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# THREE DIMENSIONAL FIELD ANALYSIS FOR FINAL FOCUS MAGNET SYSTEM AT SUPERKEKB

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*Abstract*

A final focus magnet system of SuperKEKB consists of 4-superconducting (SC) quadrupole doublets, 43 SC-correctors, 4 SC-compensation solenoids. They are aligned in a detector (Belle-II) solenoid which generates a longitudinal field of 1.5 T. These magnetic components are separately designed and the beam optics simulation has been performed with the linear-superposed-magnetic-field maps. Here, we combined these components into a magnetic-field-analysis model by using Opera3D/TOSCA and preliminary results of the field analysis are shown.

## INTRODUCTION

SuperKEKB is an upgrade project of KEKB and is a $e^+/e^-$ high energy collider for $B$-meson production. It increases the luminosity based on "nano-beam scheme" aiming at a target luminosity of $8\times 10^{35}$ $\mathrm{cm^{-2}\cdot s^{-1}}$ which is 40 times larger than KEKB [1]. In the SuperKEKB, one of the key components is the final focus magnet system (QCS); it squeezes the beam size into ~50 nm vertically at the $e^+/e^-$ colliding point (IP). The QCS consists of 8 superconducting (SC) quadrupole magnets, 35 SC-corrector coils and 8 SC-cancel coils and 4 SC-compensation solenoids.The quadrupole magnets are separately aligned on positron and electron beamlines in doublet configurations. The QCS is located in the detector solenoid of Belle-II.

These magnets have been independently designed and beam simulation has been done with linear-superposed field map of these magnets. However, since the main quadrupoles have ferromagnetic yokes or shields, they cannot be combined as linear superposition. To check how much the non-linear property affects the beam dynamics, a three dimensional analysis in which these components are integrated has been performed. We use Opera3D/TOSCA as three dimensional analysis code [2].

## THREE DIMENSIONAL MODEL FOR COMPONENTS

A schematic drawing of the QCS and Belle-detector solenoid is shown in Fig. 1; this is a cross section on a horizontal plane at the cylindrical axis of the detector solenoid. The blue and red dot-dashed lines are the electron and positron beamline, respectively. Here, electron and positron beamline are named HER and LER beamline.

The IP is located 470 mm shifted left from the center of detector solenoid in Fig. 1. The hatched regions indicate material of iron or permendur. Here, we denote QCS components on left side of IP as "QCS-L" and "QCS-R" on the right side in Fig. 1.

The IR system can be separated into four components, the detector solenoid, quadrupole magnets, corrector and cancel coils, and compensation solenoids, the models of these components will be described bellow.

### *Detector Solenoid*

The detector solenoid consists of an iron yoke and a superconducting solenoid [3]. It generates a uniform magnetic field of 1.5 T at the center of the solenoid. The superconducting solenoid is shifted by 38 mm from the center of the detector solenoid toward right side along the solenoid axis. In the 3D model, the yoke is modeled in cylindrical symmetry.

### *Quadrupole Magnets*

The quadrupoles are designed with $\cos 2\theta$ winding. Rutherford cable is wound in double-pancake form in two layers. In the 3D model, the cables are defined as line conductors. The quadrupole magnet parameters are given in this reference [4].

The quadrupole magnets except for the QC1LP/RP have yokes which cover main quadrupole magnets and shields which cover the beamline to suppress the leak field from the nearby main magnets. The dimensions of the parts are shown in Fig. 2. In the upper (lower) figure, the horizontal cross section of the yokes and the shields of QCS-L(-R) are shown. Hatched and shaded areas indicate materials of permendur and iron, respectively.

The quadrupole magnets are aligned at offset position with respect to beam line [4]. These offsets are considered in this 3D model. The offset breaks vertical symmetry.

### *Corrector and Cancel Coils*

The corrector coils generate multipole components to correct error field from main quadrupole coils. On the other hand, cancel coils compensate the external field leaking from the first LER quadrupoles, QC1LP/RP, into the HER aperture. These coils are wound on support bobbins using 0.35 mm diameter, single-strand superconducting wire [5]. In this model, the wires are defined as line current conductors. The winding pattern is same as the real coils.

