BEAM-BASED ALIGNMENT AT BESSY

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Abstract

The theoretical background for the beam-based alignment is presented. It is shown that the shift of the orbit, as the focussing strength of one quadrupole magnet is changed, can be described by the perturbed or unperturbed linear lattice parameters. This has been applied to check the longterm stability of the closed orbit with respect to the axes of the magnets, to redefine the zero readings of the standard beam position monitors, and to align the beam to the center of the quadrupole magnets at BESSY.

1 INTRODUCTION

Beam-based position measurement and alignment techniques have been used for quite some time at BESSY[1]. In the measurements the focussing strength of quadrupole magnets is changed. The resulting closed orbit distortions are observed and analysed to yield the original offsets of the beam with respect to the axes of the magnets. The theoretical background and the applied experimental techniques are explained.

The results are used either to verify the longterm stability of the closed orbit relative to the magnets or to perform beam-based alignment in order to improve the performance of the storage ring. Usually the standard beam position monitors (BPMs) are based on pickup electrodes and some kind of RF processing electronics. They suffer from drifts of the various components involved, like motion of the sensor heads, changing attenuation of the cables or drifts of the electronics. In this respect the measurement of the beam position relative to the magnets is very valuable for checking the stability of the RF BPMs or calibrating their zero readings. Centering the position of the beam inside the quadrupole magnets by beam-based alignment helps to achieve the ultimate performance in terms of high brilliance because the coupling and thus the vertical beam size are reduced.

2 THEORETICAL BACKGROUND

The variation of the focussing strength of quadrupole magnets leads to distortions of the closed orbit unless the position of the beam lies on the magnetic axes of these magnets. This fact has been and is used widely to determine the beam position relative to the quadrupole magnets[2]. The orbit distortions can be described by kicks at the locations of the quadrupole magnets. The effect of the kicks can be expressed in terms of the perturbed linear lattice parameters.

As an example the distortion of the vertical closed orbit, $y(s)$, due to the variation of the strength of quadrupole magnets is calculated. This can be done most directly using the solutions of the equation of motion[3]:

$$y_0''(s) + \mathrm{K}(s)\, y_0(s) = p_0(s)$$

$p_0(s)$ is the distribution of dipole or kick perturbations around the ring. If the focussing strength is modified the closed orbit will change to $y_1(s) = y_0(s) + \Delta y(s)$ and the equation for the shift of the closed orbit becomes:

$$\Delta y''(s) + [K(s) + \Delta K(s)] \cdot \Delta y(s) = -\Delta K(s) \cdot y_0(s)$$

This is identical to the first equation except for the modified focussing term $K(s)+\Delta K(s)$. As has been pointed out before[4] the distortion of the closed orbit, $\Delta y(s)$, is nothing but the superposition of the effects of the distributed dipole perturbations, given by $-\Delta K(s) \cdot y_0(s)$, calculated with the optics perturbed by $\Delta K(s)$.

A similar result is obtained in the horizontal plane. In electron storage rings, however, the difference orbit, $\Delta x(s)$, contains an additional contribution from the dispersion, $\eta(s)$. At a location, s_0, with non-zero dispersion, $\eta(s_0)$, the horizontal kick, θ_h, has to be accompanied by a variation of the energy in order to keep the pathlength of the closed orbit constant. The energy shift is given by: $\Delta E = -\theta_h \cdot \eta(s_0)/(\alpha \cdot C)$ with the momentum compaction factor, α, and the circumference, C.

If a single quadrupole magnet with the length L_q at the location s_0 is varied by $\Delta K(s_0)$ and if the thin lens approximation is used, the small kicks experienced by the beam in the horizontal and in the vertical plane are given by: $\delta\theta_h = \Delta K(s_0) \cdot L_q \cdot x_0(s_0)$, and $\delta\theta_v = -\Delta K(s_0) \cdot L_q \cdot y_0(s_0)$. The resulting shifts of the orbit can be described with these dipole kicks, the perturbed optics parameters, and with the well known formula for the orbit distortion by a dipole kick[3].

