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EVALUATING THE IMPACT OF DIAMOND-II POSSIBLE LATTICES ON BEAMLINES

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Abstract

At Diamond Light Source, we are considering an upgrade of the machine aiming to significantly reduce emittance (a factor 20), following a worldwide trend in similar synchrotron radiation sources. An important aspect in the design of the upgrade is the optimization of the photon beam properties, such as flux, brilliance, spot size, divergence or coherence of the new sources and how these are translated into requirements on the electron beam and on the machine design. We present a study based on a combination of accelerator physics tracking codes (AT, elegant) and of radiation codes (SPECTRA, SRW, SHADOW), with the aim at bridging the gap between machine and beamlines.

INTRODUCTION

Diamond Light Source is a third generation synchrotron machine working at a current of 300 mA, a beam energy of 3 GeV with a typical equilibrium emittance of 2.7 nm-rad and a vertical emittance of 8 pm rad.

Diamond has been in operation for over eleven years, during which a total of 32 beamlines have been integrated into the machine in three main phases. Insertion devices (ID), such as undulators and wigglers, and bending magnets (BM), are used as synchrotron radiation sources.

Initially built as a 6-fold super-period lattice based on 24 Double Bend Achromat (DBA) cells, Diamond underwent two important changes. In 2009 and 2011 two vertical mini-beta sections with horizontal virtual focusing (HVF) were introduced in straight 9 and 13. In 2016 a Hybrid Multi-Bend Achromat with 4 dipoles (4-HMBA) cell, also known as Double Double Bend Achromat (DDBA), was inserted in lieu of cell 2, creating an extra mid-straight to host a new undulator [1]. The DDBA concept, when replicated 24 times with a super-period 6, was the original baseline case for Diamond-II, giving a natural emittance of about 270 pm. A further development is the 6-HMBA cell, promising a natural emittance of about 130 pm [2]. Other low emittance lattices have been developed and are under study at Diamond [3].

The optimisation of electron and photon beams in a new machine, imposes a thorough analysis of the impact of new lattices on the performance of the beamlines, entailing the use of codes for the definition of the electron beam parameters, the generation of the photons and their propagation up to the sample or detector planes inside the beamlines, with models of the relevant optics.

In order to tackle all these issues, a dedicated Source Working Group (SWG) was created, encompassing the expertise and favouring the exchange of information within the Accelerator Physics group (AP), the Optics and Metrology group (OM) and the Insertion Devices group (ID). Interaction with beamlines is fundamental too, in order to identify possible show-stoppers and the parameters characterizing their performance.

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BEAMLINE KEY PERFORMANCE PARAMETERS

One of the main goals of the SWG is the identification of parameters aimed at quantifying the performance of a beamline. These Key Performance Parameters (KPP) help to guide the lattice design group, by defining a set of quantitative objectives to be targeted. We illustrate this by considering two beamline case-studies.

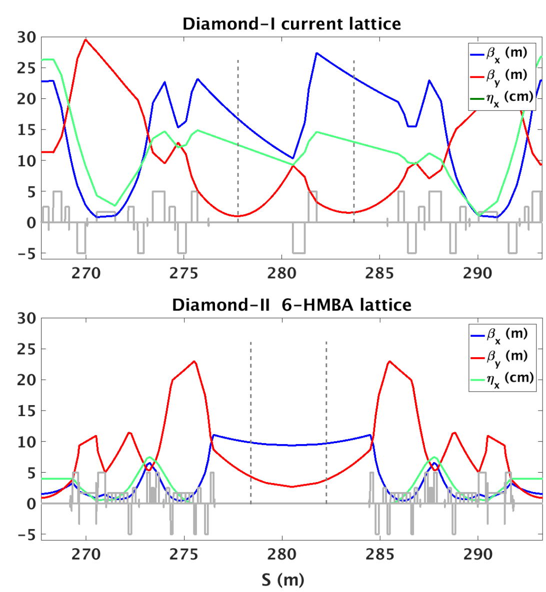

Figure 1: Twiss parameters in the I13 section: (top) present lattice, with the low mini-β_y and HVF sections clearly visible. (Bottom), the 6-HMBA lattice for Diamond-II. Undulator positions are marked by the dashed vertical bars.

