IMPLEMENTATION OF RF MODULATION IN BOOSTER FOR MITIGATION OF THE COLLECTIVE EFFECTS IN THE TRANSIENT PROCESS AFTER THE SWAP-OUT INJECTION *

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Abstract

On-axis swap-out injection is a promising injection scheme for the diffraction-limited storage rings with small dynamic apertures. However, some previous studies have shown that the initial mismatch in the longitudinal phase space may lead to transverse collective instability before approaching the equilibrium state, especially in the high bunch charge situation. We present our study of mitigating the collective effects in the transient process after injecting beam into storage rings by implementing RF modulation technique in booster. Both bunch lengthening and the increase of energy spread could be observed in the extracted bunch from booster. The reduction of particle loss in the transient process after the swap-out injection is demonstrated via simulations.

INTRODUCTION

The development of the next generation synchrotron light sources, which are based on the diffraction-limited storage rings (DLSRs), has been the frontier of the synchrotron light source community for years. Generally speaking, stronger focusing is needed to reach the ultra-low emittance, with the drawback that the natural chromaticities are usually large negative values. To correct the chromaticities to an acceptable level, one has to implement very strong sextupole magnets, which eventually, limit the dynamic aperture (DA). The limited DA of the DLSRs provides great challenges to the injection. It therefore triggers a plenty of research in developing injection schemes for the DLSRs, in which, the on-axis swap-out injection scheme [1, 2] is one of the promising injection schemes.

High Energy Photon Source (HEPS) [3], which is a 6 GeV DLSR-based synchrotron light source, is currently under civil construction in Beijing, China. The on-axis swap-out injection scheme has been chosen as the baseline injection scheme of the 6-GeV storage ring of HEPS. There are two operation modes, named the "High-Brightness Mode" (680 bunches, 200 mA) and the "High-Bunch-Charge Mode" (63 bunches, 200 mA), proposed for the HEPS storage ring. The injection of a 14.4 nC bunch, corresponding to the "High-Bunch-Charge Mode", is very challenging for both the injector and the storage ring. Recent study [4] indicated that the injection transient instability, which was essentially a ‘head-tail’ type, transverse single-bunch instability, might seriously limit the achievable single-bunch charge in the HEPS storage ring. Many possibilities to cure the injection transient instability have been also proposed and discussed in [4]. Simulations showed that the higher transmission efficiency can be expected if the length of the injected bunch can be longer. This fact inspired us to try lengthening the bunch in booster before extraction, in order to cure the injection transient instability in the storage ring. In this paper, we would like to present our studies on the implementation of RF modulation in the HEPS booster, which is one possible way to lengthen the bunch in the booster.

The rest of the paper will be arranged as follows: firstly, the basic theories of the RF modulation will be reviewed. Afterwards, the results of the tracking simulations will be presented. Conclusions and discussions will be presented at the end.

THEORY OF RF MODULATION

Generally speaking, any arbitrary signal added up to the ideal RF signal becomes the so-called RF modulation, e.g., the white noise on top of RF signal. However, this kind of broad-band modulation was usually called “RF noise” instead of “RF modulation”. In the following text, when we mentioned ‘RF modulation’, we actually limited ourselves to the situations where a single frequency sinusoidal RF modulation was considered.

In this section, we mainly followed the analyses of the effects of a single-frequency sinusoidal RF voltage modulation and RF phase modulation in [5] to understand the effectiveness of both above mentioned modulation methods. No synchrotron radiation effect was taken into account in the analyses of this section.

