Magnet Design of the PLS 2 Gev Storage Ring

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Abstract

The Pohang Light Source(PLS) is designed to be a third generation electron storage ring producing high brightness VUV and X-ray radiation from ddipole magnets and insertion devices. The storage ring lattice has a 12 period TBA structure with a full energy linac injection system. This paper is concerned with magnets that form the storage ring lattice;dipoles, quadrupoles,sextupoles,and correctors. The major design parameters of these magnets are listed. And the fabrication procedures for the magnets are presented.

Introduction

The storage ring contains four types of magnet:

1. 36 dipole magnets for bending the beam.
2. 144 quadrupole magnets to focus the beam.
3. 48 sextupole magnets for chromaticity correction.
4. 70 corrector magnets for vertical and horizontal beam movements.

In addition to the above magnets, there are auxiliary coils in the dipole and sextupole to create correction fields. The auxiliary coils of the dipole magnets can produce fields for horizontal steering. The auxiliary coils of the sextupole magnet are designed for excitation of vertical and horizontal correction fields and skew quadrupole modes.

Magnetic field calculations have been made for each of these magnets using the two-dimensional POISSON group computer codes All the magnets are optimized for 2.0 GeV operation but capable of 2.5 GeV operation. The other criteria of the magnet design are as follows:

1. The relative field quality at 2.5 GeV; integral errors of magnet are less than 10^{-3}
2. Voltage to current ratio of the power supplies holds between 0.3 and 2.0.
3. Design pressure drop of the circulating cooling water is 60 psi.
4. Input water temperature is 20°C and maximum temperature rise is 20°C.
5. The ring magnets have a C-configuration to allow easy extraction of the synchrotron radiation and to accommodate the vacuum chambers.

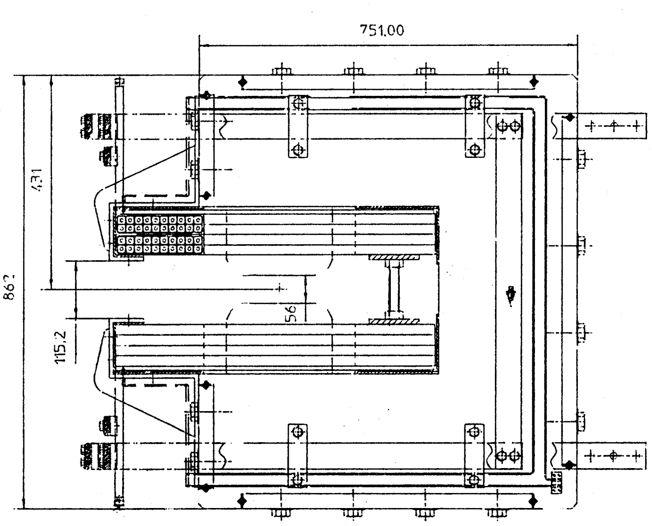

Fig. 1 End view of the dipole magnet including coil configuration

Dipole Magnets

The ring dipole is a straight magnet and a schematic diagram of it is shown in Fig.1. The major parameters for this magnet are given in Table 1. The magnet is a C-type design with a laminated steel core and water-cooled coils of square, hollow copper conductor. The magnet pole gap is 56 mm, which takes into account the vacuum chamber size and some clearances. The pole width of the magnet is determined from the width of the beam stay clear region in the magnet and the sagitta of the curved beam orbit. The magnetic field requirement at 2 GeV is 1.058 Tesla, however, the magnet has been designed to operate at magnetic fields up to 1.323 Tesla at 98.5% efficiency. This higher field of the magnet provides for a capability of 2.5 GeV operation in a future machine upgrade. Extensive POISSON magneto static computer runs were made in designing the core. The shape of the pole tip is optimized to minimize the pole base width, to maintain the required field quality, and to avoid magnetic saturation in the core. The width of the pole base is 220 mm which leads to an average flux density of 1.60 Tesla at the maximum field excitation. The results of two dimensional calculations for this core geometry, showing the systematic and the asymmetric effects of the core on the magnetic fields, are summarized in Table 2. The relative field harmonics at the beam stay clear boundary are about 10^{-6} to 10^{-5}. The n-th harmonic coefficient is denoted as b_n The field harmonics for several excitations do not change very much. The yoke ends along the beam path have 40 mm×45° chamfer to provide a smooth transition, thus minimizing saturation at the ends and reducing the multipole components.

