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DESIGN AND BEAM COMMISSIONING OF DUAL HARMONIC RF SYSTEM IN CSNS RCS

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Abstract

The CSNS accelerator achieved an average beam power on target of 100 kW in February 2020 and subsequently increased it to 125 kW in March 2022. Building upon this success, CSNS plans to further enhance the average beam power to 200 kW by doubling the particle number of the circulating beam in the RCS, while keeping the injection energy same. The space charge effect is a main limit for the beam intensity increase in high-power particle accelerators. By providing a second harmonic RF cavity with a harmonic number of 4, in combination with the ferrite cavity with a harmonic number of 2, the dual harmonic RF system aims to mitigate emittance increase and beam loss caused by space charge effects, thereby optimizing the longitudinal beam distribution. This paper will concentrate on the beam commissioning for the 140 kW operation subsequent to the installation of the magnetic alloy (MA) cavity. The commissioning process includes the optimization of RF parameters, beam studies, and evaluation of the beam quality and instability.

INTRODUCTION

The dual harmonic rf system is a key method to optimize the longitudinal beam distribution and alleviate the space charge effect, and it is also one of the important topics in accelerator physics design research for the CSNS-II RCS beam power upgrade project [1]. The beam intensity of CSNS-II RCS will be five times that of CSNS, and the increase in accumulated current intensity will bring more serious space charge effects and beam collective instability. This will be a huge challenge for beam dynamics design, optimization, and beam loss control. The dual harmonic rf system has been added to the RCS in order to alleviate space charge effect and improve beam quality. The injection energy of RCS will be increased from 80 MeV to 300 MeV. The power upgrade has been implemented in stages, and the RCS transformation plan will be carried out before the energy upgrade of the linear accelerator. Therefore, it is essential to complete the dual harmonic longitudinal dynamic design at an injection energy of 80 MeV. The installation and commissioning of the second harmonic cavity are also carried out in batches. At the beginning, the average beam power of RCS is 125 kW. By installing one magnetic alloy (MA) cavities (as shown in Fig. 1) to provide a maximum of about 72 kV second harmonic cavity voltage [2], the average power of 140 kW has been achieved. With two additional MA cavities and some effort, the plan can be to provide a maximum of about 100 kV second harmonic cavity voltage and increase the average power to 200 kW. Finally, combined with the upgrade of injection energy, the design power index of CSNS-II RCS 500 kW will be achieved [1].

The MA cavity has a higher accelerating voltage gradient compared to the ferrite cavity and also a wider bandwidth. However, the beam loading effect of MA cavities is very serious and should be considered carefully in high-intensity proton synchrotrons. To reduce the beam loading effects, a feedback system is used in the MA cavity for compensating the induced voltage.

In order to improve the longitudinal distribution of the beam, the dual harmonic rf system is often used to flatten the longitudinal potential function of the beam. Combined with momentum offset injection, the beam can obtain a larger bunching factor after injection [3]. However, due to the momentum offset, there will be a decrease in bunching factor during the first 1/4 synchrotron oscillation period, which will lead to an increase in space charge force and cause an increase in longitudinal emittance growth during the painting process and even cause beam loss during the injection stage [4]. To address this problem, a method called “matched phase scan” has been used to optimize the bunching factor both during and after the injection in order to improve this longitudinal transient effect during painting [5].

This paper will mainly introduce some issues encountered during the beam commissioning process of CSNS RCS, including beam loading effects, optimization of double harmonic rf parameters, and some related simulation results and beam experiments. The main parameter of RCS at 140 kW is shown in Table 1.

Table 1: RCS Main Parameters

Circumference	227.92 m
Harmonic number	2 / 4
Accelerating frequency	1.022- 2.444 MHz
Repetition	25 Hz
Maximum rf voltage	180 / 60 kV
Energy	0.08 – 1.6 GeV
Gap number of cavity	3
Particle number per bunch	1.092×10^{13} ppp (140 kW)

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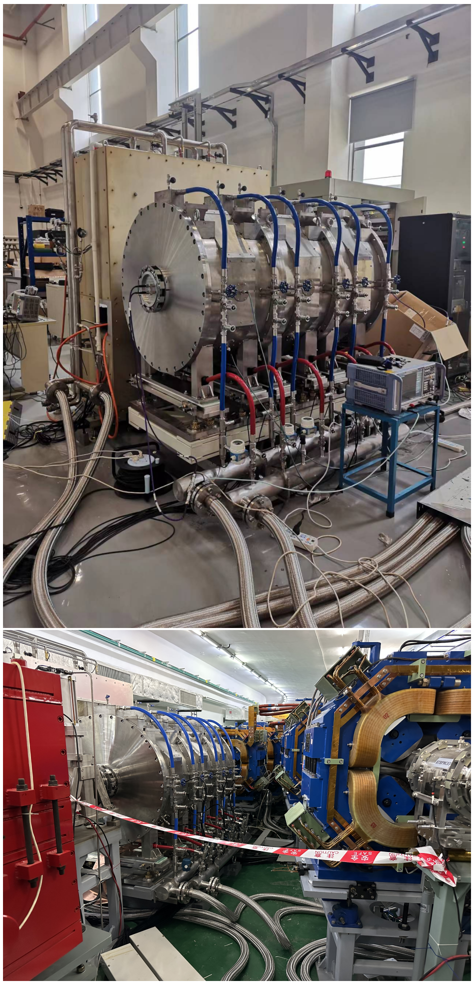

