STATUS OF THE PLS-II MAGNET DESIGN AND FABRICATION *

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Abstract

Pohang Light Source (PLS) is planning a major upgrade of the storage ring to meet the more demanding requirement from the synchrotron light users. The main features of the major upgrade are (1) increasing the electron beam energy from 2.5 GeV to 3.0 GeV for more higher energy X-ray photons, (2) decreasing the electron beam emittance from 1.89 nm to 5.8 nm to increase the photon brilliances, and (3) increasing the number of straight sections to install the insertion devices from 10 to 20 to meet the demand for insertion devices. in the upgraded PLS (PLS-II), there will be 24 combined function dipole magnets, 96 quadrupole magnets, and 144 sextupole magnets with some auxiliary magnets for electron beam injection. In this report, the physical design features, mechanical aspects of the magnet design are described.

INTRODUCTION

The magnet system of PLS-II consists of 24 gradient magnets, 96 quadrupoles, and 96 sext up ole magnets which have additional windings for horizontal correctors, vertical correctors, and skew quadrupole excitations [1] . For the injection system, 4 pulsed kicker magnets and a septum magnet are needed [2]. The major changes from the PLS design are as follows:

- The combined function gradient magnet is adopted to save lattice space for an additional short straight section. Also, the dipole field is pushed to the limit to make it shorter with the smallest possible 34 mm vertical gap. The number of dipole magnets is reduced from 36 to 24, and the effective length is increased from 1100 mm to 1800 mm.

- Also all 70 combined function horizontal/vertical correctors are removed and the corrector function is incorporated with the sextupole magnets like ALBA [1] and SPEAR3 [2]. The number of sextupole magnets are changed from 48 magnets with 2 families to 96 magnets with 4 families. 48 new combined sextupole magnets will be needed.

- The existing PLS quadrupoles will be mostly recycled. In the PLS, we had 6 families of quadrupoles with 24 magnets per each family (Q1 to Q6). Q1, Q2, and Q3 series were wired in pair across the straight sections, and Q4, Q5, and Q6 were connected in series for the whole 24 magnets for each family. In PLS-II, we have 4 families of quadrupoles, which will be powered in series with independent auxiliary windings for operational flexibility. Therefore, all quadrupole coils will be redesigned for optimum current and cooling. For PLS-II, the maximum required field gradient reaches 24.5 T/m, compared to the design limit of 18 T/m. A preliminary 2D magnetic analysis showed that the existing quadrupoles could be operated at 24.5 T/m with small changes in the higher order harmonic contents. However, the adequacy of the existing quadrupole will be determined after detailed rotating coil measurements and beam dynamics simulations.

- The kicker magnets for the injection will be mostly recylced. The space for injection straight will be readjusted to accommodate the increased septum length, and the increased kicker separation. The septum magnet will be redesigned with smaller gap and smaller leakage field which is essential for top-up operation.

The schematic layout of the PLS-II magnet system is shown in Fig. 1 where half of the superperiod is shown. The details of the magnet system for the PLS-II will be detailed in the following section.

COMBINED FUNCTION DIPOLE

A lot of smaller rings are adopting combined function dipole magnets to reduce the lattice space [1] [2] [3]. Since PLS-II should be accommodated in the existing radiation shielding wall, the circumference of the ring is nearly identical to that of the PLS. To squeeze the lattice space for the additional straight section, the space between the magnets is minimized. And the use of combined function dipole is very essential to save lattice space. The combined function dipole magnet (also called gradient magnet) has a dipole field combined with a focusing quadrupole field. With the built-in quadrupole field, the number of quadrupole magnets can be reduced. In PLS-II, the gap at the center of the magnet is 34 mm which is very small compared to the previous 58 mm. The central field is increased significantly to 1.4557 T compared to the previous 1.320 T at 2.5 GeV. This dipole field is superposed with the focusing field gradient of 4.0035 T/m. And for PLS-II DBA lattice, there are only 24 bending magnets and each bending magnet should bend 15 degrees compared to the previous 10 degree bending for TBA. The effective magnetic length of the gradient magnet is 1.800 m. The major parameters of the gradient magnet are summarized in Table 1.

There were a few limitations related to the design of the gradient magnet.

