Control survey for KEK e$^-$/e$^+$ Injector Linac

Y. Okayasu*, K. Kakihara, T. Suwada, M. Tanaka
High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
K. Hisazumi, K. Kimura, Y. Mizukawa, K. Suzuki, S. Ushimoto
Mitsubishi Electric System & Service Co. Ltd., 2-25-10 Umezono, Tsukuba, Ibaraki, 305-0045, Japan

Abstract

A conventional control survey technique using a laser tracker and a digital level has been finally introduced in the KEK e$^-$/e$^+$ injector linac in 2020. The control survey are continuously demonstrated in a machine down-time every summer. Analysis of two years data figures out a trend and a reproduction. In this contribution, systematic coordinates and their error distribution evaluated via the control survey are reported and newly encountered issues are discussed.

INTRODUCTION

The KEK e$^-$/e$^+$ Injector Linac (645-m long in total) in Tsukuba campus consists of 120-m straight section, 33-m arc section, which reverses its advancing direction, and 492-m straight section. The injector is divided into 60 units. Standard accelerator components, such as accelerator tubes, magnets, vacuum systems, and diagnostic systems are mounted on a so-called unit girder and installed in each unit.
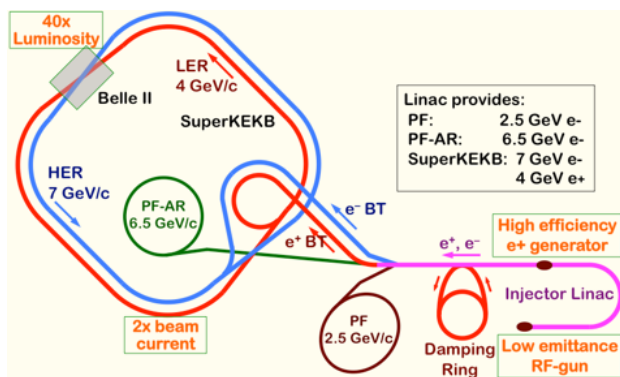

Figure 1: Schematics of the accelerator complex and their own beam energies in the KEK Tsukuba campus.

The injector simultaneously distributes electron or positron beams to total four different ring accelerators; Photon Factory (PF), PF-Advanced Ring (PF-AR), SuperKEKB high (HER) or low (LER) energy rings according to their own beam energies as described in Fig. 1.

Recent major activities of the KEK accelerator complex since the injector started its user operation are summarized as follows;

April 2009

PF/KEKB simultaneous top-up injection achieved.

June 2010

KEKB operation closed.

February 2016

SuperKEKB Phase I operation started with no beam collision.

March 2018

SuperKEKB Phase II operation started and the first beam collision achieved in April 2018.

March 2019

SuperKEKB Phase III operation started.

May 2020

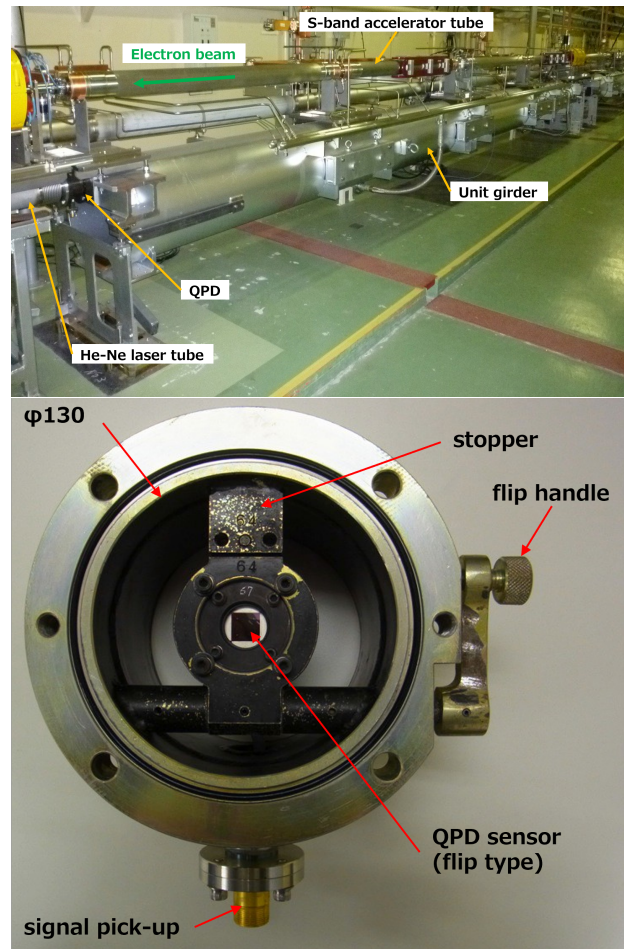The injector linac achieved 200,000 operation hours.

