OPTICS CORRECTION TECHNIQUES AND THEIR APPLICATION IN THE CSNS/RCS*

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Abstract

Optics correction has been essential to the performance of the China Spallation Neutron Source (CSNS) since its beam commissioning in 2017. The beam tuning in CSNS is divided into DC mode and AC mode. This work reviews the characteristics of the LOCO-based correction methods applied in both modes. In the AC mode, we compare the beta functions at each millisecond before and after the summer shutdown. Beyond documenting CSNS's journey, this review offers insights for future high-power proton accelerator projects.

INTRODUCTION

The China Spallation Neutron Source (CSNS) [1–3] is a high-power proton accelerator facility designed to deliver a 100 kW beam to a solid tungsten target for neutron scattering applications. Its injector system comprises a linac and a 25 Hz Rapid Cycling Synchrotron (RCS), which accelerates protons from 80 MeV to 1.6 GeV. Operating at such a high repetition rate imposes strict demands on beam quality and stability. The RCS employs a dual harmonic RF system and features a large transverse acceptance to accommodate space-charge effects at injection. Precise control of the lattice optics is therefore critical to minimize beam loss and achieve reliable high-power operation.

The beam commissioning and optics correction at CSNS have been carried out under two distinct operational modes: DC mode and AC mode. In DC mode, the synchrotron does not accelerate – it simply stores the beam at the injection energy of 80 MeV. This mode allows the use of conventional optics measurement techniques such as orbit response matrix analysis, dispersion matching, and beta-function correction under static conditions. In AC mode, the magnets follow the 25 Hz ramping cycle, and the optics vary with time. The RF frequency curve is matched to the bending magnets. The quadrupole magnetic field follows $B(t) = B_{\mathrm{DC}} + B_{\mathrm{AC}} \sin(2\pi f t + \phi)$, where the DC and AC components can be adjusted to create a controlled tune variation within each cycle. Commissioning in AC mode therefore requires dynamic measurement techniques to capture the time-varying lattice parameters and to ensure that the beam remains well-matched throughout the acceleration cycle.

For both operational modes, the Linear Optics from Closed Orbits (LOCO) [4–6] method has been employed as a key tool for optics correction. In DC mode, LOCO provides a self-consistent calibration of the model by fitting the measured orbit response matrix, enabling precise corrections of quadrupole strengths and BPM gains. In AC mode, the application of LOCO becomes more challenging because the response matrix changes along the ramp. This work reviews the adaptation of LOCO to the AC mode at CSNS, taking into account the presence of two types of dynamic magnets: QT installed in 2021 to provide local lattice correction [7], and the AC sextupole magnets (ACS) upgraded in the same year to operate with a millisecond-resolved waveform, replacing the previous DC-only sextupole configuration [8]. Rather than isolating their individual effects, this study focuses on the net result by comparing the beta functions measured with LOCO before and after the 2025 summer shutdown, highlighting the evolution of the lattice optics across the full ramping cycle.

DC MODE OPTICS MEASUREMENT AND CORRECTION

Before implementing the dynamic optics correction in AC mode, a thorough optics calibration under static conditions is essential to establish a reliable baseline lattice model. In the CSNS/RCS, DC mode operation is therefore employed with the magnets set to constant currents and the RF system operating in point-frequency mode at 1.022 MHz with three ferrite cavities each providing 10 kV. This configuration corresponds to injection energy (80 MeV) and freezes all time-varying effects, allowing the use of conventional beam-based techniques for optics characterization.

Orbit Response Matrix Measurement

The orbit response matrix (ORM) is measured by exciting each corrector magnet with a small, known deflection and recording the resulting closed orbit changes at all beam position monitors (BPMs). In the CSNS/RCS, 21 horizontal and 16 vertical correctors are used, together with 32 dual-plane BPMs distributed around the ring[1]. The response matrix **R** is defined as

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[1] Before 2021, there were 17 horizontal and 16 vertical correctors. In 2021, one vertical corrector was moved to the Ring-to-Target Beam Transport line (RTBT). In 2023, four additional horizontal correctors were installed, resulting in the current configuration of 21 horizontal and 16 vertical correctors.

$$\mathbf{R}_{ij} = \frac{\Delta x_i}{\Delta \theta_j}, \quad (1)$$

where Δx_i is the orbit change at the i-th BPM and $\Delta\theta_j$ is the kick strength of the j-th corrector. Each corrector was excited to produce a kick angle of 0.3 mrad to 0.5 mrad (corresponding to an orbit change of approximately 5 mm at the BPMs) The measurement is performed at low beam intensity (around 10 kW, double-bunch operation with a total of approximately 1.56×10^{12} particles). The typical measurement precision allows the determination of BPM gains, corrector calibrations, and the linear lattice parameters with high accuracy.

