Design and Implementation of EPICS-based Proton Accelerator Interlock Protection System

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Abstract

To ensure operational safety and controllability of proton accelerators, a distributed control system based on EPICS was designed to address the limitations of traditional centralized control systems in real-time performance and scalability. The system employs Phoenix Contact AXC3050 series Programmable Logic Controllers (PLCs) for interlock protection of vacuum and water cooling systems, and utilizes Siemens PLC S7-1511-1 together with V90PN servo drives to achieve stable motion control of motors. Both PLC systems can interconnect underlying module data via PROFINET fieldbus and enable network publication of PV data to the upper-level EPICS system, thereby enabling real-time monitoring of critical parameters including accelerator vacuum level, cooling water temperature/flow rate, and power supply status, as well as remote control of motion control components. The interlock protection logic is executed autonomously by the local PLC, capable of triggering multi-level protection mechanisms within 10 ms, effectively preventing equipment damage and safety incidents. Test results demonstrate that the system has achieved remote network monitoring of 216 water temperature channels and 100 flow rate channels, with interlock protection response times of less than 10 ms. The system has been successfully applied in proton accelerator beam commissioning experiments, providing reliable technical assurance for safe operation of high-power accelerators.

Full Text

Design and Implementation of an EPICS-Based Interlock Protection System for Proton Accelerators

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Abstract

To ensure the safety and controllability of proton accelerator operations, this paper presents the design of a distributed control system based on EPICS to address the limitations of traditional centralized control systems in terms of real-time performance and scalability. The system employs Phoenix AXC3050 series programmable logic controllers (PLCs) for interlock protection of vacuum and water cooling systems, and utilizes Siemens PLC S7-1511-1 combined with V90PN servo drives to achieve stable motion control of motors. Both PLC systems enable data interconnection among underlying modules and network publication of PV data to the upper-layer EPICS system via PROFINET fieldbus, thereby enabling real-time monitoring of critical parameters such as accelerator vacuum, cooling water temperature/flow rate, and power supply status, as well as remote control of motion control components. The interlock protection logic is executed autonomously by local PLCs, capable of triggering multi-level protection mechanisms within 10 ms to effectively prevent equipment damage and safety accidents. Test results demonstrate that the system has achieved remote network monitoring of 216 temperature channels and 100 flow channels, with interlock protection response times under 10 ms. The system has been successfully deployed in proton accelerator beam commissioning experiments, providing reliable technical support for the safe operation of high-power accelerators.

Keywords: Proton accelerator; Interlock protection system; EPICS; PLC; High reliability

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Introduction

Proton accelerators serve as essential experimental facilities widely employed in fundamental physics research, nuclear medicine, materials science, and industrial applications. By generating high-energy proton beams, they provide powerful tools for investigating microscopic material structures, exploring cosmic origins, and developing novel materials. However, accelerator control environments are highly complex, involving vast numbers of physical devices across multiple subsystems including power supply control, vacuum control, beam position monitoring (BPM), and low-level radio frequency (LLRF) systems. Consequently, designing an efficient and reliable accelerator control system is crucial for ensuring safe operation.

In recent years, major accelerator laboratories worldwide have made significant progress in control system design and application. For instance, CERN's Large Hadron Collider (LHC) employs sophisticated interlock protection systems to address potential risks from high-energy beams [?]. Additionally, the Shanghai Synchrotron Radiation Facility (SSRF) linear accelerator has successfully implemented PLC- and EPICS-based interlock protection systems [?]. These studies demonstrate the vital role of interlock protection systems in safeguarding accelerator operations. However, traditional centralized control systems suffer from inherent limitations in real-time performance, scalability, and reliability: centralized architectures easily become performance bottlenecks, system response times are constrained, and increasing device counts significantly raise system load. Moreover, failure of the central node can cause complete system paralysis. To address these challenges, distributed control architectures have been widely adopted. By introducing local processing units and intelligent devices in each subsystem, distributed architectures significantly enhance real-time response capabilities and fault tolerance while enabling more flexible and efficient system expansion to meet the complex and evolving operational demands of large-scale accelerators.

