VALIDATION OF AN IMPROVED QUADRUPOLE DESIGN FOR THE 3 GeV SPS-II STORAGE RING

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Abstract

Achieving high beam stability in the 3 GeV SPS-II storage ring critically depends on the precision of its quadrupole magnets. This work presents a crucial phase of the magnet prototype development, which is central to fostering domestic high-technology manufacturing with Thai industry partners field measurements on the initial quadrupole design featuring removable poles revealed a critical engineering issue of significant multipole errors caused by mechanical pole rotation. This error was traced to the stresses and assembly error that occurred during pole removal and re-assembly for coil installation to solve this specific problem, an improved quadrupole design was employed. The new symmetrical geometry eliminates the pole-removal step, thus intrinsically preventing the assembly error and significantly increasing structural stability and field quality. Coupled mechanical-magnetic analysis using ANSYS Workbench and Opera-3D confirms this approach. The simulations demonstrate that the improved design provides the required mechanical stability to minimize multipole field errors. The data presented validates this successful design change. The strict production tolerances were defined, and it is demonstrated precisely how the new design resolves the pole rotation issue. The presentation will feature a direct comparison of magnetic field measurements from both the initial and the improved prototypes, definitively verifying the enhanced performance necessary for SPS-II commissioning.

INTRODUCTION

The Siam Photon Source II (SPS II), Thailand's second synchrotron light source, is a 3.0 GeV fourth generation facility based on a Double Triple Bend Achromat (DTBA) lattice, delivering ultra bright photon beams with intensities up to one million times higher than the existing source. SPS II supports advanced research across multiple scientific and industrial fields and enhances regional scientific capacity within Southeast Asia through its location in the Eastern Economic Corridor of Innovation (EECi).

Quadrupole magnets are essential to the performance of DTBA storage rings, providing strong focusing required for ultralow emittance and precise control of functions and dispersion in compact lattices. [1, 2] Their field quality is critical for nonlinear cancellation, dynamic aperture, and beam lifetime, while the compact layout increases sensitivity to magnetic crosstalk, necessitating accurate modelling and multipole control.

This study compares two quadrupole magnet core designs to assess the impact of geometry, manufacturing precision, and assembly alignment on magnetic field quality. All processes adhere to the Terms of Reference (TOR) with dimensional tolerances within 20 µm, enabling reliable validation of measured fields against simulations and confirming the effectiveness of the improved design.

MAGNET DESIGN

The mechanical design of the quadrupole magnet was developed using SOLIDWORKS, where the iron-core geometry and mounting interfaces were refined following the prescribed pole-profile specifications. Structural integrity and natural frequencies were subsequently evaluated using ANSYS Workbench through finite element analysis ensure that the deformation conformed to Table 1.

Table 1. Parameter tolerance criteria for quadrupole design

Item	Tolerance
Pole rotation	≤ 250µrad
Pole positioning	≤ ±20 µm
Yoke deformation	≤ ±5 µm
Assembly reproducibility	≤ ±10 µm

Magnet type A demonstrated that pole rotation is the dominant source of sextupled and higher-order multipole errors in the initial quadrupole configuration. Even small angular deviations of the pole pieces lead to substantial, non-correctable multipole components, particularly problematic in the compact DTBA environment. [3, 4]

In this study, Magnet Type A was designed and fabricated; magnetic-field measurements revealed assembly-related errors, as illustrated in Fig. 1. Consequently, Magnet Type B was developed with fully symmetric components to minimize manufacturing and assembly deviations, thereby improving structural stability and magnetic-field quality.

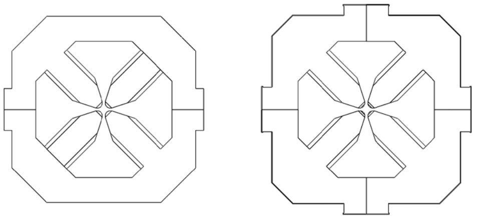

Figure 1: Quadrupole magnet type A and B.

