance of BPM electronics itself can be easily evaluated in the lab test by using the virtual beam signals that are simulated by an RF signal source and the power splitters. In this case, the standard deviation of the raw position readings reflects the position resolution directly. However, for a practical BPM system, which includes not only electronics but also signal cables, pickup electrodes, and mechanical supports, working with real beams, it is difficult to evaluate the position resolution precisely. The standard deviation of the raw position readings is hardly useful since the support vibration and the electronics noise are mixed in the real beam movement. Hence, a more powerful analysis toolkit is required.

PCA, which is introduced in the particle accelerator field as the model-independent analysis (MIA), is an

excellent candidate for this job because it works by separating the real beam motion from the raw data matrix via correlation analysis.

2 BPM system in the SSRF ring

The locations of the BPMs have been carefully selected. Each one of the total 20 cells is allocated seven BPMs: two insertion-device (ID) BPMs at the head and the tail of each cell and five arc BPMs at other positions. The ID BPMs are installed at the entrance or exit of a drift space while the arc BPMs are separated in the bending areas.

The commercial electronics used in the BPM system are called the “Libera Electron.” A more advanced version called the “Libera Brilliance” was released several years after the commissioning of SSRF. The upgrading has since taken three steps. A detailed list of the procedure is shown in Table 1. The 140 BPMs in the storage ring are designed for slightly different purposes, so the upgrades are rather complex.

The formulae in Table 1, which indicate the IDs of the BPMs, whose electronics was the Libera Brilliance, are merely mathematical expressions. They are used here to reduce the input and to avoid the waste of space, rather than to imply the motives of the upgrades or other meanings. Fortunately, these upgrades did not

Received 30 August 2013

^{*} Supported by National Natural Science Foundation of China (11075198)

1) E-mail: chenzhichu@sinap.ac.cn

2) E-mail: lengyongbin@sinap.ac.cn, corresponding author

©2014 Chinese Physical Society and the Institute of High Energy Physics of the Chinese Academy of Sciences and the Institute of Modern Physics of the Chinese Academy of Sciences and IOP Publishing Ltd

stick to a single BPM category and less bias would be involved in the results.

Table 1. The course of the BPM electronics upgrading.

milestone	libera brilliance locations	number
spring, 2009	none	0
summer, 2010	$\left[\frac{5}{4}n\right] \times 7 + 3$	15
summer, 2011	$\left[\frac{5}{9}(n+1)\right] \times 3 + \left[\frac{5}{9}n\right] \times 4 + 3$	35
summer, 2012	$\left[6 - \frac{1}{(n-1.42)^2} + n\right] \times 7 - 2$	15
	and $\left[\frac{(n+1)}{2}\right] + \left[\frac{n}{2}\right] \times 6$	40

3 Principle component analysis

3.1 Basic concept

The BPM data matrix can be decomposed into three terms by using SVD:

$$B = USV^\dagger, \quad (1)$$

where U (also called the temporal matrix) and V (called the spatial matrix) are unitary, and S (called the singular value matrix) is diagonal. Eq. (1) could also be written in the following form by using the Einstein summation convention:

$$b_n^t = u_k^t s_k^k v_n^k, \quad (2)$$

where u_k is the k th column vector of U , v^k the k th row vector of V and s_k^k the k th diagonal element of S . In this way, it is clear that the final signal is the superposition of all the linear-independent bases, both temporally and spatially. Based on the theory of PCA, the bases of the temporal matrix, u_k 's, correspond to all the physical modes of the BPM system, the bases of the spatial matrix, v^k 's, the corresponding normalized distribution functions of the BPMs along the ring, and the singular values, s_k^k 's, of the corresponding deviations of the physical modes [1–5].

3.2 Noise evaluation method

The diagonal elements of the singular matrix S provide an estimate of the modes. As a typical result of the SVD, Figs. 1 shows that there is a floor of these singular values and about a dozen modes are separable from the floor. These modes could be useful to study the beam dynamics and the floor might reflect the average noise of the BPM system [6, 7].

