INSERTION DEVICES AT DIAMOND LIGHT SOURCE: A RETROSPECTIVE PLUS FUTURE DEVELOPMENTS

Z. Patel, E. C. M. Rial, A. George, S. Milward, A. J. Rose, R. P. Walker, and J. H. Williams
Diamond Light Source, Didcot, UK

Abstract

2017 marks the tenth year of Diamond operation, during which time all insertion device straights have been filled. Diamond Light Source is a third generation, 3 GeV facility that boasts 29 installed insertion devices. Most room temperature devices have been designed, manufactured and measured in-house, and progress has been made in structure design and control systems to ensure new devices continue to meet stringent requirements placed upon them. The 'completion' of the storage ring is not, however, the end of activity for the ID group at Diamond, as beamlines map out potential upgrade paths to Cryogenic Permanent Magnet Undulators (CPMUs) and SuperConducting Undulators (SCUs). This paper traces the progress of ID design at Diamond, and maps out future projects such as the upgrade to CPMUs and the challenges of designing a fixed-gap mini-wiggler to replace a sextupole in the main storage ring lattice.

INTRODUCTION

Diamond's initial design had 24 straight sections, split into 18 short low-β ($\beta_y \approx 1.5$ m) and 4 long high-β ($\beta_y \approx 5.8$ m) straights, with the remaining two straights devoted to injection and RF cavities. Phase I of Diamond consisted of the first seven devices for seven beamlines installed for the initial commissioning of the facility in 2007 [1]. Phase II saw the installation of a further sixteen devices over the period 2007 – 2013. The most recent phase of construction of Diamond culminates in Phase III, with the final six IDs rounding out the storage ring; 3 IVUs and 3 APPLE-IIs.

PHASE I

Phase I saw the installation of seven insertion devices: five in-vacuum pure permanent magnet undulators (IVUs), one APPLE-II undulator, and a superconducting wiggler (SCW). Details of these devices are listed in Table 1. The wiggler was designed and constructed by the Budker Institute of Nuclear Physics (BINP). The measurement of five of the devices was carried out at DLS using a 5.5 m three-axis Hall probe bench and flipping coil supplied by the European Synchrotron Radiation Facility (ESRF). The devices were shimmed to optimise performance at 5 mm and 7 mm gaps. While the initial operation of the IVUs was at a 7 mm gap [1], these (and all other 2 m IVUs) are now routinely operated at 5 mm during top-up operation, and have been since late 2008.

Table 1: Installed IDs for Phase I of DLS. Peak field is given for IVU devices at 5 mm gap and I06 at 15 mm gap.

Beam -line	ID type	Period [mm]	No. of Periods	Peak Field [T]
I02	IVU	23	85	0.92
I03	IVU	21	94	0.86
I04	IVU	23	85	0.92
I06a	APPLE-II	64	33	1.10
I15	SCW	60	22.5	3.5
I16	IVU	27	73	0.98
I18	IVU	27	73	0.98

PHASE II

Diamond began to innovate its own designs during Phase II. Although the first five devices installed during Phase II at Diamond were IVUs of periods 21 mm - 25 mm, and were a continuation of the design of the Phase I devices, extra constraints were being placed on future IDs that meant that the original structures were no longer suitable. The next three IDs included a 730 mm Ex-Vacuum Undulator (EVU), a 781 mm Hybrid Wiggler (HW), and a 2 m HW. The existing structure was too large to fit in the space constraints of the short devices, and not stiff enough for the 2 Tesla wigglers, as magnet loads increased from 16 kN/m for a regular IVU to 55 kN/m for the wigglers. The solution was to move to a single column design that would both fit into the constrained space of the short devices, and was stiff enough to support a 2 m long HW. The final design would see a maximum deflection along the magnet beam of 40 μm at minimum gap that did not affect the performance of the wigglers or the EVU. Some other issues overcome with the new single column structure included:

- Elimination of tapering due to a single axis driving the magnet beams
- Moved the encoders away from the electron beam axis to overcome radiation problems
- Increased the adjustability of magnet beams and allowed for their independent removal
- Improved adjustment of structure in the storage ring

There was also a move to separate the motion control system from the protection system. Potentiometers were installed to mirror the absolute encoders on the IDs to provide a robust gap measurement for the protector system, even if the motion control encoders failed as they were known to do following beam dumps.

