MAGNETIC DESIGN OF A PROTOTYPE HYBRID IN-VACUUM UNDULATOR AND PASSIVE FORCE CANCELLATION SYSTEM FOR SPS-II

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Abstract

This paper presents the comprehensive magnetic design and simulation-based optimization of a prototype hybrid in-vacuum undulator (IVU), developed as a proof-of-concept for the 4th-generation synchrotron light source (SPS-II) at the Synchrotron Light Research Institute (SLRI). A configuration featuring a 20 mm period length and a 5 mm minimum gap was simulated at a 3 GeV electron beam energy for Small-Angle and Wide-Angle X-ray Scattering (SAXS/WAXS) techniques. The magnetic structure was subsequently modeled in 3D using the RADIA code, employing NdFeB permanent magnets and FeCo-V poles. To counteract the massive magnetic attraction force at the minimum gap, a passive force cancellation system was integrated and optimized. Simulations demonstrate that this system successfully reduces the total mechanical load by 99%, enabling a highly compact and lightweight IVU design.

INTRODUCTION

The Synchrotron Light Research Institute (SLRI) is developing a prototype hybrid in-vacuum undulator (IVU) for the 3 GeV Siam Photon Source II (SPS-II) [1]. A precise main magnetic design is essential to achieve the high-brightness hard X-ray beams required for Small-Angle and Wide-Angle X-ray Scattering (SAXS/WAXS) techniques. Although beam dynamics restrict the nominal operational gap to 5.0 mm to satisfy vertical stay-clear requirements [2], the prototype's mechanical framework must safely accommodate the storage ring's physical minimum gap of 4.2 mm. Evaluating the system at this absolute limit is critical, as the NdFeB magnets and FeCo-V poles generate a massive 17.64 kN vertical attraction force. Maintaining micrometer-level gap precision under this immense load traditionally requires bulky and costly mechanical support, posing severe installation challenges within the constrained accelerator tunnel.

To address this mechanical bottleneck, this paper presents the 3D magnetic design and RADIA-based optimization [3] of a passive force cancellation system using a secondary Pure Permanent Magnet (PPM) array [4].

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MAIN MAGNETIC DESIGN AND OPTIMIZATION

Analytical Parameters and Spectra Simulations

The conceptual design of the IVU was initially driven by the photon beam requirements of the SAXS/WAXS beamline at the SPS-II storage ring. To determine the fundamental magnetic parameters, numerical simulations of the synchrotron radiation spectra were performed using the SPECTRA code [5]. The optimization targeted a high photon flux at an energy of 9.1 keV at the 7th harmonic, corresponding to a deflection parameter (K) of 2.14 for the 3 GeV electron beam energy of the low-emittance lattice of the SPS-II. Based on these analytical calculations, a periodic magnetic length (λ_u) of 20 mm and a nominal minimum operational magnetic gap of 5 mm were selected. The prototype consists of 51 full periods, generating a peak magnetic field (B_{peak}) ranging from 1.32 T at the nominal minimum gap of 5.0 mm to 0.47 T at a 10.0 mm gap. This corresponds to a maximum K of 2.28, which provides the ample tuning margin necessary to ensure the continuous, high-brightness harmonic spectrum required for the 8-20 keV SAXS/WAXS beamline. The main parameters of the IVU prototype are summarized in Table 1.

Table 1: Main Parameters of the IVU Prototype

Parameter	Value	Unit
Electron beam energy	3.0	GeV
Number of periods	51	-
Period length	20	mm
Main magnet size	56 × 7 × 31	mm
Pole size	46 × 3 × 23	mm
Minimum magnetic gap	5	mm
Peak magnetic field range	0.47 – 1.32	T

3D Magnetic Modeling and Material Selection

The structure utilizes high-remanence NdFeB grade 38UH permanent magnets with a remanence (B_r) of 1.24 T and an intrinsic coercivity (H_{cj}) exceeding 1990 kA/m to prevent radiation-induced demagnetization. The permeable poles were modeled using FeCo-V, selected for its exceptionally high saturation polarization ($J_s \approx 2.3$ T). To ensure ultra-high vacuum (UHV) compatibility and mitigate outgassing, all magnet blocks and poles are designed to be coated with a 5 μm Titanium Nitride (TiN) layer.

