STATUS OF MAGNET DESIGN FOR THE ACCELERATOR LATTICE OF THE TPS PROJECT

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Abstract

Accelerator lattice magnets for the storage and booster rings of the Taiwan Photon Source (TPS) with energy 3 GeV have been designed. The sextupole magnet of the storage ring was designed to include corrections for horizontal, vertical and skew quadrupole fields. The combined function of the dipole and quadrupole magnets of the booster ring was designed to facilitate tuning of the chromaticity and to decrease the number of magnets and the field strength. Construction of the prototype magnets for the storage ring has begun. 50CS1300 silicon steel is used for the iron lamination sheet of the storage and booster rings. The status of the magnet design and related technical issues and construction are described herein.

INTRODUCTION

The DBA lattice of 1.6 nm rad has been designed for the TPS storage ring. The magnetic computation codes of TOSCA and RADIA software packages were used to design the magnetic circuits of the accelerator magnets. The design of a magnetic circuit must take into account both the requirements of accelerator physics and practical engineering constraints. We apply pole-edge shims [1,2] to enhance field homogeneity and end-magnet chamfers to decrease the multipole-integral field components. The calculated field *B(x)* and the integral field ∫*B(x)ds* at the mid-plane are expressed in polynomial expansions as

$$B_x(x)+i\,B_y(x)=\sum_{n=0}(a_n/n!)x^n+i\sum_{n=0}(b_n/n!)\,x^n \qquad (1)$$

$$\int B_x(x)ds+i\int B_y(x)ds=\sum_{n=0}(A_n/n!)x^n+i\sum_{n=0}(B_n/n!)\,x^n \qquad (2)$$

in which a_n and b_n are the skew and normal components, respectively. The integral field normalization at the effective field region x is defined as $|B_n/B_j| = (B_n/B_j)x^{(n-j)}$, in which j is the main component of the magnet of each kind and A_n and B_n are the integral skew and normal components.

All magnetic cores are made of 50CS1300 silicon steel sheet (thickness 0.65 and 1 mm), and the magnet cores with electric insulation and a process to prevent corrosion are on special order from China Steel Corporation. The permeability of the core material may deviate up to 5 % of the specification value. The laminations must be shuffled to ensure a uniform magnetic property. The iron laminations are made through punching and dyes. The contour dimensions of the iron are precisely controlled to within 10 μm, but the accuracy of the magnet assembly is tried to be controlled within 20 μm. The upper magnet halves are removable to install in the vacuum chamber. The reproducibility of the position after reinstallation should be controlled within 10 μm. The magnets are accurately fixed on a girder and without alignment. The criterion for the magnet design is to maintain a rise of coil temperature within 10 °C and with a safety margin greater than 20 %. The operating current density of the coil is between 2.5 and 5 A mm^{-2}.

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STORAGE RING MAGNETS

Each of six superperiods consists of four unit cells of a DBA lattice. The storage ring, of circumference 518.4 m, includes 48 bending magnets, 240 quadrupoles and 168 multifunction sextupole magnets of various lengths and families. The main design parameters for the magnet are listed in Table 1.

Table 1: Specifications of storage ring magnets.

Type	Dipole	Quadrupole	Sextupole
quantity	48	192/48	168
magnet length /m	1.1	0.3/0.6	0.25
field strength / T,T/m,T/m^2	1.191	17/15.63	478
full gap / mm	46	74	78
good field range / mm	40×30	±30	±32
turns per pole	36	54/48	26
conductor / mm^2	16×16	8×8/9×9	8×8
coolant diameter / mm	7	4/4.5	4
current / A	640	188/187	135
electronic power / kW	8.53	2.56/2.86	0.77
water velocity / m s^{-1}	1.23	1.2/1.34	0.73

Dipole Magnet

The dipole magnet is designed with a longitudinal bending curve to manage the unsymmetrical distribution of magnetic field due to the sagittal effect. Figure 1 shows the calculated field quality Δ*B*/*B* and Δ∫*B*ds/∫*B*ds of the central field and integral field of the dipole magnet. The field quality Δ*B*/*B* in the good field region was verified to be within 0.01 %. End chamfers have dimension 6 mm at the end caps, applying a 45° cut to the pole tip to prove effective in suppressing the sextupole components. According to the integral dipole field strength, for an iron magnet of length 1.018 m, we obtain an effective length 1.1 m after the end chamfer. The dipole magnet has a rectangular H-type structure. There is hence edge focus strength at both ends of the magnet so that the edge integral focus strength is -0.124 T [3].

