INJECTION CONTROL SYSTEM FOR THE SuperKEKB PHASE-2 OPERATION

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Abstract

The SuperKEKB is an electron-positron collider which aims the world's largest luminosity of 8×10^{35} cm^{-2}s^{-1}. Its injection control system is upgraded for the phase-2 operation. Both the Event Timing System and Bucket Selection are improved to realize the positrons injection with the newly constructed damping ring. The injection control system works excellently during the entire run period of phase-2. The simultaneous injections to electrons and positrons rings are carried out with the injection rates of 6.25 Hz and 12.5 Hz, respectively. The several filling patterns at main rings which are required from a variety of beam studies are realized by the Bucket Selection. The further upgrade of injection control system is planned for the phase-3 operation.

INTRODUCTION

The SuperKEKB accelerator [1, 2] is an electron-positron collider with the center-of-mass energy of 10.58 GeV. It consists of High Energy Ring (HER) and Low Energy Ring (LER) for electrons and positrons, respectively. The target luminosity of this project is to be 8×10^{35} cm^{-2}s^{-1}. It will be realized with the large beam currents of 3.6 A (HER) and 2.6 A (LER).

The phase-2 operation is carried out from March to July in this year. The first collision is observed on April 26th. Then, after iteration of several beam commissionings, we achieved the peak luminosity of 5.55×10^{33} cm^{-2}s^{-1}.

One of the most important upgrades in phase-2 is the Damping Ring (DR). The positrons are once stored into DR for suppressing the beam emittance. Then they are injected into LER. Note, the electrons are directly delivered from the injector linac (LINAC).

The injection control is implemented with the Event Timing System. It is upgraded to satisfy the requirements in phase-2 and to operate the DR for the positron injection. The upgrade is limited only on the software since the hardware has already been developed to realize the DR operation [3]. The robustness and long term stability of hardware are demonstrated with the successful phase-1 operation in 2016 [4].

The Bucket Selection system is upgraded. It selects the operation RF-bucket at DR (DR-bucket) together with the injection RF-bucket at LER (LER-bucket) in the positrons injection. The standalone operation of DR is supported.

In this report, we discuss the above mentioned upgrades and report some performance in the phase-2 operation. Besides, the necessary upgrade for the phase-3 operation is introduced.

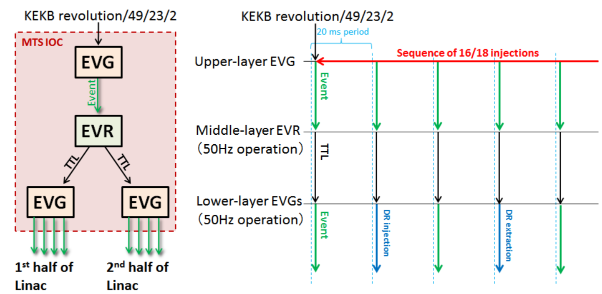

Figure 1: Trigger scheme for the injection and extraction at DR: the left figure shows the configuration of Event modules. The EVGs form two layers. Two lower-layer EVGs are triggered by the signal from the upper-layer EVG. The right figure is the time chart of module operation. The upper-layer EVG is triggered by the divided SuperKEKB revolution and provides the 50 Hz triggers. The time relation of different lower-layer EVG triggers can be perfectly controlled by the sequence of the upper-layer EVG. Therefore we can manage the injection and extraction triggers at DR.

DR OPERATION

Figure 1 explains how the Event Generator (EVG) module manages the DR operation. The injection and extraction of positrons at DR must be performed in the different LINAC pulses since the minimum storage time at DR is 40 ms. The minimum storage time is defined to secure the enough radiation damping time in terms of emittance suppression.

The upper-layer EVG provides the 50 Hz triggers. This process is triggered by the main ring (MR) revolution so that all output triggers can be utilized for the Bucket Selection.

