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THE CRYOGENIC UNDULATOR UPGRADE PROGRAMME AT DIAMOND LIGHT SOURCE

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Abstract

Diamond Light Source has installed four 2 m long, 17.6 mm period Cryogenic Permanent Magnet Undulators (CPMUs) as upgrades for crystallography beamlines since 2020, with two more planned within the next year. The CPMUs provide 2 - 3 times more brightness and 2 - 4 times more flux than the pure permanent magnet (PPM) devices they are replacing. They have been designed, built, and measured in-house. All four have a 4 mm minimum operating gap and are almost identical in their construction: the main difference being an increase in the number of in-vacuum magnet beam support points from four to five, between CPMU-1 and CPMUs 2 - 4, to better facilitate shimming, particularly at cold temperatures. The ability to shim at cryogenic temperatures necessitated the development of an in-vacuum measurement system. The details of the measurement system will be presented alongside the mechanical and cryogenic design of the undulators, including issues with the magnet foils, and the shimming procedures and tools used to reach the tight magnetic specifications at room temperature and at 77 K.

INTRODUCTION

Diamond Light Source has 24 straight sections, all of which are filled. With the exception of creating new straight sections, as with the installation of a DDBA cell [1], or replacing a sextupole magnet with a short wiggler [2], upgrading of existing insertion devices is the next major step in improving the existing machine for the beamlines.

CPMUs have become an attractive prospect as insertion devices since the manufacture of praseodymium material magnets. The remanence of PrFeB and PrNdFeB magnets increases when cooled to the cryogenic temperature of liquid nitrogen (77 K), unlike NdFeB magnets which undergo spin reorientation at 150 K [3]. Therefore, cryogenic cooling allows for a shorter period device while achieving the same, or stronger, magnetic field. An increase in the number of magnetic periods of an insertion device over the same length results in an increase in the radiation flux and brightness for the beamlines. Four in-house designed, built, and measured CPMUs have been installed at Diamond Light Source over the three years 2020 - 2022, with one new CPMU planned for installation this year, and two to be re-worked to overcome an issue with the magnet beam foil discussed later in this paper.

MAGNETIC AND MECHANICAL DESIGN

The magnetic design was developed to increase the brightness and flux of several of the Diamond crystallography beamlines (I03, I04, I11, I24, and VMXm). The design was modelled in Radia [4] using PrNdFeB magnets and vanadium permendur pole pieces, the details of which can be found in [5]. A 17.6 mm period was used for all CPMUs, chosen to cover a suitable x-ray energy range (5 - 30 keV) for the beamlines using the existing Diamond ring and the proposed Diamond-II ring.

The mechanical structure is based on the Diamond third-generation in-vacuum undulator (IVU) structure [6], shown in Fig. 1. Two out-of-vacuum beams move vertically along the two main columns of the structure by way of slides on linear guide rails. Two in-vacuum magnet girders, populated with magnets and poles, are attached to the beams by columns. A 100 µm CuNi foil is placed over the magnets and poles and attached by spring tensioners at the ends of the girders in order to reduce the wakefields produced by the electron beam as it traverses the undulator [7].