Table 1. The parameter list of the storage ring Dipole Magnet

DESCRIPTION	2.0 GeV	2.5 GeV	Trim Winding
1. Quantity of magnet [ea]	36+2+1		
(product + spare + prototype)			
2. Max flux density on orbit [T]	1.058	(1.323)	0.0121
3. 2 mrad kick at 2.0 GeV [T]			0.01213
4. Core width [mm]	751		
5. Core height [mm]	862		
6. Laminated core length [mm]	1070		
7. Magnetic length [mm]	1100		
8. Conductor area [mm^2]	215.58		9.215
9. Wt. of laminations per magnet [kg]	3996		
10. Wt. of Cu conductor per magnet [kg,⟨m⟩]	440⟨228.6 ⟩		64⟨726⟩
11. Wt. of auxiliary parts per magnet [kg]	1120		
12. Wt. of magnet [kg]	5620		
13. Good field width [mm]	30		
" height [mm]		18	
14. Magnet aperture gap [mm]	56		
15. Ampere-Turns (efficiency = 0.993 , 0.984)	47480	(59916)	543
16. Number of turns per magnet (turns)	72		112
17. Current [A]	659.44	(832.17)	4.848
18. Current density [A/mm^2]	3.059	(3.86)	0.526
19. Resistance per magnet at 40°C [mΩ]	19.67		724.76
20. Voltage drop per magnet [V]	12.97	(16.37)	3.514
per total magnets	467.0	(589.3)	126.5
21. Power loss per magnet [kW]	8.554	(13.621)	17.04[W]
of total magnets [kW]	308	(490.4)	
22. Water circuits per magnet [ea]	2	4	
23. Water flow rate per circuit [liter/min]			
at 60psi pressure drop	2.9		
at 90psi pressure drop	3.55		
24. Water temperature rise [°C]	21		
	17		

The magnetic field calculations at the ends of the magnet are carried out by slicing the magnet end, thus obtaining three dimensional magnetic fields. The field calculation of twenty different cross sections for the magnet ends is performed using the program POISSON. The core is a laminated structure using 1.0 mm ultra low carbon steel which is custom-made by POSCO. The thickness variation across the lamination is $\pm 3\mu m$ and the carbon content is less than 50 ppm. The hardness of the lamination is 55±3 on the Rockwell B scale. The magnetic induction at 100 Oe is 1.9 Tesla and the coercive force is 0.8 Oe after magnetic excitation up to 100 Oe. The production sequence for these steel sheets is as follows:

- elaboration of ultra low carbon steel in 100 ton LD converter,
- continuous casting to produce 18 ton slabs,
- heat treatment for homogenization
- hot rolling to coils, 2.5 mm thick and 950 mm wide,
- pickling in an acidic bath,
- cold rolling to 1.00 mm thickness
- heat treatment in a mixed nitrogen and hydrogen atmosphere at 780 °C for grain growth
- oiling for 12-month corrosion free storage
- flattening and shearing to sheets of 770 mm× 880 mm and packing to sea-transport criteria on three ton pallets.

Punching was performed with an 800 ton mechanical press at 20 °C . The burr height is less than 12 μm and the standard deviation of the pole profile from the ideal contour along the edge of the pole tip is 25 μm. The external structure of the core is composed of two end plates, 50 mm thick, and five side plates, 30 mm thick, as shown in Fig. 1. This structure can be used for stacking, compressing, and supporting the laminations. Core alignment bars which are mounted on a precision granite surface table are bolted to the precision machined edges of the core support plates. Using the end plates and side plates, core stacking is carried out with the above fixture.

After core stacking the lamination sheets are pressed with a hydraulic press at the four corners of one end plate. All frame plates are pinned together in this position, and the end plates are also bolted to the side support plates.

