Injection performance evaluation for SSRF storage ring*

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Abstract: The injection performance of the storage ring is one of the most important factors to consider at a synchrotron radiation facility, especially in the top-up mode. To evaluate the injection performance of the storage ring at the Shanghai Synchrotron Radiation Facility, we have built a bunch-by-bunch position measuring system based on an oscilloscope Input/Output Controller. Accurate assessment of energy mismatching, distribution of residual oscillation, and angle error of injection kickers can be achieved by this system.

Key words: injection performance, bunch-by-bunch, energy matching degree, residual oscillation, SSRF

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1 Introduction

In order to improve the efficiency and quality of light at the Shanghai Synchrotron Radiation Facility (SSRF), a top-up mode has been adopted since the end of 2012, which results in more frequent beam injections (about one injection every ten minutes) [1]. Since the injection process involves a variety of equipment, the parameters of all the components do not match each other perfectly during the transient injection process [2, 3]. Parameter imperfections can lead to a closed orbit distortion, which will leave a residual betatron oscillation after injection. For light users, this disturbance should be as little as possible [4, 5]. An appropriate analysis and diagnosis tool is needed to provide a basis for optimizing the parameters of related equipment. Typically, the following equipment parameter mismatches will occur:

(1) Excitation current waveform mismatch (such as amplitude and timing) between kickers;

(2) Energy or phase mismatch between the injected bunch from the booster ring and the stored bunches in the storage ring; and,

(3) Angle error in the kickers.

The Libera turn-by-turn data and slow acquisition data can be used to observe the average effect of bunch train disturbances. Issue (3) and part of issue (1) can be studied using these data. When the leakage fields of the kickers are non-uniform, issue (1) can be analyzed and optimized in only a very limited way. This paper comprehensively analyzes the aforementioned problems and shows the optimization of the equipment parameters by using the details of each bunch disturbance obtained with a bunch-by-bunch position measuring system based on an oscilloscope Input/Output Controller (IOC).

2 Injection system

The layout of the SSRF injection system is shown in Fig. 1. Four kickers are used to make the orbit bump and the injection point is designed at the bump orbit [6].

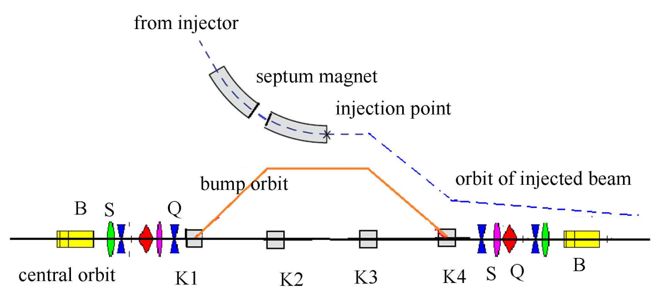

Fig. 1. (color online) Layout of the SSRF injection system.

The excitation current waveforms of the injection kickers and the injected buckets are shown in Figs. 2(a) and 2(c). Ideally, the phase difference between the excitation current waveform and the injected bunches is strictly locked. When the excitation currents of the four kickers match perfectly, forming an ideal closed orbit with no closed orbit distortion, the injection process is completely transparent for the stored beam and no residual oscillation occurs. However, the excitation current of

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the four kickers might not match in practice, as shown in Fig. 2(b), and then residual oscillation will occur because of a time-varying closed orbit distortion [7]. When the storage ring is filled with 500 bunches continuously and uniformly, the closed orbit distortions are not the same for all bunches, so the residual oscillation amplitudes of all of the bunches are not the same and may be completely reversed.

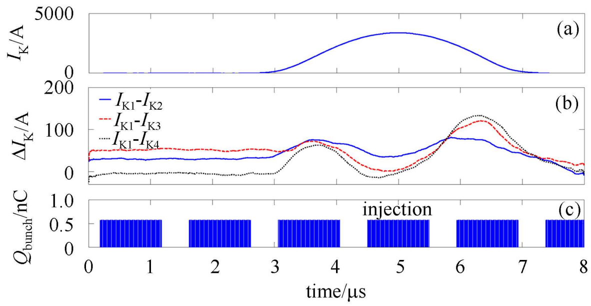

Fig. 2. (color online) Timing relation between bunch train and excitation current waveform.

