ALIGNMENT FOR NEW SUBARU RING

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1. INTRODUCTION

The New SUBARU is a synchrotron light source being constructed at the SPring-8 site. The project is supported by the local government, Hyogo prefecture. Himeji Institute of Technology is in charge of its construction in collaboration with the SPring-8. The main facility of the New SUBARU is a 1.5 GeV electron storage ring that provides light beam in the region from VUV to soft X-ray using SPring-8's 1 GeV linac as an injector. The ring, with a circumference of about 119 meters, is composed of six bending cells. Each bending cell has two normal dipoles of 34 degree and one inverse dipole of –8 degree. The ring has six straight sections: two very long straight sections for a 11-m long undulator and an optical klystron, four short straight sections for a 2.3-m undulator, a super-conducting wiggler, rf cavity and injection, etc. (Fig.1).

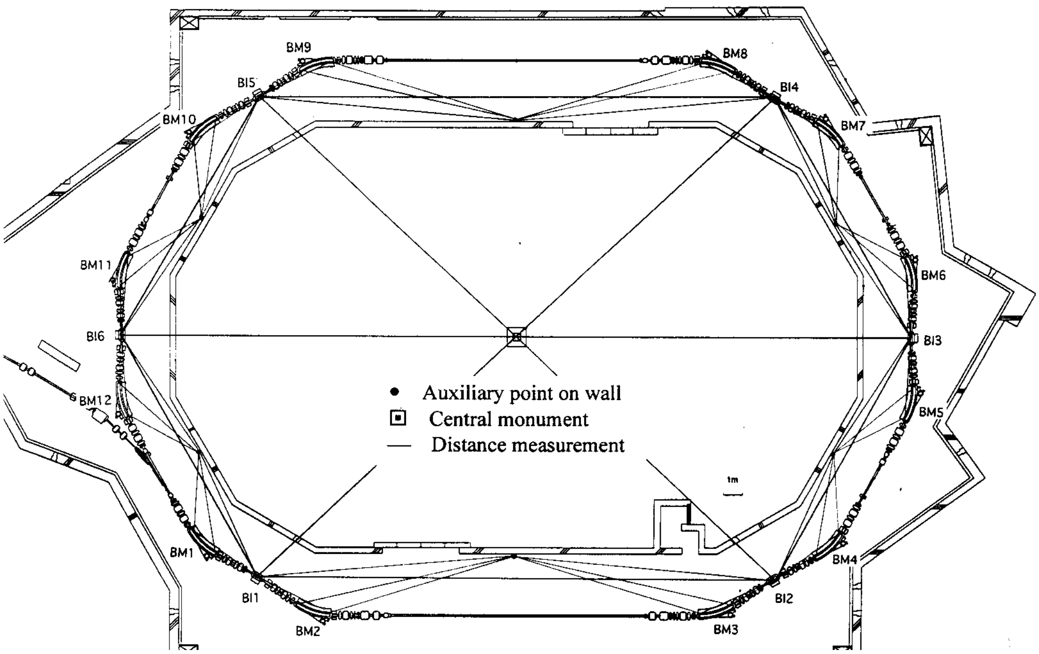

Fig.1 Layout of the storage ring of New SUBARU. The survey network is used to survey the dipoles.

The ring tunnel is built on Sayo gravel bed, which consists of conglomerate clay layer. The thickness of wall concrete is 31 cm, and the floor is 70 cm. For where there are cable pit which across tunnel floor, the thickness is 50 cm.

The magnets of the storage ring are composed of 12 dipoles (BMs), 6 invert dipoles (BIs), 56 quadrupoles and 44 sextupoles, etc. Figure 2 gives a view for the positional relations of the magnets in the tunnel.

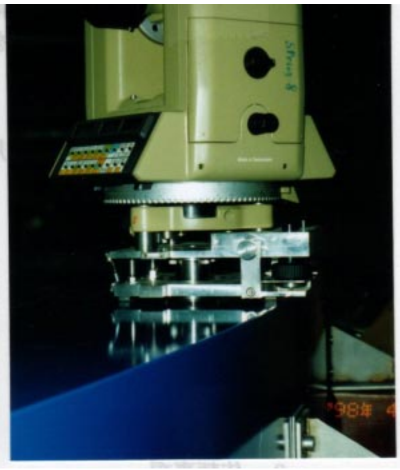

Fig.2 A view for the positional relationship of the magnets in ring tunnel.

Fig.3 A force-centerd stage for setting theodolite on the fuducial point of magnet.

