

Development of a novel tunable gradient permanent quadrupole magnet

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Addressing the demands for compactness and tunability in magnet systems for fourth-generation light sources, this paper presents the design and development of a novel tunable permanent quadrupole magnet (PQM) prototype. The prototype achieves a maximum field gradient of 65 T/m and demonstrates a continuous tuning range of 39 T/m. Within the effective aperture, normalized multipole field components are maintained below 5×10^{-4} . Experimental validation confirms that the prototype meets the engineering design requirements for the Hefei Advanced Light Facility. Compared to conventional electromagnetic quadrupoles, this PQM features a compact structure, with negligible power consumption and high magnetic field quality, representing a promising technology for advanced synchrotron radiation light sources and free-electron lasers.

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I. INTRODUCTION

High-gradient quadrupole magnets are critical components in accelerator facilities, particularly in fourth-generation synchrotron light sources that adopt multibend achromat (MBA) lattice designs [1–5], achieving beam emittances on the order of hundreds of pm rad, with some facilities approaching the diffraction limit [6–9] near tens of pm rad. The storage ring lattice primarily consists of periodic magnetic structures, including dipole, quadrupole, sextupole, and octupole magnets. Among these, quadrupole magnets provide essential transverse focusing and constitute the most numerous magnetic elements in the ring. The natural emittance ε_0 scales inversely with the cube of the number of dipoles per period (N_d^3), i.e., $\varepsilon_0 \propto N_d^{-3}$. Consequently, achieving lower emittance necessitates increasing N_d , which requires stronger intermediate quadrupole focusing fields. The resulting higher magnet density mandates greater lattice compactness.

Conventional electromagnetic quadrupoles require excitation coils and associated water-cooling systems, leading to relatively large physical dimensions and structural complexity. In contrast, PQMs [10,11], typically based on rare-earth materials such as NdFeB and SmCo, can generate high field gradients without active power supplies

or cooling infrastructure, enabling significantly more compact designs. For diffraction-limited storage rings operating with beam sizes at the micrometer or submicrometer level, PQMs also inherently mitigate beam quality degradation arising from power supply current ripple and cooling-induced mechanical vibrations common in electromagnetic quadrupoles.

In synchrotron light source facilities, a variety of errors demand quadrupole magnets with tunable gradient capability to ensure precise beam control [12]. Key challenges include gradient errors due to imperfections and tolerances in combined-function magnets [13] and reverse-bend magnets [14], as well as gradient fluctuations induced by cross talk [15,16] when varying currents of adjacent sextupole magnets. Moreover, β -function distortions arising from magnet misalignments necessitate active compensation through gradient tuning. Beyond error correction, tunable quadrupoles are critical for enabling smooth transitions between different machine modes, such as low-alpha and low-emittance configurations [17] and ensuring precise matching of arc optics to superbends. They also play an essential role in beam-based alignment [18] procedures and trajectory optimization. Collectively, these demands underscore the essential role of tunable gradient quadrupoles in maintaining high beam quality and adaptable performance in modern synchrotron light sources.

Driven by goals of energy efficiency and sustainability [19,20], reducing the substantial power consumption of large accelerator facilities is increasingly important. PQMs offer zero static power consumption by utilizing the intrinsic magnetization of rare-earth materials, thereby significantly lowering the overall energy demand of synchrotron light sources. This tunability and energy efficiency position PQMs as a compelling technology for future

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TABLE I. Fixed and variable-gradient PQMs. $\Delta G/G = (G_{\max} - G_{\min})/G_{\max}$. B_n/B_2 is for each individual multipole.

Year	Institution	$G_{\max}$ (T/m)	$\Delta G/G$ (%)	Radius (mm)	Good field region (mm)	B_n/B_2
1998	Cornell University	27.1	0	33.5	$R = 28$	1×10^{-3}
2004	Kyoto University, SLAC	289	0	7	$R = 4$	1×10^{-2}
2005	University of California	560	0	2.5	...	...
2007	LMU Munich	503	0	3	...	...
2016	ESRF	82	0	12	$R = 7$	8.4×10^{-4}
2018	Tsinghua University	90	0	11	$R = 4$	1.5×10^{-2}
2005	SLAC, Fermilab	163	90	6.5	...	...
2006	Kyoto University, SLAC	115	85	10	$R = 8$	1×10^{-2}
2012	Sirius	54.5	30	27.5	$R = 10$	1×10^{-3}
2012	CERN	575	20	4.125	$R = 1$	1×10^{-3}
2014	STFC, CERN	60.4	75	13.6	$R = 11.5$	1×10^{-3}
2014	STFC, CERN	43.8	93	13.6	$R = 12$	1×10^{-3}
2018	Peking University	100	50	12.5	$R = 9$	1×10^{-2}
2018	Peking University	102	50	12.5	$R = 9$	2×10^{-3}
2018	SOLEIL	210	47	6	$R = 4$	1×10^{-2}
2018	India	80	40	11.5	$R = 6$	1×10^{-3}
2024	NSRRC	330	9	3.5	$R = 2$	5×10^{-3}

accelerator facilities aligned with sustainable development objectives.

