Pulse-to-Pulse Modulation of Injector Linac with Event Timing System

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***Abstract*—The Pulse-to-Pulse Modulation of Injector Linac at KEK is developed for efficient injections. It automatically switch the beam mode with the real-time process. We integrated this system in 2009 to simultaneously perform the top-up filling into more than one rings with only one injector. The system is based on the Event Timing System. Recently, we upgraded the configuration of Event Timing System to satisfy the complicated requirements of SuperKEKB and developed the test procedure to understand stability of real-time process. The malfunction of real-time process at Main Trigger Station is intentionally caused when we shorten the allowed computing time as the stress test. The reasonable dependence between the malfunction rate and the allowed computing time is determined. It indicates we can evaluate the malfunction rate in case of normal operation at Main Trigger Station.**

I. Introduction

THE Pulse-to-Pulse Modulation is developed at KEK for the operation of injector linac (LINAC)[1]. LINAC provides beam-pulses into two main-rings (KEKB-HER and KEKB-LER) for the KEKB collider[2][3] and two light sources (PF[4] and PF-AR[5]). It automatically switches the direction of beam-pulses with this real-time process for raising efficiency of injection.

The basic technology is the Event Timing System[6]. The signal to instruct the change of operation parameters is delivered toward the individual components of LINAC beamline by using this system.

The Pulse-to-Pulse Modulation system has been integrated in 2009[6][7] with the surge of requirements from experiment group[8]. We performed the top-up filling into KEKB-HER, KEKB-LER, and PF, simultaneously. The luminosity tuning at KEKB became easier since its storage beam currents are stabilized[9]. It also increased the integrated luminosity at KEKB, which directly affects the accuracy of physics results.

We decide to upgrade the Pulse-to-Pulse Modulation in order to satisfy the new requirements of the coming SuperKEKB project[10][11]. The new configuration of Event Timing System is designed and its feasibility study is performed[12]. Besides, recently, the benchmark procedure to study the stability of real-time process is developed.

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In this paper, we introduce the Pulse-to-Pulse Modulation and the Event Timing System with the latest configuration for SuperKEKB. Then, the result of stability study is explained with its benchmark procedure.

II. Pulse-to-Pulse Modulation

The Pulse-to-Pulse Modulation is the real-time process which automatically switches the beam mode of LINAC. We integrated this system to perform the top-up filling into more than one accelerator-rings with only one injector. We performed the top-up filling into the three rings (KEKB-HER, KEKB-LER, and PF) in the KEKB period while we will do into four rings (additionally PF-AR) in the SuperKEKB period.

The switch of the beam modes is extremely complicated since the beam-pulses requested from individual rings are quite different as shown in Table I. The quite different injection processes are needed to produce the different beam-particle, energy, or charge per bunch. For example, the electron-pulses injected into KEKB-HER are generated at the electron gun and accelerated in the whole beamline to be the energy of 7.0 GeV. However those injected into PF and PF-AR are decelerated in the downstream part of beamline to make the required energy of 2.5 GeV and 6.5 GeV, respectively. It needs to modulate RF-phase into the decelerating phase. For KEKB-LER, electron-pulses are shot on the positron target to produce positrons. After that they are accelerated to be 4.0 GeV. The RF-phase for acceleration in this case is different since the beam-pulses have positive charge. The injection process and energy profile in each beam mode are shown in Fig. 2 and Fig. 3, respectively.

The specific feature of the Pulse-to-Pulse Modulation system is the real-time control of a large number of hardware which are separated each other in the large area. LINAC controls hardware installed belong the 600 m beamline with this system. Typically, more than 150 of LINAC parameters are changed in 50 Hz for switching the beam modes.

Additional functions related damping ring (DR) are required for SuperKEKB. DR is newly constructed to reduce the emittance of positron-pulses. The new Pulse-to-Pulse Modulation system must include following functions for positrons.

The produced positrons are once stored into DR for at least 40 ms. Then, they are accelerated and injected into KEKB-

LER. The injection process becomes longer than one injection period, 20 ms at SuperKEKB.

The first half and second half of LINAC must be operated separately. The first half of LINAC works for producing positrons and injecting them into DR while the second half of LINAC works for transporting positrons from DR to KEKB-LER with acceleration.

III. Event Timing System

The Pulse-to-Pulse Modulation is performed with the Event Timing System. The system consists of Event Generator (EVG) and Event Receiver (EVR) which are connected via the optical network with each other.

