ISBN: 978-3-95450-209-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2019-MOAPP01

CONTROL SYSTEM OF SuperKEKB

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Abstract

The control system of the SuperKEKB collider covers its 3 km beamlines. It is the distributed control system based on EPICS. There are about 200 input/output controllers which are built at the Central Control Building and 26 Sub-Control Buildings. The Operation Interface is prepared with the Python and SAD scripts and CSS BOY. The SuperKEKB control system is configured on the dedicated network which is segmented from the KEK office network by the firewall. There are several middle-layer services which are developed and operated on the server computers. The monitoring system, alarm system, data archiver system, and electronic log system are developed with open-source software. Abort Trigger System, Beam Permission System, and the timing system have their own network and implement the fast and robust transferring of the operation-related information. Abort Trigger System collects about 260 abort request signals and delivers the enable signal to the abort kicker pulse. Beam Permission System ensures the beam operation. The timing system realizes the extremely complicated injection operation of SuperKEKB. Our control system is strongly enhancing the progress of the SuperKEKB project and its future prospect is promising.

INTRODUCTION

SuperKEKB [1] is an electron-positron collider that is built at KEK. It aims the world's largest luminosity record of $8 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$. The operation is started in 2016. The first collision of two beams is realized in May 2018. The world's smallest beam size at the interaction point is achieved in June 2018. The physics run with the top-up filling operation is carried out in the 2019 spring run.

SuperKEKB has 10000 hardware components that are installed along the 3 km beamlines. Therefore the distributed control system is constructed in the Central Control Building (CCB) and 26 Sub-Control Buildings (SCBs) as shown in Fig. 1. Our system is based on EPICS [2]. The hardware components can be controlled and operated via the Channel Access (CA) protocol.

Even though the operation condition becomes much more complicated than that of the previous KEKB project [3, 4], the operation and commissioning of SuperKEKB are smooth and steadily because of the sophisticated control system. We develop a lot of new systems and services for the SuperKEKB control system.

In this report, we introduce the basic components of the control system. Then, the services and systems of the SuperKEKB control system are discussed.

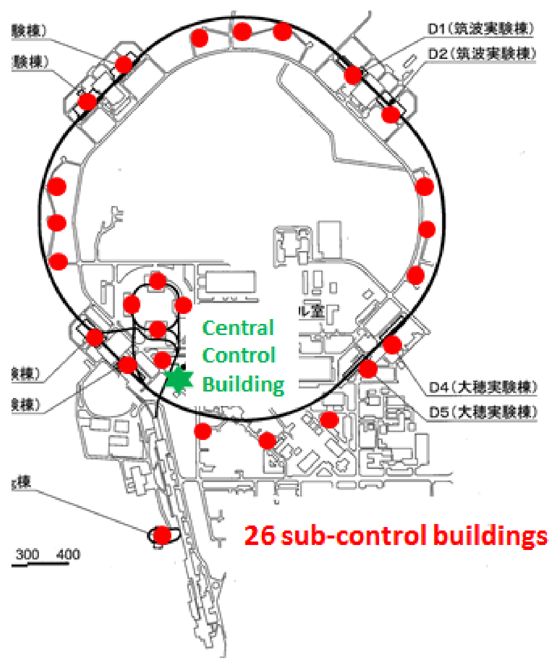

Figure 1: Location of Central Control Building, Sub-Control Buildings, and beamlines.

BASIC COMPONENTS

In this section, we introduce the basic components of the SuperKEKB control system.

Input/Output Controller

There are about 200 Input/Output Controllers (IOCs) on our EPICS control system. It is summarized in Table 1. To simplify the maintenance, most of the IOCs are constructed with the VME or PLC form-factors. In both form-factor cases, almost all IOCs are built with the SuperKEKB standard IOC, which is prepared by the control group.

