# SEXTUPOLE MAGNETS WITH VARIABLE TILT ANGLES FOR SUPERKEKB

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*Abstract*

SuperKEKB is an electron-positron collider with a design peak luminosity of $8 \times 10^{35}$ cm$^{-2}$s$^{-1}$. In order to achieve such a high luminosity, it is important to make the beam size small at the interaction point, especially in the vertical direction. Skew sextupole magnets were found to be effective in order to make the sufficiently small beam sizes during KEKB operation. At SuperKEKB, a novel idea of tilting the normal sextupole magnets to control the ratio of skew sextupole field component to normal sextupole field component has been proposed for the positron ring. Twenty-four sextupole magnets were modified and new tilting tables were fabricated to control the normal/skew component ratio by tilting the magnets. The tables were designed so that the sextupole magnets can be tilted from −30° to +30° (−523.58 mrad to +523.58 mrad), with a setting accuracy of 0.1 mrad. Magnet movers for controlling the horizontal and vertical positions, as well as the tilting angles, had previously been developed elsewhere, though a table with such a large range in the tilting angle and a 0.1 mrad setting accuracy for optics correction and luminosity tuning is unique. In this paper, we report the fabrication and the first commissioning of the tilting sextupole magnets at SuperKEKB.

## INTRODUCTION

SuperKEKB [1], an electron-positron double ring collider, is an upgrade of the KEKB accelerator [2]. The design of SuperKEKB is based on the “nanobeam scheme,” a low-emittance lattice, in which chromatic correction of the X–Y coupling at the interaction point is important. Skew sextupole magnets are found to be effective during KEKB operation [3]. At SuperKEKB, the ratio of the skew to normal sextupole field will be controlled by tilting the sextupole magnets at the precision 0.1 mrad. Twenty-four sextupole magnets [4], recycled from KEKB, were mounted on newly fabricated tilting tables to control the normal to skew sextupole field ratio for each magnet. The tables were designed to allow for the tilting of the sextupole magnets from −30° to +30° with a high setting accuracy of 0.1 mrad. Figure 1 shows a sextupole magnet mounted on a tilting table installed in the low-energy positron ring (LER). The fabrication of the tilting tables was reported before in detail [5]. The fabrication of the sextupole magnets mounted on the tilting tables is described here briefly, and the first commissioning of the tilting sextupole magnets at superKEKB is described in detail.

## MODIFICATION OF THE SEXTUPOLE MAGNETS AND FABRICATION OF THE TILTING TABLE

The high-energy electron ring (HER) and LER beamlines are placed alongside each other. The sextupole magnets required modification, especially around the cooling water tube and electrical cable routing, to ensure that they would fit in the small space between the HER and LER and that the system could be tilted. The modified routing for the cooling water tubes and the electrical cables are enclosed within the yellow circle in Figure 1.

The top half of the magnet and tilting table system is 511 mm long, 380 mm high, and 870 mm wide, and the bottom half is 650 mm long, 825 mm high, and 870 mm wide. The weight of both the magnet and tilting table combined is 700 kg.

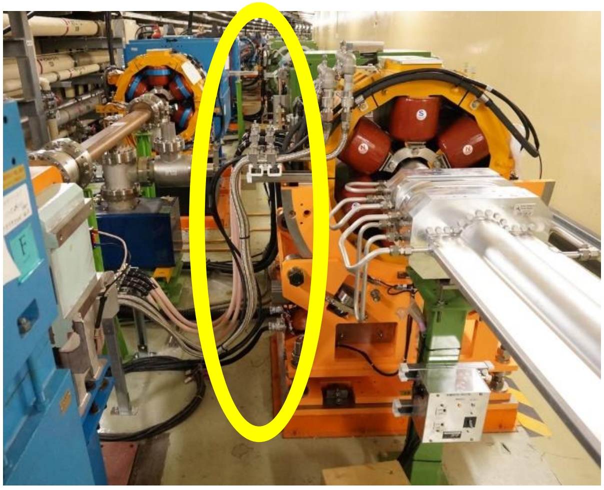

Figure 1: Sextupole magnet set on the tilting table in LER. The routing for the cooling water tubes and the electrical cables are enclosed with a yellow circle.

