ULTRA-LOW EMITTANCE UPGRADE OPTIONS FOR THIRD GENERATION LIGHT SOURCES

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Abstract

The increasing efforts in the synchrotron light sources community toward the design of a diffraction limited source at multi-keV photon energy have eventually stimulated the existing facilities to investigate possible upgrade paths to higher photon brightness and lower emittances to maintain their competitiveness within the users' community. We present a possible option for upgrading 3rd generation light sources based on a rebuild of the arcs with MBA cells, using diamond as an example. Emphasis is given to the AP design issues with a view to minimal changes to the machine layout, contained cost and minimal downtime.

INTRODUCTION

In order to remain competitive with the next generation high brightness light source [1,2], many operating light sources are investigating the possibility of upgrading the magnetic lattice to reduce significantly the horizontal emittance of their ring. In this framework Diamond has started the investigation of a lattice upgrade with the aim of reducing the horizontal emittance ten-fold to 270 pm-rad or below, thereby increasing the brightness by a factor 10 or more. The upgrade must obviously reuse the existing tunnel and beamlines. The possibility of reusing as much hardware as possible and providing a phased approach to avoid long shutdowns was also considered in the design.

Multi-bend achromats (MBA) provide effective design solutions for ultra low emittance lattices by a careful control of dispersion and beta functions in the arc dipoles. However the theoretical minimum emittance values achievable is such lattices are usually relaxed in order to ease the optimisation of the nonlinear dynamics. In large circumference machine, this strategy still allows achieving extremely small emittances [3]. In medium size machine like Diamond, however, the optimisation of the beam dynamics in lattice with emittance below 100pm remains extremely challenging. Several different lattices based on MBA cells are under investigation at Diamond. All options explored are required to maintain the length of the straight section larger than 5.3 m and to avoid offsetting their position and angle. This leaves about 22m in the arc cells: such space has been used to test MBA structure with M = 4, 5, 6, 7. As a by product of this analysis we have developed an intermediate cell design, based on a modified 4BA (a.k.a. DDBA), which allows the introduction of an additional straight section in the middle of the cell thereby doubling the capacity of the present Diamond ring. This can be achieved while still maintaining a horizontal emittance substantially lower than the present one. The possibility of introducing an additional straight section has triggered the study of the installation of two such modified 4BA cells into the present Diamond lattice. Details of this study are presented in a companion paper [4].

MODIFIED 4BA LATTICE

The layout of the modified 4BA cell is reported in Figure 1. 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 this way the number of straight sections per cell is doubled. Table 1 reports the main parameter of the modified 4BA lattice and a comparison with the present lattice design.

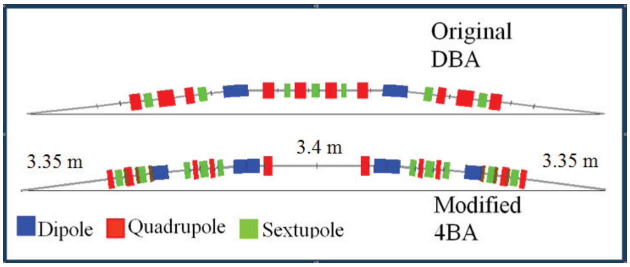

Figure 1: Modified 4BA layout with respect to the existing Diamond DBA.

Table 1: Parameters for Diamond and modified 4BA ring

Parameters	Existing DBA	Modified 4BA
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 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, bellow and correctors. The excellent control of the optic functions in this straight (shown in Figure 2) allows the uses of narrow gap ~5mm IDs without any detrimental effect on emittance and gas lifetime. The combined function dipoles play an important role in making the cell compact

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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 [5]. To achieve a more efficient chromaticity correction, we introduced a dispersion bump between dipoles one and two and dipoles three and four. Chromatic sextupoles are introduced in these locations.

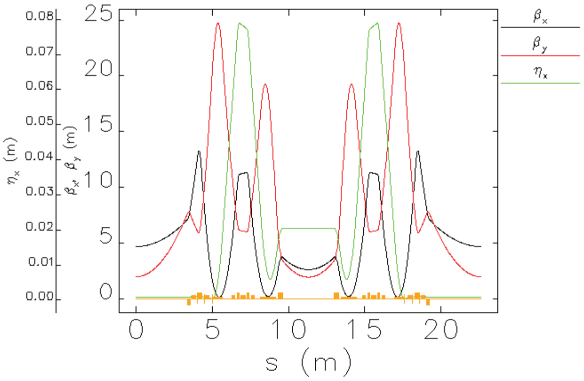

Figure 2: Optics functions for the modified 4BA cell.