The first two modes turn out to be the well-known betatron oscillation and the third mode is identified as the energy oscillation after analyzing the spatial and the temporal matrices [8–10]. Figs. 2, 3 and 4 show that

the behaviors—temporal waveforms, frequencies and the corresponding amplitudes, conformity relations between the spatial vectors, and the corresponding Twiss parameters, and even the singular point at BPM number 68—of the first three modes do fit the characteristics of the β -function and the η -function.

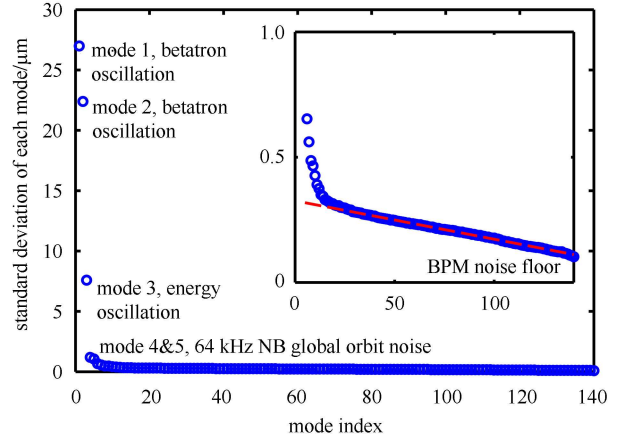


Fig. 1. Singular value plot of a typical SVD result. The noise floor reflects the average performance of global BPM system.

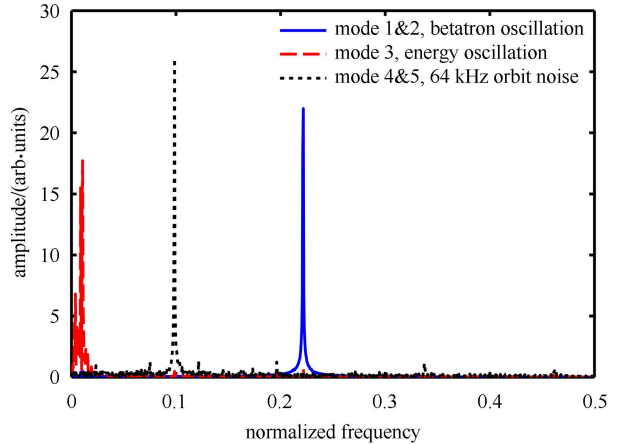


Fig. 2. Spectra of the first five modes. The first and second modes share the same spectrum with only the phase difference of $\pi/2$, and are therefore believed the bases of a single physical mode, as well as the fourth and fifth modes.

After eliminating the first five modes, which can be explained as the beam dynamics, the terms that remain should be considered measurement noise. Eq. (2) can thus be rewritten as:

$$b_n^t = u_\beta^t s_\beta^\beta v_n^\beta + u_\eta^t s_\eta^\eta v_n^\eta + u_{\text{GN}}^t s_{\text{GN}}^{\text{GN}} v_n^{\text{GN}} + u_{\text{N}}^t s_{\text{N}}^{\text{N}} v_n^{\text{N}}, \quad (3)$$

where β denotes the betatron oscillation, η the energy oscillation, GN the global narrow-band beam orbit noise, and N is the noise of the BPM system. The matrix form of Eq. (3) is

$$B = U(S_{1,2} + S_3 + S_{4,5} + S')V^\dagger, \quad (4)$$

where S_n only contains the n th diagonal element of S and $S' = S - S_{1,2} - S_3 - S_{4,5}$. Since the matrix

$$B' = US'V^\dagger \quad (5)$$

is now beam-independent, it could be used to estimate the BPM performance.

