Magnet Alignment of SPring-8 Booster Synchrotron

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1. INTRODUCTION

The SPring-8 synchrotron accepts an electron beam of 1 GeV from the linac, accelerates the beam up to 8 GeV and ejects the beam to make stacking into the storage ring with a repetition period of 1 second [1]. The synchrotron is composed of FODO lattice of 40 cells and its circumference is 396.124 m [2]. There are 64 dipole, 80 quadrupole and 60 sextupole magnets. Horizontal and vertical closed orbit distortions (COD) were induced mainly by alignment errors of the quadrupole magnets. The horizontal COD was also generated by the field-strength errors of the dipole magnets. Therefore, a rearrangement of the dipole magnets based on the field measurement was carried out to suppress the COD.

Base plates have been placed on the floor in the synchrotron tunnel with an accuracy of ±5 mm since the construction of the building. Reference points were put on the monuments with an accuracy of ±0.2 mm. In June 1995, we began the alignment of the magnets with the reference points. The alignment was finished in January 1996. The synchrotron commissioning was started in December 1996 and was finished in March 1997 [3]. The CODs were measured at the beam energy of 1 GeV and 8 GeV. After the first COD measurement, we confirmed that the alignment of the magnets was achieved within the expected accuracy.

2. ALIGNMENT TOLERANCES

Alignment tolerances of the dipole, quadrupole and sextupole magnets in radial, vertical and longitudinal directions were designed to be 0.2 mm. The tolerances of pitch and roll of the magnets were designed to be 0.2 mrad. These values were decided to be realistic alignment errors. The horizontal and vertical CODs were mainly induced by the alignment errors of the quadrupole magnets in the radial and vertical directions. To estimate the effect of the alignment error, the COD was calculated by the simulation code of “RACETRACK”. The distribution of the alignment errors was assumed to be gaussian. A root mean square (rms) of the errors is equal to standard deviation σ of the gaussian distribution. The tolerance of the alignment error was assumed to be 2σ. The alignment error which was larger than 2σ, was not inputted in the simulation. The COD also depends on an arrangement of the quadrupole magnets. Therefore, the simulation was carried out fifty times with various arrangements at random with same rms of the alignment error. Maximum distortions were picked up from fifty samples. The maximum distortion with the rms of the alignment error of quadrupole magnets is shown in Fig.1. The standard deviations of the distortions are also shown in Fig.1 as error bars.

3. SORTING OF DIPOLE MAGNETS

Integrated magnetic fields along the longitudinal direction of all dipole magnets were measured with a long-flip coil at three kinds of excitation currents which are equivalent to 1, 4 and 8 GeV [4]. The deviations between the integrated fields and the average one of all magnets were obtained as individual field errors. The errors were less than 8×10^{-4} for three values of excitation current. As the beam size at 1 GeV is maximum [5], all dipole magnets are arranged to suppress the COD at 1 GeV based on the magnetic field measurement.

The horizontal COD x(s) is shown as,

$$x(s)= \frac{\sqrt{(\beta_x(s)\,\beta_x(s_1))}}{2\sin \pi\nu_x} \cos\{ \pi\nu_x+ \mu_x(s)- \mu_x(s_1)\}\, (\Delta B/B)\theta \quad (1)$$

where s_1 is the position of the field-strength error along the s-axis, $\beta_x(s)$ is horizontal beta function, $\mu_x(s)$ is phase advance in horizontal direction, ν_x is horizontal tune of 11.73, $\Delta B/B$ is field-strength error and θ is bending angle by the dipole magnet. If two magnets with the same error are arranged so that the phase advance between the magnets is π radians, the COD due to the error is canceled. In order to confirm the effect of the rearrangement, the CODs with and without the rearrangement were calculated by the RACETRACK code. The CODs with and without the rearrangement are shown in Fig.2. The maximum distortion and the rms of the COD without the rearrangement are 1.71 mm and 0.69 mm, respectively. Those of the COD with rearrangement are 0.35 mm and 0.10 mm, respectively. The COD was expected to be decreased to about one fifth by the rearrangement. In the following section, positive sign in the horizontal and vertical directions was defined the outward and upward directions, respectively.