3 Measurement system setup

We need to build a bunch-by-bunch position measuring system to obtain the disturbance details of each bunch, to comprehensively analyze the problems mentioned above, and to guide equipment parameter optimization.

At the SSRF, the bandwidth of this system should be larger than 250 MHz, the data rates should be equal to or greater than 499.654 MHz (storage ring RF frequency), and the data buffer should be greater than 720×4000 data points (determined by the loop damping time 5–6 ms) [8]. Consequently, we use the oscilloscope IOC and four button electrodes to achieve this system.

Using a broadband scope with a high sampling rate (5 Gsps), four channels, and large memory capacity (102 Mpts per channel), we can obtain the raw data from the four button electrodes.

To get the position of each bunch which passes through a button electrode, the first step is to obtain the reciprocal of the radio frequency (RF) $T_{\rm rf}$. The most straightforward way to get it is to record the frequency readings of the signal generator used for synchronizing the whole accelerator. However, the frequency readings of the signal generator are consequentially different from the true frequency, so a Fourier transformation is used to obtain the RF frequency. To improve the precision, we use the zero-padding method, which makes the data length 128 times longer than the raw data: if the original data length is not a power of two, then zero-padding its length to a power of two makes the data length 128 times longer.

The next step is to determine the start point. Considering the mismatch between the channel time delay and the oscilloscope, and measurement accuracy, we chose the first peak as the starting point for each channel.

The bunch-by-bunch BPM signal can be obtained from the raw waveform data with the sampling interval $T_{\rm rf}$. To get the synchronized sampling points, the signals were re-sampled and the cubic spline interpolation algorithm was used. Fig. 3 gives the relationship between the sampling points and the original data points.

The bunch-by-bunch position can be obtained by using the difference over sum method (Δ/Σ). The sum of the four signals is proportional to the charge of each bunch.

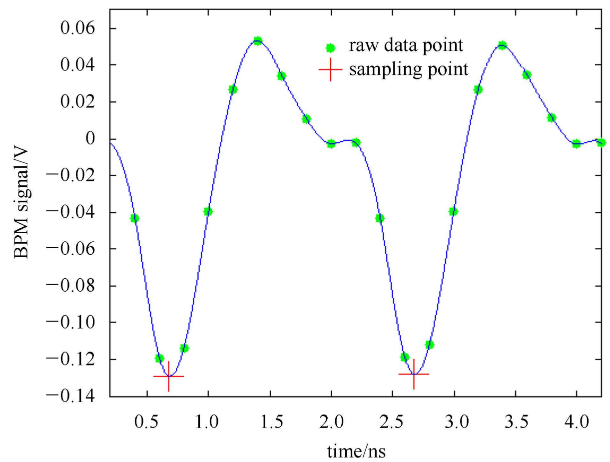

Fig. 3. (color online) Relationship between sampling points and original data points.

4 Data analysis and processing

4.1 Data processing for sum signal

The sum signal of four channels, after calibration with a DCCT, can be used to illustrate the bunch filling pattern (charge distribution in the bunch train), which indicates the uniformity of the filling pattern [9].

The injected bunch can be identified by the distribution of charge difference before and after an injection.

4.2 Data processing for position signal of the injected bunch

The spectrum of the injected bunch position signal (the red line in Fig. 4) can be obtained by harmonic analysis. The amplitude of the resonance peak of the energy oscillation can be used to evaluate the energy mismatch between the injected and stored bunches. A larger amplitude of energy oscillation means that there is a more serious energy mismatch.

As a reference, the spectrum of the stored bunch in Fig. 4 is drawn with a blue line and the amplitude of the

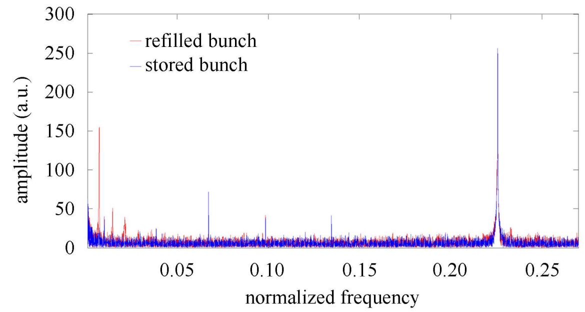

Fig. 4. (color online) Spectrum of the refilling bunch and the stored bunch position signals.

