This report features the project done by the Beam Dynamics Group, NSRRC.

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Technical Challenges of Cryogenic Permanent-Magnet Undulators at Taiwan Photon Source

X-ray beamlines of Phase II are under construction at the Taiwan Photon Source (TPS). As the spectral quality from cryogenic permanent magnet undulators (CPMUs) can be superior to that of in-vacuum undulators (IVUs), a PrFeB-based CPMU with a period length of 15 mm has been constructed to provide highly brilliant X-rays. The magnets of the CPMU must be cooled to 80 K to generate an effective magnetic field of 1.02 T at a gap of 5 mm. Two cryo-coolers, each with cooling capacity 220 W at 80 K, allow for the removal of external heat leaks up to a few hundred watts. An *in situ* and vacuum compatible field measurement system has been developed to characterize the magnetic field at cryogenic temperatures and to allow correction of gap errors due to temperature variations. The relevant techniques and challenges for the TPS-CPMU are presented here.

Introduction

Brilliant X-rays from undulators are highly desired in third-generation storage rings. The photon flux of coherent synchrotron radiation (SR) can be increased by improving the quality of the electron beam or undulator performance. Many low-emittance storage rings were recently constructed around the world to improve the quality of photon beams, but the construction is costly and a delicate multi-bend-achromat lattice is necessary. An economical option to provide more intense coherent photon flux in the hard X-ray region is hence to use undulators of short period with small phase errors. Among the most important challenges in the development of a short-period undulator is the ability to generate a sufficiently strong magnetic field. A cryogenic permanent magnet undulator can meet such goals and is thus suitable for the development of short-period undulators, which have become a recent focus of interest because most techniques for CPMU have already been developed for in-vacuum undulators.

Ultra-high-vacuum (UHV) compatibility for an undulator is an essential requirement for its installation in a storage ring. One can apply either high-temperature baking of permanent magnets (baking approach) or cool the permanent magnets (PMs) to cryogenic temperature (non-baking approach). A cryogenic permanent-magnet undulator uses the non-baking strategy while operating the undulator at cryogenic temperatures. The rate of outgassing from permanent magnets is very low as the low-temperature magnets and in-vacuum girder act as cryo-pumps.

The development project of TPS-CPMU, CU15, began in 2016 in collaboration with NEOMAX Engineering, Japan. In 2019, the CPMU has been completed and installed in the storage ring of the TPS; the development of related techniques with performance of the CPMU is described below.

Technical Challenges of TPS-CPMU

Several techniques have been developed for the TPS-CPMU, including a new grade PrFeB permanent magnet material with high remnant fields, a mechanical frame with force-compensating spring modules, a temperature-control system on the permanent magnets, a cryo-cooler to compensate for diverse sources of heat loads and compatibility with storage ring ultra-high vacuum standards. When PMs are cooled to 80 K, a CPMU can generate effective magnetic field of 1.02 T at a gap of 5 mm. The target is a minimum magnetic gap of 4 mm with an effective magnetic field of 1.32 T. **Table 1** summaries the main parameters of the TPS-CPMU. The expected brilliance energy spectrum is shown in **Fig. 1**. Compared to a standard undulator (such as an in-vacuum undulator with period length of 22 mm at TPS), an increased SR brilliance can be expected at photon energies above 10 keV.

Table 1: Main Parameters for the TPS-CPMU

Items	Unit	Cryogenic Temperature	Room Temperature
Magnet material		$Pr_2Fe_{14}B$ (NMX-68CU)	
Remanence (B_r)	T	1.67	1.40
Coercivity (H_{cj})	kA/m	6200	1689
Period length	mm	14.945	15.000
Min. magnet gap (G_{mag})	mm	5.00	–
Min. vacuum gap (G_{mag})	mm	4.80	–
Effective magnetic field	Tesla	1.02	0.86
Deflection parameter (K)		1.42	1.20
Magnetic force	kN	18.8	13.5
Number of periods		133	–
Operating temperature	K	80	300

Permanent Magnets

The performance of permanent magnets generally improves (increase in flux and coercivity) as temperature decreases. Permanent magnet materials, including NdFeB and PrFeB, are thus suitable for CPMU to operate at cryogenic temperatures. The operation of NdFeB is limited by temperature 140–150 K because of the magnet spin-orientation transition. In contrast, the remnant flux density of PrFeB increases as temperature decreases; a low temperature is suitable for the operation of a PrFeB PM. When the magnet temperature decreases, the increase of coercivity is higher than that of the remnant field. One can hence choose a magnet grade that is less resistant at room temperature but that presents a higher remnant field.