During proton accelerator operation, control systems must provide several critical functions: real-time monitoring of key equipment status parameters (vacuum, cooling water temperature/flow, power supply voltage, etc.) to ensure controllable and stable operation; rapid triggering of protection mechanisms upon detecting anomalies, such as beam cutoff or equipment shutdown, to prevent damage or safety incidents; and fault logging and alarm functions to facilitate timely operator detection and handling. Furthermore, as accelerator technology continues to evolve, control systems must exhibit high reliability and flexibility to accommodate diverse operational modes and experimental requirements.

This paper proposes a distributed control system for proton accelerators that integrates PLC and PROFINET fieldbus technology with the EPICS software architecture to achieve real-time online monitoring, precise control, and rapid protection of critical accelerator equipment. The design introduces a hierarchical EPICS architecture deeply integrated with PLCs, significantly improving system response speed and management efficiency through optimized coordination between low-level control and high-level monitoring. The communication network employs redundant PROFINET bus and industrial Ethernet designs to enhance real-time data transmission and anti-interference capability, ensuring stable operation in complex electromagnetic environments. To meet stringent safety requirements, the system implements multi-level interlock protection logic executed autonomously by PLC hardware, achieving critical protection action response times within 10 ms. Through optimized hardware selection, communication protocols, and software logic, the system not only satisfies accelerator safety requirements but also provides operators with intuitive monitoring and management capabilities, improving overall operational efficiency and stability.

1. Overall Architecture Design

The proton accelerator's operating environment is extremely complex, involving high voltage, strong magnetic fields, and high-power beam [?]. Thermal losses from beam power can easily cause cavity detuning, while vacuum leaks and cooling system failures may lead to severe equipment damage or irreversible consequences. Consequently, accelerator equipment faces extremely high safety and reliability requirements. As the core component ensuring safe accelerator operation, the interlock protection system must provide real-time monitoring of critical parameters and rapid triggering of protection mechanisms under abnormal conditions.

Traditional centralized control systems exhibit limitations in real-time performance and scalability, making them ill-suited for large-scale complex systems requiring high-speed response and flexible deployment. Centralized architectures typically rely on a single central processing unit, where increasing device counts rapidly escalate communication load and processing pressure, causing system response delays, high expansion costs, and single-point-of-failure risks. In contrast, distributed control architectures achieve flexible expansion and independent deployment of system functions through modular design that distributes control tasks across subsystems and local control units, significantly reducing performance bottlenecks from scale expansion.

Therefore, this system adopts a hierarchical EPICS architecture (Figure 1 [Figure 1: see original paper]), combining PLCs' reliable, high-performance processing capabilities with PROFINET fieldbus's efficient communication characteristics to construct an integrated interlock protection system for real-time monitoring, fault diagnosis, precise control, and rapid response. The system is divided into three layers: Operator Interface (OPI), Input/Output Controller (IOC), and device control layer [?], with specific designs as follows:

OPI Layer: Developed using CSS (Control System Studio) to provide human-machine interfaces for equipment status visualization, parameter setting, and historical data query.

IOC Layer: Communicates with underlying PLCs via the Channel Access (CA) protocol, integrating multi-source data and publishing them as Process Variables (PVs) to ensure efficient data management and interaction.

Device Layer: PLCs handle sensor signal acquisition and interlock logic processing. Based on multi-core CPU architecture and hard real-time operating systems, PLCs enable high-speed parallel execution and deterministic response of interlock logic, providing powerful real-time performance guarantees for critical accelerator protection logic. PROFINET bus achieves millisecond-level communication between PLCs and I/O modules, frequency converters, and other devices. MOXA NPort serial servers enable remote control and management of devices with RS232, RS485, and other digital communication interfaces, enhancing system compatibility and flexibility.

