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HIGH GRADIENT QUADRUPOLES FOR LOW EMITTANCE SYNCHROTRONS

S. Sharma[1*], N. A. Mezentsev[2], T. Shaftan[1], V. Smaluk[1], C. Spataro[1], T. Tanabe[1], G. Wang[1]
[1]NSLS-II, Brookhaven National Laboratory, Upton, New York, 11973, USA
[2]BINP, Siberian Branch of Russian Academy of Sciences 11, Acad., Novosibirsk, Russia

Abstract

A new lattice design has been proposed recently based on a Complex-Bend concept [1,2] for low emittance synchrotrons. The dipoles of a standard DBA lattice are replaced in the Complex Bend by high-gradient (~ 450 T/m) quadrupoles interleaved between discrete dipoles. In another version of the Complex Bend [3] the high gradient quadrupoles are displaced transversely along the beam trajectory to generate the required dipole field. In the latter version the quadrupole strength is reduced to ~ 250 T/m for a lattice that will conform to the layout of the existing NSLS-II 3-GeV storage ring. In this paper we present conceptual designs of a Halbach permanent-magnet (PM) quadrupole, a hybrid PM quadrupole, and a superconducting quadrupole, that can produce the desired quadrupole strengths for the Complex Bend application.

INTRODUCTION

A new concept for low-emittance synchrotrons has been proposed recently in which the two dipoles of a traditional double-bend achromat (DBA) are replaced by Complex Bend I or II [1-3]. In Complex Bend I the required dipole field is provided by discrete dipole magnets interleaved between focusing and defocusing quadrupoles. The dipole field In Complex Bend II is generated by horizontal offsets of the quadrupoles, thus obviating the need of discrete dipoles.

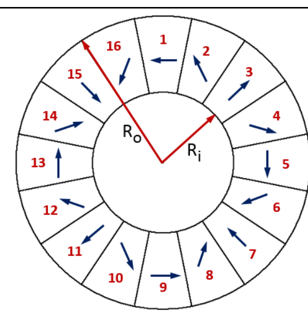
For the NSLS-II SR lattice upgrade the Complex Bend I concept with 10 cells was presented in [1,2] to replace DBA dipoles of ~ 3m arc length. It required quadrupoles of very high gradient, 450 T/m, which could be obtained only by a superconducting quadrupole with a beam aperture of 10 mm. In Complex Bend II, which allows for longer quadrupoles in the same ~ 3 m arc length, the required gradient is reduced to 250 T/m [3]. The reduced gradient makes it possible to use designs based on a Halbach PM quadrupole (Halbach PMQ [4,5]) or a hybrid PM quadrupole (hybrid PMQ [6]). Conceptual magnetic designs of these two types of quadrupoles together with the superconducting quadrupole are discussed in the following sections.

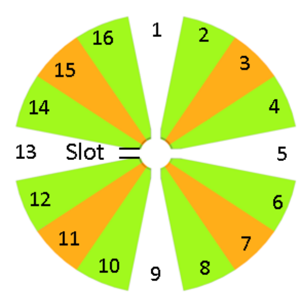
QUADRUPOLE DESIGN CONCEPTS

Halbach PMQ

The cross section of a standard 16-wedge Halbach PMQ is shown in the top figure of Table 1. The PM wedges and their magnetization directions are listed in columns 2 and 3. This standard configuration is modified to allow for a beam exit slot for the x-ray beams following the approach presented in [5]. As shown in the bottom figure of Table 1, wedge #13 is removed and a slot of the desired height is created by machining wedges 12 and 14. This configuration is repeated on the left, top and bottom to maintain a 4-fold symmetry required for good field harmonics. In the proposed conceptual designs for Complex Bend II, the inner and outer radii, Ri and Ro, are 5 mm and 40 mm, respectively. The slot height is 3 to 5 mm at the inner radius and length of the magnet is 280 mm.

