KEK ELECTRON/POSITRON INJECTOR LINAC CONTROL SYSTEM

M. Satoh[†,1,2], D. Wang[1,2], I. Satake[1], M. Sakamoto[1], F. Miyahara[1,2], T. Kudou[3], S. Kusano[3], H. Saotome[4], K. Hisazumi[3], Y. Mizukawa[3], T. Ohusa[4], T. Suwada[1], and K. Furukawa[1]
[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
[4]Kantou Information Service (KIS), Tsuchiura, Japan

Abstract

Since May 2019, the KEK electron/positron injector Linac has successfully carried out simultaneous top-up injection into four independent storage rings as well as a positron damping ring. Ensuring long-term stable beam operation under such a complex operational scheme requires maintaining a high availability of the entire control system. The original Linac control system, developed in the 1990s, was built on a proprietary in-house software framework utilizing Unix servers, VME bus systems, and PLCs. The operator interface was implemented with the Tcl/Tk scripting language and supported approximately 3,500 control points.

To improve development efficiency and ensure greater compatibility with other accelerator control systems, the Linac control system has been gradually migrated from its legacy platform to an EPICS-based architecture. This migration has expanded its capability to approximately 200,000 control points. Furthermore, Linux-based hyperconverged servers, a PXI bus system, and custom embedded front ends have also been deployed. This paper presents a comprehensive overview of the current status of the KEK injector Linac control system and discusses prospects for its future development.

INTRODUCTION

The KEK electron/positron injector Linac began operation in 1982 as a dedicated injector for the PF ring. Since then, it has provided electron and positron beams to various rings at different energies, including TRISTAN, PF-AR, and KEKB. Initially, beam injection into each ring was performed in a time-sharing mode based on scheduled injection. However, the demand for top-up injection increased among PF users since top-up injection was already common operational mode at third-generation light sources. There was also a strong request from the KEKB rings and Belle detector group to implement top-up injection for increasing the integrated luminosity. In response to this situation, a project team was launched in 2004 with the goal of achieving simultaneous top-up injection into all rings. In April 2009, simultaneous top-up injection into three rings (the KEKB electron/positron rings, and the PF ring) was successfully realized. Subsequently, with 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, the PF ring, and PF-AR) was achieved in May 2019 [1].

Currently, electron and positron beams generated at a maximum repetition rate of 50 Hz can be injected into any of the rings according to arbitrary preprogrammed injection patterns. To realize simultaneous top-up injection, a large number of developments and upgrades have been conducted, including the event based timing system [2], the low emittance photocathode rf electron gun with the complex laser system for SuperKEKB injection [3], a flux concentrator for positron capture system [4], high precision beam position monitors [5], and pulsed magnet systems [6, 7]. Currently, various modifications are being undertaken to further improve injection efficiency into both the light source and the SuperKEKB rings [8-17]. With the increasing complexity of beam operation at the injector Linac, the beam control system has also been steadily improved.

LINAC CONTROL SYSTEM

Overview

The injector Linac control system adopts a three-tier architecture that conforms to the standard client/server model. Often referred to as the standard model of control systems, it consists of the client layer corresponding to the Operator Interface (OPI), the server layer serving as the middleware, and the local control layer that directly controls the equipment. By employing this architecture, modifications to equipment at the local control layer can be absorbed by the middleware, thereby avoiding changes to the client layer. This design ensures flexible expandability of the entire system.

In the late 1990s, at the beginning of injection into the KEKB rings, the injector control system was developed based on a set of in-house libraries utilizing Remote Procedure Call (RPC). At the OPI layer, a Command Line Interface (CLI) using shell scripts and a Graphical User Interface (GUI) using the Tcl/Tk scripting language were employed.

Around the mid-operation period of KEKB, these legacy systems were gradually migrated to a control system based on the Experimental Physics and Industrial Control System (EPICS) [18]. As the KEKB rings had employed an EPICS-based control system from the outset of their operation, this migration improved compatibility between the injector Linac and ring control systems. Consequently, correlation

†masanori.satoh@kek.jp

analyses of parameters spanning both systems could be performed more readily, and fault diagnosis became significantly easier.