The coils for the dipole magnet are constructed of two flat pancakes on each pole. The coils are fabricated 16 mm square OFHC copper conductor with a 7 mm diameter cooling channel. Each pancake is composed of 9-turns of 2-layers and is wound from the bottom layer to the top layer without joints. The bare conductor is insulated with Mylar tape, 0.08 mm thick and 20 mm wide, and Dacron tape, 0.13 mm thick and 20 mm wide.

The insulated coils are wound using a one axis winding machine. After completion of winding, the coils are removed from the winding form and "ground wrapped" with 1-layer of 0.25 mm thick and 20 mm wide fiberglass tape, half wrapped. Fiberglass is chosen for the ground wrapping since it becomes transparent after epoxy impregnation, thereby allowing for the detection and filling of trapped air bubbles which could contribute to electrical shorts. After the coils are wound and tested, the coils are epoxy encapsulated in a vacuum tight mold. Finally, the epoxy is cured in an electric oven.

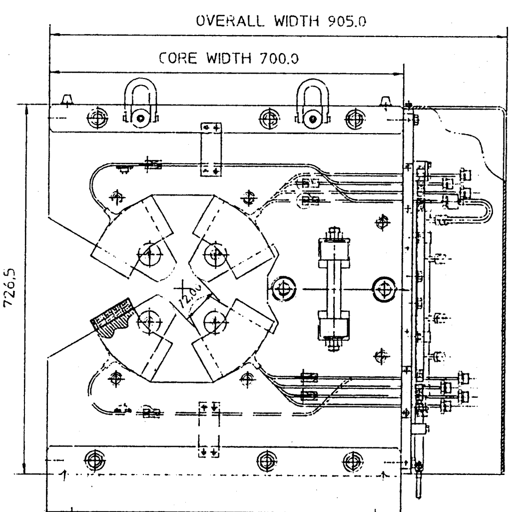

Fig. 2 The End view, pole shape and coil configurations of Q1, Q2 and Q3 magnets

Quadrupole Magnets

There are six different types of quadrupoles used in the storage ring, designated, Q1, Q2, Q3, Q4, Q5 and Q6. The major parameters for these magnets are given in Table 3, and schematic diagrams of these magnets are shown in Fig.2.

The pole shape of the ring quadrupole is conformaly mapped from a dipole geometry which satisfies the required field quality. The results of the harmonic analysis are shown in Table 2, respectively.

The cores of these quadrupoles consist of two separate sections, identical except that there are three different lengths provided, 0.494 m,0.314 m, and 0.204 m. Each laminated sheet is made from the same material as the dipole. The bore diameter is 72 mm. Die clearance will be kept to within 25 microns along the critical pole profiles. Sorting and flipping of the laminations is also performed. Each laminated sheet is stacked using a fixture containing a precision reference surface, and the laminations are compressed in each stacking step. After stacking, the fixture bars which go through the core are compressed.

A cross section of the coil of Q1,Q2 and Q3 is shown in Fig. 2. The coils are constructed as an inclined pancake. A hollow copper conductor (4.6 mm-square with 2.5 mm hole) is wound in four layers of 17 turns each. The conductor is insulated with 0.13 mm-thick and 20 mm wide Dacron tape, half wrapped, and coil pancakes are "ground wrapped" with 0.25 mm-thick and 20 mm wide fiberglass tape, half wrapped. A single coil pancake is constructed for Q4, Q5, and Q6 magnets . This coil is composed of two layers of 8 turns each using a 9.0 mm-square hollow copper conductor with a 5.0 mm diameter cooling channel. Coil winding and vacuum impregnation for both coil types are similar to that for the dipole.

After the coil pancakes are installed on each half yoke, the top and bottom halves are joined with two tie bars as shown in Fig.2. The two halves are aligned by means of a steel dowel pin in two V grooves so that the magnetic circuit is shunted, which could contribute to the random magnetic field errors. Magnetic field measurement and adjustment of the random magnet to magnet errors are performed by the same procedures as described for the dipole magnet.