Figure 2: A beam line assembly in the KEK injector linac (*upper*) and QPD cross section (*lower*).

A goal of the SuperKEKB Phase III is to achieve a challenging luminosity of 6×10^{35} cm^{-2}s^{-1} and following normalized emittances are required to do so;
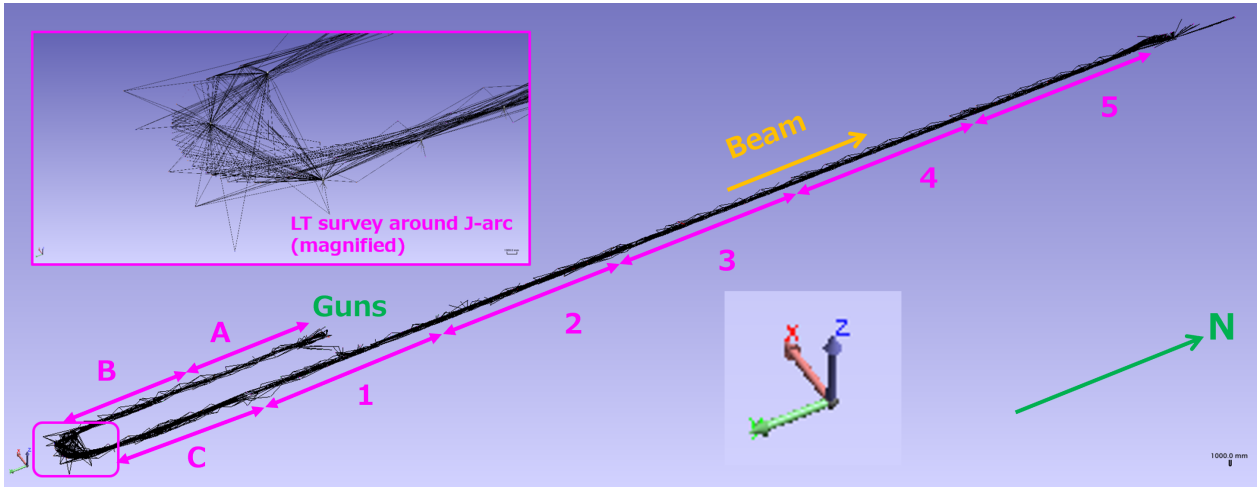
* okayasu@post.kek.jp

Figure 3: A schematic view of the control survey with the laser tracker demonstrated on 2021 in the KEK injector linac and a coordinate system definition.

Table 1: A summary of length, number of magnets and monuments on each sector. Numbers in parentheses are number of magnets which were surveyed on 2020.

	A	B	J-arc	C	1	2	3	4	5
Length [m]	48.0	76.8	36.1	81.6	83.3	92.9	69.9	79.5	76.8
# of magnets	65 (63)	14	35 (36)	18 (16)	74	90	20 (10)	16 (8)	34 (26)
# of monuments	15	19	10	21	32	32	17	19	20

e^+ : 100 (hol.) / 15 (ver.) μm,
e^- : 40 (hol.) / 20 (ver.) μm.

In order to realize these above emittances, alignment tolerances for magnets on each unit girder and neighboring two unit girders were settled as 50 μm and 100 μm, respectively. Note that these tolerances are tentative, more realistic ones are now under estimation.

Both in a construction and the SuperKEKB upgrade stages and recovery of the great east Japan earth quake on 2011, each unit girder was aligned with a He-Ne laser baseline and a quadrant photo-diode sensor (QPD), which is mounted on both ends of the girder, referring the laser pointing coordinates on the sensor [1] as shown in Fig. 2. A laser tracker (Leica AT-401) has been utilized for isolated magnets alignment until 2018.

A conventional control survey technique [2] using the laser tracker and a digital level (Trimble DiNi0.3) have been introduced in the KEK injector linac since 2020 and continuously demonstrated in a machine down-time every summer. For the control survey analysis, a geodetic line correction [3, 4], which is evaluated from both the laser QPD data and the control survey data, is applied for level data in addition to the conventional control survey analysis.

In this contribution, systematic coordinates and their error distribution are reported and newly encountered issues are discussed.