For the magnet alignment, positions of the dipoles (the BMs and BIs) are determined by network survey method. The multipoles, which are mounted on girders between the dipoles, are aligned with a laser-CCD camera system.

2. INSTALLATION FOR THE RING MAGNETS

The installation of the magnets was started in February 1998, and completed in March the same year. Installation procedure is firstly, the pre-alignment of dipoles, and then the precise alignment of dipoles and multipoles.

2.1 Pre-alignment of the dipoles

The dipoles are employed as the alignment datums. They are positional references for other components in the ring. The six BIs, together with a central monument, compose a primary measurement network (bold line in figure 1). Pre-installing dipoles is to align the magnets to about 0.5 mm range with respect to their ideal positions to reduce the movement amount in the after process of precise alignment. The mekometer ME5000 (which can extend measurement range below 20 meters with the program Promeko, Kern) and the theodolite T3000 (Wild) are set on the central monument to measure magnets' horizontal positions. And, the level N3 (Wild) is used to measure magnets' height. Six holes of 30 cm×30 cm are made on the wall of the tunnel for the line of sight. The twelve BMs were placed with the 3D laser tracker SMART 310 by referencing the BIs. Height references were made by fix the target stage that hold Ø75 mm ball on the wall with 0.1 mm accuracy. The tilt of magnets was measured with the 2D tilt sensor NIVEL20 (Leica).

Each dipole was adjusted in six dimensions simultaneously except for the BIs, its rotation about vertical axis was adjusted at the last step of dipole alignment, because only the central fiducial point of BIs is used as alignment datum.

From the results of the network survey afterwards, it was cleared that the BIs were horizontally set into 0.3 mm error range, and the BMs were about 0.5 mm at the pre-alignment process. The dipoles' height was aligned within 0.2 mm, and tilt was about 0.03 mrad (r.m.s).

2.2 Precise alignment of the dipoles

Precise alignment of the dipoles in the stage of installation was made with a survey network as shown in figure 1. The network comprised 90 length measurements and 30 angle measurements. The measurement elements of lengths were collected with the laser tracker. Angles were measured with the thodolite which sets on the fiducial points of dipoles and measurs the angle between two nearest points on the wall, or between the wall point and the nearest BI on the two sides of thodolite.

Table 1 Estimated Error Ellipses of Measurement Points

NO.	POINTS	MAX	MIN
1	B01U	0.031	0.011
2	B01D	0.023	0.01
3	BI1	0.015	0.009
4	B02U	0.021	0.01
5	B02D	0.029	0.011
6	B03U	0.034	0.009
7	B03D	0.024	0.008
8	BI2	0.014	0.007
9	B04U	0.024	0.008
10	B04D	0.034	0.009
11	B05U	0.028	0.011
12	B05D	0.02	0.01
13	BI3	0.015	0.009
14	B06U	0.023	0.01
15	B06D	0.032	0.011
16	B07U	0.032	0.011
17	B07D	0.023	0.01
18	BI4	0.015	0.009
19	B08U	0.021	0.01
20	B08D	0.03	0.011
21	B09U	0.029	0.009
22	B09D	0.021	0.008
23	BI5	0.014	0.007
24	B10U	0.021	0.008
25	B10D	0.029	0.009
26	B11U	0.029	0.011
27	B11D	0.021	0.01
28	BI6	0.015	0.009
29	B12U	0.023	0.01
30	B12D	0.031	0.011
31	C00	0.016	0.011
ml=0.01, ma=0.00023			

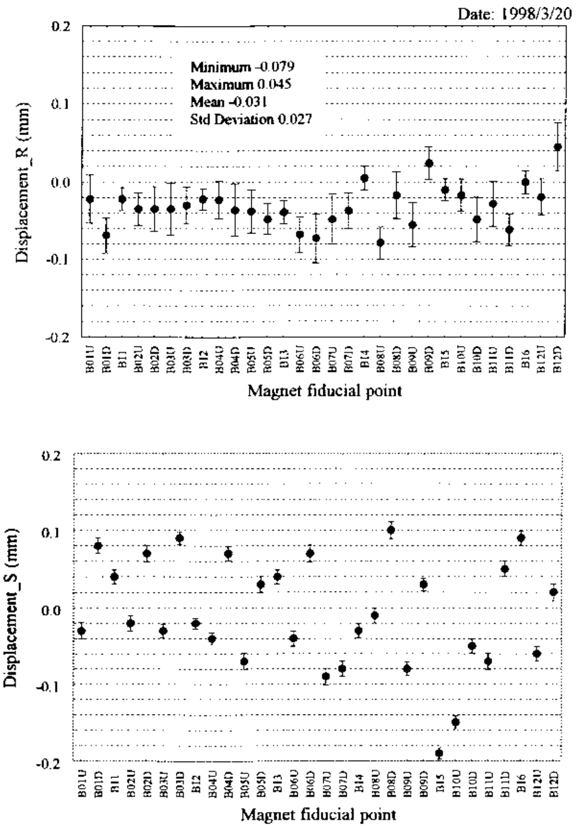

Fig.4 Magnet displacement after three rounds of position adjustments.