The lower-layer EVGs control the 50 Hz LINAC operation. They can control the injection and extraction of positrons at DR with their triggers. The time relation of individual LINAC pulses can be controlled perfectly. It is guaranteed since the processes of lower-layer EVGs are triggered by the 50 Hz from the upper-layer EVG.

UPGRADE OF INJECTION CONTROL

After successful operation in phase-1 [4], the software of Event Timing System is upgraded for realizing the more complicated injection control in phase-2. Some operation parameters, like "DR storage time", are decided. The several

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new functions are applied for the injection control. We introduce them in this section.

DR Storage Time

There are new important parameters for the injection control in phase-2. They are the DR storage time, T_{DR}, and its maximum value, $T_{\mathrm{DR}}^{\mathrm{MAX}}$. We decide them following way.

The T_{DR} is determined as the interval of two LER injections. Therefore the T_{DR} in 5 Hz (25 Hz) is 200 ms (40 ms). This determination is derived from one pulse DR operation which is carried out in the phase-2 operation.

We schedule the LER injection at even intervals so that we keep the constant T_{DR}. The T_{DR} is changed only when we change the injection frequency. It is necessary to simplify the Bucket Selection algorithm.

There is the concern with T_{DR} to make the LINAC operation unstable. The LINAC hardware must be operated with the same phase of AC power 50 Hz (AC50) to keep their stable conditions. However, with the following reason, this AC50 phase becomes unstable when the T_{DR} becomes larger.

The extraction timing must be determined T_{DR} before the operation since the Bucket Selection determines it together with the injection timing. Of course, it refers the AC50 phase. However the AC phase is unstable and always drifted. Therefore the operation timing for the DR extraction becomes different AC phase when the T_{DR} is large.

Figure 2 shows the time difference between the DR extraction trigger and AC50 in the several T_{DR} cases. The time difference becomes larger when the T_{DR} becomes larger. With these measurements, we decided the $T_{\mathrm{DR}}^{\mathrm{MAX}}$ to be 200 ms.

There is the other unavoidable limit on our Event Timing System. The sequence length of upper-layer EVG must be equal to or longer than T_{DR}. Otherwise we cannot guarantee the time relation between the injection and extraction triggers at DR.

The sequence length of upper-layer EVG is lengthened to be 16 or 18 injections for satisfying the $T_{\mathrm{DR}}^{\mathrm{MAX}} = 200$ ms. Note, they are 8 or 9 injections in the phase-1 operation [4].

Beam Mode information

We deliver the beam mode information via the data buffer of Event Timing System. It is one of software upgrades and is utilized for more complicated pulse-to-pulse modulation in phase-2. LINAC installs lots of pulsed components for phase-2. For example, the pulse quadrupole magnets are installed in the downstream section of LINAC and they utilize this beam mode information.

We deliver three kinds of beam mode on the data buffer waveform. They are the beam mode of current, next, and next-to-next injections. So individual hardware can utilize the prefer element of this waveform with respect to their latencies and control procedures.

Beam Gate Control

The upgrade of Beam Gate control is required to improve the synchronization of enable/disable controls between the electron gun and some MR components like injection kicker and septum magnets. Besides, we must synchronize also the DR components since phase-2.

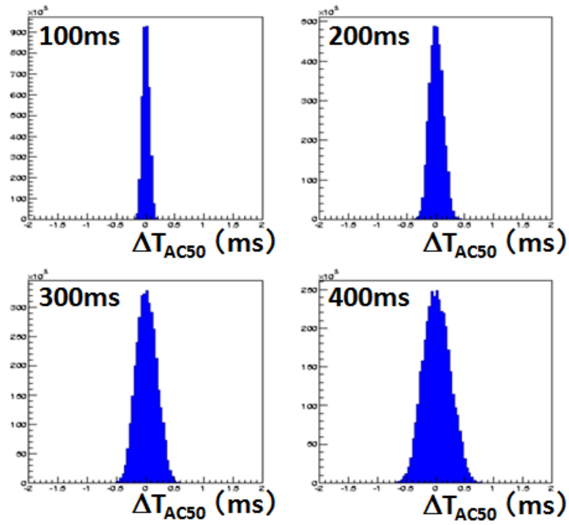

Figure 2: Time difference between the DR extraction trigger and AC50: the histograms in four DR storage time cases are shown.