BEAMLINE ALIGNMENT LIMIT

In order to reuse the beamline hardware in the existing experimental hall, the location of the straight sections for existing beamlines has been constrained to be within 1.0 cm with respect to the existing straight section. For the newly generated, middle-cell straight sections, the alignment can be relaxed. By adjusting the total ring circumference and investigating the machine footprint with respect to the original ring, we found that the required beamline alignment can be achieve by shortening the ring circumference to 561.0 m (from 561.6 m) thereby reducing the harmonic number of the ring by one unit from h = 936 to h = 935.

In the case the upgrade is implemented on a cell-by-cell basis, with one new cell per shut down, the machine will be required to operate with a shifted RF frequency that matches the new circumference, in order not to change the energy of the ring. The required frequency shift and an initial proof of the feasibility of operating the Diamond injector in these conditions has been already tested and is reported in a companion paper [6].

NONLINEAR OPTIMIZATION

The optimisation of the nonlinear beam dynamics is the most challenging aspect of the ultra-low emittance ring design. Dynamic aperture and Touschek lifetime were the target of several optimisation strategies which involved, tune scans, phase advance setting to minimise resonance driving term, higher order driving term suppression, frequency map analysis and tracking optimisation with MOGA.

The phase advance between cells was set to minimise the third order driving terms every four cells, by adding up to an integer multiple of 2π. Small tune readjustments were investigated with tune scanning to further minimise the effect of nonlinear resonances. Six quadrupoles families adjacent to the straight sections were used. For each value of the betatron tunes, we computed the frequency map and the total diffusion rate given by

$$d = \log(\Delta Q_x^2 + \Delta Q_y^2) \qquad (4)$$

where ΔQ_x andΔQ_x are tune differences between two halves of the tracking series in horizontal and vertical plane respectively. The quantity d was used to represent the quality of dynamic aperture. Misalignment errors were included in tracking. In Figure 3, areas with large diffusion rate (purple-blue) are clearly identified close to low order resonances. The tune points far from the second and third order resonance lines give small diffusion rate and hence better dynamics aperture (red). Once the best tunes regions are identified, further optimization of the nonlinear driving terms and dynamics aperture is carried out with the OPA code [7] and multi-objective genetic algorithm (MOGA) [8].

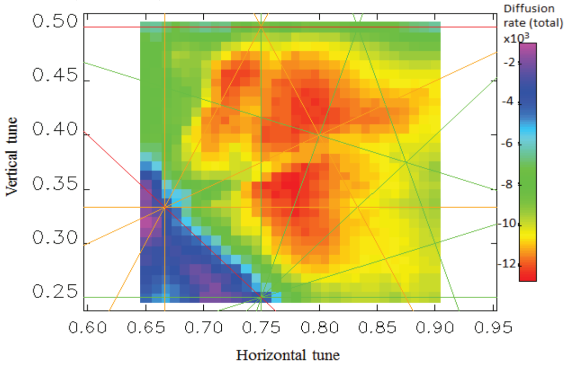

Figure 3: Total diffusion rate for different tune point.

A Multi-objective genetic algorithm (MOGA) based on NSGA-II [9] implemented in elegant [10] has been used throughout the optimisation, using dynamic aperture optimization and total diffusion rate as objective and ten sextupole families as parameters. An example of the evolution of the optimal front using such objectives is reported in Figure 4.

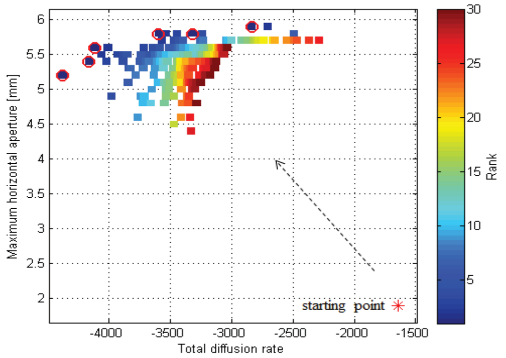

Figure 4: Objective space of maximum horizontal aperture and total diffusion rate from MOGA.

