EMITTANCE COUPLING CONTROL AT THE AUSTRALIAN SYNCHROTRON

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Abstract

Emittance coupling in the Australian Synchrotron storage ring is currently controlled using a total of 28 skew quadrupoles. The LOCO method was used to calculate the skew quadrupole settings, using measured vertical dispersion and transverse coupling. This information is used to create a calibrated model of the machine, which is then used to calculate the required skew quadrupole settings needed to minimise coupling. This method has thus far achieved encouraging results for achieving ultra low (<2pm) vertical emittance. In this study we seek to explore the validity of the LOCO model based on empirical measurements and possible improvements of this method.

STORAGE RING OVERVIEW

The Australian Synchrotron is a newly operating 3rd generation light source facility located in Melbourne, Australia. The 3 GeV storage ring is 216 metres in circumference and can store a beam of up to 200 mA current. A design overview can be found in [1]. The storage ring is a Chasman-Green type lattice designed for a horizontal emittance of 10.4 nmrads (with 0.1m dispersion in the straight sections) and is divided into 14 identical sectors, each containing and arc and straight section. As shown in figure 1, each arc segment contains 2 dipole magnets (with defocussing gradients), 6 quadrupole and 7 sextupole magnets. Orbit and coupling corrections are achieved via additional windings on the sextupole magnets, powered by small power supplies independently of the main magnet. Four sextupole magnets in each arc have the required windings to act as skew quadrupoles, although only two of these are currently powered, giving a total of 28 skew quadrupole magnets around the storage ring.

There are three source which contribute to the beam's vertical emittance in the storage ring. The first is the quantum effect and is negligibly small (0.09 pm) for our ring. The other sources are transverse coupling and vertical dispersion. Both of these effects can be manipulated using the skew quadrupoles.

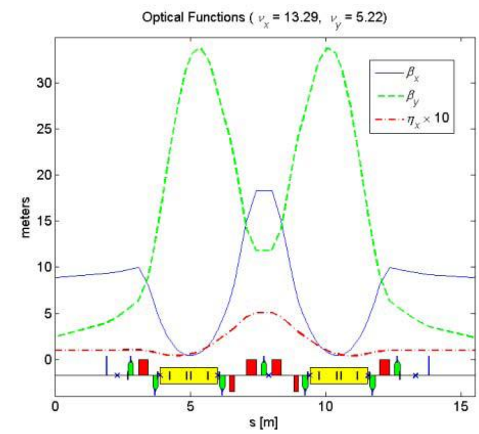

Figure 1: Storage ring magnets and lattice functions. Dipoles (yellow), quadrupoles (red) and sextupoles (green) are shown. Skew quadrupoles are located in the 2nd and 6th sextupole.

BEAM DIAGNOSTICS

There are two diagnostic beamlines at the Australian Synchrotron, an X-ray and an optical beamline. Details of the diagnostics beamlines can be found in [2]. In this study, only the X-ray beamline was used.

The X-ray diagnostic beamline uses the X-ray light from a bending magnet and passes it through a pinhole array. The multiple pinhole images are then projected onto a fluorescent screen and imaged by a CCD camera. By measuring the beam size and knowing the beta functions at the source point, it is possible to extract the beam emittance from this image. The CCD camera and beamline optics allow for resolution of the beam size to 5 μm accuracy, however the determination of the beam size is limited by diffractive effects. These effects have been studied [3] and found to introduce an uncertainty of around 50 to 60 μm. For a vertical emittance of 10 pm, the beam at the source point is expected to also be 60 μm in size and thus the uncertainty from diffraction effects becomes as large as the beam spot we are trying to measure. This limits the effective vertical emittance measurement range of this beamline to values above 10 pm.

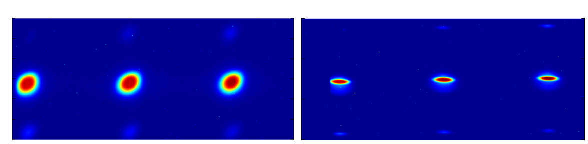

Figure 2: Typical images from the X-ray Diagnostic beamline. The left image is taken with 1.0% transverse coupling, the right with 0.01 %.

