FURTHER ADVANCES IN UNDERSTANDING AND OPTIMISING BEAM DYNAMICS IN THE DIAMOND STORAGE RING

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Abstract

We report the results of recent beam dynamics studies of the Diamond storage ring. These studies were aimed at both improving our understanding of the machine operation as well as establishing a reliable, well corrected lattice with long lifetime and high injection efficiency suitable for later top-up operation. Particular attention has been given to measuring and controlling the linear optics of the lattice, to determining the various contributions to the overall beam lifetime and to optimising the sextupole strengths for good on and off momentum dynamic aperture. For each topic, detailed comparisons with model predictions are also described.

INTRODUCTION

For modern light sources, a good understanding of both the linear and non-linear beam dynamics is crucial to achieving optimum machine performance. Typically the linear optics are studied and corrected using orbit response matrix and dispersion measurements [1]. Many tools exist for quantifying the non-linear beam dynamics, including measurements of injection efficiency, lifetime and dynamic aperture, along with the more detailed techniques of frequency map analysis [2] and the frequency analysis of betatron motion [3, 4].

Recent work at Diamond has focussed on understanding and optimising the storage ring using all these techniques, the results of which are reported here. Progress with the frequency analysis of betatron motion experiments are reported in a separate paper [4].

LINEAR OPTICS STUDIES

Investigation and correction of the linear optics at Diamond is carried out using the LOCO algorithm [1]. The original lattice optimisation performed during commissioning was very successful at correcting the linear optics, reducing the beta-beta from initial values of ~40% to below 2% peak-to-peak in both planes, and correcting the r.m.s. vertical dispersion from 8mm to 0.4mm. However, the correction process introduced large variations in quadrupole gradients of up to 4% from the family mean, much larger than expected from the magnet field measurements taken before installation.

Recent corrections of the lattice have used a version of LOCO which allows constraints to be added to the quadrupole gradient fitting process. Application of this version of the code to the Diamond storage ring shows similar correction levels, with beta-beat reduced to below 1% peak-to-peak and vertical dispersion corrected to an r.m.s. value of 0.3mm. The spread in quadrupole gradients is now much reduced, with peak quadrupole gradient variations kept below 1%. A comparison of the applied quadrupole gradient corrections using the two version of the code is shown in Fig.1.

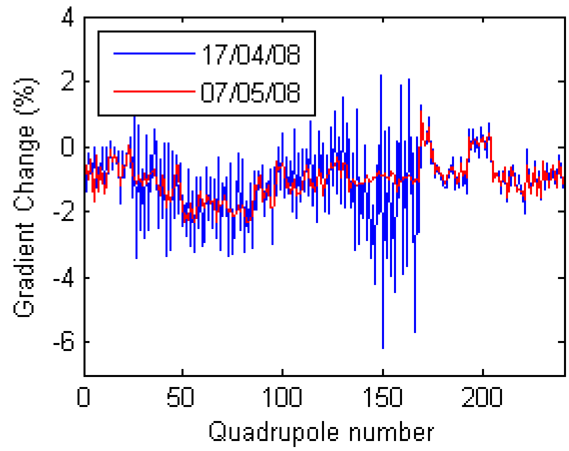

Fig. 1: Quadrupole gradient corrections applied to the storage ring using two versions of the LOCO code.

The linear coupling of the lattice is corrected using all 96 skew quadrupoles, the values for which are derived from the LOCO model. The results of the coupling correction are confirmed using images from two X-ray pinhole cameras. Based on the LOCO and pinhole camera data, the main contributions to the vertical beam-size have been established to be an equal mixture of vertical dispersion and betatron coupling, with high-frequency beam oscillations and the natural opening angle of the radiation also contributing. Although corrected coupling values below 0.1% have been routinely measured, the coupling is currently set to 1% for user operations in order to increase the lifetime.

