

IMPROVEMENT AND OPTIMIZATION OF A PERMANENT-MAGNET PHASE SHIFTER

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Abstract

A permanent-magnet (PM) phase shifter for phase matching between tandem elliptically polarizing undulators (EPUs) at the Taiwan Photon Source (TPS) has been developed, and its initial version has already been installed in the storage ring. Current efforts focus on improving the device by enhancing the mechanical precision of the gap-adjustment system, maintaining magnetic-field quality, and minimizing beam-orbit perturbations within the limited installation space. Magnet sorting and shimming techniques were used to refine the magnetic performance of the first version. At small operating gaps, strong magnetic forces introduce substantial mechanical loading and can affect the field directionality. To overcome this limitation, an upgraded design incorporating a spring-assisted compensation mechanism is under development. This work presents the optimization approach and the resulting improvements achieved through integration of the spring system, demonstrating enhanced structural stability and improved repeatability under high-force operating conditions.

INTRODUCTION

Segmented undulator systems are widely adopted in modern synchrotron light sources and free-electron lasers to provide installation space for focusing elements, beam diagnostics, vacuum components, and correction magnets between insertion-device segments. To preserve radiation coherence and maximize photon flux between adjacent undulator segments, phase shifters are required to provide controllable phase delays between the electron beam and the emitted radiation.

At the Taiwan Photon Source (TPS), a tandem elliptically polarizing undulator (EPU) system has been installed to support variable-polarization photon-beam operation. A permanent-magnet phase shifter was previously developed and installed between the tandem EPUs for phase matching. The initial PM phase shifter design, including the mechanical structure, magnet sorting process, and magnetic-field optimization methods, has been reported previously[1]. Compared with electromagnetic phase shifters, the PM design offers several advantages, including compact size, reduced fringe fields, lower power consumption, and minimal impact on the nearby storage-ring lattice. Magnetic-field optimization of the initial version was achieved through magnet sorting and shimming techniques, resulting in satisfactory field-integral performance and negligible beam-orbit perturbation.

To further improve the phase-shifting capability and operational flexibility, the minimum operating gap of the upgraded phase shifter was reduced from 20 mm to 16 mm. However, reducing the magnetic gap significantly increases the magnetic attraction force between the upper and lower magnetic assemblies. Under small-gap operation, the increased magnetic loading introduces structural deformation, backlash effects, and degradation of gap-motion repeatability. These mechanical effects become increasingly critical because stable magnetic-field quality and precise mechanical positioning are required to maintain reliable phase matching and beam stability.

The primary operating range of the phase shifter is between 16 mm and 30 mm, where the magnetic force varies rapidly with gap size. To improve mechanical stability within this region, a spring-assisted compensation mechanism was developed to reduce the variation of magnetic-force-induced loading acting on the transmission structure. Multiple compression springs were symmetrically integrated into the magnet support frame to provide balanced preload forces and suppress asymmetric deformation during gap operation.

This paper presents the upgraded mechanical design and evaluates the effectiveness of the spring-assisted compensation mechanism. Mechanical measurements, including parallelism and repeated gap-motion tests, were performed to investigate the structural stability and repeatability of the upgraded system under high-force operating conditions.

SPRING COMPENSATION DESIGN

Figure 1 shows a schematic view of the upgraded PM phase shifter with the spring-assisted compensation mechanism integrated into the magnet support frame and transmission structure. The movable magnetic assemblies are driven by a vertical screw mechanism and guided by linear guide rails to maintain stable gap motion during operation. Multiple compression springs are symmetrically distributed on both sides of the magnet support frame to provide balanced preload forces and minimize asymmetric deformation.

The preload force of each spring can be individually adjusted through threaded support structures, allowing optimization of the compensation-force distribution. Compared with a single compensation element, the distributed spring arrangement provides more uniform loading conditions and improves the mechanical stability of the transmission structure. The passive spring-assisted design allows stable compensation without additional actuators or active control systems.

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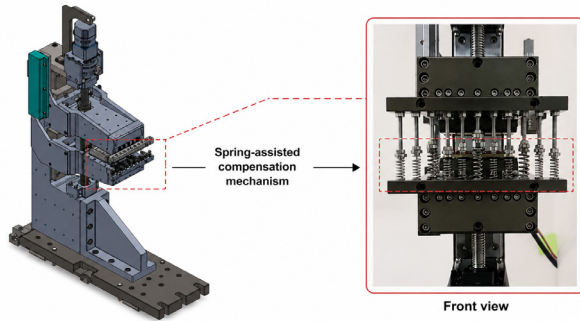


Figure 1: Schematic view of the upgraded PM phase shifter with the passive spring-assisted compensation mechanism.