The Eq.(3.111) and Eq.(3.112) in [5] represent the equations of synchrotron motion in the normalized phase space $(\phi, \mathcal{P})$ with RF voltage modulation, where $\mathcal{P}$ is the normalized momentum deviation defined by $\mathcal{P} = -h|\eta|\delta/\nu_s$. We hereby rewrote the above mentioned two equations in the (ϕ, δ) phase space, shown as Eq.(1) and Eq.(2), and carried

* Work supported by National Natural Science Foundation of China (No. 11805217, No. 11775239, and No. 11605212), NKPSTRD (2016YFA0402001), and Key Research Program of Frontier Sciences CAS (QYZDJ-SSW-SLH001)
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out the analyses from these equations.

$$\phi_{n+1} = \phi_n + 2\pi h \eta \delta_n \quad (1)$$

$$\delta_{n+1} = \delta_n + V_{RF}\left[1 + \delta V_m \sin\left(\nu_m \theta_{n+1} + \chi\right)\right] \cdot \frac{e}{\beta^2 E_0} \cdot \left(\sin\phi_{n+1} - \sin\phi_s\right) \quad (2)$$

where h represents the harmonic number; η is the the phase slip factor; E_0 represents the total energy of the reference particles; V_{RF} stands for the peak RF voltage; ϕ_s is the synchronous phase; $\delta V_m = \Delta V / V_{RF}$ is the fractional RF voltage modulation amplitude; $\nu_m = \omega_m/\omega_0$ is the modulation tune, where ω_m stands for the angular frequency of the modulation; $\theta = \omega_0 t$ is the orbital angle; χ is the phase of the modulation signal.

By plugging the optical parameters of a candidate lattice of the HEPS booster in Eq.(1) and Eq.(2) and solving the mapping equations, we could obtain the particles' distribution in the longitudinal phase space (ϕ, δ). A preliminary result, in (z, δ) phase space with the definition of $z = C\left(\phi - \phi_s\right)/2\pi h$, is shown in Figure 1. Here the modulation amplitude δV_m was set as 15%, while the modulation tune ν_m was set as $2\nu_s$. Figure 1(a) shows the particles' equilibrium distribution in the (z, δ) phase space without turning on the RF voltage modulation. Using the distribution as the initial state, and tuning on the RF voltage modulation with the above mentioned settings, we got the particles' distribution in the 20,000th turn, as shown in Figure 1(b). The structure indicating the second-order parametric resonance driven by the voltage modulation can be clearly seen in Figure 1(b).

Following the corresponding equations in [5], we've obtained the synchrotron mapping equations with RF phase modulation as Eq.(3) and Eq.(4):

$$\phi_{n+1} = \phi_n + 2\pi h \eta \delta_n + \left[\delta P_m \sin\left(\nu_m \theta_{n+1} + \chi\right) - \delta P_m \sin\left(\nu_m \theta_n + \chi\right)\right] \quad (3)$$

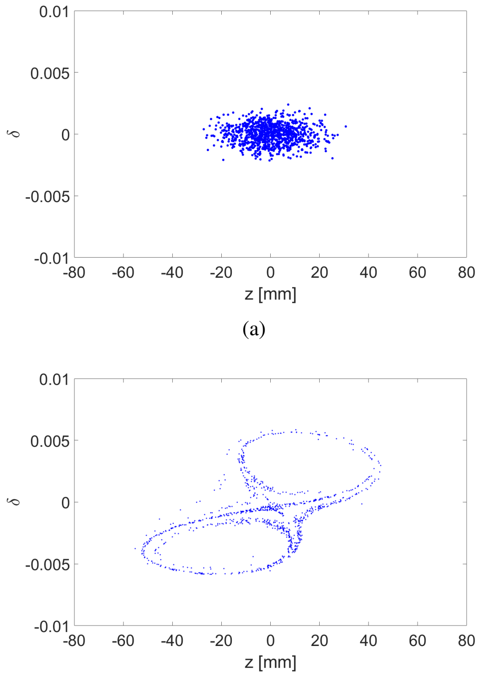
$$\delta_{n+1} = \delta_n + \frac{e V_{RF}}{\beta^2 E_0}\left(\sin\phi_{n+1} - \sin\phi_s\right) \quad (4)$$

where δP_m represents the RF phase modulation amplitude, ν_m is the phase modulation tune.

