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Magnet Alignment Method, Alignment Results and Closed Orbit Distortion for The SPring-8 Storage Ring

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Abstract

Third generation synchrotron radiation sources have high sensitivity against errors and large closed orbit distortion is generated resultantly. We found the alignment method to reduce the effective sensitivity and applied it to the SPring-8 storage ring. We succeeded to reduce the effective sensitivity substantially. Observed closed orbit distortions without correction were 1.4 mm for horizontal and 2.4 mm for vertical direction. We accomplished a first turn and storage of an electron beam without any orbit correction.

1. INTRODUCTION

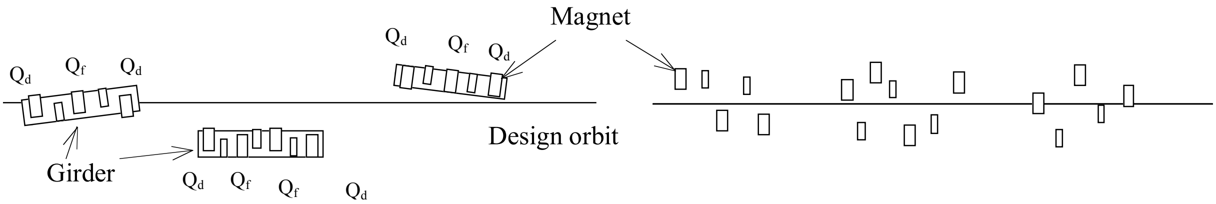
The SPring-8 storage ring is the third generation synchrotron radiation source of 7 nm natural emittance and has a 1436 m circumference with 48 cell double bend achromat lattice. An electron beam of the third generation source is focused in bending magnets by high magnetic field quadrupole magnets to reduce the beam emittance. As a result, large chromaticities are generated and high magnetic field sextupole magnets are needed for chromaticitiy correction. These high field magnets result in the high sensitivity against errors: small misalignments of quadrupole magnets generate a large closed orbit distortion (COD) and the effect of high field sextupole magnets to the coupling of betatron oscillation is large and the dynamical aperture becomes small. For example the amplification factors of SPring-8 storage ring for horizontal and vertical orbit are 126 and 84, respectively. This means that 0.4 mm standard deviation of magnet misalignment generates the 50 mm COD for horizontal direction and 34 mm COD for vertical direction. Normally this sensitivity is from 10 to 20 for the second generation light source. This high sensitivity makes it difficult to commission a ring and supply a high quality beam. Therefore small sensitivity against errors with small emittance is required as the characteristics of the third generation synchrotron radiation source. For this requirement, we proposed a method to reduce the sensitivity against errors effectively: The effective sensitivity can be reduced substantially if the quadrupole and sextupole magnets between the bending magnets are aligned on a straight line precisely[1]. According to this alignment method, small COD and small betatron oscillation coupling resulting from sextupole magnets are expected.

In this paper we describe the principle of alignment method, actual alignment method, alignment results and calculated and observed COD.

2. PRINCIPLE OF ALIGNMENT

A magnet lattice of the third generation synchrotron radiation source is the double bend achromat (DBA) or the triple bend achromat (TBA). The magnet lattice of the SPring-8 is a DBA type and contrary to the FODO lattice, quadrupole and sextupole magnets are densely arranged between the bending magnets. The DBA lattice has two bending magnets and three short straight sections in a cell and quadrupole and sextupole magnets with opposite polarities are placed closely in these short straight sections. In the SPring-8 storage ring, one focusing (QF) and two defocusing quadrupole magnets (QD) are placed on a girder at the first and third straight sections in a cell. A focusing (SF) and defocusing sextupole magnets (SD) for harmonic corrections are also placed in the same straight sections. In the second straight section two QFs, two QDs, two SFs and one SD are placed on a girder. Integrated strength of these magnets on a girder is very small. This means that if the betatron phase advance between the magnets in a girder is small and the magnetic center is aligned on a straight line, kick forces that generate COD or betatron oscillation coupling are canceled within a girder even if the girder is misaligned from the design orbit. Contrary to this, if the magnets are aligned randomly as a usual alignment, the COD is simply a sum of randomly generated CODs and no cancellation works.

