

# BPM GAINS AND $\beta$ -FUNCTION MEASUREMENT USING MIA AND FPGA BPMS AT THE APS\*

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## Abstract

The broadband BPM system at the Advanced Photon Source (APS) is being upgraded with FPGA-based beam history modules, which fix problems in the old history modules and increase functionality. Using these new turn-by-turn BPMS and the newly developed real-time feedback system, measurement of BPM gains, beta function, and other optics functions are being developed based on model-independent analysis of turn-by-turn data and model fitting, aiming at quasi-real-time and high-accuracy optics measurement. We will discuss our on-going effort and some measurement results without coupling.

## INTRODUCTION

In the APS storage ring, each of the 40 sectors has 9 button BPMS. All the BPMS were designed to have turn-by-turn broadband beam history modules. Unfortunately, the original implementation was faulty and unreliable [1], thus unsuitable for routine model-independent analysis (MIA) applications. Now, this broadband BPM system is being upgraded by gradually replacing 7 of the 9 BPMS with FPGA-based beam history modules. So far, 18 of the 40 sectors have been upgraded. To take advantage of these FPGA BPMS and the fast measurement capability of MIA, we renewed our MIA optics measurement effort, aiming at quasi real time and high accuracy.

It is well-known that the betatron phase advances between BPMS can be measured model-independently with either harmonic analysis technique for sinusoidal beam motion or with MIA for general excitations [2]. However, measurements of beta function and many other quantities depend on the BPM gains that usually can not be pre-determined reliably, especially considering that BPM performance is sensitive to many factors including beam condition. Thus, beam-based gain measurement is necessary and relies on fitting with a sufficiently good model, which is often available nowadays for storage rings. In this report, we discuss our effort on model-fitting with MIA measurements at the APS storage ring. Model-fitting with beam history measurement has been done successfully at the B-Factory of SLAC. Nonetheless, such efforts are machine-dependent and rather involved. This progress report describes our effort at the APS storage ring.

## BETATRON MODES MEASUREMENT

Extraction of high-accuracy independent betatron orbits from measured beam histories is the foundation for beam-

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history-based linear optics measurement. There are two independent orbits in each plane. If beam motions are sinusoidal oscillations, Fourier analysis can be used to extract the sine and cosine components as the independent orbits, as was done at the SLAC B-Factory with resonance beam excitation. At the APS, sinusoidal oscillation is hard to achieve even with resonance drive, because of 1) the strong nonlinearity due to strong focusing and the large number of sextupoles and 2) the strong wakefield due to small-gap insertion devices, which are typical of 3rd-generation light sources. It has been shown that MIA can extract betatron modes from all kinds of beam excitations at the APS [2]. Thus, we will use MIA betatron modes for optics measurement.

## Beam Excitation

We can excite betatron oscillation with injection kickers and a vertical pinger or with a newly installed turn-by-turn feedback system. Kick excitation is easy to control and repeatability is rather good, but the signal decoheres quickly due to strong nonlinearity. A new bunch-by-bunch feedback system was installed recently that provides a more convenient drive. Feedback excitation is basically a resonance drive. Thus it is not easy to control the excitation amplitudes, especially since beam tune can change with amplitude and instability is often excited. The main advantage of resonance drive is that the signal is continuous and FPGA BPMS can record up to about a whole second ( $2^{18}$  turns), which can yield better accuracy. Furthermore, the feedback drive can target an individual bunch and is less invasive. We have used both kick and resonance excitations.

## Overcome Obstacles from Real-life BPMS

Turn-by-turn beam histories are much more informative, yet more prone to various defects. In practice, it is a real challenge to (automatically) identify and overcome problems due to BPMS. Our new FPGA BPMS are much more stable, and thus alleviate many of the hurdles. But still, problems exist and have to be dealt with. Since we are aiming at quasi real-time optics measurement, most of the BPM analysis has to be automatic and sufficiently fast. Typical BPMS problems we encountered are [3]: 1) dead BPMS with no readings at all; 2) malfunctioning BPMS without signal (e.g., no tune line in the beam history spectrum) or with a wrong signal (e.g., beam history pattern is inconsistent with other BPMS); 3) unsynchronized BPMS whose beam histories are shifted by one or more turns; 4) noisy BPMS whose noise level and/or gain are much higher than others. The “dead” BPMS are usually BPMS used for other purposes and are easy to remove. The other BPM

