COMMISSIONING STUDY OF THE SPRING-8 STORAGE RING

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Abstract

Two commissioning schemes of the low-emittance light source storage ring are described. One is the direct commissioning of the low-emittance mode using first turn steering of the injected beam. Another is to make use of the detuned modes which are less sensitive to alignment errors. With corrector strength determined by the correction of closed-orbit distortion (COD) in the detuned modes, reduction of COD in the low-emittance mode is anticipated. Using the Chasman Green lattice designed for the SPring-8, computer simulation is made to examine the validity of the two procedures. The simulation revealed the considerable effectiveness of both schemes.

Introduction

A major goal of the new generation synchrotron light source rings is the capability of storing the low-emittance electron beam. To meet the end, lattice structures of the new light source rings, such as Chasman Green or Triple Bend Achromat (TBA) types are quite distinct from those oriented for colliding beam experiments. One common aspect of the new light source rings is the strong linear focusing of the beam at dipoles to approach the minimal emittance condition. There are, however, two large negative consequences due to the strong focusing: One is an increase in the sensitivity of the machine against quadrupole misalignments which lead to closed-orbit distortion (COD). Another is the strong nonlinearity of the machine arising from sextupoles that compensate the large chromaticities.[1] The nonlinear sextupole fields often call for the dynamic aperture considerations. Our present study focuses on the former problem.

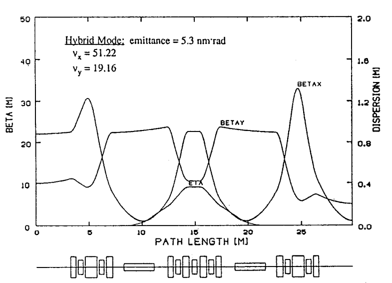

Fig. 1. Optics functions of the low-emittance mode (hybrid) designed for the SPring-8. Reflective symmetry about either end.

Figure 1 illustrates the linear optics function of the low-emittance mode employed for the SPring-8. The lattice has a Chasman Green structure. The optics shown is called the "hybrid" mode since horizontal beta function at the dispersion free sections is alternatively varied from high to low. We show in Fig. 2, the sensitivity of this mode to quadrupole misalignments. Table 1 lists the definition of the error level in the figure. Assuming the vacuum chamber size of (±40 mm × ±20 mm), we find, already at error level 2 (misalignment = 0.2 mm rms), that the maximum COD mostly exceeds the chamber dimensions. Also, large spurious dispersions are generated. It is thus of great importance to set up a strategy to enable commissioning of the low-emittance mode.

Commissioning Schemes

There are two possible strategies for commissioning the low-emittance mode: One is to make an attempt to commission the low-emittance mode directly, by reducing the magnitude of COD by means of "first turn steering" to the extent that at least stationary revolution of the beam is guaranteed. Once this is done, one can proceed with the

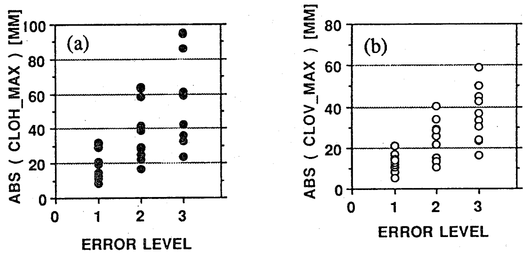

Fig. 2. Maximum COD in a ring, calculated for 10 machines. (a) Horizontal. (b) Vertical. Optics mode: Hybrid. Definition of error level is found in Table 1.

Table 1. Definition of error level employed in this study.

RMS VALUES	ERROR LEVEL 0	1	2	3
Dipole Field Error %	0.1	0.1	0.1	0.1
Tilt [mrad]	0.2	0.2	0.3	0.3
Quadrupole Field Error %	0.1	0.1	0.2	0.2
Misalignment [mm]	0.05	0.1	0.2	0.3
Tilt [mrad]	0.2	0.2	0.3	0.3

ordinary COD correction using normal pickup monitors and correctors, to make further refinements on the suppression of the residual COD.

What we mean by the first turn steering is to detect the beam position at the very first turn at some position in the ring and to steer the beam to the nominal position with correctors located upstream. This process is iterated around the ring, the iteration number depending on the sensitivity of the machine. To enable this operation, however, the monitor must either be a screen monitor (destructive) or a highly sensitive pickup monitor which is also capable of identifying the beam position in a single pass. Steering scheme will be described in the next section. We note here that the steering of the first turn beam trajectory cannot be strictly connected with the correction of COD of the machine, since the beam would inevitably have an unknown (random) betatron amplitude. Validity of this approach must therefore be examined by a computer simulation.