Table 1: Halbach PMQ with Exit Slot





Cross Section	Wedge	Phase (Degree)
(figures above)	1	180
	2	112.5
	3	45.0
	4	337.5
	5	270.0
	6	202.5
	7	135.0
	8	67.5
	9	0.0
	10	292.5
	11	225.0
	12	157.5
	13	90.0
	14	22.5
	15	315.0
	16	247.5

A 3-D Opera model of a standard 16-wedge Halbach PMQ (without slots) yields a quadrupole gradient of 358 T/m with a built-in nonlinear material model of NdFeB. A low remanent field, 1.12 T, used in the model is consistent with NdFeB of higher radiation resistant. With 12-PM wedges and slot heights of 3, 4 and 5 mm, the gradient reduces 254 T/m, 237 T/m and 215 T/m, respectively. The gradient is calculated as on-axis integrated value divided by the length of the magnet. Field harmonics calculated at r = 2 mm per 10^4 units of B_2 are shown in Table 2. The exit slot results in a large B_6 of -55.0, -75.1 and -83.8 units for

* Email: sharma@bnl.gov

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the slot height of 3 mm, 4 mm and 5 mm, respectively. Other harmonics are relatively small within the numerical accuracy of the Opera 3-D models.

B_6 can be reduced by decreasing the magnetization angle between the diagonal PM wedges (3, 7, 11, 15) and their adjacent wedges ((2,4), (6,8), (10,12), (14,16)). When this angle is reduced from its nominal value of 67.5º to 37.5º, B_6 reduces approximately by 70%. The range of B_6 that would be acceptable for complex bends is presently under evaluation.

Table 2: Field Harmonics (at r = 2 mm) of 12-wedge Halbach PMQ

Harmonic No.	Exit Slot Height					
	3 mm		4 mm		5 mm	
	A_n	B_n	A_n	B_n	A_n	B_n
1	-0.1	0.1	1.0	-1.5	1.3	0.7
2	-0.2	10^4	1.2	10^4	0.1	10^4
3	-0.3	0.1	0.4	0.1	0.4	-0.1
4	0.0	0.2	0.2	-0.1	0.1	0.0
5	0.0	0.0	0.1	-0.1	0.0	0.1
6	0.0	-55.0	0.0	-75.1	0.0	-83.8
7	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.1

Hybrid PMQ

A hybrid PMQ design as proposed in [6] for a prototype built at ESRF can be used for high-gradient quadrupoles of Complex Bend II. This design utilizes NdFeB permanent magnets and soft-iron (AISI 1006) poles. Figure 1 shows cross-sectional dimensions of the PM and soft-iron blocks in a hybrid PMQ of 135 mm-width and 80-mm height. Magnet aperture and exit-slot height are 10 mm and 4 mm, respectively.

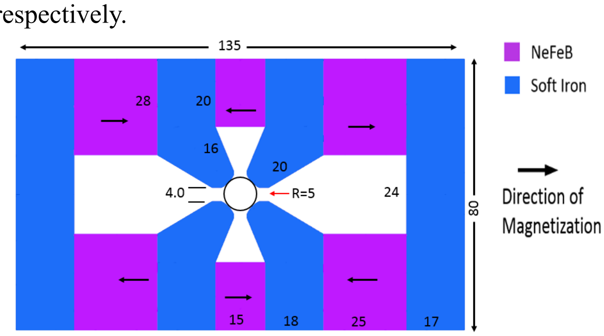

Figure 1: A hybrid PMQ based on an ESRF prototype design [6]. The dimensions are selected for its use in a new Complex Bend II geometry.

An Opera 3-D model of the hybrid PMQ of Fig. 1 yielded a quadrupole gradient of 202 T/m. The gradient can be increased to 242 T/m by doubling the heights of the PM and soft-iron blocks. The increased value is close to 250 T/m required for Complex Bend II presented in [3]. Moreover, a more recent version of Complex Bend II under investigation [7] requires a lower gradient in the range of 200 T/m.Field harmonics of the hybrid PMQ are shown in Table 3. B_6 harmonic is lower than that of the 12-wedge Halbach PMQ. These harmonics can be reduced further by shimming of the pole faces.

