ALIGNMENT OF S-LSR

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Abstract

Bending and quadrupole magnets of S-LSR was aligned using a laser tracker. Magnets were shuffled by brute force search to minimize closed orbit distortions and betatron stopbands. All fiducial points were aligned within the error of 0.1mm, 65% of them were within 0.05mm. Measured COD is the same order of calculation by alignment error, and corrected to $\pm$0.4mm.

INTRODUCTION

S-LSR[1] is an ion storage ring constructed at Institute for Chemical Research, Kyoto University. This ring takes a important part of Advanced Compact Accelerator Development project.

The main purpose of S-LSR is beam cooling. It has two cooling equipments; an electron cooler and a laser cooling system. Electron cooling is applied for 7 MeV proton beam from RFQ and Alvarez drifttube linac. While the main purpose of electron cooler of S-LSR is hot beam cooling for compact medical accelerators, it is also used for beam ordering experiment[2]. Laser cooling is applied to 40 keV $^{24}\mathrm{Mg}^{+}$ beam for investigating three-dimensional beam crystallization in ultralow temperatures.

Since both cooling method utilize the interaction of the ion beam and the laser or the electron beam, their orbit or path must be overlapped in good precision to realize strong cooling force. Therefore the closed orbit distortion(COD) becomes very important for beam cooling.

Moreover, S-LSR has a lattice that allows to form and maintain a three-dimensional crystalline beam[3]. In this theory, high superperiodicity of the ring is essential to maintain crystalline state. If there is a large COD or large errors of beta function, periodicity of the ring is reduced and the lattice no longer satisfies the maintenance condition. Consequently, it is required to reduce the errors of beta function as well as COD in the process of magnet alignment of S-LSR.

In addition, on the side of development of compact medical accelerator, it is preferable to select an efficient and generalized alignment method.

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ALIGNMENT POLICY

The method and tolerance of alignment is decided considering the ring characteristics of S-LSR. The main parameters of S-LSR are written in Table.1 and the layout drawing is shown in Fig.1.

Table 1: Specification of the ring

Circumference	22.557m
Radius	3.872m
Curvature Radius	1.05m
Ion species	p (7 MeV) $^{24}\mathrm{Mg}^{+}$ (40 keV)
Number of bending magnets	6
Number of quadrupole magnets	12

Since S-LSR is a small ring with 22.557m circumference and 3.872m radius, all magnets are placed in a single experimental hall. Because of this, the distance from the ring center to each magnet can be directly measured.

There are six bending magnets in S-LSR ring. They are excited in series and each magnet has a parallel electronic load for field correction. According to the results of field measurements, the RMS value of the BL products is 2.0×10^{-4}[4].

S-LSR has twelve quadrupole magnets. Six magnets are designed to be set at the left side(upstream) of bending magnets by the position of its current feed-through and other six are such designed to be set at the right side(downstream). Six magnets in a group are excited in series and have correction coils. Their field gradient is measured and the RMS value of the GL products is 2.2×10^{-3}[5].

Table 4 and 5 show the COD caused by magnetic field errors and misalignments of bending and quadrupole magnets. For the BL and GL products, a half of their RMS values are adopted as the typical value. COD caused by misalignments should be smaller than the one that caused by field errors.

At first, displacement tolerance is discussed. The error of 0.1mm produces the COD less than 0.24mm, which is still smaller than that by the BL product error: 0.33mm. From a technical point of view, measurement of 0.1mm precision is not so difficult by using wire distometers or laser interferometers. Therefore we decided the displacement tolerance

