SUPERCONDUCTING CORRECTOR IR MAGNET PRODUCTION FOR SUPERKEKB*

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Abstract

SuperKEKB is an upgrade project underway at KEK, to increase the KEKB b-factory luminosity 40-fold by using nanobeam Interaction Region (IR) focusing optics [1] for which the production of new superconducting IR magnets and correctors is critical [2]. SuperKEKB corrector design and production is challenging since many different coils are needed for precise control of IR magnetic fields, in order to ensure good beam lifetime and there is very little space for them. SuperKEKB corrector production is about half completed and we report here on new techniques recently developed to address production challenges.

INTRODUCTION

The SuperKEKB IR magnet layout in the left-side and right-side cryostats is shown in Fig. 1. The SuperKEKB design has 83 mrad total crossing angle to separate the e^- (E) High Energy Ring (HER) and e^+ (P) Low Energy Ring (LER) beam lines in independent non-cryogenic vacuum apertures. A few millimetres of radial space is available for corrector coils atop support bobbins that serve as the inner cold mass containment wall and the main quadrupole coils' inner surface. The corrector requirements, presented in Table 1, evolved in response to results from optics optimization and tracking studies and differ from those available before production started [3].

Left-side corrector production commenced first using preliminary specifications provided before the right-side requirements were set. Later optics studies found that sextupole coils, b_3 and a_3, not in the original design, are needed; so these coils are added to the right-side layout. The majority of the corrector coils are located inside a main quadrupole coil; however, with insufficient space inside the first IR quadrupoles, QC1LP/RP, their b_4 correctors are wound on bobbins placed just outside the main coil (along with an a_3 corrector only for QC1RP). Because these first LER quadrupoles have insufficient space for magnetic flux return yokes between their coils and the nearby HER beam, there is significant external field leakage that must be dealt with so as not to adversely impact the HER optics. Requirements for these additional external field cancel coils for the HER are discussed later.

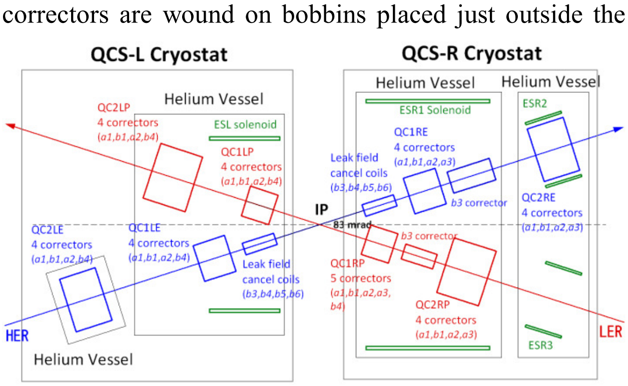

Figure 1: SuperKEKB IR magnet layout schematic.

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Table 1: Corrector Integral Field Strength Requirements. Here R/L denote left- and right-side magnets and P/E denote the LER and HER beam lines. The right-side b_3 coils are placed between main magnets. The external field cancel coils for the HER are not included in this table.

<table>
<tr><th>Magnet</th><th>R_r
mm</th><th>A_1
T•m</th><th>B_1
T•m</th><th>A_2
T</th><th>A_3
T/m</th><th>B_3
T/m</th><th>B_4
T/m^2</th></tr>
<tr><td>QC1RP</td><td>10</td><td>0.016</td><td>0.016</td><td>0.64</td><td>7.6</td><td rowspan="2">17.2</td><td>60</td></tr>
<tr><td>QC2RP</td><td>30</td><td>0.03</td><td>0.03</td><td>0.31</td><td>1.36</td><td>-</td></tr>
<tr><td>QC1RE</td><td>15</td><td>0.027</td><td>0.046</td><td>0.75</td><td>7</td><td rowspan="2">27</td><td>-</td></tr>
<tr><td>QC2RE</td><td>35</td><td>0.015</td><td>0.015</td><td>0.37</td><td>1.5</td><td>-</td></tr>
<tr><td>QC1LP</td><td>10</td><td>0.016</td><td>0.016</td><td>0.64</td><td>-</td><td>-</td><td>60</td></tr>
<tr><td>QC2LP</td><td>30</td><td>0.03</td><td>0.03</td><td>0.31</td><td>-</td><td>-</td><td>60</td></tr>
<tr><td>QC1LE</td><td>15</td><td>0.027</td><td>0.046</td><td>0.75</td><td>-</td><td>-</td><td>60</td></tr>
<tr><td>QC2LE</td><td>35</td><td>0.015</td><td>0.015</td><td>0.37</td><td>-</td><td>-</td><td>60</td></tr>
</table>

