Installation and Alignment of KEKB Magnets

R. Sugahara†, M. Masuzawa† , Y. Ohsawa†, M. Sakai‡ and H. Yamashita‡
† High Energy Accelerator Research Organization (KEK),
1-1 Oho, Tsukuba-shi, Ibaraki 305-0801, Japan
‡ Hitachi Techno Co. Ltd., 7-23-5 Minami Senjyu, Arakawa-ku, Tokyo 116-0003, Japan

1. INTRODUCTION

The KEKB is an asymmetric-energy electron-positron two ring collider [1] built to do experiments on CP violation in B particle decays [2]. The KEKB main ring consists of 8 GeV electron ring and 3.5 GeV positron ring, which were constructed in the pre-existing TRISTAN tunnel. Each ring has a circumference of about 3 km. The ring tunnel has four arc sections (north, west, south and east arcs) and four straight sections (Tsukuba, Nikko, Fuji and Oho sections). The length of a straight section is about 200 m. About 1,600 main magnets and about 1,700 steering magnets needed to be installed.

TRISTAN operation was terminated at the end of December 1995. All the magnets and other accelerator elements were removed from the tunnel in January 1996, and the construction of the KEKB ring was started.

Fabrication of the first batch of magnets was ordered in July 1995, and the final batch was delivered in March 1998. The magnetic field in all the main magnets were measured during the period from December 1996 to May 1998 [3-5].

2. PREPARATION

2.1 3-D CAD System

In designing the ring a three-dimensional CAD system was used to check for interference between magnets, and also between magnets and the tunnel structure. A two dimensional drawing of the arrangement of magnets in the tunnel was made. A three dimensional drawing of the tunnel was also made, and the real shapes of the magnets were arranged in it. As a result of the investigations, some supports for cooling water pipes had to be modified, and some valves had to be rearranged.

2.2 Magnet Transporters

It was not easy to design magnet transporters, because the path in the tunnel is narrow (1.2m wide and 2.3m high) and so many magnets had to be transported in such a limited time. Finally two sets of hover-craft type transporters were adopted. By making the surface of the floor smooth, the friction between the transporter and the floor is kept to a minimum. Merits of this type of transporter are:
(1) Height is low, because there are no wheels.
(2) It can be guided by compact guiding rails.
(3) There is little noise.
(4) It can be moved with little force.
(5) There is almost no damage to the floor.
On the other hand, the demerit is that the air compressor requires electric power as large as 15 kW.
The transporters are supplied with electric power by 200V×200A three-phase power lines installed beneath the cable rack located above the path.

2.3 Beam Level Markers

Beam level markers were installed on the tunnel wall at intervals of about 30 m in November and December 1995. These show the level of the center axis of the TRISTAN quadrupole magnets. Surveys of the height of the markers were carried out several times. Results of the surveys in July 1996, September 1997, and February and October 1998 are shown in Figures 1 and 2. After the survey in September 1997, all the markers were adjusted level. From the surveys it was found that the south arc was sinking a few milli-meters per year.

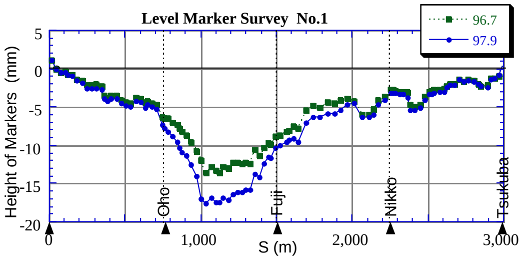


Figure 1: Height of level markers surveyed in July 1996 (solid squares) and September 1997 (solid circles). Horizontal axis, S, is the distance along the circumference of the ring.

