ELECTRON BEAM DYNAMICS STUDIES DURING COMMISSIONING OF THE DIAMOND STORAGE RING

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Abstract

The Diamond Light Source is the new medium energy 3rd generation light source located at the Harwell Science and Innovation Campus in the UK. The storage ring was successfully commissioned at full energy during the period Sept. to Dec. 2006, and is now delivering synchrotron light to users. During the commissioning period, operation of the storage ring at the design specifications was established in terms of closed orbit distortion, linear optics, coupling correction and emittance. In this report we provide details of these studies as well as more recent investigations into the zero-dispersion lattice.

INTRODUCTION

Commissioning of the Diamond storage ring at full energy began in Sept. 2006. Over the following three months, operation of the storage ring for the nominal low-emittance lattice at the design performance was established in terms of correction of closed orbit distortion, linear optics and coupling. We present here our experience during this commissioning period and a characterisation of the beam dynamics.

The Phase-I insertion devices were commissioned in parallel to the storage ring lattice, and this work is discussed in a companion paper [2].

STORAGE RING LATTICE

The nominal storage ring lattice is a 3 GeV, 24-cell double bend achromatic lattice with a low emittance of 2.7 nm.rad, obtained with finite dispersion in the straight sections. The main parameters for this lattice are quoted in Table 1, with a plot of the optical functions for one super-period shown in figure 1.

Table 1: Main parameters of the low-emittance lattice

Circumference	561.6 m
RF frequency	499.654 MHz
Tune point (Q_x, Q_y)	27.23 / 12.36
Natural chromaticity (ξ_x, ξ_y)	-79/ -35
Max beta function (β_x, β_y)	23.8 m / 26.7 m
Max horizontal dispersion	0.31 m
Momentum compaction	1.7×10^{-4}
Energy spread	0.096 %
Energy loss/turn (no IDs)	1.0 MeV
Damping times (τ_x, τ_y, τ_z)	11.2, 11.2, 5.6 ms

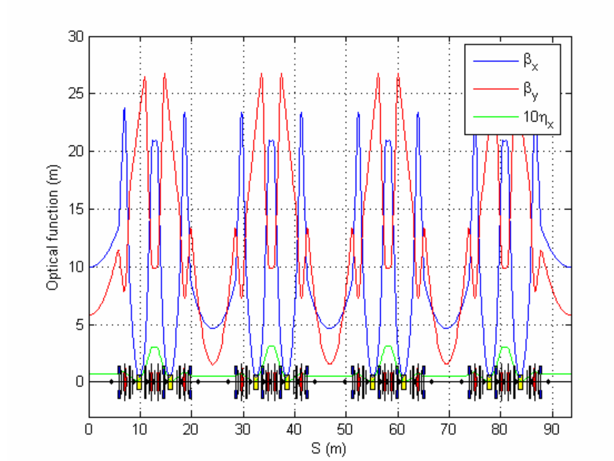

Figure 1: Optical functions for the nominal lattice.

CLOSED ORBIT CORRECTION AND BPM CALIBRATION

The storage ring global orbit correction scheme consists of 168 electron beam position monitors (BPMs) and 168 corrector magnets in each plane, with the RF frequency providing path length corrections.

An initial orbit correction was achieved from first-turn data and individual tuning of the correctors, which after optimisation of other storage ring parameters allowed the first accumulation and storage of electrons in the ring. The existence of stored beam then allowed measurements of the BPM electrical and mechanical offsets with respect to the adjacent quadrupole magnetic centres to be made. For this measurement, the Middle Layer *quadcenter* beam-based alignment algorithm was used [4].

Following an iterative process of orbit correction, BPM calibration and quadrupole gradient correction, an orbit correction to sub-micron precision was achieved, for which all singular values were retained in the inverse response matrix. Following this, a MATLAB-based slow orbit feedback running at ~1Hz was commissioned, which is now used routinely during user operation.

Since the Diamond storage ring contains 240 quadrupoles and only 168 e-BPMs and correctors, it is not possible to correct the beam orbit to the centre of all quadrupoles simultaneously. Experiments demonstrated that where BPMs are located between two quadrupoles, a reduction in r.m.s. corrector strength is achieved by calibrating the BPM as an average of the adjacent quadrupole centres. Subsequent measurements of beam position in the quadrupoles recorded r.m.s. residual displacements of 61 µm ± 14 µm horizontally and 39 µm ± 6 µm vertically, the data for which is shown in figure 2.

