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OPTIMISING THE DIAMOND DDBA UPGRADE LATTICE FOR LOW ALPHA OPERATION

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Abstract

The Diamond storage ring will be upgraded during 2016 by replacing one of the existing double bend achromat (DBA) cells with a double-DBA (DDBA) cell [1]. One requirement of the upgrade is that following the installation of the new cell, Diamond should continue to offer dedicated user time in 'low alpha' mode [2]. In this paper we describe the particular challenges relating to this task, and present the lattice design and optimisation studies undertaken so far. The paper concludes by discussing preliminary studies of adding a second DDBA cell into the storage ring.

INTRODUCTION

An upgrade of the Diamond storage ring in 2016 will replace one of the existing DBA cells with a single DDBA cell, thereby creating space for an additional insertion device beamline. At present, the Diamond storage ring is operated for several periods each year in a dedicated 'low-alpha' optics [2], and it is the intention to continue to offer this mode following the upgrade. A comparison of the magnet layout before and after the upgrade is shown in Fig. 1.

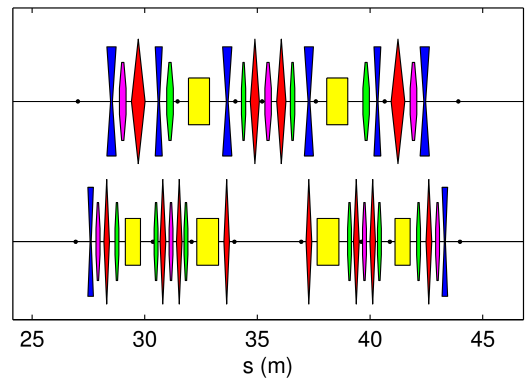

Figure 1: Existing DBA (top) and new DDBA (bottom) cell.

The existing low alpha lattice has been in operation since 2010, serving both short-pulse x-ray users on the I06 'Nanoscience' ID beamline and THz users on the B22 'MIRIAM' bending magnet beamline. Part of the success of this mode of operation is down to the combination of having both low emittance and low momentum compaction, achieved by allowing the dispersion to become negative only within the bending magnets [3]. The lattice is operated with negative momentum compaction α_1, as this is found to reduce the bunch lengthening with current and causes the leading edge of the bunch profile to become sharper, enhancing the CSR gain at shorter wavelengths.

In this paper we present the adaptation of the low alpha lattice for the DDBA upgrade. This work includes optimisation of the linear and nonlinear optics, analysis of the lattice sensitivity to errors, and an assessment of the likely injection efficiency and lifetime. The paper concludes with preliminary studies of adding a second DDBA cell to the storage ring.

LATTICE OPTIMISATION

Design Constraints

The inclusion of a single DDBA cell presents a number of challenges for the optimisation. Firstly, whilst the inclusion of four gradient sector-bends helps to keep the cell compact, the fixed defocussing gradient reduces the flexibility to tune it to different optics. As a result, the adjacent quadrupoles must also be powered with large gradients, increasing the natural chromaticity of the ring. The need to match the DDBA cell to the adjacent DBA cells leads to a higher dispersion than is otherwise the case with multi-bend achromat lattices designed for low emittance. However, the dispersion function within the cell is still relatively small compared with the remainder of the ring, and does not provide an obvious location to correct the added natural chromaticity locally. Similarly, the ability to correct for the second-order momentum compaction α_2 scales with $-S\eta_x^3$ [4], again requiring the sextupole strength S to increase in the remaining DBA cells.

The final, and perhaps most significant difficulty is in the loss of symmetry of the storage ring. In contrast to the nominal user optics, the low alpha lattice has so far been operated without powering the two mini-beta sections [5], thereby maintaining the 6-fold symmetry of the lattice. The inclusion of a DDBA cell clearly breaks this symmetry, with natural consequences on the sensitivity to errors.

Optimisation Techniques

Optimisation of the lattice is an iterative process, primarily carried out using the parallel version of elegant [6, 7]. Initially, the linear optics are adjusted using the 'particle swarm' option in the parallel optimisation module, having applied a number of constraints. Following this, the nonlinear optics are explored using a Multi-Objective Genetic Algorithm (MOGA) [8].

The constraints for the linear optics include fixing α_1 to the desired value, placing limits on the maximum β-functions around the ring, maximising β_x at the injection

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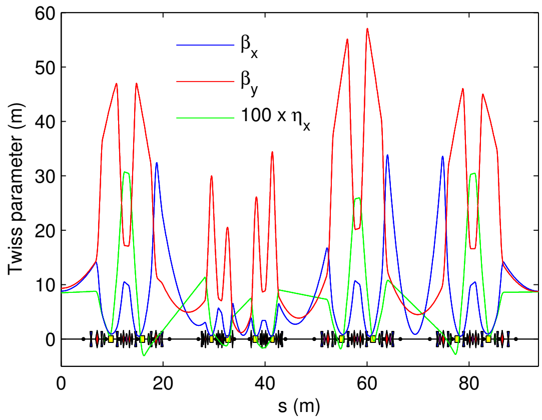

Figure 2: Twiss functions for the DDBA lattice in low alpha mode.

point, constraining the amplitude and enforcing the symmetry of β_x, β_y and η_x in all straight sections, as well as local constraints on the Twiss parameters around the DDBA cell. The tune point was fixed during the latter stages of the optimisation. A total of 20 quadrupole families were used (10 families in the existing ring, 4 in the DDBA cell, plus 2 quadrupole triplets adjacent to the DDBA cell).

