

Cryogenic permanent magnet undulator by evaporative cooling of liquid nitrogen

Jui-Che Huang^{1,*}, Hideo Kitamura², Ping-Shun Chuang^{1,†}, Hsing-Chieh Li,¹
Chih-Sheng Yang¹, Chun-Yi Wu,¹ Chih-Yu Liao,¹ Huang-Hsiu Tsai,¹ Chih-Wei Chen,¹
Wun-Rong Liao,¹ and Chin-Kang Yang¹

¹National Synchrotron Radiation Research Center, Hsinchu Science Park, Hsinchu 30073, Taiwan

²Harima Institute, *RIKEN*, SPring8, 1-1-1 Kouto, Mikazuki-cho, Sayo-gun, Hyogo 679-5148, Japan



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CUT18, a cryogenic permanent magnet undulator at the Taiwan Photon Source, represents a significant advancement in undulator technology, offering enhanced flexibility, sustainability, and reliability. It uses a cooling method based on the latent heat of vaporization of liquid nitrogen (LN₂), utilizing the facility's existing LN₂ supply line to improve resource efficiency and reduce operational costs. The LN₂ evaporative cooling system delivers exceptional thermal management, with cooling margins far exceeding the heat load at a beam current of 500 mA, ensuring stable operation even under high beam-induced heating conditions. In addition to this, the adoption of advanced NdFeB magnets, optimized with a 17° magnetization tilt, significantly enhances magnetic field performance and achieves a high deflection parameter ($K > 2$).

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I. INTRODUCTION

The concept of a cryogenic permanent magnet undulator (CPMU) was initially proposed by SPring-8 in 2004 [1]. Since then, CPMUs have been successfully implemented in various synchrotron radiation facilities worldwide [1–5]. Most existing CPMUs utilize a liquid nitrogen (LN₂) circulation cooling system to cool the magnet arrays [2–4]. However, due to concerns about LN₂ potentially leaking into the ring vacuum system, this cooling approach is prohibited by the vacuum regulations of the Taiwan Photon Source (TPS). Consequently, TPS has adopted a conduction cooling method for CPMUs to mitigate these risks. The conduction-cooled CPMU (TPS-CU15) using cryocoolers as the cooling source has demonstrated exceptional reliability and spectral performance while operating within the TPS storage ring at a beam current of 500 mA and a bunch length of approximately 16 ps [5,6].

The CU15 has experienced significant beam-induced heating loads, measured to be approximately 90–110 W through all gaps [5]. These heat loads are primarily attributed to the geometric impedance associated with transition tapers at the extreme ends of the undulator,

but microwaves entering from outside the undulator must also be considered. Despite the high heating environment, CU15 has continued to operate successfully, providing valuable insights into the mechanisms underlying beam-induced heating. The other CPMU, CUT18, presented in this paper is based on exactly this experience and is designed as a standard undulator incorporating two small LN₂ tanks as cooling sources. The findings from CU15 were crucial in evaluating the feasibility of CUT18, which features liquid nitrogen tank cooling supplied via the facility's existing infrastructure. During the design phase, multiple factors were carefully considered to ensure that CUT18 possesses sustainable features, advanced magnetic performance, and reliable operational capabilities.

1. *Optimized the magnetic field:* Advancements in permanent magnet technology have led to significant improvements in the performance of short-period undulators. Recent advancements in terbium (Tb)-diffused neodymium-iron-boron (NdFeB) magnets demonstrate magnetic properties that are comparable to those of praseodymium-iron-boron (PrFeB) magnets, which are currently favored for CPMU applications. The increasing market demand for new grades of NdFeB permanent magnets further stimulates higher performance and points to a promising future for NdFeB-based CPMU. In addition to material selection, the effective magnetic field can also be enhanced by adjusting the magnetization angle within the magnet [1]. This approach has also been studied and adopted in CUT18 to further enhance the magnetic field.

2. *Sustainability considerations:* The optimum operating temperature for CUT18, an NdFeB-based CPMU, is above

*Contact author: huang.juiche@nsrrc.org.tw

†Contact author: chuang.phd@nsrrc.org.tw

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TABLE I. Specifications of CUT18 in comparison with CU15.

Items	Unit	CU15	CUT18
Magnet temperature	K	80	160
Cooling method		Cryocooler	LN ₂ evaporation
Length	m	2	2
Magnet material		PrFeB (NMX-68CU) + Dy diffusion	NdFeB (NMX-U52SH) + Tb diffusion
Remanence, B_r	T	1.65 at 80 K	1.60 at 160 K
Coercivity, H_{cj}	kA/m	6200 at 80 K	3200 at 160 K
Magnetization tilt angle	°	0	17
Period length, λ_u	mm	14.95	17.96
Magnet gap, G_{mag}	mm	5.2	5.2
Effective magnetic field, B_{eff}	T	1.02	1.23
Deflection parameter, K		1.43	2.06
Number of periods		133	111
Taper undulator function		No	Yes
Power consumption	kW	16.0	0
LN ₂ consumption	L/h	0	8.0

150 K. Therefore, the cooling system design prioritizes sustainability based on LN₂ evaporation. Liquid nitrogen supply is shared from an existing monochromator at the x-ray beamline, eliminating the need for a dedicated LN₂ supply infrastructure. This approach results in significant cost savings in both infrastructure and operational expenses. Compared to CU15 based on cryocoolers, LN₂ evaporative cooling requires substantially less electricity and annual maintenance. This reduced energy consumption makes the CPMU more environmentally friendly and cost-effective, ensuring long-term economic viability and contributing positively to the sustainability profile of the future light sources.

