PROGRESS WITH NON-LINEAR BEAM DYNAMIC STUDIES OF THE DIAMOND STORAGE RING

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Abstract

The conflicting requirements of high brightness photon beams combined with adequate beam lifetime and high injection efficiency mean careful control of the non-linear lattice is crucial to achieving optimum performance. As part of the optimisation of the Diamond storage ring, studies have been made of both the Touschek lifetime and storage ring injection process, with the help of on-momentum and off-momentum frequency maps. The effect of chromaticity on Touschek lifetime has also been investigated and several new sextupole settings were identified achieving good Touschek lifetime and injection efficiency.

INTRODUCTION

The initial optimisation of the Diamond non-zero dispersion lattice provided the target lifetime of 10 h in multibunch mode for a current of 500 mA [1]. However, the momentum aperture for this lattice was clearly limited by a large higher order chromaticity that resulted in poor off-momentum dynamics. The effect of this higher order chromaticity was investigated in detail in recent work, and new lattice optimisations addressing the problems have been found and are reported below.

In addition to having a lifetime in excess of 10 h with good injection efficiency, a solution for the non-linear dynamics must also give positive chromaticity in order to damp collective effects. Analysis of transverse coupled bunch resistive wall instability (TCBRWI) thresholds for the storage ring has shown that absolute chromaticities as high as +5 to +8 are necessary to counteract instabilities without a feedback system [2], and as such additional effort has been spent in developing these lattices.

The effect of insertion devices on the beam dynamics has also been investigated and is discussed in a companion paper [3].

STUDIES OF EXISTING LATTICE

The non-linear optics for the nominal Diamond storage ring lattice 7-1-3 has been optimized to provide a lifetime close to the specified 10 h with high injection efficiency. However, detailed investigations highlighted a number of areas in which the solution can be further improved.

Prior to these investigations, a more accurate description of the sextupoles was introduced in the model using repeated kicks along the sextupole length, rather than one single thin lens in the middle as used previously. The on-momentum and off-momentum dynamic apertures and frequency maps were found to be significantly different when the lattice is modelled in this way. As an example, the Touschek lifetime of the bare lattice computed with 6D tracking with 1% coupling errors increased from 9 h to 11.2 h for the same set of misalignment errors and engineering apertures.

The calculated tune-shifts with momentum, shown in Fig. 1 (top), are found to cross at +5.2% and -4.3%, making the dynamics potentially sensitive to the linear coupling resonance $Q_y - Q_x$ at these values. For negative deviations, both tunes show a rapid increase and approach the half-integer resonance at approximately -4.5%. This behaviour reduces the off-momentum dynamic aperture and therefore limits the Touschek lifetime. The features at negative deviations are particularly harmful due to the peculiar beam dynamics in an RF bucket distorted by the large second-order momentum compaction of the lattice ($\alpha_1 = 1.7\times10^{-4}$, $\alpha_2 = 1.95\times10^{-3}$), as this brings particles with initial positive momentum deviations to correspondingly larger negative values.

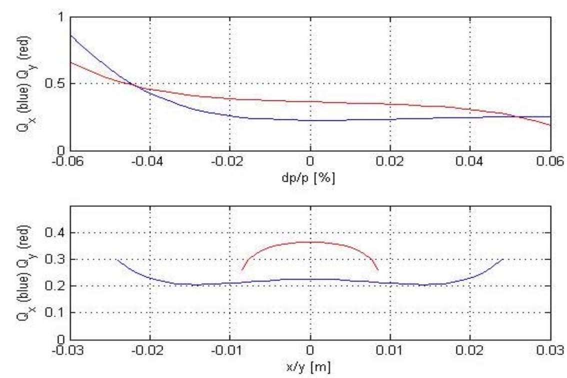

Fig. 1: Horizontal and vertical tune-shift with energy (top) and amplitude (bottom) for lattice 7-1-3.

The calculated tune-shifts with amplitude for on-momentum particles are shown in Fig. 1 (bottom). The horizontal tune is found to decrease initially with increasing horizontal amplitude before turning and increasing again. This behaviour leads to a folding of the frequency map, and it is found that particles lying beyond the fold are very likely to be lost if errors are present in the lattice [4].

The on-momentum dynamic aperture and frequency map for lattice 7-1-3 is shown in Fig. 2. Basic field and alignment errors were included in the lattice model when producing this map, and the residual linear coupling following closed orbit correction was 1%. From the dynamic aperture plot, the motion can be seen to be relatively stable up to ±17 mm in x and 7 mm in y. The fold in tune-space can clearly be seen and indeed, when higher order multipolar errors are added to the lattice, all the particles beyond the fold are lost. However, the horizontal dynamic aperture still remains acceptable at around ±15 mm.

