OPERATING THE DIAMOND STORAGE RING WITH REDUCED VERTICAL EMITTANCE

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Abstract

In a synchrotron radiation light source, a reduction in vertical emittance can potentially increase the source brightness, reduce the spot size for microfocus beam lines or increase the vertical transverse coherence of the photon beam. With this aim, the target vertical emittance for the Diamond storage ring has been recently reduced from 27 pm.rad to 8 pm.rad (0.3% coupling). In this paper we discuss the main impacts of this reduction, along with the steps that have been taken to stabilise the coupling at the new value.

INTRODUCTION

The Diamond Light Source has been operated in user mode since January 2007 [1]. As part of the continual efforts to improve the scientific potential of the facility, the operational vertical emittance has been reduced from 27 pm.rad to 8 pm.rad. Trials of this mode were initially confined to machine development periods, but following a successful two week trial during user time in October 2012, it was adopted as the standard operating mode from March 2013.

Benefits of the reduction in vertical emittance for the X-ray beamlines include an increase in the brightness and vertical transverse coherence, and a reduction in the spot size for microfocus beamlines. However, the change has also had several adverse consequences on the storage ring performance. Firstly, small perturbations in vertical emittance caused by insertion device (ID) gap changes, tune variation and long-term drift have a larger proportionate impact on storage ring performance than was previously the case, prompting the introduction of a vertical emittance feedback. Secondly, the lifetime has reduced close to the 10h ‘soft’ minimum lifetime limit defined for top-up operation. Lastly, whilst the absolute stability remains unchanged, the electron beam motion in proportion to the vertical beam size has increased. In this paper we present details of these issues, along with their solutions.

EMITTANCE MEASUREMENT

The horizontal and vertical electron beam sizes are measured at two locations in the Diamond storage ring using x-ray pinhole cameras [2]. From these, the horizontal emittance (ϵ_x), vertical emittance (ϵ_y) and energy spread (σ_E) are extracted by inverting the relationship

$$\begin{pmatrix} \sigma_{x_1}^2 \\ \sigma_{y_1}^2 \\ \sigma_{x_2}^2 \\ \sigma_{y_2}^2 \end{pmatrix} = \begin{pmatrix} \beta_{x_1} & 0 & \eta_{x_1}^2 \\ 0 & \beta_{y_1} & \eta_{y_1}^2 \\ \beta_{x_2} & 0 & \eta_{x_2}^2 \\ 0 & \beta_{y_2} & \eta_{y_2}^2 \end{pmatrix} \begin{pmatrix} \epsilon_x \\ \epsilon_y \\ \sigma_E^2 \end{pmatrix} \quad (1)$$

where $\sigma_{z,n}$ are the electron beam sizes extracted from the pinhole camera images, and $\beta_{z,n}$ and $\eta_{z,n}$ are the beta functions and dispersion at the image source points.

The vertical emittance found using this method is particularly sensitive to the vertical dispersion at the source point; to ensure the emittance calculation is using up to date values the dispersion is routinely measured after each injection. Values for $\beta_{z,n}$ are extracted from the machine model.

VERTICAL EMITTANCE CONTROL

Control of ϵ_y is achieved starting from a correction of the linear optics using LOCO [3], for which all 96 skew quadrupoles are used (4 per cell). This correction defines a vector of skew quadrupole strengths, $\overline{K_{skew0}}$, and a single iteration of LOCO is usually sufficient to bring ϵ_y to below 3 pm.rad. From this point, ϵ_y is increased to the target value by applying a constant offset δ to $\overline{K_{skew0}}$, with the magnitude of δ calculated by inverting the model response matrix R, where

$$\Delta\epsilon_y = R\delta \quad (2)$$

Note that ϵ_y varies quadratically with δ [4], so the model response matrix R should be measured at the target ϵ_y to ensure predictable gain for the feedback (see Fig. 1).

The above method for ϵ_y control, whilst simple in concept, is found to be very efficient at increasing ϵ_y through vertical dispersion only. This separates control of ϵ_y from the betatron coupling, reducing beam losses on narrow-gap vessels and minimising the residual beam tilt.

Feedback Implementation

The ϵ_y feedback algorithm uses the same principle as the initial correction, keeping the LOCO correction vector $\overline{K_{skew0}}$ constant but varying the magnitude of δ. The feedback runs at 5 Hz (matched to the frequency at which ϵ_y is measured), and applies only a fraction f of the calculated change at each iteration. To minimise the impact of noise, an Infinite Impulse Response (IIR) filter with coefficient α is used to smooth the instantaneous value of ϵ_y. The correction applied by the feedback at iteration n can therefore be written as

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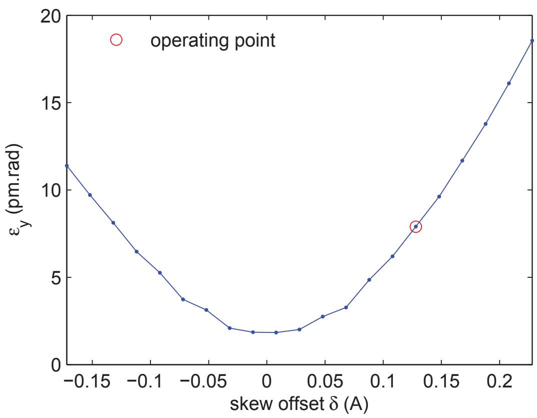

Figure 1: ϵ_y as a function of skew quadrupole offset for standard conditions (300 mA, 900 bunches, IDs closed).

