LONG-TERM VARIATION OF THE MAGNET ALIGNMENT IN SPRING8 STORAGE RING

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INTRODUCTION

The SPring-8 storage ring, with a circumference of about 1.5 kilometres, is built surrounding the hill of Mihara-kuri and constructed mostly on hard rock or medium hard rock. In some soft area the ground is refilled with artificial rock. The ring is Chasman-Green lattice of 48 cells. Each cell consists of two bending magnets and seventeen multipole magnets (10 quadrupoles and 7 sextupoles) mounted on three girders (fig.1).

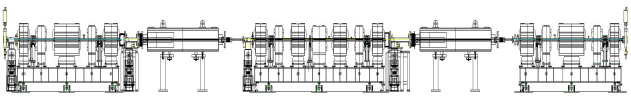


Fig.1 One of 48 cell of the magnets.

The monuments under bending magnets are surveyed in the stage of monument survey before tunnel construction. They are not used after magnet installation. To measure magnet positions in the storage ring we use the two reference points on each girder. The reference points are also used for the alignment of multipoles within girder. Total of 288 points, at an interval of 5 meters averagely, are used both for horizontal and vertical surveys.

The storage ring started commissioning in March 1997 and provided synchrotron light to user in October. From thence, the monitoring of the magnet alignments was executed in regular periods. We have 12 times of vertical surveys, and 10 times of horizontal. Because the variation of magnet alignment is very small, we didn't adjust any magnet in thirteen years. However, the observations show that deterioration of magnet alignment is in progress. On the other hand, small displacements of magnet position and inevitable measurement bias make it difficult to compare individual surveys. Here, we adopt weighted average to get rid of measurement bias. It is demonstrated a convincible method to conclude the deterioration progress of magnet alignment.

BRIEF REVIEW OF THE MAGNET ALIGNMENT PROCESS

Main events of magnet alignment

Here lists main events concerning alignment monitoring.

1993/1 First time monuments survey
1994/11 Monument survey inside tunnel
1995/4-1996/3 Ring magnet installation
1996/4 Level survey of magnets for whole ring
1996/10 Horizontal survey of magnets for whole ring
1997/1 120 angles are measured in horizontal survey
2000/7 Introduced digital level to survey
2000/7-8 Magnet in long straight sections of the ring were rearranged
2003/8-2005/3 Hydrostatic level system were set up at three places in the tunnel
2005/4 Forty-four angles are integrated to horizontal survey

The first monument survey was made in January 1993. Survey points were composed of 10 geodetic monuments outside the ring building, and 15 concrete monuments (fig.2). The concrete monuments (name with prefix 'c') are located under the bending magnet, intersection point of straight lines on both sides. Then, the building was just begun constructing, the view was broad enough to make a good measurement. Error ellipse was estimated of ±0.5mm rms.

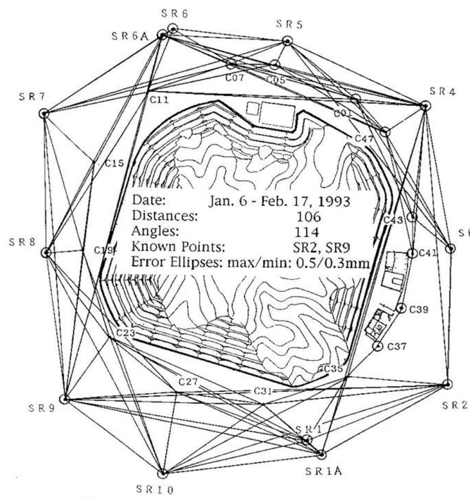


Fig.2 First monument survey in January 1993.
'SR': geodetic monument, 'c': concrete monument.

After tunnel construction was completed, surveys are isolated from outside. There is no absolute datum inside ring tunnel. Both of horizontal and vertical measurements are relative. For the horizontal, the Leica laser tracker SMART310 (LT) was used. In addition, WILD ME5000 and T3000 were utilized for long distance or angles measurements (fig.3). Simulation shows that the survey error was ±0.5mm rms, and ±1.3mm p-p for horizontal transverse [1].

