DEVELOPMENT OF LOW PERIOD CRYOGENIC PERMANENT MAGNET UNDULATORS

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Abstract

Undulators are widely employed on accelerator-based light sources. The length of these devices is usually constrained by the length of the straight sections, and this will become even more critical for Diffraction Limited Storage Rings based on existing Synchrotrons, where the required number of magnets to store the electron beam is huge. Thus, to reach high brightness and flux, the total number of periods of undulators must remain large and the magnetic period values will be reduced. Cryogenic Permanent Magnets Undulators (CPMU) are a solution to keep a high peak field value while decreasing the magnetic period. Planar CPMUs have become widely adopted in Synchrotrons worldwide and some laboratories are developing equivalent devices providing also elliptical polarizations. A review of low period CPMU installed on accelerator-based light sources is presented.

INTRODUCTION

For 30 years, In-Vacuum Undulators (IVUs) are operated on accelerator-based light source, based on the pioneering work of SPring-8. Nowadays they are in use in nearly every Synchrotron Light Source. In 2005, SPring-8 developed the first prototype of CPMU, derived from a standard In-Vacuum Undulator (IVU) design. In 2008, the ESRF was the first to install on a storage ring a full scale CPMU. Presently 38 CPMUs are installed on 10 Synchrotron Radiation Facilities worldwide (see Table 1) and 14 prototypes have been developed, which highlights the strong interest for such a technology.

CONSTRUCTION OF SHORT CPMUS AT ROOM TEMPERATURE

Choice of the Permanent Magnet Grade

First IVUs were built using SmCo magnets due to their strong coercivity with hard resistance against demagnetization induced by electron beam irradiation. Then, to enhance the magnetic field, NdFeB magnet grades have been used. This magnet grade has also been used for the first CPMUs built by SPring-8, ESRF, DLS, SLS and SSRF [1-3]. When cooled down, the coercivity of this grade increases by at least a factor of 4, so as the remanence within 15%, which reaches a maximal value around 135 K before falling at 77 K due to the Spin Re-orientation Transition (SRT) [4-6]. Then Praseodymium has been chosen due to its properties more adapted with cryogenic temperatures. As the PrFeB magnets don't exhibit SRT between 50 K and 300 K [7], they can be cooled down directly at 77 K which simplifies a lot the thermal design and the operation with such undulators on storage rings. Before starting the magnetic design of an undulator, different magnet grades have been tested at low temperatures to be able to evaluate the magnetic field produced by the undulator under these conditions and select the appropriate period meeting the beamline requirements [4].

Mechanical and Magnetic Design

The mechanical design of CPMUs is generally derived from the one of the IVUs: magnets are clamped on holders, which are fixed on aluminium or Oxygen-Free Copper in-vacuum girders, connected to external ones thanks to several pairs of rods as shown in Fig 1. On an undulator, the magnetic forces increase exponentially while the gap decreases, which can imply some deformations on the in-vacuum girders, the global carriage itself and induce heavy load on the gap-drive system. This C-shape type carriage can usually handle magnetic forces up to 30 kN. NEOMAX Engineering developed spring modules installed on the carriage to reduce the magnetic efforts seen by the carriage and prevent from phase error variations at closed gap on a large range [8]. Some studies have also been held on the number and positioning of the rods and conclude that it is not necessary to implement a huge number of pairs uniformly positioned but sometimes, four pairs of rods is the optimal number and enable to reach lower phase error values [9]. At the ESRF, the rods between the top and bottom girders are shifted in longitudinal enabling a better control of the vertical magnetic field profiles.

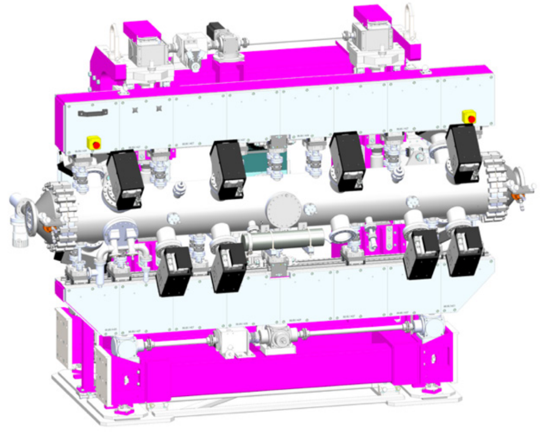

Figure 1: Mechanical design of CPMUs at ESRF.

