DESIGN AND MEASUREMENT OF THE TRANSFER LINE MAGNETS FOR THE TAIWAN PHOTON SOURCE

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Abstract

For the transfer line of Taiwan Photon Source (TPS), the segment from the Linac to the booster (LTB) comprises one dipole magnet and eleven quadrupoles but that from the booster to the storage ring (BTS) comprises two dipole magnets and seven quadrupoles. The LTB dipole magnet provides for deflections 11° from the Linac to the booster and 31° from the Linac to the beam dumper, with two operating currents. The BTS quadrupole magnets include four 0.3 m and three 0.4 m magnets that have the same cross sections as the booster quadrupole magnet but different integral quadrupole field strengths; the cooling systems are redesigned from two circuits to four. The magnetic fields were simulated with software (Opera 2D and 3D); the optimum processes are discussed. The magnets were constructed by Danfysik, Scanditronix and a local company in Taiwan. This paper discusses the features, the design concept and the results of field measurements of these transfer-line magnets.

MAGNETIC DESIGN AND SIMULATION

Taiwan Photon Source is a third-generation accelerator for a light source designed to achieve great brilliance and small emittance [1]. The transfer-line magnets required for the operation of TPS are the LTB dipole magnet, LTB quadrupole magnets, BTS dipole magnets and BTS quadrupole magnets.

LTB Dipole Magnet

The LTB dipole will be installed in the LTB line before the beam dump; when the electron beam enters the dipole magnet, it will bend 11° at current 83 A and 31° to the dump at current 232 A, as shown in Fig. 1. The pole width is 240 mm; the shape is a straight line without pole shim design. The pole angle tilts 11° for the electron beam to pass through at the middle of the pole width with two operating currents. The effective lengths are 442.2 mm for 11° passage and 446.6 mm for 31° passage. The centre field has homogeneity 0.4 % between ±100 mm and the integral field has homogeneity 1 % between ±20 mm at operating current 83 A. The other parameters are shown in table 1. The inductance is calculated (Opera 3D), which provides the stored energy *E* (Eq. 1),

$$\mathrm{E} = \frac{1}{2} L \times I^2 \qquad (1)$$

Inductance obtains Eq. 2

$$\mathrm{L} = \frac{2E}{I^2} \qquad (2)$$

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LTB Quadrupole Magnet

The operating energy is 150 MeV from the Linac to the booster ring; the quadrupole field strength is designed to be 5.0 T/m with effective length 150 mm and bore diameter 30 mm. The entire magnet is machined from an iron block for the profile, not as a lamination punch. In the simulation model (Fig. 2), the yoke of this magnet has a square shape for ease of assembly and installation. The coils of the LTB quadrupole magnet, made of copper, have a square profile 5×5 mm^2 with a coolant orifice of diameter 2 mm; the increase of the water temperature is controllable within 10 °C and the water pressure drop is 5 atm, as shown in table 1. The pole profile is shown in Fig. 3. To increase the field homogeneity, the first to third points and seventeenth to nineteenth points are pole shims. The quadrupole magnet is designed with a chamfer for its removable end caps, with a 45° arc cut with depth that is increased to 8 mm at the pole tip. Chamfering is applied to enhance the region of integral good field and to decrease the 12-pole strength.

Table 1: Parameters of the LTB Dipole and Quadrupole Magnets

LTB Magnet Parameters	Unit	Dipole	Quadrupole
Iron length	m	0.386	0.131
Normal field	T/	0.615/0.218	
Gradient field	T/m		5.0
Magnet gap	m	0.030	0.030
Coil conductor dimension	mm	9×9	5×5
Coolant hole diameter	mm	4.5	2
Number of turns/pole		32	24
Current	A	232/83	74
Resistance	Ω	0.034	0.040
Power consumption	kW	1.833/0.232	0.223
Inductance	mH	23.694	2.779
Voltage drop	V	7.886/2.803	3.001
Water pressure drop	atm	5	5
Water flow rate	L/min	2.725	0.509
Coolant temperature rise	°C	9.640/1.218	6.273
Water circuit number/magnet		2	2

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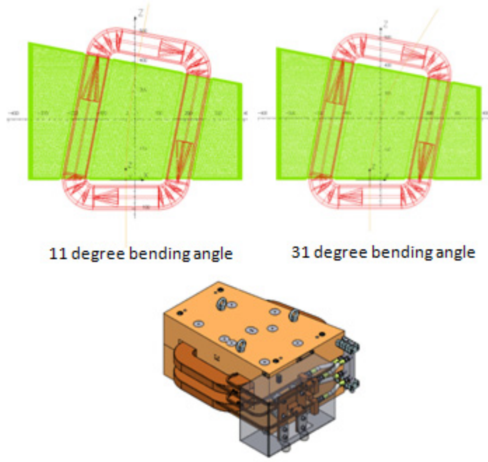

Figure 1: The yellow line shows the electron beam trajectories for 11° and 31° operation of the LTB dipole magnet. An engineering drawing is below.

