EFFECTS OF MAGNETIC FIELD TRACKING ERRORS AND SPACE CHARGE ON BEAM DYNAMICS AT CSNS/RCS*

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Abstract

The Rapid Cycling Synchrotron (RCS) is a key component of the China Spallation Neutron Source (CSNS). For this type of high intensity proton synchrotron, the chromaticity, space charge effects and magnetic field tracking errors can induce beta function distortion and tune shift, and induce resonances. In this paper the combined effects of chromaticity, magnetic field tracking errors and space charge on beam dynamics at CSNS/RCS are studied systemically.

INTRODUCTION

The China Spallation Neutron Source (CSNS) is an accelerator-based facility. It operates at 25 Hz repetition rate with the design beam power of 100 kW. CSNS consists of a 1.6-GeV Rapid Cycling Synchrotron (RCS) and an 80-MeV linac. RCS accumulates 80 MeV injected beam, and accelerates the beam to the design energy of 1.6 GeV, and extracts the high energy beam to the target. The lattice of the CSNS/RCS is triplet based four-fold structure. Table 1 and Fig.1a show the main parameters for the lattice [1] [2].

The preferred working points of CSNS/RCS are (4.86, 4.78) which can avoid the major low-order structure resonances. But because of the chromatic tune shift, space-charge incoherent tune shift and the tune shift caused by magnetic field tracking errors between the quadrupoles and the dipoles, some structure resonances are unavoidable. The chromaticity, space charge effects and magnetic field tracking errors can also induce beta function distortion, and influence the transverse acceptance and the collimation efficiency of the collimation system. In such a situation, a clear understanding of the effects of magnetic field tracking errors, space charge, and the chromaticity on beam dynamics at CSNS/RCS is an important issue.

In this paper the effects of chromaticity, magnetic field tracking errors and space charge on beam dynamics at CSNS/RCS are studied systemically. 3-D simulations are done introducing magnetic field tracking errors and space charge effects. The combined effects of chromaticity, magnetic field tracking errors and space charge on the beam dynamics for CSNS/RCS are discussed.

EFFECTS ON LATTICE

The natural chromaticity of the CSNS/RCS lattice is (-4.3, -8.2), which can produce the tune shift of (±0.04, ±0.08) for the momentum spread of Δp/p=±0.01 (The momentum aperture of the collimator is Δp/p=±0.01). The dependence of the Beta functions on the momentum spread along a super-period without chromatic correction is shown in Fig. 1b.

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Table 1: Main Parameters of the CSNS/RCS Lattice

Circumference (m)	227.92
Superperiod	4
Number of dipoles	24
Number of long drift	12
Total Length of long drift (m)	75
Betatron tunes (h/v)	4.86/4.78
Natural Chromaticity (h/v)	-4.3/-8.2
Momentum compaction	0.041
RF harmonics	2
Injection energy (MeV)	80
Extraction energy (MeV)	1600
RF Freq. (MHz)	1.0241~2.444
Accumulated particles per pulse	1.56×10^{13}
Trans. acceptance (μπm.rad)	>540

In the case of uniform distribution in transverse direction, the incoherent tune shift due to space charge effects can be expressed as:

$$\Delta\upsilon = -\frac{r_p N}{2\pi\varepsilon\beta^2\gamma^3 B_f} \quad (1)$$

where $r_p=1.53\times10^{-18}$m is the classical proton radius, N is the accumulated particles, ε_{rms} is the un-normalized emittance, B_f is the longitudinal bunching factor, β and γ are the relativistic Lorentz factors. For CSNS/RCS, the longitudinal bunching factor, just after the injection painting, is about 0.32. With the energy of 80MeV, the space charge induced incoherent tune shift is about 0.2 for the case ε =350πμm.rad, which is the acceptance of the primary collimators. For the actual beam, which deviates from the uniform distribution, the incoherent tune shift for the particles in the beam core may be much greater than 0.2.

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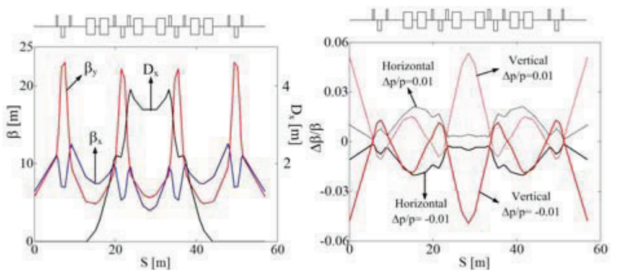

(a) (b)

Figure 1: (a), Twiss parameters of one super-period of the CSNS/RCS; (b), The dependence of the Beta functions on the momentum spread along a super-period without chromatic correction ($\Delta\beta=\beta_{\Delta p\neq 0}-\beta_{\Delta p=0}$).

