ALIGNMENT OF HIMAC SYNCHROTRONS

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1. INTRODUCTION

Heavy-Ion Medical Accelerator in Chiba **(HIMAC)** of National Institute of Radiological Sciences **(NIRS)** is dedicated to heavy-ion cancer therapy [1,2] and is the first heavy-ion medical accelerator facility in the world. As major beam specifications are summarized in Table 1, the accelerator is capable of variable particle, variable energy, and variable intensity to satisfy medical requirement such as a long residual range of 30 cm in human bodies and a high dose rate of 5 Gy/min at therapy rooms. In addition, stable and reproducible operation is strongly required.

Table1

Major beam specifications

Particle species	He to Ar
Maximum extraction energy	800 MeV/u
Minimum extraction energy	100 MeV/u
Beam intensity extracted from a ring	2.0×10^{9} pps/ring for C
Beam spill length of slow extraction	400 ms at 600 MeV/u
Repetition rate	1/3 - 1.5 Hz: 1/2 Hz at 600 MeV/u
Emittance of extracted beam	10 π mm·mrad
Momentum spread of extracted beam	0.2 %

As a bird's eye view of the entire HIMAC facility is shown in Fig. 1, the facility is divided into four systems. Main accelerator system is two identical synchrotron rings installed at upper and lower underground floors of the building. Injector system is a cascade of RFQ and Alvarez linacs preceded by two kinds of ion sources, PIG and ECR. High-energy beam transport system consists of vertical and horizontal beam lines which deliver the beam from the upper and lower rings to irradiation system, which includes three therapy rooms and experimental rooms. One of three therapy rooms is equipped with simultaneous vertical and horizontal beam irradiation ports, while the others are equipped with a vertical or horizontal port, respectively.

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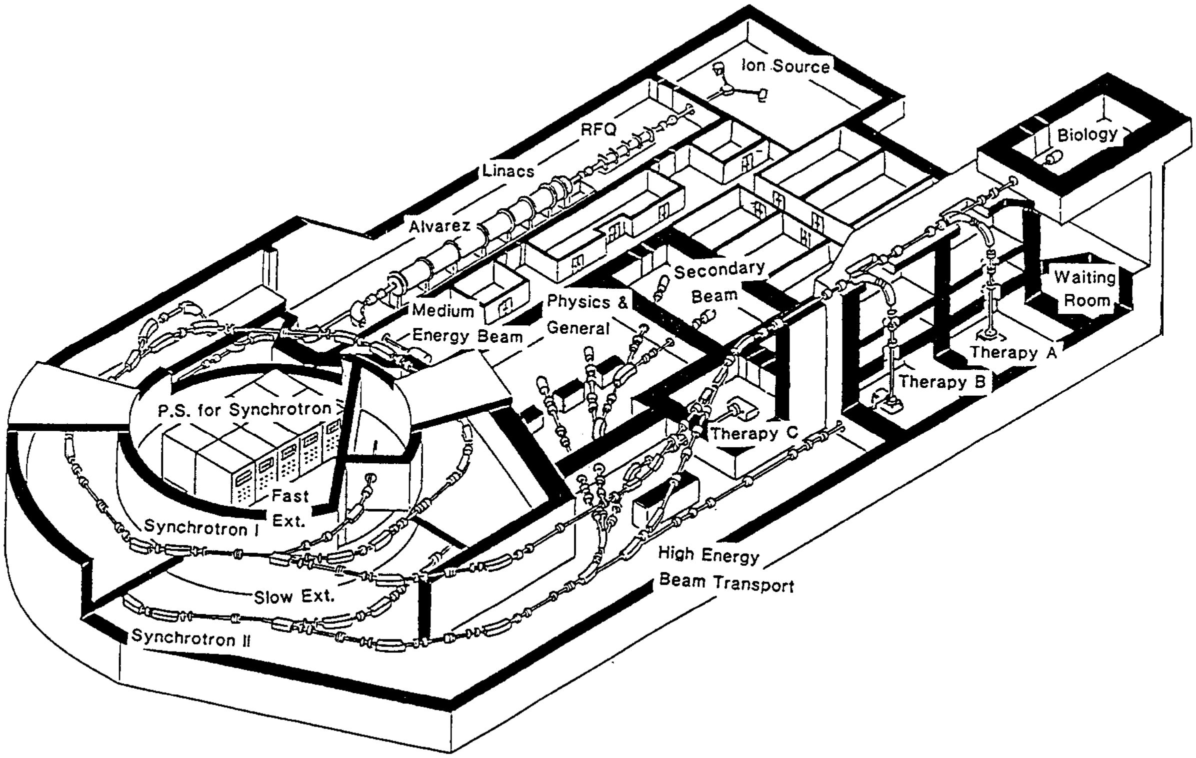

