ALIGNMENT OF SUPERKEKB MAIN RING MAGNET SYSTEM

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Abstract

SuperKEKB is an electron-positron double-ring B-factory machine, which aims to achieve a peak luminosity 40 times higher than that of KEKB by using the “nano-beam” scheme [1]. A major upgrade to the Main Ring magnet system was needed in order to realize this scheme. Approximately 2600 magnets were installed, using ~1200 reference points in the tunnel. Commissioning of the SuperKEKB main rings started in February, 2016 [2]. The circumference as measured by the beam agreed with the prediction from analysis of alignment data to within 1 ppm. The difference in circumference between the two rings was found to be 0.2 mm over ~3 km. The good alignment of the main ring magnets contributed to the smooth start-up of the SuperKEKB beam commissioning. The alignment strategy and results are presented in this report.

INTRODUCTION

SuperKEKB is a double-ring, asymmetric-energy collider. The high-energy electron ring is called the HER, and the low-energy positron ring is called the LER. It is being built utilizing the existing KEKB tunnel. We reused as many of the KEKB main ring (MR) magnets, though a major upgrade to the MR magnet system was needed to realize the “nano-beam” scheme. The upgrade includes: 1) new beam lines in the entire interaction region as well as in the straight sections on either side of the interaction point; 2) replacement of the main dipole magnets in the positron ring; 3) a completely new layout of the wiggler sections in the positron ring, and newly added wiggler section in the electron ring; and, 4) sextupole magnets with tunable tilting tables to control the ratio of skew/normal sextupole components in the positron ring [3]. More than 400 magnets were newly designed, fabricated, field-measured, installed in the tunnel and aligned in time for Phase I commissioning.

CHALLENGES

SuperKEKB construction started in 2010, and the beam commissioning without the final focus system and BELLE-II detector started in February 2016. There were many difficulties and challenges to overcome during the construction. The Great East Japan Earthquake of March 11, 2011 was one of them. It destroyed the survey network in the tunnel. We inherited the main ring alignment network from the KEKB magnet system, and were hoping to use it for replacing magnets and adding new magnets.

Fig. 1 is an example of the magnet position shift caused by the earthquake. Expansion joints, which are placed every 60~70 mm to compensate for thermal expansion and contraction of the tunnel, are clearly seen. The tunnel block units, separated by the expansion joints, moved almost randomly as a result of the earthquake. This resulted in the need to build a new survey network, independent of the old KEKB network, and also forced us to finalize the magnet positions by iterative smoothing.

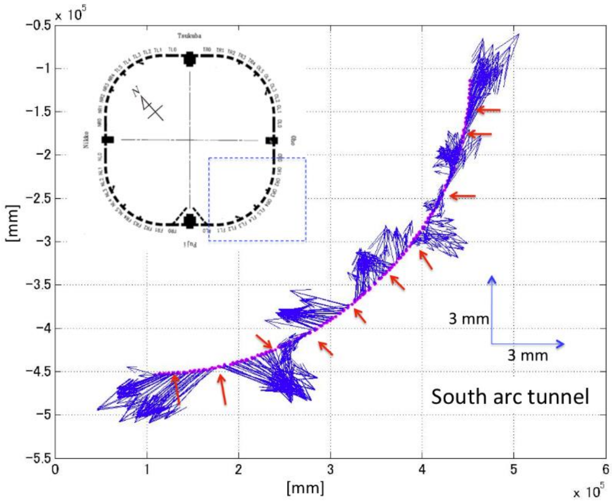

Figure 1: Magnet position shift due to the earthquake is indicated by a blue arrow for each magnet. The red arrows show the locations of the expansion joints. The entire tunnel is shown in the upper left.

The other challenges come from the tight construction schedule and electricity-saving policy of the lab. In parallel with the SuperKEKB magnet installation and alignment work in the tunnel, new utility buildings for new power supplies and water supply systems were being constructed. A new beam transport line (BT) to another accelerator complex (PF-AR) was also being built just a few meters above the SuperKEKB tunnel. The construction of the facility buildings began in 2013, just as we started building the new survey network for SuperKEKB. The construction work includes excavation of vertical shafts very close to the tunnel. The excavation sites and the new BT line to the PF-AR are indicated in Fig. 2. This heavy construction work made the establishment of the new survey network and alignment work very difficult.