Following the success of the single column structure for I04-1, I20, and J20, the design was used for the next APPLE-II devices to be installed in Diamond for the I10 beamline BLADE.

The requirements of the I10 beamline included greater independent control of the four quadrants of the ID, to allow linear polarisations to be tilted through 180° and full access to elliptical polarisations. A ‘master-and-slave’ relationship on each beam allows energy scans to be taken at circular polarisations by moving the master phase axes. This was to simplify the control system and provide smoother energy changes at circular polarisations for the beamline [2]. The I10 beamline was designed to offer 10 Hz polarisation switching through the use of a 5-magnet chicane, and as a fall-back, the IDs themselves are able to oscillate at 2 Hz.

The single column structures were successful in overcoming taper in Phase I devices, however, it was impossible to correct parallelism errors. Parallelism was not critical to the wigglers, the short EVU, or even the APPLE-II devices of I10, but the impact on phase error for longer IVU devices prompted a return to a two column design. Some phase III devices would be up to 5 m long, which would be difficult to support with a single central point.

Two of the Phase II beamlines, I13 and I09, took advantage of the long straights available to them by building two branches. A modification was made to the straights to reduce the β-function from $\beta_y \approx 5.8$ m to two shorter straights with β-functions of $\beta_y \approx 1.05$ m and $\beta_y \approx 1.35$ m, to maximise the brilliance of the sources [3]. This allowed two smaller gap IVU devices to be installed for I13, and an IVU and an APPLE-II to be installed for I09.

Phase II also saw the installation of a CPMU from Danfysik [4] and a second high field SCW from the BINP. The installation of the CPMU for I07 released a ‘spare’ 23 mm period IVU for use as a temporary source in I13. Details of phase II IDs are shown in Table 2.

Table 2: Installed IDs for Phase II of DLS. Peak field is given at minimum gap. For the APPLE-II devices this is 16 mm, except I06b which is 15 mm. The minimum gap of 104.1 and I20 is 11 mm and J20 is 15 mm. The minimum gaps of the IVUs range from 5 mm to 6.15 mm.

Beam -line	ID type	Period [mm]	No. of Periods	Peak Field [T]
I04.1	EVU	30.8	21	0.75
I06b	APPLE-II	64	33	1.00
I07	CPMU	17.7	114.5	1.20
I09	IVU	27	74.5	0.96
I09	APPLE-II	60	41.5	0.90
I10	APPLE-II	48	2x40.5	0.77
I11	IVU	22	89	0.89
I12	SCW	48	23.5	4.2
I13	IVU	22	91	0.94
J13	IVU	25	108.5	0.80
I19	IVU	21	94.5	0.86
I20	HW	83	23.5	1.90
J20	HW	83	8.5	1.53
I22	IVU	25	79.5	0.97
I24	IVU	21	95	0.86

PHASE III

Table 3: Installed IDs for Phase III of DLS. Peak field for the IVU devices is given at 5 mm gap. I05 is given at 23.5 mm and I08 and I21 are given at 16 mm gap.

Beam -line	ID type	Period [mm]	No. of Periods	Peak Field [T]
J02	IVU	21	95.5	0.80
I05	APPLE-II	140	35.5	0.80
I08	APPLE-II	50	84.5	0.84
I14	IVU	23	85	0.92
I21	APPLE-II	56	84.5	0.84
I23	IVU	27	75	0.95

The success of the structures designed at DLS paved the way for five new devices to be constructed for Phase III. I05, a 5 m long 140 mm period APPLE-II to feed the ARPES beamline [5], was the first challenge. In order to shift the higher harmonics of the device away from multiples of the fundamental energy, several horizontal magnets of the Halbach array were offset to produce a quasi-periodic array.

