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

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Abstract

To monitor and analyze the characteristics of beam loss during the operation of the 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 (BPM), and high-speed oscilloscope. The accuracy of the system's output beam loss pulse waveforms was verified through comparison between simulated and measured waveforms. Characteristic parameters of the beam loss pulse signals were extracted using a method based on asymmetric Gaussian function fitting. Combined with the HOTCAP technique, 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, beam loss during injection transients and steady-state operation after injection at the Hefei Light Source was 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, significant beam loss was observed simultaneously in the refilled bunch and the 14th stored bunch after it for the first time.

Full Text

Preamble

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

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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 HOTCAP (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 was 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 is 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 has been observed for the first time: significant beam loss has 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.

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

Introduction

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 storage ring's basic parameters 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 of 300 mA.

Hefei Light Source employs the local bump orbit injection method to inject beam, as shown in Figure 1 [Figure 1: see original paper]. Four kicker magnets are used to create an outward bump in a section of the ideal orbit, with the maximum displacement of the beam orbit corresponding to the injection point in the storage ring. A pulsed septum magnet is placed at the injection point. When the bump amplitude reaches its maximum, beam injection occurs. The injected particle beam is deflected by the pulsed septum magnet and enters the storage ring acceptance parallel to the bumped orbit, while the closed orbit contracts according to a specific pattern, allowing the incident electron beam to avoid the septum plate and vacuum chamber walls, thereby completing beam injection into the storage ring [1]. Throughout the entire process from injection to stable storage operation, multiple beam loss mechanisms exist: First, during injection, the electron beam may strike the septum magnet and vacuum chamber walls, causing beam loss. Second, the Twiss parameters of the fresh injected bunch may not match those at the storage ring injection point, leading to particle loss. Additionally, the pulsed electromagnetic fields of injection elements may perturb stored beams, inducing transverse or longitudinal beam instabilities that subsequently cause beam loss. If beam loss persistently exceeds acceptable levels during injection, it will severely limit beam injection efficiency [2] and hinder improvements in beam lifetime. Therefore, it is essential to focus on and investigate beam dynamics and beam loss during the injection process. The development of a beam loss monitoring system with bunch-by-bunch diagnostic capability could provide key technical support for monitoring and analyzing beam loss during the injection transient at Hefei Light Source.

To meet the needs of beam diagnostics and machine protection, various types of detectors have been widely employed in accelerator facilities for beam loss monitoring. Proton and heavy ion accelerators are more concerned with loss dose issues and often choose ionization chambers as beam loss detectors, which offer a large energy measurement range and strong radiation resistance. Typical cases include the Large Hadron Collider at CERN [3] and the China Spallation Neutron Source [4]. However, the response time of ionization chambers is on the microsecond scale, making them unable to resolve bunch-by-bunch structures. The Beijing Electron-Positron Collider [5], Shanghai Synchrotron Radiation Facility [6], and Hefei Light Source [7] use dual PIN diodes to monitor beam loss at different locations. These detectors are small in size, sensitive to electrons, and insensitive to gamma ray interference, making them suitable for distributed deployment. However, their dead time is 100 ns, making them only suitable for average beam loss measurement and unable to meet high-time-resolution requirements. J-PARC in Japan [8] and the European Synchrotron Radiation Facility [9] use scintillator detectors to monitor beam loss, which offer fast time response at the nanosecond level and are insensitive to X-ray interference in background noise, though scintillators are susceptible to radiation damage leading to decreased light yield. The Australian Synchrotron [10] and Siberian Synchrotron Light Source [11] use Cherenkov-based fiber optic beam loss detectors to locate beam loss. These detectors exhibit extremely fast time response (Cherenkov light is instantaneous, with overall response time primarily determined by the photomultiplier tube), are only sensitive to charged particles, but have low light yield and an energy threshold, making them more suitable for high-dose loss monitoring scenarios.