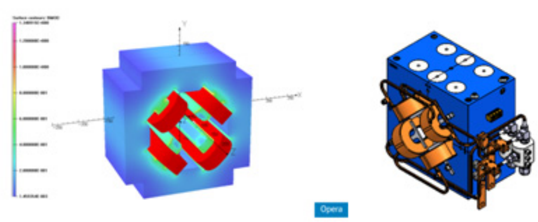

Figure 2: The model (Opera 3D) is shown at the left; an engineering drawing of the LTB quadrupole magnet is shown at the right.

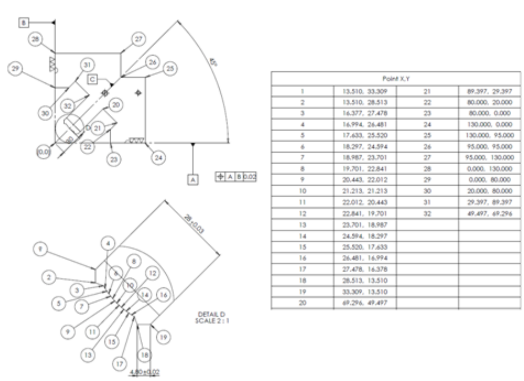

Figure 3: Pole profile points of the LTB quadrupole magnet.

BTS Dipole Magnet

The BTS dipole magnet is required to have field strength 1.012 T and effective length 0.1 m for 3 GeV operation, which will provide bending angle 101.2 mrad. The pole gap is 24 mm; the pole width is 120 mm. The height of the H-type yoke is 340 mm, and the width is 480 mm. The material of this magnet is chosen to be iron, also as an entire block without lamination. The coils, made of copper, have a square profile 13×13 mm^2 with a coolant orifice of diameter 6.5 mm; the other parameters are listed in table 2. The pole profile is modified with edge shims that are shown in Fig. 4. These shims increase the field homogeneity to be the same as for the quadrupole magnet, discussed above. After optimization, the homogeneity $\Delta B/B$ of the centre field for $X = \pm 30$ mm is within 0.01 %; the integral field homogeneity $\Delta\int Bds/\int Bds$ is modified within 0.02 % with chamfering 4 mm at the edge of the poles.

BTS Quadrupole Magnet

The cross section of the BTS quadrupole magnet is the same as that of the booster ring (BR) pure quadrupole (QP) magnet design. The field homogeneity is required to be the same as for the QP magnet but the gradient strength is up to 18 T/m with two effective lengths, 300 mm and 400 mm. From an estimate of saturation of the yoke from the field-current distribution, the distribution is still linear at operating current 130 A, but the power consumption is too huge compared to the booster ring; the number of water circuits must change from two to four to maintain the increase of the water temperature less than 15 °C. Fig. 5 shows the model (Opera 3D) and the engineering drawing. Table 2 lists parameters of the 300-mm and 400 mm BTS quadrupole magnets.

Table 2: Parameters of BTS Dipole and Quadrupole Magnets

BTS Magnet Parameters	Unit	Dipole	Q282	Q382
Iron length	m	0.965	0.282	0.382
Magnet length	m	1.000	0.300	0.400
Magnet quantity		2(+1)	4	3
Normal field	T	1.012		
Gradient field	T/m		18.0	18.0
Magnet gap	m	0.024	0.018	0.018
Coil conductor dimension	mm	13×13	5×5	5×5
Coolant hole diameter	mm	6.5	2	2
Number of turns/pole		20	18	18
Current	A	484	130	130
Resistance	Ω	0.014	0.049	0.061
Power consumption	kW	3.329	0.837	1.035
Inductance	mH	13.633	5.140	7.130
Voltage drop	V	6.872	6.430	7.946
Water flow rate	L/min	7.992	1.350	1.196
Coolant temperature rise	°C	5.968	8.9	12.4
Number of water circuits per magnet		2	4	4

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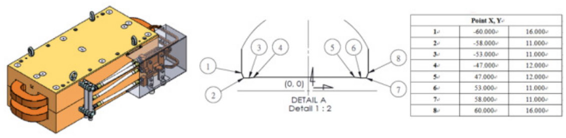

Figure 4: Pole profile points of the BTS dipole magnet

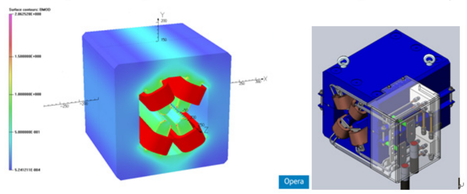

Figure 5: Model (Opera 3D) is shown at the left, and an engineering drawing of the BTS quadrupole magnet at the right.

