ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPMP006

# MAGNETIC MEASUREMENT WITH SINGLE STRETCHED WIRE METHOD ON SUPERKEKB FINAL FOCUS QUADRUPOLES

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*Abstract*

A final focus quadrupole system (QCS) was installed into the interaction region (IR) of SuperKEKB, and was aligned to accelerator coordinates on February 2017. QCS is a superconducting magnet system consisting of eight quadrupole magnets and four compensation solenoids. We performed measurements of magnetic centers and roll-angles of all quadrupole magnets of QCS based on a Single Stretched Wire method at the IR.

## INTRODUCTION

The QCS final focus magnet system for SuperKEKB [1] consists of two pairs of superconducting quadrupole doublets for each ring (eight quadrupole magnets in total) [2]. Each quadrupole magnet includes dipole ($a_1$ and $b_1$) and skew quadrupole ($a_2$) corrector magnets [3].

The production of QCS was finished on Feb. 2017, and it was subsequently installed into the IR and aligned to the accelerator rings. Alignment for this installation was performed with laser trackers referencing fiducials on the surface of the QCS cryostats which contain the quadrupole magnets and compensation solenoids. Since the helium vessels which contain the magnets are tensioned with support rods made of Ti-6Al-4V from a vacuum chamber of the cryostat, the magnetic center can be different from the nominal position indicated by the fiducials on the cryostat [4].

QCS is located in the Belle II-detector-solenoid magnet which generates a solenoid field of 1.5 T. To integrally compensate this field on the beam lines, QCS also has four compensation solenoid magnets [5, 6]. The magnetic force caused by the solenoid magnets will move the position of magnets by a few mm in the direction of the solenoid axis. Furthermore, since the weight of the Belle II detector is 1,400 tons, the subsidence is not negligible (QCSs can not be aligned after the "roll-in" of Belle II detector because they are inserted into the detector). Consequently, measurement of the magnetic centers was performed on the IR after "roll-in" of Belle II.

A Single Stretched Wire (SSW) method [7, 8] was adopted. Because the angle between the solenoid axis and the beam line axis is 41.5 mrad, the solenoid magnets generate apparent dipole fields on the beam line, which causes an apparent offset of the quadrupole axis in the transverse direction. Performing the SSW measurements with AC magnet current allowed us to distinguish the dipole field stemming from being offset in a quadrupole magnet and that of the solenoid field. Note that we did not adopt a vibrating wire method (although the method can achieve a more accurate measurement) since that requires energization of the quadrupole magnet with DC current [9].

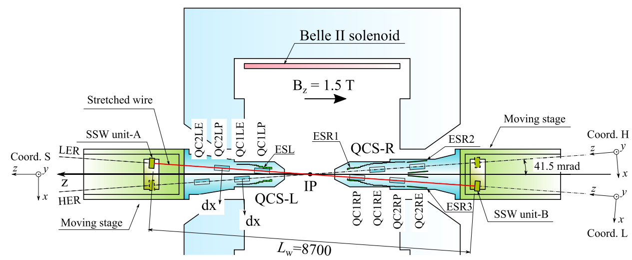


Figure 1: A schematic layout of QCS at the IR and definition of coordinate system (top view). The quadrupole magnets and the compensation solenoids are indicated with prefix character of "QC" and "ES", respectively. Coord. H and Coord. L are coordinate systems along beamlines on HER and LER, respectively. Coord. S is a solenoid coordinate system. $L_w$ is the wire length in mm. This figure is not to scale.