A force-centred stage was made for setting the theodolite on the fuducial point of magnet (Fig. 3). The stage let the vertical rotating axis of theodolite coincide with the center of fiducial point. Because angle measurement error is proportional to the offset of theodolite axis and inversely propotional to the target distance, the offset of axis must be carefully calibrated before any measurement is made.

Table 1 shows the estimated error ellipses (1σ) of the survey. Maximum error is approximately corresponding to beam transverse direction and the minimum to beam direction. Figure 4 is the positional residuals of the dipoles after three rounds of surveys and adjustments. Magnets were almost aligned to 1σ error range in the direction of horizontal transverse. While in beam direction we have no intention to adjust the error to zero because of its loose tolerance. Also, the length between the two fiducials of upper-stream (indicated with U) and down-stream (indicated with D) of each dipole is longer than designed one. The two fiducials are placed in opposite sides of zero symmetrically.

2.3 Discussion on precise alignment of the dipoles

The reason that the dipoles are chosen as alignment datum is for they are higher in elevations and more stable in positions. But we expensed unnecessarily much time to move dipole's positions to where they should be. Although it really left convenience to later installation, considering their loose tolerance, it is not necessarily so for us to adjust dipoles very precisely. We need only to know exactly their positions rather than make adjustment.

After the first two rounds of surveys and adjustments, the dipoles still had about 0.1 mm residual error. It was larger in comparison with estimated survey accuracy. The problem was realised that the digital gauges that monitor adjustment were not in the same height with the survey point (there is 0.7 m difference between the two). Therefore, the movement amount is not the same as desired one, because of simultaneous tilt change of magnets for about 0.02 to 0.2 mrad. The laser tracker replaced digital gauges to monitor the movement afterwards.

As for the survey network, the central monument is much necessary at the first stage of magnet installation. It provides a quick and reliable positional reference. Angular measurements play a key role in this survey because there is no direct distance connection between adjacent dipoles in the straight section. As a result the survey needs not very precise distance measurement. It is estimated that even if the distance error is 0.05 mm and angular error is 1 arc second, magnet positions will be still correctly determined within 0.05 mm for the whole ring. But, angle measurement consumes time and requires much care. It would be better if we measured reasonably as many angles as possible at one setting place of the theodolite rather than made more settings.

2.4 Precise alignment of the multipoles

One hundred multipoles are mounted on twenty-four girders. Horizontally, the multipoles are on the straight line of the dipoles' fiducial points. Vertically, the elevation of multipole's fiducial is 50 mm lower than that of the dipoles.

The multipoles on both end of a girder were firstly aligned with the laser tracker by referencing the dipoles. Than, the magnets between the two ends on one girder were aligned with the laser-CCD camera system on the spot of the tunnel. The laser system developed in SPring-8 is for the specific purpose of aligning magnets on a common girder (Fig.5). The strength distribution of the He-Ne laser beam of ϕ3 mm is measured by a CCD of 8×6 mm with pixel of 11×11 μm, and the centre of gravity is calculated. Effort was made to reduce interference patterns, and laser profile is online checked during alignment process. The straightness accuracy of this system is estimated within 10 μm in 5 meters.

The deviations of magnetic centre from the pole centre for each magnet were measured with the same type of laser system beforehand by the maker. Statistically, they are 0.046 mm (σx) in horizontal, and 0.035 mm (σy) in vertical. There is a significant systematic deviation of 0.13 mm in vertical direction and the reason is not well understood. These deviations were corrected at the stage of multipole's alignment. The tilt and position of the multipoles are monitored at the same time when making adjustment. Inclination is measured with the Nivel20, and finally, with the Talyvel4 (Taylor Hobson), because the Telyvel4 was used in previous process of magnetic centre measurement. It is better to use the same instrument continuously.

Fig. 5 Alignment of multipole magnets with the laser-CCD camera system.

2.5 Discussion on precise alignment of the multipoles

Since there is 50 mm hight difference between the dipole and the multipole, the fiducial points should not have used the type of tapered hole. It is not easy to raise target ball to a higher elevation with a basement. At first a rhomboid prism was attempted to lower the laser beam by 50 mm in elevation at the girder unit of the multipoles. This method turned to be given up because the two beams of different levels are hardly paralleled.

