REFINEMENT OF ARC ALIGNMENT BETWEEN TWO STRAIGHT SECTIONS FOR INJECTOR LINAC OF SUPERKEKB

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Abstract

The beam line of the KEKB injector linac is under re-alignment as the restoration after the big Earthquake in 2011, but with the refinement for the SuperKEKB in mind. The linac consists of two straight sections connected by a 180 degree ARC. Precise alignment of the ARC magnets is one of the key issues for the emittance preservation of the electron beam. The ARC beam line was defined by measuring these two straight lines. Then, the misalignment of the ARC magnets were reduced from 3 mm maximum down to 0.1mm in the errors perpendicular to the beam direction. This paper describes how we defined the ARC beam line and performed the alignment. The connection method of the laser tracker data needed for the definition of the ARC was also studied and described.

INTRODUCTION

The injector linac of KEKB is a 600-m-long linear accelerator consisting of 8 sectors[1]. As shown in Figure1, it comprises of the upstream 1.5 GeV linac with a length of 100 m (A, B sector) followed by the downstream 5.5 GeV linac with a length of 500 m (C, 1-5 sector) connected through a 180 degree ARC with a radius of 7.5 m.

Each sector is about 80 m and comprised of 8 accelerator units. In each unit the hard wares such as the accelerator tubes are set on a rigid girder of 9 m in length. The axis 420 mm down from and parallel to the beam axis is used for the alignment and defined by a laser beam whose position is measured by the segmented photo-diode (PD) detector[2] attached to the reference point located at each end of the girder.

For the emittance preservation in the injector linac of SuperKEKB[4], the local misalignment at the straight section is required to be within 0.1 mm in sigma, while global one with 0.3 mm in sigma[5]. On the other hand, the ARC magnets are set on the independent support structures and aligned independently. In order to suppress the emittance growth due to the perturbation given from the ARC misalignment, the magnet alignment is required to be within 0.1 mm. Since the misalignment of the ARC became up to 3 mm in maximum after the big Earthquake, the realignment is needed. The ARC configuration can be the same as KEKB but the refinement of the alignment is required[3]. We decided to re-define the ARC orbit design to minimize the hardware movement by taking the mutual relation between two straight sections into account. From the measurement we noticed that the bending angle was not 180 degrees so that we adopted this value for the new orbit design. On the other hand, the ARC was originally set in the horizontal plane but this time we defined the plane in the same as that of the two straight sections to get rid of the vertical kicks at the input and output of the ARC. Though the optical telescope was used to align the hard wares in the KEKB construction time, it became possible this time to align the hard wares more accurately and easily by using a laser tracker, AT401 of Leica[6]. In order to measure with the accuracy of several μrad and several μm for the alignment measurement of the ARC with its size of 15 m, the laser tracker we introduced this time was appropriate since the typical errors are ± 7.5 μm + 3 μm/m in angle, and ± 5 μm in length.

The measurement extending to 100 m distance is required for evaluation of the two straight sections. Though the tracker measurable span is ± 80 m, we thought that the alignment measurement with connecting the ± 10 m-span measurements shown in Fugure2 was better to get the 100 m-size information when considering the big errors coming from the environmental perturbations. To utilize this method, the tool to connect many short-span data to integrate into a long-span measurement became important. We have developed a method to accurately estimate with small errors by evaluating the actual measured data. This process is also described.

Following above strategy, we made the alignment of all ARC magnets, 6 bending magnets (BM),????? 13 quadrupole magnets (QM), and 5 sextupole magnets (SM). In order to use the tracker reflectors, the reflector holder bases were set on the floor, the wall, and at the arm end extending form laser PD. For magnets, three holder bases were on BM, while two on QM and one on SM.

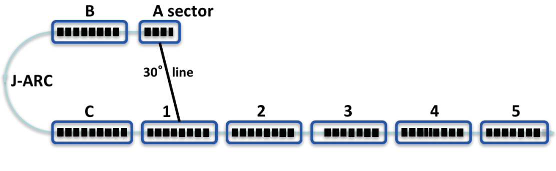

Figure 1: The outline drawing of injector linac.

DEFINITION OF ARC REFERENCE ORBIT

Before aligning the ARC, we measured B sector, ARC, and C sector with the laser tracker in June, 2013(Figure 2) and determined the two straight lines.

