BEAM BASED ALIGNMENT AT THE KEK-ATF DAMPING RING*

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Abstract

The damping rings of a future linear collider will have demanding alignment and stability requirements in order to achieve the low vertical emittance necessary for high luminosity. The Accelerator Test Facility (ATF) at KEK has successfully demonstrated the vertical emittance below 5 pm [1] that is specified for the GLC/NLC Main Damping Rings. One contribution to this accomplishment has been the use of Beam Based Alignment (BBA) techniques. The mode of operation of the ATF presents particular challenges for BBA, and we describe here how we have deduced the offsets of the BPMs with respect to the quadrupoles. We also discuss a technique that allows for direct measurements of the beam-to-quad offsets.

INTRODUCTION

The KEK-ATF has played an essential role in the demonstration of control and stability of the very low emittance beams that will be required by a future linear collider. One of the recent successes has been the achievement of vertical emittance below 5 pm, which was made possible through a variety of advanced tuning techniques and diagnostic systems, including a novel procedure for Beam Based Alignment (BBA) of the main quadrupoles. The motivation for this procedure and some early results from the ATF were presented in [2]. Briefly, the vertical emittance is generated by betatron coupling and vertical dispersion. Both effects are the result of beam offset through the quadrupoles and sextupoles. Generating an orbit to minimize the offsets depends on knowing the BPM positions with respect to the magnet centers. After steering an optimal orbit, the residual coupling can be corrected by skew quadrupoles. In the ATF, analysis and simulations showed that to achieve 5 pm vertical emittance, the BPM positions with respect to the magnet centers (the “BPM offsets”) need to be known to around 20 μm [2]. This motivated an upgrade of the BPM electronics, to improve the resolution from 20 μm to around 5 μm. Since that upgrade, and application of the results of the BBA data analysis to the low emittance tuning procedure, a vertical emittance of less than 5 pm has been achieved in the ATF [1].

We have recently applied the BBA techniques developed at the ATF to the PEP-II B-factory; this has led to a dramatic improvement in the understanding of the BPM-quadrupole offsets in PEP-II. In this paper, we review the particular challenges of carrying out BBA in the ATF, and outline the data collection procedure and the algorithms used in the data analysis. We illustrate the procedure with some results from the ATF and PEP-II.

DATA ACQUISITION AND ANALYSIS

The ATF is a racetrack lattice of 140 m circumference, with two arcs of 18 FOBO cells each, connected by long straight sections. A schematic of the arc cell, with positions of the quadrupoles, sextupoles, correctors and BPMs indicated, is shown in Figure 1. Note that most of the vertical focusing is provided by the gradient in the dipole magnet.

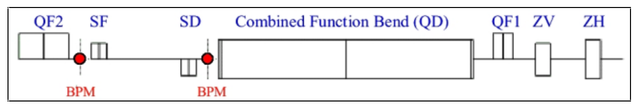

Figure 1: Schematic of the ATF arc FOBO cell.

There are 96 BPMs throughout the lattice; each BPM is able to read both horizontal and vertical orbit position. The ATF generally operates with an injection/extraction cycle of 3 Hz. Data can be read from the BPMs only once per cycle, though it is possible to specify that the trajectory be read on any selected turn after injection. Because it is not possible to collect multi-turn data directly, data collection is a fairly slow process, particularly if the resolution is improved by collecting data from a large number of orbits. Many of the BPMs have relatively large systematic dependence on such parameters as the bunch charge, which can vary from one machine cycle to the next. This makes it necessary to implement a rather rigorous data collection and analysis procedure, attempting to minimize random and systematic errors as much as possible. The upgrade of the BPM electronics, reducing the single-shot resolution from 20 μm to 5 μm, proved to be an important step in achieving the necessary quality of results.

For a quadrupole, the basic BBA procedure is as follows:

- A closed orbit bump (horizontal or vertical) is made through the target quadrupole.
- The strength of the quadrupole is varied, and the change in the orbit recorded.
- The orbit change is fitted in a lattice model, to determine the beam-quad offset.

The orbit change is determined by the change in quadrupole strength, and the initial offset of the orbit with respect to the quadrupole center. For a given bump, making several different changes to the quadrupole strength allows the orbit-quadrupole offset to be found from a fit of orbit change vs change in quadrupole strength. The final orbit-quadrupole offset (with no bump)

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is then found from a plot of orbit-quadrupole offset vs bump size.

