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DEVELOPMENT OF COMBINED FUNCTION DIPOLE-QUADRUPOLE PMQ MAGNETS FOR NSLS-II UPGRADE*

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Abstract

This paper focuses on the R&D performed for the development of permanent magnets-based dipoles-quadrupoles combined function magnets (PMQs) for the future NSLSII upgrade based on "complex bend" lattice. This new lattice uses PMQs that provide both bending (dipole) and strong focusing (quadrupole) magnetic field on the electron beam. The permanent magnet technology is suitable for the high magnetic field strengths (0.5 T, 130 T/m) required for such combine function magnets. PM technology leads to a compact magnet design that is essential in realizing the complex bend lattice concept, as well as a passive magnet solution which does not require electrical power supply, reducing power consumption by ~ 80% (from 1.7 MW to 0.3 MW for NSLS-II). Two PMQs magnets designs are under consideration: A hybrid design that uses both PM and soft iron poles, and Halbach type that is a pure PM design. Both PMQ designs present challenges in achieving the specified magnetic field quality due to their higher sensitivity to errors (mechanical tolerances and PM properties). This paper presents cost-effective designs and prototypes results for hybrid and Halbach PMQs, addressing various technical challenges while meeting the magnetic field requirements of the magnets for the NSLS-II upgrade.

INTRODUCTION

A new lattice concept, known as the "complex bend (CB)," has been adopted for the upgrade of the NSLS-II storage ring [1-3]. This lattice uses a large number of bending magnets pushing the Multi-Bend Achromat lattice (MBA) concept. Each magnet includes both bending and strong focusing fields, keeping the beta functions and dispersion oscillating at low values resulting in low emittance beam. This compact lattice design provides more space for insertion devices and other components. The requirement of compact, high-strength combined-function magnets can only be achieved with PMQs with small bore aperture of 16 mm [4].

This R&D aims to demonstrate the feasibility of such PMQs with either Halbach [5] or Hybrid [6] design. The Halbach PMQ provides the most compact design and presents almost a unique design to generate all the field specification. This magnet design has not been used in storage ring because of technical challenges related to field quality and radiation damage concern with the PM material close to the electron and X-ray beam. The Hybrid design, which is less sensitive to PMs errors with the use of iron poles, is a robust solution adopted by several other upgrade project [7]. This paper presents the magnetic design of both Halbach and hybrid PMQs, with their prototypes and magnetic measurement results. Various field harmonic correction solutions for the Halbach PMQ are presented with a correction capability of more than 100 units of the Root Square Sum (RSS) of field harmonics.

MAGNETIC DESIGN

The PMQ design parameters are presented in Table 1. The CB element use 15 CF PMQs with various field and gradient specification. The field and gradient presented in the table is the most challenging case. A vertical gap of 8 mm in the horizontal plane for the X-ray beam is specified on the outboard side. The selected PM material grade is Sm_2Co_{17} with a 1.15 T remanence for better temperature stability and radiation resistance. Ideally the magnet design should provide a gradient tuning of ~2% for flexibility. Including higher-order multipoles (e.g., sextupole) in the field is envisaged.

Table 1: Magnet Design Parameters

Parameter	Specification	Unit
Field-Gradient	0.5-130	T-T/m
Bore radius	8	mm
GFR	±3	mm
Harmonics RSS	≤10	units
Length	100	mm

Halbach PMQ Designs

The Halbach PMQ designs are presented in Fig. 1. The 3D magnetic models are built with Radia [8]. The designs use 16 PMs wedges with a magnetization angle modulation to generate the CF field and gradient with a low harmonic content (~10 units). The first design, based on CBETA magnet design [9], use a combination of magnetization

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angle and PMs radial length modulation to achieve the field requirements. The second proposed design uses symmetrical PMs wedges geometry (50 mm radial length) and achieves a similar magnetic field result based on the magnetization angle optimization. In addition, the second design will provide more space for the vacuum chamber. The field and gradient results are presented in Fig. 2 and Fig. 3.

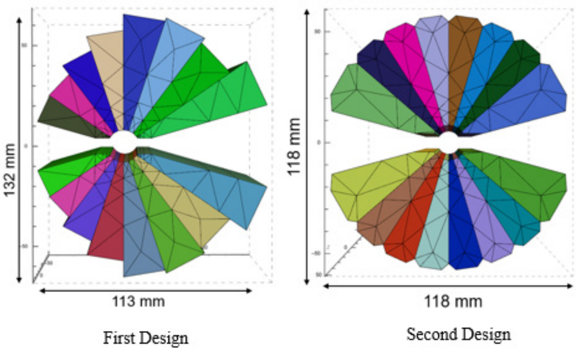

Figure 1: Halbach PMQs models. CBETA type design (left) and symmetrical design (right).

