

SUSTAINABILITY-ORIENTED CRYOGENIC PERMANENT MAGNET UNDULATOR (LN₂-ENABLED C³-CPMU)*

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Abstract

A sustainability-oriented cryogenic permanent magnet undulator, the LN₂-enabled C³-CPMU, has been successfully demonstrated at the Taiwan Photon Source (TPS). The system is designed to address cryogenic performance, thermal stability, and cost efficiency for high-current storage ring operation (up to 500 mA). The undulator employs a conduction-cooled architecture combined with an LN₂ reservoir-based cooling scheme with simplified flow and pressure control, eliminating the need for dedicated cryogenic units. Operating at an intermediate temperature of 150–160 K, the system consumes approximately 8 L/h of LN₂. Active temperature control maintains the magnet temperature within ± 0.08 K under varying beam conditions, ensuring stable magnetic field performance. The enhanced magnetic properties at cryogenic temperatures enable shorter undulator periods, while integration with existing facility LN₂ infrastructure significantly reduces system complexity and operational overhead. These results demonstrate a scalable and energy-efficient solution for next-generation synchrotron and XFEL light sources.

INTRODUCTION

As synchrotron radiation facilities pursue higher X-ray spectral brightness, cryogenic permanent magnet undulators (CPMUs) have become one of the keys enabling technologies [1]. At cryogenic temperatures, permanent magnets exhibit higher remanence and coercivity, enabling stronger magnetic fields and improved photon performance. This allows shorter undulator periods and more compact device configurations.

In modern accelerator facilities, energy efficiency and sustainability have become important considerations. As a result, undulator design is constrained not only by device performance but also by facility-level requirements such as space, energy consumption, and infrastructure. In X-ray free-electron lasers (XFELs), long undulator lines significantly increase facility size and infrastructure demand. In ultra-low-emittance sources (ULEs), limited straight-section length requires compact and short-period undulators. The challenge is to achieve high performance under constraints of space and energy use. Although CPMUs improve magnetic performance, their implementation often relies on dedicated cryogenic systems that require continuous electrical power and maintenance. This limits their

practicality for large-scale deployment. To address this, we have proposed a conduction-cooled, constant-temperature CPMU (C³-CPMU) based on LN₂ reservoir-based cooling [2]. The system maintains stable magnet temperature under varying beam conditions with existing facility LN₂ infrastructure, eliminating standalone cryogenic systems and their power consumption. The concept has been validated with the TPS CUT18 undulator under realistic operating conditions [1].

DESIGN CONCEPT AND STRUCTURE OF LN₂-ENABLED C³-CPMU

Facility-Integrated LN₂ Cooling

The LN₂-enabled C³-CPMU utilizes evaporative liquid nitrogen (LN₂) as the primary cooling source, stored in a reservoir [3] and directly supplied from the existing beam-line cryogenic infrastructure (Fig. 1). Compared with recently developed CPMUs, including cryocooler-based CPMU or LN₂-cooled CPMUs employing standalone cryogenic flow control and pressure regulation unit, the LN₂-enabled C³-CPMU adopts a simplified flow-control strategy based on standard industrial components. As a result, the initial capital cost is significantly reduced, requiring only cryogenic valves and piping infrastructure. In addition, operational costs are minimized due to the absence of continuous electrical power consumption and reduced maintenance requirements associated with cryocoolers. A typical LN₂ consumption of approximately 8 L/h (corresponding to 4 ~ 5 kW of electric power) has been demonstrated (e.g., CUT18 [2]), whereas cryocooler-based CPMUs may require continuous electrical power on the order of ~16 kW (e.g., CU15 [3]).

Conduction-Cooled and Dual-Source Operation

The C³-CPMU adopts a conduction-cooled architecture in which heat is transferred from the magnet array through high-conductivity copper feedthrough before reaching the cooling system. In this indirect cooling scheme, the thermal resistance and thermal mass of the conduction path act as a natural low-pass filter, suppressing rapid temperature fluctuations and smoothing transient disturbances. The design also ensures a “zero-leakage” configuration by isolating the cryogenic fluid from the UHV environment, thereby improving reliability and simplifying maintenance. In addition, the conduction-cooled design supports a dual-source cooling configuration [3], which enhances operational flexibility and sustainability across different

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operating phases. Depending on the application, the cooling source can be switched between cryocoolers and an LN₂ reservoir, enabling operation during commissioning, routine operation, or as a redundancy mode.

