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A MECHANICAL UNDULATOR FRAME TO MINIMIZE INTRINSIC PHASE ERRORS

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Abstract

A PrFeB-based cryogenic permanent magnet undulator (CPMU) is under construction at the Taiwan Photon Source (TPS) to generate brilliant X-rays. When magnets are cooled to 77 K, a CPMU with a period length of 15 mm can generate an effective magnetic field of 1.32 T in a gap of 4 mm. A main feature of the TPS CPMU is its low-intrinsic-phase errors by the installation of force-compensation modules on the out-of-vacuum girders in a four-support-points configuration. Moreover, adjusting the spring settings one can obtain very low undulator phase errors. In this paper, a mechanical frame design for the TPS-CPMU with force-compensating spring modules will be discussed. Observations of deformation effects of the out-of-vacuum girders on the CPMU will be presented.

INTRODUCTION

Together with a high strength parameter, low phase errors are required characteristics an undulator to allow the generation of higher harmonics without significant degradation of SR brilliance and are therefore an important consideration to evaluate the undulator magnetic field quality. The X-ray brilliance degradation (I/I_0) due to RMS phase errors scales like $I/I_0=\exp[-(n\sigma_{PE})^2]$ [1], where *n* is the undulator harmonic order and σ_{PE} the RMS phase error. The phase error derives from magnetic field errors, which can result from (1) differences of individual magnet blocks, such as remnant field and height of the magnet, (2) gap errors from manufacturing tolerances, such as the flatness of the in-vacuum girder, the length of link rods and assembly accuracy of the mechanical frame, (3) gap errors caused by mechanical deformations and (4) thermal effects in magnet arrays. During the construction of a TPS-CPMU, individual differences of magnet blocks can be greatly eliminated by magnet sorting. Gap errors from manufacturing tolerances can be corrected by adjusting gaps locally. These two error sources are of a static nature and careful corrections can be made to minimize phase errors. The gap errors caused by mechanical deformations are gap-dependent, since the magnetic forces increase exponentially with decreasing undulator gap. A counter force system, especially at small gaps, becomes necessary to retain low intrinsic RMS phase errors. Thermal effect in the magnet arrays can be corrected by temperature control systems, which however will not be discussed in this note.

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MECHANICAL FRAME WITH FORCE-COMPENSATING SPRING MODULS

The magnetic force in the CU15 reaches up to 32 kN at a gap of 4 mm and 77 K, so a conventional two-support configuration is no longer rigid enough to keep the net RMS phase errors small. Yet, an optimized four-support configuration can reduce the intrinsic rms phase errors to less than 0.5 degrees [2]. Moreover, strong magnetic forces not only cause gap errors but also the deformation of the mechanical frame and heavy load to the gap drive system. Based on these considerations, the design goal of a counter force system in a four-support configuration of the mechanical frame is not only to compensate the magnetic force but also to obtain a mostly stress-free mechanical frame. Therefore, a force-compensation spring module in a compact and moment-free design is introduced and installed on four support-points of the mechanical frame (Fig. 1). The spring module is an invention of Hitachi Metals Co. Ltd. and international patents are pending. Attractive characteristics of the force-compensating spring modules are, (1) that the system is set-up in-air, so the adjustment of springs is easy, (2) machined -springs results in good reproducibility, (3) the low weight and compact design allows easy removal of the spring module during maintenance and assembly of vacuum components and (4) effective compensation of strong magnet forces without undesirable side effects. The spring module is installed between upper and lower out-of-vacuum girder and can compensate the attractive magnetic forces by repulsive spring forces. The rotational moments of the upper and the lower girders act in opposite directions as shown in Fig. 1b. The linear guides have sufficient stiffness to allow the changes of the magnetic gap while absorbing the rotational moments since, there is no mechanical connection between spring module and the pillars of the mechanical frame. The deformed spring module can keep the mechanical frame mostly stress-free with only a small deformation.

Figure 2 illustrates the deformation of the mechanical frame with and without spring modules by a finite element analysis. With the spring module, the transverse pillar tilt becomes small and the deformation of the out-of-vacuum girder due to magnetic forces can be reduced from 2.1 um to 0.12 um for a force of 32 kN (Fig. 3). Including the in-vacuum-girder deformation, the intrinsic phase errors are estimated to be less than 1 degrees. The spring module will deform and compensate the magnetic force, so the stress and deformation of the out-of-vacuum girders and pillars are reduced.

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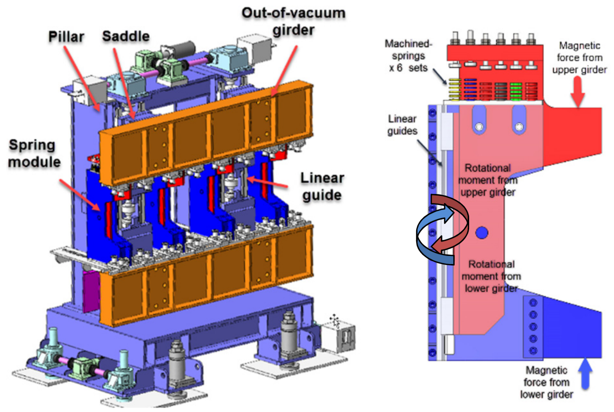


Figure 1: Force-compensating spring module on the CU15 (left) and spring module (right).

