BNL-98158-2012-CP

Direct Wind Superconducting Corrector Magnets for the SUPERKEKB IR

B. Parker, M. Anerella, J. Escallier, A. Ghosh, A. Jain, A. Marone, P. Wanderer (BNL
Y. Arimoto, M. Iwasaki, N. Ohuchi, M. Tawada, K. Tsuchiya, H. Yamaoka, Z. Zong (KEK)

Presented at the International Particle Accelerator Conference (IPAC12)
New Orleans, LA
May 21 -25, 2012

June 2012

Department/Division/Office

Brookhaven National Laboratory

U.S. Department of Energy
DOE Program Office of Science

Notice: This manuscript has been authored by employees of Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy. The publisher by accepting the manuscript for publication acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

This preprint is intended for publication in a journal or proceedings. Since changes may be made before publication, it may not be cited or reproduced without the author's permission.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Presented at the International Particle Accelerator Conference (IPAC12), New Orleans, LA - May 21-25, 2012 BNL-98158-2012-CP

DIRECT WIND SUPERCONDUCTING CORRECTOR MAGNETS FOR THE SUPERKEKB IR*

B. Parker#, M. Anerella, J. Escallier, A. Ghosh, A. Jain, A. Marone,
P. Wanderer, BNL, Upton, NY 11973, USA
Y. Arimoto M. Iwasaki, N. Ohuchi, M. Tawada, K. Tsuchiya, H. Yamaoka,
Z. Zong, KEK, Tsukuba, Ibaraki 305-0801 Japan

Abstract

Eight new superconducting interaction region (IR) quadrupoles and a variety of correction and cancel coil windings are needed for the SuperKEKB luminosity upgrade underway at KEK [1-2]. The correctors are required to fit in limited space inside the main IR quadrupole bores. Because there is insufficient space for magnetic yokes for the magnets closest to the interaction point (IP), external field cancel coil windings are needed to remove non-linear fields that would otherwise impact beams passing close to the main magnet coils. We are investigating if an additional cancel coil set would be useful to reduce detector background. The design and production of SuperKEKB corrector and cancel coils, using BNL Direct Wind magnet technology, is underway.

INTRODUCTION

SuperKEKB is an upgrade of the asymmetric e^+e^- B-factory at KEK, KEKB, with a goal of a forty-fold luminosity increase with respect to the world record KEKB performance [1]. Work at KEK is in progress to increase the high energy ring (HER) and low energy ring (LER) circulating currents and the IP spot sizes will be reduced using a nano-beam focusing scheme. As shown in Fig.1, the SuperKEKB IR layout has an 83 mrad crossing angle. With this crossing angle the HER and LER beams can be independently focussed in eight new superconducting IR quadrupoles [2], even though these new magnets are positioned closer to the IP. These magnets operate in the combined fields of the Belle-II detector and an arrangement of anti-solenoid coils [3-4].

Forty new corrector magnets and cancel coils (see Table 1) are also needed for the IR optics to work properly. The outer size for the left and right cryostats, which are cantilevered inside Belle-II, is constrained and inner space is used for minimal superinsulation around a warm beam pipe. Thus the radial space for IR correctors is extremely tight and consists of 3.9 to 5.2 mm between the cold mass wall and the inner quadrupole coil winding.

Table 1: SuperKEKB IR Magnet Properties

Main Magnet	Magnetic Yoke	Corrector Package	Cancel Coil Package
QC2RE	Iron	a_{1p}, b_{1p},a_{2p}, b_{4s}	n.a.
QC2RP	Iron	a_{1p}, b_{1p},a_{2p}, b_{4s}	n.a.
QC1RE	Iron	a_{1p}, b_{1s},a_{2p}, b_{4s}	n.a.
QC1RP	None	a_{1p}, b_{1p},a_{2p}, b_{4s} ($b_{1,3s}$,)	b_{3s}, b_{4s}, b_{5s}, b_{6s} (b_{1s},)
QC1LP	None	a_{1p}, b_{1p},a_{2p}, b_{4s}	b_{3s}, b_{4s}, b_{5s}, b_{6s}
QC1LE	Iron	a_{1p}, b_{1s},a_{2p}, b_{4s}	n.a.
QC2LP	Iron	a_{1p}, b_{1p},a_{2p}, b_{4s}	n.a.
QC2LE	Iron	a_{1p}, b_{1p},a_{2p}, b_{4s}	n.a.

