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OPERATIONAL EXPERIENCES OF TWO CPMUS AT TAIWAN PHOTON SOURCE *

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Abstract

Cryogenic permanent-magnet undulators (CPMUs) have emerged as a focal point in the development of short-period undulators. At the Taiwan Photon Source (TPS), two 2-meter CPMUs have been developed using different magnet materials and cooling techniques. Specifically, a PrFeB-based CPMU, equipped with cryocooler cooling, and a NdFeB-based CPMU, utilizing liquid nitrogen (LN_2) tank cooling, have been developed. These CPMUs are currently stable operating at TPS storage ring under a constant beam current of 500 mA.

INTROUDCTION

Cryogenic permanent magnet undulators are widely regarded as a highly promising option for the development of short-period undulators aimed at improving the brilliance of synchrotron radiation [1]. At the National Synchrotron Radiation Research Centre (NSRRC), two CPMUs, namely CU15 and CUT18, have been successfully constructed and developed, providing significantly higher brilliance X-ray than the IU22 (The IU22 has been established as a standard undulator for use at the TPS) for photon energies greater than 15 keV, as illustrated in Fig. 1. In addition to the superior brilliance performance offered by CPMUs, they also possess other desirable features such as (1) permanent magnets (PMs) is high resistance to radiation damage, (2) all cold surfaces of PMs, as well as the in-vacuum girders, serving as cryopumps, and (3) reduced resistive wall heating on the magnet cover in comparison with an IVU. The relevant technologies associated with TPS-CPMU have been extensively documented in [1-3].

Table 1 presents a comprehensive overview of the key parameters associated with the three undulators that are currently in operation at the TPS. The first CPMU installed at TPS is CU15, which possesses a period length of 15 mm. This undulator uses Praseodymium-Iron-Boron (PrFeB) magnets and features a cryo-cooler cooling system (the left plot of Fig. 2). In contrast, CUT18 has a period length of 18 mm and utilizes Neodymium-Iron-Boron (NdFeB) magnets, along with a Liquid Nitrogen (LN_2) tank cooling system (the right plot of Fig. 2). With a K value of approximately 2, CUT18 is considered to be the next standard undulator at TPS, capable of fulfilling a broad range of scientific applications.

NEW FEATURE OF CPMUS

The cryogenic system implemented at TPS-CPMUs possesses distinct features that set it apart from other facilities. The CPMU employs conduction cooling of magnet arrays to safeguard the ultrahigh vacuum (UHV) of the accelerator and is adaptable for use with both cryo-coolers and liquid nitrogen tanks as cooling sources. The cooling system can be customized based on the choice of PMs, as depicted in Figure 3. The figure also illustrates several factors that are compared between the two cooling systems. The cryo-cooler cooling system can attain a minimum magnet temperature of 50 K, whereas the LN_2 tank cooling system can only reach 115 K. Thus, for the PrFeB-based CPMU, the cryo-cooler is the preferred option for cooling. The cryo-cooler exhibits higher cooling capabilities when compared to LN_2 cooling, thereby resulting in a substantially reduced cooling duration. It is worth noting that the operational cost of LN_2-tanks cooling at NSRRC is only one-third that of cryo-coolers. This represents a notable advantage, particularly in light of the rising costs of electricity. Furthermore, while cryo-coolers require mandatory annual maintenance, the associated costs are comparatively high compared to the low cost of cooling with an LN_2 tank.

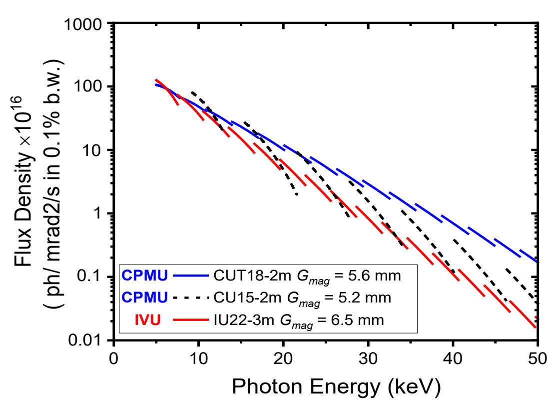

Figure 1: Spectral performance of IU22-3m, CU15-2m, and CUT18-2m. Parameters for the calculation were as follows: $E_{GEV} = 3$ GeV, $\beta_x = 5.3$ m, $\beta_y = 1.7$ m, coupling constant = 0.01, emittance = 1.6 nm rad, and energy spread = 10^{-3}.

