RF trapping and acceleration in CSNS/RCS

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Abstract In this paper, two injection scenarios with different chopping rate are discussed. The waveforms of the RF voltage are studied and optimized, respectively. Some suggestions are made, concerning chopping and momentum painting of the injected beam. Furthermore, the momentum spread and transverse tune shift are calculated so that the beam aperture and the beam loss can be estimated. Finally, the beam loss with magnet field error is analyzed.

Key words chopping, beam loss, bunching factor

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1 Introduction

The Rapid Cycling Synchrotron (RCS) of the China Spallation Neutron Source (CSNS)[1] is a space-charge limited ring with a cycling frequency of 25 Hz, which is too high for the RF trapping to be fully adiabatic. In order to calculate the trapping efficiency and the acceleration parameters in the RCS, it is necessary to use a tracking program, in which the space-charge effects are considered. Here we use the simulation code ORBIT[2] and the aim is to reduce the beam loss to the least. The ability to control beam loss is a major factor determining the highest achievable intensity of CSNS. The two main factors which lead to beam loss are the transverse beam halo and the longitudinal RF trapping, respectively.

The space-charge effect is the main reason which drives the emittance growth in high intensity proton synchrotron. The space-charge force can be described in terms of the incoherent tune shift, and the machine resonances play a major role in the emittance growth. As far as CSNS is concerned, to avoid crossing half-integer resonance is very important. That is to say, the incoherent tune shift should be less than 0.3.

In this article, we only consider the beam loss when particles are outside the RF bucket or reach a momentum deviation larger than the momentum acceptance of the machine. And we don't consider the beam loss due to transverse halo. We just calculate the transverse tune shift and estimate the possibility of beam halo.

The chopper is placed in the medium-energy beam transport (MEBT) of the injector linac. It can chop beam pulse in the phase of which the ring RF separatrix cannot accept so as to decrease the beam loss in the ring. The chopping field pulse rises and falls quickly in a pulse, and only the particles within the platform can pass through. The chopping rate is the ratio of the platform time to the pulse period. For example, chopping rate 60% means 40% of the beam is chopped and the left 60% survives.

The beam loss can be minimized by optimizing the waveform of the ring RF program and the injection parameters. The overall beam loss can be quite influenced by chopping and momentum painting the beam. In the following, we will compare the two cases with different chopping rate, and each one has the relatively most suitable injection parameters and RF program.

2 RF cycle

The RF cycle can be conveniently divided into four parts, see Fig. 1.

(1) RF trapping

RF trapping includes a multi-turn, charge-exchange injection followed by a drift. The period of injection is typically of the order of 100—200 turns and fills the transverse phase space to its nominal space-charge limit. The period of drift follows the injection and the waveforms of RF voltage and phase are important. During the injection and the drift,

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the RF bucket is stationary and its equilibrium orbit drifts toward the central orbit. This is an important period in the painting of both transverse and longitudinal phase spaces.

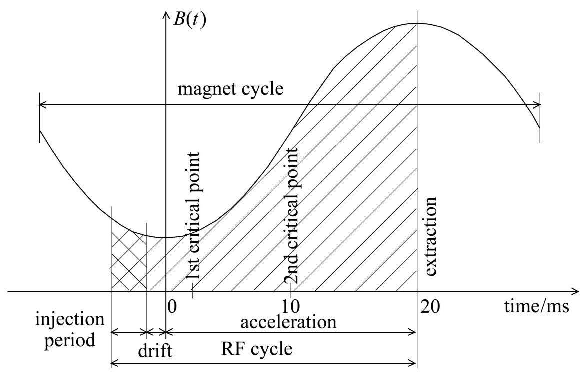

Fig. 1. Magnetic field with time and the stages of an RF cycle.

(2) Acceleration to the first critical point

From the end of trapping, the RF bucket starts to form, keeping the beam centered in the vacuum chamber. The profile of the rise of the RF voltage is an important factor in maintaining the bucket area during this period. Shortly after the minimum field, about 1 ms in the beginning of the cycling, the first critical point comes. At this point, the momentum spread reaches its maximum and an aperture limitation occurs.

(3) Acceleration to the second critical point

After the first critical point the magnetic field rises more rapidly and the RF system is exigent in such a 25 Hz synchrotron. Since the RF voltage is limited in the CSNS/RCS, it is necessary to allow the synchronous phase to increase considerably. Even with full RF voltage applied this has the immediate effect of reducing the bucket size and considerable losses can occur up to about the middle of the cycle when the rate of field change and the synchronous phase are the maximum. This is the second critical point when the synchronous phase becomes biggest and the bunch width is therefore a minimum.

(4) Acceleration to the final energy where the beam is extracted

Once the rate of field change decreases in the second half of the cycle, the synchronous phase reduces and the beam becomes small with respect to the bucket.

