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

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Abstract

To monitor and analyze the beam loss characteristics during Hefei Light Source operation, a high time-resolution synchronous monitoring system for beam loss and bunch position was developed, incorporating 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 validated through comparison of simulated and measured waveforms. Characteristic parameters of the beam loss pulse signals were extracted via asymmetric Gaussian function fitting. Bunch-by-bunch charge and position information were extracted from strip electrode signals using HOTCAP technology. The temporal offset between beam loss and position data was corrected based on the special filling pattern of the Hefei Light Source storage ring, thereby achieving data synchronization. Utilizing this system, beam loss during injection transient and post-injection steady-state operation of Hefei Light Source was monitored. The results indicate 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 transient, simultaneous significant beam loss in the refilled bunch and the 14th stored bunch thereafter was observed 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 diagnose beam instabilities and optimize accelerator performance. **[Purpose]:** This study aims to monitor and analyze the beam loss characteristics during HLS-II operation. **[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 technique (a software package for high-speed oscilloscope-based three-dimensional bunch-by-bunch charge and position measurement), bunch-by-bunch charge and position information were extracted from BPM signals. The time discrepancy between beam loss and position data was corrected 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 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 theoretical expectations for 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 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

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Abstract (English)

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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.

Hefei Light Source employs the local bump orbit injection method, as shown in Figure 1 [Figure 1: see original paper]. Four kicker magnets are used to create an outward bulge 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 orbit reaches its maximum amplitude, beam injection occurs. The injected particle beam is deflected by the pulsed septum magnet and enters the storage ring acceptance parallel to the bump orbit, while the closed orbit contracts according to a specific pattern, allowing the injected electrons to avoid the septum plate and vacuum chamber walls and complete the injection process 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 parameters of the fresh injected bunch may not perfectly match the stable operating conditions of the storage ring, leading to loss of poorly matched particles; additionally, the pulsed electromagnetic fields of injection components may disturb the stored beam, causing transverse or longitudinal beam instabilities that result in further 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 crucial to monitor and study beam dynamics and beam loss during the injection process. Developing a beam loss monitoring system with bunch-by-bunch diagnostic capability to monitor and analyze beam losses during both the transient injection process and post-injection steady-state operation would be of great significance for optimizing injection schemes, improving injection efficiency, reducing radiation dose, and ensuring personnel and equipment safety.

To meet the requirements of beam diagnostics and machine protection, different accelerator facilities select different detectors to build beam loss monitoring systems according to their specific characteristics. Proton or heavy-ion accelerators are more concerned with loss dose issues and often choose ionization chambers as beam loss detectors due to their high sensitivity, large energy measurement range, and strong radiation resistance. Typical examples include CERN' s Superconducting Super Collider [3] and China' s Spallation Neutron Source [4]. However, the response time of such detectors is on the microsecond scale, making them unsuitable for high-time-resolution beam loss monitoring in electron storage rings. The Beijing Electron-Positron Collider [5], Shanghai Synchrotron Radiation Facility [6], and Hefei Light Source [7] use dual PIN diodes to monitor beam losses 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, allowing only measurement of average beam loss dose and not high-time-resolution measurements. Japan' s J-PARC first used scintillator detectors for beam loss monitoring [8], which feature fast time response with pulse widths of tens of nanoseconds and are insensitive to X-rays in background noise. The Australian Synchrotron [9] and Siberian Synchrotron Light Source [10] use Cherenkov-based fiber optic beam loss detectors to locate beam losses. These detectors have fast time response (on the order of nanoseconds) 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 losses, but bunch-by-bunch beam loss measurement has not yet been implemented 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-level time response. Combined with previously developed bunch-by-bunch charge and three-dimensional position measurement techniques [11-13], a high-time-resolution beam loss and bunch position synchronization monitoring system was designed and built to monitor and analyze beam losses 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 for beam loss monitoring is shown in Figure 2 [Figure 2: see original paper]. When electron beams in the storage ring are lost on the inner wall of the vacuum chamber, shower particles are produced, mainly including shower electrons and gamma photons [14]. 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 wavelength 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, and finally, as they travel between the anode and the last dynode, an electrical signal is formed on the output circuit. Typically, the number of photons produced by the scintillator is proportional to the radiation energy deposited in it, so the amplitude of the output signal is also proportional to the energy of the incident radiation.