During Phase III the ‘spare’ ID was liberated from I13 when I13’s specified ID was installed, providing an opportunity to investigate what, if any, adverse effects there had been on the ID after eight years of operation. Although some burn marks were visible on the CuNi foil, nothing particularly alarming was seen. The ID was remeasured to see if there had been any impact on performance, with no difference found. The ‘spare’ ID has since been installed as a source for I14 until the final device for that beamline is constructed.

Phase III also saw the installation of a Double Double Bend Achromat (DDBA) upgrade to the storage ring [6], which created another straight capable of taking an ID installation. This 2 m long 21 mm period IVU was installed in March 2017. Details of phase III devices are given in Table 3.

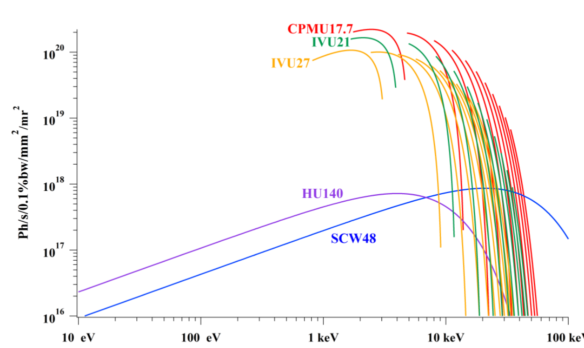

Figure 1: Brilliance vs. energy of installed IDs: IVU21, IVU27, CPMU17.7, and SCW48. To increase the photon flux to the beamlines, CPMU upgrades are on-going.

ISBN 978-3-95450-182-3

CURRENT STATUS

At present Diamond boasts 16 IVUs, 1 EVU, 8 APPLE-IIs, 1 CPMU, 2 Hybrid Wigglers and 2 SCWs serving 25 different beamlines from energies of 18 eV to 150 keV. The brilliance of several installed IDs is compared in Fig. 1. This shows the improvement in the photon flux of a CPMU compared to an IVU. The final Phase III device to be built will be a fixed gap wiggler to feed the DIAD beamline, discussed below. The ID group is focussing its efforts on a CPMU design, also described below.

DIAD

The Dual Imaging and Diffraction Beamline (DIAD) at DLS is intended to operate from 7-38 keV. As all straight sections of the DLS storage ring are now occupied, the intention is to remove a sextupole magnet upstream of the bending magnet originally made available for a beamline in this position, and replace it with a short 700 mm length fixed-gap wiggler, illustrated in Fig. 2. The DIAD wiggler will have a 116 mm period and a peak field of 1.56 T.

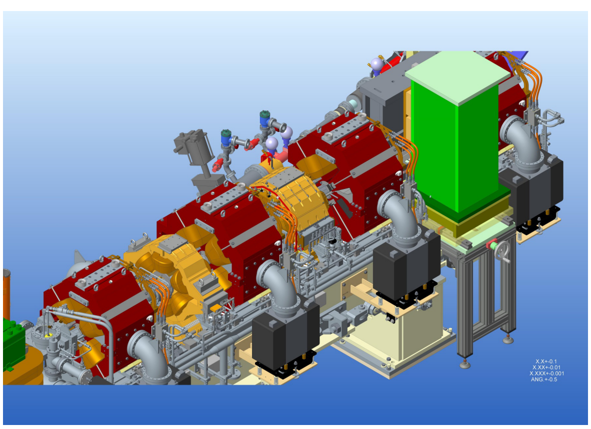

Figure 2: Model of the DIAD wiggler in place of a sextupole magnet. As there is no space available to widen the gap of the device it has been designed to be able to slide out of the electron beamline.