The distributed bus bit (Dbus) function of Event Timing System is activated and utilized to deliver control signals of individual injection hardware. The synchronization of individual control signals are guaranteed with the precisely controlled Event interruption. The details of entire system is described in Ref [5]. The control of DR hardware with Beam Gate information is separately reported in Ref [6].

Time Synchronization

The CPU time for all IOCs of both Event Timing System and Abort Trigger System [7] are synchronized. The accuracy of synchronization is ~100 ns. Therefore, we can investigate the causality between injections and aborts with this time information. The details are described in Ref [8].

UPGRADE OF BUCKET SELECTION

Bucket Selection plays many important roles in the injection control. Its general specifications are described somewhere in Ref [9, 10].

The upgrades of Bucket Selection system are required for the phase-2 operation. They are mostly related with the DR operation. We describe the new features of Bucket Selection in this section.

Subroutine to Decide Injection Timing

Bucket Selection has several subroutines to decide injection RF-bucket (HER-bucket, LER-bucket) and to determine the LINAC operation timing. We prepare new subroutines for the LER injection since the algorithm to determine the operation timing is quite different in phase-2.

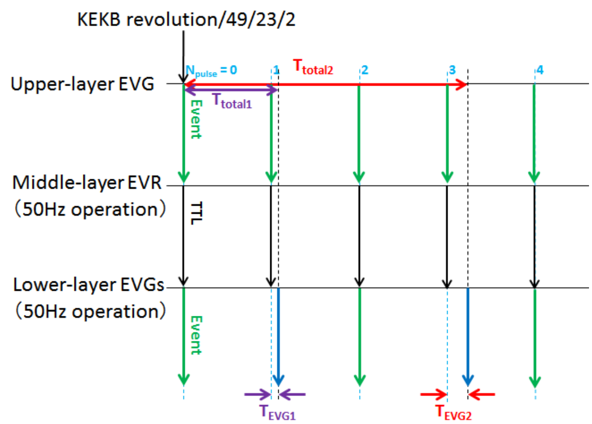

Figure 3: The schematic view of timing determination for the LER injection: it explains in the case injecting positrons into DR at pulse #1 and extracting them at pusle #3. Two black dashed lines show the operation timings of injection and extraction. The T_{total1} and T_{total2} are determined as the interval from the input trigger of upper-layer EVG while the T_{EVG1} and T_{EVG2} are determined as the interval from the individual output triggers of upper-layer EVG.

For HER, the algorithm is same as that of the phase-1 and KEKB operations which are described in Ref [9, 10].

The new subroutines for the LER injection take care of DR operations. Its specific features are: the 1st and 2nd halves of LINAC (1st LINAC, 2nd LINAC) work with the different timings. The 1st LINAC works for injecting the positron beam into DR while the 2nd LINAC works for extracting the positron beam from DR and delivering toward LER.

Figure 3 explains the procedure of timing determination for the LER injection. This example shows when we inject positrons into DR at pulse #1 and extract them at pulse #3. Therefore, N_{pulse1} and N_{pulse2} are 1 and 3, respectively, in the following discussion.