In this section, we explain the rolls of each components and the injection control for LINAC. Then, the new configuration for SuperKEKB is introduced.

A. Event Modules

Both EVG and EVR are the device based on FPGA and SFP. The system is functioned when the EVG is received a TTL trigger.

The EVG sends 2 byte data packet named "Event" to the EVR. The first half (1 byte) of Event is used to distinguish the kind of Event. Therefore there are 256 kinds of Events. The EVG controls EVR by using these Events. The second half of Event is reserved for implementing more complicated control.

The EVR is functioned when it is received the Event. The EVR controls hardware by delivering timing triggers through its output channels or interruptions to CPU module which is installed on the same bus. Such kind of functions can be programmed to the individual Events.

We use the VME type modules, VME-EVG-230 and VME-EVR-230RF, which are commercial products by MRF[13].

B. Optical Network

The star-topology optical network is configured to deliver Events. Fig. 4 is the schematic view of optical network for LINAC. We installed the EVG at the center of this network. It is the Main Trigger Station. The other edge of individual lines are connected with EVRs which are installed along LINAC beamline. The EVRs change the operation parameters of individual devices along the beamline with respect to the kind of Events.

The cables can be worked also as the trigger lines. The performance of Event Timing System as the trigger system is explained in Ref. [12] to be the timing precision of $\sim$10 ps.

C. Injection Control with Event Timing System

We use the Event Timing System for both timing delivery and instruction to change the parameters of LINAC. Therefore there are two categories of Events. They are "timing-Event" and "preparation-Event". An example of schedule for delivering Events at LINAC is shown in Fig. 5.

The timing-Event is followed by the preparation-Event related to the beam mode for next injection. They are delivered together when the EVG is triggered for each injection.

The EVR launches the timing-trigger to LINAC hardware to perform the injection when it receives a timing-Event. Then, typically 2 ms later, the EVR launches interruption to CPU on the VME64x-bus and set up parameters for next injection when it receives a preparation-Event.

The complicated interruption process can be easily programmed to each preparation-Event since it is managed by EPICS[14]. The interruption programs for the preparing each beam mode are set in advance. They are launched when the EVR receives the related preparation-Events. The MVME5500 module is used as the CPU device at LINAC.

D. New Configuration for SuperKEKB

Fig. 6 and Fig. 7 are schematic view of the new configuration of Event Timing System for SuperKEKB and the picture of modules, respectively. Only Main Trigger Station is shown here. We configure two-layers of EVGs at Main Trigger Station. At lower-layer level, two EVGs (lower-EVGs) are installed. They deliver Events toward the first-half and second-half of LINAC independently. This configuration realizes the extremely complicated injection control at SuperKEKB as follows.

The upper-layer EVG (upper-EVG) is functioned with a few seconds of sequence. A few second of injection process in 50 Hz is scheduled on this EVG. Therefore the positron injection, whose process exceeds the one injection period, can be manage within one sequence of upper-EVG.

The middle-level EVR (middle-EVR) works for delivering triggers to the lower-EVGs on the timing indicated with the Event from upper-EVG. The two lower-EVGs are precisely synchronized with triggers from the middle-EVR so that the electron-pulses can be transfered entire beamline. Besides, the Pulse-to-Pulse Modulation of lower-EVGs are performed by the interruption from the middle-EVR.

The lower-EVGs are functioned in 50 Hz with the trigger from middle-EVR. The separate operation of LINAC in case of positron injection is implemented with two lower-EVGs. The first-half and second-half of LINAC are taken care with the first and second lower-EVGs, respectively. Two lower-EVGs are synchronized when LINAC injects electrons. Also we can manage the delay of Bucket Selection[15] on these lower-EVGs.

IV. Stability Study

Recently, we developed the test procedure to benchmark the stability of Pulse-to-Pulse Modulation as the real-time system. One of important points in the performance of real-time system is stability, like the operation for a month without any problem. However the benchmark to know it in the R&D stage is always difficult.

We established the test procedure to understand what kind of malfunction is happen in the Event Timing System during the long-term operation. It provides us also the evaluation of malfunction rate with the statistical treatment.

In this section, we introduce the test procedure to study the stability of real-time process and the result for the new configuration of Event Timing System.

A. Test Procedure

As mentioned in Section III, the Event Timing System precisely controls the timing to deliver Events toward the EVR. This means we can control the time interval between the preparation-Event and the timing-Event, which is the allowed computing time for the real-time process for the Pulse-to-Pulse Modulation.