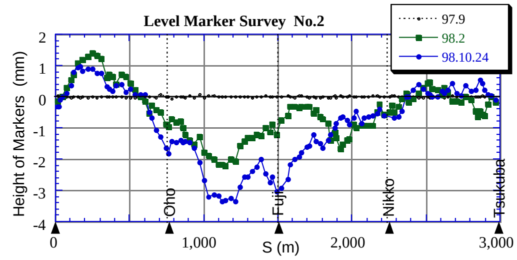


Figure 2: Height of level markers surveyed in February (solid squares) and October (solid circles) 1997. Each marker had been adjusted level in September 1997.

2.4 Reference Markers for Horizontal Position

Monuments for the center positions of TRISTAN quadrupole magnets installed in the tunnel floor were used as the reference markers for the horizontal positions of the KEKB magnets. The deviation of each marker from the TRISTAN lattice was measured by a laser tracker during the period from April to July 1996, and the coordinates for the markers were corrected. It was advantageous to use the TRISTAN monuments as references to minimize the error in the circumference because the circumference of the TRISTAN ring had been measured precisely by beams. But results from the first alignment of magnets in the north and west arcs were not good. Analyzing results, it was found that the errors were caused by thermal expansion of the tunnel floor. The air conditioner was turned

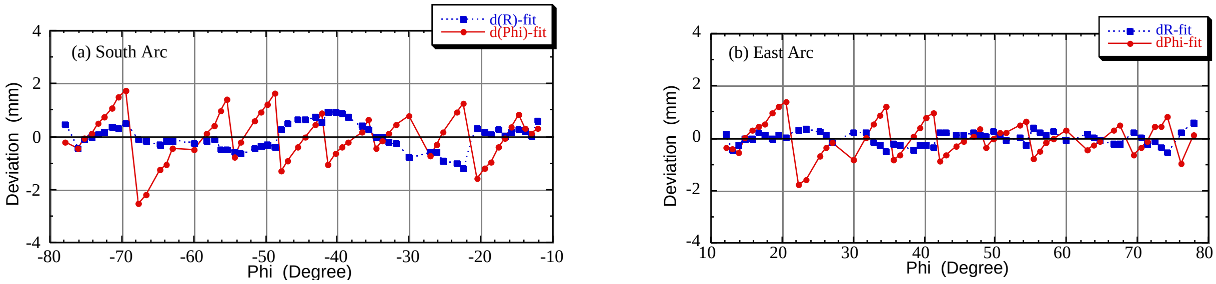


Figure 3: Results of second survey of the positions for the horizontal reference markers (a) in the south arc and (b) in the east arc. Deviations from the previous coordinate in the radial direction of the ring are shown by solid squares and those along the circumference by solid circles. The horizontal axis shows the azimuthal angle of the magnet positions in the KEKB ring. Zero degrees corresponds to the center of the Oho straight section.

off and the temperature was about 18°C at the time of the survey of the TRISTAN monuments on the floor. Later the air conditioner was turned on, and the temperature has been kept constant at around 24°C. The difference of about 6°C caused change in the length of the tunnel sections of a few milli-meters, where each section has a length of about 60 m. In the south and east arcs the reference marker positions were remeasured before the first alignment. The results are shown in Figure 3. Large errors caused by the thermal expansion of the tunnel floor can be seen in the direction along the circumference.

3. INSTALLATION OF MAGNETS

Magnet transporters were delivered in January 1997 and set-up. Installation of magnets began just after the kickoff ceremony for magnet installation held on February 26, 1997. Taking about one and a half years, the last magnet was installed in August 1998.

