High Temporal Resolution Beam Loss Monitoring Technology for Hefei Light Source

Authors: Liu Yihong, Xiao Yunzhi, Yu Lingda, Yang Xing, Ma Xiaochao, Leng Yongbin

Date: 2025-06-09T18:15:36+00:00

Abstract

To monitor and analyze the beam loss characteristics during the operation of Hefei Light Source, a high time-resolution synchronous monitoring system for beam loss and bunch position was developed based on a scintillator detector, strip-electrode beam position monitor (Beam Position Monitor, BPM), and high-speed oscilloscope. Through comparison of simulated and measured waveforms, the accuracy of the beam loss pulse waveforms output by the system was verified. Characteristic parameters of the beam loss pulse signals were extracted using a method based on asymmetric Gaussian function fitting. Combined with HOTCAP technology, bunch-by-bunch charge and position information was extracted from the strip-electrode signals. Based on the special filling pattern of the Hefei Light Source storage ring, correlation and alignment of bunch numbers between beam loss data and BPM data was achieved. Using this system, the beam loss conditions during injection transients and post-injection steady-state operation of Hefei Light Source were monitored. The results show that: during steady-state operation, bunch-by-bunch beam loss exhibits significant correlation with charge distribution, consistent with theoretical expectations for random beam loss; during injection transients, a phenomenon was observed for the first time where both the refill bunch and the 14th stored bunch thereafter simultaneously exhibited significant beam loss.

Full Text

Preamble

Vol. XX, No. X, XXX 20XX, NUCLEAR TECHNIQUES

Study on High-Time-Resolution Beam Loss Monitoring Technology for Hefei Light Source II

LIU Yihong[1], XIAO Yunzhi[1], YU Lingda[2], YANG Xing[3], MA Xiaochao[3], LENG Yongbin[1,3]
[1](School of Nuclear Science and Technology, University of Science and Technology of China, Hefei 230027, China)
[2](Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China)
[3](National Synchrotron Radiation Laboratory, University of Science and Technology of China, Hefei 230029, China)

Abstract

[**Background**]: Beam loss monitoring is essential for the stable operation of the Hefei Light Source II (HLS-II). Accurate measurement of bunch-by-bunch beam loss and position information helps to diagnose beam instabilities and optimize accelerator performance. [**Purpose**]: This study aims to monitor and analyze the beam loss characteristics during the operation of the HLS-II. [**Methods**]: A high-time-resolution beam loss and bunch position synchronization monitoring system was developed using a scintillator detector, a strip-electrode beam position monitor (BPM), and a high-speed oscilloscope. The accuracy of the system's beam loss pulse waveform output was validated by comparing simulated and measured waveforms. An asymmetric Gaussian fitting method was employed to extract characteristic parameters of the beam loss pulses. Using the HOT-CAP (a software package for high-speed oscilloscope-based three-dimensional bunch-by-bunch charge and position measurement) technique, bunch-by-bunch charge and position information were extracted from BPM signals. The bunch indexing between beam loss data and BPM data was successfully aligned based on the unique filling pattern of the HLS storage ring, achieving data synchronization. [**Results**]: This system was used to monitor beam losses during both the transient injection process and steady-state operation of the HLS-II. The results indicate that, during steady-state operation, the bunch-by-bunch beam loss exhibits a significant correlation with the charge distribution, consistent with the theoretical expectations of random beam loss. During the transient injection process, a unique beam loss phenomenon was observed for the first time: significant beam loss occurred simultaneously in the injected bunch and the 14th stored bunch following it. [**Conclusions**]: The measurement system is capable of synchronously acquiring bunch-by-bunch charge, transverse position, longitudinal position, and beam loss data from the HLS-II, providing strong technical support for diagnosing beam instabilities and optimizing accelerator performance.

Keywords: Beam loss; Bunch-by-bunch; Scintillator detector; Synchrotron radiation source

Introduction

The Hefei Light Source is a dedicated vacuum ultraviolet and soft X-ray synchrotron radiation facility, primarily consisting of an 800 MeV linear accelerator injector, an 800 MeV electron storage ring, 10 synchrotron radiation beamlines, and multiple experimental stations. The basic parameters of its storage ring are: energy 800 MeV, circumference 66.13 m, RF frequency 204 MHz, harmonic number 45, revolution period 220.59 ns, beam lifetime exceeding 10 hours, and average beam current 300 mA.