3 Parameters of CSNS

The main parameters of the machine are shown in Table 1.

The injection beam parameters are shown in Table 2.

Table 1. Mail parameters of the CSNS/RCS.

injection energy	$E_{\rm inj}$=80 MeV
extraction energy	$E_{\rm ext}$=1.6 GeV
circumference	C=230.8 m
bending radius	ρ=8.0214 m
cycling rate	f=25 Hz
transition energy	$\gamma_{\rm t}$=4.975
harmonic number	h=2
magnet field	$B(t)=B_0-B_1\cos(2\pi {\rm ft})$
	B_0=0.5727 T and B_1=0.4081 T
betatron tunes	Q_x=5.86, Q_y=5.78

Table 2. Beam parameters of the injection.

	scenario A	scenario B
chopping rate	100%	50%
phase advance	from $-\pi$ to π	from $-\pi/2$ to $\pi/2$
injection turn	100	200
momentum distribution	truncated Gaussian distribution	
RMS momentum spread	1‰	
number of protons in ring	1.88×10^{13}	

4 The trapping and acceleration cycle of scenario A

Figure 2 shows an optimized RF program for scenario A. The initial voltage is 5 kV during injection and increases quickly in the following 1 ms. The peak voltage is 165 kV and the maximum synchronous phase is 46°.

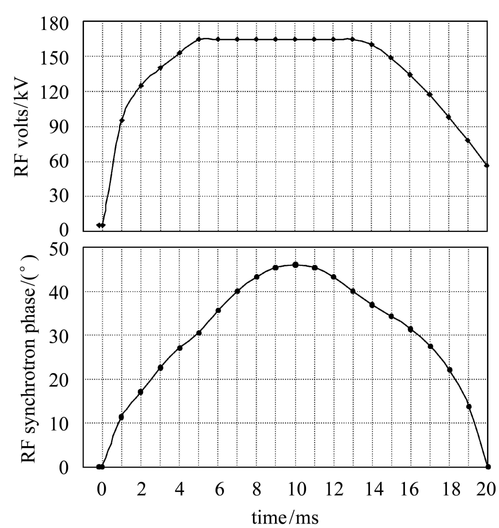

Fig. 2. The RF program for scenario A. The upper is the RF voltage variation, and the lower is the synchronous phase variation.

For scenario A, the optimization has been made so that the beam at the end of injection is nearly an unbunched beam, and the first injected beam rotates very little in the longitudinal phase space. The waveform of RF voltage is also optimized to achieve the lowest beam loss. In the drift period, there is a subtle balance between the beam loss and the maximum momentum spread. Too high voltage will give a large momentum spread and a lower voltage can't provide enough beam rotation. After the first critical point the voltage keeps increasing, and it is necessary to keep the change of the synchronous phase as smooth as possible. Otherwise there are rapid changes in the positions of the separatrices and particles can 'jump' out of the bucket.

To avoid the beam loss during the trapping and acceleration processes, large dynamic apertures are necessary for both the transverse and longitudinal planes. And to reduce the space charge effects with the limited transverse emittance, a large longitudinal emittance is requested for improving the bunching factor because the charge density of the bunch should be diluted. However, there is a limitation in which the momentum deviation should not be over 1% because of the dynamic aperture for the transverse motion.

In the 1-D longitudinal simulation, we cut off those particles whose momentum spread are more than 1%. The total loss is 1.7%, among which 99% are the loss of trapping and the rest is the loss in acceleration. For the case without chopping, the beam loss is mainly the loss of trapping.

5 The trapping and acceleration cycle of the scenario B

With the same injection turns, the chopping will increase the requirements on the current source. So we choose the injection turns to be twice that of scenario A. If we take the same RF curve as that of scenaio A, chopping will increase the betatron tune shift and increase the beam loss on nonlinear resonances.

In the scenario B, we choose 23 kV as the injection RF voltage, which is higher than that of the scenario A. The injected beam rotates quickly and paints in the longitudinal phase space. Momentum painting provides a way of influencing the uniformity of the filling of the RF bucket. Fig. 3 is the evolution of longitudinal phase space in the process of injection.

Figure 4 shows an optimized RF program for the scenario B.

Since the beam has been efficiently bunched during injection, we can increase the synchronous phase more quickly. The lower RF voltage at the first several seconds can not only decrease the momentum spread, but also accelerate the beam more efficiently. What's more, the lower RF voltage increasing rate decreases the designing difficulties of RF cavities. After one millisecond, we keep the change of the synchronous phase slow and smooth, which is suitable for acceleration.

For the scenario B, the maximum RF voltage is 165 kV and the maximum synchronous phase is 46°, which is the same as that of the scenario A.

We can control the particles' momentum deviation no more than 1% during injection and acceleration. That is to say, the beam loss may not occur as far as the longitudinal process is concerned. But it will influence the uniformity of bucket and increase the beam loss on nonlinear resonances. Here, we adopt the off-momentum injection (see later) to increase the bunching factor.