Overall, existing beam loss monitoring technologies have primarily focused on spatial localization of beam loss and evaluation of relative loss rates, while in-depth research on bunch-by-bunch beam loss monitoring is rarely reported domestically or internationally. The Large Hadron Collider at CERN uses diamond detectors with nanosecond time resolution and strong radiation resistance, albeit at high cost, to achieve bunch-by-bunch beam loss monitoring and has conducted studies on beam loss patterns caused by injection, beam loss, beam instabilities, and dust particles [12]. However, the bunch spacing in that facility is 50 ns, making bunch-by-bunch beam loss resolution relatively less challenging. In storage rings with denser bunch patterns, achieving bunch-by-bunch beam loss monitoring remains challenging. To address frequent beam loss issues in the Beijing Electron-Positron Collider II, a bunch-by-bunch beam loss monitoring system based on BPM was developed, which can effectively identify beam loss phenomena caused by RF cavity jumps, tune drift, and multi-bunch instabilities [13]. However, due to limitations in charge resolution, this system's capability for detecting small-dose beam loss remains limited.

To achieve bunch-by-bunch and turn-by-turn beam loss monitoring and analysis, this study comprehensively considered the advantages and disadvantages of various detectors and ultimately selected a scintillator detector with high radiation sensitivity and nanosecond-level time response. Combined with previously developed bunch-by-bunch charge and three-dimensional position measurement techniques [14-16], a high-time-resolution beam loss and bunch position synchronous monitoring system was designed and constructed for monitoring and analyzing beam loss during Hefei Light Source operation.

1.1 Basic Working Principle of the Scintillator-PMT Beam Loss Monitoring System

The principle of using a scintillator detector to monitor beam loss is illustrated in Figure 2 [Figure 2: see original paper]. When electron beams in the storage ring are lost on the vacuum chamber walls, shower particles are produced, primarily consisting of shower electrons and gamma photons [17]. These shower particles deposit energy in the scintillator, causing ionization and excitation of scintillator atoms. When excited atoms de-excite, they emit scintillation photons in the visible wavelength range. The scintillation photons are collected through light guides onto the photocathode of a photomultiplier tube (PMT), generating photoelectrons. These photoelectrons are multiplied progressively on the PMT's dynodes, ultimately forming an electrical signal on the output circuit as they travel 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 the High-Time-Resolution Beam Loss Monitoring System at Hefei Light Source

This study constructed a high-time-resolution beam loss and bunch position synchronous monitoring system for Hefei Light Source based on a scintillator detector, beam position monitor (BPM), and high-speed oscilloscope. The system structure is shown in Figure 3 [Figure 3: see original paper], with core components including: 1) Scintillator: ELJEN EJ-200 scintillator, 100 mm length, 22 mm diameter, emission wavelength 425 nm, optical 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 transverse and longitudinal bunch 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 digitized and stored by the high-speed oscilloscope, and offline data processing is performed using MATLAB to extract amplitude and timing 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 through two additional oscilloscope channels. The BPM signals are processed using the HOTCAP software package [18] (a high-speed oscilloscope-based tool for precise bunch-by-bunch three-dimensional charge and position measurement) developed by our research group, ultimately outputting parameters such as bunch-by-bunch charge, transverse horizontal position, and longitudinal position. Through the collaborative operation of multiple modules, this system achieves high-time-resolution monitoring of beam loss events and multi-dimensional parameter analysis.

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

When radiation interacts with the scintillator, energy deposition triggers the generation of an optical pulse composed of scintillation photons, whose temporal characteristics can be characterized by a combination of rise time and decay time, with the mathematical expression as follows [19]:

$$n(t) = n_{ph} \cdot \frac{e^{-t/\tau_0}}{\tau_0} \cdot \left(1 - e^{-t/\tau_1}\right)$$

where n_{ph} is the total number of photons in the scintillation light pulse, τ_0 is the scintillator's light emission decay time, and τ_1 is the scintillator's rise time. The response function of the photomultiplier tube to a single photon can be expressed using a Gaussian function [20]:

$$i_{sp}(t) = A \cdot \exp\left(-\frac{(t - t_0)^2}{2\sigma^2}\right)$$

where A is the PMT amplitude coefficient, representing the peak output current pulse from the PMT in response to a single photon; t_0 is the electron transit time; and 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:

$$i(t) = \int_0^t n(\tau) \cdot i_{sp}(t - \tau) d\tau$$

Further modeling the PMT current output as a current source, the relationship between the detector's output voltage pulse and current pulse is:

$$V(t) = R \cdot i(t) \cdot \left(1 - e^{-t/RC}\right)$$

where $R = 50\,\Omega$ and $C = 80\,\mathrm{pF}$ are the equivalent parameters of the voltage readout circuit. Based on the above model, numerical simulation of the entire process from energy deposition in the scintillator to voltage pulse output was performed using MATLAB. The normalized simulation results are shown in Figure 4 [Figure 4: see original paper], 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 probe 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 digitize beam loss signals, each revolution corresponds to 3529 sampling points. To extract amplitude and timing information from beam loss signals, a turn-by-turn slicing process is applied, 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 a single 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, achieving a waveform correlation coefficient of $R = 0.978$ and validating the accuracy of the system's beam loss pulse waveform output.

During steady-state operation, beam loss signal amplitudes are small with low signal-to-noise ratios, requiring filtering to enhance signal features. After filtering, an asymmetric Gaussian function is used to fit the beam loss pulses, expressed as:

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

where A determines the peak height, μ is the peak time, σ controls the pulse width, α is the asymmetry factor (with $\alpha > 0$ causing right-side broadening and vice versa), and C is the baseline offset. After fitting, the beam loss amplitude is characterized by $A - C$ and the peak time by μ.

During injection, the beam loss frequency increases significantly, leading to severe pulse stacking phenomena (dashed line in Figure 6 [Figure 6: see original paper]). To more accurately extract amplitude and timing information of stacked pulses, identification and reconstruction of the 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 pulse numbers and segmentation points. After completion, pulses are fitted sequentially using the asymmetric Gaussian function starting from the first pulse to extract amplitude $(A - C)$ and timing (μ) parameters. The fitted pulse component is then subtracted from the original signal, and this process is repeated until all pulses are resolved (solid line in Figure 6).

1.5 BPM Signal Processing Method

The raw time-domain waveform of the BPM signal measured on the Hefei Light Source storage ring is shown in Figure 7 [Figure 7: see original paper]. 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 [21]. Typical measured bunch-by-bunch charge and position data during injection are shown in Figure 8 [Figure 8: see original paper].

2 Beam Experiments

During normal operation of Hefei Light Source, beam loss is primarily concentrated in the downstream region of dipole magnets [22]. Therefore, the scintillator detector was installed behind a dipole magnet and adjacent to the BPM at that location, with the actual installation shown in Figure 9 [Figure 9: see original paper]. Beam loss during both the transient injection process and post-injection steady-state operation was monitored in constant current (Top-up) mode. 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 scatter plot of beam loss during steady-state operation was generated (Figure 10 [Figure 10: see original paper]), 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 at Hefei Light Source is 204 MHz, corresponding to a bunch filling slot width of 4.9 ns. After sampling at 16 GSa/s, each bunch filling slot corresponds to 78.4 sampling points. Based on this, the 45 bunch filling slots around the entire ring are segmented, and the average beam loss per turn for each bunch filling slot is calculated as the beam loss rate for the corresponding bunch. Since beam loss signals and BPM signals have different origins, there exists a fixed time delay difference between them, requiring data alignment. Because Hefei Light Source employs a special filling pattern during operation (a continuous bunch train of 35 bunches plus 1 isolated single bunch, as shown in Figure 8(a)), this pattern's characteristics can be used for data alignment. The specific method involves identifying the isolated bunch based on the bunch-by-bunch beam loss rate distribution and aligning it with the isolated bunch number in the bunch-by-bunch charge data, thereby achieving correlation between beam loss data and BPM bunch-by-bunch data. Figure 11 [Figure 11: see original paper] 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. This demonstrates that the system possesses 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, the beam loss frequency is extremely high, making it common for multiple adjacent bunches to simultaneously experience beam loss near the probe. This results in severe signal overlap, making it difficult to precisely locate which bunch is experiencing beam loss and calculate its amplitude within a single turn; only the approximate interval of beam loss bunches can be determined.