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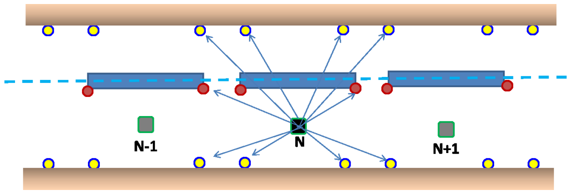


Figure 2: Measurements using a laser tracker. Blue boxes are accelerator units, red circles are tracker reflectors on PD, yellow ones reflectors on wall. Green squares are locations where laser tracker is set.

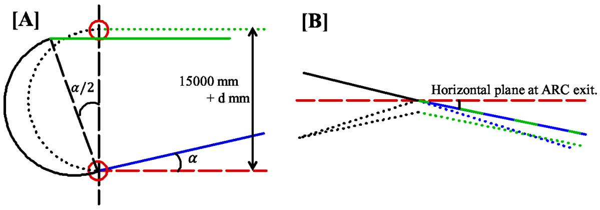


Figure 3: A is plane view, while B is the view seen from the side. The green line is A to B sector, while the blue line is C to 5 sector. Dotted lines are for KEKB while solid lines for SuperKEKB.

Definition of Rotation Plane

Firstly, the distance between the two straight sections at the ARC, i.e. the distance between the inlet point and the outlet point of the ARC, was measured to be 15 m + d = 15013 mm. The design value was 15 m but we defined the new design distance to be that with this extra ”d”.

Secondly, the angle between the two straight lines was measured so that the rotation angle along the ARC was set at this value, instead of the previous design value of 180 degrees. The measured angle offset was α=+0.114 mrad. In addition, the upstream linac section, sector A-B, was measured and found to be tangential to the ARC at the inlet point. In order to make the configuration of the two straight lines and ARC to be mirror symmetric with respect to the center line between two straight sections, the ARC was rotated by $\alpha/2$ as shown in Figure3-A.

As for the deflection angles of 6 BMs, those of the 2nd, 3rd, 4th, and 5th were set at 30 degrees, while those of the 1st and 6th at 30 degrees $+\alpha/2$.

Definition of Vertical Plane

Since the longer (downstream) one of the two straight sections connects the beginning of the C sector to the end of the 5th sector, the original ARC plane set at horizontal for KEKB in inclined with respect to the straight section. As shown in Figure3-B, the angle γ amounted to be 0.0498 mrad. As the third definition, the inclination angle of the ARC with respect to the horizontal plane was set at this value. Accordingly, it became necessary to largely move the magnets upward. Furthermore, there was found a difference of about 1 mm in height between the two straight sections, and at the ARC. Then, we have defined the height of the start and end points of the ARC to be the same as the connection point to the A-B sector.

Magnet alignment

After defining the magnet positions, the adjustment was performed with frequently tracking the position by using a laser tracker. The refinement result is shown in Figure 4 for the vertical direction. Deviations from the design value were mostly within 0.1 mm for the directions perpendicular to the beam line. Figure 5 shows the difference in the horizontal plane. For QM outside the ARC in Figure 5, we have not adjusted in the direction along the beam line. Therefore, the error vector in this direction stayed large. When performing a survey of the ARC section after finishing all of the alignment work, a displacement larger than 0.1 mm was detected. We found that the measurement coordinate system of the laser tracker was rotated by 0.3-0.5 mm / 8 m in the horizontal plane during a day. Because the beam commissioning had started just after this alignment, we have not fixed this deviation yet. As described in the next section, it should be possible to keep the angular parameters more accurately and we are planning perform the alignment again in future.

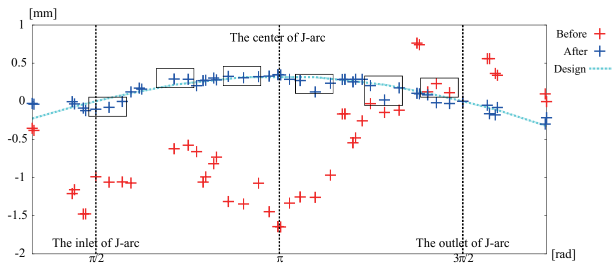
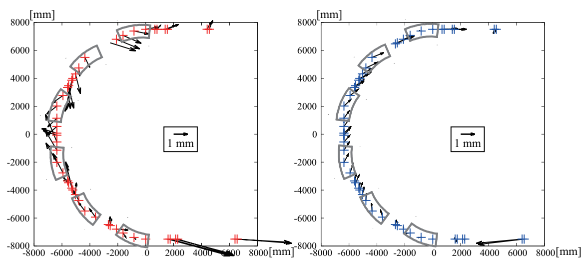


Figure 4: Measured height of magnets. Red + are before alignment work, while blue + are after work. Blue line shows design value and gray boxes are position of BMs.