Beamline I13

With its 250 m of length, I13 is the longest beamline in Diamond, comprising two branches dedicated to imaging and coherence studies.

In the present configuration the two corresponding undulators are located at two different points in one of the long straights of the machine. These were modified with the insertion of a quadrupole doublet, to generate two mini-beta sections in the vertical plane ($\beta_y = 1.0, 1.6$ m). HVF was

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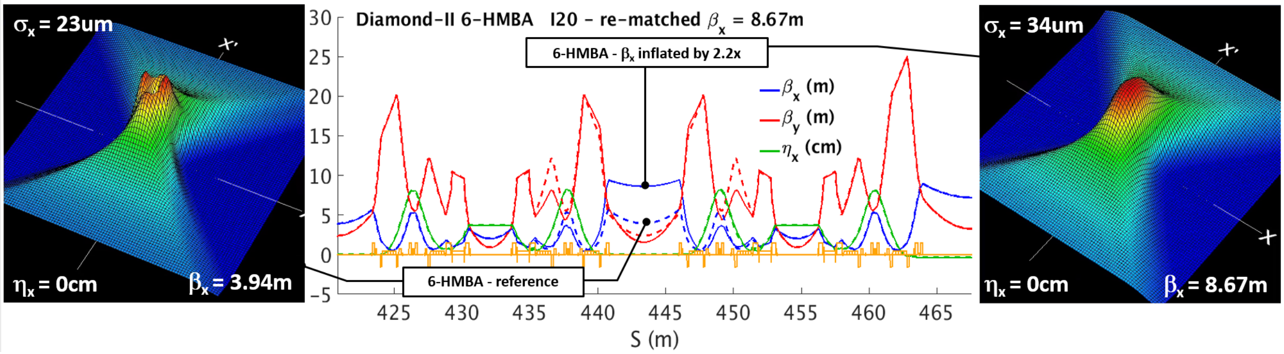

Figure 2: (Left) SPECTRA calculation of the Wigner function in the (x,x') phase space for the wiggler source of I20-scanning branch with the clearly visible double peaks. (Centre) A local re-definition of β_x from 3.94 m to 8.67 m is shown. (Right) the Wigner function smoothed out, after the re-matching of cell-20 with a new β_x.

introduced to increase the flux at the two branches, as shown in Fig. 1 (top). This structure cannot be easily replicated in Diamond-II, having strong detrimental effects both on the injection efficiency and on the lifetime of the machine.

We are therefore considering a standard long straight section (8 m) with no HVF and with two off-waist IDs (Fig. 1 (bottom)). The main requests from I13 are reported on Table 1 together with the ones coming from I09, a Surface and Interface Structural Analysis beamline whose IDs are also located in a mini-beta straight section at cell 9. Compilation of tables like this helps to identify which parameters fulfil the requirements of the beamline, and which can present issues in the implementation of the new optics.

For example, source sizes and divergences in disagreement with the KPP prescriptions might require a local re-definition of the optics, implying a re-optimisation of the beam dynamics. An example of this strategy is presented in the next section.

Beamline I20

This beamline is constituted by a scanning and a dispersive branch, illuminated by two wigglers. In typical operating mode for I20-scanning (E ≃ 8.7 keV, K_{wig} = 14.8) the wiggle amplitude is about 33 µm. The reduction in the horizontal beam size due to the new lattice (σ_x^{DI} = 134 µm → σ_x^{DII} = 23 µm), becomes then visible as a split source, as seen in Fig. 2 (left) [4]. The issue was analysed by both the AP group and the OM group. Machine-wise we produced a matched lattice with a local alteration of the horizontal beta function, inflated by a factor 2.2, as suggested by the analysis of the phase-space brilliance seen in Fig. 2 (right). The new lattice is shown in Fig. 2 (centre). As expected such change and the consequent breaking of the lattice symmetry, affects the non-linear dynamics of the system, causing drastic reductions both in lifetime (1.04 hr → 0.29 hr) and in injection efficiency (78.6% → 4.6%). An elegant MOGA [5,6] optimisation of the harmonic sextupoles for this lattice is in progress, trying to recover the aforementioned loss.

