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# PERFORMANCE OF TPS CRYOGENIC PERMANENT MAGNET UNDULATORS

Jui-Che Huang†, Chin-Kang Yang, Chih-Sheng Yang, Chih-Wei Chen, National Synchrotron Radiation Research Center, HsinChu, Taiwan
Hideo Kitamura, RIKEN SPring-8 Center, Hyogo, Japan
Tsutomu Kohda, NEOMAX Engineering Co., Ltd, Japan

*Abstract*

Development of cryogenic permanent magnet undulators (CPMUs) is the most recent activity for Phase-II beamlines at the Taiwan Photon Source. A hybrid-type CPMU with a period length of 15 mm, based on PrFeB permanent-magnet materials, is under construction. A maximum effective magnetic field of 1.33 T at a gap of 4 mm is obtained at 80 K.

## INTRODUCTION

A cryogenic permanent magnet undulator (CPMU) is regarded as a main source for highly brilliant X-rays at TPS. A CPMU with a period length of 15 mm, CU15, has been constructed in cooperation with NEOMAX Engineering Co. The main features of CU15 are the usages of (1) PrFeB permanent magnet material (PM) with remanent fields of 1.68 T at 80 K, (2) mechanical frame with force-compensating spring modules, (3) temperature control system on the permanent magnets, (4) cryo-coolers to compensate for various sources of heat loads and (5) separate vacuum to avoid conflict with storage ring ultra-high vacuum rules. The related technologies for CU15 were reported in [1-3]. The in-situ field measurement system is as important as the undulator development itself, in particular, the low temperature calibration system [4,5] and we present here the performance of CU15.

## CRYOGENIC UNDULATORS AT TPS

A CU15 was constructed and tested at NSRRC. Figures 1 and 2 show the CU15 with in-situ measurement system and a sketch of the CPMU, respectively.

Figure 1: Photograph of the TPS CPMU with an in-situ field measurement system.

† huang.juiche@nsrrc.org.tw

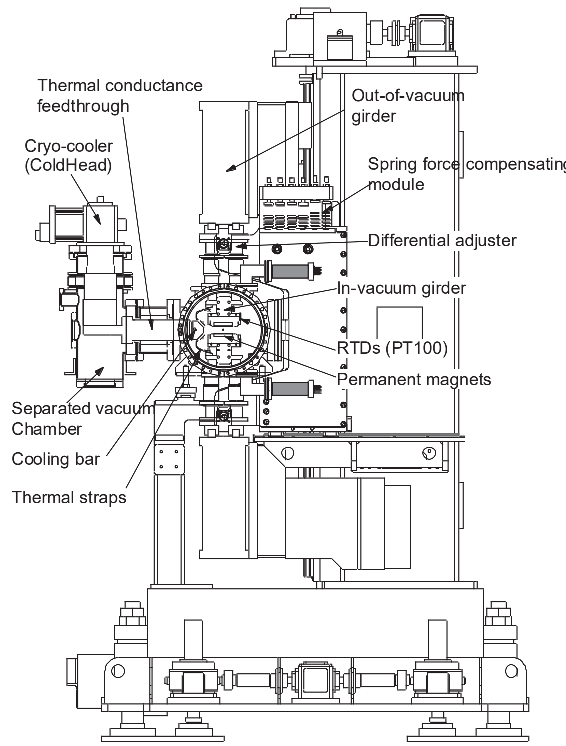


Figure 2: Sketch of the TPS CPMU.

## MAGNETIC FIELD PERFORMANCE

Low phase errors are desired characteristics for CU15 to allow the generation of higher harmonics without significant degradation of synchrotron radiation (SR) brilliance. Large RMS phase errors can be caused by magnetic field errors along the undulator axis originating from: (1) individual differences among the magnet blocks (remanent field and physical magnet dimension tolerances) and (2) undulator gap errors. By sorting and swapping magnets, the field differences among the poles can be minimized. Local gap errors derived from manufacturing tolerances (flatness of the in-vacuum girder, length of link rods) can be corrected by differential adjusters. These field-correction procedures are fundamental for in-vacuum type undulators.