Another strategy is to commission the machine firstly in other modes which are less sensitive to misalignments. The so called "detuned" optics modes are designed for this purpose.[2] Since detuning corresponds to weaker focusing, it results in higher beam emittance. The relation between sensitivity of optics modes versus emittance is shown in Fig. 3. One may expect the commissioning of detuned modes to be much facilitated. It may be such that no first turn steering is needed. The idea is to perform the COD correction to the maximum extent, and then by keeping the determined corrector strength, switch over to the lower emittance modes. In designing the detuned optics modes, one should therefore take into account that patterns of the generated COD to be closely related to that of the low emittance modes. As in the former approach, the effectiveness must be verified by a computer simulation.

In both approaches, we turn off all the sextupoles. The primary reason is to be free from dynamic aperture restrictions.[1] Moreover, there should be a considerable deterioration in the role of sextupoles itself under seriously distorted optics. Fortunately, the correction of

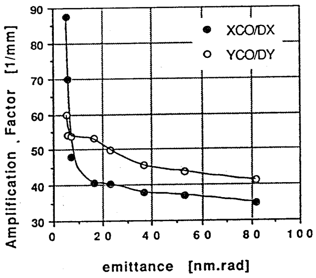

Fig. 3. Amplification factors of the SPring-8 optics modes as a function of emittance. Dark circles...horizontal, white circles...vertical.

COD should not be spoiled by adding the sextupoles in later steps. On the other hand, we may suffer from the weak beam intensity due to worsened chromatic behavior.

First Turn Steering

Let θ_i be the deflection angle in the transverse y direction given by the corrector at the position $s = s_i$ in the ring. Additional displacement $dy_i(s)$ and gradient $dy'_i(s)$ generated on the orbit at $s > s_i$ are given respectively by

$$dy_i(s) = f_i(s)\cdot\theta_i, \tag{1}$$

$$dy'_i(s) = g_i(s)\cdot\theta_i \tag{2}$$

where

$$f_i(s) = \sqrt{\beta(s)\,\beta_i}\,\sin(\mu - \mu_i), \tag{3}$$

$$g_i(s) = \sqrt{\frac{\beta_i}{\beta(s)}}\,[\cos(\mu - \mu_i) - \alpha(s)\cdot\sin(\mu - \mu_i)], \tag{4}$$

$$\mu = \int^{s} \frac{du}{\beta(u)}. \tag{5}$$

If we are to correct the beam position by an amount Δy using N correctors upstream, the following is required:

$$\Delta y = \sum_{i=1}^{N} f_i\cdot\theta_i \equiv (f, \theta). \tag{6}$$

Among several possible choices satisfying the above relation, we selected one that determines the strength by using the Lagrange multiplier method in such a way as to make the sum of N corrector strengths, namely, (θ, θ) be minimum. The i-th corrector strength is then given by

$$\theta_i = \Delta y\cdot\frac{f_i}{(f, f)} \quad (i = 1,\ldots,N). \tag{7}$$

Table 2. An example of simulation procedure on first turn steering in RACETRACK. In the given example, position steering is made at every 2 cells (at high β straight section).

--- ENTRY CORBIT ---
INITIAL COORDINATE AT THE STARTING POINT:
X0_MM = -21.49 Z0_MM = 0.13 XP0_MRAD = 0.04 ZP0_MRAD = 0.01

CORRECTION	NLAB	NTPCM	X_MM AVERAGE	X_MM IDEAL	Z_MM AVERAGE	Z_MM IDEAL	XP_MRAD AVERAGE	XP_MRAD IDEAL	ZP_MRAD AVERAGE	ZP_MRAD IDEAL
BEFORE	1	2	* 0.93	0.00	* -1.19	0.00	* 0.11	0.00	* -0.08	0.00
AFTER	1	2	0.00	0.00	0.00	0.00	0.13	0.00	-0.03	0.00
BEFORE	3	2	* -8.07	0.00	* 1.97	0.00	* 0.17	0.00	* 0.35	0.00
AFTER	3	2	0.11	0.00	-0.01	0.00	0.04	0.00	0.26	0.00
......										
BEFORE	45	2	* -1.45	0.00	* 1.41	0.00	* -0.23	0.00	* 0.21	0.00
AFTER	45	2	-0.01	0.00	0.01	0.00	-0.25	0.00	0.15	0.00
BEFORE	47	2	* 4.73	0.00	* 0.07	0.00	* -0.20	0.00	* 0.09	0.00
AFTER	47	2	0.01	0.00	-0.01	0.00	-0.13	0.00	0.09	0.00

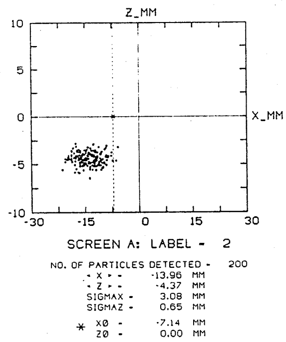

Fig. 4. Simulation of the screen monitor detecting the beam position. In this example, the beam is injected with a coherent betatron amplitude. An asterisk shows the beam beam position in a ring with no errors.

