DUAL-HARMONIC ACCELERATION STUDIES AT CSNS RCS

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Abstract

Dual harmonic acceleration is proposed to alleviate the space charge effects in the RCS (Rapid Cycling Synchrotron) at the upgrading stages of the CSNS (China Spallation Neutron Source). Different dual harmonic acceleration schemes have been studied by using a self-made parameter calculation code – RAMADH and the simulation code – ORBIT. Both complete and partial coverage of the dual harmonic RF system along the acceleration cycle have been considered. The injection by combining beam chopping and off-momentum is used in the macro-particle tracking simulations by ORBIT. In addition, a new idea that unlocks the RF frequency and the magnetic field in the injection period is found very useful in obtaining a good longitudinal painting.

INTRODUCTION

The under-construction CSNS is a large scientific facility based on a high-power proton accelerator complex mainly consisting of an H- linac and an RCS. It is designed to provide a proton beam power of 100 kW in the first phase (CSNS-I) with the upgrading capability to 500 kW in the second phase (CSNS-II) [1, 2]. As shown in Table 1, the accelerator is designed to accelerate proton beams to 1.6 GeV in kinetic energy at a repetition rate of 25 Hz. To meet the requirements for the CSNS-II, the output energy of linac is improved from 80 MeV to 250 MeV and a dual-harmonic RF system in the RCS is applied to alleviate the space charge effect at low-energy phase. Besides, at CSNS-I the partial dual-harmonic acceleration which uses a spare cavity in all eight cavities for higher-frequency component is also taken into consideration [3]. The basic parameters of CSNS RCS are listed in Table 1.

Table 1: Basic Parameters of the CSNS RCS

Project phase	**I**	**II**
Beam power /kW	100	500
Ring circumference /m	228	228
Curvature of bending magnet /m	8.021	8.021
No. of RF cavities	8 (h=2)	8 (h=2)+ 3(h=4)
Injection energy/MeV	80	250
Extraction energy /GeV	1.60	1.60
Protons per pulse /10^{13}	1.56	7.8
Repetition rate /Hz	25	25

The RF pattern plays an important role in the dual-harmonic acceleration. It not only decides the quantities of the required higher-harmonic cavities, but also affects the operation cost. In addition, it affects the achievable beam loss rate and eventually the beam power in the RCS to a large extent. Therefore, the design of good RF programs is a key point here, especially for CSNS-II where the RF program is expected to provide a large bunching factor at low-energy stage and a large bucket area in later stages.

Two codes are used in studying the dual-harmonic acceleration. One is a self-make calculation code — RAMADH, which bases on a single-harmonic acceleration code — RAMA [4]. The other is a 3D simulation code — ORBIT, which is applied to inject and trace micro-particles [5, 6]. Some related calculation and simulation results with the two codes will be presented in this paper. Besides, a new idea — stationary-bucket injection method that releases the RF frequency from the synchronization with the changing magnetic field in the injection period is found very useful in obtaining a good longitudinal painting. The feature is also added in the ORBIT code.

DUAL-HARMONIC ACCELERATION

Two bunches are accelerated at the CSNS-I by a single harmonic (h=2) RF system. At the upgrading phase， CSNS-II, a second harmonic (h=4) RF system will be added to the existing fundamental one to increase trapping efficiency and improve bunching factor or bucket area for more stable beam dynamics. This dual-harmonic RF system is defined by:

$$V = V_1\left[\sin\phi - \delta\sin(2\phi+\theta)\right] \quad (1)$$

where V_1 is the amplitude for the harmonic h=2, δV_1 (V_2) is the amplitude for the harmonic h=4, ϕ is the RF phase and θ is the phase between the first (h=2)and second (h=4) harmonic waveforms.

Bucket area and bunching factor are the most important parameters in designing the dual-harmonic RF patterns which are the results of weighing the two parameters in the course of acceleration.

Bucket Area

In the longitudinal phase space expressed by $(\phi, \Delta E/h\omega_0)$, the bucket area per bunch is given by

$$A = 8R\sqrt{\frac{2(e)V_1(1-\eta_{sc})E_0\gamma\alpha^2}{h^3c^2\pi\eta}} \quad (2)$$

where the space charge factor η_{sc} is expressed by

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$$\eta_{sc} = \frac{2\pi h^2 I_b \,\mathrm{Im}\{Z_e / n\}}{u(\phi_1, \phi_2)} \quad (3)$$

E_0 is the rest energy, γ is the relativity energy factor, c is the velocity of light, η is the phase slippage factor $(\eta = \gamma^{-2} - \gamma_t^{-2})$, and the factor α is the ratio of the bucket areas between a running bucket $(\phi_s \neq 0)$ and a stationary bucket $(\phi_s = 0)$ [7].

