# MAGNETIC MEASUREMENT FOR SUPERCONDUCTING-QUADRUPOLE MAGNETS OF FINAL-FOCUS SYSTEM FOR SuperKEKB

Y. Arimoto*, X. Wang, Z. Zong, K. Tsuchiya, M. Iwasaki, H. Yamaoka, and N. Ohuchi,
High Energy Accelerator Research Organization (KEK), Tsukuba, Japan

*Abstract*

SuperKEKB is an upgrade project of KEKB to increase its luminosity to 8 x $10^{35}$ $cm^{-2}$ $s^{-1}$ based on the nano-beam scheme. In SuperKEKB, one of a key element is a final-focus system; it reduces $e^-/e^+$ beam size to 50 nm in vertical and 10 $\mu$m in horizontal direction at an interaction point (IP). The system consists of eight superconducting quadrupole magnets and four quadrupoles are aligned on the each beam line. The quadrupole, QC1P(QC1E), which is located at the closest position to the IP on the $e^+$($e^-$) beam line, generates a field gradient of about 70 T/m. An inner diameter of coil and a magnetic length for QC1P(QC1E) are 25(33) mm and 334(373) mm, respectively. The production of all quadrupole magnets are completed. To confirm their field qualities, we performed magnetic measurement for each magnet in advance to be integrated into cryostats on the beam lines. In the measurement, the quadrupoles were cooled down to 4.2 K in a test vertical cryostat and magnetic field were measured with harmonic coils. The amplitudes of higher order harmonics for all magnets met requirements from beam optics design. In this paper we describe the measurement results.

## INTRODUCTION

SuperKEKB is a high energy collider under construction at High Energy Accelerator Research Organization (KEK) [1]. The accelerator consist of two ring, they storage a 7 GeV electron ($e^-$) beam and a 4 GeV positron ($e^+$) beam and the two beams collide in a particle detector (Belle-II) region at a high luminosity of $8\times10^{35}$ $cm^{-2}\cdot s^{-1}$. This luminosity is 40 times higher than KEKB which was operated to 2010.

The one of a key component which is necessary to achieve the luminosity is a final focus quadrupole magnets system (QCS). The QCS consists of eight-superconducting-quadrupole magnets [2] and each quadrupole magnets have corrector coils [3, 4]. The QCS is located in the Belle-II solenoid which generates uniform magnetic field of 1.5 T. To compensate the field, four superconducting solenoids are installed.

A schematic layout of the QCS is shown in Fig 1. In this figure, blue (red) arrows which direct from left to right (right to left) indicate $e^-$ ($e^+$) beam line and the two beam lines are crossing at angle of 83 mrad. On the $e^-$ beam line, QC1LE(/RE) and QC2LE(/RE) are aligned on the left (right) side of an interaction point (IP) viewing from the center of the accelerator ring. On the other line, QC1LP(/RP) and QC2LP(/RP) are aligned in the same way. The quadrupole magnets are separately installed into two horizontal cryostats which are located on a left and right side of the IP. We call QCS-L(-R) which is a set of four quadrupole magnets at the left (right) side of the IP.

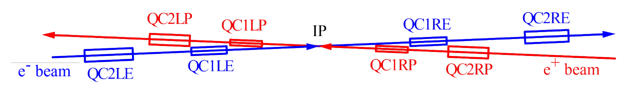


Figure 1: The schematic layout of the superconducting magnets at the interaction region (top view). Blue arrows from left to right is $e^-$ beam line and $e^+$ beam line is shown as opposite-directed red-arrows. The IP is a colliding point.

The production of the quadrupole magnets was started on June 2013 and completed on May 2015. We performed magnetic measurements for the quadrupole magnets with a test vertical cryostat before assembling into the horizontal cryostats.

## APPARATUS

### *Quadrupole Magnets*

The quadrupole magnets are superconducting magnets; the coil design is based on a set of cos $2\theta$ windings with NbTi/Cu Rutherford type cable. They are clamped by stainless steel collars which are surrounded by yoke except for QC1LP/RP. The all of four-quadrupole magnets of the QCS-L/R have different geometry. The QCS-R consists of the same four quadrupole magnets as the QCS-L except for QC2RE which has different length from QC2LE. The main parameters are listed in Table 1. In this table, QC1P, QC1E, and QC2P are QC1LP/RP, QC1LE/RE, and QC2LP/RP, respectively. Here, I.D./O.D., $G$, $GL$, $I_{des.}$ and $R_{Ref}$ are an inner diameter/outer diameter of cross section of coil conductor, a field gradient, an integrated-field gradient, a design coil current and a reference radius, respectively, and "Perm." indicates the yoke is made of permendur. Detail parameters are described in references [2, 5, 6].