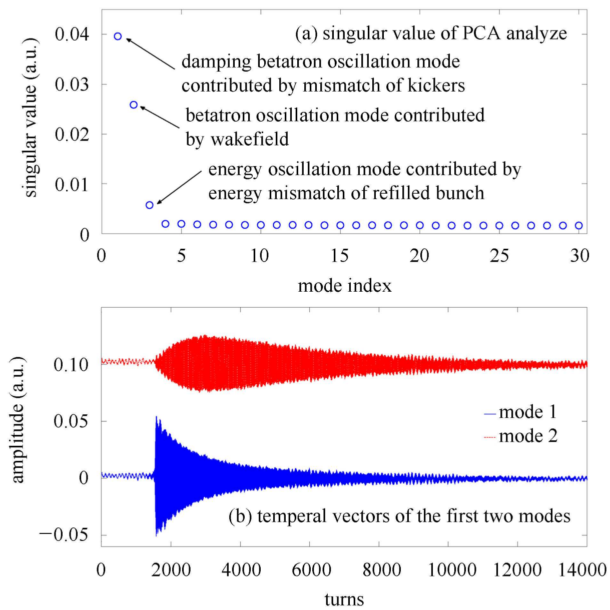

Fig. 5. (color online) (a) Singular value of PCA analysis for position signal; (b) Temporal vectors of the first two modes.

energy oscillation is below the noise floor of the measurement system.

4.3 Data processing for position signal

The PCA method is used for physical model separation and noise reduction [10]. The space vector of the damping betatron oscillation mode (mode 1) corresponds to the residual oscillation amplitude of each bunch (i.e. the mismatch between kickers), as shown in Fig. 5. Fig. 5 also shows the betatron oscillation mode contributed by the wakefield (mode 2), which will not be discussed in this paper.

4.4 Reconstruction of amplitude distribution of residual oscillation for all 720 buckets

The ideal experimental method is to make the starting point of the kicker waveform iterate through all of the buckets during single-bunch operation. However, that will need a large amount of machine study time.

Considering that the filling pattern is a series of 500 buckets during user operation, information for these buckets can be obtained during one injection.

Since the timing between the excitation current waveform of the kickers and the injected bunch is strictly synchronous, a complete residual oscillation distribution can be obtained by combining several groups of injection data, as shown in Fig. 6.

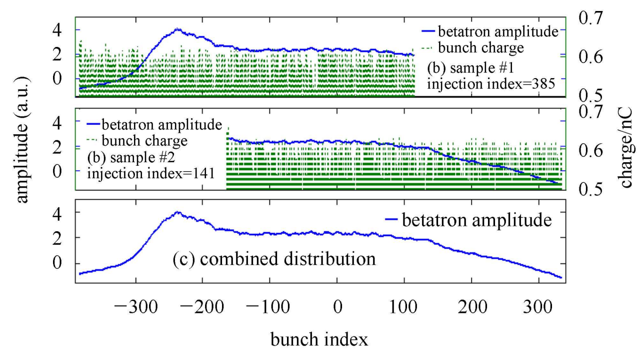

Fig. 6. (color online) Combined distribution of residual oscillations.

5 Injection performance evaluation for the storage ring

5.1 Evaluation results for the kicker angle and the kicker signal delay performance

Turn-by-turn data, regarding the bunch train as a whole, which is obtained with the charge-weighted average of the bunch-by-bunch data, can be used to observe the residual oscillations at the μs scale and evaluate the average performance of the injection system. This measurement is mainly used for the optimization and evaluation of the kicker angle and the signal delay time between the kickers.

Two optimizations performed after 2011 have achieved remarkable results in decreasing the average residual oscillation amplitude, as shown in Fig. 7.

5.2 Performance evaluation for the energy matching of the refilled bunch

The energy oscillation of the injected bunch is large at the SSRF. The oscillation amplitude and refilled charge have a strong linear dependence, which proves that the disturbance comes from the energy mismatch between the injected and stored bunches, as shown in Fig. 8. This disturbance has no obvious effect on the majority of users, but users who are sensitive to the fine structure of the light pulse can observe the disturbance of the energy oscillation.

