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APPLICATION OF THE WHITE RABBIT SYSTEM AT SuperKEKB

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Abstract

We employ the White Rabbit system to satisfy the increasing requests from the SuperKEKB operations. The SuperKEKB-type slave node was developed based on the SPEC board and FMC-DIO card. The firmware was customized slightly to realize the SuperKEKB needs. The device/driver for EPICS was developed. The five slave nodes have been operated since the 2021 autumn run. The delivery of the beam permission signal from the central control building to the injector linac is taken care of by new slave nodes. The timing of the abort request signal and the trigger for the abort kicker magnet are recorded with the distributed TDC system. More slave nodes will be installed in the next year to enhance the role of the distributed TDC system.

INTRODUCTION

There are two types of modern timing systems for the large-scale accelerator. One is the event-base system. Its most famous hardware is Event Timing System (EVT) [1]. The other is the timestamp-base system. The famous hardware in this case is White Rabbit (WR) [2].

Both EVT and WR enhance their roles because of the increasing requirements from the accelerator operation. The synchronous control of the distant hardware is indispensable to improve the performance of accelerators.

The SuperKEKB collider [3] at KEK utilizes EVT for the injection control including the delivery of the timing-triggers towards the beamline. It successfully implements the transcendental scheme in the position injections [4, 5].

We consider introducing WR in addition to EVT for taking care of the increasing requirements to the SuperKEKB control system and to replace the devices which close with their lifetime. We especially plan to develop the distributed data acquisition system (distributed DAQ).

NETWORK-BASED CONTROL SYSTEM

In the operation of the modern accelerators, fast and robust communication between the separated hardware is indispensable. In such a case, the accelerator control is realized by synchronously operating modules that are connected via the dedicated optical cable. Often, the cable length becomes more than a kilometer in the large-scale accelerators. Recently, the roles of the timing system are increased for this purpose.

The network-based control system is summarized in Table 1. The module that is employed at SuperKEKB is listed together with the future possibilities of EVT and WR for those purposes.

Table 1: List of network-based control systems: the module that is employed at SuperKEKB is listed together with the future possibilities of EVT and WR. “Commercial” is a commercial product. “Original” means an original product that is developed at KEK.

	SuperKEKB	Possibility
Trigger delivery	EVT	EVT or WR
Bucket Selection	Commercial	WR
Abort system	Original	EVT or WR
Beam permittion	Original	WR
Distributed DAQ	None	EVT or WR

In the case of SuperKEKB, the trigger delivery for the beam injection is taken care of by EVT. The commercial distributed shared memory is utilized for Bucket Selection [6]. The original modules were individually developed for the Abort Trigger System [7] and the beam permission system.

On the other hand, the WR system has several kinds of modules so that they can take care of all listed systems. We consider replacing the “Commercial” and “Original” devices with WR. Then, all network-based control systems are developed with EVT and WR. Note, the best way is to develop everything with one system. However, to develop with two systems is still better. And this experience becomes important knowledge for future colliders like Higgs factory.

APPLICATION TO SuperKEKB

In this section, we report the WR application at SuperKEKB. The entire system is discussed after introducing the specification of the SuperKEKB-type slave node.

Slave Module

Figure 1 is the pictures of the slave modules which we developed at KEK. The SPEC board [8] is selected as the slave node of WR. Only the FMC-DIO card [9] is employed in the SueprKEKB operation, so far. Two types of nodes are produced at a low cost.

The module in the upper picture of Fig. 1 is a homebuilt computer with a 2.9 GHz 6 core CPU, 8 GB of RAM, and 2.5 inch SATA III SSD. We chose the small-size commercial barebone kit with the PCIexpress slot to mount the SPEC board. All parts are mass-produced goods and can be supplied easily. The size of this module is $20 \times 25 \times 8\,\mathrm{cm}^3$.

