VERTICAL EMITTANCE MEASUREMENTS AND OPTIMISATION AT THE AUSTRALIAN SYNCHROTRON

M. J. Spencer, R. Dowd, G. Leblanc, Australian Synchrotron, Melbourne, Australia.

Abstract

Adjustment to the vertical emittance of the Australian Synchrotron storage ring [1] was made using 28 skew quadrupoles. The skew quadrupole settings were calculated using the LOCO method which uses measurements of horizontal and vertical dispersion and the response matrix. The vertical emittance was monitored indirectly through lifetime, tune crossing, an x-ray pinhole camera measurments and calibrated model calculations.

INTRODUCTION

The Australian Synchrotron light source is a Chasman-Green type lattice [1] and is designed for a horizontal emittace of ~10 nmrads (with 0.1 m of dispersion in the straights). It was expected to have a natural vertical emittance of ~100 pmrad. It has 28 independently controllable skew quadrupoles (present as extra windings on the SDA family of sextupoles). Figure 1 shows the lattice functions along with the position of the magnet families.

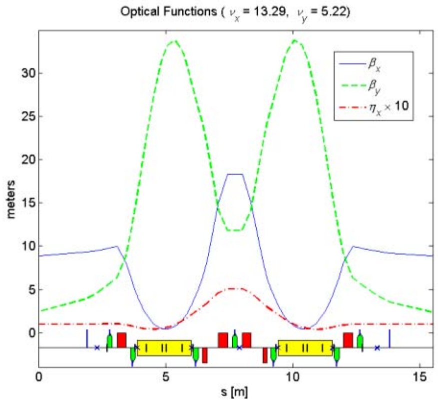

Figure 1. The Australian Synchrotron storage ring lattice functions. The families are (in order): SFA, QFA, SDA (with skew quadrupole windings), BEND, SDB, QDA, QFB, SFB.

NATURAL VERTICAL EMITTANCE THEORY AND MEASUREMENTS

There are three driving contributions to vertical emittance in a stored electron beam [2]:

- Quantum limit
- Vertical dispersion
- Transverse coupling

The first effect is a small contribution and is intrinsic to the lattice design; the second and third effects contribute significantly more to the vertical emittance of the beam and are related to imperfections in the manufacture and placement of magnets in the storage ring. It is these two effects which can be manipulated by the setting of skew quadrupole magnets.

Total emittance: Calibrated Model Beam Envelope Calculations.

Without equipment to make a direct measurement of the vertical beam emittance it is useful to make calculations from the calibrated model. A MATLAB AT model was calibrated using the LOCO code. This calibrated model has been successfully used in the past to correct the linear optics of the machine. The calibration is based on a comparison of the model and machine response matrix and dispersion measurements. The chosen fit-parameters included:

- Horizontal and vertical beam position monitors' gains and rotations
- Horizontal and vertical corrector magnets' gains and rotations
- Quadrupole strengths
- Skew quadrupole component strengths in all quadrupoles and sextupoles.

Once calibrated, the AT function 'calccoupling' was used to determine the vertical emittance. This function uses particle tracking to determine the beam envelope evolution in the storage ring [3] and therefore the magnitude of the emittance. The result for the vertical emittance was calculated as 13.4 pmrads. This value is significantly lower than the expected value of 100 pmrads.

Quantum Limit Contribution

The quantum limit to vertical emittance is related to the non-zero opening angle of synchrotron radiation and is given by [2]:

$$\varepsilon_y = \frac{C_q}{j_y}\frac{\left\langle \beta_y / \rho^3 \right\rangle_s}{\left\langle 1/\rho^2 \right\rangle_s},$$

where C_q is the 'quantum constant' (3.84×10^{-13} m), j_y is the vertical damping partition which is equal to 1, β_y is the average beta function in the dipole (~33 m) and ρ is the bending radius of the dipole (~7.7 m). The result is a value of $\varepsilon_{y,quantum}$= 0.09 pmrads. The value is about 3 orders of magnitude smaller than the expected natural vertical emittance. A similarly small value is present on all storage rings.

Vertical Dispersion Contribution

The measured vertical dispersion function η_y is shown in figure 2. This data is dominated by the coupling in the BPMs and so we see the peaks from the horizontal dispersion. In order to get a measure of the true vertical dispersion we have to rely on the calibrated model vertical dispersion with the BPM rotations set to 0. This function is shown in figure 2.