LOCO Model Calibration

In DC mode, a representative lattice configuration is first selected as the baseline for optics correction. For the CSNS/RCS, the nominal working point $(4.80, 4.86)$ in the so-called "8086" mode is used for this purpose. The LOCO algorithm is then applied to calibrate the linear lattice model against the measured orbit response matrix (ORM). The model is implemented in the Accelerator Toolbox (AT) [4], and the fit minimizes the χ^2 between the measured and calculated response matrices by adjusting a set of free parameters, including quadrupole strengths, BPM gains, and corrector calibrations.

In practice, LOCO iteratively refines the theoretical model to match the actual machine. A key aspect of this process is the derivation of "fudge factors"—scaling coefficients applied to the main quadrupole families to correct systematic field errors. In the CSNS/RCS, the lattice model has been enhanced beyond the conventional hard-edge approximation by implementing a slice-based representation that accounts for fringe fields and inter-magnet interactions [9]. This improved modeling reduces the required fudge factors and improves the convergence of the LOCO fit. For the "8086" baseline mode, the initial ORM measurement yields the bare tunes $(0.789, 0.770)$, deviating from the design values. After the first LOCO iteration, a set of fudge factors is obtained and applied, and the ORM is remeasured. Following a second iteration, the final fudge factors converge to values close to unity, and the working point returns to the design tune, as shown in Fig. 1. The final fudge factors for the five quadrupole families are as follows: (QF1: 1.0001, QD2: 0.9922, QF3: 0.9798, QF4: 0.9934, QF6: 1.0062).The corrections are validated on a different lattice configuration (e.g., the "8680" mode). This procedure ensures that the corrected lattice model accurately represents the machine optics across multiple operating points.

The successful establishment of a precise DC model, is a prerequisite for the more complex AC mode correction, which involves time-varying magnet cycles and additional dynamic effects from the AC sextupole and QT magnets, as discussed in the following sections. To validate the LOCO results, we cross-checked the corrected optics using independent methods, including the varying quadrupole technique and the MIA/ICA approach.

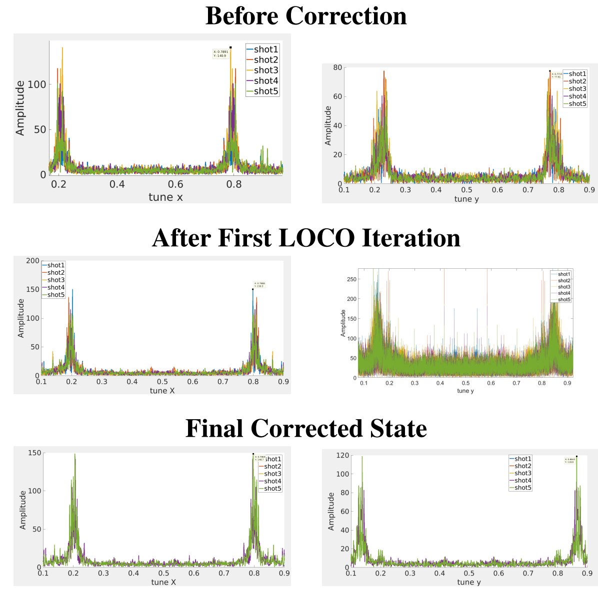

Figure 1: Evolution of horizontal (left column) and vertical (right column) optics during DC mode LOCO correction. Each row corresponds to a correction stage: top row — before correction; middle row — after first LOCO iteration; bottom row — final corrected state. The nominal working point is $(4.80, 4.86)$.

AC MODE OPTICS MEASUREMENT AND CORRECTION

Time-Resolved Response Matrix Measurement

In DC mode, the orbit response matrix is obtained by sequentially exciting each corrector magnet and recording the resulting orbit changes at all BPMs under static conditions. This approach is conceptually similar to the standard method used in light sources or colliders. For AC mode, the same principle is extended naturally to the time domain. Instead of a single static value, both the corrector kicks and the BPM readings become time-dependent waveforms synchronized with the 25 Hz ramping cycle. In the CSNS/RCS, the AC mode response matrix is therefore measured by exciting each corrector with a pulsed waveform sampled at 1 ms intervals across the 20 ms cycle, and simultaneously recording the resulting BPM waveforms with the same temporal resolution. The measurement yields a set of BPM waveform responses corresponding to each corrector waveform.

From these waveform data, the time-sliced response matrices are constructed by decomposing the waveforms into 20 discrete time slices (typically at each millisecond). For each time slice t_k, the response matrix element $\mathbf{R}_{ij}(t_k)$ is defined as the ratio of the orbit change at the i-th BPM to the kick strength of the j-th corrector, both taken at the same t_k. In practice, the measurement is repeated over several consecutive cycles to improve the signal-to-noise ratio, and the beam intensity is kept sufficiently low (50 kW; double-bunch operation with a total of approximately 7.8×10^{12} particles) to minimize space charge and collective effects that could distort the linear response. Thus, the AC mode response matrix can be viewed as a natural time-domain extension of the DC mode approach, providing a set of quasi-static response matrices that capture the lattice evolution throughout the ramping cycle.