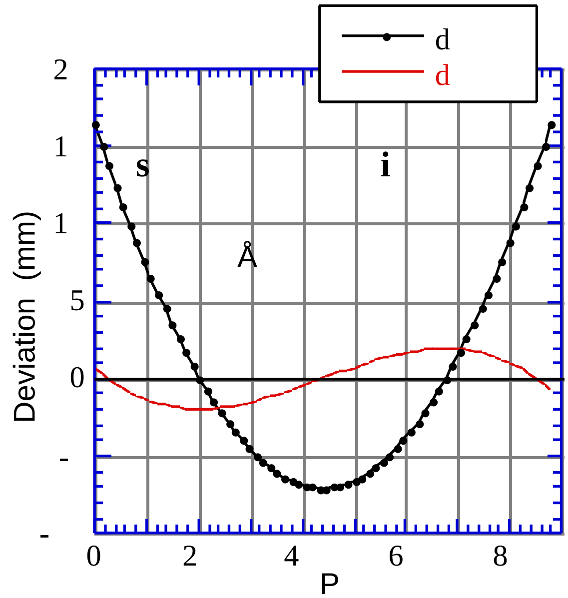
4. ALIGNMENT OF MAGNETS

4.1 Instruments

Leveling telescopes, Wild N3s, were used to measure heights. They have a range of ±5 mm, and a least count of 0.1 mm/div. The level was measured with a Carl Zeiss level, which has a range of ±10 mrad and a least count of 0.01 mrad/div. In the alignment of the positions in the horizontal plane, different techniques were adopted for the straight sections and the arc sections. In the arc sections Leica laser trackers [6,7] were used, which can measure three-dimensional coordinates. These have a range of ±20 m and a precision of 5 μm along the laser beam direction and 10 μrad in vertical and horizontal angle measurements. In the straight sections a Fogale Nanotech stretched wire system was used to measure positions perpendicular to the beam line and a mekometer, Leica ME5000, was used to measure distances between magnets. The stretched wire system has a precision of 30 μm, and the mekometer has a precision of 0.2 mm for the distance less than 200 m.

4.2 Correction for the Tracker Errors in the Multi-station Mode

As the range of the laser tracker is ±20 m, positions of the monuments or the magnets were measured in the multi-station mode. That is, the measurement in the arc section or in the Tsukuba straight section consists of some number of measurement sets, each of which covers the area of ±20 m. About a half of them overlaps with the adjacent set. Utilizing the overlapping points, all the measurement sets were connected. But the systematic error accumulates in this method. Figure 4 shows the result of a simulation for this accumulation of systematic errors in the survey of an arc section. In this simulation, the systematic error, as small as 5 ppm, is introduced in the angle measurement, and each set of data points is connected in the same way to treat real data. The vertical axis shows the deviation of the coordinates of the data points from the designed values. dR shows the deviation in the radial direction and dPhi the one along the circumference of the ring. The horizontal axis shows the azimuthal angle in the KEKB ring. These deviation curves were fitted to polynomials: a polynomial of degree 4 for dR and that of degree 3 for dPhi. The residuals in this fitting are shown in Figure 5. They are small enough. So the deviations of the measured data with the laser tracker were corrected by fitting to a polynomial of degree 4 for the radial deviations and a polynomial of degree 3 for the deviations along the circumference. Even if some distortion is left by this correction, it is unnecessary to worry about because such a smooth distortion of the ring is corrected easily by the correction magnets. Figure 6 shows the deviations of magnet positions in the HER and LER from the designed values after the first alignment in the east arc section. Almost the same deviation curves are seen between the simulation and the real measurement.



