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SEXTUPOLE OPTIMIZATION AT RAPID CYCLING SYNCHROTRON IN CHINA SPALLATION NEUTRON SOURCE

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Abstract

The China Spallation Neutron Source (CSNS) is a high-density complex with a high repetition rate of 25Hz, and the Rapid Cycling Synchrotron (RCS) is a critical component of the CSNS. The RCS utilizes sextupoles with a pulsed beam power system to maintain steady operation at 140kW. However, to achieve the target output of above 500kW, numerous aspects of the accelerator require upgrading, with the sextupole upgrade being of paramount importance for the CSNSII. By utilizing the MOGA algorithm to optimize the sextupole location, the dynamic aperture of the RCS has been significantly increased. This paper aims to provide a comprehensive review of the operation status of the sextupoles and propose several upgrade plans to enhance the performance of the CSNSII.

INTRODUCTION

The China Spallation Neutron Source(CSNS) is a high intensity proton accelerator-based facility which aims to provide 100kW beam power at CSNSI and 500kW beam power at CSNSII. CSNS consists an 80 MeV hydrogen Linac and 1.6 GeV RCS(Rapid Cycling Synchrotron). The hydrogen beam from Linac will be stripped by a carbon foil and accelerated by RCS to 1.6 GeV. The high intensity proton beam will be extracted to strike the tungsten target with a repetition of 25 Hz [1, 2]. Fig.1 shows the twiss parameters of the RCS one super-period, The CSNS-RCS lattice is based on a triplet cell and with a circumference of 227.92m. The linear lattice is comprised of 48 quadrupoles with 5 families and 24 dipoles with a single power supply. During the 2021 summer maintenance, 16 trim quadrupoles were installed in the accelerator. Additionally, the power supplies of sextupoles were changed to AC power supplies during the same maintenance period. Table 1 shows the RCS design parameters.

In the next few years, the beam power at the China Spallation Neutron Source (CSNS) will be increased to 500kW. To achieve this, several approaches will be taken in the Rapid Cycling Synchrotron (RCS), including the installation of trim quadrupoles to correct beta beat and alleviate low-order resonance, the upgrade of DC sextupoles to AC sextupoles to tune chromaticity more feasibly, the adoption of a new injection scheme including angle scan, the adoption of dual harmonic cavities to enlarge the bunch factor, and the use of momentum collimators to scratch the beam halo at the longitudinal plane. AC sextupoles will be used to correct chromaticity and suppress head-tail instabilities.

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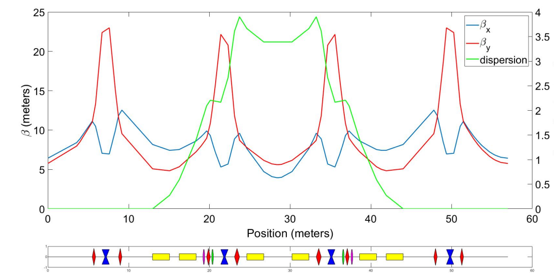

Figure 1: Twiss parameters of the RCS one super-period.

This paper is structured as follows: Section 2 presents the beam commissioning using AC sextupoles, Section 3 compares the dynamic aperture between different lattices, Section 4 describes the simulation using PyOrbit, and Section 5 summarizes the conclusions. Our paper aims to provide a comprehensive overview of the upgrade plans for the RCS at CSNS and their potential impact on the facility's performance.

Table 1: CSNS-RCS design parameters

Parameters	Values
Circumference	227.92 m
Repetition Rate	25 Hz
Superperiodicity	4
Injection energy	0.8 (MeV)
Extraction energy	1.6 (GeV)
Acceptance	540 (π mm−mrad)
Number of ring magnets	
-dipole magnets	24 with 1 family
-quadrupole magnets	48 with 5 families
-trim quadrupole magnets	16 with 16 families
-sextupoles	16 with 4 families

BEAM COMMISSIONING WITH AC SEXTUPOLES

The operation of the China Spallation Neutron Source (CSNS) in 2019 at 80kW was plagued by instability [3], as shown in Fig.2 at different tunes. To address this issue, AC sextupoles were employed to tune the chromaticity. During the beam commissioning process, the AC sextupoles cor-

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rected the natural chromaticity of -4/-9 (H/V) to -9/-9 (H/V), effectively suppressing beam instability.

However, the operational experience at CSNS suggests that the use of sextupoles can reduce beam transmission rates. Therefore, it is crucial to balance the ability of sextupoles to suppress beam instability with their impact on beam transmission rates. Our study aimed to maintain the ability of AC sextupoles to correct chromaticity while minimizing their usage to reduce their impact on beam transmission rates.

