THE FAULT ANALYSIS OF TIMING SYSTEM IN SuperKEKB

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Abstract

The high availability of an accelerator timing system is of great significance for the operation of the SuperKEKB electron-positron collider. To distribute the high precision level trigger signals for synchronizing all the relevant components in the accelerator complex, event based timing system is utilized to control the injection procedure in SuperKEKB. Another critical challenge of the timing system is to control the bucket selection of both electron and positron beam bunch. The failure in timing system would definitely affect other systems like pulsed magnet, BPM and so on, and as a consequence leading an unfavourable impact on the effectiveness of the particles collide. Additionally, a newly built positron damping ring decrease the positron emittance but meanwhile brings higher complexity of the bucket selection. In this paper, we will demonstrate the algorithm of the timing system and introduce our fault analysis system which helps up to analyze the timing error, improve the accelerator operation stability.

INTRODUCTION

The 600-meter long injector linac at KEK provides beams for 4 different rings. Two synchrotron light source facilities, 2.5-GeV PF and 6.5-Gev PF-AR, and one high luminosity electron positron collider SuperKEKB with a high energy ring (HER) and a low energy ring (LER) share the injector linac. The energy of electron and positron beam is 7.0 GeV and 4 GeV respectively [1]. The phase-to-phase modulation (PPM) is utilized to achieve the requirement. The timing system controls the filling process of different beam by distributing control signals to all over the accelerator and any faults during the filling process will require dumping the beam [2]. With respect to the pursuit of world's highest luminosity, the beam dumping should keep away from beam dumping as much as possible. The stability of the timing system is of great significance to the operation.

The bucket selection process is necessary to inject the beam into its dedicated ring properly. One 1.1 GeV positron damping ring (DR) is newly constructed to reduce the beam emittance which inevitably increase the complexity of the LER bucket selection decision. The 135.5-meter long DR locates at the middle of the linac and separates linac as upstream linac and downstream linac. To achieve a good damping effect, the positron beam should cycle inside the DR at least 40 ms. Apart from that, the beam gate system is embedded in the timing system to control the injection and extraction mode at DR as well as avoiding unnecessary beam firing at electron gun. To meet the some hardware requirements, there are some restrictions on how the injection mode can be sequenced.

During the operation, several beam abortion originating from timing system are observed. Based on the further comprehensive analysis of the timing system, the beam mode is summarized and the stabilizing method is proposed.

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TIMING SYSTEM FOR SuperKEKB

The task of the timing system is to synchronize all the accelerator devices and components like gun, pulsed magnets and BPM in a relatively sequence. A typical injection procedure works like the Fig. 1. The EPICS IOC at KEKB Control Room first reads the bunch current in the main ring (MR), calculates the delay value for bucket selection and then transfers the delay to the IOC locates at Linac Control Room by optic fiber. This delay then is applied at the electron gun to generator the beam.

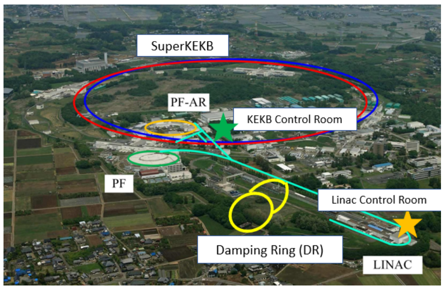

Figure 1: Over of the timing system at SuperKEKB.

Pulse-to-Pulse Modulation

The concept of PPM which originates from CERN is to modulate beam properties to improve the efficiency of the linac when different beams are needed [3]. At SuperKEKB, under 50 Hz beam repetition rate hundreds of accelerator component parameters will switch swiftly according to the injection beam mode. As the Fig.2 shows, with the change of the injection mode, the timing system generates different event codes pulse by pulse.