Furthermore, following the adoption of the EPICS environment, Python was employed as the scripting language for both GUI and CLI development, significantly reducing the development time for complex applications. In addition, to enable simultaneous top-up operation for downstream rings, an event-based timing system was introduced, allowing advanced beam control in which beams of different energies could be injected on a pulse-to-pulse basis [19].

Server Computer System

At the start of KEKB operation, six Compaq Alpha machines were used as server computers. Among these, two functioned as redundant file servers, employing clustering and RAID capabilities on the Tru64 UNIX operating system. This configuration ensured continuous file service even in the event of a failure of one machine. Thanks to this redundancy, beam operation could be maintained without interruption despite multiple server failures.

Subsequently, as support for Tru64 UNIX was discontinued and server hardware maintenance became increasingly difficult, the system was transitioned to servers running the more versatile Linux operating system. For approximately 15 years, HPE blade servers running CentOS 7 were employed. Currently, the system operates on HPE SimpliVity, a hyper-converged infrastructure introduced in 2021. Multiple virtual servers run on this platform using VMware vSphere, providing core services such as web and LDAP, as well as hosting EPICS Input/Output Controllers (IOCs). While CentOS 7 was initially used, the system is now being migrated to Rocky Linux 9 due to CentOS 7 reaching its end of life.

For storage, a NetApp FAS8200 NAS has been adopted as the core system. Redundancy is ensured with two active/active controllers, providing highly available operation. The total capacity is 25 TB, and all virtual servers on VMware utilize this NAS via NFS mounts. It serves as the disk space for user home directories, operational programs, log files, and archiver data. Although the NetApp NAS itself guarantees high reliability and employs snapshot functionality, additional periodic backups to another NAS are performed to further enhance availability.

Control Network System

Since many network-connected devices are used at the injector Linac control system, the reliability of the network system directly affects the availability of accelerator beam operation. Severe failures in the network system, along with computer failures, are highly likely to result in the suspension of accelerator operation. For this reason, the backbone of the injector network system has been designed to ensure high availability through redundancy.

During KEKB operation in the 2000s, Cisco Catalyst 4506 and Catalyst 3750 switches were employed as active/standby redundant core switches, while 45 edge switches were implemented using Catalyst 2950. Redundant optical fiber connections between the core and edge switches were arranged in a star topology, with a network bandwidth of 100 Mbps. Furthermore, not only the links between the core and edge switches, but also those between edge switches and local controllers such as Programmable Logic Controllers (PLCs), employed optical fiber connections to avoid noise generated by the high power klystron modulators.

After the end of KEKB operation, the number of network-connected devices such as cameras and magnet power supplies increased in preparation for the SuperKEKB project, making network upgrades essential. Therefore, in 2013, six Cisco Catalyst 3750X switches were installed as higher-performance core switches, configured in an active/active redundant system connected to the edge switches. Simultaneously, 47 Catalyst 2960S units were introduced as edge switches. Under this configuration, each edge switch had an uplink bandwidth of 2 Gbps during normal operation.

Because the expected end of life for network equipment is about ten years, the injector control system has also been periodically upgraded based on the end of maintenance timelines. During the summer maintenance periods of 2022 and 2023, the core switches were replaced with redundant systems using two Cisco Catalyst 9500 and two Catalyst 9200 switches. Simultaneously, the edge switches were updated with 27 Catalyst 9200 (C9200) units and 15 Catalyst 1000 (C1000) units. As a result, connections between the core switches and the edge switches C9200 now operate at 10 Gbps, enabling simultaneous transfer of numerous 50 Hz waveform data from pulsed magnets and BPMs. The links between the core and edge switches C9200 are operated in a 10 Gbps/1 Gbps active/standby redundant configuration, while the edge switches C1000 are daisy-chained under C9200 units in a 1 Gbps/1 Gbps active/standby configuration. This topology was adopted in order to reduce implementation costs by limiting the number of core switch ports. C9200 switches are installed in racks that require high bandwidth, such as BPMs and pulsed magnets, whereas C1000 switches are used in racks with rf related equipment.