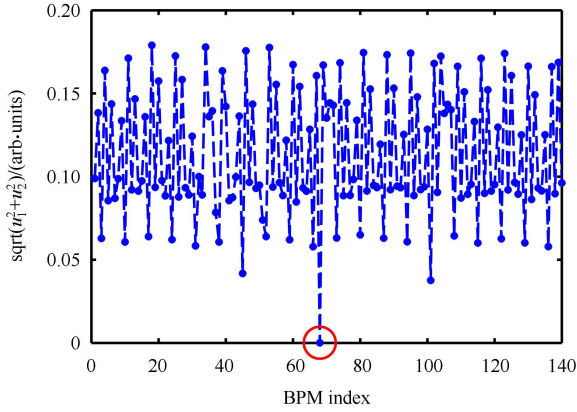


Fig. 3. (color online) Spatial vector of mode (#1, #2), which can be identified to be the betatron oscillation. The root of the quadratic sum of the first two spatial vectors is proportional to the β -function of the ring. The red circle marks the bad BPM.

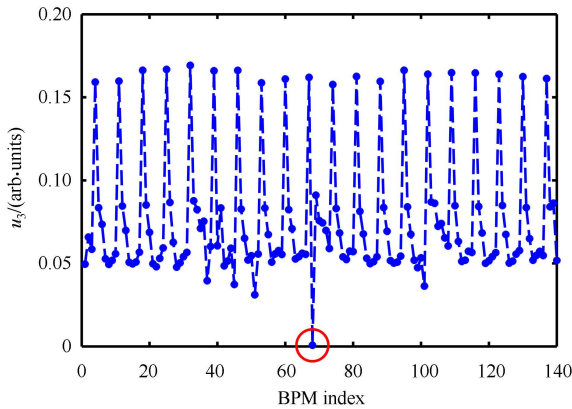


Fig. 4. (color online) Spatial vector of mode #3, which can be identified to be the energy oscillation. The spatial vector is proportional to the dispersion function of the ring. The red circle marks the bad BPM.

4 Applications

4.1 Performance evaluation of global BPM system

The resolution of the BPM system could be determined by finding the BPM noise floor of the diagonal elements of the singular matrix S , as shown in Fig. 1. Four sets of data to be analyzed are obtained by using

different BPM electronics configurations due to the upgrading procedures in SSRF. Although the BPM system gave both horizontal data and vertical data, only the horizontal ones are discussed here to avoid repetitions.

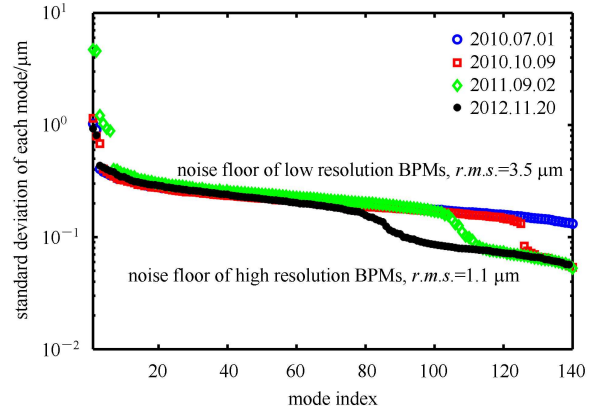


Fig. 5. Average performance evaluation for different upgrading phases using singular value plots. The upgraded BPMs are separated from the old ones.