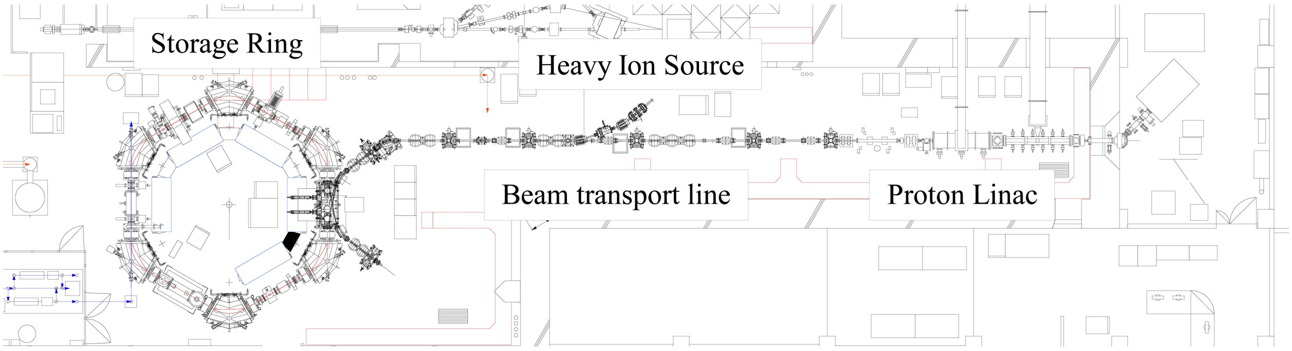

Figure 1: Layout of S-LSR

to be 0.1mm for bending and quadrupole magnets.

Rotation tolerances differ between bending magnets and quadrupole ones. COD caused by rotations of quadrupole magnets are about one order smaller than that by bending magnets. Accordingly, rotation tolerances are 0.1mrad for bending magnets, and are 1mrad for quadrupole magnets.

Table 2: COD caused by errors of a bending magnet

Error Source	Value	COD(H)	COD(V)
BL product	$\frac{\Delta BL}{BL}$=1 $\times$ 10^{-4}	0.33mm	
x displacement	Δx=0.1mm	0.24mm	
y displacement	Δy=0.1mm		0.02mm
s displacement	Δz=0.1mm	0.15mm	
x rotation	$\Delta\phi$=0.1mrad		0.12mm
y rotation	$\Delta\theta$=0.1mrad	0.15mm	
s rotation	$\Delta\psi$=0.1mrad		0.10mm

Table 3: COD caused by errors of a quadrupole magnet

Error Source	Value	COD(H)	COD(V)
GL product	$\frac{\Delta GL}{GL}$=1 $\times$ 10^{-3}		
x displacement	Δx=0.1mm	0.11mm	
y displacement	Δy=0.1mm		0.11mm
s displacement	Δz=0.1mm		
x rotation	$\Delta\phi$=0.1mrad		0.01mm
y rotation	$\Delta\theta$=0.1mrad	0.02mm	
s rotation	$\Delta\psi$=0.1mrad		

After deciding alignment tolerance, we discussed the alignment method. There were two candidates, one is measuring the distances between the ring center and the magnets, and magnets each other by wire distometers[6]. The other is measuring all positions from the ring center using a laser tracker[7]. Laser trackers have laser interferometers and rotary encoder to measure 3-dimensional coordinate value.

The precision of the distance measurement using wire distometers is 50μm for Invar wires. That of laser trackers depends on the distance to be measured. In the case of S-LSR, the distance from the ring center to each magnet is about 4m. Laser trackers have also 50μm precision for this distance range.

While precisions are almost the same, easiness to handle is quite different. Laser tracker can decide the 3-dimensional position by one measurement. It allows to align magnet one by one independently. In wire distometer measurement, we can only measure a distance between two magnets or the distance from the center to a magnet in a horizontal plane and we have to measure all magnets to decide their positions. In the view of development of compact accelerator, easiness to handle should be taken into account. Finally, we decided to use a laser tracker for the alignment.

MAGNETS SHUFFLING

Before the alignment procedure, magnets were shuffled[8] to reduce effects on beam optics. As mentioned before, COD and beta function is the essential parameter for beam cooling in S-LSR. In first order analysis, the field errors of bending magnets give effects on COD, these of quadrupole ones on beta function errors. Bending magnets have multipole components, which also causes beta function errors. Therefore bending magnets were shuffled at first to minimize COD, then quadrupole magnets were shuffled to minimize beta function errors.

Bending magnets shuffling

The source of COD is due to the deviation of the BL product of bending magnets. The errors of BL products are measured[4] as Fig.2. This error causes only a horizontal COD.