The Hefei Light Source employs the local bump orbit injection method to inject beam, as shown in Figure 1 [FIGURE:1]. Four kicker magnets are used to create an outward bump in a section of the ideal orbit, with the maximum displacement occurring at the storage ring injection point. A pulsed septum magnet is placed at the injection point. When the bump orbit reaches its maximum amplitude, beam injection occurs. The injected beam is deflected by the septum magnet to travel parallel to the bump orbit into the storage ring acceptance, while the closed orbit contracts according to a specific pattern, allowing the incoming electrons to avoid the septum plate and vacuum chamber walls and complete the injection into the storage ring. Throughout the entire process from injection to stable storage, multiple beam loss mechanisms exist: First, during injection, the electron beam may strike the septum magnet and vacuum chamber walls, causing beam loss; second, parameters of the fresh injected bunch may not perfectly match the storage ring stable operation conditions, leading to loss of mismatched particles; additionally, the pulsed electromagnetic fields of injection components may disturb the stored beam, inducing transverse or longitudinal beam instabilities that subsequently cause beam loss.

If beam loss persists above acceptable levels during injection, it will severely limit the injection efficiency and improvement of beam lifetime. Therefore, it is crucial to focus on and study beam dynamics and beam loss during injection. Developing a beam loss monitoring system with bunch-by-bunch diagnostic capability would provide key technical support for monitoring and analyzing beam loss during the injection transient at the Hefei Light Source.

To meet beam diagnostics and machine protection requirements, different accelerator facilities select different detectors to build beam loss monitoring systems according to their characteristics. Proton or heavy-ion accelerators are more concerned with loss dose issues and often choose ionization chambers as beam loss detectors, which have a large energy measurement range and strong radiation resistance. Typical cases include CERN' s Large Hadron Collider and China' s Spallation Neutron Source, but such detectors have response times on the microsecond scale and cannot be used for high-time-resolution beam loss monitoring in electron storage rings. The Beijing Electron-Positron Collider, Shanghai Synchrotron Radiation Facility, and Hefei Light Source use dual PIN diodes to monitor beam loss at different locations. These detectors are small in size, sensitive to electrons, and can ignore gamma ray effects, but their dead time is 100 ns, only suitable for measuring average beam loss dose and cannot be used for high-time-resolution measurements. Japan' s J-PARC first used scintillator detectors to monitor beam loss, with fast time response and pulse widths of tens of nanoseconds, and insensitivity to X-rays in background noise. The Australian Synchrotron and Siberian Light Source use fiber-based Cherenkov detectors to locate beam loss. These detectors have fast time response (ns scale) and are only sensitive to charged particles, but their radiation sensitivity is much lower than that of scintillator detectors. In summary, the current primary goal of beam loss monitoring technology is to determine the spatial location and relative loss rate of beam loss, but bunch-by-bunch beam loss measurement has not yet been realized in electron storage rings.

To achieve bunch-by-bunch and turn-by-turn beam loss monitoring and analysis, this study selected a scintillator detector with high radiation sensitivity and nanosecond-scale time response, combined with previously developed bunch-by-bunch charge and three-dimensional position measurement technology, to design and build a high-time-resolution beam loss and bunch position synchronization monitoring system for monitoring and analyzing beam loss during Hefei Light Source operation.

1.1 Basic Working Principle of Scintillator+PMT Beam Loss Monitoring System

The principle of using a scintillator detector to monitor beam loss is shown in Figure 2 [FIGURE:2]. When electron beam loss occurs on the vacuum chamber wall in the storage ring, shower particles are produced, mainly including shower electrons and gamma photons. These shower particles deposit energy in the scintillator, causing ionization and excitation of scintillator atoms. When the excited atoms de-excite, they emit scintillation photons in the visible light range. The scintillation photons are collected by a light guide onto the photocathode of a photomultiplier tube (PMT), producing photoelectrons. The photoelectrons are multiplied stage by stage on the PMT dynodes, finally forming an electrical signal on the output circuit during their motion between the anode and the last dynode. Typically, the number of photons produced by the scintillator is proportional to the radiation energy deposited in the scintillator, so the amplitude of the output signal is also proportional to the incident radiation energy.