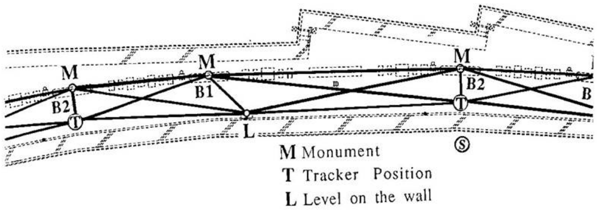
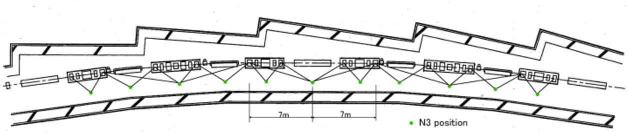


Fig.3 Monument survey inside the tunnel

The precise alignment of the multipoles on girder used a laser-CCD camera system. After rough adjustment by means of mechanical tools, the multipoles were aligned inside the tunnel [2]. We have total of 816 multipoles on 144 girders. Installation of ring magnets was divided into four phases temporally. So, at that time surveys were not closed in the ring. Calculated positions of magnets were best fitted to the monuments.

The magnets installation was completed in March 1996. From thence we could survey the whole ring using the reference points on top of magnets. Levels of magnet were measured with the Wild N3 (fig.4). Standard error was less than ±0.2mm. Figure 5 shows the magnet levels in February 1997, the displacements were very small. Because of the result of optical instrument is reliant on people's eyes or experience, we changed to the digital level Zeiss DiNi11 since 2000. Accuracy it yielded is almost the same as N3.



Dot: Wild N3; line: sight of seeing
Std. (Between units): ± 0.02mm
Error rms (For 1.5km ring): ± 0.2mm

Fig.4 Level survey for the magnets

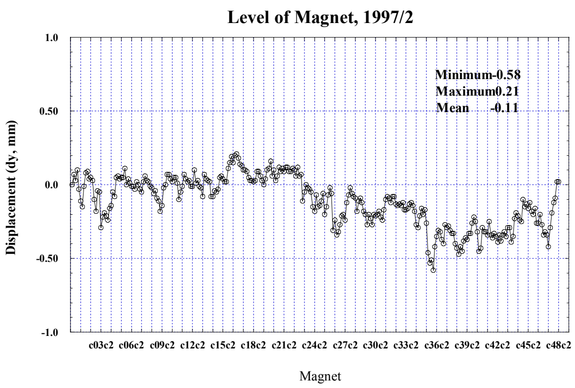
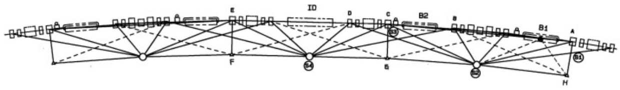


Fig.5 Levels of the magnets in February 1997

For the horizontal, the survey network was measured with the laser tracker (LT). One set up of the LT measures 8 to 9 points and the steps between set ups were about 7.5 meters (fig.6). To mostly reduce the influence of LT's angle error, locations of LT w.r.t. the targets were chosen by checking distances accuracy. The tunnel is so narrow that we have to utilized 14 angles, which were calculated from the results of monument survey, when did network computation.



Line: distance; Circle: set up of LT
Std. (Between units): ± 0.05mm
Error rms (For 1.5km ring): ±0.5mm

Fig.6 Horizontal survey for the magnets

In the survey of 1997, we measured angles between adjacent cells. There were few insertion devices at that time and we could see two neighbour cells forward and backward. Total of 120 angles were measured. The displacements of the magnets in horizontal transverse are shown in figure 7. The displacements of magnets were within +1.5/-1.0mm. It had a very smooth path and relative displacement between girders of ±0.05mm rms [3]. Please be noticed that the mean displacement was not zero but toward outside ring. It was conformed consistent with a circumference measurement separately, which showed the ring was about 2mm longer than design value.