PASSIVE FORCE CANCELLATION SYSTEM

Concept and Magnetic Configuration

The primary mechanical challenge in designing the IVU is the massive magnetic attraction between the upper and lower parallel arrays, which exponentially increases as the magnetic gap decreases. Accommodating this force typically requires an excessively large and heavy mechanical support structure, which contradicts the weight and space constraints of the storage ring. To address this, a passive force cancellation system was implemented using secondary PPM arrays [4]. These cancellation arrays are installed longitudinally alongside the main hybrid magnets (as illustrated in Fig. 1) and are magnetized to generate a repulsive force in the exact opposite direction of the main attractive force, enabling a highly compact mechanical design without compromising structural stability.

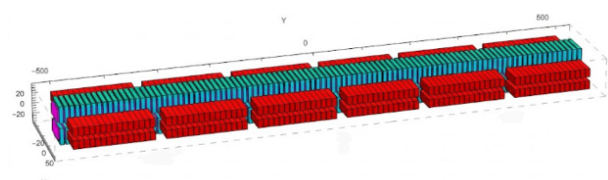

Figure 1: 3D magnetostatic model of the complete magnetic structure, illustrating the secondary Pure Permanent Magnet (PPM) cancellation arrays (red) installed longitudinally alongside the main hybrid arrays.

Optimization of Period Length and Magnet Dimensions

Achieving an effective cancellation system requires matching both the force-distance decay curve and the absolute force magnitude of the repulsive arrays to the main attractive arrays. Since the hybrid and PPM structures exhibit different decay behaviors, rigorous parametric optimizations were performed. First, to match the curvature of the force profile, the period length of the PPM array was varied from 15 mm to 20 mm (see Fig. 2). The normalized force used for this comparison is calculated as:

$$\text{Normalized Force} = \frac{(F_{\text{gap}} - F_{\min})}{(F_{\max} - F_{\min})} \qquad (1)$$

where F_{gap} is the force at a specific gap, $F_{\max}$ is the force at the minimum gap (4.2 mm), and $F_{\min}$ is the force at the maximum gap (10 mm). By comparing the normalized force profiles, a period length of 16 mm was identified as the optimal configuration, providing the most accurate match with the main hybrid array within the critical small gap region of 5 mm to 6 mm. With the optimal period length determined, the longitudinal thickness of each cancellation magnet was fixed at 8 mm, representing half of the period (2 magnets per period). The subsequent optimization phase focused on adjusting the physical dimensions to achieve the required force amplitude. While the nominal minimum operational gap of the IVU is strictly set to 5 mm, these structural optimizations were deliberately conducted down to an extreme minimum gap of 4.2 mm to establish a critical safety margin against potential mechanical over-travel. At this 4.2 mm gap, the main peak attractive force reaches 17.64 kN. Simulations revealed that the repulsive force reaches its peak magnitude at a magnet height of 14 mm. Finally, the magnet width, which demonstrated a direct linear relationship with the force magnitude, was optimized to 68 mm. This optimized geometry (8 × 14 × 68 mm) effectively generates a repulsive force of 17.63 kN, thoroughly covering the target attractive load. The mechanical design of this magnetic assembly is illustrated in Fig. 3.

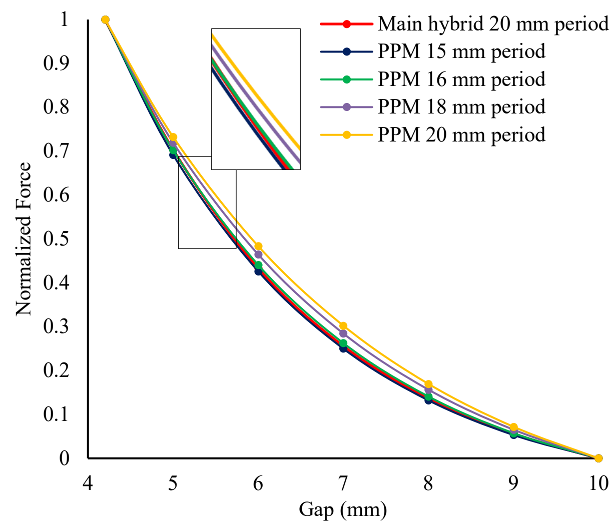

Figure 2: Normalized force-distance decay profiles comparing various PPM period lengths (15–20 mm) with the main hybrid array, highlighting the optimal 16 mm period.