RESULTS

Magnet Deformation

Structural simulation was performed to evaluate the mechanical stability of the quadrupole magnet under realistic conditions. The AISI 1006 steel core was modelled as isotropic, with appropriate contact definitions, assembly loads, and support boundary conditions applied to assess stress and deformation.

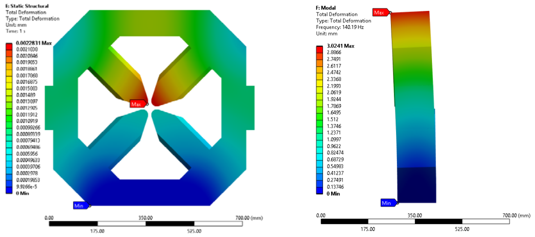

Figure 2: Magnet deformation and Natural frequency of quadruple pole magnets type A.

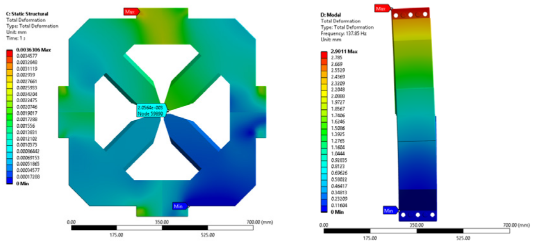

Figure 3: Magnet deformation and Natural frequency of quadruple pole magnets type B.

The finite element method (FEM) simulation results show the mechanical deformation distribution of the quadrupole magnet using colour contours, as illustrated in Fig. 2and 3 deformation in these regions is symmetric about both vertical and horizontal axes, consistent with the magnet geometry and boundary conditions. The maximum deformation is approximately −3 μm at the core contact interfaces and −1.5 μm at the pole profile, remaining well within tolerance limits and indicating sufficient mechanical rigidity to suppress unwanted multipole field errors.

Furthermore, modal analysis was performed to evaluate the dynamic behaviour during operation of magnet types A and B. The initial natural frequencies were found to be 140.19 Hz and 137.85 Hz, with maximum displacements of 3.02 mm and 2.90 mm, respectively, as shown in Fig. 2 and 3.

Magnet Measurements

Magnetic field measurements of the quadrupole magnet were performed using a stretched wire system with a field resolution of 1×10^{-6} and a wire positioning resolution of 1 μm. Careful alignment was conducted to minimize systematic errors, with angular deviations limited to below 7 mrad in pitch and yaw, and within 35 mrad in roll"as shown in Fig. 4.

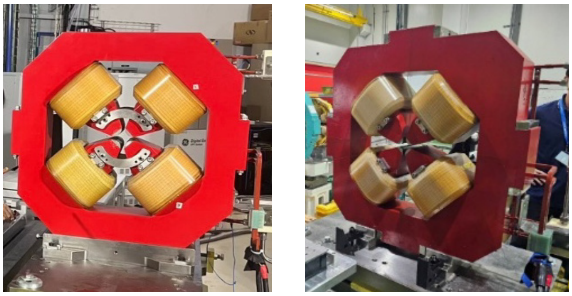

Figure 4: Installation and alignment of quadruple pole magnets type A and B.

The QD2 quadrupole magnet was operated at its nominal current of 100 A, and field deviations were measured near the magnetic centre by scanning the wire in both vertical and horizontal directions within ±5 µm. This method provides high sensitivity to higher-order magnetic multipole components, enabling reliable validation of the magnetic field model and assessment of the magnet's suitability for use in the SPS-II storage ring.

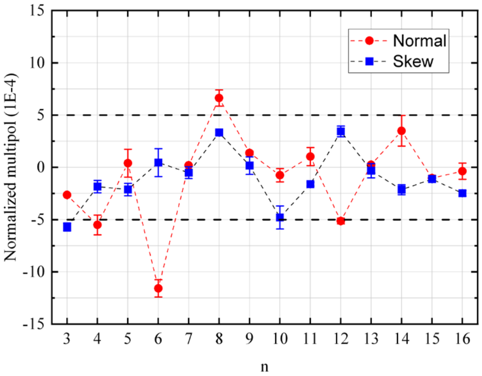

Figure 5: Normal multipole and Skew multipole of quadruple pole magnets type A.