CONTROL SURVEY IN KEK ELECTRON/POSITRON INJECTOR LINAC

The conventional control survey with the laser tracker and the digital level has been continuously demonstrated every summer for all magnets, monuments on the wall, unit girders, and accelerator tubes (partially) in the KEK injector linac since 2020 as shown in Fig. 3. Spacial intervals and number of station points of the laser tracker and the digital level are ~10 m, 62 points and ~16 m, 21 points (43 points : round-trip), respectively. Especially for the level survey, we demonstrate the round-trip survey and apply a loop-closure correction for the survey data. The spacial control survey and analysis are demonstrated with Spacial Analyzer (SA, New River Kinematics) and all measurement point names are input via QR codes in order to avoid mistype and to improve work efficiency. On the other hand, level survey is controlled by Microsoft VBA macro through a bluetooth connection between the digital level and a computer. A network analysis is demonstrated by SA with weighted and the loop-closure corrected level data.

The injector linac, which consists of 60 units, is divided into 9 sectors from upstream and called as A, B, J-arc (arc section, J), C, 1–5, respectively. All sectors are mechanically connected by several expansion joints. A configuration of all the magnets and monuments are not periodic. Beam line and monument levels are 1200 mm and 1415–1890 mm (average : 1448 mm) from the floor level, respec-

tively. Length, number of magnets and monuments on each sector are summarized in Table 1.

SURVEY RESULTS

An analysis for two years' (2020 and 2021) control survey data are completed. Here, the coordinate system definition is as follows; the origin is set on a magnet (PX_A1_M) center which is located on the beam level at A sector. Note that, only A sector has a two-storied structure. One electron beam, which is associated with the positron generation, is emitted from upstairs by a thermal electron gun, the other from the beam line level by an RF photo-cathode electron gun. y-axis is defined with PX_A1_M and another magnet (QD_B7_4) which is located at the most downstream of B sector. x-axis is orthogonal to y-axis on the beam level plane and z-axis vertical as shown in Fig. 3.
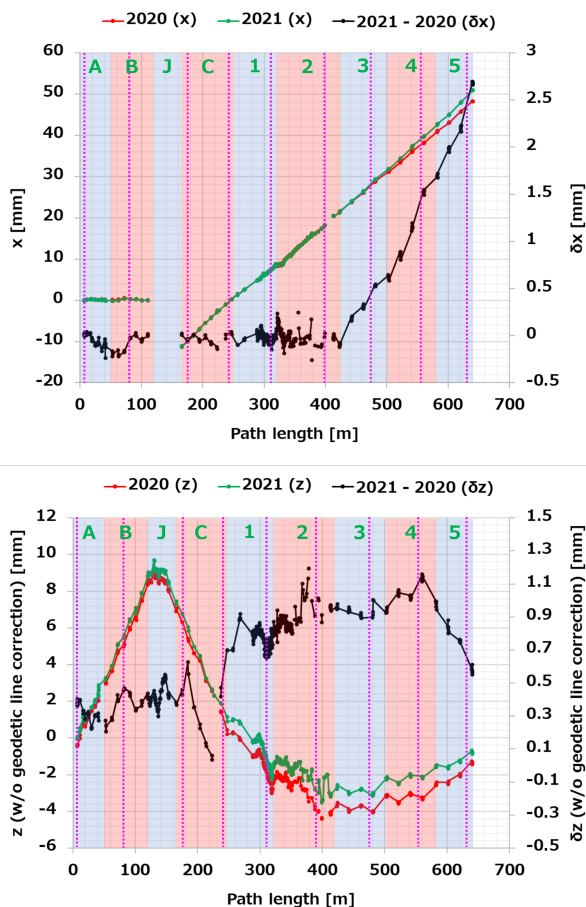

Figure 4: Evaluated x (*upper*) and z (*lower*) components which were surveyed on 2020 (*red*) and 2021 (*green*). Residuals of each component; δx and δz are overlaid as *black*-line. Hatchings and sector IDs are also overlaid for individual sectors. Positions of expansion joints are also shown as *magenta-dots*

