VERTICAL EMITTANCE CONTROL AT BESSY

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Abstract

In synchrotron radiation light sources like BESSY II the reduction of the vertical emittance can increase the brilliance of the photon beam, can improve the resolution of certain monochromators, and is required for the planned production of femto second light pulses based on bunch slicing [1]. On the other hand, running the storage ring with only few bunches favours a larger vertical emittance in order to reduce the particle density and Touschek losses. Thus flexible control of this parameter is desirable. The paper describes the steps taken to accomplish this goal.

The small vertical emittance is achieved by beam-based alignment, analysis of the coupled orbit response matrix in order to find suitable locations for skew quadrupole magnets, the minimisation of the vertical dispersion, and the decoupling of the transverse planes by observing and correcting the local normal modes at 63 beam position monitors (BPMs). In the single bunch mode the vertical emittance is increased by exciting an artificial difference coupling resonance with a time varying skew gradient field produced by striplines. This approach has certain advantages over other techniques used for blowing up the beam.

1 INTRODUCTION

The vertical emittance depends on the coupling of the longitudinal and the horizontal motion into the vertical plane. The coupling can be described by the vertical dispersion, $D_y(s)$, and the elements of the 2x2 normalised coupling matrix, $\underline{C}_{i,j}(s)$. Both parameters can be measured with sufficient accuracy by state of the art BPM systems.

According to T. Raubenheimer [2] the vertical beam size, $\sigma_y(s)$, in electron or positron storage rings at the location s, contains 3 contributions:

$$\sigma_y^2 = \beta_y(s)\cdot\varepsilon_{op.angle} + \sigma_{D_y}^2(s) + \sigma_{\beta-cpg}^2(s)$$

The first term, $\varepsilon_{op.angle}$, stems from the finite vertical opening angle of the emitted synchrotron radiation and is usually rather small. The second term, $\sigma_{Dy.}$, is produced by the spurious vertical dispersion, $D_y(s)$, which can be created and compensated for by skew quadrupole field components, for example, at a location with non-zero horizontal dispersion, $D_x(s)$. There is a local and a global contribution to σ_{Dy}:

$$\sigma_{D_y}^2(s) = D_y^2(s)\cdot(\sigma_p/p)^2 + \beta_y(s)\cdot\varepsilon_{D_y}$$

with the energy spread, σ_p/p, and the global contribution, ε_{Dy}, given like the natural horizontal emittance:

$$\varepsilon_{D_y} = \frac{C_q\gamma^2}{J_y\oint G^2 ds}\oint|G|^3 H_y(s)ds$$

with $C_q=3.83\cdot10^{-13}$m, γ the relativistic factor, J_y the vertical damping partition number, $G=\rho^{-1}$, and

$$H_u(s) = \beta_u D_u^{'} + 2\alpha_u D_u D_u^{'} + \gamma_u D_u^2$$

with u = y or x, and $\alpha_u(s)$, $\beta_u(s)$, and $\gamma_u(s)$, the Twiss parameters, and $D_u(s)$ and $D_u´(s)$ the dispersion function and its derivative with respect to s. The spurious vertical dispersion can be measured and extrapolated to regions like the dipole magnets, where BPM data usually is not available. Based on this knowledge the resulting contribution to the vertical beam size can be estimated.

The third term, $\sigma_{\beta\text{-cpg}}$, results from the coupling of the transverse planes. It contains also a local and a global contribution and both can be written in terms of the elements of the normalised coupling matrix $\underline{C}_{i,j}(s)$ introduced by Bagley, et al. [3]:

$$\frac{\sigma_{\beta-cpg}^2(s)}{\beta_y(s)} = \varepsilon_x\cdot\left[\underline{C}_{1,2}^2(s) + \underline{C}_{2,2}^2(s)\right] + \varepsilon_{\beta-cpg}$$

and the global contribution, $\varepsilon_{\beta\text{-cpg}}$:

$$\varepsilon_{\beta-cpg} = \frac{C_q\gamma^2\oint\left|G^3\right|H_x(s)\cdot\left[\underline{C}_{1,1}^2(s) + \underline{C}_{2,1}^2(s)\right]ds}{J_y\oint G^2 ds}$$