We performed stress test with this capability. We intentionally cause the malfunction by shortening this time interval as shown in Fig. 8. The rate of malfunction is determined as a function of time interval. Then, the malfunction rate in case of the usual time interval, 18 ms, is statistically evaluated.

B. Result of SuperKEKB System

We introduce the malfunction rate of lower-EVGs during the Pulse-to-Pulse Modulation. At SuperKEKB, the schedule of Event delivery at lower-EVGs are changed in each injection period. It is the key technology for Pulse-to-Pulse Modulation of LINAC.

The malfunction rates when we shorten time interval between preparation-Event and timing-Event at upper-EVG are summarized Fig. 9. The decrease of malfunction rate is determined when we lengthen the time interval. It indicates we can evaluate the malfunction rate in case of normal operation from trend of the results.

The relatively large malfunction rate at the second lower-EVG is determined. However it is reasonable since the second lower-EVG is set up after finishing the set up of the first lower-EVG.

The malfunction rate is not decreased at the time interval of 1.9 ms. We do not understand the reason so far. Possibly, it is a statistical effect. The malfunction rate with the usual time interval of 18 ms will be evaluated after understanding the reason of trend at 1.9 ms.

V. Conclusion

The Pulse-to-Pulse Modulation is developed to enhance injection capability of LINAC at KEK. We performed the top-up filling into three accelerator rings, KEKB-HER, KEKB-LER, and PF, simultaneously. PF-AR also will be operated with top-up filling mode at the coming SuperKEKB project.

We upgraded the configuration of Event Timing System which is basic technology of Pulse-to-Pulse Modulation. The two-layers of EVGs are configured at Main Trigger Station for satisfying the complicated injection control of SuperKEKB. The test procedure to benchmark the stability of real-time process is developed.

The stability of the new configuration of Event Timing System is studied with the test procedure. The malfunction at lower-EVGs is intentionally caused by shortening the allowed computing time for real-time system. The reasonable dependence between the malfunction rate and the allowed computing time is determined. We can evaluate the malfunction rate in case of normal operation from the trend of results.

Also it is worth mentioning that the Pulse-to-Pulse Modulation is one of the key technology for a range of science. It can be adopt into the other injectors regardless of structure and size of their facilities. Then, those injectors promote scientific researches which are performed with accelerators.

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TABLE I
List of beam-pulse provided by Linac

Destination	Particle	Energy	Charge
KEKB-HER	Electron	7.0 GeV	5.0 nC
KEKB-LER	Positron	4.0 GeV	4.0 nC
PF	Electron	2.5 GeV	0.2 nC
PF-AR	Electron	6.5 GeV	5.0 nC

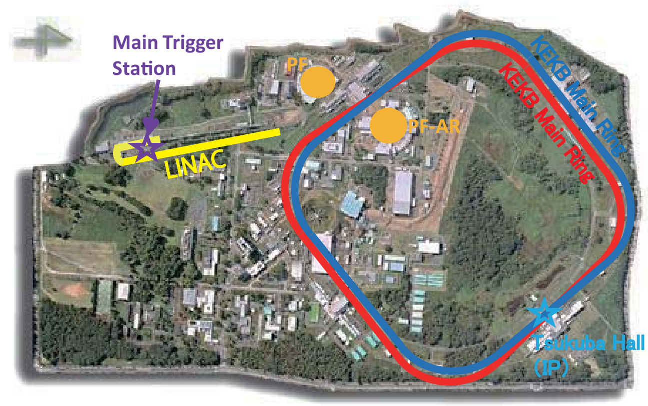

Fig. 1. Accelerators layout at KEK. KEKB-HER, KEKB-LER, PF, PF-AR, and LINAC are shown. LINAC is "J-shape" beamline which has two straight section.

