PRECISE ALIGNMENT OF MAGNETS IN THE TRISTAN MAIN RING

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The magnets of a synchrotron ring require a high positional accuracy to reduce a closed orbit distortion. To obtain the satisfactory results, the magnets were installed at the fairly accurate places at first according to an elaborate survey before the installation and aligned accurately according to the results of the precise survey. The misalignment of magnets decreased gradually with the repeated cycles of the survey and re-alignment procedures. The installation of the magnets in the TRISTAN main ring began in August, 1984 and the precise alignment finished at the beginning of October, 1986.

Introduction

The TRISTAN main ring is a electron-positron colliding synchrotron having the circumference of 3 km. Its construction was divided into two periods. The main ring tunnel is composed of four sections — that is, west, north, east and south tunnels — and four experimental halls where the electron-positron collisions take place are placed between two sections. Initially, a part of west and south tunnels, one fourth of the circumference altogether, was completed in July of 1984 and then the installation program started leaving both ends of the partially completed tunnel open. The next installation in the rest of the tunnel was delayed after the completion of whole tunnel which was due in May of the following year.

Prior to the installation the coordinates of the magnets were marked by the geographical survey with an accuracy of ± 1 mm. The tunnel floor is 11 m underground. As it was constructed excavating the ground deeply, several standard points of survey were marked on the floor while it could be looked down from the surface. They were used to determine the positions of all bending and quadrupole magnets after the completion of the tunnel.

The markings of the projected coordinates of the entrance and exit centers of the magnet aperture allowed easy placement. Magnets were hoisted down into the tunnel at the installation halls and carried by the special carriages to their places. The rate of installation was 10 bending magnets or 20 quadrupole magnets a day.

The TRISTAN main ring consists of 272 bending, 392 quadrupole, 240 sextupole and 256 steering magnets [1]. The bending and quadrupole magnets were installed following the completion of the tunnel, whereas other magnets after the insertion of the vacuum chamber.

After finishing the installation of all magnets, the precise survey of the magnet positions was done for the final alignment. Aligning the quadrupole magnets at first by an astral survey method, the bending and correction magnets were placed relative to the quadrupoles.

Initial alignment

The magnet alignment was done in two steps — the first stage alignment at the installation and precise alignment at the second step. As soon as the tunnel was delivered, the magnet positions were surveyed, which were points marked on the tunnel floor showing the azimuthal quasi-centers of the bending and quadrupole magnets. The former gives the crossing point of the beam inlet and outlet lines projected on the floor. Therefor the quadrupole center is on the line connecting the nearest neighbor centers of the bending magnets. These centers were surveyed by the similar method to the precise survey to determine the initial coordinates with an accuracy of ± 1 mm. To make sure an accuracy the high precision surveying instruments were adopted, such as the one-second reading theodolite, Wild T2, for an angle measurement, the laser interferometer, HP 5526A, for the distance measurement and the electro-optical distance meter, Kern mekometer ME3000.

For the distance measurement at the curved section, the laser interferometer was used. It was mounted on the long straight rail which was used as the precision guide of the retroreflector (cube corner). The position of the rail was adjusted to be parallel to the line connecting two points and then the distance was measured moving the cube corner from one point to another. The tilt of the cube corner was also corrected at both points to avoid the tilting error. As this method needed the skill in the measurement, therefore the additional measurement using the calibrated steel or invar tape was required to refine the data.

The makometer was used to measure the distance at the four experimental insertions, each being 200 m, where 112 quadrupoles were installed in all. It affords the means of the very accurate long distance survey and was especially useful at the places where the floor level was different. In the measurements, the optical reflector was centered accurately on a tripod using a zenith and nadir plummet, Wild ZNL and the translation stages, Wild GMT5. The centering accuracy is ± 0.03 mm and the inherent accuracy of the mekometer is ± (0.2 mm + 1.E-6 × D), where D is the distance in mm.

An offset, which is defined as the distance from the straight line stretched between the next nearest neighbor marks, was measured with the theodolite. At the curved section, the marks of the bending magnets were used as the survey points and the angles between two straight lines stretched from one point to the nearest neighbor and the next nearest neighbor points were measured with T2. The offset was calculated using both the angle and the distance obtained above. At the straight section, however, the offset was measured directly with the optical micrometer attached to the theodolite, Kern DKM3.