1.2 Structural Design of High-Time-Resolution Beam Loss Monitoring System at Hefei Light Source

This study built a high-time-resolution beam loss and bunch position synchronization monitoring system for Hefei Light Source based on a scintillator detector, beam position monitor (BPM), and high-speed oscilloscope. Its structure is shown in Figure 3 [FIGURE:3], with core components including: 1) Scintillator: ELJEN EJ-200 scintillator, length 100 mm, diameter 22 mm, emission wavelength 425 nm, light pulse rise time 0.9 ns, decay time 2.1 ns, full width at half maximum (FWHM) 2.5 ns; 2) Photomultiplier tube: Hamamatsu H10721-110

PMT, detection wavelength range 230-700 nm, peak sensitivity wavelength 400 nm, rise time 0.57 ns, FWHM 1.25 ns; 3) Beam position monitor: used to pick up bunch-by-bunch beam signals and calculate bunch transverse and longitudinal positions; 4) High-speed oscilloscope: Keysight oscilloscope configured with 16 GSa/s sampling rate, 6.3 GHz bandwidth, and 10-bit voltage resolution.

After the beam loss signal is acquired by the scintillator detector, it is digitally stored by the high-speed oscilloscope and processed offline using MATLAB to extract amplitude and time information of the beam loss signal. To correlate beam loss with bunch position, the system integrates a beam position monitor, whose horizontally distributed strip electrode signals are synchronously acquired by two other channels of the oscilloscope. The BPM signals are processed by the HOTCAP software package developed by our research group (a high-speed oscilloscope-based tool for precise bunch-by-bunch three-dimensional position and charge measurement), ultimately outputting parameters such as bunch-by-bunch charge, transverse horizontal position, and longitudinal position. Through the collaborative operation of multiple modules, the system achieves high-time-resolution monitoring of beam loss events and multi-dimensional parameter analysis.

1.3 Green' s Function Simulation of High-Time-Resolution Beam Loss Monitoring System

When radiation interacts with the scintillator, energy deposition triggers the scintillator to produce a light pulse composed of scintillation photons. Its time characteristics can be characterized by a combination of rise time and decay time, with the mathematical expression as follows:

$$I_{\text{scint}}(t) = \frac{n_{\text{ph}}}{\tau_0 - \tau_1}\left(e^{-t/\tau_0} - e^{-t/\tau_1}\right)$$

where n_{ph} is the total number of photons in the scintillation light pulse; τ_0 is the scintillator' s light emission decay time; τ_1 is the scintillator' s rise time. The response function of a photomultiplier tube to a single photon output current can be represented by a Gaussian function:

$$I_{\text{PMT}}(t) = \frac{A}{\sqrt{2\pi}\sigma} e^{-(t-t_0)^2/2\sigma^2}$$

where A is the PMT amplitude coefficient, representing the peak value of the PMT output current pulse in response to a single photon; t_0 is the electron transit time; σ is the Gaussian pulse width of the current pulse. By convolving the scintillation light pulse function with the PMT single photon response function, the expression for the scintillator detector current pulse is obtained:

$$I_{\text{det}}(t) = I_{\text{scint}}(t) \otimes I_{\text{PMT}}(t)$$

Furthermore, by modeling the PMT current output as a current source, the relationship between the detector output voltage pulse and current pulse is:

$$V_{\text{out}}(t) = R \cdot I_{\text{det}}(t) \otimes e^{-t/RC}$$

where $R = 50\,\Omega$ and $C = 80\,\text{pF}$ are the equivalent parameters of the voltage readout circuit. Based on the above model, MATLAB was used for numerical simulation of the entire process from energy deposition in the scintillator to voltage pulse output. The normalized simulation results are shown in Figure 4 [FIGURE:4], with a pulse rise time of 2.3 ns and FWHM of 7.5 ns, significantly larger than the bunch spacing at Hefei Light Source (4.9 ns). Therefore, under high beam loss rate conditions, if multiple adjacent bunches simultaneously experience beam loss at the detector location, their signals will completely overlap and become indistinguishable. However, for beam loss events from non-adjacent bunches, signals can be effectively separated using a de-stacking method, with details provided in Section 1.4.

1.4 Beam Loss Signal Processing Method

The Hefei Light Source storage ring has a revolution period of 220.59 ns. Using a high-speed oscilloscope with 16 GSa/s sampling rate to digitally acquire beam loss signals, each turn corresponds to 3529 sampling points. To extract amplitude and time information of beam loss pulses, the beam loss signal is processed turn-by-turn, with 3528 sampling points extracted per turn to form a continuous turn-by-turn dataset. Figure 5 shows a typical measured beam loss waveform for one turn after turn-by-turn slicing, with a pulse rise time of 2.8 ns and FWHM of 7.5 ns, which is highly consistent with simulation results in key parameters, with a waveform correlation coefficient of $R = 0.978$, validating the accuracy of the system' s beam loss pulse waveform output.