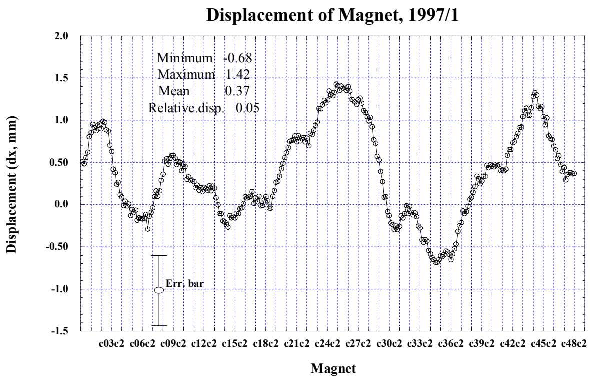


Fig.7 Displacement of magnets in horizontal transverse (January 1997)

The magnets at four long straight sections were rearranged in July - August 2000 [5]. This lattice change made it possible to make magnet free sections of 30 meters and a 27m very long undulator was installed. However, this made the passage much narrow and the width for survey network was only 2.4 meters in this area.

In the period of August 2003 to March 2005, we set up three sections of HLS (Hydrostatic level system) in the tunnel, intent to measure slow ground movement over wide area. One 50-meter system was set up above a vehicle underpass [6]. One 180-meter system was in the area of hard rock, and another 180-meter was above artificial rock area. Half-filled communication pipe of ϕ60mm was used, the diameter was considered to be near the optimal one [4]. With the capacitance sensor of FOGALE, the HLS has an irregular noise level about 0.1

μm. System has a capacity of ~2×10^{-10} resolution for the tilt (180m).

The undulators are higher than magnets and break the sight of view of survey. So, at the place of insertion device we have to make more set up of laser tracker. As the increases of undulators, we reconfigured the survey network for horizontal in April 1995 and modified the network by increase distance measurements. In the meanwhile, forty-four angles, each between two cells preceded and two cells followed, were integrated into horizontal survey.

LONG-TERM MONITORING

From 1996, monitoring of magnet alignments was executed in regular periods. We have ten times surveys of horizontal. Figure 8 shows the displacements of magnets measured from 1996 to 2009. In general, the change of the magnet alignment in horizontal is small. While, there is difficulty to make comparison between individual surveys.

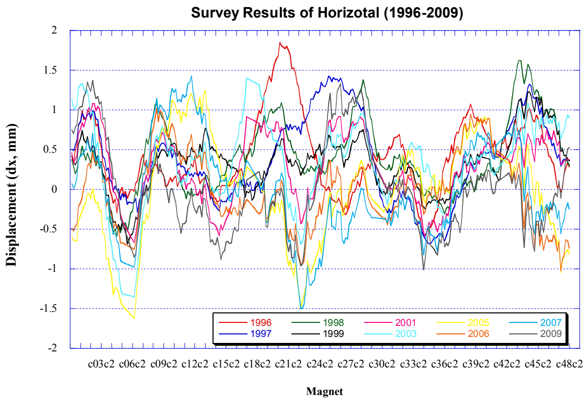


Fig.8 Horizontal displacements of magnets measured from 1996 to 2009. The plus is toward outside of ring.

Figure 9 is a simulation for the horizontal survey, supposing distances and angles have random errors. Because of error accumulation, the displacements gradually change their course. It implies that if we measure ten times we will get ten different results within certain error amplitude, because survey usually includes measurement biases or uncertainties.

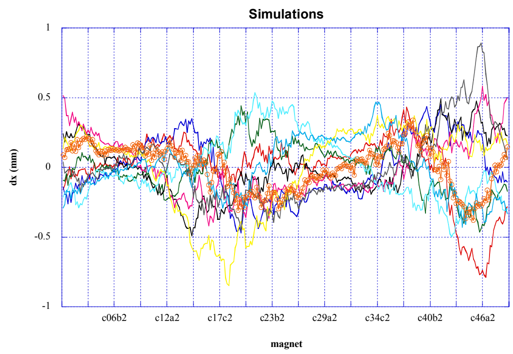


Fig.9 Ten times simulations of horizontal survey

Here, we calculate variance function between surveys:

$$V(\tau)=E((x(t+\tau)-x(t))^2)=\frac{1}{N}\sum_{1}^{N}[x(t+\tau)-x(t)]^2 \qquad (1)$$

v: variance of point relative movement, averaging over all points in the ring.