The Hardware and Software

In addition to the functionality of PPM, the basic role of a timing system is to deliver the timing signal by dedicated timing network. At SuperKEKB, the event based timing system is deployed at the VME crate with several modules. The Event Generator (EVG) and Event Receiver (EVR) provided by the MRF company are mainly used to generate and distribute the event codes to the accelerator devices [4]. The VME-based time-to-digital converter (TDC) module with a

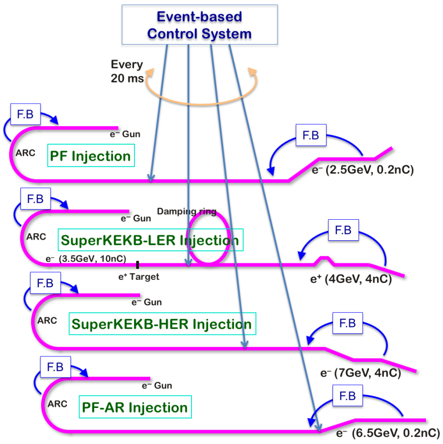

Figure 2: Pulse-to-Pulse Modulation.

resolution of 1 nanosecond developed at KEK is used to monitor the timing [5]. Furthermore, the VME-5565 Reflective Memory (RM) module provides a high-speed, low latency data sharing among several timing station nodes. The bucket selection delay value and other necessary information for beam injection and extraction which are calculated at the main ring is transmitted to the linac timing station through the RM.

The EVG receives a RF signal as the event clock and a trigger signal to send the event codes which are saved at the hardware sequencer memory. The event clock at linac is 114.24 MHz.

Beam Gate

The beam gate system is an important part of the timing system which is able to switch the beam mode and stop the beam delivery if necessary [6]. This system is of great significance during the operation by controlling the injection/extraction hardware and electron gun. Besides, the top-up injection and beam study also rely on the beam gate to control the hardware.

The beam gate information is delivered via event timing network with the help of EVG's Distributed Bus (Dbus) function. The Dbus accepts 8 TTL inputs and transmits the data via event timing network to all downstream EVRs.

Bucket Selection

The beam should be injected into the proper RF bucket to make sure the bunch always sees an accelerating voltage at the RF cavities. As a consequence, the injection delay time must be calculated in advance.

The bunch synchronization relationship between Linac and MR should be considered since their RF frequencies are different. According to the Table 1, the coincidence frequency between them is 10.385 MHz. Every 96.3 ns (49 RF buckets) the injection opportunity reoccurs to fill the bunch to the MR RF bucket. We define the "super-period" as the least timing of injecting to all the RF buckets in a ring. Thus, the super-period for HER injection is 96.3 $\times$ 5120 = 493 μs. For LER, since there are 230 RF buckets at DR, the super-period becomes much longer which is 96.3 $\times$ 5120 $\times$ 23= 11.34 ms.

Table 1: Key Parameters of SuperKEKB Timing

Parameter	**Value**
Linac RF frequency	2856 MHz
MR RF frequency	508.9 MHz
MR revolution frequency	99.39 kHz
MR harmonic number	5120
DR RF frequency	508.9 MHz
DR revolution frequency	2.21 MHz
DR harmonic number	230

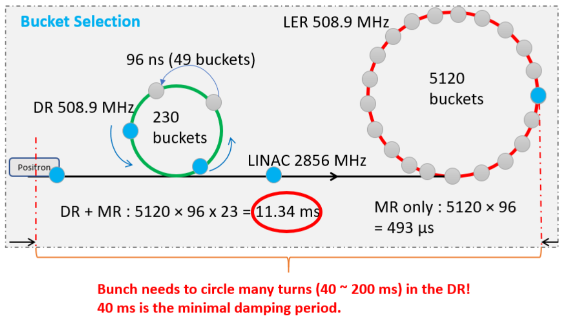

Figure 3: The synchronization between DR and LER. The positron beam is injected into the DR first and cycle for at least 40 ms. The bunch extracts from DR later and injects to the LER bucket.