Intermediate Temperature Strategy (150–160 K)

The operating temperature of 150–160 K is selected to balance magnetic performance and thermodynamic efficiency. At ~150 K, NdFeB magnets exhibit a remanence approximately 3% lower than that of PrFeB magnets at ~77 K. NdFeB magnets are selected due to their favourable balance between cost and availability, combined with widespread industrial adoption and continuous development, making them a scalable and future-ready material option. The selected intermediate temperature (150–160 K) is significantly higher than liquid nitrogen temperature (77 K), providing greater flexibility for system design. This temperature range is well suited for conduction-cooled LN₂ operation, enabling a practical implementation of the LN₂-enabled C³-CPMU.



Figure 1: CUT18 (LN₂-enabled C³-CPMU) tested with beamline LN₂ source in 2020.

Constant Temperature of Magnet

Storage rings and XFEL facilities both require precise temperature control, although the underlying constraints differ. In both cases, maintaining a stable magnet temperature and minimizing field taper induced by temperature gradients are essential. These requirements can be achieved using integrated heaters with feedback control to ensure thermal uniformity of the magnet arrays. The C³-CPMU employs an active temperature control system to maintain a nearly constant magnet temperature under varying beam conditions, including changes in beam current, bunch length, filling pattern, and undulator gap. The conduction-cooled structure suppresses rapid temperature fluctuations from the cooling sources, while integrated heaters and feedback control provide precise temperature regulation. Sensors distributed along the magnet array enable real-time monitoring and ensure uniform thermal conditions. More

importantly, the heaters effectively compensate the beam-induced heating under varying beam conditions. Unlike conventional water-cooled in-vacuum undulators, in which the magnet temperature varies with beam conditions, the C³-CPMU maintains a nearly constant temperature. Experimental results from TPS-CUT18 (Fig. 2) show that temperature fluctuations are suppressed within ± 0.08 K under transient conditions, even with a short bunch length of 16 ps. In addition, the temperature distribution along the 2 m-long CPMU is maintained within ± 0.5 K at 500 mA operation with a longer bunch length of approximately 32 ps (Fig. 3). These results ensure stable magnetic field and spectral performance of the LN₂-enabled C³-CPMU.

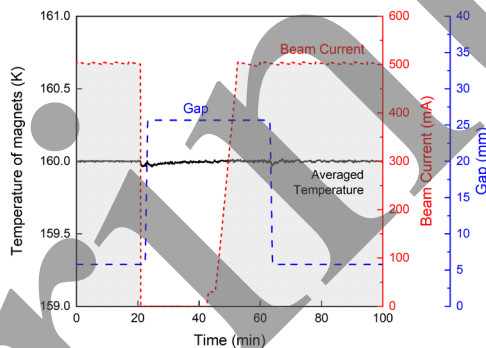


Figure 2: Temperature variation over time under different beam current and magnet gap conditions.

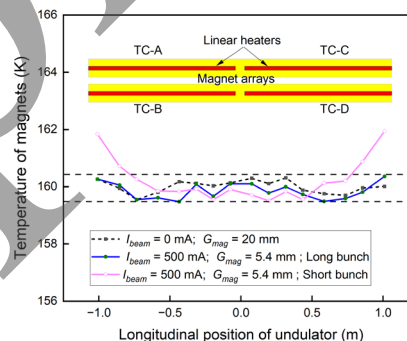


Figure 3: Temperature deviation from 160 K along magnet arrays. The dashed lines indicate an area of 160 ± 0.5 K.

SUSTAINABILITY AND FACILITY-LEVEL EFFICIENCY

Energy Efficiency

In recent CPMU implementations, cryocooler systems are required as direct or indirect cooling sources, consuming continuous electrical power and requiring periodic maintenance, which leads to high operational costs. Energy consumption in these systems scales with the number of devices and is limited to device-level optimization. In contrast, the LN₂-enabled C³-CPMU can be integrated with centralized cryogenic infrastructure, allowing its energy performance to be optimized at the facility level. As a result, overall efficiency depends on facility-wide factors,

particularly LN₂ distribution and delivery. Improvements at the device level, such as thermal insulation, play a secondary role.