The magnet with Serial number 15012 had a BL product error of 3.7×10^{-4}, which is large compared with others. To compensate this error, the field clamp of B15012 was shifted by 2mm to the magnet pole. After this adjustment, the BL error of B15012 is reduced to 1.0×10^{-4}.

The number of permutation is 6!=720, however, by rotations of other ones. Thus, the total number of actual permutation is 6!/6=120. We applied brute-force search to find the best arrangement. The COD is calculated by MAD

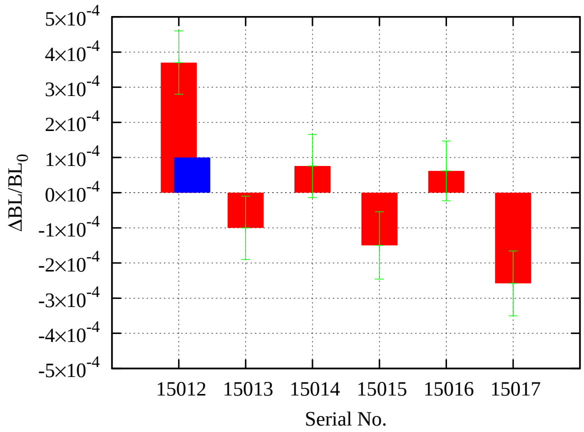

Figure 2: Deviation of the BL products

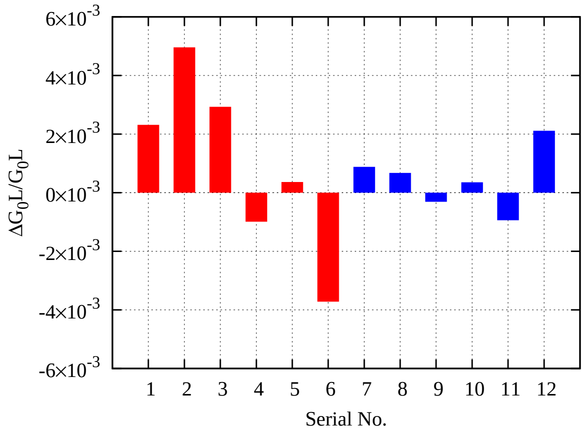

Figure 3: Deviation of the GL products

code for each arrangement.

Table.4 shows the results sorted by the RMS value of the horizontal COD. The best arrangements have 0.319mm of RMS COD.

Table 4: Results of COD Calculation

	$\mathrm{COD}_{\mathrm{max}}$	$\mathrm{COD}_{\mathrm{RMS}}$
1st	0.782mm	0.319mm
2nd	0.595mm	0.328mm
3rd	0.772mm	0.333mm
⋮	⋮	⋮
120th	1.382mm	0.746mm

Quadrupole magnets shuffling

The errors of GL products are measured[5] as Fig.3. Quadrupole magnets are divided into two groups, magnets with serial number 1-6 belong to Q1 group, placed on the left(upstream) side of the bending magnets, Serial number 7-12 belongs to Q2 group on the right(downstream) side. Magnets can be shuffled only in their groups.

Therefore the number of permutation is $6! \times 6! = 518400$. We also applied brute-force search using MAD code considering GL product errors and multipole components of bending magnets. The computation time is not negligible but enough realistic. Calculation was completed in two days by two personal computers.

The results are evaluated by betatron stopband. Stopband is written as Eq.(1); proportional to the maximum value of the error of beta function.

$$\delta\nu = 2(\nu - n/2)\left(\frac{\Delta\beta}{\beta}\right)_{\mathrm{max}} \qquad (1)$$

The square sum of them is used as a evaluation function because both horizontal and vertical stopbands must be considered. The sorted results are shown in Table.5. The best result has the stopband $(\delta\nu_x, \delta\nu_y) = (8 \times 10^{-4}, 6 \times 10^{-4})$.

Table 5: Results of stopband calculation

	$(\delta\nu_x, \delta\nu_y)_{[\times 10^{-4}]}$	$S^2{}_{[\times 10^{-6}]}$
1st	(8.00, 6.19)	1.0222
2nd	(7.47, 6.87)	1.0299
3rd	(8.19, 6.02)	1.0326
⋮	⋮	⋮
518400th	(8.00, 6.27)	1.0342

Final layout of bending and quadrupole magnets is shown in Fig.4.