τ: time interval in year

And, examine the dependence of rms relative movement σ ($=\sqrt{V}$) on time interval τ.

We had 5 movements in 1-year interval, 7 in 2-year interval, etc. Time intervals vary from one year to thirteen years. Figure 10 is the plot of the mean rms relative movement versus time intervals.

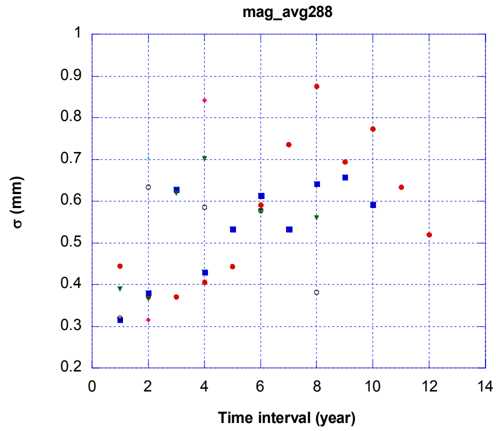


Fig.10 mean rms relative movements versus time intervals

It is can be seen that the correlation between x and y axis is weak. It implies the measurements can not be compared properly.

To derive ‘true’ displacement of magnets we always considered two issues. One is about the ‘reference’, the other is ‘comparable length’. Unlike vertical plane which has the geoid as the reference, in the horizontal there is no supper reference. However, the center of gravity of a group magnet could be a good reference, because it should not be simply moved on the whole. The fluctuations of displacements usually due to measurement bias, not magnets themselves have moved. On the other hand, measurement error is accumulated proportionally to measurement length. Therefore, we choose the center of gravity of magnets in a certain length (range) as the reference, from which magnet displacement are derived. The reference is defined as a ‘linear weighted moving average’:

$$\overline{X}_i=\frac{\sum_{k=-m}^{m} w_{i+k} * x_{i+k}}{\sum_{k=-m}^{m} w_{i+k}} \qquad (2)$$

here, we take the weight as:

$$w_{i+k}=m+1-|k| \qquad (3)$$

i: current point

m: 2m is averaging length, total number around current point

That is, current point has maximum weight of m+1 and the point going away from current is linear diminished for the weight in average. The value of average $\overline{x}_i$ depends on averaging length.

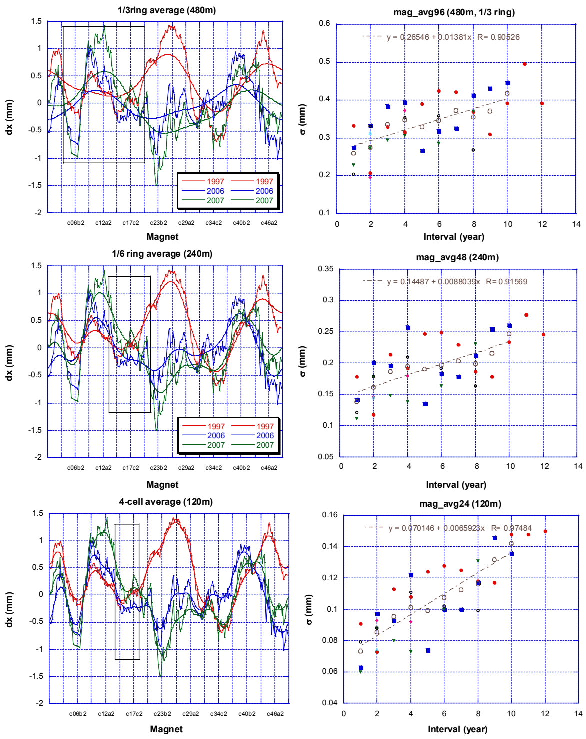


Fig.11 Left: Horizontal surveys of 1997, 2006 and 2007 and the moving average curves. The rectangle's width represents the averaging length. Right: rms vs. time interval. The circle is average rms for each year and the dotted line is linear fit to the circles.