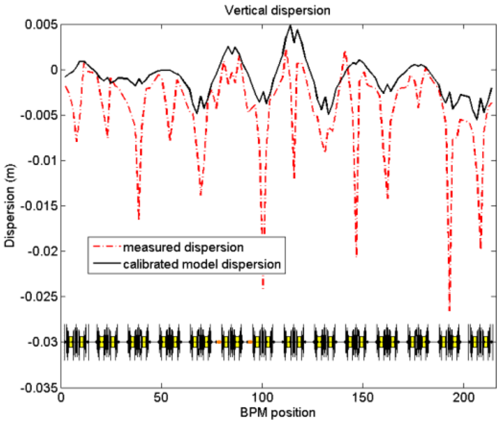

Figure 2. The observed vertical dispersion and dispersion from the calibrated model with all BPM rotations set to 0.

The emittance contribution from vertical dispersion can be calculated by [2]:

$$\varepsilon_y = \frac{C_q \gamma^2}{j_y} \frac{\left\langle H_y / \rho^3 \right\rangle_s}{\left\langle 1/\rho^2 \right\rangle_s},$$

where γ is the relativistic gamma factor (5871 for our 3 GeV beam), and $H_y = \left\langle \beta_y \eta_y'^2 + 2\alpha_y \eta_y \eta_y' + \gamma_y \eta_y^2 \right\rangle_s$ where α_y, β_y, and γ_y are the vertical twiss parameters. The value of $\varepsilon_{y,dispersion}$ was evaluated from the calibrated model as $\varepsilon_{y,dispersion} \approx 1.20$ pmrads using the AT function 'ringpara'.

Transverse Coupling Contribution

A crude estimate of transverse coupling might be made by shunting a horizontal corrector and watching the resulting vertical orbit, however, this measurement may be dominated by the effects of the particular corrector's rotation or by the BPM coupling. A better estimate has to use the calibrated model with the BPM and corrector magnet rotations set to 0. The vertical orbit can then be observed as function of horizontal kicks. The result was a vertical orbit around 3.9% the size of the horizontal orbit. Since the beam size is related to the emittance via $\sigma^2/\beta = \varepsilon$ then the emittance coupling is found via the square of this ratio. This gave an emittance contribution of $\varepsilon_{y,coupling} \approx 15$ pmrads.

METHOD FOR ADJUSTING THE VERTICAL EMITTANCE

The conventional method to influence the vertical emittance is to make a selection of skew quadrupoles at high vertical dispersion points and low beta functions and other skew quadrupoles with low vertical dispersion and high beta functions. This allows for independent manipulation of transverse coupling and vertical dispersion.

An alternative to this analysis is to utilise the results provided by the LOCO algorithm [4]. LOCO has been shown to produce good results [5-6] while avoiding the necessity of the analysis described. It was decided that the LOCO algorithm would be the focus of this study.

Skew quadrupole fit parameters were included only in the SDA family of sextupoles (where there are skew quadrupole windings).

The LOCO algorithm allows different weights to be placed on the fitting of the horizontal dispersion and vertical dispersion. By setting these weights it is possible to place more or less importance on fitting the three measurements (response matrix, horizontal dispersion, and vertical dispersion). The weights were adjusted and the results applied to the machine and the lowest emittance results found. Figure 3, below, shows the skew quadrupole settings predicted with equal weights and also the weights that were observed to give the lowest vertical emittance.

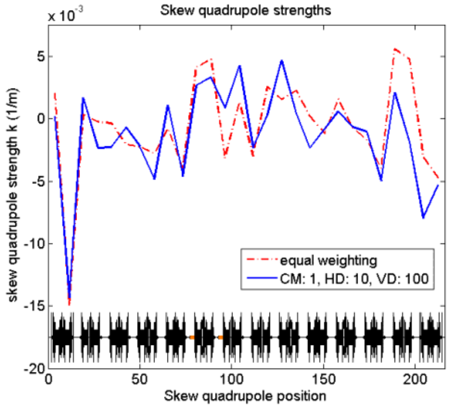

Figure 3: Skew quadrupole settings predicted by LOCO. The strengths with different weights on fitting the response matrix (CM), horizontal dispersion (HD), and vertical dispersion (VD) gave the lowest vertical emittance.

The beam was injected for 3 mA per bunch to ensure that the lifetime was Touscheck dominated. Under these conditions the emittance is proportional to the square of the lifetime.

Three configurations were investigated:

- Natural coupling; with the skew quadrupoles set to 0 strength.
- Reduced coupling; with the skew quadrupoles set to the negative of the values LOCO uses to calibrate the model.
- Increased coupling; with the skew quadrupoles set to the values LOCO uses to calibrate the model.

RESULTS OF ADJUSTMENTS TO THE VERTICAL EMITTANCE

The vertical dispersion from the calibrated model is shown in figure 3. It is obvious that although the RMS value of the vertical dispersion function is reduced slightly, the skew quadrupoles did not have a large effect on the vertical dispersion. This could be because the skew quadrupoles are not positioned at the points of highest dispersion.

