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IMPACT OF INSERTION DEVICES ON DIAMOND-II LATTICE

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Abstract

DIAMOND-II lattice is based on the ESRF-EBS cell with the central dipole replaced by a (chromatic) mid-straight, and a -I transformer, higher order achromat and dispersion bumps are used to control the nonlinear dynamics. The majority of insertion devices currently in operation in Diamond will be either retained or upgraded as part of the Diamond-II programme, and the new mid-straights allow the total number of ID beamlines to be increased from 28 to 36. Therefore, it is important to investigate how the IDs will affect the emittance, energy spread, linear and nonlinear beam dynamics. The kickmap approach has been used to model all IDs, including the APPLE-II IDs and APPLE-II-Knot with active shim wires. In this paper, the outcome of these investigations will be presented and discussed.

INTRODUCTION

The existing Diamond storage ring contains 28 insertion devices, the majority of which will be either retained or upgraded for Diamond-II [1]. In addition, several new insertion devices are to be installed in the new mid straights, and the RF cavities in straight 17 will be removed creating space for an additional beamline. The effect that these IDs will have on beam injection and lifetime needs to be investigated and suitable solutions must be found to overcome any negative impact. Insertion devices are known to introduce linear and nonlinear perturbations in the machine optics, and significant experience with operating them has been gained from Diamond. The impact of IDs in Diamond-II can be summarised as follows:

- The IDs produce linear tune-shifts. These tune-shifts are proportional to beta functions at the ID location and its length and inversely proportional to square of energy of the ring. The higher energy of Diamond-II (3 to 3.5 GeV) helps to reduce the impact.
- The linear tune-shifts cause beta-beat and break the symmetry of ring. This may excite additional sextupolar resonances and can reduce the dynamic aperture. The beta-beat is proportional to the linear tune-shifts produced by an ID.
- IDs also introduce octupole-like nonlinear magnetic fields. These can excite 4^{th} order resonances (4Qx, 4Qy, 2Qx±2Qy) and alter the amplitude-dependant tune-shifts, potentially driving the working point to dangerous resonances.
- Planar insertion devices produce linear and nonlinear tune-shifts only in the vertical plane whereas helical undulators can affect both planes.

IDs will change beam parameters such as energy spread, emittance, damping times and energy loss per turn. The impact on the emittance is particularly significant for high-field wigglers and IDs located in dispersive straights. Whereas wigglers in dispersion-free straights will tend to reduce the emittance, IDs in dispersive straights can cause an increase. Overall, the insertion devices in Diamond-II will reduce the emittance but increase the energy loss per turn and energy spread. Damping times are also reduced by the introduction of the IDs, which has a positive benefit both for helping to damp instabilities and to reduce the effects from intra-beam scattering.

When modelling the nonlinear effects of insertion devices, a kick-map approach has been used [2]. Kickmaps for all the Diamond-II IDs have been produced using RADIA [3], in formats for use in ELEGANT [4] and AT [5]. In all other cases, the standard linear model including radiation effects has been used.

ID COMPENSATION STRATEGY

A variety of methods exist to compensate for the effects of insertion devices. Typically, the optics perturbation is compensated by adjusting the local quadrupoles using alpha-matching with global tune correction [6] or a global optics correction using LOCO [7]. Alternatively, for more complex devices such as APPLE-II or APPLE-II KNOT insertion devices, active shim wires can be used [8, 9]. For each case, care must be taken that the combination of ID plus correction scheme does not break any of the phase advance constraints required for the -I transformation, Higher Order Achromat (HOA) and 24-fold symmetry used during optimization of the lattice optics. The choice of which correction scheme to employ depends both on the ID type and on its location.

A global tune correction has been found to be sufficient for the weak to moderate strength planar undulators such as the HPMUs or CPMUs. For high-field devices such as the super-conducting wigglers (SCW) or helical undulators such as the APPLE IDs, a local feed-forward optics correction scheme will be required. Detailed studies of the different types of ID have been conducted, the results of which are summarised in the following sections.

IDs IN MID-STRAIGHTS

The mid-straights all have moderate dispersion and so IDs located here will increase the emittance by an amount that depends on their magnetic field. The equilibrium energy spread will also be affected. Figure 1 shows how an insertion device in a mid-straight affects the main lattice parameters. In particular, the emittance grows

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rapidly for fields above 1.5 T. The peak field for IDs in mid-straights has therefore been limited to this value.

