BEAM COMMISSIONING AND UPGRADE PROGRESS FOR THE CSNS-II RCS*

M. Y. Huang[†, 1, 2, 3], X. Li[1, 2], H. C. Liu[1, 2], X. Qi[1, 2], Y. L. Zhang[1, 2], S. Y. Xu[1, 2], X. H. Lu[1, 2]
L. S. Huang[1, 2], H. Y. Liu[1, 2], J. L. Chen[1, 2], Y. W. An[1, 2], K. Zhou[1, 2], Y. Li[1, 2], J. J. Tan[1, 2], J. Peng[1, 2]
Z. P. Li[1, 2], Y. L. Han[1, 2], B. Z. Chen[1, 2], S. Wang[1, 2, 3]
[1]Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
[2]Spallation Neutron Source Science Center, Dongguan 523808, China
[3]University of Chinese Academy of Sciences, Beijing 100049, China

Abstract

For the China Spallation Neutron Source (CSNS), the rapid cycling synchrotron (RCS) accumulates and accelerates the injection beam to the design energy of 1.6 GeV and then extracts the high energy beam to the target. In this paper, firstly, the beam commissioning of the RCS has been comprehensively studied. In order to meet the requirements of beam power increase and stable operation of the CSNS accelerator, the RCS beam losses and radiation dose from different sources are studied and optimized. Secondly, as the second phase of the CSNS, CSNS-II will achieve a beam power on the target of 500 kW. The injection energy of the CSNS-II will be increased from 80 MeV to 300 MeV and the injection beam power will be increased about 20 times. The upgrade of the RCS will be studied in detail, including new injection system, longitudinal dynamics, closed orbit correction, transverse collimators and so on. Based on the detailed simulation and beam experimental results, the upgrade schemes of the critical systems for the CSNS-II RCS have been proven feasible.

INTRODUCTION

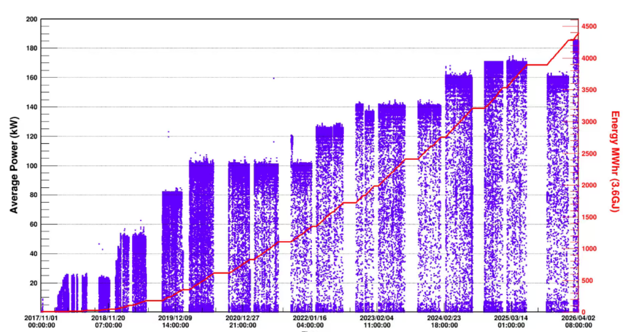

Figure 1: CSNS beam power increase history.

The China Spallation Neutron Source (CSNS) is a multidisciplinary platform [1, 2] and its accelerator consists of an 80 MeV H^- Linac and a 1.6 GeV rapid cycling synchrotron (RCS) with a repetition rate of 25 Hz [3, 4]. Through some hardware optimizations and innovative beam commissioning methods, the CSNS beam power has been increased to 185 kW, exceeding the design target by 85%. Figure 1 shows the CSNS beam power increase history.

Table 1: RCS Main Parameters

Parameters	CSNS	CSNS-II
Output beam power [kW]	100	500
Injection energy [MeV]	80	300
Extraction energy [GeV]	1.6	1.6
Pulse repetition rate [Hz]	25	25
Acceleration time [ms]	20	20
Extraction average current intensity [μA]	62.5	312.5
Circumference [m]	227.92	227.92
Number of dipoles	24	24
Number of quadrupoles	48	48
Number of QTs	0	16
Lattice structure	Triplet	Triplet
Nominal betatron tune [H]	4.86	4.86
Nominal betatron tune [V]	4.78	4.78
Acceptance [pi-mm-mrad]	540	540
Harmonic number	2	2
Particles per pulse [10^{13}]	1.56	7.8
Space-charge tune shift	0.28	0.19

As the second phase, the CSNS-II will improve the beam power on the target from 100 kW to 500 kW. Then, the ac-

† Email address: huangmy@ihep.ac.cn
* Work supported by the Guangdong Basic and Applied Basic Research Foundation (No. 2021B1515120021) and Guangdong Special Support Program (No. 2024TQ08A570)

celerator needs to be upgraded, including: the Linac upgrade, injection system upgrade, and three new Magnetic Alloy (MA) dual-harmonic cavities, and so on [5]. Table 1 shows the main accelerator parameters for the CSNS-II RCS. Figure 2 shows the layout of the CSNS-II.