Table 2. The results of magneto static analysis of the storage ring magnets

	Dipole	Quadrupole	Sextupole
Relative Deviation ($\times 10^{-4}$)	$\lvert\Delta B/B_o\rvert \leq 1.8$ for $\lvert x\rvert \leq 42$mm $\lvert y\rvert \leq 18$mm	$\lvert\Delta G/G_o\rvert \leq 1.0$ for $\lvert r\rvert \leq 30$mm	$\lvert\Delta K/K_o\rvert \leq 15$ for $\lvert r\rvert \leq 30$mm
Multipole Coefficients ($\times 10^{-5}$)	$b_1 = 0.41$ $b_2 = 2.1$ $b_3 = 0.94$ $b_4 = 1.0$ $b_5 = 0.62$	$b_5 = 1.9$ $b_9 = 2.5$	$b_8 = 2.1$ $b_{14} = 8.5$
Random Fabrication and Magnet to Magnet Error ($\times 10^{-3}$)	1.0	1.0	2.0

Table 3. The parameter list of the storage ring quadrupole magnets

Descriptions	Q1	Q2	Q3	Q4	Q5	Q6
1. Quantity of magnet [ea]						
products	24	24	24	24	24	24
spares	2	2	2	2	2	2
prototype	1	1				
2. Max. magnetic gradient [T/m]	18	18	18	18	18	18
3. Core width [mm]	700	700	700	700	700	700
4. Core height [mm]	726.5	726.5	726.5	726.5	726.5	726.5
5. Core length [mm]	204	494	314	314	494	204
6. Magnetic length [mm]	240	530	350	350	530	240
7. Conductor area [mm^2]	16.36	16.36	16.36	65.63	65.63	65.63
9. Cu conductor per magnet						
Weight [kg]	33	55	41	42	56	34
Length [mm]	226	378	280	72	95	58
10. Wt. of auxiliary parts per magnet [kg]	70	70	70	70	70	70
11. Wt. of magnet [ton]	0.62	1.38	0.91	0.91	1.38	0.62
12. Good field radius [mm]	30	30	30	30	30	30
13. Magnet aperture radius [mm]	36	36	36	36	36	36
14. Ampere-turns (efficiency=0.994)	9338	9338	9338	9338	9338	9338
15. Number of turns per pole	68	68	68	16	16	16
16. Current [A]	137.32	137.32	137.32	583.63	583.63	583.63
17. Current density [A/mm^2]	8.394	8.394	8.394	8.893	8.893	8.893
18. Resistance per magnet at 40°C [mΩ]	256.63	428.64	317.51	20.35	26.85	16.4
19. Voltage drop per magnet [V]	35.24	58.86	43.6	11.88	15.67	9.57
Voltage drop per pair	70.48	117.72	87.2			
Voltage drop of total magnets				285.12	376.08	229.68
20. Power loss per magnet [kW]	4.839	8.083	5.987	6.933	9.145	5.585
Power loss per pair	9.678	16.165	11.974			
Power loss of total magnets				166.392	219.49	134.047
21. Water circuits per magnet [ea]	8	8	8	2	2	2
22. Water flow rate per circuit [liter/min]						
at 60psi pressure drop	0.39	0.306	0.35	2.7	2.4	2.95
at 90psi pressure drop	0.478	0.375	0.429	3.307	2.939	3.613
23. Water temperature rise [°C]	22	47	31	18	27	14
	18	38	25	15	22	11

Sextupole Magnets

The PLS sextupole magnet is shown in Fig.3 and its major parameters are listed in Table 4. In addition to its primary function as a sextupole, this magnet is capable of producing horizontal and vertical steering fields, and a skew quadrupole field, as described in table 4.

The pole contour is obtained by conformal mapping from a dipole coordinate system using the POISSON computer code. The bore diameter is 78 mm, which provides clearance between the neck of the vacuum chamber and the two adjacent poles. Field quality and the results of the harmonic analysis are shown in Table 2.

The magnet yokes are constructed of three core pieces. The same material described in previous sections is used for the cores. Tolerance of the lamination sheet has to be kept at 25 microns along the critical pole profiles. Core stacking and assembly are done with fixtures similar to those for the quadrupole.