Because network failures immediately lead to suspension of accelerator operation, continuous monitoring is essential. The injector control system has introduced a network monitoring system based on Zabbix and Grafana [20]. This system enables immediate detection of increased broadcast packet traffic caused by equipment malfunctions and allows rapid identification of the faulty device. As a result, countermeasures can be implemented before severe disruptions propagate throughout the network.

Local Controller

In the local control section of the injector control system, a wide variety of devices, including VME modules and PLCs, are utilized. Table 1 summarizes the intended purpose and the number of devices for each type of local control equipment. Ladder PLCs are extensively employed for electromagnet power supplies, vacuum pumps, vacuum gate valves, and safety systems. Among these, DC electromagnet power supplies are being migrated from PLC-based control to network-attached power supplies or custom-developed embedded controllers. The signal delay modules of approximately 170 CAMAC and VME modules, which had been used for many years, were replaced around 2008 by an event-based timing system with VME64x bus. This system controls timing signals at 20 ms intervals and serves as the fundamental control system for simultaneous top-up injection. With the introduction of the event-based timing system, the number of timing devices has been greatly reduced, thereby improving the overall availability of the control system.

PLCs for klystron modulator control have been migrated to a custom-developed embedded Linux system [21]. This system allows EPICS IOCs to run directly on the embedded control devices. The Windows-based digital oscilloscopes previously used for BPM signal processing were replaced by newly developed VME modules [5]. The new system achieves a beam position measurement accuracy of less than 10 µm, playing an important role in precise beam orbit control and ultimately in maintaining a low-emittance beam.

Table 1: List of Local Controllers Used for the injector Linac Control System

Device type	Accelerator components (number of components)	Number of local controllers
VME64x	Event based timing system (MRF EVG-230, EVR-230RF)	54
Ladder based PLC	Magnet (153)	17
	Vacuum (375)	26
	Charge interlock (9)	3
	Safety	3
Network attached power supply	Magnet (113)	113
Linux based PLC	Profile monitor (108)	30
Embedded Linux	Klystron (76)	76
	DC Magnet (166)	166
Data logger	Temperature monitor (690)	28
VME based module	Beam position monitor (107)	24
NIM modules	Timing watchdog (15)	15
PXI	Pulsed magnet (107)	18
	Flux concentrator (1)	1
cRIO	Pulsed/DC magnet interlock	30
Total		604

PXI devices were introduced in 2017 with the large-scale installation of pulsed magnets [6, 7]. Initially, control software was developed and operated on Windows PCs using LabVIEW. To further improve system availability, this software has been replaced with a Linux/EPICS IOC–based control system. The new control system has reduced the failure rate from twice per month to essentially zero. Simultaneously, the interlock system for DC and pulsed magnets is being migrated to a cRIO-based system. Unlike conventional ladder PLCs, EPICS IOCs can run directly on cRIO, which is expected to enhance maintainability.

EPICS FRAMEWORK

Outline

Table 2 summarizes the number of EPICS IOCs for each subsystem. In the injector Linac control system, IOC development initially used EPICS base R3.14.9. These IOCs did not directly control hardware devices but were developed as wrappers around the existing in-house control software. However, software modifications became cumbersome whenever device information was updated, and the growing number of controlled devices increased management costs.

To address this issue, EPICS IOCs that directly control local hardware were developed and deployed, using EPICS base R3.14.12.x, and have been operated for many years. Recently, considering maintainability and other factors, the operational base is being migrated to R3.15.9. Furthermore, the introduction of EPICS 7 is planned, starting with monitoring IOCs that handle relatively large data transfers.

All operational EPICS IOCs are centrally managed via procServ, allowing all operators to monitor processes and restart IOCs as needed.