For weak coupling, that is for small coupling fields and not too close to the $Q_x\pm Q_y$-coupling resonance, $\underline{C}_{i,j}(s)$ can be expressed with the unperturbed Twiss parameters of the uncoupled motion. The $\underline{C}_{i,j}(s)$ may be written as a linear superposition of the effects produced by single thin skew quadrupole magnets, K_i located at s_i:

$$\underline{C}(s) = \sum_i \underline{dC}_i(s,s_i),$$

with the individual contributions given by:

$$\underline{dC}_i(s,s_i) = \frac{K_i\cdot\sqrt{\beta_x(s_i)\cdot\beta_y(s_i)}\cdot\begin{pmatrix} c_{1,1} & c_{1,2} \\ c_{2,1} & c_{2,2}\end{pmatrix}}{4\cdot\sin(\pi(Q_x-Q_y))\cdot\sin(\pi(Q_x+Q_y))}$$

with K_i, the integrated skew quadrupole strength, and:

$$\Delta\mu_{x,y} = \mu_{x,y}(s_i) - \mu_{x,y}(s)$$

$$c_{1,1} = \cos(\Delta\mu_y)\cdot\sin(2\pi\cdot Q_x - \Delta\mu_x) + \sin(\Delta\mu_x)\cdot\cos(2\pi\cdot Q_y - \Delta\mu_y)$$

$$c_{1,2} = \sin(\Delta\mu_y)\cdot\sin(2\pi\cdot Q_x - \Delta\mu_x) - \sin(\Delta\mu_x)\cdot\sin(2\pi\cdot Q_y - \Delta\mu_y)$$

$$c_{2,1} = \cos(\Delta\mu_y)\cdot\cos(2\pi\cdot Q_x - \Delta\mu_x) - \cos(\Delta\mu_x)\cdot\cos(2\pi\cdot Q_y - \Delta\mu_y)$$

$$c_{2,2} = \sin(\Delta\mu_y)\cdot\cos(2\pi\cdot Q_x - \Delta\mu_x) + \cos(\Delta\mu_x)\cdot\sin(2\pi\cdot Q_y - \Delta\mu_y)$$

Three of these dimensionless matrix elements, namely $\underline{C}_{1,1}(s)$, $\underline{C}_{2,2}(s)$, and $\underline{C}_{1,2}(s)$ can be determined experimentally with turn-by-turn BPMs at the location s. In the measurements the two normal modes are excited and their projection into the x,y-laboratory space, an elliptical motion, is detected. The off-diagonal element, $\underline{C}_{1,2}(s)$ is proportional to the out-of-phase component of the motion and the diagonal elements, $\underline{C}_{1,1}(s)$ and $\underline{C}_{2,2}(s)$, are proportional to the corresponding in-phase component of the motion in the two planes x and y [4]. On the basis of these measurements and the given equations the compensation of the transverse coupling can be performed with standard techniques, like SVD. The minimisation of the C-matrix around the ring is very similar to the correction of the orbit. This was suggested by Teng [5] already in 1997, however, his proposal for a beam coupling monitor was less practical.

2 VERTICAL EMITTANCE REDUCTION

The field components which couple the longitudinal and horizontal motion into vertical plane are created by vertical offsets of the beam inside the many strong quadrupole and sextupole magnets, and by tilted dipole and quadrupole magnets. At BESSY the philosophy was adopted to force the beam to go as close as possible through the centres of all quadrupole magnets. This defines the “golden” orbit. Under the assumption that the nearby sextupole magnets mounted on a common girder are aligned as well or as bad as the quadrupoles themselves the resulting vertical emittance should be rather small already. The original target was an emittance ratio of 3% which could not be reached without the additional installation of skew quadrupole magnets. Fig. 1 shows how close the orbit can go through the centres of all 144 quadrupole magnets. With beam-based alignment the RMS-values for the offsets in both planes are as small as ~0.08 mm.

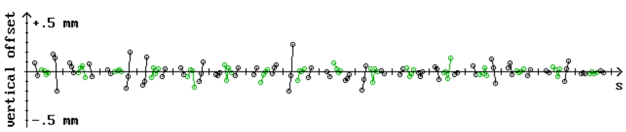

Figure 1: The vertical “golden” orbit relative to the quadrupole magnets. Magnets on a common girder are connected by a line.

2.1 Analysis of the Coupled Response Matrix

The analysis of the vertical orbit response to horizontal corrector variations and vice versa leads to the distribution of skew coupling components around the ring [6] however not to individual magnets being misaligned or tilted such that one would base a realignment on the result of the analysis [7].

