INJECTION CONTROL SYSTEM FOR THE SuperKEKB PHASE-I OPERATION

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Abstract

Injection control of the SuperKEKB accelerator is managed with Bucket Selection and the Event Timing System. Both systems have their own optical network and functions to robustly communicate among distant EPICS I/O controllers. The entire control system is ranged into both the injector linac and main rings. Bucket Selection selects the RF-bucket of main ring to be injected the next beam-pulse and calculates the operation timing of injector fitting with selected RF-bucket. The Event Timing System has been developed to provide triggers to hardware on the injector beamline. We configure Sub-timing Station to provide triggers also to main ring hardware. Both Bucket Selection and the Event Timing System are operated certainly and stably during the phase-I operation of SuperKEKB. Besides, they show the good capabilities for the the phase-II operation.

INTRODUCTION

SuperKEKB [1, 2] is the electron-positron collider which is constructed at KEK. The beam-energies are 7.0 GeV for electrons and 4.0 GeV for positrons, respectively. The target luminosity is 8×10^{35} cm^{-2}s^{-1} which is realized with beam-currents of 2.6 A for electrons and 3.6 A for positrons.

The phase-I operation of SuperKEKB has been successfully carried out from February 2016 to June 2016 [3–5]. We performed vacuum scribing operation for main rings (MRs) of SuperKEKB. The commissionings for both machine and beams are performed continuously. The beam-currents are gradually increased and achieved to be 870 mA (electron MR, HER) and 1010 mA (positron MR, LER). The integrated beam-currents at the end of phase-I operation are 662 Ah (HER) and 776 Ah (LER).

The injection control system is one of the most successful system during the phase-I operation. We choose EPICS [6] as the software of control system. EPICS is well designed for controlling the system with separated multi CPUs and suitable as the software for operating accelerators. The important hardware for the injection control system are Bucket Selection [7] and the Event Timing System [8–10]. They have fast and robust communication schemes with dedicated optical networks for distant EPICS I/O controllers (IOCs).

The injector linac (LINAC) [11] performs beam-injection into one of four rings (HER, LER, and two light sources [12, 13]) in 50 Hz. Therefore above systems transfer necessary information in every 20 ms.

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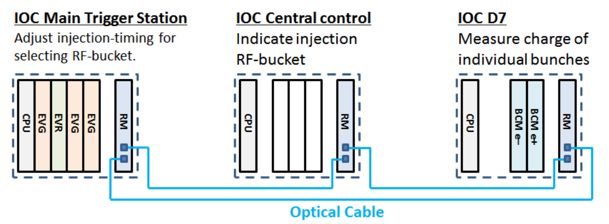

Figure 1: Schematic view of Bucket Selection: three nodes with a distributed shared memory configure the loop-topology optical network. The nodes at Central Control Building and D7 sub-control hall are placed in the MR side. The remaining one node is placed at Main Timing Station of LINAC.

In this report, we describe the specification of Bucket Selection and the Event Timing System and introduce their performance in the phase-I operation.

BUCKET SELECTION

Hardware Overview

Bucket Selection is described in ref [7]. The system consists of three EPICS IOC nodes with a distributed shared memory [14]. Figure 1 is the schematic view of the Bucket Selection nodes. Two IOC nodes are placed in the MR side and the remaining one is placed at LINAC. Three nodes configure the loop-topology network with the dedicated optical cables.

The RF-bucket of MR to be injected beam-pulse in the next LINAC operation is selected by the node at Central Control Building (CCB) in the MR side. The CCB node calculates the LINAC timing to fit with the selected RF-bucket. The timing-information is transfered via the distributed shared memory and the LINAC node implements the timing control for injection. This process is implemented in every 20 ms.

Bunch Current Equalizing

Bucket Selection has the Bunch Current Equalizing (BCE) mode. The bunch-currents become different since the beam lifetime depends on the position of stored RF-bucket. In the BCE mode, we automatically select the RF-bucket with the lowest bunch-current for the next injection.