Table 2: Number of EPICS IOCs Used for Each Subsystem

Subsystem	Number of IOCs
Safety	3
Beam monitor	57
RF	106
Magnet	233
Vacuum	3
Timing	48
Temperature	30
Operation	112
Total	592

Alarm System

Before the adoption of EPICS, the old injector Linac control system employed separate alarm systems for each subsystem. Following the transition of the injector control system to EPICS, a comprehensive alarm management scheme was implemented, adopting the EPICS Control System Studio (CSS) [22] alarm. This system employs PostgreSQL as its backend database. Currently, approximately 7,000 EPICS Process Variables (PVs) are registered as alarms. Figure 1 shows an example of the alarm system GUI, implemented with Python. This GUI displays the current alarm status: the upper section shows alarm summaries for each subgroup, with any subgroup containing triggered PVs highlighted in red. The lower section lists the specific PV names that have triggered alarms. More detailed alarm histories can also be displayed in a separate window. Similar information is easily accessible through a web browser.

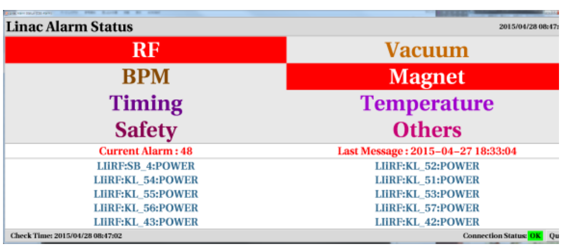


Figure 1: Example of the EPICS CSS alarm status GUI.

Data Archiver

Before the introduction of EPICS, the injector control system relied on in-house developed data archivers and display software. This system was simple, text-file based, and each subsystem employed a different format. Consequently, cross-subsystem log analysis, such as correlation studies of beam position and rf phase, was not straightforward.

After adopting EPICS, the EPICS Channel Archiver and CSS Archiver were introduced and operated. PostgreSQL was used as the backend database for the CSS Archiver. Following the end of life of the Channel Archiver, only the CSS Archiver has been maintained. To enhance availability, multiple independent CSS Archiver engines have been operated on different server computers and storage devices.

At the initial stage of CSS Archiver deployment, several issues were observed, such as archiving stopping without an error status and occasional data loss. These problems were resolved by running the CSS Archiver engines on servers with higher processing speed and larger memory. However, displaying large amounts of data could still take several hours under certain conditions. Additionally, using PostgreSQL as the backend database resulted in high data storage requirements.

To address these issues, the Archiver Appliance has been introduced and is currently in operation [23, 24]. This system enables long-term data to be displayed instantly, significantly improving operational efficiency. Although the Archiver Appliance provides its own web-based display tool, its functionality is limited, and further usability enhancements were desired. Therefore, the web application, originally developed as the Linac CSS Archiver viewer, was adapted to display data from the Archiver Appliance.

This web application was built using Apache, PHP, PostgreSQL, and Angular. It allows archive history to be accessed from a wide range of devices, including mobile platforms, as long as a web browser is available. The application offers features for efficient parameter analysis, such as correlation plots, multiple vertical axes, PV name search, and PV name autocomplete. Figure 2 shows a snapshot of this application. Currently, approximately 180,000 EPICS PVs are registered in the Archiver Appliance.

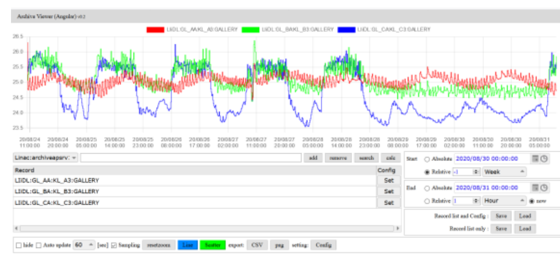


Figure 2: Screenshot of the EPICS Archiver viewer implemented as a web application.

OPERATIONAL APPLICATION

OPI

In the old injector Linac OPI before adopting EPICS, GUIs developed using the Tcl/Tk scripting language and CLIs implemented with shell scripts and C were employed. Since the mid-operation period of the KEKB project, more advanced operational software has been required to handle complex beam operation modes, such as simultaneous top-up injection into multiple rings. Consequently, the application development environment was migrated to the Python scripting language, reducing development time by leveraging its extensive library ecosystem. Communication between Python and EPICS PVs is performed using the PythonCA module, developed specifically for the KEKB project [25]. To further enhance development efficiency and software maintainability, injector-specific Python libraries have also been created and utilized.

