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LONGITUDINAL PHASE SPACE RECONSTRUCTION IN AN ELECTRON STORAGE RING

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Abstract

This paper proposes a novel technique for reconstructing the longitudinal phase space of freshly injected bunches in an electron storage ring to obtain initial parameters. This technique combines the development of a single-bunch injection phase space simulation software with the establishment of a bunch-by-bunch data acquisition and processing system, enabling high-precision determination of the initial parameters of the injected bunch during the injection process (including initial phase, initial bunch length, initial energy deviation, initial energy spread, and energy chirp). The experiment uses a high-speed oscilloscope to collect the beam injection signals, which are then processed by data processing scripts to extract the evolution information of the phase and bunch length of the injected bunch. A single data acquisition covers thousands of turns, achieving a phase measurement precision of 0.2 ps and a bunch length measurement precision of 1 ps. Additionally, a single-bunch simulation software based on the mbtrack2 package is developed, which can simulate the phase space evolution of the bunch after injection under different initial phase space distributions. Using a genetic algorithm and taking the Pearson coefficient and variance between experimental and simulated data as the fitness function, the optimal initial parameters of the injected bunch are obtained through iteration. This technique enables a deeper understanding of the longitudinal dynamics of particle beams. By obtaining the phase space distribution information of the particle beam, we can promptly detect and correct deviations and instabilities in the injection system, thereby improving injection efficiency and beam quality.

INTRODUCTION

In advanced synchrotron light sources, the injection process of electron storage rings is a critical factor affecting beam quality and stability. Optimizing the injection process can reduce beam loss, improve injection efficiency, and minimize interference with experiments. Therefore, in-depth research and optimization of the injection process in electron storage rings have significant theoretical and practical importance.

The arrival time and bunch length of freshly injected bunches can typically be measured directly using a streak camera. A streak camera can capture the changes in the longitudinal size of a bunch within a snapshot time[1-3]. However, it cannot simultaneously achieve high temporal resolution and a large dynamic range. Additionally, existing diagnostic tools struggle to provide direct and accurate measurements for parameters such as central energy, energy spread, and energy chirp[4]. These parameters are crucial for optimizing the injection process and enhancing the performance of light sources. However, there is still a lack of effective experimental methods for precise characterization and analysis.

This paper proposes a new technique for reconstructing the longitudinal phase space based on the current research status. A high-speed oscilloscope captures the beam signal during the injection process. It combines it with advanced data processing algorithms to achieve phase space reconstruction of the particle beam in a single injection process. The technique enables precise measurements by integrating this with a newly developed single-bunch tracking simulation software based on the mbtrack2 package[5-7]. It predicts and simulates the behavior of particle beams in storage rings, providing a powerful tool for optimizing injection.

STORAGE RING BUNCH-BY-BUNCH PHASE AND BUNCH LENGTH MEASUREMENT SYSTEM

We have developed a bunch-by-bunch diagnostic system that calculates the beam's three-dimensional position, charge, and bunch length based on raw data collected from the Beam Position Monitor (BPM). This system can cover several thousand turns in a single data acquisition, achieving a bunch-by-bunch phase measurement accuracy of 0.2 ps and a bunch length measurement accuracy of 1 ps. Below is an introduction to this system's calculation principles of phase and bunch length. For an ideal Gaussian-distributed beam, its time-domain expression is:

$$I(t) = \frac{Q}{\sqrt{2\pi}\sigma} exp\left[-\frac{(t-t_0)^2}{2\sigma^2}\right] \tag{1}$$

Where Q is the bunch charge, σ is the bunch length, and t_0 is the bunch phase. When the beam passes through a button electrode, the expression for the induced detection signal on the electrode is:

$$V_b(t) = \frac{\pi a^2}{2\pi b} \bullet \frac{1}{\beta c} \bullet Z \bullet \frac{t-t_0}{\sigma^2} I(t) \bullet F(\delta,\theta) \tag{2}$$

Where a,b are the physical dimensions of the button electrode, F(δ,θ)is the transverse position of the bunch, and Z is the transmission impedance of the button electrode. Thus, the bunch phase and length can be obtained by directly sampling the BPM signals. The entire system includes a data

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acquisition part and an offline processing part[8-10]. The structural block diagram of this system is shown in Fig. 1. The data acquisition system uses a high-speed oscilloscope (with a 6 GHz bandwidth, 16 GHz sampling rate, and 16-bit resolution) to capture the coupling signals from the button electrode. A single acquisition can cover several milliseconds, corresponding to thousands of particle revolution periods. The RF frequency of the Shanghai Synchrotron Radiation Facility (SSRF) is 499.5 MHz, and the signal length induced by each bunch is approximately 2 ns. This allows for acquiring 32 points per bunch signal, enabling a reasonable reconstruction of the signal waveform. Offline scripts then process the acquired data for further calculations.

