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Publication Date

2002-06-14

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BEAM BASED ALIGNMENT AT THE KEK ACCELERATOR TEST FACILITY*

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Abstract

The KEK Accelerator Test Facility (ATF) damping ring is a prototype low emittance source for the NLC/JLC linear collider. To achieve the goal normalized vertical emittance $\gamma\varepsilon_y$ = 20 nm-rad, magnet placement accuracy better than 30 μm must be achieved. Accurate beam-based alignment (BBA) is required. The ATF arc optics uses a FOBO cell with two horizontally focusing quadrupoles, two sextupoles and a horizontally defocusing gradient dipole, all of which must be aligned with BBA. BBA at ATF uses the quadrupole and sextupole trim windings to find the trajectory through the center of each magnet. The results can be interpreted to assess the accuracy of the mechanical alignment and the beam position monitor offsets.

1 INTRODUCTION

The KEK Accelerator Test Facility (ATF) [1] is designed to produce extremely low emittance in order to demonstrate and develop linear collider damping ring technology. The measured ATF vertical emittance, ε_y, is 11 pm-rad ($\gamma\varepsilon_y$ = 27 nm-rad) at the low intensity limit. To prove linear collider damping ring design and technology, we must achieve, maintain, and understand the long-term stability of the minimum vertical emittance, $\varepsilon_{y\ min}$. The goal of the beam-based alignment is primarily the latter. Vertical dispersion (η_y) and betatron coupling must be minimized and maintained in order to obtain $\varepsilon_{y\ min}$. The minimization can be done in a ‘global’ sense [1], without directly correcting the offset in each quadrupole and sextupole locally, or it can be done using a trajectory corrected in detail using BBA results. In practice, there may be more than one solution to the global correction, and it will be difficult to definitively identify sources of drift and instability.

Two steps are involved in BBA at ATF, and while neither step is fundamentally innovative, given the design of the damping ring and the need to achieve $\varepsilon_{y\ min}$, both represent a challenge. First, the offset between the magnet's mechanical center and the electronic center of the BPM must be determined. Second, the magnet alignment offsets with respect to the design orbit must be found and removed, if possible. The first step, explained in section 4, involves the generation of a sequence of closed bumps and careful BPM data acquisition and analysis for each of the optical elements in the ring. The second step, outlined in section 5, is an attempt to use ballistic, or uncorrected orbit segments, that pass as close as possible through magnet centers, and then estimate component mechanical misalignments. Once both are done, correction for offsets in the sextupole magnets and correction for closed orbit distortions (COD) can be applied locally and tracked, as a function of time, to facilitate understanding of long-term instabilities. In addition, better understanding and application of the corrections will provide lower emittances.

2 VERTICAL EMITTANCE

There are two important sources of vertical emittance growth: 1) the emission of synchrotron radiation photons in a region with non-zero vertical dispersion (η_y) [2] and 2) the direct coupling of ε_x into ε_y [3]. Minimizing the vertical alignment errors simultaneously reduces vertical dispersion and betatron coupling from the sextupoles. Since orbit offsets in the sextupoles dominate the betatron coupling over quadrupole rotations, we will focus our discussion on correction of the vertical dispersion.

For randomly distributed alignment errors, the vertical dispersion makes a contribution to the vertical emittance, given by:

$$\varepsilon_y = 2J_\varepsilon \frac{\langle \eta_y^2 \rangle}{\langle \beta_y \rangle} \sigma_\delta^2 \qquad 1)$$

Vertical dispersion, in turn, is generated entirely by COD and skew quads:

$$\eta_y(s) = \frac{\sqrt{\beta_y(s)}}{2\sin(\pi\nu_y)} \int_s^{s+C} F(s')\sqrt{\beta_y(s')} \cos\left[\phi(s') - \phi(s) - \pi\nu\right] ds' \qquad 2)$$

with

$$F(s) = (K + S\eta_x)\, y_c - K_{sq}\eta_x + G_y$$

where K, S, K_{sq} and G_y are the normal quad, sextupole skew quad strengths and vertical steering respectively and y_c is the closed orbit displacement [4]. The first term in F, $(K+S\eta_x)$, is related to the local chromaticity. If the chromaticity is properly corrected locally, K and $S\eta$ cancel each other and a simple oscillation generates residual dispersion with a magnitude roughly that of y_c. However, for example, if step 2) in the BBA procedure is misapplied and a sextupole offset is applied specifically to zero y_c without at the same time correcting y_c in the focusing magnets, the chromaticity is not corrected and $\eta_y \sim \xi_n y_c$, (where ξ_n is the natural chromaticity) which, for

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* Work supported by US Department of Energy under contracts DE-AC03-76SF00515 and DE-AC03-76SF00098

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ATF is approximately 20 times larger. Consequently, it is important to make sure that the quadrupole and sextupole BBA, which are necessarily different procedures, are both accurate and that the orbit offsets in the quads are corrected as well as those in the sextupoles.