Figure 1: The pictures of magnet alloy cavity.

PREPARATORY WORK

Firstly, we will discuss the beam loading effect of the MA cavity [6]. As shown in the upper figure of Fig. 2, it was observed that with one ma cavity, the induced voltage of h=2 can reach above 10 kV in simulation. Without any compensation, the extracted beam's energy can shift and its bunch length will increase, as shown in the lower one of Fig. 2, which confirms the necessity of beam loading feedback compensation. The induced cavity also has been measured after compensation, as shown in Fig. 3. After using multi-harmonic compensation through the feedback system of LLRF, all the components can be less than 0.8 kV.

Before optimizing the longitudinal profile, it is crucial to examine the phase and voltage of the cavity in storage ring mode. To determine the appropriate phase of the second harmonic in a dual harmonic system, a large second harmonic RF voltage was applied, and the phase was scanned to ensure that both peaks of the beam profile were of equal height in each revolution turn while the energy of the injected beam was the same as the synchrotron energy. Subsequently, the second harmonic rf voltage can be calibrated by calculating the distance between the two peaks [7].

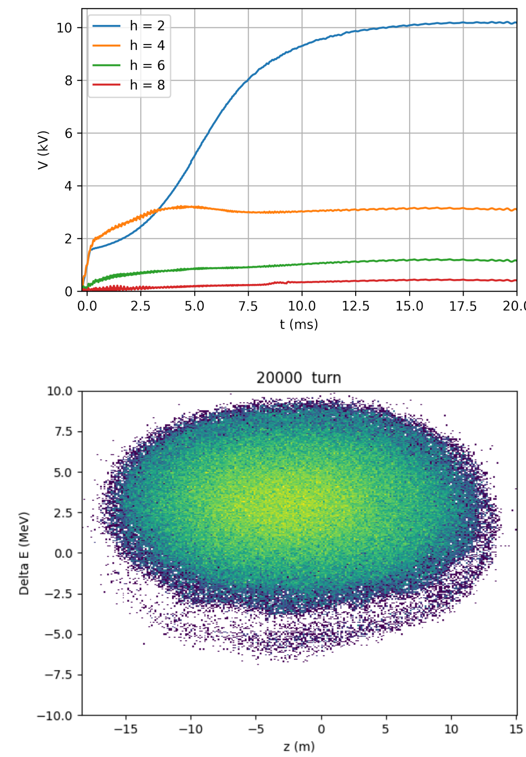

Figure 2: Induced harmonic voltage in 20ms (upper) and the longitudinal phase space of the extracted beam (lower).

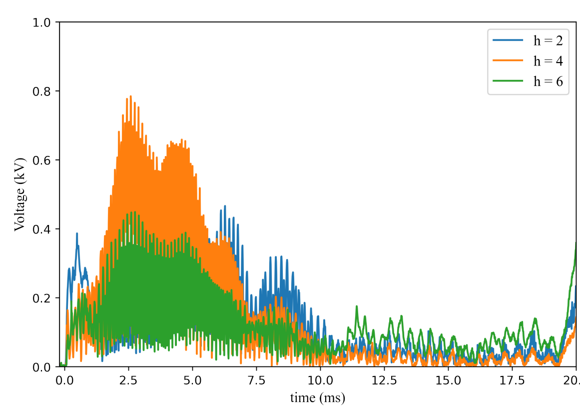

Figure 3: The induced voltage after compensation.

To ensure the timing and frequency consistency between the cavities in the acceleration mode, we also measure the beam orbit in the arc section using BPM, as shown in Fig. 4. We take the turn by turn BPM data with three different conditions: using only the MA cavity, using only the ferrite cavity, and using the dual harmonic system. The orbit in the arc section remains consistent for the first 1 ms. After that, as the single MA cavity cannot provide the same voltage as the total eight ferrite cavities, the orbit decreases. However, the results obtained so far have demonstrated accurate timing frequency.