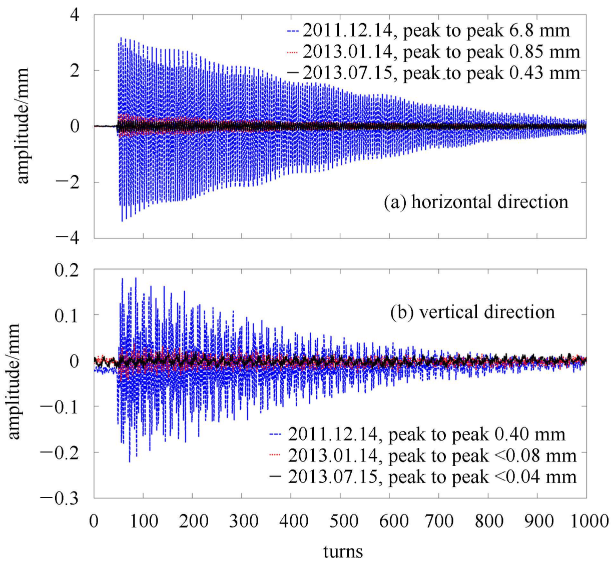

Fig. 7. (color online) Results of two optimizations, in 2011 and 2013.

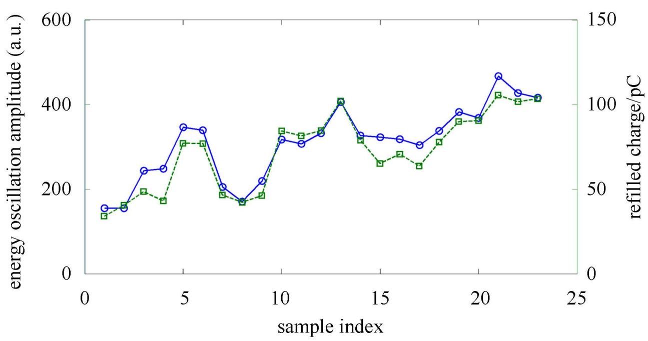

Fig. 8. (color online) Relationship between oscillation amplitude and refilled charge.

The energy oscillation amplitude is proportional to the charge of the injected bunch (as shown in Fig. 8). This index can be improved by optimizing the energy matching degree of the injection bunch and stabilizing the injection bunch charge.

5.3 Determination of the distribution of the residual oscillation

To evaluate the reproducibility, we monitored the residual oscillation over several days (as shown in Fig. 9). We find that the distributions are basically the same, but the amplitudes vary. This result means there are random fluctuations in the disturbance of the bunch, which is not conducive to building feed-forward compensation.

5.4 Effects on the bunch train of a non-uniform distribution of the residual oscillations

Regarding the bunch train as a whole, the average residual oscillation amplitude is the charge weighted average of each bunch oscillation amplitude in the storage ring. Based on the distribution of the residual amplitude above, the relationship between the average residual amplitude and the index of the injected bunch is shown in Fig. 10 when the storage ring is continuously filled with 50, 100, 200, and 500 bunches.

In Fig. 10, we find that the average residual amplitude is periodic, i.e. the disturbance to the bunch train is not constant during injection, and it is not favorable to feed-forward compensation. This effect should be observable in the accumulation of the beam current.

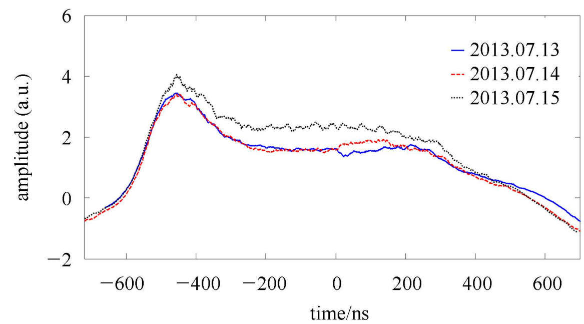

Fig. 9. (color online) Reproducibility of the distribution of residual oscillations.

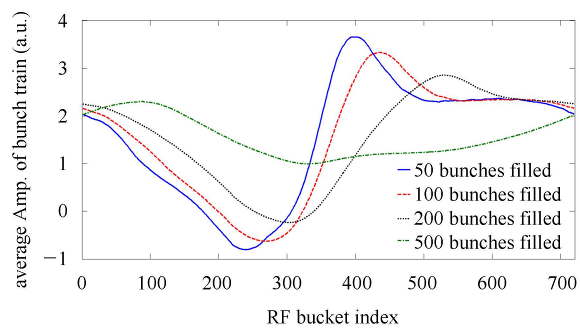

Fig. 10. (color online) Relationship between the average residual amplitude and the index of the injected bunch.

