UPDATE ON OPTICS MODELLING FOR THE ATF DAMPING RING AT KEK

K. Kubo[*], S. Kuroda, T. Okugi, KEK, Tsukuba, Japan.

M.D. Woodley, SLAC, Menlo Park, CA, USA.

A. Wolski, K. Panagiotidis, University of Liverpool and the Cockcroft Institute, UK.

Abstract

One of the goals of the Accelerator Test Facility (ATF) at KEK is to demonstrate ultra-low vertical emittance for linear colliders. Highly precise correction of the vertical dispersion and betatron coupling will be needed to achieve the target of 2 pm (which is specified for ILC). Optics correction and tuning must be supported by an accurate model, which can be developed from a variety of beam measurements, including orbit response to dipole kicks, beta functions at the quadrupoles, etc. Here, we report experimental data and the status of the model and low-emittance tuning.

LOW EMITTANCE TUNING IN ATF DAMPING RING

The damping ring of the Accelerator Test Facility (ATF) is designed to produce an extremely small vertical emittance beam as a test accelerator for future linear colliders. The ring has two straight sections and two arc sections. Each arc is 41.7 m and each straight section is 27.6 m in length; circumference of the ring is 138.6 m. There are 48 horizontal and 50 vertical steering magnets for the orbit correction, and 96 beam position monitors (BPMs) in each plane. There are 34 focusing and 34 defocusing sextupole magnets in the arc sections. For the purpose of coupling correction, the trim windings of all 68 sextupole magnets have been arranged to produce skew quadrupole fields. There are no skew correctors in the dispersion free region.

Our usual tuning procedure for low emittance in the ATF damping ring consists of three consecutive corrections: orbit correction, vertical orbit-dispersion correction, and coupling correction. In the orbit correction, the readings of BPMs are minimized using steering magnets. In the vertical-dispersion correction, dispersion and orbit are minimized simultaneously (with certain relative weights) using steering magnets, where dispersion is obtained as the difference of orbits measured with different frequencies of RF accelerating cavities. In the coupling correction, we measure vertical orbit response to a pair of horizontal steering magnets. Then, the responses are minimized using skew correctors. The performance of the tuning with misalignment of magnets and errors in the BPMs was studies by simulations [1].

Using this procedure, we had achieved and confirmed very low emittance beam, of around 4 pm [2, 3] in 2004. However, since then, and until recently, pursuit of low emittance was not a major study item at ATF, and the emittance deteriorated. However, over the past year, renewed efforts have been made to achieve very low

emittance once again, and the performance is now starting to be recovered. In April 2009, the vertical emittance after tuning was typically less than 10 pm. In the following sections, we report some of the efforts related to beam measurement.

BEAM BASED ALIGNMENT

Simulations have shown that the vertical emittance after tuning depends strongly on offset errors of BPMs with respect to the nearest magnet field centre (magnet to BPM offset) [1]. To try to reduce these errors, we perform beam based alignment measurement (BBA).

BBA is performed with each pair of quadrupole (or sextupole) magnet and the nearest BPM, one by one. Since the vertical position is more important than the horizontal position for the vertical emittance tuning, we first concentrated on the vertical offsets of BPMs.

For a quadrupole–BPM pair, vertical local bump orbits of several different amplitudes are set, where the beam position change at the magnet should be the same as at the BPM. Then for each bump setting, the response of the vertical orbit in the whole ring (beam position at all BPMs) to the strength change of the magnet is measured. If the beam is at the field center of the magnet, there should be no orbit response. The procedure is similar for a sextupole magnet–BPM pair. Each sextupole magnet has trim windings to produce a skew quadrupole field, and BBA is performed for that skew quadrupole field. So, for each vertical bump setting, the response of the horizontal orbit to the strength change of the magnet is measured.

For improving the resolution of the BBA, we use the response of many BPMs. For each setting of a vertical local bump, the root mean square (RMS) of the position changes at many BPMs (all, except for noisy BPMs) is calculated. This RMS Δ_{RMS} is fitted as a function of the position at the BPM attached to the magnet (y) with three free parameters (a, b, c) as,

$$\Delta_{RMS} = b\sqrt{c^2 + (y-a)^2}$$

a is the required value of the offset between quadrupole field center and the BPM's zero position. Fig. 1 shows an example for one quadrupole and one sextupole magnet. The typical error of the offset, estimated from fluctuations of the BPMs, is about 30 micron for quadrupole magnets and about 80 micron for sextupole magnets. The error is larger for sextupoles because the horizontal orbit is not as stable as the vertical, probably because of residual synchrotron oscillations.