### *Cryostat*

In the magnetic measurement, we used a vertical cryostat [7]. The cryostat has a liquid helium (LHe) vessel which is surrounded by thermal radiation shield of liquid nitrogen ($LN_2$). The $LN_2$ shield is separated by vacuum layer from LHe vessel and atmosphere. The LHe vessel is 0.5 m in inner diameter and is 2 m in depth. Excitation current is provided via current leads equipped on a top flange through

* yasushi.arimoto@kek.jp


ISBN 978-3-95450-147-2

Table 1: Main Parameters of Quadrupole Magnets [2]

| | QC1P | QC1E | QC2P | QC2LE/RE |
|---|---|---|---|---|
| I.D. | 25.0 | 33.0 | 53.8 | 59.3 |
| O.D. | 35.5 | 70.0 | 93.0 | 115.0 |
| $G$ | 76.4 | 91.6 | 32.0 | 36.4/40.9 |
| $GL$ | 25.5 | 34.2 | 13.1 | 19.5/16.5 |
| $I_{\mathrm{des.}}$ | 1800 | 2000 | 1000 | 1250/1350 |
| $R_{\mathrm{ref}}$ | 10 | 15 | 30 | 35 |
| Yoke | - | Perm. | Perm. | Iron |

radiation baffles. The current leads are cooled by evaporated-helium-gas flow to reduce heat leak. LHe is transferred from a LHe dewer from the top flange. A magnet is installed in the LHe vessel and it is immersed in LHe at temperature of 4.2 K.

At the center axis of the cryostat, a double layer pipe is equipped; this is used as a guide pipe for a harmonic coil.

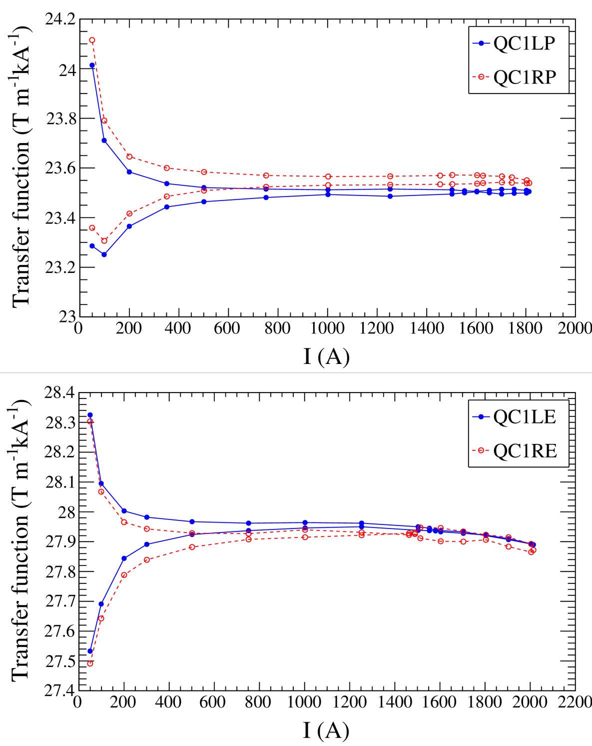


Figure 2: Transfer functions of quadrupole term at different current level in steady-state. Top: QC1LP (closed circles with solid line) and QC1RP (open circles with dashed line). Bottom: QC1LE (closed circles with solid line) and QC1RE (open circles with dashed line).

### *Harmonic Coils*

We measured the magnetic field with harmonic coils. We use two set of harmonic coils, they are different in coil radii ($r$ = 12mm and $r$ = 20 mm); we used the smaller radius system for measurements of QC1s and are used the larger one for QC2s [7]. A set consists of short-length (20 mm) windings and long-length (600 mm) windings; the all windings are placed inside precisely machined grooves on the insulating cylinder which is made of glass reinforced epoxy, G10. The short and long windings are used for measurements of the field profile and the integral field, respectively. Both of the windings consist of a tangential winding (T), three dipole windings (D0, D1, D2) and three quadrupole windings (Q0, Q1, Q2). The D0 and Q0 are used for analog bucking of T to eliminate large dipole and quadrupole components. A pair of the Q1 and the Q2 are used for digital bucking. The D1 is used for the center-offset correction of quadrupole field. The D2 was not used in this measurement.