This paper presents an overview of the NdFeB-based CPMU (CUT18) installed at the Taiwan Photon Source and addresses the challenges related to beam-induced heating that occurred during its operation. The technical sections begin from Secs. II to IV. Section II highlights the uniquely key features, while Secs. III and IV demonstrate its cryogenic and magnetic performance, respectively. Section V focuses on the operational results when CUT18 operates at a beam current of 500 mA in the TPS storage ring.

II. FEATURES OF CUT18

A. Specifications of CUT18

Two short-period undulators, namely, CU15 and CUT18, have been constructed and developed for TPS, a typical medium-energy storage ring. Both undulators are CPMUs and share a common design philosophy, employing a conduction cooling method. However, as shown in Table I, there are key differences in the cooling techniques and magnet materials used in these two CPMUs. Differently from the CU15 undulator cooled with cryocoolers, the CUT18 undulator cooled by LN₂ evaporation employs a LN₂ tank as its cooling station (Fig. 1). Since the

cooling capacity of the LN₂ tank system depends on the latent heat of vaporization of LN₂, it is difficult to lower the temperature of the magnet array below 80 K. For this reason, instead of using PrFeB magnets, NdFeB magnets are utilized, as they exhibit superior magnetic properties at intermediate temperatures of approximately 150–160 K.

CUT18 has been specifically designed as a standard undulator for a variety of scientific applications, with the primary goal of achieving a deflection parameter, K , greater than 2. In order to enhance the magnetic field strength and achieve a higher K value, CUT18 uses high-remanence NdFeB magnets with an optimized magnetization tilt angle within its magnetic circuit. CUT18 was constructed based on the considerations outlined above, and successfully



FIG. 1. TPS-CUT18 installed in the TPS storage ring.

commissioned in the TPS storage ring in December 2021, becoming fully operational for user experiments in 2023.

B. Cooling station with LN₂ tank

As shown in Fig. 2, one of the features of the conduction-cooled TPS-CPMU is its ability to operate with either a cryocooler or a liquid nitrogen tank as the cooling source. This design enables the use of cryocoolers during magnetic field measurements in the laboratory, which can later be replaced by LN₂ tanks for operation in the storage ring, without disassembling the magnet arrays. This flexibility increases operational adaptability by allowing the user to choose between two cooling methods depending on available resources and experimental requirements. This configuration is especially beneficial when performing magnetic field measurements and various corrections in laboratories where LN₂ supply lines are not available. In addition, all components, including the heat transfer feedthroughs, thermal straps, and in-vacuum girders, which require high thermal conductivity properties, are made of oxygen-free copper and contribute to the overall efficiency of the heat transfer mechanism.

The CUT18 design incorporates two cooling stations located in a vacuum environment separated from the ultrahigh vacuum of the ring. Figure 2 shows one of these cooling stations, featuring an LN₂ tank that is directly connected to the facility's LN₂ supply line. Notably, this LN₂ supply line is shared with the monochromator cooling system at the x-ray beamline, demonstrating a resource-efficient approach by utilizing shared LN₂ infrastructure.

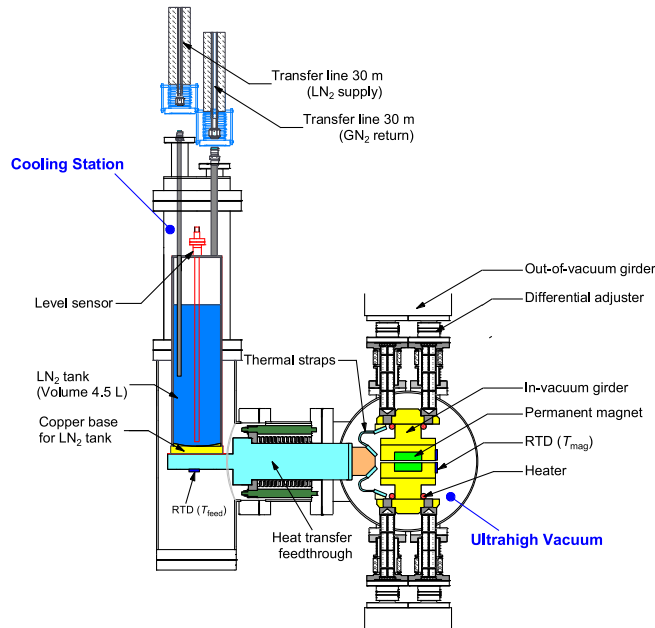


FIG. 2. Cooling station with a LN₂ tank. The tank can be replaced with a cryocooler if necessary. RTD denotes a resistance temperature detector.

A LN₂ tank integrated into the cooling station is connected via two transfer lines: one designated for LN₂ supply and the other for the return of gaseous nitrogen (GN₂). In total, four transfer lines serve the two cooling stations at CUT18, passing through the accelerator tunnel wall.

The LN₂ tank has been specifically designed to store liquid nitrogen as a cooling source for a CPMU. The base of the LN₂ tank is constructed from oxygen-free high thermal conductivity copper to enhance heat transfer efficiency, while the body is made of stainless steel to ensure durability and withstand the pressure of cryogenic operation. Each of the two compact LN₂ tanks used in the system has a total capacity of 4.5 L, which is adequate for cooling purposes for a CPMU. To ensure reliable monitoring of the LN₂ levels, each tank is equipped with two level sensors—one for measuring the LN₂ level during standard operation, and the second serving as a backup to provide redundancy.

