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JOINT ANALYSIS OF BEAM LOSS AND BEAM POSITION DURING THE INJECTION PROCESS AT HEFEI LIGHT SOURCE

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Abstract

The Hefei Light Source is a synchrotron radiation facility operating in the vacuum ultraviolet and soft X-ray regions. If the evolution of beam parameters and beam loss during the injection transient process can be observed synchronously, analyzing their correlation can provide more quantitative guidance for further optimizing the injection process. To achieve this goal, a monitoring system capable of synchronously capturing the 3D position of each bunch and rapid beam loss has been established at the Hefei Light Source. Experiments investigated both TOP-UP injection and empty-ring injection processes. Thanks to the unique multi-parameter synchronous diagnosis capability of this system, some previously unnoticed special phenomena have been captured, and a deeper analysis of the correlation between bunch parameters can be conducted. TOP-UP mode exhibited maximum beam loss in the injected bunch, with secondary losses at the 14th subsequent bunch. Peak beam loss occurred immediately after injection in both modes, followed by rapid attenuation within several turns. Loss resurgence appeared after ~85 turns (TOP-UP) or 180 turns (empty ring), followed by oscillatory decay.

INTRODUCTION

Hefei Light Source (HLS), completed and operational in April 1989, is a dedicated vacuum ultraviolet (VUV) and soft X-ray synchrotron radiation source. The basic parameters of its storage ring are as follows: 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 [1].

For an electron storage ring, beam loss is inevitable during the running period. It reduces the beam current and shortens the beam lifetime. Therefore, a beam loss monitoring (BLM) system is needed to evaluate the condition of beam loss and help researchers to optimize the parameters of the ring.

The optimization of the injection process is of great importance for synchrotron radiation facilities [2]. The injection system of HLS using a nonlinear kicker (NLK) which the injected off-axis beam passes through and receives a kick to achieve the injection [3]. The nonlinear kicker should be designed to bring the injected beam to the acceptance of the storage ring without considerable disturbance to the stored beam. 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 wall, leading to beam loss. Second, a mismatch between the Twiss parameters of the freshly injected bunch and those at the injection point of the storage ring may cause particle loss. Additionally, the pulsed electromagnetic fields of injection elements could perturb the stored beam, triggering transverse or longitudinal beam instabilities and consequently resulting in beam loss. If beam loss consistently exceeds acceptable levels during the injection process, it will severely limit the improvement of beam injection efficiency and beam lifetime. Therefore, it is essential to study beam dynamics and beam loss during injection.

The nanosecond-level time response of scintillators enables bunch-by-bunch beam loss monitoring. In recent years, scintillator-based beam loss monitors have been employed at facilities such as J-PARC [4], the European Synchrotron Radiation Facility (ESRF) [5], and SOLEIL [6].

In this paper, we report a bunch-by-bunch beam loss measurement system based on a plastic scintillator, PMT, and high-speed oscilloscope. Combined with the already installed bunch-by-bunch beam position measurement system, it forms a synchronized monitoring system with nanosecond-level high time resolution for beam loss and bunch position. This system is used to monitor and analyse beam loss during steady-state operation and injection processes at the Hefei Light Source.

BEAM LOSS MONITORING SYSTEM

Measurement Principle

When a lost high-energy electron hits the storage ring's vacuum chamber, it initiates a secondary particle shower (or cascade). This shower consists of a multitude of secondary particles, including photons (gamma-rays), electrons, positrons, and sometimes neutrons. A particle from the shower enters the scintillator material. It deposits its energy within the material and the deposited energy excites the molecules/atoms of the scintillator. As these excited states return to their ground state, they emit flashes of light. The light pulses travel to a Photomultiplier Tube (PMT), which is optically coupled to the scintillator. The PMT's photocathode absorbs the photons and, via the photoelectric effect, releases photoelectrons. These few photoelectrons are accelerated and multiplied through a series of dynodes within the PMT. This cascade effect creates a large, measurable electrical pulse which is captured by a high-speed oscilloscope.

Design of the BLM System at the HLS

The high temporal resolution beam loss monitoring system consists of a scintillator-based radiation detector, a beam position monitor, and a high-speed oscilloscope. The

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specific structure is illustrated in Fig. 1, and the main components are as follows:

- Beam Position Monitor: Used to acquire beam bunch position information and calculate the transverse and longitudinal positions of the beam bunch.
- Scintillator: Utilizes the EJ-200 scintillator from ELJEN, with a decay time of 2.1 ns.
- Photomultiplier Tube (PMT): Selects the H10721-110 PMT from Hamamatsu, with a rise time of 0.57 ns.
- High-Speed Oscilloscope 1: Keysight oscilloscope, with a sampling rate of 16 GSa/s, bandwidth of 6.3 GHz, and voltage resolution of 10 bits.
- High-Speed Oscilloscope 2: Siglent oscilloscope, with a sampling rate of 10 GSa/s, bandwidth of 2 GHz. and voltage resolution of 12 bits.

