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BEAM COMMISSIONING EXPERIENCE OF CSNS/RCS*

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Abstract

The China Spallation Neutron Source (CSNS) is an accelerator-based science facility. 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 Beam commissioning of CSNS/RCS has been commissioned recently. Beam had been accelerated to 1.6 GeV at CSNS/RCS on January 18, 2018 with the injection energy of 80 MeV. The machine parameters are measured and optimized. The beam power is increased step by step. The beam power achieved 50kW in January, 2019. In this paper, the commissioning experiences are introduced.

INTRODUCTION

The Chinese Spallation Neutron Source (CSNS) is an accelerator-based science facility. 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 rapid cycling synchrotron (RCS). The function of the RCS accelerator is to accumulate and accelerate protons from the energy of 80 MeV to the design energy of 1.6 GeV at a repetition rate of 25 Hz [1, 2]. The Beam commissioning of CSNS/RCS has been commissioned recently. Beam had been accelerated to 1.6 GeV at CSNS/RCS on July 7, 2017 with the injection energy of 61 MeV, and 1.6 GeV acceleration was successfully accomplished on January 18, 2018 with the injection energy of 80 MeV. The beam power achieved 25 kW in March, 2018, and beam power achieved 50 kW in January, 2019.

BEAM COMMISSIONING AT DC MODE

For a start, the beam commissioning of CSNS/RCS was started at DC mode without acceleration. CSNS/RCS operates as a storage ring at DC mode.

The lattice design of CSNS/RCS is based on hard edge model of quadrupoles. Because of the large aperture of quadrupoles, fringe field effect is an important issue. The effects of fringe field and interference of quadrupoles [3,4] at CSNS/RCS was considered in the calculation of Online-Model. The slicing model was adopted to analyze the fringe field effects of quadrupoles in CSNS/RCS [5].

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After the match of B field, RF frequency of CSNS/RCS and the injection energy was performed, and the optimization of injection painting timing, the beam transmission achieved 100% at DC mode.

The tunes were measured by using Beam Position Monitor (BPM) located in CSNS/RCS. By performing Fast Fourier Transform (FFT) to Turn-By-Turn (TBT) data of BPM, the tunes were obtained. As shown in Fig. 1, the measured tunes were 4.855/4.783 at DC mode, which were very close to the nominal value of 4.860/4.780 based on slicing model.

The fudge factors of the quadrupoles were analysed based on both hard edge model and slicing model. The fudge factors were analysed by using the LOCO (Linear Optics from Closed Orbit). LOCO technique is a powerful tool to tune linear optics in the ring. As shown in Fig. 2, the analysed fudge factors based on slicing model were less than 1%, while the analysed fudge factors based on hard edge model were up to 4%.

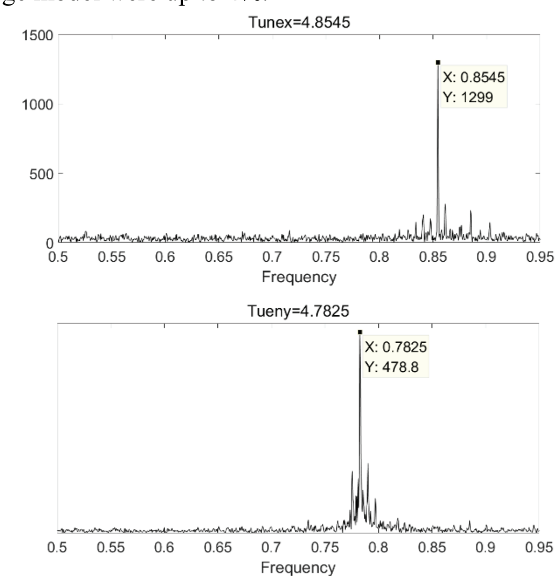

Figure 1: The measured tune of CSNS/RCS at DC mode.

The quadrupole factors were applied to CSNS/RCS, and the closed orbit was corrected and the beta functions were analyzed at DC mode. The comparison of the COD before and after COD correction at DC mode is shown in Fig. 3. The COD at DC mode was minimized form ±10 mm to ±3 mm by COD correction. Betatron functions were measured by using the Closed Orbit Distortion (COD) formula:

$$u(s) = \theta \frac{\sqrt{\beta_0 \beta(s)}}{2 \sin \pi\nu} cos(\pi\nu - |\psi(s) - \psi(s_0)|) \qquad (1)$$

where $u(s)$ is the closed orbit, θ is the closed orbit error which is generated by the corrector, ν is the betatron tune,

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$\psi(s)$, ψ_0 are the betatron phase advance at s, s_0 respectively, and $\beta(s)$, β_0 are the values of the betatron functions at s, s_0 respectively. 30 BPMs are installed inside of the corrector magnets, and the betatron phase advance between the corrector and corresponding BPM can be neglected. The betatron function at each BPM is given as a function of closed orbit response:

$$\beta(s) = \frac{2\Delta u_i(s)}{\theta} tan(\pi v) \qquad (2)$$

where i represents the i-th BPM, θ is the kicker angle of the corrector, $\Delta u_i(s)$ is the difference of the closed orbit between two measured values with and without kicker of the corrector, v is the measured tune, and $\beta(s)$ is the betatron function at each BPM.