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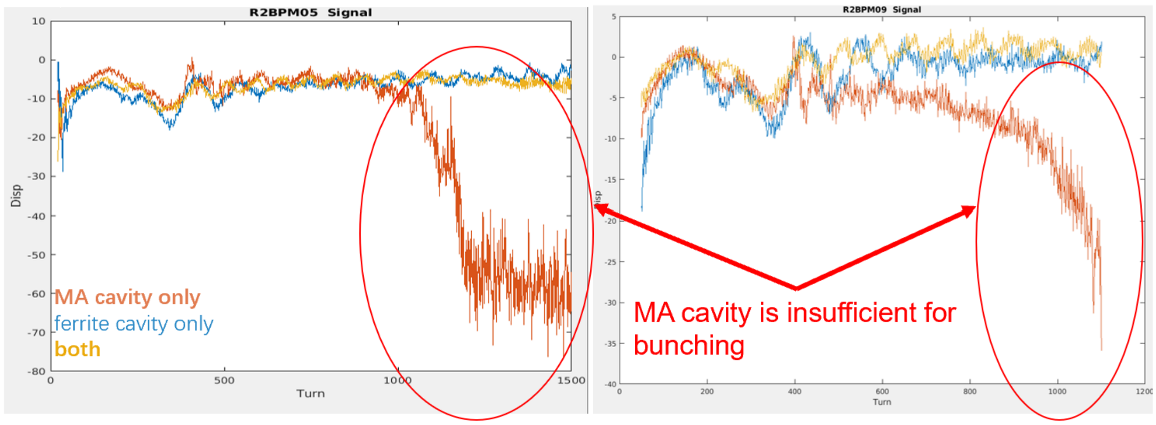

Figure 4: Comparision of the beam orbit at the arc section under different conditions. The orange line represents the beam orbit when only the MA cavity is used, the blue line represents the beam orbit when only the ferrite cavity is used, and the yellow line represents the beam orbit within the dual harmonic RF system.

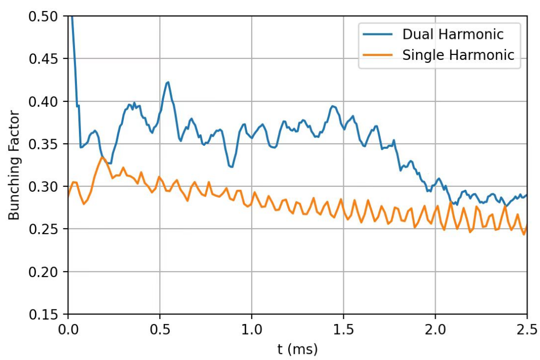

Figure 5: Comparison of the measured bunching factor with and without MA cavity.

After some preliminary experiments, the voltage, phase, and frequency of the second harmonic has been corrected. The bunching factor is then measured with and without the MA cavity,as shown in Fig. 5. The results demonstrate a significant increase in the bunching factor within the dual harmonic RF system. This indicates a more uniform longitudinal distribution, reduced peak current, and alleviation of the space charge effect.

OPTIMIZATION OF RF PARAMETERS

The longitudinal phase space optimization can be achieved by combining the momentum offset and the large second harmonic cavity voltage to increase the bunching factor at the lower energy stage of acceleration. The momentum offset is defined as the difference between the momentum of injected beam and the lowest energy in the RCS acceleration period. In the beam commissioning process, we have conducted experiments at various rf voltages to measure the bunching factor. Additionally, we have investigated the effect of combining the injection momentum offset with a large second harmonic RF voltage under two different fundamental harmonic RF voltages, as shown in Fig. 6. The results indicate that this combination leads to a more significant increase in the bunching factor.

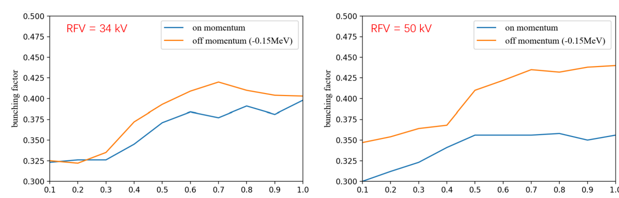

Figure 6: The measured bunching factor under different condition.

With a nonzero momentum offset of the injected beams, a large bunching factor can be achieved at the end of the multi-turn painting injection process. However, the nonzero momentum offset can increase the instantaneous beam peak current during the first 1/4 synchrotron period, causing a reduced bunching factor during the beam injection process. To address this issue, a matched phase sweep method is developed [5]. By matching the synchrotron oscillation frequency and beam injection period, an optimal phase setting can be directly obtained. Fig. 7 shows the longitudinal phase space distribution of the beam with and without the second harmonic phase sweep based on the simulation of CSNS RCS. The term “without the second harmonic phase sweep refers to setting the second harmonic phase to zero throughout the injection phase, with the same high-frequency cavity voltage in both cases. It can be seen that the application of the second harmonic phase sweep method significantly improves the longitudinal distribution of the beam during the injection phase. By using this method, the longitudinal distribution of the beam in the first few milliseconds is better optimized, and the beam loss is further reduced.