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Table 1: Summary of the SuperKEKB IOC

Group	VME	PLC	Total
Magnet	9	27	36
RF	7	10	17
Beam Monitor	47	6	53
Beam Transport	15	24	39
Control	20	0	20
Vacuum	0	23	23
Safety	0	5	5

There are 98 VME IOCs. We choose MVME5500 as the standard CPU module. Excepting the small amount of IOCs[1], the VME IOC is constructed with this CPU module.

There are 95 PLC IOCs. The CPU module of the standard IOC is F3RP61 [5]. The analog input/output modules for the control signals are integrated on the PLC IOC so that it does not have the fieldbus. The CAMAC based control system operated in the KEKB era is replaced with the standard PLC IOC. The high-grade CPU module, F3RP71, is utilized only for the 13 PLC IOCs. It is required from the vacuum control system.

There are software IOCs which are running on the servers. It works as the middle-layer system of the SuperKEKB EPICS system.

Operation Interface

In the accelerator operation, the IOCs are controlled with the Operation Interface (OPI). Figure 2 is an example of OPI.

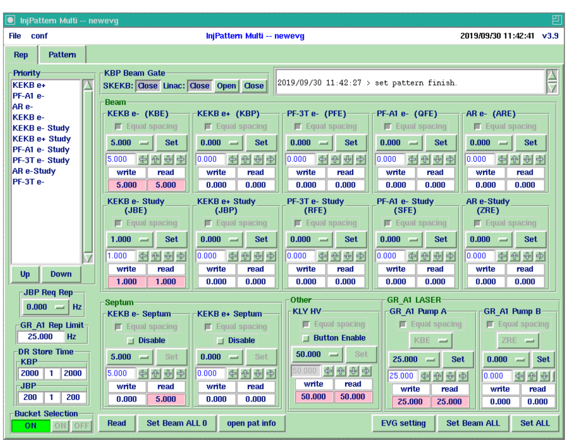

Figure 2: An example of OPI.

One of the ways to make an OPI is the script language such as Python and SAD [6]. Both scripts include the Tk Toolkit as GUI. Besides, the module for Channel Access is included.

The other way is Control System Studio (CSS) BOY [7]. This is the Eclipse-based all-in-one package software developed in the EPICS community. There are several advantages to use the standard software of the EPICS community. We can receive several kinds of supports when we mature it. Besides, we can share the latest information.

Network

The SuperKEKB control system is developed on a dedicated network [8]. It is segmented from the KEK office network by the firewall. There are two core switches installed at CCB. The redundant network is configured towards SCBs with the virtual switching system.

We lay the Leaky Coaxial cables in the entire SuperKEKB tunnel. Therefore the network can be utilized in the entire beamlines. It is very useful when we have maintenance works in the tunnel.

The VLAN segmentation is implemented on this network. There are the EPICS VLAN and 3 hardware VLANs. The hardware components which utilize the ether network as their fieldbus are installed on the individual hardware VLANs. By this segmentation, we protect hardware from the large EPICS broadcast.

Server and Console

There are about 10 servers mounted on the 19-inch rack and 14 blade servers. They are the Linux servers and work as the hosts of the middle-layer services in the SuperKEKB control system. The monitoring system, alarm system, archiver system, and the electronic log system are running on these servers. The tens of the software IOCs are built. And the operating environment for the Python script is prepared.

The other role of these servers is the test bench for developing the new control system. The upgrade of the SuperKEKB control system is steadily continued. Therefore, the R & D of the new systems and services are performed.

There are 8 servers which are called "SAD cluster". They are the operation servers for the SAD script. Their OS is FreeBSD. Half of them are operated in the SuperKEKB network and the remainings are operated in the KEK office network.

The consoles for operators are installed at CCB. Figure 3 is the picture of the main room at CCB. There are many PCs as the console in this room. Their OS is not unified and the Linux, Windows, and Mac machines are utilized. They basically work as the x-terminal to show the OPI developed with the SAD or Python scripts. However, for the load balancing, the individual consoles locally operate also the OPIs with CSS BOY.

MONITORING SYSTEM

The monitoring system of the SuperKEKB control system is economically developed with open-source software [9]. However, it has excellent usability. All status information can be monitored from everywhere via the web-browser. The quick and detailed monitoring keeps our control system healthy.