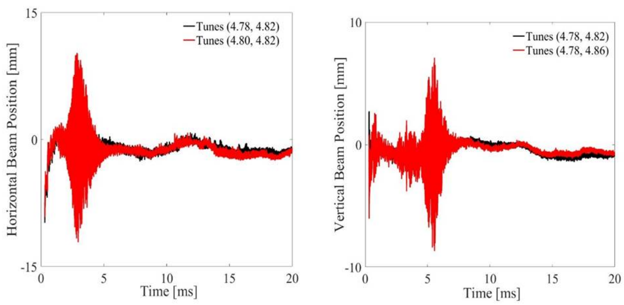

Figure 2: Beam instability occured without sextupoles

DYNAMIC APERTURE OPTIMIZATION

Numerous studies have investigated the impact of sextupole magnets on the dynamic aperture. For a single sextupole magnet, the dynamic aperture can be expressed as [4]

$$\Delta x_{max} = \frac{\sqrt{2\beta_x(s)}}{\sqrt{3\beta_x(s_1)^3}}\left(\frac{\rho}{b_2 L}\right), \tag{1}$$

where Δx_{max} is the maximum allowable transverse deviation, b_2 is the field strengths of the sextupole magnet, L is the length of the sextupole magnet, and β is the beta function of the particle in that region. The operational experience of CSNSI shows that in order to suppress the head-tail instability of the particle beam, the machine's chromaticity must be maintained in the range of -9/-9. In the study, we changed the position of the sextupole magnet, hoping to find a new design that would allow for a smaller sextupole magnet strength under the same chromaticity setting. The research results show that when the sextupole magnet is positioned appropriately close to the Q222 magnet, the strength of the sextupole magnet will be smaller under the same chromaticity setting.

Table 2 shows the sextupole magnet strength values corresponding to different chromaticities before and after optimization at different sextupole magnet positions. These results demonstrate that the appropriate positioning of the sextupole magnet near the Q222 magnet can lead to a smaller sextupole magnet strength under the same chromaticity setting. The dynamic aperture corresponding to the chromaticity of -9/-9 before the optimization of the sextupole magnet position is shown in Fig.3, while the dynamic aperture corresponding to the chromaticity of -9/-9 after the optimization of the sextupole magnet position is shown in Fig.4.

Table 2: Sextupole strength corresponding to different chromaticities before and after optimization

chromaticity	**-0.5/-0.5**	**-10/-10**
before optimization	$3.67\,m^{-3}$	$-2.94\,m^{-3}$
	$-2.9\,m^{-3}$	$1.7\,m^{-3}$
after optimization	$2.91\,m^{-3}$	$2.49\,m^{-3}$
	$-2.28\,m^{-3}$	$1.33\,m^{-3}$

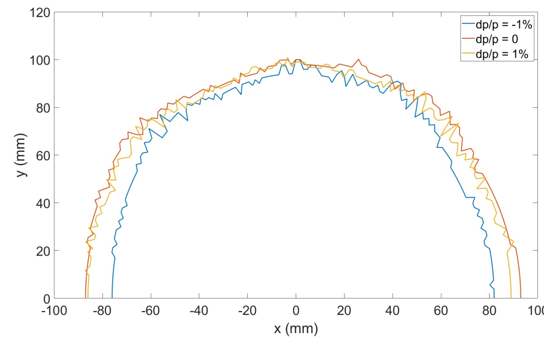

Figure 3: the dynamic aperture before the optimization of the sextupoles.

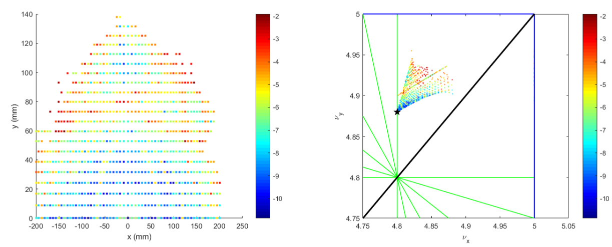

Figure 4: The dynamic aperture after the optimization of the sextupoles.

SIMULATION FOR CSNSII

CSNSII aims to deliver a power of 500 kW, which is five times that of CSNSI. In this section, we will study the dynamic characteristics after the optimization of the sextupole magnet position.

PyORBIT [5] is an open-source software package for simulating beam dynamics in accelerators. It is written in Python and C++ and is designed to be modular and easily extensible. PyORBIT can simulate a wide range of accelerator components, including magnets, RF cavities, and beam diagnostics, and can be used to study a variety of beam dynamics phenomena, such as beam instabilities, beam loss, and beam emittance growth. In simulation studies, we use a macro-particle number of 2.15e5. Fig.5 shows the tune spread corresponding to different chromaticities. It can be seen from the figure that as the chromaticity increases, the tune spread decreases.