Analysis of SHADOW [7] simulations conducted by the OM group, reveals that the intrinsic aberrations in one of the beamline focusing mirrors can mitigate the double peak effect by spreading the beam spot in the horizontal plane, relaxing the requirements on β_x discussed before. More detailed results based on SHADOW are shown in the next paragraph.

Table 1: KPPs for beamlines I09 and I13. The colour code refers to the changes due to the implementation of the 6-HMBA lattice in Diamond-II w.r.t. the present set-up. (Green) the change meets the beamline requirements, (amber) the effect of the change needs further evaluation, (red) the change does not meet the requirements of the beamline.

	I09		I13	
KPP	soft X	hard X	coh.	imag.
need HVF?	no	no	yes	no
V mini-β?	no	no	yes	yes
flux at FE	>	>	>	>
σ_x	<	<	<	no request
σ_x'	>	>	< 7 µrad	no request
σ_y	no request	no request	≃	no request
σ_y'	<	<	≃	no request

INTEGRATED APPROACH

As described in the previous sections, the SWG aims at identifying the KPPs for all the beamlines, to facilitate the transition towards a new machine. Past experience shows that an integrated approach with a complete simulation from the electrons generating the synchrotron radiation, to the final sample plane could be a valuable tool for a general optimisation of the system. To this goal we are developing a code, wrapping up the main pacakges commonly used in the Accelerator Physics and in the Synchrotron Radiation and Optics communities. This program, named electron to sample (e2s) is written in Python, and at present is making use of the codes elegant, for the accelerator part, and SRW [8] or SHADOW for the propagation of the photons.

An input file defines the run to be implemented, specifying the lattice to be used, the source position in the storage ring and the parameters defining the ID. The choice between

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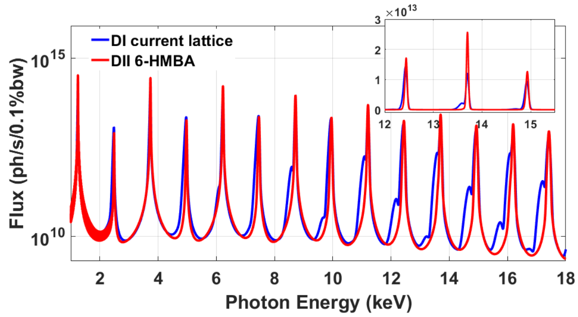

Figure 3: Partial flux at I13-coherence FE (slit of [300,120] μm), showing the increase due to the reduced emittance.

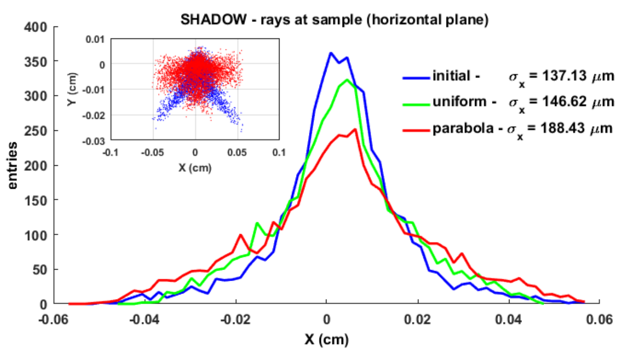

Figure 4: Beam spot horizontal projection at sample from SHADOW ray-tracing calculation for I20-scanning branch. (Blue) initial distribution, beamline optimization with a flat (green) and with a quadratic (red) penalty function (see text). Inset: (X,Y) beamspot at sample for two chosen solutions.

SHADOW and SRW is also defined at this stage. The program starts by launching an elegant session and by calculating the Twiss parameters at the chosen source point. These parameters are then translated into beam sizes and passed to the photon code performing a wave-front propagation in the case of SRW or a ray-tracing calculation in the case of SHADOW.