Dispersion Measurement in AC Mode

In AC mode, the dispersion is measured using the RF frequency modulation method, adapted to the time-sliced framework. For each time slice, the RF frequency is scanned to produce a relative energy variation of ±0.3% in steps of 0.1%. The resulting orbit change is recorded, and the dispersion is extracted from the linear slope. Fig. 2 shows representative results at 1 ms and 19 ms.

(a) t = 1 ms (b) t = 1 ms dispersion

(c) t = 19 ms (d) t = 19 ms dispersion

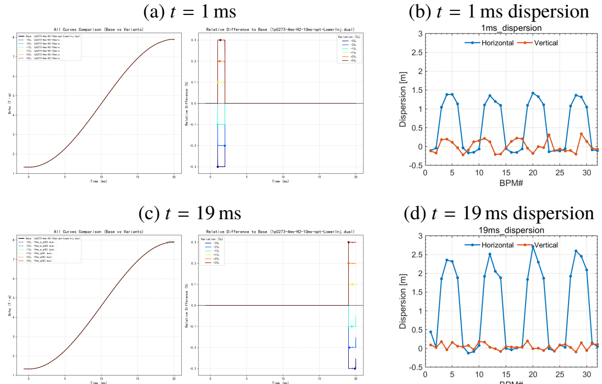

Figure 2: Dispersion measurement at 1 ms (top) and 19 ms (bottom). Left: RF frequency modulation; right: linear fit for dispersion extraction.

Correction Results and Verification

The effectiveness of the AC mode correction was validated during the 2025 summer shutdown, where a systematic optics correction campaign was conducted. Fig. 3 shows the reconstructed horizontal beta functions (β_x) before and after the upgrade, obtained from LOCO analysis across different time slices. The figure consists of four rows: the first row displays the corrected β_x in the early ramp (1–5 ms), and the second row shows the relative difference between the pre- and post-upgrade optics. The third and fourth rows present the same for the later part of the ramp (6–10 ms). The corresponding results for the vertical beta function (β_y) are shown in Fig. 4, following the same layout.

These improvements directly contribute to reduced beam loss and enhanced transmission efficiency (when the corrected optics is applied to high-power operation at 180 kW, the transmission efficiency rises from 80 % to 97 %, based on BLM and DCCT measurements). The corrected lattice also provides a reliable foundation for operating the pulsed octupole magnet, which requires accurate knowledge of the time-dependent tune and chromaticity to effectively damp instabilities [2]. The successful implementation of AC mode LOCO correction marks a key milestone for CSNS, enabling stable high-power operation and offering valuable insights for future rapid cycling synchrotron projects.

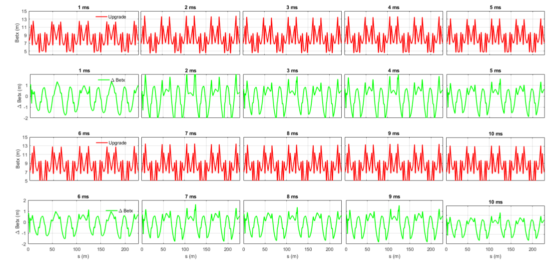

Figure 3: Horizontal beta function before and after the 2025 summer upgrade. The four rows correspond to: (row 1) corrected β_x for 1 ms to 5 ms; (row 2) relative difference for 1 ms to 5 ms; (row 3) corrected β_x for 6 ms to 10 ms; (row 4) relative difference for 6 ms to 10 ms.

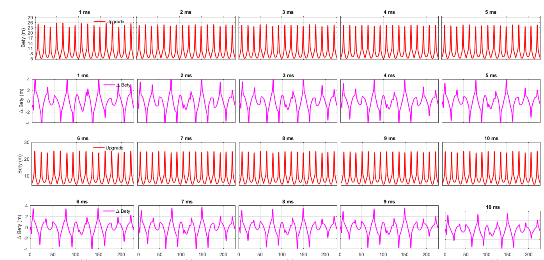

Figure 4: Vertical beta function before and after the 2025 summer upgrade. The four rows correspond to: (row 1) corrected β_y for 1 ms to 5 ms; (row 2) relative difference for 1 ms to 5 ms; (row 3) corrected β_y for 6 ms to 10 ms; (row 4) relative difference for 6 ms to 10 ms.

CONCLUSION

Since beam commissioning began at the CSNS in 2017, optics correction has been essential for achieving stable high-power operation. This work has reviewed the systematic efforts in beam tuning, optics measurement, and lattice model correction, focusing on the evolution of methodologies for both DC and AC modes.

The methodologies developed—particularly the two-step LOCO correction strategy and the integration of dynamic magnetic elements into the lattice model—offer valuable insights for future high-power proton accelerator projects. The comprehensive optics correction framework established at CSNS has proven effective across both static and dynamic regimes, providing a solid foundation for reliable accelerator operation and serving as a reference for similar facilities under design or construction.

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