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THE PHASE LOOP STATUS OF THE RF SYSTEM IN CSNS/RCS

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Abstract

The Rapid Cycling Synchrotron (RCS) of the China Spallation Neutron Source (CSNS) is a high intensity proton accelerator. The acceleration system consists of eight ferrite loaded cavities. The RCS is the space charge dominant machine and it is mitigated through the bunch factor optimization in the beam commissioning, so the injected beam will occupy a larger bucket size and unavoidable mismatch with the bucket, thus the dipole oscillation is excited. The phase loop scheme is designed to restrict the oscillation in the RF system, but the transmission efficiency is reduced by the phase loop and the bunch factor also increases, so the phase loop scheme is studied. To keep the phase loop but also maintain the transmission efficiency, we optimized the original phase loop scheme, but the beam loss still increases small when the loop on.

INTRODUCTION

The China Spallation Neutron Source [1, 2] (CSNS) is a high intensity proton accelerator-based facility. The accelerator complex includes a negative hydrogen (H-) linac and a rapid cycling synchrotron (RCS). The H- beam is injected into the RCS through a multi-turn charge-exchange process. The beam is painted in longitudinal plane with the energy deviation between the injected beam energy and the RCS synchronous particle energy. The designed momentum filling is 0.82. The beam is extracted to the target with the beam power of 100 kW. The power will increase to 500 kW by increasing the injection energy to 300 MeV to decrease the space charge effects and increase the beam intensity in the RCS. The CSNS beam commissioning started in 2016 and it was finished in February, 2020, reaching the designed beam power of 100 kW.

Figure 1 shows the accelerator layout of the CSNS. The RCS is the core of the CSNS and the main parameters are listed in Table 1. The RCS accumulates and accelerates proton beam from 80 MeV to 1.6 GeV with the repetition rate of 25 Hz. The RF acceleration system consists of eight ferrite loaded cavities. The maximum cavity voltage is set to be 165 kV with a maximum synchronous phase of 45 degrees. The RF frequency is driven by a bias power supply, allowing it to be synchronous changed with beam energy. The RCS is the space charge dominant machine. The space charge effects for the beam with high intensity are dominant before 5 ms and result in beam loss. Therefore, the space charge mitigation is the key task of the beam commissioning. A good way to mitigate the strong space charge effects is to uniform the longitudinal beam distribution, namely to improve the bunch factor.

The beam phase is the beam core in longitudinal plane and it is given from the fast-current-transformer (FCT) signal after the digital I/Q demodulation [3]. As the bunch factor increases, the injected beam will occupy a larger bucket size and unavoidable mismatch with the bucket, which will lead to the dipole oscillation in the longitudinal plane. The oscillation will exist long time in the proton ring and it reduces the stability region in longitudinal plane and affects the cavity operation. Therefore, the RF system is designed with a phase loop scheme to damp the oscillation. The beam phase with a digital filter and 90 degrees shift is adopted as a feedback in the loop. However, the transmission efficiency is reduced about one percent after introducing the scheme. The phase loop is introduced and optimized in the paper.

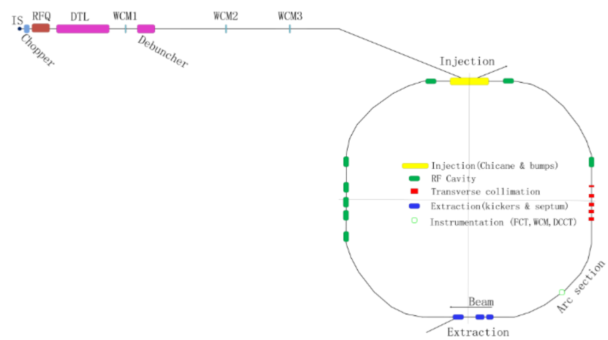

Figure 1: The layout of CSNS accelerator: linac and RCS.

