SUPERCONDUCTING MAGNET DESIGN FOR BEPC-II INTERACTION REGION

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Abstract

There are two sets of superconducting magnets in the BEPC-II interaction region. The magnets are inside the BES detector and nearby the interaction point. The magnet preliminary design was finished. The details of the design which include the coil structure, field calculation, stray field shielding, cryostat design, quench protection, magnet support and installation are discussed in this paper.

1 Layout of BEPC-II Superconducting Magnets

According to lattice design of BEPC-II Double Rings, there are two sets of superconducting magnets in the interaction region. Each set of superconducting magnet includes one quadrupole named SCQ, one anti-solenoid named ASOL and one bending magnet named SCB which used for synchrotron radiation. In order to obtain good results for anti the field of BES solenoid, the ASOL is divided in to two parts, ASOL_1 and ASOL_2. The SCB and SCQ are inside the ASOL_1 and ASOL_2, respectively. The magnets are located symmetrically at the two sides of the interaction point. The overall of the superconducting magnets of BEP-II Double Rings is shown in Figure 1. The given requirement for the magnets was listed in Table 1.

Table 1 Requirement of superconducting magnets of BEPB-II Double Rings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ASOL</th>
<th>SCB</th>
<th>SCQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance to IP</td>
<td>0.6 m</td>
<td>0.6</td>
<td>1.15 m</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>0.4 m</td>
<td>0.4 m</td>
<td></td>
</tr>
<tr>
<td>Integral Field strength</td>
<td>2.6Tm</td>
<td>0.32252</td>
<td></td>
</tr>
<tr>
<td>Main field strength</td>
<td>0.8063T</td>
<td>G=17.6T/m</td>
<td></td>
</tr>
<tr>
<td>Steering dipole</td>
<td></td>
<td></td>
<td>Bx=200Gs</td>
</tr>
<tr>
<td>Vacuum tube aperture</td>
<td>Ø106</td>
<td>Ø120</td>
<td></td>
</tr>
<tr>
<td>Maximum diameter</td>
<td>Ø280 at SCB,</td>
<td>Ø450 at SCQ</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1 Superconducting Magnets of BEPC-II

2 Coil design

2.1 Basic consideration

The basic considerations in the coil design are as the followings: (1) No iron yoke. The superconducting magnets are located inside the BEPC Spectrometer (BES). There is about 1 T field inside the BES. Any iron yoke around the magnets will be magnetized. Consequently, there are not any iron yoke around the magnets. (2) Separate beam vacuum tube from the magnet to facilitating for installing the beam tube from two side of interaction point. (3) ASOL, SCB and SCQ are installed in same cryostat to easy for supporting and for installing the magnets into BES detector. (4) Use the same kind of NbTi superconducting cable in the all of coil design to simplify superconducting cable selection. The cable is round with diameter Ø1.09 mm.

2.2 Coil Design for SCQ

The SCQ magnet is located inside the ASOL-2. The field gradient in the aperture is 17. 6 T /m and its magnetic length is 0.4 m. The requirement of field quality in the useful field region is $B_n/B_2$ (at $R=43$ mm)$\leq 1\times10^{-4}$.

(a) Coil composition of SCQ

The SCQ coils are composed of a quadrupole coil and a vertical steering dipole coil. The quadrupole coil is inner coil. The steering dipole coil is beside the quadrupole coil. Both quadrupole coil and steering dipole coil are a set of cylindrical current shell with the angular wedges. The cross section of SCQ is shown in Figure 2.

(b) Coil structure parameters

The Figure 2 shows the SCQ cylindrical current shells with the angular wedges. This kind of coil structure is simple for the coil winding. If the parameters design is suitable, the field quality in the useful field region will be good enough.
Assume that the current shell angular is $a_0$, the wedge angular are $a_1$ and $a_2$ (see fig. 3) and the current shell have the inner radius $R_i$ and the outer radius $R_o$. The current density is $J$. Then the quadrupole field $B_2$ is given by

$$B_2 = \frac{2\mu_0 J}{\pi} \ln\left(\frac{R_o}{R_i}\right) \left[\sin 2a_0 - \sin 2a_1 + \sin 2a_2\right]$$

If set $a_0=33.63765$, $a_1=26.0763$, and $a_2=21.58955$ for quadrupole coil, the high order field produced by the coils will be $B_6=B_{10}=B_{14}=0$. In the SCQ design, we set $a_0=33.6^\circ$, $a_1=26.1^\circ$ and $a_2=21.6^\circ$. For the steering dipole coil, in the same way, the quadrupole field $B_1$ is

$$B_1 = \frac{2\mu_0 J}{\pi} \left(\frac{R_o}{R_i} - 1\right) \left[\sin a_0 - \sin a_1 + \sin a_2\right]$$

In order to obtain $B_3=B_5=B_7=0$, then need to set $a_0=67.2753$, $a_1=52.1526$, and $a_2=43.1791$. In a similar fashion, set $a_0=67.1^\circ$, $a_1=52.2^\circ$ and $a_2=43.2^\circ$ then rotating a angular of $90^\circ$ were selected for the vertical correction dipole coil. The quadrupole coils of SCQ have 3 double layers of conductor and its thickness is about 9.9 mm. The inner diameter of the SCQ quadrupole coil is Ø188mm and the outer diameter is Ø201.2mm. The steering dipole coils have one double layer with inner diameter of Ø210 mm and outer diameter of Ø216.6mm.