Figure 2 shows the close view picture of the gear part of the table. A large helical gear of 450 mm radius is installed under the top part of the table where a magnet is fixed. A straight worm gear is installed on top of the base part. The two gears are engaged with each other. The straight worm gear is rotated by a pulse motor, and its rotation is transferred to the large helical gear, causing the table to tilt. The tilting table is supported and guided by four large roller wheels (two at each side) in the vertical direction. Moreover, the side of the helical gear is guided by four large roller wheels (two at each side) in the horizontal direction. Adjusting bolts are installed at the four corners of the plate, where the magnet is fixed, to adjust the center position of the magnet to the rotation center in the horizontal and vertical directions. Adjusting bolts are also installed at the four corners of the base plate to adjust the whole tilting sextupole magnet system to the beamline.

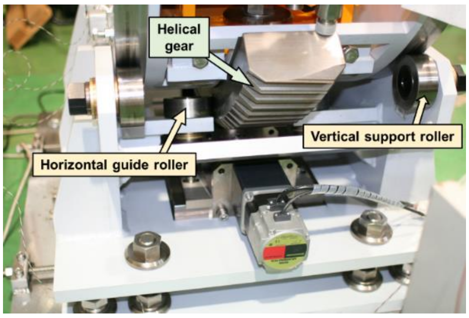


Figure 2: The straight worm gear and the helical gear engaged. A pulse motor attached at the end of the straight worm gear can be seen.

## ADJUSTMENT OF THE MAGNET CENTER TO THE ROTATION CENTER

The magnet mechanical center was adjusted to the rotation center to prevent its movement during the rotation of the tilting table. To perform this adjustment, crosshairs were made at both ends of the magnet by stretching thin beryllium-copper wires of 0.1 mm diameter between the pieces of the magnet return yoke to connect the opposite facing gaps, as shown in Figure 3 by yellow arrows. Three stretched wires can be seen on the end face of the magnet in the figure 3. We observed these crosshairs at both ends with a theodolite (E2, Leica), and measured the horizontal and vertical positions of the crossing points of the crosshairs as shown in Figure 4.

Figure 3: Crosshairs made by thin beryllium-copper wires stretched between opposite facing gaps of the pieces of the magnet return yoke. The positions of crosshairs are shown by yellow arrows.

First, the magnet system was adjusted to be level, using the three leveling blocks on which the magnet is placed, and by referring to a precision level placed on the alignment base plate at the top of the magnet. Then the position and the angle of the theodolite were adjusted so that its optical axis lay along the line connecting the near and far crossing points of the crosshairs.

The tilting table was rotated to +30° and the positions of the near and far crossing points of the crosshairs were measured. The tilting table was then rotated to −30°, and the positions of the near and far crossing points of the crosshairs were measured again.

The displacement of the magnet center from the rotation center can be calculated from these measurements. This displacement was corrected horizontally and vertically by adjusting the magnet position with the adjusting bolts. This procedure was repeated until the displacement became less than 0.1 mm.

Figure 4: Measurement of the position of the near and far crossing points of the crosshairs with a theodolite.

## CALIBRATION OF INCLINOMETERS

The calibration of the inclinometers is important because the precision of the tilt depends on that of the inclinometers, as described in the next section. Figure 5 shows the inclinometers (LCI-30, Jewell Instruments) installed on the front face of the table.

First, the table was rotated to +30°, and the output voltage from the inclinometer was recorded. Simultaneously, an adequate bar was inserted into the sine-bar tool placed perpendicular to the magnet center axis on the alignment base plate at the top of the magnet, as shown in Figure 6. The small tilt angle of the top plate of the sine-bar tool was measured with a precision digital level placed on the top plate of the sine-bar tool. The real tilt angle of the magnet was calculated from the length of the inserted bar and the tilt angle measured with the precision digital level. The table was then rotated by −5°, and the output voltage from the inclinometer and the real tilt angle were recorded. These procedures were repeated until the tilt angle of the magnet became −30°.