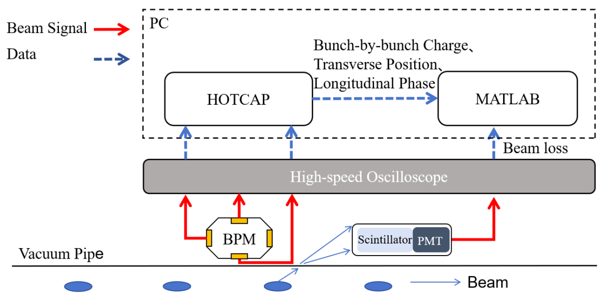

Figure 1: Schematic diagram of the beam loss and beam position monitoring system at the HLS.

Data Processing Method

Figure 2(a) shows a typical beam loss waveform output by the beam loss monitor, with a rise time of 2.8 ns and a full width at half maximum (FWHM) of 7.5 ns. The bunch spacing at the Hefei Light Source is 4.9 ns. During the injection process, the beam loss generated by the beam is significant, and adjacent bunches may experience continuous beam loss, resulting in signal stacking in the measured data. To maximize the time resolution and distinguish beam loss events from different bunches during injection, deconvolution processing is required for the original signal.

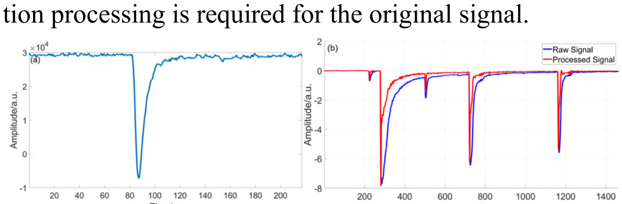

Figure 2: Signal processing: (a) Typical waveform of beam loss. (b) Signal after being processed with the trapezoidal filtering technique.

A trapezoidal filter is applied to the original signal, with a trapezoidal shaping rise time of 2 ns and a flat-top width of 1 ns. The specific effect is shown in Fig. 2(b). After filtering, the signals that were originally stacked on the falling edge of the preceding signal are no longer overlapping, significantly improving the time resolution. By performing peak detection on the filtered signal, the time and amplitude information of all beam loss signals can be obtained.

The revolution period of the Hefei Light Source is 220.59 ns, and the bunch spacing is 4.9 ns. By segmenting the beam loss time information obtained through the above steps accordingly, the specific turn numbers and bunch numbers responsible for the beam loss can be identified.

The BPM signals from the Hefei Light Source storage ring are also simultaneously acquired with the beam loss signals by the same high-speed oscilloscope. Using the HOTCAP software package developed by our research group [7-8], the turn-by-turn variations in bunch charge, transverse position, and longitudinal phase can be extracted [9-12].

BEAM LOSS DURING INJECTION

According to previous studies, beam losses at the Hefei Light Source primarily occur downstream of the secondary magnets. Therefore, beam loss monitors are installed near the BPMs downstream of the secondary magnets, as shown in Fig. 3. A high-speed oscilloscope is used to synchronously sample both beam loss and beam position signals. Since significant beam loss occurs during the injection process, simply setting a higher trigger threshold for the beam loss signal is sufficient to fully capture the beam loss and beam position information before, during, and after injection.

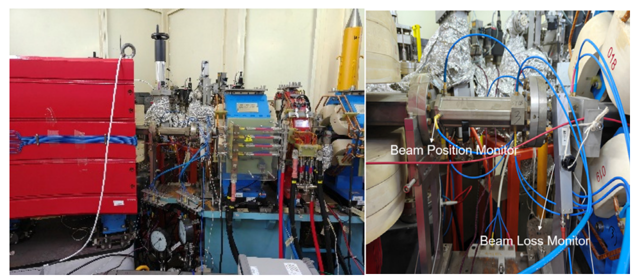

Figure 3: Photos of the BPM and BLM detectors.

Beam Loss at TOP-UP Injection

Under the TOP-UP operation mode of the Hefei Light Source, beam refilling is performed when the beam current decreases by 5 mA. The injection process generates significant beam loss. Using the beam loss and beam position monitoring system and data processing method mentioned above, the following results can be obtained. Figure 4(a) shows the beam loss occurring in each bunch per turn, where the horizontal axis represents the bunch number (45 bunches per turn), the vertical axis represents the turn number, and the color mapping indicates the relative amplitude of beam loss. Figure 5 displays the turn-by-turn changes in the horizontal positions, as well as the longitudinal phase, of the bunch experiencing the maximum beam loss.

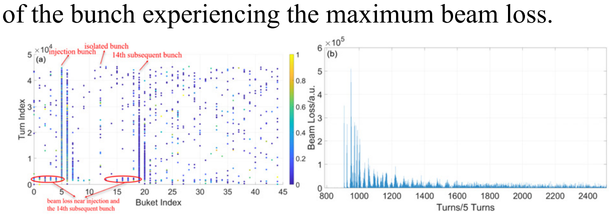

Figure 4: Beam loss at TOP-UP injection. (a) Beam loss scatter plot during TOP-UP injection. (b) Variation of the beam loss amplitude with the number of turns at TOP-UP injection.