Fig. 1 Bird's eye view of entire HIMAC facility

In synchrotrons, it is essential for high beam quality to exactly position such ion optical elements as dipole magnets, quadrupole magnets, and beam position monitors with respect to a closed orbit. A specification of overall alignment tolerance has been optimized so that specifications of a gap of the dipoles, an aperture of the quadrupoles, a measuring accuracy for beam position, and an alignment method have been taken into account, because the specifications of them are related to each other.

The present alignment method is based on a reference point method in which the points are settled on extension lines of beam axis outside ring elements. Consequently radial alignment of elements of HIMAC synchrotrons are carried out on straight lines connecting between the reference points by means of angle measuring instruments.

This paper briefly describes main feature of geodetical settlement of reference points and the results of alignment accuracy of synchrotron elements together with alignment procedure, instrumentation, and software.

2. TOLERANCE OF SYNCHROTRON ALIGNMENT

A tighter alignment tolerance leads to a narrower gap of the dipoles and a smaller aperture of the quadrupoles due to a smaller closed orbit distortion (COD). COD has been simulated on an assumption of deviation of the dipoles and quadrupoles from theoretical positions. The tightest alignment tolerance for the elements is required for the quadrupoles. The alignment accuracy between neighbouring quadrupoles is essential for a small COD. In addition, a COD correction has been incorporated with the assumed measuring accuracy of 1 mm of beam position including displacement of the beam monitors themselves. Vertical COD correction, however, turns out ineffective because the realistic accuracy of 1 mm is not sensitive enough to improve the distortion. Thus, no vertical correction magnets are brought in the rings and the dipoles with a wide gap are designed to accept a raw value of vertical COD without correction.

Taking into account of specifications of elements due to the COD value, we have decided specifications of the overall alignment tolerance for a radial direction as 0.1 mm, a vertical direction as 0.1 mm, a beam direction as 0.3 mm, and a tilt as 0.2 mrad.

3. ALIGNMENT METHOD

As seen from the above alignment tolerance, the required accuracy for the beam direction is less severe than those for both radial and vertical directions. Such alignment is achievable by the measurement for angle when elements are positioned on the basis of well positioned reference points which are accurately settled on extension lines of the beam direction. In this alignment concept, we have considered that a measuring accuracy for angle possibly exceeds that for distance within the same expense. This alignment method is also advantageous so as to give a straight-forward positioning procedure for the dipoles because of no reference points on them. However, it requests several careful operations to handle the instruments well because no numerical data on alignment error is available due to the angle measurement.

In order to realize highly accurate positioning of the reference points by means of an instrument having its own measuring accuracy, a network consisting of the reference points and supplementary points is formed. These points are thus settled by measurement of distance only, which is observed by an electromagnetic distance meter (EDM) with the help of iterative network calculation described later.

The reference points forming double hexagons as described later in detail are settled on extension lines of the beam axis for the dipoles as shown in Fig. 2.

