THE SUPERKEKB INTERACTION REGION CORRECTOR MAGNETS

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Abstract

The Interaction Region (IR) quadrupoles for the SuperKEKB luminosity upgrade at KEK have multiple superconducting correction coils that are needed to fulfill performance goals. These correctors were produced at BNL and undergo system tests and measurement at KEK before final installation of the completed systems in the IR hall. Here we report on measurement results.

INTRODUCTION

The SuperKEKB upgrade looks to achieve a forty-fold luminosity increase of the asymmetric e^+e^- B-factory KEKB [1]. The SuperKEKB IR uses new magnets, located in cryostats, that must conform to deep insertion from both sides into the upgraded Belle-II experimental detector [2]. The left side SuperKEKB cryostat in its cantilever support structure is shown in Fig 1. The SuperKEKB optics makes use of 43 IR corrector magnet coils integrated with the main magnets for precise field control and error compensation [3-5]. The layout of the coils in the left side cryostat structure is indicated in Fig. 2.

The corrector coils were wound on their support bobbins via the BNL Direct Wind technique [6]. Since corrector fields are much weaker than their associated main quadrupoles, corrector field quality has not been a major concern in the past; however, for SuperKEKB a localized field error excursion of more than a few tens of gauss can have a perceptible impact on luminosity lifetime. Thus special attention was given to corrector coil design and production.

During production a given correction coil's field quality, field angle and transfer function were measured warm via a rotating coil measurement system before and after critical manufacturing steps for quality assurance. The SuperKEKB physical magnet apertures differ depending upon distance from the IR point, and different warm measurement coil radii were used as appropriate.

Figure 1: SuperKEKB left side cryostat at KEK.

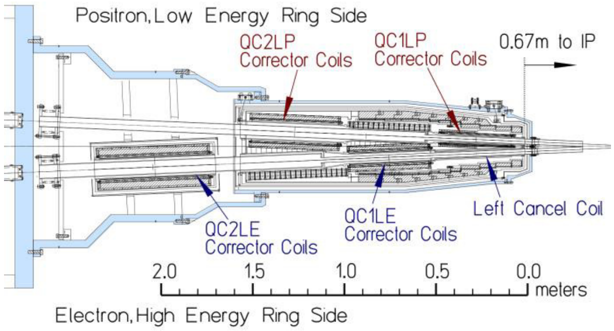

Figure 2: SuperKEKB left side cryostat plan view.

The corrector coils are constructed with 0.35 mm diameter wire and could only be safely excited warm to a small fraction of their nominal 60 A cold operating current. To compensate for background field, the coils were excited with both positive and negative current polarity and field harmonics were then extracted by fits to the slope with current. During production most coils exhibited field errors of at most a few units (1 unit = 10^{-4} error relative to corrector's design multipole) and were deemed acceptable for SuperKEKB use. In a few instances production issues arose where coils were removed and then rewound.

The most challenging field parameter to control was found to be the corrector field angle, which sometimes deviated by a few mrad from the desired value relative to fiducial features on the support bobbins. While the field angles varied by more than optimistic expectations set before the start of production, the final production results met SuperKEKB needs. The BNL warm measurements agree with the cold measurements performed later at KEK that are discussed in the next section.

INTEGRAL MEASURMENTS

When each set of correctors was completed by BNL, it was shipped to KEK for cold measurement in vertical dewars and each coil was run at full current to verify operation margin. At this point BNL coil production is completed, all correctors are measured cold and they meet SuperKEKB coil acceptance requirements.

Once the construction of the first IR cryostat assembly, (the left side one shown in Figs. 1 and 2), was completed final field measurements of the magnetic system were started. Long rotating coils are used to measure the integral harmonics and short rotating coils are used to perform step wise longitudinal, z-scans, of the field profile.

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Table 1: The KEK Measured Integral Harmonics for the QC1LE and QC2LE Correctors of the Left Side Cryostat

	QC1LE Integral Harmonics Measured at Rref = 10 mm								QC2LE Integral Harmonics Measured at Rref = 25 mm							
	b1 Corrector		a1 Corrector		a2 Corrector		b4 Corrector		b1 Corrector		a1 Corrector		a2 Corrector		b4 Corrector	
n	bn	an	bn	an	bn	an	bn	an	bn	an	bn	an	bn	an	bn	an
1	**10000**	0.00	0.00	**10000**	0.00	0.00	-74.10	59.40	**10000**	0.00	0.00	**10000**	0.00	0.00	-24.79	2.14
2	2.35	4.29	-2.35	-4.29	0.00	**10000**	54.70	182.00	5.02	10.22	-3.42	7.87	0.00	**10000**	8.35	20.29
3	-6.45	-0.29	-0.28	6.45	6.91	-5.94	0.00	0.00	-1.02	-1.05	-0.11	-0.29	-6.08	-3.41	0.00	0.00
4	-0.16	-0.43	-0.16	-0.43	-0.40	-1.30	**10000**	0.00	-0.98	0.27	-0.73	-0.24	-1.02	3.22	**10000**	0.00
5	-1.42	0.07	-0.07	-1.41	-0.16	0.21	12.54	4.74	-5.06	-0.84	0.56	4.64	0.43	-0.56	-8.86	-1.26
6	0.00	0.04	0.01	-0.04	-0.07	-0.96	-5.74	3.59	-0.15	0.37	-0.23	0.58	-0.33	-2.46	-1.60	-1.15
7	-0.03	-0.02	-0.02	0.03	-0.04	0.02	-0.28	1.33	-0.53	-0.33	-0.28	-0.53	-0.30	-0.54	-0.83	-0.20
8	0.01	0.00	0.01	0.00	0.01	-0.02	-3.65	-0.18	0.20	0.16	0.16	0.03	0.45	0.20	-7.59	-0.46
9	0.01	0.00	0.00	0.00	0.00	0.01	-0.89	0.33	-0.15	-0.04	-0.02	0.06	-0.19	0.08	-0.71	0.44
10	0.00	0.00	0.00	0.00	0.00	0.01	0.35	-0.85	0.04	0.00	-0.01	-0.03	0.10	-0.09	0.43	-0.95

