LINEAR COUPLING AND TOUSCHEK LIFETIME ISSUES AT DIAMOND STORAGE RING

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Abstract

In synchrotron light sources correction of the linear coupling is an important issue related to the brightness of the photon beam and to the beam lifetime. The vertical emittance of the electron beam in the DIAMOND storage ring can be controlled using 168 skew quadrupoles embedded in the sextupoles of the ring. In this paper we report the linear coupling estimates for the expected misalignment errors and the results of coupling correction based on the analysis of the cross response matrix. Touschek lifetime estimates are also discussed.

INTRODUCTION

The DIAMOND storage ring is designed to operate with a 2.7 nm·rad horizontal emittance and a lifetime larger than 10 hours with a 300 mA stored current, with 500 mA as a later goal. Since the coupling is expected to be controlled to less than 1%, a vertical emittance smaller than 27 pm·rad is foreseen[1]. However, the inevitable alignment errors in the storage ring generate a coupling between the two transverse planes of motion and a non–zero vertical dispersion that may increase the vertical emittance above 1% of the horizontal emittance.

Skew quadrupoles are generally used to minimize these effects. DIAMOND sextupole magnets will also be capable of generating independent skew quadrupole and horizontal and vertical dipole fields. In this way a set of 168 skew quadrupoles can be used to control the coupling, taking into account that, a coupling too small will be harmful for the Touschek lifetime of the e–beam.

In this paper we estimate the coupling generated by the expected misalignment errors for DIAMOND. We outline the correction method based on the analysis of the cross response matrix. Finally we report the results of detailed numerical estimates for the Touschek lifetime and the effect of coupling correction.

LINEAR COUPLING ESTIMATES FOR DIAMOND

The linear coupling generated by random misalignment errors of magnetic elements was estimated by means of a statistical analysis on a realistic DIAMOND lattice model. The physical quantity used as a measure of the linear coupling is the emittance ratio

$$\chi = \varepsilon_z / \varepsilon_x \tag{1}$$

where ε_x and ε_z are the emittances projected in the horizontal and vertical plane. This quantity is measurable with high precision using an X–ray pinhole camera.

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The emittance ratio χ was evaluated numerically by generating a set of 150 random realizations of the misalignment errors, assuming a Gaussian distribution with r.m.s. values of Tab. 1.

Table 1: Errors assumed for DIAMOND Storage Ring alignments and BPM reading

Quadrupole transverse displacement	0.1 mm
Sextupole transverse displacement	0.1 mm
Dipole transverse displacement	0.05 mm
Dipole longitudinal displacement	0.05 mm
Dipole Field Errors	0.1 %
Quadrupole roll errors	0.2 mrad
Dipole roll error	0.2 mrad
BPM transverse displacement	0.05 mm
BPM reading	0.5 µm

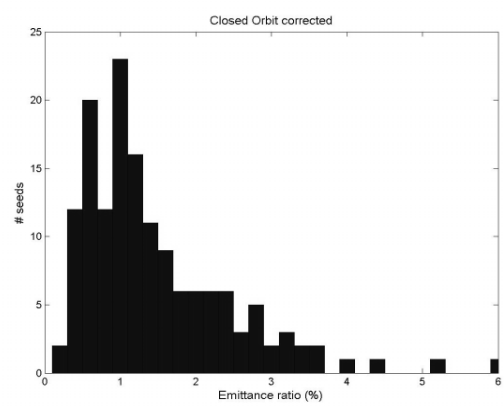

Figure 1: Distribution of emittance ratio χ over 150 random seeds, after closed orbit correction.

The distribution of the emittance ratio values after closed orbit correction is reported in Fig. 1. The corresponding parameters of the distribution are summarised in Tab. 2. The residual orbit has an r.m.s. value of about 100 µm in both planes and the maximum value for the correctors obtained on the 150 random seed are both well within the specified 0.8 mrad for the dipolar correctors embedded in the sextupole magnets [1]. The major contribution to linear coupling comes from the vertical misalignment of the sextupoles. The average coupling coefficient is about 1.5 % and some seeds achieve a substantial coupling showing that closed orbit correction alone will not be sufficient to control the linear coupling.

Table 2: Parameters of the distribution over 150 random seeds after closed orbit correction is applied.