1.2 Structural Design of the High-Time-Resolution Beam Loss Monitoring System for 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. The system structure is shown in Figure 3 [Figure 3: see original paper], with core components including: 1) Scintillator: ELJEN EJ-200 type, length 100 mm, diameter 22 mm, 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 type, 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 model, sampling rate 16 GSa/s, bandwidth 6.3 GHz, voltage resolution 10 bits.

After the beam loss signal is collected by the scintillator detector, it is digitized and stored by the high-speed oscilloscope, and offline data processing is performed using MATLAB to extract the amplitude and time information of the beam loss signal. To correlate beam loss with bunch position, the system integrates a beam position monitor, and its horizontally distributed strip electrode signals are synchronously collected through two other channels of the oscilloscope. The BPM signals are processed by the HOTCAP software package [15] (a high-speed oscilloscope-based tool for precise bunch-by-bunch three-dimensional position and charge 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, the 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 scintillator to produce an optical pulse composed of scintillation photons. The temporal characteristics can be characterized by a combination of rise time and decay time, with the mathematical expression as follows [16]:

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

where n_{ph} is the total number of photons in the scintillation pulse, τ_0 is the scintillator' s light decay time, and τ_1 is the scintillator' s rise time. The response function of the photomultiplier tube to a single photon output current can be expressed by a Gaussian function [17]:

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

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

$$I(t) = \int_{-\infty}^{\infty} i(\tau)n(t-\tau)d\tau$$

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

$$V(t) = R \cdot I(t) + \frac{1}{C}\int I(t)dt$$

where $R = 50\,\Omega$ and $C = 80\,\text{pF}$ are the equivalent parameters of the voltage readout circuit. Based on the above model, numerical simulation of the entire process from scintillator energy deposition 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, which is significantly larger than the bunch spacing of 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, the signals can be effectively separated using a de-stacking method, as detailed 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. A high-speed oscilloscope with a sampling rate of 16 GSa/s is used for digital acquisition of beam loss signals, corresponding to 3529 sampling points per turn. To extract the 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 a single turn after turn-by-turn slicing, with a pulse rise time of 2.8 ns and FWHM of 7.5 ns, which shows high consistency with the 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.

During steady-state operation, the beam loss signal amplitude is small and the signal-to-noise ratio is low, requiring filtering to enhance signal features. By comparing the power spectral distributions of beam loss pulses and noise signals (Figure 6 [Figure 6: see original paper]), significant differences were found in the normalized frequency range below 0.048π rad/sample, which was used to determine the passband cutoff frequency of the low-pass filter as 0.048π rad/sample.

A Kaiser-window low-pass filter (stopband attenuation 60 dB) was used to preprocess the signal and suppress high-frequency noise interference. After filtering, an asymmetric Gaussian function was used to fit the beam loss pulse, expressed as:

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

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 $\alpha > 0$ indicates 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 is determined by μ.

During injection, the beam loss frequency increases significantly, leading to pulse stacking phenomena (dashed line in Figure 7 [Figure 7: see original paper]). To more accurately extract the amplitude and time of stacked beam loss pulses, identification and reconstruction of the stacked pulses are required. First, the same low-pass filter is used to eliminate background noise. Then, MATLAB' s peak-finding function is used to identify the number of pulses and segmentation points. After completion, the asymmetric Gaussian fitting is performed sequentially on the first pulse according to the segmentation points to extract the amplitude $(A-C)$ and time (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 7).