The measured integral harmonics for two left side corrector assemblies, QC1LE and QC2LE, are given in Table 1. Since the correctors listed in Table 1 are surrounded by superconductor of a main quadrupole coil, care is taken to discriminate each coil's natural geometric harmonics from superconductor magnetization effects. An example of these measurement data are the QC2LE B1 corrector plots shown in Fig. 3. Harmonic data are taken over a range of currents extending through a full current loop cycle. Magnetization shows up as a spread in area between the up and down ramp sections of these excitation curves. The geometric harmonics are extracted from these data via the slopes of linear fits to these curves.

The measurements shown in Fig. 3 display minimal magnetization for the linear (a_1, b_1, $a_{2,}$ and b_2,) harmonics due to scale, but it can be seen clearly for the first allowed normal sextupole (b3) term. Other data, not shown in Fig. 3, extend up the 20-pole (n = 10) and in Table 1 we see that the high order geometric multipoles are quite small. The higher order harmonic data have correspondingly small magnetization and their geometric values are in line with the BNL warm harmonic measurements.

In Table 1 we find that for the linear correctors of both magnets (B1, A1 and A2) the harmonics higher than sextupole are less than about 5 units in magnitude. The two octupole (B4) correctors do have larger b_5 values of 12.5 and -8.9 units, which could be due to small errors during coil winding, but these harmonics are relative to the octupole correction strength. In the SuperKEKB optics the octupole correction strength is small and the octupole corrector harmonic errors are not significant in the overall combined field error budget.

The BNL field measurements used gravity sensors to relate the desired field direction to support bobbin fiducials. At KEK when the correctors are integrated with the main quadrupoles in the cryostat, the corrector field angles are again measured cold and referenced to the main quadrupole field direction. The warm to cold correlation is good with average difference of less than 0.5 mrad. The average deviation of the field angles from design in these two magnets is about 3 mrad with a total spread twice as large. Because SuperKEKB has available a complete set of linear correctors, it is possible to completely control the effective dipole and quadrupole correction roll angles and the measured roll errors for the linear correctors are acceptable. A 4.5 mrad roll angle determined for the two octupole correctors is tolerable due to the small octupole strength used for SuperKEKB operation.

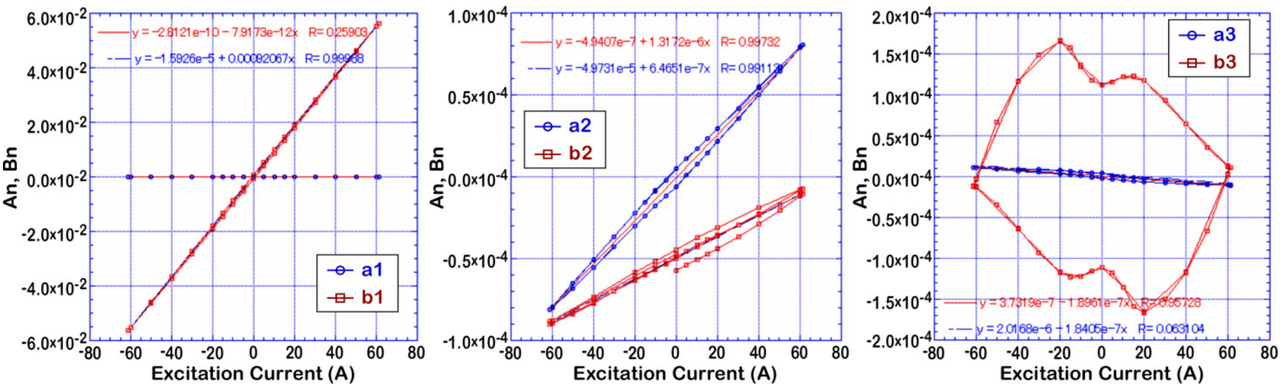

Figure 3: Excitation curves for the B1 corrector inside QC2LE measured cold at KEK.