Magnetic field measurements of the QD2 Type-A quadrupole magnet using a stretched wire system reveal significant multipole field errors, including both normal and skew components. The acceptance criterion was defined as normalized multipole errors not exceeding $5\times10^{-}4$ for all orders, excluding the second order term corresponding to the main quadrupole field.

Several normal multipole components (orders 6, 9, and 10) and skew components (orders 3 and 14) were found to exceed the tolerance limits, indicating magnetic field asymmetries. These errors are attributed to pole-profile inaccuracies, assembly misalignment, or rotational asymmetry, and may introduce transverse coupling that degrades storage ring beam dynamics, degrading beam dynamics and overall storage-ring performance as shown in Fig. 50

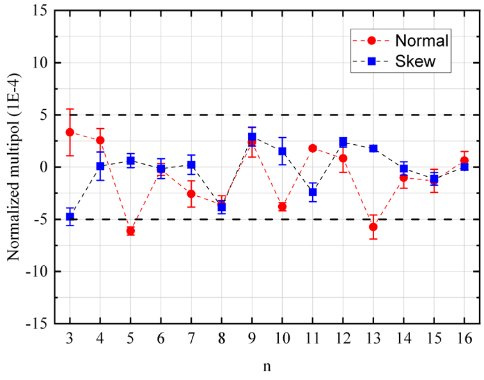

Figure 6: Normal multipole and Skew multipole of quadruple pole magnets type B.

Magnetic field measurements in Fig. 6 of the QD2 Type-B quadrupole magnet show that only a few normal multipole components, specifically orders 5 and 13, exceed the acceptance criteria, while all skew multipole components remain within the specified tolerance limits. Compared with the QD2 Type-A magnet, which exhibited multiple normal and skew multipole errors beyond tolerance, the Type-B magnet demonstrates a clear improvement in magnetic field quality.

This improvement is most evident in the strong suppression of skew multipole components, which are critical for beam stability due to their role in transverse coupling. The reduced skew errors indicate that the mechanical design improvements such as enhanced structural symmetry, elimination of pole disassembly and reassembly, and improved pole positioning accuracy effectively mitigate rotational asymmetry and assembly related errors. Although a small number of higher order normal multipole components remain above tolerance, their impact on beam dynamics is limited, confirming the superior magnetic field performance of the QD2 Type-B design relative to Type-A.

Validation

The validation of the quadrupole magnetic-field model developed using OPERA-3D was performed by comparing the simulation results with experimental magnetic field measurements obtained using a stretched-wire system.

The measurements were carried out over a current range from 10 to 150 A, covering operating conditions from low excitation to near the maximum specified current, in order to evaluate the consistency of the magnetic model under various operating regimes. The comparison results show that the magnetic flux density trends predicted by the simulation are in good agreement with the experimental measurements throughout the entire current range. The relative deviation between the simulated and measured values remains within 5%.

These results demonstrate that the OPERA-3D magnetic field model provides sufficient accuracy for predicting the operational behaviour of the quadrupole magnet under realistic conditions. Consequently, the validated model can be reliably employed as a design and optimization tool for further structural improvements and for assessing magnetic-field quality of quadrupole magnets intended for use in the SPS-II storage ring.

CONCLUSION

Compared with the QD2 Type-A magnet, which exhibited multiple normal and skew multipole components exceeding tolerance limits, the Type-B magnet shows a clear improvement in magnetic field quality. This improvement is most notable in the significant reduction of skew multipole components, which are critical for beam stability due to their role in transverse coupling. The suppression of skew multipoles confirms the effectiveness of the mechanical design improvements, including enhanced structural symmetry, elimination of pole disassembly, and tighter control of pole positioning. Although some higher-order normal multipoles remain above tolerance, their impact on beam dynamics is limited. Furthermore, the good agreement between OPERA-3D simulations and measurements validates the model for accurate performance prediction and future SPS-II design optimization.

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