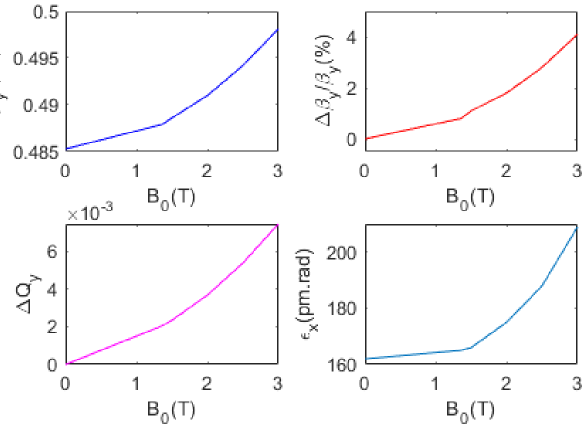

Figure 1: Impact on machine optics for a 1.5 m long, 17.7 mm period CPMU in a mid-straight location. Top left: variation of the '-I' condition between the chromatic sextupoles, top right: induced beta-beat, bottom left: change in ring tune, bottom right: variation in emittance.

An initial concern about placing IDs in the mid-straights was that the changing gap or field strength would alter the phase advance between the chromatic sextupoles and break the -I transformer conditions. However, since the tune-shifts due to the IDs are small, this was found to have only a minor impact on the dynamic aperture and active correction is not necessary. In fact, since the cells are tuned to slightly below 3 π and π phase advance, closing the planar IDs was found to be beneficial. In contrast to the planar devices, the APPLE-II undulators cause a further detuning in the horizontal plane. Overall, the impact of the mid-straight IDs has been found to be minimal. These IDs are generally relatively low-field devices, have relatively few periods and are located where the beta-functions are small. A comparison between the on-momentum dynamic and momentum apertures with and without the mid-straight IDs over 20 seeds of 'reduced' errors is shown in Fig. 2. Details of the reduced errors can be found in [1].

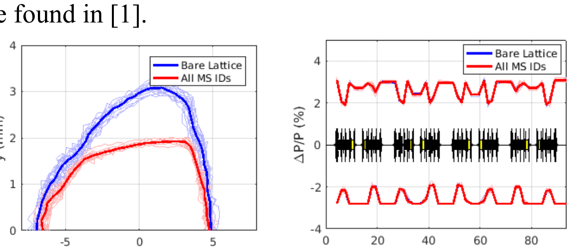

Figure 2: Dynamic aperture (left) and momentum aperture (right) for the case of with and without mid-straight IDs over 20 seeds of the reduced error. The dynamic apertures are calculated at the centre of the long straight, with Twiss parameters as given in [1].

IDs IN STANDARD STRIGHTS

The highest-field IDs in the standard straights are the two super-conducting wigglers (SCW) I12 (4.2 T) and I15 (3.5 T). As can be expected, these generate the largest linear tune-shifts and beta-beat of all the installed IDs. This beta-beat can in principle be corrected either using alpha-matching and a global tune correction or using LOCO. Although alpha-matching was found to suppress the beta-beat in the majority of the ring, the phase advance in the region close to the ID was altered such that the cell symmetry and higher-order achromat phase conditions were broken. Correction using LOCO was found to restore the correct phase advance to a higher degree, improving the lifetime compared to alpha-matching. The next most significant devices in the standard straights are the APPLE-II IDs. These can be operated in different polarization modes such as circular, vertical, horizontal or inclined. To investigate how operating the IDs in the different modes affects operations, separate kickmaps for each mode have been generated. As with the wigglers, LOCO correction for these IDs was found to restore the machine optics better than alpha-matching resulting in a longer lifetime.

