The Cryogenic Undulator Upgrade Programme at Diamond Light Source

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Introduction

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; all designed, built, and measured in-house.

The CPMUs provide 2 - 3 times more brightness and 2 - 4 times more flux than the pure permanent magnet (PPM) devices they are replacing. The remanence of PrNdFeB magnets increases when cooled to the cryogenic temperature of liquid nitrogen (77 K), unlike NdFeB magnets. Therefore, due to PrNdFeB magnets, cryogenic cooling allows for even shorter period devices while achieving the same, or stronger, magnetic field.

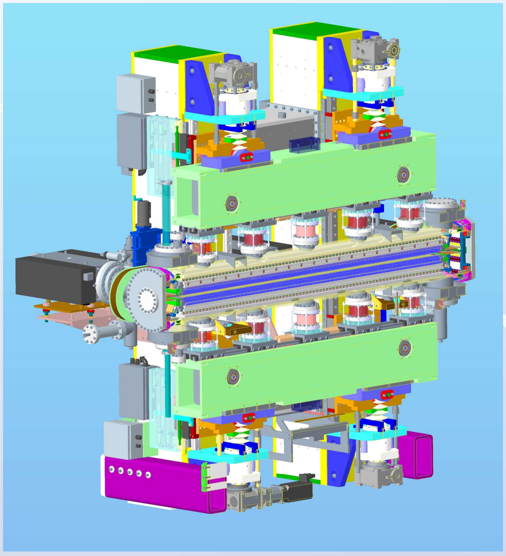
Magnetic & mechanical design

The CPMU parameters have been chosen such that they will work for all the beamlines where they are replacing the PPM undulators.

The magnetic design was modelled in Radia using PrNdFeB magnets & vanadium permendur pole pieces.

Parameter	Value
Period [mm]	17.6
Total length [m]	2
Number of full periods	113
Peak magnetic field [T]	> 1.35 (at 4 mm gap)
Beamline energy range [keV]	5 - 30

The mechanical structure is based on the Diamond third-generation in-vacuum undulator (IVU) structure.
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 minimise wakefields



Cooling

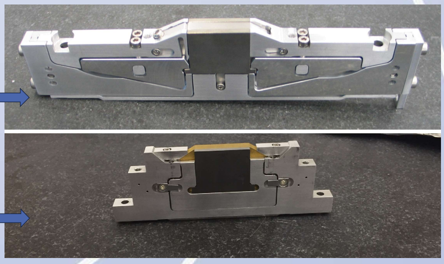
- Recirculating LN2 cryocooler
- 77 K reached in 6-7 hours
- The cold mass acts as a cryo-pump
- 8 mm contraction of magnet girders, therefore columns are mounted on slides
- ~30% increase in force on the structure when cold compared to room temp.

Motion control

- Each axis is independent:
  - tilt, taper, and individual axis and girder movements are possible
- Gap range is 4 mm to 29 mm
- CPMUs 1-3: Delta Tau Geo brick motion controller
- CPMU 4 onwards: CK3M motion controller

Left: model of CPMU-3 with the vacuum chamber cut away. Green: out-of-vacuum magnet beams, red: columns with bellows attached, blue: magnet & pole holders

Design evolution



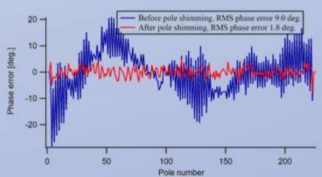
Triplet (pole-magnet-pole) & singlet (magnet) holders originally used for CPMUs 1 & 2 – did not retain pole positions well.
There were also issues with the cold measurement system Hall probe beam needing to be thicker at the same time.
Doublet holder (magnet-pole) design developed to be 30% narrower with simpler pole clamping. Used for all in-house CPMUs, including CPMUs 1 & 2.

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. The number of columns was increased to five for the subsequent CPMUs. 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 unequal contraction around the off-centre fixed columns of CPMU-1.