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Table 1: Parameters of the Combined Function Gradient Magnet

Parameter	Value	Unit
No. of Magnets	24	EA
Bend Angle	15	degree
Central Field	1.4557	Tesla
Nominal Gradient	4.0035	T/m
Gap at the Center	34.0	mm
Effective Mag. Len.	1.800	m
Magnetic Efficiency	0.95	
Ampere Turns	40.49	kA
No. of Turns	48	
Nominal Current	843.8	A
Current Density	4.57	A/mm^2
Voltage Drop/magnet	38.1	Volt
Cond./Cool. Hole Dia.	11.8/10.3/6.0	mm
No. of Pancakes/pole	4	
Resistance	21.5	mOhm
Power per Magnet	15.3	kW
Inductance/magnet	29.0	mH
No. of cooling channel	4	
Coolant Flow Rate	10.9	liters/min
Coolant Velocity	1.60	m/sec
Coolant Temp. Rise	20.2	K
Coolant Pressure Drop	700.0	kPa

- Since the effective magnetic length is long and the bending radius is small, the sagitta of the orbit is very large. Half sagitta reaches 28.7 mm. If we make the core of the magnet straight along the orbit, we need to increase the pole width to include the sagitta which results in a bulky, and heavy magnet. To avoid this problem, the pole should be curved following the trajectory. Manufacturing wise, this approach might be challenging but the magnet will be more compact and cost effective.

- Using one lamination for the core is more cost effective and accurate. But the thickness of the coil pancake is limited to the minimum opening in the gap region. In our case, the center gap is 34 mm and the minimum opening is 28.8 mm. Therefore, the thickness of a pancake should be less than 28.8 mm for the coil assembly.

A simple 2D FEM analysis is carried out using a pole contour which is conformal mapped from the SPEAR3 pole profile[4]. The conforming mapped shims are adjusted to results in optimum flux distribution in the good field region. The flux shape is shown in Fig. 1. The multipole contents are well within the physics requirements for this ideal geometry. However, there is a possibility of end saturation which may results in worse higher harmonic content and higher saturation. Also manufacturing tolerance will also contribute to the multipole contents.

The uniformity of the gradient magnet is defined using the following formula.

$$\frac{\Delta B}{B} = \frac{B_y(x) - (B_0 - G_0 x)}{B_0 - G_0 x} \tag{1}$$

Here, B_0 is the magnetic field at the magnetic center and G_0 is reference field gradient at the center of the magnet. The field uniformity is optimized at the nominal excitation and the profile is different for slightly different excitation (I/I_n=1.00, 1.016, 1.044, 1.106) , shown in Fig. 2. This implies that the field uniformity profile depends on the saturation characteristics of the pole material; therefore, the final field profile will be very sensitive to the material properties since the magnet is operated in well saturated regime.

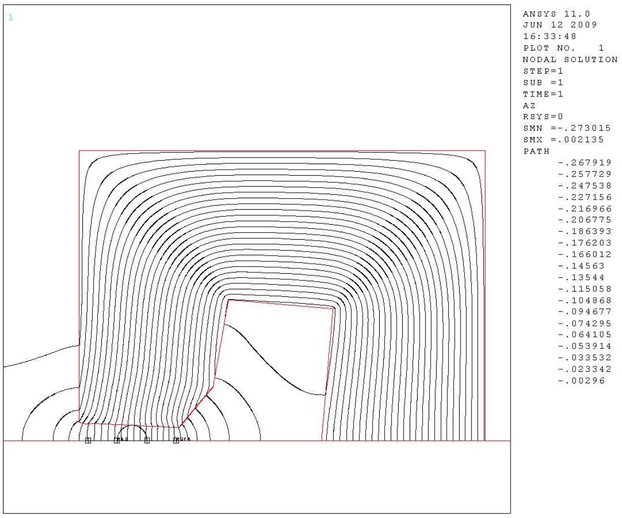

Figure 1: Typical flux shape of the combined function dipole magnet at the nominal excitation.

QUADRUPOLE MAGNETS

There are four different types of quadrupoles used in the PLS-II, designated as Q1, Q2, Q3, Q4. The major parameters of these magnets are shown in Table 2.

The quadrupole magnets of the PLSI will be mostly recycled for PLS-II. However, there are a few required changes which are listed below.

- In the PLS storage ring, Q1, Q2, Q3 magnets were powered in pairs, and Q4, Q5, Q6 were powered in series of 24 magnets to save power supply costs. Compromising between more flexibility for accelerator operation and the economy of serially powered quadrupoles, the main coils of the PLS-II quadruples will be powered in series with small auxiliary independent powered coil for maximum operational flexibility.