Alternatively, the unperturbed linear lattice functions can be used in this formula. This is an advantage for on-line calculations since only the original Twiss parameters have to be known. In this case the horizontal and vertical kicks change to:

$$\delta\theta_h^0 = \Delta K(s_0) \cdot L_q \cdot x_0(s_0) \cdot \frac{\left(1-\cos(2 \cdot \pi \cdot Q_0^x)\right) \cdot \alpha_0}{\left(1-\cos(2 \cdot \pi \cdot Q_1^x)\right) \cdot \alpha_1}$$

$$\delta\theta_v^0 = -\Delta K(s_0) \cdot L_q \cdot y_0(s_0) \cdot \frac{\left(1-\cos(2 \cdot \pi \cdot Q_0^y)\right)}{\left(1-\cos(2 \cdot \pi \cdot Q_1^y)\right)}$$

Also the modified momentum compaction factor, α_1, can be calculated from the perturbation, $\Delta K(s_0) \cdot L_q$, and the unperturbed parameters:

$$\alpha_1 = \alpha_0 + \eta_0^{\,2}(s_0)\cdot\Delta K(s_0)\cdot L_q \cdot \frac{\left(1-\cos(2\cdot\pi\cdot Q_0^x)\right)}{\left(1-\cos(2\cdot\pi\cdot Q_1^x)\right)} \quad \text{with}$$

$$\frac{\left(1-\cos(2\cdot\pi\cdot Q_0^{x,y})\right)}{\left(1-\cos(2\cdot\pi\cdot Q_1^{x,y})\right)} = \frac{\tan(\pi\cdot Q_0^{x,y})}{\tan(\pi\cdot Q_0^{x,y}) \mp \frac{1}{2}\cdot\beta_0^{x,y}\cdot\Delta K(s_0)\cdot L_q}.$$

Q is the tune, β is the beta function, and the index 0 or 1 indicates unperturbed or perturbed parameter. The derivation is very lengthy and tedious so only the final results have been given.

2 BEAM-BASED POSITION MEASUREMENTS

At the synchrotron radiation light source BESSY I the closed orbit is measured by means of 16 RF beam position monitors (BPM). Usually the stability of the BPM system can be trusted. In addition the orbit is regularly cross checked by the experiments at a few beamlines around the ring with scanning wires, optical imaging systems, or blade monitors. A corresponding number of target positions for the vertical and horizontal plane represent the "golden" orbit which has evolved over the years from the balance between user and machine requirements. The actual closed orbit is adjusted according to the 16 readings of the RF BPMs. A few years ago the additional hardware was installed to vary the strength of individual quadrupole and sextupole magnets. The system is used from time to time in order to check the long term stability of the orbit with respect to the axes of quadrupole magnets. Therefore, a fast and simple, never the less rather accurate technique has been developed for the measurement of the closed orbit relative to the quadrupole magnets without having to center the beam.

The measurements are done in the following way: First the orbit is measured with 16 RF BPMs and with 1 optical imaging system. The focussing strength of one quadrupole magnet is changed by a known amount and the orbit is measured again. This is done by the computer for all 36 quadrupole magnets at BESSY I within 30 minutes. The difference orbits are now fitted by a kick perturbation at the location of the corresponding magnet and from the kick the position of the beam relative to the center of the quadrupole magnet is obtained. The unperturbed linear lattice parameters are used so that the optics has to be calculated only once. A typical result is shown in Fig.1. The marked quadrupole magnet was changed by $\Delta K = .018\ m^{-2}$ and the resulting difference orbit together with the fit is displayed. At BESSY I shifts of the beam position can be measured with an accuracy of $\approx 10\ \mu m$. This together with the imperfect knowledge of the optics leads to a final relative uncertainty of the beam position inside the quadrupole magnet of approximately 1% or 10 ... 20μm.

It should be noted that this accuracy is achieved without moving the beam to the center of the magnet. State of the art BPM systems achieve accuracies of better than 1μm for relative measurements. Under these circumstances the uncertainty for the beam position will be dominated by the quality of the linear model for the storage ring. Obviously, centering the beam inside the magnet with local bumps is always possible with an accuracy given roughly by the resolution divided by two times the root of the number of BPMs. In this case knowledge of the optics is not required, however, in order to get absolute beam positions the excursion inside the bump has to be known quite accurately.

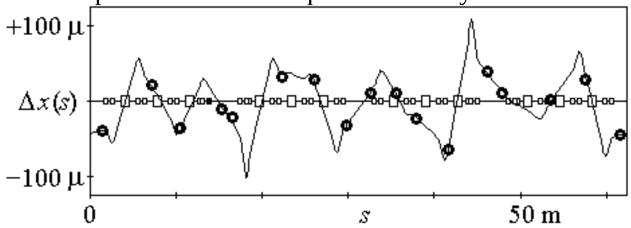

Figure: 1 Measured (circles) and fitted (solid line) closed orbit distortion created by a small gradient variation in the quadrupole magnet marked in black.