The valve control system for the cooling stations (as shown in Fig. 3), which includes valve tanks, gaseous nitrogen pressure controllers, and LN₂ level regulators, is located in the experimental hall. This strategic placement minimizes radiation exposure and facilitates easier maintenance. The regulation of LN₂ supply and GN₂ pressure control valves is handled by a Programmable Logic Controller (PLC, Siemens TP900), which ensures automated and precise system control. Specifically, LN₂ levels are regulated by control valves (CV1 and CV2), based on inputs from level sensors (LPT1 and LPT2), while pressure control valves (CV3 and CV4) are managed in coordination with pressure sensors (PT1 and PT2). During normal operation, the LN₂ level within each tank is maintained between 65% and 75% of total capacity, and

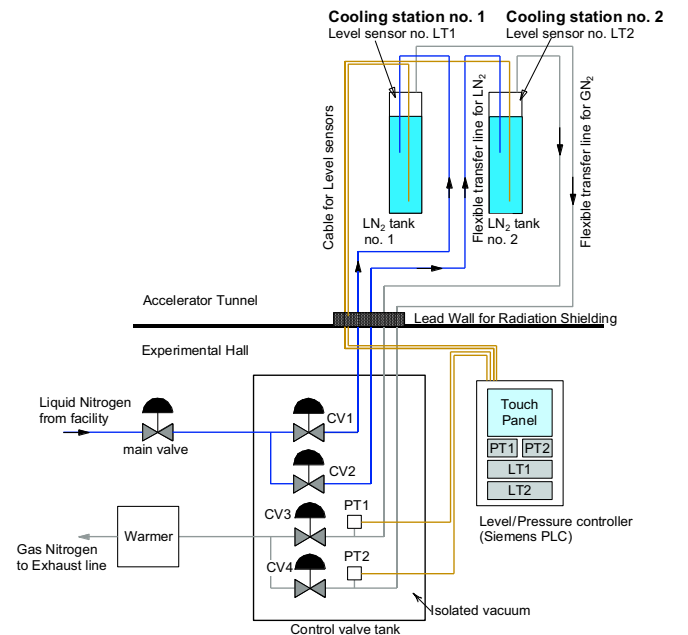


FIG. 3. Control valve for LN₂ level and nitrogen gas pressure.

the internal pressure is regulated to remain within a range of 1.05 to 1.1 bar.

III. COOLING PERFORMANCE OF CUT18 WITH LN₂ TANK

A. Cooling process of CUT18

The cooling process of CUT18 after filling the LN₂ tanks is shown in Fig. 4. The cooling process takes approximately 60 h for the magnet to reach its lowest recorded temperature of 110 K. During the initial phase of cooling, a significant amount of nitrogen gas is generated due to the vaporization of LN₂ upon contact with the higher-temperature copper base. This rapid vaporization creates a layer of nitrogen vapor between the LN₂ and the copper. The presence of this vapor layer impedes direct contact between the LN₂ and the copper, substantially reducing the rate of heat transfer. This phenomenon, known as film boiling, results in inefficient cooling and significantly slows down the cooling process.

As the cooling process continues, the temperature at the bottom of the LN₂ tank gradually decreases. After approximately 42 h, the bottom temperature reaches 93 K, at which point a sharp temperature drop is observed. This marks a critical transition from film boiling to nucleate boiling, as shown in Fig. 4, where the rate of decrease in magnet temperature accelerates significantly. This transition demonstrates the higher heat transfer efficiency of nucleate boiling, as the insulating vapor layer is eliminated, allowing for direct liquid-solid contact that greatly enhances heat dissipation.

B. Evaluating cooling margins: From film boiling to nucleate boiling

The “cooling margin” represents the available cooling capacity to counteract beam-induced heating in a CPMU.

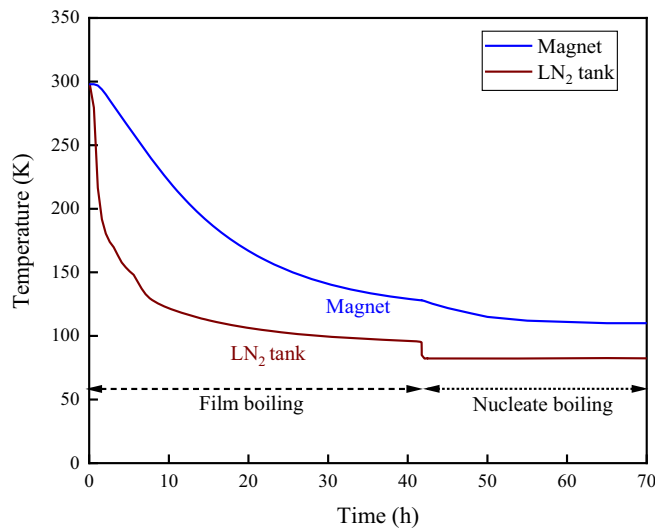


FIG. 4. Temperature of magnets and LN₂ tank changing over time during the cooling process.

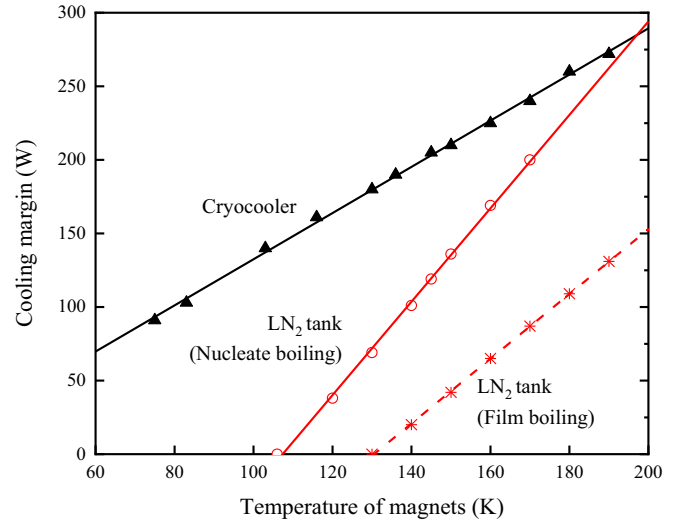


FIG. 5. Comparison of the magnet temperature dependence of the cooling margin between LN₂ tank and cryocooler cooling at CUT18, with a magnet gap (G_{mag}) of 20 mm.