Among the parameters, δ and θ are the key ones to build a flat-long bucket [8]. When V_1 and δ are given in the dual-harmonic RF waveform, the different θ markedly affects the bucket area. Taking the parameters of CSNS-II as an example: $B_{\min} = 0.3032$ T, $B_{\max} = 0.9808$ T, $V_1 = 165$ kV and $\delta = 0.38$, where $B_{\min}$ and $B_{\max}$ are the minimum and maximum of the bending magnet field. At the moment of 8 ms with the origin moment at the lowest magnetic field, the relationship of the bucket area and θ calculated by RAMADH is showed in Figure 1. In the figure, we can find the variation of the bucket area with its maximum at about $\theta_{\mathrm{A}} = 50°$.

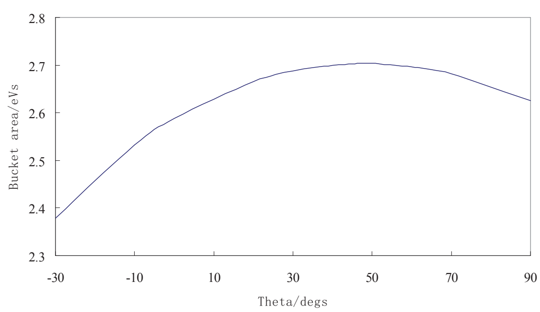

Figure 1: Bucket area varying with θ at 8 ms for CSNS-II.

Bunching Factor and Tune Shift

The dual-harmonic acceleration is an effective way to improve the bunching factor, which is helpful to alleviate the space charge effects. Bunching factor is defined as the ratio of the average current to the peak current of a beam bunch, namely, the ratio of the bunch length to the wavelength of periodic bunches. The Laslett tune shift [9] related to bunching factor is usually used to evaluate the averaged incoherent tune shift in a synchrotron:

$$\Delta\nu = -\frac{r_p n_t}{2\pi\beta^2\gamma^3 \varepsilon B_f} \quad (5)$$

where $r_p = 1.53\times10^{-18}$ m is the classical radius of proton, n_t is the accumulated particles in the ring, β and γ are the Lorenz' velocity and energy for the beam, ε is the transverse emittance and B_f is the bunching factor.

STATIONARY-INJECTION METHOD

In the RCS, a stable bunch shape is expected after injection. Generally, the RF frequency and phases are synchronized with the ring magnet fields, which leads to bucket shrinking and the change in off-momentum during the injection with the magnet field following a sinusoidal waveform. For this reason, the injected beam seems irregular in the bucket. Here, we propose a method called stationary-bucket injection, which unlocks the relation between the RF and the magnetic field during the injection time, but locks it again after injection. Using this method, the simulation results show that a much regular and uniform beam distribution can be obtained after injection. Taking the injection at CSNS-II as an example, a chopping factor of 65% and 0.1% off-momentum are used. The distributions after injection with or without the stationary-bucket injection method are shown in Figure 2.The simulation shows that the bunch is a little longer and flatter and the beam loss rate is lower after using the stationary-injection method.

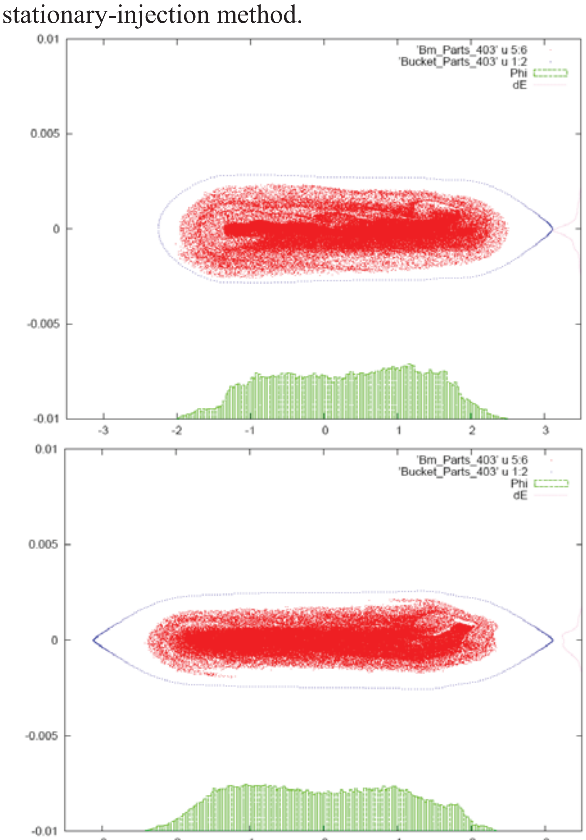

Figure 2: Distributions after injection for CSNS-II (upper: with usual injection method; lower: with the stationary-bucket injection method).