The survey was also divided into two periods due to the construction schedule of the tunnel. At first one fourth of the circumference was surveyed and the surveyed data were analyzed assuming the rest of the marks were on the correct points. The marks displaced more than 1 mm were corrected. After correcting these marks, the supplemental survey were followed. These data were used together with the surveyed data of the rest of the ring obtained in the following years for the complete analysis of the coordinates of the marks. It was impossible to correct the marks of the previous year, because they were under the magnets. So the high precision measurement was essential even at this stage.

The positional error of the marks was estimated as ± 1 mm from the accuracy of the measurements. The positions, where the magnets were settled, were determined from the marks with an accuracy of ± 1 mm. Thus, the overall error of the magnet installation was estimated as ± 2 mm. Fig. 1 shows the displacements of the marks which was left uncorrected. Misalignments at this stage were corrected at the next stage. Fig. 2 is the photo of magnets in the main ring tunnel.

Precise alignment

All quadrupole magnets were separated at the median plane, that is devided into two pieces, and lowered by 50 mm for the insertion of the vacuum chamber. For this purpose the special jack was devised to lower and

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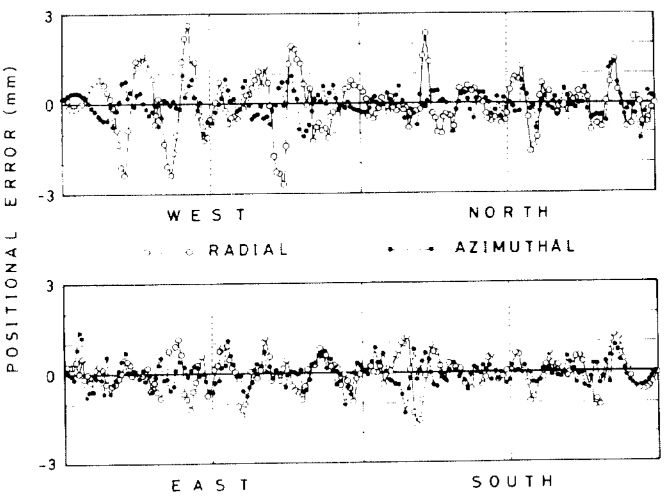

Fig. 1 Uncorrected errors of the point marks of the tunnel floor.

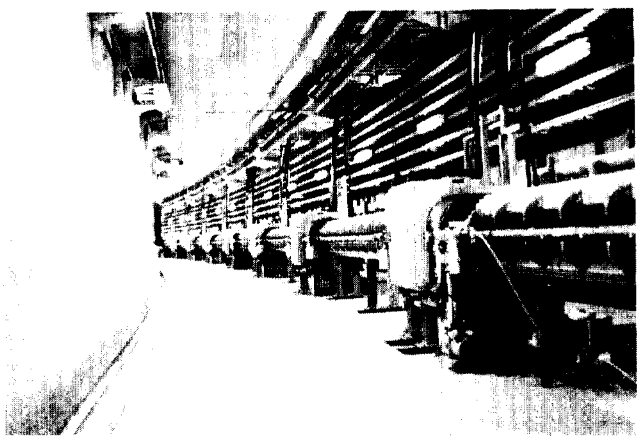

Fig. 2 Magnets aligned in the main ring tunnel.

life the quadrupole cores. The top half cores were removed beforehand and brought back after the insertion of the vacuum chamber. Then the precise survey of the positions of the quadrupole magnets began for the final alignment.

In the course of the precise alignment, many works — such as wiring of the power cables of the magnets, the current test of the power supply, the calibration of the beam position monitors, etc. — were being done by different companies in the main ring tunnel. These works were scheduled tightly not overlapping at the same place and at the same time. Most conflicting one was the current test exciting the magnets. To avoid the conflictions, the excitation was limited locally in the daytime and the circuits extending all over the ring were tested in the night after finishing the daily alignment routine. It took about four months to finish the precise alignment.