The decision on the next RF-bucket is made by two nodes in the MR side. The node at D7 sub-control hall measures individual bunch-currents for the RF-buckets and put them

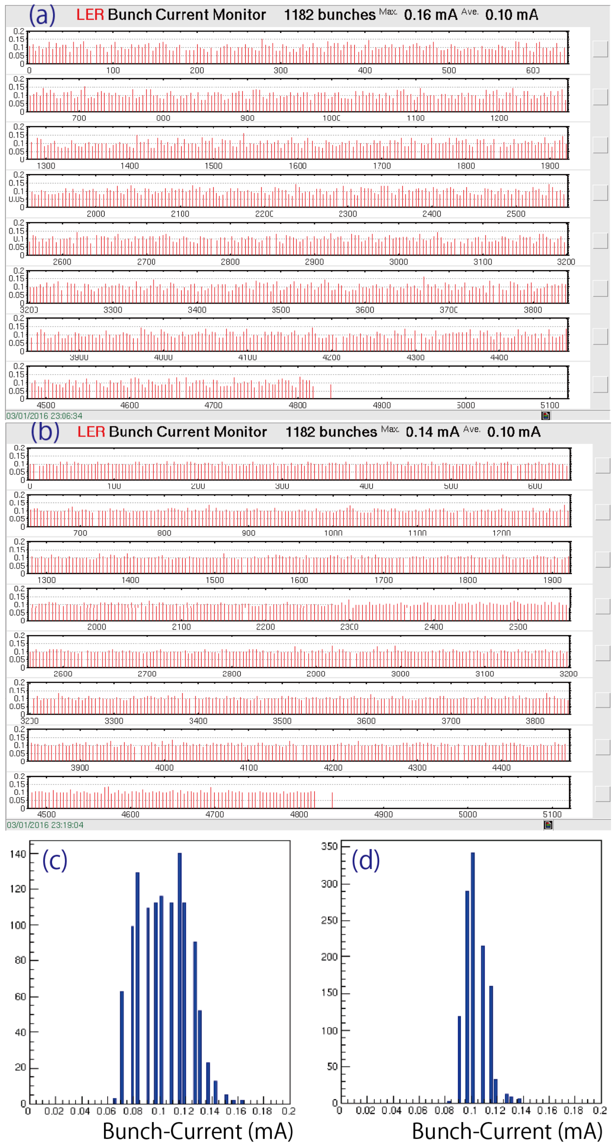

Figure 2: Performance of BCE: the bunch-current for the RF-bucket at LER is shown before and after the BCE operation in (a) and (b), respectively. They are shown also as histograms in (c) and (d). The r.m.s. of bunch-currents is 0.019 mA (before BCE) and 0.009 mA (after BCE).

into the distributed shared memory. Then the CCB node selects the RF-bucket with the lowest bunch-current.

The performance of BCE is demonstrated in Figure 2. The bunch-currents of LER around 11pm of March 1st, 2016 are shown. Even though we injected beam-pulses into individual RF-buckets in the same number of times, the bunch-currents became different as shown in Figures 2 (a) and (c). Then, 13 minutes after turning "ON" BCE, the bunch-currents became equal as shown in Figures 2 (b) and (d).

Beam Gate Control

Two months after starting the phase-I operation, we received the requests to integrate the functions to quickly close the beam gate[1]. Therefore we developed two kinds of quick close signals in the Bucket Selection network.

One is the beam-current limitation. The injection is immediately stopped by closing the beam gate when the current is exceeded the threshold. We set the threshold to both the total beam-current and individual bunch-currents. The threshold is necessary to protect the MR hardware.

We integrated quick close signal from the MR nodes to the LINAC node. It is processed when the bunch-current or total current measured with the D7 node exceed the threshold.