With the injection period close to the slowest change in the magnetic field, the off-centering at dispersive arcs due to the stationary RF is about a few millimetres which can be tolerated. Therefore, the stationary-bucket injection method can be easily put into practice in real machine. In

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the simulations, a parameter – bindTime is added in the ORBIT code to create a stationary-bucket injection period from the start-time to the bindTime. In addition, this method can also be used during the extraction period to meet some special requirements such as raising the beam away from reference orbit for easy extraction.

ACCELERATION SCKEMES AT CSNS-II AND CSNS-I

At the upgrading stage, three second-harmonic ferrite cavities (*h*=4, abbr. H4) will be added to the eight existing fundamental-harmonic cavities (*h*=2, abbr. H2) to form the dual-harmonic RF system. Since the beam power at CSNS-II is 5 times as high as the one at CSNS-I, the beam loss and tune shift during the acceleration period must be controlled more strictly. After increasing the linac output energy and applying the dual-harmonic acceleration method, one can expect that the tune shift at CSNS-II is less than -0.2.

At CSNS-I, eight identical ferrite-loaded RF cavities are installed in the RCS, where seven of them can supply the required RF voltage of 165 kV and the remained one is reserved in case of cavity breakdown. It is also possible to exploit the spare cavity to compose a dual-harmonic acceleration mode in the low energy range before the maximum frequency reaches. The study shows that it can provide a considerable improvement in bunching factor at low energy stage, thus reduces beam loss rate. Besides, it will also act as the rehearsal of the dual-harmonic acceleration at CSNS-II.

Acceleration Schemes at CSNS-II (500 kW)

At low energy stage of CSNS-II, the RF program is designed to increase the bunching factor. However, at higher energy, the RF program will be changed to meet new requirements. With the energy growing, the space charge effects weaken, but the longitudinal beam emittance may rise due to the space charge or other nonlinear forces during the course. Therefore, the RF program should be adjusted to provide larger bucker area to encase beam particles as many as possible. It may also need a slowly-changing RF program during the transitional time between the two stages. Taking all these factors into account, a RF program in the whole acceleration period is designed and optimized by using RAMADH and ORBIT.

The first-harmonic and second-harmonic RF voltages, calculated by RAMADH for CSNS-II/RCS, are given in Figure 3, where V_1 and V_2 are the 1st and 2nd harmonic components, respectively. As discussed above, θ plays an important role in obtaining bucket shape and bucket size. Figure 4 shows the θ curve in the whole acceleration period. In the figure, in the first 4 ms a θ pattern with the largest bunching factor, is chosen to obtain long-flat longitudinal distribution. From 9 ms to the extraction, the θ pattern is optimized to supply the largest bucket area under the maximum RF voltage limits ($V_1 = 168$ kV, $V_2 = 63$ kV). Between the two θ modes, a smooth transition is needed to avoid large changes in bucket and bunch shape between 4 ms and 9 ms. As shown in Figure 4, the synchronous phases stay at high value in most part of the time to meet the required acceleration rate due to the de-acceleration action of the second harmonic component.

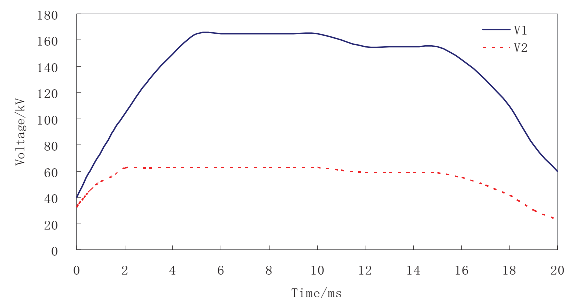

Figure 3: The first and second harmonic RF voltages for CSNS-II/RCS.

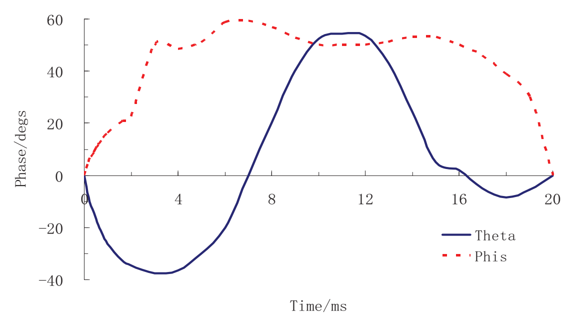

Figure 4: Synchronous phase (ϕ_s) and relative phase (θ) of the dual-harmonic RF systems for CSNS-II/RCS.

