THE DESIGN STUDY ON THE LONGITUDINAL BEAM DYNAMICS FOR CSNS/RCS*

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Abstract

Rapid Cycling Synchrotron (RCS) is the key part of China Spallation Neutron Source (CSNS) accelerators. The RCS accumulates and accelerates 80 MeV beam from linac to 1.6 GeV. The particle number is 1.56e13 for each pulse, with repetition rate of 25 Hz. In the RCS, longitudinal beam dynamics plays a crucial role in achieving high intensity beam with low beam loss. Longitudinal parameters are studied and optimized for efficient RF trapping of the beam in the longitudinal phase space. Beam performance is investigated by particle tracking simulations. Beam dynamic issues related to the high order mode induced by the RF generator are studied with a new developed code. Primary study on the adoption of dual harmonic cavity for higher beam power is also addressed.

INTRODUCTION

The accelerator complex of the CSNS consists of an 80 MeV Linac and 1.6 GeV RCS [1]. The RCS lattice has a four fold structure with four straight sections dedicated to beam injection, transverse beam collimation, extraction, and RF systems [2]. Eight RF cavities with harmonic number of 2 will be adopted in the RCS. Seven RF cavities provide total RF voltage of 165 kV, with one additional cavity for redundancy. Dual harmonic cavities will be added in the future upgrade for higher beam power. The layout of the RF cavities around the ring is shown in Fig.1. The physical aperture of the RCS is designed with momentum acceptance of 1%.

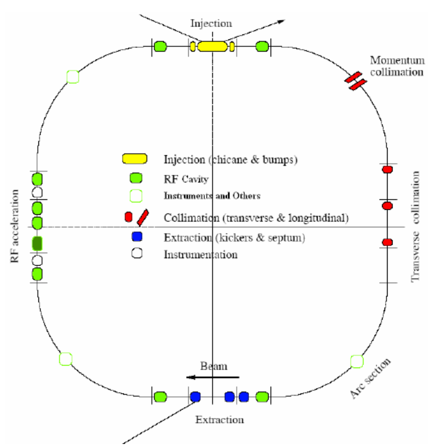

Figure 1: Schematic view of the layout of the RF cavities in the RCS.

In the physical design of the RCS, the longitudinal beam dynamics design and study are crucial for achieving high beam power. Many woks have been done to optimize the RF voltage and phase curves [3]. The related parameters are carefully studied to obtain high transmission efficiency and to decrease the beam loss due to space charge effect [3-5].

In this paper, the design of the longitudinal beam dynamics is first described, and the simulation results of multi-particle tracking are also presented. Then, beam dynamics under the influence of the high order mode induced by the RF generator are investigated. Finally, the design of dual harmonic RF for higher beam power is studied with a new developed code. The main parameters used in the studies are listed in Table 1.

Table 1: The Main Parameters of CSNS RCS

Parameters	Symbol, unit	Value
Injection energy	E_{inj}, GeV	0.08
Extraction energy	E_{ext}, GeV	1.6
Circumference	C, m	228
Beam population	N_p, $\times10^{13}$	1.56
Harmonic number	h	2
Repetition frequency	f_0, Hz	25
RF frequency range	f_{rf}, MHz	1.022 ~ 2.444

LONGITUDINAL BEAM DYNAMICS DESIGN

The main function of the RF system in the RCS is to provide acceleration voltage for the circulating beam. The key issues of longitudinal beam dynamics design are keep efficient longitudinal RF trapping during injection and to provide enough RF bucket to keep low loss during the acceleration. As space charge is the dominant origin of beam loss and emittance growth in low energy rings, large bunching factor is preferred to alleviate the space charge effect. Meanwhile, the variation of the RF voltage or phase should not be too steep considering the provision of the RF cavities.

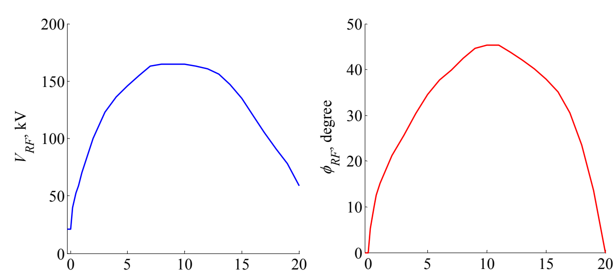

Figure 2: The RF voltage and phase pattern in one RF cycle.

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The RF voltage and phase pattern are primarily calculated by using the code RAMA [6]. Further optimizations considering the coupling between the longitudinal and transverse phase space are done with the code ORBIT [7]. The RF voltage and phase as function of time in one RF cycle are shown in Fig. 2.