The other is the BCE limit, which is implemented only in the BCE mode. We set the threshold in the number of injections to individual RF-buckets and do not select one exceeding the threshold even though it is with the lowest bunch-current. This function is integrated to avoid the mis-operation when the bunch current monitor cannot measure correct beam-current.

The BCE limit is useful also to know an imbalance in the lifetime among RF-buckets since BCE performs to inject the RF-bucket with short lifetime, more frequently. The alarm message is popped up on the operation console when one of RF-buckets achieves the threshold.

Two beam gate functions are quickly integrated during the operation period. They can be carried out with the only software upgrade since the complicated functions of Bucket Selection are programmed in C language on the multifunctional hardware. The flexibility and expandability of Bucket Selection are shown in these upgrades. They will be an advantage in the phase-II operation.

EVENT TIMING SYSTEM

Hardware Overview

The configuration of Event Timing System for the SuperKEKB accelerators is described elsewhere [8–10]. The star-topology optical network is configured with Event Generators (EVGs) and Event Receivers (EVRs). We normally utilize the MRF products, VME-EVG-230 and VME-EVR-230RF [15] for the EVG and EVR modules.

We build MR Sub-timing Station at CCB. It is configured at one edge of Event network and manages the complicated timing-triggers for the MR components which are operated on the injection timing.

MR Sub-timing Station

Figure 3 is schematic view of MR Sub-timing Station. We install the EVG and EVR modules produced by Shanghai Institute of Applied Physics (SINAP). The SINAP-EVG can receive upstream-Event directly and launch sequence-Events. The set of SINAP-EVG and SINAP-EVR modules produces 15 kinds of outputs, in 50 Hz, with only one upstream-Event from LINAC.

The SINAP-EVG eliminates the large timing-jitter of upstream events. This timing-jitter is produced through the long distant (approximately 1 km) transportation of Event

[1] This system controls the enable/disable of injection from the MR side.

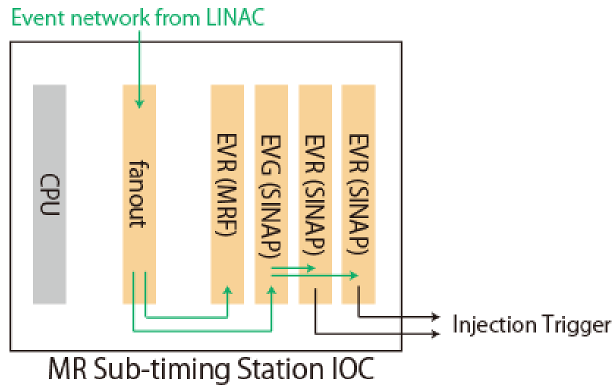

Figure 3: Schematic view of MR Sub-timing Station: the green arrows indicate Event network. The Event from LINAC Main Timing Station is divided and delivered to EVG (SINAP) and EVR (MRF). Note, the EVG (SINAP) can receive upstream-Event directly and launch sequence-Events. EVRs (SINAP) are connected on the downstream of EVG (SINAP).

Figure 4: Timing precision of output trigger from SINAP-EVR: the result of only one channel are shown here as a example. The jitter of all output triggers from SINAP-EVR are around 10 ps. The output triggers are synchronized with both the injection-timing and the MR's RF clock.

between LINAC and MR. The MR's RF clock is put into the SINAP-EVG so that events delivered from SINAP-EVG are synchronized with it precisely. Therefore all outputs from SINAP-EVR are synchronized with this RF clock and its precision is to be ∼10 ps. Figure 4 shows the timing-jitter of output triggers from MR Sub-timing Station. Note, this precision is same level as both that measured at the test study for SINAP modules [16] and that of MRF Event modules. Of course, the output triggers from SINAP-EVR are synchronized also with the injection-timing to which Bucket Selection is considered.

VME-EVR-230RF is installed for receiving data buffer and for the time synchronization with LINAC in the future operation.