The short and long type windings are connected to a same shaft made of G10 and rotated by an AC motor at rotation frequency of 0.21 Hz. The relative angle is obtained from a rotary encoder attached at an end of the shaft. Electric leads from these coils are connected to integrators (PDI 5025: Metrolab co.) through a mercury rotary connector. Encoder signal is declined to $2^7$ per one rotation cycle and goes to trigger inputs of the integrators.

## MEASUREMENT RESULTS

### *Integral Fields*

Integral fields were obtained by the long-length windings. Magnetization hysteresis of the integral fields was measured for all quadrupole magnets. In this measurement, excitation current is ramped up from zero to the design current shown in Table 1 and is ramped down to zero in step wise. Measured transfer functions of quadrupole terms for QC1LP/RP and QC1LE/RE are plotted in Fig. 2; the transfer function is a field gradient divided by the excitation current. These magnets show small hysteresis (0.1~0.2%) at current range of 500 to 1500 A; these hysteresis are caused by persistent current in superconducting wire. For QC1LE/RE at higher current of more than 1500 A the transfer function is slightly decreasing, and this is caused by a saturation of the permendur yoke. Since QC1LP/RP has no yoke, the transfer functions do not decrease even at the design current of 1800 A.

The measured-integral-field gradient are shown in Table 2 comparing with design values. In the gradients of QC1LP and QC1RP which have no yoke, the difference from design value was smaller than 0.5%. On the other hand, the other magnet which have yoke outside shows more than 1% different. However we can accept these differences because we can achieve the design gradients by adjusting excitation current.

Table 2: Integral Field Gradients

| Magnet | $I_{\mathrm{op}}$ [A] | $GL_{\mathrm{d}}$ [T] | $GL_{\mathrm{m}}$ [T] | Ratio [%] |
|---|---|---|---|---|
| QC1LP | 1624.9 | 23.00 | 22.91 | -0.4 |
| QC1LE | 1577.1 | 26.94 | 26.44 | -1.9 |
| QC2LP | 877.4 | 11.50 | 11.39 | -1.0 |
| QC2LE | 976.95 | 15.27 | 14.83 | -2.9 |
| QC1RP | 1623.9 | 22.98 | 22.96 | -0.1 |
| QC1RE | 1548.2 | 26.45 | 25.64 | -3.1 |
| QC2RP | 882.1 | 11.56 | 11.48 | -0.7 |
| QC2RE | 1068.5 | 8.606 | 8.685 | 0.9 |

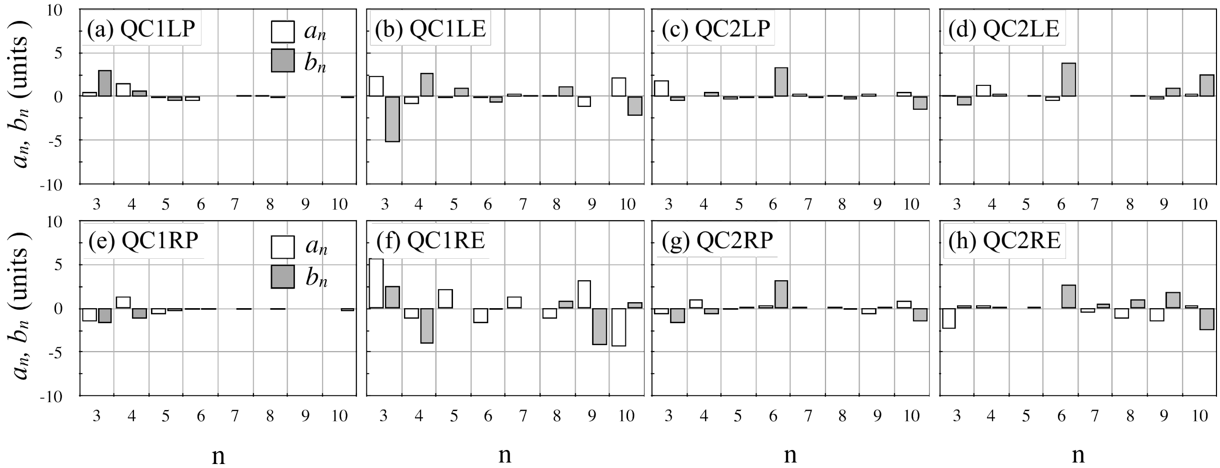


Figure 3: Higher order harmonic amplitudes for all quadrupole magnets. The shaded and un-shaded bars are normal and skew components in *units*, respectively.

