STUDIES ON SHORT-BUNCH EXTRACTION AT CSNS RCS

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Abstract

White neutron application requires short proton pulse length to obtain high time resolution for nuclear data measurements. Back-streaming neutron beam at the CSNS spallation target is to be exploited as a white neutron source. The available high RF voltage in the high intensity rapid cycling synchrotron (RCS) of the CSNS makes it possible to extract very short bunches by using the bunch rotation method. Special attentions have been paid to the bunch rotation during the slow acceleration, space charge effect and beam loading effect in the high-intensity RCS. Different extraction scenarios together with the changes in the injection have been studied. Together with the calculations, multi-particle simulations have been carried out to show the effectiveness of the method. With a sacrifice of about two-third beam power, the rms bunch length of the extracted beam can be reduced to about one eighth of the one in the nominal operation mode. Other scenarios also show the improvement in the bunch length.

INTRODUCTION

Back-streaming neutrons from the spallation target of CSNS (China Spallation Neutron Source) are very strong and harmful to the proton beam transport line if they are not well treated [1]. The studies found that the neutron beam has excellent properties of wide energy spectrum and time structure, and has been proposed to build a white neutron source for nuclear data measurement [2, 3]. The neutron pulse length is critical in defining the neutrons' energy by the time-of-flight method, and should be reduced as short as possible. The time structure of the back-streaming neutrons is jointly determined by the pulse length of the impinging proton beam and the thickness of the spallation target. Simulations show that the target thickness dominates the time resolution for the lower energy part of the wide-range energy neutrons, while the proton pulse length dominates the higher energy part. As the target length cannot be changed for this parasitic application, it would be interesting to shorten the proton pulse length by designing a special dedicated working mode for the CSNS accelerators. This paper presents the study about using the bunch rotation method in the RCS (Rapid Cycling Synchrotron of CSNS) to obtain very short proton beam bunches.

CSNS is a multi-disciplinary research facility under construction [4], which is to be built in two or three phases. In the first phase, the RCS is to accelerate beam from 80 MeV to 1.6 GeV in a repetition rate of 25 Hz, and the extracted beam power is 100 kW. Figure 1 and Table 1 show the layout and some parameters of the RCS.

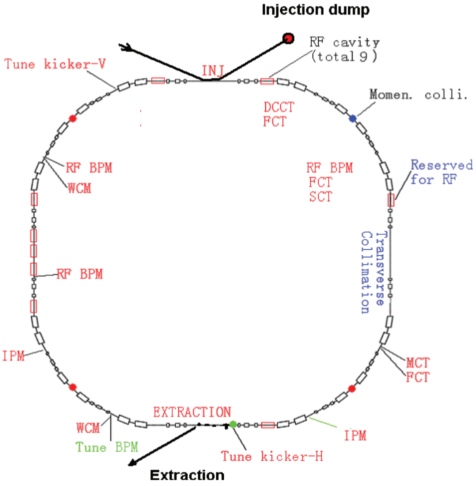

Figure 1: Layout of the CSNS RCS.

Table 1: Some Parameters of the CSNS RCS

Circumference (m)	227.92
Injection energy (GeV)	0.08
Extraction energy (GeV)	1.6
Maximum RF voltage (kV)	165
Betatron tunes (h/v)	4.82/4.80
RF harmonics	2
Transverse acceptance (πmm.mrad)	540
Collimation acceptance (πmm.mrad)	~350

SHORT-BUNCH EXTRACTION METHODS

There are two bunches per pulse in the extracted proton beam in the normal operation mode. The bunch length is determined by the RF voltage pattern and the longitudinal painting. The longitudinal painting is optimized to alleviate the space charge effects in such a high-intensity synchrotron. Compared with the simple method by designing a high RF voltage at the extraction, the bunch rotation method is more effective in shortening the bunch length for the extracted beam [5, 6]. The principle of the bunch rotation method is as follows: the RF voltage is adiabatically decreased from the normal extraction voltage to a low one, during which the bunch becomes gradually flat to follow the change of the RF bucket as long as the bucket still contain the beam with some margin. Then the RF voltage is quickly or non-

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adiabatically increased to a high value. The mis-matched bunch will rotate in the enlarged RF bucket. After a quarter of synchrotron period, the bunch will reach the minimum length and then the single-turn extraction can be applied.