Based on the above reasoning, the material PrFeB, NMX-68CU (Hitachi Metals, NEOMAX Engineering), was chosen because sufficiently low temperatures can be achieved with cryo-coolers. When these PrFeB magnets were measured at 77 K, the remnant flux density was 1.67 T; the coercivity was 6211 kA/m. The remnant field of NMX-68CU at 77 K is 35% higher than that of NdFeB PMs (NMX-38EH) used for the TPS in-vacuum undulators at room temperature.

Spring Force-compensating Modules

To operation with a small phase error is desired for an undulator to allow the generation of higher harmonics without significant degradation of the SR brilliance. Behaving with a small phase error is hence an important consideration to evaluate the quality of an undulator magnetic field. Phase errors describe the fluctuation of phase difference between an electromagnetic wave from an undulator and a reference wave.

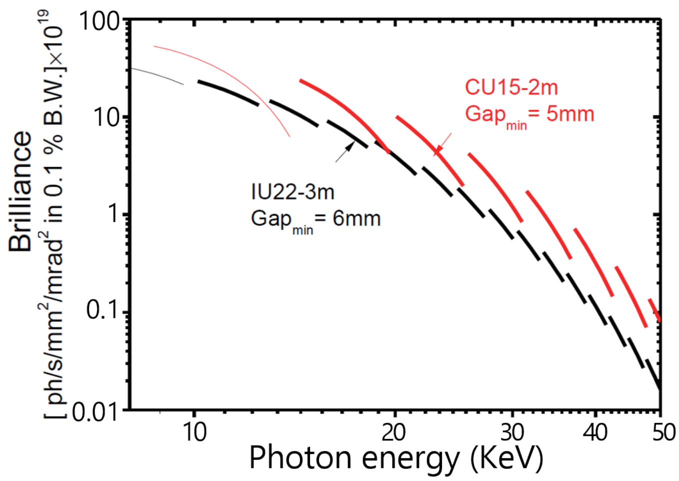

Fig. 1: Comparison of spectral brilliance between CPMU-2m and IU22-3m evaluated with SPECTRA. The parameters used for the calculation were E_{GEV} = 3 GeV, β_x = 5.3 m, β_y = 1.7 m, coupling parameter 0.001, emittance 1.6 nm·rad and energy spread 10^{-3}.

In a CPMU, phase errors are derived from gap errors caused by mechanical deformations and thermal effects in magnet arrays. Gap errors caused by mechanical deformations are gap-dependent coming from strong magnetic forces at small gaps. The magnetic forces increase exponentially with decreasing undulator gap. As a result, a conventional two-support configuration is no longer sufficiently rigid to keep the mechanical deformations small enough. A counter-force system (spring modules) in a four-support configuration of the mechanical frame was developed, as shown in **Fig. 2**, not only to compensate for the magnetic forces but also to obtain a mechanical frame mostly free of stress. Nevertheless, an optimized four-support configuration can maintain gap errors of the magnet arrays small.

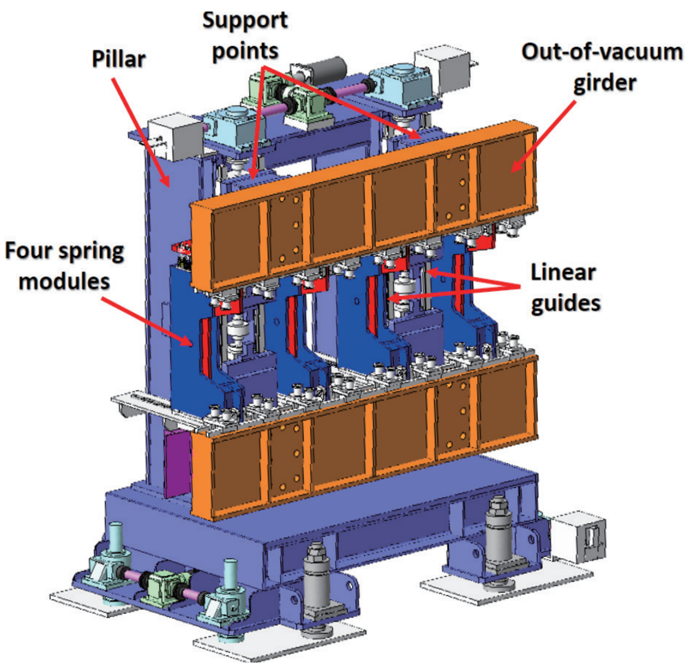

Fig. 2: A mechanical frame with spring force-compensating modules.