## MEASUREMENT APPARATUS

**SSW bench** The single stretched wire (SSW) system used for measurements is a newly redesigned version of the SSW system developed and used at Fermilab, and also provided for use at CERN, for over 20 years [8, 10]. The system consists of two precision X-Y stage units, electronics, and software for measurement and control. The stage units precisely control wire movement and are situated on flat, portable, base plates. The x-linear stage and the y-linear stage are ANT130- 160-L (Aerotech Inc.) and ATS100-150-UF (Aerotech Inc.), respectively. The typical repeatability for the x-stage and the y-stage are 0.1 µm, and 0.7 µm, respectively. The stages are driven by an Aerotech Ensemble Epaq controller. Fixturing which holds and tensions the wire is mounted to the x-linear stage on each unit. The wire is supported at each end on a guide which consists of two 1.2 mm ceramic-ball bearings [8]. The wire-end-position is precisely known with respect to targets on the stage that can be measured with a laser tracker. The wire used is made of Be-Cu with diameter 0.1 mm. Wire tension is controlled by a rotary motor (AEROTECH, BMS35) with feedback provided by a tension gauge. The wire voltage was measured with a FDI2056 Metrolab integrator. The control, data acquisition, and analysis system is based on the EMMA framework which has been recently developed at Fermilab [11].

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Table 1: Design Parameters of the Quadrupole Mangets. z, x, y are magnets positions on each main ring. $I_{\rm op}$ is nominal operation current of the quadrupoles and $L_m$, $G$, and $R_{\rm ref}$ are magnetic length, field gradient, and reference radius, respectively.

| Quads. name | Main ring | z [mm] | x [mm] | y [mm] | $\theta_{\rm roll}$ [mrad] | $I_{\rm op.}$ [A] | $L_{\rm m}$ [mm] | $GL_{\rm m}$ [T] | $GL_{\rm m}/I$ [T/A] | $R_{\rm ref}$ [mm] |
|---|---|---|---|---|---|---|---|---|---|---|
| QC1LE | HER | -1410 | 0.7 | 0 | 0 | 1577 | 373.1 | 26.94 | 0.01708 | 15 |
| QC2LE | | -2700 | 0.7 | 0 | 0 | 977 | 537 | 15.27 | 0.01563 | 35 |
| QC1RE | | 1410 | -0.7 | 0 | 0 | 1486 | 373.1 | 25.39 | 0.01708 | 15 |
| QC2RE | | 2925 | -0.7 | 0 | 0 | 1155 | 419 | 13.04 | 0.01129 | 35 |
| QC1LP | LER | -935 | 0 | 1.5 | -13.65 | 1622 | 333.6 | 22.96 | 0.01415 | 10 |
| QC2LP | | -1925 | 0 | 1.5 | -3.725 | 876 | 409.9 | 11.48 | 0.01311 | 30 |
| QC1RP | | 935 | 0 | 1 | 7.204 | 1622 | 333.6 | 22.96 | 0.01415 | 10 |
| QC2RP | | 1925 | 0 | 1 | -2.114 | 881 | 409.9 | 11.54 | 0.01311 | 30 |

**Magnets layout** Figure 1 shows a schematic layout of the magnets and SSW stage units. The crossed lines indicate accelerator beamlines of electron (HER) and positron ring (LER). The quadrupole magnets are contained in two cryostats, with one located at the left side of the interaction point (IP) as seen from the center of SuperKEKB main ring (QCS-L), and the other located at the right side (QCS-R). The cryostats are inserted into Belle II detector and therefore are exposed to a large solenoid field of 1.5 T. Each cryostat contains four quadrupoles for electron/positron beam. The quadrupole magnets, QC1L(R)P, QC2L(R)P, QC1L(R)E, and QC2L(R)E are contained in the QCS-L(-R) cryostat. The compensation solenoid ESL is contained in QCS-L, the other ones (ESR1,2,3) are contained in QCS-R. All compensation solenoid axes are coincident with that of the Belle II solenoid. The designed transverse-positions of quadrupole magnets are shifted with respect to each coordinate axis in vertical or horizontal direction as shown in Table 1. We measured the magnetic center relative to this design position. Designed roll-angle of the median plane of quadrupole field on LER is slightly rotated with respect to horizontal plane as shown in Table 1.

**Set up of SSW units** The SSW stage units are situated on QCS-L/R moving stages [12] located at both ends of the Belle II detector; longitudinal length of the detector is 7.2 m. The wire was stretched through the four quadrupole magnets on the HER or LER line and the wire length was 8.7 m. The return wire of the flux loop was fixed on the bottom of the warm bore of the quadrupole magnets. We used two laser trackers to align the wire. One was set on the moving stages for the SSW units on QCS-R side and the other was set behind the QCS-L moving stage. The trackers defined accelerator coordinates by referencing fiducials around the IR (fiducials on accelerator magnets, wall, floor, etc.). The wire ends were aligned to the beamline by the two trackers referencing the fiducials on the wire fixtures. The leveling of the SSW stage units was performed with a high-precision digital level (Digi-Pas: DWL-3500XY) put on the base plates.