Phase advance of horizontal and vertical oscillations of the SPring-8 storage ring is 0.1 π between the quadrupole magnets on both ends of a girder. This means that if we can align the magnet center precisely in short straight sections, kick forces are canceled within a straight section and sensitivity against error can be reduced effectively. Fortunately the distance between the both ends of the girder is 4 to 5 m and short enough to align the magnetic center precisely on a straight line.



(a) Our method: Magnets on a girder are aligned on a straight line very precisely.

(b) Usual method: Magnets are randomly distributed around the design orbit.

Fig. 1 Principle of our alignment method.

We decided to adopt our alignment method to the SPring-8 storage ring. Figure 1 shows the principle of the alignment method. In our alignment method, magnets on a girder are aligned on a straight line very precisely. Girder alignment is not so important as magnet alignment on a girder. Girders are allowed to distribute randomly around the design orbit. Girder is like a large magnet in which the opposite polarity magnets are placed. In this case, closed orbit can be approximated as follows.

$$u = \frac{\sqrt{\beta}}{2\sqrt{2}\sin\pi\nu}\left\{\sum_{i=1}^{m}\left[\sum_{j=1}^{n}\beta^{1/2}\left(\xi_j\right)K\left(\xi_{ij}\right)\delta\left(\xi_{ij}\right)\right]^2\right\}^{1/2} ,\cdots(1)$$

where, β is the betatron function, K is the strength of quadrupole magnets, δ is the magnitude of the misalignment, m is the number of girder and n is the number of magnets on a girder. Contrary to our alignment method, in normal alignment, magnets are aligned on a design orbit and distributed around the design orbit. In this case, closed orbit is expressed as,

$$u = \frac{\sqrt{\beta}}{2\sqrt{2}\sin\pi\nu}\left\{\sum_{j=1}^{k}\left[\beta^{1/2}\left(\xi_j\right)K\left(\xi_{ij}\right)\delta\left(\xi_{ij}\right)\right]^2\right\}^{1/2}, \cdots (2)$$

where k is the total number of magnets. Kick forces in case of our method are summed over a girder and squared and summed over all girders as shown in eq. (1). In usual case they are the simple sum for magnets as shown in eq. (2).

3. REALIZATION OF THE METHOD

For the realization of our method, the most important thing is to align the quadrupole and sextupole magnets on a straight line as precise as possible. For this purpose we developed a He-Ne laser and a CCD camera system[2].

Using these equipments, we aligned the magnets as follows. First, magnetic centers of quadrupole and sextupole magnets were measured. Second, girders were aligned with normal alignment accuracy[3] and then bending magnets were placed. Finally, alignment for the quadrupole and sextupole magnets on girders was done with high accuracy[4].

3.1 He-Ne Laser System and Magnetic Center Measurement

The He-Ne laser consists of collimator, pinhole, spacial filter, ND(neutral density) filters and a laser source. The diameter of laser beam is 3 mm. Laser beam is detected by a CCD camera and acquired by a VFG(Video Frame Grabber) board. Stability of laser beam was measured and was obtained ±2 mm fluctuation of beam position.

Magnetic center was measured by this laser system as shown in Fig. 2. First a magnet is set on a moving table and the magnetic center is measured by rotating coil. Then magnet is moved till the deviation of magnetic center from rotating coil center becomes less than two micron. Position of two moving table fiducial points and two magnet fiducial points are measured and the deviation of magnet position from the line that are made by connecting two moving table fiducial point are obtained. After measuring the magnetic center, the magnets were set on a girder and the magnetic centers were aligned on a line.