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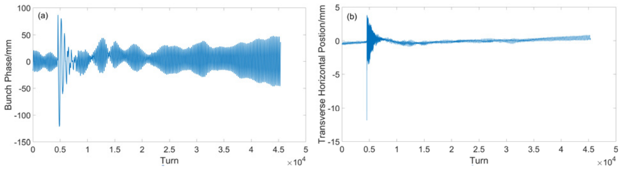

Figure 5: Turn-by-turn beam position. (a) Turn-by-turn variation of the longitudinal phase, (b) Turn-by-turn variation of the transverse horizontal position.

As can be seen from Fig. 4(a), the refill bunches exhibit the highest beam loss, and the 14th subsequent bunch also shows significant beam loss. The beam loss in the injected bunch can be attributed to the incomplete matching between its Twiss parameters and the Twiss parameters at the injection point of the storage ring. The beam loss in the 14th subsequent bunch may be caused by wakefield effects between bunches. Additionally, shortly after injection, noticeable beam loss occurs near both the injection bunch and the 14th subsequent bunch (the area circled in red in Fig. 4(a)). This is likely not caused by beam loss generated by other bunches but is instead due to the continuous beam loss occurring near the beam loss detector by the injection bunch and the 14th subsequent bunch. The varying arrival times of shower particles at the beam loss detector lead to this phenomenon, which has been validated in subsequent empty-ring injection experiments.

Figure 4(b) illustrates the variation of the beam loss amplitude with the number of turns after injection. As can be seen from the figure, the beam loss immediately reaches a maximum value after injection, then rapidly decreases. It suddenly increases again after about 85 turns before finally decaying and diminishing, potentially due to the dynamic interplay between phase space mismatch and synchrotron radiation damping.

Although the beam loss and beam position signals are acquired by the same oscilloscope, there remains a time delay between them due to differences in signal propagation and electronic delays, which requires synchronization. The specific method is as follows: The filling pattern of the HLS is 35+1. The isolated bunch can be clearly identified from the beam loss map, while the BPM detector can also obtain the charge quantity per bunch to determine the individual bunch. Based on this, the signals from the BPM and BLM can be aligned, thereby obtaining the position information of the refill bunch with the highest beam loss. Figure 5 shows that after injection, the transverse position and longitudinal phase of the refill bunch undergo significant oscillations, leading to beam loss.

Beam Loss at Empty Ring Injection

Experiments on empty ring injection were also conducted at the Hefei Light Source. Starting from the empty ring, the beam was continuously injected into the same bucket, and its beam loss was monitored during this process. The results are shown in Fig. 6.

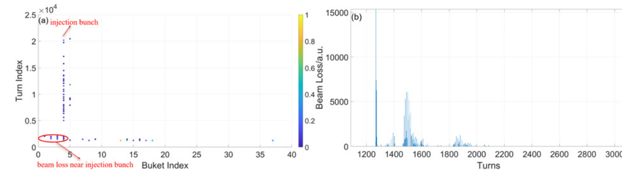

Figure 6: Beam loss at empty ring injection. (a) Beam loss scatter plot during empty ring injection. (b) Variation of the beam loss amplitude with the number of turns at empty rings injection.

As can be seen from Fig. 6(a), the beam loss is almost entirely concentrated in the injected bunch. Shortly after injection, beam loss also occurs near the injected bunch, as indicated by the red circle. This phenomenon is similar to the results observed in TOP-UP mode. Since there was only a single bunch in the entire storage ring during empty ring injection, this further validates our hypothesis from the TOP-UP injection experiments: the beam loss observed shortly after injection is not caused by the surrounding bunches but rather results from continuous beam loss near the beam loss monitor by the injected bunch itself.

Figure 6(b) shows the variation of the beam loss amplitude with the number of turns during empty ring injection. The overall trend is similar to that of TOP-UP mode injection: beam loss occurs immediately after injection, decreases rapidly, then suddenly increases around the 180 turn before decreasing again.

CONCLUSION

In this study, a synchronous beam loss and beam position monitoring system was established at the Hefei Light Source to monitor beam loss and beam position during both TOP-UP mode injection and empty ring injection processes. The beam loss signals during injection exhibited significant signal pile-up. To address this, a trapezoidal filtering method was employed, which substantially reduced the degree of signal pile-up and improved the time resolution of beam loss measurements. The beam loss occurs immediately after injection, decreases rapidly, then suddenly increases after ~85 turns (TOP-UP) or 180 turns (empty ring) before decreasing again.

The synchronized beam loss and beam position measurement system developed in this work can provide guidance for optimizing the injection process in storage rings and for radiation protection. Limited by the time response of the current scintillator, the system does not yet fully support bunch-by-bunch beam loss measurement. Using a scintillator with faster time responses and combining it with the trapezoidal filter method for data processing, full bunch-by-bunch beam loss measurement could be achieved. Additionally, due to the limited number of oscilloscope channels, it is currently not possible to simultaneously collect data from four BPM probes and one BLM probe. Using an oscilloscope with more channels would enable more accurate beam position information acquisition, thereby facilitating more in-depth correlation analysis between beam position and beam loss.

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