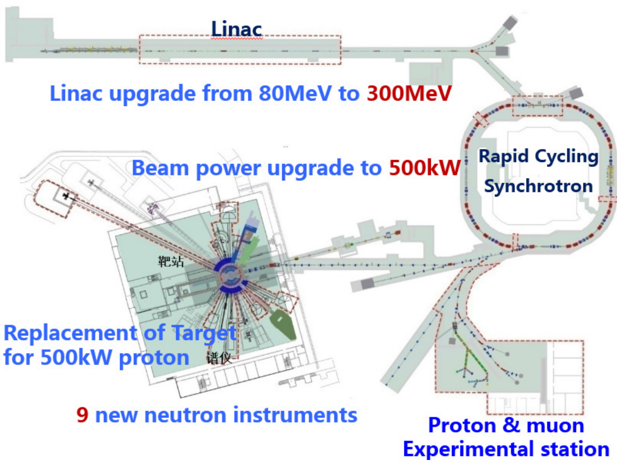

Figure 2: Layout of the CSNS-II.

BEAM COMMISSIONING FOR THE CSNS

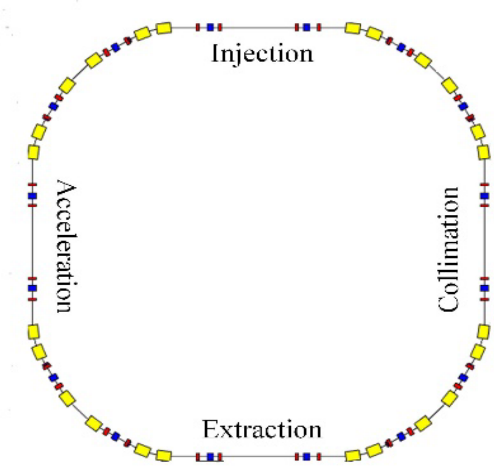

Figure 3: Layout of the RCS.

The RCS adopts a fourfold symmetric lattice, including four 11-meter-long drift sections. These sections are used to accommodate hardware for the beam injection, fast extraction, RF acceleration, and transverse beam collimation, ensuring that the functions of these systems remain relatively independent. The lattice of the CSNS RCS is shown in Fig. 3.

Low Intensity Beam Commissioning

In the early stage of beam commissioning, low intensity beam commissioning is primarily performed [6]. After measurement, the measured tunes were (4.855, 4.783) in the DC mode, which were very close to the nominal value of (4.860, 4.780). Regarding the response matrix and beta function, the theoretical design and actual measurements are in good agreement, as shown in Figs. 4 and 5. Therefore, the online model agrees with the theoretical design in the low intensity mode. It has been verified that the theoretical design and magnetic field measurement results are good.

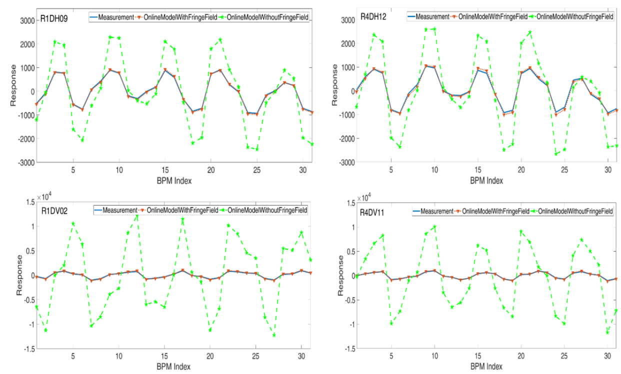

Figure 4: Comparison of response matrices between theoretical design and measurement in the low intensity mode.