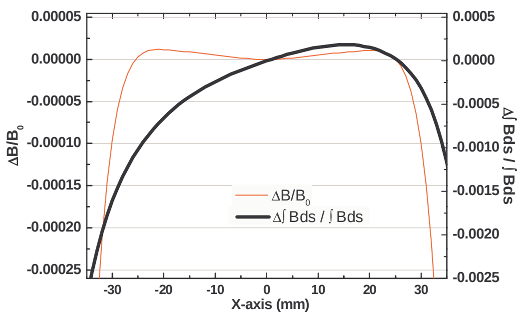

Figure 1: Field homogeneity of central and integral fields on the transverse *x*-axis; $\Delta B/B_0= [B(x)-B(0)]/B(0)$ and $\Delta\int Bds/\int B_0 ds=[\int B(x)ds-\int B(0)ds]/\int B(0)ds$.

The laminations are stacked and glued to a steel frame. The coil was designed considering the number of turns, the height of the pole gap, the specifications of the power supply and the water-cooling system. The coil is insulated with a layer (thickness 0.5 mm) of fiberglass that is impregnated with epoxy resin in vacuum. Fibreglass (thickness 1.5 mm) serves for the ground insulation of each coil pancake.

Quadrupole Magnets

For the quadrupole magnets that have two yoke lengths, the bore radius R=37 mm is determined according to the dimensions of the vacuum chamber and the dynamic aperture of the beam. The cross section of the contour equation is $xy = R^2/2$. According to a standard procedure, removable end caps have a 60° cut of depth increasing to 14 mm and 12 mm up to the pole tip for the short and long quadrupole magnets, respectively. Figure 2 reveals the field deviation of the central field $\Delta B/B$ and the integral field $\Delta\int Bds/\int Bds$ distributed along the transverse *x*-axis. The field quality $\Delta B/B$ in the good field region is within 0.01 %.

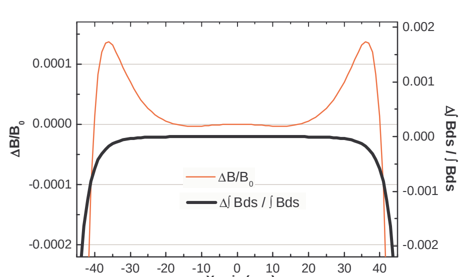

Figure 2: Field homogeneity of central and integral fields of the quadrupole magnet in the transverse direction; $\Delta B/B_0= [B(x)-(b_0+ b_1x)]/B(x)$ and $\Delta\int Bds/\int B_0 ds = [\int B(x)ds-(B_0+ B_1x)]/\int B(x)ds$.

Two quadrants are assembled as half magnets, each top and bottom. Each half is connected mechanically with aluminium or stainless-steel spacers of varied shape to accommodate the vacuum chamber for extraction of the photon beam. The quadrant laminations are shuffled after precise punching and accurately stacked during the magnet construction. The top and bottom halves are aligned relative to each other with precise circular holes and pins. The two magnet halves should be keyed with respect to each other in the longitudinal direction with an accuracy ±0.05 mm. A precise reference base plate is attached to the quadrupole magnet.

Sextupole and Corrector Magnets

The sextupole magnet is designed for not only the main sextupole field but also field correction of the vertical and horizontal dipoles and the skew quadrupole. A bore radius R=39 mm was decided according to requirements of field quality and a space constraint between the vacuum chamber and the pole contour. The equation for the pole tip contour is $3x^2y - y^3 = R^3$. The pole contour R is 39.1 mm so as to decrease the 30-pole strength. The parameters for the sextupole magnetic appear in Table 1.

According to a standard procedure, we chamfered the end caps, applying a 45° cut of depth increasing to 5 mm up to the pole tip for the sextupole magnet. Figure 3 shows the calculated field deviations of the central field $\Delta B/B$ and the integral field $\Delta\int Bds/\int Bds$ that is distributed along the transverse *x*-axis. The calculated field quality $\Delta B/B$ in the good field region is within 0.03 %. If the main coil and all corrector coils become excited, the multipole field strength is, however, larger than that without the charging corrector.

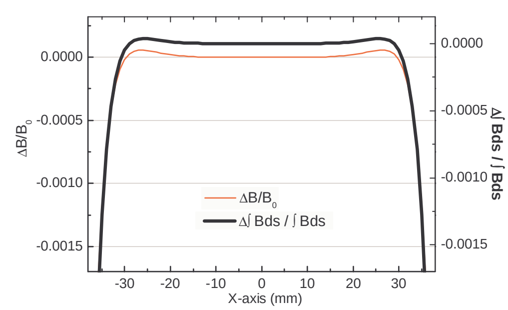

Figure 3: Field homogeneity of central and integral fields of the sextupole magnet in the transverse direction; $\Delta B/B_0= [B(x)-(b_0+ b_1x+ b_2x^2)]/B(x)$ and $\Delta\int Bds/\int B_0 ds = [\int B(x)ds-(B_0+ B_1x+ B_2x^2)]/\int B(x)ds$.