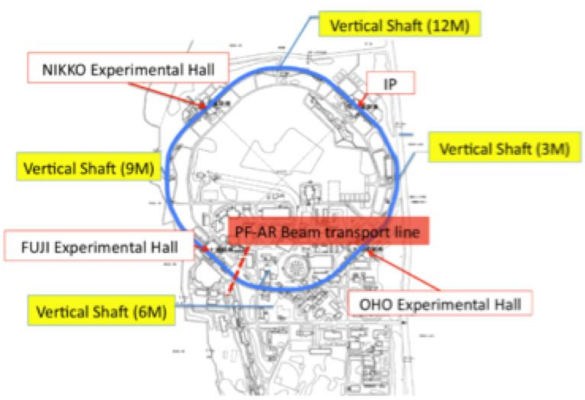

Figure 2: SuperKEKB Main Ring is indicated in blue and the new facility construction sites on the ground surface are shown with yellow labels. The PF-AR BT tunnel is shown with red label.

The tunnel air temperature was not controlled for most of the construction and survey periods due to the electricity-saving policy. Figure 3 shows the tunnel temperature variation monitored at some locations in the tunnel from September 2013 and July 2014. Seasonal effects in the tunnel temperature are seen. The tunnel air temperature exceeds 25 degree Celsius in the summer, but goes below 15 degree Celsius in the winter. The large temperature variation affected the tunnel level. Figure 4 shows the level changes between February 2014 and October 2013, and between June 2014 and October 2013, observed at the Nikko section. The jumps seen in the variation between February 2014 and October 2013 correspond to the expansion joints in that area. There are no such jumps when June 2014 and October 2013 levels are compared. This is because the temperature was similar in June and October while the temperature is much lower in February. The jumps are as large as 0.5 mm, which degrades the alignment severely. The tunnel expansion locations and area names are shown in Fig. 5.

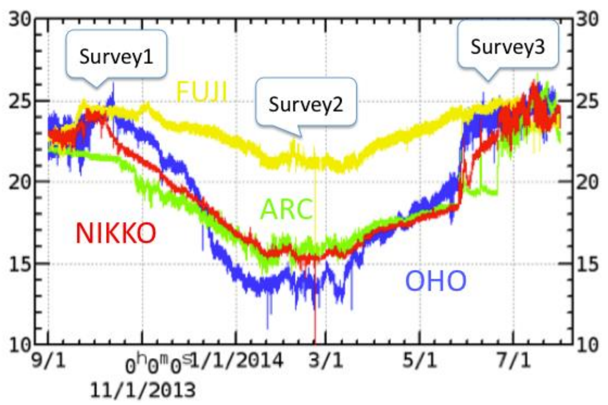

Figure 3: Tunnel temperature variation plotted from Sept. 2013 to Jul. 2014.

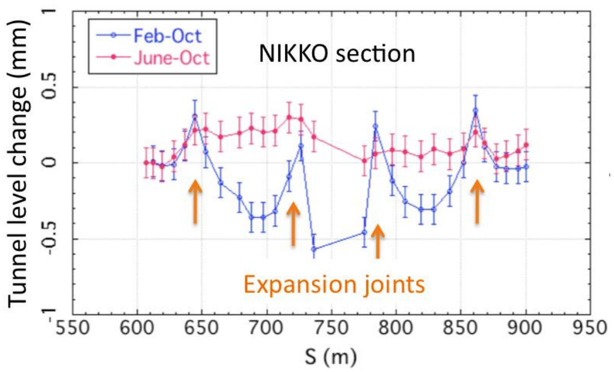

Figure 4: Tunnel level variations in two different periods are shown. Magenta and blue symbols correspond to the periods between June 2014 and October 2013 and February 2014 and October 2013, respectively. The locations of the expansion joints are indicated by the arrows.

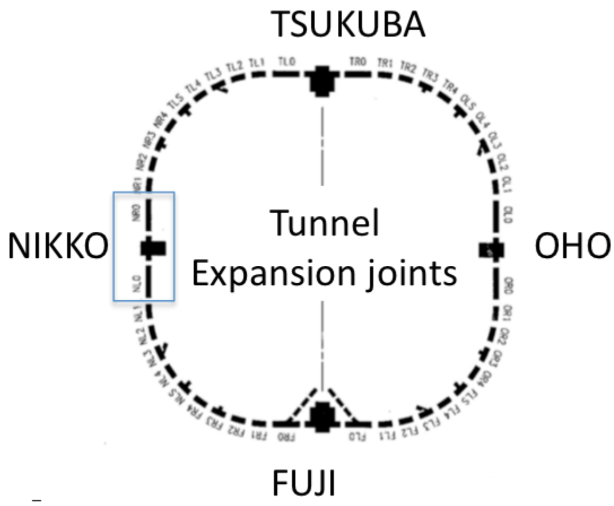

Figure 5: Expansion joints and section names are shown.