Pre-trigger for Septum Magnets

One of the most important roles of MR Sub-timing Station is the production of the pre-triggers for the septum magnets. The pre-trigger is launched different way from other injection-triggers. For the operation of septum magnets, the pre-trigger must be delivered on 18 ms earlier from the main injection-trigger. As we has already described, MR Sub-timing Station is operated by the upstream-Event in 50 Hz. So the pre-trigger is produced in one pulse previous operation with one pulse previous upstream-Event.

Figure 5 is the schematic view to explain the timing relation between the pre-trigger and main injection-trigger of septum magnet. For compensate the difference in the timing for Bucket Selection, we set the delay, D_{pre}, on the pre-trigger output of SINAP-EVR. It is calculated with following formula:

$$D_{\mathrm{pre}} = D_{\mathrm{main1}} - D_{\mathrm{main0}} + 2\ \mathrm{ms} \qquad (1)$$

where D_{main0} (D_{main1}) is the delay scheduled on the EVG at LINAC Main Timing Station when we launch pre-trigger (main injection-trigger). They are determined to fit injection-timing with the RF-bucket selected by Bucket Selection on the individual injection-pulses. The timings of upstream-Events have already included these delays.

The D_{pre} is calculated and deliver from the EVG at LINAC Main Timing Station. The MR Sub-timing Station receives it with the VME-EVR-230RF module via the data buffer transportation.

The successful production of pre-triggers during the phase-I operation shows the good feasibility of upgrades which we plan for more complicated injection control in the phase-II operation. There are two thing to note in the production of pre-trigger.

One is the timing relation between the pre-trigger and main injection-trigger. They are produced in the different upstream pulses with different delays for Bucket Selection. However we produce the precise time interval of 18 ms thanks to the new Event Timing System of SuperKEKB [8–10]. We developed the new LINAC EVG IOC to schedule delays for coming several injections and it will be needed for damping ring operation.

The other is the data buffer transportation of Event Timing System. This brand-new technology will be utilized in the future operation at LINAC. We will control the individual phases of RF cavities in 50 Hz with the data buffer transportation.

CONCLUSION

The injection control system is successfully operated during the phase-I of SuperKEKB. Bucket Selection and the Event Timing System are the key hardware for the injection control. They have their own network to robustly communicate among the distant EPICS IOCs.

The Bucket Selection system well manage the MR RF-bucket to be injected the LINAC beam-pulse. The individual

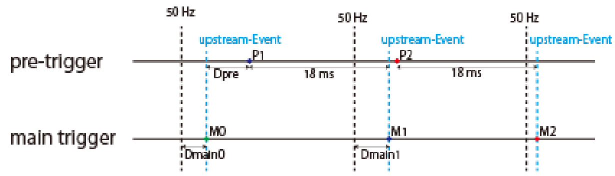

Figure 5: Schematic view of relation between the pre-trigger and main injection-trigger of septum magnet: for example, "P1" and "M1" indicate the timing of pre-trigger and main injection-trigger which are a pair for one injection. The pre-trigger is launched on one pulse before with an additional delay, D_{pre}.

bunch-currents of RF-buckets are properly equalized in the BCE mode. The flexibility and expandability of Bucket Selection are well shown through the quick upgrades during the operation period.

The timing control at LINAC is implemented by the Event Timing System. The main Event IOC at LINAC Main Timing Station receives timing information via Bucket Selection and set it into EVGs. MR Sub-timing Station is configured on one downstream edge of Event network in the MR side. The 15 kinds of triggers including the pre-triggers for the septum magnets are produced with only one upstream-Event from LINAC. The pre-triggers are successfully delivered on 18 ms earlier from the main injection-triggers. The data buffer transportation of Event Timing System is performed from EVG at LINAC to EVR at MR Sub-timing Station.

Above mentioned systems work certainly and stably during the phase-I operation. We finally deliver integrated beam-currents of 662 Ah and 776 Ah to HER and LER, respectively. Also they show their capabilities become good advantages for the phase-II operation.

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