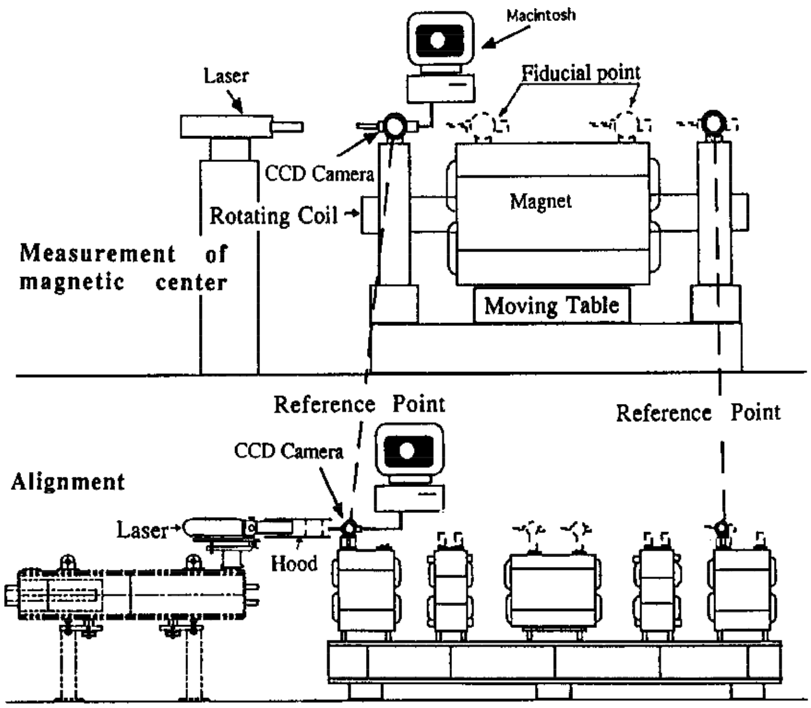


Fig. 2 Measurement of magnetic centers and alignment of magnets.

3.2 Girder Alignment

The girders are set in a tunnel and magnets are placed on the girders. Levels of the both ends of girders were adjusted to the fiducial point of the wall that were made beforehand. An optical level N3 was used for the level measurement. Then magnets on the both ends of a girder are aligned on a line made by connecting the monuments on a floor that were surveyed beforehand. These magnets were used as fiducial points of a girder. Survey network for girder alignment was constructed and the girder position was measured by the laser tracker SMART310. Deviation from the ideal position was calculated. We adjusted the girder position so that the relative deviation between the neighboring girders was less than 0.1 mm. We repeated this procedure three times before quadrupole and sextupole alignment. After chamber baking we measured the level. Some girder level was changed largely. We readjusted twenty one girders. After the level adjustment girder survey was done and twenty nine girder position was corrected.

3.3 Bending Magnet Alignment

Bending magnets were positioned by monitoring the fiducial point on a magnet with a laser tracker SMART310 and a tilt meter NIVEL. Coordinates were determined using quadrupole magnets and the fiducial point on a wall.

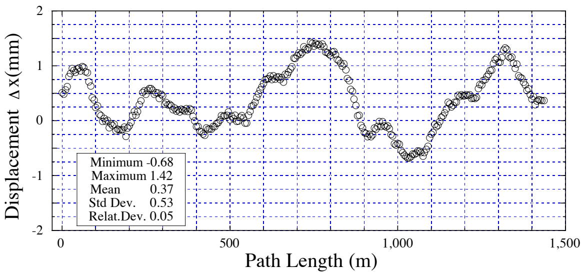
3.4 Quadrupole and Sextupole Magnet Alignment

The laser was set on a bending magnet. Air conditioners near the girder were switched off to reduce the laser beam fluctuation and the area where the alignment was done was shielded by the curtain to prevent the air flow. First the magnet position of both ends of a girder was measured and the line was made by connecting these two fiducial points. Other magnets on a girder were aligned on this line by measuring the magnet position by the laser and CCD camera system. Tilts of the magnets were measured by a tilt meter (Tayler Hobson Talybel 4).

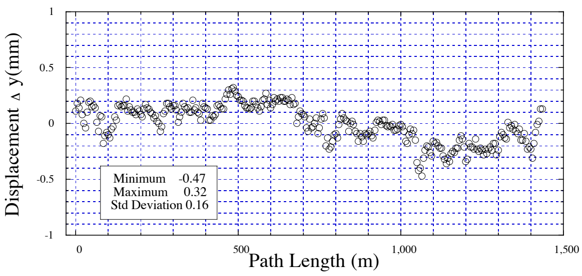
4 RESULTS

4.1 Girder

Alignment results are shown in Fig. 3. At first, relative horizontal accuracy between girders was 0.04 mm, but after ten month later it was changed to 0.06 mm. This was considered to be due to the temperature change in the tunnel and the division and recovery of the magnets for chamber installation and the chamber baking. We corrected the position of 29 girders out of 144 girders. As the final value before commissioning we obtained 0.05 mm relative accuracy. In the same reason, vertical accuracy was deteriorated. We corrected the vertical position for 21 girders and obtained 0.04 mm relative accuracy.