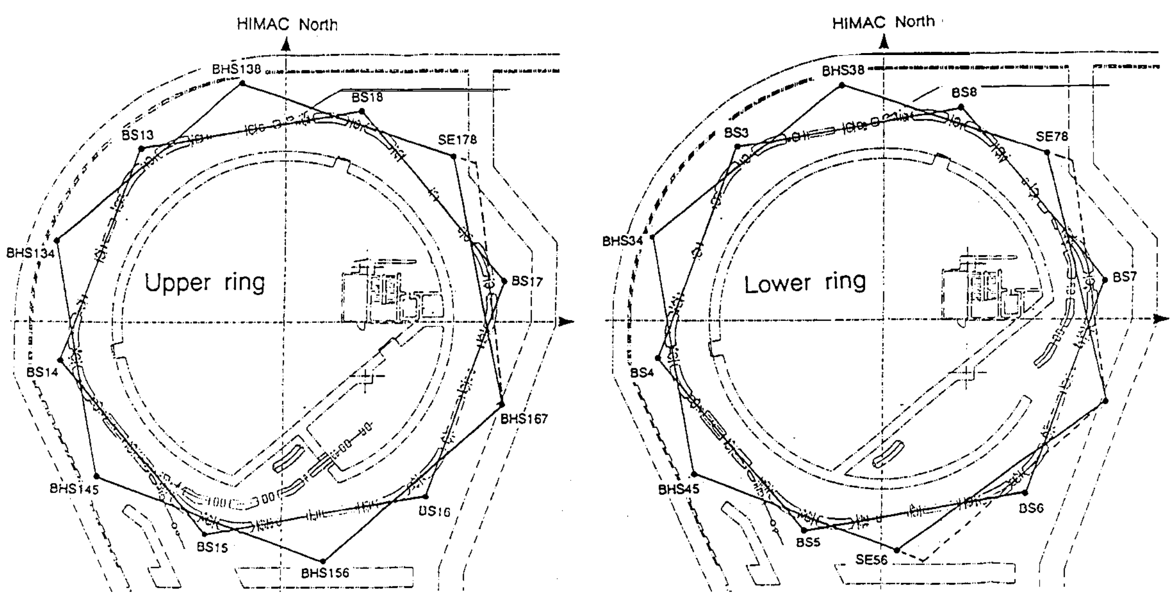

Fig. 2 Network of double hexagons for reference points for alignment: dotted lines show the beam axis for the shifted points.

Measured distance data between the points are stored in a computer and are processed by a software for network calculation to give probable distances between points and probable positions of the points. Based on the calculated values, the positioning of the reference points is carried out to decrease a displacement from theoretical position and is repeated to reach at acceptable tolerances.

After the settlement of the reference points, all dipoles are firstly positioned by angle measuring instruments, theodolites, from two directions formed by two crossing lines based on reference points. This alignment significantly eases positioning of the dipoles because of no distance measurement. For the final check, however, distances between the neighbouring dipoles are measured by EDM. As described later, distances of six short straight sections slightly differ to each other similarly to six long straight sections.

After the distance check between the dipoles, the quadrupoles are positioned in combination of the angle measurement with the theodolite located at the reference point and the distance measurement with EDM located at a central target of the dipoles. Because distances between the dipoles slightly differ, defocusing quadrupoles are positioned at a center of short and long straight sections while focusing quadrupoles are positioned on the basis of a design value of a distance from the dipole.

Refering the exactly positioned quadrupoles, other elements such as sextupole magnets and the beam position monitors are then positioned in combination of the same angle measurement and distance measurement with an inside micrometer or with a S-dimensional measuring system on the basis of a design value of a distance from the quadrupole.

This alignment method is preferable because all the neighbouring elements within the same straight section are well aligned on the single straight line. Along this alignment concept, most of all elements such as the quadrupoles, the sextupoles, the beam monitors, an electrostatic inflector, and electrostatic deflectors have two target stations on its upper plane for the beam direction: while the dipoles have three target stations for two directions. These stations are also machined to have a flat surface for a tilt measurement.

4. NETWORK FOR REFERENCE POINTS

In order to position the reference points accurately, the network is formed by 19 points consisting of 12 reference points for the alignment as shown in Fig. 2 and 7 supplementary points not shown in Fig. 2. On the basis of the choice of alignment method, 12 reference points are positioned on extension lines of the beam axis for the dipoles.

Since the extension lines form double hexagons of which radii are different depending on short and long straight sections of the ring, tops of each hexagon are the unique positions for the reference points. Six (denoted as BS's in Fig. 2) of them are just positioned at tops of a regular hexagon corresponding to the long straight sections. The other six are planned at tops of another regular hexagon corresponding to the short sections, but two of the lower ring or one of the upper ring (denoted as SE's in Fig. 2) of them are shifted from the tops because of space interference with the building wall or such facility as air-conditioning package. Because the reference points (denoted as BHS's in Fig. 2) opposite to the shifted points, SE's, are exactly positioned at the top, the correct beam axis around the shifted points is formed by means of angle shift from the reference points, BHS's, positioned at the tops exactly. The shifted amount is 5 degrees.

The supplementary points are efficiently introduced to strengthen the network calculation in order to give more accurate probable values for position of the reference points. Especially, a ring center is one of the supplementary points. Distances between the ring center and five of the six tops of the regular hexagon, BS's in Fig. 2, are measured directly through doorways and holes passing through building wall.