The injection and extraction timings of positrons must be determined before the DR injection. After deciding the LER-bucket, N_{LER}, we determine the timing of 2nd LINAC operation, T_{EVG2}, as follows:

$$N_{\mathrm{LER}} = \mathrm{MOD}\left(\frac{T_{\mathrm{total2}} \cdot 49}{96.3}, 5120\right), \quad (1)$$
$$T_{\mathrm{EVG2}} = T_{\mathrm{total2}} - N_{\mathrm{pulse2}} \cdot 20000000, \quad (2)$$

where T_{total2} is the timing to decide the LER-bucket which is illustrated in Fig. 3. The T_{total2} and T_{EVG2} are shown in unit of ns. The denominator, 5120, of Eq (1) is the harmonic number of MR. Note, the T_{total2} has the periodic solutions. Therefore we choose one which is nearest to the AC50 phase.

The next step is the determination of DR-bucket, N_{DR}:

$$N_{\mathrm{DR}} = \mathrm{MOD}\left(\frac{T_{\mathrm{total2}} \cdot 49}{96.3}, 230\right), \quad (3)$$

The denominator is changed to be 230, which is the harmonic number of DR.

Then, the timing of 1st LINAC, T_{EVG1} is determined to inject positrons into N_{DR}:

$$N_{\mathrm{DR}} = \mathrm{MOD}\left(\frac{T_{\mathrm{total1}} \cdot 49}{96.3}, 230\right), \quad (4)$$
$$T_{\mathrm{EVG1}} = T_{\mathrm{total1}} - N_{\mathrm{pulse1}} \cdot 20000000, \quad (5)$$

where T_{total1} is the timing to decide the DR-bucket which is illustrated in Fig. 3. The T_{total1} and T_{EVG1} are shown in unit of ns.

Note T_{EVG2} is buffered until the extraction pulse of LINAC while T_{EVG1} is immediately set on EVG for the DR injection.

Also the subroutines for the DR standalone operation are developed. They are utilized for the DR commissioning which is carried out just before phase-2.

Information for Injection Control

Here we summarized the operation parameters which are decided by Bucket Selection and are provided to the Event Timing System. The parameters related with DR are added since phase-2.

RF-bucket numbers at DR and MRs

The HER-bucket and LER-bucket are informed with their number. They are delivered via the data buffer of Event Timing System.

The information is utilized at the Belle-II detector to veto the DAQ at the timing of injected bunches. Besides, some accelerator components at MR utilize to monitor those condition [11].

Besides, the DR-bucket is delivered since phase-2.

Timing of Main- and pre-triggers (1st LINAC)

The operation timing of 1st LINAC is determined. This timing coincides with the injection DR-bucket for the LER injection while it coincides with the HER-bucket for HER.

In addition to the main-trigger timing, we determine the pre-trigger timing. The pre-trigger timing is determined as following formula:

$$T_{\mathrm{pre1}} = T_{\mathrm{EVG1}} - T'_{\mathrm{EVG1}} + 5000000, \quad (6)$$

where the T'_{EVG1} is the operation timing of 1st LINAC in the one pulse before (previous injection period). The T_{EVG1} and T'_{EVG1} are defined with unit in ns.

After providing to the Event Timing System, the T_{EVG1} is set on the delay of Event delivery while the T_{pre1} is delivered via the data buffer.

Timing of Main- and pre-triggers (2nd LINAC)

The main- and pre-triggers of 2nd LINAC are provided. The pre-trigger timing is determined in the same way with Eq (6).

The timings of 2nd LINAC are treated on the 2nd lower-layer EVG while those of 1st LINAC are treated on the 1st lower-layer EVG.

Number of bunches per injection pulse

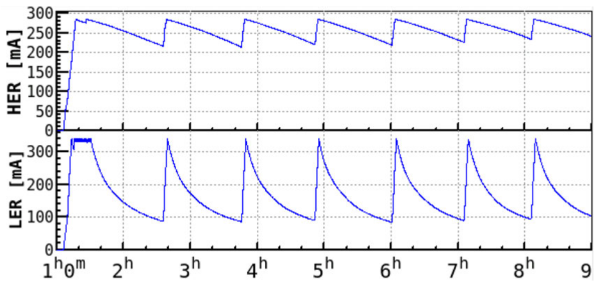

Figure 4: MR beam currents during the luminosity run: the beam current is shown for both HER and LER. They are measured with the DCCT from 1am to 9 am of the June 7th, 2018.