The firmware and software of the starting kit [10] are utilized with small customization. The transition timing of the input or output signals is informed in both higher or lower transitions while that is informed only in higher transition with the original firmware. The software runs on the Ubuntu 18.04 OS. We developed the device/driver for EPICS.

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Figure 1: Pictures of the slave node: the upper picture is SPEC on the homebuilt computer. In the lower picuture, SPEC is housed in the 19-inch box with 1U height. It can be operated from RaspberryPi.

Followings are the functions of SuperKEKB-type slave node:

- Detect the transition of the TTL level signal for both input and output channels and inform the GPS synchronized timestamp.
- Transport the status of an input signal to the other nodes and enforce output.
- Output the TTL level signal according to the status of the received signal from other nodes.
- Output the pulse-per-second (PPS) signal which is synchronized with GPS.

The module in the lower picture of Fig. 1 is SPEC with RaspberryPi. In the 19-inch rack box, the SPEC board and the RaspberryPi 3 model B+ are assembled with the power supply units. This system utilizes the standalone feature of SPEC. The SPEC board is controlled via a mini USB port. It is successfully configured as the slave node. The test operation under the WR network at SuperKEKB was successfully carried out. However, the development of the EPICS device/driver is still ongoing.

Installation to Beamline

We installed the five SPEC nodes and two WR switches [11], so far. Their location is indicated in Fig. 2. Three SPEC nodes and one WR switch were installed at Central Control Building (CCB). For the WR switch as the grand-master module, the PPS signal and 10 MHz reference clock are provided from the rubidium clock which is synchronized with GPS. The slave nodes measure the arrival

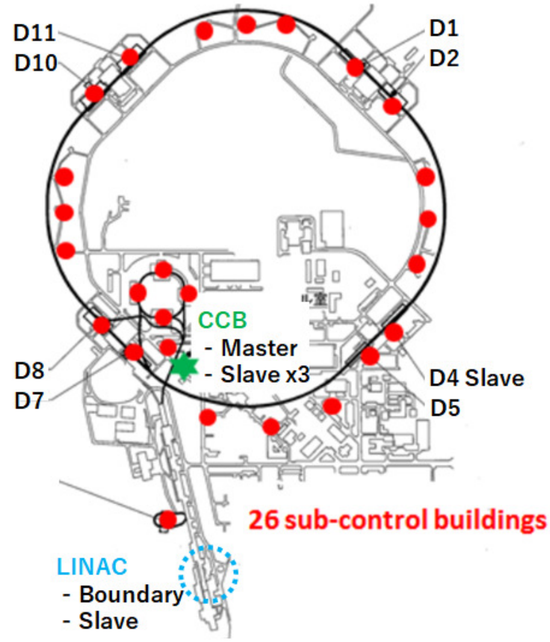

Figure 2: Map of the slave nodes at SuperKEKB: The WR modules were installed at D4, CCB, and LINAC buildings.

timings of the abort request signal at CCB and the delivery timing of the TTL triggers to the abort kicker magnet. The Beam Gate signal is input into one of the slave nodes. It is transferred to the injector linac (LINAC) [12]. Besides, the 99176 divided revolution signal (~ 1.002 Hz) is produced.

The SPEC node at the D4 building provides the PPS signal to the beam size monitor for the electron ring (X-ray monitor) [13]. Since the PPS signal from the WR slave node is synchronized with GPS, it indicates the absolute time of the measured data of the beam size monitor. The system is being tested in the 2021 autumn run.

Figure 3 is a picture of WR modules at LINAC. One WR switch is installed as the boundary module. One SPEC node is installed under this boundary module. It is utilized to receive the Beam Gate signal and delivers the TTL level control signal to the LINAC components such as the electron guns. In the future, more slave nodes will be installed under this boundary module to understand the LINAC hardware status with the common clock.