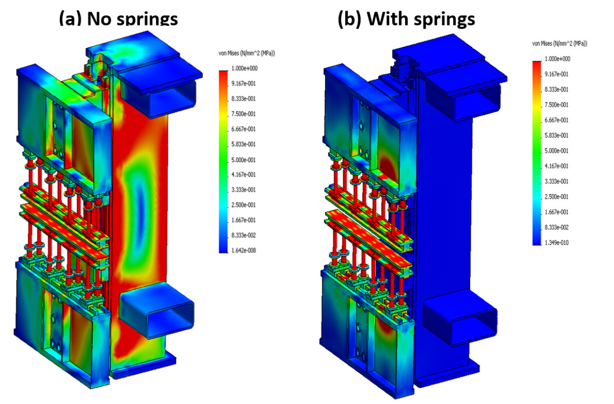


Figure 2: Stress distributions of the mechanical CU15 frame with and without spring modules under magnetic load of 32 kN.

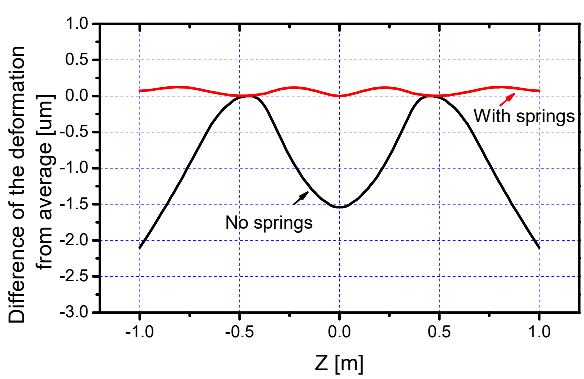
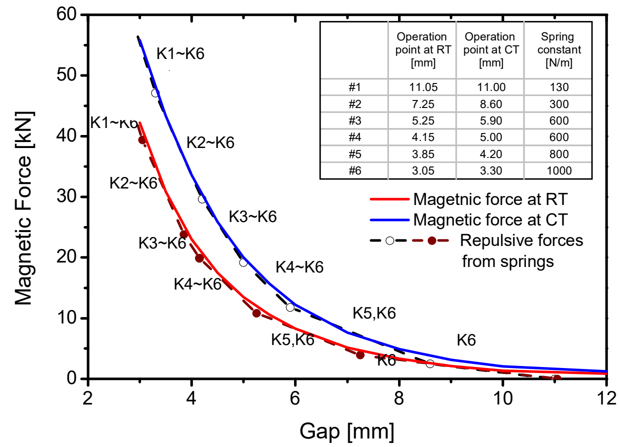


Figure 3: Finite element analysis on a deformed out-of-vacuum girder d with and without spring modules under magnetic load of 32 kN.

The spring module consists of six sets of machined-springs with various coefficients to allow a close fit to the exponential characteristics of the magnetic forces. The weakest spring start engaging at gap of 11.05 mm and then as the gap is reducing additional springs come into play. Figure 4 shows the repulsive force generated by the springs to compensate the magnetic force with exponential characteristics at CT and RT. The spring settings must be adjustable when the CPMU is cooled down and therefore easy access and tuning in air is desired.



	Operation point at RT [mm]	Operation point at CT [mm]	Spring constant [N/m]
#1	11.05	11.00	130
#2	7.25	8.60	300
#3	5.25	5.90	600
#4	4.15	5.00	600
#5	3.85	4.20	800
#6	3.05	3.30	1000

Figure 4: Dependence of magnetic (solid lines) and repulsive (dashed lines) forces on gap size at 300 K and 77 K.

DEFORMATION OF OUT-OF-VACUUM GIRDERS

The spring modules can reduce gap errors caused by the deformation of out-of-vacuum girders and to monitor the gap errors, we use 16 digital SONY magnescale gauges (DF-830SLR) with a resolution of 0.1 um. A pair of gauges are located along the magnet arrays as shown in Fig. 5. The forces at a gap of 15 mm are negligibly small and we quantify gap errors by the difference between deformed and undeformed (gap of 15mm) structure. Figures 6 and 7 show the effect of the spring modules on gap error and transverse tilt of the out-of-vacuum girder, respectively. When there are no springs used for force compensation, the gap error is around ± 3 um at a gap of 5 mm although this gap error and transverse tilt of out-of-vacuum girder can be reduced with the spring modules. The gap errors can further increase when the gap is less than 5 mm but can be reduced again for different spring settings. Larger gap errors were observed in contrast to simulations (Fig. 3). Since, the springs can only compensate magnetic loads, other errors, for example, coming from the drive system, may be included in the observation but not in the simulation.

Figure 5: Gap error measurement setup on out-of-vacuum girder.

