TUNE OPTIMIZATION FOR ALLEVIATING SPACE CHARGE EFFECTS AND SUPPRESSING BEAM INSTABILITY IN THE RCS OF CSNS

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Abstract

The design Betatron tune of the Rapid Cycling Synchrotron (RCS) of China Spallation Neutron Source (CSNS) is (4.86, 4.80), which allows for incoherent tune shifts to avoid serious systematic Betatron resonances. When the operational bare tune was set at the design value, serious beam instability in the horizontal plane and beam loss induced by half-integer resonance in the vertical plane under space charge detuning were observed. The tunes over the whole acceleration process were optimized based on space charge effects and beam instability. The optimized tune pattern was able to well control the beam loss induced by space charge and beam instability. The beam power of CSNS achieved the design value of 100 kW with small uncontrolled beam loss.

INTRODUCTION

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. The 1.6 GeV proton beam is extracted to the target at a repetition rate of 25 Hz. The RCS is designed to extract a beam power of 100 kW, corresponding to 1.56×10^{13} protons per pulse in two bunches. The lattice of the RCS is a four-fold structure based on triplet cells. The entire ring comprises 16 triplet cells, with a circumference of 227.92 m. In each super-period, an 11 m long drift space is available between two triplet cells, providing uninterrupted space for accommodating the injection, extraction, acceleration, and transverse collimation system, as shown in Fig. 1. Table 1 provides the primary parameters of the RCS [1, 2].

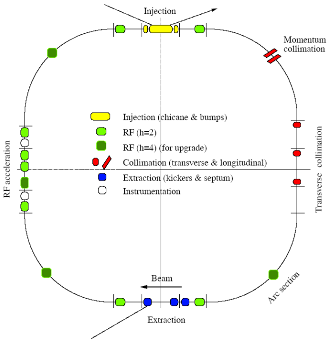

Figure 1: The schematic layout of the RCS of CSNS.

The designed tune of the RCS is (4.86, 4.80), which allows for incoherent tune shifts to avoid serious systematic Betatron resonances. Figure 2 illustrates the resonance map around the design tune, where the red lines signify the structure resonances up to the 4th order. However, serious beam instability in the horizontal plane with the design tune was observed in the beam commissioning.

Table 1: The Primary Parameters of the RCS of CSNS

Parameters	**Value**
Output Beam Power (kW)	100
Injection Energy (MeV)	80
Extraction Energy (GeV)	1.6
Pulse repetition rate (Hz)	25
Ramping Pattern	Sinusoidal
Acceleration Time (ms)	20
Circumference (m)	227.92
Number of Dipoles	24
Number of Quadrupoles	48
Lattice Structure	Triplet
Nominal Betatron Tunes (H/V)	4.86/4.80
Mode of Chromaticity Sextupoles	DC
Natural Chromaticity (H/V)	-4.0/-8.2
Ring Acceptance (πmm-mrad)	540
Number of Bunches	2
Number of Particles per Pulse	1.56×10^{13}
Space-Chare Tune Shift	-0.28

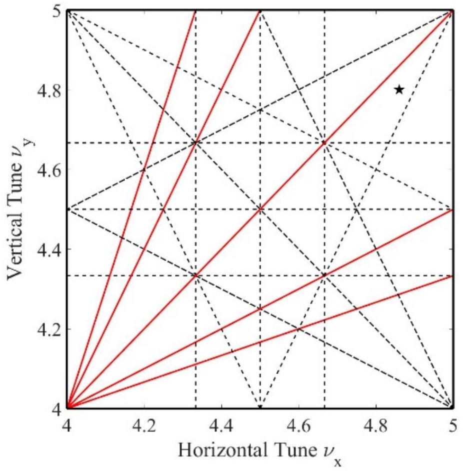

Figure 2: The design tune location in the resonance map, in which the red lines represent the structure resonances up to 4th order.

