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DITHER COILS FOR THE SUPERKEKB FAST COLLISION FEEDBACK SYSTEM*

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Abstract

The collision feedback system for the SuperKEKB electron-positron collider at KEK will employ a dither feedback with a roughly 100 Hz excitation frequency to generate a signal proportional to the offset of the two beams. The excitation will be provided by a local bump across the interaction point (IP) that is generated by a set of eight air-core solid-wire magnet coil assemblies, each of which provides a horizontal and/or vertical deflection of the beam, to be installed around the vacuum system of the SuperKEKB Low Energy Ring. The design of the coils was challenging as large antechambers had to be accommodated and a 0.1% relative field uniformity across a good-field region of Âś1 cm was aimed for, while keeping reasonable dimensions of the coils. This led to non-symmetric, non-flat designs of the coils. The paper describes the magnetic design and the method used to calculate the magnetic field of the coils, the mechanical design and the field measurement results. Tracking in the lattice model has indicated acceptable performance.

INTRODUCTION

The SuperKEKB asymmetric e^+e^- collider [1] will employ a fast dither feedback scheme similar to the one developed for PEP-II [2,3] to maintain collision between the two beams. [4] "Dither coils" are air-core magnet coils used to wiggle one of the two beams across the collision point by a small distance at a frequency near 100 Hz. Any offset between the two beams reveals itself in a modulation of the luminosity signal with the dither frequency. The coils are mounted around the vacuum chamber near the interaction point. Each coil assembly is to provide both horizontal and vertical deflection. In SuperKEKB, there are 8 coil assemblies to be able to independently vary the beam coordinates at the interaction point (IP) independently in position and angle in both directions while keeping the orbit change localized and correct for any coupling. The parameters of the coils are given in Table 1.

The coils will be mounted onto the vacuum chamber. The vertically deflecting coils have to go around the antechamber of the vacuum system. If flat rectangular coils were to be used, this would lead to very large coils with a large gap in between; inefficient magnetically and requiring a large support structure, and causing significant stray field. In order to keep the coils compact, a wrap-around design was adopted that brings the conductor relatively close to the vacuum chamber. Figure 1 shows the two different chamber cross sections that were accommodated and the schematic shape of the coils. Three different coil shapes had to be wound: a common shape for the horizontal deflectors and a narrow and a wide shape for the vertical deflectors depending on the chamber they are to be placed around.

Table 1: Design Parameters of the Coils

Parameter	Unit	Value
Overall Length	cm	25
Aperture radius	cm	5.24
Wire diameter	mm	1.291 (#16 AWG)
# of turns per coil		39
Coil cross section (h×v)	mm^2	19×3.8
Resistance/coil (vert. field, 20°C)	Ω	0.36
Resistance/coil* (horiz. field, small, 20°C)	Ω	0.40
Coil resistance* (horiz. field, large, 20°C)	Ω	0.53
Coil inductance (approx.)	mH	1…2
Field integral* (horizontal)	Tm	4.51×10^{-4}
Field integral* (vertical)	Tm	5.92×10^{-4}
Good-field region	cm	1
Field uniformity (rel.)	1	$\pm 1 \times 10^{-3}$

*: Measured parameter

COIL MODELLING AND DESIGN

The magnetic design of the coils was done in *Maple*®. [5] We use equations (4), (5) and (6) given by Misakian [6] for the field of a flat, rectangular coil with vanishing wire size. The complex shape of each coil is modeled as a sum of flat rectangular subcoils in the proper orientation with respect to each other. This required us to be able, programmatically, to rotate and translate the subcoils in space thus building a whole coil assembly from the individual pieces. Maple's "Record" data structure allows one to do this by defining a general prototype (which knows about its orientation in space) and creating and translating/rotating/reflecting each instance until the assembly model is complete. Each horizontal-field coil is modeled as three subcoils; the field at each point in space is then the sum of the contributions from each individual subcoil per coil and the two coils making

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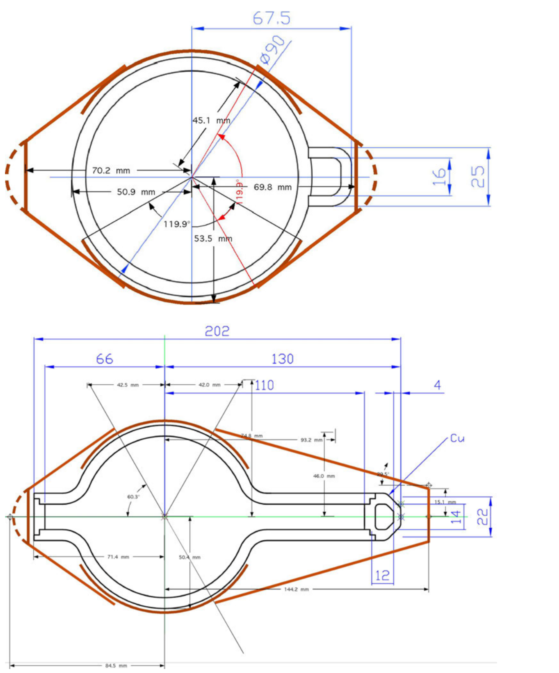