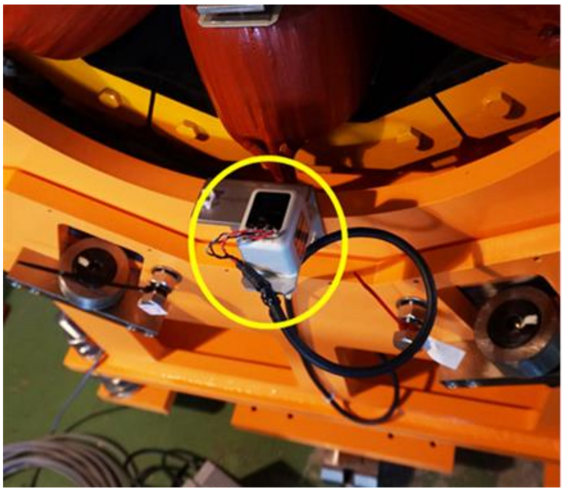

Figure 5: An inclinometer, enclosed within a yellow circle, is installed on the front face of the tilting table.

The output voltage data obtained from the inclinometers and the tilt angles of the magnets were fitted to fourth-order polynomials. The measurement was performed twice. The deviations of the data in the two measurements for a tilting table from the curve fitted to the second measurement data are shown in Figure 7 as an example. The root mean squares of the deviations are mostly less than 0.1 mrad in the calibration of all inclinometers. It was found that the inclinometers contained magnetic substances after the first calibration. Therefore, the inclinometers were recalibrated after exciting the magnets and magnetizing them at the maximum operation current. The property of the inclinometers did not change when the magnets were excited at a current lower than the maximum operation current.

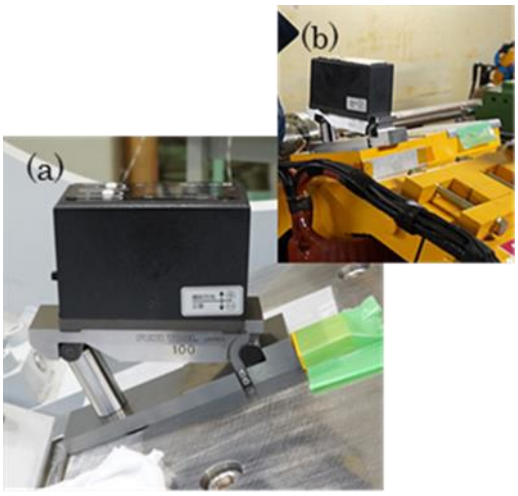


Figure 6: (a) Sine-bar tool and digital level to measure large tilting angle, and (b) Sine-bar tool placed on the alignment reference plate of the sextupole magnet.

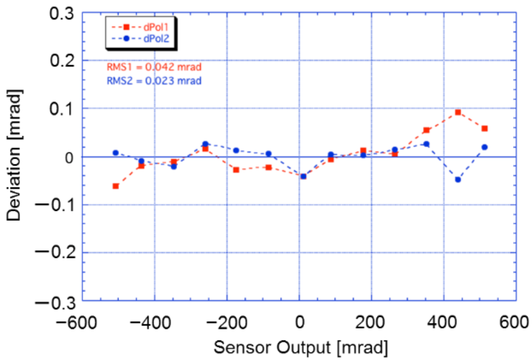


Figure 7: Deviations of the data in two measurements from the fourth-order polynomial curve fitted to the second measurement data.

