Design and Implementation of the Main Vacuum Control System for the Hefei Domestic Superconducting Proton Cyclotron

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Abstract

The superconducting proton cyclotron is one of the most advanced medical radiotherapy devices independently developed in China. As a critical subsystem of the accelerator, the vacuum system provides the necessary operating environment for particle acceleration. This study aims to design a vacuum control system for the accelerator to maintain a stable high-vacuum environment. Based on the vacuum design requirements of the accelerator, this paper presents the design of the vacuum control system utilizing a Siemens Programmable Logic Controller (PLC) hardware system and the Experimental Physics and Industrial Control System (EPICS) software framework. The design encompasses the overall architecture of the control system, system operation logic, user interface design, and safety interlocks, among other aspects. The results demonstrate that during long-term operation, the system can maintain a high vacuum level in the vacuum system, with control performance and stability meeting the design requirements, thereby ensuring the stable operation of the accelerator.

Full Text

Design and Implementation of the Main Vacuum Control System for the Domestic Superconducting Proton Cyclotron in Hefei

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Abstract

The superconducting proton synchrotron is one of the most advanced domestically developed medical radiation therapy devices in China. As a crucial subsystem of the accelerator, the vacuum system provides the necessary operational environment for particle acceleration. This study aims to design the vacuum control system for the accelerator to maintain a stable high vacuum environment. Based on the vacuum design requirements of the accelerator, the design of the vacuum control system was accomplished using Siemens Programmable Logic Controller (PLC) hardware and the Experimental Physics and Industrial Control System (EPICS) software framework. The content includes the overall structure of the control system, system operational logic, user interface design, and safety interlocks. The results indicate that, during long-term operation, the system maintains a high vacuum level, and the control performance and stability meet the design requirements, ensuring the stable operation of the accelerator.

Keywords: Proton accelerator, vacuum control system, EPICS, monitoring interface, safety interlock
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Introduction

The therapy system cyclotron was officially installed at the Domestic Superconducting Proton Clinical Medical Verification Center (Hefei Ion Medical Center Phase II). The accelerator control system comprises multiple subsystems, including the superconducting magnet system, ion source system, and vacuum system. As one of the controlled systems of the accelerator, the primary task of the vacuum system is to maintain a high-vacuum environment in the acceleration cavity by monitoring and controlling vacuum equipment to achieve the preset vacuum level and reduce interference from gas molecules on the proton beam [5]. However, the vacuum control system for proton cyclotrons faces several challenges and difficulties. The control system must possess high reliability and safety to ensure long-term stable operation while maintaining high vacuum levels. The vacuum system requires the control system to monitor, control, and process data from multiple devices. Simultaneously, the control system must be tightly integrated with other accelerator subsystems to achieve coordinated and optimized overall operation.

This paper aims to conduct an in-depth study and analysis of the vacuum control system for the 240 MeV superconducting proton cyclotron developed by Hefei Zhongke Ion Medical Technology Equipment Co., Ltd., and to design and implement a highly reliable vacuum control system. The main contributions and innovations can be summarized as follows:

First, for the design of the vacuum control system, this paper adopts a distributed control architecture based on Programmable Logic Controllers (PLC) combined with the Experimental Physics and Industrial Control System (EPICS) software framework. From both hardware structure and software process perspectives, a complete vacuum control system has been constructed. This system achieves comprehensive monitoring and flexible control of the accelerator vacuum system, providing solid technical support for efficient operation.

Second, the paper clearly defines the operational logic of the accelerator vacuum system, including switching between automatic and manual modes, as well as the execution of startup, operation, shutdown, and venting processes. This design ensures efficient and stable operation of the vacuum system under different working conditions, making system operation more flexible and controllable.

Third, this paper innovatively designs the information exchange and control coordination between the vacuum control system and the safety interlock system. By setting threshold, alarm, and command interface signals, safe operation of the vacuum system under both normal and abnormal conditions is achieved. This safety interlock mechanism effectively prevents risks such as vacuum leaks, equipment damage, and personnel injury, enhancing overall system safety.