Figure 6 shows the tunnel level changes caused by the Great East Japan Earthquake of 2011, and the excavation of the vertical shafts along the SuperKEKB tunnel. The dips and jumps in the level variation after the earthquake correspond to the expansion joints. The gaps caused by the earthquake can be as large as 2 mm in places. The level change from 2012 and 2015 includes the sinking of the tunnel, which has been reported elsewhere and the effects of the excavation. The local dips caused by the excavation are as large as 2.5 mm. The most recent data obtained in the summer of 2016 indicate that the tunnel level variation is settling down, though it never went back to where it was before the earthquake and the excavation of the shafts along the tunnel.

In order to monitor tunnel floor level variation continuously, we installed 18 capacitive Hydrostatic Levelling System (HLS) units manufactured by BINP in the local chromaticity correction sections, which extend to ~100 m from the interaction point (IP) on either side. It is shown that the floor level also changes due to rainfall and air pressure[4].

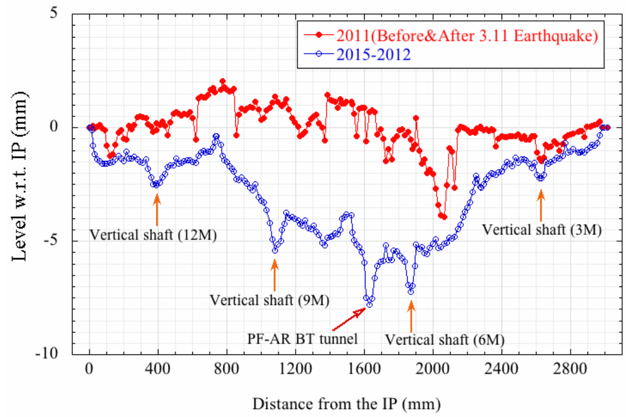

Figure 6: Solid and open circles correspond to the level changes after the Great East Japan Earthquake in 2011

and during the SuperKEKB construction, respectively. The effects of the excavation work are clearly seen.

STRATEGY

Faro laser trackers (Ion and Vantage) were used for the magnet survey. There are about 2000 magnets, and each magnet has at least 2 reference points to be used for surveying. The total number of points surveyed added up to about 5000, which includes the points on the tunnel wall and floor. We usually perform survey work with three or four groups in parallel, to save time. The construction schedule was tight, and we were sometimes forced to work in the evening in order to avoid interference with other work in the tunnel, such as cabling, vacuum leak test and RF conditioning.

The survey was performed by repetition of local area measurements along the LER and HER rings. Adjacent areas share some targets for measuring magnet positions by laser tracker, so that consistency of the survey results can be tested. The magnet pitch and roll angles were measured using digital inclinometer independently during the alignment. The laser tracker data were used to adjust the horizontal and also vertical positions of the magnets. Summer of 2015 was chosen for the survey, followed by alignment in the autumn. This time was chosen because the tunnel temperature is the highest then, and closest to the temperature during the actual beam operation. We gave up on aligning the magnets to the design positions, as most of the quadrupole magnets in the arc sections are re-used from KEKB and they were already shifted by 20 mm from their ideal positions as shown in Fig.7.

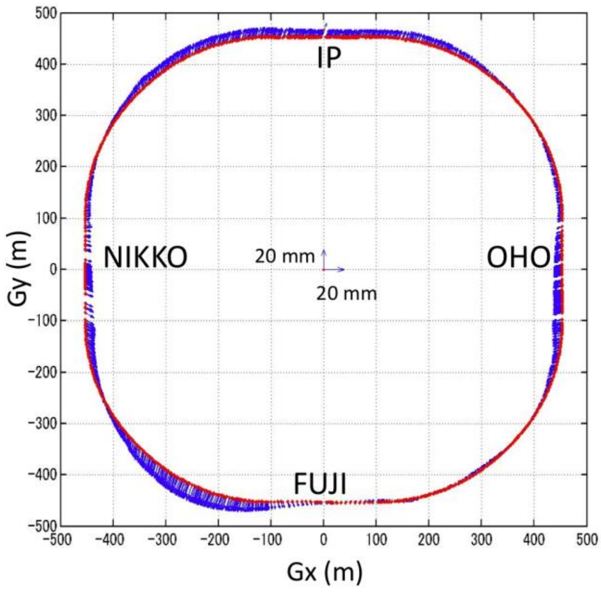

Figure 7: Laser tracker network analysis results by PANDA. The arc section between NIKKO and FUJI sections are shifted outwards while the OHO and NIKKO sections are shifted inwards.