At CUT18, two different cooling sources can be utilized: cryocoolers or LN₂ tanks. For LN₂ tank cooling, the cooling margin was measured under both film boiling and nucleate boiling conditions, as shown in Fig. 5. When film boiling becomes dominant, the cooling margin decreases significantly—by approximately 50% compared to nucleate boiling. Therefore, nucleate boiling must be ensured for LN₂ tank cooling due to its superior heat transfer efficiency. Accordingly, all subsequent discussions will focus on LN₂ tank cooling under nucleate boiling conditions.

Figure 5 further shows that the cooling margin provided by cryocoolers is approximately 20% greater than that provided by LN₂ tanks at a magnet temperature of 160 K. However, the difference in cooling performance between the two methods is not substantial. This implies that the current conduction-cooling design for CUT18 can effectively utilize either cryocoolers or LN₂ tanks without the need to modify the conduction cooling mechanism. Since the cryocooler is intended as an emergency backup, maintaining an unchanged cooling mechanism design and enabling a swift transition from LN₂ to cryocooler is particularly important. Additionally, the cooling margin exhibits a linear dependence on magnet temperature. When NdFeB magnets are at 160 K, the cooling margin exceeds 170 W, which is sufficient for operating the CUT18 at the TPS storage ring with a beam current of 500 mA. This indicates that LN₂ tank cooling is not only adequate but also provides a reliable safety margin for CPMU operation under high beam current conditions.

To ensure effective cooling in CUT18, two critical requirements must be met: (1) the design of the LN₂ tank must meet nucleate boiling conditions, and (2) the temperature control systems should be activated only after

nucleate boiling is fully established. Activating temperature control on the magnets before nucleate boiling is established could prevent the LN₂ tank from reaching nucleate boiling conditions, resulting in persistent film boiling with poor cooling performance.

C. Cooling capacity of LN₂ tank

The cooling capacity of a cryocooler can either be measured through an independent experimental setup or provided directly by the manufacturer. However, determining the cooling capacity of LN₂ tank independently poses significant challenges to measure it accurately. Therefore, the cooling capacity of the LN₂ tank was estimated based on the rate of LN₂ consumption. In this method, the supply of LN₂ is stopped, and the mass of LN₂ consumed, denoted as M , is measured in kilograms over a defined time period, T , in seconds. Using the specific latent heat of vaporization for LN₂, $L = 199.2$ kJ/kg, the cooling capacity (P_{cooling}) of the LN₂ tank can be estimated using the following equation:

$$P_{\text{cooling}} = \frac{M \times L}{T}$$

This estimation is made at a specific magnet temperature, with heater power applied to concurrently measure the cooling margin, represented by the heater power under no-beam conditions ($P_{\text{heater},0}$). However, it is important to note that this method only provides a rough estimate of the cooling capacity and may introduce some error. The total system heat load, P_{system} , can be estimated by subtracting the heater power from the cooling capacity:

$$P_{\text{system}} = P_{\text{cooling}} - P_{\text{heater},0}$$

The dependence of the cooling capacity (P_{cooling}), cooling margin (P_{margin}), and system heat load (P_{system}) on the magnet temperature (T_{mag} in Kelvin) is provided in Table II.

IV. MAGNETIC PERFORMANCE

A. Choice of magnet material

PrFeB permanent magnets are considered the preferred choice for constructing CPMUs [7], particularly when the

TABLE II. Dependence of P_{cooling} , P_{heater} , and P_{system} on the magnet temperature, T_{mag} (K), with $G_{\text{mag}} = 20$ mm.

T_{mag} (K)	P_{cooling} (W)	$P_{\text{heater},0}$ (W)	P_{system} (W)
110	130	0	130
130	193	71	123
150	259	139	119
160	285	170	115

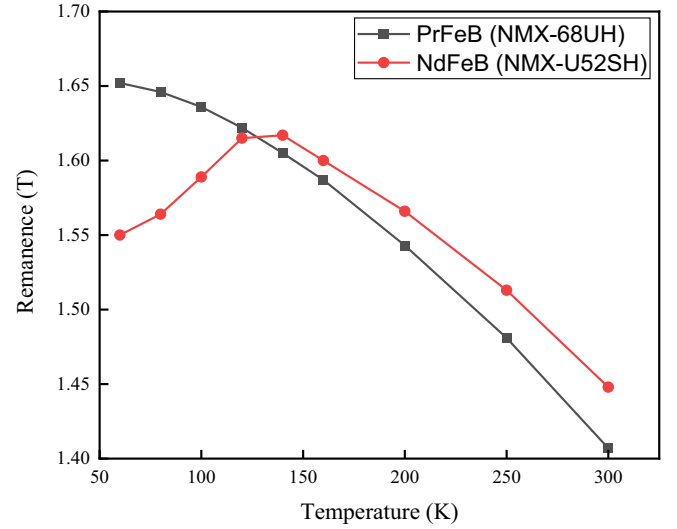


FIG. 6. Comparison of remanence between PrFeB magnet (NMX-68UH) and NdFeB magnet (NMX-U52SH) at various temperatures.

operating temperature is 80 K or lower. This preference arises because PrFeB retains and enhances its magnetic properties at such low temperatures, as illustrated in Fig. 6. However, the high production costs and limited market demand for PrFeB have restricted further research and development into new grades of this material. As a result, the high cost and limited availability of PrFeB have posed challenges for its selection as the primary material for CPMUs. NdFeB magnets offer an alternative to PrFeB for CPMU applications. The remanence of NdFeB magnets (e.g., NMX-U52SH) reaches a maximum value of approximately 1.6 T at a temperature of 150 K. In comparison, as shown in Fig. 6, PrFeB magnets (e.g., NMX-68UH) exhibit a remanence of 1.65 T at 80 K. The difference in remanence between PrFeB and NdFeB magnets is relatively small—approximately 3%. This minor difference suggests that both PrFeB and NdFeB possess the potential to be utilized in the design of future CPMU designs. Furthermore, with proper temperature control, NdFeB magnets can be effectively employed in CPMUs.

