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ACHIEVEMENT OF 100-kW BEAM OPERATION IN CSNS/RCS*

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Abstract

The China Spallation Neutron Source (CSNS) is designed to accelerate proton beam pulses to 1.6 GeV kinetic energy, striking a solid metal target to produce spallation neutrons. CSNS has two major accelerator systems, a linear accelerator (80 MeV Linac) and a 1.6 GeV rapid cycling synchrotron (RCS). The RCS accumulates and accelerates the proton beam to 1.6 GeV and then extracts the beam to the target at the repetition rate of 25 Hz. The beam commissioning of CSNS/RCS had been started since May 2017. The most important issue in high-power beam commissioning is the beam loss control, as well as the control of induced activities, to meet the requirement of manual maintenance. A series of beam loss optimization work had been done to reduce the uncontrolled beam loss. At the end of February 2020, CSNS reached the design beam power of 100-kW with very low uncontrolled beam loss.

INTRODUCTION

The function of the rapid cycling synchrotron (RCS) of China Spallation Neutron Source (CSNS) is to accumulate and accelerate protons from the energy of 80 MeV to the design energy of 1.6 GeV at the repetition rate of 25 Hz [1, 2]. The CSNS/RCS beam commissioning was started in May, 2017 with the injection energy of 61 MeV, and the beam was successfully accelerated to 1.6 GeV in July 7, 2017. 1.6 GeV acceleration with the injection energy of 80MeV was successfully accomplished on January 18, 2018. We first performed the closed orbit distortions (COD) correction, Lattice calibration, the matching between the dipole field and RF frequency during the acceleration process, and the tuning of the injection beam using a low intensity beam, and the beam power of CSNS/RCS was increased step by step. In January 2019, the beam power was increased to 50-kW with low beam loss level [3, 4]. The limitation in realizing higher intensity beam operation was large beam loss induced by space charge and beam instability. The bunching factor and injection painting were optimized to reduce the space charge induced beam loss [5, 6]. The tunes during the beam acceleration were compared and optimized based on the space charge tune shift and beam instability. By performing the bunching factor optimization, the injection painting optimization, and the tune optimization in the RCS, in February, 2020, the beam power of CSNS achieved the design value 100-kW within permissible beam loss levels [7]. Figure 1 shows the beam power upgrading process of CSNS/RCS.

LOW-INTENSITY BEAM COMMISSIONING OF THE RCS

The beam commissioning started with a low intensity beam. The COD correction, Lattice calibration, the matching between the dipole field and RF frequency during the acceleration process, the tuning of the injection beam was performed. The orbit and lattice correction is the foundation for beam loss optimization.

DC Mode

In the first step, the beam commissioning of the RCS was started with DC mode. In the DC mode, the RCS is operated like a storage ring at the injection energy. In DC mode, the timing of the injection painting magnet and the injection painting bump are calibrated, the optical parameters are measured and corrected, and the orbit matching between the injection beam and circulating beam of the RCS was performed. The measurement and correction of the main optical parameters is the basis of AC mode beam commissioning.

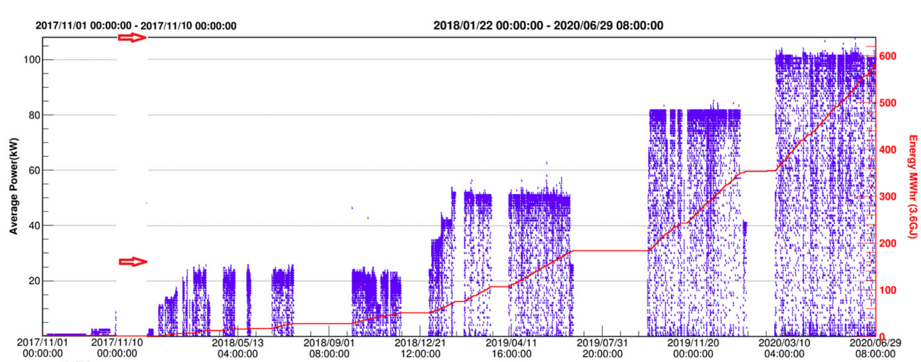

Figure 1: Beam power ramp-up history of CSNS/RCS, where the blue bars correspond to the beam power, while the red line shows the accumulated beam power.