Fitting the change in the orbit due to a change in the quadrupole strength needs to be done with care, since the change in the orbit has two contributions: the first is from the change in the field seen by the beam off-center with respect to the quadrupole; the second is from the change in the focusing. The correct expression for the change in the (vertical) orbit is [3]:

$$\Delta y_{co}(s) = -y_{bq} \frac{C_{34}^{(1)}(s;s_0)K^{(1)} - C_{34}(s;s_0)K}{1 - C_{34}(s_0;s_0)K} \qquad (1)$$

where $\Delta y_{co}(s)$ is the change in closed orbit at location s in the lattice; y_{bq} is the initial offset of the beam with respect to the quadrupole center; K is the initial integrated quadrupole focusing; $K^{(1)}$ is the integrated quadrupole focusing after the change in quadrupole strength. $C_{34}(s;s_0)$ is the closed-orbit response at s from a dipole kick at s_0:

$$C_{34}(s;s_0) = \frac{\sqrt{\beta_y(s)\beta_y(s_0)}}{2\sin(\pi\nu_y)} \cos(\pi\nu_y - |\psi(s) - \psi(s_0)|)$$

where $\beta_y(s)$ is the beta function at s, $\psi(s)$ is the betatron phase at s, and ν_y is the betatron tune. C_{34} must be calculated both for the original quadrupole strength and the quadrupole strength after variation. Note that some references [4,5] report an erroneous expression for the change in orbit resulting from a change in quadrupole strength. In the data from the ATF, equation (1) gives excellent agreement between the measured orbit change, and that predicted from the model.

BBA RESULTS FROM KEK-ATF

The BBA procedure has been applied to all QF2 arc quadrupoles in the ATF. Figure 2 shows a typical change in the measured orbit resulting from a change in quadrupole strength.

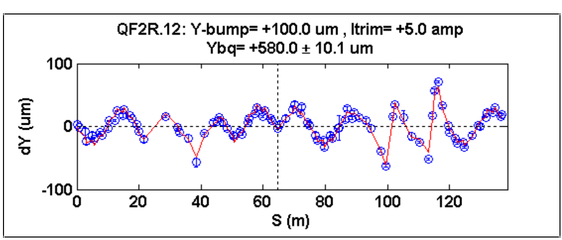

Figure 2: Change in orbit resulting from change in strength of quadrupole QF2R.12. The points show the BPM readings averaged over 20 orbits; the line shows a fit from a lattice model using equation (1).

Figure 3 shows the fitted offset as a function of the bump. For each bump, the offset y_{bq} is deduced from equation (1), using a range of quadrupole strengths $K^{(1)}$. From Figure 3, we can deduce the reading on the BPM, corresponding to the beam passing through the center of the quadrupole. The full set of BPM offsets are used to determine an "ideal" orbit for low-emittance tuning of the lattice.

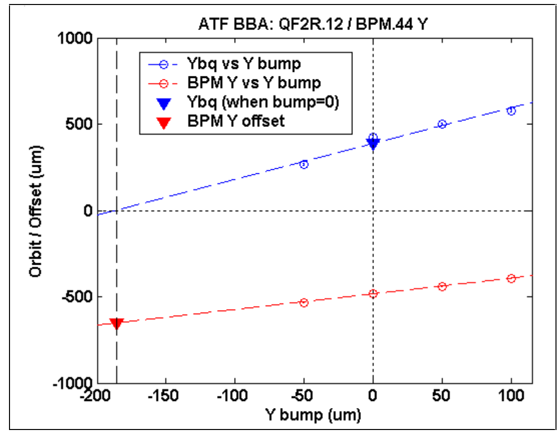

Figure 3: Beam-quad offset ("Ybq"), derived from changes in quadrupole strength, as a function of a vertical bump in that quadrupole. Also shown is the Y reading of the associated BPM versus the bump.

Figure 4 summarizes the results. Each point is the weighted average of up to five different data sets; the error bars combine the error on the fitted offset from each data set with the spread of fitted offsets over all data sets. The BPMs have offsets that are large compared to the survey alignment of the quadrupoles (less than 100 µm). The primary sources of the BPM offsets are believed to be electronic [2]. The results of the BBA have been used in low-emittance tuning, by steering a vertical orbit that passes close the centers of the quadrupoles. This minimizes the vertical steering, and the vertical dispersion arising from the steering. The dominant remaining contribution to the vertical dispersion comes from vertical beam offsets in the sextupoles; however, this can be corrected simultaneously with the betatron coupling, by use of the skew quadrupole windings on the sextupoles.

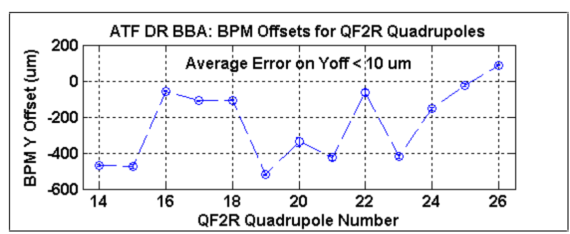

Figure 4: Offsets of BPMs with respect to centers of adjacent QF2 arc quadrupoles.