(a) Horizontal direction.

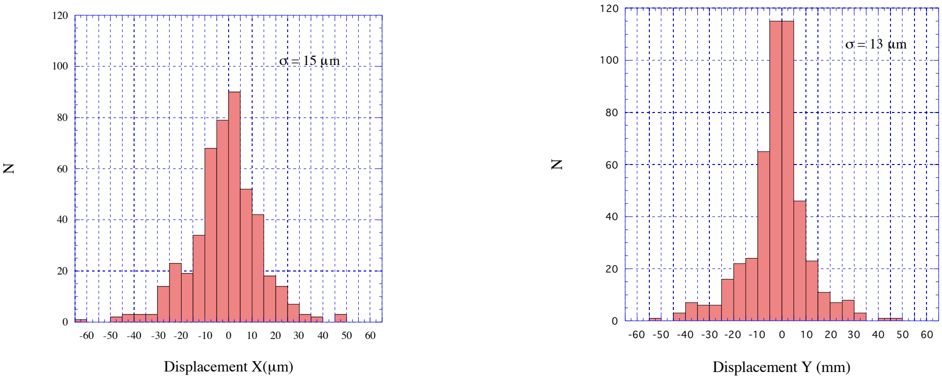


(b) Vertical direction.

Fig. 3 Girder alignment results.

4.2 Quadrupole and Sextupole Magnet

Alignment results are shown in Fig. 4. This accuracy means the deviation from the straight line that is made by connecting the two fiducial points of the magnets on the both ends of a girder. There are two fiducial points on a magnet and upper stream fiducial points were chosen as fiducial points when making the straight line. Alignment accuracy measured by laser beam was about 6 μm just after adjustment. However it was made worse due to magnet division and recovery for chamber installation. Chamber baking also deteriorated the accuracy. Final accuracies for horizontal and vertical directions were 15 μm and 13 μm, respectively. Standard deviation of the magnet tilt was 31 μm.



(a) Horizontal direction. (b) Vertical direction.

Fig. 4 Alignment results of quadrupole magnet on girders.

4.3 Bending Magnet

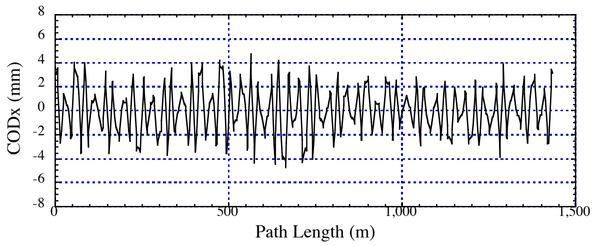
Bending magnet were positioned with the accuracy of 0.13 mm, 0.11 mm and 0.08 mm for horizontal, vertical and longitudinal direction, respectively. After evacuating the chamber, bending magnets were moved downstream by 0.26 mm in average.

5 CLOSED ORBIT DISTORTION

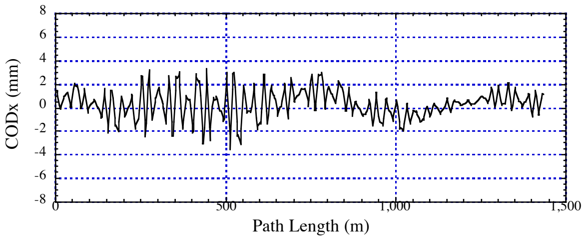
Closed orbit distortion is generated by two kinds of misalignment of quadrupole magnets: One is the misalignment from the straight line on a girder, the other is the girder misalignment itself. For horizontal direction, field strength error of bending magnets and systematic movement to the downstream direction due to the atmospheric pressure is added as the source of the closed orbit distortion. CODs were calculated based on the measurement results of alignment. Calculated results are shown in Fig. 5 and Fig. 6 and are summarized in Table 1.

