CLOSED ORBIT AND REALIGNMENT IN THE CSNS RCS

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Abstract

Closed orbit distortion is one of the key factors affecting the operational performance of accelerators, and realignment is an effective solution to mitigate orbit distortion and reduce beam loss. To address the severe orbit distortion observed in the Rapid Cycling Synchrotron (RCS) of the China Spallation Neutron Source (CSNS), a systematic analysis was performed during the 2025 summer shutdown for the renovation of the injection region. Based on high-precision alignment data, the CSNS magnet orbit smoothing method and the MAD-X program were combined in the analysis, and the transverse adjustment of only four quadrupole magnets was proposed. After realignment, the maximum bare horizontal orbit is reduced from 23.45 mm to 20.7 mm, and the maximum bare vertical orbit is reduced from 9 mm to 7 mm. The results validate that the partial magnet realignment strategy can effectively mitigate orbit distortion, providing a feasible and efficient maintenance approach for high-power proton accelerators with limited alignment resources.

INTRODUCTION

For high-power proton accelerators, extremely high beam orbit stability is required. Factors such as installation errors and ground settlement can lead to beam orbit distortion, subsequently causing beam loss, making components radioactive, and limiting operational power. While orbit correction systems can partially mitigate this issue, realignment is a more fundamental approach.

Similar efforts have been undertaken at several domestic and international facilities. Following the major earthquake in 2011, the J-PARC RCS completed a large-scale realignment in 2013, laying the foundation for a 1 MW power upgrade [1]. The Shanghai Synchrotron Radiation Facility (SSRF) experienced unsatisfactory orbit correction performance due to uneven ground settlement. In 2022, a comprehensive realignment was carried out, reducing the closed orbit distortion from 280 μm 50 μm. At ISIS, after five main dipole magnets were adjusted in early 2025, vertical deviations and beam loss were significantly reduced [2].

Since it officially started operation in 2018, the bare orbit in the CSNS RCS, particularly in the horizontal direction, has exhibited significant distortion, with orbit exceeding 20 mm recorded by some Beam Position Monitors (BPMs). Due to the use of common power supplies, conventional beam-based alignment (BBA) methods are inapplicable, and orbit correction has shown unsatisfactory effectiveness, severely constraining beam commissioning efficiency and operational reliability. As the upcoming CSNS-II upgrade demands higher orbit quality, further mitigation of the orbit distortion is urgently required. To this end, taking advantage of the 2025 summer shutdown window for renovating the injection region, this paper proposes a realignment scheme that adjusts only a small number of magnets based on high-precision alignment measurement data. The effectiveness of the scheme is then validated through numerical simulations and beam experiments.

STATUS OF ORBIT AND ALIGNMENT

The China Spallation Neutron Source [3] is a pulsed neutron source facility driven by a proton accelerator. As the core component of CSNS, the RCS undertakes the critical task of accelerating 80 MeV proton beams injected from the linac to 1.6 GeV, which subsequently strike a tungsten target to produce high-flux neutrons. The design beam power for the CSNS Phase I is 100 kW, while its upgrade project, CSNS-II, aims for 500 kW.

The CSNS RCS has a circumference of 227.92 m and adopts a four-fold symmetric lattice based on triplet focusing structure. Table 1 lists the magnet types and their corresponding number in the RCS ring. For orbit measurement and correction, a total of 32 bidirectional BPMs and 37 dipole correctors are installed around the ring.

Table 1: Summary of Magnets for the CSNS RCS

Magnet Type	Number
Dipole	24
Quadrupole	48
Horizontal Corrector	22
Vertical Corrector	15
Trim Quadrupole	16
Sextupole	16
Octupole	8

High-intensity proton synchrotrons have stringent requirements for beam loss (typically less than 1 W/m). Although the overall requirements are currently satisfied, the relatively large transverse emittance of the beam in the RCS ring, coupled with the significant horizontal orbit distortion, lead to elevated radiation doses in some areas, increasing maintenance challenges. Figure 1 shows the bare orbit of the CSNS RCS before realignment in 2025. The maximum bare horizontal orbit reaches 23.45 mm, while the vertical orbit is close to 10 mm. Even after orbit correction, the horizontal closed orbit still exceeds 10 mm.