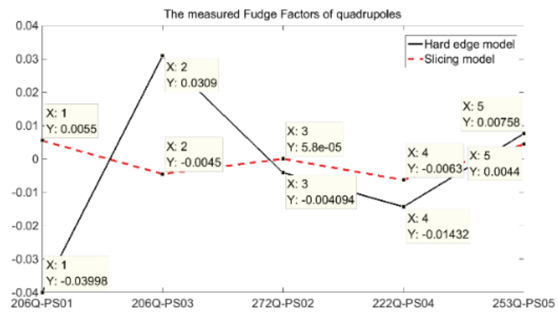

Figure 2: The analyzed fudge factors of quadrupoles based on the hard edge model and slicing model.

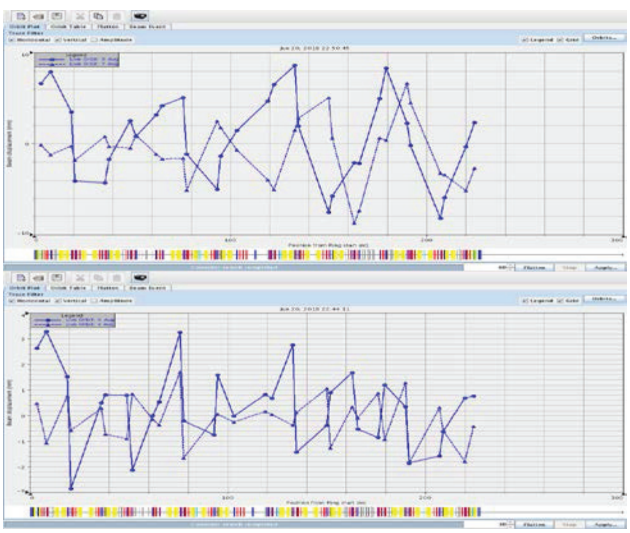

Figure 3: The comparison of the COD before and after COD correction at DC mode. Top: before COD correction; below: after COD correction.

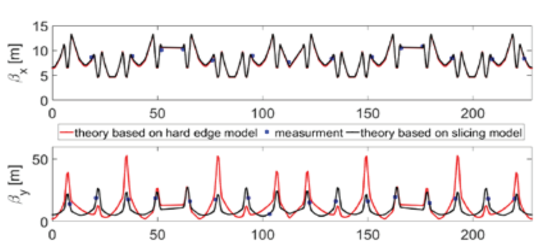

Figure 4: The measured beta functions and the theoretical values based on hard edge model and slicing model.

Figure 4 shows the comparison of beta functions between the measured results and the calculated values based on hard edge model and slicing model. The measured beta functions are very close to the calculated values based on slicing model.

BEAM COMMISSIONING AT AC MODE

The AC mode beam commissioning of CSNS/RCS with the injection energy of 80 MeV was started on January 18, 2018, and 1.6 GeV acceleration was successfully accomplished for the first beam shot. However, there was serious beam loss. The beam displacement at dispersion section was large and changed greatly during the beam acceleration. The timing of magnet power supply at CSNS/RCS was shifted to match the injection beam, and the match of the bottom of dipole magnetic field and injection energy was performed. The timing of RF was shifted to match the magnet timing. The beam transmission rate got 100% with the injection particle number of 0.8×10^{12} on January 18, 2018.

The match between the dipole magnetic field ramping function and the RF frequency pattern was performed by using the BPMs in dispersion area. Eight BPMs are used to perform the B-RF match. The phase advance between the two BPMs in every super period is 0.98π, very close to π. The dispersion at every BPM is 1.7m. After performing the B-RF match, the average beam displacement at eight BPMs is almost zero. The deviation of the RF frequency from the dipole magnetic field ramping function during the beam acceleration process is less than 3×10^{-4}. The COD correction was done after performing the B-RF match. After the COD correction, the COD is less than ±3mm in vertical direction, and less than ±5mm in horizontal direction except for four BPMs in dispersion area.

A new method of wave form compensation for RCS magnets was investigated at CSNS/RCS magnets [6]. By performing wave form compensation, the magnetic field ramping function for RCS magnets can be accurately controlled to the given wave form, which is not limited to sine function. The new method wave form compensation was used at CSNS/RCS to reduce the magnetic tracking errors between different magnets. The tune was measured during acceleration process over one cycling period at the mode with the normal tune (4.85, 4.83). The beam transmission is high with the tune (4.85, 4.83) at DC mode. The measurement results of tunes are shown in Fig. 5. The variation of horizontal tune is less than 0.01, and the variation of vertical tune is about 0.02.

