ANALYSIS OF AC LINE FLUCTUATION FOR TIMING SYSTEM AT KEK

D. Wang*, K. Furukawa, M. Satoh, H. Kaji, H. Sugimura, Y. Enomoto, F. Miyahara, KEK, Japan

Abstract

The timing system controls the injection procedure of the accelerator by performing signal synchronization and trigger delivery to the devices all over the installations at KEK. The trigger signals is usually generated at the same phase of an AC power line to reduce the unwanted variation of the beam quality. This requirement originates from the power supply systems. However, the AC line synchronization conflicts with the bucket selection process of SuperKEKB low energy ring (LER) which stores the positron beam. The positron beam is firstly injected into a damping ring (DR) to lower the emittance before entering desired RF bucket in LER. A long bucket selection cycle for DR and LER makes it difficult to coincide with AC line every injection pulse. This trouble is solved by grouping several injection pulses into various of injection sequences and manipulating the length of sequences to adjust the AC line arrival timing. Therefore, the timing system is sensitive to drastically AC line fluctuation. The failure of timing system caused by strong AC line fluctuation and solutions are introduced in this work.

INTRODUCTION

The electron/positron collider, SuperKEKB, is upgraded from the KEKB project since 2010 at KEK, whose goal is to update the world highest luminosity record and discover new particle physics by Belle II experiment [1]. The timing system at the 700-m long injector linear accelerator (LINAC) is responsible for the injection of all accelerator complex which consist of a 7 GeV electron high energy ring (HER), a 4 GeV positron low energy ring (LER), a 2.5 GeV Photon Factory (PF) and a 6.5 GeV PF-AR ring (see Fig. 1). During the phase-2 operation in 2018, a 1.1 GeV positron Damping Ring (DR) is constructed at the middle of LINAC to lower the positron beam emittance [2].

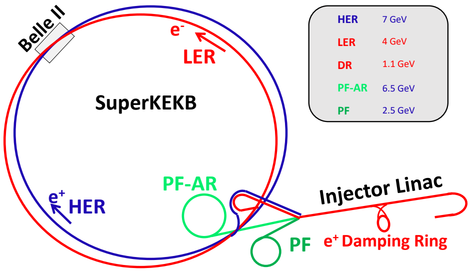

Figure 1: Overview of LINAC, SuperKEKB, and PF/PF-AR.

The event-based timing system at LINAC is required to switch the beam properties at 50 Hz by changing the event codes and additional control data. Totally 12 kinds of beam modes are defined to perform the pulse-to-pulse modulation. The master trigger signal of the timing system comes from the AC line to follow the fluctuation of power line and keep the beam energy stable. The bucket selection is implemented by adding delays to the master trigger signal. However, a long bucket selection cycle which caused by the DR makes it difficult to coincide with the AC line. A scheme called sequence shift is developed to synchronize with the 50 Hz AC line [3]. With the growth of the system complexity, several failures of timing system are observed and analyzed based on the fault diagnosis system [4].

In this paper, the reason of such failures are identified and some efforts to improve the reliability and stability of timing system are introduced.

BUCKET SELECTION FOR LER

The primary task for bucket selection is to provide the ability to select an arbitrary RF bucket in the ring for a single injection pulse. This can be achieved by adding a proper delay time to the gun triggering signal after defining the fiducial bucket in the ring. As the stable phase of RF cavity coincides based on the common frequency (CF) between LINAC and two main rings (MRs), the injection is performed based on the period of the CF [5]. After h times injection, all RF buckets are filled. The period during which all ring RF buckets can be filled is defined as a bucket selection cycle (BSC) and the period of BSC can be represented as

$$T_{\text{BSC}} = h_{MR} * T_{CF} \tag{1}$$

where h is the harmonic number (i.e., the number of RF buckets), T_{CF} is the period of common frequency between LINAC and MR.

According to the requirements of RF synchronization, several significant frequencies for timing system can be calculated in Table 1. Note that the BSC for DR only is practically useful when performing DR-injection-only mode for beam study.

