17th Int. Conf. on Acc. and Large Exp. Physics Control Systems ICALEPCS2019, New York, NY, USA JACoW Publishing
ISBN: 978-3-95450-209-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2019-MOPHA073

RECENT UPDATES OF THE RIKEN RI BEAM FACTORY CONTROL SYSTEM

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Abstract

We report on two of the latest updates for the RIKEN Radioactive Isotope Beam Factory (RIBF) control system. First, the successor of the existing beam interlock system (BIS) has been recently developed. The new interlock system is based on a programmable logic controller (PLC) and uses a Linux-based PLC-CPU. This allows the Experimental Physics and Industrial Control System (EPICS) programs to be executed in addition to a sequence CPU. By using two kinds of CPUs properly in accordance with the speed required for each signal handled in the system, we have succeeded in reducing the response time to less than one third of the existing BIS using a prototype.

Second, a trial was performed to extend coverage of the alarm system. We have applied the Best Ever Alarm System Toolkit (BEAST) in addition to the Alarm Handler over several years (mainly for vacuum components). We have attempted to include the magnet power supplies but found difficulties in treating older power supplies that have large fluctuations of read-out values for their excitation currents. Our trials to overcome this problem are presented in this paper.

INTRODUCTION

The RIKEN Radioactive Isotope Beam Factory (RIBF) is a cyclotron-based accelerator facility aimed at the development of nuclear physics, material science, and life science. RIBF consists of two heavy-ion linear accelerator injectors, five heavy-ion cyclotrons including the world's first superconducting ring cyclotron (SRC). Cascades of the cyclotrons can provide the world's most intense RI beams over the entire atomic mass range by using fragmentation or fission of high-energy heavy-ion beams [1]. For example, a 345-MeV/nucleon ^{238}U beam of 72 pnA and a 345-MeV/nucleon ^{124}Xe beam of 173 pnA have already been obtained.

The components of the RIBF accelerator complex (such as the magnet power supplies, beam diagnostic devices, and vacuum systems) are controlled by the Experimental Physics and Industrial Control System (EPICS) [2] with a few exceptions such as the control system dedicated to RIBF's radio frequency system [3]. However, all the essential operation datasets of EPICS and other control systems are integrated into the EPICS-based control system. In addition, two types of interlock systems that are independent of the accelerator control systems are also operated in the RIBF facility: a radiation safety interlock system for human protection [4] and abeam interlock system (BIS) for hardware protection from recent high-power heavy-ion beams [5].

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UPGRADE OF BIS

The hardware configuration and the process flow in the existing BIS are shown in Fig. 1. The BIS was developed based on the Melsec-Q series programmable logic controllers (PLCs). It was designed to stop beams within 10 ms after receiving an alarm signal from the accelerator and beam line components. Upon receiving an alarm signal, the BIS outputs a signal to one of the beam choppers that immediately deflects the beam just below the ion sources. It also inserts one of the beam stoppers (Faraday cup) installed upstream of the problem component. After inserting the relevant beam stopper, the beam chopper can be switched off, and beam delivery can resume up to the inserted beam stopper. This feature is particularly useful during beam tuning because beam tuning is conducted in a step-by-step manner from an injector to a final-stage accelerator. The inserted beam stopper can then be extracted from the beam line after the problem is fixed.

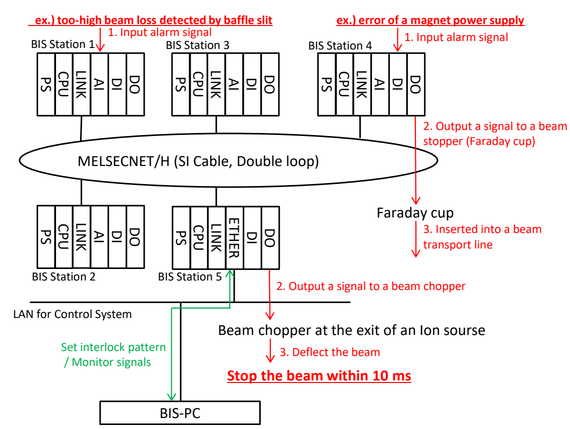

Figure 1: Example of the hardware configuration and process flow in BIS. The green line signifies communication via Ethernet.

The BIS began its operation in 2006. The recent response time is 15 – 20 ms (greater than its design value) because too much information is shared among each station through optical links in the BIS and increasing input signals. The beam power has already exceeded 10 kW, and beam operation at the level of several tens of kilowatts is expected in the near future [6]. To operate higher-power beams more safely, a response speed of 10 ms or less is required for the BIS. In addition, a greater number of components than those included in the present BIS have to be carefully monitored. This is because subtler

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failures can potentially cause severe accidents in the case of very high-power beams. Therefore, we have commenced the development of the next-generation BIS (hereinafter, BIS2) in 2017, which is designed to exhibit superior performance and convenience in operation compared to the existing BIS. This is because there is a limit for the existing BIS to reduce the response speed for the increasing number of associated components.

