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STUDY OF HIGH-INTENSITY BUNCH MERGING AND ITS EXPERIMENTAL APPLICATION ON RAPID CYCLING SYNCHROTRONS

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Abstract

Longitudinal beam manipulation have been widely employed for various scientific and industrial applications in many hadron (heavy ion or proton) synchrotrons. One of the most important manipulations is the longitudinal bunch merging based on the dual rf system. For high-intensity hadron beams, longitudinal space-charge matching and cavity beam loading matching and compensation are of practical concern to minimize the emittance blow-up for merging of high-intensity beams. For rapid cycling synchrotrons, a trade off should be made between the limited bunch merging time and the high-intensity effects. This paper discusses the schemes for high-intensity hadron bunch merging and proposes a fast bunch merging scheme for rapid cycling synchrotrons. Some experimental preparations for the bunch merging in the CSNS/RCS are also introduced.

INTRODUCTION

In hadron synchrotrons, bunch merging refers to the process of longitudinal merging of two bunches by slowly adjusting the rf voltages in a dual-harmonic rf system. Since proposed in 1983 [1], the bunch merging scheme has been successfully applied on the CERN-PS for producing antiproton beam [2–6], and on the RHIC for generating one single bunch [7, 8]. Compared to the conventional de-bunching and re-bunching methods, the bunch merging scheme has several distinct advantages. Firstly, for an ideal (adiabatic) bunch merging, the longitudinal emittance remains constant with negligible phase space dilution. Secondly, the beams are always focused within rf buckets during the merging. In comparison, the drifting beam during de-bunching (or re-bunching) process is left uncontrolled and the full ring is filled with particles [2].

The scheme of bunch merging can be applied not only for slow cycling synchrotrons or accumulator rings, but also for rapid cycling synchrotrons (RCS). For instance, the RCS of the CSNS (the China Spallation Neutron Sources [9, 10]) has two operation modes, the double-bunch mode and the single-bunch mode for different experimental goals. The double-bunch mode, in which two bunches with 410 ns time interval per pulse in the extracted proton beam, is chosen as the normal operation mode to provide high neutron flux. However, for some experiments of nuclear data measurement by using the back-streaming neutrons [11], the energy resolution in the double-bunch mode is worse than the single-bunch mode due to the time-of-flight dispersion. Therefore, such experiments should be carried out under the single-bunch mode with sufficient energy resolution [12]. The proton intensity and consequent spallation neutron flux in the single-bunch mode (one bunch per pulse) is halved than that in the double-bunch mode, and limit the quality of those experiments. In the upcoming second stage of the CSNS (abbreviated as CSNS-II in the following), the output beam power is planned to increase up to 500 kW. In order to alleviate the increased space charge effects, a dual harmonic rf system will be installed to flatten the longitudinal beam profile and increase the bunching factor [13]. The utilization of the combined system of the fundamental and second rf cavities makes it possible to conduct a bunch merging process before beam extraction to double the proton beam intensity in the single bunch operation mode for the back-n white neutron source experiments. In this paper, the scheme of fast bunch merging for high-intensity rapid cycling synchrotrons is proposed, and the experimental preparations for the upcoming bunch merging experiments in the CSNS/RCS are introduced.

BUNCH MERGING

Matched External RFf Voltage and Phase Shift

The rf voltages on each harmonic should be matched to bunch parameters before and after merging to achieve an ideal result. For elliptical bunch model [14] the matched rf voltage amplitude can be calculated via,

$$\hat{V}_{\mathrm{rf0}} = \frac{2\pi\gamma_0 m|\eta|R^2\beta^2c^2}{qh}\left(\frac{\delta_m}{z_m}\right)^2, \quad (1)$$

in which m and q is the mass and the charge of the particle, respectively; γ_0 the relativistic factor; R the radius of the synchrotron; η the slip factor; βc the velocity; h the harmonic number. z_m and δ_m are the half bunch length and the momentum spread of the bunch, respectively. For a parabolic bunch distribution of the elliptical model, we have $z_m = \sqrt{5}\tilde{z}_m$ and $\delta_m = \sqrt{5}\tilde{\delta}_m$, where the symbol $\tilde{\cdot}$ denotes the corresponding rms values.

The second parameter is the relative rf phase shift between harmonics. During bunch merging, the phase shift of the two

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harmonics should be set in such a way that the two bunches can be merged symmetrically in the dual harmonic system.

