

MAGNET DESIGNS FOR THE MULTI-BEND ACHROMAT LATTICE AT THE ADVANCED PHOTON SOURCE*

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Abstract

The Advanced Photon Source (APS) is currently investigating replacing the existing two-bend 7 GeV lattice with a 6 GeV seven-bend achromat magnet lattice in order to achieve a low electron beam emittance [1]. This new lattice requires 1320 magnets, of which there are nine types. These include high strength quadrupoles (gradient up to ~97 T/m), sextupoles with second derivative of field up to ~7000 T/m², longitudinal gradient dipoles with field ratio of up to 5, and transverse gradient dipoles with gradients of ~50 T/m and central field of ~0.6 T. These field requirements and the limited space available pose several design challenges. This paper presents a summary of magnet designs for the various magnet types developed through a collaboration of APS with FNAL and BNL.

INTRODUCTION

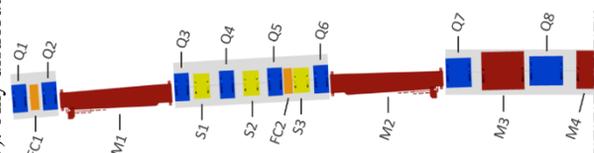


Figure 1: Half sector with magnet identifications.

The storage ring consists of forty sectors. There are 7 dipoles, 16 quadrupoles, 6 sextupoles, and 4 fast steering correctors, totalling 33 magnets in each sector. A representation of a half sector is shown in Fig. 1 along with magnet identifications. Table 1 lists the magnets and their respective lengths and maximum strengths. All magnets are solid core magnets with the exception of the corrector magnet, which requires a laminated core. The minimum pole tip radius for all magnets is 13 mm. For quadrupole, sextupole, and corrector magnets the minimum vertical gap between the poles is 10 mm and minimum vertical gap between the coils is 16 mm to allow for extraction of the photon beam. The fractional field deviation for each unwanted harmonic is limited to a maximum of 10⁻⁴ at a 10 mm reference radius. Any discrepancies in magnet harmonics are evaluated on a case-by-case basis.

VANADIUM PERMENDUR

Analysis shows that making quadrupole pole tips out of vanadium permendur (VP) can increase the field by 9% compared to steel core tips at the same magnetic

*Work supported by the U.S. Department of Energy, Office of Science, under Contract No. DE-ACO2-O6CH11357.

efficiency. Figure 2 shows a plot of simulated integrated quadrupole field vs. insertion length for mushroom VP, mushroom steel, and straight steel tips. This plot was used in the lattice design to estimate obtainable quadrupole strengths for a given insertion length. Similar plots were developed for sextupole, Q7, and Q8 magnets. VP is expensive (~200x more than steel) so minimizing or eliminating the use of VP is desirable. During design, steel pole tips are the material of choice, unless the field could not be achieved for a given length.

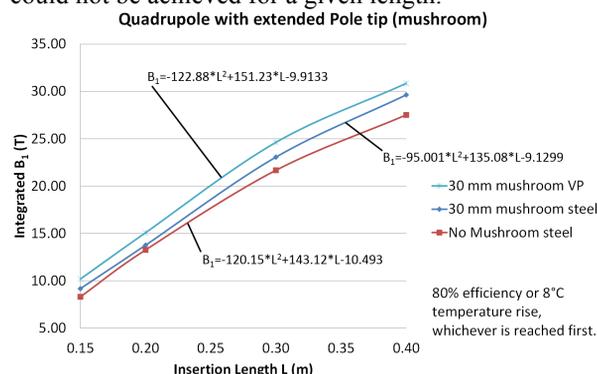


Figure 2: Quadrupole integrated field vs insertion length for VP and steel mushroom poles.

QUADRUPOLE MAGNETS

All quadrupole magnets are made of solid steel, two-piece (top and bottom) yokes with removable poles and pole tips. The Q1 through Q6 have long mushroom style pole tips. Figure 3a shows a magnet model of a Q1 magnet. The long mushroom style pole tips allow higher integrated field gradients at high saturation compared to straight pole tips at the same saturation. The Q1 quadrupole magnet operates at a high field gradient and requires VP pole tips. Prototypes of quadrupole magnets are under construction at APS and are expected to be ready for measurement in September 2015.

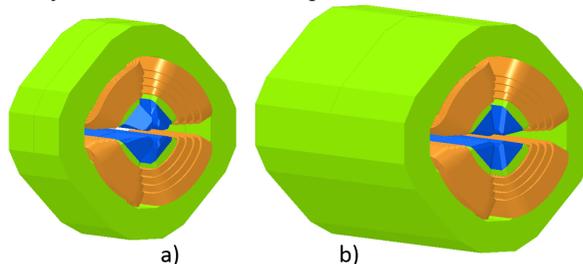


Figure 3: a) Q1 quadrupole magnet model. b) Q8 quadrupole magnet model.