Higher order harmonic amplitudes are shown in Fig. 3. The harmonics are reduced values at the reference radius corresponding to the magnets as shown in Table 1. Shaded and un-shaded bars are normal and skew components in *units*, respectively. The horizontal axis is harmonic numbers (for example, n=3 for sextupoles). Fig. 3-(a)∼(d) (upper plots) are the harmonics amplitudes for the QCS-L quadrupole magnets and Fig. 3-(e)∼(h) (lower plots) are those for the QCS-R. Those plots exhibit small amplitudes at higher than $n = 3$ for all magnets. Sextupole terms which are sensitive to beam-life time of the accelerator are also small for QC1LP/RP, QC2LP/RP, and QC2LE/RE. The terms for QC1LE/RE are larger than 5 units. However, they can be corrected because the QCS-R has normal and skew sextupole correctors [3]; they have an ability to correct sextupole terms up to 10 units.

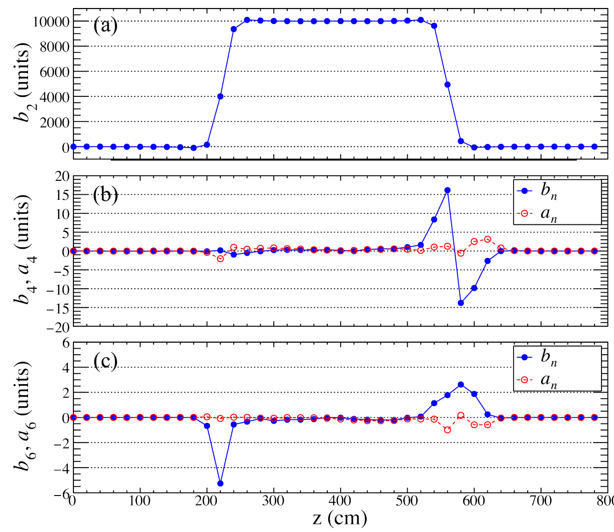


Figure 4: Axial profiles of (a) quadrupole , (b) octupole and (c) dodecapole term in the QC1LP.

### *Field Profiles*

Field profiles obtained by the short-length windings for QC1LP are shown in Fig. 4. Here closed circles and open circles indicate normal and skew terms, respectively. Fig. 4-(a) is quadrupole terms plotted as a function of axial positions. This profile shows plateau at the magnet body and it falls off smoothly at the coil ends. In Fig. 4-(b), profiles of octupole field is shown. This profile shows over and under shoot at lead end although this term is un-allowed harmonics. This is because the magnet consists of a pair of quadrant coils which are mirror symmetric at lead end. Fig. 4-(c) shows profiles for first allowed multipole of dodecapole. At the body region, the terms exhibits quit small amplitudes. At the coil ends, under/over shoots are exhibited and they are canceling each other.

## SUMMARY

Production of the all quadrupole magnets of the final focus system in SuperKEKB are completed. We measured magnetic fields for the all quadrupole magnets in advance of integrating into the horizontal cryostats for the interaction region. We confirmed that the field qualities satisfy qualities demanded by accelerator optics study.

## REFERENCES

[1] Y. Ohnishi, *et. al.*, Progr. Theor. Exp. Phys., vol. 2013, no. 3, 03A011, 2013.

[2] N. Ohuchi, *et. al.*, in *Proc. of NA-PAC'13*, Pasadena, CA USA, Jun. 2013, p. 759.

[3] B. Parker, *et. al.*, in *Proc. of NA-PAC'13*, Pasadena, CA USA, Jun. 2013, p. 1241.

[4] B. Parker, *et. al.*, in *Proc. of IPAC'16*, Busan, Korea, May 2016, TUPMB041B, this conference.

[5] N. Ohuchi, *et. al.*, IEEE Trans. Appl. Supercond., vol. 25, no. 3, 4001204, 2015.

[6] N. Ohuchi, *et. al.*, in *Proc. of IPAC'16*, Busan, Korea, May 2016, TUPMB033, this conference.

[7] N. Ohuchi, *et. al.*, " in *Proc. of IPAC'14*, Dresden, Germany, Jun. 2014, p. 2693.




ISBN 978-3-95450-147-2