[1] The Abort Trigger System is developed with the MVME4100 module. Only one MVME6100 module is utilized for the master IOC of the Event Timing System.

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Figure 3: Picture of the main room at CCB. There are a lot of monitors for the operator consoles.

We utilize the Grafana to show the status of components. The alive monitoring of control system components and the metrics like the CPU load and the RAM usage for servers are collected with Zabbix. Figure 4 is an example to monitor the CPU and RAM status. In this system, we integrate the function to collect the pvAccess data of EPICS 7. It enables us to collect more complicated information and improves the extendability of the monitoring system.

Figure 4: An example of the metrics monitoring.

The Elastic stack is utilized to monitor the log message. For example, the “ps”, “caSnooper”, and “casw” commands are periodically implemented in the middle-layer system of the servers and those results are collected and recorded with Elastic search. The broadcast of the EPICS protocol is monitored with Wireshark including the cashark plugin. The results are shown with Kibana.

ABORT TRIGGER SYSTEM

Abort Trigger System collects the abort request signals from the individual hardware of SuperKEKB and enables the operation pulse towards the abort kicker magnet.

This system makes its own optical network with the Abort Trigger modules [10]. Figure 5 is the schematic view of the Abort Trigger network and the picture of the Abort Trigger module. The Abort Trigger module collects 8 optical signals from the downstream and launches one signal to the upstream.

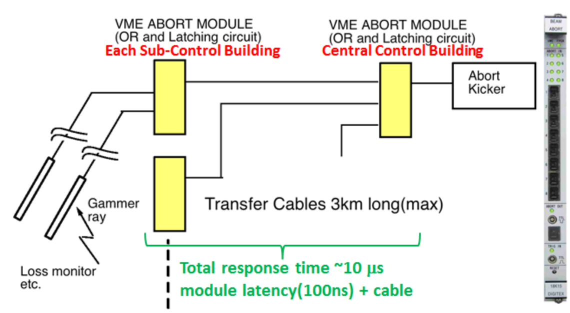

Figure 5: Schematic view of the Abort Trigger network (left) and the picture of the Abort Trigger module (right).

The abort requests are firstly collected at the SCB in each region. After that, they are collected at CCB. Totally 260 abort request signals are collected to the master module of the Abort Trigger network. Finally, the enable signal of the abort kicker pulse is provided.

There is the function to uniform the timestamp of all Abort Trigger IOCs [11]. Therefore, we can know the abort request signals in chronological order. This is useful information to know what causes the beam abort. Usually, several related hardware provides the abort request signal in a single problem.

This summer, we carried out the upgrade of Abort Trigger System to shorten the entire response time. More quick beam abort is strongly required to protect the components at the interaction point. The circuit to provide the abort kicker pulse is upgraded and its response time becomes about 3 μs shorter. Besides, we decide to operate the SuperKEKB beam

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with two abort gaps condition. Therefore the waiting time which synchronizes the abort kicker pulse to the abort gap becomes half and to be 0-5 μs.

ALARM SYSTEM

The alarm function is integrated on the EPICS Process Variables (PVs) which are especially important in the accelerator operation. Two kinds of alarm statuses like, "major" and "minor", are defined for the individual PVs and these statuses are put into their severity field.

The status of alarm PV is monitored with the CSS alarm system [12]. Figure 6 is the schematic view of the SuperKEKB alarm system. The 15000 PVs are monitored as the alarm objectives in the SuperKEKB control system.

In our operation policy, if one PV shows the "major" alarm, the operator immediately informs the expert who has the responsibility. And the expert must clear the problem even though it is mid-night. If one PV shows the "minor" status, the operator informs the expert. However, it is not urgent. The e-mail information is fine when it is not office hours.