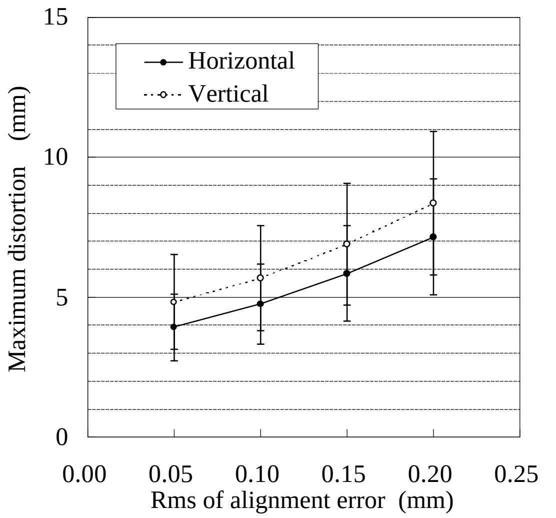

Fig.1 Maximum distortions with the alignment error of the quadrupole magnet. Solid and broken lines indicate the distortions in the horizontal and vertical directions, respectively. Error bar shows one standard deviation of the distortion of fifty samples with various arrangement of quadrupole magnets.

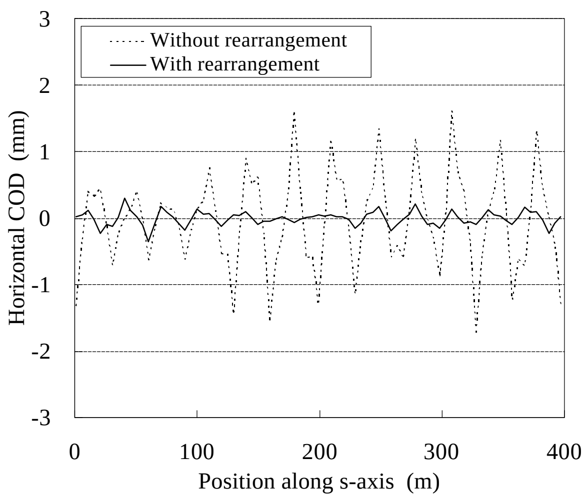

Fig.2 Horizontal COD with the position along s-axis. The zero point of the s-axis indicates the injection point from the linac. The solid and broken lines indicate the CODs with and without rearrangement, respectively.

4. ALIGNMENT METHOD

A SMART310 system, a theodolite and level gauges of Wild N3 were used for the alignment. The SMART310 has a laser tracker system to measure a position in three dimensions. A reflector made from two glass hemispheres was used for a target of the SMART310. The reflector was put on the pedestal of the target points at the same height, and x-y coordinates of the target points were measured. A laser sensor was used to take data at a rate of up to 500 points per second.

The outline of the synchrotron is shown in Fig.3. Coordinate axes of the synchrotron are defined as X_{sy} and Y_{sy}. Base plates have been placed at the positions of R1~R6 and S1~S8 with an accuracy of ±5 mm since the construction of the building. Reference points were put on the the base plates with an accuracy of ±0.2 mm. Two reference points R1 and R2 were put on the injection line from the linac using the theodolite. The injection point of I1 was put on the injection line using the theodolite. The distance between the I1 and R2 was adjusted to the designed value using the SMART310. The reference points of R3 and R4 were put on to determine the straight line for the injection. The theodolite was set on the I1, and the angle between the injection line and the straight line connecting the R3 and the R4 was adjusted to designed value. The distance between these points and the I1 were adjusted to the designed value with the SMART310. The reference points of R5 and R6 were put on the perpendicular bisector of the straight line for the injection.