Both the corrector and cancel coils are attached to support bobbins via the BNL Direct Wind technique [4] using 0.35 mm diameter, single-strand superconducting round wire from Furukawa with a 1:1 Cu:NbTi ratio and critical current at 4.2K greater than 130 amps in a 5 T background field [5]. The wire is Kapton® overwrap insulated and adhesive coated to be compatible for use with BNL Direct Wind ultrasonic bonding technology.

CORRECTION COIL PRODUCTION

The SuperKEKB corrector requirements span a broad range of field harmonics and focusing strengths and are manufactured in many radius and length combinations. In order to make the best use of the available space attention to detail is needed regarding the careful nesting of coil layers. The QC2LE multi-layer arrangement shown in Fig. 2 offers an example of how lead management is an important consideration. At the bottom of the QC2LE coil stack is a single layer planar pattern [6] dipole winding over which skew dipole and then skew quadrupole planar coils are wound. The skew quadrupole is topmost because its ends, with fewer turns, are naturally shorter than those of the layers below and its four pole regions line up with

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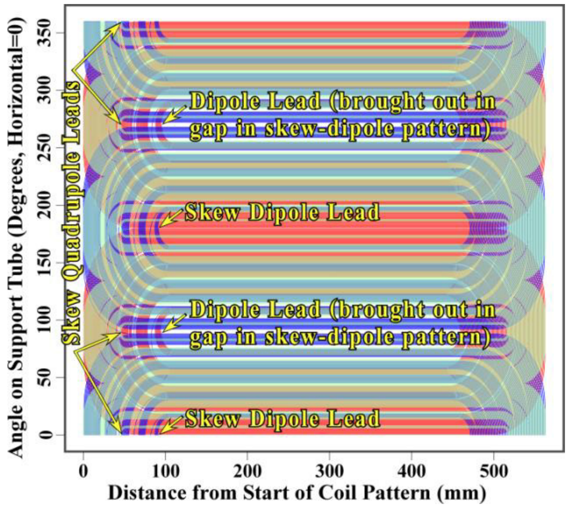

Figure 2: Multi-layer corrector coil winding example.

the lower pole regions. Thus it is possible to "see" the other current leads under the skew quadrupole pattern to bring them out over the top of the final coil package. But with this lead arrangement the dipole leads would be blocked by the skew dipole coil pack if we did not also open the mid-plane gap shown in the skew dipole pattern.

SuperKEKB beam lifetime is fairly sensitive to IR local field errors; so we use several field tuning spacers, in both the coil body and ends, to try to limit local field harmonic design errors to the level of a few gauss. For clarity a final b_4 coil winding is omitted from Fig. 2. The QC2LE b_4 integrated strength requirement is sufficiently small that we can use a short b_4 pattern that does not extend over the region of the previously wound coil leads

For some coils, such as the b_1, of QC1LE/RE, the current to reach the Table 1 value would be excessive with only a single coil layer. In this case we wind a_1 and a_2 layers first and move the b_1, coil out where we can use a shortened two-layer Serpentine style coil pattern [7] that does not block the a_1 and a_2 leads. The Serpentine pattern lets the b_1 leads exit cleanly even with a b_4 pattern of the same length wound on top of it [6].

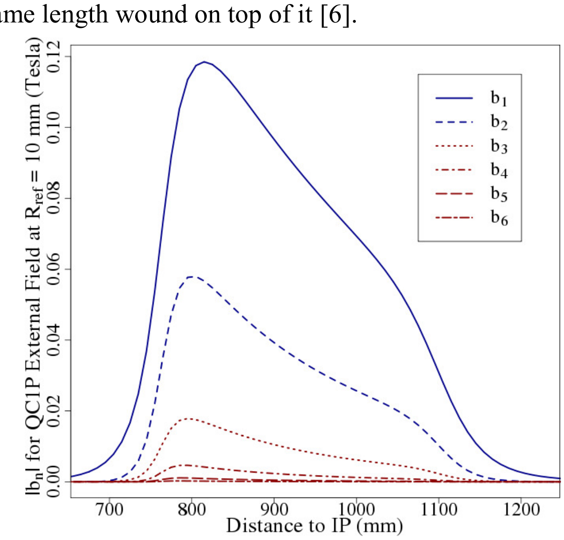

Figure 3: Decomposition into magnetic multipoles for QC1P external field plotted as a function of distance to the IP, for 10 mm reference radius, at the HER beam line.