**Gap sensors** Capacitor-type gap sensors are mounted on surfaces of the two QCS cryostats to monitor transverse movements of the QCS. They measure gap distances between the inner bore of a drift chamber in the Belle II detector. The sensors are located at distances of 940 mm (near QC1LP), and 1334 mm (near QC1RE) from the IP for QCS-L and QCS-R, respectively.

## MEASUREMENT

### *Procedures*

The measurement was performed under cryogenic conditions. We measured for all quadrupole magnets under two conditions; the all solenoids were energized to nominal currents and no solenoid was energized.

Measurements were performed with the quadrupole magnet energized with AC current having frequency 7.8125 Hz and amplitude 9.6 A. The sampling frequency of flux measurements was 200 Hz. The wire was moved co-directionally, where both of the wire ends are moved to same direction. The step distance of the wire was 7 mm; the distance was limited by inner diameter of the warm bore at QC1P/E. To remove the wire sag from measured y-offset, the y-offset was measured at six tensions for each quadrupole magnet. We obtained y-offset as a function of square inverse of wire vibration frequency. The sag was estimated by the extrapolation of the linear function to infinite tension. The obtained sag was 0.8 mm at QC1RP/QC1LP.

### *Results*

The measurement results are summarized in Table 2. Figure 2 shows measured x-offset of quadrupole center. The x-offset is defined as $x_{\rm offset} = x_{\rm meas} - x_{\rm design}$. Here, $x_{\rm meas}$ and $x_{\rm design}$ are measured and design magnetic center on each beamline coordinate, respectively. Solenoid-on indicates that the all solenoids were energized, and solenoid-off means that no solenoid (including Belle II solenoid) was energized. Statistical errors were less than 10 µm for HER magnets and 20 µm for LER magnets. Uncertainty on the laser tracker survey is around 60 µm. In Fig. 2, x-position in the solenoid coordinate system is plotted against z-position. The crossed lines indicate the beamlines. The x-offset vectors are lines which have diamond and circle markers; the marker expresses an arrowhead of the vector. The length of

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the vector is multiplied by 200 in order to be able to see it on the scale of the beamline positions. Quadrupole magnets in QCS-R are shifted to minus x-direction. QC1RP exhibits a large x-offset of 0.64 mm. The difference between solenoids on and off was 0.1 mm, while the gap sensor exhibited a small shift less than 0.01 mm. This means the helium vessel in the cryostat was moved by magnetic force while cryostat did not moved in the x-direction.

Measurement results of y-offset are shown in Table 2 and Fig. 3. Statistical errors are less than 10 µm for HER magnets and 30 µm for LER magnets. In these errors, sag correction error is included. It can be seen that almost all magnets are aligned in lower positions. Y-offset of QC2LP is the largest and is −0.68 mm. The two gap sensors showed 0.1 mm movement of the cryostats by the magnetic force and QC1LP and QC1RE which are located near the gap sensors also showed 0.1 mm movement. It is deduced that the cryostats are pushed out from the Belle II solenoid by the magnetic force and the moving stage is fixed on linear guides on the floor of the accelerator tunnel, so the cryostats were lifted up.

Roll angles were obtained by measuring x-offsets at five y-positions. The roll angles are calculated from a gradient, $dx_{\mathrm{xoffset}}/2dy$. Figure 4 shows measured roll angle with respect to design value given by, $\Delta\theta = \theta_{\mathrm{meas}} - \theta_{\mathrm{design}}$. The result shows no significant effects on roll angle by the magnetic force. The roll angle of the LER quadrupoles shows larger deviation from design value compared to HER ones. Statistical errors of the LER magnets are less than 0.2 mrad while those of the HER magnets are 0.5~0.8 mrad. The large errors on the HER magnets is caused by unknown fluctuations during this HER measurement.