Gap errors caused by mechanical deformations at small gaps are of a dynamic nature. Such gap errors are gap-dependent, since the magnetic forces increase exponentially with decreasing undulator gap. The magnetic force per unit length reaches around 16 kN/m at a gap of 4 mm, and therefore, four spring force compensating modules are located

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at four optimal support points of the girders to keep the deformations small. Each spring module consists of six sets of machined-springs with different coefficients to allow a close fit to the exponential characteristics of the magnetic forces. Therefore, gap errors from the out-of-vacuum girders can be reduced by setting the touching points of the springs. Figure 3 shows the repulsive force generated by the springs to compensate the magnetic force at room temperature (RT) and cryogenic temperature (CT). By tuning each spring at each module, we can reduce the phase errors to less than 2 degrees for all gaps at RT.

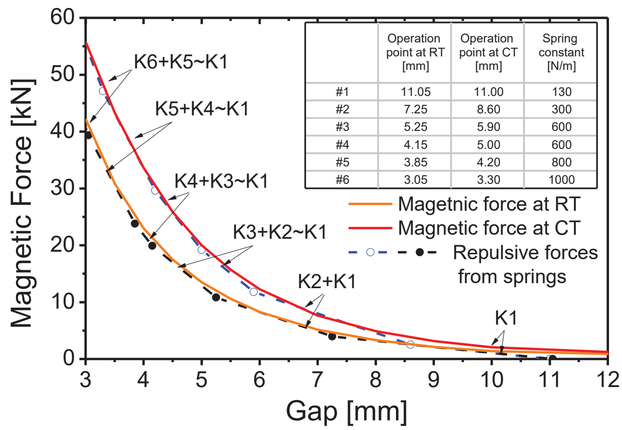


Figure 3: Dependence of magnetic (solid lines) and repulsive (dashed lines) forces as a function of gap size at 295 K and 77K.

When the CU15 operates at a low temperature of (80K), the field error due to thermal effects can be derived from the variation of the remanent field and contraction of materials. As a result, a temperature control system is implemented on magnet arrays to compensate the residual temperature gradient of magnets. A maximum local gap error of 8 um was corrected by adjusting the differential adjusters at a gap of 12 mm. In such a gap, the magnetic force is small and gap errors mainly originate from the material contraction of the in-vacuum girder. The force increases from RT to CT (Fig. 3), so the re-setting of spring touching positions to maintain the small phase errors becomes necessary.

## COOLING METHOD

For the majority of CPMUs around the world, LN2 magnet cooling is adopted. For CU15, however, two cryo-coolers (with a cooling capacity of 200W per each at 80K) inside a separated vacuum are connected to the magnet arrays via flexible thermal straps and thermal conductance feedthroughs (Fig. 1). Therefore, neither leaky weld seams nor UHV pipe connections generate a vacuum risk. Another advantage in such a design is that the cooling bar can be used as a thermal shield for the magnets when the NEG pumps are under high-temperature activation. The system heat load can be evaluated from the temperature of the cold-head and temperature dependence of the cryocooler capacitance. Table 1 shows the estimated heater power and measured temperature at each component.

Table 1: Magnets and Cold Head Temperatures

| **Averaged Magnet Temperature [K]** | **140** | **120** | **100** | **80** | **55** |
|---|---|---|---|---|---|
| Averaged Cooling bar temperature [K] | 115 | 105 | 85 | 70 | 52 |
| Averaged Cold-head [K] | 61 | 57 | 53 | 50 | 45 |
| Estimated heater power [W] | 120 | 95 | 68 | 45 | 0 |
| Total heat load [W] * | 340 | 320 | 300 | 280 | 240 |

* includes radiation heat load from the in-situ measurement system.