Table 1: The RCS Main Parameters

Parameters	Units	Values
Circumference	m	227.92
Injection energy	MeV	80
Extraction energy	GeV	1.6
Injection energy spread	%	0.05 ~ 0.5
Momentum acceptance	%	1
Momentum filling factor		0.82
Proton per pulse	E13	1.56
Transition γ		4.9
Repetition Rate	Hz	25
Harmonic		2
Bunch number		2
Cavity number		8
Maximum voltage	kV	165
Synchronous phase	degrees	0 ~ 45
Cavity frequency	MHz	1.02 ~ 2.44

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THE DESIGNED PHASE LOOP AND TEST

The phase loop of the RCS is designed to damp the phase oscillation and the phase loop control system is designed based on the FPGA board card. The schematic of the phase loop is shown in Fig. 2. The FCT signal is acquired with the sampling frequency of 60 MHz and the beam phase is obtained from the FCT signal after the digital A/D converting and the digital I/Q demodulating, then the feedback scalar is given by the phase after the digital low-pass filtering with the shift phase of 90 degrees, which means that the first derivative of the beam phase is used as the loop scheme.

The left of Fig. 3 gives the beam phase with and without the designed phase loop. Without the loop, the beam phase oscillation is clear and it can be damped as soon as possible after introducing the loop scheme. However, the transmission efficiency is reduced about one percent and the beam loss in the arc section is bigger than that without any phase loop. Furthermore, the bunch factor is also calculated and compared in the right of Fig. 3. The bunch factor obviously increases when the loop is used and the beam distribution is changed by the loop. The beam dynamic with the loop is simulated based on the longitudinal dynamic code [4] and the simulated bunch factor curve in an acceleration cycle is consistent with the measured result. The maximum feedback scalar is given for the beam without phase deviation and the biggest absolute value of the first derivative of the beam phase, so the beam distribution is changed.

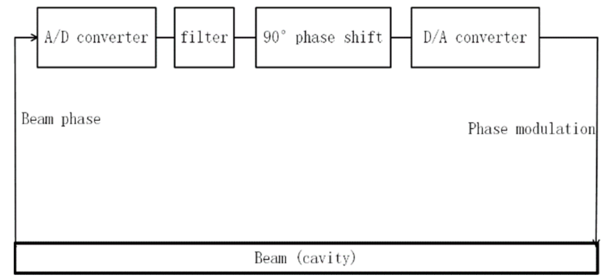

Figure 2: The schematic of the designed phase loop in the RF system of the RCS.

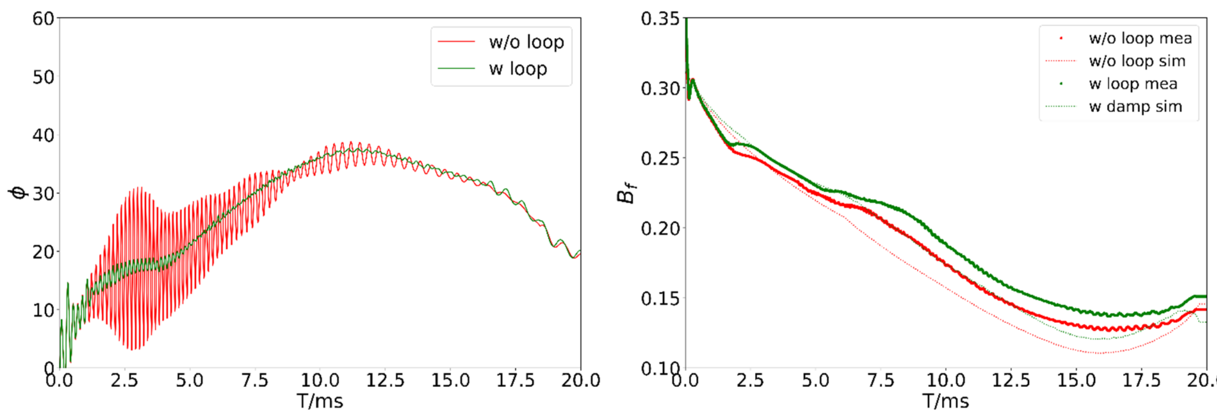

Figure 3: The left shows the measured beam phase with and without the designed phase loop. The right shows the bunch factor with and without the loop: measurement and simulation.

AN OPTIMIZED PHASE LOOP AND TEST

The bunch factor is changed by the original phase loop scheme because of the loop based on the derivative of the bean phase and the nonlinear beam dynamics in longitudinal plane. With big momentum filling factor in the RCS, the beam is easier lose when the loop is adopt. The phase loop is studied and optimized in the beam commissioning. The digital filtering, the phase shift, the beam phase and the second derivative of the phase are tested. The phase without the phase shift of 90 degrees in Fig. 4 is finally used as the optimized scheme, which means in fact that the feedback scalar is proportional to the beam phase deviation.