Angle steering can be done similarly by replacing Δy and f by $\Delta y'$ and g, respectively in the above expression. Formulas for simultaneous correction of both the position and the angle can also be obtained straightforwardly.

We added a routine to simulate the first turn steering in the computer code RACETRACK.[3] In Fig. 4 we show an example of the simulation detecting the beam position by a screen. An example of position steering procedure is shown in Table 2.

Numerical Results

A simulation study has been made to examine the validity of two commissioning schemes described previously. Computer code RACETRACK is used for this purpose.[3] Table 3 summarizes the conditions of simulations. To avoid any misleading conclusion, all the computations are made for 10 machines each having a different random Gaussian distributed errors. Six correctors are installed per unit cell for each of the two transeverse directions, in optimal locations.

Table 3. Conditions of the commissioning simulation.

Beam Injection Point	High Beta Straight Section	
	Off Axis Injection	On Axis Injection
Amplitude of Bump Orbit	-12.4 mm	-21.7 mm
Coherent Betatron Amplitude	9.3 mm	0 mm
Physical Aperture Limitation	Normal Chamber	@ Thin Septum
Horizontal	± 40 mm	(-16.2 mm, +40 mm)
Vertical	± 20 mm	± 20 mm
Distribution of Injected Beam	Gaussian	
Horizontal Emittance	200 nmrad (Coupling 10%)	
Particle Number	200	
Number of Tracking Turn	50	

<u>(I) Direct commissioning of the low-emittance mode:</u>

Behavior of the machine is pursued starting from error level 0 to level 2 (Table 1). These error levels take account also of field and tilt errors of dipoles and quadrupoles, but, in principle, the level expresses the degree of quadrupole misalignment which is the main source of the COD. At each level, injection efficiency was calculated by tracking 200 particles over 50 turns (Table 3).

At level 0 (misalignment = 0.05 mm rms), the injection was made successfully without any steering for all 10 cases.

At level 1 (misalignment = 0.10 mm rms), nearly half the cases turned out to be unsuccessful without steering. Comparison between on-axis and off-axis injections was also made, but no prominent difference is found. We presumed that on-axis injection would give better results under such situations, but simulations indicated that, due to seriously distorted optics, the beam possesses equally large random betatron amplitudes, as compared to the off-axis cases. Next, we performed the first turn position steering with screens located at every 2 cells at high β straight sections. A limit was set on the maximum corrector strength, which was tentatively taken to be 0.2 mrad. With position steering, all cases turned out to be successful. This can be understood from the large reduction of maximum COD in the ring, after steering is made. Large reduction is found with spurious dispersions as well.

At level 2 (misalignment = 0.20 mm rms), unsuccessful cases now appear even after position steering. Again, no notable difference is found between on-axis and off-axis injections. Starting from corrector strengths determined by position steering, the steering was repeated for unsuccessful cases now including, in addition, angle steering at low β section where the angle deflection is large. We should mention, however, that angle steering, in practice, may not be easy since it requires 2 adjacent screens with which one must identify the beam center within the accuracy of ~ 1 mm. A high reproducibility must also be required for the injection. Nevertheless, angle steering turned out to be quite effective in further reducing the COD as shown in Fig. 5. Accordingly, the injection turned out to be successful for all cases.

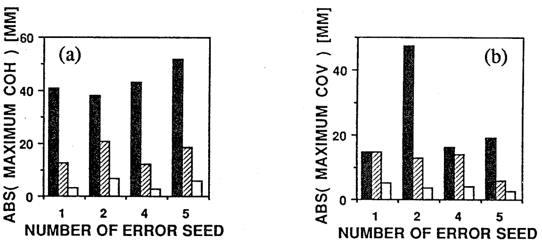

Fig. 5. Maximum COD in a ring with 0.2 mm rms quadrupole misalignment. (a) Horizontal. (b) Vertical. Only 4 cases for which injection ended unsuccessfully after position steering are shown. Dark bars...no steering. Slant lined bars...with position steering. White bars...with additional steering of position and angle.