During the beam commissioning, several main changes were made to the fundamental harmonic rf voltage, as shown in Fig.8. First, the voltage was reduced in the low energy

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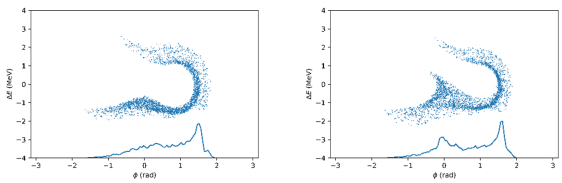

Figure 7: Comparison of the longitudinal phase space without(left) and with(right) phase sweep.

stage to increase the ratio between the second harmonic and fundamental harmonic voltage equivalently. Then, the synchronous oscillation period was matched with the injection turns. The maximum voltage of the fundamental harmonic was then increased to ensure sufficient bucket area and reduce the beam loss on the arc section. At the same time, due to the increase of bunch length, the cavity voltage was also increased in the extraction stage .

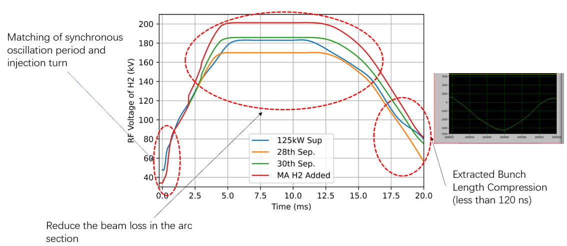

Figure 8: Iteration of the fundamental harmonic rf voltage curve in beam commissioning.

BEAM STATUS AND CHALLENGES

After a series of optimizations, the transmission rate of the beam in the RCS can reach more than 98% at 150 kW. However, the beam loss is concentrated in the arc section, which makes it difficult to control the beam loss position by optimizing the collimator settings. To this end, we have designed a momentum collimator to better control the beam loss position. So the CSNS operates at 140 kW beam power now.

Beside the space charge effect, another important factor limiting the increase of beam power is the transverse instability. It appears as a coherent oscillation as show in Fig. 9. Also, it has been found that there is a correlation between the transverse instability and the longitudinal bunching factor. Octupoles have been designed to increase Landau damping for alleviating the instability. And we will continue to look for the sources of instability and possible method to depress the instability. In addition, we found a parasitic impedance of the MA cavity at 21.6 MHz, as shown in Fig. 10. Although the simulation results show that the current phase has barely no influence on the beam current. The effects at higher beam power are continuing to be studied.

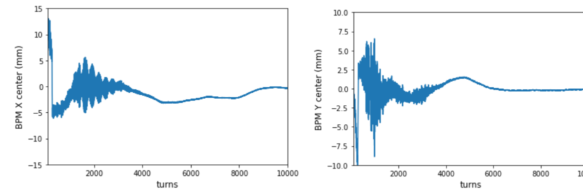

Figure 9: The measured beam center position from turn by turn BPM.

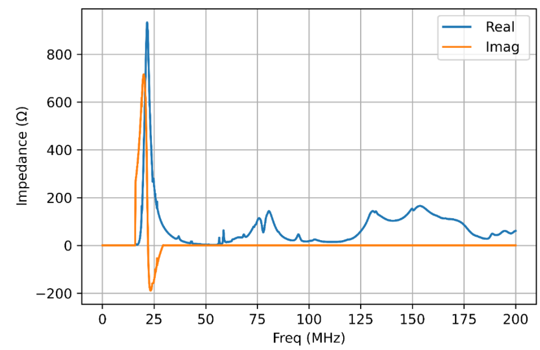

Figure 10: Parasitic impedance at 21.6 MHz.

SUMMARY

The commissioning process with the first MA cavity has been successfully completed, resulting in a beam power of 140 kW, which exceeds the design target by 40%. Subsequently, an additional MA cavity was installed during the summer of 2023. To achieve this goal, we have made a series of efforts, including the correction of rf cavity voltage and phase, the optimization of bunching factor, and the compensation of beam loading effects. At the same time, we also confirmed the problems that will be faced with further increase in beam power, which are the beam loss on the arc section and the beam instability. To solve these problems, a momentum collimator has been designed and octupoles have been installed to enhance Landau damping. The future goal is to further increase the beam power to 200 kW with a linac energy of 80 MeV.

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