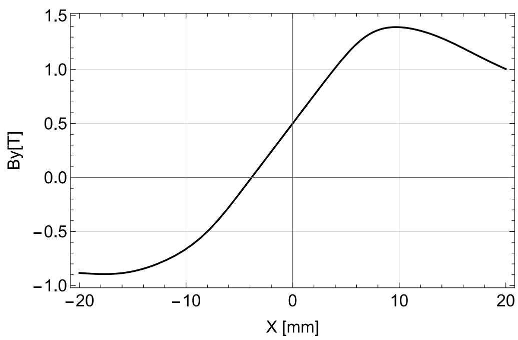

Figure 2: Halbach CF dipole-quadrupole magnetic field profile. The on-axis field is 0.5 T.

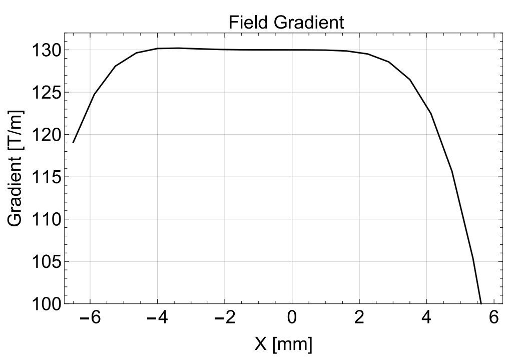

Figure 3: Halbach CF dipole-quadrupole field gradient.

Halbach PMQ Magnet Field Correction

The Halbach PMQ design is sensitive to PM's parameters and magnet assembly errors. Furthermore, for given tolerances, the impact on the field quality is higher for smaller magnet bore aperture. The design tolerances are presented in Table 2. These tolerances are tight for production, especially the magnetization angle tolerance. An estimation of the expected field quality with these tolerances was done. Thousand simulations with random errors applied on the PMQ model parameters in the range of the tolerances is performed. The resulting harmonics RSS maximum variation is 100 units. This estimation is close to the prototype measurement results.

Table 2: Halbach PMQ Tolerance Specifications

Parameter	Tolerance	Unit
B_R	1	%
Angle	1.5	Degree
Assembly	100	µm

The expected field harmonics error of the Halbach PMQ is much larger than the specification. Different field harmonics correction methods have been developed and tested. The first method is based on the modulation of the inner bore aperture (Fig. 4), by electric-discharge machining the PMs wedges or with radial displacement of PM wedges [10]. The second method uses an assembly of small PM block namely “Magic Fingers” located at the longitudinal extremity of the magnet that generate the correction field (Fig. 5). The third method uses iron shunt plates of different thicknesses for each PM wedges to control their strength.

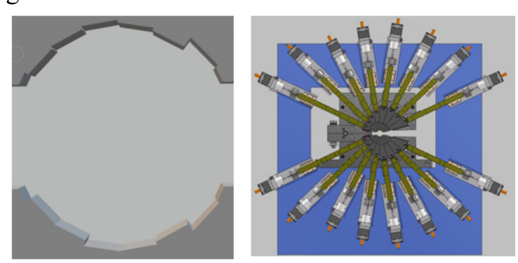

Figure 4: Inner bore electric-discharge machining profile (left), PMs wedges radial displacement (right).

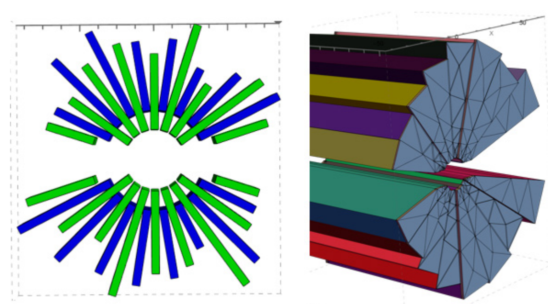

Figure 5: Magic finger assembly (left), iron shunt plates with different thicknesses (right).

Field measurements of the correction methods on the Halbach PMQ prototype have confirmed harmonics correction exceeding 100 units for the three methods. The radial displacement method is most efficient in term of correction performance, precision and flexibility, and saving longitudinal space. An automated in-situ correction system on the magnetic measurement bench is being developed for a large-scale production of Halbach PMQ.

A gradient tuning system based on iron shunt plate moved longitudinally toward the magnet edge is developed. This simple method provides a 2% gradient tuning

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with a 5 mm thickness iron plate, displaced within 10 mm longitudinal range based on the simulation results.

Hybrid PMQ Design

The hybrid PMQ design is presented in Fig. 6. It is a left-right asymmetric structure, with the right-side pair of poles receiving more magnetic flux from the PMs. This asymmetry creates the on-axis field offset for the dipole component. The highest magnetized pair of poles uses cobalt-iron material with saturation of ~2.35 T. the remaining iron part uses soft iron material AISI 1006.

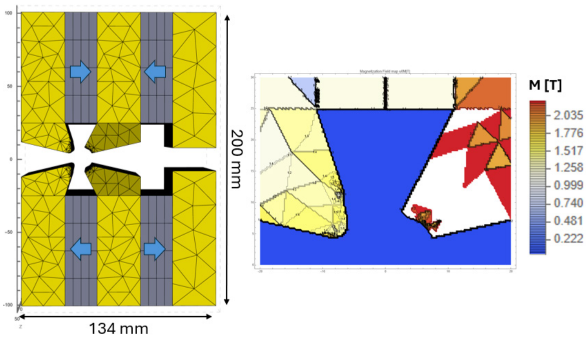

Figure 6: Hybrid PMQ design (left), pole shape and pole magnetization (right).

