DEVELOPMENT OF A CRYOGENIC PERMANENT MAGNET UNDULATOR FOR THE TPS

Jui-Che Huang[†], Chin-Kang Yang, Cheng-Hsing Chang, Chih-Sheng Yang, Ting-Yi, Chung,
Jyh-Chyuan Jan, Ching-Shiang Hwang, National Synchrotron Radiation Research Center,
HsinChu, Taiwan
Hideo Kitamura, RIKEN SPring-8 Center, Hyogo, Japan

Abstract

Development of a cryogenic permanent magnet undulator (CPMU) at the Taiwan Photon Source (TPS) is the most recent activity toward a new light source for the Phase-II beamlines. A hybrid-type CPMU with a period length of 15 mm is under construction with PrFeB permanent-magnet materials. A maximum effective magnetic field of 1.77 T at a gap of 3 mm is expected when the magnets (PMs) are cooled down around 77 K. The features desired for the TPS CPMU are low-intrinsic-phase-error characteristics and high thermal budget for various kinds of heat loads. The design of the TPS CPMU is discussed in this paper.

INTRODUCTION

A CPMU follows a recent trend for the development of short period undulators across the world because of its attractive characteristics: (1) 20-30 % higher field compared to room temperature (RT) in-vacuum undulator (IVU) of equal design, (2) high resistance against radiation damage, (3) easy extrapolation from well understood IVUs designs, (4) lower image current heating on the magnet cover compared to an IVU and (5) a thermal budget up to several hundred watts [1]. The development of the TPS CPMU, CU15, has been made since 2016 in cooperation with NEOMAX Engineering. Main features desired for CU15 are low-intrinsic-phase-error characteristics and high thermal budget for various kinds of heat loads. To minimize the intrinsic phase errors derived from the magnetic force, the mechanical frame is equipped with the four-support-point configuration together with a spring module on the out-of-vacuum girder. Another source increasing an intrinsic phase error is the temperature variations in the magnet arrays. As a solution, optimal locations for cooling points (thermal straps) together with precise temperature controls (via platinum resistance thermometers (PT100) and heaters) will be implemented to keep temperature variations to be less than 0.5 K/m.

The thermal budget for beam-induced heat load, conduction via bellows-link rods and radiation heat transfer can reach up to 400 watts at 80 K by using two Sumitomo CH110 cryo-coolers. The in-vacuum girder, made of oxygen-free-copper (OFHC), has a higher thermal conductance compared to an aluminum girder, which lead to a smaller temperature variation of the magnet array. A feed-forward table, correlating encoder and actual vacuum gap, will be prepared by an optical micrometer system with an accuracy of ± 1 µm. The table will be implemented for the operation of CU15 in the TPS ring. In the present paper, the technical challenges and design issues for CU15 will be reported.

MAGNETIC CIRCUIT DESIGN

A PrFeB permanent magnet (NMX-68CU) in hybrid design is adopted for CU15, the parameters of which are compiled in Table 1. The minimum operating gap may be limited to 4 mm during the commissioning stage while a gap smaller than 4 mm will be tested, being aware, however, of possible avalanche meltdown of the magnet cover.

Table 1: Main Characteristics of the TPS CPMU, CU15

Items	Unit	Value
Magnet structure		Hybrid
Magnet material		$Pr_2Fe_{14}B$ NMX-68CU
Remanence (*Br*)	T	1.4 at 293 K 1.67 at 77 K
Coercivity (*Hcj*)	kA/m	1689 at 295 K 6200 at 77 K
Magnet size (x,y,z)	mm^3	2.25 × 56 × 20
Pole material		Vanadium Permendur
Pole size (x,y,z)	mm^3	3 × 46 × 16
Period	mm	15
Min. magnetic gap (G_{mag})	mm	3 (4)
Min. vacuum gap (G_{vac})	mm	2.8 (3.8)
Effective magnetic field at min. gap	T	1.77 (1.32)
Deflection parameter		2.48 (1.85)
Number of periods		133
Magnetic force	kN	57.2 (31.8)
Total length	m	2

The CPMU, CU15 (shown in Fig. 1) will be installed in the 7-m straight section with non-achromatic lattice functions (see Table 2). Considering the combined effect of high field and finite dispersion, we expect an increased emittance of 2.7 %/0.7 % at a magnetic gap of 3 mm/4 mm, respectively. The energy spread increases by 0.39 % for a gap of 3 mm and actually decreases by 0.08 % for a 4 mm gap [2]. Compared to a standard undulator (IU22-3m) at TPS, CU15 operating at 4 mm provides a 160 % increase in SR brilliance at 10 keV and is even more significant at higher photon energies.