MAGNET ALIGNMENT

The storage ring multipole magnets in each arc sector are mounted onto one of 3 adjustable girders, with the dipole being independently supported and aligned. The girder support system and alignment techniques are detailed in [4]. In the middle of 2008 a full storage ring survey and re-alignment was conducted. The average magnet offsets before and after this re-alignment are shown in table 1. After this alignment, the natural coupling of the ring was found to have decreased from 0.1% to 0.06%.

Table 1: Alignment Survey Results Before and After Re-alignment

Survey	σ quadrupole	σ dipole
Before 07/2008	58 $\mu m \pm$ 16	45 $\mu m \pm$ 16
After 07/2008	26 $\mu m \pm$ 8	18 $\mu m \pm$ 8

LOCO BASED COUPLING ADJUSTMENT.

The method used to control the transverse coupling in our storage ring utilises the Linear Optics from Closed Orbits (LOCO) algorithm [5]. LOCO has been used extensively at the Australian Synchrotron to correct and control our storage ring optics [6]. The LOCO algorithm combines response matrix and dispersion measurements from the machine and compares them to the storage ring model. It then adjusts model parameters such as: BPM gains and couplings, Corrector gains and couplings, Multipole strengths and skew components.

These parameters are adjusted (over several iterations) in the model until the model behaviour matches the measured machine via a minimisation algorithm. We refer to the final adjusted model as the 'calibrated model', which can now be used in simulations to predict beam parameters and behaviour under certain conditions. In previous work on coupling control [7] a model with adjustable skew components in only the skew quadrupole magnets was fit to the machine, resulting in LOCO blaming all magnet induced couplings on the skew quadrupoles. To minimise the coupling we then applied the inverse of these fitted skews strengths to the skew quadrupoles on the real machine. While this method was successful in reducing the emittance coupling (to around 0.012%), one problem encountered was that LOCO would often fit a skew k value to one of the skew quadrupoles that was larger than the ability of the power supply to generate. This meant that we could not apply the correct inverse settings to the machine, resulting in sub-optimal coupling reduction.

For this study, the LOCO fit is done with skew components in all multipoles. The resulting skews are then fixed in the model and the horizontal and vertical emittance is calculated using the MATLAB Accelerator Toolbox (AT) function 'calccoupling', which uses particle tracking to determine the beam envelope evolution in the storage ring [8] and gives the horizontal and vertical emittances. This calculated emittance ratio is then fed to a minimisation algorithm which varies the skew quadrupole strengths (within the $\pm$ 5 Amp power supply limitation) to find the optimal configuration of skew quadrupole settings which minimise the emittance ratio (and thus the vertical emittance). These settings are then applied onto the machine and another LOCO run is performed to make a measurement for the machine emittance via the calibrated model.

The use of this minimisation algorithm also allows for arbitrary emittance ratio settings to be achieved simply by modifying the value that the algorithm is seeking to minimise. In this way a series of coupling configurations were determined, allowing the storage ring coupling to be set in 0.1% increments from 0.1% to 1.0%. These settings were applied, and LOCO measurements taken to determine the coupling and ϵ_y. The results are shown in table 2. As a further measurement of the coupling, the Tousheck dominated lifetime (discussed below) was measured for each setting by injecting a single 7 mA bunch into the machine.

Table 2: Results from emittance coupling adjustments

Set	Measured	ϵ_y (pm)	τ (h)
0.0%	0.009%	0.9	1.49 ± 0.06
0.1%	0.12%	12.2	3.15 ± 0.25
0.2%	0.23%	23.5	4.13 ± 0.25
0.3%	0.33%	33.7	5.58 ± 0.44
0.4%	0.43%	43.9	6.35 ± 0.40
0.5%	0.54%	55.1	6.76 ± 0.42
0.6%	0.64%	65.3	7.29 ± 0.49
0.7%	0.74%	75.5	8.14 ± 0.74
0.8%	0.84%	85.7	8.55 ± 0.60
0.9%	0.92%	93.8	9.01 ± 0.39
1.0%	1.04%	106.1	9.16 ± 0.50

BEAM TILT ANALYSIS

While we have a great amount of confidence in the LOCO analysis of our machine, it does rely on a properly calibrated model and there is no guarantee that the LOCO fit is the correct solution. With this in mind we tried to find some other way to confirm the validity of the calibrated model. A direct measurement of the beam emittance using an interferometer is also being attempted, although is not yet available. This paper will concentrate on other methods used to support the LOCO calculated emittance.