B. Tilted magnetization angle

The effective magnetic field (B_{eff}) of a CPMU can be improved by adjusting the magnetization angle (Fig. 7) of the magnets in the magnetic circuit [1]. The simulation results presented in Fig. 8, obtained using ELF-MAGIC [8], demonstrate that B_{eff} reaches its maximum when the magnetization is tilted at an angle of approximately 17°, resulting in an enhancement of about 5%. The mechanism behind this enhancement can be explained as follows: when the magnetic gap decreases, the permendur poles within the magnet arrays approach magnetic saturation. Under these conditions, the magnetic flux generated by the magnets with tilted magnetization is more effectively directed

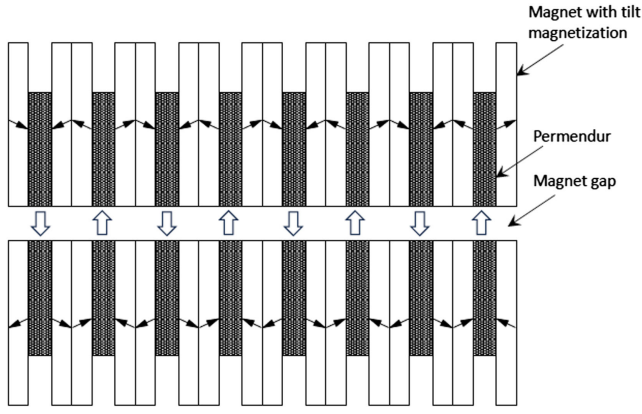


FIG. 7. Magnets with tilted magnetization for CUT18.

toward the center of the undulator, thereby enhancing the effective magnetic field. At cryogenic temperatures, permanent magnets exhibit significantly improved properties, including increased magnetic remanence and coercivity, whereas the magnetic properties of the permendur poles remain unchanged since the B-H curve is not significantly affected by temperature reduction. As a result, the effective magnetic field (B_{eff}) at cryogenic temperatures is enhanced more substantially compared to room temperature, primarily due to the increased magnetic flux density directed into the magnetic gap from the magnets with tilted magnetization.

In the CU15, PrFeB magnets have a magnetization angle of 0° and a remanent magnetic field of 1.65 T at 80 K (Table I). In contrast, the CUT18 utilizes NdFeB magnets with a magnetization angle of 17° and a remanent field of 1.60 T at 160 K. Additionally, the magnetization angle is specified to be within $\pm 1^\circ$, with a measured standard

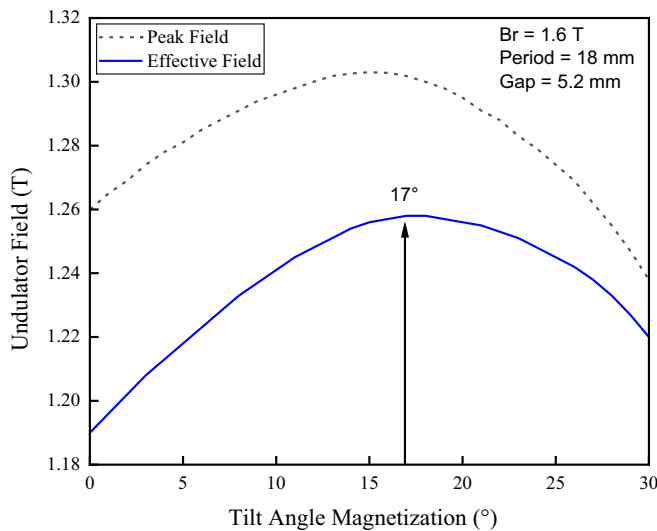


FIG. 8. Dependence of the peak and effective fields on the tilt angle (simulation).

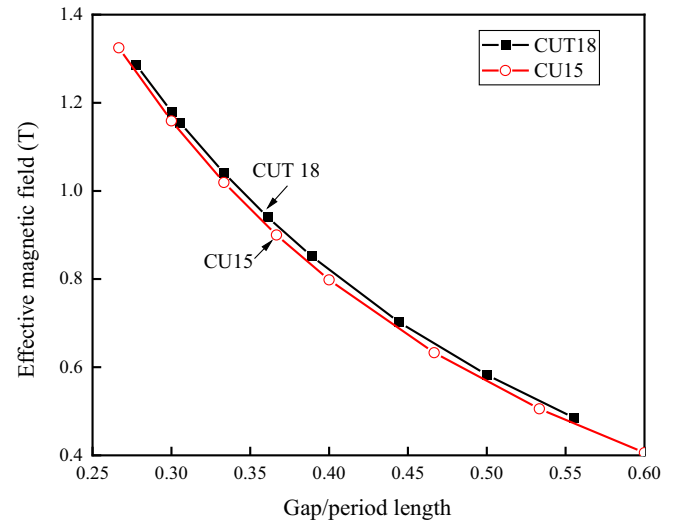


FIG. 9. Dependence of the effective field of CUT18 on the gap normalized by period length in comparison with that of CU15. The effective magnetic field is defined as $B_{\text{eff}} = \sqrt{\sum_n B_n^2/n^2}$, where B_n represents the n th harmonic component of the magnetic field obtained from a discrete Fourier transform [9].

