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BEAM COUPLING IMPEDANCE ANALYZE USING BUNCH-BY-BUNCH MEASUREMENT*

X. Y. Xu[1], Shanghai Institute of Applied Physics, CAS, Shanghai, China
Y. B. Leng†, Shanghai Advanced Research Institute, CAS, Shanghai, China
[1]also at University of Chinese Academy of Sciences, Beijing, China

Abstract

Beam coupling impedance is very important parameters for advanced synchrotron radiation facilities. Till now there is no online method to measure beam impedance directly. But some beam parameters such as betatron tune amplitude and frequency, synchrotron phase, bunch lifetime and so on, can be modulated by beam impedance effects. So wake field and beam impedance information could be retrieved by measuring bunch-by-bunch beam 3D positions and analyzing bunch index dependency of above beam parameters. A bunch-by-bunch 3D positions and charge measurement system had been built at SSRF for this purpose and the performance is not good enough for beam impedance analyze due to cross talk between bunches. We upgraded the measurement system to minimize cross talk and improve resolution this year. New beam experiment results and corresponding analyze will be introduced in this paper.

INTRODUCTION

The advanced synchrotron radiation light sources have the following basic characteristics: ultralow beam emittance (few nmrad or even tens of pmrad), ultra-high beam stability (orbital feedback control accuracy is mostly micron or submicron level), high average beam current (above 300mA), small-aperture beam vacuum pipe (below 30mm in diameter), a large number of vacuum inserts in , top-up operation mode, small dynamics aperture, with high time resolution experiment ability (time resolution ps order) and so on. The use of small-aperture vacuum pipes and a large number of inserts makes the problem of beam instability caused by the wakefield particularly prominent. Under this condition, the problem of strong beam wakefield (large beam impedance) will become a key issue that limits the further improvement of light facility performance [1]. Correspondingly, how to optimize the beam impedance in the design stage and how to accurately target the source of beam impedance during the commissioning and operation stage to give optimization opinions is the key technical issues that must be resolved when development of the next generation of advanced synchrotron radiation facility.

Under ideal conditions, the particles move steadily in the storage ring. Due to the action of the strong focusing principle and the principle of automatic phase stabilization, the particles make β oscillations around the closed orbit in the transverse. The synchronous particles in the longitudinal direction make synchronous oscillations. When the oscillation amplitude is small, the transverse oscillation can be considered as simple harmonic vibration. The bunches running in the pipeline will excite the wakefield. If the wakefield decays slowly, it will have an effect on the subsequent bunches. The oscillation amplitude of the bunches under the effect of the wakefield may increase, causing instability. Because its effect is that many bunches are coupled together through the wakefield, it is called coupling instability. The wakefield that can produce coupling instability must not be attenuated before the next bunch arrives. The impedance corresponding to such a wakefield is an impedance with a higher quality factor Q value, or narrow-band impedance. These narrow-band impedances correspond to the higher-order modes of the cavity-like.

At present, the research methods of beam wakefield and impedance mainly include four methods: analytical method, simulation calculation method, emulation test, and beam machine research.

The above methods have their own advantages and limitations in application. The analytical method has the most complete theory, but it can only calculate simple and regular structures, which is not suitable for a new generation of high-performance light sources with many IVU. The simulation calculation method has great application value in the pre-research stage of the accelerator storage ring, but as the structure of the storage ring becomes more and more complex, the device structure cannot be perfectly reconstructed in the software, which has a great influence on the accuracy of the simulation results. In addition, the complicated storage ring structure also brings about the problems that the algorithm cannot converge normally, the calculation time is long, and the resources are occupied. The emulation test method can measure the impedance of some devices in the laboratory. Its disadvantage is that on the one hand, the cold test result in the experiment cannot be completely equal to the result after installation. On the other hand, it is inevitable that the connector will be tightened during the electrical signal input process. The transition section excites a lot of noise signals and causes measurement errors. In order to tighten and straighten the center wire, it is impossible to make it very thin, and there is a certain systematic error. The beam machine research method can directly measure the accelerator beam wakefield, but most of the existing methods require specially designed machine research experiments to measure the wakefield in a special bunch filling mode. The storage ring structure will be adjusted during operation (for example,

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† lengyongbin@sinap.ac.cn

the magnetic gap of the insert in the vacuum will change at any time according to user needs), which will affect the wakefield function in real time, relying on special machine research to traverse all states to determine the corresponding beam wakefield, will inevitably take up a lot of equipment running time, reducing equipment operating efficiency.