Table 1 Calculated and measured closed orbit distortion.

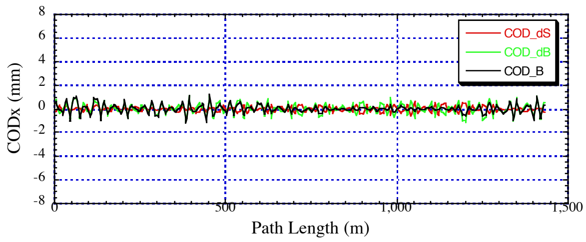
	σ_{CODx}	σ_{CODy}
Quadrupole	2.0 mm	0.9 mm
Girder	1.3 mm	1.0 mm
Bending magnet	0.4 mm	-------
ΔB	0.4 mm	
$B_{\Delta S}$	0.2 mm	
Total	2.7 mm	1.6 mm
Measured	1.4 mm	2.4 mm



(a) Horizontal closed orbit distortion resulting from quadrupole misalignment on girders.

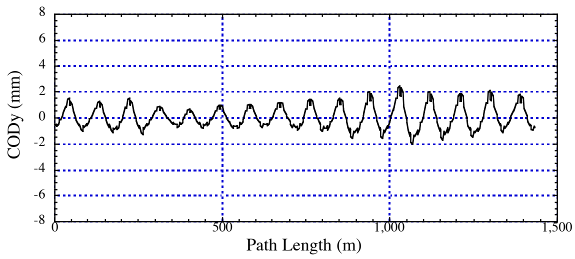


(b) Horizontal closed orbit distortion resulting from girder misalignment.

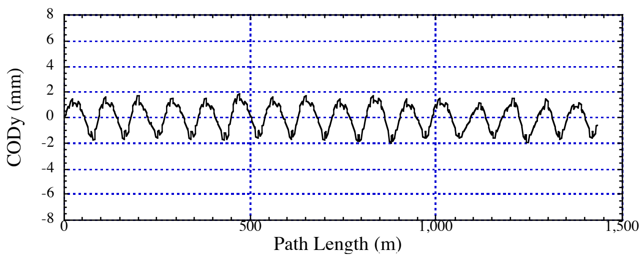


(c) Horizontal closed orbit distortion resulting from bending magnet movement and magnetic field error.

Fig. 5 Calculated horizontal closed orbit distortion.



(a) Vertical closed orbit distortion resulting from quadrupole misalignment on girders.

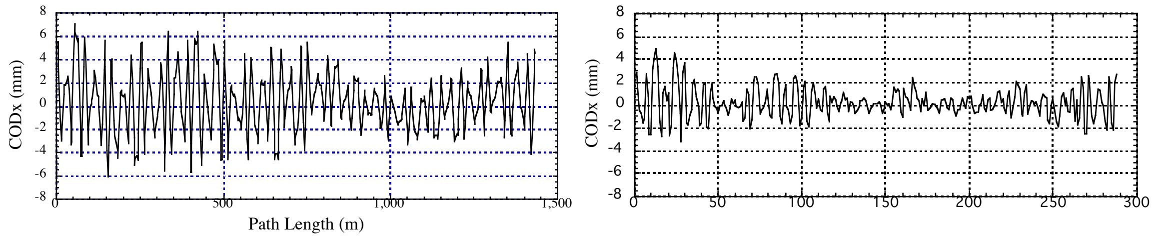


(b) Vertical closed orbit distortion resulting from girder misalignment on girders.

Fig. 6 Calculated vertical closed orbit distortion.