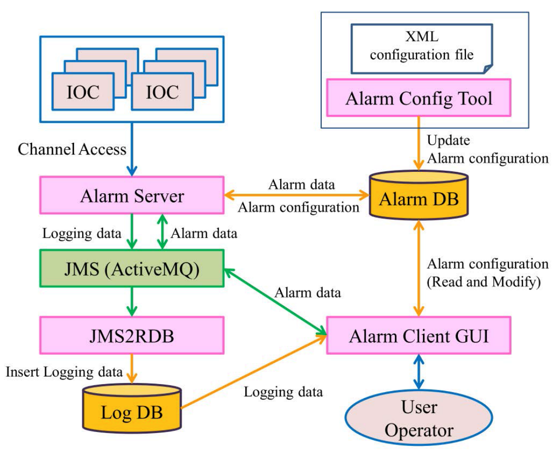

Figure 6: Schematic view of the SuperKEKB alarm system. It is developed based on the CSS alarm system.

BEAM PERMISSION SYSTEM

Beam Permission System controls the enable and disable of the electric gun and other pulsed components at the injector linac (LINAC). Therefore the beam operation can be started and stopped independently from the operation schedule loaded on the timing system. There are two roles on the beam permission. One is to avoid abnormal operation. The other is to keep the operation current at the SuperKEKB main rings (MRs).

Figure 7 is the schematic view of the Beam Permission logic. The Beam Permission logic consists of the hardware logic and software logic. The hardware logic is configured in the FPGA circuit. The software logic is configured with PVs on the VME IOC. The logic is defined to protect the accelerator hardware from the abnormal operation. The beam operation is possible when the all necessary devices are running in the normal status. This status is defined with the "and" logic. The "or" logic enables us to select the operation mode. The individual inputs of "or" logic show the status of the individual operation modes. We can operate the accelerator when one of the operation modes is ready. For example, the damping ring (DR) standalone operation mode can be possible even if some MR components are not ready.

The Beam Gate function is integrated as the one input status of the Beam Permission logic. This is the switch for the operators which turns on and off the LINAC operation. The automatic operation sequence to control Beam Gate is prepared at the OPI level. It is utilized to keep the operation current at MRs.

In the most downstream part of the logic, the delivery of the permission signals to the electric gun and the other LINAC components are managed by the Event Timing System. Its specification is reported in Ref. [13].

The details of the entire logic will be reported in the separated paper.

DATA ARCIVER SYSTEM

The archiver system records the information of the EPICS PV. We utilize "KEKBLog", which has been developed in the KEKB project. The details of KEKBLog is reported in Ref [14]. KEKBLog records 130000 PVs which are especially necessary for the SuperKEKB operation.

Figure 8 is an example of recorded data. We can retrieve and plot the data which has been taken in the past operation. The detailed studies and reviews are performed with these data to decide the next plan of the SuperKEKB operation.

In addition to KEKBLog, the CSS archiver system is secondarily utilized. This system is prepared for satisfying the detailed requests from the individual users. For example, the users can build their own CSS archiver during the limited-term for the R & D of their hardware.

Also, the new archiver system with EPICS Archiver Appliance [15] is developed. We plan to integrate the functions of the above two archivers on Archiver Appliance. The full service will be provided in this Autumn operation.

ELECTRONIC OPERATION LOG SYSTEM

We utilize the electronic operation log system named Zlog [16]. It is developed with Zope which is the Python-based open-source for the web application server. The Zlog system is operated from the previous KEKB project. We developed it in the very short term since we have established Python experts. And it has high maintainability since Zope is the object-oriented software.

The Zlog system is a web-based service so that all users can easily access to read and write the operation log. It is a strong advantage to promote the operation and tuning of SuperKEKB. Figure 9 is an example of operation logs. We can put both the log messages and pictures.