PQMs, initially proposed by Halbach in the 1980s [21–24], have evolved into two primary categories: fixed-gradient and variable-gradient designs, each serving distinct accelerator applications. Early research predominantly focused on fixed-gradient PQMs, with an emphasis on generating high-quality quadrupole fields. Notable prototypes include a Halbach-type PQM developed at Cornell University in 1998, which achieved a gradient of 27.1 T/m [25], a compact PQM designed by Kyoto University and SLAC in 2004, reaching 289 T/m [26], and an H-type hybrid structure PQM prototype developed by ESRF in 2016, which attained a gradient of 82 T/m [27].

Variable-gradient PQMs were introduced to provide enhanced operational flexibility. In 2004, Kyoto University and SLAC constructed a rotatable-ring PQM with a tunable gradient range of 16.5–115 T/m [28]. In 2012, hybrid configurations combining permanent magnets and correction coils were implemented at Sirius, achieving a gradient of 24.5 T/m with a 30% gradient tuning range [29]. CERN also reported a design in 2012 capable of gradients between 460 and 575 T/m for the CLIC project [30]. Subsequently, two mechanically tunable PQMs were developed by CERN and STFC Daresbury in 2014, covering gradient ranges of 15–60.4 T/m and 2.9–43.8 T/m, respectively [31]. In 2018, SOLEIL and SigmaPhi [32,33] developed a tunable PQM for the COXINEL project, which achieved a maximum magnetic field gradient of 201 T/m with a wide tuning range of up to 100 T/m.

Additionally, several other institutions [34–39] have made significant advances in the development of related devices, further contributing to the progression of permanent magnet

quadrupole technology. Table I presents a summary of the PQM developments.

This paper presents the design, simulation, fabrication, and experimental measurement of a variable-gradient PQM prototype that achieves continuous gradient tuning by mechanically rotating tuning modules to alter their excitation direction. The underlying tuning principle is thoroughly analyzed, and the pole geometry is subsequently optimized using the Opera-3D simulation framework [40]. The prototype was fabricated with tightly controlled manufacturing precision, and extensive metrology was conducted to verify the pole profiles, module geometry, and magnetization alignment. An open-loop control system, implemented with PLC and Autoshop software, allows real-time gradient adjustment. Magnetic field measurements demonstrate that integrated harmonic field components from the third to the sixth order remain below 5×10^{-4} across the full tuning range and are further suppressed to below 1×10^{-4} within the core gradient range of 26.94–64.19 T/m. The integrated gradient spans 2.99–7.34 T, and the magnetic center deviation is maintained within 20 μm in the broader tuning range from -64° to 86° . The results confirm that the PQM prototype meets key specifications for gradient tunability and magnetic field precision, validating its feasibility for advanced light source applications.

II. TUNABLE PQM DESIGN FOR HALF

A. Structure and physical design

To satisfy the operational requirements of the quadrupoles at HALF, the PQM is designed with a physical length of 100 mm and an aperture diameter of 28 mm. The magnetic field gradient tuning range spans 30–65 T/m,

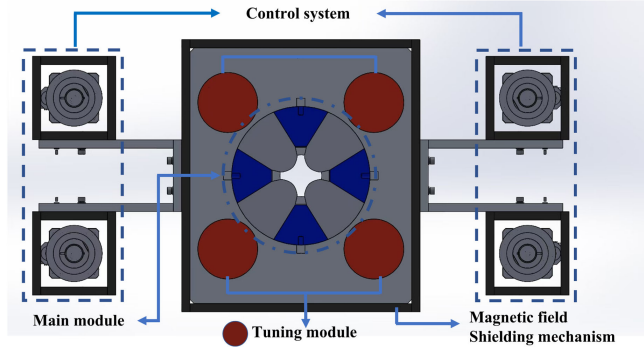


FIG. 1. Mechanical structure of the PQM.

with normalized multipole field components maintained below 5×10^{-4} . The mechanical structure of the PQM, illustrated in Fig. 1, consists of a main module (radius 83 mm) and a tuning module (radius 36 mm). The main module, a hybrid assembly of alternating permanent magnet blocks and ferromagnetic poles, primarily determines the quadrupole field quality within the central aperture. Gradient tuning is accomplished by adjusting the excitation direction of the tuning module [41,42]. Both the main and tuning modules use NdFeB permanent magnets of grade 35UH. This grade was chosen because the designed tunable gradient range requires a relatively high remanence, while a high intrinsic coercivity is also necessary to satisfy radiation protection requirements.

Figure 2 illustrates the magnetization directions of the main and tuning modules, along with the magnetic field distributions and field flux lines under the minimum and maximum gradient configurations. In Fig. 1(a), the main module adopts a fixed magnetization pattern, arranged from top to bottom and left to right, with magnetization angles of 180° , 90° , 0° , and -90° relative to the x axis. The tuning module consists of four permanent magnets, labeled PM1 through PM4, whose magnetization directions are defined by angles β_1 , β_2 , β_3 , and β_4 with respect to the x axis.

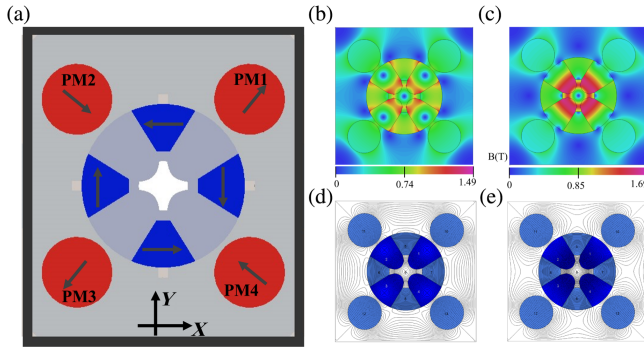


FIG. 2. Physical design and magnetic field characteristics of the PQM. (a) Magnetization directions of the main and tuning modules; (b),(c) magnetic field distributions at $k_{\min}$ and $k_{\max}$; (d),(e) magnetic field flux lines at $k_{\min}$ and $k_{\max}$.