The MOGA optimisations targeted the Touschek lifetime and injection efficiency directly via 6D particle tracking. In both cases the physical apertures were included, and systematic and random higher order multipole errors were applied to all magnets. Following the DDBA upgrade, the Diamond storage ring will contain a total of 12 sextupole families, 4 of which are in the DDBA cell. Only 9 of these were treated as free parameters in the MOGA optimisation however, with the remainder used to fix the transverse chromaticities and α_2. As with the linear optics, tune point and chromaticity were initially allowed to vary during the optimisation, but were left fixed during the fine-tuning of candidate solutions.

Working Solution

The Twiss parameters for one super-period of the low alpha DDBA lattice are shown in Fig. 2, and a comparison of the main lattice parameters to the existing low alpha solution are given in Table 1.

Table 1: Lattice Parameters

	DBA	DDBA
Q_x / Q_y	29.389 / 8.285	29.372 / 8.299
Nat. Chrom. (ξ_x / ξ_y)	-62.9 / -48.4	-61.9 / -59.2
Emittance (nm.rad)	4.41	5.12
α_1	-1×10^{-5}	-1×10^{-5}
α_2 (uncorrected)	0.0047	0.0048
$\beta_{x,max}$ / $\beta_{y,max}$ (m)	27.6 / 41.7	33.6 / 58.2
$\beta_{x,ID}$ / $\beta_{y,ID}$ (m)	1.4 / 5.3	1.9 / 3.9
$\beta_{x,inj}$ (m)	4.87	8.70
σ_0 at 3.4MV(ps)	2.3	2.3

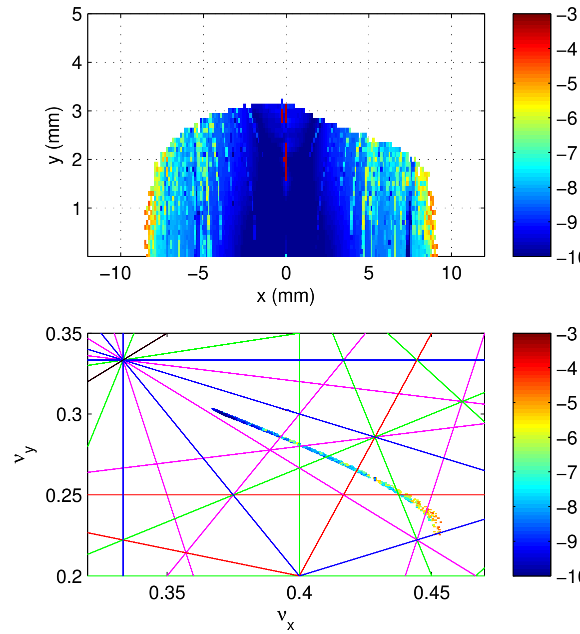

Figure 3: Dynamic aperture (top) and frequency map (bottom) for the low alpha lattice.

The first point to note is that the tune points for the two lattices are very similar, despite the lower β-functions in the DDBA cell. Initial optimisations of the lattice attempted to match in the DDBA cell without changing the optics in the remainder of the ring. This gave an increase of Q_x by ~1 and Q_y by ~0.5, alongside a 10% increase in the required sextupole strengths. No adequate non-linear solution could be found for this lattice, and instead the linear optics were adjusted to relax the requirements on the sextupole strengths. This proved beneficial for the dynamic aperture, but resulted in an increase of the maximum β-functions.

The physical apertures within the DDBA cell are relatively narrow as a result of the small bore / high gradient quadrupole magnets. This means that β_x must also be kept small here in order to avoid losses on the chamber walls. To meet this requirement, it was necessary to allow non-zero values of α_x in the adjacent ID straights. Compared to the existing lattice, β_x has been increased in the injection straight in order to ease the injection process.

The on-momentum dynamic aperture and frequency map for the ideal lattice including physical apertures are shown in Fig. 3. At present, injection into the storage ring is at -8.3 mm offset from the stored beam, and so the dynamic aperture shown here is too small to allow reasonable injection efficiency. To counter this, the existing injection process has been optimised, with the result that the septum magnet is to be moved 4 mm closer to the stored beam and the nominal beam separation will be reduced to 6.8 mm [9].

The momentum acceptance for one super-period of both the existing and DDBA lattices are shown in Fig. 4. Overall, the reduction in momentum acceptance is of the order ±0.5%, with good acceptance within the DDBA cell.