It was noticed that when adjusting the coupling of the storage ring the beam image on the XDB would change its tilt angle. Using a 2 dimensional gaussian fitting algorithm the tilt angle of the beam at the XDB could be extracted. This could then be compared to the local tilt at the XDB source point that is calculated by the calibrated model. With this method we could only measure the local tilt at the XDB source point, so in order to increase the number of data points for comparison each skew quadrupole power supply was individually shunted up and down by up to 5 Amps from its current set point (to a max amplitude of $\pm$ 5 Amps). The same shunting was applied in the calibrated model and the calculated local tilt was compared to the measured tilt giving an additional 56 data points. The comparison of the two tilts showed very good agreement for the different coupling configurations. Figure 3 shows the comparison of the 0.01% coupling model and measured local beam tilt at the XDB source point for each skew shunt (with the first result being the tilt when no shunts are applied). Errors in the model prediction were estimated by assigning a ± 1 cm uncertainty on the source position. From this very high correlation between the model and measured values, we can draw a high degree of confidence in the LOCO calibrated model.

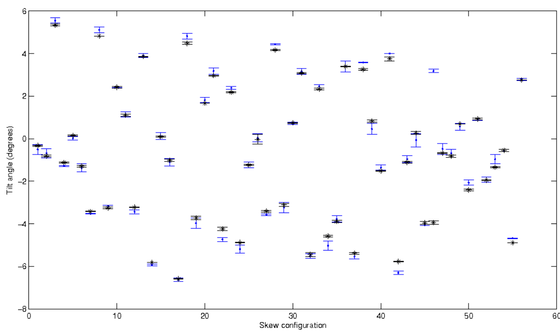

Figure 3: Model (blue) vs Measured (black) tilts. Each data point is a measurement made at the same position in the ring, but with a different skew quadrupole configuration.

TOUSHECK LIFETIME

Another way of independently verifying the model predictions is to look at the how the Tousheck lifetime of the beam changes with different coupling settings. The Tousheck lifetime is given by:

$$\frac{1}{\tau} = \frac{N r_e^2 c}{8\pi\sigma_z\gamma^2}\left\langle\frac{D(\epsilon)}{\delta_{max}^3\sigma_x\sigma_y}\right\rangle, \epsilon = \left(\frac{\delta_{max}\beta_x}{\gamma\sigma_x}\right)^2 \qquad (1)$$

Important for this analysis is the way the Tousheck lifetime depends on vertical beam size, σ_y. Since $\sigma_y = \sqrt{\epsilon_y\beta_y}$, if we only vary the ring emittance coupling, then ϵ_y will vary while the β functions remain the same, so:

$$\tau \propto \sigma_y \propto \sqrt{\beta_y\epsilon_y} \propto \sqrt{\epsilon_y} \qquad (2)$$

ϵ_y is dominated by the coupling from ϵ_x, so the coupling can be substituted in for the emittance whilst preserving the proportionality. Figure 4 shows a plot of the Tousheck dominated lifetime results plotted against the square root of the LOCO determined emittance coupling. A line of best fit has been added and shows a clear linear relationship between the two variables, indicating that the emittance is indeed changing as predicted by the calibrated model.

CONCLUSION

We have developed a method to allow arbitrary emittance coupling control of the our storage ring through the

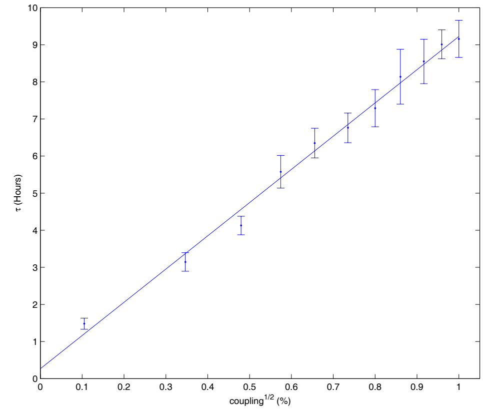

Figure 4: Single bunch Tousheck dominated lifetime vs square root of emittance coupling. A line of best fit is shown.

use of a LOCO calibrated machine model. While a direct measurement of the vertical emittance is currently not possible, indirect tests have so far confirmed the validity of the calibrated model's predictions. If we then assume the model is accurate, it indicates that we have achieved a vertical beam emittance of around 1 pm rad. This would be the current lowest achieved vertical emittance in the world and we hope to be able to confirm with a direct measurement using an interferometer in the near future.

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