Each quadrupole has two precise sockets on the top which were used for setting of the surveying instruments. Their centers are just above the magnet center line and the levels of the sockets are same with an accuracy of ± 0.05 mm. The beam center height and tilt of all bending and quadrupole magnets have been adjusted within the tolerable limits using the precision level, Wild N3, the coincidence level of Carl Zeiss Jena and the height gauges. The movement of the height and tilt thus adjusted had been kept as small as possible in the following alignment.

The astral survey in the horizontal plane consists of two kinds of measurements, the short chord and offset measurements. These are same as in the first stage measurements but different in the survey instruments. The short chords were measured with the invar wires of 1.65 mm in diameter using "Distometer" of Kern. Whenever the invar wires were used, they were calibrated on the long bench with the 14 m rail and sockets using the laser interferometer mentioned above. On the other hand the offset was obtained measuring the shortest distance to the nylon string stretched between the next nearest neighbors with a reading microscope. The microscope can move along the screw shaft by rotating it with the screw knob. A rotation gives the movement of 2 mm. The rough scale of 1 mm spacing can be read along the shaft and the fine scale of 0.01 mm spacing on the knob. These scales were also calibrated with the laser interferometer on the same bench [2].

The data of the astral survey were processed by the least-squares method with the computer to obtain the individual displacement of magnets [3,4]. The memory required for the program was 2 MBytes. The raw result was so large due to the errors of measurement that it was unable to correct the displacement within the allowable limit of the adjusting mechanism. To eliminate the spurious and inconsequential components from the raw result, it was decomposed into the Fourier components. The consequent result was reflected immediately in the alignment. A set of survey and alignment was repeated three times to attain the tolerable state. Fig. 3 shows the error reduction of the measurements as the survey was repeated. It was obtained by comparing two successive measurements and the magnet displacements. The saturating limit of the curves was decided to be the end of the precise alignment.

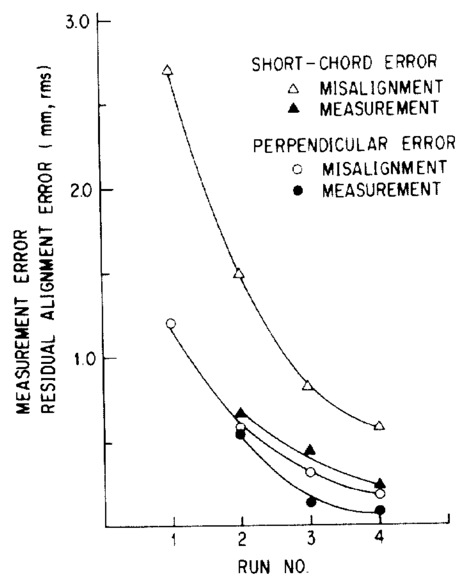

Fig. 3 Error reduction in the repeated survey.

The numbers of the surveyed data were 392 short chords and 392 offsets and the data were pre-processed to convert to the input data of the computer program because the measured data gave the fractional and uncalibrated ones.

As four long straight sections for the experiments are inserted equidistant along the ring, the quadrupole magnets at both ends of the straight sections were displaced at each time repeated. So the inclinations of the straight sections were corrected every time. The quadrupole magnets in the experimental insertions were aligned on the straight line connecting the centers of two quadrupole magnets at both ends with the theodolite.

Influence on the closed orbit

The residual misalignment of the quadrupole magnets is given in Fig. 4. The rms errors are 0.2 mm radially, 0.3 mm azimuthally and 0.2 mm vertically. The azimuthal error affects little, so it is ignored here. The 0.1 mm rms positional error of the quadrupole magnets gives rise to the 3 mm rms orbit distortion in the TRISTAN main ring.