Analysis of beam loss monitoring data from four injection processes at Hefei Light Source is shown in Figure 12 [Figure 12: see original paper]. In addition to significant high-dose beam loss in the injected bunch, significant beam loss also occurs near the 14th stored bunch following the injected bunch.

Beam loss in the injected bunch may result from incomplete matching between the Twiss parameters of the fresh injected bunch and those at the storage ring injection point. This can be mitigated by optimizing injector parameters and adjusting storage ring injection system parameters to improve matching and minimize beam loss. The beam loss near the 14th stored bunch following the injected bunch may be caused by beam instabilities induced when the beam deviates significantly from its steady state during injection. Specifically, during injection, the beam experiences large transverse and longitudinal deviations from the equilibrium position, exciting strong transient wakefields that, through inter-bunch nonlinear interactions, trigger instabilities in subsequent bunches. The underlying physical mechanism requires more detailed correlation analysis through dedicated beam experiments combined with bunch-by-bunch three-dimensional position data for further investigation.

Limited by the time resolution of the currently used scintillator detector, the system cannot yet achieve strict bunch-by-bunch beam loss monitoring at Hefei Light Source. Under steady-state operating conditions at Hefei Light Source, beam loss signals rarely undergo complete stacking, allowing precise identification of specific bunches experiencing beam loss through correlation analysis with BPM signals. However, during injection or other high beam loss rate conditions, if adjacent bunches simultaneously experience beam loss near the probe, signals will completely overlap, making individual pulses indistinguishable.

To evaluate under what bunch spacing conditions this system can achieve bunch-by-bunch beam loss resolution, this study conducted simulations using asymmetric Gaussian functions fitted from measured pulse waveforms to construct beam loss signals. In the simulation, the amplitude of the first pulse was fixed at 1, while the amplitude of the second pulse was increased from 0.1 to 10. For each amplitude ratio, the time interval between the two pulses was gradually increased from 0 to 20 ns to generate stacked signals. When the stacked signal met the set peak discrimination condition and could just resolve two overlapping peaks, the corresponding time interval was defined as the resolvable time for that amplitude ratio condition. The simulation results are shown in Figure 13 [Figure 13: see original paper]. When the amplitude ratio is approximately 0.51, the minimum resolvable time is only 5.6 ns. Assuming the amplitude ratio of adjacent bunches' beam loss is typically within the range of 0.3–3, the corresponding maximum resolvable time is about 9.7 ns. It can thus be inferred that in storage rings with bunch spacing greater than 9.7 ns, this system possesses the capability to achieve bunch-by-bunch beam loss monitoring.

To expand the system's applicability and achieve bunch-by-bunch beam loss monitoring, future optimizations can be pursued in several directions: First, employ beam loss detectors with faster time response, such as Cherenkov-based fiber optic beam loss detectors, to improve time resolution. Second, develop advanced signal processing algorithms to shape the original beam loss waveform into narrower pulses, further enhancing resolution capability. Third, incorporate 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 precision and applicability, providing reliable support for beam loss monitoring in more accelerator facilities.

Conclusion

This study designed and successfully implemented a high-time-resolution beam loss and bunch position synchronous monitoring system on the Hefei Light Source storage ring based on a scintillator detector, beam position monitor, and high-speed oscilloscope. The measured experimental results perfectly match numerical simulation results, validating the accuracy of the system's beam loss pulse waveform output. To address pulse stacking phenomena during injection, an asymmetric Gaussian model fitting method was proposed, enabling precise extraction of amplitude and timing information from stacked pulses. Experimental results demonstrate that the system can effectively monitor bunch-by-bunch beam loss characteristics in electron storage rings, achieving 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 in the 14th stored bunch following the injected bunch significantly exceeded that of other storage ring bunches, suggesting this effect may be related to coupling instabilities caused by inter-bunch wakefields or perturbations from pulsed magnets. 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 under high bunch density or high beam loss frequency scenarios. In the future, by employing detectors with faster time response and combining machine learning techniques to optimize signal parsing algorithms, the system's bunch-by-bunch monitoring capability can be further enhanced, providing broader application support for various types of accelerator facilities.

Author Contributions

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

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Note: Figure translations are in progress. See original paper for figures.