## CONTROL SYSTEM AND OPERATION

The tilting tables are remotely controlled from the central operation room of the SuperKEKB accelerator. In the previous KEKB project, the sextupole magnets were placed on the X–Y movers and remotely controlled from the central operation room. The X–Y movers were replaced with tilting tables for the 24 magnets installed in the LER in the interaction region. The 24 tilting tables were connected to three surface local control rooms: the 10 tables on the left were connected to L8, the central 4 tables to the electric power control room, D2, and the 10 tables on the right to L3, using the same control cables used for the X–Y movers. The local control rooms are connected to the central accelerator operation room through the KEKB communication network. The tilting of the tables is driven by pulse motors installed at the ends of the straight worm gears, and the tilt angles are measured with inclinometers installed on the front face of the tables as shown in Figure 6. Programmable Logic Controller (PLC) devices have been installed in the local control rooms to control the pulse motors and to receive signals from the inclinometers. The signals from the inclinometers are read every time after the tilt angle is changed. If the tilt angle deviates from the target value larger than 0.1 mrad, then a small rotation is performed to correct the error. By repeating this procedure two or three times, a precision of 0.1 mrad is achieved.

## COMMISSIONING OF TILTING SEXTUPOLE MAGNETS

Phase-1 commissioning of SuperKEKB main ring started in February 2016 and ended at the end of June. During commissioning, we checked the remote operating system for tilting the sextupole magnets and the measured misalignment of the magnetic center. The following steps were carried out for ten magnets. First, each magnet was tilted to −30° from 0° by remote control without a beam current. Figure 8 shows the sextupole magnet tilted by −30°. The tilting tables moved smoothly and accurately.

Figure 8: Sextupole magnet tilted by −30°.

The magnetic center of the tilted sextupole magnets was checked using low current beams. The beams were stored to 40 mA and the magnetic center was measured by Beam Based Alignment (BBA) [7] using the quadrupole windings of the sextupole magnets. The beams were kept stored while tilting the sextupole magnet from −30° back to 0°. The beams orbit before and after the tilt was examined for one of the magnets. Figure 9 shows the shift of the beam orbit between 0° and −30°. No large orbit distortion was seen.

Figures 10 (a) and (b) show the offsets of the magnet center of the sextupole magnet tilted by 0° and −30°. The blue and red points show the deviations in the vertical and horizontal directions, respectively. The offsets with 0° were found to be less than 0.2 mm for most of the magnets, and the average was 0.04 mm with sigma of 0.1 mm. However, the offsets of the magnetic center at −30° increased, with a sigma of 0.3 mm. One magnet presented a larger deviation of approximately 1 mm. We will investigate the reason for this large deviation and resolve the problem before the Phase-2 commissioning starts.

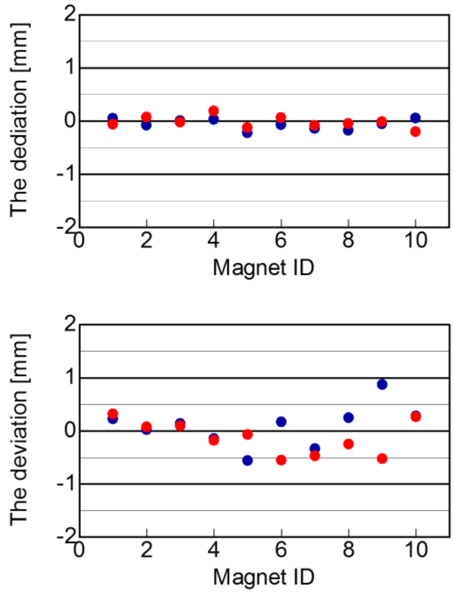


Figure 10: The deviations of magnet center sextupole magnet tilted by (a) 0° and (b) −30°. Blue and red points show differences in horizontal and vertical directions, respectively.