At BESSY seven skew quadrupole magnets were installed in regions with large contributions to the coupling as found by the analysis of the response matrix. The 128 sextupole magnets installed in the ring have additional coils on each pole piece in order to use them as vertical and horizontal correctors or as skew quadrupole magnets. Two out of the seven magnets are located in regions with large horizontal dispersion for compensating a large fraction of the spurious vertical dispersion. This is shown in Fig. 2. The compensated dispersion (RMS-value of 2.3 mm) creates an estimated global emittance contribution of roughly $2\cdot10^{-12}$ πmrad. The local contribution to the beam size is always less than 4 μm with a measured natural energy spread of $8\cdot10^{-4}$.

Setting the remaining five skew quadrupole magnets is less obvious. The strategy was a combination of efforts to reduce the orbit coupling, reducing the strength of the nearby coupling resonance ($\Delta Qx - \Delta Qy \sim 0.1$), and the reduction of the tilt angle of the pin hole images of the beam. This decreased the vertical emittance even further however the chosen approach is time consuming and not suitable for assuring a good reproducibility.

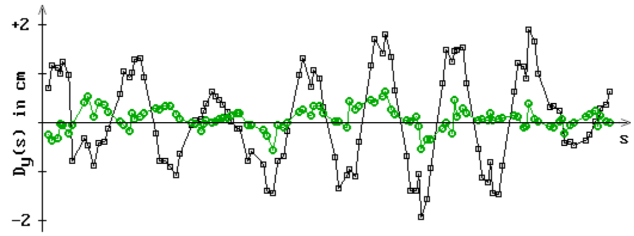

Figure 2: Compensation of the vertical dispersion with two strategically placed skew quadrupole magnets: black – uncompensated and green – compensated.

2.2 Analysis of the Normal Modes

The two normal modes can be excited by shaking the beam resonantly in the horizontal or vertical plane. In both cases the motion in the x,y-laboratory space is elliptical. At BESSY this motion can be followed turn-by-turn for up to 32k turns. Since data acquisition at each BPM is only possible from one electrode at a time [8], turn-by-turn position data must be repetitive. The x,y-motion of the normal modes can be reconstructed from the phase of the external force which is recorded simultaneously. In the experiment the beam is excited at a fixed frequency. During the time of the measurement (0.5 s) the response of the beam should not vary. This requires very stable power supplies and because of the non-zero chromaticity a high stability of the RF phase.

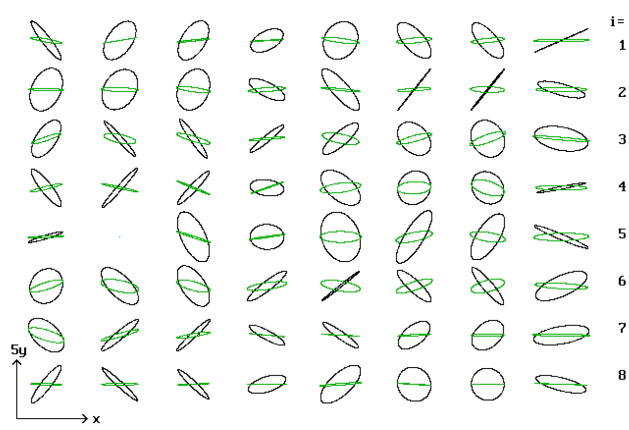

Figure 3: Appearance of the horizontal normal mode in the x,y-laboratory space with compensated vertical dispersion (black) and additional minimisation of the C-matrix (green).

The measured and reconstructed x,y-motion from the “horizontal” normal mode is shown in Fig. 3 with and without the skew quadrupoles tuned to minimise the C-matrix elements around the ring. The tilt angle of the ellipse is related to the matrix element $\underline{C}_{22}$ and the ratio of the minor to the major axes is related to the $\underline{C}_{12}$ element.

At BESSY these and the $\underline{C}_{11}$ element can be measured with an uncertainty of the order of 10^{-3}. As expected from the formulae given in the introduction, the minimisation with the remaining five skew quadrupole magnets of $<\underline{C}_{22}^{2}>$, $<\underline{C}_{12}^{2}>$, or $<\underline{C}_{22}^{2}+\underline{C}_{12}^{2}>$ produced nearly identical results. The minimisation of the coupling resulted in a severe reduction of the lifetime of 38% at a rather moderate beam current of 100 mA and an increase of the Touschek related loss rates [9] by nearly a factor of two. The vertical beam size measured with two pinhole x-ray imaging systems [10] was smaller by 8 and 18 % and the tilt angles of the ellipses relative to the horizontal plane were much smaller. If coupling to the longitudinal plane can be neglected then the tilt angle is simply given by the $\underline{C}_{22}$-matrix element. In the meantime and based on the remaining coupling four additional skew quadrupole magnets were installed which should allow a further reduction of the $\underline{C}$-matrix elements by a factor of two.