Figure 5 shows the residual vertical dispersion after low-emittance tuning at the ATF on three occasions: November 2002, March 2003 and May 2003. The new BPM system with 5 µm resolution (reduced from 20 µm) was installed between November 2002 and March 2003. The results are summarized in Table 1.

Table 1: Results of low-emittance tuning in the ATF.

Date	BPM Resolution	BBA Used	Residual Dispersion	Vertical Emittance
11/02	20 µm	No	5.8 mm	> 10.5 pm
3/03	5 µm	No	4.2 mm	6 – 10 pm
5/03	5 µm	Yes	1.7 mm	3.5 – 5 pm

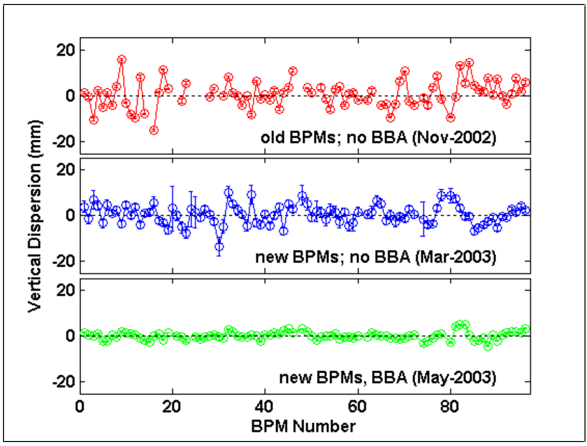

Figure 5: Residual vertical dispersion in the ATF after low-emittance tuning.

The contribution to the vertical emittance from the vertical dispersion is given approximately by:

$$\varepsilon_y = 2J_\varepsilon \frac{\langle \eta_y^2 \rangle}{\langle \beta_y \rangle} \sigma_\delta^2$$

With the ATF parameters (J_ε=1.4, $\langle \beta_y \rangle$=4.5 m, σ_δ=5.6x10^{-4}), the results given in Table 1 are consistent with a roughly constant vertical emittance contribution of 3–4 pm from the betatron coupling. Reducing the total emittance to below 5 pm was the result of improving the BPM resolution, and using the results of the BBA analysis.

BBA RESULTS FROM PEP-II

The BBA procedure developed at the ATF has been adapted for use in PEP-II. These two machines have many differences in terms of the lattices and diagnostics; however, the same basic procedure can be applied in both cases. One significant difference is that the betatron coupling in the PEP-II lattices is very much larger than in the ATF. This makes it necessary to use a modified version of (1) that takes into account the simultaneous change in horizontal and vertical orbit resulting from the change in a quadrupole strength: details are given in reference [3].

Figure 6 shows the beam position in a PEP-II LER quadrupole as a function of the amplitude of a closed horizontal orbit bump. The coupled analysis gives simultaneously the horizontal and vertical beam offset with respect to the center of the quadrupole. For a horizontal bump, the vertical offset is roughly constant; the horizontal offset tracks the bump. The reading on a nearby BPM also tracks the bump, but with a different slope because of the change in beta function between the quadrupole and the BPM. Also shown in Figure 6 is the deduced BPM-quadrupole offset. A fully coupled analysis of the BBA data is necessary to obtain consistent results. Further studies are needed to understand the stability of the BPM-quadrupole offsets over time.

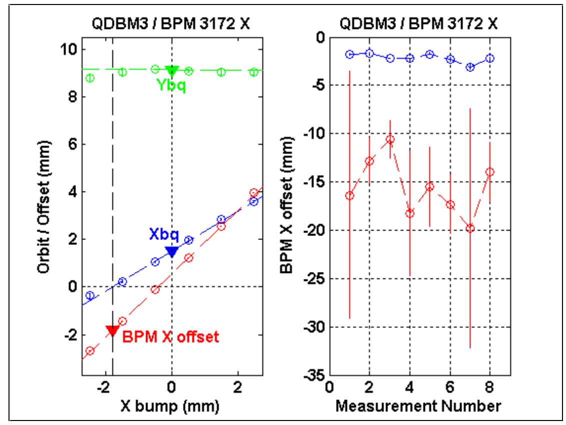

Figure 6: Left: Beam position in a PEP-II LER quadrupole as a function of closed bump amplitude (blue: horizontal; green: vertical; red: nearby BPM). Right: Horizontal BPM offset from data sets taken over a one month period (red: uncoupled analysis; blue: coupled analysis).

CONCLUSIONS

The ATF has now demonstrated the 5 pm vertical emittance that will be necessary for the damping rings for a future linear collider. This was achieved as a result of improved BPM resolution, and the use of BBA results to determine a vertical orbit passing close to the centers of the quadrupoles. The analysis developed at the ATF is now being applied at PEP-II. In the future, we hope to demonstrate high-resolution BBA of the sextupoles in the ATF, with the aim of further reducing the emittance.

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