Figure 7 is the result of the network average calculation by PANDA (Software Package for the Adjustment of geodetic Networks and Deformation Analysis)[5], where the magnet position deviations from their ideal positions are shown. The low-order variation of the orbit is not critical, so we decided to adjust the magnets to a smoothed reference curve.

Another software package called PAG-U (Universal Program for Adjustment of any Geodetic Network) [6] was used for the network average calculation. The results are shown in Fig.8. The PAG-U results are similar qualitatively to the PANDA results.

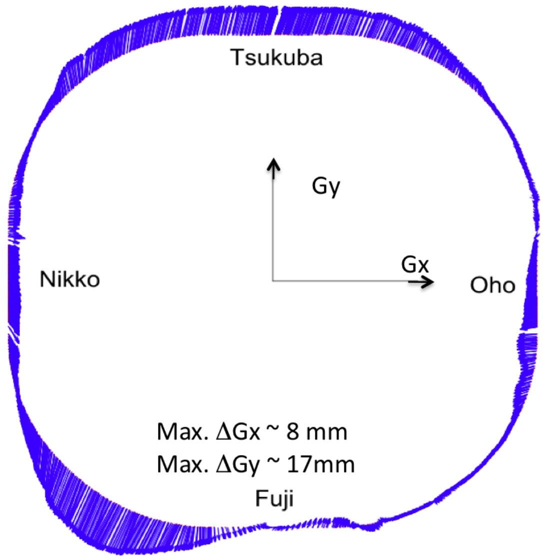

Figure 8: Network average calculation results by PAG-U. The small arrows indicate the deviations from the design positions.

Choice of the smoothed curve

When choosing the reference curve, we imposed two conditions, 1) the curve has to be periodic and 2) the number of terms should be on the same order as the betatron tunes. We tried Fourier series of 30th order and 60th order and compared the number of magnets that needed to be adjusted. There was a significant difference in number of magnets to be adjusted between the 30th and 60th order series, and we decided to use the Fourier series of 60th order as the reference curve. Fourier series of cosine and sine functions are serialized as followings;

$$y_i = a_0 + \sum_{n=1}^{N}\left(a_n \cos n\theta_i + b_n \sin n\theta_i\right) \equiv \sum_{k=0}^{2N} c_k F_k(\theta_i)$$

where

$$F_0(\theta) = 1$$

$$F_k(\theta) = \cos k\theta \quad k = 1,2,\cdots N$$

$$= \sin(k-N)\theta \quad k = N+1,\cdots,2N$$

Coefficient c_k can be given by the least squares fit.

$$\chi^2 = \sum_{i=1}^{M} \left(y_i - \sum_{k=0}^{2N} c_k F_k(\theta_i) \right)^2 = \min$$

$$\frac{\partial \chi^2}{\partial c_k} = 0$$

Figures 9 and 10 show the deviations from the reference curve, decomposed in the directions transverse to the beam (*dt*) and perpendicular to the beam (*ds*) for the LER and HER, respectively. It is seen that the deviation is larger in *ds*. This is due to the thermal expansion and contraction of the tunnel. Since the air temperature of the tunnel was not controlled during the survey and alignment period, we had no choice but to give up on precision alignment in the beam direction. We therefore applied loser tolerance on *ds* than on *dt*. The tolerances were determined by the optics/beam tuning group. They are summarized in Table 1. These numbers were chosen to achieve sufficient alignment within the given amount time for construction for SuperKEKB Phase I commissioning, where no collision takes place. It should be noted here that some of the main goals of the Phase I commissioning are 1) to achieve sooth beam circulation; 2) to confirm that the circumferences of the LER and HER match within a few mili-meters; 3) to do debugging of various hardware and software systems; and, 4) to understand the basic features of the machine and to learn about low-emittance tuning methods.

There are about 500 magnets that needed to be aligned to satisfy the tolerances. We made two survey-check teams to follow the alignment team, to detect any misalignment right away. Figure 11 shows the alignment results in the HER. One magnet was found to be misaligned by the survey-check team. It was re-aligned before the beam commissioning.