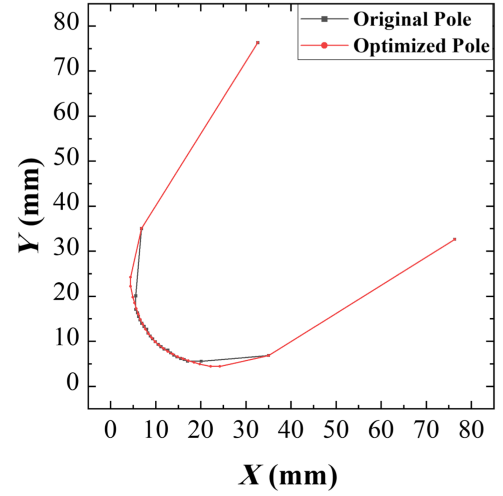


FIG. 3. Comparison of the pole profile before and after optimization. The gray line is the original pole, the red line is the optimized pole.

According to previous works [43], in order to ensure the formation of a quadrupole field at the central aperture during the tuning process, the magnetization directions of the tuning module are subject to the constraints given in Eq. (1).

$$\begin{aligned} \beta_1 + \beta_2 &= 0, & \beta_3 + \beta_4 &= 0 \\ \beta_1 + \beta_4 &= \pi, & \beta_2 + \beta_3 &= -\pi \end{aligned} \quad (1)$$

Compared to conventional electromagnetic quadrupoles, the PQM design offers a significantly more compact mechanical structure by eliminating bulky excitation coils and associated water-cooling systems. The core magnet assembly has dimensions of $345 \times 345 \times 195$ mm, while the complete prototype, including the integrated control system, is confined within an overall external dimensions of $655 \times 345 \times 195$ mm.

B. Pole profile optimization

Following the completion of the magnet's structural design, a magnetic model was made and analyzed using the Opera software package. Figure 3 shows the comparison

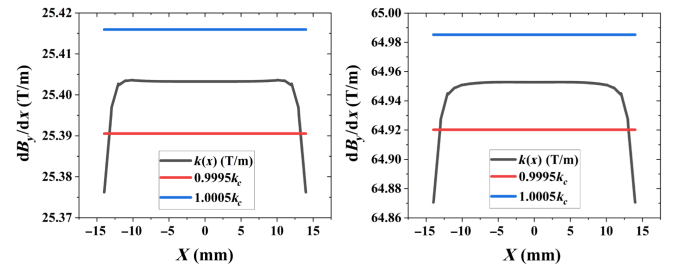


FIG. 4. Magnetic field gradient distribution in the horizontal plane ($Z = 0$). Left: $k_{\min}$; right: $k_{\max}$.

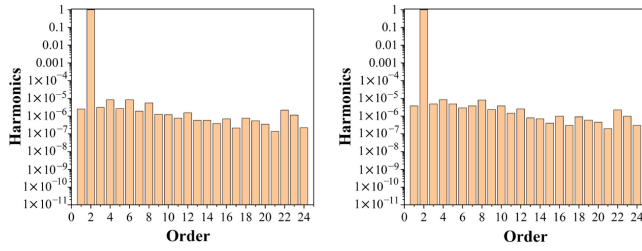


FIG. 5. Higher-order harmonics at the quadrupole center ($r = 11$ mm). Left: $k_{\min}$; right: $k_{\max}$.

of the pole profiles before and after optimization. Starting from an initial hyperbolic shape, the pole contour was refined using an intelligent optimization algorithm to achieve improved field quality. In the practical model implementation, the contour segment connecting coordinates (32.64, 76.31) mm and (76.31, 32.64) mm was approximated by a circular arc with a radius of $r = 83$ mm. The simulated performance metrics obtained after optimization, as shown in Figs. 4 and 5, include the tuning range of the field gradient, the good field region, and the relative multipole field components, where each harmonic component is normalized to the quadrupole field (B_2). The good field region is defined as the lateral range within which the magnetic field gradient deviates by no more than $\pm 5 \times 10^{-4}$ from the central magnetic field gradient.

Following pole profile optimization, the tunable PQM exhibited a substantially extended magnetic field gradient tuning range of 25.40–64.95 T/m, corresponding to a total span of 39.55 T/m. The good field region was simultaneously expanded to approximately ± 13.2 mm, ensuring high field quality over a wider aperture. In addition, higher-order harmonic analysis revealed effective suppression of normalized multipole components, which were reduced below 1×10^{-5} at a radius of 11 mm. The extended tuning range, enlarged good field region, and mitigated higher-order harmonics collectively underscore the effectiveness of the optimization, enabling consistently high field quality and enhanced operational flexibility.

III. FABRICATION OF THE PROTOTYPE

A. Pole profile measurement

The four pole profiles of the PQM are critical in defining the magnetic field quality. To ensure the precision of the resulting field, accurate measurements of their surface morphology were carried out as a key validation step. After being machined and assembled according to the design specifications, the morphology of the poles was thoroughly measured. The assembled poles within the main module are depicted in Fig. 6.