The relationship between the injection opportunities and the RF bucket in DR and MR can be calculated though the Eq. (1) and Eq. (2), respectively. By means of these equations, the relationship between the bucket selection candidates and the delay time are listed at Table 2

$$BKT_{DR} = INJ_{turn} \times 49 \pmod{230} \tag{1}$$

$$BKT_{MR} = INJ_{turn} \times 49 \pmod{5120} \tag{2}$$

CONSTRAINTS

However, some restrictions exist during the real operation. Firstly, the injection point should close to the AC power line (AC50) because of the klystron hardware requirement. Moreover, only 2 ms fluctuation near the AC50 is the allowed for a stable accelerating. For LER injection, the beam storage time in DR makes it impossible to finish the injection in 20 ms. Another restriction which comes from the DR kicker magnets will reduce the injection opportunities when performing the two-bunches-one-pulse injection.

AC50 Synchronization

To inject into the LER, the bucket selection delay should be calculated based on the damping period. Since the solution appears every MR super-period (493 μs), the one which

Table 2: Bucket Selection Calculation

Injection Turn	Delay	DR Bucket	MR Bucket
0	0 ns	0	0
1	96.3 ns	49	49
2	192.6 ns	98	98
3	288.9 ns	147	147
...	...	...	...
230	22.1 μs	0	1030
...	...	...	...
5120	492.9 μs	180	0
...	...	...	...
20,771	1.99 ms	29	4019
20,772	2 ms	78	4068
...	...	...	...
117,760	11.34 ms	0	0

is nearest to the AC50 is selected. Within the 2 ms range, only 4 of 23 MR buckets combinations can be realized. Take Fig.4 as an example. The DR injection happens at pulse number 1 and extraction happens at pulse number 3. The delay value for extraction should be buffered and sent out at two pulses later. Both delay values are based on the AC50. The AC50 can be read from the TDC module at every pulse.

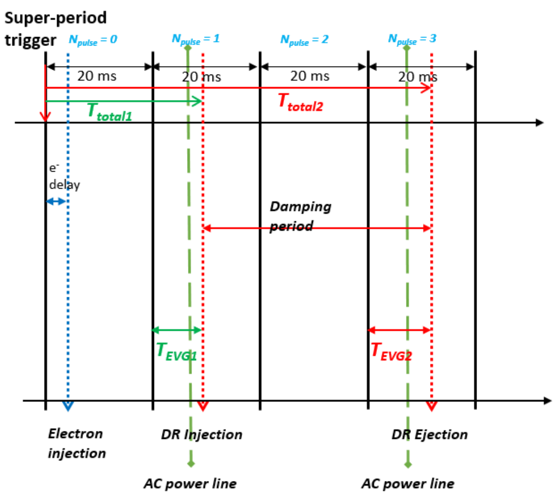

Figure 4: Bucket Selection calculation of LER.

Damping Ring Kicker

Owing to the 100-ns kicker magnets field rising time, if the distance between newly injected bunches and stored bunches is smaller than 100 ns, the stored bunches would be affected by the magnetic field. Under this circumstance, only 31 DR buckets can be selected. This process is demonstrated in Fig.5.

RF Phase Shift

Considering both restrictions, only 2887 MR buckets can be selected during the two bunches LER injection. Figure 6 shows the allowed buckets at DR and LER. To select all the

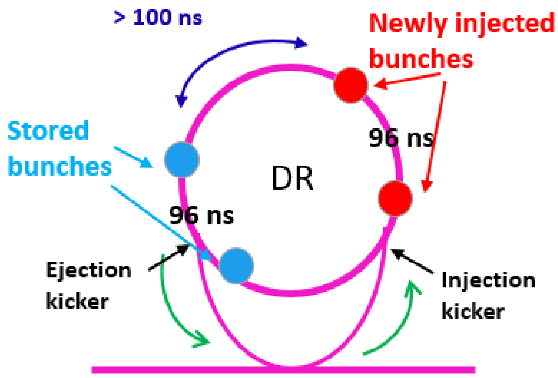

Figure 5: Schematic view of allowed RF buckets at DR in the two bunches injection.

MR bucket in every pulse, a possible solution is to modulate the RF phase in the Linac between DR and LER. By shifting the Linac RF phase pulse by pulse, the coincidence opportunities increase and much more MR buckets are available. Now the RF phase shift is still under experiment.