EXPERIMENTAL RESULTS

The LTB dipole, quadrupole magnets and BTS dipole magnets are manufactured by Danfysik, the coils of the BTS quadrupole magnets by Scanditronix and the yokes by a local company in Taiwan. The fields of the LTB and BTS dipole magnets are measured with a Hall probe system, the LTB quadrupole magnet by Danfysik, and the BTS quadrupole magnets with a NSRRC BR rotating coil system.

LTB Dipole Magnet

The current is cycled, five times, from 0 to 310 A before measurement of the dipole magnet. The centre field strength is 0.218 T operated at 82.6 A; the simulation current is 83 A; the error is less than 0.5 %. When the centre strength attains 0.615 T, the current is 232.5 A, greater than simulation by 0.2 %. The central field homogeneity is 0.013 % within $X = \pm 20$ mm at 11^o operating current; the homogeneity is 0.011 % at 31^o operation. The central field homogeneities are all smaller than the simulation result, 0.1 %. The integral field homogeneity at 11^o operation is 0.3 % within $X = \pm 20$mm, which is also better than the simulation result, 1 %. For the 31^o operation, the result is 0.3 % within $X = \pm 10$mm, which is also better than the simulation result, 3 %.

LTB Quadrupole Magnet

Eleven LTB quadrupole magnets will be installed in the TPS; two magnets are spares for the future. In total, 13 magnets are manufactured and tested by Danfysik. The average integral gradient field strength is 0.87 T at operating current 74 A; this result is greater than simulation by 16 % because the designed iron length is 131 mm, but the actual iron length is 150 mm in manufacture. The multipole error results of 13 magnets provided by Danfysik; the results are all within specification, 10×10^{-4}.

BTS Dipole Magnet

The BTS dipole magnet is also charged with cycling five times for the current from 0 to 650 A. The normal centre field strength is 1.0136 T; the integral strength is 1.0600 T m at 484 A. The length of the iron is 1.0 m and the effective length is 1.0457 m; the fringe field is larger than simulation by 1.0 %. When the current operates at 484 A, the water temperature rises from 25 ^{o}C to 30.9 ^{o}C; the result of the coolant system is the same as predicted. The integral field homogeneities of the three magnets are 0.07 %, which is better than specification 0.1 % within $X = \pm 25$ mm. Even the pole shape is made straight, not a bending pole; the region of good field is adequate for the electrons to pass through the BTS line.

BTS Quadrupole Magnet

The BTS quadrupole magnet called Q282 has iron of length 282 mm and effective length 300 mm; for the iron length 382 mm, the magnet is called Q382. The quadrupole magnets were punched, CNC machined and assembled in Taiwan local company. In total, eight magnets are finished manufacture and measured, but multipole B3 is much larger than simulation, as listed in table 3. With regard to the CMM results, the B3 term is caused by an imperfect pole profile. To treat this problem, one can use a yoke shim cut to decrease the B3 value, and the other multipole terms do not alter. The water temperature of Q282 increases from 25 ^{o}C to 33 ^{o}C, which result is less than calculation by 1 ^{o}C. The water temperature of Q382 increases from 25 ^{o}C to 36 ^{o}C, which result is also less than calculation by 1 ^{o}C.

Table 3: The BTS Quadrupole Yoke Shim Results

Magnet number/ Result	B3 without yoke shim /10^{-4}	B3 with yoke shim /10^{-4}
Q282-001	-19.1	-2.3 (-150μm)
Q282-002	-16.4	1.0 (-140μm)
Q282-003	-16.5	1.7 (-150μm)
Q282-004	-1.2	-
Q382-001	-9.8	-1.9 (-70μm)
Q382-002	-10.6	-3.0 (-70μm)
Q382-003	-9.5	-0.8 (-70μm)
Q382-004	2.4	-

CONCLUSION

The designs, calculations and results of measurements of the TPS transfer line magnets are presented in this paper. The experimental results of the magnetic field meet the specifications. The cooling results for the magnets also fit the simulation results, but the BTS quadrupole magnets are imperfect in manufacturing. A salient point is that the process of a yoke shim can decrease the value of B3, which provides a good opportunity to manufacture an accelerator magnet, to find the machine error and to correct these problems.

REFERENCES

[1] C. C. Kuo, et al., “Design of Taiwan future synchrotron light source”, Proceedings of the EPAC’06, June 2006, p. 3445 (2006).

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