The ORBIT code is used to simulate the injection and tracking of the particles. For the injection, beam chopping and off-momentum are considered to paint the beam in the longitudinal phase space. After analyzing different combinations of chopping factor and off-momentum, we find that the injection with 65% chopping factor and 0.1% off-momentum is a good combination for CSNS-II. With the stationary-bucket injection method applied, simulations show no beam loss occurred in the whole period. The injection parameters in the simulation are given in Table 2, where $\varepsilon_{\ln}$ is the normalized longitudinal emittance, ε_0 is the transverse emittance after painting.

Table 2: Injection Parameters in the Simulation for CSNS/RCS

Stages	Chopping factor	Off-momentum	Injection time (ms)
CSNS-II	65%	0.1%	-0.5 ~ 0
CSNS-I	80%	0	-0.3 ~ 0

As shown in Figure 2 (lower one), we can see that the bunch just after injection is a fairly long-flat shape in

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spite of the strong space charge effects, where the bucket shape is kept stationary with the stationary-bucket injection method. The bunches remain long-flat in the low-energy stage (before 4ms) as shown in Figure 5. With the largest-bucket-area mode after 9 ms, all the particles are encased well in the bucket till extraction.

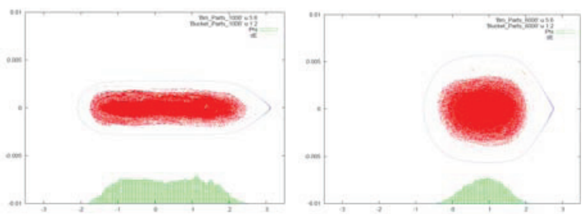

Figure 5: The longitudinal beam distributions for CSNS-II (left: with the largest bunch factor mode at about 1.0 ms; right: with the largest-bucket-area mode at 6.6 ms).

The space charge causes transverse tune shift and tune spread, which may lead to beam losses due to the whole or part of particles crossing through resonances. An analysis which shows the dependence of the tune shift with the local longitudinal charge density along the bunch is taken. Using the equation (5), the detailed information of tune shifts such as the average and maximum tune shifts can be obtained by cutting the bunch into slices. Figure 6 gives a schematic working-point after injection for CSNS-II, where the assumed naked tunes are Q_x/Q_y: 4.86/4.78, the red mark shows the average tunes after shifting; the red, pink, cyan, green lines are 1st, 2nd, 3rd, 4th order resonances, respectively.

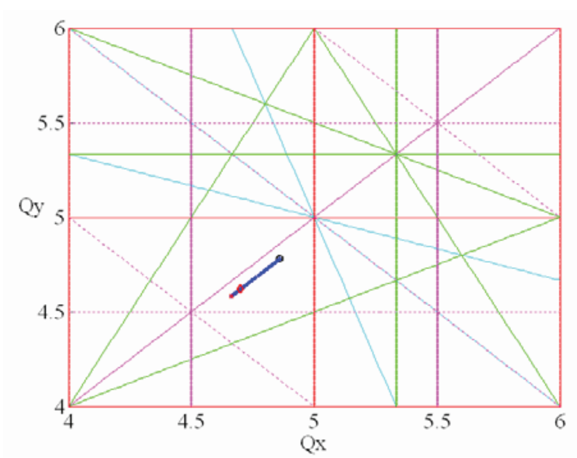

Figure 6: Working-point spread due to the difference in the local charge density in a bunch after injection for CSNS-II (The naked Q_x/Q_y: 4.86/4.78, the red mark shows the average tunes after shifting).

Dual-Harmonic Acceleration Schemes at CSNS-I (100 kW)

The possibility of using the spare cavity to form a partial dual-harmonic RF system is also studied here. The calculation and simulation results show that it offers a considerable help to reduce the tune shift excursion.

The RF voltage of each cavity is given in Figure 7. The RF voltage of each ferrite cavity is limited under 24 kV. The RF frequency sweeps from 1.02 MHz to 2.44 MHz for the first harmonic cavity and from 2.04 MHz to 2.44 MHz for the 2nd harmonic one at CSNS-I. The tune shifts by applying the partial dual-harmonic acceleration and applying only single harmonic acceleration are shown in Figure 8. We can see that with the partial dual-harmonic method the tune shift in the low energy stage is reduced significantly.