[A] Before. [B] After.

Figure 5: Magnet positions in ARC plane. A is before realignment, while B is after. Vectors are differences between magnet positions and design values. Gray boxes show BMs.

CONNECTION METHOD OF TRACKER MEASUREMENTS

To combine the short-span laser tracker data into a common coordinate system, we have used the following three methods for evaluating coordinate transformation matrices of two measurements of adjacent tracker locations.

Method 0

For a preliminary determination of the angle parameters α and γ for the ARC magnet realignment, we used the software, "Polyworks v12"[7] by InnovMetric Software Inc., recommended by LEICA for the data connection. Nevertheless, accuracy of the calculate positions of the data points were not clear. Hence, we have developed the following two methods and compared the results.

Method I

First, a set of four points are selected out of the common points from measurements at locations 1 and those at 2 to calculate the coordinate transformation. The matrix $\mathbf{M}$ is defined as a homogeneous coordinate transformation of 12 parameters, including linear transformation for the XYZ coordinate system and parallel translation. We can obtain the matrix $\mathbf{M}$ by solving the linear equation as shown below by requiring that the four points overlap.

$$\mathbf{B} = \mathbf{MA} \tag{1}$$

$$\mathbf{A} = \begin{pmatrix} x & y & z & 1 \end{pmatrix}^T, \mathbf{B} = \begin{pmatrix} x' & y' & z' & 1 \end{pmatrix}^T$$

Here $\mathbf{A}$ is the homogeneous coordinate value of the common point at the location 1, while $\mathbf{B}$ is those at the location 2. All the possible combinations are calculated and we cite the matrix which gives the smallest sum of squares of the residual for all the points other than the four point.

Method II

The transformation matrix $\mathbf{M}$ is the same as the method I. However, we calculate the χ^2 value of the data from all of the common points as shown below.

$$\chi^2 = \sum_{i=1}^{n} (\mathbf{B} - \mathbf{MA}), \tag{2}$$

where n is the number of common points. We obtain the $\mathbf{M}$ by minimizing this.

Connection Result

We applied these three methods to the laser tracker data, determined the orientations of the two straight sections and evaluated the angle parameters α and γ. The method 0, I, II gave slightly different values ranging as α=0.11-0.16 and γ=0.050-0.086. Here, we could not have any confident criteria which result to cite. Then, in order to check the accuracy of the coordinate transformation in the method above, we measured again wider region from A-B sector to C-1-2 sector through ARC. Note that in this measurement region, there was included a straight line connecting a point at sector 1 to another point at sector A (30° line in Figure1). Then a closed loop is formed, so that the deviation of the end point from the start point, actually the same point, indicates the degree of error in doing connection of many data. A deviation of 6 mm was obtained in the horizontal direction by the method I, while that of the method II within 1.5 mm, smaller than the former but still remains big. Thus, we could not get any confidence at this stage and we concluded that the measurement method and the connection method to calculate the transformation matrix should further be improved.

SUMMARY AND PERSPECTIVE

For the upgrade to SuperKEKB, the misalignment of the beam line components in the straight lines of the injector linac are required to be locally within 0.1 mm in sigma. In turn, the magnets of ARC are required to set within 0.1mm and the laser-tracker based present method can meet the requirement. For doing this alignment, the ARC design orbit was determined by measuring two straight sections of the linac and trying to define the ARC plane and bending angle to be close to the present situation. Because we could not solve a problem when using the laser tracker for a long time, we will realign the ARC in the future especially the location of the large errors. Furthermore, it is necessary to obtain the better tool to connect the accurately measured data to estimate the alignment along long straight lines. Aiming to this accuracy improvement, we started the development of the data processing system. A transformation system by taking the minimum χ^2 value gave us a better result but we think that the tracker measurement method and the calculation of the transformation matrix should be improved.

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