In order to control the beam loss in the longitudinal phase space, enough margins between the bucket and the beam are needed. Figure 3 shows the compare of the bucket area and bunch area during the acceleration.

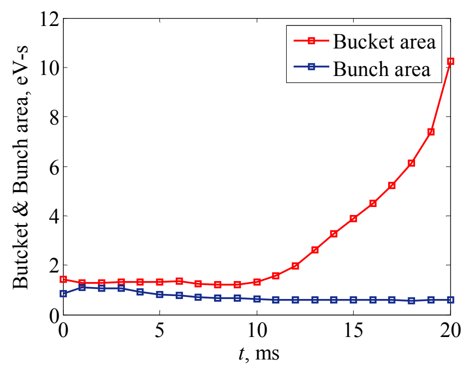

Figure 3: The bucket area and bunch area during the acceleration.

Using the RF voltage pattern above, the tracking simulations are performed with the code ORBIT. Multi-turn painting injection with chopped linac beam is used in CSNS RCS. The injection continues about 200 turns, and then the beam is accelerated to 1.6 GeV before extracted to the target. A chopping factor of 50% has been used in the calculations. Momentum offset of the injection beam with respect to the synchronous particle is chosen for achieving high bunching factor.

The simulation results show that the beam loss is less than 1% during the whole cycle. Most of the beam loss happened during the first three millisecond with an average energy of 100 MeV. The longitudinal phase space distribution at the beginning of acceleration and end of acceleration are presented in Fig. 4.

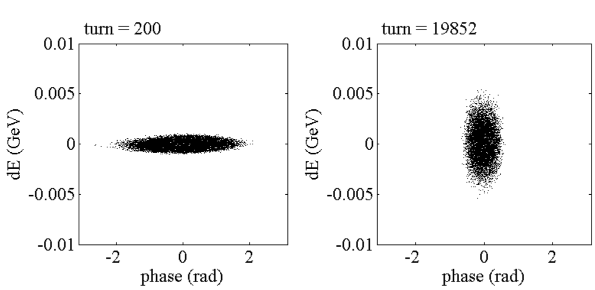

Figure 4: The longitudinal profile of the circulating beam at the beginning of acceleration (left) and at the end of acceleration (right).

The influence of the injection beam on the longitudinal beam dynamics in the RCS is also estimated. Figure 3 shows the loss rate of the beam versus different energy spread of the injection beam. The beam shows best performance at moderate injection energy spread around 0.08%. The beam loss increase dramatically when the energy spread becomes larger than 0.1%. That's because, with larger energy spread, more particles with large momentum deviations can easily escape from the rf bucket. On the other hand, when the energy spread decreases, the particles are over-condensed in the longitudinal phase space. This will enhance the space charge effect in the transverse plane, and result in extra losses.

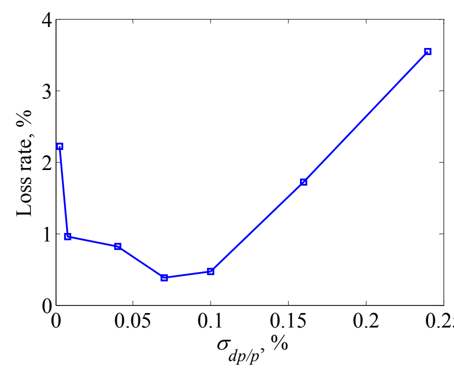

Figure 5: Loss rate of the beam with different energy spread of the injection beam.

ANALYSIS OF HIGH ORDER MODES INDUCED BY THE RF GENERATOR

During the test of the prototype of the RF cavity, higher order mode of the RF cavity has been found [8]. The mode is induced by the coaxial links on the RF cavity, and will distort the fundamental RF field. Therefore, it is often called the stray field. The resonant frequency of the stray field is around 7 MHz. The amplitude ratio between the stray field and the fundamental RF is about 18%, and the phase of the stray field shifts from 90° to −90°. By increasing the inner bar diameter of the coaxial links, the resonance frequency can be shifted to 7.75MHz, and the amplitude reduced to 8% of the fundamental RF. The stray field might affect the beam dynamics and induce extra beam loss.

The influence of the stray field on the beam is studied by a new developed code [9]. In the code, the energy gain of a particle contributed by the stray field is described by

$$\Delta E = \sum_m V_m \sin(m\varphi - \varphi_m)\,, \tag{1}$$

where ΔE is the energy gain of a particle during one turn, m is the order of the stray fields, V_m is the amplitude of the stay field, and φ_m is the phase advance of the stray field compare to the fundamental RF.