The total beam loss of scenario B is only 1.53‰, which is much less than scenario A. From the above analysis, we can see that chopping and suitable momentum painting can decrease the beam loss greatly.

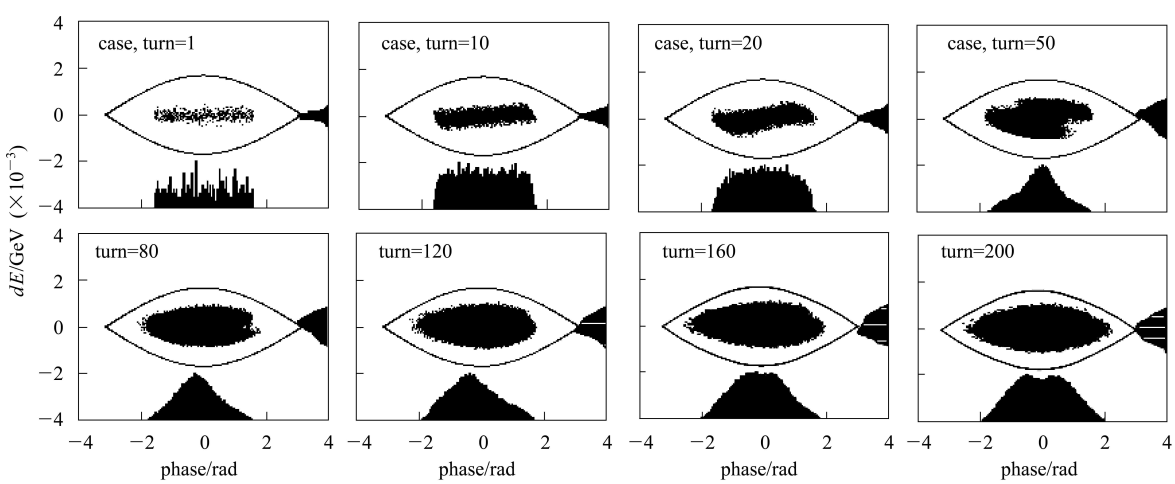

Fig. 3. Evolution of longitudinal phase space during injection. The horizontal axis represents phase (rad), the vertical axis represents energy deviation ($\times 10^{-3}$GeV).

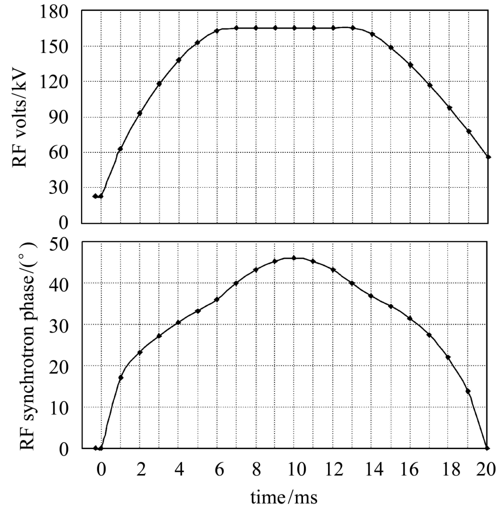

Fig. 4. The RF program for scenario B. The upper is the RF voltage variation, and the lower is the synchronous phase variation.

6 Off-momentum injection

The relation between the bunching factor and the tune shift due to space charge effect can be expressed by:

$$\Delta Q = -\frac{r_{\rm p} N}{2\pi\varepsilon\beta^2\gamma^3 B_{\rm f}} , \qquad (1)$$

where $r_{\rm p} = 1.53\times10^{-18}$ m is the classical proton radius, N the accumulated particles, ε the unnormalized emittance, $B_{\rm f}$ the bunching factor, β and γ are the Lorentz factors. To decrease the beam loss driven by nonlinear resonance, we must decrease the tune shift. That is to say, we should control the bunching factor big enough.

If the macro bunch from linac is just injected into the center of the RF bucket of RCS as shown in the former of Fig. 5, the charge density at the center of the RF bucket becomes fairly high. So the bunching factor should be very small. In order to avoid such a case, it is planned that the macro bunch from linac is injected with a momentum offset as shown in the latter of Fig. 5, then the charge density can be flattened and the bunching factor can get bigger.

After simulating all kinds of momentum offsets, we found the suitable momentum offset is 0.2% for the scenario B. And the evolution of such a case is shown in Fig. 3.