CSNS/RCS employs painting injection to achieve a uniform beam distribution and to suppress the space charge effect. In the painting injection, the mismatch between the injection and the circulating beam orbit can cause non-uniform beam distribution and larger emittance, which may lead to beam loss. To match the injection beam orbit and the circulating beam orbit, it is necessary to identify the injection beam orbit relative to the circulating beam orbit at the injection point. However, the relative injection beam orbit is hard to measure directly. Theoretically, the relative injection beam orbit can be deduced from the turn-by-turn

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beam position of a single-turn injected beam, but in the RCS of CSNS, the intensity of a single-turn injected beam is too low to measure with a sufficient signal-noise ratio using a beam position monitor. An effective method based on multi-turn injection and turn-by-turn beam position data was developed to perform the match between the injection and the circulating beam orbit [7]. Simulation results and practical application during the beam commissioning of the RCS of CSNS show the validity of the methods. The detected betatron oscillation was clearly suppressed after the correction, indicating that the injection and the circulating beam orbit were well matched, as shown in Fig. 6.

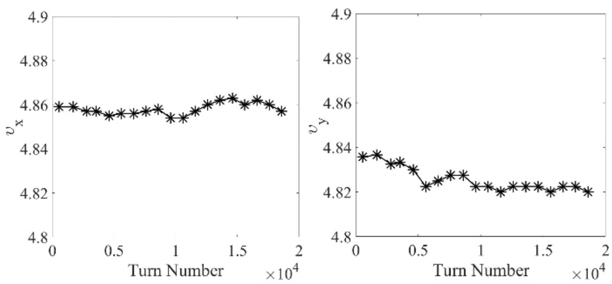

Figure 5: The tune variation during acceleration process over one cycling period at the mode with the normal tune (4.85, 4.83).

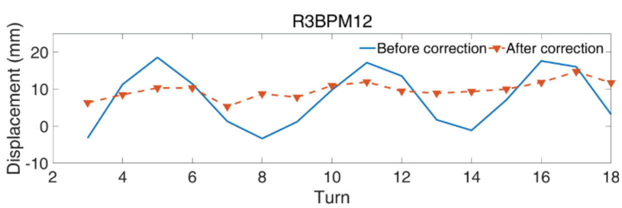

Figure 6: The detected betatron oscillation at R3BPM12 before (blue solid lines) and after (red dashed lines with triangles) the correction for the injection beam.

LEBT CT01	27.47	mA	RTBT CT02	8.02	E12
LEBT CT02	1.42	mA	RTBT CT03	8.12	E12
MEBT CT01	5.51	mA	MEBT Trans	99.8	%
MEBT CT02	5.50	mA	DTL Trans	100.0	%
LRBT CT01	5.50	mA	LRBT Trans	100.0	%
LRBT CT02	5.49	mA	EXT Trans	100.6	%
LRBT CT03	5.50	mA	RCS Trans	99.8	%
DCCT-INJ	7.99	E12	RTBT Trans	101.2	%
DCCT-EXT	7.98	E12	Beam Power	51.44	kW
RTBT CT01	8.03	E12			

Figure 7: The beam transmission of CSNS accelerators with the beam power of 50kW.

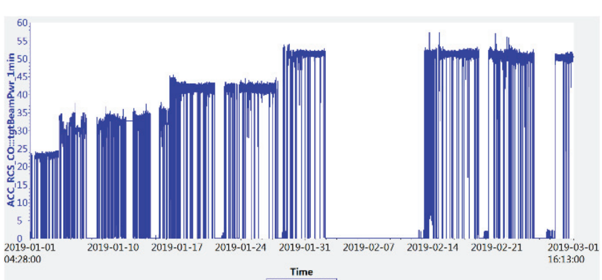

Figure 8: The beam power upgrading process of CSNS/RCS.

With the optimized machine parameters, the equivalent beam power achieved 50kW with the acceptable uncontrolled beam loss on 1st, January 2019. The beam transmission is larger than 99%, as shown in Fig. 7. The beam power on the target was increased step by step. From 29th, January 2019, CSNS operates at the beam power of 50kW, as shown in Fig. 8.

CONCLUSION

Careful preparation work was performed before the beam commissioning of CSNS/RCS. Because of the large aperture of quadrupoles, the effects of fringe field and interference of quadrupoles at CSNS/RCS was considered in the calculation of Online-Model. The measured results of optics agree very well with the calculated values based on slicing model. A new method wave form compensation was applied to CSNS/RCS to reduce the magnetic tracking errors between different magnets. The variation of horizontal tune is less than 0.01, and the variation of vertical tune is less than 0.02. B-RF match, COD correction, injection beam orbit match was performed at CSNS/RCS. With the optimized machine parameters, the equivalent beam power achieved 50kW with the acceptable uncontrolled beam loss on 1st, January 2019.

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