PAL-XFEL MAGNET DESIGN AND MAGNETIC MEASUREMENT*

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Abstract

We have designed and tested magnets for PAL-XFEL of 10GeV in Pohang, Korea. These magnets consist of 6 families of 46 dipole magnets, 11 families of 209 quadrupole magnets, and 4 families of 96 corrector magnets. Two Hall probe benches are used to measure the magnetic field. This paper reviews the main parameters of these magnets and the results of magnetic field measurements.

INTRODUCTION

The PAL(Pohang Accelerator Laboratory)-XFEL is a 0.1-nm hard X-ray FEL project starting from 2011. Three hard X-ray and two soft X-ray branches are planned. As the first phase of this project, one hard X-ray (HX1) and one soft X-ray (SX1) which consist of 46 dipole and 209 quadrupole magnets will be constructed [1].

We have designed all magnets on our own by using OPERA and ANSYS codes [2, 3]. Every magnet was designed to satisfy the requirements for magnetic field and to maintain the maximum temperature rise of coils below 20 K for 120% of the nominal currents. In the process of the design, it was helpful to parameterize the main variables of the magnets in a spread sheet for easy estimation by changing some parameter.

Now we have manufactured, tested, and installed the magnets. Two Hall probe measurement benches were used to measure the magnetic field for the dipole magnets and the quadrupole magnets respectively. The measurement range, coordinate directions of magnetic field, and multipole component definition were chosen after discussion with the beam physics group.

DIPOLE MAGNETS

The dipole magnets were classified into six kinds according to pole gap, effective magnetic length, and maximum magnetic field. The results of the classification are listed in Table 1.

Most dipole magnets have the same pole gaps of 30 mm except D6 of 15 mm for the self-seeding. D1, D2, and D4 have H-type core shape, and D3, D6, and D7 have C-type. All dipole magnets of D1~D6 for the bunch compressor, the chicane, and the self-seeding have the trim coils with 1% of the main field.

The laminated cores are used for the magnets D2 and D3 which quantities are more than 10 magnets, and the solid cores are used for the rest of the dipole magnets which quantities are less than 10.

The field uniformities were improved by the small pole bumps. The requirements for the field uniformity are different from each magnet. We used Hall probe along straight line, and confirmed that the field uniformity of field integral along straight line was very similar to that along the curved orbit by calculations.

Table 1: Families of Dipole Magnets (D5 was replaced with D2.)

Family	**Magnetic length [m]**	**Max. field [T]**	**Qty**	**Position**
D1	0.20	0.80	6	BC1
D2	0.70	1.00	19	BC2,BC3, BAS1
D3	1.44	1.30	11	BAS2,3,4
D4	0.17	0.312	4	Laser heater
D6	0.30	0.485	4	Self-seeding
D7	0.75	1.164	2	Tune-up dump

Most magnets satisfied the field requirements. But D1 and D7 didn't satisfy those slightly. So we added shims (10x10 mm^2 wide, 1mm thick, steel plates) to improve the field uniformity. The shims were placed on the chamfer sides of front and end sides of lower and upper poles. We have calculated the magnetic field with using B-H table of Chinese low carbon steel (DT4), and manufactured magnets of the same materials. But a little difference between the calculated and measured field uniformities has arisen. Figure 1 shows the field measurement scene and the results of seven D1 dipole magnets.

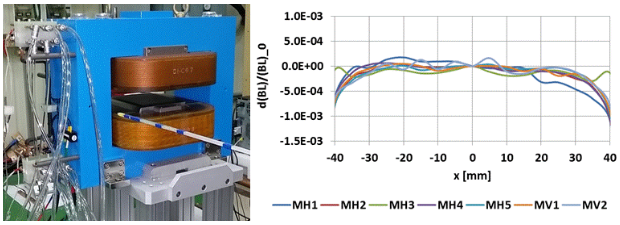

Figure 1: Field measurement scene and 3D field uniformity of seven D1 dipole magnets.

D4 dipole magnets were used for a laser heater. The measurement results of D4 are shown in Figure 2, where the 3D field uniformities of five magnets are compared, and the repeatability test results are shown. The maximum field uniformity deviation is about 4E-4, considering the magnetic field of 0.312 T and the magnetic length of 0.144 m, the average field deviation is deduced about 1 Gauss that is smaller than the tolerance of our measurement system [4]. The field uniformity requirement of D4 is less than 1.0E-4, which is not easy to measure it.