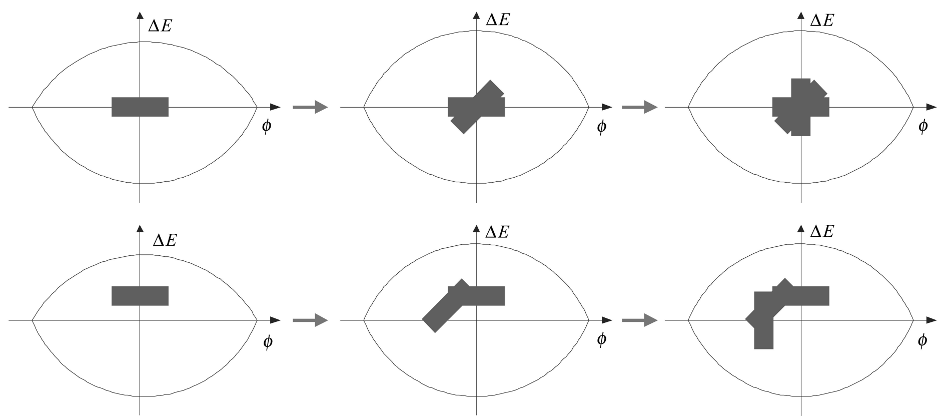

Fig. 5. The upper is multi-turn injection without momentum offset, and the bottom is that with momentum offset.

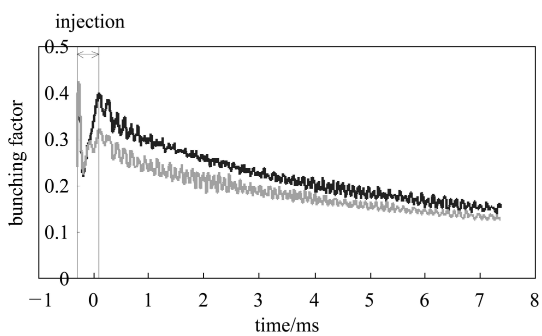

Fig. 6. The bunching factor variation with different momentum offset. (The darker represents that with 0.2% momentum offset, and the lighter represents the case without momentum offset).

Figure 6 compares the bunching factor variation with different momentum offset. We can see that off-momentum injection can improve the bunching factor obviously. From these results, the tune shift is under 0.24 for 300 πmm·mrad transverse beam emittance and 0.2 for 360 πmm·mrad, respectively.

At present, the acceptance of the vacuum pipe is 540 πmm·mrad$\pm1\%\Delta p/p$, and the acceptance of the primary collimator is 360 πmm·mrad$\pm1\%\Delta p/p$. It is reasonable for enough dynamic aperture and acceptable space charge tune shift.

7 Magnet error effects

In current conceptual design of CSNS/RCS, the dipole magnet field error can be controlled within ±0.1%[3] because of the instabilities of magnet current. This error will lead to either more beam loss in the longitudinal plane or less bunching factor.

Now, let's consider the worst magnet field error 0.1% and −0.1%, the parameters of injection and acceleration are the same as the scenario B.

There is no additional beam loss occurring when the magnet field error is −0.1%, but the bunching factor is much less than the others (shown in Fig. 7). When the magnet field error is 0.1%, the bunching factor is a bit improved, but the total beam loss in longitudinal plane is 1.76%.

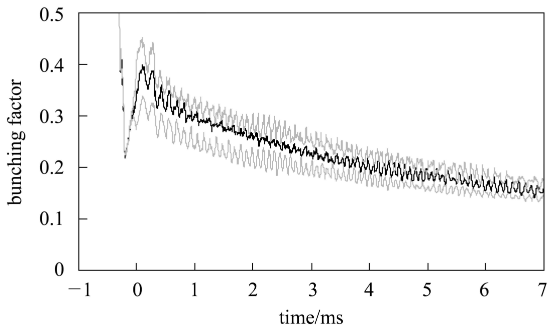

Fig. 7. The bunching factor variation with different magnet field errors. (The black curve represents that without magnet field error, the upper gray curve represents the case with 0.1% error, and the lower gray curve represents the case with −0.1% error).

The bunching factor variations with different magnet field errors are shown in Fig. 7. The bunching factor with magnet field error waves harder than that without error. This indicates the uniformity of longitudinal painting phase space is influenced by the magnet field error more or less.

8 Summary and discussion

In CSNS/RCS, 50% chopping and 0.2% off-momentum injected beam cause very little beam loss, even with the magnet field error less than 0.1%. And off-momentum injection can improve the bunching factor after injection. These results give us confidence that the irradiation in CSNS/RCS will be well under control in its beam dynamics design.

The higher chopping rate will lead to more particles lost in the longitudinal plane and has not any advantage in controlling the bunching factor except that in the injection period.

The lower chopping rate will increase the space charge tune shift at the injection, which will lead to non-uniformity of the transverse beam distribution and beam loss will happen. What's more, more injection turns will also lead to more halo particles for the beam crossing the stripping foil during the injection. Thus suitable transverse painting injection scheme is also important to the design of CSNS/RCS.

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