The fiducial plane on the multipole is made with aluminium plate. The plates were found to be deformed by the force of tightening the fixing screws as to it is difficult to determine a medium plane.

The laser-CCD camera system is proved to be very precise and has good repeatability. Alignment residuals of the multipoles were 15 μm of σx and 12 μm of σy.

After precise alignment, Taylor Hobson's telescope was used to check the straightness of magnet poles within a common girder. The deviations are 0.03 mm of σx and 0.04 mm of σy respectively, with a maximum displacement of 0.2 mm in vertical. It is hard to be understood that the deviations of magnet poles from magnetic centres are so large. Also, deviations of magnet poles in vertical seem to cohere with of the data of the measurement for magnetic field centres. The COD of beam orbit are calculated with the data of magnet survey. Similarly, the result that without magnetic centre correction is more close to measured COD. In consequence, the reliability of the measurement for magnetic field centres is doubted.

3. RE-SURVEY FOR THE RING MAGNETS

3.1 Our method of surveying with the laser tracker

Usually, surveying for component's positions is executed accoording to predetermined scheme, and the scheme has to be thoroughly planned by experienced people. Our method of surveying with the laser tracker is quite flexible. There are many freedoms in this survey method. Firstly, the number of measuring points is free. We measure reasonably as many points as we want at one station (the setting place) of the laser tracker. Secondly, the position of the laser tracker is free. The laser tracker is moved to an approximate position and it need not to adjust height and inclination. Thirdly, the coordinates of auxiliary points are free. We need not to know exactly the coordinates of auxiliary measuring points. All measurement points are known only for their approximate coordinates, but kept within few millimeters of height coherence.

Following aspests are considered to be beneficial when surveying with the laser tracker or designing a survey network:

1) Directly use the length from the laser tracker to the object (measuring distance),
2) Making fully use of the width of tunnel,
3) Measurement sets at each station are arranged symmetrically as far as possible,
4) Each measuring point is measured at least three or four times from different directions.

The reasons for above considerations would be knowleged when considering the measuring distances as 'rigid pipes'. The 'pipe' fixes relative positions of measurement points along its extension line. The knots of network could be considered as 'hinges'. As long as the 'network band' has sufficient width the pipes will be also firm in positions of transverse direction. Symmetric configuration of measuring distances is to reduce measurement bias that may caused by systematic errors such as the change of index of refraction, calibration error of the laser tracker. The systematic errors induce enormous bias for large accelerator.