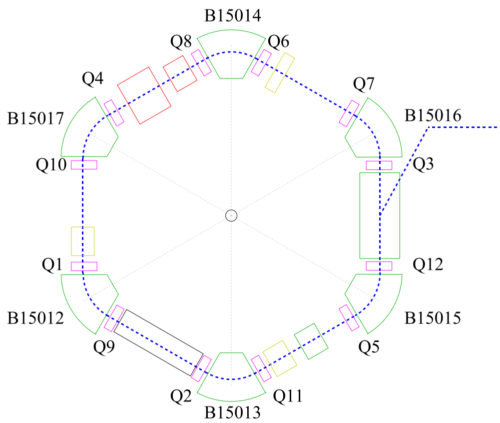

Figure 4: Final layout of magnets

ALIGNMENT

Alignment procedure is carried out in December 2004 and January 2005. We used a laser tracker “SMX tracker4500” and a total station “Leica TDA5005”. The laser tracker emits He-Ne laser and keeps tracking a mirror target observing the reflection. The target can be attached to fiducial holes of magnets. There are 3 holes on bending magnets and 2 holes on quadrupoles. The laser tracker can measure the 3-dimensional position of these fiducial points. The position is represented in Cartesian coordinates. After the measurement of a magnet, we adjusted the magnet position using dial gauges according to the measured position displacement. Measurement and adjustment is repeated until all displacements are reduced within the tolerance of 0.1mm.

The displacements of fiducial points after alignment are shown in Fig.5 and Fig.6. All displacements are less than 0.1mm, 65% of them are less than 0.05mm.

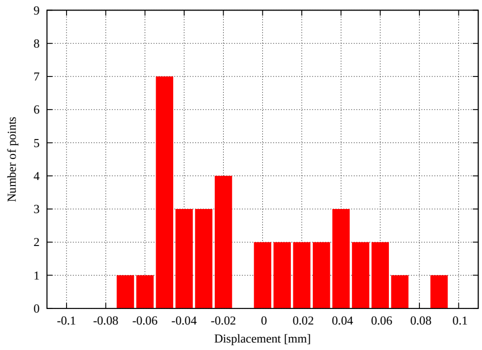

Figure 5: Histogram of displacements of bending magnets

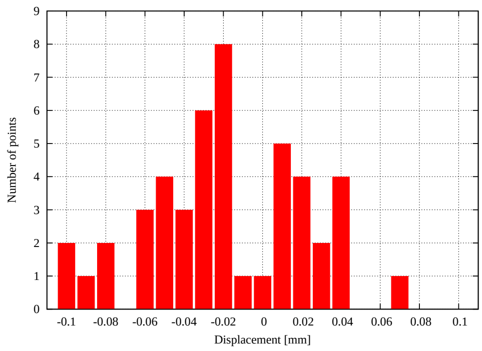

Figure 6: Histogram of displacements of quadrupole magnets

Magnet pole length measurement

We used this laser tracker for another purpose: magnet pole length measurement because the actual pole length is not directly measured in manufacturing process. Knife-edge style contact probe is used as a target and attached on the first step of Rogowski cut. Three positions are measured to determine the line of the plane. Since this probe cannot be fixed well, the measurement precision is 0.2mm.

The results are shown in Table.6. Almost all lengths are within the margin of error, but downstream side of BM3(B15012) is significantly short. It is discovered that the large BL product error of this magnet shown in Fig.2 is overestimated. Actual value is 1.0×10^{-4}, and -1.7×10^{-4} with the field clamp adjustment. After recalculation, it was found that the COD becomes small when the position of field clamp is returned. After this change the COD is 1.0mm in maximum and 0.4mm in RMS; enlarged but still small enough.