Figure 2 shows the magnetic force, spring compensation force, and resulting net force acting on the vertical screw mechanism as functions of the magnetic gap. As the operating gap decreases, the magnetic attraction force increases rapidly in the small-gap region. The compensation springs provide an opposing preload force that increases correspondingly with gap reduction, thereby reducing the net loading variation acting on the transmission structure.

To optimize the compensation conditions, the loading behavior of the vertical screw mechanism was evaluated under different operating gaps. The results indicate that the loading condition becomes relatively stable when the operating gap approaches 30 mm. Therefore, the spring stiffness and preload conditions were selected so that the effective loading condition within the operating range remains close to that of the 30-mm-gap operating condition.

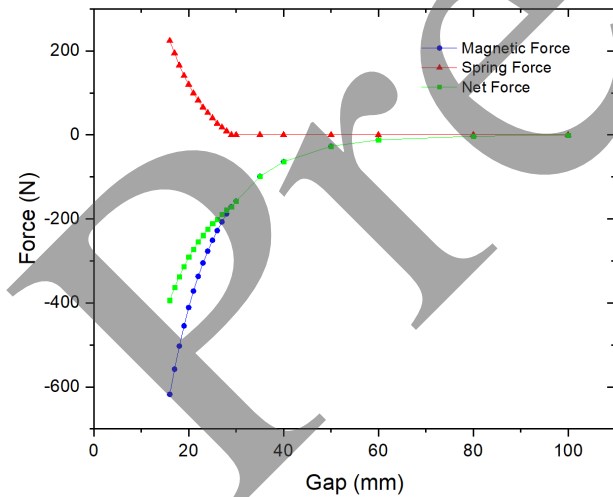


Figure 2: Magnetic force, spring compensation force, and net force versus operating gap.

Finite-element analysis was also performed to evaluate the structural deformation under spring compensation conditions. Figure 3 compares the deformation distributions of the transmission structure at a 16-mm operating gap for configurations without spring compensation and with spring compensation activated at a 30-mm operating gap.

Without spring compensation, the transmission structure exhibits relatively large deformation due to strong magnetic loading at the minimum operating gap. After introducing the spring-assisted compensation mechanism, the structural deformation is significantly reduced. The results indicate that the optimized spring preload condition effectively suppresses magnetic-force-induced deformation and improves structural stability within the primary operating range.

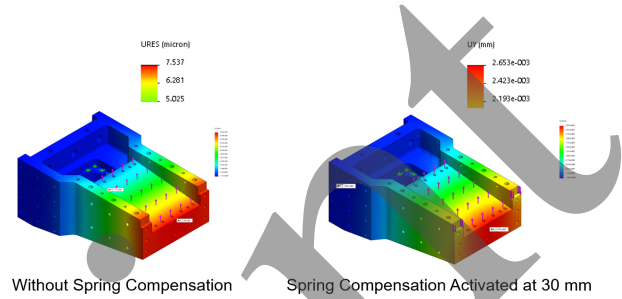


Figure 3: Structural deformation analysis with and without spring compensation at a 16-mm operating gap.

Figure 4 shows the bending moment acting on the transmission structure with and without the spring-assisted compensation mechanism as functions of the operating gap. Without spring compensation, the bending moment increases rapidly as the operating gap decreases, indicating substantial magnetic-force-induced loading under small-gap operation. The maximum bending moment occurs near the minimum operating gap, where the magnetic attraction force is strongest.

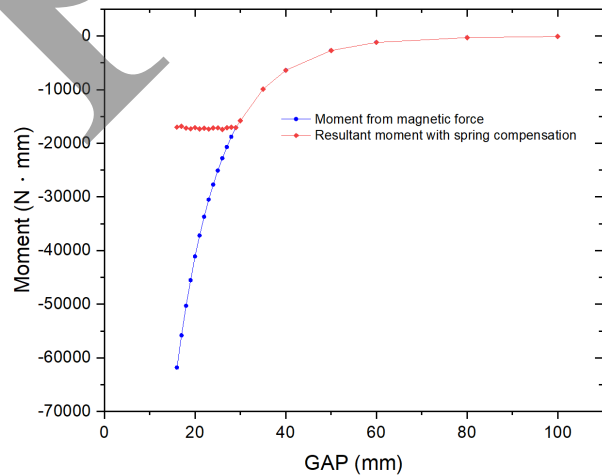


Figure 4: Bending moment acting on the transmission structure with and without spring compensation.

After integration of the spring-assisted compensation mechanism, the bending moment distribution becomes significantly flatter throughout the operating range. The spring system effectively counteracts the magnetic-force-induced loading and suppresses the rapid increase in structural loading at small gaps. As a result, the loading condition acting on the transmission structure remains relatively

stable within the primary operating range, thereby improving mechanical stability and reducing deformation during gap operation.

MECHANICAL PERFORMANCE EVALUATION

Mechanical measurements were performed to evaluate the effectiveness of the spring-assisted compensation mechanism under different loading conditions. The measurements focused on the parallelism stability and repeatability of the transmission structure within the primary operating gap range of 16 mm to 30 mm.