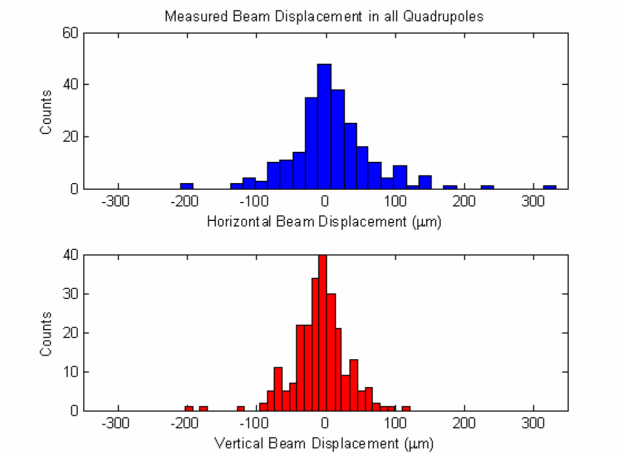

Figure 2: Beam displacement in storage ring quadrupoles following BPM calibration and orbit correction.

MEASUREMENT OF THE STORAGE RING OPTICAL FUNCTIONS

Measurement and correction of the storage ring linear optics has been carried out using LOCO [5]. The basic principle behind the LOCO algorithm is to compare orbit response matrix and dispersion measurements made on the machine to those predicted using the model, and then to perform an SVD fit to determine how to adjust the model quadrupole strengths in order to give the best reproduction of the measured data. Having determined the changes required to make the model match the storage ring optics, the problem can then be turned around and the corrections applied to the machine.

As with orbit correction and BPM calibration, correction of the linear optics was an iterative process. The 240 storage ring quadrupoles are all individually powered, and were all included as free parameters in the LOCO fit. First attempts to correct the linear optics of the machine in this way brought the uncorrected beta-beating from around 40% in both planes to below 3%, but introduced a large variation in strengths within each family of quadrupoles of up to 4%. Further applications failed to reduce the measured beta-beating further, and it was found that the required quadrupole gradient corrections were not converging to a stable solution. Of the ten families of quadrupoles, four of the families were drifting further away from their initial values with each iteration.

Following this observation, and after an improvement in the quality of orbit correction and BPM calibration, all quadrupoles were returned to a common starting value within each family. The singular value threshold rejection parameter was reduced from 1×10^{-3} to 5×10^{-4}, and the optics correction procedure was repeated. This time, strength variations within each family were kept to below 2%, the fitted corrections converged to stable values after 2-3 iterations, and the measured beta-beating was reduced to 1-2% in both planes. Figure 3a shows an orbit response matrix measured on 6th Dec. after optics correction, figure 3b shows the singular values retained in the LOCO fit and figure 3c shows the beta-beating at the BPMs.

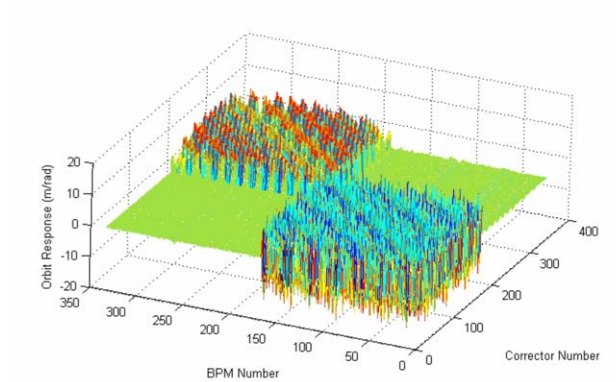

Figure 3a: Orbit response matrix measured on 6th Dec. 2006 following optics correction using LOCO.

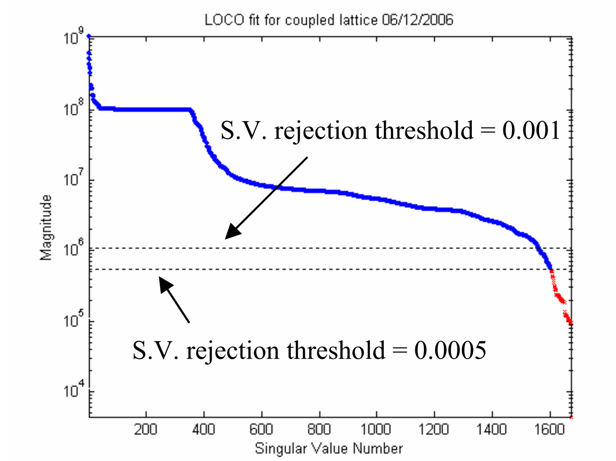

Figure 3b: Singular values from LOCO fit. Retained values are shown in blue, rejected values in red.