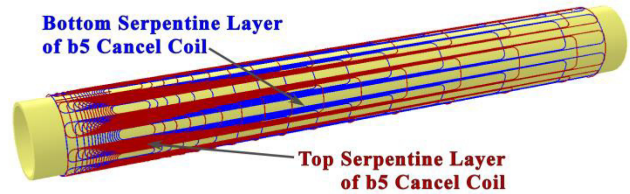

Figure 4: Final twisted b5 cancel coil winding used to generate the b5 and a5 fields shown in Fig.5. This pattern is a dual-layer Serpentine style coil winding with end turn spacing adjusted in both layers to achieve the desired field falloff with distance to the IP. Note that there are a large number of different sized coil end spacer gaps that must be filled with custom sized Nomex paper inserts.

CANCEL COIL PRODUCTION

External field leaking from the first LER quadrupoles, QC1LP\RP into the HER aperture, decomposed as a field multipole expansion, is plotted in Fig. 3. The linear, b_1, b_2, external field components are not of concern as they are easily included in the SuperKEKB IR optics; however, the non-linear fields shown in Fig. 3 would adversely impact HER beam lifetime. Via iterative adjustment of coil end turn spacing, four independent cancel coil windings, b_3, b_4, b_5 and b_6, are tailored to match the different external field profiles plotted in Fig. 3 that arise as the beam separation increases away from the IP.

We find that dual-layer Serpentine patterns, such as that shown in Fig. 4, are especially suited for use as cancel coils because they exhibit a simple, direct relationship between the straight section "body fields" and the end fields. At 10 mm reference radius the cancel coil's main harmonic dominates the total field until close to each coil end; so we developed fast codes that approximate the cancel coil field shape based on scanning at a single

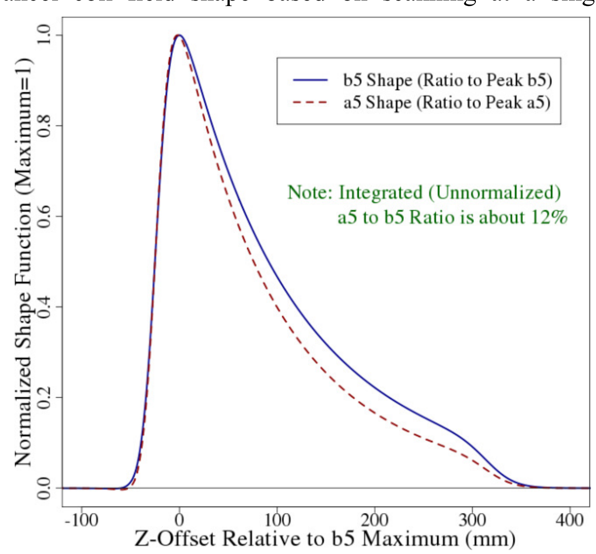

Figure 5: Normal and Skew Field Falloff Comparison. We plot b5 and a5 external field multipoles, with common peak normalization, to highlight their different shapes. A simple coil rotation cannot generate the correct a5 distribution from a pure b5; thus we must "twist" the coil pattern as a function of length along the coil support tube.

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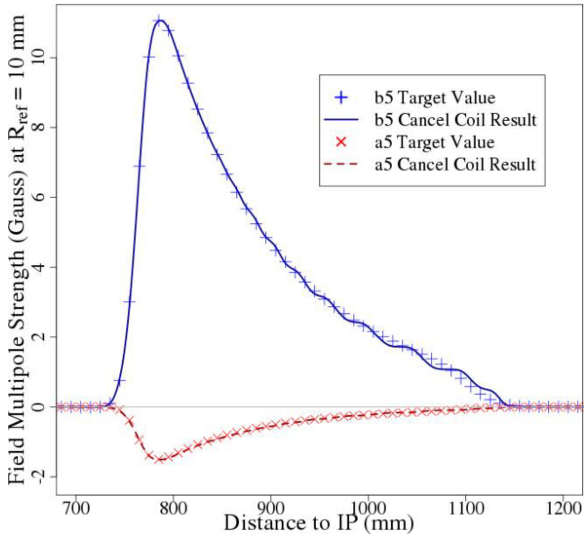

Figure 6: The b5 and a5 field multipole distributions generated by the b5 cancel coil with an applied twist transformation are compared here to the target goals set for perfect QC1P external field cancellation.

azimuthal angle rather than having to do a much more calculationally intensive full-angle range z-scan.