BOOSTER MAGNETS

Each of six superperiods comprises eight cells of a combined function FODO lattice. A concentration booster ring, with circumference 496.8 m, therefore includes 54 bending magnets, 98 quadrupoles, 24 sextupole, and 54 horizontal and 60 vertical corrector magnets. The main parameters of their magnet design are listed in Table 2.

Dipole Magnet

Bending magnets of two kinds are designed for the booster ring. The BD and BF dipole magnets are combined-function magnets with lengths 1.6 and 0.8 m, respectively. The dipole field is 0.819 T at 3 GeV and 365 G at 150 MeV. The defocusing quadrupole and sextupole field components are combined in the bending magnet. To enhance the uniformity and to decrease the effect of eddy currents, a laminated construction is adopted. Silicon iron sheets 50CS1300 of thickness 1 mm will be used for the iron laminations of the dipole magnet. We chose an H-type design for the dipole magnets to keep a symmetric field and to reinforce the mechanical strength. The BD and BF dipole magnets have sagitta is 23.3 and 11.6 mm, respectively. The curve of the dipole magnet will hence be designed to decrease the magnet dimensions and mass. Iron blocks of parallelogram-like form will be assembled to serve as the whole curved magnet with angles 0.85^{o} and 2.56^{o} so that their axes make an angle 7.5^{o} with the central section axis.

The BD dipole magnet includes the dipole field, quadrupole field and sextupole field strengths specified in Table 2. The profile equation combines $3x^2y - y^3 = R^3$ and $y = (2q/w)\ x$ to create the main dipole, quadrupole and sextupole field strengths, with q=0.764, R=6804, w=64.

Table 2: Specifications of booster ring magnets.

Type	Dipole BD/BF	Quadrupole Q_F/ $Q_{1,2,M}$	Sextupole S1/S2
quantity	42/12	48/36	12/12
magnet length / m	1.6/0.8	0.3	0.2
field strength / T, T/m, T/m^2	0.819, -1.73, -12.4	11.3,26/14.4	200
full gap / mm	24	36	36
good field range/mm	±15	±15	±15
turns per pole	8	18	22
conductor / mm^2	(13×13)	5×5	3×2
coolant diameter / mm	6.5	2	---
current / A	1034	82/104	7.3
electronic power /kW	6.4/3.3	0.14/0.22	0.004
water velocity / m s^{-1}	2.3/1.2	0.5/0.8	---
voltage drop / V	22/11.5	5.6/7.1	1.5

Quadrupole Magnets

Quadrupoles in four families match the beta functions in straight sections. Forty-eight quadrupoles in the same family of quadrupoles (Q_F) are combined with the focusing sextupole field components. Quadrupole magnets in three families – $Q_{1,2,M}$ – of pure types have the same iron lamination but are excited with a varied current. The bore radius is 18 mm for the combined and pure quadrupole magnets. The pole profile equation $xy = R^2/2$ was selected for the pure quadrupole magnet; R = 17.7 mm to decrease the 20-pole strength. The pole profile of the combined quadrupole magnet is, however, the same as that of the pure quadrupole magnet but with an angle 0.82^0 of rotation in the clockwise direction of the upper two quadrants to create the sextupole field strength. The bore radius of the first quadrant is maintained at 18 mm, but the pole location of the second quadrant is moved 18.16 mm along the 135°-direction line to cancel the dipole field strength. Different end shims are applied on the first and second quadrants of the combined quadrupole magnet to enhance the good field region. The designed method of construction is to assemble the upper and lower half part quadrants to form the whole magnet. This method facilitates the control of mechanical precision and effects cost economy.

Sextupole and Corrector Magnets

Pairs of extra sextupoles are put in a dispersion suppressor section to correct the chromaticities during ramping. Two families of sextupole and numbers of 114 dipole field correction with horizontal and vertical correctors are used in the booster ring for field correction. The nominal sextupole field strength of the sextupole magnet is 200 Tm^{-2}; the dipole field strength of the dipole corrector is about 1 mrad operating at extraction energy 3 GeV.

There is only one lamination for the 24 sextupole magnets. The magnet core must be divided into two identical segments to simplify the magnet core fabrication and to increase the precision of construction. A bore radius R = 18 mm is selected for the sextupole magnet; this bore radius is used also for the equation ($3x^2y - y^3 = R^3$) of the pole contour. Lamination shuffling and flip stacking will average the permeability of the magnet and eliminate systematic punching errors.

SUMMARY

The magnetic circuits and engineering design have been completed for the storage and booster ring magnets, and construction of a prototype magnet for the storage ring has begun. Various field-measurement systems – a Hall probe, rotating coil, and stretch-wire system – have been prepared for control of the magnet quality. The prototypes of magnets of each kind will be completed and their fields measured before the end of 2009.

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