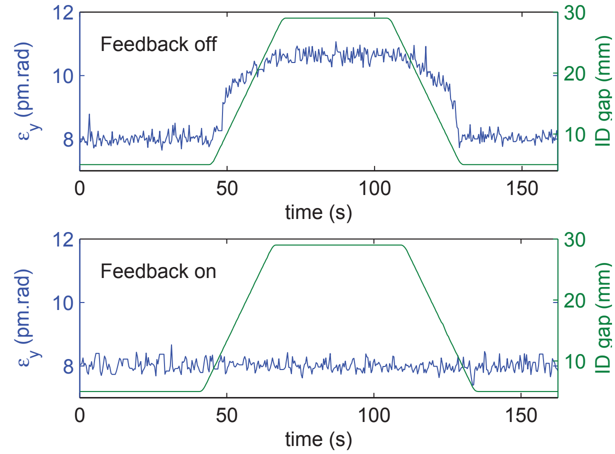

Figure 2: ϵ_y variation with I02 gap, with and without vertical emittance feedback (f and α set to 0.5).

$$\begin{aligned}\epsilon_{y,filt}(n) &= \alpha\epsilon_y(n) + (1-\alpha)\epsilon_{y,filt}(n-1)\\ \Delta\epsilon_y(n) &= \epsilon_{y,filt}(n) - \epsilon_{y,target}\\ \delta(n) &= \delta(n-1) - fR^{-1}\Delta\epsilon_y(n)\\ \overline{K_{skew}(n)} &= \overline{K_{skew0}} + \delta(n)\end{aligned} \tag{3}$$

Various checks on the integrity of the data are made by the feedback before applying any correction to the machine. These include checks on $\epsilon_y(n)$ to make sure it lies within a tolerance window around $\epsilon_{y,target}$, and that step-changes in its value are small to avoid spurious corrections. Similar checks are made on the correction values applied to the skew quadrupoles. Additionally, a check is made on the timestamp of $\epsilon_y(n)$ to ensure only fresh data is used, and that top-up injection is not in progress. Finally, the DCCT is read to make sure that stored beam is present.

The feedback has been implemented in python, running on the same IOC that controls the Slow Orbit Feedback, RF feedback and emittance monitoring tool.

Operational Performance

An earlier implementation of the feedback aimed to stabilise the emittance coupling ratio χ rather than ϵ_y. This version was first enabled during user operations in March 2013, one week after $\epsilon_{y,target}$ was set to 8 pm.rad (see Fig. 3). However, it soon became clear that this method was sensitive to changes in the horizontal beam size caused by beta-beat driven by ID gap changes, rather than true variation in ϵ_x or ϵ_y. Additionally, the application used a mean value of χ averaged over 20 samples rather than the instantaneous value, limiting the feedback frequency to 0.2 Hz. This was sufficient to correct for long-term drift in the coupling value, but allowed significant, transient deviations in χ from the target value to appear on ID gap change.

The switch to feeding back on $\epsilon_y(n)$ rather than χ_{mean} was made at the beginning of Run 2 in April 2013. This change has had the effect that transient deviations of $\Delta\epsilon_y$ are now kept to a minimum, and substantially reduces the step-changes in lifetime that occur during ID gap and phase changes. An example showing the effectiveness of the feedback in stabilising ϵ_y during one such change is shown in Fig. 2.

Conservative feedback parameters of $f = 0.15$ and $\alpha = 0.25$ are currently in use, as these have been identified to allow stable and reliable operation of the feedback, as well as maintaining the ability to react to ID changes on a reasonable timescale. With these settings, variations in ϵ_y during ID gap and phase changes are in general below the noise floor of the ϵ_y reading (measured to be 0.12 pm.rad). The exception to this is the in-vacuum device I02, for which transient deviations in ϵ_y of up to ~0.6 pm.rad are observed, with the total deviation lasting for less than 5 seconds. Over a typical 10 minute period, $\epsilon_y(n)$ is stabilised to a mean value of 8.00 ± 0.13 pm.rad, with r.m.s. changes in $\delta(n)$ of the order 0.7 mA. Note that the variations in ϵ_y with feedback running are comparable to the natural fluctuations in the ϵ_y reading.

LIFETIME OPTIMISATION

The lifetime in the Diamond storage ring is dominated by Touschek scattering. Since the scattering rate varies in proportion to the vertical beam size, the reduction in ϵ_y has led to a drop in lifetime of 45%. To combat this, renewed efforts to increase the storage ring momentum acceptance via sextupole tuning have been made. These include a model sextupole optimsation using a multi-objective genetic algorithm tied to ELEGANT [5], followed by an online suppression of the sextupole resonance driving terms [6]. A comparison of the lifetime before and after this tuning is shown in Fig. 4.