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Fig. 4 compares x (*upper*) and z (*lower*) components surveyed on 2020 (*red*) and 2021 (*green*) and their resid-

uals (δx and δz, *black*) of all magnets along the path length of the injector linac. Positions of expansion joints are also overlaid as *magenta-dots* as reference. Here, the geodetic line corrections are not yet applied for z component. In each figure, hatchings are overlaid for individual sectors. Note that x components in J-arc are not displayed, and in C–5 sectors, x components are subtracted by -15000 mm which is corresponding to a designed distance from A–B and C–5 sectors in order to represent data in one scale. δx is increased up to 2.5 mm from 3 sector. Two candidates can be considered for the residual increase; 1) the number of magnets after 3 sector is different between 2020 and 2021 as shown in Table 1, and 2) building itself is deformed. Standard deviation for x components of both A–B and C–5 sectors are estimated as 146–152 μm and 372–522 μm, respectively, referring to straight lines which connect both ends of A–B and C–5 sectors. For z components without the geodetic line corrections, both 2020 and 2021 data have maximum at J-arc and minimum at 3 sectors. Two pulse magnets were newly installed in C sector on 2021, thus δz in C sector is discontinuous. Further discussion about z components are provided below with a treatment of the geodetic line correction.

Geodetic line correction for the level survey

As introduced above, the KEK injector linac has two straight sections; A–B sectors (∼120 m) and C–5 sectors (∼492 m), and each unit girder coordinates (x and z) have been measured by the He-Ne laser base-line and QPD sensors in between until 2018. Since the control survey also measures each QPD level, which is certainly depends on the geodetic line, the lines are evaluated from the QPD and the control survey level data sets for both two straight sections. Fig. 5 shows QPD levels measured by the laser baselines (*orange*, PD_level) and levels measured by the control survey after reducing PD_level (*blue*, dz) for A–B sectors (*upper*) and C–5 sectors (*lower*) along path lengths. The procedure for the geodetic line correction is as follows.

1. Fit the level data dz with a polynomial function.

2. Rotate the function as its levels at both ends correspond to ones by the laser base-line measurement (PD_level)

3. Subtract the rotated function from all magnet levels measured by the control survey on the straight section.

Fitting functions are also overlaid on each histograms in Fig. 5. Note that, the geodetic line correction is not applied for J-arc section.

After the geodetic line correction, levels (z) of all magnets in the injector linac measured on 2020 (*red*) and 2021 (*green*) are compared and their residuals (*black*, δz) are also overlaid in Fig. 6. The beam line level corresponds to $z = 0$ mm. Standard deviation of levels estimated as ∼425 μm and maximum difference ∼1.6 mm from the beam line are evaluated in J-arc. As noticed above, newly installed two pulse magnets at the end of C sector in 2021
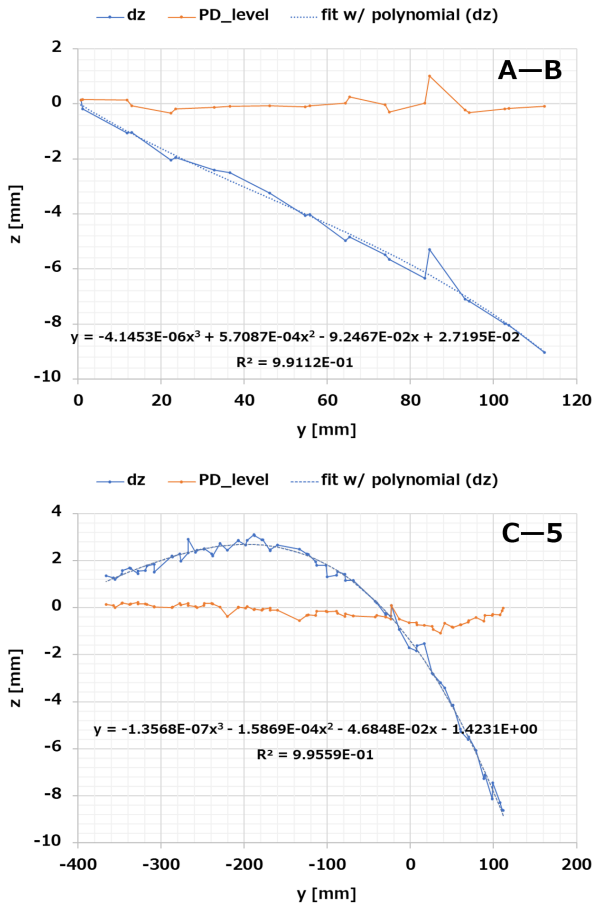
Figure 5: QPD levels measured by the laser base-line (*orange*, *PD_level*) and levels measured by the control survey after reducing *PD_level* (*blue*, *dz*) for A–B sectors (*upper*) and C–5 sectors (*lower*). Fitting functions (*blue-dots*) and χ-squares are also overlaid.
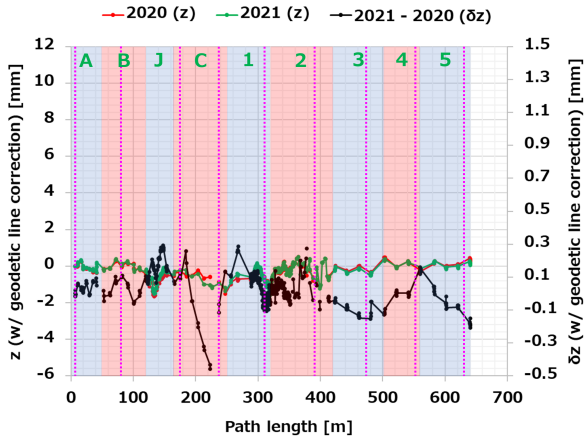