3 PREDICTIONS FOR ATF

3.1 Optics Design

The ATF ring consists of two 18-cell arcs and two wiggler straight sections. As BBA is most important in the arcs when the wigglers are off, as is typical in present operation, we've restricted our analysis to these regions. A standard 2.5 m cell, shown in figure 1, has a 1 m long gradient dipole, a pair of horizontally focusing magnets, two sextupoles, a horizontal and a vertical corrector (labeled ZH and ZV in the figure).

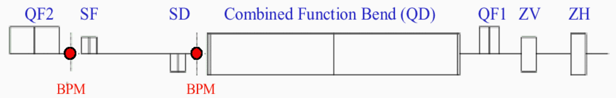

Figure 1: Schematic of the ATF arc FOBO cell. Each sextupole has secondary windings power that generate a skew quadrupole field.

Planned linear collider damping rings include a mover system to precisely correct offsets in optical elements [5]. ATF is not equipped with magnet movers, so secondary skew quad windings, separately powered and built into the each sextupole, are used to generate an effective offset shift. Likewise, the dipole corrector near the strong focusing magnet QF2 functions as its effective 'mover'.

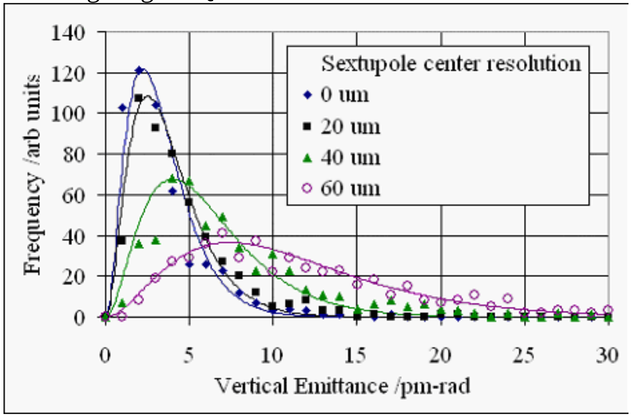

Figure 2. Simulated vertical emittance measurements for varied BBA accuracy.

3.2 Simulated effects of misalignments

Results of the simulated BBA and correction procedure are shown in figure 2 for various sextupole BBA accuracies. The simulation consists of a set of random ring 'seeds' in which the correctors are used to position the beam in center of each QF2 and the skew correctors are used to accommodate the measured offset in each sextupole. The figure shows that vertical emittances as low as ε_y ~3 pm-rad are typical for 20 μm BBA accuracy. The opening angle of the synchrotron radiation places a lower limit on the vertical emittance of 0.12 pm-rad. [2]. Dipole alignment errors are neglected in the simulation.

3.3 Correction

Using the dipole correctors and the skew correction windings installed in each sextupole, we can correct for the offsets of both sextupoles and the strong focusing magnet QF2. Errors in the positioning of the combined function dipole and the very weak quad QF1 must be corrected mechanically. The focal length of the combined function dipole is small, 0.87 m, making the dipole BBA important. From figure 2, we see the sextupole BBA resolution must be 20 microns to reach $\varepsilon_{y\ \min}$ much less than 11 pm-rad.

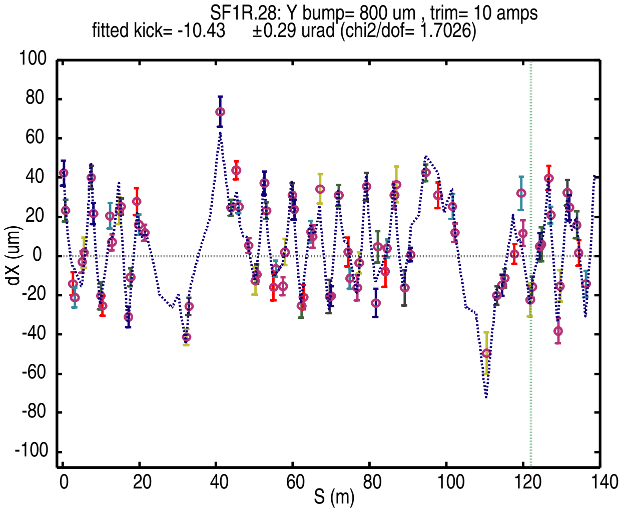

Figure 3. Example orbit with the superimposed fit. The dashed line shows the location of the sextupole under test.

4 DATA

Magnet-BPM offsets for each magnet are estimated using a 'shunt technique' in which a 6 x 5 matrix of difference orbit data sets is taken as both a local bump, at the magnet under test, and the magnet trim excitation is varied. For sextupoles, the skew quadrupole trim, (maximum strength K_{sq}=0.01 m^{-1}), is used. Since the damping ring has, by design, a lifetime of about 2 minutes, it is hard to use sine wave field modulation as done previously [6,7,8]. BPM data averaging and filtering is used. The data-taking process is fully automated and has been implemented remotely, from the SLAC site, in a manner suggested by the 'Global Accelerator Network' initiative proposed by DESY [9].