Each pole of the sextupole magnets has a coil assembly containing two separate coil pancakes. Outer coil pancakes are constructed from 13-turns of a 6.5 mm-square hollow copper conductor with a 3.0 mm cooling channel; 13-turns consist of 7-turns of inner layer and 6-turns of the outer layer. Conductor insulation, coil winding, and vacuum impregnation with epoxy resin are followed in a similar process to that for the quadrupole. Inner coil pancake around each pole is divided into two separate coils with 2.5 mm square insulated wire, one of 78 turns, and the other of 156 turns. A water circuit is attached to a copper heat conductor sheet to provide cooling for the coils.

Table 4 summarizes the maximum trim coil excitations at each pole. The pole numbering begins counterclockwise from the right pole of the upper core. A vertical steering field can be created by applying current I_v at poles 1 and 6, and $-I_v$ at poles 3 and 4. Currents I_h at poles 1 and 3, $-I_h$ at poles 4 and 6, 2 I_h at pole 2, and -2 I_h at pole 5 produce the horizontal steering field such as no sextupole component in this excitation. The skew quadrupole component is created by a current at auxiliary coils of the poles 2 and 5.

Table 4. The parameter list of the storage ring Sextupole Magnet

DESCRIPTION	SD	SF	VS	HS	SQ
1. Quantity of magnet [ea] (products+spares+prototype)	24+1+1	24+1	-	-	-
2. Max second derivative field [T/m^2]	-320	320	-	-	-
3. Max steering field [T] (2mrad at 2 GeV, 1.6mrad at 2.5 GeV)	-	-	0.0667	0.0667	
4. Skew quadrupole gradient [T/m]	-	-	-	-	1.0
5. Core width [mm]	578.28	578.28	-	-	-
6. Core height [mm]	667.8	667.8	-	-	-
7. Yoke length [mm]	180	180	-	-	-
8. Magnetic length [mm]	200	200	-	-	-
9. Conductor area [mm^2]	34.97	34.97	4.48	4.48	4.48
10. Wt. of L.C.S. per magnet [kg]	356	356	-	-	-
11. Wt. of Cu conductor per magnet [kg]	26.0	26.0	39.7	-	-
12. Wt. of auxiliary parts per magnet [kg]	24	24	-	-	-
13. Wt. of magnet [kg]	445.7	445.7	-	-	-
14. Good field radius [mm]	30	30	-	-	-
15. Magnet aperture radius [mm]	39	39	-	-	-
16. Ampere-Turns (efficiency=0.995)	2569	2569	1968	1136	1250
17. Number of turns per pole (turns)	13	13	-	-	-
Pole : 1&6, 3&4	-	-	156	-	-
Pole : 1&3, 4&6	-	-	-	78	-
Pole : 2&5	-	-	-	156	-
Pole : 2&5	-	-	-	-	78
18. Current [A]	198	198	12.62	15.15	16.67
19. Current densisty [A/mm^2]	5.66	5.66	2.82	3.38	3.72
20. Resistance per magnet at 40°C [mΩ]	30.32	30.32	1390.0	2140.0	534.0
21. Voltage drop per magnet [V]	6.0	6.0	17.50	32.4	8.9
Voltage drop at total magnet	144	144	420	777.6	213.6
22. Power loss per magnet [kW]	1.188	1.188	0.221	0.491	0.149
23. Power loss of total magnets [kW]	28.512	28.512	5.304	11.784	3.576
24. Water circuits per magnet [ea]	3	3	-	-	-
25. Water flow rate per circuit at 60psi pressure drop [l/min]	0.965	0.965	-	-	-
25. Water temperature rise [°C]	10	10	-	-	-

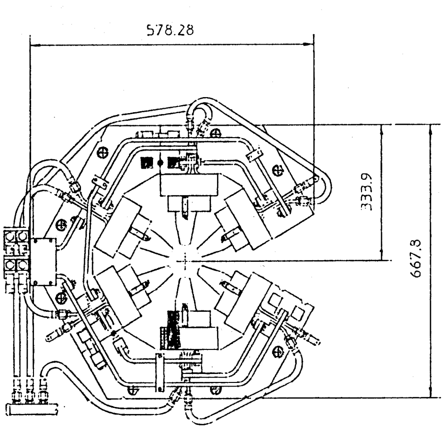

Fig. 3 The End view of SD and SF magnets including coil configuration

Corrector Magnets

The designed corrector magnet is shown in Fig. 4 and its major parameters are given in Table 5.