Partial Fluxes and Tuning Curves

Calculation of partial fluxes through SRW is easily implemented in e2s. Figure 3 shows a comparison between the present lattice and the 6-HMBA case for the I13-coherence branch previously discussed.

Tuning curves are calculated in elegant using the `sddsfluxcurve` method [5], taking into account the non-zero emittance and the beam energy spread through a convolution on the single electron yield.

Beamline Optimization

For the aforementioned case of I20, a Python optimization script was interfaced to e2s whose goal was to level the beam spot at sample as per the beamline request. Using a Nelder-Mead simplex optimization we found a better set of values for the radius of a focusing cylindrical mirror and final position of the sample. The result is summarized in Fig. 4. Two penalty functions were used to weigh the initial photon distribution at sample: a uniform function and a parabola, both zeroed outside a [-200,+200] μm interval. The result of the optimization suggests an improvement in the quality of the photon pattern connected with the parabolic penalty function. This improvement comes with a reduction in the photon flux inside the [-200, +200] μm window, being -6% for the uniform function case and -17% when the parabolic penalty is applied.

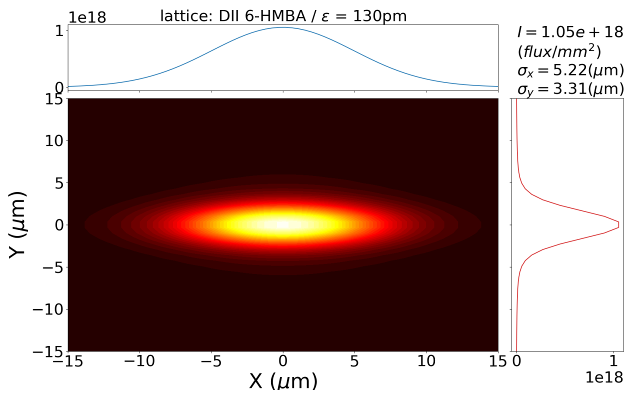

Figure 5: Beam spot intensity at the sample plane of beamline I04.

Table 2: QRM for the I04 beamline. Rows represent the percentage variation of a KPP for a 1% change in a quadrupole family.

	Q_{F1}	Q_{D2}	Q_{D3}	Q_{F4}	Q_{D5}	Q_{F6}	Q_{F8}
$\frac{\Delta I_{ph}}{\Delta Q}$	-0.4	1.9	3.2	-10.1	3.4	-1.2	-3.4
$\frac{\Delta \sigma^x_{ph}}{\Delta Q}$	-0.8	0.4	-0.2	6.3	-0.3	-2.1	0.6

KPP Response to Machine Variations

A well established technique in storage ring control, is the use of response matrices to change a certain status by means of alterations of magnets. Typical cases include the control of the orbit and of the tune. Indeed the interplay between a lattice and the beamlines can be studied by introducing small alterations to, *e.g.*, the storage ring quadrupoles and by recording the variations of some KPPs. Figure 5 shows an intensity plot at the sample plane for beamline I04, where radiation is focused by means of a Kirckpatrick-Baez system.

The beam spot is characterized by its peak intensity I_{ph}, and its spatial standard deviations in the two planes $\sigma^{x,y}_{ph}$. With e2s we calculated the fractional changes of these KPPs for a fractional variation in the quadrupole strength, defining a Quadrupole Response Matrix (QRM) for I04 (as shown in Table 2).

A similar calculation has been done using the Twiss parameters variations at the beamline source point.

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CONCLUSION AND FUTURE WORK

Optimising the photon beam properties in view of a machine upgrade is a complex task, involving a large number of beamlines each with specific requests and concerns. The SWG at Diamond is completing the round of investigations to clarify these aspects. Accelerator Physics and Optics codes are in use to tackle the problem and a code (e2s) merging these two physical aspects is under development. Among the future application of e2s we can anticipate the study of effects of magnet or Twiss parameter variations on beamline KPPs, and a global optimisation of the lattices based on KPP objectives.

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