A coordinate measuring machine was employed to precisely assess the pole morphology of the PQM prototype. Measurements were taken at three axial positions (10, 50, and 90 mm from the end) for each pole. The acquired



FIG. 6. Mechanical structure of the PQM.

data were compared with the ideal pole profile to determine displacement errors at each measurement point. These measurements are used to provide a detailed evaluation of the machining accuracy and morphology deviations for each pole.

Figure 7 displays the measured morphology errors for the four poles. The measurements show that most points deviate by less than 20 μm , with only a few outliers approaching 30 μm . Furthermore, the poles demonstrate high morphological consistency across the three axial positions, indicating that the machining accuracy meets the requirements for assembly and field quality.

B. Magnetization direction measurement

The magnetization direction of the permanent magnets is also a key factor affecting the magnetic field quality of the PQM prototype. To ensure compliance with design specifications, the magnetization directions of all permanent magnets were measured, with results summarized in Table II. For the main module, the magnetization direction of the permanent magnet blocks is designed to align with the y axis of the measurement coordinate system. Thus, the deviation of θ_y from 0° can be used as an indicator of the magnetization direction error for the main module blocks. All four magnets exhibit magnetization direction deviations within $\pm 1^\circ$. Previous error analysis [43,44] confirms that such deviations have a negligible effect on the field quality, especially with hybrid designs including ferromagnetic poles. For the tuning module, while the measured θ_x and θ_y values vary due to differences in the angular positioning of the magnet blocks during measurement, the deviation of θ_z from 90° reflects the magnetization direction error, with all four cylindrical magnets exhibiting deviations within $\pm 0.2^\circ$. These results verify that the magnetization accuracy of all permanent magnets satisfies the assembly and performance requirements.

C. Prototype assembly and control system

After completion of the pole profile and permanent magnet magnetization measurements, and after all components