Using the similar approach as mentioned above for the study of RF voltage modulation, we set up the RF phase modulation amplitude and modulation tune as $\delta P_m = 0.1$ rad and $\nu_m = 2\nu_s$, respectively. The equilibrium particles' distribution without RF phase modulation is given in Figure 2(a). The particles' distribution in the 20,000th turn after turning on the phase modulation is given in Figure 2(b). Similarly, the effectiveness of the phase modulation was demonstrated as the parametric resonance structure shown in Figure 2(b).

TRACKING SIMULATIONS

In the previous section, we demonstrated the effectiveness of both the RF voltage modulation and the RF phase modulation on bunch lengthening using the existing theories. However, we got information [6] that the RF phase modulation is generally less challenging than the voltage modulation



(a)

(b)

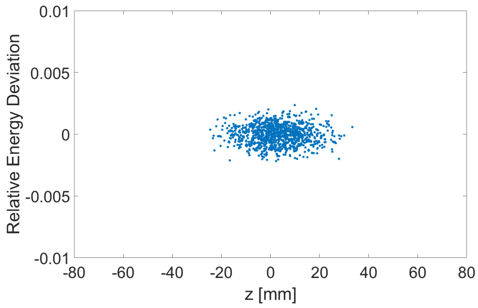
Figure 1: Particles' distributions in the longitudinal phase space (z, δ). (a): equilibrium distribution without voltage modulation; (b): particles' distribution in the 20,000th turn after turning on the voltage modulation with the amplitude $\delta V_m = 15\%$ and the modulation tune $\nu_m = 2\nu_s$.

in the high-power operation of the cavities. We therefore would like to continue the study of RF phase modulation only as suggested.

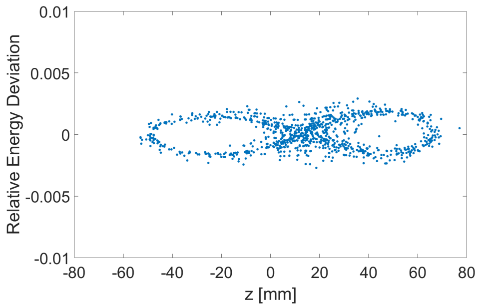
However, the main purpose of implementing the RF modulation technique in booster is to suppress the injection transient instability in the storage ring. Therefore, the demonstration of the effectiveness of RF modulation is only the first step. The second step is to double check whether the injection efficiency can benefit from the modulated bunch. We hereby first generated the turn-by-turn bunch distribution by multi-particle tracking (the multi-particle tracking code `elegant` [7] was used), and then used these distributions as initial bunches for the storage ring to study the injection efficiency. Element-by-element tracking, with the consideration of both the transverse and longitudinal broad-band impedance, was carried out to check the injection efficiency.

We first carried out the multi-particle tracking in booster with RF phase modulation. The modulation amplitude and the modulation tune are set as $\delta P_m = 10°$ and $\nu_m = 2\nu_s$, respectively. The turn-by-turn data of both the bunch length and energy spread are shown in Figure 3.

Figure 3 indicates that both the bunch length and energy spread oscillate violently turn-by-turn. However, it's very difficult to make sure always extracting the bunch at a certain bunch length. We selected the data in 100 continuous turns as examples, and carried out element-by-element tracking in

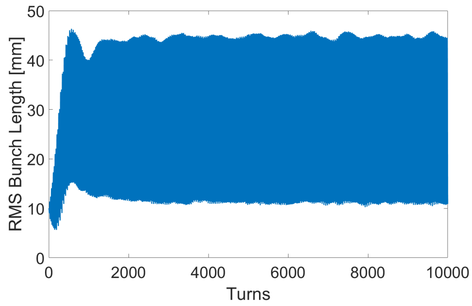


(a)



(b)

Figure 2: Particles' distributions in the longitudinal phase space (z, δ). (a): equilibrium distribution without phase modulation; (b): particles' distribution in the 20,000th turn after turning on the phase modulation with the amplitude $\delta P_m = 0.1$ rad and the modulation tune $\nu_m = 2\nu_s$.