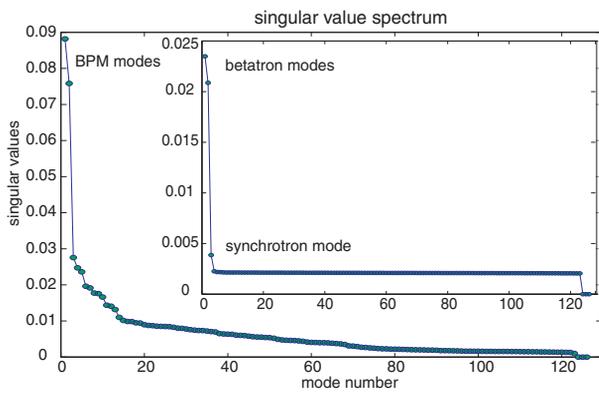


Figure 1: Singular-value spectra showing the effect of flattening the noise floor. The main figure is the spectrum of the raw data. The inset is the spectrum of the data normalized by the estimated rms noise of the BPMs. Note that the first two singular values in the raw spectrum are NOT from betatron modes but due to BPMs. The betatron and synchrotron modes are among the following modes (and mixed with BPM modes). In contrast, the normalized data shows a remarkably clear spectrum. Three dead BPMs shown up at the tail.

problems could be difficult to deal with. SVD modes have been shown to be useful for diagnosing problematic BPMs [1]. However, since SVD modes tend to pick out BPMs with large noise and mix betatron modes among them, it can be difficult to automatically identify and extract the betatron modes. We found a simple but very effective technique to work around this. First, the relative rms noise in beam histories are estimated by cutting off major beam signals with a high-pass filter, assuming the noise spectra of all BPMs are the same. Then, the beam histories are normalized by their rms noise. This effectively flattens the noise floor of the singular-value spectrum and lets the betatron modes stand out as shown in Fig. 1. Using the betatron modes as well as any problematic BPM modes, we identify potentially malfunctioning BPMs and remove them. Using the betatron modes, phase advances can be computed and compared with the model. The unsynchronized BPMs will show a phase error close to a multiple of the tune, assuming the errors in lattice are typically small. Based on this, beam histories are shifted to synchronize the data. However, ambiguity may exist, especially when there are multi-turn offsets. Note that the amplitude of such determined betatron modes can be far from the truth, which will be corrected by fitting with an adequate model.

## MODEL FITTING

There are various ways to fit the measurement with the model. The obvious method is to fit the phase advances because they can be measured accurately and are independent of BPM gains. The disadvantage of this is that the phase advances are global quantities, thus they can be affected by lattice errors far from the involved BPMs. The

localized quantities are the transfer matrix elements. Since only beam positions can be measured, not all matrix elements can be measured except the Green's-function elements such as  $R_{12}$ . Measurement of these matrix elements depends on BPM gains and excitation strength, which are unknown and have to be fitted with the lattice all together. This approach has been successfully used at SLAC [4, 5]. We will briefly describe our implementation of these two methods for the uncoupled cases.

### Fitting Phase Advances

To limit the disadvantage of fitting global quantities, we do not fit the phase advances directly. Instead we choose to localize the fitting to 4 BPMs based on the fact that

$$\frac{\sin \psi_{12} \sin \psi_{34}}{\sin \psi_{13} \sin \psi_{24}} = \frac{R_{12}^{12} R_{12}^{34}}{R_{12}^{13} R_{12}^{24}}, \quad (1)$$

where  $\psi_{ij}$  and  $R_{12}^{ij}$  are the phase advance and the  $R_{12}$  element between  $i$ -th and  $j$ -th BPMs, respectively. Although the phase advances are global, the left-hand-side (LHS) combination is not because the right-hand-side (RHS) quantity depends on local transfer matrix only. There is no gain dependence as well. We have yet to generalize this to the fully coupled case.

### Fitting Transfer-matrix Elements

From the spatial vectors of two betatron modes  $u$  and  $v$ , one can calculate the  $R_{12}$  between two BPMs at the locations  $s_1$  and  $s_2$  as [6]

$$\begin{vmatrix} u_1 & v_1 \\ u_2 & v_2 \end{vmatrix} = g_1 g_2 R_{12}(s_1 \rightarrow s_2) W(s_1), \quad (2)$$

where  $g$  is BPM gain, and  $W$  is the Wronskian function. The subscripts indicate BPM locations. The Wronskian of any two betatron orbits is invariant if beam energy is constant. It is proportional to the action of beam motion. Analogous expressions for the fully coupled case has been worked out in [4].

### Algorithms for Fitting

The LHS of Eqs. (1) and (2) can be computed from measured betatron modes, while the RHS can be computed from a model. Let  $M$  be the quantity to be fitted, assuming lattices errors are small and thus responses to deviations are linear, we can expand the model around a solution set  $\xi_0$  as

$$M^{\text{mod}} = M(\xi_0) + \sum_{\xi} \left. \frac{\partial M}{\partial \xi} \right|_{\xi_0} \delta \xi + \dots, \quad (3)$$

and neglect high-order terms. Least-squares fitting is used to solve for the minimum corrections needed to minimize the difference between measurement and model, i.e.,  $\|M^{\text{mod.}} - M^{\text{meas.}}\|$ . The solution can be written as

$$\delta \xi = (A^T A)^{-1} A^T [M^{\text{meas.}} - M(\xi_0)], \quad (4)$$

where the design matrix  $A = [\partial M / \partial \xi]$ . If there is (close-to) degeneracy, a pseudo inverse of  $A$  is used with noise cutoff in place of  $(A^T A)^{-1} A^T$ , a common algorithm available as a MATLAB built-in function. Usually many iterations are needed to converge, if it can. Similar, if not the same, fitting algorithms are used for the response-matrix method and orbit-fitting at B-Factory at SLAC.