We use the moving average to adjust comparison range of surveys. It is shown that the dependence of rms displacement on time interval appears linear when averaging length becomes shorter. Figure 11 shows the curves of the displacements and the moving average. For obviousness only three surveys of 1997, 2006 and 2007 are plotted in left graph. After abstracting the moving average from survey data, variance functions are calculated, and mean rms relative movement against time intervals are plotted in right graph. When averaging length shorter than 480 meters (1/3 ring) the correlation of them appears linear. The line in the figures is approximation of this dependence, it gives

$$\sigma = a_0 + a_1 T \qquad (4)$$

where, T is time interval in year.

Furthermore, the coefficients a_0 and a_1 both show linearly dependence on averaging length, as shown in figure 12.

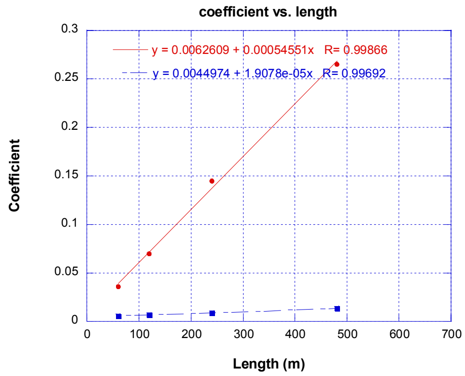


Fig.12 The coefficients in equation (4) versus averaging length for horizontal

At last, it is yield that in horizontal plane, mean rms displacement can be approximately concluded by equation

$$\sigma = (0.005+1.9e\text{-}5L)\ T \ \ (\text{mm}) \qquad (5)$$

where, L is averaging length (or inspection range) in meter; T is time interval in year. The variance is composed of two parts. The first is a constant rate; the second part is an inspection length dependent rate.

Deterioration of horizontal is 0.014mm/year for the ring.

By abstracting common average for certain length, we can compare the surveys and get two conclusions for the horizontal. Firstly, the amplitude of displacement has no evident enlargement. However, the smoothness of the path along magnets becomes very rough. This can be seen in figure 13.

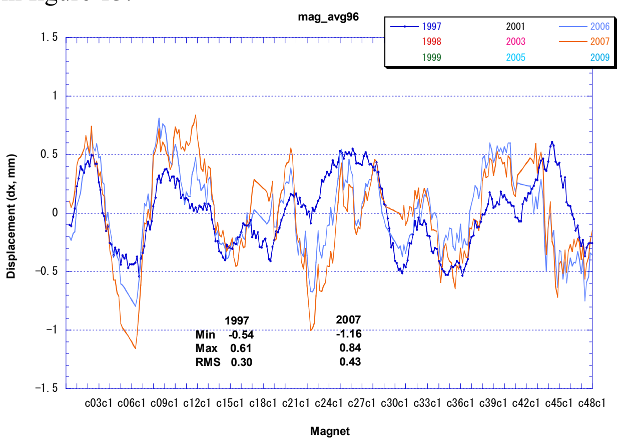


Fig.13 Displacements of magnets after abstracting the moving average. Smoothness of the path of magnets becomes very rough during 10 years.

Secondly, relative displacement of 60-m range deteriorates from 0.05mm to 0.12 mm (fig.14). Because this length is in the order of betatron oscillation wavelength (~36m) of electron beam, it gives the roughness that electron beam felt.

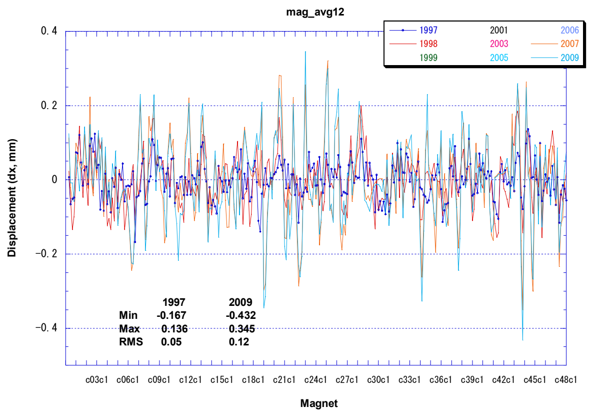


Fig.14 Magnet relative displacements of 60-m average

For the vertical plane, figure 15 gives the survey results of magnet levels measured from 1996 to 2008.