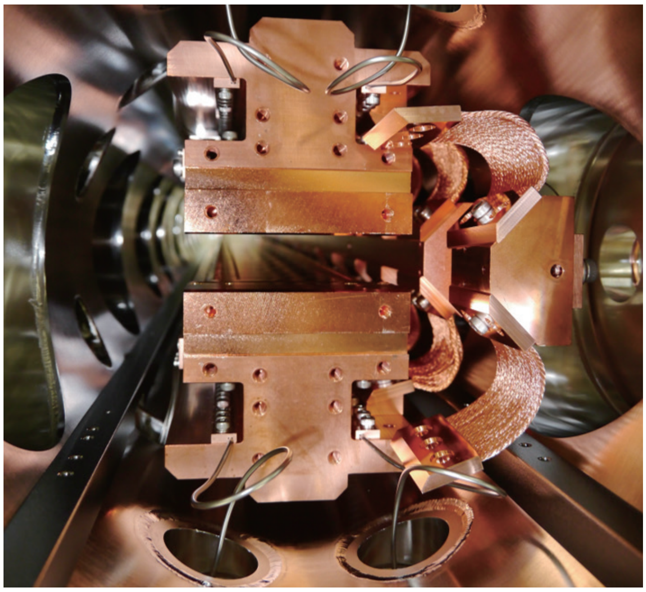

Fig. 3: Inner structure of the CU15.

Temperature Control System

The temperature of PM varies with beam-induced heat load, which includes resistive wall heating, SR from upstream bending magnets and absorption of scattered SR in the vacuum chamber. A constant temperature of a PM is desired to maintain the stability of the magnetic field and to obtain reproducible energy spectra of a CPMU under varied beam currents, fill patterns and gaps. A system to control temperature, including eight heaters, was installed along the magnet array with high-speed proportional-integral-derivative (PID) controllers to stabilize the PM temperatures. Moreover, the heaters can compensate a residual temperature gradient to eliminate field errors both from gap errors caused by material deformations dependent on temperature and from variations of remanent fields along the PM magnet arrays.

Cooling System

Most CPMU at other light sources use liquid nitrogen (LN_2) for cooling, which can provide a cooling power up to several kW. Direct cooling with either LN_2 or cooler-heads can be used for the PrFeB-CPMU because the PM temperature can be at or below 80 K. Cooler-heads were chosen for the CU15 at TPS because the initial investment for the cooling system is small; a suitable supply fo LN_2 is unavailable at the laboratory. Another important advantage is to avoid a vacuum risk because no weld seam exists nor is there an UHV pipe connection in the vacuum chamber of a CPMU. The two cryo-coolers are connected to the magnet arrays *via* flexible thermal straps and thermal conductance feedthroughs, as shown in **Fig. 3**. The cryo-cooler vacuum is designed to be separated from the vacuum of the storage ring, so that an annual maintenance of cold-heads can be performed without breaking the ring vacuum and completed within a brief interval. Prospective disadvantages associated with cryo-coolers include, for example, large operating costs and required annual maintenance; a cryo-cooler must be selected with low vibration. Commercial low-vibration cryo-coolers with cooling capacity 220 W at 80 K (Leybold 250MD) can serve to ensure stable operation of a storage ring.

Measurement System *in Situ* for the CPMU

A main task in the development of a CPMU is to allow the characterization of the magnetic field to correct gap errors due to assembly tolerances and temperature variations. Field corrections and measurements in a CPMU are typically performed outside the vacuum chamber at room temperature for easy access to the magnet array gap. PMs are cooled followed by the reassembly of magnets into a vacuum chamber; as a result, the field errors at cryogenic temperature might lead to temperature variations along the magnet arrays. A field-measurement system *in situ* is desirable to verify accurately the magnetic field and to correct errors. A Hall sensor is cooled with nearby cold magnets, therefore, a temperature-dependent calibration is necessary. All components of the system must be UHV-compatible to avoid contamination.

The measurement system *in situ* developed at TPS, as **Fig. 4** shows, is based on laser-positioned components and includes a feedback system. The Hall-probe carrier is moved along a customized rail located in the vacuum chamber between the undulator magnet arrays; its longitudinal position is determined with a laser interferometer. The transverse position of the Hall probe can be determined with laser beams in two sets and position-sensitive detectors (PSD). The probe sits on a rail, which is movable in the vertical/transverse direction with motorized stages; the offset of the probe from the proper position can be corrected automatically. Except for the laser system and PSD, the measurement system is enclosed in the vacuum chamber. A multiple-axis rotatable table allows movement in all degrees of freedom (orientation and displacement); the duration of system assembly in the CPMU chambers is brief.