The main lattice parameters measured for the Diamond storage ring are quoted in Table 1, with the target values for each parameter also given for reference. Typical values for the majority of the lattice parameters are close to those predicted using the model. However, there still exists a large discrepancy between measured and expected natural chromaticity values, thought to be due primarily to a poor knowledge of the main dipole field during the measurement rather than a true discrepancy between model and machine. This does not exclude the possibility of an error in the calculated value due to inaccurate modelling of the off-energy edge focussing or fringe field effects in the dipoles.

Table 1: Summary of main lattice parameters

	Target	Measured
Emittance	2.74 nm.rad	2.6-2.9 nm.rad
Energy Spread	0.096%	0.09-0.11%
Coupling	<1%	<0.1 to >3%
Tunes (x/y)	27.225/12.363	27.225/12.363
Nat. Chrom. (x/y)	-79 / -35	-68 / -28
Bunch Len. (2MV)	13.5ps	~14.5ps
Mom. Comp. fact.	1.71×10^{-4}	1.76×10^{-4}

NON-LINEAR BEAM DYNAMICS

Direct application of the model sextupoles to the machine leads to measured horizontal and vertical chromaticities of -0.9 and -1.4, compared to the theoretical values of +1.7 and +0.9. In order to give positive chromaticity for suppression of instabilities, the focussing and defocusing chromatic sextupoles are increased by 6.3% and 8% in the machine, resulting in measured chromaticities of +1.9 and +1.8. For the purposes of the non-linear beam dynamics studies the model chromatic sextupoles have been increased by the same factors. However, the discrepancy between model and machine linear chromaticities remains, with new values of +4.5 and +4.2 found using the model.

As with the natural chromaticity measurement, the discrepancy between measured and theoretical linear chromaticity is thought to be due in part to an inaccurate modelling of the off-energy edge-focussing and fringe fields of the dipole. Once the chromaticity of the machine has been adjusted to match the model, the higher-order terms show good agreement (see Fig. 2).

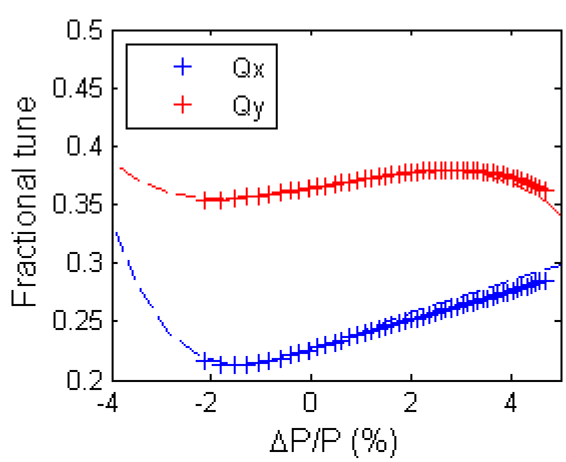

Fig. 2: Comparison of measured and model non-linear chromaticity. Model values are marked as dashed lines.

Dynamic Aperture

The edge of the dynamic aperture has been investigated using two complimentary techniques. The first method involves monitoring lifetime as a function of horizontal and vertical collimator aperture, leading to measured half-aperture values at the centre of the long straight of 11.2 ± 0.5mm horizontally and 4.5 ± 0.25mm vertically. Measurements of stored beam current as a function of "pinger" magnet strength has also been used to probe the edge of the dynamic aperture (see Fig. 3). The horizontal dynamic aperture of 11.4 ± 0.2mm measured in this way is in good agreement with the collimator data. However, the value in the vertical plane is 2.8 ± 0.1mm, significantly less than the value found using collimators. The limiting aperture in the horizontal plane is expected to be the end of the septum plate at 16mm (corresponding to 15.9mm at the centre of the straight), and in the vertical plane it is the ends of the narrow-gap ID vessels at 5.5mm half-aperture (5.7mm at the reference point). The measured aperture is clearly less than the physical aperture in both planes.