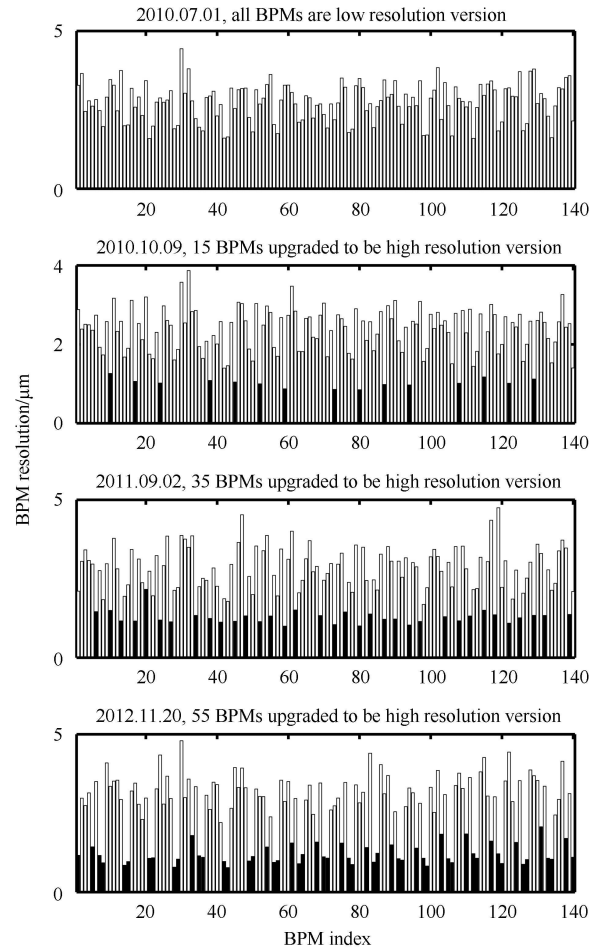


Fig. 6. Spatial resolutions of individual BPM at different upgrading phases. Dark bars indicate the upgraded BPMs.

The results in Fig. 5 show that the floor had been split into two levels. The split implied that there were two different kinds of equipment with different resolutions. The numbers in the lower group coincided with the ones in Table 1. There are also intermediate states due to the entanglement of the noise modes. The horizontal resolutions of the global BPM systems with Libera Electron and Libera Brilliance are $3.5 \mu\text{m}$ and $1.1 \mu\text{m}$, respectively.

4.2 Performance evaluation of individual BPM

Each column of the noise matrix (5) contains the random noise that was recorded by the corresponding BPM, so that the deviation of the column waveform indicates the resolution of the BPM. After calculating the standard deviations of the BPMs in different upgrading phases, the changes of the performance of individual BPM were studied. The BPMs upgraded in Table 1 are marked black in Fig. 6 and they had a qualitatively better performance than the old electronics, as they claimed.

By using the method routinely, one could easily calculate the vertical resolutions. Fig. 7 shows the results of the Libera Electron (in drift sections or arc sections) and Libera Brilliance. It can be seen that both the resolution and the stability of the Libera Brilliance electronics are significantly improved.

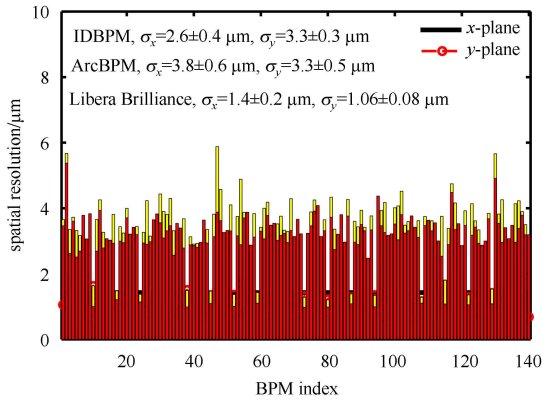


Fig. 7. Horizontal and vertical BPM resolution results.

4.3 Beam status dependency

The resolution of the BPM is actually related to the beam current due to signal-noise ratio. The relation between the beam current and the corresponding BPM global resolution can be calculated by using the method discussed in the previous section. Fig. 8 shows that the resolution and stability of the system kept improving while the beam current was increasing. A comparison in Fig. 9 has been made to show that, without the elimination of the beam dynamics, the standard deviation of the raw data not only underestimated the BPM performance but also saw the beam instability (there was some

kind of current related instability that had a threshold of $200 \mu\text{m}$). These beam dynamics and instabilities were the actual signals and they should not be regarded as part of the random noise.