In small-amplitude or linear synchrotron motion approximation, the rms bunch length and height σ_τ and σ_δ in a matched RF bucket are expressed by

$$\sigma_\tau = \sqrt{\frac{A_{rms}}{\omega_0}}\left(\frac{2|\eta|}{\pi heV\beta^2 E|\cos\varphi_s|}\right)^{\frac{1}{4}}, \quad (1)$$

$$\sigma_\delta = \sqrt{\frac{\omega_0 A_{rms}}{\pi\beta^2 E}}\left(\frac{heV|\cos\varphi_s|}{2\pi\beta^2 E|\eta|}\right)^{\frac{1}{4}}, \quad (2)$$

where A_{rms}, ω_0, η, h and φ_s denote the invariant rms phase space area in eV-s, revolution frequency of the reference particles, phase-slip factor, harmonic number and synchronous phase, respectively. Suppose the RF voltage changes from the nominal setting V_i to V_1 adiabatically, and then to the maximum available value V_2 non-adiabatically. According to Eq. (1), the bunch extension ratio of the rms bunch length is equal to

$$\mathrm{r}_{c\ max,V_i\rightarrow V_1} = \frac{\sigma_{\tau,i}}{\sigma_{\tau,m}} = \left(\frac{V_1}{V_i}\right)^{\frac{1}{4}} \quad (3)$$

where $\sigma_{\tau,i}$ and $\sigma_{\tau,m}$ denote the initial bunch length and the medium-stage bunch length, respectively.

After the non-adiabatic RF voltage change from V_1 to V_2, the bunch performs rigid quadrupole mode oscillations. After 1/4 of synchrotron period, the rms bunch length reaches the minimum, and can be expressed by

$$\sigma_{\tau,f} = \sqrt{\frac{A_{rms}}{\omega_0}}\left(\frac{2|\eta|}{\pi h\beta^2 E|\cos\varphi_s|}\right)^{\frac{1}{4}}\frac{(eV_1)^{1/4}}{(eV_2)^{1/2}}, \quad (4)$$

where $\sigma_{\tau,f}$ denotes the final bunch length. The compression ratio of the rms bunch length from V_1 to V_2 can be expressed by

$$\mathrm{r}_{c\ max,V_1\rightarrow V_2} = \frac{\sigma_{\tau,m}}{\sigma_{\tau,f}} = \left(\frac{V_2}{V_1}\right)^{\frac{1}{2}}, \quad (5)$$

The total compression ratio of the rms bunch length from the initial voltage (V_i) to the low voltage (V_1) then to the final voltage (V_2) can be expressed as

$$\mathrm{R}_{c\ max,V_i\rightarrow V_1\rightarrow V_2} = \frac{\sigma_{\tau,i}}{\sigma_{\tau,f}} = \left(\frac{V_1}{V_i}\right)^{\frac{1}{4}}\left(\frac{V_2}{V_1}\right)^{\frac{1}{2}}, \quad (6)$$

The bunch compression ratio depends only on the RF voltage ratio according to Eq. (6).

However, in practice, there are limitations to apply the bunch rotation method. In a high-intensity RCS, one has to consider the space charge effects during the bunch rotation process and the beam loading effect. The space charge effect may become strong when the bunch shortens during the bunch rotation. The initial beam emittance is also determined by the beam dynamics at the lower energy of the acceleration cycle, due to the space charge effects and the longitudinal microwave instability. The beam loading effect means that the circulating beam current detunes the RF cavities and becomes very important when the RF voltage is very low. To avoid the instability in the low-level RF control system, the ratio of the circulating beam current and the driving current from the RF amplifier should be controlled below a certain value, e.g. 6. This also limits the lowest RF voltage for V_1. The accumulated particles should be decreased to ease the above problems, and this leads to the reduction of the extracted beam power.

Different from its usual applications in compressor rings [7, 8] or slow cycling synchrotrons [9], in a high-intensity RCS, another important issue which should be considered seriously is the slow acceleration during the bunch rotation when the magnetic field is still ramping. The asymmetric RF bucket will deform the bunch shape and increase the final bunch length. The bunch rotation process should be started close to the maximum magnetic field, and this will delay the extraction moment slightly.

SIMULATION RESULTS

Multi-particle simulations with space charge with the ORBIT code [10] have been carried to show how effective the method in realistic cases is. Different injection scenarios and beam powers are studied in the simulations. The simulations are performed only in 1D longitudinal, while the transverse motion is kept in mind only by maintaining reasonable tune shifts with bunching factor because the transverse motion has no influence on the longitudinal one. In most cases, the chopping factor of 50% (defined as beam duty in the ring RF frequency) which is the one in the nominal working mode is used. With a reduced beam power or less accumulated particles, the RF voltage during the injection is reduced to obtain a small longitudinal emittance. In the nominal operation mode with full beam power, the RF voltage at injection is 29 kV. In a dedicated mode with 30% beam power, the RF voltage is decreased to 8.7 kV to keep the similar beam loading effect. Both chopping factors 50% and 30% are studied with the second giving smaller longitudinal emittance. The minimum and maximum RF voltage (V_1, V_2) before the bunch rotation are taken as 8.7 kV and 160 kV, respectively. During the last few turns of the bunch rotation which lasts about 0.2 ms or 200 turns, the Laslett tune shift reaches about -0.066, which is considered quite safe in a high-intensity RCS.