The BIS2 implements interlock logic fundamentally equivalent to that of the existing BIS. We decided to develop the BIS2 system from scratch and designed it to reduce the amount of data shared between different stations in order to reduce response time. In the BIS2, only the output signal status is shared among stations. We adopted the FA-M3 PLC system to satisfy the above requirements [7]. We constructed a two-station-configuration BIS2 as a prototype without a technical limit to increase the number of stations and the number of I/O points.

Figure 2 shows the hardware constitution and the process flow of the BIS2 prototype. The system employs a multi-CPU configuration. The sequence CPU, I/O modules, and FL-net module are mounted on both stations, and the Linux-based CPU (hereinafter, F3RP61 CPU) is mounted on only one of the stations. Interlock logic is implemented in the sequence CPU because high-speed processing and high reliability are required. High-speed processing is not necessary for setting and monitoring the interlock signal. These functions are implemented in the F3RP61 CPU and will be operated coupled with the main RIBF control system. We execute EPICS on the F3RP61 CPU and access it from the upper-level PC via Ethernet [8]. The monitor and setting information of the signal (which is connected to the I/O module of each station) is stored in a register on the sequence CPU of the same station. The EPICS PV executed on the F3RP61 CPU accesses the sequence CPU via the PLC-bus in the case of the sequence CPU in the same station. It accesses the sequence CPU on the other station via the Ethernet using netDev, which was developed by the control group of KEK and RIKEN Nishina Center in 2004 aiming at controlling various types of PLCs, and the in-house controller developed by the RIKEN Nishina Center [9]. As each BIS2 station is planned to be distributed in the accelerator facility as well as BIS, there are cases that an input signal and a corresponding output signal may be connected to the I/O module of different stations. The interlock signal information transfer between the two stations is performed through FL-net (an open network protocol used for interconnection between controllers). As a result of oscilloscope-measured signal transmission speed, the average response time observed is 1.4 ms and 3.8 ms for the operation within one station and using two stations, respectively. Thus, the time used for data transmission through the FL-net is 2.4 ms which is consistent with the specification listed in the catalog. The measured response speed is better than the specification required in the BIS2 development.

After confirming the basic performance of BIS2 prototype, we applied it to a small part of the RIBF facility, namely the Azimuthally Varying Field (AVF) cyclotron and its low-energy experimental facility, as a first step in the RIBF BIS upgrade. The AVF cyclotron has three ion sources and four beam lines downstream of it. Three of the beamlines are used for low-energy experiments and the other transports a beam to the next heavy-ion cyclotron RRC. Thus, the interlock logic should be changed properly according ion source choice and the beamline depending on each experimental condition. The interlock signals implemented in the BIS2 prototype are the same as the existing BIS including errors in the magnet power supplies used such as excessive beam loss detected by baffle slits installed at the AVF cyclotron, beam transport lines, and so on. As a result, 43 digital input and 23 analog input signals are registered in addition to 8 output signals of the beam choppers and Faraday cups.

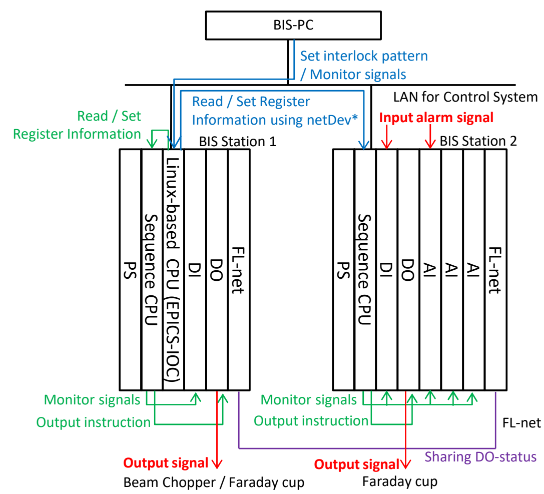

Figure 2: Hardware constitution and process flow in BIS2. Blue lines signify communication via Ethernet, green lines signify communication via PLC bus, and purple lines signify communication via FL-net.

As each signal registered in BIS2 may or may not be necessary depending on the choice of the beamline used for experiment, it is necessary to set the validity of each signal in both BIS2 and BIS before beginning the experiment. For example, when an experiment is performed using beamline-A, an abnormal signal from a device on beamline-B is unnecessary barring a few exceptions. BIS2 provides a bi-type EPICS PV for setting signal validity and sets the signal pattern for each experiment by writing 0/1 to the EPICS PV from the upper level. Writing to the EPICS PV is executed through graphical user interfaces (GUIs) or shell programs. We are developing GUIs using EPICS Motif Editor and Display Manager (MEDM) [10] and Control System Studio (CSS) Best OPI, Yet (BOY) [11]. Furthermore, each interlock history is recorded in the PostgreSQL database using CSS's Best Ever Alarm System Toolkit (BEAST) [12]. By recording the interlock history in the database used by BEAST, not only can the history be easily traced from the BEAST client

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GUI, but the data can be used in various ways as required. The CSS operating environment used here is described in the next paragraph. Figure 3 shows the sample GUIs of BIS2.