Table 6: The errors of actual pole length

S/No.	Location	Error upstream	Error downstream
15012	BM3	0.0mm	-0.4mm
15013	BM4	-0.1mm	-0.1mm
15014	BM5	0.0mm	-0.1mm
15015	BM1	-0.1mm	-0.2mm
15016	BM6	0.0mm	0.2mm
15017	BM2	0.1mm	-0.1mm

EFFECT TO BEAM OPTICS

Based on these Cartesian alignment results, the effect to the beam optics is estimated. At first, displacements in Cartesian coordinate taken by laser tracker are translated to displacements and rotations in Frenet-Serret coordinate. Translated values are shown in Table.7. Not only displacements but also rotations are kept within the alignment tolerance.

The beta function error and the COD are calculated based on this result, and compared with the measured result.

Beta function

Errors of quadrupole magnets effect on beta function. Beta function is measured by betatron tune shift by changing currents in correction coils of quadrupole magnets. Measurement is carried out using 40keV Magnesium beam with the betatron tune (1.644, 1.197), where the currents of both quadrupole groups(QM1,QM2) are the same: -10.5A. Correction current is changed from -10A to +10A. Only horizontal beta function is measured so far because the vertical electrodes of RF knockout are used as pickups for other experiment.

The results are shown in Table.8. Differences of measurement and calculation is about 5% and the deviation of measured values of beta function is about 6%. This is larger than the estimation before alignment. We also measured betatron stopband around half integer tune: $\nu = 1.5$. The result shown in Table.9 matches well to the calculated value. Beta function error derived from this result is $\Delta\beta_x/\beta_x = 2\times10^{-3}$ and $\Delta\beta_y/\beta_y = 6\times10^{-3}$. These values are much smaller than direct beta measurement. The precision of direct beta measurement may not be enough; we are trying to improve the precision of measurement.

Table 7: Misalignments in Frenet-Serret Coordinates

	D_x[mm]	D_y[mm]	D_s[mm]	D_ϕ[mrad]	D_θ[mrad]	D_ψ[mrad]
BM1	-0.017	0.003	0.049	-0.037	-0.027	0.020
BM2	-0.010	0.027	-0.013	-0.007	-0.104	0.007
BM3	0.053	0.040	0.009	0.000	-0.032	-0.040
BM4	-0.029	0.043	0.008	-0.013	0.006	-0.010
BM5	0.031	-0.090	0.039	-0.037	-0.004	-0.013
BM6	0.048	-0.027	-0.004	-0.040	-0.018	-0.007
QM11	0.002	0.050	-0.026	-0.020	-0.169	-0.010
QM12	0.048	-0.030	0.012	0.030	0.174	-0.020
QM21	-0.050	-0.040	-0.032	0.010	-0.076	-0.010
QM22	0.003	0.080	-0.030	0.070	-0.130	-0.010
QM31	0.027	0.060	0.020	-0.020	-0.725	0.000
QM32	-0.019	-0.010	0.029	0.000	0.077	-0.050
QM41	0.046	0.000	-0.042	-0.030	0.277	-0.050
QM42	0.003	0.050	0.071	-0.030	-0.421	-0.020
QM51	-0.058	-0.070	0.084	-0.070	0.163	0.030
QM52	-0.032	-0.070	-0.079	-0.030	0.270	0.040
QM61	-0.017	-0.050	0.019	0.050	0.205	-0.040
QM62	-0.052	-0.070	-0.030	0.050	0.108	0.010

Table 8: Result of beta function measurement

Position	β_x(meas)	β_x(calc)
QM11	2.137	2.252
QM21	2.184	2.256
QM22	2.149	2.253
QM32	2.089	2.254
QM41	2.164	2.255
QM51	2.164	2.254
QM61	2.179	2.253

Table 9: Result of stopband measurement

Direction	$\delta\nu$(meas)	$\delta\nu$(calc)
Horizontal $\delta\nu_x$	1.1×10^{-3}	0.8×10^{-3}
Vertical $\delta\nu_y$	1.2×10^{-3}	0.6×10^{-3}

COD measurement and correction

The COD calculated from magnet and alignment error is shown in Fig.8 and Fig.9. To magnesium beam, earth magnetism gives non-negligible kicks mainly in vertical direction. Calculation includes this effect is also shown in these figures.

The actual COD is measured using 6 triangle-plate electrostatic beam position monitors(BPM). The signal from each plate is amplified by +46dB and added or subtracted in the logarithm amplifier Bergoz BB-BPM. The layout of correction devices are shown in Fig.7.