In the offline processing script, the phase extraction algorithm considers the effects of bunch length and charge. A response function is constructed for each bunch individually. Based on these response functions, a lookup table is established by iterating all possible phases with a step size of 0.1 ps. The correlation function method is used to find the element with the highest correlation to the measured data.

As for bunch length calculation, when the signal period(T) of a single bunch is obtained, the original sampled data (a one-dimensional array) is reorganized into a three-dimensional array (bunch-by-bunch, turn-by-turn, bunch waveform) by slicing the data for each bunch and each turn according to the measured signal period(T). A harmonic analysis is performed on the voltage waveform data of the sliced bunch signals to obtain the voltage signal spectrum. This spectrum is multiplied by the transmission impedance to obtain the current signal spectrum. A Gaussian fit is applied to the current signal spectrum, and the reciprocal of the frequency domain distribution σ yields the bunch length in the time domain.

SIMULATION DEVELOPMENT AND SINGLE BUNCH TRACKING

To better understand bunches' longitudinal phase space evolution during the injection process in an electron storage ring, we developed a single-bunch simulation tool based on the mbtrack2 and PyQt5 software packages. This tool is used to track the longitudinal phase space distribution of bunches after injection. The user interface of the software is shown in Fig. 2:

- Top Left: Displays the phase space distribution of the bunch at a specified turn after injection.
- Middle Left: Shows the phase evolution results.
- Bottom Left: Displays the bunch length evolution results.
- Top Right: Initial parameter input area, which includes parameters such as initial bunch length, initial energy spread, initial phase, initial energy offset, and initial energy chirp, allowing control of the initial phase space distribution of the injected bunch.
- Bottom Right: Control area, used for selecting the turn to be viewed, displaying the phase and bunch length of the current turn, saving data, saving images, etc. `boxit` option.

The software supports reading external machine parameter files, allowing it to be adapted to any accelerator by modifying the machine parameter files. All simulations use a single-bunch model, with 10,000 simulated particles and 5,000 turns (parameters are adjustable).

Figure 3 illustrates the evolution of the longitudinal phase space of a particle bunch in an electron storage ring obtained using the developed simulation software. Each subfigure corresponds to a specific turn, where the X-axis represents the phase time difference (τ), and the Y-axis represents the energy deviation (δ).

During the evolution process, the phase space trajectory of the particle bunch gradually bends, with noticeable filamentation effects appearing at the head and tail of the bunch, indicating the influence of nonlinear effects in the later stages. After 2,500 turns, the bunch gradually stabilizes, forming a compact distribution, and the system reaches an equilibrium state with reduced nonlinear effects.

Table 1: SSRF Main Parameters

Parameter	Value
Energy(E)	3.5GeV
Current(I_0)	200mA
RF frequency(f_{rf})	499.654MHz
Buckets(h)	720
Designed bunch length (σ)	18ps
Revolution Frequency(f_0)	694kHz
Synchrotron tune(υ_s)	0.007

BEAM EXPERIMENT

We collected multiple data sets during the empty ring injection in the Shanghai Synchrotron Radiation Facility (SSRF). The main machine parameters of the SSRF are listed in the Table 1. When a bunch is injected, the oscilloscope captures the trigger signal and records the data, taking samples at intervals over time. Using the developed bunch-by-bunch diagnostic system script, we calculated a single bunch's longitudinal phase and length evolution over several thousand turns during the injection process. The following is the reconstructed two-dimensional distribution of bunch length versus phase based on the calculation results from a typical data set (Fig. 4a).