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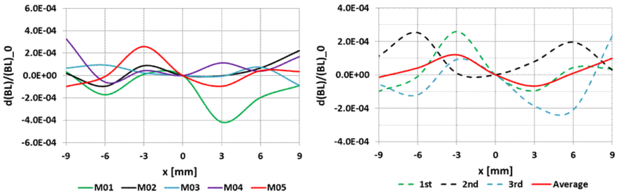

Figure 2: Field measurement results of D4 dipole magnet (left) and repeatability test (right).

Table 2 shows the comparison of 3D field uniformities between calculation and measurement results. These measured results are the worst case of all dipole magnets.

Table 2: Field uniformities of dipole magnets

Family	Good field region [mm]	3D Field uniformity	
		Calculated	Measured
D1	±17	< 1.0E-4	1.9E-4
	±41	< 5.0E-4	1.1E-3
D2	±16	< 1.0E-4	1.0E-4
	±22	< 5.0E-4	2.3E-4
D3	±23	< 5.0E-4	4.2E-4
	±43	< 1.0E-3	1.1E-3
D4	±9	< 1.0E-4	3.3E-4
D6	±5	< 1.0E-4	4.0E-4
D7	±23	< 5.0E-4	5.6E-4
	±43	< 1.0E-3	7.5E-4

QUADRUPOLE MAGNETS

The quadrupole magnets were classified into 11 kinds according to aperture diameter, effective length, and maximum field gradient. The result of the classification is listed in Table 2.

Some quadrupole magnets (Q1, Q2, Q3, Q6, and Q9) have the horizontal and vertical steering fields for the bunch compressors and the inter-undulator.

Table 3: Families of Quadrupole Magnets

Family	Aperture diameter [mm]	Magnetic length [m]	Max. gradient [T/m]	Qty
Q1	30	0.065	15	20
Q2	30	0.13	25	60
Q3	30	0.18	25	18
Q4	44	0.20	25	6
Q5	22	0.40	35	14
Q6	16	0.13	40	31
Q7	80	0.50	18	3
Q8	22	0.25	30	19
Q9	16	0.08	32	18
Q10	44	0.50	25	4
Q11	44	0.10	10	16

The multipole components were calculated by using an equation, the radial component: $B_r(r_0,\varphi) = \Sigma_n\{A_n \sin(n\varphi) + B_n \cos(n\varphi)\}$, where r_0 is the reference radius that is the good field radius. All magnets are optimized to have the relative multipole components less than 1.0E-4 in 3D calculations. Figure 3 shows the half pole contour. In this figure, the o-m line follows along an ideal hyperbola, the m-n is a straight line and a curve after n point. We could satisfy the multipole requirements by manipulating the position and the length of the straight section.

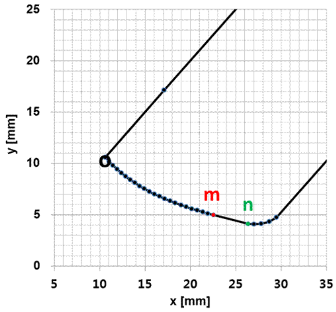

Figure 3: The half pole of quadrupole magnet.

We measured the magnetic field of quadrupole magnets by only Hall probe. Figure 4 shows the field distribution of FEM model and the field measurement scene of Q4 quadrupole magnet.

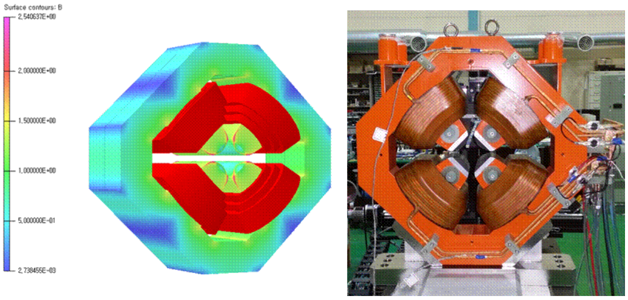

Figure 4: FEM model and field measurement scene of Q4 quadrupole magnet.

Figure 5 shows the vertical magnetic field of Q4 along the center line (x=y=0) (left graph), and the vertical magnetic field along transverse (x) direction at the magnetic center (z=0) (right graph). We could check a stacking state of the laminated core and a measurement error by Figure 5.