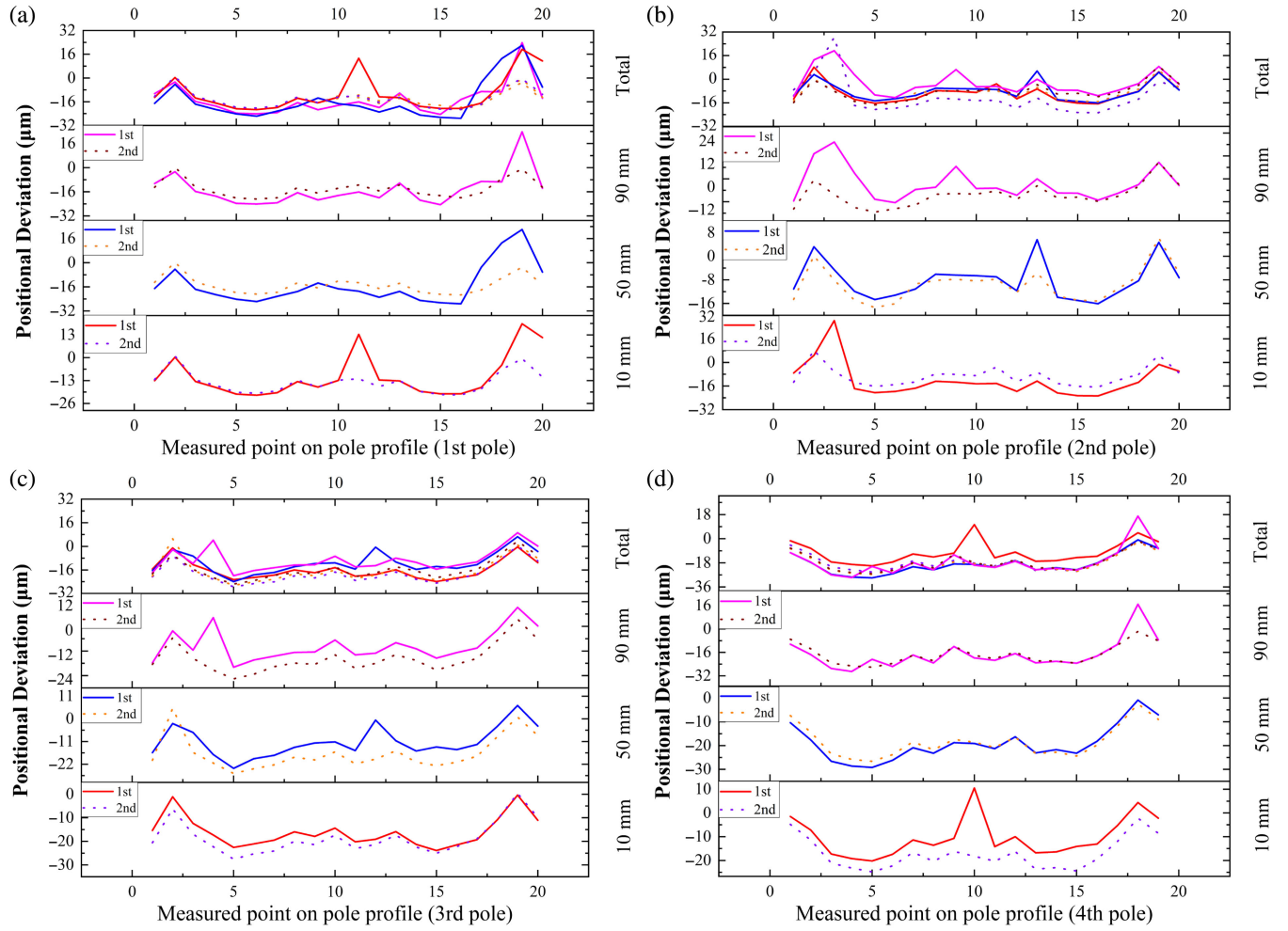


FIG. 7. Profile error distributions of the PQM prototype: (a) first pole, (b) second pole, (c) third pole, and (d) fourth pole. For each pole, positional deviations along the longitudinal direction are presented at three cross-sectional heights (10, 50, and 90 mm), as well as for the total integrated profile. The results from the first and second measurement results are compared, demonstrating the consistency and repeatability of the pole profiles.

had been fabricated and verified, assembly of the PQM prototype commenced. The installation process of the main module is shown in Fig. 8. To ensure precise positioning and alignment with the design specifications,

TABLE II. Magnetization direction test results of the prototype main and tuning modules.

Module type	Block	θ_x (°)	θ_y (°)	θ_z (°)
Main	1	89.86	0.71	89.30
	2	89.54	0.87	89.26
	3	89.79	0.64	89.39
	4	89.65	0.96	89.10
Tuning	1	47.15	42.85	89.94
	2	41.95	48.05	89.91
	3	30.29	59.71	89.89
	4	26.33	63.67	89.82

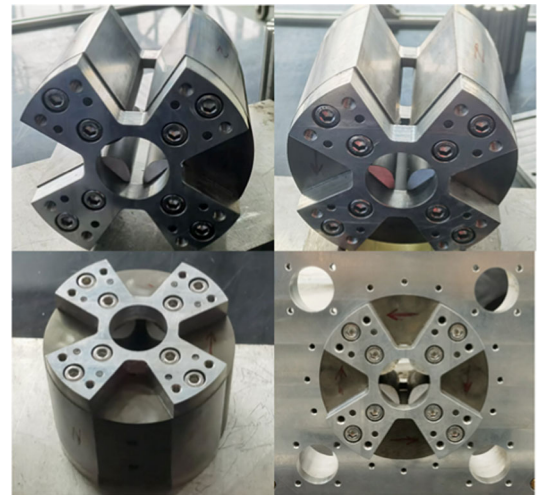


FIG. 8. Main module installation process of the PQM.

TABLE III. Force and torque measurements under different β_1 angles.

β_1 (°)	F_x (N)	F_y (N)	T_x (Nm)	T_y (Nm)
45°	-757.81	-757.81	-37.89	37.89
65°	-398.06	-398.06	-19.90	19.90
85°	-137.88	-137.88	-6.89	6.89
105°	-120.12	-120.12	-6.00	6.00
125°	-384.64	-384.64	-19.23	19.23
145°	-848.27	-848.27	-42.41	42.41
165°	-1332.68	-1332.68	-66.63	66.63
185°	-1619.21	-1619.21	-80.96	80.96
205°	-1576.33	-1576.33	-78.82	78.82
225°	-1259.01	-1259.01	-62.95	62.95

TABLE IV. Physical parameters of the motor.

Parameter	Value	Unit
Base dimension	60	mm
Holding torque	2.5	Nm
Motor length	118.5	mm
Max rotational speed	3000	rpm
Mass	1.65	kg

the magnetization directions were premarked on the four permanent magnet blocks of the main module. These blocks were then carefully assembled with the poles to achieve both structural stability and the intended magnetic field distribution.

Following the assembly of the main module, the permanent magnets of the tuning module were installed sequentially. To ensure structural stability during this process, the four magnets were mounted in two diagonal pairs: the first two along one diagonal, followed by the remaining two along the opposite diagonal. A magnetic cage was then installed around the prototype to provide magnetic shielding. It shielded the motor's magnetic components from the forces exerted by the prototype's permanent magnets, while also mitigating external magnetic interference with the prototype's central magnetic field, thereby enhancing overall magnetic field stability. An open-loop control system, incorporating a programmable logic controller (PLC) and AutoShop software, was established to enable online tunability of the magnetic field gradient. The angular accuracy of the rotation system is 0.01° .

Computational analysis using the Opera-3D software package was carried out to evaluate the forces and torques acting on the permanent magnet tuning blocks across the full tuning range. Due to the inherent symmetry of the design, the analysis focused on a single tuning block. Table III summarizes the calculated forces, with the corresponding torque values computed relative to the geometric center of the block's end face, located at (87.69, 87.69) mm.

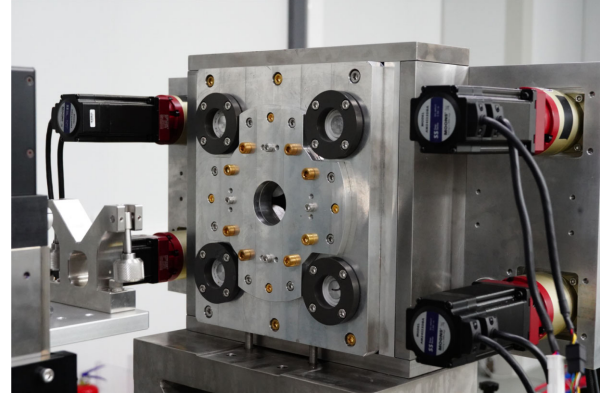


FIG. 9. PQM prototype.