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Table 1: List of Full-scale Cryogenic Permanent Magnet Undulators Operated Worldwide or in Construction

Date	Laboratory	Beamline	Period (mm)	Length (m)	Gap (mm)	Magnet Material	Field (T)	Cooling system	Op. temp. (K)
2008	ESRF	ID06	18	2	6	NdFeB	0.88	Closed Loop Cryocooler	150
2010	DLS	I07	17.7	2	5	NdFeB	1.04	Closed Loop Cryocooler	150
2011	SOLEIL	NANOSCOPIUM	18	2	5.5	PrFeB	1.15	Closed Loop Cryocooler	77
2012	ESRF	ID11	18	2	6	NdFeB	0.99	Closed Loop Cryocooler	150
2013	SPring-8		15	1.4	3	NdFeB	1.64	He Cryocooler	140
2014	SSRF		18	2.6	6	PrFeB	0.96		77
2015	ESRF	ID31	14.4	2	5	NdFeB	0.967	Closed Loop Cryocooler	80
2015	SLS	MS	14	5	3.8	NdFeB	0.835	Closed Loop Cryocooler	135
2017	SOLEIL	ANATOMIX	18	2	5.5	PrFeB	1.15	Closed Loop Cryocooler	77
2017	SSRF		20	1.6	6	NdFeB	1.04		140
2018	HZB	EMIL	17	2	5.5	PrNdFeB	1.12	Closed Loop Cryocooler	80
2018	HZB		15	2	2	PrNdFeB	2.08	Cold head	80
2019	NSRRC		15	2	5.2	PrFeB	1.01	Cold head	83
2020	ESRF	ID15	18	1.5	6	PrFeB	0.952	Closed Loop Cryocooler	80
2020	DLS	I24	17.7	2	4	NdPrFeB	1.4	Closed Loop Cryocooler	80
2021	ESRF	ID16	20.8	2	6	PrFeB	1.05	Closed Loop Cryocooler	80
2021	DLS	I03	17.7	2	4	NdPrFeB	1.4	Closed Loop Cryocooler	80
2021	DLS	I04	17.7	1.55	4	NdPrFeB	1.35	Closed Loop Cryocooler	80
2022	ESRF	ID27	18	2	5	PrFeB	1.19	Closed Loop Cryocooler	80
2022	DLS	I24	17.7	2	4	NdPrFeB	1.4	Closed Loop Cryocooler	80
2022	NSRRC		18	2	5.4	NdFeB + Tb	1.18	LN_2 tank	170
2023	ESRF	ID29	16.4	2	5	PrFeB	1.1	Closed Loop Cryocooler	80
2023	ESRF	ID03	16.4	2	5	PrFeB	1.1	Closed Loop Cryocooler	80
2023	SSRF	13W	18	2.6	6	PrFeB	0.96		80
2023	ANSTO	NANO	18	3	5.2	NdFeB	1.23	Cold head	170
2024	ESRF	ID14	18.6	2	6	PrFeB	0.98	Closed Loop Cryocooler	80
2024	DLS	VMXm	17.7	2	4	NdPrFeB	1.35	Closed Loop Cryocooler	80
2024	SOLEIL	CRISTAL	18	2	5.5	PrFeB	1.15	Closed Loop Cryocooler	77
2024	HEPS	B3	12	2		PrFeB			80
2026	SOLEIL	COXINEL	15	3	3	PrFeB	1.74	Closed Loop Cryocooler	77
2026	ESRF	ID20	20.5	2	6	PrFeB	1.096	Closed Loop Cryocooler	80
2026	ESRF	ID20	20.5	2	6	PrFeB	1.096	Closed Loop Cryocooler	80
2026	DLS	I03	17.7	2	4	NdPrFeB	1.35	Closed Loop Cryocooler	80
2026	DLS	I11	17.7	2	4	NdPrFeB	1.35	Closed Loop Cryocooler	80
2027	ESRF	ID18	18.6	2.5	5	PrFeB	1.266	Closed Loop Cryocooler	80
2028	ESRF	ID11	20.5	2	6	PrFeB	1.096	Closed Loop Cryocooler	80
2028	DLS	K02	17.7	2	4	NdPrFeB	1.35	Closed Loop Cryocooler	80
	HZB	SoTeXS	20	1.46	6	PrNdFeB	1.15	Closed Loop Cryocooler	77

Most of the CPMUs are assembled from individual keepers, each corresponding typically to half a period. The keepers must be stiff enough to handle the magnetic forces and flexible enough to permit the adjustment of the poles to tune the magnetic field errors. The goal of the magnetic field tunning is both improving the radiation performance of the undulator and minimizing the effect of the undulator on the electron beam. At DLS, the keeper design has been improved to reduce the number of elements on it enabling to reduce the costs, save the assembly time and improve the stiffness to limit the deformations due to the magnetic forces. At SOLEIL, an efficient concept has been developed for CPMU12, called Supermodule. This keeper has been designed to hold 9.5 periods of 12 mm with magnets and full poles in the central part and half-poles at both extremities. Due to the symmetry and half pole structure, only one module type is needed to build the whole undulator by rotating this module. Some screws inside the module are dedicated to the pole adjustment for phase error and trajectory distortions corrections. This approach significantly reduces the number of components and simplifies the assembly, provided that fabrication tolerances are maintained.

