NOVEL LATTICE UPGRADE STUDIES FOR DIAMOND LIGHT SOURCE

R. Bartolini[1,2], C.P. Bailey[1], M.P. Cox[1], N.P Hammond[1], J. Kay[1], E.C. Longhi[1], S. Mhaskar[1], T. Pulampong[2], R.P. Walker[1]
[1]Diamond Light Source Ltd, Oxfordshire, OX11 0QX, UK and
[2]John Adams Institute, University of Oxford, OX1 3RH, UK

Abstract

Many synchrotron radiation facilities are studying lattice upgrades in order to lower the natural emittance and hence increase the radiation brightness. At Diamond we are pursuing a novel alternative, not targeting the minimum possible emittance but instead introducing additional insertion device (ID) straights and hence increasing the capacity of the facility, while still possibly achieving a more limited reduction in emittance. The new scheme involves converting some of the DBA lattice cells into a double-DBA or DDBA, with a new ID straight between the two achromats. We present here the design concept and preliminary lattice design, and discuss the challenging magnet and engineering issues.

INTRODUCTION

Since the beginning of operation in January 2007 [1], Diamond has already completed several operational upgrades (e.g. Top-Up operation [2], low alpha lattice for short radiation pulses [3], low coupling operation [4]). To keep Diamond competitive with the newly built synchrotron light sources and the upgrade programmes at existing light sources, an ultra-low emittance lattice upgrade has been considered [5]. In the context of a 4BA lattice upgrade, it became apparent that it is possible to modify the 4BA cell to leave space for a mid-cell straight section: this creates an additional straight section while still achieving an emittance substantially lower than the present Diamond ring. While modified DBA lattices have already been proposed [6], key to this new lattice design is the careful control of the optics function in the newly created mid straight section in a 4BA cell, by minimizing the dispersion function and generating a minimum of the vertical beta function to allow the operation of in-vacuum insertion devices. The length of the mid-straight section was forced to be long enough to host an in-vacuum ID including the necessary space for tapers, flanges, bellows and BPMs. For this reason a 3.4 m straight section was created. The fact that each bend is essentially being converted into a DBA has led to this being termed a “double-double bend achromat (DDBA)” lattice.

The benefits intrinsic with this solution have triggered a review of the plans for some of the upcoming Diamond Phase-III beamlines. The “Dual Imaging And Diffraction” (DIAD) beamline [7], originally meant to operate using a Superbend [8], can potentially gain at least two orders of magnitude in brightness at 10 keV. Another Phase-III beamline, with two branches called VMXi and VMXm [9], was originally proposed to be fed by two canted IDs in the same straight section, an in-vacuum ID at the centre of the straight section and a short out-of-vacuum ID at the end of the same straight section. With a DDBA arrangement however, the latter ID will be substituted by an additional ID in the new straight section, with a significant gain in the performance of the beamline.

Given this strong interest, we therefore decided to investigate further the implementation of one or more such modified DDBA cells in the present Diamond layout. While this approach offers interesting opportunities for R&D toward a possible upgrade of the whole ring, it is to be stressed that due to the limited time available within the scheduled plan for the beamline construction, we have decoupled the aim of our studies, no longer requiring that the modified cell design produce a lower emittance, as long as it does not increase the present operating value of 2.7 nm.

MODIFIED CELL LAYOUT

The modified cell is shown in Fig. 1 where the existing DBA cell is also shown. It consists of four dipoles, ten quadrupoles and eight sextupoles. A mid-straight of 3.4 m is created between the two quadrupoles in the new straight section and there are no sextupoles in the mid-straight section.

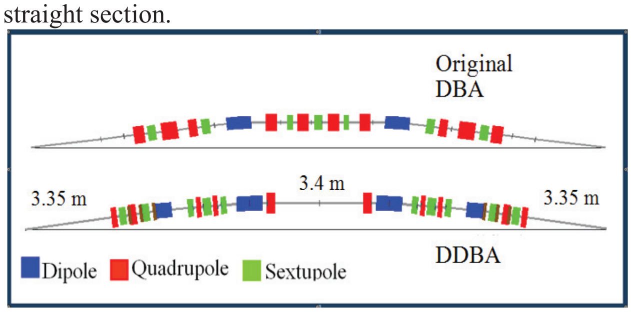

Figure 1: Layout of the DBA cell (top) and of the modified DDBA cell (bottom).

The space between the two outer dipole pairs is used to generate dispersion bumps which provide ideal locations for chromatic sextupoles and was beneficial during the optimisation. The behaviour of the optics function in the modified DDBA cell is reported in Fig, 2. This cell was inserted in the present Diamond lattice and matched to the corresponding optics function at the beginning and end of the standard straight section so that the insertion is as transparent as possible. In particular the dispersion is no longer matched to zero in the straight section and the optics is not tailored to reduce the emittance. The analysis was first focused on inserting one single modified DDBA cell. Two such cells were installed subsequently and matched. They were initially located in symmetric

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positions around the ring. However, it was soon realised that there is no space in the experimental hall for such a symmetric layout and the two modified cells will have to be moved accordingly.