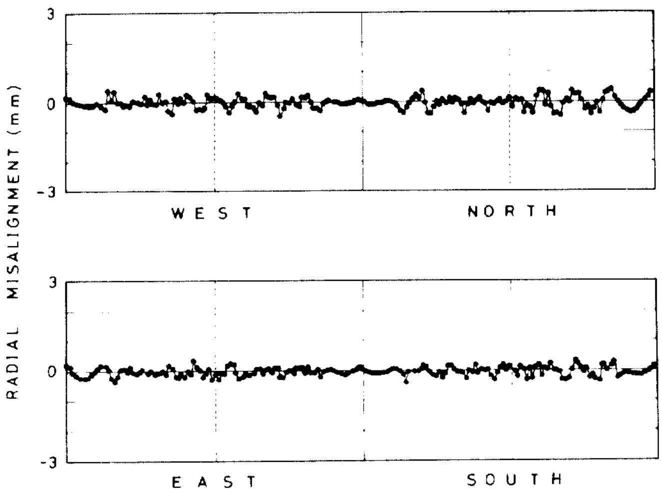

Fig. 4 Final misalignment of the quadrupole magnets.

As the dominant harmonics in the misalignment which affect the closed orbit distortion are those close to the betatron frequency [5], the harmonics far from it were omitted from the re-alignment. The lower order harmonics reflecting the measurement errors were also rejected simultaneously. The harmonics to be suppressed were determined by the computer simulations. The expected and observed closed orbit distortions [6] are listed in Table 1. As the closed orbit differs depending on the optics of the synchrotron, the listed data assume a typical optics.

Table 1 Closed orbit distortion (COD)

	RUN 3	RUN 4	RUN 5
Horizontal misalignment (mm, rms)			
0-19th harmonics reduced	0.56	0.30	0.26
0-28th harmonics reduced	—	0.20	0.17
Horizontal COD (mm, rms)			
calculated	(22.7,7.4)	(9.1,4.4)	(5.4,3.0)
observed	—	—	4.0
		RUN 1	RUN 2
Vertical misalignment (mm, rms)			
0th harmonic reduced		0.59	0.51
0-19th harmonics reduced		0.21	0.16
0-28th harmonics reduced		0.19	0.14
Vertical COD (mm, rms)			
calculated		(3.3,13.2)	(2.6,4.5)
observed		—	3.4

The misalignment data in the table give the results of the computer analysis after reducing the specified harmonics. The calculated closed orbit distortion does not depend on the harmonics reduction. Two figures in the parentheses were obtained using two different optics which are being used for the machine operation. An example of the closed orbit is shown in Fig. 5, where the field error of the individual bending

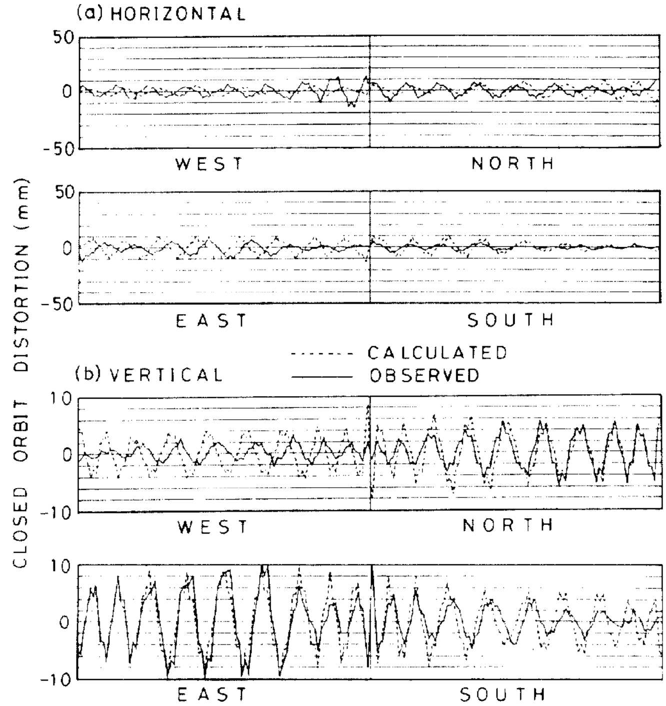

Fig. 5 Comparison of the calculated and measured closed orbit distortions.

magnet is taken into consideration. The contribution of the field error is about one fifth of the closed orbit distortion.

The authors are grateful to Dr. H. Fukuma for preparing the data of the closed orbit.

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