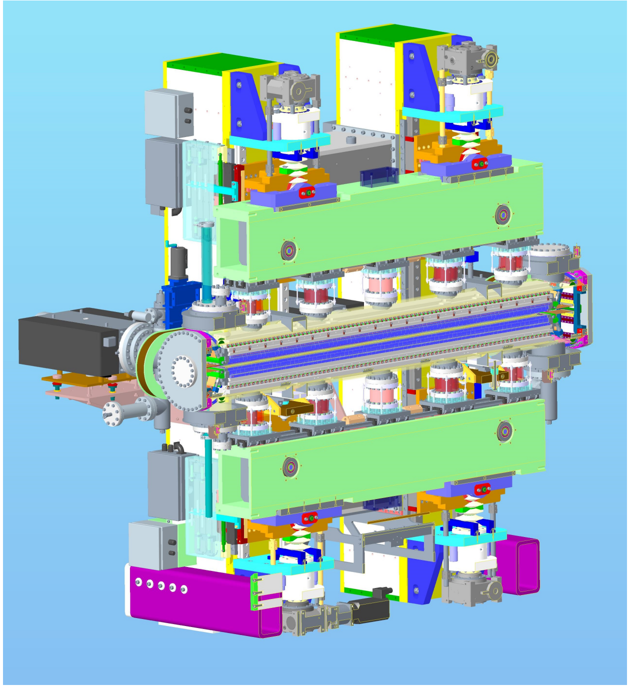

Figure 1: Model of CPMU-3 with the vacuum chamber cut away. The beams are light green with the bellows of the columns shown in red.

Cooling pipes are welded to the magnet beams in order to cool the magnets using a recirculating LN_2 cryocooler, supplied by FMB Oxford. The CPMUs typically reach 77 K

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(LN_2 temperature) within 6 to 7 hours, with the cold mass acting as a cryo-pump. There is an 8 mm reduction in the length of the aluminium girders due to contraction upon cooling which is why the columns are mounted on slides. There is also a ~30% increase in force on the CPMU structure compared to a standard IVU, from 16 kN to 21 kN at a 4 mm gap, due to the increased magnet force when the magnets are cooled. Finite Element Analysis (FEA) in ANSYS [8] showed the standard structure was capable of withstanding the increased forces.

The motion control of the CPMU structure is the same as standard in-vacuum devices: 4 independent axes each with a linear encoder. CPMUs 1-3 use a Delta Tau Geo brick motion controller whereas CPMU-4 uses the newer Omron CK3M controller due to obsolescence of the former. The gap can be varied from 4 mm to 29 mm as well as tilt, taper, and individual axis and girder movements.

Design Evolution

The original builds of CPMU-1 and CPMU-2 were made with triplet (pole-magnet-pole), shown in Fig 2, and singlet (magnet) holders. These CPMU builds progressed to magnetic measurements, at which stage it was discovered that the holders did not retain the positions of the poles well enough. There was also an issue with the cold measurement system Hall probe beam deforming at cold temperatures at the same time. Therefore, the holder design was simplified to a doublet (magnet-pole) to simplify the pole clamping, and made 30% narrower to allow more room in the vacuum chamber for a thicker Hall probe beam. The doublet holder design has been used for all in-house built CPMUs at Diamond.

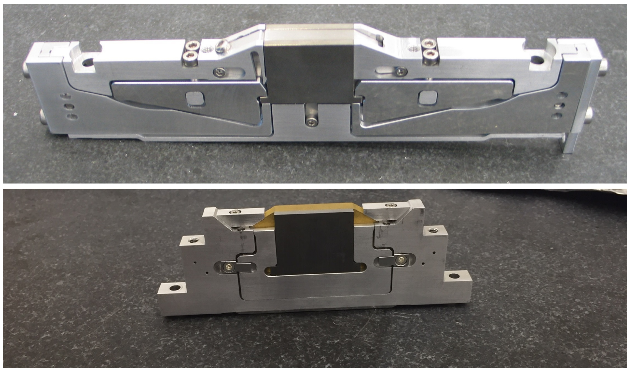

Figure 2: Above: The triplet holder initially used for CPMUs 1 and 2. Below: The doublet holder used for CPMUs 1-5.

The first CPMU had only 4 columns. Upon cooling the CPMU it was found that four columns was too few to correct the device satisfactorily. Following some FEA work, the number of columns was increased to five for the subsequent CPMUs. The addition of further columns had diminishing returns in reducing the girder deformation. Using an odd number of columns also meant that the centre columns could be fixed and the girders would contract equally around the centre columns upon cooling, rather than the unequal contraction around the off-centre fixed columns of CPMU-1.