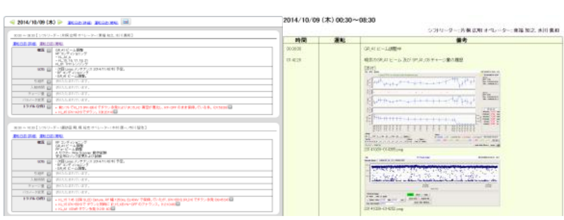
Electronic Logbook System

A web-based electronic operation logbook system is one of the essential tools for efficient accelerator beam operation. It enables efficient and rapid sharing of operational information among accelerator operators, beam commissioning staff, and engineering staff. At the injector Linac, an operation log using Microsoft SQL 6.5 was developed in 1995 and has been in operation for a long time. The GUI was implemented using Microsoft Access and the Visual Basic language.

After the commencement of simultaneous top-up injection into the KEKB and PF rings, the frequent switching of beam injection modes caused the database size to increase dramatically. The existing system faced challenges in managing such large databases and incurred high costs for porting to new operating systems. For these reasons, a new operation log system was developed in 2010. This log system was developed using Apache, Flex, PHP, and AMFPHP, with PostgreSQL as the backend database. Later, due to the end of life of Flex, the system was reconstructed using Angular.

Figure 3 shows an example of the operation log screen. The log consists of summary information and detailed information. As shown in Figure 3(a), the summary displays the names of the accelerator operators and safety shift personnel for each shift, as well as an overview of equipment malfunctions. As shown in Figure 3(b), more detailed information can be displayed on a separate screen. Similar to the previous log system, representative parameter changes, including beam repetition changes, are automatically recorded. More detailed entries, such as equipment malfunctions and corresponding countermeasures, can be entered by accelerator operators or engineering staff using the web application.

The operation log allows the inclusion of image information, such as snapshots from various OPIs, facilitating a detailed understanding of beam adjustment conditions. Furthermore, it features a high-speed information search function using multiple keywords. In the event of a failure, past similar cases can be quickly retrieved to reference the appropriate countermeasures. In the future, integration with business chat tools such as Mattermost will be enhanced, and additional features will be implemented to further improve operational efficiency.



(a) Summary information. (b) Detailed information.

Figure 3: Snapshot of the Linac operation electronic logbook system based on web application.

CONCLUSION

At the KEK electron/positron injector Linac, simultaneous top-up injection into four independent storage rings and a positron damping ring has been carried out since May 2019. This complex operational scheme is supported by a robust control system based on the EPICS framework. Essential operational software such as the Data Archiver, alarm system, parameter management tools, and various feedback systems have already been established. AI/ML-based beam tuning software has also been implemented to support day-to-day beam operation [26, 27]. In future work, analysis tools will be developed to rapidly identify the causes of beam quality degradation. In addition, migration from aging infrastructure such as VME to high-bandwidth bus systems like MicroTCA is under consideration.

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 Sept. 2nd, 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, 2022, pp.2914-2916.

[4] 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, 2021, 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 (2019).

[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. 31-Aug. 3, 2024, pp.608-612.

[9] Z. Xiangyu *et al.*, “TEMPORAL RESHAPING OF LASERS THROUGH THE COHERENT PULSE STACKING TECHNIQUE IN THE SuperKEKB ELECTRON/POSITRON INJECTOR”, in *Proc*. PASJ2024, Yamagata, Japan, Jul. 31-Aug. 3, 2024, pp.399-402.

[10] T. Natsui *et al.*, “DESIGN OF THE GUN AND THE MAGNET FOR S-BAND 80 MW MULTI-BEAM PULSED KLYSTRON”, in *Proc*. PASJ2024, Yamagata, Japan, Jul. 31-Aug. 3, 2024, pp.605-607.