THE CPMU PROJECT

The construction of two in-house designed CPMUs is currently under way for beamlines I03 and I24. Both devices will have a 17.6 mm period, giving a peak field of 1.2 T; slightly higher than the peak field of these beamlines' existing devices, but more importantly will deliver a greater number of photons, as shown in Fig. 3.

The proposed structure design is based on the existing IVU devices installed at Diamond. The magnet design is that of a hybrid configuration containing NdPrFeB permanent magnets and iron poles. These will be cooled using a closed-loop liquid nitrogen cooler to an operating point at 80 K.

A number of challenges arise from designing, constructing, and measuring a CPMU. For instance, standard IVUs use a Cu/Ni foil to reduce wakefields and image current in

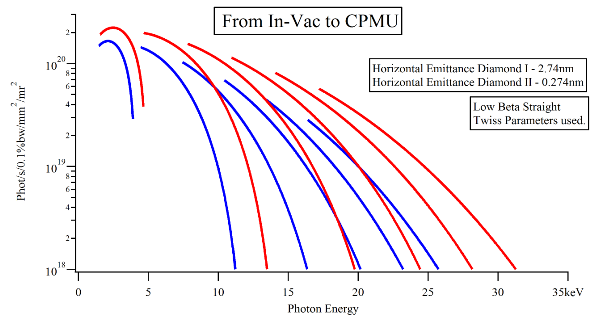

Figure 3: Brilliance plot of I03's existing structure (IVU21) and the proposed CPMU (CPMU17.6) replacement.

the devices. However, due to the differences in Al and Cu/Ni thermal contraction, an aluminium foil will be used.

There are also more stringent requirements placed on the design compared to a standard IVU device, arising from the increased forces on the structure, and obtaining and keeping a uniform and stable temperature.

The CPMU will be measured when cold to assess how the thermal contraction of the aluminium beams and stainless steel support columns impact the magnetic performance of the ID. If necessary, the columns will be shimmed to correct phase errors arising due to inhomogeneous thermal contraction. In order to measure the device cold, a new in-vacuum measurement bench is being designed that includes a Hall probe and a stretched wire.

SUMMARY

With all the straight sections of Diamond filled with insertion devices, the way forward is now through upgrading existing beamlines to CPMUs/SuperConducting Undulators (SCUs). Progress with CPMUs is more advanced than with SCUs, therefore the focus of the insertion device group is to build and install CPMUs to replace IVUs. Several challenges, such as building a new in-vacuum measurement bench must be met in order to achieve this.

REFERENCES

[1] E. C. Longhi, R. T. Fielder, I. P. S. Martin, J. C. Schouten, B. Singh, and R. Bartolini, "First Year's Experience of Diamond Insertion Devices", in *EPAC'08*, Genoa, Italy, 2008, paper WEPC119, p. 2285

[2] E. C. Longhi *et. al.*,"Developments in Polarization and Energy Control of APPLE-II Undulators at Diamond Light Source" Journal of Physics: Conference Series 425, Part 3, 2013, 032011

[3] B. Singh *et. al.*, "Double Mini-Beta Y Plus Virtual Focussing Optics For Diamond Storage Ring", in *PAC'09*, Vancouver, BC, Canada, 2009, paper TH6PFP033, p. 3772

[4] C. W. Ostenfeld, and M. Pedersen, "Cryogenic In-Vacuum Undulator at Danfysik", in *IPAC'10*, Kyoto, Japan, 2010, paper WEPD006, p. 3093

[5] M. Hoesch *et. al.*, "A facility for the analysis of the electronic structures of solids and their surfaces by synchrotron radiation photoelectron spectroscopy", *Review of Scientific Instruments*, vol. 88, no. 1, p. 013106, 2017

[6] R. P. Walker *et. al.*, "The Double-Double Bend Achromat (DDBA) Lattice Modification For The Diamond Storage Ring", in *IPAC'14*, Dresden, Germany, 2014, paper MOPRO103, p. 331

ISBN 978-3-95450-182-3