Figure 6: Evaluated magnet levels z with the geodetic line correction are compared between 2020 (*red*) and 2021 (*green*) survey. Level residuals (*black*) of the two years are also overlaid. *Magenta-dots* are positions of expansion joints.

reflect the discontinuity of residuals δz at the corresponding area. Also this installation is considered as one candidate to cause the drastic decrease of δz at the end of C sector.

Comparison with designed coordinates

Next, residuals of horizontal coordinates (Δx (*blue*) and Δy (*red*)) between two years of survey data; 2020 (*upper*) and 2021 (*lower*) and designed one are compared and shown in Fig. 7.
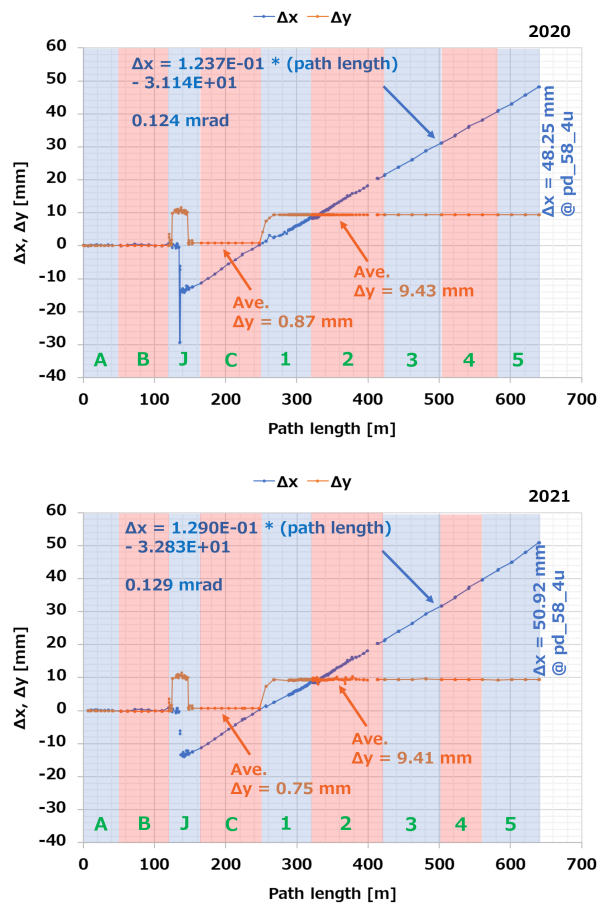

Figure 7: Residuals between survey and designed data of the horizontal coordinates Δx (*blue*) and Δy (*red*) are compared with 2020 (*upper*) and 2021 (*lower*).