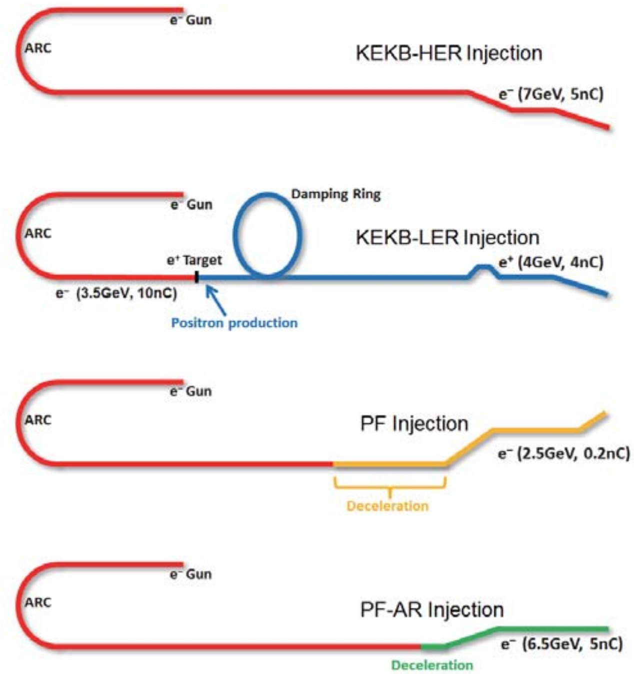

Fig. 2. Injection procedures for each beam mode: the difference of injection procedures are schematically explained. The electrons for KEKB-HER are accelerated to be 7.0 GeV. The positron-pulses for KEKB-LER are produced by shooting the primary electron-pulse straight the positron target. The produced positrons are once stored at Damping Ring for 40 ms during the SuperKEKB period. Then they are accelerated to be 4.0 GeV. The electrons for PF and PF-AR are decelerated in the downstream part of beamline to make energy of 2.5 GeV and 6.5 GeV, respectively.

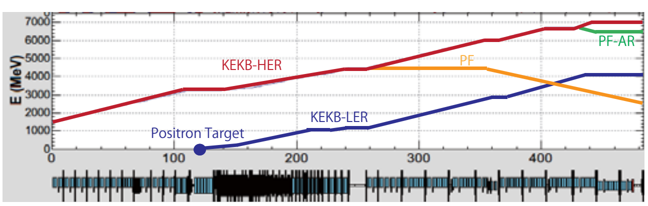

Fig. 3. Energy of beam-pulse at LINAC beamline: the energy of beam-pulse at each point of LINAC is shown for KEKB-HER (red), KEKB-LER (blue), PF (orange), and PF-AR (green). The only downstream 500 m after arc-section is shown here.

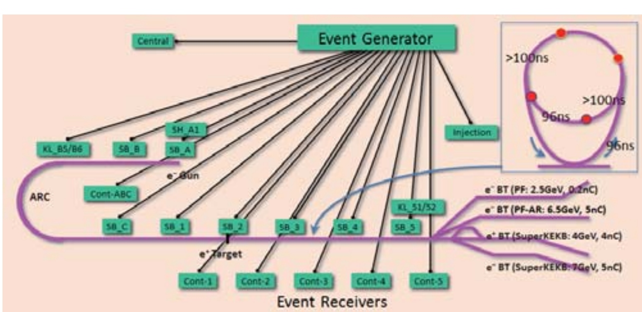

Fig. 4. Schematic view of Event Timing System at LINAC: the star-topology network is configured to deliver Events toward the EVR installed along the LINAC beamline.

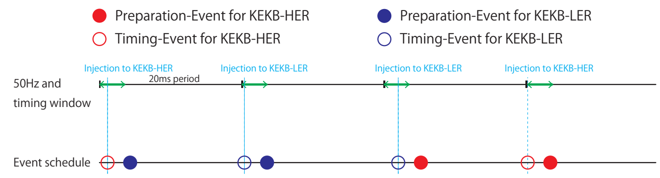

Fig. 5. An example of schedule for delivering Events at LINAC: in each injection period, the pair of timing-Event and preparation-Event is delivered to the EVR when EVG receives the TTL trigger. The timing-Event is followed by the preparation-Event related to the beam mode of next injection. The EVR launches the interruption to set up the parameters of next beam mode when it received the preparation-Event.