[†] huang.juiche@nsrrc.org.tw

Table 2: TPS Accelerator and Lattice Parameters

Parameters	Unit	Value
Beam energy	GeV	3
Beam current	mA	500
Emittance	nm.rad	1.6
Circumference	m	518.4
Number of Bunches		600
Bunch length	ps	15.5
Energy spread		0.001
Emittance coupling		0.1%
Horizontal betatron function	m	5.35
Vertical betatron function	m	1.73
Dispersion function	m	0.088

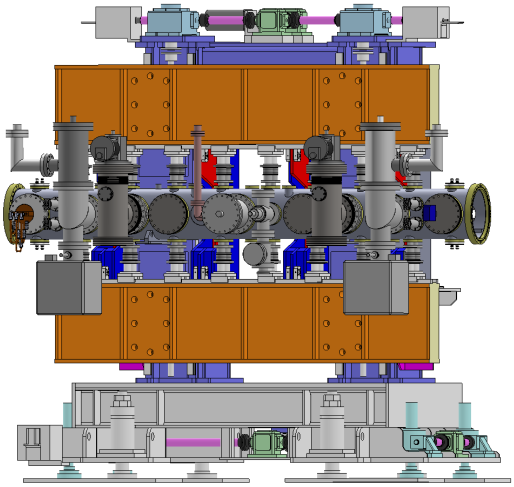

Figure 1: Cryogenic Permanent Magnet Undulator CU15 at TPS (schematic).

THE MECHCANICAL FRAME

When the CPMU magnets are cooled down from RT to LNT, deformation of the support girders may occur due to increased magnetic forces leading to intrinsic phase errors [3]. At a gap of 3 mm, the magnetic forces reach 57 kN and a conventional 2-support configuration is no longer rigid enough to keep the net RMS phase errors to less than 2 degrees. Therefore, a four-support-point configuration with spring compensation modules of moment-free type, will be introduced at each of the four support points. The OFHC in-vacuum girders have smaller deformation because of higher Young's modulus and lower thermal contraction compared to that of aluminium. The number of bellows-link rods must be a compromise between maintaining a low phase error caused by the deformation of the in-vacuum girders and keeping low conductive heat transfer from the bellows-link rods. And therefore, eight sets of bellows-link rods at an interval of 0.25 m are designed. Figure 2 shows the intrinsic RMS phase errors estimated for CU15 at various gaps by using a 2-dimensional deflection code. To obtain more accurate values, a 3-dimensional code, SolidWorks or ANSYS, is necessary. In this case, the calculated values may be about twice larger. Nevertheless, the true intrinsic RMS phase errors less than 1 degree is expected at a magnetic gap of 3 mm.

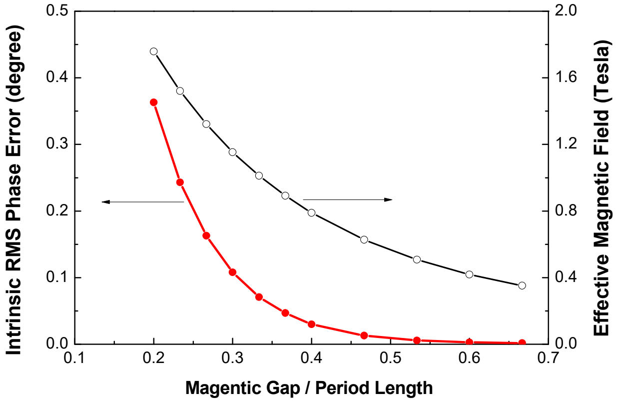

Figure 2: Intrinsic RMS Phase errors calculated for the TPS CPMU, CU15.