The transmission system is responsible for precisely orienting the tuning blocks. It comprises a Moons' AM24SS3DBA integrated servo stepper motor (parameters listed in Table IV), coupled via a FASTON FKS060-L2 planetary gearbox with a 20: 1 reduction ratio, driving four identical gear sets, each providing an additional 3: 1 torque multiplication. The total available static torque from this system is 150 Nm (calculated as $2.5 \text{ Nm} \times 20 \times 3$). As indicated by the results in Table III, the maximum static torque required to adjust a single permanent magnet tuning block is 80.96 Nm. The available torque comfortably exceeds the required load for magnetic field tuning, ensuring a substantial operational margin.

With the main and tuning modules installed and the transmission system fully integrated, the control system was connected and subjected to tuning control tests, confirming its ability to dynamically adjust the magnetization direction of the tuning module via the servo motor. A photograph of the fully assembled prototype is shown in Fig. 9.

IV. MAGNETIC MEASUREMENT

Magnetic field measurements of the PQM prototype were performed using two primary methods: a rotating coil system and Hall probe field mapper (Fig. 10). Gradient tuning was achieved by synchronously rotating these four blocks via stepper motors to alter their effective magnetization directions. Key magnetic parameters were measured at various angles, referenced to the absolute angular position of tuning block no. 1, denoted as β_1 . The experiment adopted a stepwise tuning mode, with each block rotated in 10° increments. Measurements covered an angular range from -74° to 96° , spanning a total tuning range of 170° . Although the theoretical maximum is 180° , the boundary regions within 5° at both ends were excluded due to reduced field quality and minimal gradient change, indicating proximity to the adjustment mechanism's physical limits (discussed further in the magnetic field gradient analysis section).

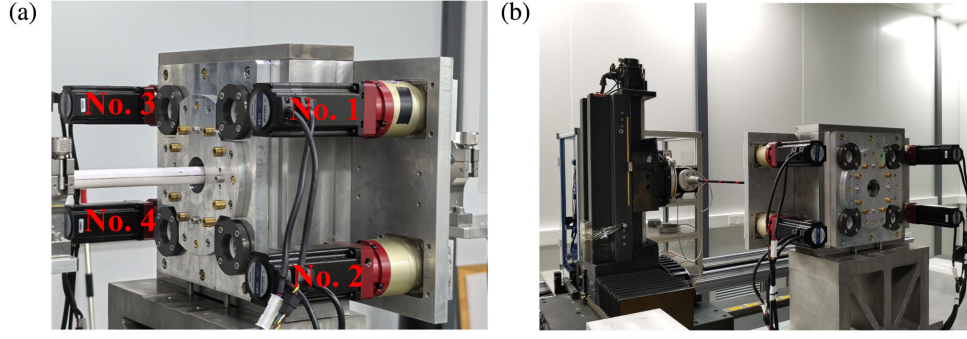


FIG. 10. Measurement setup of the tunable PQM. (a) Rotating coil; (b) Hall probes.

A. Harmonic components

Figure 11 shows the measured normalized multipole field components (B_n/B_2) of the PQM prototype across the full angular tuning range, evaluated at a reference radius of 10 mm (the coil radius). The measured B_3/B_2 remains below 5×10^{-4} throughout the entire range and is further suppressed to below 1×10^{-4} within the angular range of -60° to 80° . The higher-order components B_4/B_2 , B_5/B_2 , and B_6/B_2 consistently stay below 1×10^{-4} across the full tuning range. These results demonstrate excellent agreement with design specifications and simulation predictions for the magnetic field quality.

B. Magnetic field and integrated gradient

The magnetic field gradient measurement and simulation results are presented in Fig. 12. The experimental data closely follow the simulation trend, validating the accuracy and reliability of both the mechanical design and the magnetic field modeling approach. The measurements

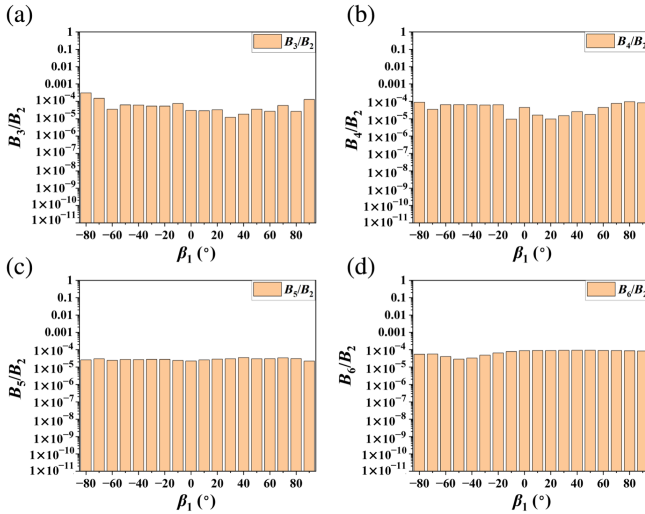


FIG. 11. Normalized higher-order multipole field components as a function of the angle of tuning block no. 1: (a) B_3/B_2 , (b) B_4/B_2 , (c) B_5/B_2 , and (d) B_6/B_2 . All components remain below 5×10^{-4} across the full tuning range.

show that as the tuning mechanism rotates continuously from -74° to 96° , the field gradient decreases monotonically from 65.68 to 26.69 T/m, yielding a total tuning range of 26.69–65.68 T/m, corresponding to a modulation range of 38.99 T/m.

