Integral Dipole Field Calibration of the SRRC Storage Ring Combined Function Bending Magnets

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Abstract

Due to the presence of fringe field on both magnet edges, the real trajectory traced out by the beam will deviate from expectation. The integral dipole strength seen by the beam will then have a discrepancy to design value. The beam tracing method is employed to correct fringe field effect and to calibrate integral dipole strength of the bending magnets by tuning magnet current. Final correction factor was achieved in the condition of simulated results meet to design requirements. During machine commissioning, the measured betatron tunes were found different from modeling and a correction factor was applied to correct this tune differences. This factor is in well agreement with that predicted by the beam tracing method.

I: Introduction

The bending magnet for the SRRC storage ring is a C-type magnet. It is an assembly from lamination iron plates with its pole face tilted to combine dipole field and quadrupole field. Though the magnetic field has been well measured, the measurement is based on ideal trajectory, curve in bending region and straight for the other section. For the presence of fringe field at magnet edges the real trajectory of the beam would deviate from ideal one. The magnetic field seen by the beam will have a little difference due to this trajectory discrepancy. It implies a fine calibration is necessary if the difference has significant effect. In this report, beam tracing method is employed to check this difference by taking the eighth mass produced bending magnet as an ensemble. A tracing program is written to simulate the real trajectory of the electron in real magnetic field and the dipole field is calibrated based on this simulated trajectory. Since simulated trajectory dependent on the field the beam encounted, there are several way to get the correction by changing field distribution such as shifting, rotating the magnet[1] or changing its power current. However it is very difficult to take into account shifting (rotating) factor in installation. Correction on power current is selected for field adjusting tool.

In this paper, results from tracing prediction are compared with that obtained from commissioning. Algorithm for the beam tracing method is described in section II. Error estimation of the tracing program and the tracing prediction are also given in section II. Commissioning results for this topics can be found in section III. The consistency of these two approaches are quit good.

II: Tracing program and tracing prediction

The beam tracing program simulates the median plane trajectory of the electron and obtains related parameters from the measured magnetic field. Cartesian coordinate system (X,Z) is used for tracing study with X the horizontal and Z the longitudinal coordinate respectively. Origin of the coordinate system is chosen at the magnet center. The motion of the electron in the median plane obeys[2]

$$\frac{X''}{\left(1 + X'^2\right)^{3/2}} = -\frac{B}{B_0\rho} \tag{1}$$

in which X is the horizontal position of tracing point, $B_0\rho$ is the ring rigidity and B the vertical magnetic field of tracing point, which is interpolated from measured field by three or four-point bivriate method[3]. Since no significant difference between these two field interpolated method, less than 2×10^{-7}, three-point bivriate method is used. The differentiation in equation (1) is w.r.t. the longitudinal. Interpolation from one point to the next point is calculated from equation (1) by Runge-Kutta method. Since rigidity includes the information of beam energy, the program can simulate the trajectory for fixed energy of electron in the known field distribution or, on the contrary, to get the information of beam energy and simulated trajectory in the fixed field distribution. The former situation is applied in this report while the latter can be applied to measure the beam energy[4].

A testing tracing was first performed to check the accuracy of the tracing program by ideal isomagnet field distribution with design field value and effective length. Error bar of the traced parameters in this testing tracing are all within 0.007%, which is quite enough for the study, and position error for testing tracing point is also within the alignment tolerance. Accuracy of the tracing program would be increased a little bit in real field tracing for it has continuous field distribution instead of hard edge one.

In tracing simulation, the following strategies were considered: a) integral dipole strength (bending angle) within design requirement, b) symmetry simulated trajectory w.r.t. magnet center, c) position error for tracing points outside effective bending within alignment tolerance. Strategy a) ensures the electron beam will be bent to a circle within a tolerable error. Strategies b) and c) push simulated trajectory meeting to ideal trajectory except that in effective bending section. These considerations are very important for the beam diagnostics.

Since field measurement extended far away from the magnet, the magnetic field outside the measured area is assumed to zero for the field is neglectable small at this large distance. The tracing step is the same as that used in testing tracing, 5mm for far away region and 0.2mm for points close to the magnet. Under above conditions, design energy of electron were traced in the ensemble field distribution, which is measured at the median plane of the eighth mass produced bending magnet powered at nominal current. Table 1 lists this uncorrected tracing results.

Table I
Comparison of the raw data tracing results with the ideal
values, in which Bl integral strength, l_{eff} effective length, θ
bending angle, B_c center field, subindex s indicates tracing
starting point, t the magnet entrace point, e the magnet exit
point, and d the tracing ending point.