CRYOGENIC PERFORAMNCE

Knowing the cooling capacity is an important issue for the development of a CPMU. When the CPMU is operating in the absence of the electron beam, the following equation holds at equilibrium.

$$P_{cooler} = P_{system} + P_{heater}, \qquad (1)$$

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Table 1: Specifications of the TPS in-vacuum undulators (IU22, CU15, and CUT18)

Parameter	Unit	IU22	CU15	CUT18
Type		IVU	CPMU	CPMU
Length	m	3	2	2
Magnet material		NdFeB (NMX-38EH)+ Dy diffusion	PrFeB (NMX-68CU)+ Dy diffusion	NdFeB (NMX-U52SH)+ Tb diffusion
Remanence B_r	T	1.24 at RT	1.67 at CT	1.57 at CT
Coercivity H_{cj}	kA/m	2743 at RT	6200 at CT	2854 at CT
Period length λ_u	mm	22.000	14.945	17.962
Magnet gap G_{mag}	mm	6.5	5.2	5.6
Effective magnetic field	T	0.86	1.02	1.18
Deflection parameter		1.77	1.43	1.98
Number of periods		140	133	111
Magnet temperature	K	300	80	170
Cooling method		Water	Cryo-cooler	Liquid nitrogen

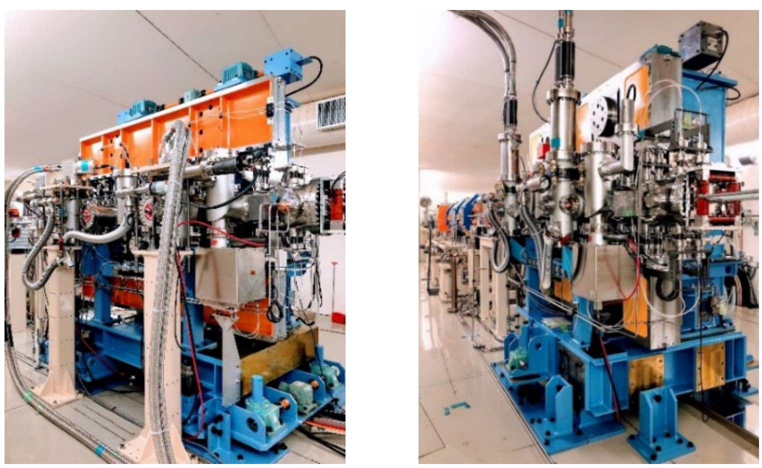

Figure 2: (left) CU15 installed for the high-resolution powder diffraction TPS 19A beamline; (right) CUT18 installed for the advanced microcrystal chemical crystallography TPS 15A beamline.

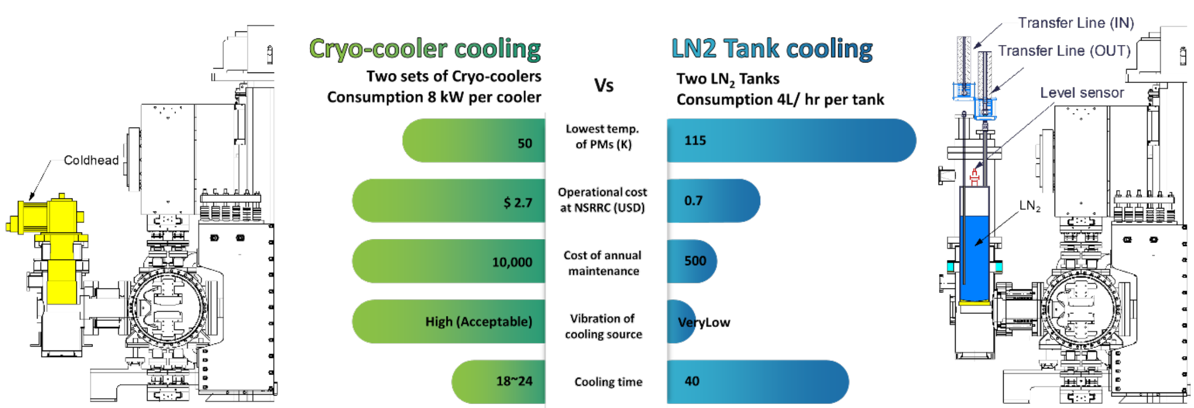

Figure 3: An overview of the comparisons between using a cryocooler and a liquid nitrogen-cooled system at TPS-CPMU.

