ULTRA-LOW EMITTANCE UPGRADE OPTIONS FOR THE DIAMOND LIGHT SOURCE

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Abstract

Many synchrotron radiation facilities are studying lattice upgrades in order to lower the natural emittance and hence increase the radiation brilliance and transverse coherence. While large circumference rings are favoured for reaching ultra small emittance, recent advances in design and optimisation tools allow also medium size rings to reach emittances down to the some 100s of pm region, with workable lattices. Diamond is investigating a novel design whereby low emittance is conjugated with doubling of the capacity of the ring, based on a double-double bend achromat (DDBA) cell. Plans for the installation of one or more low emittance cells will be presented. This will serve as a prototype for a possible full phased upgrade of the storage ring in the longer term.

INTRODUCTION

The Diamond Light Source is actively pursuing a research programme for the development of an ultra-low emittance upgrade of the storage ring in order to achieve emittances in the range of 270 pm and below [1,2] which would improve the present emittance by a factor 10 or more. This emittance will allow the facility to remain competitive with the next generation high brightness light sources by substantially increasing the brilliance and the transverse coherence of the synchrotron radiation.

Accelerator physics studies have shown that lattices based on Multiple Bend Achromats (MBAs) can produce appealing emittance even with medium size rings such as the 561.6 m of the Diamond storage ring. The Diamond lattice upgrade is constrained by the requirement of maintaining the tunnel geometry and the position of the beamlines. The possibility of phasing the upgrade on a cell-by-cell basis to avoid long shutdowns was also considered in the studies. Reusing as much hardware as possible was considered, however it turned out that the magnets of the present lattice are not adequate for a reduced emittance lattice and so new magnet designs are now developed. Other technical subsystems are also under design, notably vacuum and diagnostics, while the RF system [3] and the power supplies will be reused. In this report we present the advances on the accelerator physics design.

MBAs have been proposed in the early '90s as a promising lattice design that allows reducing the emittance towards the diffraction limit [4] in the hard X-ray region. We therefore investigated the possibility of replacing our DBA lattice with an MBA. Various options were analysed starting with a very aggressive 7BA design with 45 pm emittance but with a very small dynamic aperture. More relaxed lattices 5BA and 4BA produced slightly larger emittance, 150 pm and 270 pm respectively. These values are in any case meeting the 10-fold emittance reduction target. In the analysis of the 4BA lattice it transpired that the 4BA cell can be split in two, inserting a new straight section in the middle of the cell. We later found that a similar concept was proposed in [5]. In this way the lattice strongly resembles again a DBA, despite the fact that the outer and inner dipoles in the cell have different lengths, and was therefore named "Double Double Bend Achromat" (DDBA). The additional straight section in the middle of the cell allows doubling the capacity of the present Diamond ring for Insertion Devices (IDs), while still maintaining a very small horizontal emittance.

The possibility of introducing an additional straight section has triggered the study of the installation of one or more such DDBA cells into the present Diamond lattice. The VMX [6] and the DIAD [7] beamlines have expressed strong interest in utilising a DDBA cell located in cell 2 and cell 11 respectively. A third modification of the lattice in cell 20 would allow the installation of a third harmonic cavity for bunch lengthening which will support the increase in the operational current to 500 mA and is in line with the potential phased upgrade of the full lattice.

The installation of the DDBA cells in the present lattice will provide the opportunity of testing many critical areas of a possible full upgrade of the machine. In particular it has kick-started the necessary R&D on several technical subsystems such as magnets, vacuum, diagnostics and the engineering integration of the subsystems.

MBA LATTICE STUDIES

The first options investigated to replace the existing DBA was a 7BA lattice, providing an emittance of 45 pm. The basic cell, shown in Fig. 1, is built on gradient dipoles with 0.45 T and 30 T/m quadrupole component and 90 cm length. The larger number of dipoles is accommodated by slightly reducing the lengths of straight sections. The natural chromaticity of this lattice is very high and requires strong sextupoles for correction. A dispersion bump is created between dipole 1 and 2 and symmetrically between dipole 6 and 7 to locate the chromatic sextupoles and reduce their required strength. The lack of a proper phase advance (π or 3π usually) between the chromatic sextupoles in the cell prevents the cancellation of the geometric driving terms. The phase advance was matched to complete 2π within one super period (4 cells). Most of the resonance driving terms (RDTs) can be cancelled in one super period in this way

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[8]. However, higher order terms are still large, difficult to compensate and the resulting dynamic aperture is only ± 1mm. With such a small dynamic aperture, off-axis injection is excluded and a major reconsideration of the injector system would be required. Furthermore the effect of intra-beam scattering quickly blows up the emittance for beam currents under consideration: at 300 mA in 900 bunches and 10% coupling, the emittance is double to 90 pm. Given the constraints on the geometry and layout of the beamlines, we do not have the flexibility to install damping wigglers to compensate for this effect. It was therefore decided not to pursue this option further for the moment.