Table 2: Measured x-Offset, y-Offset and Roll Angle Relative to Design Parameters. Units of length and angle are mm and mrad, respectively.

| Quads. | X-offset | | Y-offset | | $\Delta\theta$ |
|---|---|---|---|---|---|
| | Solenoid | | Solenoid | | Solenoid |
| | on | off | on | off | on |
| QC1LE | −0.21 | −0.16 | −0.29 | −0.56 | −1.6 |
| QC2LE | 0.13 | 0.11 | −0.54 | −0.68 | −1.5 |
| QC1RE | 0.25 | 0.14 | −0.37 | −0.54 | 0.0 |
| QC2RE | 0.08 | 0.07 | −0.58 | −0.63 | −0.7 |
| QC1LP | −0.03 | −0.14 | −0.21 | −0.38 | −1.7 |
| QC2LP | −0.31 | −0.41 | −0.68 | −0.83 | −4.0 |
| QC1RP | 0.64 | 0.69 | −0.30 | −0.43 | 2.0 |
| QC2RP | 0.43 | 0.45 | 0.04 | −0.19 | −1.7 |

## SUMMARY

We performed measurements of magnetic center and roll angle for final-focus-quadrupole magnets for SuperKEKB at the IR. We applied the Single Stretched Wire method and used the SSW system developed by Fermilab. Although large offsets of 0.64 mm and 0.68 mm were measured for x-offset and y-offset, respectively, the dipole correctors have

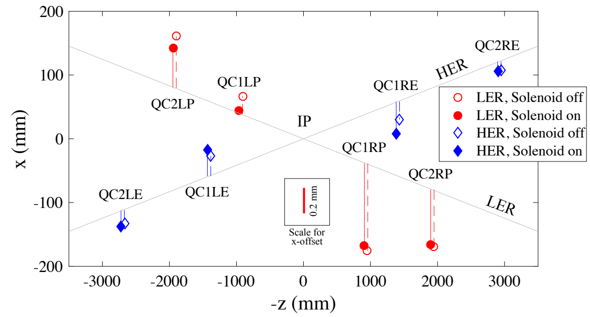


Figure 2: Measured x-offset relative to the design position. The x-offset is described with length of lines with marker which express arrowhead of a vector (these have been multiplied by 200 to be visible on the vertical scale).

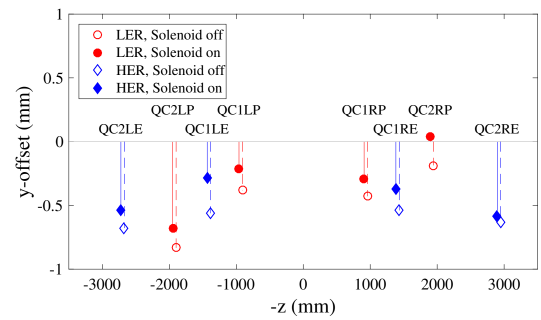


Figure 3: Measured y-offset relative to the design position.

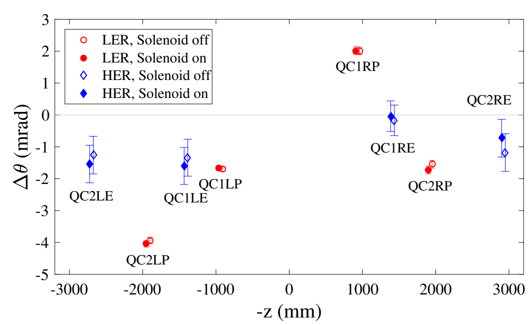


Figure 4: Measured roll angle relative to the design angle.

enough strength to correct these transverse offsets. Almost all magnets are aligned in a direction vertically downward. The Belle II detector "rolled-in" to the IR after the alignment work of QCS. So, it is possible that QCSs moved lower because of floor subsidence from the weight of the Belle II detector. The roll angle measurement shows the deviation of −4 mrad from design value at maximum. This deviation also can be corrected with the $a_2$ correctors. It was found that the magnetic force moved the magnets around 0.1 mm in transverse direction.

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