BEAM GATE SYSTEM "D0D0"

Beam Gate is a part of the beam permission system. The beam permission system permits or inhibits the provision of the beam pulse from LINAC. In general, the system monitors the accelerator hardware and inhibits the injection when some hardware is in an abnormal condition.

In the case of Beam Gate at SuperKEKB, the injection is enabled and disabled dynamically by the operator. It is managed to keep the beam current at two main rings (MR). The stored beam at MR is decayed and the operation beam current is decreased gradually. Beam Gate is opened and

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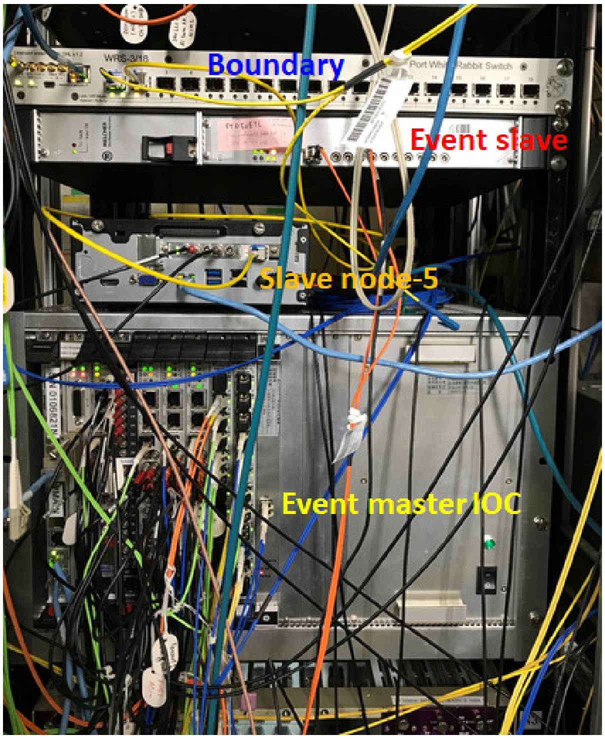

Figure 3: Picture of LINAC node: the WR switch and SPEC node were installed near the master IOC of EVT.

implements the beam injection when the operation beam current becomes the lower acceptable limit. Then, Beam Gate is closed when the operation beam current reached the target value of the experiment.

The beam permission signal is delivered from MR to LINAC via 800 m optical cable. It is inputted to the SPEC node at CCB and transferred to that at LINAC. This new system is named "D0D0". The name of the system is decided from the setting of the FMC-DIO card at LINAC[1].

One of the advantages of the D0D0 system is to know the accurate timing of both enabling and disabling the beam injection with GPS time. It is reliable information when we inspect the relation between the injection and problems which happened at MR.

The slave node can transfer the input signal to more than one node. So, in the future prospect, the Beam Gate signal can be delivered not only LINAC but the injection and extraction control of the damping ring (DR). In that case, the extraction system of DR must be controlled at least 40 ms later than the injection system. The signal transfer with the SuperKEKB-type node can take care of such kind of delay.

Besides, all beam permission logic can be included in the FPGA of SPEC. The Mock Turtle framework may uncomplicate the management.

[1] It is "**iD0D0**". Note, the setting of channels 2 and 4 is zero and is not the capital letter "O". However, we pronounce our system like "dóudou".

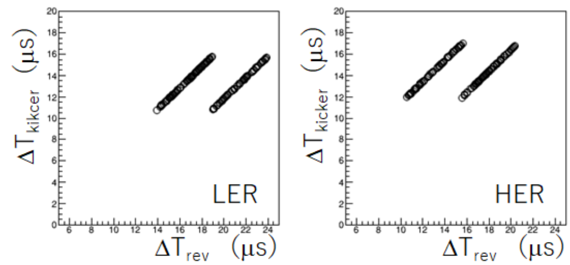

Figure 4: Measurement of correlation between abort response time, ΔT_{kicker}, and the revolution, ΔT_{rev}: the details of the setup of this measurement are explained in Ref. [15]. The results for both the positron and electron rings are shown in the left and right plots, respectively.