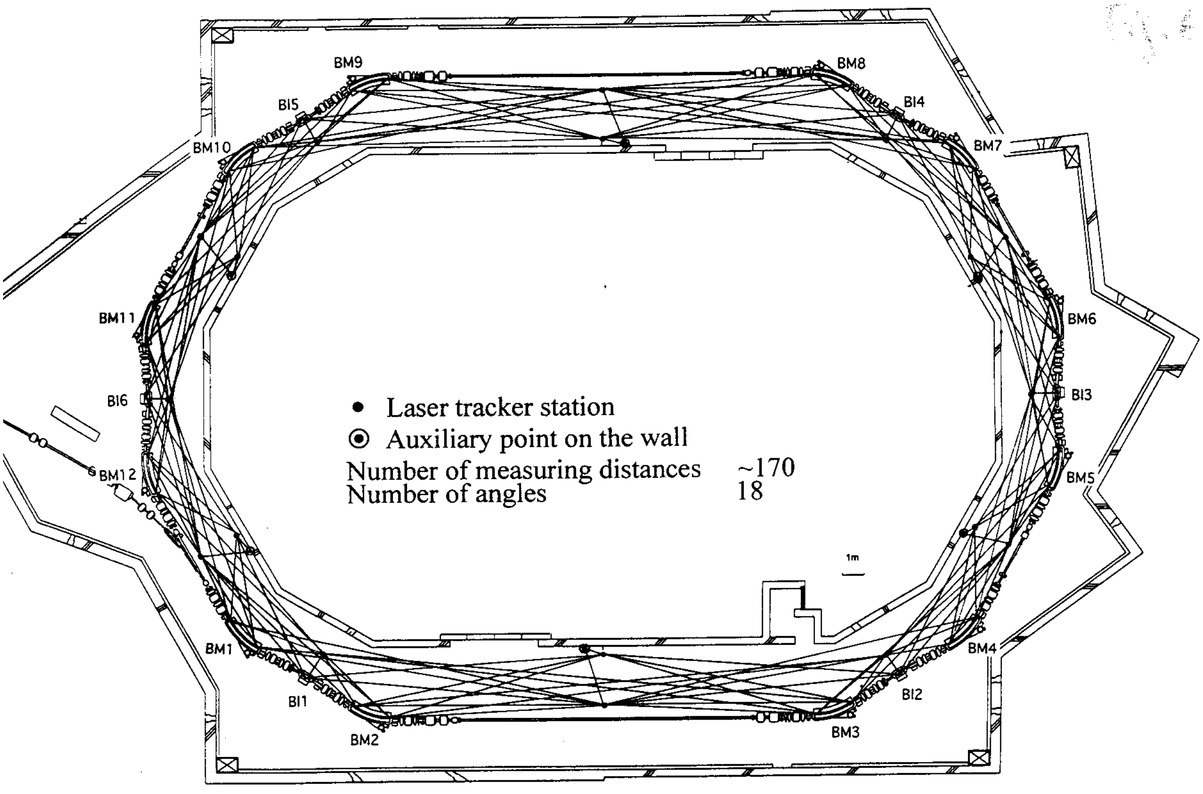

Fig. 6 Measurement configuration of surveying the magnets of New SUBARU.

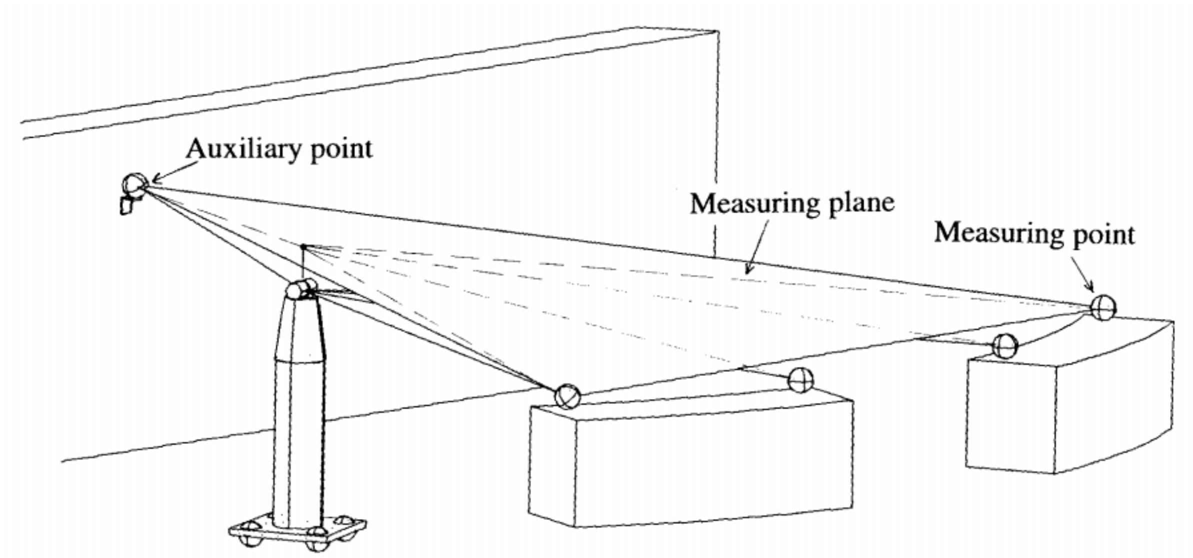

Fig. 7 Sketch of the Direct Distance Measurement Mothed.

Figure 6 showes the configuration of distance measurement for surveying magnets of the New SUBARU. At each BI three angles are also measured among nearest BIs and the points on the wall. Actually, the measuring distances are not in a same plane. The ‘measuring plane’ is therefore defined as the plane that fiducials and auxiliary points composed. All measurement distances are normalized to the measuring plane, and the coordinates of laser tracker stations as well as measuring points are calculated in this plane.

Figure 7 showes the sketch of the Direct Distance Measurement. Each distance name comprises two parts of the station name and measuring point name separated by an underscore. that is,

Station name_Measuring point name

This is benefit for automatic calculating the coordinates of measurement points with computer program. The computation process is illustrated as following. This process is automatical and need not manual intervention.

Input the measured distances, and the designed coordinates
of the measuring points (for the auxiliary point input approximate coordinate).

For each distance, station name and measuring point name is sapareted. Distances
from the laser tracker to measuring points are obtained.

To define a measuring plane, at each station select three fully departed points with condition (a).
Then, calculate height diffirence from laser tracker to the measuring plane.
And, all distances are normalized to this plane.
(a): A*B*C*(a+b+c)=max, A,B,C : inner-angles, a,b,c : sides.