The Q7 and Q8 have vertical and horizontal dipole corrector windings. The magnets are identical except for length. Saturation must be minimized in order to decouple the corrector and main fields. The pole tips on the Q7 and Q8 are straight (not mushroom). Straight pole tips allow higher integrated field gradients at low saturation

compared to mushroom pole tips at the same saturation. The Q8 quadrupole magnet is capable of achieving a central field gradient of 97.3 T/m. Figure 3b shows a magnet model of a Q8 magnet. A prototype of a Q8 quadrupole magnet is being developed at the APS and is expected to be ready for measurement in 2016.

Table 1: Selected Parameters for APS Multi-bend Achromat (MBA) Lattice Magnets

Description	I.D.	Length (m)	Maximum integrated field		Comments
Quadrupole	Q1 to Q6	0.238	18.88	T	82.8 T/m max. central field gradient
Quadrupole	Q7	0.438	34.35	T	88.1 T/m max. central field gradient
			0.006	T-m	vertical and horizontal dipole
Quadrupole	Q8	0.592	53.27	T	97.3 T/m max. central field gradient
			0.006	T-m	vertical and horizontal dipole
Sextupole	S1 to S3	0.256	1433.3	T/m	B''=7028 T/m ² max. central field
			0.0096	T-m	vertical dipole
			0.0055	T-m	horizontal dipole
L-Bend dipole	M1	2.100	0.4867	T-m	0.636/0.127 T max/min fields
L-Bend dipole	M2	2.117	0.4567	T-m	0.318/0.115 T max/min fields
Q-Bend dipole	M3	0.780	0.4313	T-m	constant integrated dipole field for +/- 5% change in quadrupole
			37.16	T	51.8 T/m max. central field gradient
Q-Bend dipole	M4	0.650	0.3933	T-m	constant integrated dipole field for +/- 5% change in quadrupole
			32.22	T	55.1 T/m max. central field gradient
			0.006	T-m	vertical dipole
8-pole-corrector	FC1 and FC2	0.160	0.006	T-m	horizontal dipole
			0.25	T	skew quadrupole

SEXTUPOLE MAGNETS

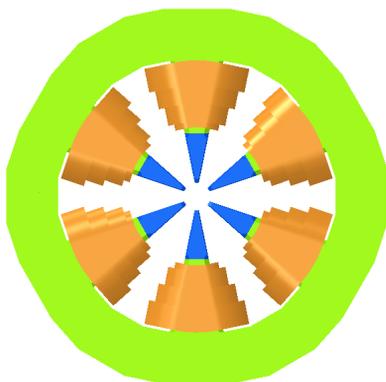


Figure 4: S2 sextupole magnet model.

All sextupole magnets are made of solid steel, two-piece (top and bottom) yokes with removable poles and

pole tips. The S2 sextupole magnet operates at a higher field than the S1 and S3 magnets and requires VP pole tips while the S1 and S3 have steel pole tips. The sextupole magnets also have vertical and horizontal dipole corrector windings. The corrector windings will only be used on the S1 and S3 sextupole magnets. The correctors in the S2 sextupole will not be used due to high saturation.

The sextupole magnets are designed with a 14 mm pole tip radius and a 10 mm vertical gap between the poles. This combination gives an 18-pole error of 300×10^{-4} . This 18-pole error in the sextupole magnet has been shown not to influence the stored beam [2]. Figure 4 shows a model of an S2 sextupole magnet. A prototype of a sextupole magnet is under construction at APS and is expected to be ready for measurement in September 2015.

L-BEND DIPOLE MAGNETS

Longitudinal gradient dipole (L-bend) magnets have a dipole field that varies through the length of the magnet. The M1 L-bend dipole magnet has a higher field than the M2 L-bend dipole magnet. Figure 5 shows a plot of the hard edge field profile for an M1 L-bend dipole magnet.

Two styles of L-bend dipole magnets are currently under evaluation at the APS: a tapered gap design and a five pole design. The tapered gap design has been developed by Fermi National Accelerator Laboratory (FNAL). A prototype [3] designed and built at FNAL is now undergoing measurements.

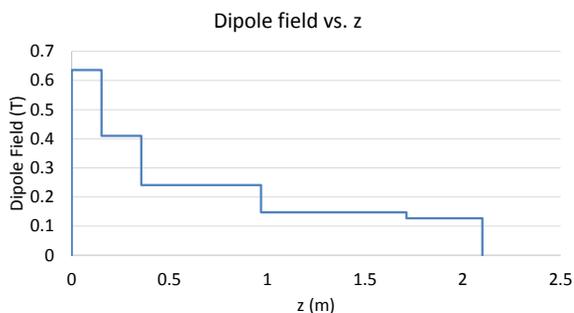


Figure 5: M1 L-bend dipole magnet hard edge field profile.