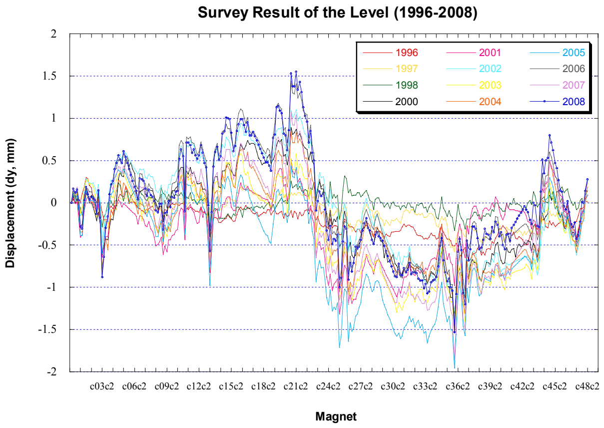
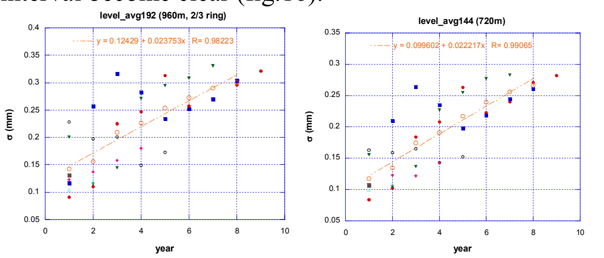


Fig.15 Levels of the magnets measured from 1996 to 2008

Survey of level is three times accurate than that of horizontal. So, the variances of magnet alignment are almost obvious in this figure. But still, measured displacements fluctuate from year to year, because of measurement biases. Also, the residual displacements from moving average are examined.

When averaging length shorter than 2/3 of ring (960m) the correlation between mean rms displacement and time interval become clear (fig.16).



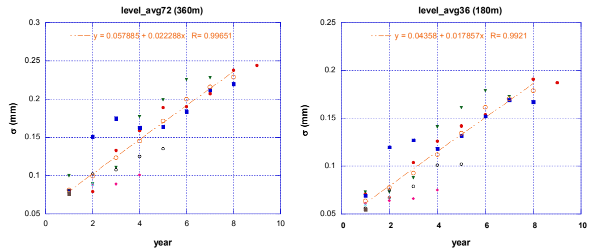


Fig.16 Correlation between mean rms displacement and time interval, after abstracting the moving averages in lengths of 2/3, 1/2, 1/4, 1/8 of the ring respectively. The circle is the average of each year and the dotted line is linear fit to the circles.

The line in the figure is the approximation and has the form of $\sigma = a_0 + a_1T$. Again, the coefficients a_0 and a_1 are both linearly dependent on averaging length as shown in figure 17.

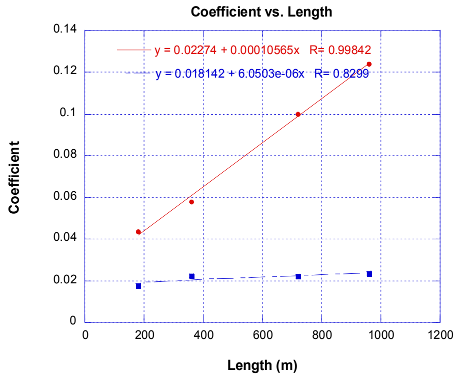


Fig.17 The coefficients in equation (4) versus averaging length.

It is estimated that for the vertical, mean rms displacement varies at a rate of

$$\sigma = (0.02+6.05e\text{-}6L)\ T \ \text{(mm)} \qquad (6)$$

where, T: time interval; L: inspection length

The coefficients denote that the level has a constant deteriorate rate of 0.02mm/year, in addition of an inspection length dependent rate.

The deterioration in level is 0.024mm/year for average.