3 VERTICAL EMITTANCE DILUTION

Not many users at BESSY do require an extremely small vertical emittance. Most of them prefer a longer lifetime accompanied by a larger emittance. Touschek losses can be reduced with a couple of techniques [9, 11]. During the first weeks of running in single bunch mode at BESSY the excitation of an artificial difference coupling resonance was used in order to blow up the vertical beam size in a controlled and stable fashion. The resonance condition is Q_x-Q_y=$n \cdot F_o \pm F_{ext}$ where n is an integer, F_o is the revolution frequency, and F_{ext} is the frequency of the time varying skew quadrupole field. This field is created with striplines arranged and powered as shown in Fig. 4. The same arrangement is employed also for the excitation of normal modes. In this case the phasing of the striplines is different.

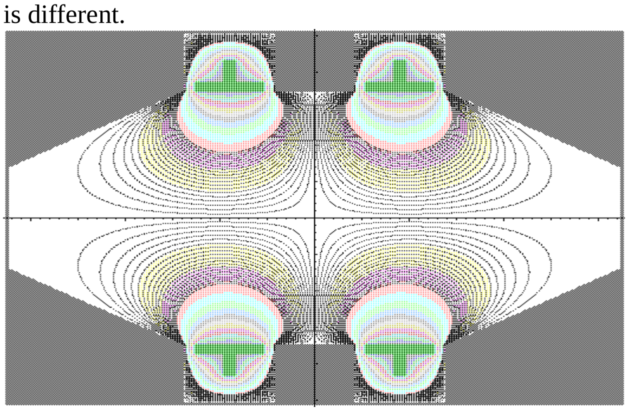

Figure 4: Skew quadrupole-like field distribution in the centre of the stripline arrangement.

Due to small tune variations produced by scanning insertion devices or by beam current variations the external excitation is frequency modulated at 100 Hz. The modulation depth is adjusted such that the beam will always be resonantly coupled. Since the integrated skew gradient field component is small the coupling introduced competes with the natural single particle damping times. Even on resonance the "coupling ratio" can be adjusted easily by the power level supplied to the striplines. This resulted in an improvement of the lifetime by a factor of two at 15 mA stored in a single bunch. At the same time the vertical beam size measured with the pinhole imaging systems appeared to be enlarged by only 25%.

4 CONCLUSION

The vertical emittance was systematically reduced based on beam-based alignment of the orbit relative to the centres of the quadrupole magnets and by measuring and compensating the effects of coupling the vertical plane to the horizontal and longitudinal motion. An increase of the vertical emittance can be achieved by exciting an artificial difference coupling resonance with a time varying skew quadrupole field.

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REFERENCES

[1] S. Khan, private communication

[2] T. Raubenheimer, "Tolerances to Limit the Vertical Emittance in Future Storage Rings", SLAC-PUB-4937 Rev., August 1991

[3] P. Bagley and D. Rubin, "Correction of Transverse Coupling in a Storage Ring" PAC'89, p. 874

[4] D. Sagan, et al., "Betatron Phase and Coupling Measurements at the Cornell Electron/Positron Storage Ring", Phys. Rev. Spec. Topics, Acc. And Beams,3, 092801 (2000)

[5] L.C. Teng, "Global and Local Horizontal-Vertical Decoupling", PAC'97, p. 1359

[6] R. Nagaoka, "Modelling of a Linearly Coupled Machine using the Coupled-Response Matrix", EPAC'98, Stockholm.

[7] C. Steier and D. Robin, "Fully Coupled Analysis of Orbit Response Matrices at the ALS", EPAC'00, Vienna.

[8] P. Kuske, et al., "Experience with the Beam Position Monitor System of the BESSY II Storage Ring", PAC'99, New York.

[9] P. Kuske, "Accelerator Physics Experiments with Beam Loss Monitors at BESSY", DIPAC 2001 Proceedings, ESRF, Grenoble, p. 31

[10] K. Holldack, et al., "Review of Emittance and Stability Monitoring Using Synchrotron Radiation Monitors", DIPAC 2001 Proceedings, ESRF, Grenoble, p. 16

[11] P. Kuske, "Emittance Manipulations at BESSY I" EPAC'98, Stockholm.