(c) Field quality of SCQ

The magnetic field distribution in two dimensions was calculated by using program OPERA-2D. When the current density in the coil is 223A/mm² (the excitation current is 496 A) the field gradient at the center is 17.6 T/m. The maximum flux density in the coil is 2.26 T. The ratio of the operating current with respect to the critical current ($I_{op}/I_c$) is 60%. From Figure 3, the field quality in the useful field region is good enough. In the useful field region (R≤53 mm), the field gradient error is less than $1\times10^{-4}$. For SCQ with the simple coil head, the magnetic field distribution in three dimensions was calculated by using a 3D-program. The field distributions along z-axis are shown in Figure 4. When the length of the coil straight section is 308.55 mm, the field effective length is 400 mm.

For the field produced by steering dipole coil, when the current density is 10A/mm² the field $B_x$ at the center is 200 Gs.

2.3 Coil Design for SCB

The superconducting bending magnet used for synchrotron radiation (SCB) is located inside the ASOL-1. The field strength $B_y$ in the aperture is 0.8063 T and its magnetic length is 0.4 m. The requirements of field quality in the useful field region is $B_n/B_1\leq1\times10^{-4}$.

(a) Coil structure

In the SCB design, set $a_0=67.1^\circ$, $a_1=52.2^\circ$ and $a_2=43.2^\circ$. The SCB coils have 2 double layers of conductor and its thickness is about 6.6 mm. The inner diameter of the SCB coil is Ø188 mm which is as the same as the SCQ. Its outer diameter is Ø201.2 mm.

(b) Field quality

The field distribution produced by SCB coil is shown in Figure 5. When the current density is 180.1A/mm² the field $B_x$ at the center is 8063 Gs. In the useful field region of 76 mm, the field relative error $\Delta B/B_0$ are less then $1\times10^{-4}$. The excitation current is 327.8 A. The

Figure 2 Cross section of SCQ

Figure 3 Field gradient error distribution of SCQ

Figure 4 The SCQ field distributions in three dimensions

Figure 5 Field distribution of SCB
maximum flux density in the coil is 1.3T. The I / Ic is
40%.

2.4 Coil Design for Anti-Solenoid

The requirements of the Anti-Solenoid (ASOL) are as
the followings: (1) Its integral field will be anti the
integral field of BES solenoid. (2) Shielding the detector
field in the SCQ region. The field distribution of the BES
solenoid is uniform in the center region, but it drops
down intensively in the SCQ region. So we need to use a
special shape of anti solenoid coil to achieve above two
requirements. Figure 6 shows the coil structure of ASOL
inside BES detector and is field flux map. The ASOL coil
consist of two solenoid parts. One part is main solenoid
named ASOL-1 located outside the SCB. Its thickness is
9.9 mm (3 double layers of conductor). Considering the
space of the SCB, the inner diameter of the ASOL-1 coil
is 204 mm and its outer diameter is 223.8mm. Another
part of the ASOL is a shield solenoid named
ASOL-2. It locates outside the SCQ. Also, considering
the SCQ space, the inner diameter of the ASOL-2 coil is
220 mm and its outer diameter is 226.6mm. The
ASOL-2 coil have 1 double layers of conductor and its
thickness is about 3.3 mm. In order to shield the BES
field in SCQ region well, the ASOL-2 coil is divided to
two parts. One part nearby ASOL-1 is longer than
another part.

The field produced by both ASOL coils and BES detector
solenoid are shown in Figure 6. Figure 7 shows the field
distribution along the z-axis. When the current density in
ASOL coils is 200.6 A/mm², the integral field of ASOL
is just anti the BES integral field. Within the SCQ region,
the field become to very low, less than ±300 Gs.

3 Magnet Structure

The whole structure of the superconducting magnet is
shown in Figure 8. The SCQ, SRB and ASOL coils are
installed in one cryostat. The structure keep the magnet
separated from beam vacuum tube to facilitating for
installing the beam tube from two side of interaction
point. The SCQ and SRB are winding on the same
diameter size of supporting tube.

Figure 8 Whole structure of the superconducting magnet

The Cross section of the magnet at SCQ1 and SSOL is
shown in Figure 13. The beam tube shape in the magnet
is round with inner diameter of 126 mm and outer
diameter of 130 mm. The coil support tube is round
with outer radius of 188 mm and with thickness of 6
mm. The SCQ1 quadrupole coil and steering dipole coil
are winded round the support tube. The shield solenoid
coil (SSOL) is winded round another support tube with
diameter of 244 mm. The maximum diameter of SCQ1
magnet is 350 mm.

REFERENCES

[1] Mini-workshop, lecture by Dr. Brett Parker, BNL,
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dipole and quadrupole magnets for Particle Accelerators.