The above coils are directly bound to the inner cold mass containment tube, which serves as a support bobbin, using the BNL Direct Wind technique [5]. All coils must be ready ahead of the main quadrupoles because the main coils are assembled around the correctors, before being mounted in cryostats; the corrector production schedule is ambitious. For these correctors we will use round, 0.35 mm diameter single-strand superconducting wire procured from Furukawa [6] with a 1:1 Cu:NbTi ratio and critical current at 4.2K greater than 130 amps in a 5 T background field. The wire will be Kapton® overwrap insulated and adhesive coated to be compatible for use

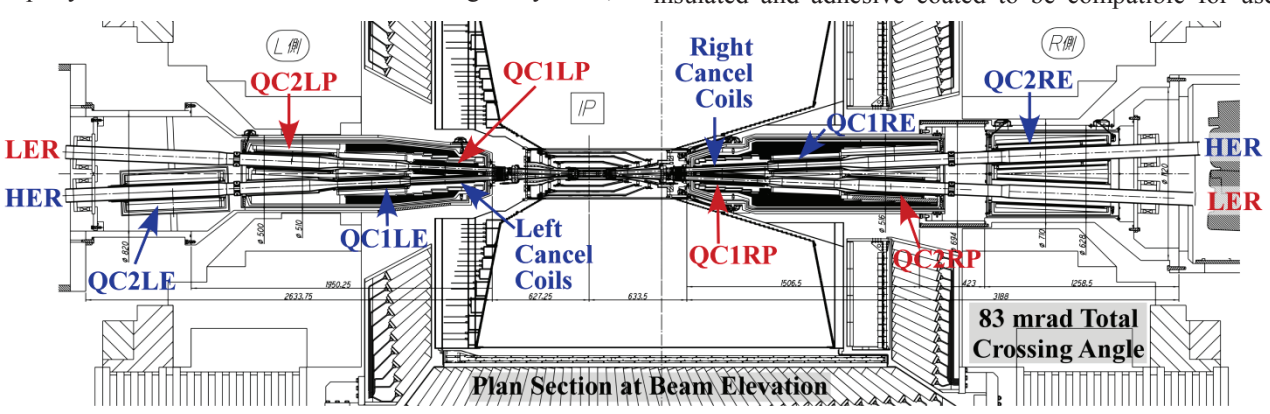

Figure 1:. SuperKEKB IR layout inside Belle-II with high energy, e^-, (HER) and low energy, e^+, (LER) rings indicated.

#parker@bnl.gov

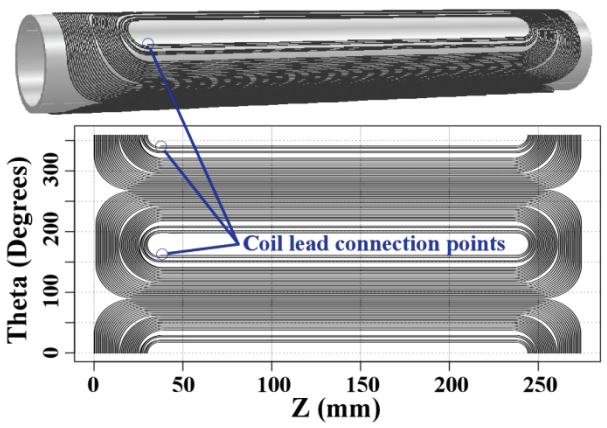

Figure 2: A planar pattern coil winding example, the single layer skew dipole pattern for QC1PL. Single layer planar coils have leads trapped at the poles.

with BNL Direct Wind ultrasonic bonding technology.

The innermost correction coils operate at elevated temperature, due to heat transfer from the warm beam tube (limited space for superinsulation) and all the coils operate in the presence of significant quadrupole and solenoidal background fields. The design maximum current for the corrector and cancel coil is 70 A to stay below 65% of critical current at a temperature of 5 K.

CORRECTION COIL DESIGN

The eight main IR quadrupoles listed in Table 1 come with different design parameters (coil radii, lengths and focusing strengths) but they all require skew and normal dipole, a_1 and b_1, skew quadrupole, a_2, and octupole, b_4, correction coil windings. The subscript *p* or *s* in Table 1 denotes whether the coil is a planar or a Serpentine style coil winding [7]. A typical planar winding is shown in Fig.2 and a Serpentine example in Fig.3. There is just enough radial space in most locations to fit, in ascending order, a two layer Serpentine octupole winding and three single planar layers consisting of a set of skew dipole, normal dipole and skew quadrupole windings.