## CONCLUSION

Sextupole magnets mounted on large-angle precision tilting tables were proposed to control the normal to skew sextupole field ratio for SuperKEKB. Twenty-four sextupole magnets near the interaction region were modified to fit in the narrow space in the accelerator tunnel and to enable tilting of the sextupole magnets from −30° to +30°. A high tilting precision of 0.1 mrad is achieved by monitoring the output from the inclinometers after tilting and correcting the small angle when the output from the inclinometer deviates from the target value by 0.1 mrad or greater. To achieve the expected precision, the magnet mechanical center was adjusted carefully to the rotation center of the table by observing the near and far crossing points of the crosshairs with a theodolite. Furthermore, the

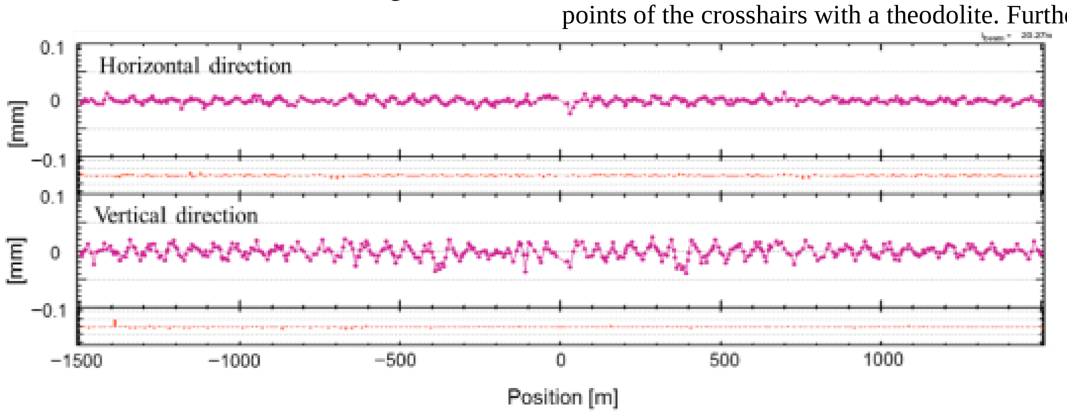


Figure 9: The shift of beam orbit from −30° to 0° degrees for one of the sextupole magnets. Upper and lower graphs show differences in horizontal and vertical directions, respectively.

inclinometers were calibrated carefully by rotating the tables from +30° to −30° in steps of 5°. At each step, the output from the inclinometers was recorded, and the actual tilt angle of the magnets was measured with a sine-bar tool and a precision digital level. The calibration curves of fourth-order polynomials were obtained from these data. The reliability of this system was assured by tilting the tables more than 10 times from −30° to +30° during the calibration for the inclinometers in the tunnel.

The first beam test using the tilting sextupole magnets was carried out in the SuperKEKB Phase-I operation. The orbit distortion was found to be small and no beam abort was caused by tilting the magnets. The shift of the magnetic center was checked using BBA and found to be small enough for most magnets. The tilting table that presented a large shift in the magnetic center will be investigated before the Phase-II commissioning starts in 2017. We also plan to install remote control via Experimental Physics and Industrial Control System for Phase-II.

## ACKNOWLEDGMENT

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## REFERENCES

[1] Y. Ohnishi et al., "Accelerator Design at SuperKEKB", *Prog. Theor. Exp. Phys. 2013* (2013) 03A011.

[2] "KEKB B-factory Design Report", KEK Report 95-7, August 1995.

[3] T. Abe et al., "Commissionimg of KEKB"*Prog. Theor. Exp. Phys. 2013,* (2013) 03A010.

[4] K. Egawa et al., "Magnet System for the KEKB Main Ring", *Nucl. Instrum. Meth*. A499 (2003) 24.

[5] Y. Iwata et al., "Design of a superconducting rotating gantry for heavy-ion therapy", *Phys. Rev. Accel. Beams.* 15 (2012) 044701.

[6] M. Yamada et al., "The Novel Method of Focusing-SANS with Rotating Magnetic Sextupole Lens and Very Cold Neutrons", in *Proc. 1st Int. Part. Accel. Conf. 2010* (IPAC'10), Kyoto, Japan, May 2010, (2010) MOPEB067.

[7] M. Masuzawa, et al., "Beam-Based Calibration of Beam Position Monitors and Measurement of the Sextupole Magnet Offsets at KEKB", in *Proc. Eur. Part. Accel. Conf. 2000*, Vienna, Austria, June 2000, (2000) 1780.