	Ideal Value	tracing Results	Error
Bl (T*m)	1.513666	1.521917	0.54 %
l_{eff} (m)	1.22	1.222098	—
θ (deg)	20	20.10779	0.54 %
B_c (T)	1.24071	1.245336	—
x_s/z_s (mm)	-912.198/-106.928	-912.198/-106.928	—
x_t/z_t (mm)	-606.998/-53.113	-606.998/-53.418	—
x_e/z_e (mm)	607.002/-53.114	607.002/-54.872	—
x_d/z_d (mm)	911.002/-106.660	911.002/-108.789	—

From the data shown in table 1 it is clear that design energy of electron is overbent by about 0.5% as magnet is powered at nominal current. The 0.5% overbent has been taken into account the effect from trajectory as well as the contribution of fringe field. It is straightforward to scale down the magnetic field by this amount approximately and design energy of electron is traced again in this scaled down field. After some efforts the final correction factor for the magnetic field is 0.575% instead of 0.5%. This small discrepancy is coming from the magnetic field seen by design energy of electron is slightly changed due to different trajectory followed. Table 2 lists these corrected tracing results.

Table II
Comparison of the corrected tracing results with the ideal
values.

	Ideal Value	Tracing Results	Error
Bl (T*m)	1.513666	1.513827	0.01 %
l_{eff} (m)	1.22	1.223162	—
θ (deg)	20	20.00821	0.04 %
B_c (T)	1.24071	1.237635	—
x_s/z_s (mm)	-912.198/-106.928	-912.198/-106.928	—
x_t/z_t (mm)	-606.998/-53.113	-606.998/-53.417	—
x_e/z_e (mm)	607.002/-53.114	607.002/-53.583	—
x_d/z_d (mm)	911.002/-106.660	911.002/-106.958	—

Correction on the magnetic field is achieved by tuning its power current. The necessity of 0.575% reduction on the magnetic field also reveals nominal current is too large for design energy of electron. From the good field uniformity and the linear relation between the field and its power current within this small range, final correction factor on the current is also predicted by 0.575%.

The tracing results listed in table 2 are in good agreement with the design except magnet center field and effective length. These discrepancies are coming from simulated trajectory deviated from ideal. As we known the main function of the bending magnet is to bend design energy of electron with the desired angle. Hence bending angle and integrated dipole strength are the most important parameters to be considered. The error of integrated dipole strength (bending angle) is within 4×10^{-4}, which is well within the specification of 1×10^{-3}. From above simu-

lated results it is clear that integral dipole strength has been well calibrated from reducing the nominal current by 0.575%.

III: Experience in the storage ring commissioning

In storage ring commissioning, the measured tunes are found not consistent with modeling. The tune difference makes the application program, which is based on modeling, don't work well. With the study and correction of the tune differences, a model closing to real machine is gotten. The tunes of machine are then measured under different lattices and compared with that predicted by modeling, as shown in table 3.

Table III
Tune Differences between measurement and modeling before
correction.

Lattice	measured ν_x/ν_y	modeling ν_x/ν_y	$\Delta\nu_x/\Delta\nu_y$
A	7.353/4.080	7.4448/4.1133	0.0918/0.0333
B	7.232/4.080	7.3220/4.1151	0.0900/0.0351
C	7.236/4.080	7.3210/4.1120	0.0850/0.0320
D	7.206/4.092	7.2927/4.1272	0.0867/0.0352
F	7.210/4.087	7.2949/4.1186	0.0849/0.0316
G	7.227/4.091	7.3147/4.1228	0.0877/0.0318
H	7.221/4.086	7.3078/4.1169	0.0868/0.0309
I	7.235/4.082	7.3245/4.1121	0.0895/0.0301

The contribution of individual quadrupole in tunes are also investigated by the formula

$$\delta\nu = \frac{1}{4\pi}\int k_1\beta ds \simeq \frac{\overline{\beta}}{4\pi}\frac{1}{f} \qquad (2)$$

with $\overline{\beta}$ is averaged β function and $\frac{1}{f} = k_1 l$ the inverse of focus length, and results of one super-period in the 6-fold symmetry lattice are shown in table 4.

Table IV
Estimated $\delta\nu_x/\delta\nu_y$ in one super period with k_1 strength (T/m), l
length (m), and β_x/β_y beta functions (m).