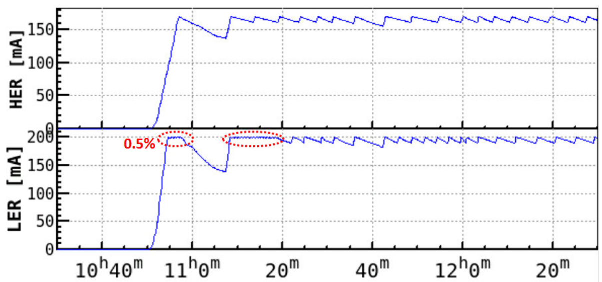

Figure 5: Demonstration of auto injection: the beam currents during the auto injection is shown. The Beam Gate is opened when the beam current is decreased 5 %. Partially, it is operated with the 0.5 % loss.

LINAC can generate and operate one or two bunches in every pulse. Bucket Selection decides also the number of injection bunches. For example, we cannot implement two bunches injection at the tail of bunch train at MR.

Bucket Selection can switch one bunch and two bunches injections in pulse-by-pulse. Besides, the zero bunch injection is possible. It is implemented when the timing system has something abnormal. The beam operation of LINAC can be stopped immediately with the zero bunch injection mode.

Control flags of injection septum and kicker (DR)

Bucket Selection provides control flags which enable or disable the operation of injection septum and kicker magnets. Even though the LINAC pulse mode is the LER injection, the trigger delivery to those hardware is stopped with the disable condition.

We make the "AND" logic between these flags and Beam Gate signal on the Event IOC. The 1st lower-layer EVG delivers the results via the Dbus. Then the Event Receiver (EVR) controls the trigger channels of septum and kicker with the received information.

We do not lay any new optical fibers for the delivery of these control signals since the Dbus shares the optical line with the Event delivery. Another advantage is the Dbus can deliver 8 different signals in parallel so that the kicker and septum magnets are controlled separately with the individual control flags. Therefore, the abnormal operations for the hardware studies can be realized with this function.

Control flags of extraction septum and kicker (DR)

The control flags for extraction septum and kicker magnets are provided. Their specifications are same as those of injection kicker and septum magnets. However the control flags are treated on the 2nd lower-layer EVG.

The control flags for injection and extraction components realize a variety of DR operations. They are utilized for the DR commissioning. For example, we can store positrons and perform the beam study at DR. It can be realized by enabling the injection components and disabling the extraction components. After this beam study, we can throw the positrons with the opposite condition.

When the LER injection rate is less than 5 Hz, the interval of two LER injection pulses is longer than the T_{DR}^{MAX}. In this case, two different LER injection modes are scheduled to realize $T_{DR} = T_{DR}^{MAX}$. The positrons injection (extraction) is carried out by operating only the 1st LINAC (2nd LINAC). The control flags are utilized also in a such kind of case.

PERFORMANCE ON PHASE-2

Figure 4 is an example of MR operation in phase-2. We carried out simultaneous injections for both LER and HER with the large injection rates. Typically we perform the injections with the rate of 6.25 Hz (HER) and 12.5 Hz (LER).

We take the only ~10 minutes to stack beam currents from zero to those for luminosity run, 285 mA (HER) and 340 mA (LER). The re-filling after beam decays with their lifetime is quite fast. We suppress the down time of luminosity run with the intelligent injection control.

The upgraded Beam Gate system is operated excellently. The system becomes fast and robust even though the control becomes complicated.

The auto injection system is implemented correctly during the vacuum scrubbing operation. Figure 5 demonstrates its performance. Typically we open the Beam Gate and re-fill the beams when the current loss becomes 5%. The auto injection with the 0.5% loss is tested and succeeded.