To try to understand this discrepancy, the model dynamic aperture has been calculated using the Tracy-II tracking code [5], in which random higher-order multipole errors have been included in the quadrupoles and sextupoles (see Fig. 4). The computed dynamic aperture shows stable beam motion out to 13mm horizontally, at which point the motion shows a high diffusion rate due to the $3Q_x + Q_y$ skew-octupole resonance. The vertical motion is regular out to the edge of the physical aperture, with the largest stable amplitude found to be 5.3mm.

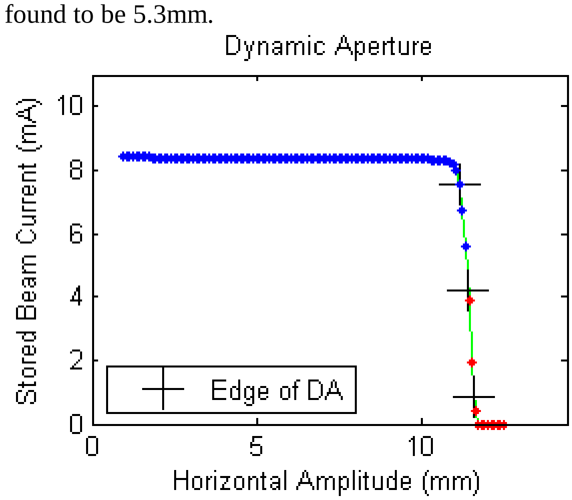

Fig. 3: Measurement of the horizontal dynamic aperture using "pinger" magnets. Beam losses of 10%, 50% and 90% beam current are marked.

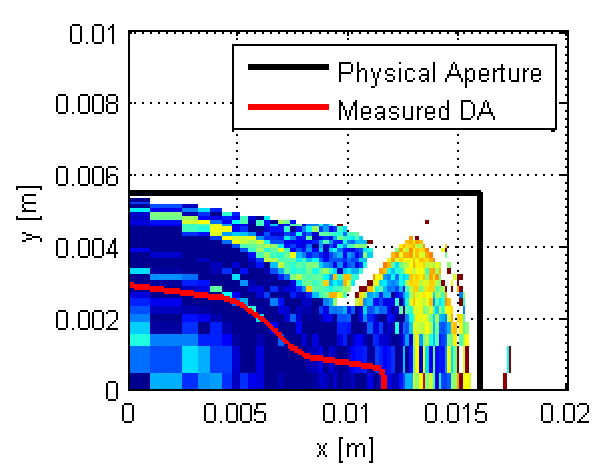

Fig.4: Dynamic aperture calculated using Tracy-II.

Frequency Map Measurement

Frequency maps calculated using the model and measured on the machine are shown in Figs. 5 and 6 respectively. These maps were generated using a grid of 225 points in the range of 0 to 7.7mm horizontally and 0 to 1.3mm vertically. The two maps show similar trends for both planes, but there is a clear discrepancy in the amplitude of tune-shift, the exact cause of which is yet to be explained. Also, the tune-shifts with amplitude measured in the machine cross the $3Q_x + Q_y$ resonance line found to limit the stable horizontal motion in the model without loss, so it is unlikely that this line is the cause for the reduction in horizontal dynamic aperture we measure. From the frequency map, the $3Q_y$ skew sextupole resonance appears to be a more likely candidate (present as random errors in the quadrupoles).

Further work is required to understand how multipole errors and fringe fields in the bending magnets, quadrupoles and sextupoles influence the beam dynamics. In particular, systematic octupole errors in the quadrupoles could be present due to construction errors, and these would affect the tune-shifts with amplitude of the machine. Uncertainties in the sextupole calibration factors based on magnetic measurements before installation must also be considered.

