

# COMMISSIONING AT THE TUNES BELOW HALF-INTEGER FOR CSNS RCS\*

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## Abstract

Based on the beam commissioning of CSNS-I RCS, the current tune above half-integer exhibits extremely small parameter margins and severe instabilities. Therefore, to further increase beam power in Phase II, significant optimization of the tune is required. Through extensive simulations, we identified that the tunes below half-integer (near 4.3/5.3) show no instabilities, which is crucial for power enhancement in Phase II. To verify stable operation at the tunes of this region in the actual machine, we conducted a series of machine studies. The results demonstrate that the tunes below half-integer is instability-free and can achieve stable beam supply at 140 kW (corresponding to 700 kW in Phase II under equivalent tune shift due to space charge).

## INTRODUCTION

The China Spallation Neutron Source (CSNS) [1, 2] is a high-intensity proton accelerator-based facility serving as a neutron source. Its accelerator complex comprises two main components: an H<sup>-</sup> linac and a Rapid Cycling Synchrotron (RCS). The RCS accumulates a beam with an energy of 80 MeV through a multi-turn charge-exchange scheme and accelerates the beam to 1.6 GeV at a repetition rate of 25 Hz. The target beam power for CSNS is specified at 100 kW with a total proton of  $N_p = 1.56 \times 10^{13}$ . The approval of CSNS Phase II (CSNS-II) [3] aims to enhance the beam power to 500 kW by increasing the linac beam energy to 300 MeV, thereby reducing space charge effects at low energy and improving current intensity in the RCS, corresponding to a total particle of  $N_p = 7.8 \times 10^{13}$ . Additionally, trim quadrupoles will be adopted in Phase II. A comparison of the parameters between Phase I and Phase II is shown in Table 1.

Table 1: CSNS RCS design parameters

Parameter (Unit)	Phase I	Phase II
Extraction Beam Power (kW)	100	500
Injection Beam Power (MeV)	80	300
Extraction Beam Energy (MeV)	1600	1600
Repetition Rate (Hz)	25	25
Space Charge Tune Shift	0.28	0.19
Beam Average Current ( $\mu$ A)	62.5	312.5
Number of Dipoles	24	24
Number of Main Quadrupoles	48	48
Number of Trim Quadrupoles	/	16

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For the RCS, betatron tunes are of critical importance. Drawing on the beam commissioning experience of Phase-I, the presently adopted tune setting provides only marginal parameter margins and induces severe beam instabilities [4]. Accordingly, substantial tune optimization is indispensable in Phase-II to accommodate elevated beam power. Extensive numerical simulations have therefore been performed. Simulation results indicate that tune values below the half-integer resonance avoid instability issues entirely while maintaining high beam transmission under higher-power operating conditions. To validate the simulation predictions, dedicated machine studies were conducted under the Phase-I beam configuration. Current experimental results confirm that tunes below the half-integer remain free of instabilities and enable stable beam delivery at 140 kW, which is equivalent to a 700 kW beam performance in Phase-II when accounting for identical space-charge tune shift conditions. This strongly demonstrates that the optimized tune scheme can support reliable and stable 700 kW beam operation in future Phase-II commissioning.

## SIMULATION

To address the transverse coupled-bunch instability (TCBI) effectively, it is beneficial to optimize the tune, shifting the betatron oscillation frequency away from the resonance of ceramic chamber, with an ideal target of between 0 and 0.5 [5]. So, we simulated the range for selecting tunes: 4.35-4.45 in x plane and 5.25-5.45 in y plane (below half-integer resonances).

For 100 kW, the transmission rate reached above 99% and there is no beam instabilities, as shown in Fig. 1. However, for 140 kW, under the same conditions, the beam transmission rate is only approximately 97.2%, as shown in Fig. 2. With the help of the Trim Quadrupoles (QTs) [6], the vertical emittance is reduced, thereby optimizing the transmission rate to over 99%, as shown in Fig. 3.

## BEAM COMMISSIONING

The space charge effect of 100kW-160kW (Phase I) is equivalent to that of 500kW-800kW at an injection energy of 300MeV(Phase II).

### 100 kW

At the beginning of beam commissioning, the beam loss in the injection region has decreased significantly and the transmission rate of the RCS was very low (<97%).