The left of Fig. 5 gives the beam phase with and without the optimized phase loop. The beam phase oscillation is also damped by the loop scheme. The transmission efficiency is also maintained. The measured bunch factor in the right figure is same with that without the loop and it is proved by the simulation. Compare with the result of Fig. 3, it is clear that the phase shift in the original loop scheme changes the beam distribution. The optimized scheme is tested with the beam power of 100 kW. Actually, the beam loss monitors signal still small increases and a little proton loses in the RCS when the phase damping rate is fast. The momentum filling factor is designed as 0.82 in the RCS, as in fact, it is much bigger than 0.82 in the real machine, so it is challenge to control the beam lose, specially when the loop is used.

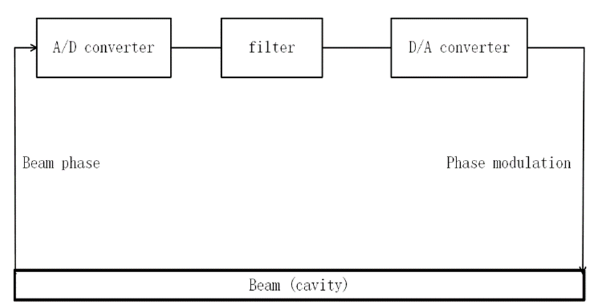

Figure 4: The schematic of the optimized phase loop in the RF system of the RCS.

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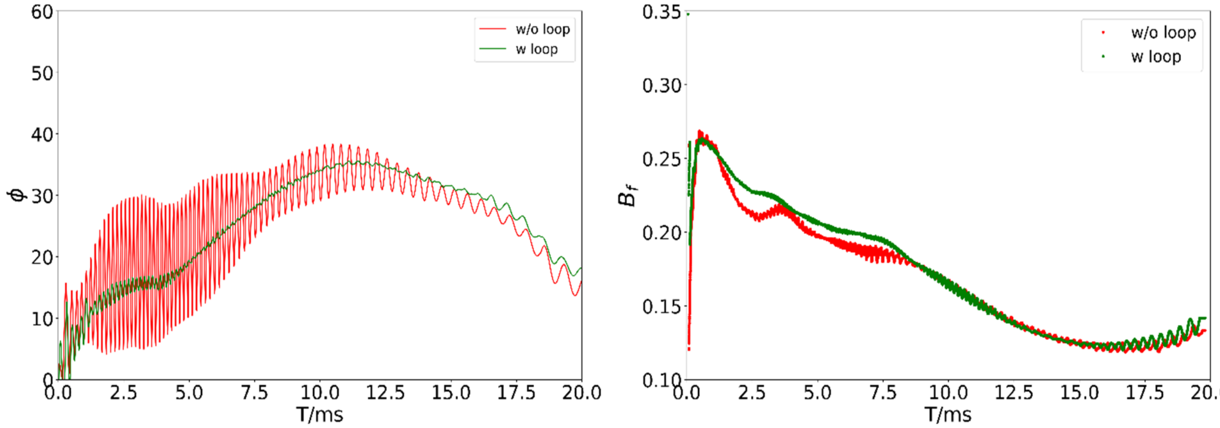

Figure 5: The measured beam phase (left) and the bunch factor (right) with and without the optimized phase loop. The measured signal and data processing give the bunch factor difference before 8 ms in the right.

CONCLUSION

The phase oscillation is similar to the oscillation of the simple pendulum. The best way to damp the phase oscillation is making the first derivative of the phase to zero. The accumulate beam occupies large bucket size in the RCS and the momentum filling is actually bigger than 0.82, which means the spare stable region for the loop is small and the phase loop is a challenge for CSNS/RCS. The first derivative of the phase is adopted by the original phase loop. However, the transmission efficiency decreases and a few protons lose in the arc section. The point is that the beam distribution is changed by the loop. The feedback based on the first derivative means the maximum feedback is received for the beam without phase deviation. The phase oscillation is also damped by the loop with the beam phase scheme, which means that the feedback is proportional to the beam phase deviation and the beam distribution can be maintained. The damping speed is proportional to the feedback scalar. Unfortunately, a little proton loses when the oscillation is damped in a few milliseconds. The author looks forward to the opportunity of further discussion through the introduction of the paper.

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