The pole shapes were optimized with a regularized Gauss-Newton algorithm [11]. The resulting field harmonics RSS is below 10 units. The magnetic axis where the field and gradient are obtained is shifted to 0.7 mm in the horizontal plane from the axis. The gap present in the return yoke will be adjusted for field correction and tuning. The poles shapes will be machined in the assembled PMQ with a wire Electric-discharge-machining of 10 µm precision. The estimated harmonics RSS deviation from the model is about 5 units with the tolerances. The fringe field of the hybrid PMQ extends beyond the magnet extremity. The CB lattice is dense and uses close spacing magnets (~15 mm). The magnetic interaction between the adjacent PMQs (crosstalk) in the CB element will be studied.

PROTOTYPES AND MEASUREMENT

The prototypes of the Halbach and Hybrid PMQs are shown in Fig. 7. Both prototypes use a C-shape clamshell structure to accommodate the vacuum chamber exit slot for the X-ray beam. The clamshell material is aluminum for the Halbach prototype and stainless steel for the hybrid prototype. The calculated deflection of the clamshells from finite-element model is less than 30 µm. The clamshell of the hybrid PMQ will be changed to aluminum to reduce the weight and the cost. 15 Halbach PMQ prototypes (9 defocusing and 6 focusing) were built by VacMagnetics company (Fig. 8) and an in-house prototype was built at BNL. A rotating coil (RC) bench with a 12 mm probe diameter and 0.1-unit precision was used for the magnetic measurements of the PMQ prototypes [12]. The field and gradient strengths of the 15 Halbach prototypes are in good agreement with the design expectations. The measured field harmonics errors (RSS) of the 15 PMQs were 80 units on average. The best Halbach prototype achieved 50 units with optimal assembly. At this stage, for an initial field harmonics RSS of 130 units for the In-house PMQ prototype (out of assembly tolerance), a field quality close to 10 units has been achieved with magic-fingers and bore-profiling correction methods.

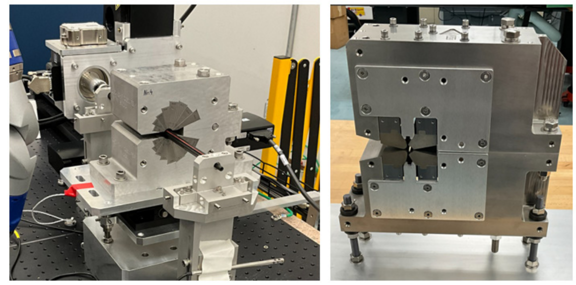

Figure 7: Halbach PMQ prototype on the RC measurement bench (left), hybrid PMQ prototype (right).

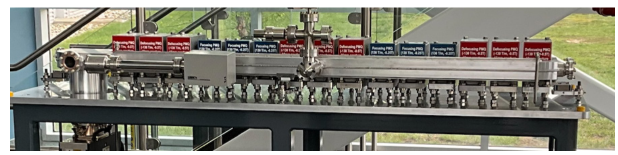

Figure 8: CB assembly composed of 15 Halbach PMQs magnets and the vacuum chamber.

RADIATION RESISTANCE TEST

The operational lifetime of the NSLS-II storage ring is 30 years. The long-term field stability of the PMQs in radiation environment will be investigated experimentally. The PM material is subjected to demagnetization with X-ray and electron beam scattering. A six-months experiment in a dedicated beam front end is planned. The X-ray from an undulator is scattered in the magnet bore (Fig. 9), and the magnetic field change of the PMQ will be monitored [13]. The test of a complex bend assembly in the current NSLSII storage ring is planned to validate the CB lattice concept and the magnetic stability of the PMQs.

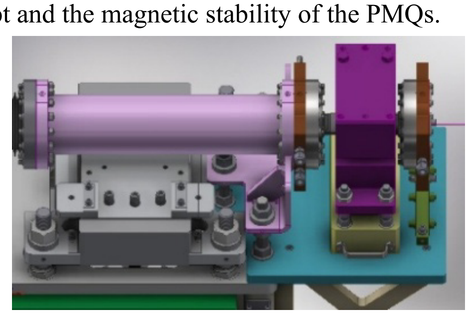

Figure 9: Halbach PMQ on the Radiation-Resistance test setup on a beamline front-end.

CONCLUSION

Compact high field strength CF Halbach and hybrid PMQs magnets are developed for the NSLSII upgrade CB lattice. Both Halbach and hybrid PMQ designs can meet the specifications with field correction methods. Further development and tests are planned for PMQ's long-term stability, field correction, field tuning and crosstalk. This will pave the way for the production of more than 2700 PMQs for the future NSLSII storage ring.

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