KEK ELECTRON/POSITRON INJECTOR LINAC SAFETY SYSTEM

M. Satoh[†,1,2], I. Satake[1], A. Shirakawa[1], K. Hisazumi[3], T. Kudou[3], S. Kusano[3]
[1]High Energy Accelerator Research Organization (KEK), Accelerator Laboratory, Tsukuba, Japan
[2]The Graduate University for Advanced Studies (SOKENDAI), Accelerator Science Program, Tsukuba, Japan
[3]Mitsubishi Electric System & Service Co., Ltd (MSC), Tsukuba, Japan

Abstract

At the KEK electron/positron injector Linac, simultaneous top-up injection into four independent storage rings and a positron damping ring has been successfully carried out since May 2019. To ensure long-term stable beam operation under such a complex operational scheme, high availability of the control system is critically essential. In addition, a reliable safety system is also required to prevent personnel radiation accidents and to protect machine components. At the KEK injector Linac, the control system has been developed based on the EPICS framework, which is widely adopted in the accelerator community. However, the safety system was originally developed independently of EPICS. To enhance compatibility between the control and safety systems, an EPICS IOC for the safety system was implemented using the netDev device support. Furthermore, a newly developed beam-operation logic status GUI enables rapid identification of invalid linac operating conditions. This paper presents an outline of the safety system and its recent improvement at the KEK injector Linac.

INTRODUCTION

The KEK electron/positron injector Linac began operation in 1982 as a dedicated injector for the PF ring, and subsequently has supplied electron and positron beams to rings of different energies, including TRISTAN, PF-AR, and KEKB. Initially, beam injection into each ring was carried out using a time-sharing scheme based on fixed-time injections. However, the demand for top-up injection, which was becoming common in third-generation synchrotron light sources, increased among PF users, and the KEKB ring also requested top-up injection to improve integrated luminosity. In response to this situation, a project team aiming for simultaneous top-up injection into all rings was established in 2004, and in April 2009, simultaneous top-up injection into three rings (the KEKB electron/positron rings and PF ring) was realized. After the construction of a dedicated injection beam transport line for PF-AR in 2012, simultaneous top-up injection into four rings (the SuperKEKB electron/positron rings, PF ring, and PF-AR) and a positron damping ring was achieved in May 2019 [1]. Currently, the injector Linac can deliver electron and positron beams generated at up to 50 Hz to any ring according to prescheduled injection patterns.

To realize simultaneous top-up injection, an event timing system [2], a laser-driven low-emittance RF electron gun [3], a flux concentrator for positron capture [4], high-precision beam position monitors [5], and a pulsed magnet system [6, 7] have been developed and implemented. Various modifications are currently underway to improve injection efficiency into both synchrotron light sources and the SuperKEKB rings [8]. As beam operations have become more complex, the beam control system has also become more sophisticated. Under such a complex operational scheme, ensuring the soundness of both personnel and accelerator equipment in the injector Linac and downstream rings increasingly requires a robust safety system. Although the safety system is constructed independently of the control system, as beam operation logic becomes more complex, it is essential to promptly identify and resolve any failures of beam operation conditions to maintain the operational availability of downstream rings. Therefore, to ensure seamless operation, the compatibility between the safety system and the control system should be enhanced, enabling safety system data to be integrated within the control system framework.

INJECTOR LINAC SAFETY SYSTEM

Overview

In general, accelerator safety systems are broadly classified into the Personnel Protection System (PPS), which ensures human safety, and the Machine Protection System (MPS), which protects accelerator equipment. During injector Linac operation, which accelerates electron and positron beams, radiation exceeding the permissible dose for humans can be generated inside the tunnel where the accelerator is installed. Therefore, a necessary condition for injector Linac operation is that the PPS requirements are satisfied, thereby ensuring human safety. When human safety is guaranteed and injector operation is permitted, the system is said to be in the “LINAC READY” state. This indicates that the PPS requirements of not only the injector

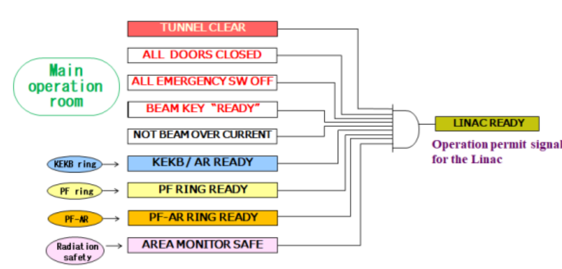

Figure 1: Block diagram of the injector Linac safety system interlock signal logic.

†masanori.satoh@kek.jp

Linac but also all downstream rings permit injector Linac operation.