Horizontal C.O. r.m.s.	0.10 mm
Vertical C.O. r.m.s.	0.11 mm
Average Linear Coupling χ	1.5 %
r.m.s. Linear Coupling	1.0 %
r.m.s. H corrector strength	0.32 mrad
r.m.s. V corrector strength	0.27 mrad

ANALYSIS OF THE CROSS RESPONSE MATRIX

The analysis of the response matrix, dipolar correctors vs BPM readings, is a well known tool for closed orbit correction. In the presence of coupling one can build an extended response matrix whose columns will contain both the horizontal and vertical BPM readings for each corrector. The off–diagonal block of this matrix will contain information about the coupling[2,3]. Therefore, the basic idea of the method is to set the skew quadrupoles to perform a least squares minimization of the off–diagonal matrix elements. Also the residual vertical dispersion can be included in the minimization procedure as an additional column in the extended response matrix. This procedure is implemented in the BETA–LNS[4] code.

The coupling correction was performed using the skew quadrupole fields that can be produced in the ring sextupole magnets. In Tab. 3 we report the result of the analysis of 150 seeds is reported for the cases where all the 168 skew quadrupoles were used to correct only the emittance ratio generated by betatron coupling and for the case where the vertical dispersion was also minimized.

Table 3: Parameters of the distribution over 150 random seeds, after betatron coupling correction 1) and vertical dispersion minimization 2)

	1)	2)
Horizontal C.O. r.m.s.	0.10 mm	0.10 mm
Vertical C.O. r.m.s.	0.11 mm	0.11 mm
Average Linear Coupling χ	0.10 %	0.03 %
r.m.s. Linear Coupling	0.11 %	0.07 %
r.m.s. H corrector strength	0.32 mrad	0.32 mrad
r.m.s. V corrector strength	0.27 mrad	0.27 mrad
r.m.s. Skew Quad strength	0.02 m^{-1}	0.02 m^{-1}

The maximum value for the integrated skew quadrupole strength $0.33 \cdot 10^{-2}$ m^{-1} correspond to a skew quadrupole gradient of 0.11 T/m for the skew quadrupole correctors of length 0.3 m, well within the specified 0.36 T/m for the skew quadrupole correctors[1]. A reasonable control of linear coupling can be obtained also with a limited number of skew quadrupole correctors. We used 36 correctors choosing six skew quadrupoles per superperiod in the ring. The coupling coefficient has been reduced to 0.7% on average, however the maximum value of the skew quadrupole correctors is now increased to 0.21 T/m in the skew quadrupoles.

TOUSCHEK LIFETIME ESTIMATES

The e–beam lifetime in DIAMOND is dominated by Touschek scattering. Since the Touschek lifetime has a strong dependence on the momentum aperture, extensive numerical simulations were performed using a realistic DIAMOND model to obtain a reliable estimate of the expected momentum aperture.

The momentum aperture is the smallest of the RF aperture and the momentum aperture determined by the physical aperture and the dynamic aperture of the ring. While the RF aperture ε_{RF} is determined analytically

$$\varepsilon_{RF} = \sqrt{\frac{2eVc}{\omega L E \eta_{tr}}\left(2\cos\phi_s + (2\phi_s - \pi)\sin\phi_s\right)} \quad (2)$$

where V is the peak RF voltage, ϕ_s the synchronous phase, L the ring circumference, ω the angular revolution frequency, E the e–beam energy, η_{tr} the slip factor, the momentum aperture is determined by the 6D tracking of Touschek scattered particles. The variation of the optical functions with momentum deviation and the non–linear contribution to the dispersion function also contribute to the reduction of the Touschek lifetime. For the DIAMOND storage ring, a nominal voltage of 3.3 MV gives an RF aperture of 5% for the bare lattice (1.05 MeV losses per turn). Considering the operation at 500 mA e–beam with a 2/3 filling pattern, (single bunch current of 0.8 mA) the Touschek lifetime is 26.5 h. Bunch lengthening effects are neglected.

Effects of second order momentum compaction on Touschek Lifetime

The request for small emittances and small bunch lengths requires the operation with very small values of the momentum compaction factor. Higher order terms in the expansion of the momentum compaction factor with momentum deviation $\alpha = \alpha_1 + \alpha_2\delta + O(\delta^2)$, significantly affect the e–beam dynamics[5]. In the case of DIAMOND the first order momentum compaction is $\alpha_1 = 1.708 \cdot 10^{-4}$ and the second order is $\alpha_2 = 1.9 \cdot 10^{-3}$.

The momentum aperture computed by tracking should take into account these terms in the non–linear synchrotron motion. The asymmetry in the RF bucket structure shown in Fig. 2 generates an asymmetry in the momentum aperture shown in Fig. 3. The positive side of the momentum aperture is reduced by the RF bucket deformation and it is responsible for the reduced lifetime. Including these effects the Touschek lifetime is reduced from 26.5 to 17.2 hours.