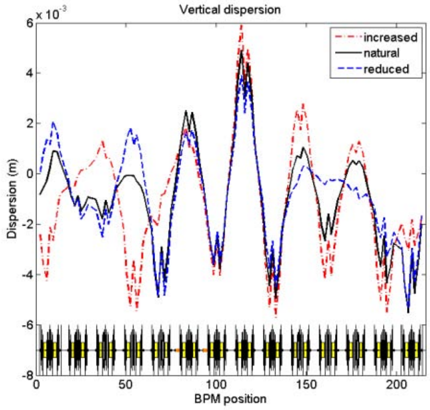

Figure 4: Vertical dispersion in the calibrated model for the three different skew quadrupole settings.

The vertical orbit which results from a horizontal orbit in the calibrated model is shown in figure 3. The results show that the transverse coupling has a significant response to the different skew quadrupole settings.

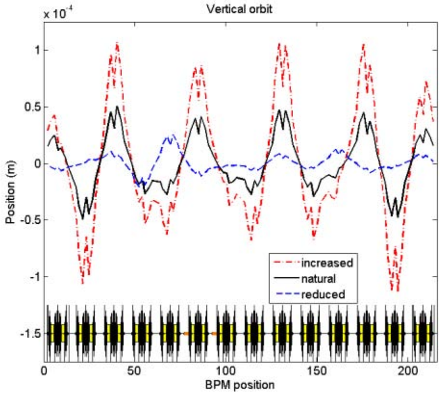

Figure 5: The vertical orbit which results from a horizontal orbit of around 1.5 mm. The orbits are shown for the three investigates skew quadrupole settings.

Measurements made of the machine during the application of each set of skew quadrupole strengths are shown in table 1.

The pinhole camera measurements are known to be untrustworthy as an absolute measure of beamsize but they do confirm a reduction in vertical emittance.

The lifetime measurements show a factor of 6.3 reduction in vertical emittance from the natural lattice to the reduced emittance lattice. This is in agreement with the combined effects of the vertical dispersion and transverse coupling which show a factor of 6.8 reduction in emittance.

The tune crossing measurement is known to only account for the linear coupling. The large value for the betatron coupling at increased emittance may indicate a problem with the measurement.

Unfortunately, from the measurements shown in table 1 it is difficult to determine both the absolute value of the vertical emittance and the amount that the vertical emittance was reduced. However, it is possible to conclude that the skew quadrupoles are significantly reducing the vertical emittance simply because the lifetime showed a significant reduction.

Table 1: Results of setting the skew quadrupoles.

	Increased Emittance	Natural Emittance	Reduced Emittance
X-ray pinhole Vertical beamsize (sigma)	68μm ±3μm (139 pmrads)	58μm ±3μm (102 pmrads)	52μm ±3μm (83 pmrads)
Lifetime	12.0h ±0.05h	6.16h ±0.05h	2.45h ±0.05h
Tune crossing measurement	3.2% (320 pmrads)	0.32% (32 pmrads)	0.02% (2 pmrads)
Beam envelope	89.5 pmrads	13.4 pmrads	1.2 pmrads
Vertical dispersion	1.55 pmrads	1.20 pmrads	1.18 pmrads
Transverse coupling	0.62% (62 pmrads)	0.15% (15 pmrads)	0.012% (1.2 pmrads)

CONCLUSION

The difficulty in obtaining an absolute value for the vertical emittance may be rectified by undertaking an interferometric measurement [7]. However, the most reliable measurements indicate a reduced vertical emittance of less than 2.5 pmrads. This value is low when compared to other storage rings.

The fact that the vertical dispersion does not respond to skew quadrupole changes means that it may be necessary to introduce skew correctors into the lattice at the high points in the vertical dispersion.

REFERENCES

[1] J. W. Boldeman, D. Einfeld, 2004 Nucl. Instr. And Meth. A 521, 306

[2] H. Wiedermann, “Particle Accelerator Physics II, Nonlinear and Higher-Order Beam Dynamics”, Springer, 2nd edition, 2003

[3] Kazuhito Ohmi, et al. “From the beam-envelope matrix to synchrotron-radiation integrals”, 1994 Physical Review E, 49, 751

[4] J. Safranek, “Experimental determination of storage ring optics using orbit response measurements”, Nuclear Instrument and Methods, 388 (1997), 27-36.

[5] C. Steier et al, “Coupling Correction and Beam Dynamics at Ultralow Vertical Emittances in the ALS”, PAC’03, Portland, May 2004, p. 3213 (2003); http://www.JACoW.org

[6] C. C. Kuo, “Coupling Correction Study at NSRRC”, PAC’03, Portland, May 2004, p. 3213 (2003); http://www.JACoW.org

[7] T. Naito et al, in Proceedings of the Particle Accelerator Conference, New York, 1999, (IEEE, Piscataway, NJ, 1999), p. 492-494.