The five-pole L-bend dipole magnet design has varying Ampere-turns at each pole. A prototype of the five-pole L-bend dipole magnet is scheduled to be designed and built at the APS in 2016. Figure 6 shows a model of both styles of L-bend dipole magnets.

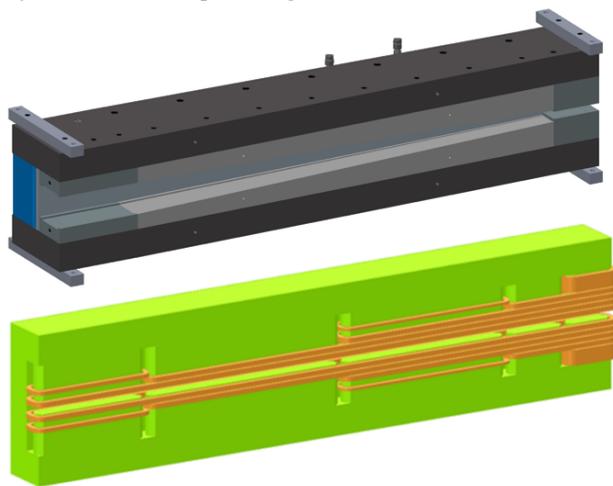


Figure 6: M1 L-bend dipole magnet, top) tapered gap L-bend dipole magnet. Bottom) five-pole L-bend dipole magnet.

Q-BEND DIPOLE MAGNETS

Q-Bend magnets are dipole magnets with a field gradient in the transverse direction. The Q-Bend dipole magnet design resembles a curved quadrupole magnet with the beam running horizontally displaced relative to the geometric center of the magnet. The strength of the quadrupole component can be adjusted between 95% and

105% of nominal. Horizontally-deflecting dipole windings are required to allow adjustment of the quadrupole strength while maintaining a constant dipole component to keep the beam trajectory fixed. Figure 7 shows a close-up of the curved poles on an M4 Q-Bend dipole magnet. A prototype of an M4 Q-Bend dipole magnet is under development at APS and is expected to be ready for measurement in 2016.

The core and coils are straight
 The pole tips are curved

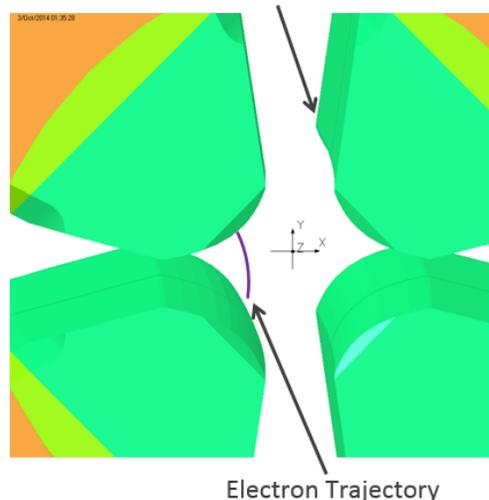


Figure 7: Pole tips of an M4 Q-Bend dipole magnet.

8-POLE-CORRECTOR MAGNETS

8-pole-corrector magnets are fast steering magnets capable of producing vertical and horizontal dipole fields as well as a skew quadrupole field. These magnets have a laminated silicon steel core. Each circuit uses a different number of turns on each pole to obtain the best possible field quality. A prototype of the 8-pole-corrector magnet is under development at Brookhaven National Laboratory (BNL) and is expected to be ready for testing towards the end of 2015. Figure 8 shows a magnet model of the 8-pole-corrector magnet.

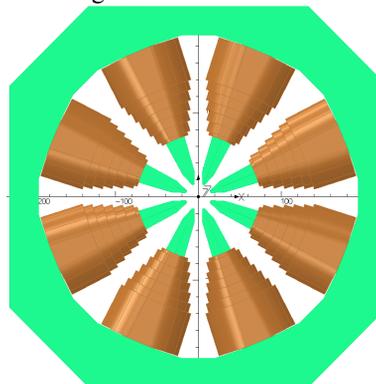


Figure 8: 8-pole-corrector magnet.

CONCLUSION

A summary of the magnets for the 6 GeV seven-bend achromat magnet lattice under investigation at APS has

7: Accelerator Technology

T09 - Room Temperature Magnets

been presented. Schedules for development of prototypes for these magnets have been given. Final designs of the magnets will be generated after testing and evaluation of the prototype magnets.

REFERENCES

- [1] M. Borland et al., Hybrid Seven-Bend-Achromat Lattice for the Advanced Photon Source Upgrade, these proceedings.
- [2] Private communication with Michael Borland.
- [3] V. S. Kashikhin, Longitudinal Gradient Dipole Magnet Prototype for APS at ANL, manuscript in progress.