2. System Hardware Design

The distributed monitoring and protection system for the proton accelerator controls equipment including needle valve motors, water chillers, vacuum gauges, pump valves, solid-state power sources, and magnet power supplies. The system selects Phoenix AXC3050 PLCs, whose cycle time advantages stem from high-performance multi-core CPU architecture, hard real-time operating systems, and deeply optimized industrial network protocols, making them significantly superior to traditional PLCs in high-speed, high-precision, and complex multi-tasking scenarios [?]. Integrating PLCs into the EPICS framework enables unified management of I/O hardware devices.

PLCs are responsible for acquiring signals from input modules, performing logical operations, and sending control instructions to output modules to drive actuator operation. For the ion source needle valve gas inlet system, the system employs SIMATIC S7-1511-1 PN controllers, SINAMICS V90 PN drives, and SIMOTICS S-1FL6 servo motors. The controller receives external input signals and generates precise control commands, the drive adjusts internal current and voltage outputs according to these commands to drive the servo motor, and the servo motor converts electrical energy into mechanical energy through electromagnetic action to achieve precise rotational motion, thereby controlling needle valve opening. To improve the dynamic response and stability of the gas inlet system, the system introduces a high-precision PID closed-loop regulation algorithm based on servo control. By real-time acquisition of flow feedback signals and dynamic adjustment of servo motor position commands, the system effectively suppresses gas flow fluctuations during operation, achieving high-precision stable gas flow control and providing reliable guarantee for stable ion source discharge.

In terms of software architecture, the OPI layer is developed based on CS-Studio running in Windows environment to achieve human-machine interaction interfaces with intuitive monitoring and operation functions. The IOC layer's EPICS Base software package runs on Ubuntu 22.04, implementing data recording and processing by calling underlying hardware drivers (such as TCP/IP protocol drivers for PLC communication modules). The overall system architecture is shown in Figure 2 [Figure 2: see original paper]. This solution fully combines the advantages of high-performance PLCs, real-time bus communication, and EPICS architecture to achieve precise control and efficient management of critical accelerator equipment, ensuring system safety, reliability, and scalability.

The control network architecture adopts a redundant network design integrating PROFINET and industrial Ethernet [?] to ensure high communication reliability and efficiency. At the backbone network layer, H3C S5130 switches construct a hierarchical tree topology supporting link redundancy, effectively enhancing network communication stability and reliability to establish a solid communication foundation for efficient system operation. At the field layer, Phoenix AXC3050 PLCs connect to remote I/O stations via PROFINET bus with a cycle time of only 4 ms, representing a 50% improvement in communication speed compared to traditional bus technologies and significantly enhancing system real-time performance and response capability to meet field devices' rapid control requirements. For sensor interfaces, the system configures access modules for 100 flow channels, 216 temperature channels, and 14 vacuum signals, all using Phoenix AXL F series modules. Analog signals connect through AXL F AI8 analog input modules, while digital signals are acquired by AXL F DI16 modules. These modules feature optical isolation and surge protection, effectively enhancing system anti-interference capability and stability to ensure accurate sensor signal transmission and safe equipment operation. This architecture fully leverages PROFINET's high-speed communication advantages and industrial Ethernet's flexibility to achieve an efficient and stable control network, providing strong support for safe and reliable proton accelerator operation.

3.1 Interlock Protection System Design

In the proton accelerator's distributed monitoring and protection system, primary interlock triggers include cooling water temperature, vacuum level, cooling water flow rate, power supply voltage, cavity patch temperature, and core equipment operational status. Accelerator normal operation imposes strict requirements on high reliability and stability of all components. Frequency deviation caused by power detuning can significantly impact overall accelerator operation [**?**] and even cause cavity damage, making frequency stability a critical factor for ensuring continuous normal operation and imposing higher demands on interlock protection system stability and response speed.

To ensure stable and reliable interlock system operation and achieve rapid response during faults, the system employs control methods independent of upper-layer software, with all logic executed autonomously by PLCs to improve response speed and system independence. PLC logic control functions consist of three main components:

Interlock Input Processing: High-speed acquisition modules real-time read sensor signals and equipment status, employing filtering and threshold discrimination mechanisms to eliminate abnormal pulses and noise signals, ensuring acquisition data accuracy and stability.