- The maximum field gradient for PLS was 18 Tesla/m. For PLS-II, we need maximum 24.5 Tesla/m field gradients. To check the multipole contents at this level of excitation, a simple 2D FEM analysis is carried out. Neglecting the C-shape structure, only one pole is simulated.

- The multipole contents are well within the physics requirements. However, there is a possibility of end saturation which may results in worse higher harmonic content. The existing quadrupoles will be measured with 24-25 T/m excitation to check the field quality in near future. Since we are planning to operate the existing quadrupole at higher excitation, the number of cooling circuits are increased to limit the maximum temperature rise less than 20 K.

- Small auxiliary winding which is about 6% of the main winding will be added for the operational flexibility like ID matching and beam based alignment.

Table 2: Major Parameters of the Quadrupole Magnet

Parameter	Value	Value	Unit
Magnet ID	Q1/Q4	Q2	Unit
No. of Magnets	24	24	EA
Magnetic Length	0.220	0.329	m
Max. Field Gradient	24.1	25.4	T/m
Aperture Radius	36	-	mm
Core length	204	314	mm
Ampere Turns/pole	13.06	13.30	kA
Magnetic Efficiency	0.95	0.95	
No. of Turns	16	-	
Current Density	12.4	12.7	A/m^2
Cond./Cool. Hole Dia.	9.5/9.5/5.5	-	mm
Power/magnet	10.94	14.28	kW
Nominal Current	816.4	831.1	A
Voltage Drop/magnet	13.4	17.2	Volt
Resistance/magnet	16.4	20.7	mOhm
Inductance/magnet	2.19	3.38	mH
No. of cool. channel	4	-	
Coolant Flow Rate	21.1	18.2	l/min
Coolant Velocity	3.70	3.20	m/sec
Coolant Temp. Rise	7.40	11.2	K
Coolant Pressure Drop	700.0	-	kPa

SEXTUPOLE MAGNETS

There were two different types of sextupole magnets in PLS, each series was powered in series. In PLS-II, there are 4 types of sextupoles and 2 sextupoles from each types are used for each super-period resulting in 96 sextupole magnets. The existing 48 PLS sextupole magnets will be reused without modifications. The other 48 sextupoles with some spares will be manufactured with same core cross section with the existing sextupole magnet.

In addition to its primary function as a sextupole, this magnet should also operate as horizontal and vertical correctors, and a skew quadrupole magnet. The horizontal and vertical combined function correctors used in the PLS storage ring are removed and the function is incorporated in the combined function sextupole magnet to save the lattice space. Still, there is an issue related to the strength of the correctors. PLS design is based on 2 mrad kick at 2.0 GeV electron beam energy. This translates to 1.33 mrad kick for 3.0 GeV electron beam for 200 mm long sextupole and 1.00 mrad for 150 mm long sextupole magnets.

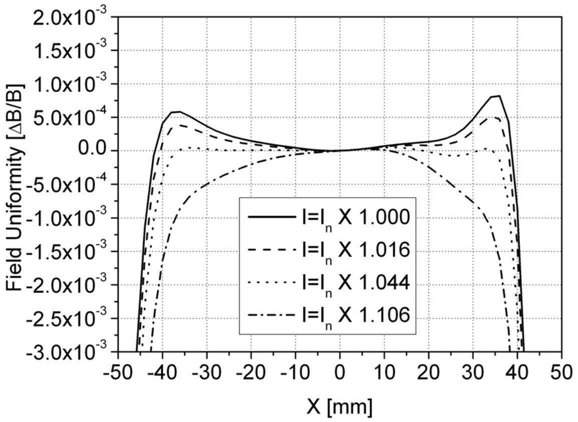

Figure 2: Field uniformity of the gradient magnet for various excitation currents.

SUMMARY

In this report, the magnet system for PLS-II is described. The dipole magnets will be redesigned and replaced with the combined function gradient magnet to reduce the longitudinal space. Magnetostatic analysis is carried out to meet the design requirements with minimizing the pole width and weight of the magnet. Quadrupole magnets will be mostly recycled with modifications adding 6% auxiliary windings for operational flexibility. Also sextupole magnets will be recycled with 120 additional newly manufactured magnet with different length. The quadrupole will reach 24.5 T/m field gradient and the performance at this level will be measured using rotating coil system to verify that the quadrupoles are adequate for PLS-II system. The sextupole will also operate at 550 T/m^2 2nd derivative while it is designed for 320 T/m^2.

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