The temperature of the PMs is controlled at 80 K. Therefore, the cooling margin for the CU15 is approximately 45 W, which is sufficient for the temperature control system (see Table 1).

A potential issue associated with cryo-coolers is vibration property, which is of particular importance for not only the field measurements but stable operation in the storage ring. The vibration characteristics were studied for two commercial cryo-coolers with a cooling capacity of 200 W at 80 K. One is Solvay cryocooler type (SHI CH110) and the other is Gifford-McMahon (G-M) type (Leybold 250MD). The vibration amplitude on the cold-head was measured in a special chamber and a frame. The vibration amplitudes of the Solvay and G-M type are ± 2.0 (X), ± 6.0 (Y) , ± 2.5 um (Z), and ± 4.0 (X), ± 1.8 (Y), ± 3.0 (Z) um, respectively. The vibration frequency of the cold-head is more complicated in the Solvay cold-head, and therefore, a G-M cooler was adopted to minimize the undulator vibration amplitude.

## TEMPERATURE CONTROL SYSTEM

The temperature of the magnet arrays with the length of 2 m must be constant for different undulator gaps, beam currents or fill patterns. Figure 4 shows the beam-induced heat load (due to synchrotron radiation and image current heating (IMG)) in the CU15 under the assumption that the SR is passing along the undulator axis. The actual heating is higher because indirect SR from simple reflection, fluorescence or Compton scattering is difficult to estimate for quantitative evaluation. Therefore, eight sheath heaters (38Wx8) are installed along the magnet arrays with high precision PID temperature controllers (RKC HA900). The temperature distribution along the magnet arrays are shown in Fig. 5 as obtained from 32 calibrated resistance temperature detectors (RTDs) with a tolerance of ± 0.1K. As a result, the temperature variation is controlled at 80.0 ± 0.4 K in the magnet array.

A response test with a preset temperature change by 1 K was performed for CU15 with optimum PID control parameters. As shown in Fig. 6, the response time is around 10 mins while the temperature overshoot is around 0.2 K, and it takes an extra 15 mins to reach a stable value. The long term temperature variation is obtained within ±0.05 K. In the figure, the gap changes due to the material contraction is observed around 2.5 um/K by using optical

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micrometers. From Fig. 5, the gap errors derived from material contraction can be estimated to be around 2 μm along the undulator axis. During a non-stop test for 30 days, the current temperature control system has been shown to provide a stable temperature within ± 0.05 K and a constant gap within ± 0.125 um.

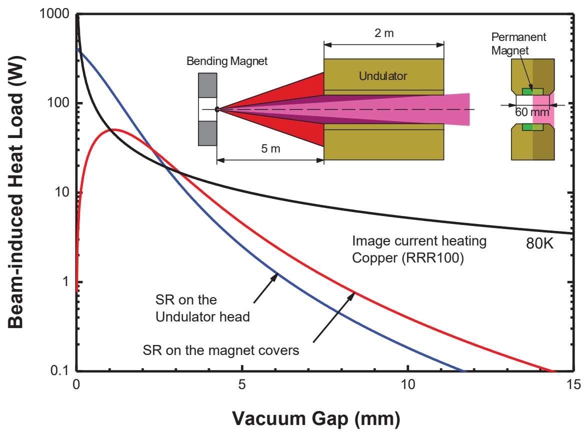


Figure 4: The beam-induced heat load (SR and IMG) The calculation is based on TPS parameters, $E_{GeV} = 3$ GeV, $I_b$ = 500 mA, 600 bunches, bunch length = 4.65 mm (15.5 psec), circumference = 518 m, bending radius = 8.353 m and a distance of 5 m from the next upstream dipole magnet end to the undulator entrance.