At first, the dipole magnets were installed. The mounting points of the dipole magnets were scribed on the floor using the theodolite and the SMART310 with an accuracy of ±1 mm. The 64 dipole magnets were named as BM1~BM64 clockwise from the injection point. The distances between two adjacent dipole magnets are about 5 m for BM2~31 and BM34~63 called as normal cells, about 10 m for BM1-2, BM31-32, BM33-34 and BM63-64 called as dispersion suppresser cells and about 35 m for BM1-64 and BM32-33 called as straight cells [5]. The points of S1~S8 were set as supplementary reference points based on the mounting points of the dipole magnets or reference points of R1~R6. The cross-hairs mark was scribed on the base plates at the supplementary points with ±1 mm accuracy. Since these points was not fixed points, the points were mounted on x-y adjusters. Monuments were set up over the reference and the supplementary reference points. The height of the monument is equal to that of the dipole magnet. A schematic top view of the dipole magnet are shown in Fig.4. Length of the yoke of the dipole magnet is 2870 mm. There are three fiducial points on the yoke with a hole of 40 mm in diameter. A center fiducial point is named BMC. Upstream-side and downstream-side fiducial points are named BMU and BMD, respectively. The distance between the BMU and the BMD is 2800 mm. The BMC of n-th magnet is called BMCn.

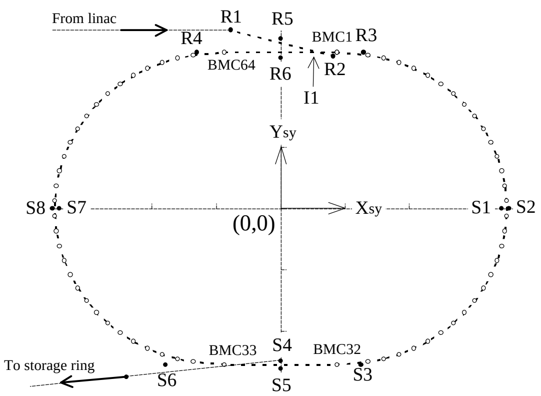

Fig.3 The outline of the synchrotron. The point I1 is injection point from the linac. The points R1~R6 are fixed reference points. The points S1~S8 are supplementary reference points. The points BMC1~BMC64 indicate the center fiducial point of the dipole magnets (refer to Fig.4). The symbols of X_{sy} and Y_{sy} indicate the coordinate axes of the synchrotron.

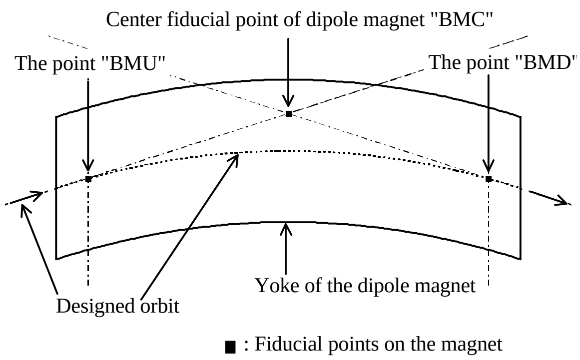

Fig.4 A schematic top view of the dipole magnet. There are three fiducial points on the yoke of the magnet. Two fiducial points “BMU” and “BMD” are put on the designed orbit at upstream and downstream side, respectively. The center fiducial point “BMC” is put on the intersection point of the two tangential lines with the designed orbit at the BMU and BMD.

Next, the quadrupole and sextupole magnets were adjusted to the dipole magnets. Length of the yoke of the quadrupole and sextupole magnet are 570 mm and 150 mm, respectively. There are two fiducial points on the yoke with a hole of 20 mm in diameter. These fiducial points are put on the designed orbit of upstream-side and downstream-side. The distance between the two fiducial points of quadrupole magnets and those of sextupole magnets are 420 mm and 100 mm, respectively.

Water levels were put on the fiducial points of the dipole, quadrupole and sextupole magnets. The alignment of the pitch and roll of the magnets was carried out with the level. Alignment methods of the magnets in vertical, radial and longitudinal directions are shown in detail in the following section.

4.1 Vertical direction

The height of the dipole magnets were measured by the N3. A sphere target for the N3 was positioned on the BMCs. The target has a pattern of concentric circles with an central dot of 0.2 mm in diameter. The reference of the height was the same with that of the linac. The height of BMC1 and BMC64 were adjusted to the reference. The alignment of the magnets in the vertical direction was carried out in two directions. One is clockwise from the BM2 to the BM32 and the other is counter-clockwise from the BM64 to the BM33. The N3 was installed in the middle of two neighboring magnets during every adjustment to cancel the influence of the curvature of the earth. The height of the quadrupole and sextupole magnets was adjusted to the neighbor dipole magnets. In every adjustment, dial gages were put on the girder of the magnet and their pins were attached to the yoke of the magnet to check the horizontal shift of the magnet.