After obtaining the optimized initial parameters, we used them with the simulation software to acquire a single bunch's longitudinal phase space evolution results under these initial conditions. Figure 4c shows a comparison between the simulation results and the experimental results. It can be seen that the 2D distribution of bunch length versus phase reconstructed by the simulation is highly consistent with the experiment, indicating the accuracy of the simulation software and reflecting the high precision of the bunch-by-bunch

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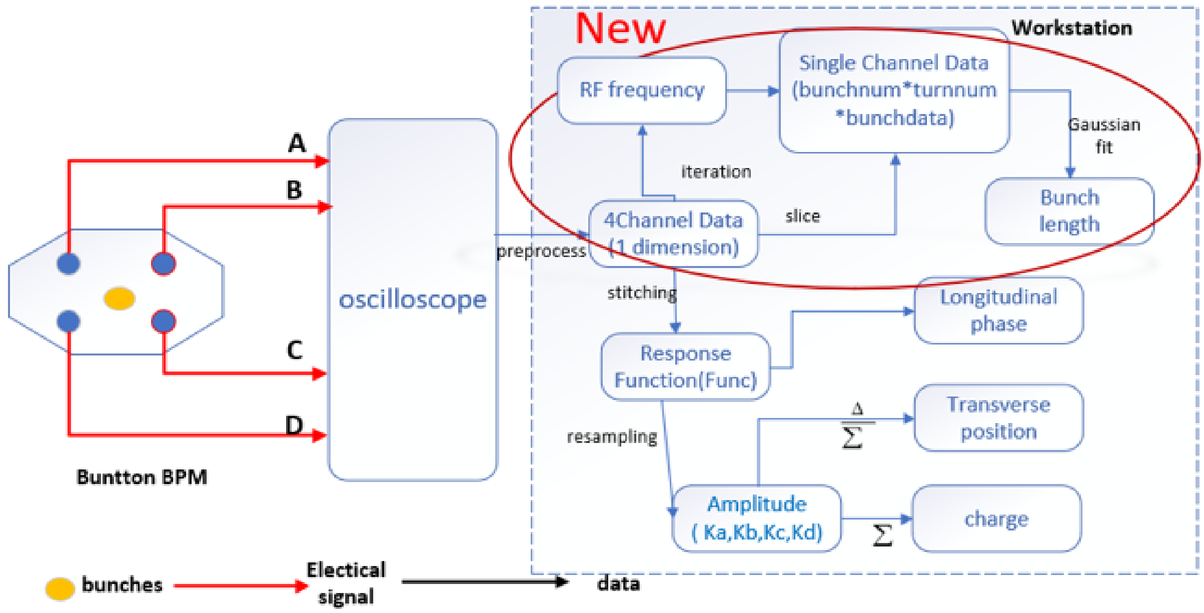

Figure 1: Structural diagram of bunch by bunch diagnostic system.

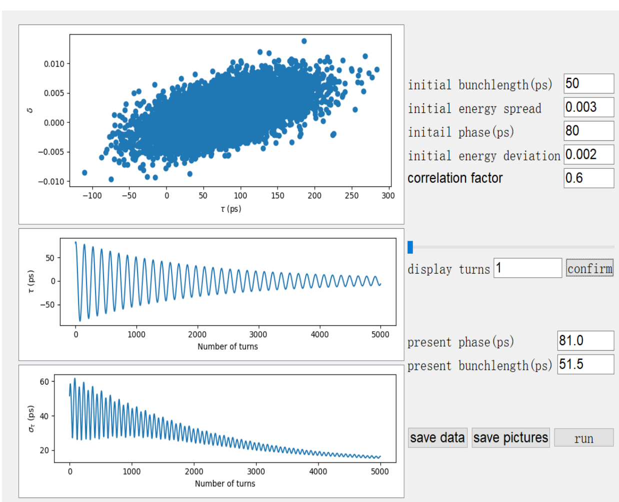

Figure 2: Single beam longitudinal phase space simulation software interface.

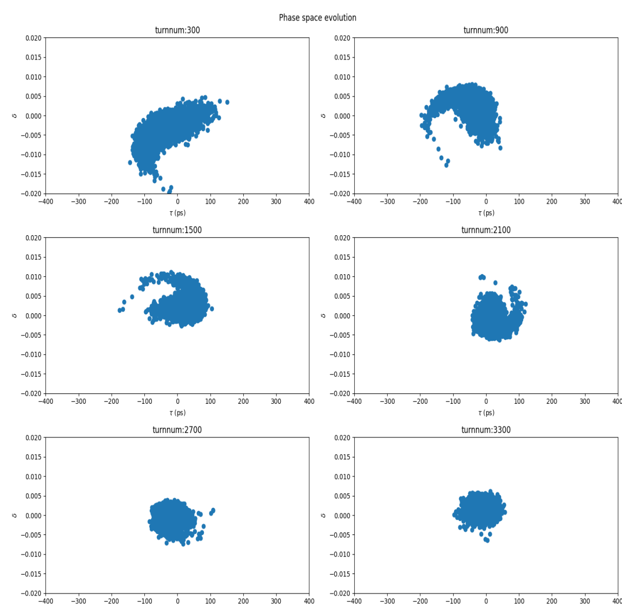

Figure 3: Longitudinal phase space evolution of a single bunch.