We adopted the following optimization methods:

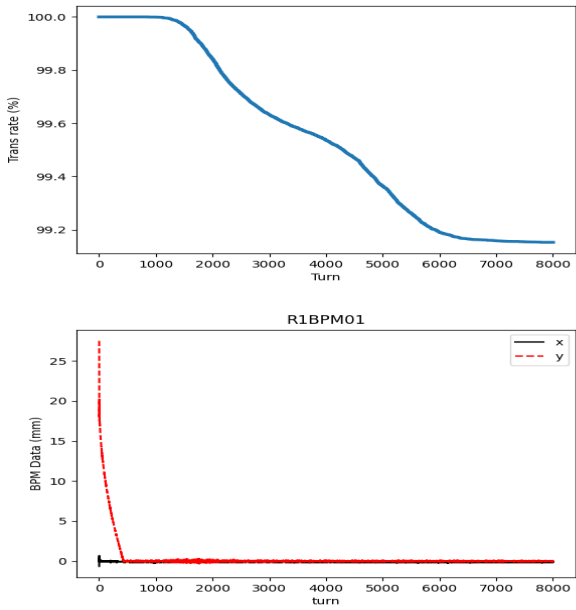


Figure 1: The simulation results at the tunes below half-integer for 100 kW.

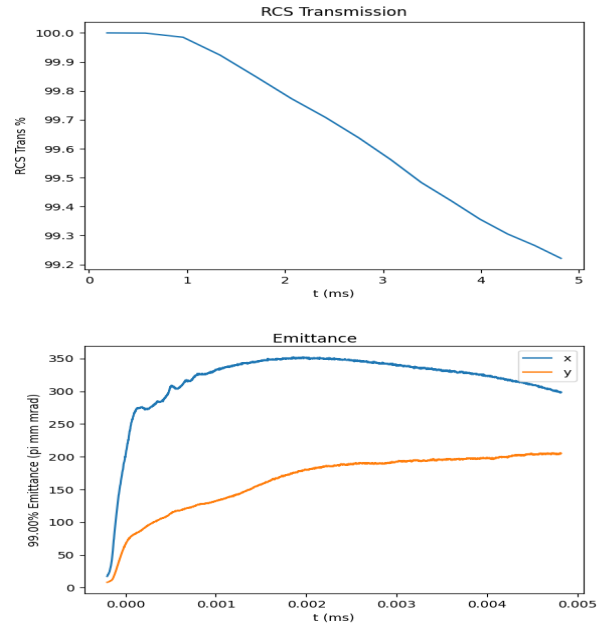


Figure 3: The simulation results at the tunes below half-integer for 140 kW (with QT).

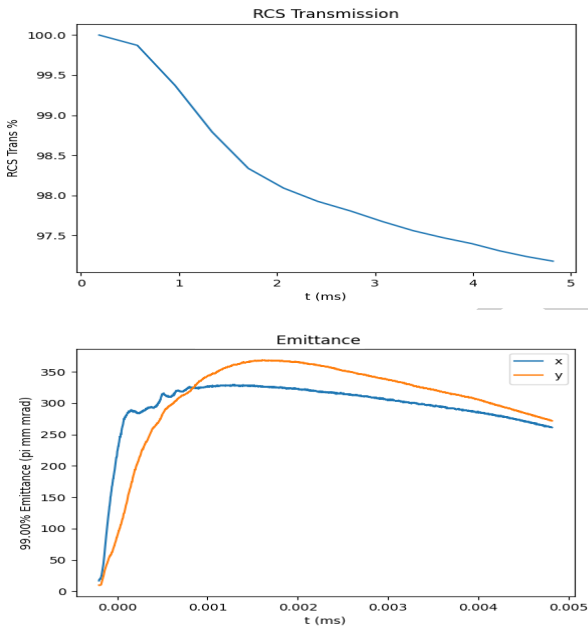


Figure 2: The simulation results at the tunes below half-integer for 140 kW (without QT).

1. Optimize the global orbit.
2. Replace the RF curve. Since there is no instability, there is no need to consider using longitudinal methods to suppress instability, and the trans. rate has been significantly improved.
3. Optimize several saturated beam loss points via local bump.

4. Perform scanning on K2 of the main quadrupoles using Bayesian optimization.

Finally, the transmission rate reached above 99.5% at 100kW and the beam loss meets the beam supply standards shown in Fig. 4.