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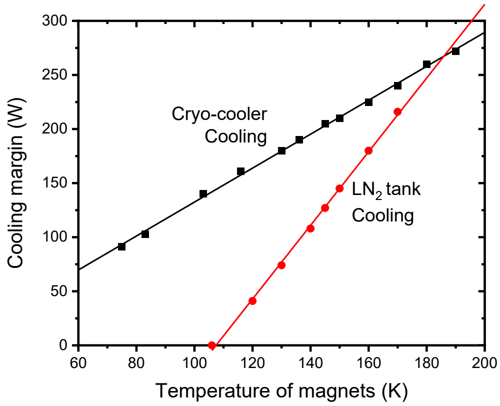

Figure 4: Dependence of the cooling margin, P_{margin}, on the average temperature of magnets.

In Equation 1, P_{cooler} represents the cooling capacity of the cooling sources; P_{heater} represents the output power of the heaters. Specifically, eight sheath heaters have been installed along the magnet arrays to allow for temperature adjustments of the PMs. System heat-load P_{system} is the sum of heat conduction power and thermal radiation power. P_{system} is estimated to be approximately 100 W and 150 W when CPMU is operating of 170 K and 80 K, respectively.

Maintaining a stable temperature for the magnets is critical, and to achieve this, sufficient cooling capacity is necessary. The term "cooling margin" is defined to determine the amount of available power required to counteract the heat generated by the electron beam. Equation 2 represents the cooling margin, which can be measured by the quantity of heater power necessary to maintain an equilibrium temperature in the absence of the beam.

$$P_{margin} = P_{heater} \tag{2}$$

Figure 4 shows the cooling margins of two cooling systems. The findings indicate that a cryo-cooler can provide a significantly higher cooling capacity in comparison to an LN_2 tank cooling system, particularly when the temperature of PMs is below 180 K. It is worth noting that the cooling margin is a linear function of magnet temperature, and that a higher margin can be achieved at elevated magnet temperatures. Based on prior operational experiences, the cooling margin shall be set at a level 20% higher than the amount of the beam-induced heating to ensure the stability and reproducibility of the photon energy spectra.

BEAM -INDUCED HEATING

Heaters used in CPMUs serve a dual purpose: not only do they control the temperature of magnets, but they also measure the heating generated by the electron beam. By monitoring changes in heater power, the additional beam-induced heating, P_{beam}, can be determined.

$$P_{margin} = P_{beam} + P_{heater} \tag{3}$$

Following several tests with varying beam currents at a fixed gap of 20 mm, Fig. 5 illustrates that the amount of heating and beam current can be adequately fitted with a quadratic function. This finding suggests that the primary cause of the heating mechanism is related to the broadband impedance. Had the synchrotron radiation been the source of heating, a linear relationship between the beam current and beam-induced heating would have been expected. Notably, both CU15 and CUT18 produced similar beam-induced heat loads owing to their identical inner vacuum structures. Further investigation into the beam-induced heating mechanism is presently underway

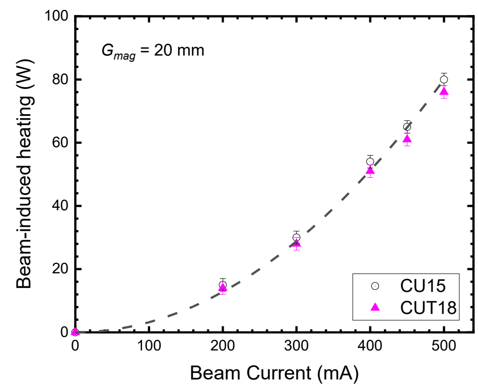

Figure 5: Beam-current dependence of beam-induced heating. The undulator gap is 20 mm.

SUMMARY

Two CPMUs have successfully operated at a high current of 500 mA in the TPS storage ring, showcasing their magnetic and cryogenic performance that exceeds the required specifications. These CPMUs possess distinct features in their cryogenic system, including conduction-cooling of magnet arrays. This unique feature not only prevents damage to the accelerator's ultra-high vacuum but also ensures compatibility with both cryocoolers and liquid nitrogen tanks as cooling sources. Furthermore, a temperature control system has been implemented to stabilize the temperature of the magnets, ensuring that the CPMUs provide stable and reproducible photon energy spectra.

The investigation and feedback from beamline manager indicate that the photon flux at 20 keV using the CU15-2m is three times higher than that obtained using the IU22-3m. Consequently, replacing the IU22 with the CU15 can lead to a reduction in experimental time to one-third of the previous time, resulting in more efficient experiments.

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