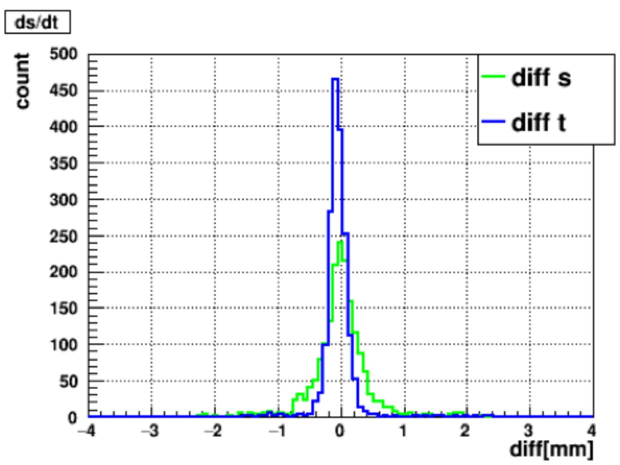

Figure 9: Magnet position deviation from the reference curve in the LER. Green and blue lines indicate the deviation in *ds* and *dt*, respectively.

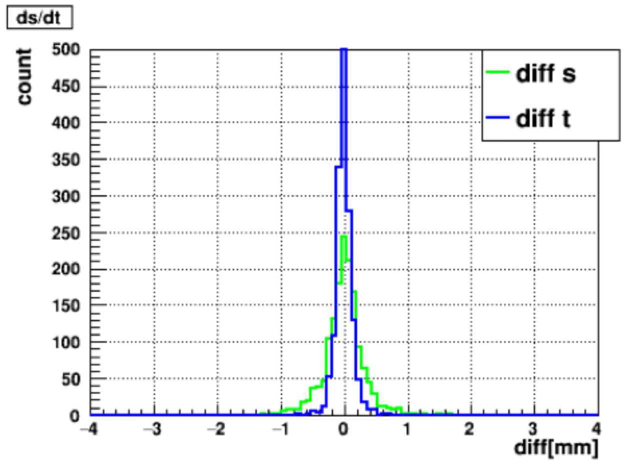

Figure 10: Magnet position deviation from the reference curve in the HER. Green and blue lines indicate the deviation in *ds* and *dt*, respectively.

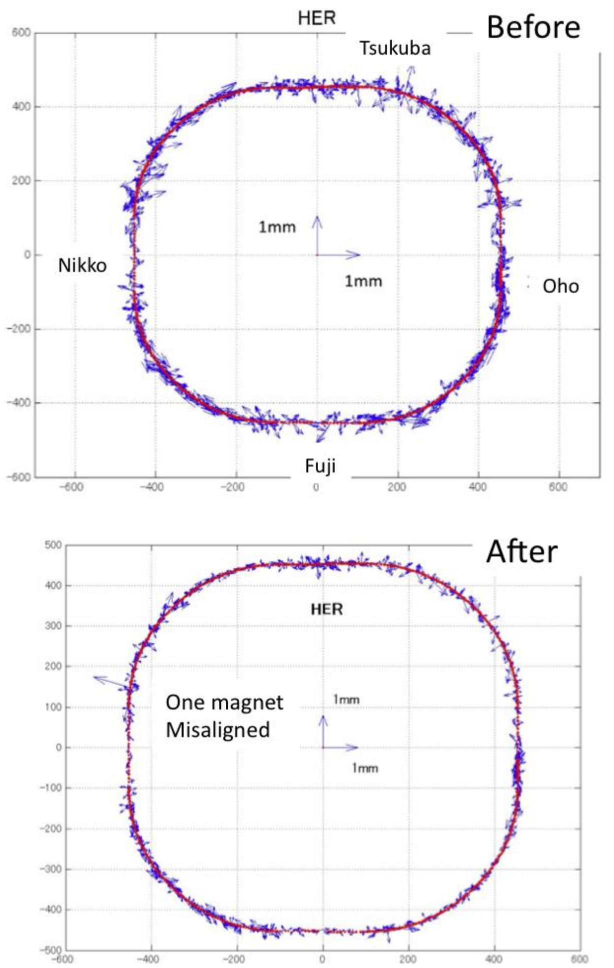

Figure 11: Magnet deviations in the HER before (top) and after (bottom) the alignment.