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The Synchronicity Between the Dipole Magnetic Field and the RF Frequency Pattern

The mismatch between the dipole magnet field and the RF frequency can cause large orbit deviation in the arc and dipole oscillation in the longitudinal plane. Two BPMs at dispersion section in every super period were used to perform matching between the RF frequency ramping function and the dipole field pattern. Based on the average COD measured by eight BPMs at dispersion section in the four periods of the RCS, the RF frequency was tuned to match the dipole field pattern. The beam displacement variation at dispersion section during acceleration process was greatly reduced.

COD Correction

After performing the matching between the RF frequency ramping function and the dipole field pattern, the residual COD was corrected by modifying the steering field patterns of 17 horizontal steering magnets and 17 vertical steering magnets. As shown in Fig. 2, the variable COD was finally corrected to within 3 mm in vertical direction, and within 5 mm in horizontal direction except for two BPMs in dispersion section.

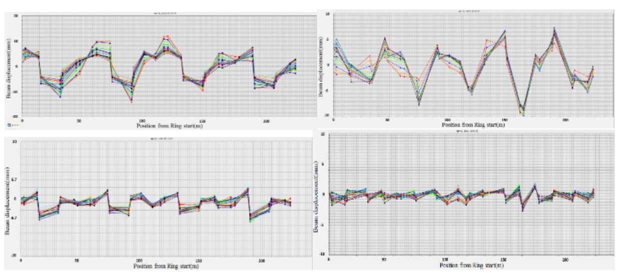

Figure 2: Measured COD on ring BPMs without (upper) and with (lower) the COD correction by the steering magnets, where 20 CODs are plotted for each at 1 ms regular intervals over the acceleration cycle (20 ms).

Lattice Calibration

To suppress the space charge effects, the RCS employs large aperture quadrupoles to provide a large acceptance. The large aperture of quadrupoles causes serious fringe field effects. For some quadrupoles, since the integral between the quadrupole and its neighbour magnet is comparable to the aperture of quadrupole, the effect of field interference is another important issue. The lattice the RCS was rematched and optimized considering the fringe field effects and fringe field interference [8]. Because of the magnetic saturation and the eddy current effects, the magnetic field tracking between different magnets is an important issue in AC mode. In CSNS/RCS, the maximum magnetic field tracking error between different magnets is larger than 2.5% over the acceleration process. To reduce the magnetic field tracking errors between different magnets, waveform compensation on CSNS/RCS magnets was performed. The maximum magnetic field tracking error between different magnets was reduced to less than 0.1% [9].

The Betatron function at every BPM was measured by using the closed orbit distortion formula. After the rematched lattice and the waveform compensation on CSNS/RCS magnets were applied to the beam commissioning of the RCS, the measured Betatron functions are very close to the theoretical values, as shown in Fig. 3.

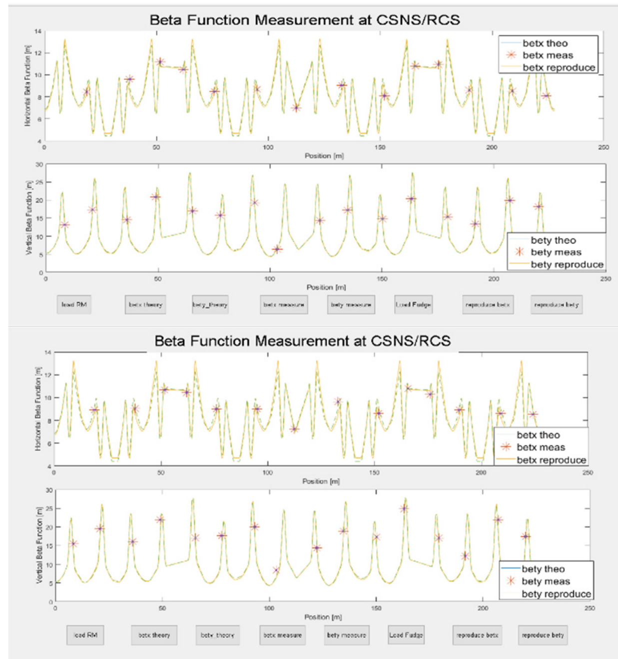

Figure 3: The comparison of the measured beta functions and the theoretical values at 1 ms (upper) and 10 ms (lower).