(II) Indirect commissioning via detuned modes:

Figure 6 illustrates the optics functions of the detuned mode employed.[2] As compared to the hybrid mode, the

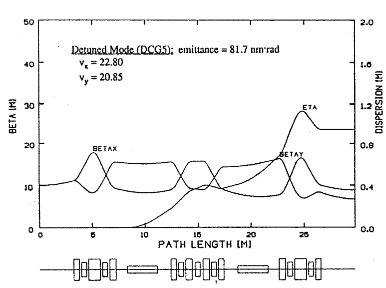

Fig. 6. Optics functions of the detuned mode (DCG5) designed for the SPring-8. Reflective symmetry about either end.

amplification factor is reduced by less than a factor of 2 in the horizontal, 1.5 in the vertical (Fig. 3). To see the feasibility of commissioning this mode, injection without steering was firstly made at error level 2 (Table 1). Although presence of successful cases does indicate the facilitation of commissioning as compared to the hybrid mode, the results show that the first turn steering would still be necessary at this error level. Situation improves for 0.15 mm rms, but still not adequate.

Next, correction of COD has been made at error level 2 to the maximum extent, ~ 0.1 mm COD rms at monitors. By keeping the corrector strengths fixed, we switched the mode to a "high β" mode (emittance = 5.7 nm·rad), in which low β sections of the hybrid mode (Fig. 1) are replaced by those of high β's. Amplification factors are ~ 20% smaller than those of the hybrid mode. Injection in the high β mode turned out to be sucessful for all cases but one. The

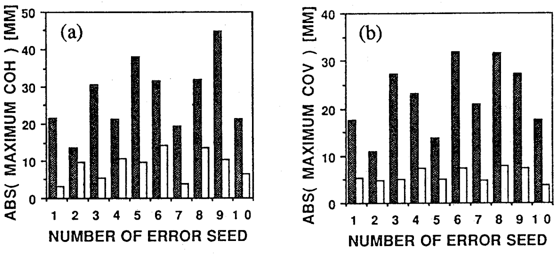

Fig. 7. Maximum COD in a ring with 0.2 mm rms quadrupole misalignment. Optics mode: High β. (a) Horizontal. (b) Vertical. Dark bars...without correctors. White bars...with correctors determined in the detuned mode.

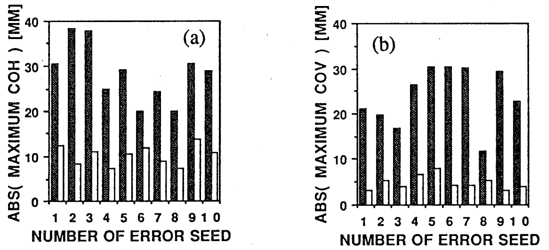

Fig. 8. Maximum COD in a ring with 0.2 mm rms quadrupole misalignment. Optics mode: Hybrid. (a) Horizontal. (b) Vertical. Dark bars...without correctors. White bars...with correctors determined in the high β mode.

effectiveness of the correctors can be confirmed in the reduction of maximum COD in the ring (Fig. 7).

In regard to the single unsuccessful case encountered, a further inspection revealed that the beam is lost at the septum wall where it is the only section in the whole ring with only 16.2 mm horizontal extention (Table 3). Taking account of the ratio of square root of horizontal β function at septum and the maximum β of the ring, which is usually ~0.8, we find that the septum wall must be away from the nominal orbit by at least ~33 mm, to be consistent with the horizontal aperture of ± 40 mm in the rest of the ring.

The above procedure was repeated with high β mode to commission the hybrid mode. With the corrector strength obtained from COD correction in the high β mode, injection in the hybrid mode ended successfully for all cases (Fig. 8).

Summary

Two approaches for commissioning of low-emittance storage rings were discussed. Their effectiveness were examined by computer simulation using Chasman Green lattice designed for the SPring-8.

In the direct commissioning scheme, it was found that first turn steering is vital and that it greatly reduces the COD of the machine. However, for machines with quadrupole misalignment of 0.2 mm rms, position steering at every high β section was not adequate to achieve the stationary revolution of the beam.

In the indirect commissioning scheme using detuned optics modes, the performance of COD correction in the detuned modes turned out to be effective in suppressing the COD of the low-emittance mode as much as to enable commissioning of the low-emittance mode.

For future extention of the present work, further case studies need be done taking account of possible errors not included so far.

References

1. R. Nagaoka et al., RIKEN Accel. Progress Rep., 227(1988).
2. K. Tsumaki et al., in this report.
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