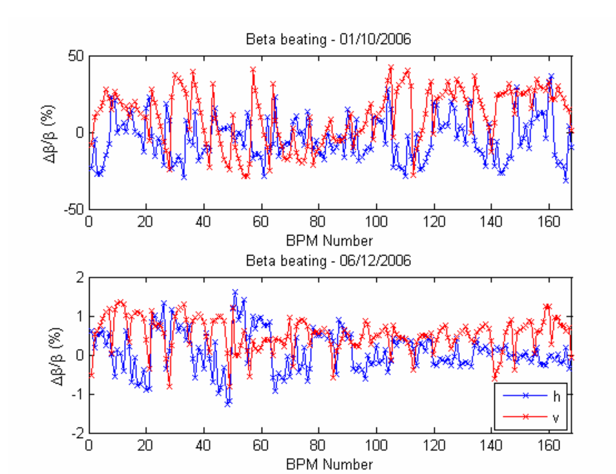

Figure 3c: Fitted values for the beta-beating at the BPMs before (top) and after (bottom) optics correction.

LINEAR COUPLING MEAUREMENT AND CORRECTION

Control of linear coupling in the storage ring is provided by 96 skew-quadrupoles located in the sextupoles. To correct for coupling errors, the results from the LOCO analysis were applied to the machine, and the results cross-checked using pinhole camera measurements and measurements of the tune closest approach.

According to Guignard's formula [6], the linear betatron coupling of a lattice (χ) can be computed from the minimum distance between horizontal and vertical tune when the working point is moved through the difference resonance Q_x - Q_y = 1:

$$\chi = \frac{\left(c/\Delta\right)^2}{1/2 + \left(c/\Delta\right)^2}$$

where Δ is the distance between horizontal and vertical tunes at the nominal working point and c is the minimum tune separation as the resonance is crossed. Measurements of this type recorded betatron coupling of 0.47% with no coupling correction, and 0.002% with skew-quadrupole corrections applied (see figure 4). Corresponding measurements made using pinhole cameras give emittance coupling values of 1.3% and 0.17% respectively.

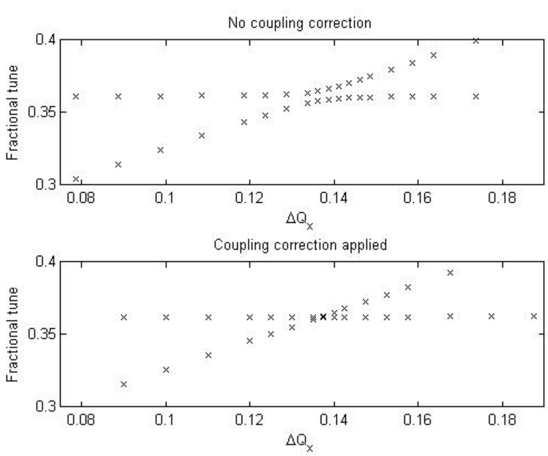

Figure 4: Measurements of closest tune approach with and without skew-quadrupole coupling correction.

Although correction of linear coupling to small values has been demonstrated, initial operation of the storage ring has been carried out with skew-quadrupoles set to give 1% emittance coupling. This provides a longer lifetime suitable for beam-line commissioning, along with an improved stability of the photon beams relative to the beam-size dimensions at the source point. It is envisaged that operation with smaller coupling values will be more suitable once top-up operation and a fast orbit feedback system have been introduced.

EMITTANCE AND ENERGY SPREAD MEASUREMENT

Emittance and energy spread are routinely measured from beam-size images taken with pinhole cameras on dipoles 1 and 2. After optics and coupling correction, the measured values are 2.8 nm.rad and 1.1×10^{-3} respectively However, this measurement is subject to some uncertainty due to the imprecise knowledge of the optical function and location of the source point.

ZERO DISPERSION LATTICE

Recent studies have begun to characterise the performance of the zero-dispersion lattice, in which the achromatic conditions are maintained for the arc-sections Two machine development shifts were sufficient to produce a lattice file giving high injection efficiency (above 90%), reasonable lifetime and beta-beating of less than 5%. The measured horizontal dispersion of thi lattice is shown in figure 5 below.

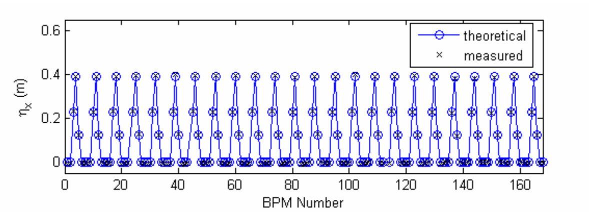

Figure 5: Dispersion measured on 19th May 2007 for the zero-dispersion lattice.

CONCLUSIONS

Initial commissioning of the Diamond storage ring was completed in Dec. 2006, with performance at the design specifications achieved in many areas. Characterisation and monitoring of the low-emittance lattice is continuing with in-depth investigations into the non-linear beam dynamics planned following the installation of "pinger" magnets in Summer 2007. The linear optics of this lattice is well-understood and controlled with LOCO, and this has been confirmed through coupling, tune and emittance measurements using complementary techniques.

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