Table 3: Field Harmonics (at r = 2 mm) of a Hybrid PMQ with an Exit Slot Height of 4 mm

n	1	2	3	4	5	6	7	8
A_n	0.0	-0.4	1.1	-0.1	0.0	0.0	0.0	0.0
B_n	-0.3	10^4	-0.1	1.4	0.0	6.3	-0.1	0.0

Superconducting Quadrupole

A superconducting quadrupole (SCQ) with soft iron (AISI 1006) poles placed at 20 mm diameter can generate a high gradient that can meet the requirement of even Complex Bend I (~ 450 T/m). In the SCQ the vacuum chamber is inside the magnet aperture as shown Fig. 2 in contrast to Halbach PMQ or hybrid PMQ which are envisioned to be placed inside the vacuum chambers.

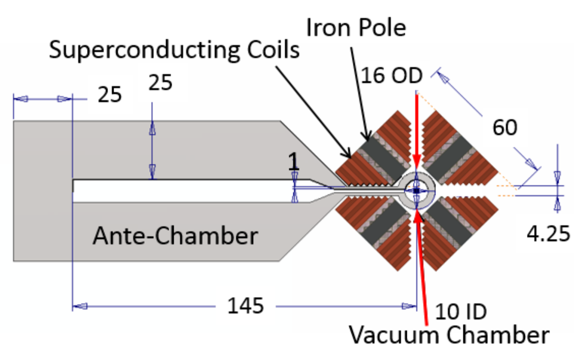

Figure 2: Conceptual design of a superconducting quadrupole with soft-iron poles. A vacuum chamber of 10 mm ID and 4 mm wall thickness is placed inside the magnet aperture of 20 mm.

The cross-section of the vacuum chamber is optimized to minimize its deflection under vacuum pressure. The wall thickness in the magnet aperture and the exit port are 4 mm and 1 mm, respectively. Structural support is provided by the 25-mm thick ante-chamber limiting the deflection to 0.05 mm. The exit slot has a comparatively lower height of 2.25 mm which may be too restrictive for the x-ray beams.

For a quadrupole gradient of 450 T/m, the superconducting coils (Fig. 2) carry 11,400 A (current density of 950 A/mm^2). The field quality of the SCQ is excellent as can be seen from the field harmonics listed in Table 4.

Table 4: Field Harmonics (at r = 2 mm) of the SCQ

n	1	2	3	4	5	6	7	8
A_n	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
B_n	0.0	10^4	0.0	0.0	0.0	-0.4	0.0	0.0

For the lower gradient requirement of Complex Bend II (250 T/m) the magnet aperture can be increased which will increase the slot height. In addition, the coil area can be reduced to allow room for additional coils that will generate the required dipole field. This will, however, further increase the complexity of the SCQ design with its limited length (~ 280 mm).

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DIPOLE FIELD FOR COMPLEX BEND II

Dipole Field by Transverse Offsets of Quadrupoles

The required dipole field for Complex Bend II can be generated by offsetting the Halbach PMQs or hybrid PMQs in the transverse X-direction. For the NSLS-II upgrade lattice [3] the defocusing and focusing PMQs will need offsets of ~1 mm and ~ 2 mm to provide the required dipole fields of 0.26 T and 0.49 T, respectively. These offsets are large compared to the magnetic aperture (10 mm) and result in large values of B_3, B_4, B_5 and B_6 harmonics. Table 5 shows field harmonics of a 12-wedge Halbach quadrupole with a 4-mm exit slot and a transverse offset of 1 mm. The effect of large B_3 to B_6 on the beam orbit is presently under evaluation.