deviation of less than 0.15° . Figure 9 shows the normalized dependence of the effective magnetic field on the gap for both CPMUs, demonstrating that the NdFeB-based CUT18 exhibits superior performance even after normalizing for gap/period. Despite the 3% lower remanent field, CUT18 achieves a higher effective magnetic field than CU15 due to the optimized magnetization tilt. These results highlight the effectiveness of optimizing magnetization direction through tilting, as implemented in CUT18, to enhance the effective magnetic field in CPMUs.

C. Magnetic field variation with temperature

The NdFeB magnet reaches its maximum magnetic field strength in the temperature range of 140–160 K due to a magnet spin-orientation transition phenomenon. It is therefore crucial to determine the optimal operating temperature based on this effective magnetic field, ensuring the magnet operates at maximum performance. The effective magnetic field was measured at a gap of 5.0 mm from 200 to 140 K. Figure 10 illustrates that the magnet field reaching an optimal point at 160 K.

Figure 11 demonstrates that the effective magnetic field increases by approximately 9% as the temperature decreases from 300 to 160 K. This indicates that the magnetic properties become enhanced at lower temperatures. It is expected that the effective magnetic field strength will increase by around 10% compared to the remanent field at room temperature (details can be found in Fig. 6). Additionally, when the gap is 5.2 mm, the undulator parameter (K) exceeds a value of 2, signifying that the CUT18 is successfully achieving its design objectives.

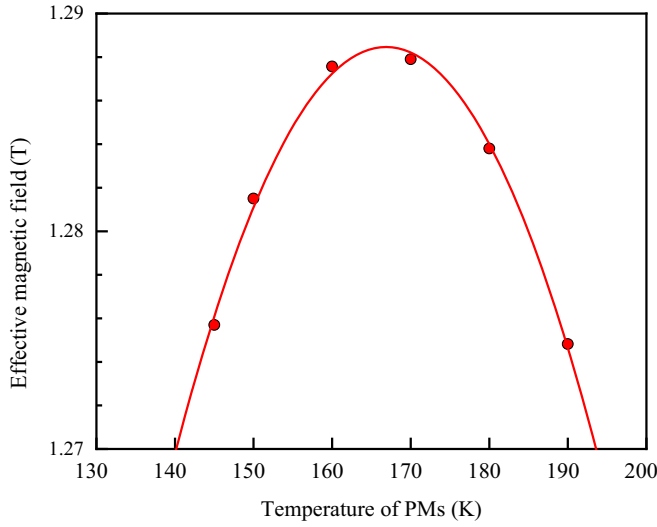


FIG. 10. Magnet temperature dependence on the effective field of CUT18, while $G_{\text{mag}} = 5.0$ mm.

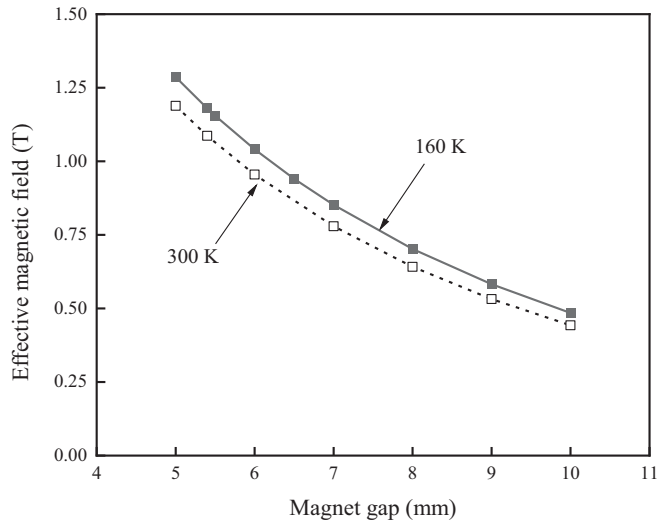


FIG. 11. Gap dependence of the magnetic field in CUT18 at 300 and 160 K.

D. Phase errors

Maintaining a low rms phase error is critical to the performance of advanced undulators and is often a key specification parameter. Figure 12 shows the K value dependence of the rms phase error in CUT18 at room temperature 300 K or low temperature 160 K. Although the differential adjusters and spring modules [10] had to be readjusted as the magnetic field value increased with lower temperature, a phase error of less than 2.2° was obtained at a practical maximum K value of 2.15.

V. OPERATION WITH ELECTRON BEAM

During routine operation, the LN_2 consumption of the CUT18 cooling system is approximately 8 L per hour.

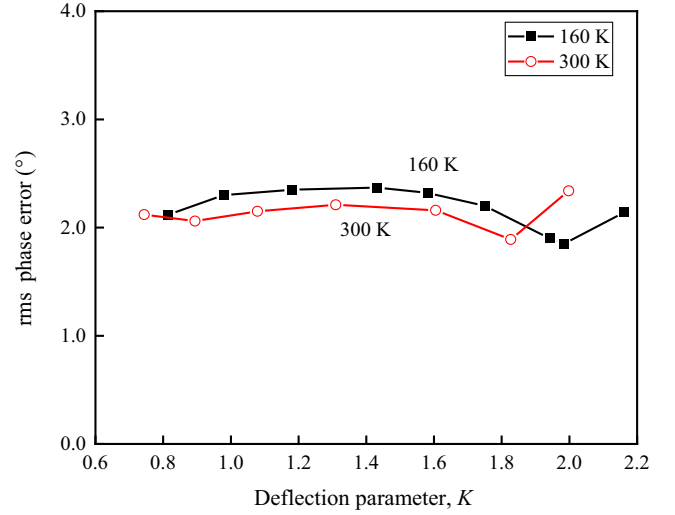


FIG. 12. Dependence of rms phase error of CUT18 varies on deflection parameter, K .