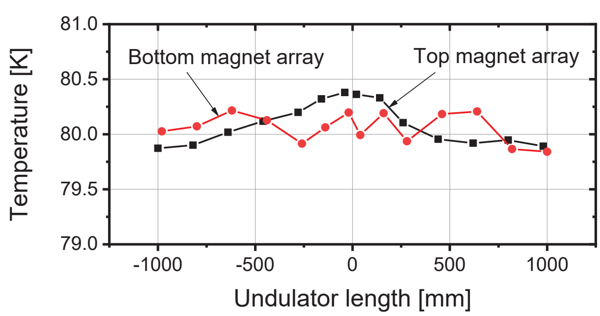


Figure 5: Temperature distribution along a magnet array with active temperature control system.

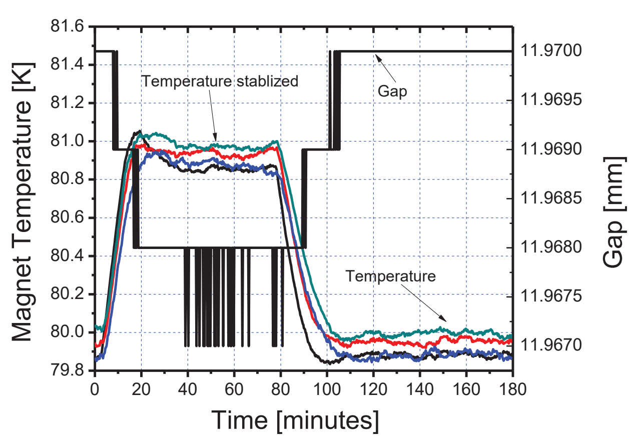


Figure 6: Time variation of undulator gap and temperature of the magnet arrays after the preset temperature change by 1 K.

## TRANSITION TAPER

Transition tapers are installed at both ends of CU15 (Fig. 7), where the flexible transition must have a displacement allowance for gap variations or thermal contraction during CPMU cool down. Unlike transition tapers for ordinary in-vacuum undulators, a water-cooling channel is not necessary. The transition taper of the CU15 should have a low thermal conductance to keep low heat flow from room temperature vacuum chamber to cryogenic magnet. The flexibility can be obtained by 0.2 mm BeCu foils. One end is fixed on the magnet arrays and the other is mounted on the vacuum duct with a sliding mechanism. Such a design can prevent unnecessary thermal stresses in the transition tapers during low temperature cool down.

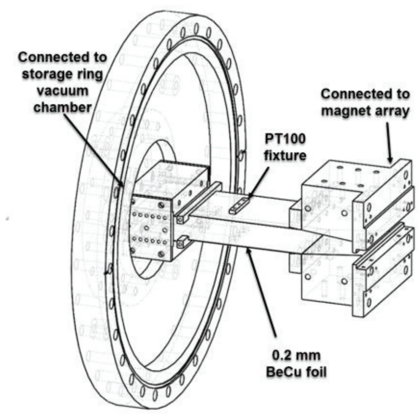


Figure 7: Transition taper for a CU15.

## REFERENCES

[1] J.C. Huang et. al., “Challenges of in-vacuum and cryogenic permanent magnet undulator technologies” Phys. Rev. ST Accel. Beams, vol. 20, pp. 064801-18, 2017.

[2] J.C. Huang et. al., “Development of a cryogenic permanent magnet undulator for the TPS”, in Proc. IPAC’17, pp.1562-1565.

[3] J.C. Huang et. al., “A Mechanical Undulator Frame to Minimize Intrinsic Phase Errors”, in Proc. MEDSI’18, pp.69-71.

[4] C.K. Yang et al., “Field Measurement System In Vacuum for a cryogenic permanent-magnet undulator at NSRRC” IEEE Trans. Appl. Supercond., 4, 26, 2016.

[5] C.K. Yang et al., “A Hall Probe Calibration System at Low Temperature for the TPS Cryogenic Permanent Magnet Undulator” IEEE Trans. Appl. Supercond., 3, 28, 2018.