To monitor tunnel settlement and component position changes in the CSNS RCS ring, the alignment group has conducted annual alignment measurements since 2018. For

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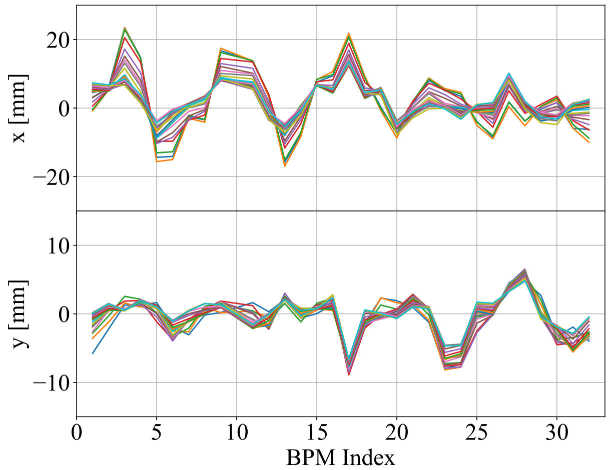

Figure 1: February 2025 CSNS RCS closed orbit before realignment.

horizontal survey, CSNS adopts the laser tracker measurement method, with the horizontal position accuracy better than 0.2 mm. For elevation survey, CSNS combines laser tracker measurement with leveling measurement, achieving an elevation position accuracy better than 0.15 mm. Figure 2 illustrates the evolution of the absolute transverse deviations of the RCS quadrupole magnets from 2018 to 2025. Overall, the alignment data have changed little from 2018 to 2024, indicating a solid foundation for the CSNS facility. However, in 2025, due to the excavation of the high-energy proton application beamline tunnel, the third quadrant of the RCS ring experienced a systematic outward tilt of approximately 1 mm. Over the entire eight-year monitoring period, despite limited ground deformation, significant static deviations from the ideal design reference orbit persist. The maximum horizontal deviation reaches 3.7 mm, while the vertical deviation is approximately 1.7 mm. These deviations are primarily attributed to the tight schedule during the initial installation, which precluded a full-ring, high-precision global alignment.

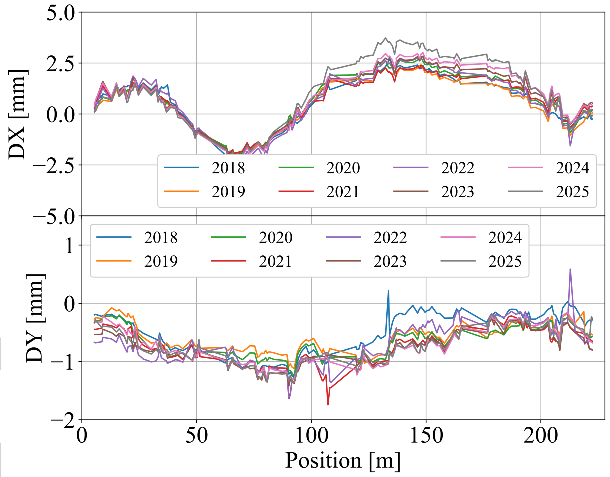

Figure 2: Evolution of absolute transverse deviations of quadrupole magnets from 2018 to 2025

REALIGNMENT SCHEME AND ANALYSIS

During the 2025 summer shutdown, modifications were made to the RCS injection region, requiring the removal and reinstallation of magnets in this section. Considering that the injection region typically experiences the highest radiation doses and that future power upgrades demand higher standards for operation and maintenance, this study proposed a realignment for some magnets near the injection region. Meanwhile, based on orbit smoothing theory and closed-orbit error calculations, additional adjustments were made in other areas.

It is well known that, compared to absolute magnet alignment errors, closed orbit distortion is more closely related to the position errors between adjacent elements, i.e., the smoothness of the orbit at the center of the magnet. Therefore, under tight schedule constraints, instead of realigning the entire ring, it is sufficient to perform smoothing on a selected set of magnets. There are various methods for magnet orbit smoothing, including the averaging method [4] and the polynomial fitting method [5]. The CSNS alignment group has also proposed a novel orbit smoothing method [6], introducing two evaluation metrics: Single Difference and Double Difference, along with their tolerance thresholds. This method has been successfully applied at the High Energy Photon Source (HEPS).

Magnet orbit smoothing can significantly reduce initial orbit distortion, but it is difficult to directly obtain the optimal adjustment results. Therefore, further steps involve incorporating alignment data into an accelerator model to compute the expected closed-orbit distortion and identify the best adjustment strategy. The specific steps are as follows: (1) Preliminary candidate quadrupole magnets are identified using the magnet orbit smoothing method proposed by CSNS; (2) The impact of transversely shifting each candidate by ±0.5 mm on the orbit distortion around the entire ring is simulated via the accelerator optics code MAD-X [7]. The measured angular rotations of the dipole magnets are small and have negligible impact on the closed orbit. Therefore, only the transverse deviations of quadrupole magnets, which contribute significantly to orbit distortion, are considered in the calculation. Additionally, magnetic field errors are not considered in this paper. (3) Magnets that have no clear positive effect on orbit correction or even exacerbate the distortion are excluded; (4) Finally, four quadrupole magnets that contribute most significantly to the closed orbit distortion and are highly feasible to adjust are selected, as shown in Table 2. Among them, R1QF03 and R4QF01 are near the injection area.