Table 1: Bucket Selection Frequencies at KEK LINAC

Frequency	Period	Remarks
2856 MHz	350 ps	RF frequency for LINAC
508.89 MHz	1.97 ns	RF frequency for DR & LER
114.24 MHz	8.75 ns	Event clock
2.21 MHz	452 ns	DR revolution frequency
99.39 kHz	10.06 µs	LER revolution frequency
45.15 kHz	22.15 µs	BSC for DR only
2.03 kHz	493 µs	BSC for LER only
88.19 Hz	11.34 ms	BSC for DR and LER
50 Hz	20 ms	Beam repetition rate

---

[*] sdcswd@post.kek.jp

ISBN: 978-3-95450-221-9 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2021-THPV028

The harmonic number h_{MR} at two MRs are 5120, and the injection opportunity arises at the common frequency of 10.385 MHz between LINAC and the SuperKEKB MR (i.e., every 96.3 ns). According to the Table 1, all RF buckets can be selected within 493 µs, and the bucket selection process can be easily accomplished every 20 ms. Nevertheless, if DR is considered, the complexity of the bucket selection system grows. The harmonic number at DR is 230 and the least common multiple between the DR and LER harmonic numbers is 117760; thus, the BSC for DR and LER becomes 11.34 ms (i.e., 88 Hz).

AC LINE SYNCHRONIZATION

It is usually necessary to maintain the beam intensity and quality on the same level for consecutive triggers. Some devices are sensitive to the AC line phase and might not satisfy the stability requirement when working at different AC line phases. The klystron is a good illustration of this. Some klystrons use the AC-powered filament or heater to heat the electron cathode, and the changing AC phase might generate a magnetic field that eventually affects the velocity modulation process of the klystron. The frequency of the AC line is not ideal 50 Hz. The Tokyo Electric Power Company, which supplies AC power for KEK, adjusts the frequency of the AC power line within 50±0.2 Hz to balance the supply and demand requirement of the electricity market [6]. The timing system is required to follow the drift of AC50.

For HER injection, the BSC is 493 µs and the gun timing can be calculated based on the coincidence between AC50 and BSC. However, for LER injection with DR, the BSC is longer and to be 11.34 ms, so it cannot coincide with AC50 every 20 ms. Therefore, a method called sequence shift is utilized to deliver the triggers at the same phase of AC50, while it is also synchronized with the BSC.

SEQUENCE SHIFT

A set of injection pulses are grouped as an injection sequence. By shifting the length of the sequence, the synchronization between BSC and AC line becomes possible.

8/9 Pulses Sequence Shift

For HER injection, the BSC is 493 µs and the gun timing can be calculated based on the coincidence between AC50 and BSC every 20 ms. However, for the positron injection process, the bunch is first injected from LINAC into DR and then extracted from DR into LINAC after a pre-defined storage time. Hence, the BSC for the combination of DR and MR is 22.68 ms; therefore, synchronization with AC50 at every pulse is impossible. Consequently, an 8/9-pulse injection sequence was developed.

As shown in Fig. 2, the core ideology of the 8/9-pulse sequence is to define the 50 Hz fiducial point and record the AC50 arrival time and BSC timing. Inside the 8/9-pulse injection sequence, the bucket selection delay value for the positron can be acquired based on the fiducial point and current pulse number. After an 8-pulse sequence (i.e., 160 ms), the next sequence can synchronize with the BSC again if the next pulse starts 1.25 ms early. Similarly, launching the next pulse 1.4 ms after 9 pulses (180 ms) also meets the synchronization requirement (see Fig. 3). Using this method, the fiducial value for the BSC in every pulse can be calculated using the pulse number, and it is possible to operate the injection into DR and the extraction from DR at different pulses. The determination of the next sequence length is based on the AC50 value, which is measured by TDC for every pulse.

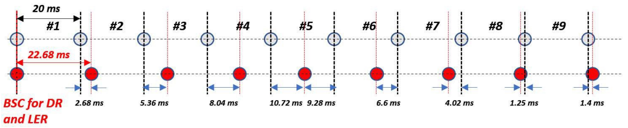

Figure 2: By shifting the injection sequence, the BSC for DR and MR injection can synchronize with the 50-Hz AC50.