As a conclusion, the variance of magnet alignment could be approximately modeled as following temporally and spatially.

$$\sigma = (A_1+A_2L)\ T \qquad (7)$$

where, T is time interval in year; L is inspection length in meter; and σ is mean rms displacement during T. The coefficients A_1 represents constant variance factor, and A_2 is the factor of length dependence.

It is in some way similar to the ATL law while has different content. The ATL law studies the variance of diffusive motion of two distant points [7]. Here we are estimating the rms displacement of a point within an inspection range L.

The levels of magnets with respect to the common reference, linear weighted moving average, are derived and shown in figure 18. RMS relative displacement varies from 0.1mm to 0.42mm in twelve years.

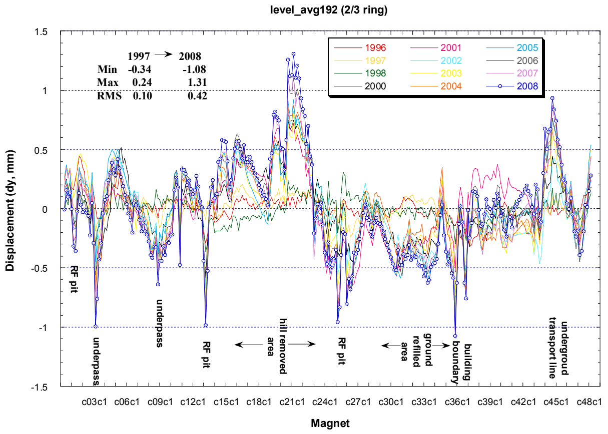


Fig.18 Displacements of magnet levels from 1996 to 2008

The levels of magnets appear many peaks where usually have underground structures as indicated in graph.

Relative displacement in 180-m average range is given in figure 19. This length is in the order of vertical betatron oscillation wavelength. Mean rms displacement changed from 0.08 to 0.24mm, three times deteriorated.

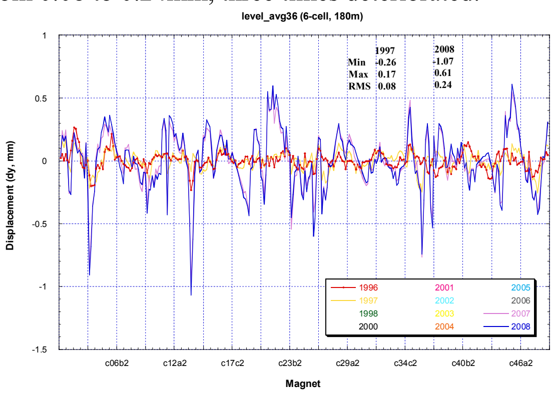
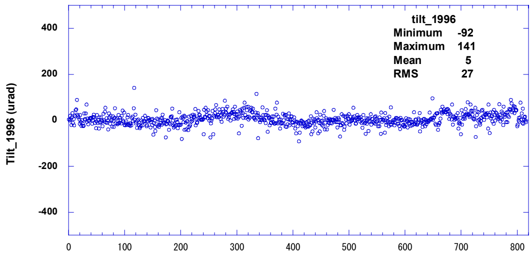


Fig.19 Displacements of magnet's levels after abstracting the moving average of 180 meters.

The rolling of magnets are measured with TaylorHobson Talyvel, in 1996, 2003 and 2009, for over 800 magnets. Comparing the year of 1996, rms tilt changed from 27μrad to 68 μrad in 2003, after 7 years. However there was almost no change in following 6 years, from 2003 to 2009 (fig.20). It can say variance of the rolling of magnet stopped.



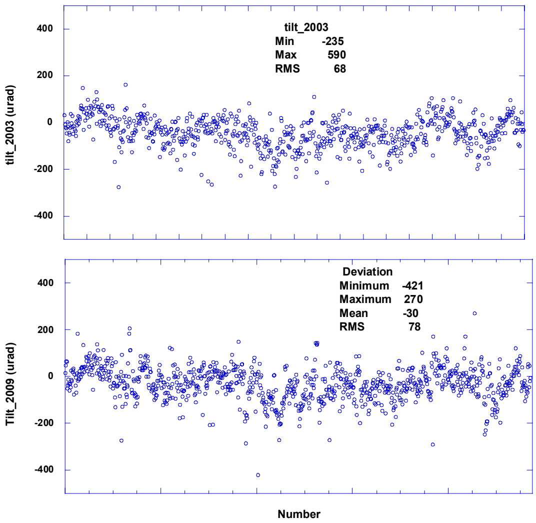


Fig.20 Tilts of the rolling of magnets, measured in 1996, 2003 and 2009. Time intervals between them are almost same while there was no change from 2003 to 2009.