By comparing the power spectral distribution of beam loss pulses and noise signals, significant differences were found in the range below normalized frequency 0.048 rad/sample. Accordingly, the passband cutoff frequency of the low-pass filter was determined to be 0.048 rad/sample.

During steady-state operation, beam loss signal amplitude is small and signal-to-noise ratio is low, requiring filtering to enhance signal features. After filtering, an asymmetric Gaussian function is used to fit the beam loss pulse, with the expression:

$$s(t) = A \exp\left(-\frac{(t-\mu)^2}{2\sigma^2}\right)\left[1 + \operatorname{erf}\left(\frac{\alpha(t-\mu)}{\sqrt{2}\sigma}\right)\right] + C$$

where A is the amplitude, determining the peak height of the function; μ is the peak time; σ is the pulse width, controlling the narrowness of the pulse; α is the asymmetry factor, where $\alpha > 0$ causes right-side broadening and vice versa for left-side broadening; C is the baseline offset. After fitting, the beam loss amplitude is characterized by $A - C$, and the peak time is determined by μ.

During injection, beam loss frequency increases significantly, leading to pulse stacking phenomena (dashed line in Figure 6). To more accurately extract amplitude and time of stacked beam loss pulses, identification and reconstruction of piled-up pulses are required. First, the same low-pass filter is applied to eliminate background noise. Then, MATLAB' s peak-finding function is used to identify the number of pulses and segmentation points. After completion, the first pulse is fitted with an asymmetric Gaussian function sequentially according to the segmentation points to extract amplitude ($A - C$) and time (μ) parameters. Subsequently, the fitted pulse component is subtracted from the original signal, and this process is repeated until all pulses are resolved (solid line in Figure 6).

A Kaiser window low-pass filter (stopband attenuation 60 dB) is used for signal preprocessing to suppress high-frequency noise interference.

1.5 BPM Signal Processing Method

The raw signal time-domain waveform measured by the BPM on the Hefei Light Source storage ring is shown in Figure 7 [FIGURE:7]. This signal carries multi-dimensional information including bunch charge, bunch length, transverse position, and longitudinal phase. In the experiment, two horizontally distributed strip electrode signals were synchronously acquired by the high-speed oscilloscope and input into the HOTCAP software package for data processing and analysis, enabling extraction of bunch-by-bunch charge, turn-by-turn transverse horizontal position variation, and turn-by-turn longitudinal phase variation information. Typical measured bunch-by-bunch charge and position data during injection are shown in Figure 8 [FIGURE:8].

2 Beam Experiments

During normal operation of the Hefei Light Source, beam loss is mainly concentrated in the downstream region of dipole magnets. Therefore, in the experiment, the scintillator detector was installed behind a dipole magnet and adjacent to the BPM at that location. The on-site installation is shown in Figure 9 [FIGURE:9]. In top-up operation mode, beam loss during both the transient injection process and post-injection steady-state operation was monitored. During the experiment, 35 bunches were filled in the storage ring with an average current of 300 mA.

2.1 Beam Loss During Steady-State Operation

Using the beam loss signal processing method described in Section 1.4, a beam loss scatter plot for steady-state operation was generated (Figure 10 [FIGURE:10]), where the horizontal axis represents sampling points (3528 points per turn), the vertical axis represents turn number, and color maps the relative beam loss amplitude.

The RF frequency of the Hefei Light Source is 204 MHz, corresponding to a bunch interval (bucket) width of 4.9 ns. After sampling at 16 GSa/s, each bucket corresponds to 78.4 sampling points. Based on this, the 45 buckets around the ring are segmented, and the average beam loss per turn for each bucket is calculated as the beam loss rate for the corresponding bunch. Since beam loss signals and BPM signals have different origins, there is a fixed time delay difference between them, requiring data alignment. Because Hefei Light Source operates with a special filling pattern (a continuous bunch train of 35 bunches plus 1 isolated single bunch, as shown in Figure 8(a)), this pattern can be used for data alignment. The specific method is: identify the isolated bunch based on the bunch-by-bunch beam loss rate distribution and align it with the isolated bunch index in the bunch-by-bunch charge data, thereby achieving correlation between beam loss data and BPM bunch-by-bunch data. Figure 11 [FIGURE:11] shows the aligned bunch-by-bunch beam loss rate distribution, which is consistent with the storage ring filling pattern, and no significant beam loss signals appear at empty bunch positions, demonstrating that the system has bunch-by-bunch beam loss resolution capability under steady-state, low-dose-rate conditions. Weak signals at empty bunch positions can be attributed to detection noise from environmental scattered radiation.