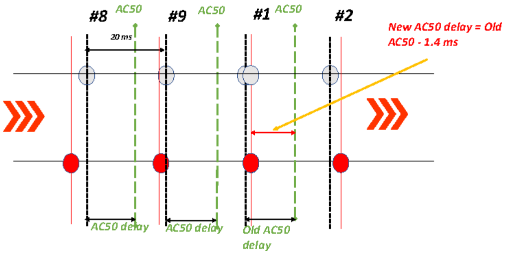

Figure 3: AC50 position in a pulse is manipulated by the sequence shift.

16/18 Pulses Sequence Shift

The DR operation is carried in 2018. To achieve a satisfactory damping effect, a DR storage time of at least 40 ms is required. There also exists a restriction of the maximum storage time in the DR. The injection and extraction delay are calculated together, and both follow the AC line phase at the injection pulse. Thus, the extraction timing trigger has a larger discrepancy at the downstream LINAC for a long storage time. The difference between the extraction timing and AC50 arrival timing at extraction pulse becomes larger when the storage time increases. Consequently, the maximum storage time is chosen to be 200 ms, while the minimum storage time is 40 ms. To supply the requirement of the maximum DR storage time (200 ms), the sequence length is doubled to apply the 16/18-pulse sequence shift in 2018, and the sequence shift values are enlarged to 2.5 and 2.8 ms [2].

Sequence Shift Algorithm

The algorithm of the sequence shift is based on the AC50 timing of the previous pulse and uses it as an estimation the AC50 value in the near future. A reference value is also required to act as a comparison point. Obviously, there are only two sequence types, i.e., 16-pulse sequence and 18-pulse sequence. Therefore, the AC50 shift value, i.e., 2.5

and -2.8, can be used to represent the sequence types 16 and 18, respectively. Because the program operation requires some time, the sequence shift decision should be done at the start of the current sequence. It is then easy to calculate the next sequence type based on the current sequence type and the AC50 timing of the starting pulse. The detail of the sequence shift algorithm can be referred from [7].

TIMING SYSTEM FAILURES

The timing system, which satisfies the requirements to operate the DR for the positron injection, was installed and commissioned in 2018 [2]. As the growth of the system complexity comes from the bucket selection and 16/18-pulse sequence shift, several failure modes of the timing system are observed. An event code log system, which monitors and saves all event codes received in EVR, is developed to diagnose the failure modes in 2019 [4]. The severity of some timing system failures is minimal because the trigger signals for devices are masked and inhibited by beam gate system [8] when some abnormal events are transmitted. On the other hand, a timing system failure that stops the delivery of event codes for a few minutes is severe for the physics run because it usually triggers the beam abort system to dump all the beams at SuperKEKB. It normally takes 10 minutes for the operator to check the status of the devices and restart the injection. The occurrence of such kind of failure is rare (i.e., 9 times) in 2020. However, the number of failures increases to 18 times in a month since the 2021 spring, and the beam operation is frequently interrupted. Thus, it is urgent and significant to understand the failure cause and stabilize the operation. By analyzing the event code log system and auxiliary timing data, such malfunction of the timing system is caused by strong AC50 drift.

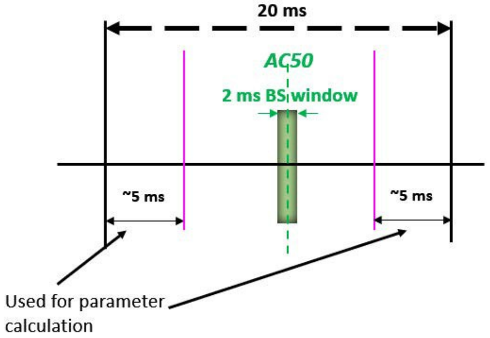

Figure 4: If AC50 arrives too early or too late in the 20 ms pulse, the logic of timing system may fail

As Fig. 4 shows, every pulse the timing system needs some time to process the data. If AC50 drifts continuously, the AC50 arrival time may comes too early or too late. Therefore, the timing system logic may fail.