Detailed analysis reveals distinct modulation characteristics across the tuning range. At the extremities, the gradient response to angular adjustment is notably weak: from -74° to -64° , the gradient changes by only 0.182 T/m, and from 86° to 96° , by 0.250 T/m. More broadly, the combined ranges of -74° to -55° and 66° to 96° (totaling 50°) contribute just 3.586 T/m, accounting for about 9.2% of the full 38.99 T/m range. In contrast, the central tuning range of -55° to 66° (approximately 121° , or 71% of the full range) delivers over 90% of the total modulation. These results confirm that the measured 170° angular span effectively captures the practical limits of the PQM prototype's magnetic field gradient tuning capability.

The measured tuning range of the PQM integrated gradient is 3.00 – 7.34 T, as shown in Fig. 13. This range exhibits modulation characteristics similar to those observed for the magnetic field gradient.

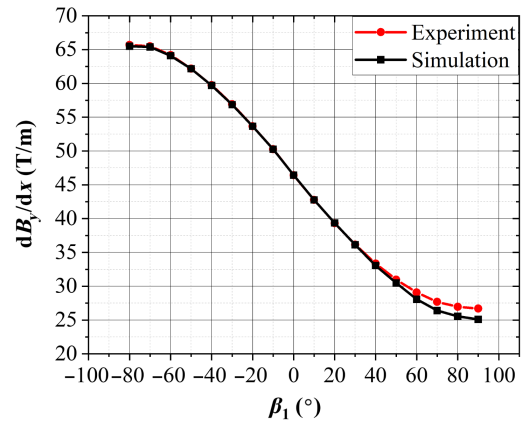


FIG. 12. Magnetic field gradient measurement results. The black line represents simulation data, and the red line shows experimental measurements.

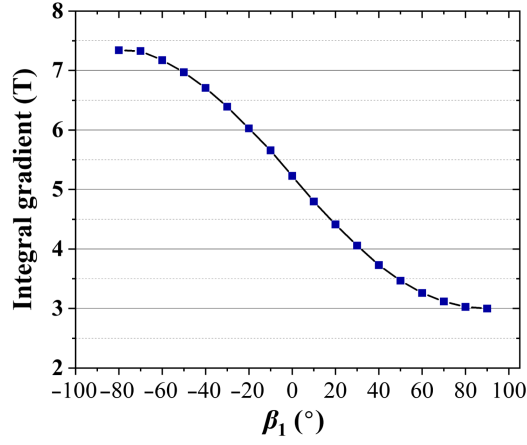


FIG. 13. Measurement of the integrated gradient along the tuning range.

C. Field uniformity

The uniformity of the integrated magnetic field for the PQM prototype was measured across various tuning ranges. As shown in Fig. 14, the maximum value of $(\Delta B_y L / B_y L)_{\max}$ was evaluated within horizontal ranges of ± 10 , ± 9 , and ± 8 mm to assess field uniformity across the effective aperture. The results show that the maximum integrated field nonuniformity remains below 2.75×10^{-4} within ± 10 mm, improves to below 2.42×10^{-4} within ± 9 mm, and further reduces to below 2.09×10^{-4} within ± 8 mm. This demonstrates excellent magnetic field uniformity, fully meeting the design requirements within the specified aperture.

D. Magnetic center offset

To ensure high-precision measurements, the rotation coil was first aligned with the magnet axis using a laser tracker.

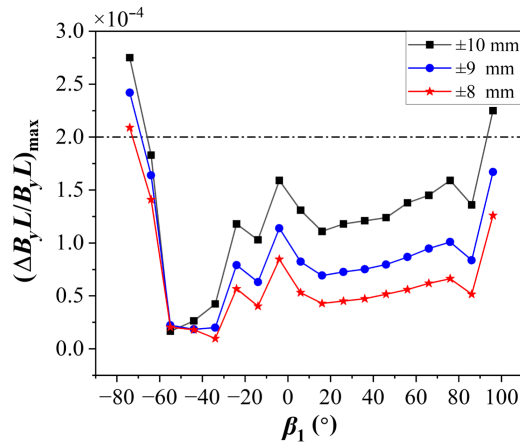


FIG. 14. Uniformity of the integrated magnetic field, expressed as $(\Delta B_y L / B_y L)_{\max}$, as a function of the tuning angle of block no. 1. Results are shown for the maximum values measured within transverse ranges of ± 10 , ± 9 , and ± 8 mm.

The measurement started at the 0° tuning position, where the coil center was precisely adjusted to coincide with the magnetic center, with an alignment accuracy better than $1 \mu\text{m}$. The initial magnetization directions of the permanent magnets in the tuning module were then roughly calibrated using a Gaussmeter. During initialization, one magnet was fixed while the remaining three were adjusted to suppress high-order harmonic components below 1×10^{-4} .