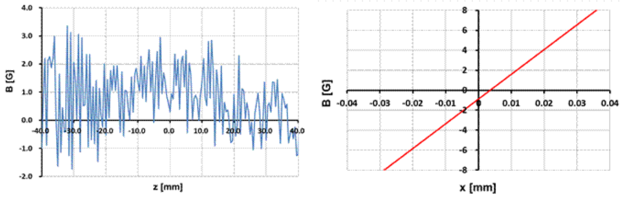

Figure 5: Magnetic field distribution of Q4 quadrupole magnet along center line (x=y=0) (left), along transverse line (y=z=0) (right).

Q4, Q10, and Q11 have the same cross section of the lamination shape and the same coil size with different core length for convenient manufacture. Figure 6 shows the relative field gradient integral deviations of Q4, Q10, and Q11. A couple of exceptional magnets became spare ones after remeasurement.

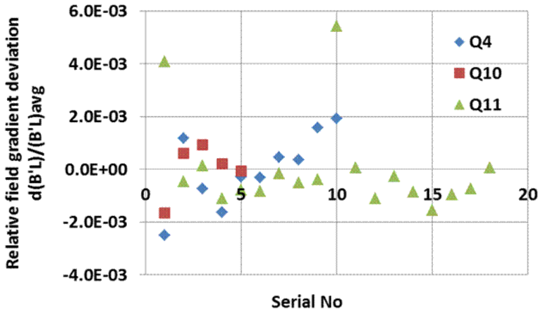

Figure 6: Relative field gradient integral deviation of Q4, Q10, and Q11.

Quadrupole magnets (Q1, Q2, Q3, Q5, Q6, Q8, and Q9) have the indirect cooling system (heat sink), and the rest quadrupole magnets (Q4, Q7, Q10, and Q11) have water cooling system. Table 4 shows the temperature rises of calculation and measurement.

Table 4: Temperature Rise of Quadrupole Magnets

Magnets	Calculated Temperature rise [K]	Measured Temperature rise [K]
Q1	2	5
Q2	11	11
Q3	11	12
Q4	17	12
Q5	10	17
Q6	13	19
Q7	12	12
Q8	10	11
Q9	8	14
Q10	12	11
Q11	2	3

CORRECTOR MAGNETS

The dipole magnets and the quadrupole magnets for the chicanes, beam analysis, and the undulator sections have the trim coils or the horizontal/vertical steering coils respectively. Beside these, we prepared the independent corrector magnets of four families of 96 magnets.

Figure 7 shows the corrector magnets, where C1, C2, and C3 are for linac and BTL, and UC is for undulators. UC has an air core in order to maintain no remanent field. Table 5 shows the main parameter of corrector magnets.

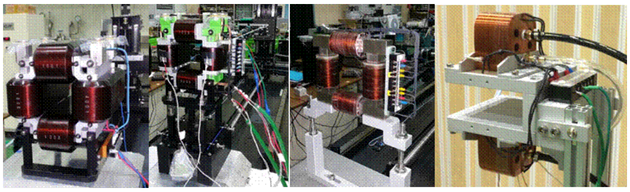

Figure 7: Corrector magnets (C1, C2, C3, and UC).

Table 5: Main Parameters of Corrector Magnets

Corrector type	**C1**	**C2**	**C3**	**UC**
Core	iron	iron	iron	air
Cooling type	air	heat sink	air	heat sink
Field integral [Gcm]	5000	5000	500	450
Magnet length [mm]	295	144	54	79
Current density [A/mm^2]	1.1	2.6	0.7	5.04
Temperature rise [K]	7	12	9	9
Quantity	36	6	8	58

CONCLUSION

When we designed and classified the magnets, we had to consider the connection condition of magnets in series or stand alone and the electrical properties of magnets as well as cost-effective manufacturing.

We have designed, tested, and installed all magnets. Also we confirmed magnetic performance and the temperature rises of coils that were below 20 K.

REFERENCES

[1] Heung-Sik Kang, “Current Status of PAL-XFEL Project”, IPAC13, Shanghai, China
[2] Vector Fields software, http://www.cobham.com
[3] ANSYS software, http://www.ansys.com
[4] Ki-Hyeon Park, “Magnetic Field Measurement System for PLS-II Magnets”, IPAC10, Kyoto, Japan