At the beginning of September, a part of the aforementioned signals were connected to the BIS2, and the remaining signals will be connected before the start of the next beam service scheduled this October.

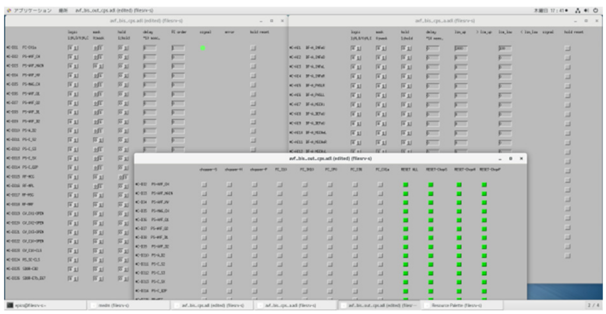

Figure 3: Sample GUIs of BIS2.

MAINTENANCE OF ALARM SYSTEM

Besides the BIS, we operate an alarm system. The role of the alarm system is to notify accelerator operators of an anomaly signal via a monitor display and sound. We have applied the alarm system mainly to signals that have a slight time delay before they drastically affect the safe operation of the facility (> 10 ms) and to signals that cannot be connected to the BIS due to the signal number limitation of BIS. For example, in the vacuum system, the BIS works when the gate valve on the beam transport line is unexpectedly closed due to deterioration of vacuum pressure or valve failure. However, an alarm system detects unexpected vacuum pump stoppages that cause gradual deterioration of the vacuum pressure. As another example, when sudden shutdown of the operating magnet power supply causes the read-out value of the excitation current (ADC) to read 0 A, the BIS is activated. In contrast, when the ADC changes at a certain ratio for the set value of the output current (DAC), the alarm system notifies the operator of its situation.

In accordance with the above, we are monitoring the status of the following equipment with an alarm system:

1. Vacuum pumps and valves associated with the pump system. For example, whether the Turbo Molecular Pump on the beam line is on or off (normally, on).
2. Vacuum pressure at the cyclotrons and the beamlines.
3. Various devices in the AVF cyclotron and the ion sources for it.
4. The ratio of difference between DAC and ADC of the magnet power supply.

The number of signals listed above is 213, 74, 17, and 763 in total at the moment, respectively. At the RIBF accelerator facility, various acceleration modes are available by changing the combination of the accelerators used. Therefore, the signal necessary for the experiment at that time is selected and monitored. Depending on the type of experiment, we monitor approximately 1000 signals with an alarm system.

The signal monitoring listed in 4 is especially effective during the beam delivery for the experiment. When the beam condition is changed due to sudden unexpected variation of output current from a magnet power supply, it needs more time to identify the troubled one among hundreds of magnet power supplies in operation from the GUI for control. Therefore, it is meaningful to check the difference between DAC and ADC with an alarm system regularly to ensure they do not have a large difference between them. However, as some of the ADCs used for our old magnet power supplies have large fluctuations of readout values, it has not worked well for some time. Therefore, we have determined the alarm setting rates by examining fluctuation of each magnet power supply. As a result, alarm ratio was set in 3 patterns according to the level of the fluctuation of ADC. In descending order of the fluctuation of ADC, a minor alarm is output when the difference between DAC and ADC exceeds ±10%, ±20%, ±50% of the DAC. A major alarm is output when the difference exceeds ±20%, ±30%, ±90%. Large values of 50% and 90% are mainly applied to old magnet power supplies for steering magnets with small rated currents. In the region where the excitation current of the magnet power supply is relatively stable, the alarm system is useful for setting under these conditions.

There is another factor that makes it difficult to set the alarm level. The fluctuation of the ratio of ADC to DAC is extremely large when the operating current is nearly 0 A (for example, a power supply used for a beam steering magnet). We are currently investigating how to deal with differences in ADC stability due to the output current region within the same magnet power supply. Currently, magnet power supplies that output current of nearly 0 A during the experiment are excluded from the monitoring targets of the alarm system manually before each experiment. In the next beam service scheduled this October, we will attempt to improve the alarm setting. At present, the threshold value is limited to be universal for all the excitation currents, but it causes the difficulty mentioned above. We will modify the alarm setting so that a proper threshold value can be automatically selected and applied within the multiple levels predetermined depending on its excitation current.

The RIBF alarm system has been operated using Alarm Handler [13]. Since 2012, CSS BEAST has been introduced and operated alongside. When newly registering an alarm signal, CSS BEAST is used. We employed the CSS version 4.5.0 for the alarm server, and execute it on Linux CentOS 7. For the client, we use both CSS version 3.2.16.3 and 4.5.8 on both Linux and Windows PC, in relation to the existing CSS BOY programs. In addition, with reference to the case of KEK, EPICS PVs dedicated to the alarm system are created separately from the EPICS PV used to control the equipment. They are operated on the IOC dedicated to the alarm system. Thereby, the control of the device is not affected by the change or issues of the alarm PV.

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