Assembly, Measurements and Corrections at Room Temperature

CPMUs are usually assembled period per period using dedicated in-house software tools (SORT at HZB [10-11], OPT-ID at DLS, ID-Builder at SOLEIL [12]). At HZB, the magnets are characterized for dipole errors and inhomogeneities using an automated Helmholtz coil bench and a mini-stretched wire bench [10]. Then magnets are installed on girders and predictions with SORT shows an excellent agreement with the magnetic measurements. Then the poles are inserted and Hall probe scans can be performed. The magnets are adjusted within 20 µm and poles within 40 µm to compensate the magnetisation errors of the blocks, mechanical and alignment errors. At DLS, the magnets are also adjusted within 20 µm and the poles within 5 µm on the support. After the assembly, shimming of the rods is performed so as the shimming of the poles in altitude or tilt to reach a phase error below 2° at room temperature. At SOLEIL, a particular attention is paid to avoid large on-axis field integral variations from one period to the next one to avoid trajectory distortions and phase error variations. Thanks to this new process, CPMUs of SOLEIL doesn’t need any shimming post assembly. Three applications using industrial robotic arms have also been developed to:

- position all the modules of an undulator one by one on the girders to conduct rotating coil and Hall probe measurements;
- adjust all the poles of a supermodule within 20 µm;
- perform the magnetic optimization of the supermodules by conducting Hall probe measurements so that all the peaks on a Supermodule are within 0.5%.

The objective of this optimisation at room temperature is both improving the radiation properties of the undulator and minimizing its effect on the electron beam.

CORRECTION OF CPMUS AT CRYOGENIC TEMPERATURE

Due to the cooling down of the undulators, several mechanical changes appear leading to an increase of the phase error which was previously optimized at room temperature. Usually, field integrals and straightness of trajectories in both planes are not impacted. It is crucial to optimize this phase error at 77 K, for this reason, magnetic measurements benches are embedded inside vacuum vessels.

Cooling and Thermal Design

Two main options are commonly used regarding the cooling down of CPMUs, whether with a cold head or closed-loop liquid nitrogen (LN_2) cryocooler.

Two cold heads are installed on the vacuum vessel of the CPMU, one at each extremity, with an average cooling power of around 200 W each. The initial investment is low but running and maintenance cost are high since maintenance must be performed every year. Other advantages are that there is no need of LN_2 or helium connections in the laboratory or in the tunnel so there is no risk of leakage in the undulator vacuum vessel. The cold heads are usually cooling down thermal feedthrough connected to an in-vacuum copper plate with the same length as the girders to avoid longitudinal thermal gradients. This copper plate is connected to the in-vacuum girder where the magnets are installed thanks to flexible copper strips enabling gap movements as shown in Figure 2. The vibrations induced by these cold heads have to be small enough to be able to run precise magnetic measurements and not induce perturbation on the electron beam.

Figure 2: Copper plate and strips connected to in-vacuum girders of the CPMU15 at SPring-8.

Another solution to cool down the CPMU is by using closed loop LN_2 cryocoolers. One device is connected to the undulator with a cooling power which is higher than cold heads (typically 1500 W) with no vibrations as this device can be installed far from the undulator or out of the tunnel. The girders are drilled in longitudinal so that the LN_2 directly flows in the girder to efficiently cool down the magnets. Thus, weldings are needed at both extremities so that girders can ben linked together via flexible tubes enabling gap movements. A particular attention must be paid to these weldings that must be tested under high pressure during one or two days to avoid any leakage of LN_2 in the vessel of the undulator that could affect the vacuum pressure of the storage ring. The consumption of LN_2 with these systems is around 20 l/hour. At SPring-8, SLS and ANSTO [3, 13] Oxygen-Free Copper in-vacuum girders equip the CPMU, enabling to improve the cooling efficiency and the thermal conductivity with a lower thermal expansion coefficient but a density multiplied by a factor of 3.

Measurements and Corrections at Cryogenic Temperature

Due to the cooling down of the undulator, two main mechanical changes appear:

- the rods, coupling the out-vacuum girders which are at room temperature and the in-vacuum ones which are at cryogenic temperature, are contracting. This contraction can be measured thanks to resistivity measurements using the stretched wire bench or via optical sensors;
- the girders are shrinking by approximately 11 mm for a 2 m long aluminium girder and 8 mm for an OFCH one implying a reduction of the magnetic period of the undulator. During the assembly at room temperature, a sufficient airgap between magnets should be inserted to avoid any extra efforts on magnets which could create local errors.