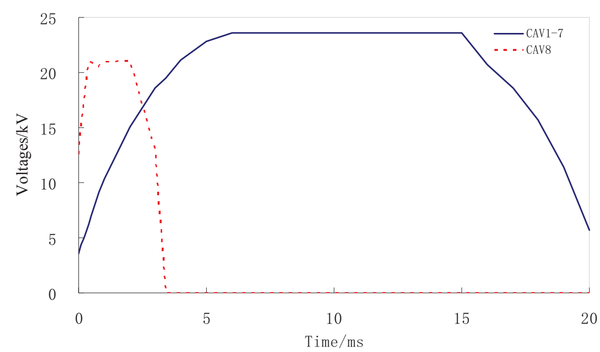

Figure 7: RF voltages of each cavity in CSNS-I.

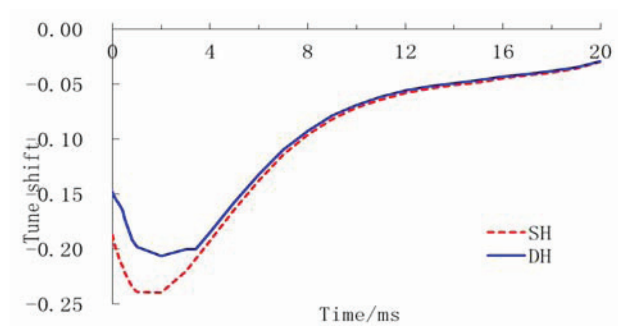

Figure 8: Tune shifts of the partial dual-harmonic and single-harmonic acceleration.

The longitudinal phase-space distribution after injection the partial dual-harmonic RF is presented in Figure 9. Using the stationary-injection method, an injection scheme with a chopping factor of 80% and no off-momentum is applied in the simulation. A flatter and longer bunch is obtained by using the partial dual-harmonic RF compared with the one using the single-harmonic RF. The macro-particle simulation by ORBIT shows a stable dynamics around the moment of the turning off the 2nd harmonic cavity. Further studies about the partial dual-harmonic acceleration for CSNS-I are underway.

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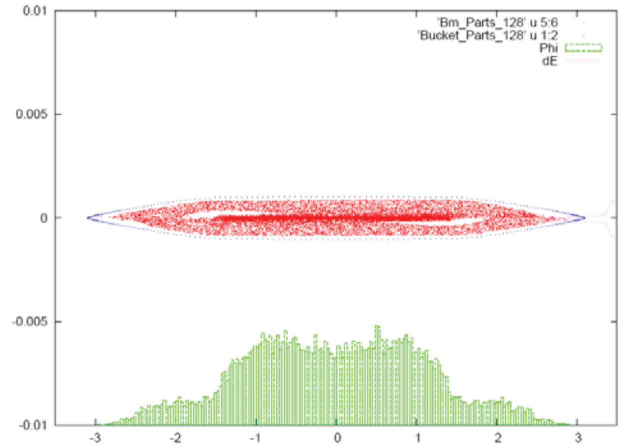

Figure 9: longitudinal phase-space distribution after injection for CSNS-I.

CONCLUSIONS

Dual-harmonic acceleration schemes are studied for CSNS-II and CSNS-I. The calculation and simulation results show the dual-harmonic acceleration method is very helpful in alleviating the space charge effect at the low energy and enhancing the beam stability at the middle energy stage. The study also shows that the relative phase between the two harmonic components plays an important role in the bucket shape and size. Besides, the stationary-bucket injection method proposed here seems to effective in obtaining a good longitudinal bunch distribution.

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REFERENCES

[1] S. Fu, H. Chen, Y. Chi, et al., 2011.
[2] S. Wang, Y. W. An, S. X. Fang, et al., SCIENCE CHINA Physics, Mechanics & Astronomy (2011) p. 1-6
[3] J. Y. Tang, S. N. Fu, and L. Ma, in Proceedings of HB2010, Morschach, Switzerland 2010, p. 38.
[4] R. Baartman and H. Schonauer, eds., RAMA: A Computer Code Useful for Designing Synchrotrons, TRI-DN-86-15, TRIUMF, 1986.
[5] J. Galambos, J. Holmes, D. Olsen, et al., eds., ORBIT User Manual Version 1.10, SNS Building MS-8218, ORNL, 1999.
[6] J. A. Holmes, in Proceedings of IPAC2010, Kyoto, Japan, 2010, p. 1901.
[7] S. Y. Lee, ed., Accelerator Physics, World Scientific Publishing, Singapore, 1999.
[8] J. F. Chen and J. Y. Tang, Chinese Physics C 34 (2010) 1643.
[9] L. Laslett, in Proceedings of 1963 Summer Study on Storage Rings, BNL Report 7534, 1963, p. 325.

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