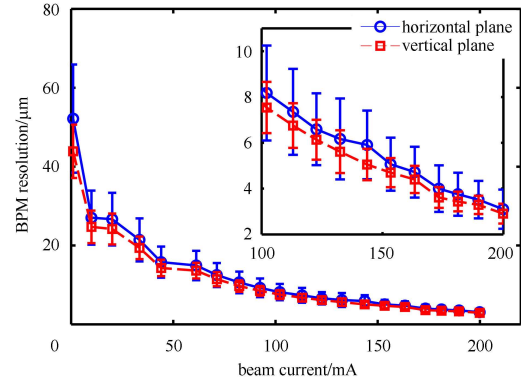


Fig. 8. Resolutions under different currents.

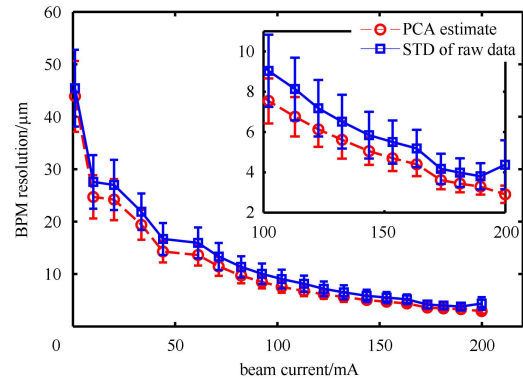


Fig. 9. Comparison between the SVD and the standard deviation results of the BPM performance.

Another experiment was done to check whether the operation status could influence the BPM resolution. The transverse feedback and the injection kicker were switched to “on” or “off,” and the physical modes were affected (e.g., the betatron oscillation was suppressed or invoked in different situations), as can be seen in Fig. 10. Nevertheless, the noise floor did not seem to be affected and the pattern of the split was kept unchanged. Therefore, the results of the BPM resolution would be the same, in spite of the machine status. Fig. 11 shows that, for most BPMs, $\pm 10\%$ accuracy would be guaranteed if the injection kicker was turned on and $\pm 20\%$ accuracy would be assured if the transverse feedback system was also turned off.

4.4 BPM configuration dependency

The resolutions calculated in the previous sections were believed to be the noise from the electronics. The geometrical layout coefficients, denoted by $k_{x,y}$, were used to verify this assumption. These coefficients were

determined by the coordinates of the probes and were used to process the output signals. The resolution of the electronics noise is proportional to k but the coefficient is unknown and varies from BPM to BPM.

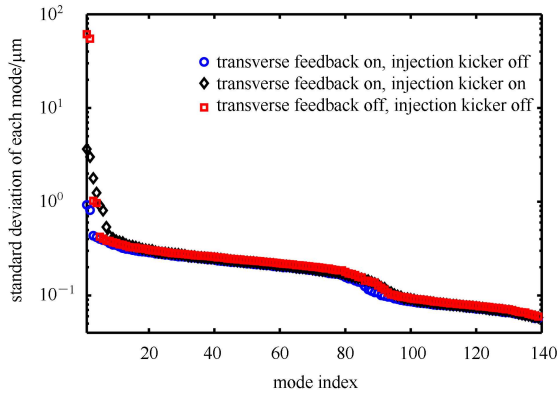


Fig. 10. Singular value plots of different data sets.

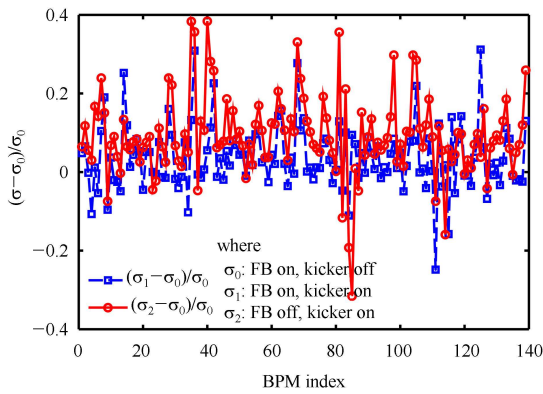


Fig. 11. Relative resolution calculation deviations of each BPM.