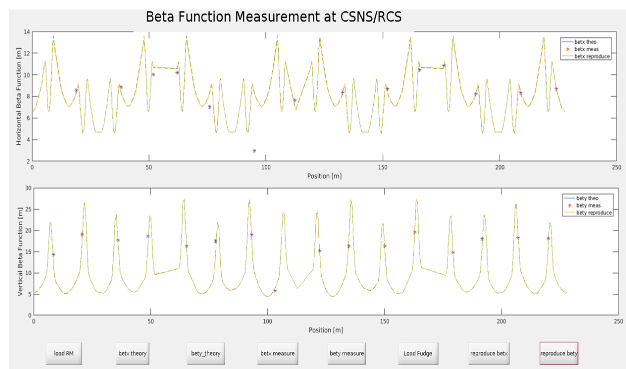

Figure 5: Comparison of beta function between theoretical design and measurement in the low intensity mode.

Intense Beam Issues

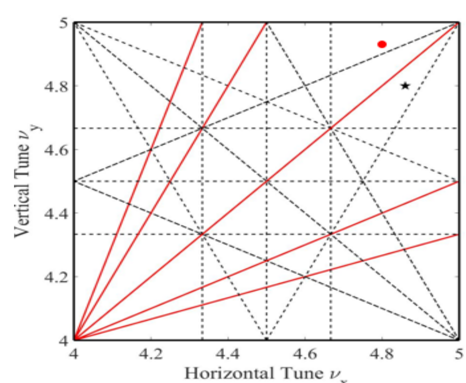

Figure 6: Tune optimization.

During the beam commissioning, when the beam power exceeds 50 kW, the intense beam effects become very strong, including the space charge effects and beam instability. Tune pattern plays an important role in the control of the intense beam effects. In order to reduce the space charge effects induced beam loss, the tunes at the injection were changed from (4.81, 4.87) to (4.81, 4.87), as shown in Fig. 6. In order to suppress the beam instability, the tunes were moved downward, as shown in Fig.7. Meanwhile, it can be seen from Fig. 7 that the measured tune curves are in good agreement with the theoretical design curves.

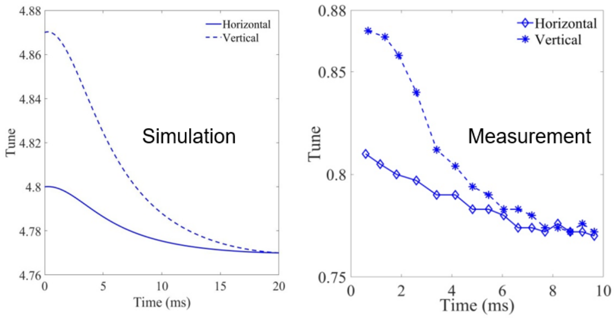

Figure 7: Simulated and measured tune curves.

Table 2: Methods to Increase Beam Power

Beam power [kW]	Methods to increase the beam power
50→80	By using the correlated painting instead of the anti-correlated painting
80→100	Optimization of the tune and chromaticity
100→125	Slight modification of injection system; installation of AC trim quadrupoles and AC sextupoles
125→140	Installation of a dual harmonic MA cavity
140→160	Injection beam pulse width increased by 30us; installation of a secondary dual harmonic MA cavity
160→170	Vertical painting area increased by about 40%
170→185	New injection system and painting method

During the beam commissioning process, various methods have been found to increase the beam power on the target, as shown in Table 2. As can be seen from the table, there are two main ways to increase the beam power. Firstly, upgrading or adding key hardware systems, such as the injection system and magnetic alloy cavities. The other way is to propose innovative commissioning methods, such as new painting methods.