BEAM STABILITY

The reduction in vertical beam size has brought the beam stability marginally above the target value of 10% of beam size in the 1-1000 Hz bandwidth in the vertical plane, as

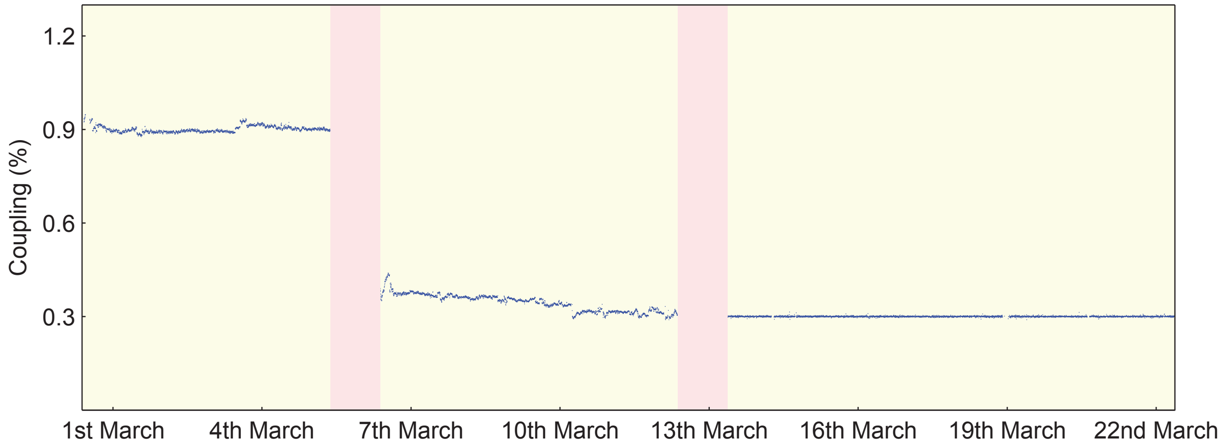

Figure 3: Emittance coupling ratio during three weeks of user operation. The period covers operation at 1% coupling, the switch to 0.3% coupling and 0.3% coupling with feedback enabled. Machine development days are highlighted in red.

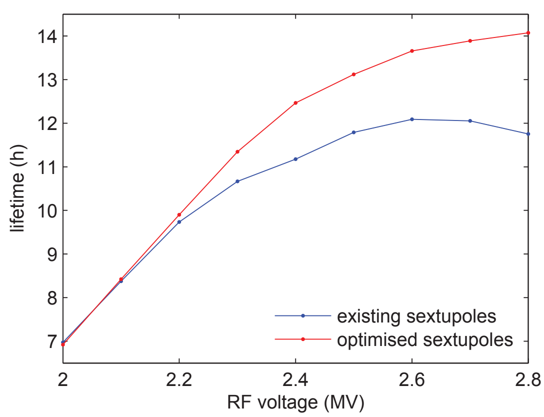

Figure 4: Comparison of lifetime as a function of RF voltage for two sets of sextupoles. Data recorded for standard user conditions (300 mA, 900 bunches, ϵ_y = 8 pm.rad, IDs closed).

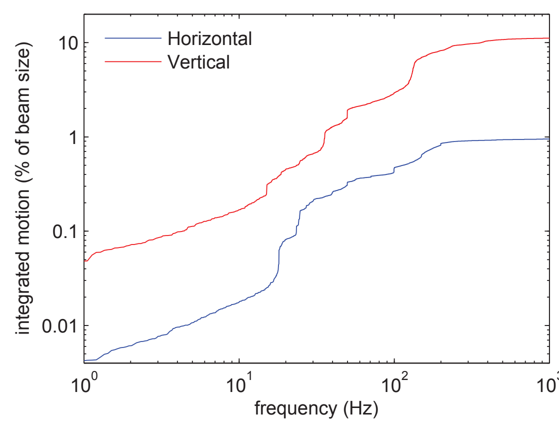

Figure 5: Projected electron beam motion at the centre of a standard straight with fast orbit feedback running. Data plotted as a percentage of electron beam size (ϵ_x = 2.7 nm.rad, ϵ_y = 8 pm.rad).

shown in Fig. 5. To combat this, a program to replace the subset of faulty corrector power supplies which are known to excite beam motion in the 100-200 Hz bandwidth has begun.

CONCLUSIONS

A vertical emittance feedback application is now in use on the Diamond storage ring. The feedback aims to stabilise ϵ_y directly rather than the emittance coupling, removing any dependance of the vertical beam size on fluctuations in ϵ_x (real or otherwise). With feedback enabled, ϵ_y is maintained at a value of 8.00 ± 0.13 pm.rad, with the variations limited by noise on the emittance monitor value.

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