2.2 Beam Loss During Injection

During injection, beam loss frequency is extremely high, making it common for multiple adjacent bunches to simultaneously experience beam loss near the detector, resulting in severe overlap of beam loss signals from different bunches. It is difficult to precisely locate which bunch experienced beam loss and calculate its amplitude within a single turn; only the approximate interval of lost bunches can be determined. Analysis of beam loss monitoring data from four injection processes at Hefei Light Source is shown in Figure 12

. In addition to significant beam loss in the injected bunch, significant beam loss also appears near the 14th stored bunch after the injected bunch.

Beam loss in the injected bunch may result from incomplete matching between fresh injected bunch parameters and storage ring parameters, which can be minimized by optimizing injector parameters and storage ring injection system parameters to improve matching. Beam loss near the 14th stored bunch after injection may be caused by beam instabilities induced when the beam deviates significantly from its steady state during injection, i.e., when the beam experiences large transverse and longitudinal deviations from equilibrium during injection, exciting strong transient wakefields that cause subsequent bunch instabilities through inter-bunch nonlinear interactions. The physical mechanism requires more detailed correlation analysis through dedicated beam experiments combined with bunch-by-bunch three-dimensional position data for further in-

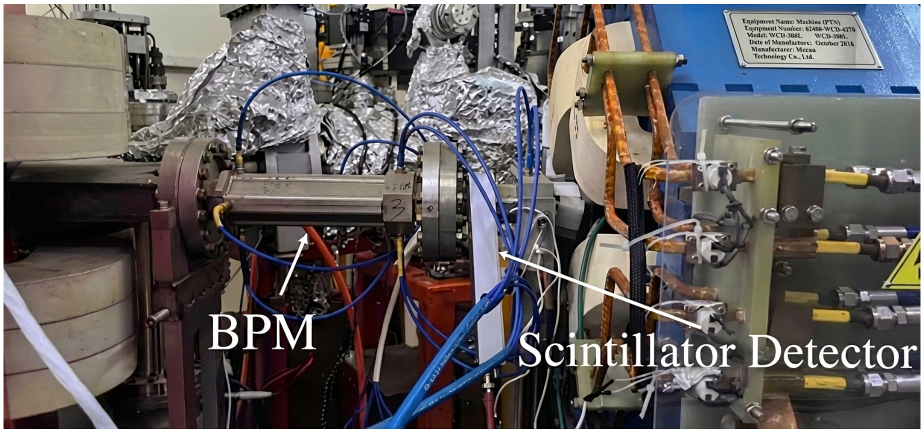

Figure 1: Figure 12

vestigation.

Limited by the time resolution of the scintillator detector (typical FWHM of 7.5 ns), the system cannot obtain strictly bunch-by-bunch beam loss measurement data. When the bunch spacing in the storage ring is greater than 7.5 ns, the system can achieve complete separation of bunch-by-bunch signals, meeting bunch-by-bunch beam loss monitoring requirements. For accelerators with bunch spacing less than 7.5 ns, under low beam loss dose steady-state operation conditions, the bunch from which beam loss originates can be precisely located through correlation analysis between beam loss signals and BPM signals. However, for injection processes or other high beam loss rate operating conditions, if multiple adjacent bunches experience beam loss near the detector, bunch-by-bunch resolution cannot be achieved, and errors in beam loss amplitude extraction increase significantly.

To expand the system' s applicability and achieve strict bunch-by-bunch monitoring, future improvements may consider: first, adopting beam loss detectors with faster time response, such as fiber-based Cherenkov detectors, to improve time resolution; second, combining machine learning or deep learning techniques to optimize pulse de-stacking algorithms to address complex signal parsing requirements in high beam loss rate scenarios. These improvements will further enhance the system' s diagnostic accuracy and applicability, providing reliable support for beam loss monitoring at more accelerator facilities.