Table 2: Alignment Adjustment Values for Selected Magnets

Magnet Name	Dx [mm]	Dy [mm]
R1QF03	-0.5	0.0
R1QF06	0	0.4
R4QF04	-0.4	0
R4QF01	-0.2	0.0

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Figure 3 shows the theoretical closed orbit distortion calculated before and after adjustment. After adjustment, the theoretical horizontal orbit distortion is reduced by approximately 2 mm, and the vertical distortion is reduced by about 4-5 mm.

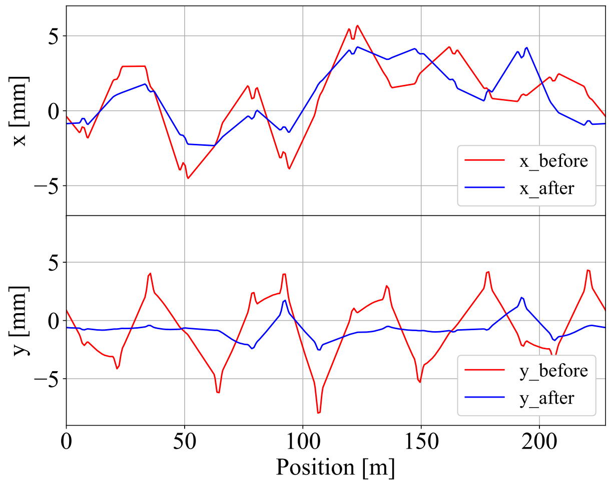

Figure 3: Comparison of theoretical closed-orbit distortion before and after adjustment.

EXPERIMENT AND DISCUSSION

After the realignment was completed in September 2025, the bare orbit was measured with the correction system turned off. The results are shown in Fig. 4: the maximum bare horizontal orbit and bare vertical orbit are 20.7 mm and 7 mm, respectively. Compared with the state before realignment (Fig. 1), the maximum distortions in the horizontal and vertical directions were reduced by approximately 2.7 mm and 2 mm, respectively. However, these results differ from the theoretical orbit changes calculated above, and the discrepancy is even larger when compared with the magnitude of the closed orbit itself. The primary reason is that the current model fails to account for all error sources, such as magnetic field errors, BPM offsets, and other unaccounted alignment errors.

SUMMARY AND FUTURE PLANS

Based on high-precision alignment data from the CSNS RCS during the 2025 summer shutdown, this paper proposes and implements a realignment scheme that only adjusts four quadrupole magnets. Experimental results show that the bare horizontal and vertical orbits are reduced by 2.7 mm and 2 mm, respectively. This study confirms that small-scale magnet realignment based on magnet orbit smoothing and MAD-X simulation can effectively improve the closed orbit, providing a feasible maintenance approach for high-power proton accelerators with limited alignment resources.

Future work will focus on the following three aspects: (1) further analyzing the contributions of magnetic field errors, other alignment errors, and BPM offsets to the closed orbit; (2) utilizing the upgrade window for the linear accelerator to

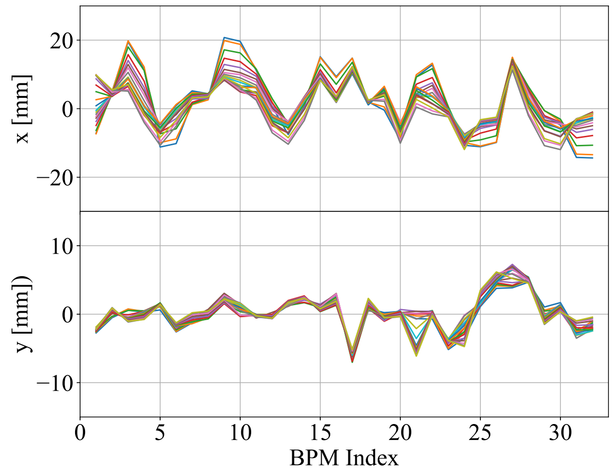

Figure 4: September 2025 CSNS RCS closed orbit after adjustments.

consider the resorting and realignment of RCS magnets; and (3) exploring a neural network-based online identification method for BPM offsets.

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