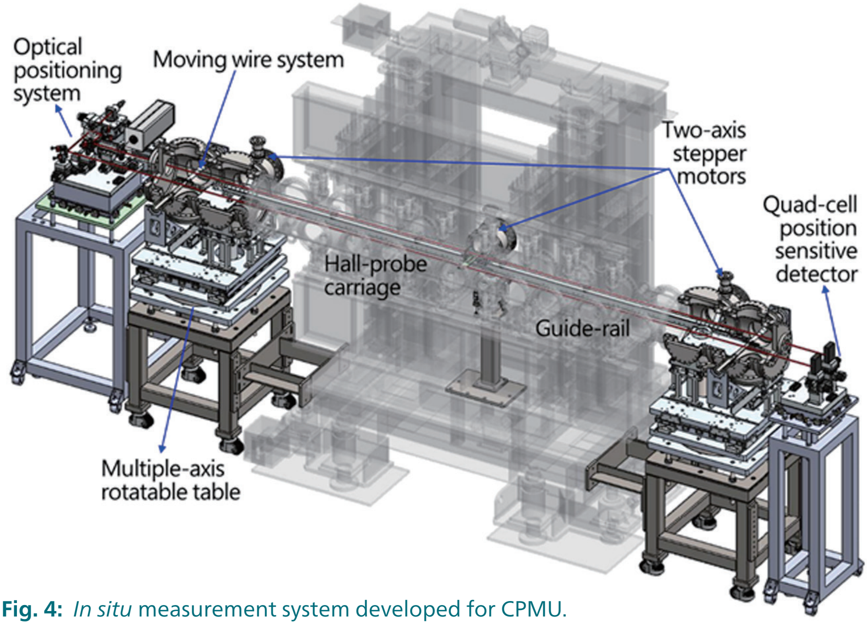

Fig. 4: *In situ* measurement system developed for CPMU.

Installation of CU15

Since 2019 September, the CPMU has been installed in the TPS tunnel, as shown in **Fig. 5**. The first cooling proceeded satisfactorily with no electron beam. After cooling for 30 h with two cryo-coolers, magnet temperature 80 K was attained.

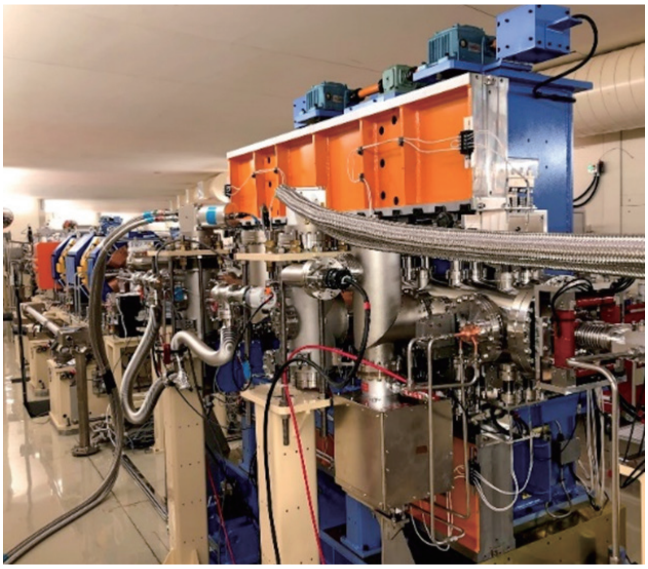

Fig. 5: CPMU installed at TPS storage ring.

The temperatures of the magnet array are controllable within 80 ± 0.4 K; the vacuum pressure reached 10^{-8} Pa. The undulator has been tested with electron beam 300 mA showing satisfactory performance, but some adjustments are necessary to allow operation at a greater beam current. (Reported by Jui-Che Huang)

This report features the work of Magnet Group, NSRRC.

Construction of a 500-MHz, 80-kW RF Transmitter with Solid-State RF Power Modules

An electrical impulse generated with a radio frequency (RF) cavity, which is a metallic chamber containing an electromagnetic field oscillating at a radio frequency, drives the acceleration of charged particles within the particle accelerators. The associated RF power provided by the RF power amplifier is transmitted to the RF cavity to create a high-voltage (HV) AC accelerating electric field. The RF power required for an electron beam to circulate inside the vacuum chambers of the booster and storage rings of NSRRC is at present generated with