5. INSTRUMENTATION AND SOFTWARE

Measurement for settlement of reference points and alignment of synchrotron elements are made on direction, angle, distance, height, inclination, and plumbing. Instrumentation is listed in Table 2.

Table 2

Geodetical instruments

quantity	instrument	model	accuracy
direction & angle	theodolite	Wild T-3000	0.1"
distance			
up to 1 m	inside micrometer		0.1mm
4 to 50 m	EDM*	Kern MEKOMETER ME5000"	0.2mm or 0.2ppm
1 to 50 m	3-D system	PASCO	
	theodolite	Nikon NE-1	1"
height		Wild N3	1:200,000
inclination	1st order level		0.02mm/m
plumbing	plummet	Wild NL	0.02mm

*EDM: Electromagnetic Distance Meter with control software PASMEKO by PASCO CORPORATION

Precisely adjustable 2-dimensional stages with a centering plate (Kern) having a tolerance of 0.030 mm are mounted on pillars for the reference points. The pillars are demountable but are fixed during a period for the measurement and the alignment for each ring. Supplementary points are fixed on tripod mounting during a period for the measurement while the ring center point is fixed on a pillar.

Target stations have precise holes for mounting of optical targets and other measurement targets. Several types of target (invar staff for height, targets for direction and plumbing) are prepared according to types of measurement.

A distance between two points is doubly measured from both directions. Concerning a given point, several distances relating to the point are measured. Total number of measured distances is 240 for 19 points.

The measured distance data are stored in a computer. A probable distance between two points and a probable position of each reference point are then calculated, respectively, by a software, PAG-U[3].

Main feature of PAG-U relevant to the present work is summarized as follows. All the measured data are managed for data base. A probable distance called a corrected distance is calculated on the basis of a net adjustment by a least square method in order to give confident and plausible value of the distance within a given accuracy of the measuring instrument. A probable position of the point is then calculated together with a displacement from theoretical position and a standard deviation of error ellipse through the network calculation based on the corrected distances.

6. BUILDING MOVEMENT AND REFERENCE POINTS

The reference points for the rings had been once positioned in September, 1992, just before the initial installation of ring elements. The networks for two rings were positioned to agree in size and direction at that time. After the initial installation, positions of the points were measured by a plummet in January, 1993. Apparent deviation of about 1.5 mm was observed within a ring itself and between two rings, and seems to be due to such uniform movement as rolling and pitching of the building as a whole.

This kind of movement of the building has been noticed to be unavoidable during the initial installation because there was no enough time between construction of the building and the installation. Detectable movement seems to occur within one month or so. The accurate alignment of accelerator elements not only of the synchrotrons but also of the other system such as the high-energy beam transport lines has been extensively made in a short period as possible in order to overcome this problem.

The final alignment of the injection and extraction beam lines had been finished before the final alignment of ring elements. Consequently we should abandon the agreement in vertical direction between two rings because of no enough margin for the shift of rings as a whole, while the size of them is kept at the same value because of rather uniform movement.

The final positioning of the reference points for two rings has been made for each ring itself. However, because rotation and shift of the networks between two rings are required to match the existing injection and extraction beam lines, the reference points have been again to be settled to minimize the displacement of the ring elements while keeping specified hexagonal shape among the reference points. Amounts of rotation and shift have been calculated by one of sub-programs of PAG-U, FREENET, which is capable of searching such minimum displacement while keeping the shape.

7. RESULTS

Results based on the final measurement of positions of the reference points for the upper and lower rings are summarized in Table 3. A displacement from the theoretical value is within 0.26 mm and a standard deviation of error ellipse is within 0.05 mm. However, the great semiaxis of the points, BS's, seems to be smaller than that of other points, BHS's and SE's. As expected, this is due to that BS's are measured from the ring center, while BHS's and SE's are not.

An average of 240 measured distances is 17 m and a standard deviation of the corrected distances is 0.09 mm while the maximum correction of all the measured distances is 0.28 mm. Overall measuring accuracy is considered to be reasonable in comparison to the accuracy of the instrument, EDM.