Search for the two fiducials that with laser tracker composing max.product of inner angles.
Positional relation of the laser tracker to the two fiducials is judged with condition (b).
Approximate coordinate of station is calculated from the coordinates of the two fiducials.
(b):direction of the vector product of **SF1 •~*SF2*, *SF1*** from laser tracker to fiducial point 1.

let ***x=x₀+dx, y=y₀+dx,*** where, *x,y*are most probable and ***x₀, y₀*** are approximate coordinates
Each distance is expansed at approximate coordinates, and we get
the error equation matrix ***V=BdX+L,*** *v* is distance corrective value,
b is expansion coefficient of first order, *l* is constant concerning distance.

Least square solution of dx, dy are obtained when let
[VWV]=min,and ***[dXdX]=min.*** where *w* is the weights of distances.
(The most probable coordinates of x, y obtained on these conditions are the fitting results
to the designed positions, no known (or reference) coordinates are needed.)

The last, measurement errors and the error ellipeses
of measuring points are estimated.

Table 2 The Laser Tracker Measurements

MEAS. POINT	X	Y	Z
SBI1_B12D	1342.347	-10344.3	-16.33
SBI1_B12U	549.008	-11913	-11.52
SBI1_B1D	2305.533	-1770.41	-21.84
SBI1_B1U	2525.221	-3514.49	-23.31
SBI1_B2D	-404.379	4459.622	-5.274
SBI1_B2U	557.427	2988.254	-11.03
SBI1_B3D	-17060.4	17681.76	97.778
SBI1_B3U	-15440.3	16999.64	87.731
SBI1_BI1	1265.093	547.857	-15.5
SBI1_BI2	-19588.3	17939.88	113.17
LW2B_B1D	-3797.97	-15535.4	39.975
LW2B_B1U	-5111.46	-16703.7	45.653
LW2B_B2D	-195.68	-9775.17	17.611
LW2B_B2U	-864.326	-11400.9	23.321
LW2B_B3D	1277.547	11440.05	-36.35
LW2B_B3U	1632.193	9718.304	-33.06
LW2B_B4D	-1909.69	17440.05	-44.05
LW2B_B4U	-836.083	16048.07	-42.99
LW2B_BI1	-2475.6	-13365.6	31.71
LW2B_BI2	59.486	13670.24	-39.1
LW2B_LW2	-2329.28	182.742	-1.941

Table 3 Distances of Laser Tracker to Measur. Point and Meas. Plane

STATION	FIDUCIAL	DISTANCE	HEIGHT DIF.
SBI1	B12D	10431.023	7.72
SBI1	B12U	11925.615	7.72
SBI1	B1D	2906.9328	7.72
SBI1	B1U	4327.6818	7.72
SBI1	B2D	4477.9146	7.72
SBI1	B2U	3039.8107	7.72
SBI1	B3D	24570.543	7.72
SBI1	B3U	22965.149	7.72
SBI1	BI1	1378.6908	7.72
SBI1	BI2	26562.257	7.72
SLW2B	B1D	15992.98	6.41
SLW2B	B1U	17468.29	6.41
SLW2B	B2D	9777.1401	6.41
SLW2B	B2U	11433.604	6.41
SLW2B	B3D	11511.218	6.41
SLW2B	B3U	9854.468	6.41
SLW2B	B4D	17544.349	6.41
SLW2B	B4U	16069.893	6.41
SLW2B	BI1	13592.938	6.41
SLW2B	BI2	13670.42	6.41
SLW2B	LW2	2336.4285	6.41

Table 2 is the example of the measurement data of laser tracker. Here, measurements at two stations named SBI1 and LW2B are listed. Table 3 showes the distances of laser tracker to the measuring plane (height difference), and to the measuring points that are normalized to this plane. These distances and the approximate coordinates of fiducial points are used to derive the most probable coordinates of surveying points.

Table 4 is estimated survey errors of the dipoles. The fiducial points on the dipoles are expected to be determined with mere 20 μm error along the tunnel. In November 8-9, 1999, the dipoles of the ring were surveyed twice to confirm the measurement accuracy. The result was quite satisfying as one can understand from table 5 and figure 8. Repeatability of the two round surveys is within 20 μm except one magnet. The same set of the 18 angle data was used in this comparison.