4.2 Radial and longitudinal direction

The alignment of the dipole magnets in the radial and longitudinal directions was performed using the SMART310 and the theodolite. The distance between BMC1 and R3 was adjusted to the designed value within the allowance of ±0.2 mm. The distance between BMC64 and R4 was adjusted similarly. The BMC1 and BMC64 were fixed. The straight line of BMC1-BMC64 was defined as x-axis. The line crossed with the x-axis perpendicularly was defined as y-axis in the plane of the same height. To measure the x-y position of the BMC2, the SMART310 was installed in the middle of the BMC1 and BMC64, and the position data of these points were stored. According to the measurement, the position of BMC2 was adjusted to the designed value. The BMCs were also adjusted from the BM3 to the BM32 in the same way. The SMART310 was moved every nine magnets since the distance of over 25 meters could not be measured with guarantee. After the movement, the new x-axis and y-axis were defined again according to the position data of two adjusted magnets on the upstream-side. The adjustment were performed clockwise from the BM2 to the BM32 and counter-clockwise from the BM64 to the BM33. The position of the supplementary reference points were also adjusted. To check the adjustment, the theodolite was put on the BMC and the angle made by the both sides of neighboring BMC was measured for all dipole magnets. To align the rotations of the dipole magnets around the vertical axis to the x-y plane, the positions of BMU and BMD were adjusted to designed value for all magnets.

In order to obtain the position of the magnets, triangulations were carried out on the basis of two fixed points of BMC1 and BMC64. The points BMC1~BMC64, S1~S8 and R2~R6 were selected as the vertexes of the triangles. The lengths of three sides of the triangles were measured with the SMART310. The inside angles of them were measured with the theodolite. The length of the sides were decided not to be over 25 meters because of the limit. Based on the difference between the calculated positions and the designed ones, the displacement of the magnets were estimated and the realignments was performed. These processes were repeated three times.

The positions of the quadrupole and sextupole magnets in the radial and longitudinal directions were adjusted to the dipole magnets. In the radial direction, these magnets were set with the SMART310 on a straight line connecting the centers of the neighboring two dipole magnets. In the longitudinal direction, these magnets were adjusted by measuring the distance between the magnets and the nearest dipole magnet with a inside-micrometer. Since the distances of the straight cells were ten meter or more, the inside-micrometer could not be used. The distances were adjusted with the SMART310.

5. RESULTS

The displacement of ΔX_{sy}, ΔY_{sy} between the measured position of BMCs and the designed ones is shown in Fig.5. The maximum displacement of X_{sy} and Y_{sy} were about 0.2 mm, respectively. The error of the ΔX_{sy} and ΔY_{sy} were determined by considering the resolution of the SMART310 and the theodolite, reading error of the target position and setting error of the theodolite. The error of the ΔX_{sy} and ΔY_{sy} are largest at the points of BMC32 and BMC33 since the distance from the fixed points of BMC1 and BMC64 are longest. The errors of the ΔX_{sy} and ΔY_{sy} of BMC32 and BMC33 were estimated to be 0.16 mm and 0.09 mm, respectively. The difference between the measured circumference of the synchrotron and the designed one was estimated to be 0.21.1 mm by this measurement.

The relative alignment error in the vertical and radial directions are shown in Fig.6. The maximum values of the relative alignment errors in vertical and radial directions were 0.15 mm and 0.11 mm, respectively and they were less than the specifications of ±0.2 mm. The rms of the alignment errors in the vertical and radial directions were 0.048 mm and 0.050 mm, respectively. The relative alignment errors and the rms of pitch and roll of the dipole, quadrupole and sextupole magnets are shown in Table 1.