Fig.6 shows the variation of beam transmission efficiency corresponding to different chromaticities. Interestingly, with the increase of sextupole magnets, the beam transmission rate decreases. Without sextupole magnets, the transmis-

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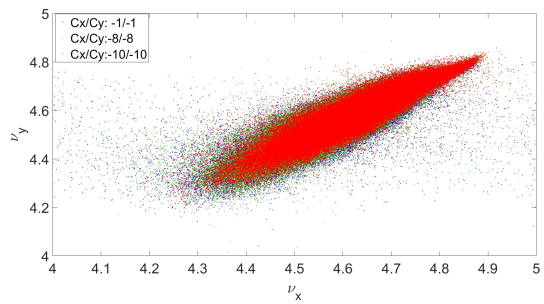

Figure 5: tune spread at different chromaticities

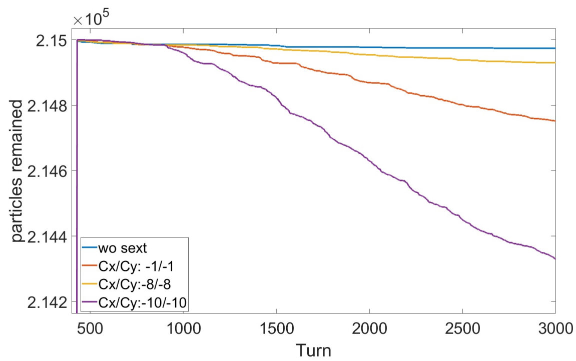

Figure 6: beam transmission rate at different chromaticities

sion rates with chromaticity correction of $-1/-1$, $-8/-8$, and $-10/-10$ are 99.98%, 99.88%, 99.97%, and 99.71%, respectively. The reason for this is also easy to understand. The natural chromaticity of RCS is -4/-9. The sextupole magnet strength required for chromaticity correction to -8/-8 is the smallest, followed by -1/-1, and the sextupole magnet strength required for chromaticity correction to -10/-10 is the largest.

Fig.7 shows the beam losses along the entire ring corresponding to different chromaticities. It can be seen from the figure that there are losses in both the arc section and the straight section, and the beam loss is greater for the sextupole magnet mode with lower transmission rates.

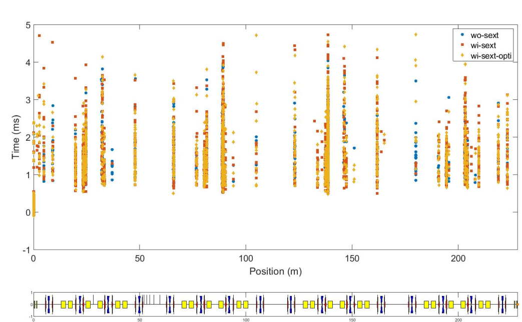

Figure 7: beam loss at different chromaticities

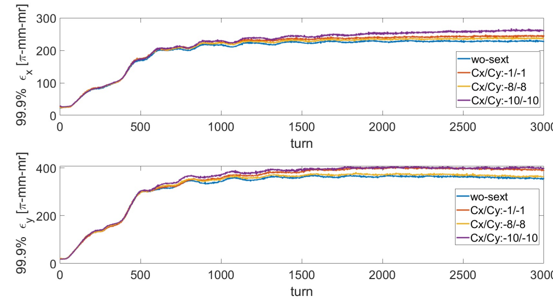

Figure 8: Emittance comparison at different chromaticities

The case of beam 99.99% normalized emittance is shown in Fig.8. It can be seen from the figure that the evolution of beam emittance is related to the beam loss. Without sextupole magnets, the beam emittance is the smallest. When the machine chromaticity is corrected to -8/-8, the beam emittance increases. However, when the machine chromaticity is adjusted to -1/-1 or -10/-10, the beam emittance increases sharply due to the increase of sextupole magnet strength.

CONCLUSION

In this study, sextupole magnets were utilized for correcting chromaticity and addressing head-tail instability in the beam. However, increasing the strength of the sextupole magnets can lead to a reduction in the beam transmission rate. To address this issue, we optimized the location of the sextupole magnets and discovered that their strength could be reduced while still meeting the same chromaticity requirements. Through simulations using Py-Orbit, we observed an increase in the dynamic aperture from the FMA and a reduction in beam loss.

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