Conclusion

This study designed and successfully built a high-time-resolution beam loss and bunch position synchronization monitoring system on the Hefei Light Source storage ring based on a scintillator detector, beam position monitor, and high-speed oscilloscope. Experimental results match numerical simulation results perfectly, validating the accuracy of the system' s beam loss pulse waveform output. To address beam loss pulse stacking during injection, an asymmetric Gaussian model fitting method was proposed, which can accurately extract amplitude and time information of stacked pulses. Experimental results demonstrate that the system can effectively monitor bunch-by-bunch beam loss characteristics in electron storage rings, enabling synchronous monitoring of multi-dimensional parameters including charge, transverse horizontal oscillation, and longitudinal phase. During injection, a phenomenon was observed where the beam loss rate of the 14th stored bunch after the injected bunch significantly exceeded that of other stored bunches, suggesting this effect may be related to inter-bunch wakefield coupling or nonlinear dynamics perturbations. Future dedicated beam experiments are needed to further investigate the physical mechanism and optimize the injection process to reduce beam loss and improve injection efficiency. The system's capability to synchronously acquire bunch-by-bunch charge, transverse position, longitudinal position, and beam loss data provides excellent technical support for analyzing such complex beam dynamics processes.

Limited by the time response characteristics of the scintillator detector, the system's bunch-by-bunch beam loss diagnostic capability has certain limitations in high bunch density or high beam loss frequency scenarios. In the future, by adopting detectors with faster time response and combining machine learning techniques to optimize signal parsing algorithms, the system' s bunch-by-bunch monitoring capability is expected to be further enhanced, providing broader application support for more types of accelerator facilities.

Author Contributions

LIU Yihong was responsible for numerical simulation, data processing and compilation, and drafting and revising the final manuscript; XIAO Yunzhi was responsible for data processing and compilation; YU Lingda was responsible for beam loss equipment support; YANG Xing was responsible for BPM data processing; MA Xiaochao was responsible for beam loss detector installation and commissioning; LENG Yongbin was responsible for proposing the research, guiding the methodology, and revising the final manuscript.

References

1. 刘淑会. HLS 储存环脉冲四极磁铁注入系统设计研究 [D]. 合肥: 中国科学技术大学, 2011.
   Study of Injection Scheme Using Pulsed Quadrupole for HLS Storage Ring[D]. Hefei: University of Science and Technology of China, 2011.

2. 黄明阳, 许守彦, 卢晓含, 等. 中国散裂中子源加速器注入束流损失调节研究 [J]. 原子能科学技术, 2019, 53(09): 1708-1714. DOI: 10.7538/yzk.2019.53.09.1708.
   HUANG Mingyang, XU Shouyan, LU Xiaohan, et al. Study on Injection Beam Loss for China Spallation Neutron Source Accelerator[J].

Atomic Energy Science and Technology, 2019, 53(09): 1708-1714. DOI: 10.7538/yzk.2019.53.09.1708.