With an end turn spacing parameterization versus turn number that maps to specific shape features (e.g. regions of constant slope, a peak or a shoulder falloff), we can vary the end spacing in a smooth manner and after a few iterations come close to the desired external field target shape. With this candidate solution in hand we do a full harmonic z-scan to verify that unwanted higher-order end field harmonics are sufficiently small. A typical target normal-harmonic field shape curve, b_5, is plotted in Fig. 5. Note that in addition to b_5 there is a second a_5 curve shown that has a different falloff with distance from the IP. A similar shape difference between normal and skew occurs for all of the QC1P external field multipoles and this presented an unexpected design challenge.

The SuperKEKB quadrupoles experience a combined background field from the detector and compensation solenoids and are rotated in order to achieve the desired optics for the beam eigenplanes; the corrector magnets are rotated the same amount. A naive expectation was that the cancel coils could also be similarly rotated to provide the proper mix of normal and skew cancel fields; however, the SuperKEKB IR layout has some HER and LER quadrupoles at different vertical offsets to reduce needed corrector strengths. Unfortunately this combined rotation and offset results in our having to match different normal and skew external field target shape curves.

To alter the skew/normal field ratio we must rotate different sections of the coil pattern by different amounts, i.e. we have to twist the coil pattern. A uniform twisting of a pure b_5 coil pattern produces the required a_5 field profile as illustrated in Fig. 6. The most obvious field deviations from target values are the small constant field "shoulders" that result from the limited number of b_5 end turns available to optimize. The b_3 and b_4 cancel coils have more turns and smoother field profiles while the b_5 and b_6 coils, with fewer turns, have the largest relative tail deviations. Still the target b_5 and b_6 fields are already so small that these errors really do not matter.

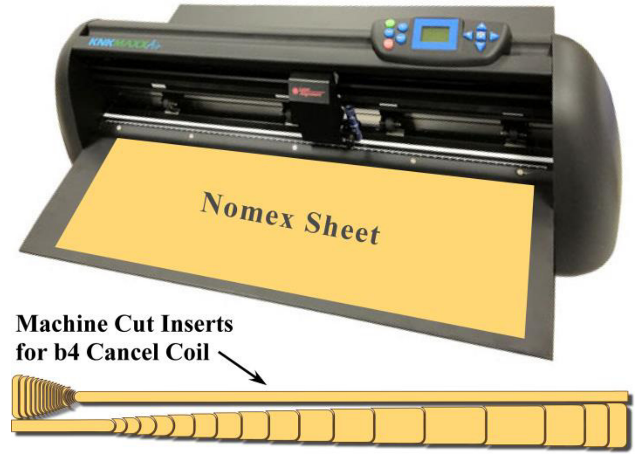

Figure 7: This machine automatically cuts coil end spacer inserts from Nomex sheets using information derived from a computer winding file. The pattern for a single b4 pole is also shown. The cut outs have tab connections to keep inserts in place until needed and avoid hand sorting.

While it is convenient for optimizing a magnetic design to use the large number of spacers shown in the patterns of Fig. 2 and Fig. 4, it is also a production nightmare to ask technicians to cut so many tiny fill pieces by hand. For SuperKEKB production we developed an automated procedure where the coordinates of the coil pattern are fed into Pro-Engineer software [7] that follows the coil path in 3 dimensions and then unwraps it to a flat pattern. To have a proper gap between the fill spacers and coil, this flattened path is thickened to simulate wire thickness and offset by a small amount. Additional processing removes extraneous lines and leaves only the shapes to be cut. That file is then read by the computer controlled flat pattern cutter shown in Fig. 7 that uses a small steel blade to cut the pattern from a sheet of Nomex [8].

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[7] Now marketed as PTC Creo, see www.ptc.com.

[8] 24" Maxx Air from Klic-N-Kut, see knkusa.com.

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