Table 1: Table 1: Alignment tolerances

Magnet type	dt (mm)	ds (mm)
Dipoles Wigglers	0.4	0.8
Quadrupoles Sextupoles	0.2	0.4

Circumference

Prediction of the circumference was important for achieving smooth circulation of the beam. The adjustments of the magnets mentioned above do not necessarily guarantee the circumference prediction to be correct. We estimated the circumference by using the magnet positions obtained from the network average calculation by PANDA and PAG-U. We also carried out a direct distance measurement using an AT401. The results are compared in Fig. 12. The distances between quadrupole magnets are calculated or measured and compared with the design values. The difference between the calculated/measured distance and the design is summed along the distance from the IP, anti-clockwise and plotted as a function of the distance from the IP in Fig.12. The calculation by PANDA agrees well with the direct distance measurement by AT401. Both predicted the circumference be larger than the SuperKEKB design by about 17 mm. We therefore told the beam operation team to pre-set the RF frequency to accommodate this difference. It should be noted that the KEKB ring was already about 10 mm larger than its design circumference, as indicated in Fig.13.

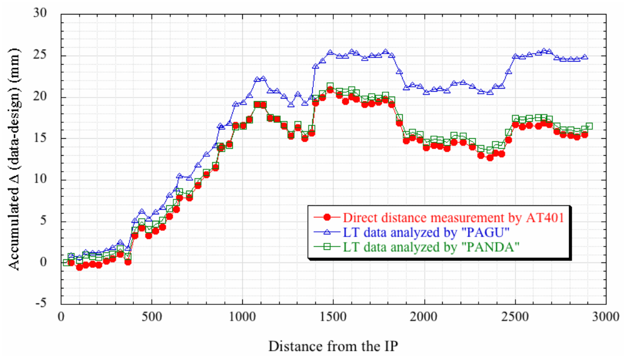

Figure 12: Distances between quadrupole magnets along the ring compared with the design distances. Solid circles are the direct distance measurements by AT401. The triangles and squares correspond to the calculations results from PAG-U and PANDA, respectively.

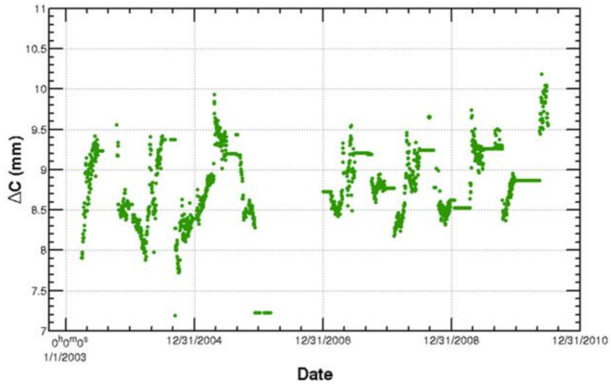

Figure 13: The circumference calculated from the RF frequency of the KEKB main ring. This indicates that the ring was already larger than the KEKB design by about 10 mm at the end of the KEKB operation.

RESULTS

The SuperKEKB Phase I operation started in February 2016. The LER was commissioned first, and the HER commissioning followed after about a week. The injection to the LER went very smoothly, and the circumference obtained agreed within 1 mm (0.3 ppm) with our PANDA/AT401 prediction. For the HER injection, we used the tunnel sinking data to pre-set the vertical steering magnets. The circulation was achieved by tuning a few steering magnets. This is an encouraging example of survey data actually being used for beam commissioning.

The circumferences of the two rings were obtained exactly by RF frequencies, and it was found that the difference between the LER and the HER is about 0.2 mm.

Our survey strategy worked well for the SuperKEKB Phase I commissioning, and contributed greatly to the very smooth start-up of the machine.

Phase I ended in June, 2016, and now we are preparing for Phase II, for which the final focus system with superconducting magnets is being installed. We have already installed one of the cryostats in the interaction region, after leveling the floor by the "self-leveling" method. The other cryostat will be ready and installed at the end of 2016.

Expanding the tunnel level monitoring system is also being considered.

REFERENCES

[1] M. Masuzawa, "Next Generation B-factories", IPAC 2010, Kyoto, May 2010, FRXBMH01, p. 4764, 2010
[2] Y. Funakoshi et al., "Beam Commissioning of SuperKEKB", IPAC 2016, Busan, May 2016, TUOBA01
[3] R. Ueki et al.," Sextupole magnets with variable tilt angles for SuperKEKB", proceedings of IWAA2016.
[4] T. Kawamoto et al., "Level Change in the SuperKEKB Main Ring Tunnel", proceedings of IWAA2016.
[5] http://www.geotec-gmbh.de/en/panda/
[6] ww.pasco.co.jp/products/lasertracker/ (Japanense)