HIGH-INTENSITY BEAM COMMISSIONING OF THE RCS

The limitation in realizing higher intensity beam operation in the RCS was large beam loss induced by space charge and beam instability.

Bunching Factor Optimization

In high intensity proton synchrotrons, the bunching factor should be increased to suppress the space charge tune shift which can result in the beam losses. Longitudinal injection painting was used to obtain a uniform longitudinal particle distribution. Longitudinal injection painting makes use of a controlled momentum and phase offset to the RF bucket. Figure 4 shows the comparison of measured bunching factor with different injection momentum offset. The simulation results agree with the measurement results. With the increasing of injection momentum offset, the bunching factor increases. The space charge induced tune shift are suppressed by performing the longitudinal injection painting, and the space charge induced beam loss are effectively minimized.

Tune Optimization

The design tunes of the RCS are (4.86, 4.78), which enable incoherent tune shifts to avoid serious systematic resonances. In the high intensity beam commissioning, serious beam instability was observed, as shown in Fig. 5. The tunes during the beam acceleration were optimized

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based on the effects of space charge and collective beam instability. The tunes at injection are set at (4.81, 4.87) to move the beam away from the half integer resonance. The tunes are moved downward to suppress the beam instability, as shown in Fig. 6. The beam coherent oscillation in RCS operation is depressed by using the new tune pattern.

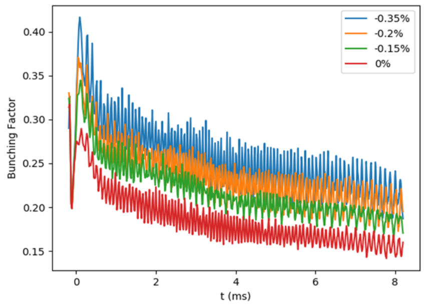

Figure 4: The measured bunching factor with different injection momentum offset.

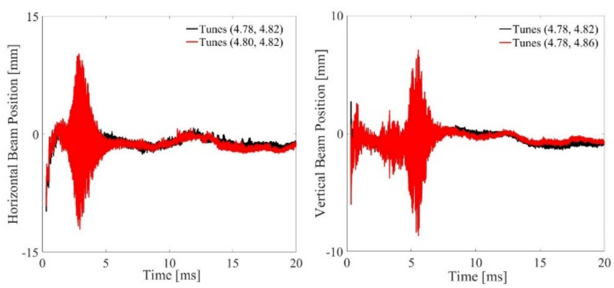

Figure 5: Measured beam positions over the whole time of 20-ms with different tunes.

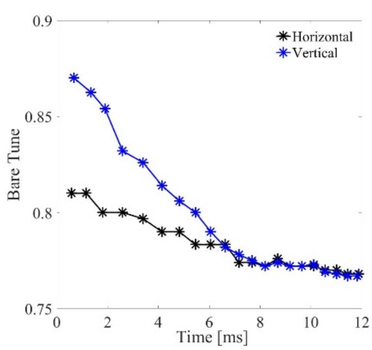

Figure 6: The measured tune variations during acceleration.

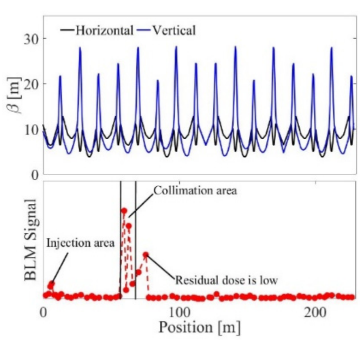

Figure 7: BLM signals along the RCS after the beam loss optimization.

Uncontrolled Beam Loss

After a series of beam loss optimization approaches, to the end of February 2020, CSNS reached the design beam power of 100-kW, with small uncontrolled beam loss. Most of remaining beam loss is well localized at the collimator section, as shown in Fig. 7.

SUMMARY AND OUTLOOK

Now, CSNS operates at 100-kW stably. A number of CSNS upgrade options are under study. We plan to update the dc sextupole to ac sextupole to enhance the Landau damping through momentum spread to suppress the beam instability. We also plan to install pulsed-type quadrupole correctors to compensate the beta function beating induced by edge focusing of injection bump magnets, and manipulate the Betatron tunes during acceleration. We also plan to add the second harmonic RF cavity to increase the bunching factor. CSNS is expected to achieve 200-kW after the upgrading.

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