Finally, to verify the performance and reliability of the vacuum control system, system testing and validation were conducted. Through leak rate detection, execution logic testing, and long-term operational stability testing of the vacuum system, the system's excellent performance was successfully verified, ensuring it meets the requirements of the high-vacuum environment for proton cyclotrons. This series of work provides strong theoretical and practical support for research and application in the field of accelerator vacuum systems.

2 Vacuum System Overview

The vacuum system is used to maintain a high-vacuum environment in the acceleration cavity to reduce interference from gas molecules on the beam. Based on the accelerator's performance requirements, parameters such as minimum pressure, maximum leak rate, and maximum gas load for each component are specified, as shown in Table 1 . The vacuum system must also possess reliability, safety, and controllability, enabling long-term stable operation through remote operation and equipment safety interlocks.

According to system requirements and functions, vacuum equipment selection considered factors such as gas load, pumping time, conductance, pumping speed, and leak rate [6,7]. The following vacuum equipment was selected: mechanical pumps, Roots pumps, turbomolecular pumps, cryopumps, angle valves, gate valves, vacuum measurement instruments, etc. These devices provide functions including high-efficiency pumping, volume compression, volume variation, valve control, pressure measurement, and gas analysis. A Roots pump unit is used as the forepump, turbomolecular and cryopumps as high-vacuum pumps, pneumatic gate valves control the connection between the pumping system and the acceleration cavity, and vacuum gauges monitor the vacuum level inside the acceleration cavity.

3 Control System Structure

The vacuum control adopts a distributed control architecture based on Programmable Logic Controllers (PLC). Figure 1 [Figure 1: see original paper] illustrates the overall structural design of the vacuum control system. The core of the hardware structure employs Siemens PLC1500, which features high performance, high reliability, and high safety characteristics [8-10]. The PLC communicates with the host computer system via the OPC UA protocol to implement data reading/writing and command reception. The PLC1500 serves as a local controller, responsible for receiving and processing signals from various vacuum equipment to achieve monitoring and control of the accelerator vacuum system. The PLC controls mechanical pump sets, gate valves, and pneumatic angle valves to realize equipment start/stop and valve switching operations. Simultaneously, through the RS485 communication network, the PLC exchanges data with turbomolecular pumps, cryopumps, and vacuum gauges to achieve data extraction and control. To ensure communication accuracy between vacuum equipment and the PLC controller, MOXA Nport5430 devices are used to convert RS485 communication to Ethernet access. Additionally, it is necessary to ensure that the three NPort5430 Ethernet ports share the same network segment as the PLC PROFINET module, unifying all RS485 and RS232 communications.

The software architecture of the control system is built upon the EPICS software framework, which is the mainstream software toolkit for control systems of large scientific facilities such as particle accelerators. Under this architecture, the entire control system employs industrial Ethernet as the backbone network, with all distributed PLC stations accessing the network through PROFINET interfaces, thereby ensuring efficient and stable system communication [11]. The system utilizes the EPICS software architecture to implement data processing functions for the vacuum control system. EPICS IOC (Input/Output Controller) and CSS (Control System Studio) technologies are employed to achieve communication with the PLC and transmit operation commands. EPICS IOC is a software component for communicating with hardware devices, encompassing device drivers, databases, records, and scan engines. Configuring the IOC requires first defining the communication protocol (RS485) and addresses for devices such as turbomolecular pumps and cryopumps; the vacuum gauge communication protocol is TCP/IP with an address of 192.168.*.**. Subsequently, device driver programs are written to enable data exchange and control command transmission with the equipment. Further, database files are written to define device record types, fields, attributes, and initial values. Finally, startup scripts are written to load device drivers and database files and initiate the IOC service.

4 System Design

4.1 User Interface Design

The user interface employs EPICS configuration software as the development tool, combined with Phoebus and CSS technologies to customize and optimize the monitoring interface. Phoebus is utilized to process real-time data, operational status, and alarm information from the vacuum system, displaying them on the monitoring interface in an intuitive and readable manner. CSS defines styles and layouts, making the interface more aesthetically pleasing, readable, and consistent, while providing operation commands and feedback information to facilitate system operation and troubleshooting for users.