IDs IN LONG STRAIGHTS

Of the six long straights in Diamond-II, five of them will be used for IDs. Straight I05 currently has an APPLE-II ID with active shim wires for optics correction [8, 9]. The active shims will be retained for Diamond-II, but the ID will be replaced with an APPLE-II KNOT device. Straights 9 and 13 previously contained additional quadrupoles to provide double mini-beta optics and space for two canted IDs [10]. Due to space constraints the mini-beta optics will not be included in Diamond-II, however, the IDs and chicanes will remain. Straights 17 and 21 will contain APPLE-II IDs. As with the mid and standard straight IDs, a study of how well the different correction schemes compensate for the long straight IDs was conducted. LOCO correction was again found to out-perform alpha-matching. Using active shim wires was found to be beneficial for correcting the I05 device, reducing the tune shifts and beta-beat. Active shim wires for I17 and I21 were also found to reduce the optics distortions in simulation, however, a decision has not yet been reached on whether to implement these in practice. As such, final ID studies have been conducted assuming purely a LOCO-based compensation has been applied for all devices other than I05 which contains active shims.

IMPACT OF ALL IDs

The impact of the IDs on the lattice and beam parameters before optics correction is summarised in Table 1 and broken down into the different types of straight section and in combination. This data was calculated assuming the IDs are all at maximum strength and in the most disruptive polarisation state for the helical undulators.

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Table 1: Impact of IDs on Emittance and Energy Spread

IDs Straight	ε_x [pm.rad]	σ_E [%]	$\Delta\beta_{x,y}/\beta_{x,y}$ [%]	$\Delta Q_{x,y}$
Mid	178	0.092	0.0,1.3	0.00,0.01
Standard	115	0.115	8,19.4	-.01,0.07
Long	145	0.090	28,11	-.03,0.03
All	121	0.109	24.3,19.7	-.04,0.11
Bare	162	0.094	-	-

The beta-beat before and after optics correction is shown in Fig. 3 and the corresponding frequency map and tune shifts with amplitude and energy are shown in Figs. 4 and 5 respectively. The 6D dynamic and momentum apertures including RF and radiation damping over 20 reduced error seeds [1] are shown in Fig. 6. All results presented in this paper have been produced using AT.

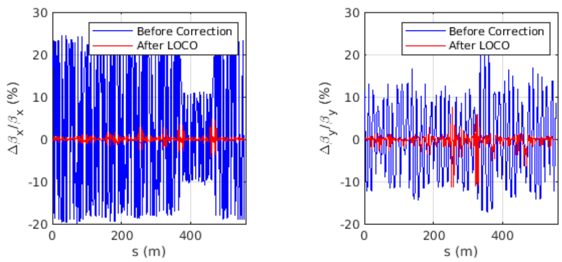

Figure 3: Horizontal (left) and vertical (right) beta-beat with all IDs before and after optics correction. Some optics distortions remain close to the SCWs in I12 and I15 and around the APPLE-II IDs in I17 and I21.

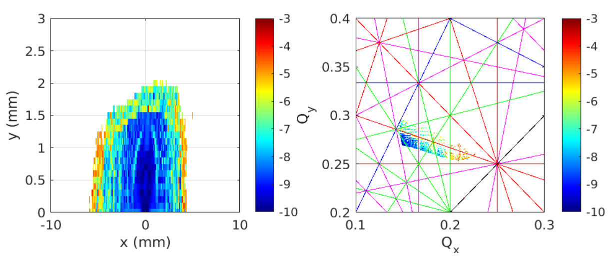

Figure 4: Dynamic aperture and frequency map for the ideal lattice including all IDs after optics correction with LOCO. The dynamic aperture is calculated at the centre of the long straight.

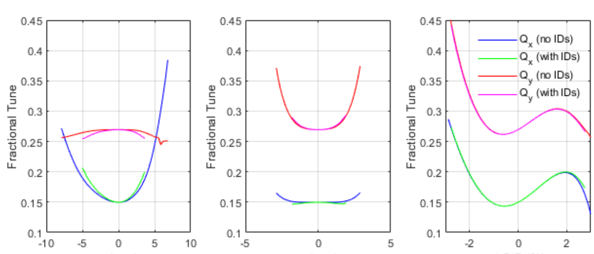

Figure 5: Tune shift with amplitude and energy, with and without IDs calculated at the centre of the long straight.