WAKEFIELD ANALYSIS BY BUNCH-BY-BUNCH POSITION

If the basic parameters (charge amount, three-dimensional position, etc.) of all bunches in storage ring can be independently measured, and the measurement accuracy is high enough, then we can use all the bunches in the storage ring as sources and witnesses. When the wakefield effect is strong enough, the required wakefield information can be obtained by analyzing the changes of the bunch parameters. In the normal operation of synchrotron radiation light source, if we can find a suitable physical process in which the wakefield effect is sufficiently obvious, then we can achieve real-time in-situ beam wakefield measurement without changing the beam conditions and without affecting the user's experiment [2–4].

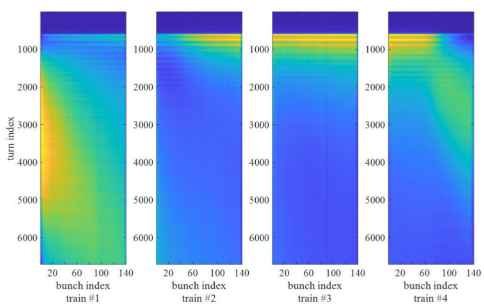

Figure 1: Transverse position during injection transient at x-axis.

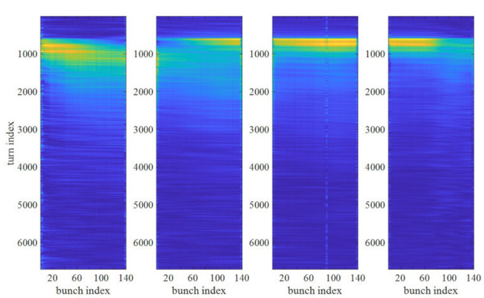

Figure 2: Transverse position during injection transient at y-axis.

For the transverse wakefield, only when the excitation bunch has a relatively large transverse position offset, it is possible to excite a sufficiently large field strength to generate a physical quantity to be measured that can meet the measurement accuracy requirements. During the normal operation of the synchrotron radiation source, such beam conditions are not available most of the time. However, in the transient process of injection, due to the existence of the kicker field, almost all the bunches will deviate greatly from the equilibrium orbit (on the order of millimeters) at the moment of injection, and then perform a transversely damped simple harmonic oscillation (coherent Beta oscillation) to excite The stronger transverse wakefield becomes the excitation bunch (shown in Fig. 1 and Fig. 2). At the same time, all bunches will be affected by this transverse wakefield to produce incoherent Beta oscillations, and at the same time become the witness bunches. Therefore, as long as we can capture the transient process of injection, accurately determine the change in the transverse position of each bunch during this process, and separate the coherent Beta oscillation and incoherent Beta oscillation of each bunch, we can use fitting Incoherent Beta oscillation waveform to obtain the information of the transverse wake field. The capture of injection process data can be achieved by using the amplitude jump of the BPM signal at the injection time as a trigger condition. The separation of coherent Beta oscillation and incoherent Beta oscillation data can be realized by analyzing the multi-bunch multi-turn data matrix by using the principal component analysis method (PCA). We hope to find a wakefield function that can satisfy the transverse oscillation evolution of each bunches. If under the effect of the wakefield potential, the transverse oscillation evolution process predicted by the model is consistent with the measured data, then this wakefield function is worthy of trust.

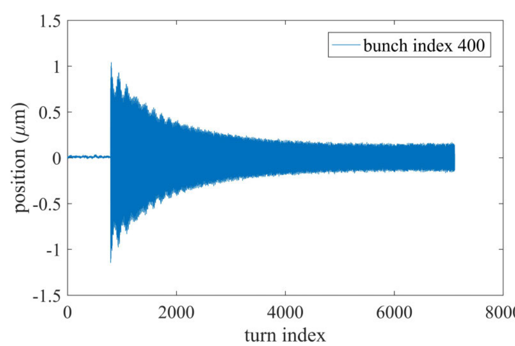

Figure 3: Transverse position of bunch 400 at y-axis.

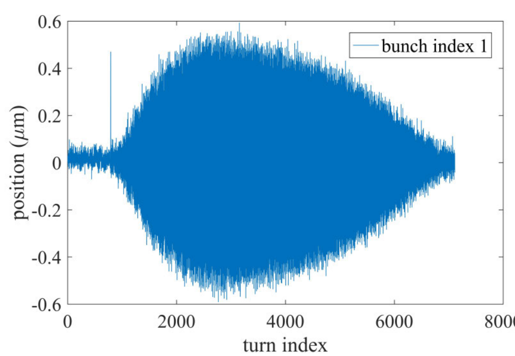

Figure 4: Transverse position of bunch 1 at y-axis.