diagnostic system. Additionally, we selected several key time points to reconstruct the simulated bunch's 2D phase space distribution projections along the time axis. Based on the experimental measurements of bunch length and phase, we also restored the corresponding Gaussian distribution of the bunch in real space (as shown in Fig. 4b). It can be observed that the match between the two is relatively high, even with the presence of phase space filamentation. Moreover, based on the evolution of the projections, it is observed that under the effect of synchrotron radiation damping, the bunch phase space distribution continuously contracts towards the center and eventually approaches a standard Gaussian distribution.

CONCLUSION

Using the bunch-by-bunch data processing script, we can obtain the initial phase and initial bunch length of the injected bunch and their evolution over several thousand turns and reconstruct the 2D phase space distribution. However, the script cannot determine the injected bunch's initial energy deviation or initial energy spread. Therefore, we developed a simulation script based on the mbtrack2 software package for single bunch injection's longitudinal phase space evolution. By providing the initial parameters of the injected

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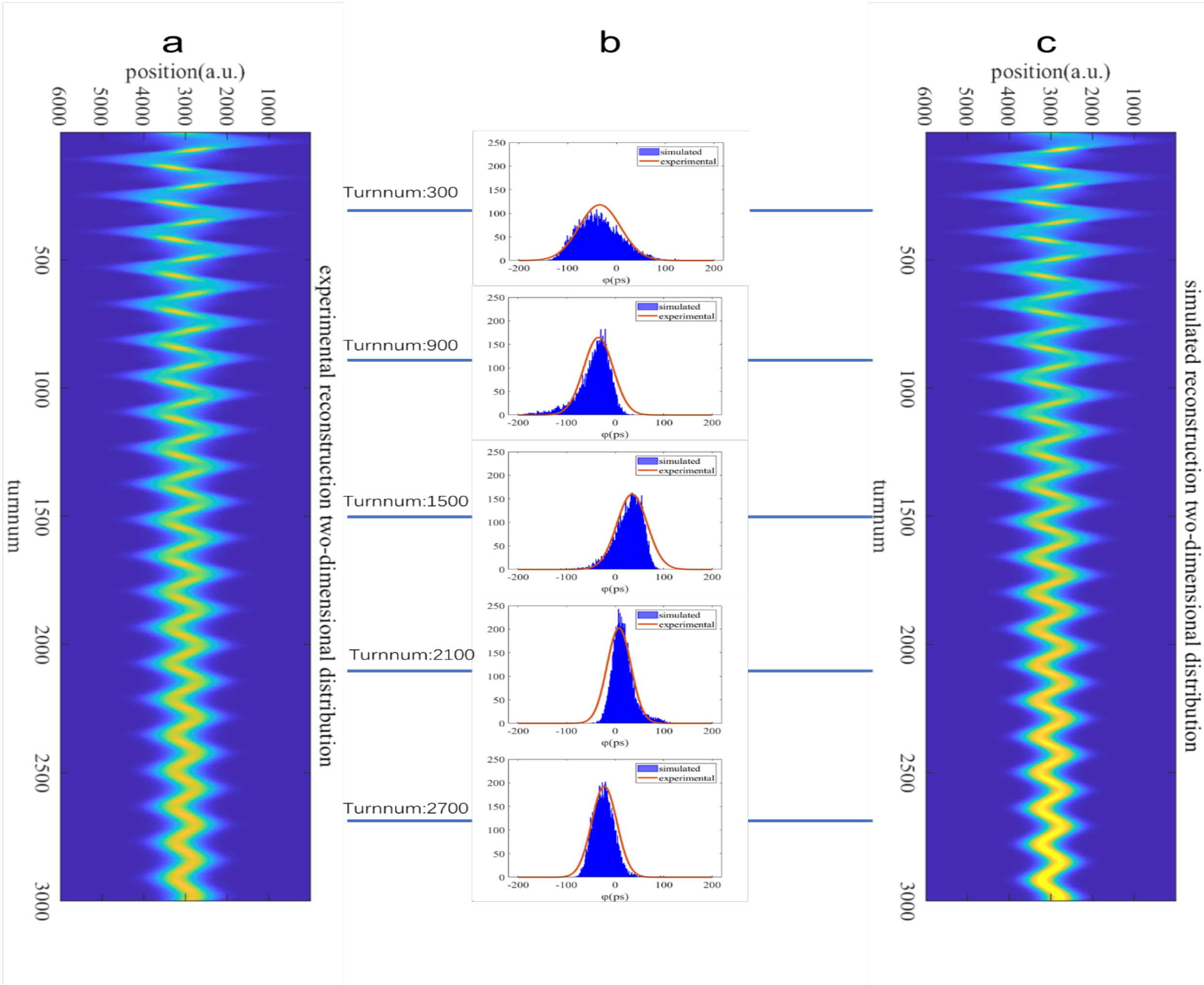