COOLING SYSTEM OF THE TPS CPMU

The cooling system for CU15 consists of two cryo-coolers connected to the magnet arrays via flexible thermal straps. Since cryo-coolers are attached to the vacuum flanges, flexible thermal conductors between magnet arrays and cryo-coolers are necessary for a variable gap undulator. For these reasons, OFHC thermal straps with high flexibility are proposed for CU15 as shown in Fig. 3. The OFHC straps are UHV compatible and designed for one million bending cycles. Although the thermal conductivity of the straps with a braid length of 70 mm is measured to be 0.3 W/K at RT, it is improved to 3 W/K at 40 K with the vacuum annealing treatment.

As the temperature of PMs shall be stabilized during the operation of a CPMU to obtain a reproducible energy spectrum under different beam conditions, heaters are assembled along the side of the magnet arrays to compensate the variation of beam-induced heat load conditions. Another purpose of the heaters is to compensate the residual temperature gradient.

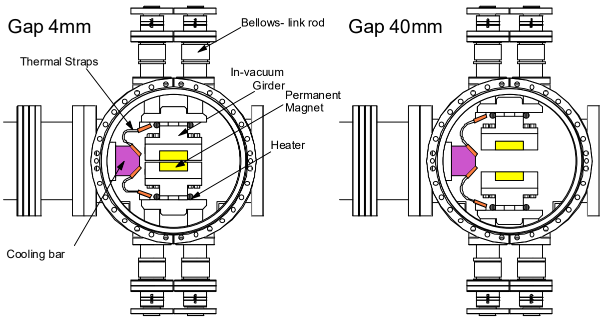

Figure 3: Cross-sections of magnet arrays and flexible conductors (schematic).

From the experience of a CPMU at SOLEIL [4], about 50 % of the heat load comes from the bellows-link rods. A hollow link rod filled with insulation material is designed to reduce the heat conduction by a factor of seven compared to the bellows-link rods used at the TPS IVUs (shown in Fig. 4). The thermal conductance of the hollow rod is estimated to be 2.3 W. The bulkhead design is adopted to suppress the air circulation inside the hollow space of the rods, which prevents condensation on the surface of the bellows-link rods, especially, the ones located at the bottom part.

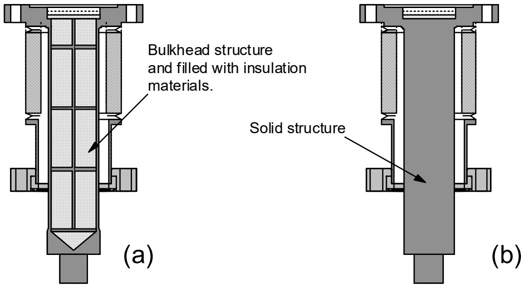

Figure 4: Sketch of bellows-link rods for the TPS (a) CPMU (b) IVU.

The calculated heat load in CU15 is compiled in Table 3 based on the parameters shown in Table 2. The bending radius of the upstream dipole is 8.353 m and the distance from the dipole magnet end to the undulator entrance is 5 m. Since the electrical resistivity of copper decreases with decreasing temperature, the image current heating on the magnet cover, made of a nickel-plated copper sheet, becomes one third of that at RT under the same beam condition. However, if the electron beam is miss-steered in the upstream bending magnet, the SR from there can irradiate the cover leading to dramatically increased heating. As a result, the miss-steering of the electron beam passing through the upstream bending magnet shall be controlled within 0.02 mrad and 0.1 mrad for G_{vac} = 2.8 mm and 3.8 mm, respectively, to keep the linear power density on the magnet cover lower than 10 W/m.

Table 3: Various Heat Loads in The TPS CPMU, CU15 at a Temperature of 77K

Items			**G_{vac} = 2.8mm**	**G_{vac}= 3.8 mm**
Conduction heat transfer [W]	Bellows-link rods (32pcs)		75.8	
	Transition tapers (4pcs)		10.7	
Radiation from the vacuum chamber surface [W]			50	
Beam-induced heat-load. 3 GeV, 500 mA 600 bunches	Image Current Heating [W]	PMs	18.6	13.7
		Transition tapers	3.3	2.9
	SR from upstream BM [W]		21.2	10.2
Total heat load [W]			179.6	163.3