The optimized phase error at room temperature is degraded after the cooling down of the undulator. The new optimisation can be performed only by shimming the rods outside of the vacuum vessel. Only few micrometres movement on specific rods is usually needed to correct the vertical magnetic field profile and recover a low phase error. The magnetic field of cryogenic undulators is enhanced at low temperature by 15% typically.

For this reason, magnetic measurement benches are embedded in the vacuum vessel of the undulator, a Hall probe for the magnetic field profiles and a stretched wire for field integrals measurements. Usually during these measurements at cryogenic temperature, vessels extensions are installed at both extremities of the main one to install a longer Hall probe bench, the stretched wire, and all the connectors (controllers, thermal sensors, heaters, Hall probe and stretched wire signals). SPring-8 developed the SAFALI method [14-15] which ensure that the Hall probes follow the magnetic axis while scanning along the undulator. One or two lasers at one extremity emit light that passes through irises on the Hall probe support. This light is then received on Position Sensitive Detectors at the other extremity, depending on the Hall probe position. Some piezo-electric stages under the Hall probe corrects on-fly its transverse position regarding the signal measured by the PSD.

PERFORMANCES ON THE BEAM

Due to their low heatproof temperature of the magnets, CPMUs can not be baked as standard IVUs leading to a degradation of the vacuum pressure of the undulator at room temperature. At SOLEIL, all the elements included in the vacuum vessel during the operation, except the magnets, are pre-baked before the assembly of the undulator, this process helps reaching lower pressure values. However during the cooling down of CPMUs, usually the vacuum pressure is improved between one or two decades, which compensate the fact that these undulators can not be baked. At SPring-8, a comparison of the vacuum pressure a non-baked CPMU and a baked IVU show after 5 months of conditionning on the machine pressures reach respectively of $8x10^{-8}$ Pa and $5x10^{-8}$ Pa. However in case of a failure of the cooling system, the vacuum pressure will immediately rise and exceed the acceptable pressure for storage ring operation which can cause a beam interlock. At SOLEIL or the ESRF, this interlock appears 4 hours after the warming up of the undulator. At the ESRF, a beam can be re-injected after this interlock, the machine can be operated with one or more CPMUs at room temperature with the gap fully opened and the associated the beamline front-end closed.

Several thermal sensors are usually installed on the magnets of the CPMUs to monitor the temperature. At TPS these are also key components of four thermal control feedback loops which enable to maintain the temperature of the magnets within 1 K whatever the gap between 5.2 mm and 25 mm and the stored beam current.

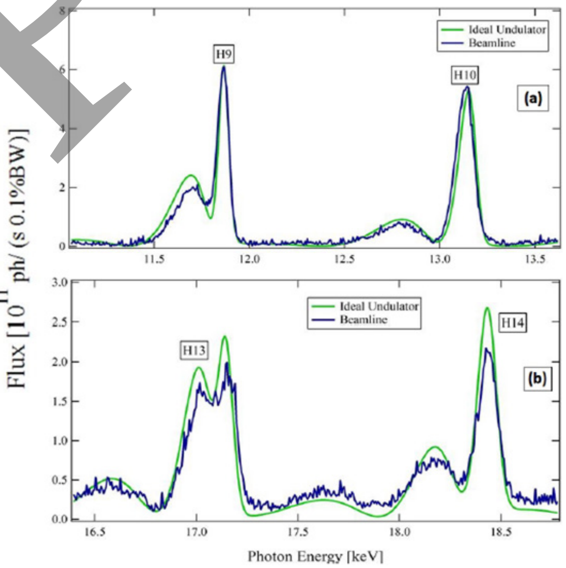

Figure 3: Comparison of spectra of an ideal CPMU18 and the one measured on Nanoscopium beamline at SOLEIL at 77m from the source for a gap of 5.5 mm.

Figure 3 shows the radiation spectra of the CPMU18 of Nanoscopium beamline at SOLEIL measured 77 m away from the source [16-17]. The intensity of the harmonics are in good agrement and in all cases, the measured and ideal harmonic line bandwidths are consistant, underlying the low phase error value and the good quality of the undulator magnetic field. Similar measurements have been performed at SLS on CPMU14 [3] and the measurements with the beamline show a very good agrement with calculations with SRW from the magnetic measurements.

CONCLUSION

Numerous CPMUs have been built and operated for 15 years on 10 different synchrotron radiation facilities. The smooth commissioning and successful operation over many years reflects the reliability of these devices. They are now a mature technology and the transition from building IVUs to CPMUs is relatively straightforward. The trend for the following years regarding this technology would be still to shorten the period values using PrFeB at 77 K, some concepts have been proposed to still enhance the magnetic field values, or even in a more challenging direction, to change the polarization using a CPMU. Some laboratories currently working on this topic, thermal and mechanical studies are running at HZB, and a 1 m long prototype is under preparation.

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