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The simulation result is shown in Fig. 6. We can see from the plots that before optimization, the beam is seriously distorted by the stray field, and particles spill out of the RF bucket. After optimization, the bunch shape becomes much more stable. But still a small part of particle will leak out from the bucket. As a result, further optimization is needed to shift the resonant frequency further away from the fundamental frequency with lower amplitude.

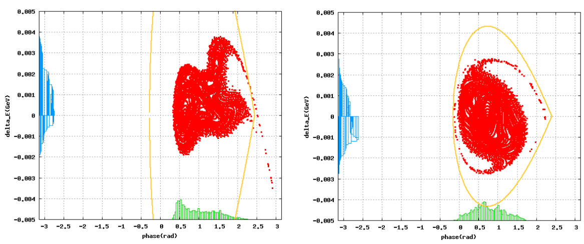

Figure 6: Comparison of beam distribution with the influence of different stray field (Left: f = 7 MHz, V_m/V_1 = 0.18; Right: f = 7.75 MHz, V_m/V_1 = 0.08).

DUAL HARMONIC RF ACCELERATION FOR HIGHER BEAM POWER

The upgrade of CSNS is going to increase the beam power from 100 kW to 500 kW. The injection energy of the RCS is upgraded to 250 MeV to reduce the space charge effect. The space charge effect at low energy is still one of the major reasons of beam loss in the upgrade RCS. In order to reduce the space-charge effects at high intensity, dual harmonic RF system will be used to enlarge the bunching factor.

The longitudinal beam dynamics design was done and optimized by using the new developed code [9]. The voltage ratio between dual harmonic and fundamental rf is about 50%. This continues about 3 ms until the second harmonic RF gradually reduced to zero in the following 4 ms. The phase of the dual harmonic RF is shifted from 0° to 108° during the process. The corresponding patterns of the RF voltage of the fundamental and dual harmonic RF are shown in Fig. 7.

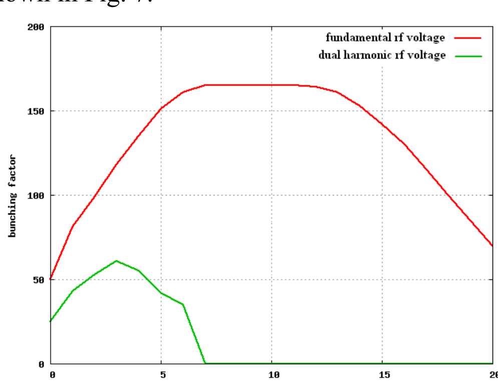

Figure 7: The fundamental and dual harmonic RF voltage.

The comparison of beam distribution after painting injection with single and dual harmonic RF is shown in Fig. 8. The plots illustrate that the bucket has been enlarged by introducing the dual harmonic cavity, the increased margin between the rf bucket and the beam reduced the beam loss. Figure 9 shows the comparison of the bunching factor for the upgrade CSNS/RCS with fundamental and dual harmonic RF systems.

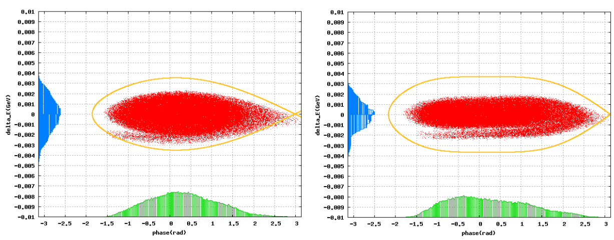

Figure 8: Longitudinal phase space distribution after injection with single RF (left) and with dual harmonic RF (right).

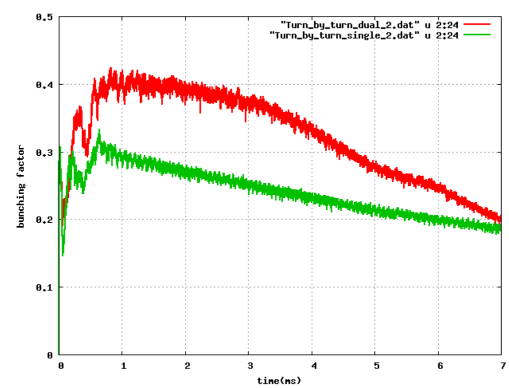

Figure 9: The bunching factor as function of time for the upgrade CSNS/RCS.

CONCLUSIONS

The longitudinal beam dynamics in CSNS RCS is studied. The RF voltage and phase pattern are presented for low loss design. The influence of the RF stray fields to the beam behaviour is studied. The stray fields can affect the beam dramatically when the characteristic frequency of the stray fields resonates with the fundamental frequency. Dual harmonic RF acceleration for higher beam power is studied. The bunching factor is enlarged to about 0.4 at low energy and the beam loss is reduced.

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