TEMPERATURE DISTRIBUTION ALONG THE MAGNET ARRAYS

The intrinsic phase errors in a CPMU at LNT may be increased from those at RT due to not only the girder deformation derived from the magnetic forces (as discussed in the previous section) but also the thermal effects on the magnet arrays. From the experience of the CPMU at ESRF [5], a temperature gradient along the magnet arrays causes a gap tapering and changes in the magnet performance. Mixture of gap errors and changes of PMs remanence can cause field and phase errors. Figure 5 shows the combination of all the effects on RMS intrinsic phase errors. For the same temperature variation along the magnet arrays, the intrinsic phase errors increase with decreasing magnetic gap. Therefore, the temperature gradient should be controlled to within 0.5 K/m (± 0.25 K/m) to keep the intrinsic phase error less than 1 degree.

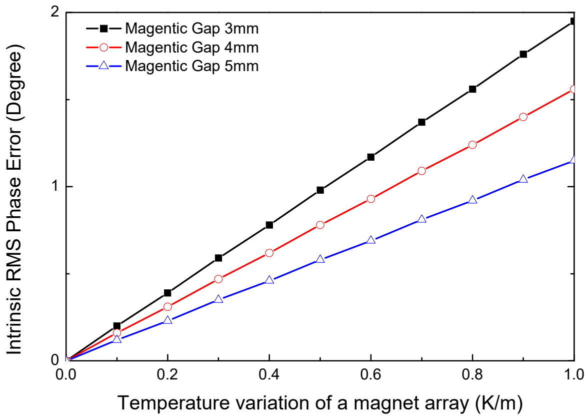

Figure 5 : Dependence of the intrinsic RMS phase errors on the temperature gradient along the magnet arrays.

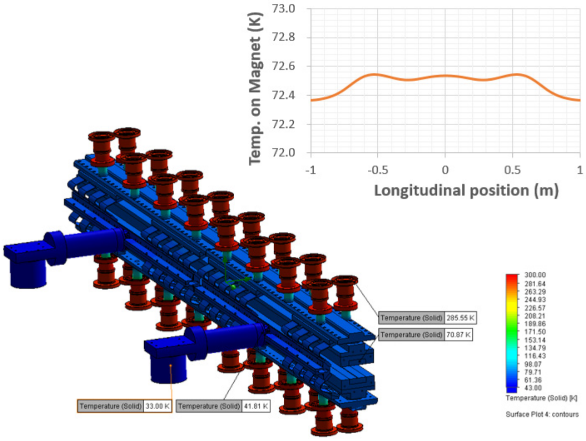

Figure 6 : Temperature distribution along the TPS CU15.

The temperature of PMs is balanced between cooling power and diverse heat loads as shown in Table 3. The final temperature of the magnet arrays (see Fig. 6) is calculated with the SolidWorks Flow Simulator. The beam-induced heat load of 40 W (G_{vac} = 2.8 mm) and the total heater power of 60 W are assumed in the calculation. Besides, we consider the thermal contact resistance of 0.5×10^{-4} m^2K/W between the surfaces of the assembled copper components. The positions of the thermal straps are chosen such as not to exceed a temperature variation of ± 0.25 K. The equilibrium temperature of PMs is estimated to be around 72 K.

REFERENCES

[1] J.C. Huang, “Challenge of In-vacuum and Cryogenic Undulator Technologies” , in *Proceedings of the 7th Int. Particle Accelerator Conf. (IPAC’16)*, Busan, Korea, May 2016, paper TUZB02, pp.1080.

[2] J. C. Huang *et. al.,* “Design of a magnetic circuit for a cryogenic undulator in Taiwan Photon Source”, *AIP Conf. Proc.*, vol. 1741, 020016-4 ,2016.

[3] R. P. Walker , “Phase errors and their effect on undulator radiation properties”, *Phys. Rev. ST Accel. Beams*, vol. 16, pp. 010704-16 ,2013.

[4] C. Benabderrahmane *et. al.* “Development and operation of a Pr2Fe14B based cryogenic permanent magnet undulator for a high spatial resolution x-ray beam line”, *Phys. Rev. ST Accel. Beams*, vol. 20, pp. 033201-14, 2017.

[5] J. Chavanne *et. Al.* ,"Construction of a cryogenic permanent magnet undulator at ESRF ”, in *Proc. EPAC’08*, 2008, Genoa, Italy, pp.2243-2245.