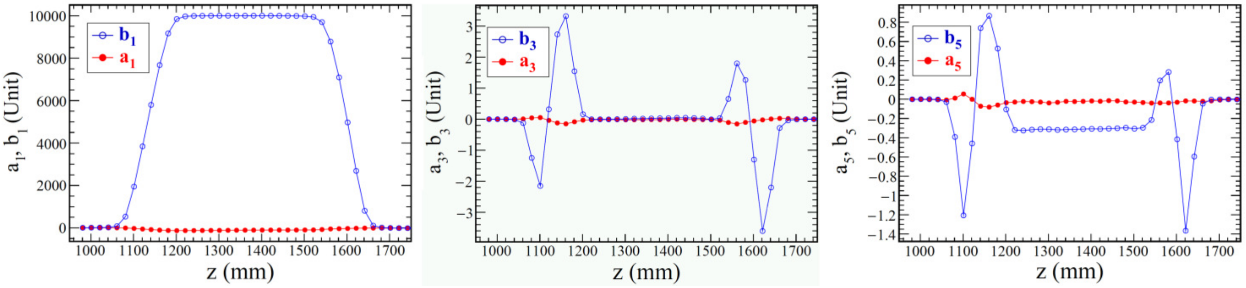

Figure 4: Axial profiles of various allowed terms in the B1 corrector inside QC2LE measured at KEK.

The correctors listed in Table 1 have iron yokes and their measured transfer functions are enhanced with respect to the BNL warm measurements and KEK cold vertical measurement values which both did not include yokes. The low order, B1 and A1 coil transfer functions are enhanced the most, while B4 values are unchanged and the A2 correctors' enhancements are in between; all this is consistent with computer magnetic field models.

Z-SCAN HARMONIC MEASUREMENTS

Z-scans of the field distribution, like those in Fig 4 for the QC2LE B1 corrector, were obtained using short rotating coil offset by different longitudinal increments. In the first plot the measured b_1 fundamental harmonic falls off smoothly at the coil ends. The next plots of the first two B1 allowed harmonics, b_3 and b_5, show small values in the body of the magnet and minimal field overshoot and undershoot in the transition region near the coil ends. This result is typical for all the main quadrupole correctors measured and the measured end field variations satisfy the SuperKEKB local field excursion limit requirements.

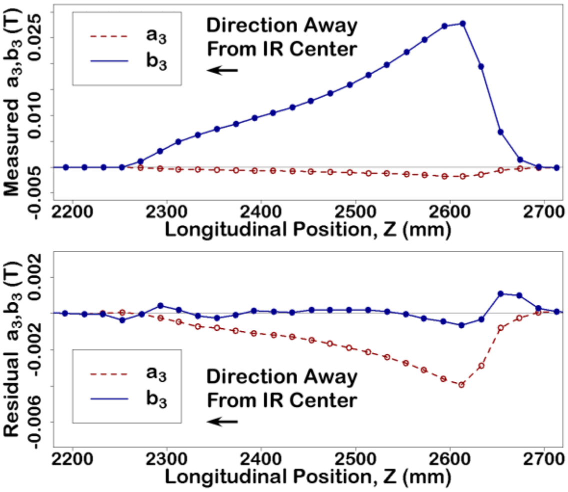

Figure 5: Left side B3 cancel coil z-scan field data.

A z-scan for a special corrector, an external field cancel coil, is shown in Fig 5. The first quadrupole on either side of the IR point has no flux return yoke and produces external field at the neighboring beam. The non-linear components of this external field are cancelled by a set of b_3, b_4, b_5 and b_6 cancel coil correctors. The local cancel coil field is tailored to fall off with distance from the IR point to match the drop in external field as the beamlines separate. The top plot in Fig. 5 shows the measured B3 cancel coil normal and skew profile data; these data are in close agreement with the coil's design calculations.

In the lower plot the main quadrupole coil is energized to generate an external field to cancel and the residual b_3, a_3, field profiles after cancellation are plotted. While the dominant b_3 external field component is well canceled, a small a_3 remains. The other b_4, b_5 and b_6, cancel coils exhibit the same normal versus skew field behavior. Since a small field angle offset can easily spoil the degree of skew field cancellation, the most likely explanation for the residual skew fields is due to the difficulty we had in setting the absolute roll angle of a coil during winding. Nevertheless, amongst all of the resulting skew fields, only the a_3 term plotted in Fig. 5 is large enough to be of any concern for the SuperKEKB optics. The a_3 deviation will be accounted for in optimizing the IR sextupole compensation using sextupole and skew-sextupole correctors at other IR magnet locations.

CONCLUSIONS

The SuperKEKB IR design optics utilizes many correction elements to reach its stated luminosity upgrade goals. All of these correctors are now produced and their performance verified at KEK by cold magnetic measurements in vertical dewars. The final integration of these corrector magnet packages with their associated main magnets in cryostats is nearing completion. Magnetic measurements performed of the first available cryostated system indicate that the challenging SuperKEKB requirements, that indeed go beyond what has been customary in past collider projects, have been satisfied.

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