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Some bunches that were originally stable in transverse position increased rapidly after injection (shown in Fig. 3). The envelope is an exponential decay, so it could be considered as a betatron damping oscillation invoked exclusively by the kickers mainly. The spatial vector indicated that the kickers fields influencing the bunches were not constant. In bunch index 1, this effect of kickers is very small. Therefore, the change of the transverse oscillation amplitude of 1st bunch is mainly affected by the wakefield (shown in Fig. 4). The wake oscillation of a bunch is determined by the betatron oscillations of all bunches. The propagation coefficient of the wakefield is considered a constant once the drive bunch and the witness bunch are decided, so the amplitude of second mode of a bunch is a linear combination of the amplitudes of the first modes of all bunches (including itself). Due to the special filling mode, there are more than 40 empty buckets in front of bunch 1st. Therefore, the length of the global wakefield of the storage ring is much longer than dozens of bunches.

$$W_x(j-i) = \frac{\Delta x_i}{q_i q_j} \cdot x_j \qquad (1)$$

According to the definition of wakefield, we define the global equivalent wakefield with Eq. (1). Where $W_x(j-i)$ is the influence on the oscillation amplitude in y-axis after $j-i$ buckets. x_i and x_j is transverse oscillation amplitudes of bunches. q_i and q_j are charges of bunches. Taking the oscillation amplitude of each bunch in the current turn as known data, calculate the transverse position of the follow thousands of turns according to the equivalent global wakefield and damping coefficient as parameters, and compare it with the measured value. Taking the minimum residual error between the predicted position value and the measured position value as the optimization goal, we found a rough equivalent wakefield function shown in Fig. 5.

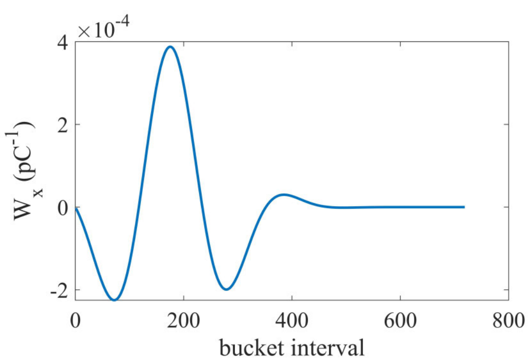

Figure 5: A specific solution of equivalent wakefield function in x-axis shows the coupling relationship between the bunches.

There are more than 500 bunches in the storage ring under normal operation in SSRF. The coupling relationship between bunches is very complicated, so there is more than one solution of the equivalent wakefield function that can satisfy the evolution trend of each bunches transverse amplitudes. In the future, it is necessary to eliminate the error solution of the equivalent global wakefield by different filling modes data. In addition, considering the effect of the driving force of the transverse movement of the bunches, the wakefield force influence on the transverse oscillation of the bunch is related to the oscillation phase, so the model needs to be further optimized.

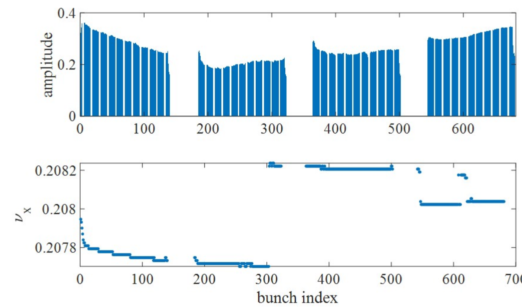

Figure 6: The frequency shift of betatron oscillation at x-axis.

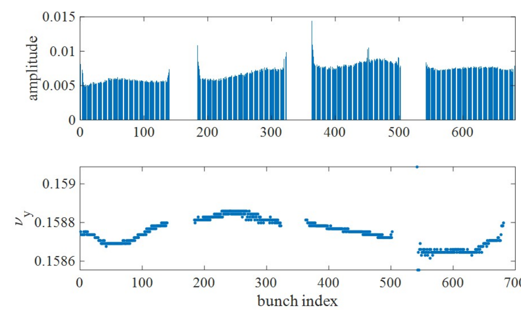

Figure 7: The frequency shift of betatron oscillation at y-axis.

The frequency shift of betatron oscillation has been observed (shown in Fig. 6 and Fig. 7). Due to transverse quadrupolar wakefield, the frequency of betatron oscillation is dependent on bunch index. This means that transverse quadrupolar wakefield are expected to be extracted from the bunch-by-bunch position data. However, the impact of the transverse quadrupolar wakefield into tune is very small, which places high requirements on the measurement accuracy. In the next step, more experiments need to be done to determine whether the difference in operating points is always present, rather than caused by measurement errors.