Magnetic assembly & shimming

Opt ID is used to sort the magnets based on Helmholtz coil measured data.
Magnetic assembly & shimming steps at room temperature are:

- Assemble magnets & poles with nominal shim in holders onto girders
- Adjust height of magnets and poles until they are within ±20 µm (±10 µm typically achieved)
- Mount girders on to structure
- Column shim to straighten long-range undulation of the magnetic peak field (B_p)
- Pole shim using in-situ height measurement tool to reduce the local B_p errors: pole height & tilt adjusted in micron steps (maximum ±50 µm) to reduce trajectory and phase errors
- Magic finger shimming to correct field integrals to reduce the undulator's impact on the beam



Phase error plot before and after pole shimming on CPMU-3 at a 5 mm gap

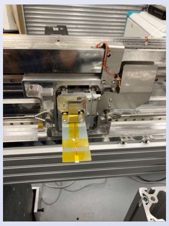
Cold measurement system

When the CPMU cools down, the force between girders increases, causing deflection of the unconstrained sections of the girders. This is corrected by column shimming and measured using a cold in-vacuum measurement system installed alongside the magnet girders.

The cold in-vacuum measurement system consists of a Hall probe and stretched wire for field mapping and field integral measurements respectively.

Hall probes

Arepoc and PT100 sensors on a 4 mm thick ceramic holder were originally used but were replaced with a SENIS S-type probe mounted on a 4 mm epoxy glass holder, and then a 1 mm thick epoxy glass holder to measure smaller gaps.
The SENIS Hall probe has been calibrated at low temperatures, as it experiences a 35 – 40° drop during a Hall scan.

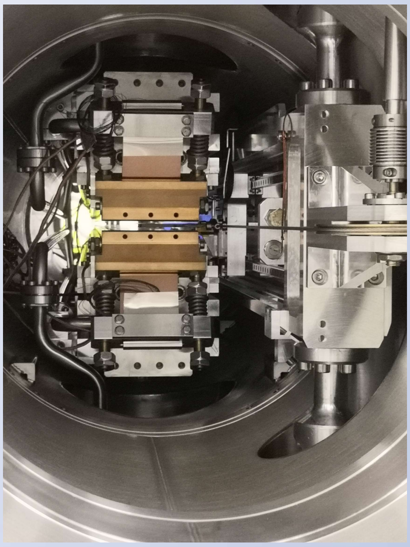


Hall probe motion

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. 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.

Column shimming

When the CPMUs cool down the phase error increases as shown in the table.
A few iterations of column shimming reduces the phase error to an acceptable value.



Above: 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 cooling pipes can be seen.

CPMU name	RMS phase error [deg.] at a 5 mm gap		
	@296 K	Initial @77 K	Final @77 K
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 reworked	2.1	*to be measured*	

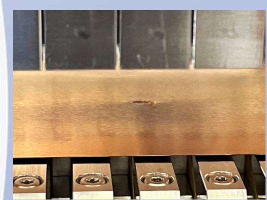
Installed performance

Upon installation, beam-based alignment is performed as with a standard IVU. 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

CPMUs 1 & 2 have experienced restricted apertures following thermal cycles in the storage ring that has not been seen in CPMUs 3 & 4. The main differences between the two sets of CPMUs is that:

1. The poles are 0.1 mm proud of the magnets in 1 & 2 but flush in 3 & 4
2. The CuNi foil is pre-stretched on 3 & 4 but only rolled over the magnets and poles in 1 & 2



Above: burn mark in the CuNi foil of CPMU-1

CPMU	Thermal cycle	Outcome
CPMU-1	1st cooled	Gap restricted
	Re-cooled after investigation	Gap restricted
	Re-cooled after investigation	No gap restriction
	Re-cooled after cooler service	Gap restricted
CPMU-2	1st cooled	No gap restriction
	Re-cooled after cooler service	Gap restricted
CPMU-3	1st cooled	No gap restriction
	Re-cooled after CPMU-4 LN_2 pipework installation	No gap restriction
	Re-cooled after cooler service	No gap restriction
CPMU-4	1st cooled	No gap restriction
	Re-cooled after cooler fault	No gap restriction
	Re-cooled after faulty valve fix	No gap restriction

CPMU-1 is in the process of being re-worked: the heights of the poles have been set flush to the magnets & the foil will be pre-stretched instead of rolled. CPMU-2 will also be re-worked.

Conclusions & future work

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 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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