BUNCH MERGING WITH HIGH-INTENSITY EFFECTS

For high intensity hadron beams, the effect of longitudinal space charge and cavity beam loading should be taken into account. The voltage profile $V(z)$ can thus be divided into the external rf voltage part V_{rf}, the space charge part V_{sc} and the beam loading part V_{bl},

$$V(z) = V_{\mathrm{rf}}(z) + V_{\mathrm{sc}}(z) + V_{\mathrm{bl}}(z). \qquad (2)$$

The space charge part is (see, for example, Ref. [15, 16])

$$V_{\mathrm{sc}}(z) = -q\beta c R X_{\mathrm{sc}}\frac{\partial\lambda}{\partial z}, \qquad (3)$$

in which βc is the velocity of the synchronous particle, λ the line density of the bunch and X_{sc} the space charge reactance. For round beams in a round beam pipes, we have $X_{\mathrm{sc}} = g/(2\epsilon_0\beta c\gamma^2)$ with the g-factor $g = 1 + 2\ln(b/a)$, with b the pipe radius and a the beam radius.

The beam loading part can be written as the Fourier series

$$V_{\mathrm{bl}}(z) = -\sum_{n=0}^{\infty} I_n Z_n e^{inz/R}, \qquad (4)$$

where $I_n = q\beta c\lambda_n$ and Z_n represent the n-th harmonic of beam current and cavity impedance, respectively.

Space-Charge Matching and Correction

In the presence of space charge, the external rf voltage amplitude should be increased to compensate the space charge defocusing (i.e., space charge correction). Based on the self-consistency of the elliptical bunch model, the amplitude of the space charge voltage can be written explicitly as

$$\hat{V}_{\mathrm{sc}} = \frac{3q\beta c X_s N R^2}{2hz_m^3}. \qquad (5)$$

For the bunch merging with constant bunching factor, one can easily find the relation of space charge voltage amplitude at the beginning and at the end of bunch merging, $\hat{V}_{\mathrm{sc,i}} = 2\hat{V}_{\mathrm{sc,f}}$. The space-charge-matched rf voltage amplitude consists of a linear superposition of the matched rf voltage $\hat{V}_{\mathrm{rf}}$ and the space charge voltage $\hat{V}_{\mathrm{sc}}$,

$$\hat{V}_{\mathrm{rf,sc,i}} = \hat{V}_{\mathrm{rf,i}} + \hat{V}_{\mathrm{sc,i}} \qquad (6)$$

for the initial harmonic and

$$\hat{V}_{\mathrm{rf,sc,f}} = \hat{V}_{\mathrm{rf,f}} + \hat{V}_{\mathrm{sc,f}} = \frac{1}{2}\hat{V}_{\mathrm{rf,sc,i}} \qquad (7)$$

for the final harmonic. Equations (6) and (7) can be used for space charge correction during bunch merging.

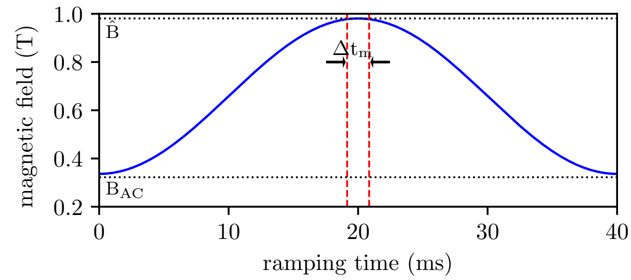

Figure 1: The magnetic field ramping in one cycling period in CSNS-II/RCS. The dotted lines represent the amplitudes of the maximum magnetic field $\hat{B}$ and the ac component B_{AC} of the dipoles, respectively. The dashed lines denote the duration time of the merging process.

Beam-Loading Matching and Compensation

The longitudinal space charge effect in a symmetrical bunch distribution generates a symmetrical defocusing self-field, and can be well “corrected” via increasing the external rf voltage. In comparison, the beam loading induced voltage is asymmetrical to the beam center, causing collective dipole oscillations and distortion on bunches. Specifically, in the presence of beam loading, the bunch trajectories are shifted in such a way that the asymmetry of the beam-loading effect acting on the bunch center is “compensated” via the external rf voltage, resulting in a vanishing accelerating voltage,

$$V_{\mathrm{rf,bl}}(z_{\mathrm{c,bl}}) = V_{\mathrm{rf}}(z_{\mathrm{c,bl}}) + V_{\mathrm{bl}}(z_{\mathrm{c,bl}}) = 0 \qquad (8)$$

with $V_{\mathrm{rf}}(z_{\mathrm{c,bl}}) = -V_{\mathrm{bl}}(z_{\mathrm{c,bl}}) = \hat{V}_{\mathrm{rf}}\sin(\phi_{\mathrm{c,bl}})$. Here, $z_{\mathrm{c,bl}}$ is the shifted position, satisfying $z_{\mathrm{c,bl}} = z_c + \Delta z_{\mathrm{bl}}$, where z_c is the bunch center without beam loading effect and Δz_{bl} the shift for beam-loading matching, and $\phi_{\mathrm{c,bl}} = hz_{\mathrm{c,bl}}/R$. Two beam loading shifts can be introduced for beam loading compensation: 1) The *matching shift* Δz_{bl} is for initial beam-loading matching of individual bunches in the simulation; 2) The *symmetry shift* Δz_{h} is for recovering the symmetry of the two moving bunches during merging with respect to the final rf bucket.