3. Saccani M, Effinger E, Viganò W, et al. The Beam Loss Monitoring System after the LHC Long Shutdown 2 at CERN[C]//11th International Beam Instrumentation Conference (IBIC' 22), Kraków, Poland, 11-15 September 2022. JACOW Publishing, Geneva, Switzerland, 2022: 220-224. DOI: 10.18429/JACoW-IBIC2022-TUP03.
4. 曾磊, 田建民, 邱瑞阳, 等. CSNS 束流损失测量系统设计 [J]. 强激光与粒子束, 2019, 31(01): 84-89. DOI: 10.11884/HPLPB201931.180198.
Zeng Lei, Tian Jianmin, Qiu Ruiyang, et al. Design of the CSNS beam loss monitor system[J]. *High Power Laser and Particle Beams*, 2019, 31(01): 84-89. DOI: 10.11884/HPLPB201931.180198.
5. 何俊, 赵晓岩, 汪林, 等. BEPC 束损系统研究 [J]. 核技术, 2015, 38(10): 15-21. DOI: 10.11889/j.0253-3219.2015.hjs.38.100103.
HE Jun, ZHAO Xiaoyan, WANG Lin, et al. Study on beam loss system of BEPC [J]. *Nuclear Techniques*, 2015, 38(10): 15-21. DOI: 10.11889/j.0253-3219.2015.hjs.38.100103.
6. 侯磊. 上海光源储存环束流损失监测系统研制与应用 [D]. 北京: 清华大学, 2009.
Design and Application of the Beam Loss Monitoring System for the Storage Ring of SSRF[D]. Beijing: Tsinghua University, 2009.
7. 陈裕凯. 合肥光源（HLSII）储存环束流损失监测系统的研究 [D]. 合肥: 中国科学技术大学, 2015.
The Study of the New Type BLM System for the HLSII Storage Ring[D]. Hefei: University of Science and Technology of China, 2015.
8. Miura A, Maruta T, Sako H, et al. Beam loss detected by scintillation monitor[C]//The second International Particle Accelerator Conference (IPAC' 11), JACoW Publishing, Geneva, Switzerland, 2011: 1257-1259.
9. Giansiracusa P J, Boland M J, Holzer E B, et al. A distributed beam loss monitor for the Australian Synchrotron[J]. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 2019, 919: 98-104. DOI: 10.1016/j.nima.2018.12.054.
10. Maltseva Y I, Ivanenko S V, Khilchenko A D, et al. Beam loss monitoring system for the SKIF synchrotron light source[J]. *Journal of Instrumentation*, 2022, 17(5): T05004. DOI: 10.1088/1748-0221/17/05/t05004.
11. 邓又铭, 冷用斌, 周逸媚, 等. 电子储存环逐束团诊断技术研究进展 [J]. 核技术, 2024, 47(10): 18-28. DOI: 10.11889/j.0253-3219.2024.hjs.47.100201.
DENG Youming, LENG Yongbin, ZHOU Yimei, et al. Current status and latest developments in electron storage ring bunch-by-bunch diagnostic techniques[J]. *Nuclear Techniques*, 2024, 47(10): 18-28. DOI: 10.11889/j.0253-3219.2024.hjs.47.100201.

12. Yang X, Wang H S, Zhou Y M, et al. Determining beam transverse absolute position by triangulation of multi-electrode signal phase differences[J]. *Nuclear Science and Techniques*, 2024, 35(8): 133. DOI: 10.1007/s41365-024-01498-y.

13. Deng Y M, Leng Y B, Xu X Y, et al. Ultrahigh spatiotemporal resolution beam signal reconstruction with bunch phase compensation[J]. *Nuclear Science and Techniques*, 2024, 35(5): 89. DOI: 10.1007/s41365-024-01444-y.

14. Vylet V, C. Liu J. Radiation protection at high energy electron accelerators[J]. *Radiation Protection Dosimetry*, 2001, 96(4): 333-343. DOI: 10.1093/oxfordjournals.rpd.a006622.

15. Xu X Y, Leng Y B, Gao B, et al. HOTCAP: a new software package for high-speed oscilloscope-based three-dimensional bunch charge and position measurement[J]. *Nuclear Science and Techniques*, 2021, 32(11): 131. DOI: 10.1007/s41365-021-00966-z.

16. 汪晓莲, 李澄, 邵明. 粒子探测技术 [M]. 合肥: 中国科学技术大学出版社, 2009.
WANG Xiaolian, LI Cheng, SHAO Ming. *Particle Detection Technology*[M]. Hefei: University of Science and Technology of China Press, 2009.

17. Chen Z, Li X, Li X, et al. A correction method for range walk error in time-correlated single-photon counting using photomultiplier tube[J]. *Optics Communications*, 2019, 434: 7-11. DOI: 10.1016/j.optcom.2018.10.041.

18. 杨星, 冷用斌, 周逸媚. 逐束团三维信息提取软件 HOTCAP 的实时性能优化 [J]. 核技术, 2024, 47(02): 27-34. DOI: 10.11889/j.0253-3219.2024.hjs.47.020102.
YANG Xing, LENG Yongbin, ZHOU Yimei, et al. Real-time optimization of bunch-by-bunch 3D information extraction software HOTCAP[J]. *Nuclear Techniques*, 2024, 47(02): 27-34. DOI: 10.11889/j.0253-3219.2024.hjs.47.020102.

19. 李玉雄, 李珏忻, 李为民, 等. 一种新的储存环束流损失监测系统 [J]. 中国科学技术大学学报, 2007(Z1): 500-504. DOI: 10.3969/j.issn.0253-2778.2007.04.027.
LI Yuxiong, LI Juexin, LI Weimin, et al. A new storage ring beam loss monitoring system[J]. *Journal of University of Science and Technology of China*, 2007(Z1): 500-504. DOI: 10.3969/j.issn.0253-2778.2007.04.027.