Figure 1 shows the interlock signal logic for injector Linac operation. The following conditions must be satisfied within the injector Linac PPS:

- The accelerator tunnel is unoccupied.
- All doors involved in interlocks are closed.
- Emergency stop switches are not pressed.
- The beam key at the safety control console is in the "READY" state.
- Emergency stop switches are not pressed.
- The integrated beam charge does not exceed the limit.

The injector Linac can operate only when all of the above conditions are satisfied, 'READY' signals are received from all downstream rings, and no alarms are being triggered by the radiation monitors.

System Description

Programmable Logic Controllers (PLCs) are used for the actual signal transmission/reception and logical processing of the safety system. PLCs, also called sequencers, were developed as replacements for relay circuits. They allow more flexible logic modifications compared to relay circuits, and in the injector Linac, they are also used to control other subsystems, such as the vacuum and magnet control systems.

The injector Linac safety system uses three YOKOGAWA ladder PLCs, with one main PLC located in the injector Linac main control room and two sub-PLCs in the ABC sub-control room. Approximately 300 safety signals are input into these PLCs. These signals indicate the status of conditions such as READY signals from downstream rings, door open/close status of buildings or high-voltage power supply cabinets, and emergency stop signal activation. The signals are read by the PLC's DIO modules, processed through the safety logic, and output as approximately 200 signals. These outputs are used, for example, as trigger enable signals or high-voltage power supply enable signals. Communication among the three PLCs is performed using DC 24 V contact signals.

In addition to the three PLCs mentioned above, two communication-dedicated PLCs are operated as gateways to transmit safety system information to computers on the control network. To prevent any impact on the safety system in the event of a control network failure, computers on the control network are only allowed to read information from the PLCs. Figure 2 shows the connection diagram between the safety PLCs and the control network.

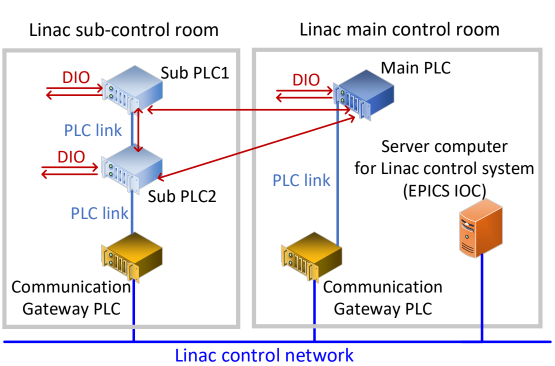

Figure 2: Block diagram of the injector Linac safety system using PLC and Linac control network.

Figure 3 shows the GUI that displays the interlock status of the safety system. Originally developed in Microsoft Visual Basic 6.0 (MSVB6), it was later migrated to Visual Basic .NET after support ended. The GUI monitors the status of the safety PLCs via the communication PLCs, providing a quick overview of READY signals from each ring as well as the open/close status of doors incorporated into the PPS. Injector Linac operation is permitted only when all status indicators are green. If operation cannot be initiated due to unsatisfied PPS conditions, the GUI highlights the specific causes in red, allowing rapid identification of the issues preventing operation.

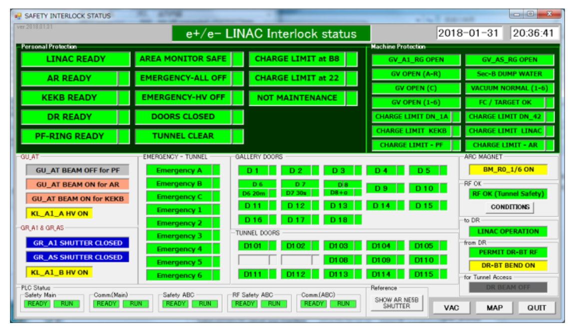

Figure 3: Interlock status GUI of the injector Linac safety system developed with Microsoft Visual Basic .NET.

SAFETY SYSTEM UPGRADE

Personnel Key System

In the injector Linac safety system, entry into the tunnel is controlled by a personnel key: the key must be removed and carried before entering, and returned to the key system

Figure 4: Photograph of the exterior view of personnel key system at the KEK injector Linac.

upon exiting. Injector operation can only be initiated when all keys have been returned. Figure 4 shows a photograph of the personnel key system.

This system has been in operation since the construction of the injector Linac and underwent a major upgrade about 20 years ago, during which the number of keys was increased to 50 and the layout modified, while retaining much of the underlying system. Consequently, core components such as the internal control circuitry and limit switches behind the key cylinders have significantly aged. Malfunctions could prevent keys from being removed, block tunnel entry, or stop the injector from transitioning to an operational state. Therefore, updating the personnel key system has become an urgent task.