In order to further study this phenomenon, a special beam experiment was done. In this experiment, we turned off the transverse feedback system and turned off the insert vacuum undulators (IVU) in turn. Due to the closing of the feedback system, the transverse oscillation of the bunch will be maintained at a relatively large magnitude for a long time. The relationship between the average tune of bunches and the state of IVU is shown in Fig. 8. It can be seen that the average tune becomes larger with the opening of IVU.

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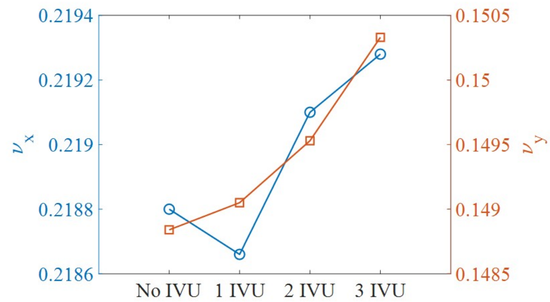

Figure 8: The frequency shift of betatron oscillation with different IVU status.

CONCLUSION

The analysis of coupling impedance and wakefield is of great significance for optimizing the structure of the IVU and finding the source of beam instability. This paper proposes some methods for in-situ analysis of the wakefield in the normal operation model of the storage ring. These methods are based on the bunch-by-bunch three-dimensional position measurement and charge measurement technology. In the storage ring, hundreds of bunches are both the source and the witness. By monitoring the position of each bunch, the evolution process of the bunch position under the action of the coupled wakefield is clearly seen. Using the PCA method, the wakefield oscillation mode can be separated.

In theory, if a sufficiently complete mathematical model is established, the value of the wakefield function between the bunches can be solved. With the existing computing resources, a relatively simple model was established to describe the evolution of the transverse oscillation amplitude of each bunch over time under the combined action of the wakefield and the damping term. We use this model to predict the evolution trend of the transverse oscillation amplitude of these bunches in the follow thousands of turns through the transverse oscillation amplitudes of all bunches in the current turn. The model works well in some data sets, but it is not universal, and the wakefield solution applicable to a set of data is not unique. Therefore, more data is needed to screen the solutions of the wakefield. The data with different IVU states are analyzed. When the insert is very close to the beam, the beam is affected by a large short-range impedance wall and shows obvious instability in the string. In addition, the difference in the transverse oscillation frequency of the bunch can be observed, which is the basis for analyzing the quadrupole wakefield.

The analysis of the coupled wakefield has just begun. The current simplified model can only roughly agree with the transverse oscillation evolution process of bunches in some cases. Since the predicted value is used to calculate the future position, the cumulative error is quickly amplified after thousands of turns. The equivalent coupled wakefield function found by the current model needs to be further verified. In the future, our model needs to be further improved. For example, the influence of the transverse oscillation phase difference of the bunches will be accepted into the model. For the longitudinal wakefield, we plan to start from the longitudinal balance phase of each bunch, and calculate the longitudinal wakefield function through the difference of the acceleration phase.

REFERENCES

[1] H. Tanaka, "Trends and Challenges in the Future Storage Ring Light Sources", presented at the 60th ICFA Advanced Beam Dynamics Workshop (FLS'18), Shanghai, China, Mar. 2018, paper MOA2PL01, unpublished.

[2] Adolphsen, C. and Bane, K. and Higo, T. and Kubo, K. and Miller, R. and Ruth, R. and Thompson, K. and Wang, J, "Measurement of Wake-Field Suppression in a Detuned *X*-Band Accelerator Structure," *Phy. Rev. Lett.*, vol. 74, no. 13, p. 2475-2478, Mar. 1995. doi:10.1103/PhysRevLett.74.2475

[3] Chen, Zhichu and Yang, Yong and Leng, Yongbin and Yuan, Renxian, "Wakefield measurement using principal component analysis on bunch-by-bunch information during transient state of injection in a storage ring," *Phys. Rev. ST Accel. Beams*, vol. 17, p. 112803, Nov. 2014. doi:10.1103/PhysRevSTAB.17.112803

[4] X. Y. Xu, Y. B. Leng, and Y. M. Zhou, "Machine Learning Application in Bunch Longitudinal Phase Measurement", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 2625–2628. doi:10.18429/JACoW-IPAC2019-WEPGW064