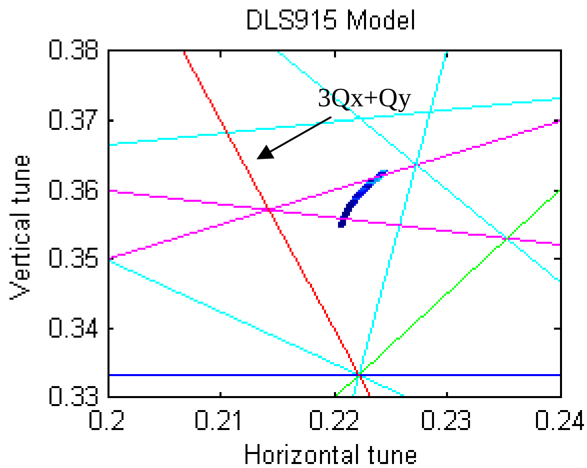

Fig.5: Model frequency map calculated using Tracy-II.

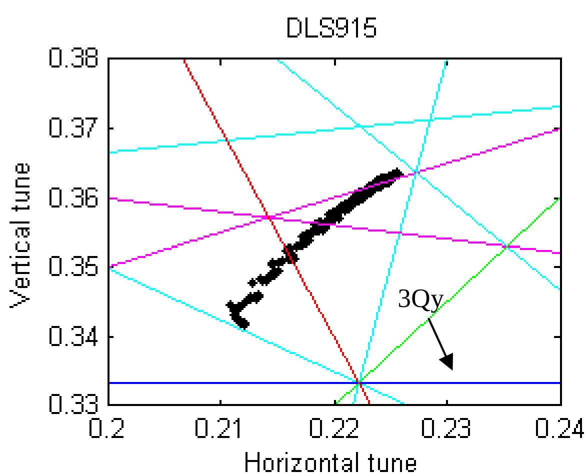

Fig.6: Frequency map measured on the machine.

Lifetime

The Diamond storage ring is Touschek-dominated for bunch currents greater than 0.1mA, and under these conditions the lifetime as a function of RF voltage gives a good measure of the off-momentum dynamic aperture of the lattice. Shown in Fig. 7 is a comparison between model and machine lifetime for 0.2% coupling as a function of total accelerating voltage. Theoretical lifetime values include measured contributions of 113h for the elastic gas lifetime and 146h from all remaining lifetime effects.

The two curves show the expected behaviour of an initial quadratic increase in the lifetime with RF voltage, during which the momentum acceptance is limited purely by the size of the RF bucket. The off-momentum dynamic aperture starts to limit the acceptance at around 2MV, before saturating at 2.6 to 2.7MV (corresponding to an energy acceptance of +3.5%/-5%). Above this, the lifetime reduces due to the reduction in bunch length with RF voltage. The measured and model lifetime curves do not overlap exactly, indicating a possible error in the linear coupling or RF sum voltage values.

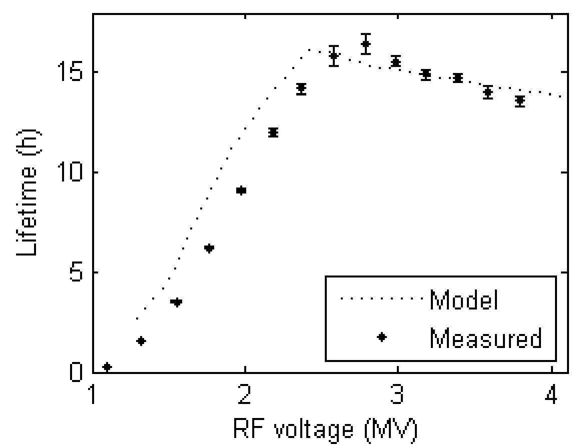

Fig.7: Storage ring lifetime as a function of RF voltage assuming 100mA stored beam and 0.2% coupling with a 2/3 fill pattern.

CONCLUSIONS

The linear and non-linear beam dynamics of the Diamond storage ring have been investigated using a variety of techniques with good agreement found in many areas, particularly for the linear lattice. Some discrepancies still exist, with the linear chromaticity and tune-shifts with amplitude in particular requiring further investigations.

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