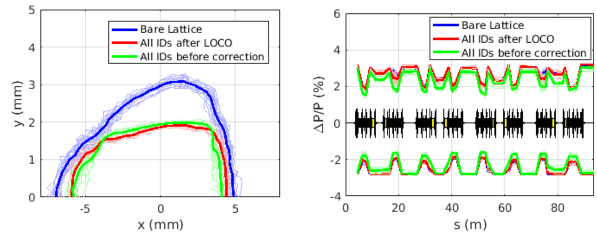

Figure 6: Dynamic aperture (6D) (left) and momentum aperture (right) including all IDs before and after optics correction using LOCO for 20 reduced error seeds. The bare lattice results are also shown for reference. The dynamic apertures are calculated at the centre of the long straight.

The Touschek lifetime has been calculated using 20 seeds of the reduced errors with the RF voltage adjusted to maximise the lifetime. The vertical emittance has been fixed at 8 pm rad, the bunch charge is 0.6 nC and the natural bunch length of 3.6 mm has been assumed. The injection efficiency has been calculated for 1000 particles, 2500 turns and 4 mm injection offset. These simulations have been carried out with all IDs after an optics correction with LOCO and for the bare lattice (without IDs) in presence of all apertures. These results are shown in Table 2. More details can be found in [1].

Table 2: Impact of IDs on Touschek Lifetime and Inj.Eff.

Case	Touschek lifetime [h]	Inj. Eff. (%)
All IDs with LOCO correction	2.10±0.03	99.15 ± 0.13
Bare (No IDs)	2.18 ± 0.02	99.99 ± 0.02

CONCLUSIONS

The impact of IDs on the Diamond-II lattice can be reduced to an acceptable level if LOCO is used to restore the linear optics. Alpha-matching could also be employed to correct the linear optics locally for the high field IDs, however, the lifetime is then significantly degraded due to the impact on the local phase advance constraints.

One strategy for applying the LOCO correction would be to correct for the super conducting wigglers only, neglecting the other IDs at this stage. This method causes a 10% degradation of lifetime and 5% drop in injection efficiency compared to if LOCO is used with all IDs in their final configuration. Alternative correction strategies for the IDs are still being considered. However, the evidence found in these studies is that the lifetime can be restored to close to the ideal values by correcting optics using LOCO, compared to a factor 2 reduction in lifetime if no correction is applied.

REFERENCES

[1] "Diamond-II Technical Design Report", Diamond Light Source, to be published, `https://www.diamond.ac.uk/Home/About/Vision/Diamond-II.html`

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[2] P. Elleaume, "A New Approach to the Electron Beam Dynamics in Undulators and Wigglers", in *Proc. EPAC'92*, Berlin, Germany, Mar. 1992, pp. 661-664.

[3] P. Elleaume, O. Chubar, and J. Chavanne, "Computing 3D Magnetic Fields from Insertion Devices", in *Proc. PAC'97*, Vancouver, Canada, May 1997, paper 9P027

[4] M. Borland,"elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation", Advanced Photon Source LS-287, Sep. 2000.

[5] A. Terebilo, "Accelerator toolbox for MATLAB", No. SLAC-PUB-8732, Stanford Linear Accelerator Centre, Menlo Park, CA, USA, 2001.

[6] J. Galayda and A. M. Fauchet, "Operation of Synchrotron Light Sources with Insertion Devices", ANL/CP-73326, Dec 1991.

[7] J. Safranek, "Experimental Determination of Storage Ring Optics using Orbit Response Measurements", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 388, pp. 27-36, 1997. doi:10.1016/S0168-9002(97)00309-4

[8] J. Bahrdt, W. Frentrup, A. Gaupp, M. Scheer, and G. Wuestefeld, "Active Shimming of the Dynamic Multipoles of the BESSY UE112 APPLE Undulator", in *Proc. EPAC'08*, Genoa, Italy, Jun. 2008, paper WEPC097, pp. 2222-2224.

[9] B. Singh et al., "Active Shimming of Dynamic Multipoles of an APPLE II Undulator in the Diamond Storage Ring", in *Proc. IPAC'13*, Shanghai, China, May 2013, paper TUPWO057, pp. 1997-1999.

[10] B. Singh, R. T. Fielder, I. P. S. Martin, G. Rehm, and R. Bartolini, "Implementation of Double Mini-beta Optics at the Diamond Light Source", in *Proc. IPAC'11*, San Sebastian, Spain, Sep. 2011, paper WEPC042, pp. 2103-2105.