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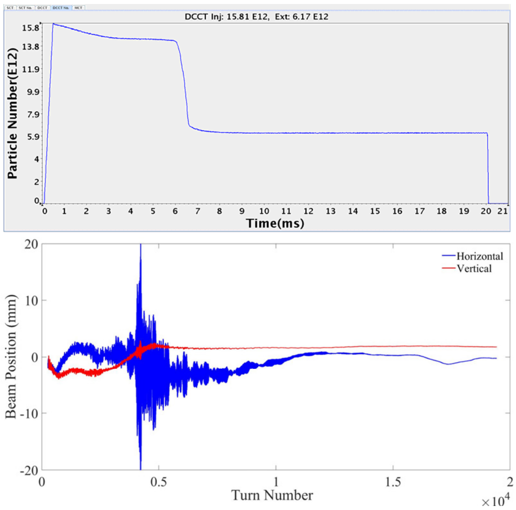

Figure 3: The beam transmission, measured using DCCT, and the measured beam positions over the whole time of 20ms for the beam power of 100 kW, with a total of 1.56×10^{13} particles per pulse.

Figure 3 shows the beam transmission and measured beam positions over the whole 20 ms for a beam power of 100 kW, where the number of particles per pulse totalled 1.56×10^{13}. Serious beam centroid oscillation in the horizontal direction was observed, with the beam transmission lower than 50%. Beam instability occurred after the 3000th turn, which corresponds to 5 ms. During the first 3 ms, the beam loss was mainly induced by space charge effects. To mitigate the space charge effects and suppress beam instability in the RCS of CSNS, the tunes were optimized during the beam acceleration process. This paper introduces the progress of the tune optimization at the RCS of CSNS.

SPACE CHARGE EFFECTS IN THE RCS OF CSNS

As shown in Fig. 3, more than 10% particles are lost at the beginning 3 ms where the space charge effect is large because of low beam energy. Transverse space charge peaks during the trapping process, as the beam bunches at low energy. For a beam intensity of 100 kW in the RCS of CSNS, the peak incoherent RMS tune shift approaches -0.28 in the bunching stage.

Like many lower energy, high intensity proton rings, with a tune below the integer value, the RCS of CSNS may experience significant beam loss due to the action of half integer resonances under space charge. To investigate the dependence of space charge induced beam loss on the tune, different tunes are simulated and compared using the Py-ORBIT code [3]. Figure 4 illustrates the simulated results of beam loss at 100 kW beam power with different tunes. The simulations demonstrate that beam loss decreases as vertical tunes move up and away from half integer resonance line. Due to dispersion effects, the beam size in the horizontal direction is larger than that in the vertical direction, resulting in a smaller space charge tune shift in the horizontal direction, as shown in Fig. 5. Furthermore, the horizontal natural chromaticity of the CSNS RCS is small, leading to a smaller horizontal tune spread induced by space charge and chromaticity than the vertical tune spread. The beam loss is more sensitive to the vertical tune.

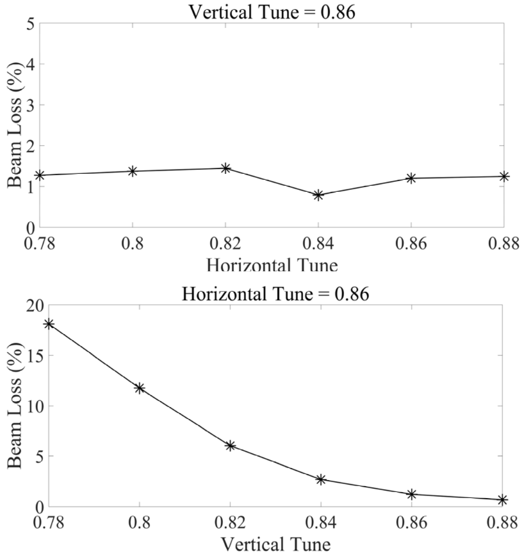

Figure 4: The simulation results for beam loss at 100 kW beam power with different tunes.