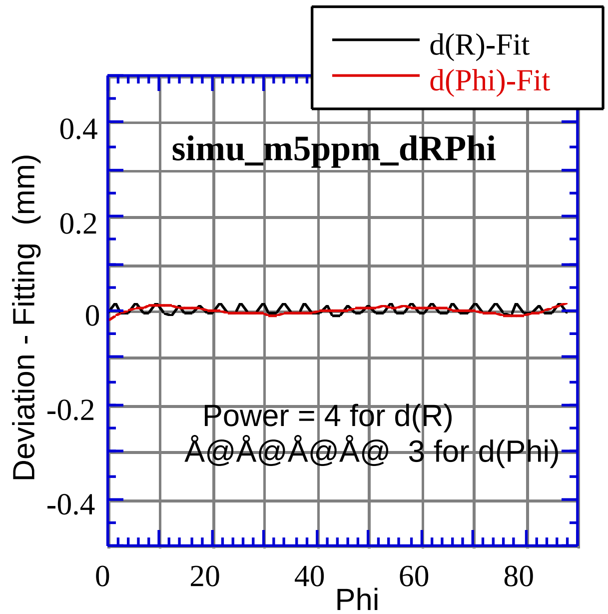


Figure 4: The simulated deviation of measured data points in an arc section caused by small systematic errors in the angle measurement with the laser tracker. The deviation in the radial direction, dR, is shown by the solid line with solid circles, and the other solid line shows the deviation along the circumference of the ring, dPhi.

Figure 5: The residuals in the fitting of the simulated deviations to a polynomial of degree 4 for dR, and that of degree 3 for dPhi.

Table 1: Tolerances for alignment errors

Horizontal position	
Perpendicular to the beam line	0.15 mm
Along the beam line	0.5 mm
Height	0.15 mm
Level	0.1 mrad
Circumference	10 mm

4.3 Alignment

Tolerances for alignment errors are listed in Table 1. Although the tolerance for the circumference is difficult to achieve, it was thought that the error should be small because the error in the circumference of the TRISTAN ring had been known to be less than 1 mm and the monuments for the center positions of the TRISTAN quadrupole magnets were used as the reference markers

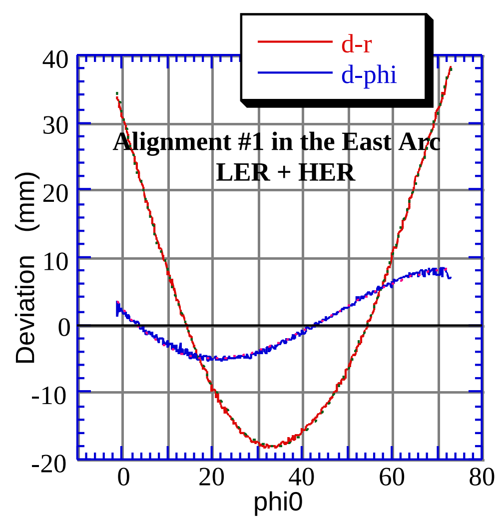


Figure 6: Deviations of magnet positions in the LER and HER from the designed values after the first alignment in the east arc section. The larger deviation show those of dR, and the other those of dPhi.

for the KEKB beam lines. After the beam commissioning the circumference was obtained from beam operation. The difference in the circumference between the measured value and the designed one is +5.1 mm for the LER and +5.4 mm for the HER. The alignment of magnets was started in each arc and straight section independently using reference markers on the tunnel wall for height and those on the floor for horizontal position. The alignment of magnets was repeated three times in the north and west arcs because of the thermal expansion of the tunnel. On the other hand, the alignment in the other areas converged in two repetitions, the first alignment and its fine correction, because the error caused by the thermal expansion of the tunnel was corrected beforehand. As an example, results for alignment in the west arc are shown in Figure 7. The vertical axis shows the deviation of magnet position from its designed value. Histograms of these deviations are shown in Figure 8. It can be seen that the standard deviation for these distributions is less than 0.15 mm both in the radial direction and along the circumference of the ring. The standard deviation for alignment errors in each section is summarized in Table 2. It can be seen that errors well satisfy the tolerances listed in Table 1. As the alignment was carried out independently in each section, there are some kinks in the beam lines in each connection area between an arc section and a straight section. Values are listed in Table 3. The kink of 0.09 mrad in the connection area between the west arc and the Nikko straight section (Nikko Left side) is the largest. Consulting with the members of the beam optics group, those values were found to be tolerable.