With the Serpentine style octupole we avoid having many inter-subcoil conductor splices by winding a

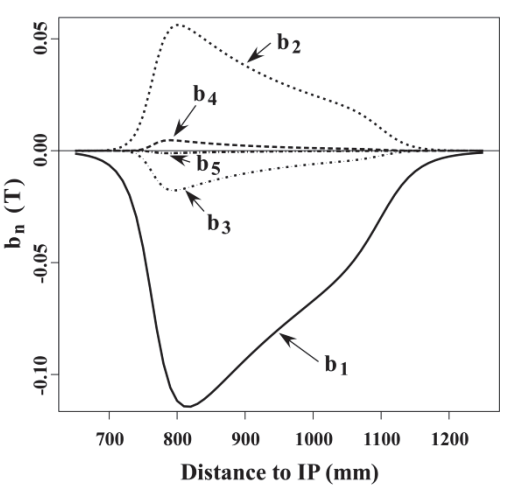

Figure 4: Harmonic content of the QC1P external field.

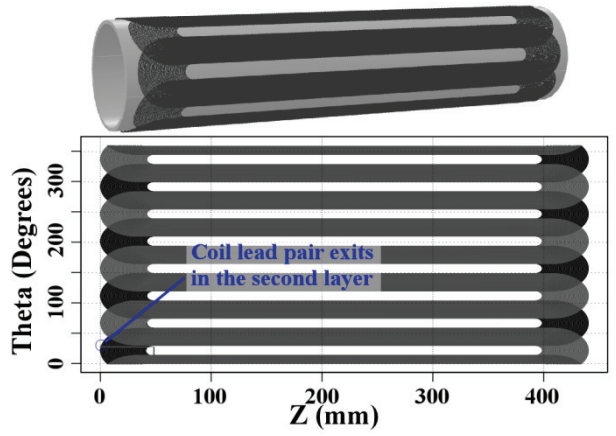

Figure 3: A Serpentine style coil winding example, the dual layer octupole pattern for QC2EL. Here the coil is wound using a continuous length of wire and the lead pair exits via an open ended pole in the second layer.

continuous length of conductor and then bringing a single lead pair out via an open pole end in the second layer. There is not adequate radial space for all correctors to be dual layer Serpentine patterns, so we must take care to manage the lead connections for the three planar coils. We wind the skew quadrupole coil last because the dipole and skew dipole lead connections line up at the same angular location as the skew quadrupole poles. We must also introduce a small midplane gap in the dipole coil pattern to access the skew dipole leads. All these planar pattern leads are then routed outside of the coil package.

Because these correctors are located at the largest-beta (Twiss function) peaks in the lattice optics, we design the coils for good field quality. Their higher-order design harmonics are typically a few parts in 10^4 of their fundamental at 10 mm reference radius. Also at the QC1PL(R) locations we bring the leads to the IP side of the magnet (the same as is done for main quadrupoles) to have local field perturbations due to the leads occur where the beams are smaller and field errors have less impact.

QC1PL(R) also have the least inner radial space for correctors. So their octupole correctors are located on a tube just outside the main coil collars. Tracking studies show that beam lifetime suffers if the octupoles do not overlap the quadrupole magnetic lengths; otherwise we could have wound to the side of the QC1PL(R) main coils. Additional dipole integrated strength is needed for QC1EL(R) to handle the kick, due to the external dipole field dipole component shown in Fig.4, from the QC1PL(R) magnets. For QC1EL(R) we then use a two layer Serpentine winding for added dipole transfer function but then have just enough space for a single layer octupole Serpentine winding.

CANCEL COIL DESIGN

The linear, b_1, b_2, external field components from QC1PL(R) are included in the SuperKEKB IR optics baseline lattice. But the other non-linear external field components shown in Fig.4 would adversely impact the nearby e^--beam and are dealt with via four dedicated

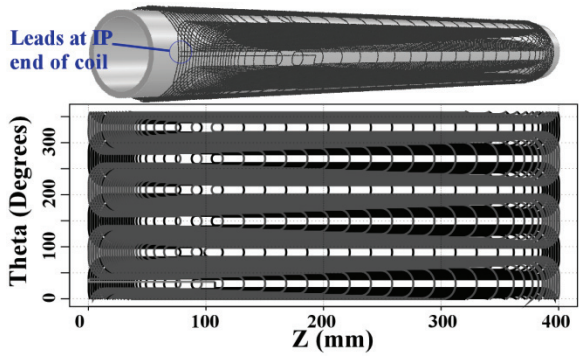

Figure 5: Example of lowest order, b_3, cancel coil pattern. The leads come out at the IP end of the magnet (same as for main coil). Non-lead end turn spacing is dramatically increased to make the sextupole gradient follow the desired cancel coil field fall-off profile.

cancel coil windings for b_3, b_4, b_5 and b_6. Tracking studies indicate that the non-linear fields need to be locally cancelled. The cancel coil fields are therefore tailored to follow the external field multipole distributions that drop in magnitude as the beam line separation increases with distance from the IP.