STABILIZATION OF TIMING SYSTEM

As Fig. 5 shows, compared with the 16/18-pulse injection sequence, the 8/9-pulse injection sequence increases the robustness of the sequence shift algorithm. Switching to the 8/9-pulse injection sequence is a possible method to solve the timing failure because the AC50 adjustment speed is faster.

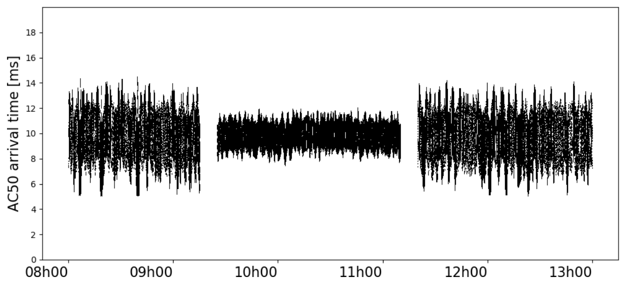

Figure 5: Comparison of AC50 arrival timing between 16/18-pulse sequence and 8/9-pulse sequence.

The restriction of the sequence length originates from the DR storage time and the root reason is the coupling of DR injection and extraction calculation. Shifting the RF phase at downstream LINAC is an efficient way to increase the DR extraction opportunity and relieve the stress of long sequence management. The DR extraction delay is calculated based on the shifted RF phase at downstream LINAC. Under these circumstances, the dependency between DR and MR injections can be removed. The operation of 8/9-pulse sequence shift is possible as the DR injection and extraction delay calculations can be separated. More descriptions about RF phase shifting can be found in [9].

Apart from the 8/9-pulse sequence shift, the sequence shift algorithm can be further improved by considering the AC50 drift value. Currently, the estimated AC50 arrival time is used to determine the next sequence type. If strong AC50 drift happens, the estimated value has a large deviation from the real value. The timing system could enter race conditions when an inappropriate sequence type is selected. To avoid such a situation, the sequence shift algorithm is modified and the average AC50 drift value in recent pulses is utilized to help the sequence shift algorithm to estimate the AC50 arrival time. The new estimation becomes closer to the real value even when AC50 fluctuates strongly.

According to our simulation, the new algorithm can handle an AC50 drift ranging from $-156\,\mu s$ to $158\,\mu s$. Figure 6 shows a timing system failure which is caused by the strongest AC50 drift situation that we have recorded during the past two years. The data was recorded by TDC in 2019. The AC50 drift value reached $120\,\mu s$ and lasted for several seconds. Figure 7 compares three sequence shift schemes, 16/18-pulse sequence shift which is currently using, 8/9-pulse sequence shift, and 8/9 pulse sequence shift with the functionality of using the past AC drift value. The results show that the new algorithm can handle the most significant AC50 drift situation.

The 8/9-pulse sequence operation with AC50 drift compensation has been planned from the 2021 summer.

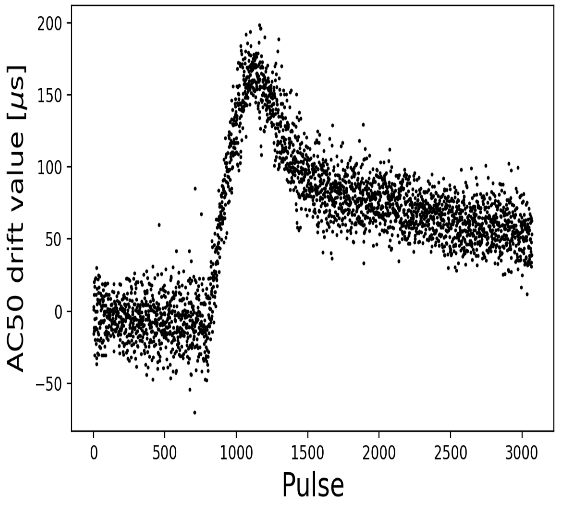

Figure 6: Extremely strong AC50 drift recorded by TDC.