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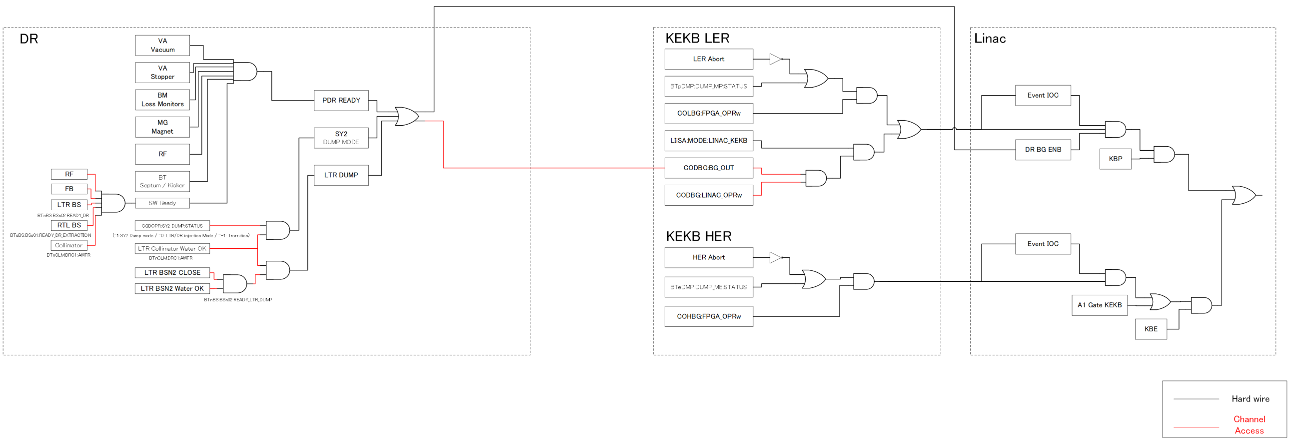

Figure 7: Schematic view of the Beam Permission logic. The black and red lines indicate the hardware and software logics, respectively.

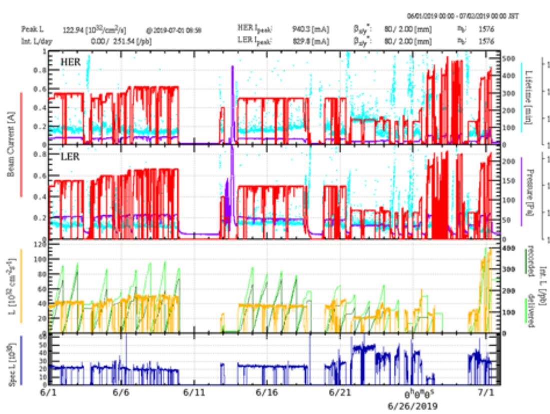

Figure 8: An example of the recorded data from KEKBLog.

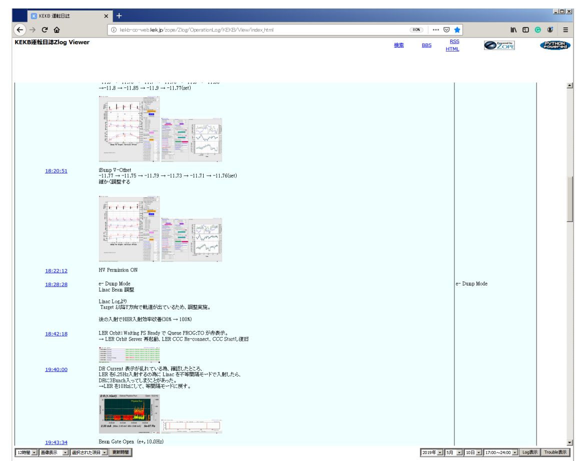

Figure 9: An example of Zlog. Basically, all messages are written in Japanese.

All standard OPIs which are developed with the SAD or Python scripts include the snapshot function. And the operators take the snapshot of OPI when they implement some important operations or when the alarm status is popped up. Therefore, people at off-site can easily understand the operation and trouble statuses of SuperKEKB by monitoring the Zlog system.

Table 2: Summary of beam-pulses at LINAC. Note, HER and LER are two MRs at SuperKEKB. PF and PF-AR are the light source rings.