Interlock Condition Judgment and Calculation: Processed signals undergo comprehensive analysis based on preset safety thresholds and logical rules. The system introduces hierarchical multi-level protection strategies: abnormal conditions are prioritized—when critical indicators show anomalies (e.g., sudden cooling water flow drop, vacuum deterioration), the system prioritizes fast beam cutoff commands; for general faults, a latching mechanism records fault sources and maintains fault status until manual reset, preventing secondary risks from accidental fault clearance.

Interlock Output Processing: When interlock trigger conditions are met, PLCs immediately execute protection actions including beam cutoff, equipment shutdown, high-voltage power supply cutoff, or multi-level alarm signals, with redundant verification mechanisms ensuring reliable and timely command execution.

3.1.1 Interlock Signal Analysis After connecting the proton accelerator with the interlock protection system, interlock signals can be categorized into two types based on function and purpose: interlock fault input signals that monitor and receive abnormal conditions from various system parts to trigger corresponding protection mechanisms upon fault detection, and interlock control output signals that send commands to controlled equipment to ensure necessary safety measures during interlock states, thereby guaranteeing safe and stable system operation. Table 1 shows the connected equipment, signal quantities, and types involved in the interlock system.

3.1.2 Interlock Signal Processing Flow When interlock input signals indicate fault status, the interlock protection system adopts corresponding protection measures according to preset logical procedures and outputs corresponding interlock protection signals [**?**]. The interlock protection system can only be reset after operators confirm fault-free conditions. Even when interlock input signals return to normal, operators must verify system status before interlock release. Interlock protection output signals have two distinct states:

Enable: When interlock is released, this state allows target equipment to resume normal operation, equivalent to removing equipment restrictions so devices can continue executing predetermined functions.

Disable: In this state, certain functions of target equipment are restricted or stopped to ensure devices do not execute potentially risky or unsafe operations under specific conditions.

The interlock signal processing flow is shown in Figure 3 [Figure 3: see original paper]. In bypass mode, interlock input signal responses can be temporarily masked during system debugging without affecting overall interlock functionality, ensuring normal debugging and testing. Input signals are first processed through PLC DC optical isolation modules before reception by input modules. Output signal control is handled by PLC relay output modules. Output signal closure typically indicates normal equipment operation, while disconnection triggers alarm mechanisms. Throughout this process, PLC internal status registers play a crucial role in real-time monitoring whether interlock protection operations have been executed, ensuring response times remain within 10 ms for fast and reliable interlock protection.

3.1.3 IOC Program Design IOC is a critical component in EPICS systems, responsible for connecting computers with various experimental devices, instruments, or industrial control systems to implement read/write operations, data acquisition, and automated control. Through IOC, users can conveniently monitor and control experimental equipment or industrial processes [**?**].

In TCP/IP protocol-based communication between IOC and PLC, transmission messages adopt fixed-length data structures. Bidirectional communication links (uplink/downlink) allow definition of differentiated message lengths. Transmission variables undergo binary packaging according to pre-configured sequences, with each data element achieving byte-level positioning accuracy through address offsets to ensure correct data reading and parsing. EPICS-supported Process Variables (PVs) are compatible with multiple data types, and byte order supports adaptive adjustment (big-endian/little-endian). In the startup IOC script file, driver configuration requires the following command: `phoenixplcConfigure (PLCname, IPaddr, port, inSize, outSize, bigEndian, recvTimeout, sendInterval, redundancy)`

3.1.4 Upper-Layer User Interface Figure 4 [Figure 4: see original paper] shows the upper-layer user interface of the proton accelerator interlock protection system, enabling operators to real-time monitor interlock signals, on-site parameters, and critical controlled device operation status to ensure system safety and stability. When the system detects any interlock signal such as power source failure, chiller anomalies, vacuum or water cooling system failures, the protection mechanism responds according to preset procedures [**?**]. First, the system triggers high-voltage protection mode for the Chopper beam cutoff power supply, then sequentially executes multi-level interlock measures including reducing ion source high voltage to safe thresholds, cutting off power source and microwave generator energy output, and driving the Faraday cup into the beam transport path. Through this rigorous and efficient response sequence, the system can reliably cut off beam within 50 ms, ensuring safe operation of the accelerator body and auxiliary systems.