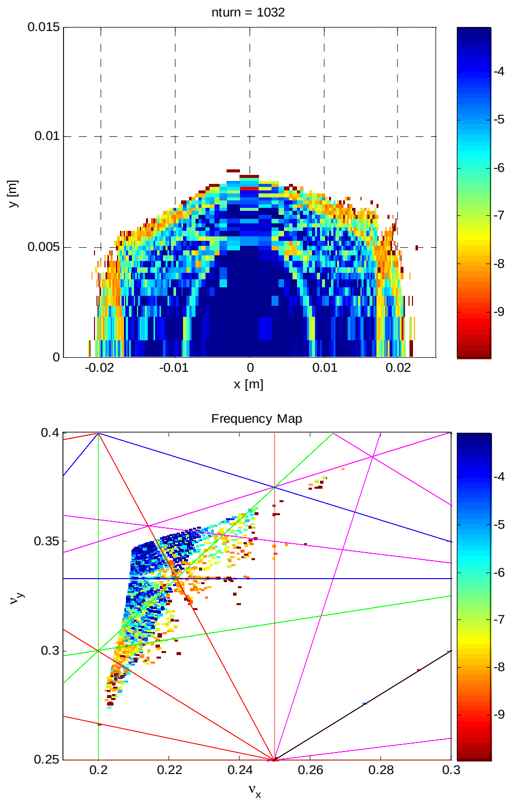

Fig. 2: Dynamic aperture (top) and corresponding frequency map (bottom) for lattice 7-1-3. The map was computed including misalignment errors, orbit corrections and residual coupling of 1% coupling, with no physical apertures in the simulation.

Injection into the storage ring is -8.3 mm from the closed orbit, and including the physical dimensions of the injected bunch, transverse oscillations of up to ±10.5 mm occur for the injected electrons. To fully accommodate the injected bunch length of 2.6 cm from the booster, an energy acceptance of +2%/-3% is also found to be necessary [5]. In this condition the computed injection efficiency of the lattice 7-1-3 is 93%.

Off-momentum frequency maps allowed to understand in detail which resonances are limiting the injection efficiency. Plotting the horizontal dynamic aperture as a function of momentum deviation, shown in Fig. 3, the region traversed by the injected particles can be seen to be relatively stable except for the resonance lines $Q_x + 2Q_y$ (which particles traverse at around -1.5%) and $3Q_x + Q_y$ (which crosses at -8 mm for on-momentum particles). The sextupole resonance $Q_x + 2Q_y$ is thought to contribute towards particle loss during injection. As such, the lattice optimisations described in the next section sought to avoid particles crossing this line at low amplitudes and at low momentum deviations. The main features of optimisation of the nominal lattice 7-1-3 are summarized in Table 1.

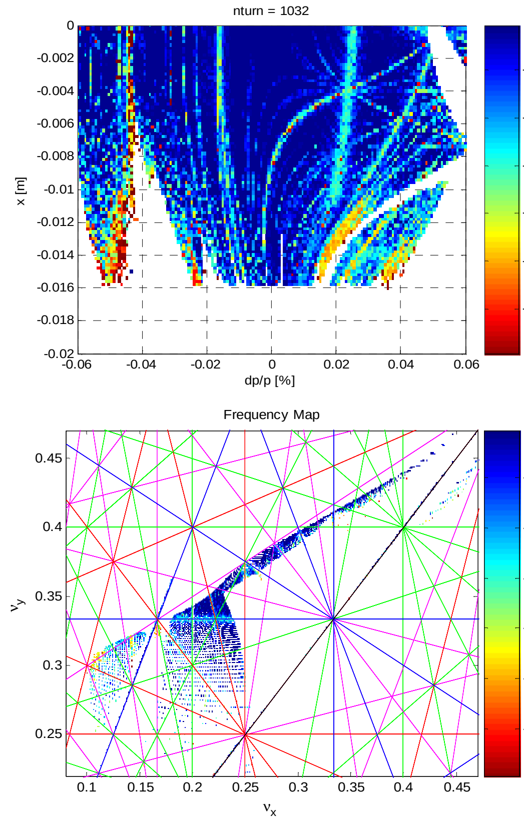

Fig. 3: Horizontal dynamic aperture as a function of momentum deviation (top) and corresponding frequency map (bottom) for lattice 7-1-3. The map was computed with misalignment errors, orbit corrections and residual coupling of 1% coupling and with physical apertures in the simulation.

Table 1: Main parameters for lattice 7-1-3.

Parameter	Value
Horizontal/Vertical Tune	27.226 / 12.363
Horizontal/Vertical Chromaticity	-0.17 / -0.85
Touschek Lifetime	11.2h
Injection efficiency	93.0%

NEW SEXTUPOLE SETTINGS

In the light of these studies, considerable effort was spent in identifying non-linear lattice solutions with smaller higher-order chromaticity, tune-crossing points at larger momentum deviations and which avoid problem resonance lines where possible. Only minor changes were made to the linear focussing so that previous work (e.g. on BSC, beam size, etc.) remains valid.