It is found that Δx for both 2020 and 2021 lean to west with slopes of 0.12 and 0.13 mrad from C sector. This slope indicates that a designed reverse angle of 180° at J-arc is not strictly reproduced in actual alignment and the slope of 0.11 mrad was already recognized at the installation stage which could not be modified due to the approaching SuperKEKB operation. On the other hand, Δy has constant displacements of ~10 mm in J-arc and below 1 sector. The former is considered that magnet alignments are not reflected as designed ones and the latter is already found that designed coordinates in the 3D models are not correct.
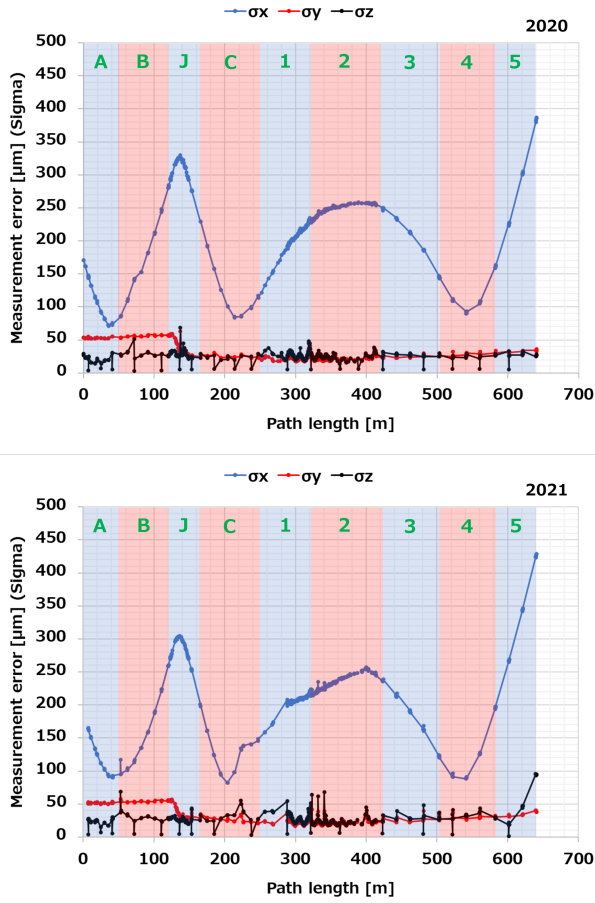
Figure 8: Uncertainties of evaluated three dimensional coordinates σ_x (*blue*), σ_y (*red*), and σ_z (*black*) via the network analysis using SA are compared with 2020 (*upper*) and 2021 (*lower*).

Evaluated uncertainties of the control survey

Uncertainties of evaluated three dimensional coordinates σ_x (*blue*), σ_y (*red*), and σ_z (*black*) via the network analysis using SA are compared with 2020 (*upper*) and 2021 (*lower*) in Fig. 8.

σ_x has minimums at a boundary of A and B sectors, C sector and 4 sector while maximums at J-arc and 2 sector in each year. σ_x of both year gradually increase from 4 sector up to 390–430 μm. This increase is considered to be a relative lack of magnet and monument point densities in 3–5 sectors. Furthermore, σ_x distributions of 2020 and 2021 are different especially in C–2 sectors which is considered as a contribution of an additional tracker station point located on 2021 in a bypass directly connecting A and 1 sectors. On the other hand, σ_y have relatively higher constant uncertainties of ~50 μm from A sector to a center of J-arc for both 2020 and 2021. One candidate of reasons for this phenomenon is considered as a difference of air conditioning controls in the corresponding area where the building

was extended as SuperKEKB upgrades. σ_z distributions have no remarkable difference in between 2020 and 2021 while a slight increase can be recognized in 5 sector for 2021 data.

SUMMARY

The conventional control survey with the laser tracker and digital level has been introduced in KEK e$^-$/e$^+$ injector linac since 2020 and continuously demonstrated every summer. It is found that standard deviations of horizontal coordinates x in A–B sections and C–5 sections are 146–152 μm and 372–522 μm, respectively while vertical z with the geodetic line correction is 423–428 μm for entire region. The residual of x between 2020 and 2021 gradually increases from 3 sector up to ~2.5 mm which is considered as the effect of increase of magnet control points in 2021.

Residuals of the survey data sets and designed ones for horizontal Δx and Δy are compared between 2020 and 2021. For both years, Δx has a slope of 0.12 or 0.13 mrad in west direction in the latter straight section from C–5 sectors which is due to the reverse designed angle of 180° was not strictly reproduced in the initial construction stage. Δy has the constant displacement of ~10 mm in J-arc and below 1 sector. The former is considered that magnet alignments are not reflected as designed ones and the latter is due to the incorrect designed coordinates in the 3D models.

Uncertainty distributions of horizontal σ_x are different between 2020 and 2021. The additional tracker station point in bypass, which directly connects A and 1 sectors, can be considered to affect the deformation of the distribution. σ_y distributions of both 2020 and 2021 have the constant uncertainties of ~50 μm from A sector to the center of J-arc where the building was extended as SuperKEKB upgrades and its air condition systems are different to other sections. σ_z distributions of both 2020 and 2021 have no distinguished difference.

Since the configuration of monument points are currently not periodic, number of control points and station points has still a room for optimization and a numerical calculation with SA are under going to do so.

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