UPGRADE PROGRESS FOR THE CSNS-II RCS

As the second phase, the CSNS-II will achieve a beam power on the target of 500 kW. The injection energy of CSNS-II will be increased from 80 MeV to 300 MeV and the injection beam power will be increased about 20 times. Compared with the CSNS, the space charge induced tune shift for the CSNS-II is much smaller. Table 3 shows the space charge induced tune shift for different machines in the world.

Table 3: Space Charge Induced Tune Shift

	Injection energy [MeV]	Beam power [kW]	Tune shift
CSNS	100	100	0.28
CSNS-II	300	500	0.19
J-PARC	400	1000	0.12
SNS	1000	1000	0.08
ISIS	70	160	0.40

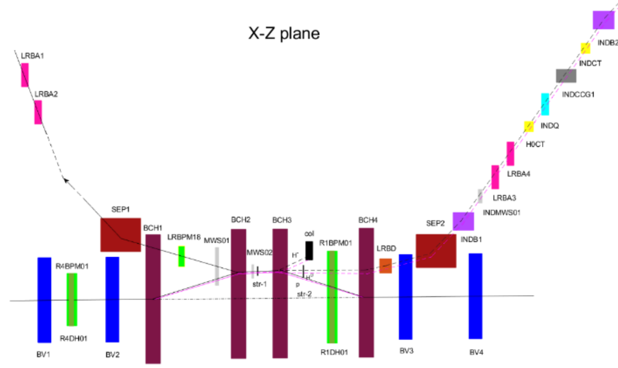

Figure 8: Layout of the CSNS-II injection system.

For the CSNS-II, there are many challenges for the beam injection. The peak temperature of the stripping foil is too high, which approaches or exceeds its melting point. The beam dynamics is greatly affected by the edge focusing effect of horizontal chicane bump. The single fixed painting method may not be suitable for the future operational scenarios. To address these challenges, a new painting injection method is proposed. The chicane bump and horizontal painting bump are combined into one bump. The horizontal painting is performed by using the position and angle scanning at the same time. Figure 8 shows the layout of the CSNS-II injection system. The new painting method has many advantages. The foil peak temperature can be greatly reduced. The edge focusing effect of bump magnets is greatly reduced. Both correlated and anti-correlated painting can be performed. The difficulty of large aperture near the injection point required by angular scanning is solved. It saves a set of bump magnets and is easier to optimize the layout of the injection system.

Table 4: Measured Lifetime of Main Stripping Foil

State	Foil lifetime
Before upgrade	~ 3 weeks
After upgrade	> 4 months

After the injection system upgrade, the feasibility of new injection system design scheme has been verified in the beam commissioning. The injection beam loss and radiation dose are significantly reduced. The foil peak temperature is significantly reduced, and its lifetime is greatly increased. From Table 4, it can be found that lifetime of the stripping foil has increased significantly, from 3 weeks to 4 months.

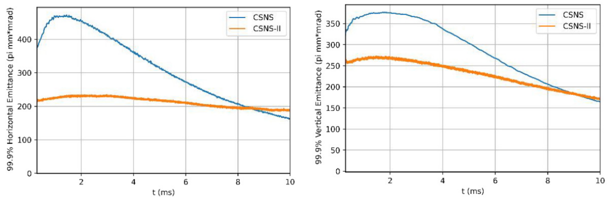

Figure 9: Comparison results of the transverse emittance between the CSNS and CSNS-II.

Although the particle number increased by a factor of 5, the space charge effects have been significantly reduced due to the increase in injection energy from 80 MeV to 300 MeV, the addition of three magnetic alloy cavities to improve the bunching factor, and the adoption of a new painting method. Simulation results show that, compared to CSNS, the transverse emittance for the CSNS-II RCS is significantly reduced, as shown in Fig. 9.