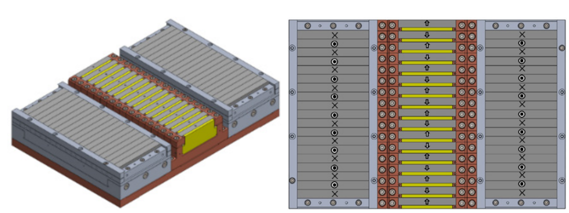

Figure 3: Detailed CAD rendering of the optimized magnetic structure assembly, showing the main hybrid arrays and the secondary PPM cancellation arrays. The ⊙ and × symbols denote the upward and downward magnetization directions of the secondary PPM arrays, respectively, in one module unit.

Force Reduction Performance

Following the geometric optimization, the complete cancellation system (16 mm period, 8 × 14 × 68 mm magnets) was simulated in conjunction with the main arrays across a gap range of 4.2 mm to 10 mm (as shown in Fig. 4). The results demonstrated exceptional mechanical compensation, with the repulsive force profile symmetrically mirroring the attractive force profile across the entire range. At the extreme 4.2 mm safety margin gap, the massive initial load of nearly 17.64 kN was drastically mitigated, resulting in a net residual force of merely 13.8 N. This represents a 99% reduction in the total vertical mechanical load. The near-zero and highly stable residual force profile ensures that the support frame will not be subjected to extreme stresses, successfully fulfilling the objective of minimizing the structural size and weight of the undulator. The resulting streamlined and compact mechanical frame design, directly enabled by this force mitigation, is illustrated in Fig. 5.

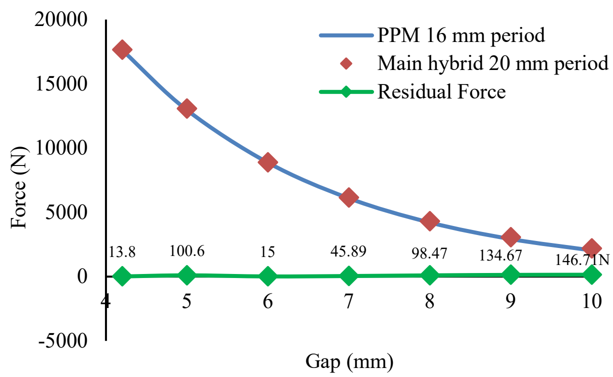

Figure 4: Simulated vertical force profiles demonstrating the 99% mechanical load reduction. The optimized PPM cancellation array neutralizes the main attractive force, leaving a near-zero residual force at the critical 4.2 mm gap.

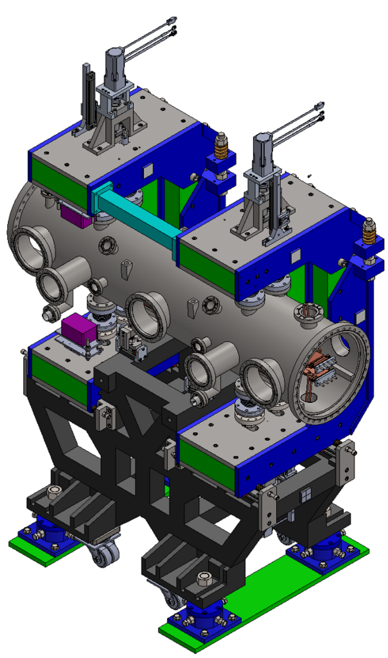

Figure 5: 3D CAD model of the complete IVU prototype, highlighting the compact support structure enabled by the force cancellation system.

CONCLUSION

The magnetic design and RADIA-based optimization of a prototype hybrid IVU with a passive force cancellation system have been successfully completed for the 3 GeV SPS-II. At the extreme 4.2 mm safety margin gap, the primary magnetic arrays generate a massive 17.64 kN attractive force. By integrating optimized secondary PPM arrays featuring a 16 mm period length and 8 × 14 × 68 mm magnets, a precise repulsive force was generated to counteract this load. This system successfully reduced the net vertical force by 99%, leaving a highly manageable residual force of only 13.8 N. Consequently, the need for bulky mechanical support frames is eliminated, enabling a highly compact and lightweight IVU design. Engineering drawings are now finalized, and procurement for the prototype assembly is currently underway.

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