Since the LN_2 transfer lines and valves are integrated into the facility's cryogenic system, no specific annual maintenance is required for the CUT18 cooling setups. In addition to this, there is almost no vibration due to LN_2 tank cooling.

A. Beam-induced heat load

Figure 13 shows the gap dependence of the beam-induced heat load in CUT18 at the beam current of 500 mA in comparison with those in CU15. The data indicate that as the magnet gap is reduced, the beam-induced heat load correspondingly increases. Specifically, at a magnet gap of 5 mm, the heat load increases by approximately 25 W compared to the heat load observed at

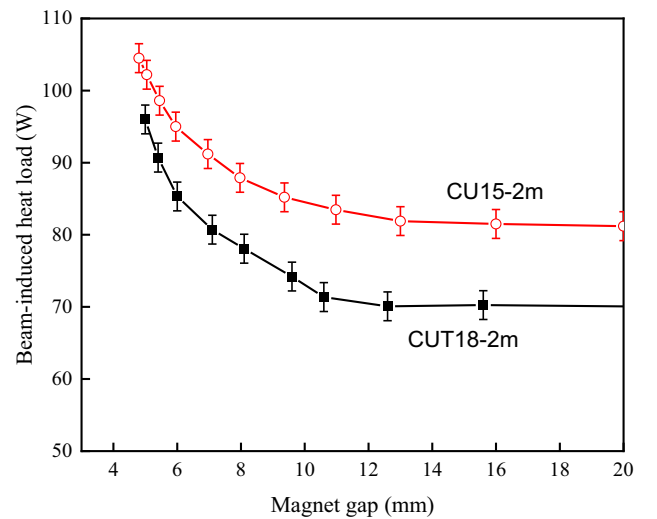


FIG. 13. Magnetic gap dependence of beam-induced heat load for CU15 and CUT18 at 500 mA beam current and 17 ps bunch length.

a gap of 20 mm. The maximum measured heat load was approximately 95 W at a magnet gap of 5 mm, which corresponds to a bunch length of 17 ps under an rf voltage of 3.0 MV.

The CUT18 undulator shares the same structural design as CU15, including key components such as the conduction cooling mechanism and transition tapers. However, the beam-induced heat load measured for CUT18 is consistently about 10 W lower than that observed for CU15 across all magnet gaps. This discrepancy appears to be independent of the magnetic gap, indicating that the difference likely originates from external heating sources. In particular, it is attributed to microwave power losses associated with the geometric impedance of the surrounding vacuum components. The vacuum components near CU15 and CUT18—such as the configurations of diagnostic devices, strip kickers, and vacuum pumps—differ from one section of the ring to another. As a result, the beam-induced heating differs between CU15 and CUT18 despite their identical internal structures. This observation suggests that the beam-induced heat load of a CPMU is not only determined by its internal structure design, but also by the configuration of upstream and downstream vacuum components.

Based on these observations, the current design of the CUT18 system, which relies on conduction cooling via two LN₂ tanks, appears to be effective in managing the observed heat load. The cooling margin of the system is approximately 70 W above the maximum observed beam-induced heat load. This cooling capacity is sufficient to ensure that CUT18 operates at a gap of 4 mm at 500 mA.

B. Temperature profile and stability of the magnet arrays

Figure 14 shows the temperature distribution along the magnet array in CUT18 for three different combinations of beam current and gap value, as shown in Table III. In the CUT18 system, 32 resistance temperature detector (RTD) sensors are uniformly placed along the upper and lower magnet arrays to monitor temperature along the entire 2-m length. These sensors, along with 4 heaters, are divided into four temperature control loops (upstream: TC-A and TC-B; downstream: TC-C and TC-D) enabling independent control of the front and rear sections of the magnet array. An EPICS-based PID software control approach was implemented [11] together with use EtherCAT I/O modules.

TABLE III. Operating conditions for beam current and magnet gap.

Case	Beam current (mA)	Gap (mm)
I	500	5.2
II	0	25
III	500	25

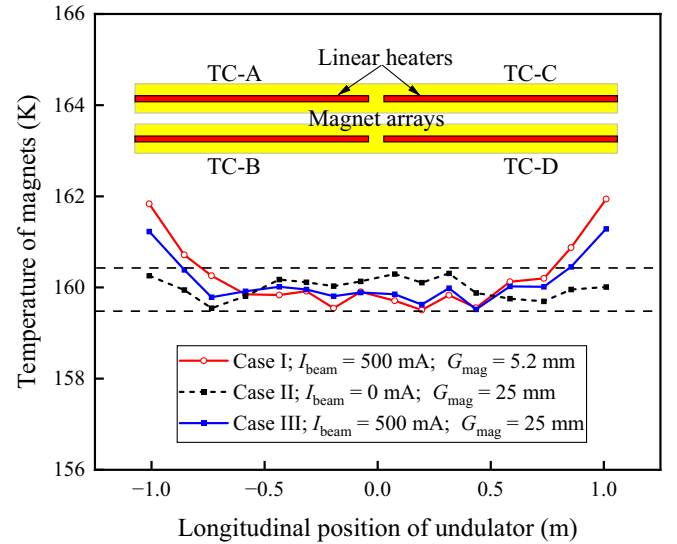


FIG. 14. Temperature deviation from 160 K along magnet arrays at gaps of 5.2 and 25 mm. The dashed lines indicate an area of 160 ± 0.5 K. The temperature at each longitudinal position shown in the figure is the average of the temperature at the corresponding position in the upper and lower magnet arrays.