Ring	**Particle**	**Energy (GeV)**	**Charge (nC)**
HER	e^-	7.0	5.0
LER	e^+	4.0	4.0
PF	e^-	2.5	0.2
PF-AR	e^-	6.5	5.0

TIMING SYSTEM

The timing system is one of the most important components of the SuperKEKB project. There are several reports related to the injection control and timing system [17–19].

Our timing system manages not only the operation timing but also the parameters of the injection components.

LINAC provides beam-pulse towards 4 independent rings at KEK. Table 2 is the summary of beam-pulses that LINAC provides towards the individual rings. They are quite different and more than 150 of the LINAC parameters must be switched when we change the destination ring. We perform the top-up filling operations of 4 rings, simultaneously. Therefore the switching of beam direction is implemented on pulse-by-pulse, in 50 Hz.

We utilized the Event Timing System. The delivered Events in our system are utilized for both providing timing triggers to the hardware and launching the network interruptions. The LINAC parameters can be switched by the network interruption, synchronously, in 50 Hz. Therefore, simultaneous top-up filling operations are realized.

The DR operation is started since 2018. It is utilized only for the positron beam-pulse and makes the timing system difficult because of the following conditions. The required damping time is at least 40 ms. It is longer than the one pulse

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period of LINAC. Therefore, the positron operations before and after DR must be implemented in the different LINAC pulse. Besides, the RF-buckets for the DR operation and the MR injection must be selected with the complicated combination rule which is derived from the harmonic number difference between DR (230) and MR (5120).

We configure the two EVG layers on the master IOC of Event Timing System. The upper-layer EVG manages about 350 ms operation schedule. Therefore the entire schedule of the positron operation can be managed. The lower-layer EVG manages the operation timing of the individual LINAC pulses such as the timing tuning for the RF-bucket selection at DR and MR.

We realized the DR operation with our sophisticated Event Timing System and are successfully providing a lot of positron pulses to the SuperKEKB MR.

The timing system will be upgraded for further requirements in the future high current operation. The two pulses operation at DR is required in the future SuperKEKB operation. In this case, the Event Timing System plans to control the RF phases at LINAC on pulse-by-pulse.

We plan to develop our own Event modules with the open-source to enhance the functions of Event Timing System. Figure 10 is the test bench for the new EVR development. The R & D is ongoing with the AES-PZCC-FMC-V2-G board [20].

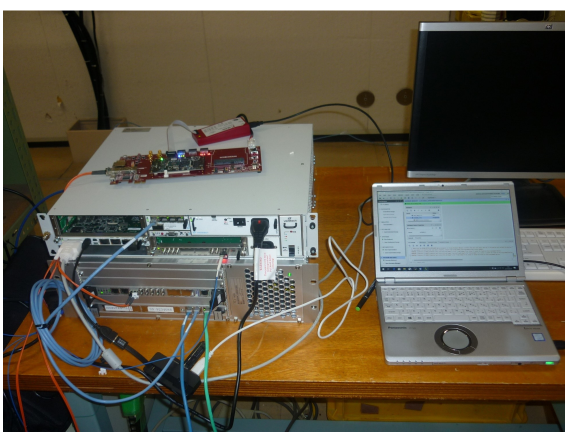

Figure 10: Picture of the test bench for the EVR development. The red board on the left rack is the AES-PZCC-FMC-V2-G board.

CONCLUSION

The SuperKEKB project has been operated since 2016 and smoothly attained its milestones. This project is strongly supported by the sophisticated control system based on EPICS. About 200 IOCs built at CCB and SCBs are running without any serious problem. The operator can control this huge system through the OPIs developed at CCB.

In addition, the SuperKEKB control group develops and provides several middle-layer services. They are strongly enhancing the progress of SuperKEKB. We keep developing and upgrading these middle-layer services for satisfying the increased requests from the SuperKEKB operation.

The timing system is one of the advantages to realize the extremely complicated SuperKEKB operation. It has been operated since 2016. The DR operation in the positron injection is realized. Further upgraded is planned for the future high current operation. Besides, the project to develop the standalone EVR modules is ongoing.

The future prospect of the SuperKEKB project is promising since it is supported by the control group's efforts.

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