A similar design based on a 5BA providing an emittance of 156 pm also showed similar, albeit mitigated, difficulties: the dynamic aperture is only ±3 mm. The layout of the optics function in the cell for these two options is shown in Fig. 1. The main parameters of the two lattices are reported in Tab. 1.

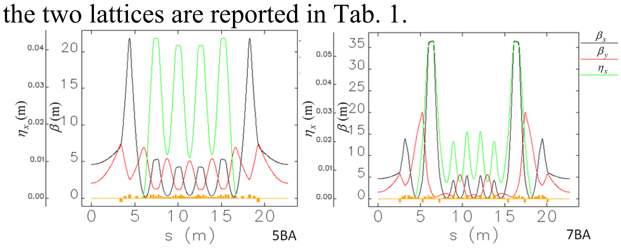

Figure 1: Optics functions for 5BA and 7BA lattices.

Table 1: Parameters for 5BA and 7BA Lattices

Parameters	5BA	7BA
Circumference [m]	561.6	561.6
Emittance [pm.rad]	156	45.7
Tune Point [Q_x / Q_y]	53.66/ 28.87	75.42/52.17
Chromaticity(ξ_x / ξ_y)	-130 / -50	-348/ -119
Length of straights [m]	9.5 / 6.5	8.0 / 5.0
Momentum compaction	1.30e-04	7.98e-05

THE DDBA LATTICE

Given the above difficulties, more relaxed optics were then considered. The usual 4BA cell, based on standard TME cells and matching cells, has been modified to accommodate an additional straight section in the middle of the cell, in the so called DDBA cell shown in Fig. 2. In this way the number of straight sections per cell is doubled. Table 2 reports the main parameters of the DDBA lattice and a comparison with the present lattice design.

The length of the additional middle straight section is a parameter of the optimisation and it turned out that a good matching can be achieved only up to 3.4 m. This length is sufficient to install one of the existing 2m in-vacuum ID and leaves sufficient space for flanges, BPMs, bellows and correctors. The excellent control of the optic functions in this straight allows the use of narrow gap ~5mm IDs without any detrimental effect on emittance and gas lifetime.

Table 2: Parameters for Existing DBA and DDBA Lattices

Parameters	Existing DBA	DDBA lattice
Energy [GeV]	3.0	3.0
Circumference [m]	561.6	561.0
Emittance [pm.rad]	2750	276
Tune Point [Q_x / Q_y]	27.20/ 13.37	50.76/18.36
Chromaticity(ξ_x / ξ_y)	-80.4 / -35.6	-128/ -94
Length of straights [m]	11.3 / 8.3	9.1- 6.7 / 3.4
Mom. compaction	1.66e-04	1.02e-04

The combined function dipoles play an important role in making the cell compact as almost all the vertical focussing is provided by the gradient in such dipoles. The maximum gradient of all quadrupoles and combined function dipoles was limited at 55 T/m and 15 T/m respectively. The dipole at the edge of the cell is shorter than the middle dipole by the factor of $3^{1/3}$ in order to minimise the contribution to the beam emittance and matching to zero dispersion in the straight section [9]. To achieve a more efficient chromaticity correction, we introduced a dispersion bump between dipoles 1 and 2 and dipoles 3 and 4. Chromatic sextupoles are introduced in these locations.

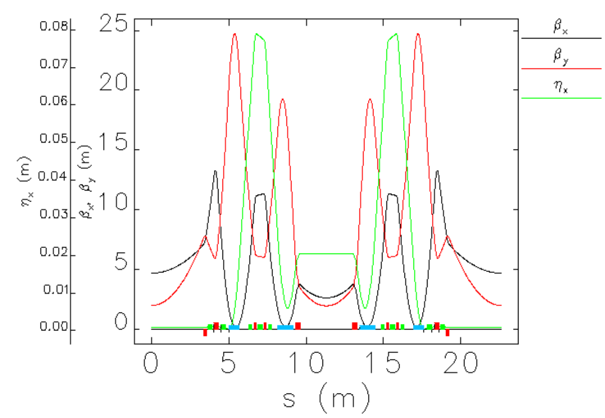

Figure 2: Optics functions for the DDBA cell.

The dynamic aperture and the momentum aperture were further optimised with a Multi-Objective Genetic Algorithm (MOGA) implemented in elegant [10], using the 10 sextupole families in the ring. The dynamic aperture is about ± 5 mm while the momentum aperture exceeds ±2 % everywhere in the ring and corresponds to a Touschek lifetime of 2.2 h. While the dynamic aperture is still too small for off-axis injection we believe that a more thorough search for the optimal phase advance per cell and using more sextupole families can improve the dynamic aperture to values compatible with our off axis-injection that currently produces a residual oscillation of 8.3 mm. This work will be the subject of forthcoming investigation. More details on the nonlinear dynamics optimisation can be found in ref. [1]. Alternative injection schemes in small dynamic apertures are under investigation [11].