Figure 2 [Figure 2: see original paper] shows the human-machine interaction interface of the vacuum control system, used for controlling vacuum equipment and displaying device status. In the top-left menu bar, users can select different operation modes (automatic or manual) and view system information and help documentation. In the top-right toolbar, functions such as user permissions, parameters, alarms, and logging can be configured. In the left navigation bar, users can switch between monitoring interfaces for different vacuum equipment, such as mechanical pumps, turbomolecular pumps, and cryopumps. In the right main interface, users can view and control vacuum equipment working status, pressure values, switch commands, and other information.

The system features the following functions: (1) Vacuum monitoring: collects vacuum level data through vacuum gauges and displays and records it via computer; (2) Vacuum regulation: by setting target vacuum levels, the vacuum control system automatically adjusts vacuum pump and valve switching to achieve the target vacuum; (3) Vacuum protection: by setting protection ranges, the vacuum control system automatically shuts down vacuum pumps and opens atmospheric valves when vacuum levels exceed the range, protecting equipment and samples; (4) Vacuum alarming: by setting alarm ranges, the vacuum control system issues audible and visual alarms when vacuum levels exceed the range, alerting operators; (5) Vacuum recording: by setting recording intervals, the vacuum control system periodically records vacuum level data and saves it on the computer; (6) Vacuum management: by setting user permissions, users at different levels can perform different operations such as viewing, modifying, and deleting.

4.2 System Control Logic

The vacuum control system has two operation modes: automatic mode and manual mode. In automatic mode (as shown in Figure 3 [Figure 3: see original paper]), the PLC automatically executes startup, operation, shutdown, and venting processes according to preset thresholds and sequences without manual intervention. In manual mode, the PLC performs corresponding equipment switching operations based on commands sent by users through the host computer or local controller, requiring manual intervention.

The vacuum control system has four operational processes: startup process, operation process, shutdown process, and venting process. The startup process refers to the procedure from when the accelerator vacuum level is greater than 1000 Pa until it falls below the cryopump activation threshold, mainly including equipment self-check, and starting mechanical pump sets, Roots pump sets, turbomolecular pump sets, and cryopump sets. The operation process refers to maintaining a stable vacuum environment in the acceleration cavity during normal accelerator operation, mainly including monitoring equipment status, processing alarm information, and switching operation modes. The shutdown process refers to the procedure from when the accelerator stops operating until the vacuum level exceeds 1000 Pa, mainly including closing gate valves, turbomolecular pump sets, Roots pump sets, and mechanical pump sets. The venting process refers to the procedure of increasing pressure in the acceleration cavity after accelerator shutdown for maintenance or component replacement, mainly including opening nitrogen valves and pneumatic angle valves.

4.3 Safety Interlock

The safety interlock mechanism refers to the information exchange and control coordination implemented between the VCS (Vacuum Control System) and SIS (Safety Interlock System) through hardware cables and software protocols. Its function is to coordinate the operational status of various subsystems, ensuring safe operation of the VCS system under both normal and abnormal conditions, and avoiding risks such as vacuum leaks, equipment damage, and personnel injury, as shown in Figure 4 [Figure 4: see original paper].

Vacuum system control involves prerequisite conditions, ready status, pumping status, and coordination with the ion source system. When the vacuum system fails, it is necessary to quickly shut down the ion source and RF system and communicate with external vacuum personnel to determine whether vacuum shutdown is required. Interface signals between VCS and SIS include power on/off, start operation, emergency conditions, system status, pressure thresholds, etc., indicating status through high/low level changes and transmitting control commands. When vacuum leaks, equipment abnormalities occur, or the SIS safety system actively requests, the VCS immediately terminates vacuum pumping, closes all gate valves, and maintains the current cavity pressure.

To ensure safe and effective operation of vacuum equipment, the control system has strictly debugged threshold ranges for key parameters. For example, activation vacuum thresholds for Roots pumps and rotational speed activation thresholds for turbomolecular pumps have been set. Through these, equipment status can be monitored and corresponding measures taken when necessary. To ensure the effectiveness and reliability of the safety interlock mechanism, regular inspection and testing are required.