Table 1: Tolerances for alignment errors

Horizontal position	
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Along the beam line	0.5 mm
Height	0.15 mm
Level	0.1 mrad
Circumference	10 mm

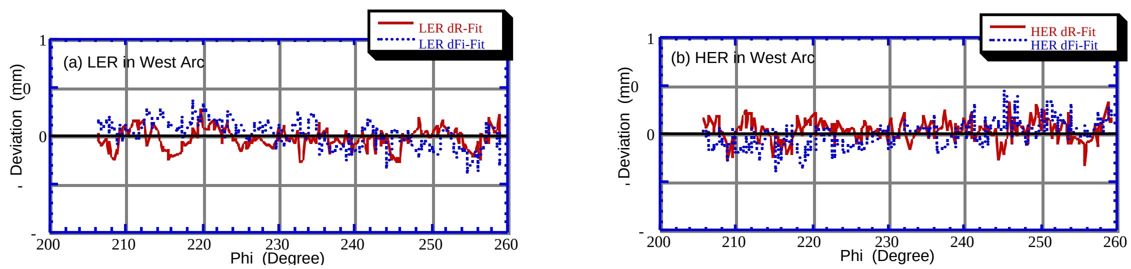

Fig. 7: Results of magnet alignment in the west arc for (a) LER and (b) HER. Vertical axis shows the deviation of magnet position from the designed value. Deviation in the radial direction is shown by solid lines and that along the circumference is shown by dotted lines.

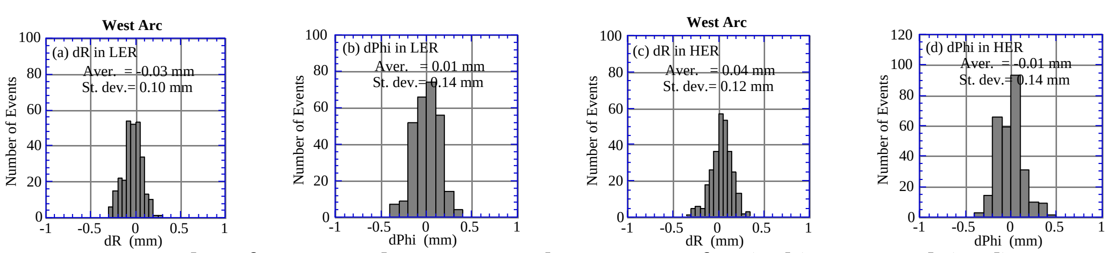

Figure 8: Results of magnet alignment in the west arc for (a, b) LER and (c, d) HER. (a) and (c) show the deviation in the radial direction, dR. (b) and (d) show the deviation along the circumference, dPhi.

Table 2: Summary of the standard deviations of the alignment errors. The units are milli-meters.

	LER		HER	
Area	dR	dPhi	dR	dPhi
Tsukuba	0.08	0.09	(<-- LER + HER)	
North Arc	0.09	0.12	0.10	0.10
West Arc	0.11	0.14	0.12	0.14
South Arc	0.09	0.10	0.11	0.10
East Arc	0.10	0.17	0.11	0.16
All Arc Sections	0.10	0.14	0.11	0.13
Nikko	0.01	0.27	0.03	0.11
Fuji	0.01	0.27	0.03	0.19
Oho	0.04	0.08	0.03	0.14
All Straight Sect.	0.02	0.22	0.03	0.15
Tolerance	0.15	0.50	0.15	0.50

5. SUMMARY

The installation and alignment of the KEKB magnets were difficult tasks as the available time was very limited and the required precision for alignment was relatively high as shown in Table 1. The job was accomplished in three years. Two sets of laser trackers were used in the alignment of the arc sections. In the straight sections a stretched wire system and a mekometer were used. Errors in the circumference are +5.1 mm for the LER and +5.4 mm for the HER. Alignment errors for the magnets are well below tolerances as shown in Table 2.

Table 3: Kink angles of the beam line in the connection areas between arc sections and straight sections.

Area	R-side (mrad)	L-side (mrad)
Tsukuba	0.04	0.04
Nikko	< 0.01	0.09
Fuji	0.07	< 0.01
Oho	0.05	< 0.01

6. ACKNOWLEDGMENT

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