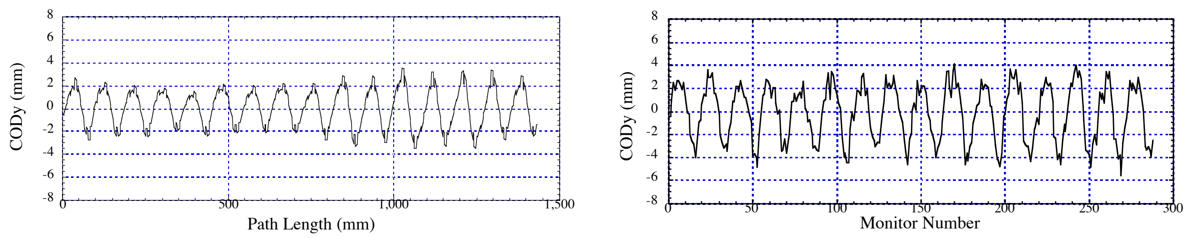
Effect of bending magnets is very small compared to the quadrupole misalignment and the contribution of quadrupole magnet on a girder is the largest even though the misalignments are only 15 μm for horizontal and 13 μm for vertical. Expected amplification factors are $\sigma(CODx)/\sigma(\Delta x)=117$ and $\sigma(CODy)/\sigma(\Delta y)=54$. Though the misalignments between the girders are much larger than that of on a girder, contribution to the COD is the same order of magnitude. Their sensitivities are σ(CODx)/σ(Δx)=2.4, σ(CODy)/σ(Δy)=6.2 for absolute error and σ(CODx)/σ(Δx)=25, σ(CODy)/σ(Δy)=25 for relative error. These values are very small compared to the amplification factors for the case of normal alignment method. These results show the effectiveness of our alignment method, which reduce the sensitivities against the errors.

First measured closed orbit distortions without orbit corrections are shown in Fig. 7 and Fig. 8 with the calculated one. Observed standard deviations of COD are 1.4 mm and 2.4 mm for horizontal and vertical direction, respectively. Calculated COD for horizontal direction is larger than the measured one. There is a possibility of overestimation of quadrupole magnet alignment errors on girders. If the increment of the alignment error from 6 μm to 15 μm is due to the magnet division for chamber installation, lower part of the magnets do not move and only upper half of the magnets move. Therefore we assumed the 6 μm alignment errors that are the initially obtained results and calculated the closed orbit distortion. Results are shown in Fig. 9. Agreements between the calculated and observed CODs are good. This implies that the quadrupole alignment errors on girders are smaller than the final results.



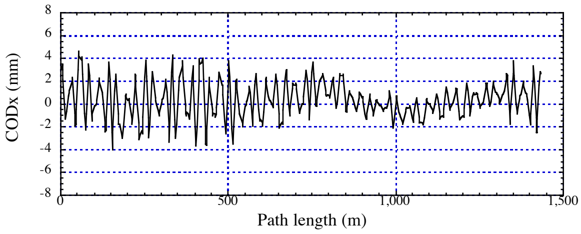
(a) Calculated horizontal closed orbit distortion. (b) Measured horizontal closed orbit distortion.

Fig. 7 Calculated and measured closed orbit distortion for horizontal direction.

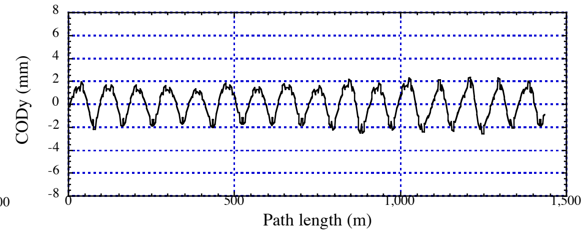


(a) Calculated vertical closed orbit distortion. (b) Measured vertical closed orbit distortion.

Fig. 8 Calculated and measured closed orbit distortion for vertical direction.



(a) Calculated horizontal closed orbit distortion.



(b) Calculated vertical closed orbit distortion.

Fig. 9 Calculated closed orbit distortion. Quadrupole alignment errors on girders are assumed to be 6 μm for both directions.

In 1997 on March 14, an electron beam from a synchrotron was injected into the storage ring and first turn of the electron beam was accomplished without any orbit correction. After some tuning, RF power was fed into RF cavities and the electron beam was stored with the closed orbit as shown in Figs 7 and 8.

5 CONCLUSION

We have adopted a new alignment method to the SPring-8 storage ring, which can reduce effective sensitivity against errors substantially. Closed orbit distortion was calculated based on the alignment data and small orbit distortion was foreseen. Electron beam was stored without COD correction as expected. Observed CODs were 1.4 mm for horizontal and 2.4 mm for vertical direction, which agreed to the calculated results. We confirmed the effectiveness of our alignment method from these results.

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