Table 4 Estimated Error Ellipses

	Dipole	MAX	MIN
1	B1U	0.013	0.007
2	B1D	0.013	0.007
3	BI1	0.011	0.007
4	B2U	0.016	0.008
5	B2D	0.017	0.008
6	B3U	0.019	0.009
7	B3D	0.018	0.008
8	BI2	0.012	0.008
9	B4U	0.016	0.008
10	B4D	0.017	0.008
11	B5U	0.017	0.007
12	B5D	0.014	0.006
13	BI3	0.009	0.007
14	B6U	0.014	0.007
15	B6D	0.017	0.008
16	B7U	0.014	0.006
17	B7D	0.014	0.006
18	BI4	0.012	0.007
19	B8U	0.016	0.008
20	B8D	0.017	0.008
21	B9U	0.015	0.007
22	B9D	0.015	0.007
23	BI5	0.011	0.006
24	B10U	0.015	0.007
25	B10D	0.015	0.007
26	B11U	0.013	0.006
27	B11D	0.012	0.006
28	BI6	0.009	0.005
29	B12U	0.013	0.006
30	B12D	0.014	0.006
	ml=0.0101		
	ma=0.00014		

Table 5 Comparison of two rounds of surveys for the dipoles

Dipole	dr_99a	ds_99a	dr_99b	ds_99b	ddr	dds
B1U	0.136	-0.15	0.136	-0.151	0	0.001
B1D	-0.11	0.068	-0.101	0.068	-0.009	0
BI1	-0.068	0.161	-0.042	0.153	-0.026	0.008
B2U	-0.069	0.152	-0.039	0.14	-0.03	0.012
B2D	-0.02	0.356	0.017	0.346	-0.037	0.01
B3U	0.009	-0.169	0.03	-0.183	-0.021	0.014
B3D	0.129	0.052	0.147	0.04	-0.018	0.012
BI2	0.151	0.218	0.168	0.2	-0.017	0.018
B4U	0.311	0.056	0.326	0.039	-0.015	0.017
B4D	0.372	0.266	0.392	0.255	-0.02	0.011
B5U	0.295	-0.161	0.304	-0.181	-0.009	0.02
B5D	0.333	0.057	0.335	0.04	-0.002	0.017
BI3	0.362	0.321	0.357	0.313	0.005	0.008
B6U	0.385	-0.341	0.372	-0.355	0.013	0.014
B6D	0.376	-0.124	0.365	-0.135	0.011	0.011
B7U	-0.019	-0.494	-0.033	-0.499	0.014	0.005
B7D	0.089	-0.28	0.072	-0.289	0.017	0.009
BI4	-0.289	1.154	-0.304	1.151	0.015	0.003
B8U	-0.157	0.046	-0.174	0.042	0.017	0.004
B8D	-0.228	0.264	-0.243	0.261	0.015	0.003
B9U	-0.223	-0.049	-0.229	-0.047	0.006	-0.002
B9D	-0.136	0.045	-0.145	0.05	0.009	-0.005
BI5	0.156	0.025	0.14	0.03	0.016	-0.005
B10U	-0.04	0.046	-0.057	0.05	0.017	-0.004
B10D	0.203	0.253	0.185	0.26	0.018	-0.007
B11U	0.218	-0.049	0.207	-0.035	0.011	-0.014
B11D	0.403	0.179	0.387	0.189	0.016	-0.01
BI6	0.326	-0.349	0.317	-0.338	0.009	-0.011
B12U	0.238	-0.26	0.222	-0.243	0.016	-0.017
B12D	0.265	-0.027	0.246	-0.013	0.019	-0.014