DISTRIBUTED TDC

The distributed Time-to-Digital Converter (distributed TDC) is one part of the distributed DAQ. The key technology of the distributed DAQ is the timestamp synchronization among the data acquisition devices which are distributed along the long beamline of accelerators. The utility of the timestamp synchronization among the separated beam monitors was demonstrated with the injection archiver of SuperKEKB [14].

The WR system is a strong tool to take care of timestamp synchronization. By using the SuperKEKB-type slave node as TDC, we can measure the timing of events that occur in the entire accelerator and can sort them in the time order with the accuracy of 8 ns.

We plan to measure the timestamp of the TTL reference-signal from the individual Abort Trigger modules [7] with the SuperKEKB-type slave node. The Abort Trigger System collects the request signal of the beam abort from the accelerator hardware and monitors. Therefore, we can make the time order of abort requests and know which component launches the abort request firstly. They are valuable data to diagnose the source of the problem. The time resolution of the abort request measurement will be 8 ns and becomes much precise than that in the current system[2]. We installed the slave node only at CCB, so far, and all modules will be installed in the next year.

The feasibility of the WR system in the abort timing measurement is demonstrated in Ref. [15]. In this case, only two modules were installed at the D2 building and CCB. Figure 4 is the update of the result with more large data set. The correlation between the abort kicker timing and the revolution was clearly observed. The variation of the abort response time can be explained by the timing of the abort gap.

[2] Note, the low accuracy part still remains in the upgrade system. The accuracy of the timestamp comparison among the channels on the same Abort Trigger module is 100 ns. It comes from the internal clock rate of 10 MHz.

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We are discussing further improvement. We plan to receive the signal directly from the beam loss monitor which has a high time resolution and will be installed soon.

TRIGGER DELIVERY

The trigger delivery from the WR node is the other valuable method to configure distributed DAQ. Since the WR node knows the precise timing of signal output, WR can fetch the GPS synchronized timestamp to data taken with its trigger. So far we can provide the following two kinds of triggers.

Pulse-to-Pulse

All slave nodes with SPEC and FMC-DIO can provide the PPS signal which is accurately synchronized with GPS. We provide the PPS signal to the X-ray monitor for the electron ring at the D4 building. It is the first step for this kind of distributed DAQ. The operation test is ongoing in the 2021 autumn run.

One-Herz Revolution

The 99176-divided revolution signal can be delivered from the WR slave node. Note the revolution of SuperKEKB is ~ 100 kHz. Therefore, the rate of this signal becomes ~ 1.002 Hz. The DAQ rate of some monitors at SuperKEKB is quite less than the revolution and is from 1 Hz to 10 Hz. This signal can use a such kind of case.

The signal is made from the 2254-divided revolution which is the source of the injection trigger. It is inputted into one of the WR slave node at CCB. Further 44 times division is implemented on the CPU process. The signal transfer to other nodes is implemened once in the 44 inputs while that process is vetoed in the remaining cases.

The trigger resolution in the current system is 8 ns. And there is a possibility of a future upgrade with FMC-TDC and FMC-DLY. In this case, the resolution of the revolution signal becomes less than a nanosecond. It will advance machine commissioning and the study of beam physics. For example, if we carry out the bunch-by-bunch measurement at SuperKEKB, the time resolution must be smaller than 4 ns.

CONCLUSION

The operation of WR has been started at SuperKEKB. The SPEC and FMC-DIO are employed as the slave node. By applying the small customization to firmware and software, the SuperKEKB-type slave node provides a lot of benefits to the accelerator operation. The Beam Gate system “D0D0” provides a more smooth operation of SuperKEKB. The distributed TDC system plays important role in the beam loss diagnostic.

The development of the distributed DAQ system with WR is continued and it will provide large benefits in the accelerator operations.

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