MAGNETIC ASSEMBLY AND SHIMMING

Opt ID [9] is used to sort the magnets based on Helmholtz coil measured data. The magnetic assembly procedure has evolved during the last five CPMUs and has now been simplified to: assembling the magnets and poles onto the girders with nominal shim, measuring the heights and adjusting the shim until both magnets and poles are within ±20 μm tolerance (typically less than ±10 μm is achieved). This is the procedure CPMU-5 has recently undergone, where room temperature shimming has proved successful. CPMUs 1 - 4 were assembled in magnet-only configuration with the assumption that correcting a magnet-only device would leave minimal pole correction needed. However, it was found that pole height is the dominating factor in magnetic errors of the device, and any errors in the magnets are easily compensated by pole height and tilt corrections.

Once assembled, the CPMU is aligned to the out-of-vacuum measurement bench, consisting of a Hall probe and flipping coil. Column shimming is first performed to straighten the long-range undulation of the peak magnetic field, B_p. In-situ pole shimming is then used to reduce local errors in B_p, reducing trajectory and phase errors; the two main figures of merit for undulator performance. Pole height and tilt can be adjusted in micron steps, limited to a maximum of 50 μm to avoid large step changes in height which can cause ripples on the CuNi foil, causing impedance to the beam, and to avoid large peak-to-peak deviations in the field, causing an increase in the local phase error. The final magnetic correction at room temperature is made with the addition of magic finger magnets, placed at the ends of the girders, to reduce field integrals and, therefore, the impact of the undulator on the storage ring.

COLD MEASUREMENT SYSTEM

Once the shimming of the CPMU at the out-of-vacuum bench is complete, the magnet girders are installed in the vacuum chamber, along with the cold in-vacuum measurement system in order to measure and shim the CPMU while cold. As discussed earlier, when the CPMU cools down to 77 K the force between the two magnet girders increases. This causes deflection of the unconstrained sections of the girders (between the column positions), which can be corrected for using column shimming. The cold measurement system consists of a Hall probe and stretched wire for field mapping and field integral measurements respectively. The Hall probe has evolved from Arepoc and PT100 sensors mounted on 4 mm thick ceramic (CPMUs 1 - 3), to a SENIS S-type probe in a 4 mm thick epoxy glass holder (CPMU-4), to the same SENIS probe mounted on a 1 mm thick epoxy glass holder (to be used for CPMU-5), in order to take measurements at smaller gaps. The Hall probe experiences a 35 - 40° temperature drop during the 45 minute Hall scan, therefore it was necessary to calibrate the voltage sensitivity with temperature. More details on the Hall probes and temperature calibration may be found in [10].

The Hall probe is mounted on a carriage that moves along an aluminium beam on rails, driven by a pulley system coupled to an out-of-vacuum motor, shown in Fig. 3. The longitudinal position of the Hall probe is measured with a Renishaw laser tracker. The sag of the aluminium beam is measured by a Leica laser tracker and a compensation table is applied to the Geo brick motor controller to move the beam vertically to compensate the sag as the probe travels the length of the CPMU.

The RMS phase errors of the CPMUs increase at cold temperatures due to the girder deformation, as shown in table 1. Column shimming is performed to reduce the phase error to the required value.

Table 1: RMS phase errors of CPMUs 1 - 5 measured using the out-of-vacuum measurement bench at room temperature and the in-vacuum measurement system upon initial cooling to 77 K, and the final value at 77 K after column shimming.

CPMU Name	**RMS phase error [deg.] at 5 mm gap**		
	@296K	**Initial@77K**	**Final@7K**
CPMU-1	2.1	8.2	4.6
CPMU-2	2.3	7.5	3.7
CPMU-3	1.8	6.6	3.2
CPMU-4	2.1	10.3	3.2
CPMU-5	2.0	*to be measured*	
CPMU-1*	2.1	*to be measured*	