3.2 Needle Valve Inlet System The ion source needle valve system requires micrometer-precision gas flow needle valve displacement adjustment. SIMOTICS S-1FL6 servo motors equipped with high-resolution encoders (such as multi-turn absolute encoders) provide $±$0.01 mm repeat positioning accuracy. Combined with V90 PN drive's internal position control mode (EPOS), the system can adjust valve opening through preset program steps or Modbus real-time commands, ensuring gas flow stability and high process repeatability to effectively avoid ion source instability caused by gas fluctuations.

3.2.1 PLC Program Design PLC programs are designed based on TIA Portal V18. This paper adopts function block diagram programming, implementing a TCP/IP protocol-based communication architecture through EPICS communication modules. The PLC is configured as server while IOC acts as client, with data exchange conducted through PLC IP address and port numbers. First, PLC components require configuration, including detailed hardware module setup such as CPU, communication modules, and I/O modules to meet specific control requirements. Additionally, process object configuration is needed to implement needle valve motor motion control.

PLC programs are developed using TIA Portal V18 software with LAD function block language, achieving modular design. The entire program structure is clear and consists of several core components: defining basic parameters and function blocks for needle valve control, implementing specific needle valve control logic, and converting engineering quantities for motor speed and valve opening. For data communication, integration with EPICS systems is achieved using the _ _ library. This integration scheme provides a solid foundation for system reliability and stable operation. The partial PLC program flowchart for the needle valve inlet system is shown in Figure 5 [Figure 5: see original paper].

3.2.2 IOC Program Design The IOC (Input/Output Controller) for the needle valve inlet system includes designing and building a real-time operational database for storing and managing dynamic system data, as well as developing device adaptation and driver programs for Siemens PLC network communication modules. Based on the EPICS framework, the system constructs a distributed real-time database achieving millisecond-level acquisition and dynamic storage of process parameters such as needle valve position and gas flow. Meanwhile, Channel Access protocol ensures efficient and stable communication with upper-layer monitoring systems (such as CSS/EDM).

In Linux environment, the system deploys EPICS base 3.14.15.2 development platform and integrates S7nodave driver module to achieve PROFINET communication with S7-1511-1 PLC. By configuring TSAP addresses to establish mapping relationships with PLC data blocks, the system supports real-time read/write of DB block data, ensuring efficient and precise control capability.

S7nodave devices support direct reading and writing of PLC memory addresses, with device address fields INP and OUT specifying PLC device addresses recognized by S7nodave [**?**]. In the makefile file under the application source code directory, S7nodave library and DBD files must be added to ensure correct loading of S7nodave device support modules: `example_{DBD} += s7nodave.Dbd`. Additionally, in the IOC program's st.cmd file, system DB blocks and related commands must be added to achieve efficient access and control of PLC data, ensuring real-time and stable data interaction.

3.2.3 User Upper-Layer Interface Figure 6 [Figure 6: see original paper] shows the human-machine interface of the proton accelerator needle valve control system, used for real-time monitoring of needle valve position and operation status while supporting precise adjustment of valve opening to control ion source inlet gas flow. The PID controller formula describes the relationship between needle valve opening setpoint and actual position feedback: $u(t) = K_p e(t) + K_i \int e(\tau) d\tau + K_d \frac{de(t)}{dt}$. Through this interface, operators can intuitively view current valve opening, target setpoint, inlet gas flow, and related system parameters to ensure gas supply stability. Users can input setpoints through the interactive interface, and the system automatically adjusts the needle valve to target opening based on high-precision servo control and real-time feedback mechanisms to meet process requirements. The interface also provides functions such as historical data query, alarm prompts, and remote control, supporting dynamic monitoring of critical parameters and abnormal handling to ensure efficient and stable ion source operation.