### *Compensation Solenoids*

The four compensation solenoids generate magnetic fields directed to the cylindrical axis of the detector solenoid. The compensation solenoids are adjusted so that

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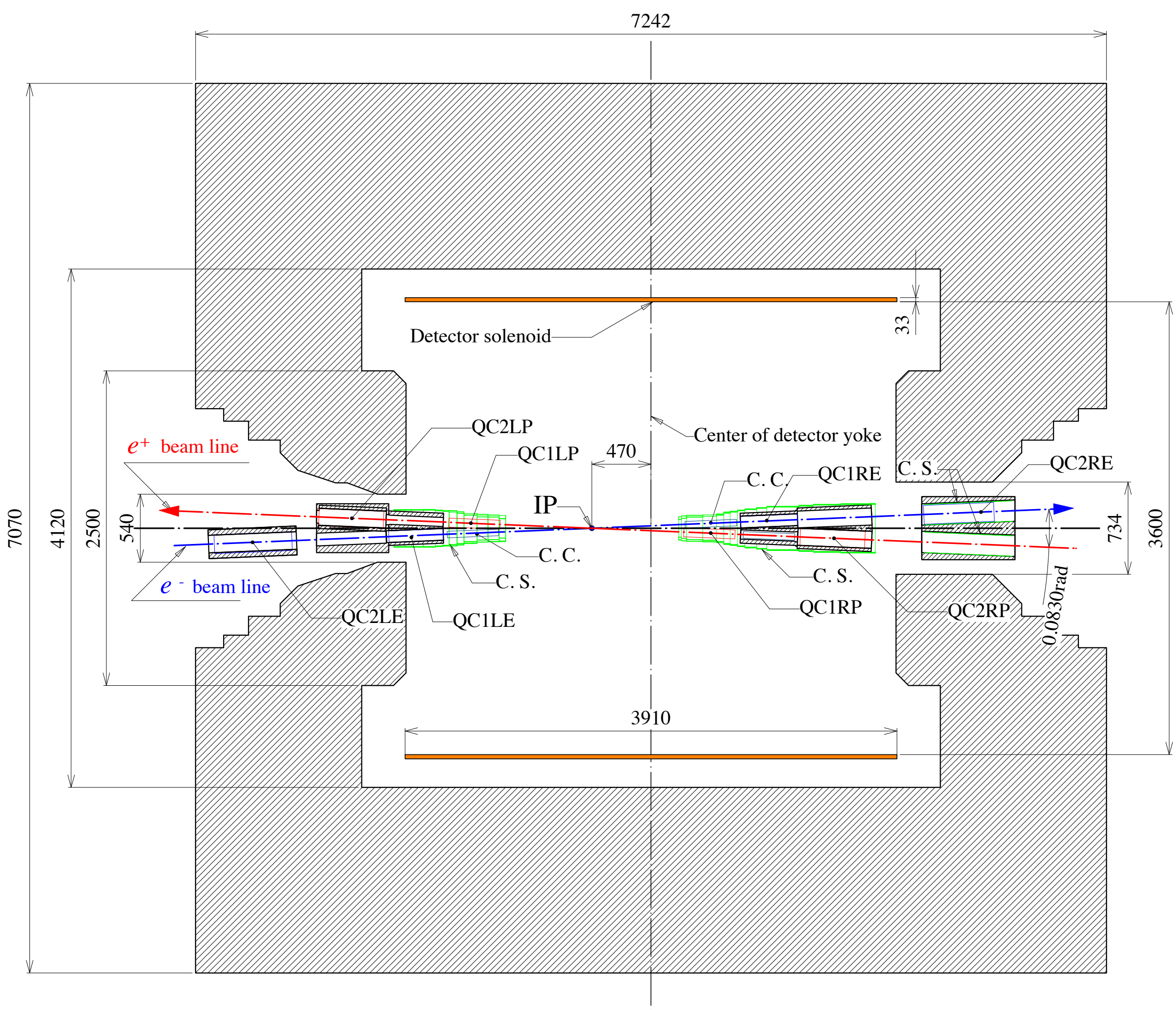


Figure 1: Entire layout of the interaction region with the QCS (plan view). Hatched area indicates material made of iron or permendur. Here C.S. and C.C. indicate a compensation solenoid and a cancel coil, respectively

the integral superposed field with the detector solenoid is zero by using ANSYS [6]. Two solenoids cover QC1LP, QC1LE and QC2LP and QC1RP, QC1RE, and QC2RP. They are aligned on the same axis of the detector solenoid. The other two solenoids are located inside yoke and shield of QC2RE magnet and they compensate the solenoid field between QC2RP and QC2RE. The parameters of the compensation solenoids slightly modified from [6] because the end-cap shape of the detector yoke was changed.

## FULL MODEL CALCULATION

To perform the full model calculation, calculation time constrains calculation accuracy; the full model consists of the detector solenoid, the compensation solenoids, the yokes and the shields of the quadrupoles, and the corrector and the cancel coils. Usually, calculation volume can be reduced by using symmetric geometry, but there is no symmetry in this model so it cannot decrease calculation volume. To save calculation time, we produced a model which consists of a full size of the detector solenoid and the QCS-

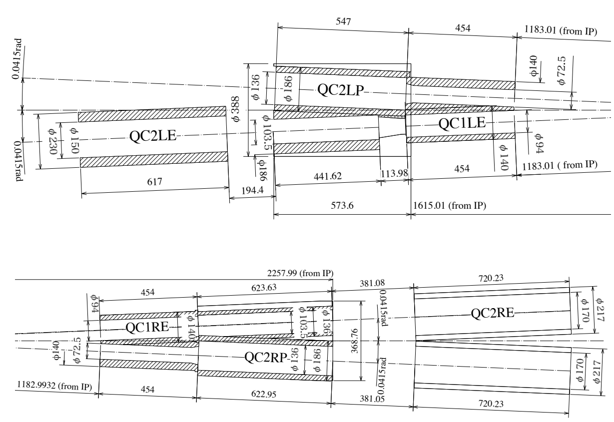


Figure 2: The yokes and the shields of QCS-L (upper) and QCS-R (lower). Shaded area: iron. Hatched area: permendur.