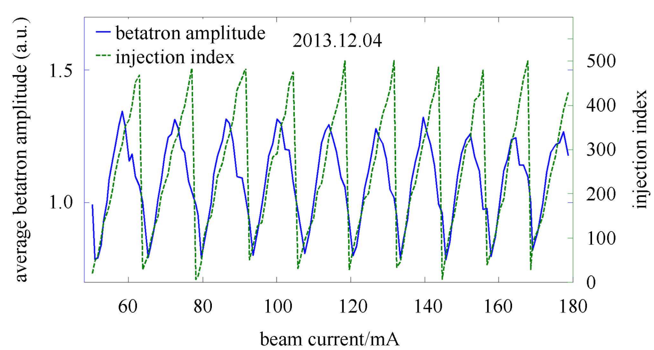

Fig. 11. (color online) Relationship between betatron oscillation amplitude, injection bunch index, and average current.

To verify this inference, we use Libera to get turn-by-turn data in the process of beam accumulation. On 4 December 2013, the beam current in the SSRF storage ring was raised from 50 mA to 179 mA (continuously filled with 500 bunches). During this process, we simultaneously recorded the average current, the charge distributions of the bunch train, and the turn-by-turn transverse position data. After processing the data, the relationship obtained between the betatron oscillation amplitude, the injection bunch index, and the average current is shown in Fig. 11. We can see that the average amplitude of betatron oscillation depends linearly on the injection bunch index.

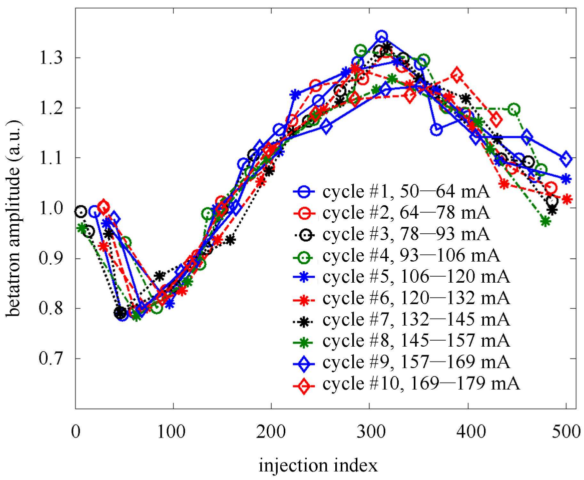

Fig. 12. (color online) Relationship between the amplitude of average residual oscillation and the index of the injected bunch over 10 cycles.

Rearranging the data above by taking the injection bunch index from low (1) to high (500) as one cycle, the whole process of beam accumulation can be divided into 10 cycles. By using injection bunch index as the abscissa axis and the amplitude of average residual oscillation as the ordinate, we can get the dependency relationship between them, as shown in Fig. 12. This shows that the average residual oscillation amplitude is a periodic function of the injection bunch index. The reproducibility is very good over the 10 cycles, and it is consistent with our expectations.

6 Conclusion

The bunch-by-bunch position measurement system is very effective in the performance evaluation of the injection process as an analysis and diagnosis tool at the SSRF. Compared with the turn-by-turn data, it can obtain much more transient information for the injection process and is more conducive to optimizing the equipment.

We achieved evaluation of the energy matching degree of the injection bunch. The result shows that the energy matching degree of the refilled bunch is poor. The fluctuation of the charge of the injected bunch is large. Therefore, the kickers can be further optimized.

Reconstruction of the amplitude distribution of the residual oscillation for the whole turning period caused by the kicker leakage field is accomplished. According to the measurement, the distribution of this amplitude has a periodic structure. The average disturbance amplitude of the stored bunch train depends on the injected bunch index and it also has a periodic structure. This inference is supported by the turn-by-turn experimental data.

The analysis of multiple sets of data indicates that the shape distribution of the kicker leakage field is stable but a slow drift in amplitude still exists, which is not conducive to feed-forward compensation. More effort is needed to improve the stability of the excitation current waveform of the kickers.

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