Figs. 2 and 3 show the longitudinal beam distributions just before the extraction in the nominal operation mode and in the dedicated operation mode, respectively. From the figures, one can see that a much shorter bunch length can be obtained in the dedicated operation mode. Fig. 4 shows the phase distribution of the extracted beam. For comparison, the rms bunch lengths for the extracted beam with different scenarios on injection and beam power reduction are shown in Table 2. With 30% chopping factor and 30% beam power together with the bunch rotation method, the rms bunch length of the extracted beam can be reduced to about one eighth of the one in the nominal operation mode. This can improve the time resolution of back-streaming neutrons almost by an order of magnitude at higher energy.

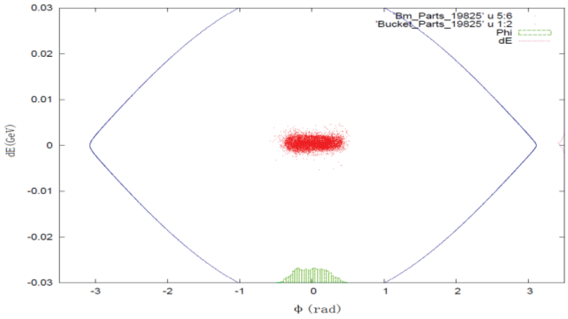

Figure 2: Longitudinal beam distribution just before the extraction in the nominal operation mode.

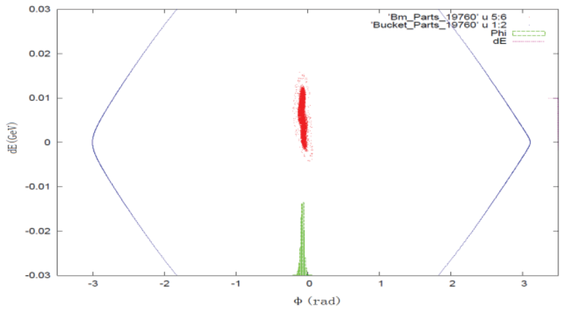

Figure 3: Longitudinal beam distribution just before the extraction in the dedicated operation mode with 30% chopping and 30% beam power.

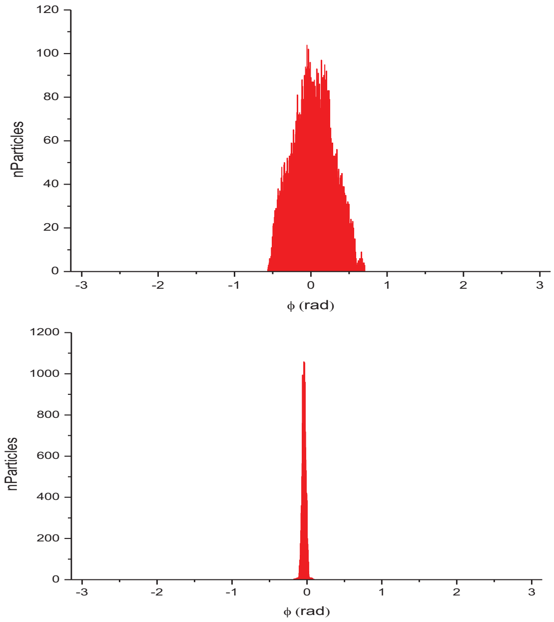

Figure 4: Phase distribution of the extracted beam. (Left: in the nominal operation mode; right: 30% beam chopping factor and 30% beam power).

Table 2: Rms Bunch Length with Different Chopping Factors and Beam Powers

Chopping factor (%)	Beam power remained (%)	rms length without rotation (ns)	rms length with rotation (ns)
50	100	13.0	7.5
50	50	11.0	3.5
50	30	9.3	3.3
30	30	7.2	1.7

CONCLUSIONS

The simulation studies show that the bunch rotation method by RF voltage manipulations is an effective one in short-bunch extraction in CSNS/RCS. In dedicated cases when the white neutron applications with high resolution are stressed, one can obtain a very short bunch length of about one eighth of the one in the nominal operation mode with a sacrifice of about two third beam power. Although the studies have been carried out with the CSNS parameters, the method should be applicable to other high-intensity proton synchrotrons with high available RF voltage.

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