Figure 1: Top frame: Cross section of the small coil; bottom frame: Cross section of the large coil.

up the deflector in one direction. The finite width of the coil pack is modeled by overlaying subcoils for the inner, center and outer dimension of the coil. It was found empirically that the thickness of the coil did not affect the result in an appreciable way, due to the rather flat geometry of the coil. Figure 2 shows the modeled field of the smaller of the two assembly types. The field on the beam axis is dominated by the conductor parallel to the beam; the details of the shape on the return leg around the cooling channels or the antechamber has no appreciable effect on the calculated field shape. The vertical-field coils were modelled in 11 segments closely approximating the saddle-shape of the winding.

For a rectangular, symmetric Helmholtz coil pair the best field uniformity is achieved when the subtended angle of

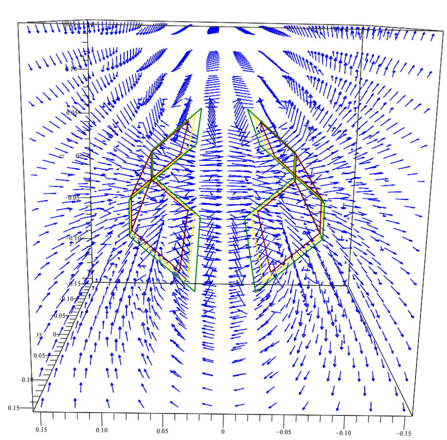

Figure 2: Field plot of the symmetric coil

each coil as seen from the center is 120°. For the finite width of our coils this is not quite the case. In order to optimize the field uniformity the model was parametrized in terms of this angle to allow easy variation and optimizing the coil with one parameter only. The signature for the optimum was near zero curvature of the field *vs* both horizontal and vertical coordinates. Expressed in field harmonics this corresponded to minimizing the sextupolar component. For the large asymmetric coil a second step to cancel any gradient was undertaken by only varying the subtended angle of the larger coil.

MECHANICAL DESIGN

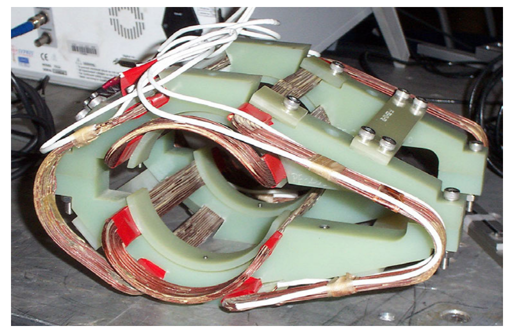

Figure 3: Completed assembly of the large coil.

The coils are wound to shape on a mandrel using enameled #16 (AWG) wire and stabilized with epoxy ("wet layup"). They are supported by two G10 frames, which also ensure the shape is as intended and provide keying surfaces for the individual coils. The frames are connected by two tie plates; one of them providing a convenient place for a terminal strip. The whole assembly splits in two halves plus the vertical deflector coils for relatively easy assembly around the extant vacuum system. The horizontally deflecting coil is held in place by two half-cylindrical G-10 pieces that also provide the interface to the chamber. The vertically deflecting coils are held in place by “coil dogs,” small G-10 pieces screwed in place with M6 screws. All threads in the G-10 material are reinforced with threaded steel inserts. Figure 3 shows a completed large coil assembly.

COIL PERFORMANCE

A rotating coil was used to measure the integral field harmonics including the first (dipole) harmonic. Due to the relatively low field and absence of iron, care had to be taken to avoid the earth magnetic field spoiling the result. The *BL/I* value is within less than 1% of the designed value for the horizontal field (vertical deflection) while exceeding the design value by about 10% for the vertical field (horizontal deflector). The field uniformity measurements initially indicated significantly worse uniformity than designed. The cause for this was traced in some instances to the coils being able to slide along their wide direction by more than 1 mm. This was mitigated by tying the coils together with Nylon ties such that they are forced to sit tight against the defining

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surfaces of the G-10 frame. For some of the coils, shims were inserted between the G-10 frame and the wide coil side to improve the field uniformity. Figure 4 shows a typical result for one of the coil assemblies. It is noted that the residual gradient of the asymmetric coils does not significantly differ from that of the symmetric coils.