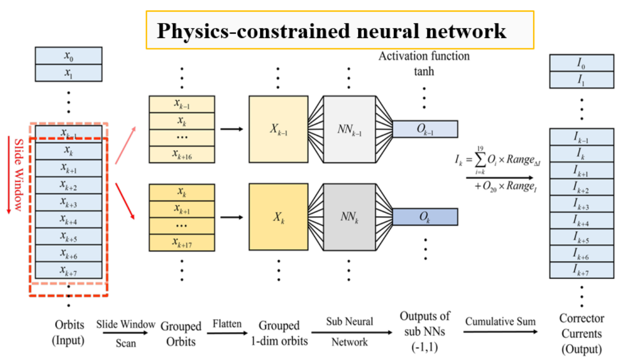

Figure 10: A neural-network-based closed orbit correction scheme.

Closed orbit correction is a key issue in beam commissioning and power ramp-up. For the CSNS, the correction of horizontal orbit has always been a challenge for the RCS. BPM offsets are difficult to measure. Energy mismatch makes the closed orbit correction in the dispersion region difficult. To address these challenges, a neural-network-based orbit correction scheme is being investigated to search for improved correction solutions beyond conventional algorithms, as shown in Fig.10.

Compared to the CSNS, the beam power of the CSNS-II is significantly higher, requiring stricter control of the beam loss. Therefore, the transverse collimation system needs to be upgraded. After in-depth study, the design scheme of the transverse collimator system that accommodates both single-stage and two-stage collimation for the CSNS-II has been completed. Figure 11 shows the comparison of collimation schemes between the CSNS and CSNS-II. After simulation and optimization, the collimation efficiency of the CSNS-II collimation system reaches 96%.

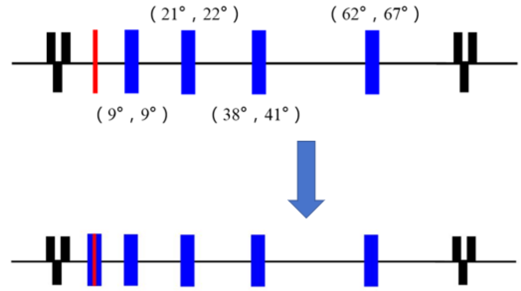

Figure 11: Comparison of collimation schemes between CSNS and CSNS-II.

CONCLUSION

In this paper, for the CSNS, the beam commissioning of the RCS has been comprehensively studied. In the beam commissioning process, various methods have been found to increase the beam power on the target. For the CSNS-II, the challenges of the RCS have been introduced in detail. The upgrade scheme of the RCS has been studied in detail, including: the new injection system, longitudinal dynamics, closed orbit correction, transverse collimation system, and so on. Based on the detailed simulation and beam experimental results, the upgrade schemes of the critical systems for the CSNS-II RCS have been proven feasible.

REFERENCES

[1] S. Wang *et al.*, “Introduction to the overall physics design of CSNS accelerators”, *Chinese Physics C*, vol. 33, pp. 1-3, June 2009. doi: 10.1088/1674-1137/33/S2/001

[2] CSNS Project Team, “China Spallation Neutron Source Feasibility Research Report”, Chinese Academy of Sciences, 2009 (in Chinese).

[3] J. Wei *et al.*, “China Spallation Neutron Source - an overview of application prospects”, *Chinese Physics C*, vol. 33, pp. 1033-1042, Nov. 2009. doi:10.1088/1674-1137/33/11/021

[4] M.Y. Huang *et al.*, “Effects of injection beam parameters and foil scattering for CSNS/RCS”, *Chinese Physics C*, vol. 37, p. 067001, June 2013. doi:10.1088/1674-1137/37/6/067001

[5] M. Y. Huang, S. Wang, and S. Y. Xu, “Preliminary Study on the Injection System Upgrade for CSNS-II”, in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 2037-2039. doi:10.18429/JACoW-IPAC2019-TUPTS048

[6] S. Xu *et al.*, “Beam commissioning and beam loss control for CSNS accelerators”, *Journal of Instrumentation*, vol. 15, p. 07023, July 2020. doi:10.1088/1748-0221/15/07/P07023