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IMPLEMENTATION OF ONE DDBA CELL

The DDBA cell opens the possibility of adding new straight sections to the ring and therefore accommodating new beamlines. This opportunity was used to modify the layout of the VMX beamline [6] by implementing one DDBA cell in the present cell 2 of the lattice. The VMX beamline was originally designed with two branches which were served by one in-vacuum ID and one short ex-vacuum ID respectively. With the DDBA cell, both branches can be served by 2m in-vacuum IDs with a considerably better performance. The modified lattice is shown in Fig. 3.

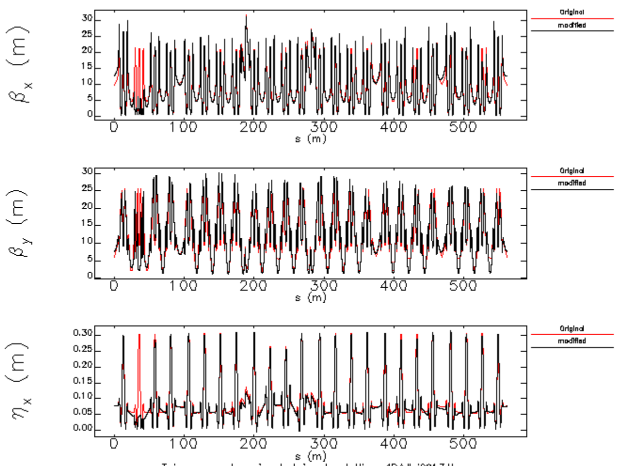

Figure 3: Optics functions with cell 2 upgraded to a DDBA cell.

The optimisation of the beam dynamics with MOGA showed that the insertion of the DDBA can be made almost transparent, as the dynamic aperture and Touschek lifetime of the ring are restored to the values of the original lattice. Figure 4 shows the DA of ±15 mm and the corresponding frequency map. The computed Touschek lifetime is 27h compared to the 29h of the original lattice.

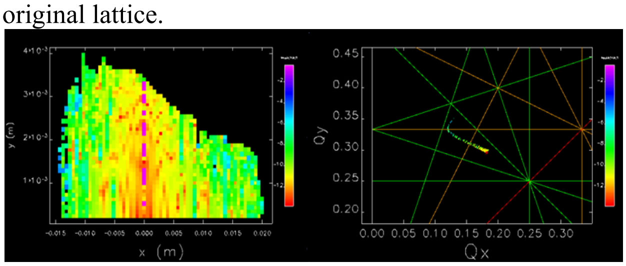

Figure 4: Dynamic aperture and frequency map for the Diamond lattice with one DDBA cell.

TWO AND MORE DDBA CELLS

In following studies, cell 11 was altered to a DDBA cell in correspondence of the DIAD beamline [7]. A new set of extensive numerical simulation was set up to optimize the dynamic aperture and the Touschek lifetime. Also in this case MOGA was used to set the values of ten existing sextupole families as parameters and the sextupoles in the new cell 11. A marginal readjustment of the sextupoles in the DDBA cell2 was required. The result presently achieved shows that the dynamic aperture is still about ±15 mm. The Touschek lifetime is 18h, that is a reduction to 62% of the existing value of the Touschek lifetime. We believe that, while already very promising, these values can still be improved to make also the second cell installation transparent to the operation of the existing ring.

Consequently we have started the analysis of a third DDBA cell. While this exercise is driven by the requirement to install a third harmonic cavity for bunch lengthening, it is also in line with the concept of a phased upgrade of the full ring and serves to prove the flexibility of our lattice. The lattice functions were matched as reported in Figure 5. The study of nonlinear beam dynamics will be carried out in the near future.

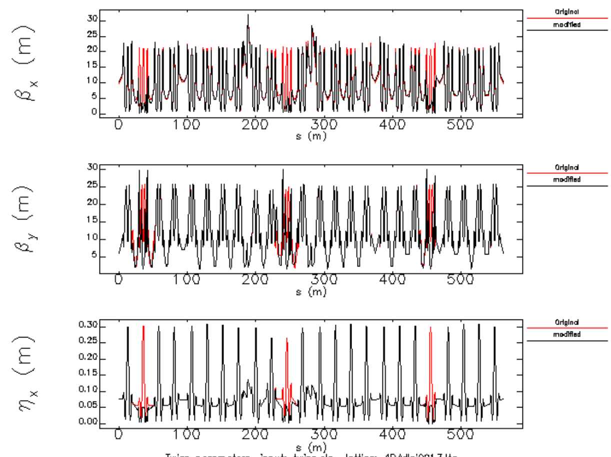

Figure 5: Optics functions with three cells upgraded to a DDBA (cell 2, cell 11 and cell 20).

CONCLUSION

Several MBA lattice options are considered for a possible low emittance upgrade of the Diamond storage ring. Lattices based on 7BA cells promise very small emittance, but their optimisation appears to be challenging. A modified 4BA lattice providing small beam emittance and doubling the number of beamlines appears to be a strong candidate for the upgrade of Diamond. The beam dynamics optimisation of one and two DDBA cells in the present lattice has shown that their installation will not compromise the operation of the ring, while providing substantial benefits for the corresponding beamlines. The implementation of a third DDBA cell is under investigation.

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