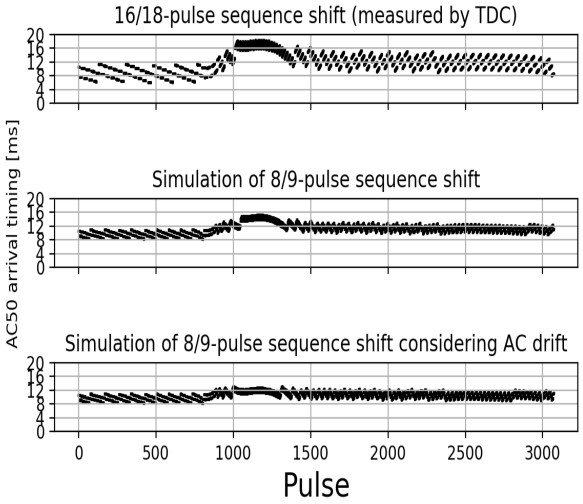

Figure 7: Comparison of different sequence shift schemes.

SUMMARY

The timing system failures that happened at LINAC frequently interrupt the operation of SuperKEKB. We analyzed the algorithm of the injection sequence shift, the timing system failures caused by strong AC50 fluctuation are solved after upgrading the sequence shift by applying short sequence length and performing a reliable AC50 estimation. The simulation results show that the new method can handle the most severe AC drift situation we have ever met in the last two years. The analysis procedure and solution for a timing system with a long bucket selection cycle can be referred to for the design of future circular accelerators.

REFERENCES

[1] Y. Ohnishi *et al.*, “Accelerator design at SuperKEKB,” *Progress of Theoretical and Experimental Physics*, vol. 2013, no. 3, 26, 2013, doi:10.1093/ptep/pts083

[2] H. Kaji, H. Sugimura, Y. Iitsuka, and T. Kudou, “Injection Control System for the SuperKEKB phase-2 operation,” in *Proceedings of the 15th Annual Meeting of Particle Accelerator Society of Japan*, 2018, pp. 124–128, https://www.pasj.jp/web_publish/pasj2018/proceedings/PDF/THOM/THOM03.pdf

[3] H. Kaji *et al.*, “Installation and commissioning of new event timing system for SuperKEKB,” in *Proceedings of the 12th Annual Meeting of Particle Accelerator Society of Japan*, 5–Aug. 7, 2015, pp. 223–227, http://www.pasj.jp/web_publish/pasj2015/proceedings/PDF/FROL/FROL15.pdf

[4] D. Wang *et al.*, “The Fault Diagnosis of Event Timing System in SuperKEKB,” in *Proceedings of the 17th International Conference on Accelerator and Large Experimental Physics Control Systems (ICALEPCS’19)*, 2019, pp. 741–745, doi:10.18429/JACOW-ICALEPCS2019-TUBPR04

[5] H. Kaji *et al.*, “Bucket Selection System for SuperKEKB,” in *Proceedings of the 12th Annual Meeting of Particle Accelerator Society of Japan*, 5–Aug. 7, 2015, pp. 1278–1281, https://www.pasj.jp/web_publish/pasj2015/proceedings/PDF/THP1/THP100.pdf

[6] Tokyo Electric Power Grid Co., “Rule of frequency adjustment, supply and demand,” 7, 2020, pp. 24–26, https://www.tepco.co.jp/pg/consignment/rule-tr-dis/pdf/freq-j.pdf

[7] D. Wang *et al.*, “Analysis and stabilization of AC line synchronized timing system for superKEKB,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 1015, p. 165 766, 2021, doi:10.1016/j.nima.2021.165766

[8] H. Sugimura, H. Kaji, M. Satoh, F. Miyahara, and S. Sasaki, “Trigger control system with Beam Gate at SuperKEKB injector LINAC and Damping Ring,” in *Proceedings of the 15th Annual Meeting of Particle Accelerator Society of Japan*, 7–Aug. 10, 2018, pp. 1078–1081, https://www.pasj.jp/web_publish/pasj2018/proceedings/PDF/THP0/THP091.pdf

[9] H. Kaji, “Bucket Selection for the SuperKEKB Phase-3 Operation,” in *Proceedings of the 15th Annual Meeting of Particle Accelerator Society of Japan*, 2018, pp. 1114–1116, https://www.pasj.jp/web_publish/pasj2018/proceedings/PDF/THP1/THP100.pdf