L. In the QCS-L, the QC1LE magnet is introduced. The QCS-R and -L are placed at some distance, so the magnetic

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coupling between them is so small that they can be linear superimposed.

As a first step, we performed the field analysis with three models as follows.

- Model A: The detector solenoid, the compensation solenoids and magnetic components in the QCS-L and the QC1LE quadrupole magnet integrated.
- Model B: The detector solenoid and the compensation solenoids and magnetic components in the QCS-L integrated.
- Model C: Only QC1LE quadrupole (calculated based on Biot-Savort low)

The calculation conditions are shown in Table 1. The three dimensional view of the model A is shown in Fig. 3; the model is cut away in the horizontal plane. Model-A is compared to a superposition of magnetic field by the modeles-B and -C. Fig. 4 shows calculated multipole fields as a function of distance from the IP on the HER axis. Multipole fields are calculated at a reference radius of 1.5 cm. In the model-C, the current of the QC1LE was scaled so that the $B_1$ component is the same as model-A. Solid and dashed curves indicate normal and skew components of multipole-expansion coefficients, respectively. Blue and red lines are calculated results for the model-A and model-B+C, respectively. Figs. 4-(a),-(b),-(c), and -(d) show the field profiles of dipole, quadrupole, sextupole, and octupole, respectively. A large difference is not found in these profiles, while the normal octupole component exhibits a few tens of a Gauss difference between the two models. The cause of this difference is not clear, so it is needed more investigation.

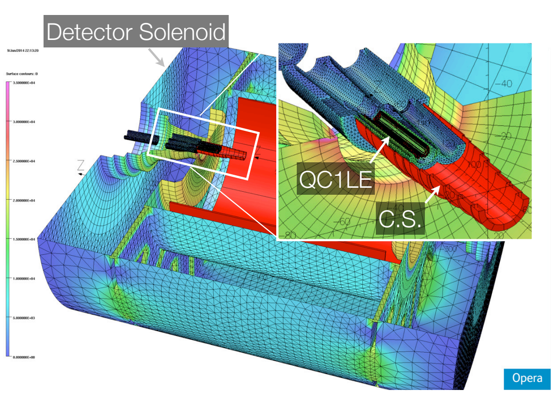


Figure 3: Three dimensional model of the detector solenoid and QCS-L (modeled by Opera3D).

## SUMMARY

A three dimensional model of QCS with the detector solenoid was developed. The calculation of QCS-L was performed including the QC1LE main quadrupole. In comparison between the model-A and the model-B+C, the multipole profile exhibits some difference in the skew octupole profile. In the next step, field analysis with the other main magnets, correctors, cancel coils will be performed. Since these calculation results will be used for beam optics simulation, mesh size should be smaller.

Table 1: Calculation Conditions

| | |
|---|---|
| Mesh size of QCS-L yoke/shield | 1 cm |
| Mesh size of Detector yoke | 10-20 cm |
| Number of nodes | 11179811 |
| Number of elements | 7785283 |
| Tolerance | $1 \times 10^{-3}$ |
| Calculation time | 21 hr |
| CPU | X5687 |
| Clock | 3.6 GHz |
| Number of cores | 4 |
| Number of Processors | 8 |

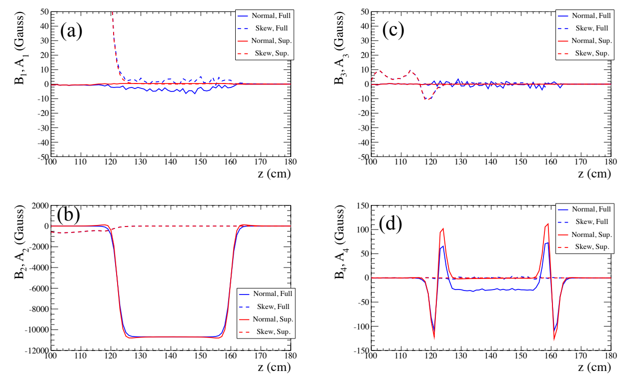


Figure 4: Calculated profile of multipole components on three dimensional analysis. (a) Dipole components, (b) quadrupole components, (c) sextupole components, and (d) octupole components. Horizontal axis is distance from IP along HER axis.

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