In April 2009, we performed BBA for all the main quadrupole magnets in the arc sections and for all of one

family of sextupole magnets. We also performed BBA for the same set of quadrupole magnets in April 2008. Fig. 2 shows the difference in the results for the quadrupole magnets between the two sets of measurements. Considering the estimated error, the change is significant for most of the magnets. It suggests that BBA should be performed more frequently.
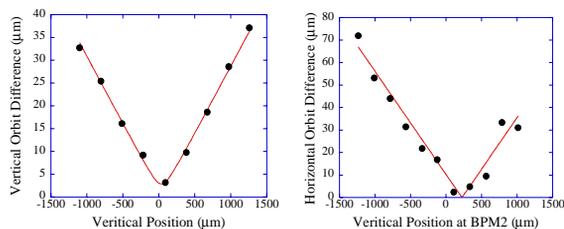
Figure 1: Examples of BBA data analysis. Orbit change (RMS at many BPMs) as a function of vertical bump amplitude. Left: quadrupole magnet, Right: sextupole magnet (skew quadrupole field).
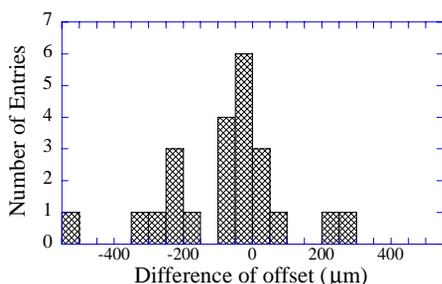
Figure 2: Difference of estimated vertical BPM-magnet offsets between data of April 2008 and April 2009. Distribution for 26 main quadrupole magnets.

BETA-BEAT CORRECTION

Simulations have also shown that optics matching can be important for achieving low emittance. Fig. 3 shows the vertical beta functions for two different optics matching conditions. The top plot shows the calculated beta function from the magnet strength settings in December 1999, when we observed small vertical emittance (about 5 pm). The bottom shows a worse condition, calculated from the settings in May 2008, when we could not achieve low emittance (more than 20 pm). In the data from 2008, there are obvious beatings in the arc sections.

We have studied the effects of the optics mismatch by applying the same simulation to different matching conditions. The results suggest that the mismatch will enhance the sensitivity to errors (magnet misalignment).

Recently, we set a new optics that, in calculation, has no beta-beat. Then, the beta functions at every quadrupole magnet were measured, by observing the betatron tunes as functions of the strength of each magnet. Since there are errors in the optics model (e.g. strengths of quadrupole magnets and misalignment of sextupole magnets), there remained some beta-beat. We tried to correct the residual beta-beat based on model calculations. First, the strengths of the quadrupole magnets were fitted to reproduce the measured beta-function. Then, the strength of each magnet was changed by an amount given by the difference between the fitted strength and the strength in the design optics. However, we found that the fitted beta-function had some difference from the measurement, and the fitted model was not good enough for predicting the beta function after the correction. For a precise beta-beat correction, more careful study will be necessary.
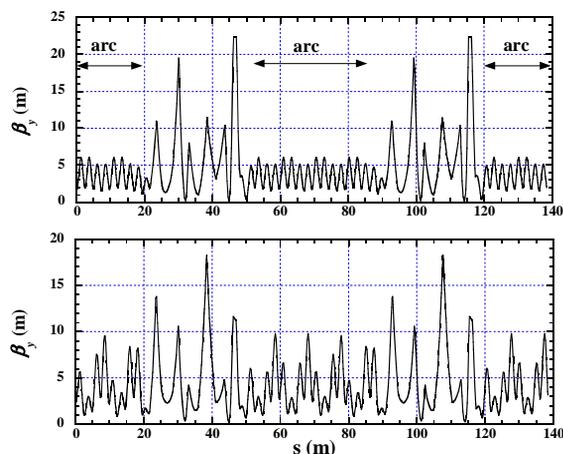
Figure 3: Calculated vertical beta functions of two different optics matching conditions. Top: From December 1999, when a small vertical emittance (about 5pm) was observed. Bottom: From May 2008, when a low emittance could not be achieved.

We still could reduce the beta-beat by a somewhat empirical technique, though the results are not completely satisfactory. In this correction, we concentrated on the beta function at magnets of one family in the arc sections (magnets named QF1R). Then, using model calculations, we looked for quadrupole magnets whose change would partly correct the beta-beat in that region. Fig. 4 shows, as an example of the correction, the vertical beta function at all the quadrupole magnets of one family in the arc sections, before and after the correction. For matched optics, the line should be flat.