The kick amplitude at the test magnet for each of the 30 difference orbits is estimated from an orbit fit as shown in figure 3. Since K_{sq} is small, both orbit averaging and accurate knowledge of the ring optics are required. For each bump setting, the fitted kick is linear as a function of the trim excitation. The fitted kicks can be interpreted as an offset in the magnet. Figure 4 shows these offsets as a function of the nearby BPM reading. The *x*-intercept of the line, where the bump is set such that there is no kick as the trim is changed, is the BBA offset, giving the central trajectory.

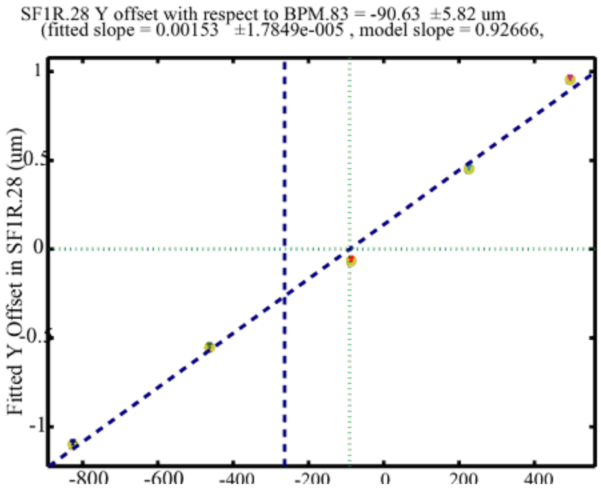

Figure 4: Fitted offsets, derived from trim kicks, as a function of the reading in the nearby BPM. The reported error in the intercept is 6 microns.

5 RESULTS

To date, the BBA process has been done for all quads and sextupoles in ATF. In each case, most of the offset is electronic in nature; the mechanical BPM construction errors are below the BBA resolution. The QF2 BBA is well behaved and allows a determination of the center close to the desired resolution. Table 1 shows results for repeated applications of BBA taken on two dates. The measurements were repeated three times on 3/1/2002. The rightmost column shows the offset measurement repeatability to be close to the goal of 20 μm. The typical sextupole BBA rms repeatability is about 150 microns, not adequate for the emittance minimization process to begin. In order to improve the resolution of the sextupole BBA, we plan to install higher performance BPMs [10].

Table 1:Y offsets for 8 of the 26 QF2R magnets from 1/23/2002 and 3/1/2002 in microns.

Q #	1/ 23	3/1 #1	3/1 #2	3/1 #3	rms
18	54.0	73.0	62.6		9.5
19	-421.2	-422.5	-426.5		2.8
20	-239.8	-200.9	-246.2	-243.1	21.2
21	-503.7	-551.7	-626.3	-586.2	52.1
22	47.1	-6.0	39.3	23.5	23.5
23	-211.0	-385.7	-295.4	-286.0	71.5
24	-255.6	-303.1	-294.8	-245.6	28.4
25	88.1	60.7	129.6	104.3	28.9

Ballistic steering is done by determining a start and stop datum for a trajectory segment. Figure 5 shows the offset subtracted positions from the BPM's near each QF2 in one of the 2 arcs. The figure shows the vertical trajectory through the arc, with all correctors up to BPM # 100 off. From the relatively smooth nature of the trajectory in the left of the figure, it is possible to infer that the dipole magnet misalignments are not large in that part of the arc. Downstream of BPM 95 we suspect systematic misalignments of the dipole magnets of about 100 microns cause the apparent oscillation.

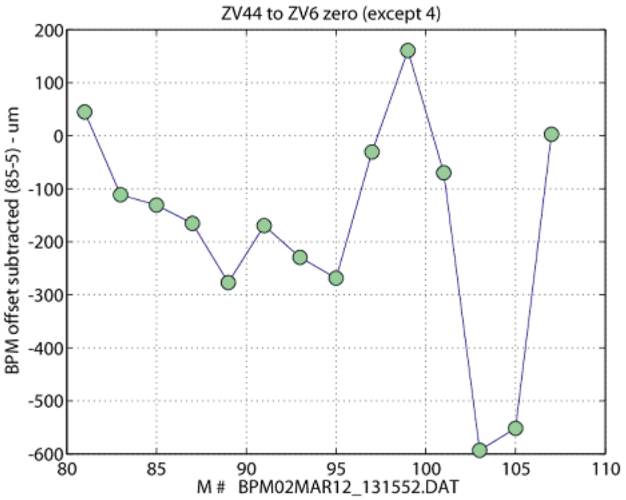

Figure 5: BBA offset subtracted BPM data for a ballistic vertical trajectory through an ATF arc vs the BPM monitor number.

6 ACKNOWLEDGEMENTS

The authors would like to thank our ATF hosts for help with the data acquisition, analysis and interpretation.

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