The non-linear optimisation of lattice 7-1-3 was performed using MAD8 and BETA-LNS [6], based on the minimisation of semi-analytical quantities computed from the perturbative theory of the non linear betatron motion, such as detuning with amplitude and resonance driving terms. However, the perturbative theory can fail to predict the characteristics of the beam motion at off-momentum deviation as large as those considered in the optimisation of the Diamond storage ring lattice. For this reason, numerical tracking data were directly used to optimise the off-momentum dynamics, by determining how each of the sextupole families affects the tune-shift with momentum. A sensitivity matrix that defines the variation of the betatron tunes with sextupole strength at a number of off-momentum values was computed with the aim of reducing the tune shift with momentum. The matrix is then inverted using SVD to calculate which sextupole changes minimise the tune-shift variation with momentum in a least-squares sense. The sextupole settings obtained with this approach generally require some further optimisation of the on-momentum dynamics, but they often proved to be a valid alternative to the solutions provided by the standard perturbative approaches [6].

Several new sextupole settings have been identified following optimisations of this type, all of which have improved tune-shift with momentum curves. The key parameters for two of these lattices are listed in Table 2, and the tune-shift with momentum curve for lattice 7-1-5 is shown in Fig. 4. It is interesting to note that a slightly positive chromaticity improved both the Touschek lifetime and the injection efficiency.

Table 2 Parameters for re-optimised lattices.

Parameter	7-1-5	7-2-6
Q_x / Q_y	27.23/12.36	27.22/12.35
Q_x' / Q_y'	1.41/0.71	1.42/0.35
τ_T	13.2h	14.3h
Inj. Eff.	98.5%	98.8%

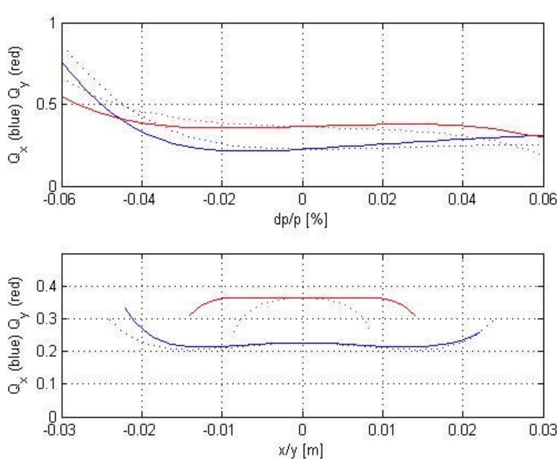

Fig 4: Horizontal and vertical tune-shift with energy (top) and amplitude (bottom) for lattice 7-1-5. Lattice 7-1-3 is shown in dashed for comparison.

OPERATION AT POSITIVE CHROMATICITY

Since Diamond may be required to run with positive chromaticity in order to counteract collective instabilities, viable lattices with higher chromaticities have also been identified. Analysis of TCBRWI thresholds for the storage ring shows that chromaticities as high as +5 to +8 are necessary to counteract instabilities without a feedback system. Chromaticities of up to +30 can be produced by varying just the chromatic S1A and S2A families of sextupoles, but this leads to a severely limited on-momentum dynamic aperture. The operation with moderate positive chromaticity (<5) has a beneficial effect on the off-momentum dynamics, in that the large tune shifts for negative momentum deviations are immediately reduced, increasing the Touschek lifetime. However, the simultaneous control of both on-momentum and off-momentum dynamic apertures has proven to be highly challenging.

Several sextupole configurations have been analysed, and initial solutions have been found for Q_x' and Q_y' up to +5. Details of these lattices are given in Table 3. For Q_x', Q_y' ≈ 5 the Touschek lifetime is still well above 10 h, but the injection efficiency is reduced due to the poor on-momentum dynamic aperture. Optimisation work on lattices with positive chromaticity continues, but it is clear from these initial studies that transverse multibunch feedback system will be necessary for Diamond.

Table 3 Parameters for lattice optimisations with positive chromaticity.

Lattice	Q_x'	Q_y'	τ_T	Inj. Eff.
7-1-8a	4.69	2.69	17.8h	80%
7-1-8b	4.69	5.17	11.7h	77%
7-1-8c	5.57	5.09	12.8h	71%
7-1-8d	5.76	5.16	13.8h	65%

CONCLUSIONS

Extensive studies have been made of the non-zero dispersion lattice for the Diamond storage ring, analysing the non-linear beam dynamics using frequency map analysis and 6D particle tracking.

The problematic higher-order chromaticity and crossing of the tune-shift with momentum curves highlighted by this study have been improved with the determination of new sextupole settings. Initial lattices with positive chromaticities of +5 have been identified, and the optimisation of lattices with this and higher values is to be continued in future work.

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