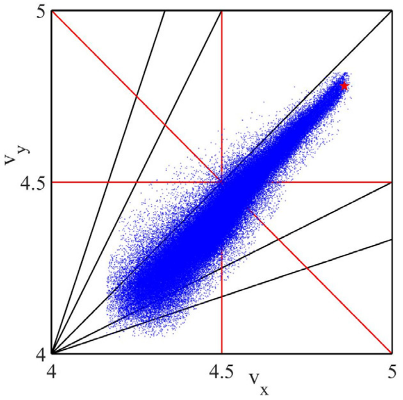

Figure 5: The simulated tune footprints during the trapping process with the tune (4.86, 4.80), where the black lines show systematic resonances up to fourth order.

BEAM INSTABILITY WITH DIFFERENT TUNES

The simulation results and experimental experiences in the RCS of CSNS demonstrate that beam loss decrease as tunes are moved up and away from half-integer resonance lines, as illustrated in Fig. 4. However, instabilities arise when the tune approaches an integer from below. Reproducible collective oscillations and significant beam losses occur when the horizontal tune reaches 4.76 or the vertical tune reaches 4.87 with natural chromaticity.

Experimental observations indicate that the growth rates of instabilities increase rapidly as the tune approaches the integer value of 5. The appearance of these instabilities as the tune approaches an integer from below strongly suggests that the Resistive-Wall impedance, which is higher for slower frequencies, may be the driving force. The resistive wall instability is a common issue in many high intensity accelerators [4, 5].

TUNE PATTERN OPTIMIZATION

As previously discussed, both PyORBIT simulations and experimental observations indicate that emittance growth and beam loss decrease as tunes are moved up and away from half-integer resonance lines. However, instabilities arise as the tune approaches an integer from below. Suppressing beam instability while reducing beam loss caused by space charge effects is an important topic in the RCS of CSNS. The tunes for the entire acceleration process were optimized based on space charge effects and collective beam instability.

During the trapping process, transverse space charge peaks occur as the beam bunches at low energy. Due to a larger space charge tune shift in the vertical direction, the early 2 ms vertical tune should be set away from the half-integer resonance line. As the beam energy increases, the space charge detuning decreases. To suppress instability, the tunes should be moved away from the integer (Qx, y=5) in both horizontal and vertical directions.

The optimized tune pattern during acceleration is depicted in Fig. 6. The injection tunes were set at (4.81, 4.87) to minimize emittance exchange during injection painting and avoid half-integer resonance. As the beam energy increases, the space charge-induced tune shift decreases, and the tunes are ramped down to prevent beam instability. After the tune optimization, the beam transmission rate reaches 99.4% [6].

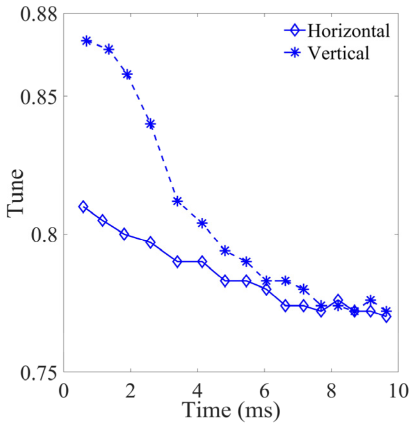

Figure 6: The measured tune variations during acceleration after the tune optimization.

CONCLUSION

Uncontrolled beam loss posed a significant challenge to achieving higher beam intensity and power for the CSNS accelerators, particularly for the RCS. Large beam loss induced by space charge and beam instability was the primary limitation we faced in realizing higher intensity beam operation. To address this, we optimized the tunes during beam acceleration based on the space charge tune shift and beam instability. During injection, the tunes are set at (4.81, 4.87) to avoid half-integer resonances. As the beam energy increases, the space charge-induced tune shift decreases, and the tunes are ramped down to prevent beam instability. After the tune optimization, CSNS achieved its design value of 100 kW beam power with small uncontrolled beam loss.

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