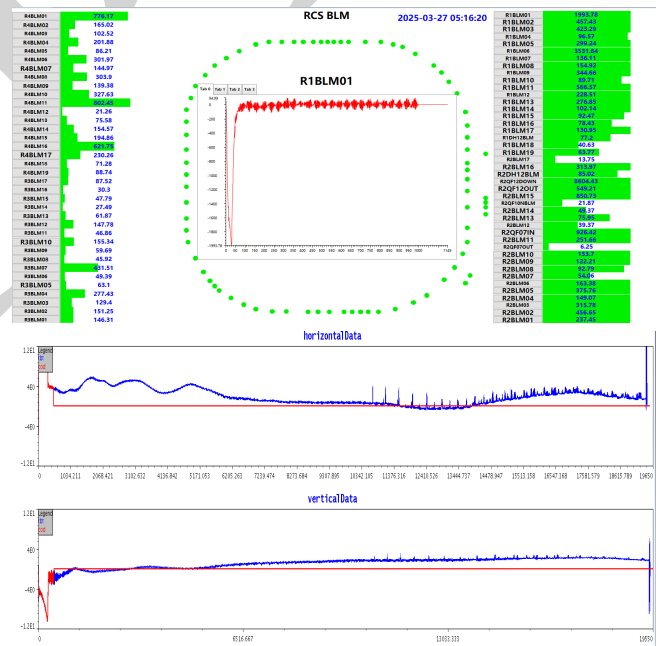


Figure 4: The results of the beam commissioning at 100kW.

### 140 kW

Building on the beam commissioning at 100 kW, we directly increased the power to 140 kW and the transmission rate of the RCS was very low (<94.4%). Since no instability

exists in the vicinity of the tunes, the 140 kW commissioning primarily consists of operational mode adjustment rather than instability suppression.

We adopted the following optimization methods:

1. Trim Quadrupoles, to restore the superperiod of the lattice of RCS and adjust the beta function. The transmission rate was increased to 96.7%.
2. Bayesian optimization, to scan the amplitude and phase of high-order harmonic components, as well as the phase of the 25Hz component, in the resonant power supplies for the main dipole magnets and quadrupole magnets. The transmission rate was increased to 98.6%.
3. Local bump, to optimize R4BLM16, R2BLM02-05, and the beam loss in their vicinity. The transmission rate was increased to above 99%.

Finally, the transmission rate reached above 99% at 140kW and the beam loss meets the beam supply standard as shown in Fig. 5. The results confirm that these tunes remain instability-free and can achieve stable beam supply at 140 kW (corresponding to 700 kW in Phase II under equivalent space charge tune shift conditions). This provides strong evidence that the selected tunes can support stable 700 kW beam operation during Phase II commissioning.

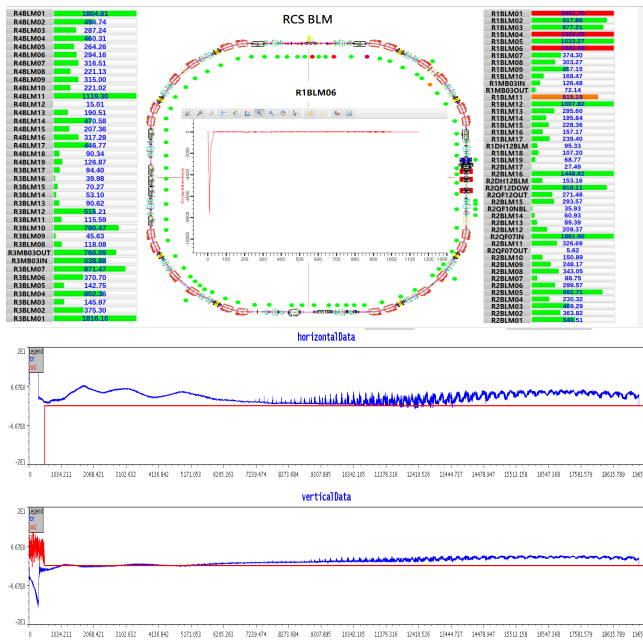


Figure 5: The results of the beam commissioning at 140kW.

## CONCLUSION

To meet the needs of the Phase II upgrade, we have attempted to change the tune to below the half-integer to avoid beam instability. The relevant beam commissioning was conducted during Phase I to verify the feasibility of this tune. During the beam commissioning process, a variety of methods were tried, all of which have contributed to the phased success of the commissioning. For this work, the beam commissioning still needs to further increase the power to tap the potential of this tune as much as possible. During this year's summer maintenance, the injection region of RCS has been renovated, enabling it to accommodate a larger injection beam size. This will also relax the requirements for the injection beta function in the subsequent commissioning and reduce the difficulty of future commissioning to a certain extent.

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