A representative cancel coil pattern is shown in Fig. 5. Like the corrector octupoles, we use dual layer Serpentine patterns for the cancel coils to avoid having numerous subcoil splices. But unlike the correction coils the cancel coils' lead and non-lead end turn spacing are quite different. In Fig.5 we see that the non-lead coil-end is "stretched out" and comprises most of the length of the magnet. This geometry effectively puts more straight section length near the cancel coils' lead ends and yields higher gradients closer to the IP with gradients falling off naturally with increasing distance to the IP.

Please note that both Serpentine layers in Fig.5 have their end turns at identical longitudinal positions. Independent optimization of end turn spacing in these two layers permits finer gradient distribution adjustments, but can lead to generating small localized skew multipole fields. During optimization the integral skew component field can be made zero, but it seems preferable to avoid generating any skew fields in the first place. With the cancel coils energized the calculated residual non-linear field excursions, expressed at 10 mm reference radius, are of the order of a couple of Gauss and any unwanted integrated multipole fields are tweaked to be very nearly zero. We note that the cancel coils themselves generate external fields that act back in the QC1PL(R) aperture. But we do have correction coils to compensate linear fields and the non-linear components from the cancel coils are fortunately small.

This completes a description of the baseline design; however, on-going Belle-II detector studies, that include the uncompensated b_1 external field component, exhibit increased particle loss in later IR magnets. In Fig.1 we see that the right side IR magnets protrude deeper into the Belle-II detector than on the left. So it should not be a surprise that background generated by particle loss on the right side is much more problematic than that from the left. We mitigate this background by adding tungsten and other shielding inside and outside the cryostats. But since detector space is quite precious and we should not block cables and other access to critical subsystems, some options for b_1 cancellation on the right side are presently under consideration that could be used to increase contingency for background reduction.

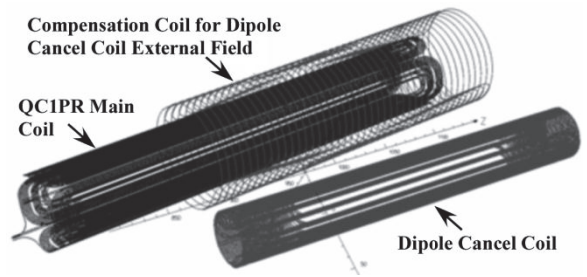

Figure 6: An integral field dipole cancel coil proposal.

True local cancellation of the b_1 external field component has been found difficult to achieve within the space available but an integral field cancel coil scheme, as shown in Fig.6, looks to be promising. Since the external field from a b_1 cancel coil falls of more gradually than from the b_3-b_6 coils discussed so far, care must be taken to avoid creating significant non-linear fields inside QC1PR. The main culprit here is the external b_3 component since we already have b_1, b_2 and b_4 adjustment knobs and higher order fields are sufficiently small.

The b_3 external field is addressed in this scheme via an additional dipole compensation coil located outside QC1PR (see Fig.6) that has a controlled admixture of higher dipole allowed, b_3, b_5, etc., harmonic terms. The procedure for generating the desired amount of b_3 (and higher odd multipole) compensation is straightforward since we do not look to add even, e.g. b_2 and b_4, harmonic terms. For this first design iteration the cancel dipole and compensation coil currents are very nearly identical and it should be possible to implement a cancel coil solution where these coils can be run in series to avoid need for any extra cryogenic system current-lead feedthroughs.

REFERENCES

[1] H. Koiso, "Colliders for B-Factories," Proceedings of IPAC2011, WEZA02, pp. 1931-1935.

[2] M. Tawada, et. al., "Design study of final focusing superconducting magnets for the SuperKEKB", Proceedings of IPAC11, WEPO027, pp,2457-2459

[3] T. Abe et al, arXiv:1011.03502, http://xxx.lanl.gov /abs/1011.0352

[4] H. Yamaoka, et al., "Solenoid field calculation of the SuperKEKB interaction region,". Contribution THPPD023, this conference.

[5] B. Parker, et al., "BNL Direct Wind Superconducting Magnets," contribution 4FO-6 to MT22, Marseille, France, September, 2011.

[6] Furukawa Electric Co., Ltd., Tokyo 100-8322, Japan.

[7] B. Parker and J. Escallier, "Serpentine Coil Topology for BNL Direct Wind Superconducting Magnets," PAC05, Knoxville, TN, May, 2009, pp. 737-739.