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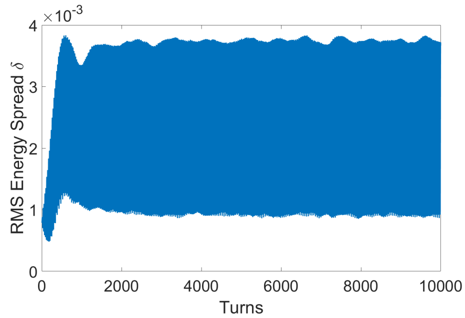
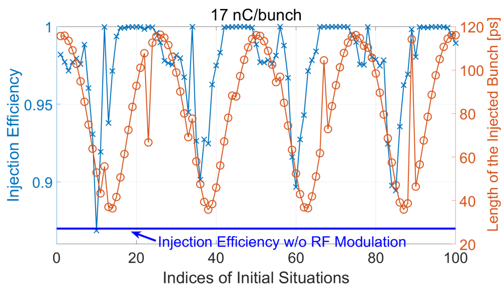
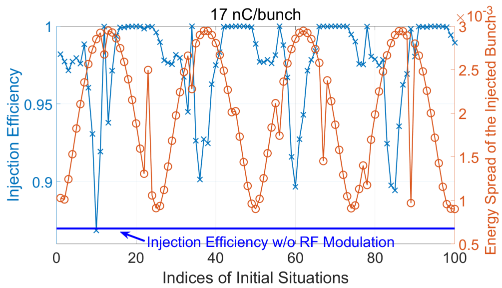


(b)

Figure 3: Turn-by-turn data after turning on RF phase modulation at the 0th turn. (a): RMS bunch length vs. turns; (b): RMS energy spread vs. turns.



(a)



(b)

Figure 4: Turn-by-turn data after turning on RF phase modulation at the 0th turn. (a): RMS bunch length vs. turns; (b): RMS energy spread vs. turns.

the storage ring for each case. The injection efficiency, RMS bunch length, and RMS energy spread of the 100 cases are given in Figure 4.

Comparing to the injection efficiency without RF modulation, one can see clearly that most of the cases with RF modulation correspond to higher injection efficiency. The cumulative distribution function shown in Figure 5 shows that the possibility of getting injection efficiency higher than 95% is above 80%, which is significantly higher than the injection efficiency without RF modulation (about 87%).

CONCLUSIONS AND DISCUSSIONS

For improving the injection efficiency in HEPS storage ring, we proposed to implement RF modulation technique in the booster before extracting bunches.

The effectiveness of both RF voltage modulation and RF phase modulation on bunch lengthening was demonstrated using the existing theories. We then continued the studies of RF phase modulation and the influence on injection efficiency by carrying out multi-particle tracking. Tracking results confirmed the effectiveness of RF phase modulation on increasing the injection efficiency.

However, in the preliminary studies, we didn't pay much attention in the optimization of the settings. There are still many parameters, such as the modulation tune and the modulation amplitude, needed further optimizations. Furthermore, many technical tests, proposed by us together with our RF experts, are needed to double check the possibility of implementing RF phase modulation in HEPS Booster.

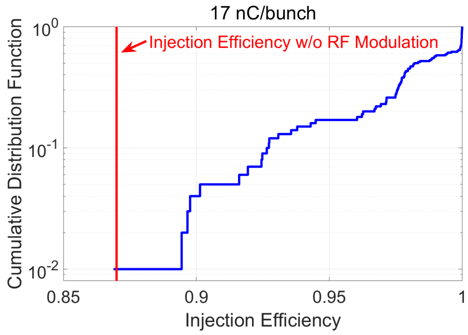


Figure 5: Cumulative distribution function

ACKNOWLEDGMENT

The authors would like to thank the colleagues in Accelerator Physics Group of IHEP for the fruitful discussions.

The simulations were mainly carried out on the cluster operated by the IHEP computing center. The authors would like to thank the staff in the IHEP computing center for their kind support.

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