[11]N. Iida *et al.*, “INVESTIGATION OF EMITTANCE BLOWUP IN THE POSITRON BEAM TRANSPORT LINE FOR THE SuperKEKB”, PASJ2024, Yamagata, Japan, Jul. 31-Aug. 3, 2024, pp.616-620.

[12] K. Uemura *et al.*, “ESTIMATION OF CRITICAL PARAMETERS FOR THE KEK ELECTRON/POSITRON INJECTOR LINAC TUNING USING EXPLAINABLE AI ALGORITHM”, in *Proc*. PASJ2024, Yamagata, Japan, Jul. 31-Aug. 3, 2024, pp.637-642.

[13] T. Toufuku *et al.*, “OPERATION STATUS OF RF SYSTEM IN KEK ELECTRON-POSITRON

LINAC(FY2023)”, in *Proc*. PASJ2024, Yamagata, Japan, Jul. 31-Aug. 3, 2024, pp.770-773.

[14] S. Ushimoto *et al*., “STATUS OF SLED TUNING AT KEK ELECTRON-POSITON LINAC”, in *Proc*. PASJ2024, Yamagata, Japan, Jul. 31-Aug. 3, 2024, pp.777-780.

[15] F. Miyahara *et al*., “CURRENT STATUS AND PERFORMANCE EVALUATION OF THE POSITRON GENERATION OF KEK INJECTOR LINAC”, in *Proc*. PASJ2024, Yamagata, Japan, Jul. 31-Aug. 3, 2024, pp.831-834.

[16] K. Furukawa *et al*., “ANALYSIS OF OPERATIONAL STATISTICS AT KEK INJECTOR LINAC”, in *Proc*. PASJ2024, Yamagata, Japan, Jul. 31-Aug. 3, 2024, pp.907-911.

[17] S. Kusano *et al*., “DEVELOPMENT OF GigE CAMERA CONTROLLER USING RASPBERRY PI”, in *Proc*. PASJ2024, Yamagata, Japan, Jul. 31-Aug. 3, 2024, pp.943-945.

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

[19] K. Furukawa *et al*., “Pulse-to-pulse Beam Modulation and Event-based Beam Feedback Systems at KEKB Linac”, in *Proc*. IPAC’10, Kyoto, Japan, May 23-28, 2010, pp.1271-1273.

[20] Itsuka Satake *et al*., “Introduction of network monitoring system using Grafana in the KEK electron/positron injector linac”, in *Proc*. PASJ2022, Online (Kyushu University), October 18-21, 2022, pp.305-308.

[21] Y. Yano *et al*., “RF CONTROL SYSTEM FOR SUPERKEKB INJECTOR LINAC”, in *Proc*. PASJ2014, Aomori, Japan, August 9-11, 2014, pp.624-628.

[22] http://controlsystemstudio.org/ (accessed Sep. 3rd, 2025).

[23] Itsuka Satake *et al*., “Introduction of Archiver Appliance in KEK electron positron injector linac”, in *Proc*. PASJ2019, Kyoto, Japan, July 31-August 3, 2019, pp.861-864.

[24] Itsuka Satake *et al*., "Operation status of Archiver Appliance in KEK electron positron injector linac", in *Proc*. PASJ2020, , Online (Kyushu University), September 2-4, 2020, pp.735-738.

[25] https://pypi.org/project/PythonCA/ (accessed Sep. 3rd, 2025).

[26] Gaku Mitsuka *et al.*, " Machine-learning approach for operating electron beam at KEK electron/positron injector linac", *Phys. Rev. Accel. Beams 27, 084601*, https://doi.org/10.1103/PhysRevAccelBeams.27.084601 (accessed Sept. 5th, 2025).

[27] T. Natsui *et al*., “UPGRADE OF KEK ELECTRON/POSITRON INJECTOR LINAC USING PULSED MAGNETS AND MACHINE LEARNING”, in *Proc*. IPAC’25, Taipei, Taiwan, June 1-6, 2025, pp.1622-1626.