4. Main Performance Testing

The system can remotely monitor and record temperature and flow data of proton accelerator cavity water circuits, automatically activating interlock protection mechanisms during faults to ensure equipment safety. This design not only meets high-reliability control requirements during stable operation and commissioning of proton accelerators but also ensures timely protective measures during anomalies to prevent system failures from affecting normal accelerator operation. During beam commissioning, the two curves in Figure 7 [Figure 7: see original paper] respectively show monitored temperature and flow data for a cooling water circuit of the proton accelerator. Through high-precision temperature control systems (such as PID closed-loop control modules [**?**]), temperature control accuracy reaches approximately 0.1°C, ensuring water circuit temperature remains at optimal operating conditions. Meanwhile, flow fluctuation is controlled within 0.4 L/min, guaranteeing stable cooling effects and providing reliable support for efficient accelerator operation.

Figure 8 [Figure 8: see original paper] shows the response of interlock protection action output signals during reliability testing of the interlock system. Interlock protection signals can be rapidly triggered when accelerator operation faults occur, ensuring timely system response and implementation of corresponding protective measures.

In ion source systems, needle valve opening directly determines gas flow into the discharge chamber, and gas flow variations significantly affect plasma density, thereby influencing final beam intensity. When needle valve opening increases, gas flow rises, plasma density in the discharge chamber increases, and ion source beam intensity strengthens accordingly.

During needle valve control, proper opening range setting is crucial to ensure gas flow remains at optimal operating points for stable beam output [**?**]. Through long-term testing and operation, the ion source inlet control based on PLC and servo systems has proven stable and reliable, supporting entire device commissioning and achieving 0.1° positioning accuracy. Testing verified the relationship between needle valve motor opening and gas flow/beam intensity. Results show that within 20%-80% opening range, system response is relatively linear and suitable for conventional control. In non-linear regions (<20% or >80%), flow and beam intensity changes become complex, requiring compensation control strategies to optimize beam stability. Additionally, experiments analyzed vacuum fluctuation effects on system stability, providing critical data support for subsequent optimization. The stable and reliable ion source inlet control is shown in Figure 9 [Figure 9: see original paper].

The distributed monitoring and protection system for proton accelerators designed in this paper, based on EPICS software architecture combined with PLC and PROFINET fieldbus technology, achieves real-time monitoring and rapid interlock protection of critical accelerator equipment. The system features high response speed, high measurement accuracy, and good stability, effectively ensuring safe accelerator operation and providing reliable technical support for high-energy physics research. Future work will further optimize system structure and control performance, such as sharing the same PROFINET controller for interlock protection and motors, adding closed-loop automatic control between beam intensity and needle valve, and exploring application potential in more complex environments.

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Abstract: To ensure the safety and controllability of proton accelerator operation, a distributed control system based on EPICS was designed to address the shortcomings of traditional centralized control systems in real-time performance and scalability. The system uses Phoenix AXC3050 series programmable logic controllers (PLC) for interlock protection of vacuum and water cooling systems, and employs Siemens PLC S7-1511-1 and V90PN servo drives to achieve stable motion control of motors. Both PLC systems can realize data interconnection of underlying modules and network release of PV data from the upper EPICS system through PROFINET fieldbus, thereby enabling real-time monitoring of key parameters such as accelerator vacuum, cooling water temperature/flow, and power supply status, as well as remote control of motion control components. The interlock protection logic is autonomously executed by the local PLC, capable of triggering multi-level protection mechanisms within 10 ms, effectively avoiding equipment damage and safety accidents. Test results show that the system has achieved remote network monitoring of 216 water temperature channels and 100 flow channels, with interlock protection response time less than 10 ms. The system has been successfully applied in proton accelerator beam tuning experiments, providing reliable technical support for the safe operation of high-power accelerators.

Keywords: Proton accelerator; Interlock protection system; EPICS; PLC; High reliability

Note: Figure translations are in progress. See original paper for figures.