Table 5: Field Harmonics (at r = 2 mm) of a 12-wedge Halbach PMQ with a 4-mm Exit Slot and Offset of 1 mm

n	1	2	3	4	5	6	7	8
A_n	0.0	1.1	0.2	-0.1	0.0	-0.1	0.0	0.0
B_n	5008	10^4	-92	-185	-186	-76	-2.1	-1.6

A hybrid PMQ with a 4-mm exit slot also produces significant B_3 to B_6 harmonics (see Table 6) when displaced transversely by 1 mm. These are, however, one order of magnitude smaller than those of the 12-wedge Halbach PMQ and it may be possible to reduce them further by shimming of the poles.

Table 6: Field harmonics (at r = 2 mm) of a hybrid PMQ with an exit slot of 4 mm and transverse offset of 1 mm

n	1	2	3	4	5	6	7	8
A_n	0.0	-3.4	3.0	1.2	0.0	-0.1	0.0	0.0
B_n	4999	10^4	10.1	17.5	15.7	5.6	-1.3	-1.2

External Dipole Field

An external magnetic field can be superimposed [5] on Halbach PMQs because of full saturation ($\mu \approx 1.0$) of the permanent magnets. A conventional electromagnetic dipole can, therefore, be used to provide the required dipole field for Complex Bend II. For the Halbach PMQs with outer radius of 40 mm a minimum gap of 90 mm between the poles is required accounting for ~ 5 mm thickness of the vacuum chamber. An H-shaped dipole with a pole width of ~ 250 mm and coil current of 18,000 A (current density of ~ 4 A/mm^2) can generate the required field of 0.49 T in arc lengths occupied by defocusing quadrupoles. To reduce this field to ~ 0.26 T in arc lengths occupied by focusing quadrupoles the pole gap is increased to ~ 220 mm.

A truncated dipole consisting of 3 small apertures of 90 mm and 2 large apertures of 220 mm (Fig. 3 (a)) was modeled by Opera 3D. The chamfered saw-tooth poles, 110 mm at the tip and 200 mm at the base, are placed 165 mm apart. The H-shaped soft-iron (AISI 1006) magnet is 700 mm in width and contains two coils of 48 mm x 96 mm in cross-section. This dipole generates a nearly sinusoidal dipole field with maximum and minimum field values in the required range (Fig, 3(b)).

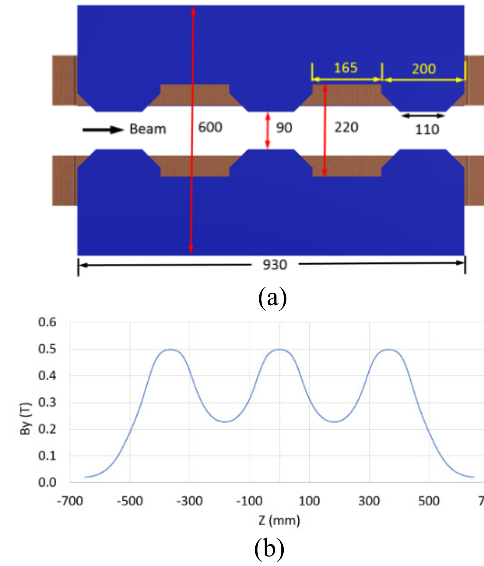

Figure 3: External dipole for Complex Bend II, (a) variable aperture along the beam direction, (b) dipole field along the beam direction.

CONCLUSION

Three conceptual designs for high-gradient quadrupoles were studied for their use in Complex Bends of low-emittance synchrotrons with a beam aperture of 10 mm. A modified Halbach PMQ provides the desired gradient of ~ 250 T/m for Complex Bend II and can be used with an external dipole field. An ESRF-type hybrid PMQ can also provide a gradient in this range but it cannot be used with an external dipole field. To generate the required dipole field the hybrid PMQs need to be offset transversely by 1 to 2 mm which adversely affects their field harmonics. It may be possible to reduce the field harmonics to acceptable range by shimming of the poles. An SCQ, although inherently more complex in implementation, can produce very high gradient (~ 450 T/m) and, for a lower gradient of Complex Bend II, may also be able to generate the required dipole field with additional superconducting coils.

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