Figure 5 shows the parallelism measurement results for three configurations: the support frame only, the support frame with magnetic loading, and the support frame with both magnetic loading and spring compensation. Without magnetic loading, the parallelism variation remains relatively stable throughout the operating range. After installation of the magnetic assemblies, the strong magnetic attraction force significantly increases deformation of the transmission structure, particularly in the small-gap region below 20 mm. The maximum parallelism deviation reaches approximately 26 μm at the minimum operating gap.

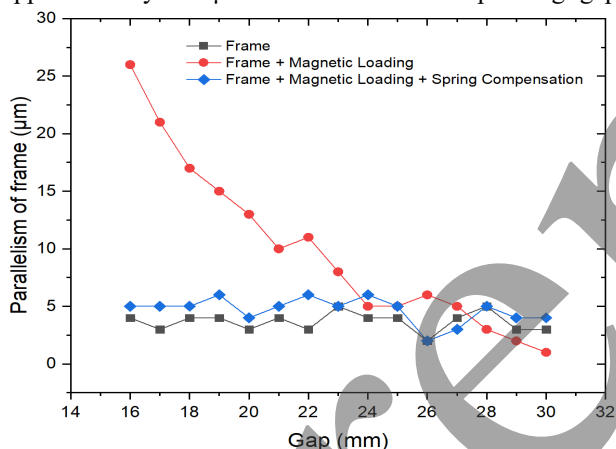


Figure 5: Parallelism measurements under different loading conditions.

After integration of the spring-assisted compensation mechanism, the parallelism deviation is substantially reduced throughout the operating range. The measurement results indicate that the compensation system effectively suppresses deformation induced by magnetic loading and stabilizes the transmission structure during gap motion. Compared with the uncompensated configuration, the compensated system maintains significantly improved and more stable parallelism performance in the small-gap region.

Repeated gap-motion measurements were also performed to evaluate the parallelism repeatability of the upgraded mechanism during cyclic operation. Figure 6 shows the parallelism repeatability measured during repeated gap-cycling tests between 16 mm and 30 mm. The measurements were conducted under both closing-gap and opening-gap operating sequences for two repeated cycles.

The results indicate that the parallelism variation remains within approximately 1–5 μm throughout the operating range. No significant hysteresis or accumulated deformation behavior was observed during repeated motion cycles. These results demonstrate that the spring-assisted compensation mechanism effectively stabilizes the transmission structure and suppresses backlash-induced variation during repeated gap operation.

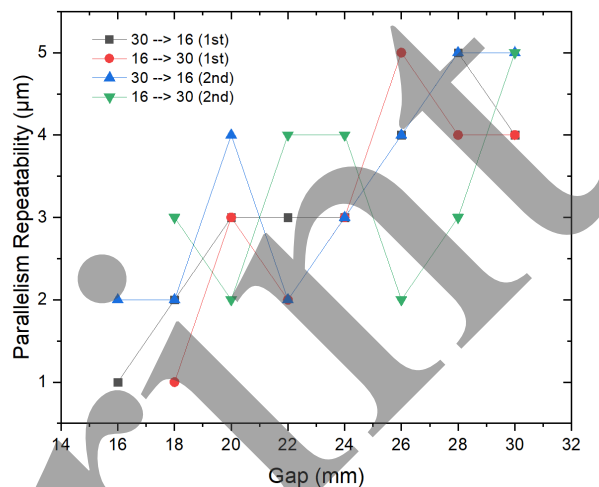


Figure 6: Parallelism repeatability during repeated gap-cycling operation.

CONCLUSION

An upgraded permanent-magnet phase shifter with a passive spring-assisted compensation mechanism has been developed for tandem elliptically polarizing undulators at TPS. The upgraded design effectively reduces the variation of magnetic-force-induced loading acting on the transmission structure during small-gap operation.

Mechanical measurements demonstrate that the passive spring-assisted compensation mechanism improves the parallelism stability and repeatability of the gap-adjustment system under high magnetic loading conditions. The distributed spring system effectively suppresses structural deformation and stabilizes the transmission structure during repeated gap operation.

Compared with active compensation approaches, the proposed passive compensation design does not require additional power supplies, actuators, or control systems, thereby simplifying mechanical integration within the limited installation space of the storage ring. The upgraded PM phase shifter demonstrates improved structural stability and operational reliability under repeated high-force operating conditions, providing a practical solution for compact insertion-device applications with stringent mechanical stability requirements.

REFERENCES

- [1] C.S. Yang *et al.*, "Constructing a Permanent Magnet Phase Shifter" *IEEE Trans. Appl. Supercond.*, vol. 28, no. 3, p. 4100405, Apr. 2018. doi:10.1109/TASC.2017.2777849