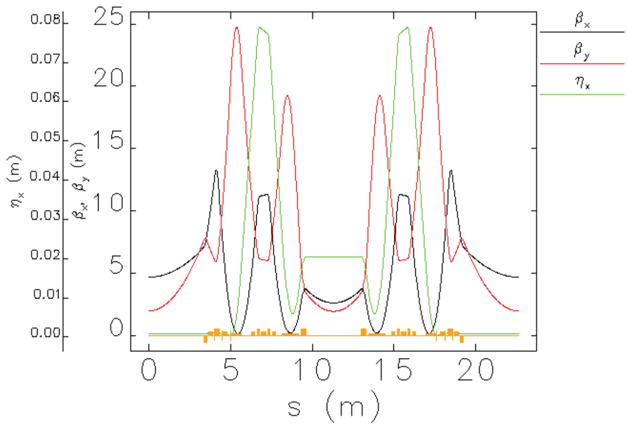

Figure 2: Optics functions of the modified DDBA cell.

The full machine optic functions with two modified DDBA cells and a comparison with the existing optics are reported in Fig. 3

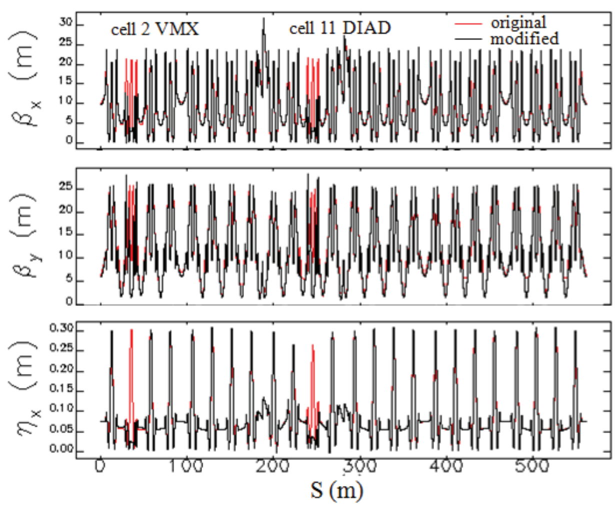

Figure 3: Optics functions of the whole Diamond ring. The DDBA cell are inserted in place of cell2 and cell 11.

The main lattice parameters for the original Diamond lattice and the one with two DDBA cells are summarized in Tab. 1

Table. 1: Main parameters of Diamond lattice and modified lattice with two DDBA cells

	DLS	2 DDBA
emittance	2.75 nm	2.50 nm
betatron tunes	27.20/12.37	29.18/13.30
nat. chromaticity	-79/-35	-81/-43
mom. compaction	$1.6{\cdot}10^{-4}$	$1.5{\cdot}10^{-4}$

ACCELERATOR PHYSICS

The linear optics of the two DDBA lattice was optimized by matching the DDBA cells to the standard straights of the Diamond lattice. Matching was done with elegant [10] using the ten quadrupoles in the cell. A combined function dipole was used, in view of developing a possible prototype for the 4BA upgrade. Additional parameters of the optimisation were the length of the dipoles and the position of the various magnets in the cell. The optimisation targeted not only the matching to the standard straight section but also the minimisation of dispersion and constrained the beta functions at the centre of the new straight section. The distance between dipoles one and two, and symmetrically between dipoles three and four, was lengthened to allow a dispersion bump and chromatic sextupoles were included. The impact of a longer mid-cell straight section was also studied, in order to accommodate more comfortably one of Diamond's 2m in-vacuum IDs. However, the result of such optimisation proved too complicated to go beyond 3.4 m.

The nonlinear dynamics was optimised using the eight sextupole families of the ring and the additional four families introduced in the DDBA cell. Multi-Objective Genetic Algorithms (MOGA) were heavily used to define the optimal sextupole strengths. The constraints were setting the operation with a positive chromaticity of 2 in both planes, maximising the dynamic aperture and the Touschek lifetime. A proxy for the dynamic aperture, given by the sum of the diffusion terms in the betatron tune space, was used. Typical runs using the Diamond AP cluster (240 Intel CPUs) were longer than one week CPU time. The lattice with a single DDBA cell has almost the same dynamic aperture and Touschek lifetime as the original lattice. With two DDBA cells the dynamic aperture is slightly below 10 mm. The Touschek lifetime is significantly reduced with respect to the original Diamond lattice however, at this stage of the optimization, it already reaches 9h which gives us confidence in the possibility of operating such lattice with a further modest improvement of the beam dynamics.

IDS PERFORMANCE

The optics functions in the mid-cell straight section allow the introduction of a 2m in-vacuum ID with ~5mm gap without impacting the limiting aperture of the existing ring and with negligible impact on emittance and energy spread.