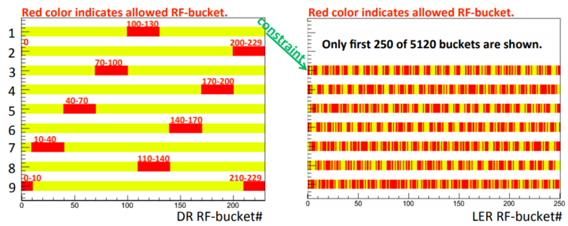

Figure 6: If DR bucket number 0 and 49 are already occupied, only bucket 100 to 130 are available for the new bunches. This constraint also decrease the available buckets at LER.

8/9 Pulses Sequence Shift

The LER super-period is 11.34 ms which can not coincide with AC50 every pulse. To overcome this, a method called 8/9 pulses sequence shift is utilized. As shown in Fig.7, inside the 8/9 pulses sequence the LER delay value can be acquired based on the fiducial point and current pulse number. After 8 pulses sequence, next sequence can synchronize with super-period again if next pulse starts 1.25 ms early. Similarly, the next sequence is launched 1.4 ms later than usual 20-ms period [7]. By means of this method, every pulse is able to coincide with the super-period. The determination of next sequence length is based on the AC50 value. The AC50 should come at the middle of the 20 ms pulse to keep a stable operation.

FAILURE MODE ANALYSIS

For continuous injection, the injection sequence includes many beam pulses. The operator can change the injection sequence based on the operation situation. The sequence varies from 2 (40 ms) to 500 (10 s). Owing to the buffered bucket selection of DR extraction, the bunch stored at DR might not be extracted if the buffered delay value is lost

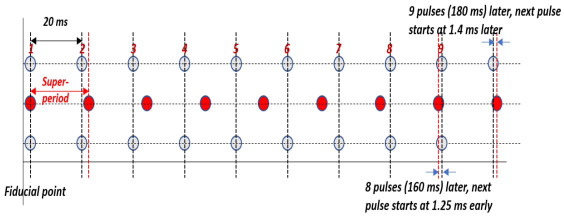

Figure 7: Timing relation between 8 pulses injection, 9 pulses injection and LER super-period.

during the sequence shift. To avoid this situation, currently the beam gate must be closed during the sequence shift by the operator. But this process is not robustness enough.

Another failure is caused by the AC50 drift. Since the injection needs to synchronize with AC50 every pulse, normally the 8/9 pulses sequence shift is able to handle the slightly drift and always keeps the AC50 comes at the center of every pulse. However, sometimes the AC50 drifts severely and the program processing time might be limited if the AC50 comes too late [8].

Timing System Upgrade Plan

To solve these failures, we plan to refactor the bucket selection software and add critical data monitoring part to diagnose and eliminate the error as the Fig.8 shows. Considering the high VME CPU load, a new EPICS IOC will be added to monitor these data shared by reflective memory. The original event codes are important to help us identifying the failure source. A high-speed event codes logging system has already been developed. Furthermore, many critical data monitoring and aggregation need to be done. The commissioning will be performed on the end of 2020.

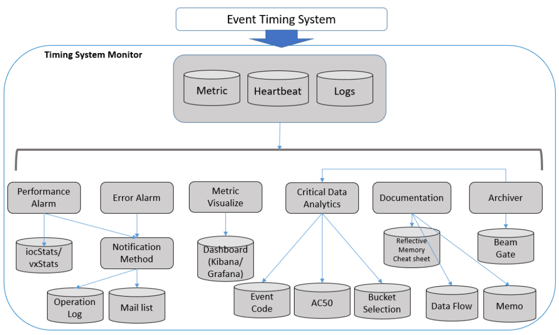

Figure 8: The failure mode monitoring and analysis system of the Event Timing System.

SUMMARY

With the upgrade of the timing system at the SuperKEKB, both hardware and software has encountered several failures. One of the reason is the high complexity of the whole system. To diagnose and improve the stability and maintainability of the timing system, the structure and algorithm need to be fully analyzed. Several requirements are also demonstrated. Then, the failure modes based on the event code log and data analysis are briefly explained.

After the distinction of different failure modes, several solutions are proposed which include dedicated monitoring IOC, high-speed event code logging and bucket selection program refactoring.

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