In this configuration, the average temperature from six RTD sensors is used as the input signal for the PID controller, excluding the highest and lowest values to mitigate the impact of potential sensor malfunctions on each control loop. The heaters are then adjusted accordingly to control the temperature of each part of the magnet arrays (TC-A, TC-B, TC-C, and TC-D).

Figure 14 shows that at zero beam current, the temperature of the magnet array is maintained within the range of 160 ± 0.5 K. However, at a beam current of 500 mA, there is a significant temperature increase at both ends of the array and that this trend is even more pronounced at narrower gaps. In all cases, the temperature profile is symmetrical in the middle of the magnet array, with increased temperature near both ends. This symmetrical distribution suggests that heating is not primarily caused by synchrotron radiation or resistive wall heating. Instead, it is likely attributed to microwave power incident from outside the undulator and beam-induced heating generated by the geometric impedance at both ends of the magnet array.

Nonuniform temperatures within the magnet array can lead to variations in the gap, which, in turn, increase phase errors. However, the temperature nonuniformity in CUT18 is relatively small—approximately 2 K—and occurs only at the ends of the magnet array. Based on analysis [7], the resulting increase in phase error is estimated to be around 0.2° . This level of gap error is sufficiently minor that it does not degrade the spectral performance of CUT18.

Figure 15 illustrates the gap change of CUT18 and the corresponding temperature variations in the four magnet array sections (TC-A, TC-B, TC-C, and TC-D) over a 2-h period before and after an electron beam abort and

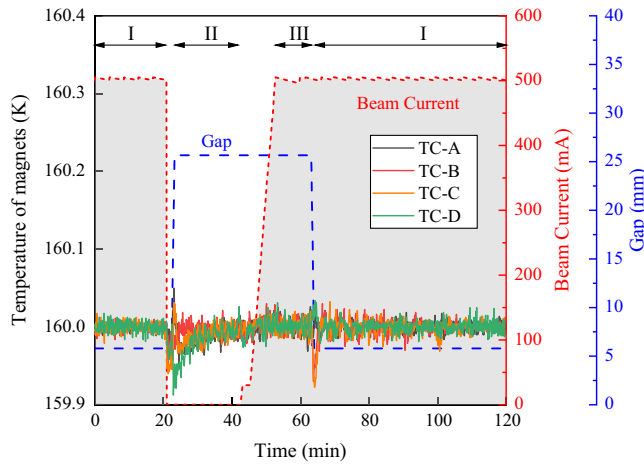


FIG. 15. Temperature variation over time under different beam current and magnet gap conditions. The combinations correspond to the cases listed in Table III.

restorage. This figure captures the thermal response of each section during transitions between three operational states: from case I to case II (electron beam abort), case II to case III (electron beam reinjection and restorage), and case III back to case I (gap close). During the transition from case I to case II, the temperature variation in each section reaches approximately ± 0.08 K. Despite this change, the resulting increase in phase error is found to be negligibly small. Similarly, during the transition from case III to case I (gap changes from 25 to 5.2 mm), the temperature change is around ± 0.06 K, again resulting in minimal impact on phase errors. Under steady-state conditions in case I, temperature stability is maintained within ± 0.015 K. These results demonstrate that the implemented temperature control scheme provides a highly effective approach, enabling stable and reliable operation of the CUT18 under typical storage ring conditions.

VI. CONCLUSION

The development and successful operation of the CUT18 undulator, which employs liquid nitrogen evaporative cooling and readily available NdFeB magnets, represents a major advance in short-period undulator technology for synchrotron light sources. TPS-CUT18 integrates advanced features that not only enhance its operational performance and reliability but also align with sustainability goals for modern storage ring concepts. Key advancements in LN₂ tank cooling, magnetic optimization, temperature control, and system adaptability demonstrate CUT18's suitability for demanding scientific applications. (1) Flexible cooling approach allows the use of either liquid nitrogen tanks or cryocoolers, offering exceptional operational adaptability. The LN₂ tank cooling system is integrated with the facility's LN₂ supply lines, enhancing resource efficiency, while use of LN₂ reduces energy consumption and

operational costs. A critical aspect of the LN₂ tank design is its ability to support the onset of nucleate boiling to enhance heat transfer performance for stable and effective cooling. (2) CUT18 uses high-remnance Tb-diffused NdFeB magnets, optimized for operation at temperatures of magnets between 150 and 160 K. Compared to PrFeB magnets, NdFeB offers comparable magnet remanence with promising potential for future applications. Additionally, the magnet has the optimized magnetization tilt angle significantly enhances the effective magnetic field, advancing the performance of short-period CPMU in synchrotron light sources. (3) With LN₂ tank cooling, CUT18 exhibits exceptional operational reliability, offering substantial cooling margins to meet the high heat load demands of beam currents up to 500 mA. Its spectral performance confirms that CUT18 successfully meets its design objectives. (4) The present temperature control approach is highly effective for the current cryogenic permanent magnet undulator operation. It was observed that the time variation of the magnet array temperature with the change in gap value was suppressed within ± 0.08 K at worst and within ± 0.015 K for a constant gap value.

These achievements in the CUT18 undulator not only improve the robustness of CPMUs aimed at enhancing spectral performance and operational sustainability but also reinforce the role of CPMU designs in modern light source facilities.

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DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

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