Name	k_1	l	$\overline{\beta_x}$	$\overline{\beta_y}$	$\delta\nu_x$	$\delta\nu_y$
Q_1	-1.50815	0.35	12.3	5.9	-0.51189	+0.24783
Q_2	2.87048	0.35	18.8	4.6	+1.50304	-0.36777
Q_3	-1.15592	0.24	6.2	9.9	-0.13687	+0.21857
DM_1	-0.37	1.22	1.2	10.81	-0.04311	+0.38831
Q_4	2.73087	0.35	6.3	2.5	+0.47318	-0.19015
DM_2	-0.37	1.22	1.82	5.71	-0.06538	+0.20511
Q_4	2.73087	0.35	6.3	2.5	+0.47318	-0.19015
DM_1	-0.37	1.22	1.2	10.81	-0.04311	+0.38831
Q_3	-1.15592	0.24	6.2	9.9	-0.13687	+0.21857
Q_2	2.87048	0.35	18.8	4.6	+1.50304	-0.36777
Q_1	-1.50815	0.35	12.3	5.9	-0.51189	+0.24783

If we add up all of the contribution of quadrupole elements in tunes in table 4, ratio for the summation of horizontal tune to the vertical is around 3.1434, which is very close to the difference tune ratio for individual element in table 3. This fact indicates the

discrepancy in tunes between real machine and modeling could come from one source, by which all of the quadrupole strength in the ring can be scaled up or down. The beam energy, which is used as a normalization factor in modeling program, is suspected to produce this scaling factor. If the beam energy increased by a factor of 0.5% then the tune difference between measurement and modeling is reduced to reasonable level, as shown in table 5.

Table V

Tune differences between measurement and modeling with correction factor 0.995.

Lattice	measured ν_x/ν_y	modeling ν_x/ν_y	$\Delta\nu_x/\Delta\nu_y$
0715-00	7.230/4.082	7.2449/4.0793	0.0149/-0.0027
0715-01	7.208/4.092	7.2220/4.0913	0.0120/-0.0007
0715-02	7.244/4.079	7.2619/4.0750	0.0179/-0.0040
0715-03	7.226/4.088	7.2410/4.0864	0.0150/-0.0016
0715-04	7.235/4.080	7.2514/4.0770	0.0164/-0.0030
0715-05	7.261/4.081	7.2778/4.0787	0.0168/-0.0023
0715-06	7.251/4.086	7.2666/4.0850	0.0156/-0.0010
0715-07	7.276/4.078	7.2946/4.0743	0.0186/-0.0037
0715-08	7.258/4.088	7.2736/4.0857	0.0156/-0.0023
0715-09	7.267/4.080	7.2841/4.0762	0.0171/-0.0038
0715-10	7.203/4.083	7.2127/4.0798	0.0097/-0.0032
0715-11	7.193/4.088	7.2012/4.0858	0.0082/-0.0022
0715-12	7.218/4.079	7.2301/4.0756	0.0121/-0.0034
0715-13	7.200/4.089	7.2086/4.0868	0.0086/-0.0022
0715-14	7.208/4.080	7.2191/4.0774	0.00111/-0.0026
0715-15	7.174/4.083	7.1807/4.0803	0.0067/-0.0027
0715-16	7.295/4.080	7.3106/4.0781	0.0156/-0.0019

This indicates the integral dipole strength is too strong for design energy of electron and need to be reduced. After some efforts, final scaling factor is 0.99448. That means the correction factor in dipole field and its powered current is 0.552%, which is in good agreement with that predicts by the tracing simulation.

IV: Conclusion

The beam tracing method is a good tool to calibrate the magnetic dipole field w.r.t. its powered current as well as for the study of beam energy and its possible tracing trajectory in the known field distribution. In above study design energy of electron is used to calibrate the magnetic field and its powered current by beam tracing method. Design energy of electron is found to be overbent by the dipole at its nominal current setting. The excessive factor for integral dipole strength is around 0.5%. As dipole current is reduced by 0.575%, a good results was found with a symmetry trajectory w.r.t. magnet center and position error outside the magnet within alignment tolerance. Integral dipole strength and bending angle are also well within the specification after this reduction. From storage ring commissioning a tune discrepancy between real machine and model prediction was found. This discrepancy finally is indicated to be coming from magnetic dipole field is too strong. As the magnet powered current is reduced by 0.552% the discrepancy in tunes is canceled. This fact shows the good consistency of these two approaches, tracing prediction and the commissioning verication.

In this paper the linear relation between dipole field and its powered current is assumed. Within a small range of variation this linear assumption is a very good approximation. While as the deviation is too much the linear assumption is not hold again and the tracing study need to be performed at this deviated field distribution to give precise prediction.

Since SRRC bending magnet is a combined function one, correction on the dipole field will slightly change the combined quadrupole field. While the correction algorithm for bending magnet is to correct the dipole field first. Due to the good tunability of the chosen lattice, error of the combined quadrupole field in bending magnet is easier to be overcame by triplet quadrupoles outside the achromate.

Acknowledgement

Reference

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