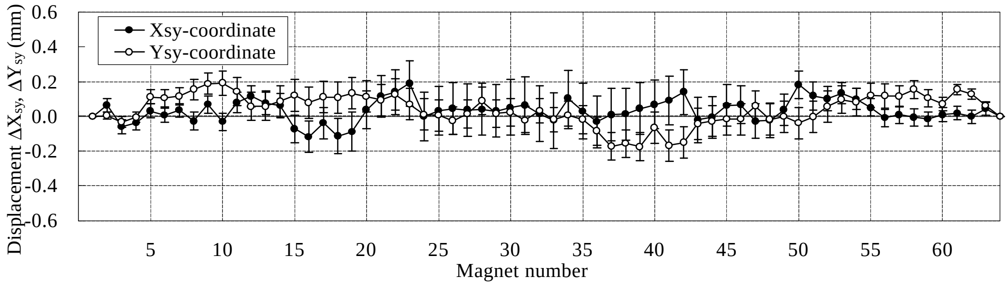

Fig.5 The deviation between the measured position of BMCs and designed ones is expressed in the synchrotron coordinate system. Closed and open circles indicate the deviation of X_{sy} and one of Y_{sy} coordinates, respectively.

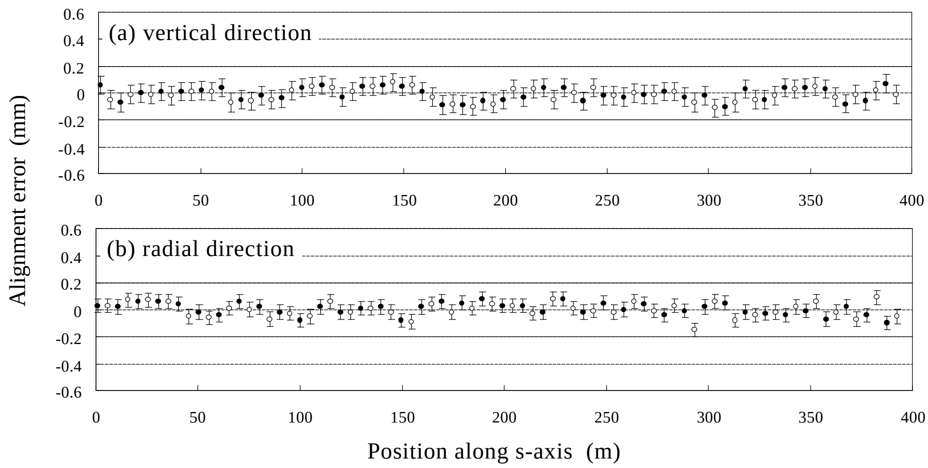

Fig.6 The relative alignment errors of quadrupole magnet. Upper figure indicates the error in the vertical direction and lower figure indicates the error in the radial direction. Closed and open circles indicate the focusing and defocusing quadrupole magnets, respectively.

Table 1 Summary of rms of relative deviations of dipole quadrupole and sextupole magnets.

Magnet	Number	Relative alignment error (mm) vertical	radial	longitudinal	Alignment error (mrad) pitch	roll
Dipole	64	0.051	0.087	0.059	0.032	0.054
Quadrupole	80	0.048	0.050	0.037	0.039	0.035
Sextupole	60	0.043	0.036	0.042	0.047	0.039

6. DISCUSSION

We measured the horizontal and vertical CODs by eighty BPMs [6] at the beam energy of 1 GeV and 8 GeV. The COD at 1 GeV is shown in Fig.7. The maximum distortions in the horizontal and vertical directions were 3.69mm and 3.74mm, respectively. The rms of the CODs were 1.31mm and 1.55mm, respectively. If the CODs were generated only by the alignment error of the quadrupole magnets, the maximum distortion and the rms of the CODs were corresponds to the case of the rms alignment error of 0.05 mm in Fig.1. This rms alignment error is equivalent to the relative deviations in Table 1.

The average of the COD should be equal to zero if the electron beam oscillates around the designed orbit. The average value of the beam position in the vertical direction is negligible small. But the average value of the beam position in the horizontal direction is not zero. This is caused by the difference of the circumference from the designed value. In order to estimate the deviation, the horizontal COD with the radio frequencies were measured. The horizontal COD with the radio frequencies are shown in Fig.8. The average COD with the radio frequency are shown in Fig.9. The beam orbit was not changed in the straight cell (BPM35~41, BPM75~80 and BPM1) due to the dispersion free region. In the other region, the beam passes through more outside as the radio frequency is lower because the total length of the orbit is longer. When the radio frequency was 4 kHz lower than the designed value of 508.58 MHz, the average COD was almost zero. It means that the circumference is 3.1mm longer than the designed value.