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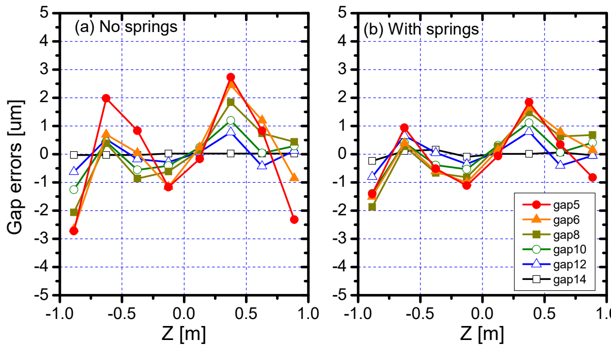

Figure 6: Effect of spring modules on gap errors for out-of-vacuum girders.

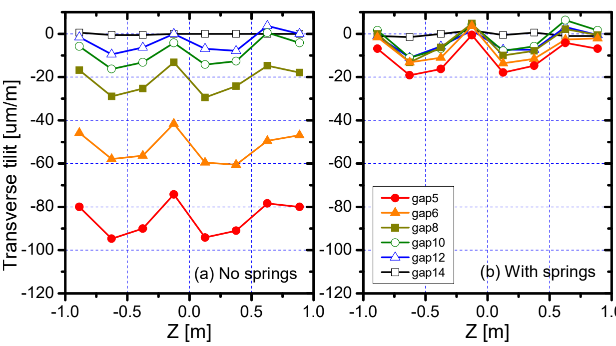

Figure 7: Effect of spring modules on the transverse tilt of out-of-vacuum girders.

GAP ERRORS CAUSED BY OPERATIONAL ERRORS

In the gap range of 15 to 25mm, where the magnetic force is negligibly small, the gap errors from magnetic loads can be ignored. Figure 8 shows observed gap errors at the inner side, near the ball screws/linear guides, and the outer side of the frame being ± 2 um and ± 1 um, respectively. These results suggest that the errors come from the drive system, for example, from tolerances in the parallelism of the linear guide resting on the pillars. We assume such gap errors to be caused by operation and to eliminate them in the measurement, gap errors were measured for small gap changes only (1 mm step of gap closing), so that gap errors come mainly from the magnetic load. When the gap is changed from 4 to 3 mm, a gap error of ± 0.7 mm is generated by magnetic forces of up to 20 kN (Fig. 9), which, while ignoring operational errors, can be compensated by the spring module.

The source of operational errors could come from poor parallelism of the linear guides. When the gap changes, angular errors are introduced at support positions, and as a result, the internal forces cause deformation of the out-of-vacuum girders. Figure 10 illustrates gap errors derived from such operational error. The CU15 mechanical frame has an assembly tolerance for the linear guides of around 1 um and the deformation of the out-of–vacuum girders is around ± 2 um. If a gap error in the sub-micrometre-range is required, one could add a sliding mechanism to the connection between out-of-vacuum girders and support points of the frame like the mechanism used for tapered-undulators at the TPS.

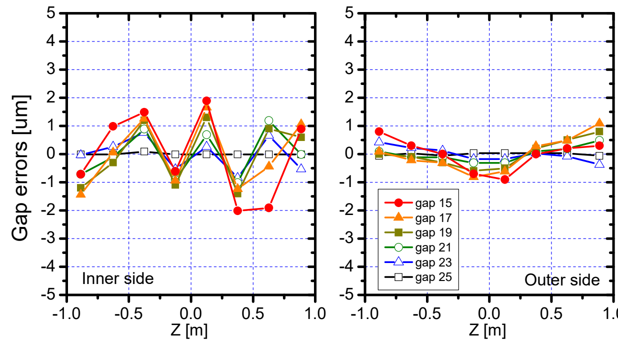

Figure 8: Gap errors of out-of-vacuum girders due to operational errors.

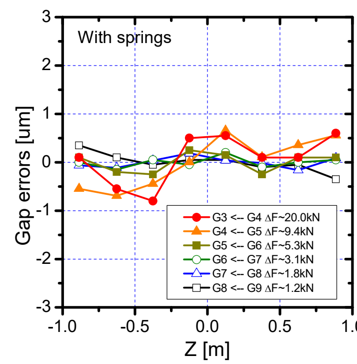

Figure 9: Gap errors of out-of-vacuum girders due to magnetic forces.

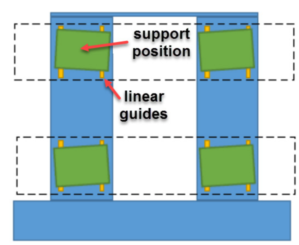

Figure 10: Sketch for the deformation of out-of-vacuum girders due to tolerances in the parallelism of the linear guides.

SUMMARY

Adoption of spring module, the gap errors are less than the TPS IVUs. A rms phase-error of 2 degree less at gap 4 mm to 10 mm can be obtained by fine adjustment of spring modules. At current design, the gap errors derived from a combined effect of operational errors and magnetic loads. A new tapered function mechanical frame with spring compensation modules will be used in the next TPS undulators to reduce the operational errors.

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