Fortunately, the horizontal and vertical k settings were not identical for all BPMs and the ratio σ_x/σ_y could be used to cancel the irrelevant coefficient to see if it matched k_x/k_y (as shown in Fig. 12). The (k_x, k_y) values of the ID BPMs and the arc BPMs are (12.1 mm, 11.9 mm) and (19.1 mm, 13.4 mm), respectively. Although there were still beam related components and alignment errors, so that some of the BPMs did not get

a perfect match, the pattern could be confirmed within reasonable amounts of error. On the other hand, the results of the standard deviations of the raw data did not show the pattern and the ratios of σ_x and σ_y were dominated by the horizontal oscillation, despite the transverse feedback suppression of the betatron motion, so that they were relatively larger than the theoretical values.

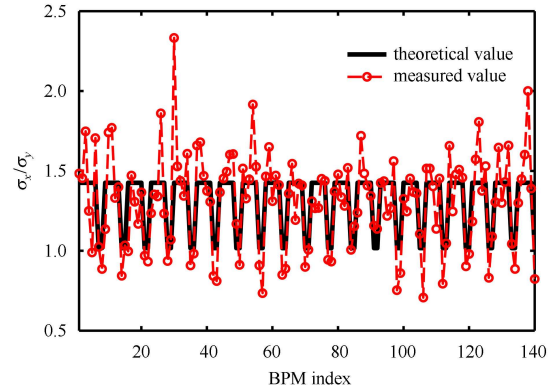


Fig. 12. Comparison between σ_x/σ_y and its theoretical value k_x/k_y .

5 Conclusion

PCA is good at separating linear-independent signals, which is exactly what is needed in the resolution estimate. The main physical modes were successfully extracted and identified from the raw data by using the SVD to decompose various of signals. The rest of the modes were considered to be the instabilities of the measurement system. The beam based resolution measurement of the BPM system was then done by using the noise matrix.

Our experiments have shown that the PCA could not only be used to discover the beam dynamics signals but was also capable of distinguishing one type of electronics noise from another by singular values. Furthermore, the characteristics of the horizontal and vertical resolutions met the geometrical coefficients of the BPM probe. These experiments have proved that the validity of this method.

References

- 1 Irwin J, WANG C X, YAN Y T, et al. Physical Review Letters, 1999, **8**: 1684–1687
- 2 WANG Chun-Xi. Physical Review Special Topics–Accelerators and Beams, 2004, **7**: 114001
- 3 WANG Chun-Xi, Rama Calaga. Proceedings of EPAC 2004, 2004. 1470–1472
- 4 WANG Chun-Xi. Proceedings of EPAC 2004, **2004**: 1473–1475
- 5 Calaga R, Tomás R. Physical Review Special Topics–Accelerators and Beams, 2004, **7**: 042801
- 6 WANG Chun-Xi, Michael Borland, Vadim Sajaev et al. Proceedings of the 2001 Particle Accelerator Conference, 2001. 1354–1356
- 7 Wolski A, Ross M C. Proceedings of EPAC 2002, 2002. 1205–1207
- 8 WANG Chun-Xi. Proceedings of the 2003 Particle Accelerator Conference. 2003. 3407–3409
- 9 WANG Chun-Xi. Proceedings of the 2003 Particle Accelerator Conference. 2003. 3410–3412
- 10 WANG Chun-Xi, Vadim Sajaev, YAO Chih-Yuan. Physical Review Special Topics–Accelerators and Beams, 2003, **6**: 104001