The magnet yoke is constructed from 0.5 mm silicon steel (PN-14 POSCO product) laminations coated with a C-5 insulating film to give a fast magnetic response capability to the steering components. Tolerance of the punched sheet has to be kept within 50 microns along the critical pole profiles. The yoke is also of a C-configuration to allow installation around the vacuum chamber. The pole gap and the width of the laminated sheet, 122 mm and 100 mm respectively, can accommodate the vertical steering coil and the vacuum chamber.

The coils for the horizontal steering fields are constructed as pancakes of 4.62 mm square copper conductor with a 2.39 mm diameter cooling channel, wrapped with insulation tape and impregnated with epoxy resin. The vertical steering is provided by winding a 6.5 mm-square hollow copper conductor with a 3.5 mm diameter cooling channel, wound in four layers along the pole face of the magnet. The coil is epoxy impregnated for rigidity and for additional electrical insulator.The coil is composed of 3 packettes of 13,3,11· turns per layer in each of four layers.For the positioning of the three packettes the expressions for the skew harmonic components derived analtically using a complex/conformal technique were used in order to minimize the skew harmonic components and get the desired skew dipole components.[1] The designs will be verified by building a full scale prototype and by measuring the magnetic field.

References

1. Ross D. Schlueter,Harmonics Supression in Electromagnets with Application to the ALS Storage Ring Corrector Magnet Design,LBL,1991

Table 5.The parameter list of the storage ring H/V corrector magnet

DESCRIPTION	2.0 GeV H	2.0 GeV V	2.5 GeV H	2.5 GeV V
1. Quantity of magnet [ea] (products+spares+prototype)	70+4+1			
2. Magnet flux density [T]	0.06	0.06	0.07	0.07
3. Bend angle [m-rad]	2			
4. Core width [mm]	296			
5. Core length [mm]	110			
6. Good field width [mm]	30			
Good field height [mm]	18			
7. Pole gap [mm]	122			
8. Magnetic effective length [mm]	232			
9. Wt. of laminations per magnet [kg]	208			
10. Wt. of copper conductor per magnet [kg]	24.	50.7		
11. Length of copper conductor per magnet [m]	164	180		
12. Wt. of magnet [kg]	290			
13. Ampere turns per pole	2873	11543	3567	14329
14. Number of turns per pole	80	108		
15. Current [A]	35.9	106.9	44.6	132.7
16. Copper conductor area [mm^2]	16.36	34.85		
17. Current density [A/mm^2]	2.2	3.38	2.73	4.2
18. Resistance per pole at 40°C [Ω]	0.093	0.0475		
19. Voltage drop per pole [V]	3.34	5.67	4.15	7.03
20. Power loss per pole [KW]	0.12	0.611	0.19	0.93
21. Water flow rate per water circuit [l/min] at 60psi	0.17	0.53		
22. Water temperature rise [°C]	8.1	16.0	12.5	25.3
23. Water circuits per magnet [ea]	2	2		

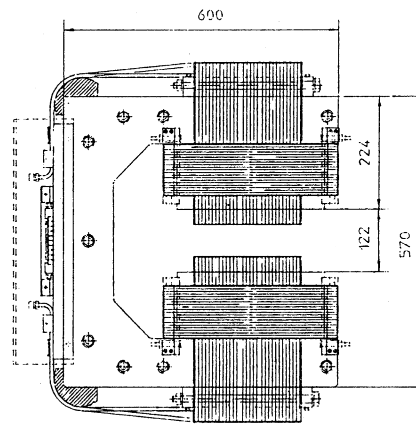

Fig. 4 The end view of H/V corrector magnet