The measured magnetic center offset as a function of the angular tuning position is presented in Fig. 15. Across the full angular range from -74° to 96° , the maximum observed offsets were $40.87 \mu\text{m}$ in the vertical (y) direction (at -74°) and $16.60 \mu\text{m}$ in the horizontal (x) direction (at 76°). Both maximum deviations are within the specified tolerances of $\leq 20 \mu\text{m}$ in x and $\leq 41 \mu\text{m}$ in y . Within the high-precision tuning range, spanning angles from -55° to 6° —corresponding to magnetic field gradient range of 48.42 – 64.19 T/m—the magnetic center deviation remains well controlled within $\pm 10 \mu\text{m}$ in both directions. Even in the broader tuning range from -64° to 86° , covering gradient range of 26.94 – 65.50 T/m, the deviation is consistently maintained within $\pm 20 \mu\text{m}$ in both directions.

These results confirm that the PQM prototype exhibits excellent magnetic center stability across the full gradient modulation range (26.94 – 65.50 T/m), meeting the stringent beam alignment requirements necessary for advanced light source applications.

E. Summary

Table V summarizes the key measured parameters of the PQM prototype alongside the corresponding design specifications. The prototype achieves a tunable magnetic field gradient range of 26.69 – 65.68 T/m, fully covering the design target of 30 – 65 T/m. The integrated field uniformity is maintained below 2.75×10^{-4} within a ± 10 mm transverse range, satisfying the design criterion of $< 5 \times 10^{-4}$. The normalized multipole field components

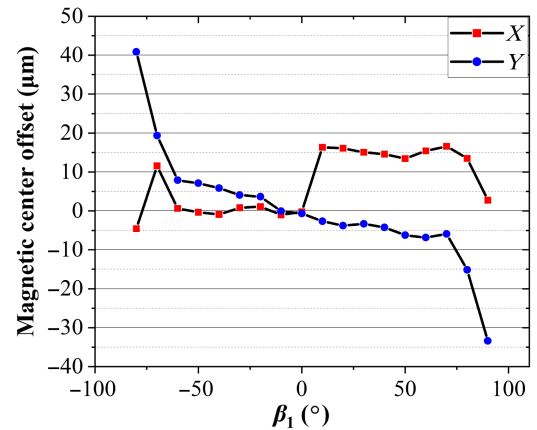


FIG. 15. Measurement results of the magnetic center offset over the tuning range.

TABLE V. Physical parameters of the PQM prototype.

Physical parameters	Design requirements	Results
Physical aperture (diameter)	28 mm	28 mm
Physical length	100 mm	100 mm
Dimensions of the main structure	$345 \times 345 \times 195$ mm	$345 \times 345 \times 195$ mm
Magnetic field gradient adjustable range	30–65 T/m	26.70–65.68 T/m
Magnetic center offset	≤ 30 μm	≤ 20 μm ($26.96 \leq k \leq 64.19$ T/m)
Integrated gradient homogeneity	$< 5 \times 10^{-4}$	$< 2.75 \times 10^{-4}$
Higher-order harmonic components	$\frac{B_n}{B_2} < 5 \times 10^{-4}$ ($n \neq 2$)	$\frac{B_n}{B_2} < 1 \times 10^{-4}$ ($26.96 \leq k \leq 64.19$ T/m)

remain below 1×10^{-4} across the gradient range of 26.94–64.19 T/m (evaluated at $r = 10$ mm), meeting the requirement of $< 5 \times 10^{-4}$ for all multipole orders. In the broader tuning range from -64° to 86° , corresponding to a gradient range of 26.94–65.50 T/m, the magnetic center offset is consistently maintained within ± 20 μm in both horizontal and vertical directions. These results collectively demonstrate that the PQM prototype meets the design requirements for both gradient tunability and magnetic field quality, confirming its suitability for applications in advanced light sources.

V. CONCLUSION

The PQM developed in this study demonstrates excellent magnetic field quality, with higher-order harmonics controllable to the level of 5×10^{-4} . The integrated magnetic field uniformity within a ± 10 mm transverse range is below 2.75×10^{-4} , meeting the stringent magnetic field precision requirements for next-generation light source facilities. In addition, the PQM's magnetic field gradient can be continuously tuned over a range of approximately 39 T/m. By selecting different combinations of main and tuning modules, the PQM structure allows flexible realization of various gradient strengths and tuning ranges, making it adaptable to different design requirements. The integrated gradient design substantially reduces both the design and calibration workload for quadrupole magnets, thereby accelerating the engineering implementation process.

In terms of physical design, the PQM employs a fully permanent magnet scheme, eliminating the need for excitation coils or water-cooling systems. This avoids issues such as magnetic field microvibrations caused by fluctuations in power supply current, current ripple, and turbulent cooling water, thereby enhancing magnetic field stability and ensuring beam quality. Furthermore, its compact mechanical structure (with maximum dimensions of $345 \times 345 \times 195$ mm) conserves longitudinal space, supporting the compact layout requirements of the MBA lattice structure in fourth-generation synchrotron light sources. This design effectively addresses challenges associated with the dense magnet population and tight spacing in bending sections, while also eliminating the energy and

water consumption inherent to traditional electromagnetic quadrupoles. As a result, both energy consumption and operational costs are significantly reduced.

The successful development of this PQM serves as an important milestone, providing a technological foundation for the future development of permanent dipole magnets, permanent sextupole magnets, and combined-function magnets.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available because they contain commercially sensitive information. The data are available from the authors upon reasonable request.

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