While this optimisation is still ongoing it already produced a dynamic aperture of about -4 to +6 mm for operation with appositive chromaticity of 2 in both planes, including misalignment errors. These values are likely to increase with more dedicated CPU time. However it is clear that the modified 4BA lattice is substantially more challenging than the standard DBA lattice of Diamond, having much larger natural chromaticity as reported in Table 1. Alternative injection scheme in small dynamic apertures are under investigation as reported in a companion paper [10].

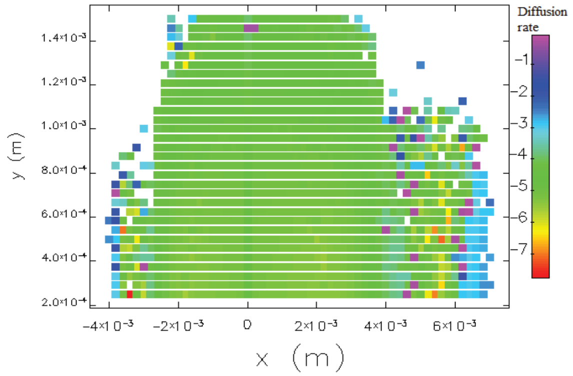

Figure 5: Dynamics aperture for modified 4BA lattice.

5BA AND 7BA LATTICES

Lower horizontal emittances were obtained with 5BA and 7BA lattices whose cells are shown in Figure 6. The larger number of dipoles is accommodated by slightly reducing the lengths of straight sections. The main parameters of the two lattices are reported in Table 2.

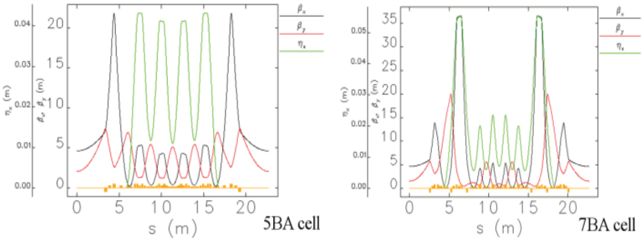

Figure 6: Optics functions for 5BA and 7BA cell.

Table 2: Parameters for 5BA and 7BA

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

To reduce the chromatic sextupole strength, in the 7BA, a dispersion bump adjacent to the outer dipoles of the cell has been introduced. 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 [11]. However higher order terms are still large and spoil dynamics aperture. Further nonlinear terms and dynamics aperture optimization is ongoing using OPA and MOGA.

INTRA BEAM SCATTERING

In such ultra-low emittance lattices, intra beam scattering (IBS) can spoil the emittance for sufficiently high operating currents. Emittance increase due to IBS effect was calculated by using Bjorken and Mtingwa's formalism in Elegant as a function of the stored current assuming 900 bunches with 10% coupling. Figure 7 shows clearly that emittance increase most rapidly for 7BA, 5BA and 4BA lattice respectively. Operating the 7BA lattice at 300 mA will more already double the design emittance.

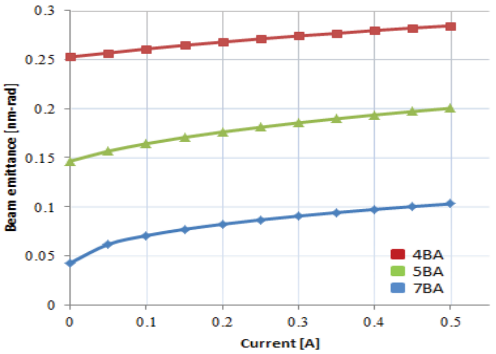

Figure 7: Intra beam scattering effect on beam emittance for each lattice for various beam current.

CONCLUSION

A modified 4BA lattice providing very small beam emittance and doubling the number of beamlines appears to be a strong candidate for the upgrade of Diamond. Further optimisation of dynamics aperture and Touschek lifetime will continue in order to assess conclusively the feasibility of this design. Other upgrade options with 5BA and 7BA cells are also under investigation: while they promise a much smaller emittance, their optimisation appears to be more challenging. Furthermore, in absence of damping wigglers, the emittance reduction is compromised when operating at 300 mA or above due to intrabeam scattering. The complications of using MBAs cells, with M larger than 5, make such choice questionable. Magnet design and engineering integration of such lattices are under investigation, however no irresolvable issues have yet been identified.

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