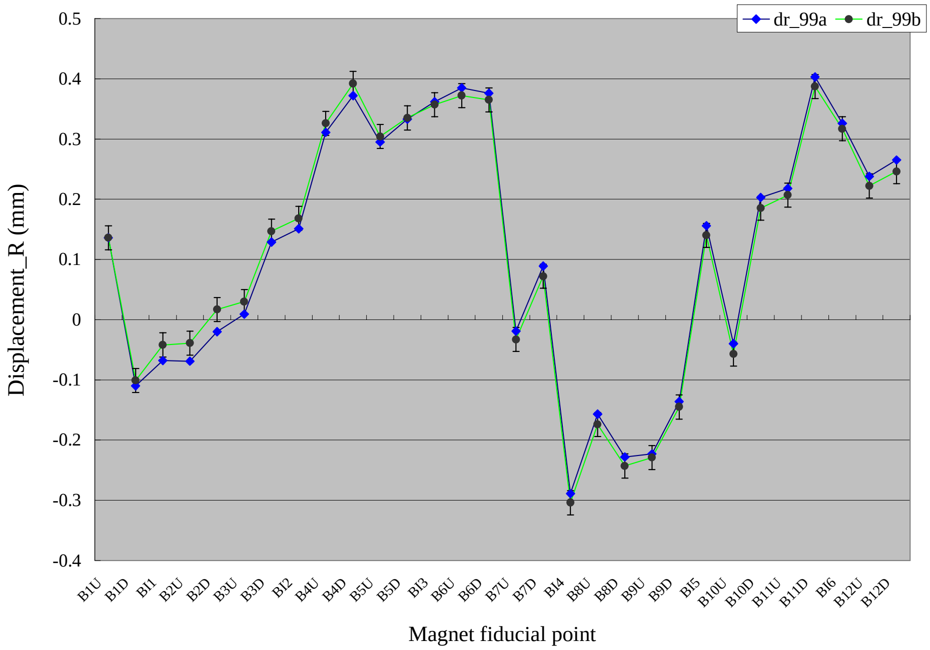

Fig. 8 Repeatability of two round surveys in horizontal plane for the dipoles positions.

Magnet positions in vertical plane are suveyed with the N3 by the schdule shown in Figure 9. Measurements are composed of the short ranges that measure adjacent magnets and the long ranges. The height diffirence measurement of long range gives a check to the short one. Any rough error that exceed a limitation is picked up at that time.

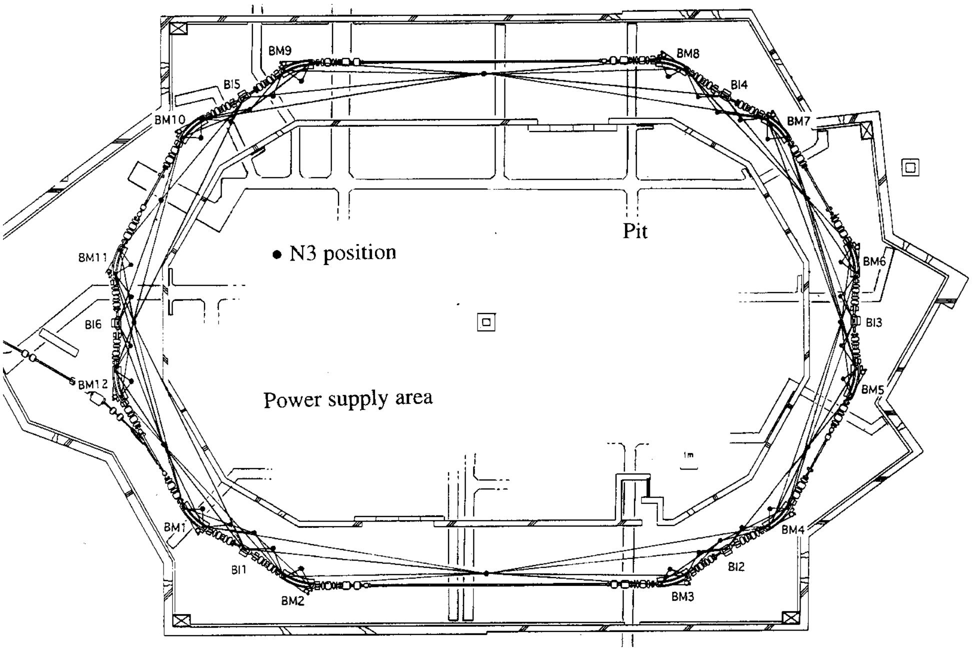

Fig. 9 Survey for elevations of the magnets.

3.2 Discussion on survey with the laser tracker

Surveying with the laser tracker is often used at this stage. The laser tracker is undoubtedly an very convenient instrument for determining component's position. It is accurate and saves manpower. It has precise distance resolution of about 1 micrometer. However, its angular accuracy is incompatible with distance measurement. It get worse in the environment of fluctuation of refractive index or vibration.

Control network that measured with conventional instrumentation is also essential for a large machine. Laser tracker has limited measurement range at one station and the measurements between adjacent stations had to be overlapped at some points. Global coordinates of measuring points can be obtained by fitting the common points along measurement path. But survey in this way results large acumulation error[1]. It does not surpass conventional method with theodolite if there are no sufficient control points.

At the Spring-8 we practiced using directly the distance data of laser tracker. This method was proved satisfying. Moreover, a new method would be derived from this practice. That is, now that distance-only method can give a much precise survey, an interferometer that with rotating head to track the reflector is enough to collect the survey elements of distances. That will save not only the manpower but also the money.

4. References

[1] C.Zhang, S.Matsui, Proceedings of IWAA97, APS, Argonne, USA. October 13-17, 1997. http://www.aps.anl.gov/conferences/iwaa97/fin_pap.html