A standard U21 in-vacuum ID was assumed in calculations for the DIAD beamline, although a CPMU is also under consideration. Fig. 4 compares the flux output for both types of ID with a standard bending magnet and the previously proposed Superbend [8]. The flux density is computed over an aperture of 3x2 mm^2 located at 20 m from the source point. The improvement in flux with the new source is evident up to 40 keV. A similar improvement is obtained with the VMXi beamline where the brightness of the planned U30 out-of-vacuum undulator of 0.7 m length, operating at 11.4 mm gap has to be compared with a new 2 m in-vacuum device operating at 5 mm gap.

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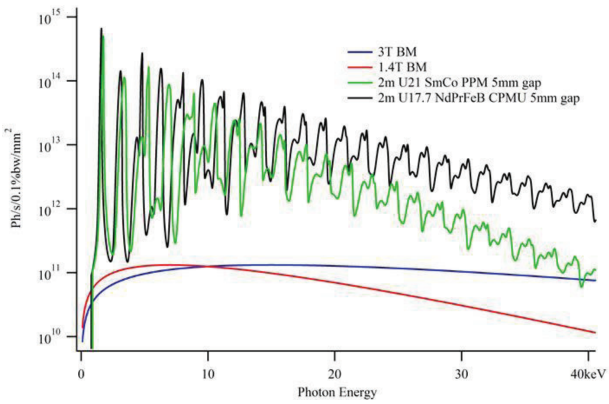

Figure 5: Comparison of flux density from standard bend (red), Superbend (blue), standard in-vacuum ID (green) and CPMU (black).

MAGNETS

The strong focusing required to control the optics functions in the new DDBA cell is achieved by introducing a horizontal defocusing quadrupole gradient in the dipole and very strong quadrupoles in the cell. All these magnets require a new design with significantly smaller bore radius and cannot be accommodated around the existing beam pipe. In view of the rather tight space constraints we also investigated a permanent magnet design for the four dipoles in the DDBA cells, to reduce the space taken by the coil overhang. Beam dynamics simulations show that the quadrupole gradients required reach 70 T/m and the quadrupole gradient in the dipole is 15 T/m while the dipole field is 0.8 T. Sextupoles are limited to a gradient of 4000 T/m^2. While these gradients are challenging and far exceed the present gradients used in the Diamond ring, they do not appear to be prohibitive. A 3D design of such a quadrupole achieves 70 T/m with a bore radius of 15 mm and current density of 4.5 A/mm^2. The relative gradient variations are within 10^{-3} at half bore radius. The overall dimension of the yoke cross section is within 22 cm^2. A similar design for a maximum sextupole gradient up to 4000 T/m^2 was achieved providing a relative gradient uniformity within 10^{-2} at half bore radius. The sextupole will also provide independent horizontal and vertical correctors and skew quadrupole following the same concept as the one used in the present Diamond lattice.

The engineering layout of the DDBA cell shows that the photon beam extracted from the ID crosses the downstream magnetic elements but does not require any modification of the iron yokes. The width required for the photon pipe is computed considering the radiation fan of the planned in-vacuum ID. Misteerings of the electron beam are considered assuming the closed orbit feedback will clamp the orbit within ±250 μm at the primary BPMs. The resulting photon extraction pipe has an outer diameter of 13mm. The magnet coils are designed to leave a 17mm gap in the median plane, thus allowing 1 mm alignment tolerance and clearance between coils and pipe.

VACUUM AND ENGINEERING

Due to the reduced magnet aperture a complete new design of the vacuum pipe is under consideration. The present concept is based on an oval copper tube with distributed cooling on the side illuminated by the photon beam. No antechamber is necessary in this design. Dipole ray tracing is ongoing to investigate the positioning of a crotch absorber where the photon pipe separates from the electron beam pipe as well as finger absorbers and a taper to cast a shadow on the downstream uncooled vessels. Special transitions to stainless steel vessels will be considered at the locations of fast correctors for the fast orbit feedback as well as transitions from the existing straight sections to the arcs of the DDBA cell. Given the small cross section and the limited access for pumping, extensive NEG coating is considered with ex-situ activation followed by installation into split half magnets

In order to maximise the space available for the ID, care has been taken in the design of the transitions to the ID vessel. DN63 valves have been replaced with DN40 size and flanges, bellows and tapers are under scrutiny to minimise their length. At present, the space available for the ID between flanges has been extended from 2.49 m of the IDs presently installed at Diamond to 2.77 m.

The alignment of the existing straight sections at the beginning and end of the DDBA cell will not be altered and the new mid-straight section is conveniently offset by 12 cm toward the inner side of the ring so that the new ID source point is in line with the existing bending magnet aperture in the ratchet wall. The slight reduction in the circumference of the machine, estimated to be 2.5 cm per additional cell, can be easily accommodated by shifting the operating RF frequency of the machine.

CONCLUSION

We have presented the design of a new cell based on a modified 4BA lattice called DDBA. This concept allows the possibility of converting bending magnet beamlines into much more powerful insertion device beamlines and is currently being studied for implementation in two cells of the ring. While accelerator physics and engineering studies are still ongoing, the preliminary results in terms of dynamic aperture and lifetime are encouraging and no irresolvable issues have yet been met in the engineering realization of this upgrade, however there is still much work to be done.

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