If individual magnets can not be varied one could change the strength of a family of quadrupole magnets and use the linear superposition of the effects of small kicks in order to obtain the offsets in individual magnets. In most cases there are more locations at which the position of the beam can be measured than there are magnets in a family. For example in light sources of the third generation the quadrupole magnets in straight sections, adjacent to insertion devices, are grouped in pairs. This allows for the local compensation of some of the focussing errors introduced by the insertions. In this case additional hardware is not required. At BESSY II[5] this corresponds to more than 50% of all quadrupole magnets. In general, the kicks from quadrupoles are difficult to separate if the phase advance between the magnets is small. This can cause severe problems if the linear optics model is imperfect.

Table 1.
Horizontal offsets, Δx, measured by changing the focussing strength of individual magnets or varying a family of 4 magnets.

quadrupole magnet	Δx[mm] (individual magnets)	Δx[mm] (family of 4 magnets)
QUA18R	-1.34	-1.34
QUA21R	+1.52	+1.40
QUA38R	+0.67	+0.73
QUA41R	+0.05	-0.01

As a test the focussing strength of a quadrupole family of 4 magnets was changed and the shift of the closed orbit was measured at 17 locations. Now the fit of the difference orbit was done with 4 free parameters and the perturbed lattice parameters. Considering the small number of measurements and the limitations of the optics model, the uncertainty for the offsets inside the individual magnets is rather small. The results given in Table 1 agree to better than 0.15 mm with the measurements done by varying the fields locally.

3 BEAM-BASED ALIGNMENT

Fig. 2 shows the development of the “golden“ orbit in the vertical plane measured relative to the magnetic axes of the 36 quadrupole magnets from September 1994 to May 1996 (dots). To guide the eye the individual measurements have been connected by straight lines. Over this period of time only some of the changes were intended others have to be attributed to undesired drifts.

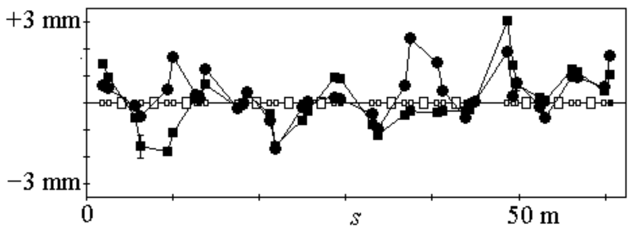

Figure: 2 The “golden“ vertical orbits as measured with respect to the axes of the quadrupole magnets in 1994 and 1996.

The orbits are not at all centered in the magnets. In order to align the beam, the vertical measurements were used to redefine the zero readings of the BPMs. With the corrected zero offsets the standard correction procedures could be applied because with a vertical tune of 3.3 the number of 16 RF BPMs is just sufficient to really define an orbit. The result is shown in Fig. 3. The corrected orbit was much closer to the centers of the magnets except for a few cases where some of the lately installed additional magnets[6] were misaligned similar to what was found at MAX[7].

In the horizontal plane another approach for the orbit correction had to be chosen. With a tune of 5.6 the orbit is not really well defined with only 16 target positions. In this case the eigenvalue decomposition technique[8] was used in order to find the most efficient and most effective settings of the 21 steering elements from the 36 offsets inside the quadrupole magnets. The result of a few iterations is shown in the bottom of Fig. 4.

After the orbit was corrected in both planes, the vertical beam size, and the vertical tilt of the image of the beam was reduced considerably. Unfortunately the higher brilliance and the potential for spectroscopy with improved resolution do not yet outweigh the time and effort required to realign the beamlines. Therefore, in the daily operation the old “golden“ orbit is still used.

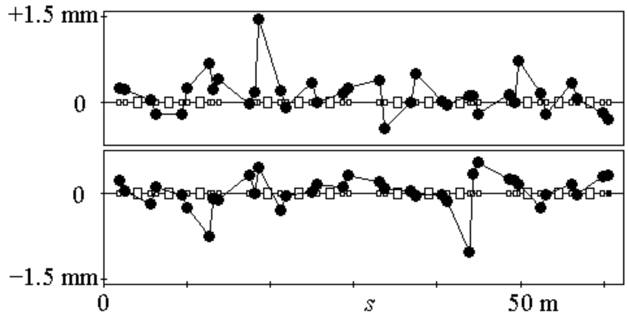

Figure: 3 Corrected vertical and horizontal orbit in the quadrupole magnets (top and bottom).

4 CONCLUSIONS

At BESSY I the position of the beam with respect to the axes of quadrupole magnets is measured only by changing the quadrupole strength without using additional orbit bumps. The analysis is done with the unperturbed Twiss parameters. This can be done with high accuracy by varying single magnets and with reduced precision but without additional hardware by changing families of magnets. The results have been used to check the stability and to define the zero calibration of the RF BPMs and to center the beam inside the quadrupole magnets.

5 ACKNOWLEDGEMENTS

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