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 8 [Figure 8: 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 collected 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, and turn-by-turn longitudinal phase information [18]. Typical bunch-by-bunch charge and position data measured during injection are shown in Figure 9 [Figure 9: see original paper].

2 Beam Experiments

During normal operation of Hefei Light Source, beam losses are mainly concentrated in the downstream region of the second dipole magnet [19]. Therefore, in the experiment, the scintillator detector was installed behind the second dipole magnet and adjacent to the BPM at that location. The on-site installation is shown in Figure 10 [Figure 10: see original paper]. In top-up operation mode, beam loss conditions were monitored during both the transient injection process and post-injection steady-state operation. 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 11 [Figure 11: see original paper]), where the horizontal axis represents sampling points (3528 points per turn), the vertical axis represents turn number, and the color maps the relative beam loss amplitude.

The RF frequency of Hefei Light Source is 204 MHz, corresponding to a bunch spacing (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 in the full ring were segmented, and the average beam loss per turn for each bucket was calculated as the beam loss rate for the corresponding bunch. Due to a fixed time delay difference between the beam loss signal and BPM signal, the data from the two must be aligned through timestamp matching. Because Hefei Light Source employs a special filling pattern in operation (a continuous bunch train of 35 bunches plus one isolated single bunch, as shown in Figure 9(a)), this filling pattern feature 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 12 [Figure 12: see original paper] shows the aligned bunch-by-bunch beam loss rate distribution, which is consistent with the storage ring filling pattern. No significant beam loss signals appear at empty bunch positions, indicating that the system possesses bunch-by-bunch loss resolution capability under steady-state, low-dose-rate conditions. The 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 detector, resulting in severe signal overlap. It is difficult to precisely locate which bunch is experiencing loss and calculate its beam loss amplitude within a single turn; only the approximate interval of the lossy bunch can be determined. Analysis of beam loss monitoring data from four injection processes at Hefei Light Source is shown in Figure 13 [Figure 13: see original paper]. In addition to significant beam loss in the injected bunch, notable beam loss also appears near the 14th stored bunch following the injected bunch.

The beam loss from the injected bunch most likely results from incomplete parameter matching between the fresh injected bunch and the storage ring parameters. This loss can be minimized by optimizing injector parameters and adjusting storage ring injection system parameters to improve matching. The beam loss near the 14th storage ring bunch after injection is most likely attributable to beam instabilities caused by the beam deviating from steady state during injection. Specifically, during injection, the beam deviates significantly from its equilibrium position in both transverse and longitudinal directions, thereby exciting relatively strong transient wakefields. Through inter-bunch nonlinear interactions, this induces instabilities in subsequent bunches. The underlying physical mechanism requires more detailed correlation analysis through targeted beam experiments combined with bunch-by-bunch three-dimensional position data for further investigation and confirmation.

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 directly. 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 the requirements for bunch-by-bunch beam loss monitoring. For accelerators with bunch spacing less than 7.5 ns, under low beam loss dose steady-state operation conditions, the lossy bunch 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 where multiple adjacent bunches experience beam loss near the detector simultaneously, bunch-by-bunch resolution cannot be achieved, and the error in beam loss amplitude extraction increases significantly.

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

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. The beam experiment results match the numerical simulation results perfectly, 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, which can accurately extract amplitude and time information from stacked pulses. Experimental results demonstrate that the system can effectively monitor bunch-by-bunch beam loss characteristics in electron storage rings while simultaneously monitoring 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 storage ring bunches, suggesting this effect may be related to inter-bunch wakefield coupling or nonlinear dynamic perturbations. More targeted beam experiments are needed in the future to further investigate and analyze the physical mechanism and optimize the injection process to reduce beam loss and improve injection efficiency based on these findings. 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 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 more types of accelerator facilities.

Author Contributions: LIU Yihong was responsible for numerical simulation, data processing and organization, and drafting and revising the final 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 detector installation and commissioning; LENG Yongbin was responsible for research proposal, scheme guidance, and final manuscript revision.

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