A complete system replacement would require substantial investment. Accordingly, it was decided to retain the existing system and update only the critical underlying components. Figure 5 shows a photograph of the control board currently used in the system. As shown in the figure, the system relies on an outdated dedicated control board, for which equivalent replacements are no longer available. During the summer maintenance period of 2024, the functionality of this board was replaced by a PLC.

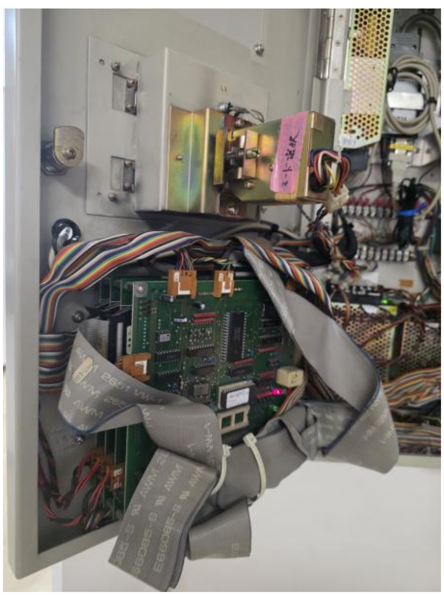

Figure 5: Photograph of the personnel key system control board.

Data Transfer to Injector Linac Control System

The injector Linac control system is entirely built on the EPICS framework [9]. Unified operation is realized through EPICS IOCs, which control individual devices in coordination with the CSS alarm system and the Archiver Appliance. Traditionally, the injector Linac safety system consisted of ladder PLCs, I/O modules, and electromechanical relays, operating independently of the main control system. Related components such as status display GUIs and state-transition records were developed and maintained separately.

To improve compatibility with the control system and enhance maintainability by standardizing mechanisms such as data archiving and alarms, the safety system was integrated to expose its information as EPICS PVs. Since the safety system is based on YOKOGAWA ladder PLCs, its EPICS IOC was implemented using netDev, a widely used EPICS device support module in the injector Linac control system [10]. Approximately 1,200 signals are converted into EPICS PVs, all of which are recorded in the archiver. The EPICS IOC for the safety system runs on the same control system server computers shown in Fig. 2.

Figure 6 presents a logic diagram and a GUI that display the status of each signal required for injector beam operation. This GUI clearly indicates the signal states and logic conditions necessary for beam extraction from the thermionic electron gun. Using this interface, operators can quickly identify which prerequisite is not satisfied when beam operation cannot be initiated. Similar GUIs are also available for RF electron gun operation and for the main timing station. These tools enable rapid startup of beam operation, even after long-term maintenance periods.

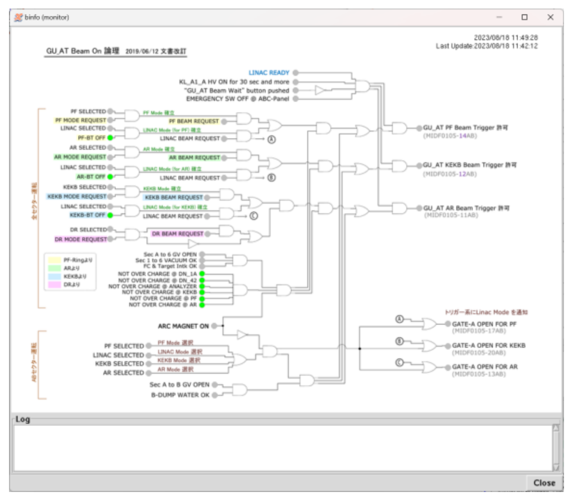

Figure 6: Example of the injector Linac beam operation logic status GUI developed with Python.

Key Checkout System

At the injector Linac, in addition to the personnel key system, approximately 100 keys are managed using wall-mounted key storage boxes. Traditionally, records of key lending and returns were maintained manually in a notebook. However, due to the large number of keys with complex names and the frequent lending of certain keys in the history logs, the key management records were digitized to improve operational efficiency. Specifically, the QR code attached to each key tag is scanned using a tablet or similar device, after which the required information is entered into the key management web page, as shown in Fig. 7. This system has significantly reduced the labour involved in frequent key lending and returning, particularly during long-term maintenance periods such as the summer maintenance term.

Figure 7: Snapshot of the key checkout system web page.

Digitization of Radiation-Generating Equipment Usage Records

Since the injector Linac is a radiation-generation device, a radiation-generation equipment usage record (usage record) has been created and printed for each operational shift. The printed usage record was signed by the Linac staff member serving as the safety shift leader for that shift and subsequently archived. The usage record includes detailed information such as the location of use, maximum beam output power, maximum beam energy, and the purpose of use. Over years of operation, the printed usage records have accumulated in large quantities, occupying many bookshelves, and managing them has become a significant administrative burden.