Infrastructure Integration

The LN₂-enabled C³-CPMU is designed to integrate directly with existing facility LN₂ infrastructure, eliminating the need for standalone systems such as cryocoolers or closed-loop cryogenic systems. In many accelerator facilities, LN₂ is already available as a standard utility for beamline components such as monochromators or optical systems. By leveraging this existing infrastructure, centralized LN₂ supply and control can be implemented using an optimal architecture based on standard industrial components. This approach avoids the high capital cost associated with dedicated cryogenic systems, and improves adaptability for facility-wide integration. In addition, the C³-CPMU design enables retrofitting of existing in-vacuum undulators (IVUs) by replacing conventional water-cooling circuits with cryogenic interfaces, allowing reuse of high-value components such as vacuum chambers and mechanical frame.

Operational Reliability

Operational reliability is a critical requirement for accelerator operation. The LN₂-enabled C³-CPMU provides stable and reliable operation through improved demagnetization resistance, stable temperature control, and a cryogenic design that eliminates leakage risk to the vacuum system. Demagnetization effects at small-gap operation have been reported in various facilities, including in-vacuum undulators and elliptically polarizing undulators, in both storage rings and XFEL facilities. At cryogenic temperatures, the intrinsic coercivity (H_{cj}) of permanent magnets is significantly increased, improving resistance to radiation-induced demagnetization. This enhanced magnetic stability enables reliable operation at small gaps and contributing to extended operational lifetime. The active temperature control system maintains a nearly constant magnet temperature under varying beam conditions. The conduction-cooled architecture further enhances reliability by physically isolating the cryogenic medium from the UHV environment. These advantages are mentioned in the previous section.

In addition, the LN₂ supply is provided by the facility cryogenic system, which typically operates with multiple layers of protection and control. Compared with standalone cooling systems, this centralized infrastructure offers more stable and reliable operation.

Scalability

Scalability in modern accelerator facilities is governed by the ability to achieve high performance within constrained system resources, including available space, energy consumption, and cryogenic and utility infrastructure. This requirement becomes particularly critical in both ultra-low-emittance sources (ULESs) and X-ray free-electron laser (XFEL) facilities, although the underlying constraints differ. In ULESs, the adoption of multi-bend achromat (MBA) lattices reduces the electron beam emittance

to increase coherent photon flux within limited straight-section lengths. The use of long undulators operating at higher harmonics is generally less effective [1], making short-period and compact undulators more favorable. Conventional in-vacuum undulators (IVUs) typically require longer undulator lengths to achieve the desired spectral performance due to their limited magnetic field strength. This limits scalability in ULESs, where compact device footprints are essential.

In XFEL facilities, the primary constraint shifts from lattice matching to total accelerator length. IVU-based undulators require long sections to reach SASE saturation due to limited magnetic field strength, increasing demands on vacuum systems and facility utilities. Superconducting undulators can significantly reduce saturation length through higher magnetic fields, but require dedicated cryogenic infrastructure and high energy consumption. CPMUs provide an intermediate solution. The LN₂-enabled C³-CPMU enables shorter undulator periods and reduced device length without requiring dedicated cryogenic systems, offering a practical balance between performance and facility-level resource demands. As a result, the C³-CPMU provides a practical solution for both compact undulator design in ULESs and reduced undulator length in XFEL facilities.

SUMMARY

This work presents a conduction-cooled, constant-temperature CPMU (C³-CPMU) enabled by LN₂ reservoir-based cooling for next-generation accelerator facilities. By integrating LN₂ cooling with existing facility infrastructure, the system reduces energy consumption and simplifies cryogenic architecture. Operation at an intermediate temperature (150–160 K) enables high magnetic performance while maintaining system efficiency. Experimental validation using the TPS-CUT18 undulator demonstrates the feasibility of this concept. The LN₂-enabled C³-CPMU provides a scalable and sustainability-oriented solution through the co-optimization of magnetic performance, thermal stability, and facility-level integration.

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