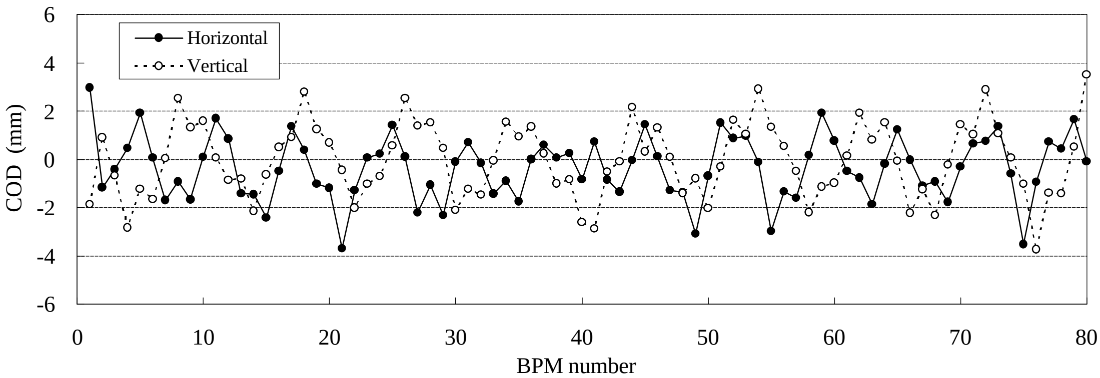

Fig.7 Horizontal and vertical COD without orbit correction. Closed and open circle indicate horizontal and vertical COD.

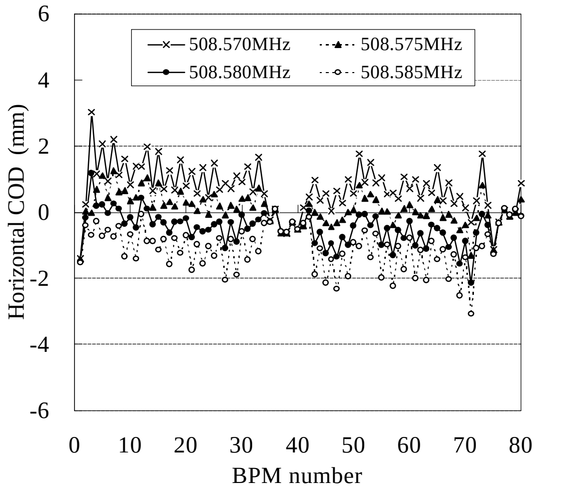

Fig.8 Horizontal COD with the radio frequencies.

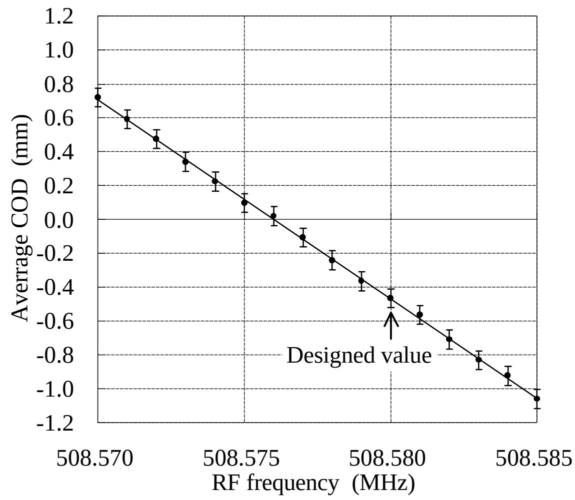

Fig.9 Average of horizontal COD with the radio frequencies.

7. SUMMARY

The alignment of the lattice magnets were completed. It was confirmed that the alignment of all the magnets were satisfied with the specification. The measured alignment errors were compatible with the evaluated alignment errors based on the measurement of the CODs.

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