For the rapid cycling synchrotron, magnetic field tracking errors between the quadrupoles and the dipoles can induce beta function distortion and tune shift. The tune shift induced by magnetic field tracking errors can be expressed as:

$$\Delta\upsilon=\frac{1}{4\pi}\oint_C \Delta K\beta(s)ds=-\frac{\Delta K}{K}\xi_{uncorrected} \tag{2}$$

where $\xi_{uncorrected}$ is the natural chromaticity. The CSNS/RCS focusing structure consists of 24 dipole magnets and 48 quadrupole magnets, which can be divided into four types: QA, QB, QC and QD. In order to assure a close tracking between them, the RCS quadrupole magnets are designed so that the saturations of the fields are within 2% for QA and within 1.5% for the other three types of quadrupole magnets [3]. In the measurements of the prototype quadrupole magnet of CSNS/RCS, it is confirmed that the tracking errors can be adjusted within 0.1% by compensating by using higher frequency waves [4]. In the actual operations, 8 or 16 quadrupole magnets are powered by the same power supply. Due to the differences between the quadrupole magnets powered by the same power supply, it is impossible to compensate the magnetic field tracking errors with higher frequency waves very well for all the quadrupole magnets. In this paper, -2% tracking errors for QA and -1.5% tracking errors for QA, QC, QD are considered preparing for the worst case. The effects of magnetic field tracking errors on Beta functions are shown in Fig. 2. The tune shift induced by magnetic field tracking errors is (-0.087, -0.095).

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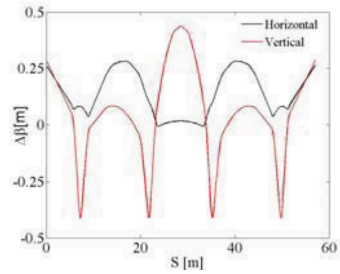

Figure 2: The effects of magnetic field tracking errors on Beta functions ($\Delta\beta=\beta_{with\text{-}error}-\beta_{no\text{-}error}$).

The combined effects of chromaticity and magnetic field tracking errors on tunes are shown in Fig. 3. Sixty different tunes plotted in Fig. 3 are obtained with different Δp/p and magnetic field tracking errors, which vary in the range of (-2%, 0) for QA and (-1.5%, 0) for QA, QC, QD. Due to the combined effects of chromaticity and magnetic field tracking errors, the Betatron tunes can be close to the resonances $2\upsilon_x$-$2\upsilon_y$=0 and $2\upsilon_y$=9, which are dangerous resonances for CSNS/RCS [5] [6].

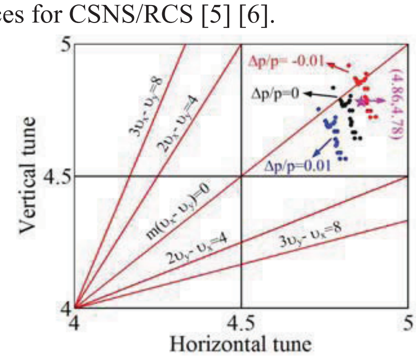

Figure 3: The combined effects of chromaticity and magnetic field tracking errors on tunes.

Table 2: The Effects of the Magnetic Field Tracking Errors on the Main Parameters of the Lattice

	Tunes (H/V)	Physical Acceptance (H/V, πμm.rad)	Acceptance of the Primary Collimators (H/V, πμm.rad)	Acceptance of the Secondary Collimators (H/V, πμm.rad)	β_x/β_y at the Injection Point of RCS(m)
Case-1	4.86/4.78	542/556	350/350	400/400	6.425/5.757
Case-2	4.773/4.685	515/546	345/345	385/380	6.688/6.043
Case-3	4.775/4.834	515/555	346/354	389/406	6.622/5.525
Case-4	4.839/4.643	552/534	342/344	379/378	6.802/6.078

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Table 3 The Simulation Results

	Painted 99% Emittance (H/V, πμm.rad)	Beam Loss during Injection Painting	Collimation Efficiency	Beam Loss during acceleration	Collimation Efficiency
Case-1	229/241	0.19%	86.7%	0.53%	92.0%
Case-2	218/250	0.25%	88.1%	2.4%	92.2%
Case-3	202/302	6.2%	93.4%	1.6%	92.7%
Case-4	191/293	2.8%	93.7%	6.3%	92.7%

3-D SIMULATIONS

3-D simulations with different magnetic field tracking errors (Case-2, Case-3, Case-4 in Table 2) are done by using the code ORBIT, and the simulation results are compared with the case without tracking errors (Case-1 in Table 2). The effects of the magnetic field tracking errors on the main parameters of the lattice are shown in Table 2. In the simulations, the acceptances of the primary and secondary collimators are set to 350πmm·mrad and 400 πmm·mrad respectively for the case without tracking errors [7]. As shown in Table 2, the tracking errors can distort Beta functions, and the physical acceptance and the acceptances of the collimators are changed, with the collimators aperture unchanged.

The simulation results are shown in Table 3. There is much beam loss for cases with magnetic field tracking errors, especially for Case-3 and Case-4. The possible reasons induced serious beam loss may be as follows: larger painted emittance (Case-3, Case-4); decreased collimators acceptance (Case-4); some dangerous resonances. The detailed study on the beam loss with magnetic field tracking errors is under going.

SUMMARY

The chromaticity, space-charge effects and the magnetic field tracking errors between the quadrupoles and the dipoles can induce beta function distortion and tune shift, and induce resonances. The physical acceptance and the acceptances of the collimators may be affected. 3-D simulations for different cases are done by using the code ORBIT, and the simulation results are compared. For cases with magnetic field tracking errors, there is serious beam loss, which may be induced by larger painted emittance, decreased collimators acceptances or some dangerous resonances. The detailed study on the beam loss with magnetic field tracking errors is under going.

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