More systematic methods of beta-beat correction and the effect of such corrections on the performance of low emittance tuning are still under investigation.
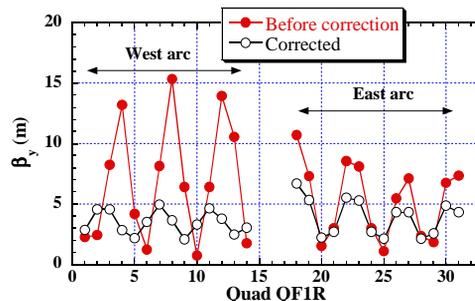
Figure 4: Vertical beta function at all quadrupole magnets of one family in the arc sections, before and after a beta-beat correction (measured March 10, 2009). For matched optics, the line should be flat.

ORBIT RESPONSE MATRIX ANALYSIS

Orbit response matrix (ORM) analysis is a well established technique for identifying and correcting optics errors [4]. Briefly, one measures changes in the closed orbit with respect to changes in strength of a number of orbit correctors, and then fits a machine model to the data, by adjusting parameters such as quadrupole strengths, BPM gains and couplings, and corrector magnet strengths and tilts. At ATF, the orbit response matrix is measured using all BPMs in each plane, and all steering magnets. The data are fitted using parameters including the strengths of 34 skew quadrupoles distributed through the arcs. This procedure effectively projects the betatron coupling sources onto the skew quadrupoles, and thus allows the determination of skew quadrupole strengths required to cancel the coupling sources.

Previous studies [5] have validated the ORM analysis technique by showing that known changes in skew quadrupole strengths can be identified from fitting ORM data taken immediately before and after the changes were made. We obtained similar success during more recent attempts at coupling correction, see Fig. 5.
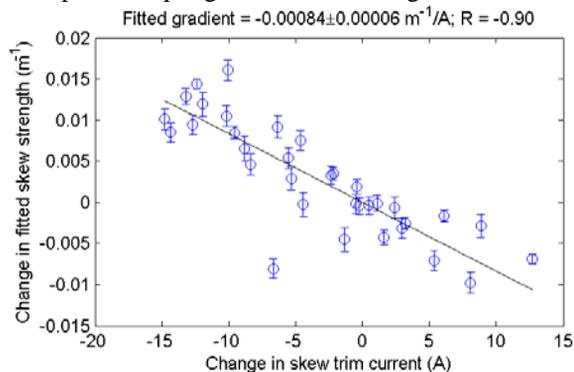
Figure 5: Correlation between changes in skew quadrupole strengths determined from ORM analysis, and known changes in currents.

Unfortunately, we have not been able to confirm any additional significant reduction in the vertical emittance (after the usual tuning procedure) using the skew quadrupole strengths determined from ORM analysis. On one occasion, there was a modest reduction in the vertical beam size measured by the x-ray synchrotron radiation monitor, from approximately 11 μm, to just under 10 μm. The reasons for this lack of success are not completely clear, but it is possible that a poor vertical orbit may play a role. The model fitted to the ORM data does not include orbit distortion (which is not well determined from ORM measurements). Thus, vertical dispersion generated by vertical steering will not be well-fitted or corrected by the skew quadrupole strengths determined by ORM analysis. If the vertical steering makes a dominant contribution to the vertical emittance, then correction of the betatron coupling will not have a significant effect in reducing the emittance. In this case, systematic and effective use of BBA to minimize vertical orbit distortion will be necessary before ORM will be of any real help.

Another possible limitation on the effectiveness of ORM analysis is the possibility of degeneracy between errors that cause coupling (such as quadrupole tilts or sextupole alignment errors) and errors in the diagnostics that only give the appearance of coupling in the ORM data (such as BPM couplings or corrector magnet tilts). These degeneracies have been investigated in simulation [6], and it is possible that they may limit the vertical emittance that can be achieved at the ATF using ORM analysis to around 5 pm.

CONCLUSIONS

After recent efforts using a variety of techniques to reduce the emittance in the ATF damping ring, a vertical emittance less than 10 pm was achieved in April 2009. The effectiveness of each individual technique still needs to be understood.

In order to achieve even smaller emittance (2 pm is the target), more studies on the tuning procedure and analysis of beam measurements will be necessary. In addition, it is planned to upgrade all BPM electronics (20 out of 96 BPMs were already upgraded [7]), and to carry out a re-alignment of the magnets.

ACKNOWLEDGEMENT

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