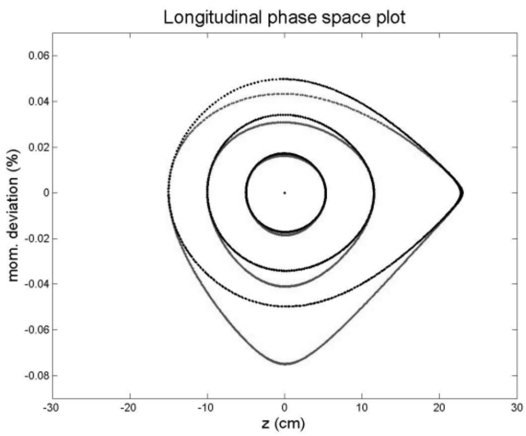

Fig. 2: Longitudinal phase space plots for DIAMOND, with the second order momentum compaction (red line) and without (black line).

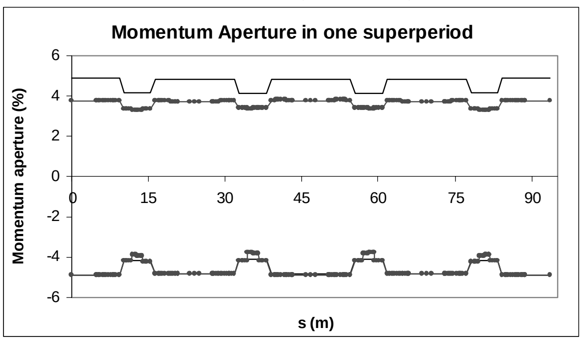

Fig. 3: Momentum aperture in a DIAMOND superperiod with the second order momentum compaction (red line) and without (black line).

Effects of narrow gap vessel on lifetime

DIAMOND operation foresees the use of several narrow gap in–vacuum ID's. Their small vertical aperture is the limiting aperture for the lifetime in the vertical plane. The Touschek lifetime was computed using several values for the ID half aperture in the DIAMOND short straight sections, ranging from 3.5 mm down to 2.5 mm. Fig. 4 shows the lifetime as a function of the coupling.

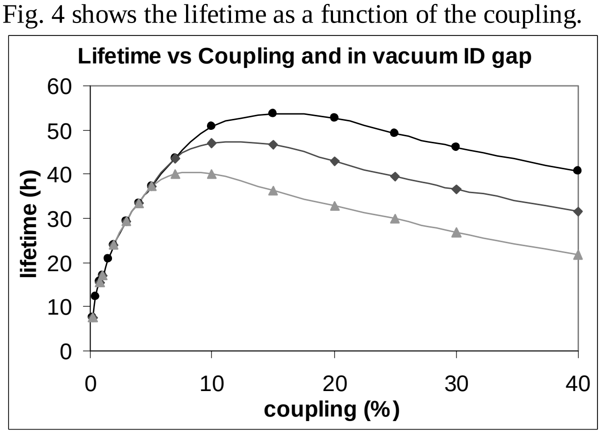

Fig. 4: Touschek Lifetime as a function of coupling for different values of narrow ID half aperture (3.5 mm, black; 3.0 mm red; 2.5 mm green)

At large coupling the lifetime decreases because of particle loss in the vertical aperture, while at small coupling the lifetime decreases due to the smaller e–beam volume. These computations assumed a well corrected closed orbit and residual vertical dispersion. They give an upper estimate of the Touschek lifetime that can be achieved when residual orbit errors and a non perfect compensation of the vertical dispersion will be taken into account. At the design value of 3.5 mm for the half aperture the lifetime is affected only at coupling value larger than 10%.

Effects of a Third Harmonic Cavity for Bunch Lengthening

The effect of a third harmonic cavity for bunch lengthening was investigated. Preliminary calculations on a passive superconducting cavity of ELETTRA type [6] show that a two–cell system can generate a 1.1 MV voltage required to lengthen the bunch by a factor three. The effect of voltage induced in the third harmonic cavity on the momentum aperture is negligible, therefore a lifetime by a factor three can be foreseen. The effect of the transient beam loading due to un–even filling pattern foreseen for DIAMOND operation is under investigation.

CONCLUSIONS

A linear coupling correction scheme for the DIAMOND storage ring was investigated. The skew quadrupole fields that can be produced in the sextupole magnets are sufficient to control the coupling coefficient to very small values (0.03 %). Touschek lifetime computations based on tracking with a more realistic simulation were performed, including non–linear terms in the dependence of the momentum compaction factor with momentum deviation. A first assessment of the beneficial effect of a third harmonic cavity on the Touschek lifetime was carried out. Future analysis will deal with the effect of higher order magnetic errors and with the effects of IDs. Finally, the valuable help of J. Payet is gratefully acknowledged.

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