The major limitation in lattice fitting is that there are usually not a sufficient number of BPMs to uniquely solve the lattice parameters such as quadrupole strengths. In other words, the system is under-constrained when the rank of the design matrix  $A$  is less than the number of parameters in the model. Though not obvious, Eqs. (1) and (2) yield equivalent sets of equations in terms of lattice fitting, i.e., no extra information can be gained. Nonetheless, fitting both together may improve the fitting algorithm's stability.

### BPM Gain Determination

It is important to note that, even if the lattice fitting is under-constrained, the BPM-gain fitting is always over-constrained and thus should be reliable as long as the fitting residual is sufficiently small. This is because, ignoring the Wronskian term for the moment,  $\|\Delta \ln M\| = \|A_g \delta g + A_R \delta q\| \leq \|A_g \delta g\| + \|A_R \delta q\|$ , where  $A_g$  is the response to the BPM gain variation, and  $A_R$  is the lattice response to the quadrupole strength deviations  $\delta q$ , etc. It is easy to see that  $A_g$  is full-ranked and independent of  $A_R$ . If the model is sufficiently good, both terms should be minimized to zero. Because  $A_g$  has full rank, the solution must be unique, which is the actual BPM gains (up to an overall scaling factor for all BPMs due to the unknown Wronskian). However, because of the intrinsic nonlinear nature of the problem, it is possible that the global minimum solution is not found and both the lattice parameters and gains are incorrect, in which case, the residual will be large, indicating a bad fit. Figure 2 shows an experimental confirmation of BPM gain measurement.

### Beta Function Measurement

Using the measured BPM gains, the beta function can be determined from the betatron modes. Figure 3 shows the measured (dots) and fitted (red circles) beta function and phase advances. The relative beta function difference and absolute phase difference between the measured and

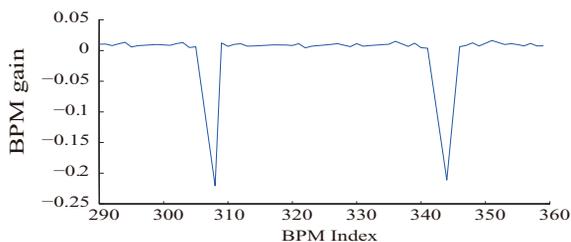


Figure 2: BPM gain measurement test. Gains of two BPMs were changed between two measurements. The measured gain differences are plotted here. The two peak values agree well with the given changes.

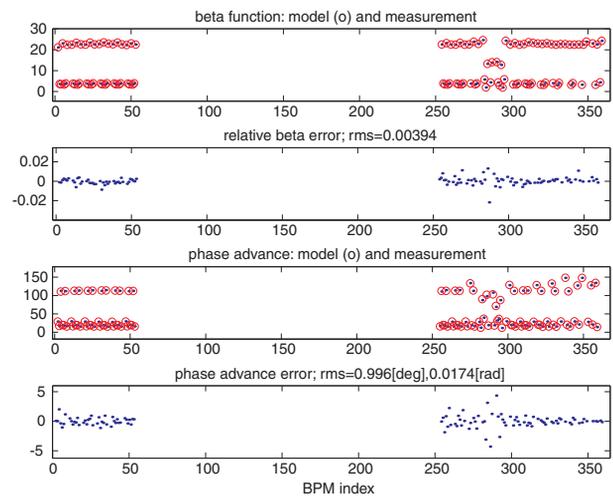


Figure 3: Measured (dots) and fitted (red circles) beta function and phase advances. The middle part is yet to be filled with installation of more FPGA BPMs.

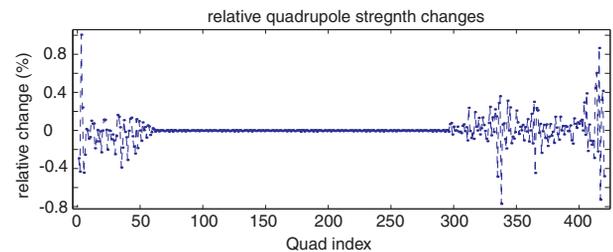


Figure 4: Quadrupole strength changes resulting from the fitting. The localized nature of the fitting is evident.

fitted model lattice are also shown, whose rms values are 0.4% and 1°, respectively. The associated quadrupole adjustments are shown in Fig. 4. Further improvements may include x-y coupling, sextupole misalignments, wakefield effects, as well as estimation of measurement errors.

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