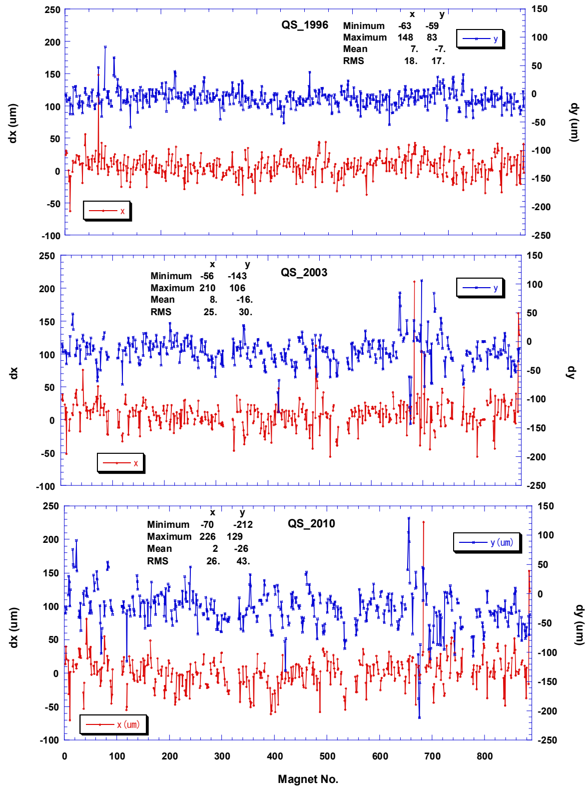


Fig.21 The linearity of multipole magnets within girder measured in 1996, 2003 and 2009 with the laser alignment system of CCD-camera.

The linearity of the multipole magnets within girders was also measured in 1996, 2003 and 2009 with the laser alignment system of CCD-camera. For the statistics, mean rms displacements varied 8 μm and 26 μm in horizontal and vertical planes respectively in thirteen years. And, there is almost no change during 2003 to 2009 in horizontal. By contrast, the vertical makes a constant progress of 2 μm/year (fig.21).

CONCLUSION

After the installation of SPring-8 storage ring in 1996, the observations of magnet alignment are executed in regular periods. Until 2009 we had 12 times surveys for the vertical, and 10 times for horizontal. The linearity of magnets within girder, also the rolling of magnet were measured in 1996, 2003 and 2009.

To compare between individual measurements, and to get rid of measurement bias, we adopt linear weighted moving average as reference. After abstracting the common reference, the variances of magnet alignment become obvious. Mean relative movement of magnets could be approximated as

$$\sigma = (A_1+A_2L)\ T$$

where, T is time interval in year; L is inspection length in meter; The coefficients A_1 represents constant variance factor, and A_2 is the factor of length dependence.

In horizontal plane, the amplitude of displacement has no evident enlargement. The deterioration rate is 0.014mm/year. While smoothness of the path along magnets become very rough. RMS relative displacement in 60-m range deteriorates from 0.05mm to 0.12 mm.

In vertical plane, RMS relative displacement varies from 0.1mm to 0.42mm for the ring, and from 0.08mm to 0.24mm for a range of 180-m, three times deteriorated,.

Rolling of magnets changed from 27 - 68 μrad (rms) for average in first 7 years, but had no variance in following 6 years. It can say the variance of magnet rolling stopped.

Linearity of the magnets within girder varied 8 μm in horizontal, and 26 μm in vertical in thirteen years, while for the horizontal there was almost no change after 2003. By contrast, the vertical makes a constant progress of 2 μm/year.

Because the variation of magnet alignment is very small, we didn't adjust any magnet for thirteen years.

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