Table 3

Measured deviation of position of reference points

	Upper ring						Lower ring				
	displacement		error ellipse				displacement		error ellipse		
	Azim**	L(mm)	Azim*	a(mm)	b(mm)		Azim**	L(mm)	Azim*	a(mm)	b(mm)
BS13	15	0.17	100	0.03	0.03	BS3	305	0.12	136	0.02	0.02
BS14	223	0.08	75	0.05	0.03	BS4	118	0.17	79	0.03	0.02
BS15	208	0.15	14	0.03	0.02	BS5	162	0.06	4	0.02	0.01
BS16	166	0.05	158	0.03	0.03	BS6	147	0.05	150	0.02	0.02
BS17	114	0.09	88	0.04	0.03	BS7	231	0.18	87	0.03	0.02
BS18	345	0.18	45	0.04	0.03	BS8	349	0.09	15	0.03	0.02
BHS134	179	0.21	107	0.06	0.03	BHS34	78	0.22	110	0.04	0.02
BHS138	199	0.11	167	0.07	0.04	BHS38	9	0.26	169	0.05	0.02
BHS145	109	0.02	49	0.07	0.03	BHS45	247	0.09	49	0.04	0.02
BHS156	241	0.12	174	0.06	0.03	SE56	157	0.13	0	0.04	0.02
BHS167	254	0.03	110	0.06	0.03	BHS67	264	0.01	107	0.04	0.02
SE178	58	0.22	47	0.10	0.03	SE78	261	0.14	51	0.05	0.02

* Azim(deg): direction of great semiaxis vectors to HIMAC north,
a: great semiaxis, b: small semiaxis
**Azim(deg): direction of displacement vectors to HIMAC north,
L: length of vectors

After the dipoles are aligned on the straight lines connecting between reference points by means of theodolites, distances between central targets of the dipoles have been measured by means of EDM. The distance data along short and long straight sections are summarized in Table 4. The maximum difference in distances within a ring is 0.9 mm for both short and long

Table4

Measured distance between dipoles

Dipoles	Upper ring	Lower ring
Short sections	(mm)	(mm)
BM2 - BM3	5,480.28	5,479.65
BM4 - BM5	5,480.04	5,479.31
BM6 - BM7	5,480.81	5,479.40
BM8 - BM9	5,479.91	5,479.43
BM10- BM11	5,480.55	5,479.59
BM12- BM1	5,480.42	5,479.88
Long sections	(mm)	(mm)
BM1 - BM2	16,278.81	16,279.64
BM3 - BM4	16,279.17	16,279.54
BM5 - BM6	16,279.04	16,279.62
BM7 - BM8	16,279.56	16,279.76
BM9 - BM10	16,278.68	16,278.85
BM11- BM12	16,278.84	16,278.86

straight sections. This deviation is mainly accounted for the displacement of the reference points in both direction and amplitude because of geometrical configuration between the lines and the dipoles. Because two beam axis cross just on a dipole in a relatively small angle of 30 degrees, magnification of a position accuracy of the reference points occurs to the distance deviation of the straight sections.

This kind of distance difference seems to cause the deviation of position of elements for beam direction beyond its specification within 0.3 mm. Improvement of the difference, however, is not easy because more accurate positioning of the reference points is required.

On the other hand, measurement after the final alignment of all the ring elements shows that other elements such as the quadrupoles and the beam monitors on the same straight section are exactly aligned within the tolerance of both radial and vertical direction within 0.1 mm, beam direction within 0.3 mm, and a tilt within 0.2 mrad.

These values within the same straight section, especially for the most severe tolerance required for the quadrupoles, are satisfactorily achieved by the present reference point method, when the slight distance difference for short and long straight sections between the dipoles is allowed.

8. SUMMARY

In order to achieve accurate alignment of the elements for the HIMAC synchrotron rings, we have chosen the alignment based on the reference point method so that the dipoles are aligned with theodolites on two straight lines connecting between the reference points. The settlement of the points is made by network with help of the distance measuring instruments and the computer system. The measured positions not only of the reference points but also of the dipoles are satisfactory because the neighbouring elements are accurately positioned in both radial and vertical directions, although positions of the dipoles themselves in beam direction deviates slightly due to the geometrical configuration between the reference points and the dipoles. The present method is useful because of easy positioning procedure for the dipoles and other elements.

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REFERENCES

[l] Y. Hirao et al., HIMAC Project at NIRS - Japan, Proc. 2nd Euro. Part. Act. Conf., (1990) 280.

[2] Y. Hirao et al., Heavy Ion Medical Accelerator in Chiba - A Design Summary and Update, HIMAC report - 001 (December 1992).

[3] T. Harada, Universal Program for Adjustment of Any Geodetic Network (PAG-U), J. Geodetic Society of Japan, 26 (1980) 147.