*reworked

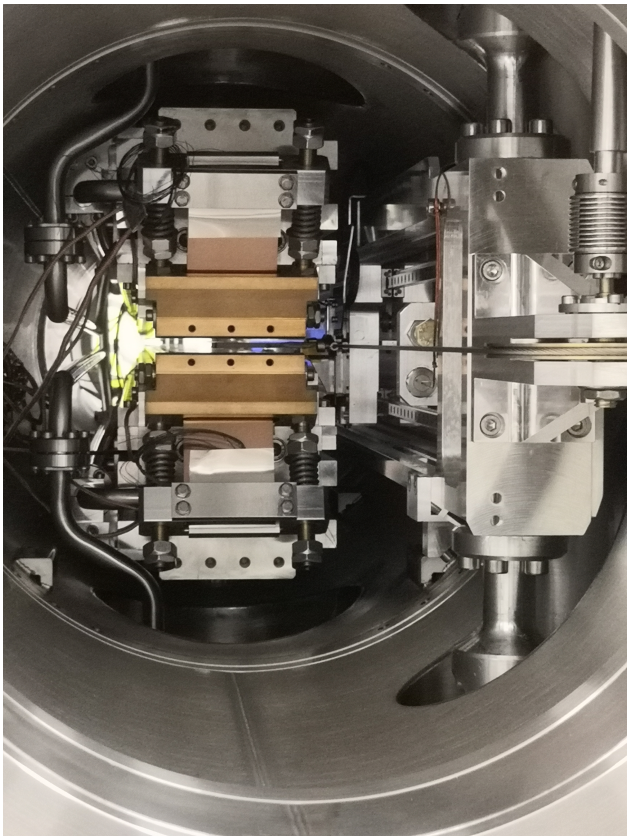

Figure 3: The cold measurement system Hall probe beam installed in the vacuum chamber alongside CPMU-1. The pulley system with its coupling to the out-of-vacuum motor is visible on the right. On the left the LN_2 pipes can be seen.

INSTALLED PERFORMANCE

Upon installation, beam-based alignment is performed as with a standard IVU [11]. Energy scans, using the beamlines' double crystal monochromators, show that the flux has increased on all beamlines that have been upgraded by CPMUs. At the main energy of interest, 12.6 keV, the flux has increased by a factor of two on average. The flux gain is greater still for the higher harmonics (higher x-ray energies).

CuNi Foil Issues

Following installation and cool-down of CPMU-1, a restriction on the aperture was found, which limited the minimum gap to 6.5 mm, that then disappeared following two thermal cycles. A further thermal cycle for a cryocooler service caused it to reappear. The tension of the foil was thought to be the cause and it was therefore increased by 50% for CPMU-2. However, the aperture of both CPMU-1 and CPMU-2 have both been found to change with thermal cycling of their cryocoolers. While there is limited thermal cycling of CPMU-3 and CPMU-4, what evidence there is shows no restriction of their apertures. The main differences between CPMUs 1 and 2 and CPMUs 3 and 4 are the height of the poles relative to the magnets, and the method of foil fitting. The poles were initially set 0.1 mm proud of the magnets for the first two CPMUs, whereas in the latter two they are set flush. The CuNi foil on CPMUs 1 and 2 was rolled over the magnets and poles and then tensioned, whereas for CPMUs 3 and 4 the foil was pre-stretched and placed over the magnets and poles before tensioning.

CPMU-1 has recently been removed from the storage ring and replaced by CPMU-3. CPMU-1 has been reworked, by removing the height offset of the poles and magnets, and pre-stretched foil will be attached at the appropriate assembly stage. It was clear from the visible burn marks that the original CuNi foil had bunched into the gap at the centre of the undulator. CPMU-2 will follow suit next year, and will be replaced with the reworked CPMU-1.

CONCLUSION

The cryogenic undulator upgrade programme at Diamond Light Source has largely been a success, increasing the flux on three beamlines over the energies of interest. However, the foil issue is still to be fully understood and overcome on CPMUs 1 and 2. While there is reticence regarding warming and cooling the CPMUs unnecessarily, further cooling cycles of CPMUs 3 and 4 for cryocooler maintenance will provide evidence that setting the pole heights flush with the magnets and/or the pre-stretching of foil is the required fix.

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