COD correction based on simplex method is applied. Horizontal correction is applied by 6 bending correction currents. For vertical correction, 6 BPMs are used as an electrostatic kicker. There are two apertures for alignment of the beam and the laser in the chamber of the laser cooling section. They have holes with diameters of 10mm, 6mm, 3mm and 2mm and can move vertically. The beam orbit and the laser path are adjusted to pass through the hole on the level of quadrupole centers. With these apertures, the crossing angle of the beam and the laser is reduced to less than 0.2mrad.

The measured CODs before and after correction are shown in Fig.8 and Fig.9. Maximum COD at all BPM is reduced to be less than 0.4mm.

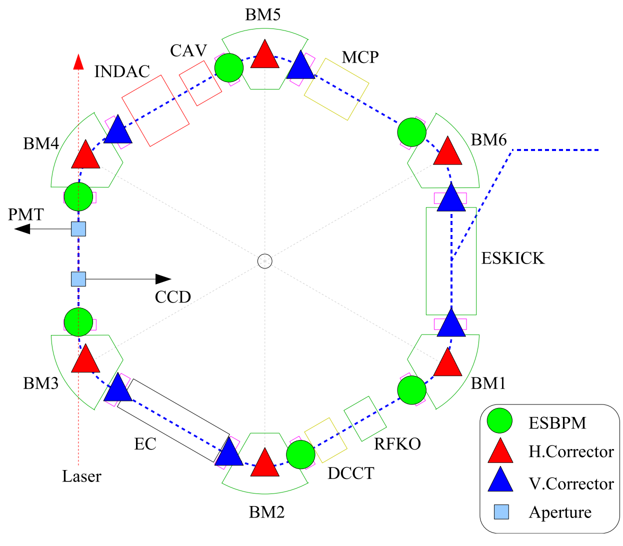

Figure 7: Device layout of COD correction

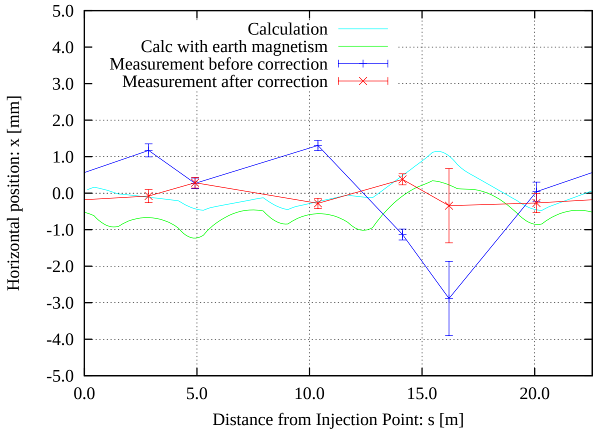

Figure 8: Horizontal COD

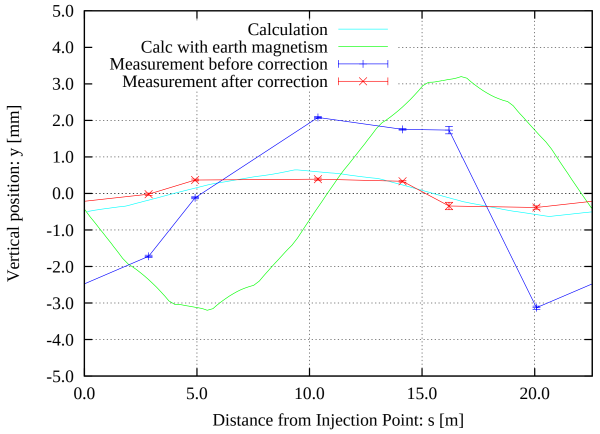

Figure 9: Vertical COD

SUMMARY

Bending and quadrupole magnets of S-LSR were aligned using a laser tracker. Magnets are shuffled to minimize COD and betatron stopband. All measured fiducial points have been aligned within the error of 0.1mm, 65% of them have been aligned within the error of 0.05mm. Measured COD is the same order of calculation by alignment error, and corrected to be less than ± 0.4mm.

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