After discussions with the staff at the Radiation Science Center, it was determined that a signature from the safety shift personnel was not strictly necessary, and the information included in the record could be reconsidered. Based on this, the decision was made to fully digitize the usage records without retaining printed copies. Figure 8 shows examples of the old and new usage records. In the original format as shown on the left of Fig. 8, one page recorded a single 8-hour operational shift. To improve accessibility during periodic radiation inspections conducted every five years, the new usage records were redesigned to record all three shifts of a single day on one page, as shown on the right in Fig. 8. The new usage records have been in operation since April 2024, and all records can be easily accessed via a web page. Instead of signing, safety shift personnel now verify the usage records for their shift online, confirming that no values exceed the prescribed limits. This approach simplifies administrative work while maintaining safety.

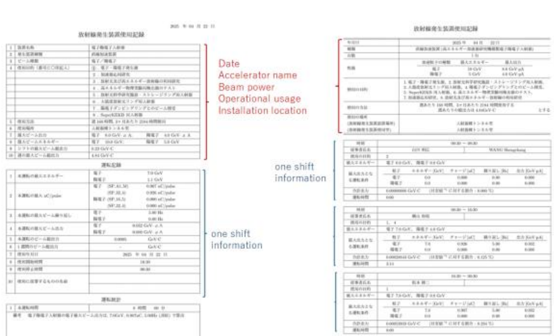

Figure 8: Image of the original (left) and the new (right) document for the radiation-generating equipment usage record.

CONCLUSION

The safety system of the KEK electron/positron injector Linac is a robust PLC-based architecture that ensures the protection of both personnel and equipment, playing a vital behind-the-scenes role in supporting simultaneous top-up injection into four independent storage rings and a positron damping ring. Over the years, the system has been progressively upgraded to replace aging components and to accommodate evolving operational modes. Processes that were previously managed on paper, such as key checkouts and the signing of radiation-generating equipment usage records, have also been digitized. Furthermore, a GUI has been developed to monitor complex operational conditions, enabling the rapid identification of causes when transitions to beam operation are not possible.

REFERENCES

[1] K. Furukawa *et al*., “Achievement of 200, 000 Hours of Operation at KEK 7-GeV Electron 4-GeV Positron Injector Linac”, in *Proc*. IPAC'22, Bangkok, Thailand, Jun. 2022, pp. 2465-2468.

[2] Di Wang *et al*., "Analysis and stabilization of AC line synchronized timing system for SuperKEKB", *Nuclear Inst. and Methods in Physics Research, A* 1015 (2021) 165766, https://doi.org/10.1016/j.nima.2021.165766 (accessed Aug. 28th, 2025).

[3] R. Zhang *et al*., “LASER SYSTEM FOR SuperKEKB RF GUN IN PHASE III COMMISSIONING”, in *Proc*. IPAC’22, Bangkok, Thailand, June 12-17, pp.2914-2916.

[4] Y. Enomoto *et al*. “A New Flux Concentrator Made of Cu Alloy for the SuperKEKB Positron Source”, in *Proc*. IPAC’21, Campinas, SP, Brazil, May 23-28, pp.2954-2956.

[5] F. Miyahara *et al*., “HIGH POSITION RESOLUTION BPM READOUT SYSTEM WITH CALIBRATION PULSE GENERATORS FOR KEK e+/e- LINAC”, in *Proc*. IBIC2015, Melbourne, Australia, September 13-17, 2015, pp.369-372.

[6] Y. Enomoto *et al*., “Pulse-to-pulse Beam Modulation for 4 Storage Rings with 64 Pulsed Magnets”, in *Proc*. LINAC2018, Beijing, China, Sept. 16-21, 2018, pp.609-614.

[7] Y. Enomoto *et al*., “Pulsed Magnet Control System Using COTS PXIe Devices and LabVIEW”, in *Proc*. ICALEPCS2019, New York, NY, USA, Oct. 5-11, 2019, pp.946-949.

[8] H. Ego *et al.*, “UPGRADE STATUS OF KEK ELECTRON/POSITRON INJECTOR LINAC FOR IMPROVEMENT ON BEAM INJECTION TO SuperKEKB”, in *Proc*. PASJ2024, Yamagata, Japan, Jul.-Aug. 2024, pp.608-612.

[9] https://epics-controls.org/ (accessed Sep. 3rd, 2025).

[10] https://github.com/shuei/netDev/ (accessed Sep. 3rd, 2025).