Beam performance has been studied with the measured higher multipoles of the dither coils using the SAD code. No horizontal nor vertical emittance growth with the orbit bumps created by the dither coils was observed. Also tracking shows that there is no effect on the dynamic aperture with the orbit bumps.

The vacuum chamber induces a delay in the field penetration which is dependent on the resistivity of the material and the thickness. Figure 5 shows the results of calculations and measurements for 6 mm thick copper and stainless steel

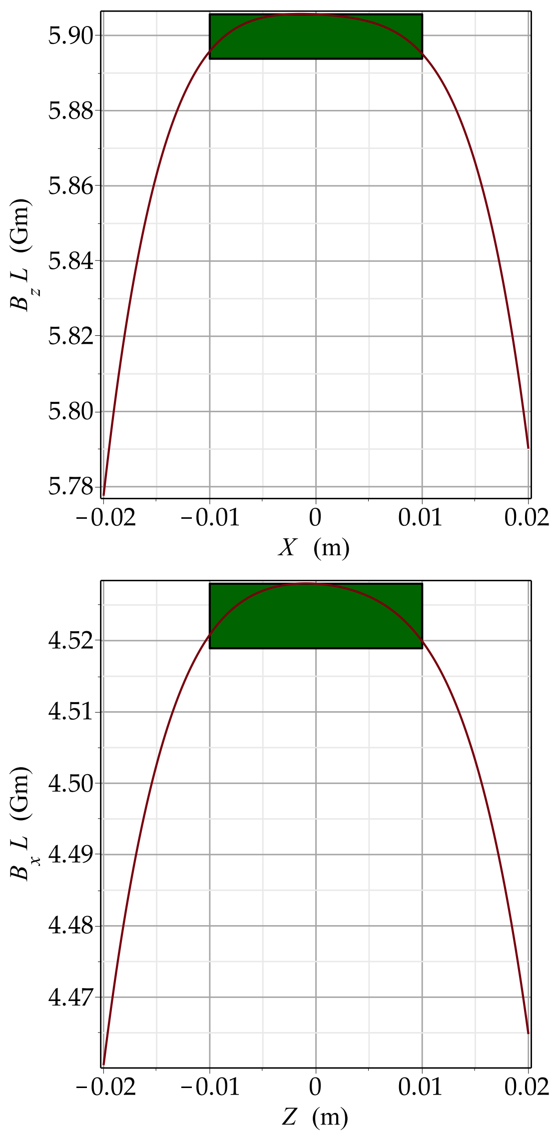

Figure 4: Top frame: Vertical field *vs.* horizontal coordinate. Bottom frame: Horizontal field *vs.* vertical coordinate. The box represents ±0.1% tolerance over ±1 cm

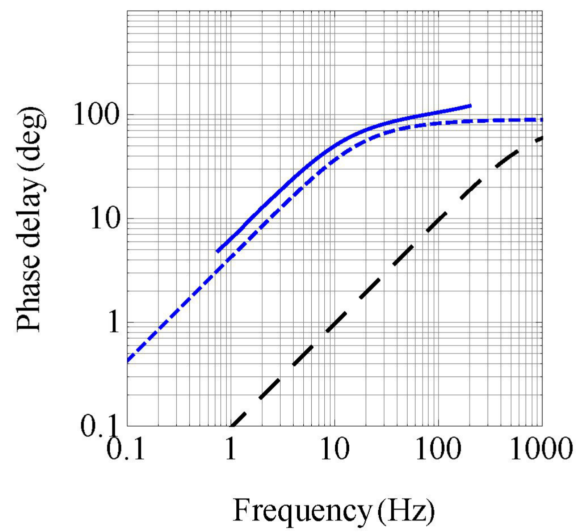

Figure 5: Phase shift *vs* frequency due to the vacuum chamber. Blue lines are calculations (solid line) and measurements (dashed line) for copper chamber; the black dashed line of the calculation for a stainless steel chamber. Wall thickness is 6 mm in all cases.

pipes. Even in case of stainless there is about 10° phase shift, which is significant and needs to be taken into account in the feedback system. The effect on the field uniformity is small for round pipes.

CONCLUSION

The coils performed within the requirements and will be installed in SuperKEKB soon. The project validated the wrap-round design of the coils to accommodate antechambers without unduly large coil sizes. It further demonstrated the ability to design coils with 10^{-3} tolerances using what are in essence analytic methods.

The *Maple*® classes implementing the rectangular coil and its transformations are available from the author.

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