These two shifts can be included easily in numerical simulations. In practice, the beam-loading matching method can be implemented in a feedback system. Specifically, the matching shift Δz_h and the symmetry shift Δz_{bl} can be put into the feedback system to bring the bunch train to a stable matched state more effectively during bunch merging. The right phase difference between the initial and the final harmonic is determined by the smallest emittance growth during bunch merging.

FAST BUNCH MERGING IN RAPID CYCLING SYNCHROTRONS

For rapid cycling synchrotrons (RCS) such as CSNS-II/RCS, the magnetic field ramping for beam acceleration is driven by a resonant power supply with a sinusoidal waveform. For the bunch merging process in the ramping process, the non-zero synchronous phase can deform the symmetrical

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Figure 2: The magnetic alloy cavity employed for the second rf system in the CSNS-II

rf bucket, causing dipole coherent oscillations. To solve this problem, a desynchronization method can be employed [17]: the resonant frequency and the phase of the rf cavities are set to be desynchronized from the magnetic field to generate a stationary rf bucket with zero-synchrotron phase while the magnetic field is still ramping slowly, which ensures a symmetry merging process. Fig 1 displays one acceleration cycle of CSNS-II/RCS with its repetition rate 25 Hz. For the bunch merging with the adoption of the desynchronization method, the slow ramping approaching to the maximum magnetic field at extraction can cause a non-synchronism between the beam momentum and the reference momentum. The longer the merging proceeds, the larger the difference becomes. It can be proved that the optimized merging time is 1.7 ms (more details can be found in [18]).

EXPERIMENTAL PREPARATIONS IN THE CSNS/RCS

Beam Commissioning with Dual RF System

The magnetic alloy (MA) rf cavity (see Fig. 2) was successfully installed as the second harmonic cavity in the CSNS/RCS in Sep. 2022. The MA rf cavity, along with the fundamental ferrite-loaded rf cavity forms a dual rf system to alleviate the space charge effect. Since then, beam commissioning with the dual rf system was performed step by step. Fig. 3 shows the longitudinal profile measured by wall current monitor (WCM) with the sampling rate of 100 MHz. By measuring the longitudinal synchronous oscillation frequency and the distance of two bunch-peak in different second harmonic and fundamental cavity voltage ratio, both the voltage and phase of MA cavity were calibrated.

The longitudinal phase space distribution of beam is also measured (reconstructed) via the tomography scheme [19]. In the near future, this tomography method will also be applied to measure the energy dispersion during bunch merging, as shown in Fig. 4.

Fast Bunch Merging Schemes in the CSNS/RCS

The bunch merging will be conducted in the CSNS/RCS in two steps. First, a preliminary experiment is performed in non-accelerated mode to confirm the merging time and the corresponding RF parameters. Then in the accelerated mode, the bunch merging process with different conditions will be studied, namely for several beam intensity, initial and final RF voltage, merging times, and initial bunch length before merging.

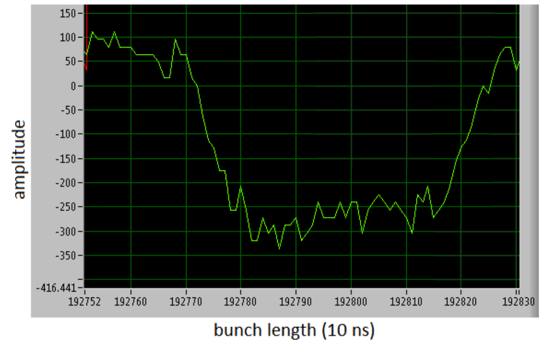

Figure 3: Longitudinal beam profile observed from the wall current monitor (WCM)

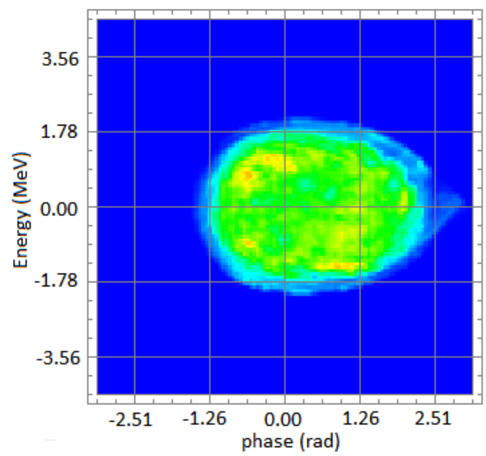

Figure 4: Reconstruction of longitudinal phase space distribution in the dual rf system in the CSNS/RCS via using tomography schemes

CONCLUSION

The longitudinal merging of high-intensity proton bunches in synchrotrons, including the combined effects of longitudinal space charge and cavity beam loading has been investigated. A fast bunch merging scheme for rapid cycling synchrotrons is proposed for the CSNS-II.

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