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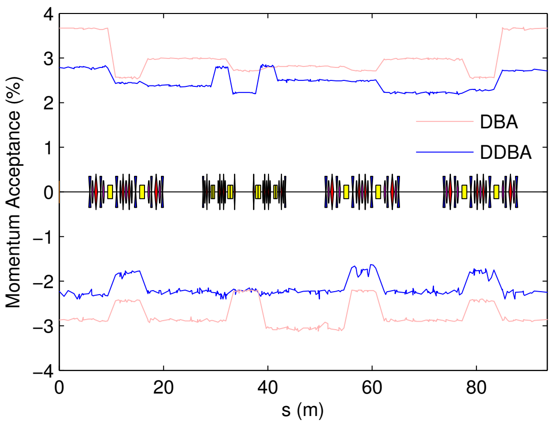

Figure 4: Momentum aperture for one super-period of the existing and upgraded rings in low alpha optics.

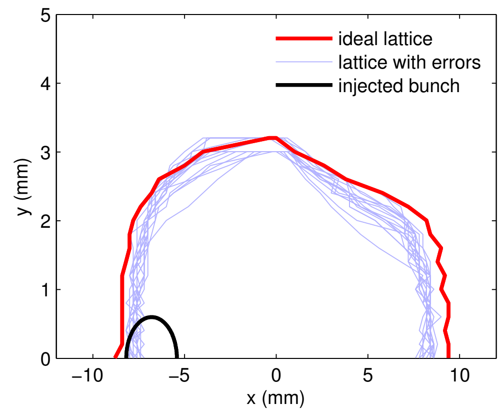

Figure 5: On-momentum dynamic aperture over 25 error seeds. The injected beam area for $2\sigma_x \times 2\sigma_y$ is highlighted for clarity.

ERROR ANALYSIS

The sensitivity of the lattice to errors has been assessed using two error scenarios. The first scenario assumed relatively large alignment and gradient errors located only within the DDBA cell in order to investigate initial commissioning of the lattice. This investigation concluded that the cell was likely to introduce initial closed orbit errors in the 5-10 mm range, and 15-20% β-beating. Required corrector strengths are well within the power supply capabilities.

Following this, a set of smaller alignment and gradient errors were applied to all magnets, along with higher order multipole errors in order to investigate how the lattice is likely to perform after an initial correction of the linear optics. Orbit, tune and chromaticity correction was applied, resulting in β-beat of the order 5% and residual peak closed orbit distortion of 50-100 μm, depending upon the seed.

A plot of the on-momentum dynamic aperture over 25 such errors seeds is shown in Fig. 5, calculated using 6D tracking with radiation damping. The injected bunch is super-imposed for clarity, indicating the injected bunch still lies partially outside the dynamic aperture, even with the reduced offset of -6.8 mm. Over 50 seeds, the calculated injection efficiency is 23.4%±1.8% (compared to 21.1%±1.8% calculated for the existing lattice). Analysis shows that it is primarily particles at the head and tail of the relatively long injected bunch which are being lost, as these are taken to large energy deviation due to synchrotron motion. Using the same set of errors, the Touschek lifetime calculated over 25 seeds is 21.4 h ± 2.0 h (compared to 30.3 h ± 0.4 h for the existing lattice).

TWO DDBA CELLS

In parallel to the studies for adding a single DDBA cell, feasibility studies are under-way for adding a second DDBA cell to the Diamond storage ring [10]. Development of a workable low-alpha optics for this ring is at an early stage; however, a promising solution for the linear part has been identified (see Fig. 6). In order to match in the two DDBA cells whilst keeping the β-functions to reasonable amplitudes, it has been necessary in this case to increase the tune point to Q_x=30.413, Q_y=10.282. This in turn has led to a further increase in the natural chromaticity of the ring and therefore an increase in the sextupole requirements. The emittance for the lattice is also slightly higher than the one DDBA ring at 5.17 nm.rad. An acceptable solution for the nonlinear lattice remains to be found.

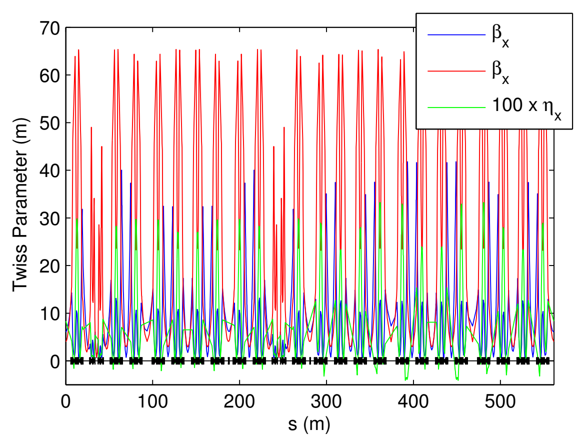

Figure 6: Twiss parameters for the present two-DDBA lattice solution for low alpha optics.

CONCLUSIONS

A low emittance, low alpha lattice suitable for the single-cell DDBA upgrade has been developed for the Diamond storage ring. It is anticipated that the x-ray pulse-duration and THz spectrum will be unaffected by the upgrade, with a moderate (acceptable) reduction in lifetime predicted from simulations.

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