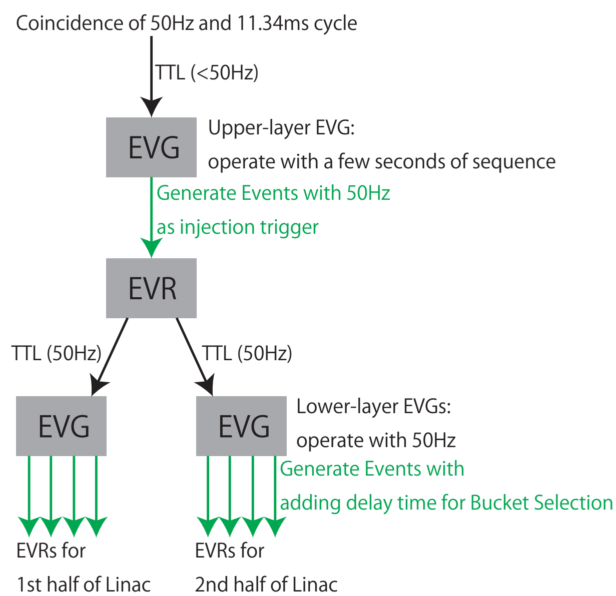

Fig. 6. Schematic view of the new configuration of Event Timing System for SuperKEKB: the only Main Trigger Station part is shown. The upper-EVG is operated with a few second of sequence. The Events for $\sim$100 injections are delivered when the upper-EVG is functioned. The lower-EVGs is operated in 50 Hz for the individual injections. The upper-EVG and middle-EVR are connected via optical cable while the middle-EVR and lower-EVGs are connected via the LEMO cables which deliver TTL signals.

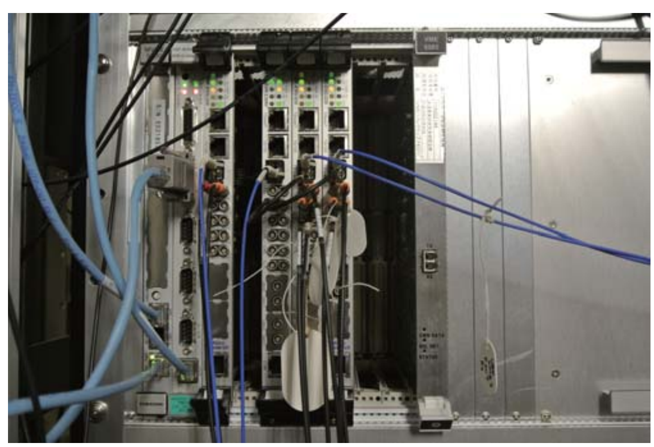

Fig. 7. Picture of Event modules at Main Trigger Station: from left, the CPU (MVME5500), RAS, upper-EVG, middle-EVR, and lower-EVGs are installed in the same VME64x-bus. The blue lines are optical cables which transfers the Events.

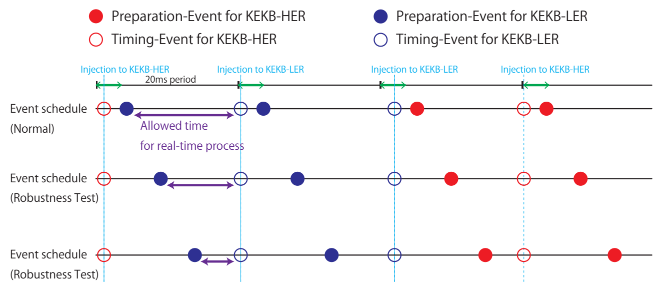

Fig. 8. Schedule of Event delivery to study the stability of real-time process: the schedules in cases of the normal operation and two test operations are shown. The allowed computing time for real-time process can be shorten precisely by changing the time interval between preparation-Event and timing-Event. It intentionally causes the malfunction of real-time process. The allowed computing time for real-time process in each case is shown with the purple line with arrow. The malfunction rate in case of normal operation can be statistically evaluated from results with various time interval.

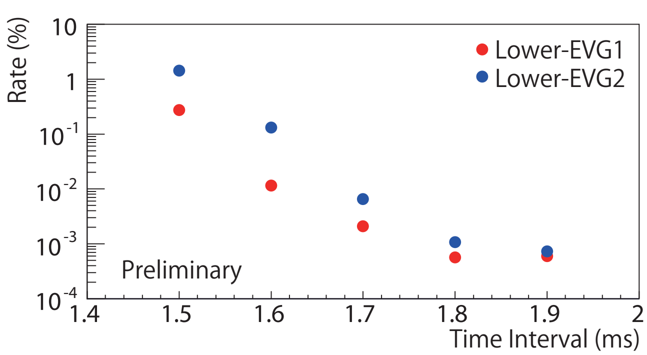

Fig. 9. Malfunction rate as a function of time interval (computing time): the malfunction rate in cases of allowed computing time, 1.5-2.0 ms, are determined as the stress test. The allowed computing time for the normal operation at Main Trigger Station is typically 18 ms.