Figure 4: a,c: Experimental and simulation reconstruction of the two-dimensional distribution map of phase and bunch length. b: real space projection.

bunch, we can simulate the phase space evolution data under various injection conditions. Then, by combining experimental data with a genetic algorithm to optimize the initial parameters, we match the simulation data with the experimental data to obtain the initial parameters of the experimental data. The acquisition of these parameters provides a powerful tool for optimizing the injection system.

REFERENCES

[1] J. M. Byrd *et al.*, "Nonlinear longitudinal dynamics studies at the ALS", in *Proc. PAC-99*, New York, NY, USA, in PAC-99, vol. 1.IEEE, pp. 382-386. `doi:10.1109/pac.1999.795711`

[2] J. M. Byrd and S. De Santis, "Longitudinal injection transients in an electron storage ring", *Phys. Rev. Spec. Top. Accel. Beams*, vol. 4, no. 2, Feb. 2001, p. 024401. `doi:10.1103/PhysRevSTAB.4.024401`

[3] T. Watanabe *et al.*, "Measurement of Longitudinal Dynamics of Injected Beam in a Storage Ring", in *Proc. IPAC'11*, San Sebastián, Sep. 2011, paper THPC031, pp. 2978-2980. `https://jacow.org/IPAC2011/papers/THPC031.pdf`

[4] D. Teytelman, *et al.*,"Control and Measurements of Longitudinal Coupled-Bunch Instabilities in the ATF Damping Ring", in *Proc. PAC'07*, Albuquerque, NM, USA, Jun. 2007, paper MOPAS067, pp. 584-586. `https://jacow.org/p07/papers/MOPAS067.pdf`

[5] M. Kim, I. Hwang, S. J. Park, K. R. Kim, J. Huang, S. Nam and S. Shin, "Tracking study of transient behaviors at beam injection of the PLS-II ring", *J. Korean Phys. Soc.*, vol. 63, pp. 2072-2079, Dec. 2013. `doi:10.3938/jkps.63.2072`

[6] N. Yamamoto, A. Gamelin and R. Nagaoka, "Investigation of Longitudinal Beam Dynamics With Harmonic Cavities by Using the Code Mbtrack", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 178-180. `doi:10.18429/JACoW-IPAC2019-MOPGW039`

[7] A. Gamelin, W. Foosang, and R. Nagaoka, "mbtrack2, a Collective Effect Library in Python", in *Proc. IPAC'21*, Campinas, SP, Brazil, May 2021, pp. 282–285. `doi:10.18429/JACoW-IPAC2021-MOPAB070`

[8] H-S. Wang *et al.*, "Bunch-length measurement at a bunch-by-bunch rate based on time–frequency-domain joint analysis techniques and its application", *Nucl. Sci.Tech.*, vol. 35, no. 80,

ISBN: 978-3-95450-249-3 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2024-THP35

2024. doi:10.1007/s41365-024-01443-z

[9] Y-M Deng *et al.*, "Ultrahigh spatiotemporal resolution beam signal reconstruction with bunch phase compensation". *Nucl. Sci.Tech.*, vol. 35, no. 89, 2024. doi:10.1007/s41365-024-01444-y

[10] X. Yang *et al.*, "Determining beam transverse absolute position by triangulation of multi-electrode signal phase differences", *Nucl. Sci.Tech.*, vol. 35, no. 133, 2024. doi:10.1007/s41365-024-01498-y