Bucket Selection realizes the several filling patterns. Figure 6 shows the bunch current distribution at LER. Typically, the 789 bunches operation is performed in the luminosity run. The number of bunches is increased to 1576 in case of vacuum scrubbing since it needs large beam currents.

IMPROVEMENT FOR THE PHASE-3

We need the upgrade of injection control system. The phase-3 operation is performed with more larger beam currents. Therefore the high frequency injections are required. Especially the LER injection with >25 Hz is performed since the beam lifetime becomes shorter and to be ~5 minutes.

The two pulse operation at DR is necessary for the LER injection with >25 Hz. The DR storage time is doubled in the two pulse operation with the fast-in-fast-out rule. This is important to secure the enough damping time. The minimum storage time of 40 ms can be satisfied up to the 50 Hz injection when we perform the two pulse DR operation.

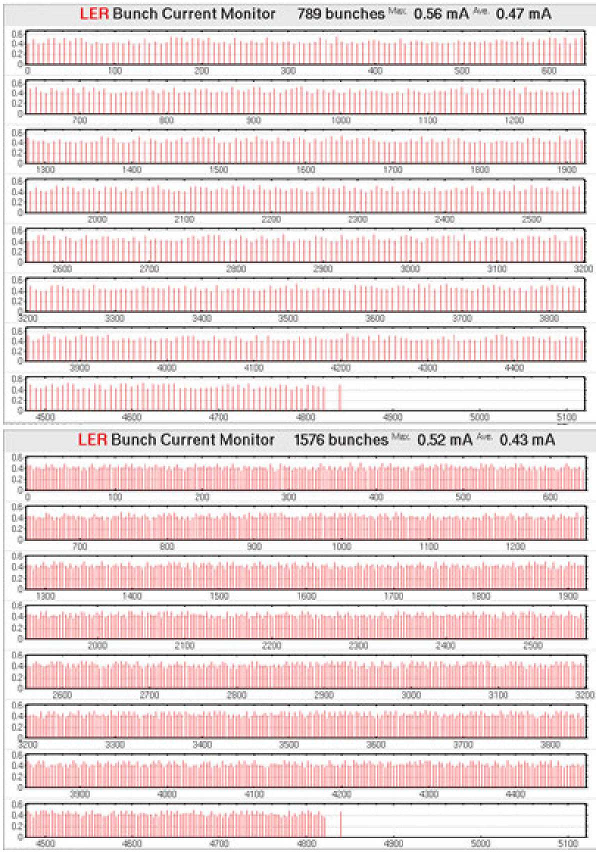

Figure 6: Example of LER bunch currents: the bunch currents in typical two filling pattern cases are shown. The upper figure shows 789 bunches operation which is utilized in the luminosity run while the lower figure shows 1576 bunches operation which is utilized in the vacuum scrubbing.

There is the concern to degrade Bucket Selection in the two pulse DR operation. We modulate the RF phase at 2nd LINAC in pulse-by-pulse to avoid this deterioration. The details of its Bucket Selection logic is described in Ref [10]. In addition to the Bucket Selection software, the master IOC of Event Timing System must be upgraded.

CONCLUSION

The injection control system of the SuperKEKB collider is upgraded for the phase-2 operation. The new system satisfies the requirements to operate the DR.

Some operation parameters on the master IOC of Event Timing System are modified. Besides, the software upgrade is performed to activate new functions of Event Timing System. They are utilized for the Beam Gate system, time synchronization, and so on.

Also Bucket Selection is upgraded. The new subroutines to select the DR-bucket together with LER-bucket are developed.

The injection control system works excellently in the phase-2 operation. The simultaneous injections for both HER and LER are carried out with the injection rate of 6.25 Hz and 12.5 Hz, respectively. The several filling patterns at MR which are required from a variety of beam commissionings are realized with the Bucket Selection.

The further upgrade is planned for the phase-3 operation.

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