5 System Testing and Validation

5.1 System Leak Rate Detection

Vacuum system leak rate detection is a critical step aimed at ensuring the stability and normal operation of the vacuum system. Several methods exist for system leak rate detection: Mass Spectrometer Leak Detection, Helium Leak Detection, and Pressure Rise Test. Considering the overall structure and vacuum requirements of the accelerator, the helium leak detector was selected for testing. By spraying helium gas onto suspected leak points and then using a probe to detect helium signals, the location and size of leaks can be determined. This method is highly sensitive and can detect minute gas leaks. Figure 5 [Figure 5: see original paper] shows the leak detector interface during operation.

After conducting leak rate detection on vacuum valves (such as gate valves and angle valves), vacuum pipelines (such as pipe joints, flanges, and sealing components), gas tubes, and cooling water pipes, the helium detector showed no significant helium leak signals. This indicates that the sealing of valves, pipelines, and other critical components in the tested areas is good, meaning the detection results meet requirements.

5.2 Execution Logic Testing

The execution logic of vacuum equipment was tested and verified under different processes. Through these tests, the normal operation and stability of vacuum equipment during various operational phases were ensured. Figure 6 [Figure 6: see original paper] shows the accelerator vacuum level variation curve in automatic mode, displaying how the vacuum level changes over time after various control system components begin operation, starting from a vacuum level greater than 1000 Pa.

At time t1, the ion source begins gas injection, causing the vacuum level to rise. Between t1 and t2, the ion source continues gas injection. At time t2, the ion source stops gas injection, and the vacuum level begins to decrease. After t2, as various vacuum pumps operate, the vacuum level gradually decreases, exhibiting a stepwise declining curve. Subsequently, the system reaches a stable state with a vacuum level of approximately 1$×$10-5 Pa.

5.3 System Long-term Operation Stability Test

Figure 7 [Figure 7: see original paper] shows the vacuum level curve of the vacuum system under long-term operation, including commissioning of startup, operation, shutdown, and venting processes. The curve in Figure 7 includes several phases corresponding to different vacuum processes:

The first phase is the startup and operation process, beginning on July 4. During this phase, the vacuum level decreased from above 1000 Pa to approximately 1$×10−5*Pa, exhibitingastepwisedecliningcurve.Thevacuumsystemsequentiallyactivatedmechanicalpumpse*
5 Pa with essentially no variation. The vacuum system maintained a stable vacuum environment in the acceleration cavity during normal accelerator operation without any abnormalities or alarms.

The second phase is the shutdown process, occurring on the morning of July 6. During this phase, the vacuum level increased from approximately 1$×10 − 5*Patoabove*1×$10-2 Pa, exhibiting a stepwise rising curve.

The third phase is the venting process, beginning on the evening of July 6. During this phase, the vacuum level increased from approximately 1$×10 − 5*Patoabove*1×$10^4 Pa, exhibiting a stepwise rising curve. This occurred because the vacuum system sequentially opened nitrogen valves and closed cryopump sets, turbomolecular pump sets, Roots pump sets, and mechanical pump sets according to the preset sequence.

5.4 Summary

After system commissioning, leak rate detection using the helium leak detector covered vacuum components, pipelines, gas tubes, and cooling water pipes. Leak points were repaired, ensuring the system leak rate is below 2$×$10-8 Pa·m3/s, which meets the accelerator's maximum leak rate requirements. Through testing of system logic execution, switching between automatic and manual modes, as well as the accuracy and reliability of startup/shutdown, operation, and venting processes were verified. Actual operational stability testing demonstrated that the system remains stable long-term under actual accelerator operating conditions with no abnormal monitoring parameters. In summary, this system can be used to maintain the high-vacuum environment of the proton cyclotron, ensuring normal and safe accelerator operation.

As a critical component of the proton cyclotron, the vacuum control system is a prerequisite and guarantee for accelerator operation, directly affecting the overall performance and operational efficiency of the accelerator. The quality and stability of the vacuum system are crucial for maintaining the low-pressure environment inside the accelerator and ensuring stable beam transmission. Based on experience from vacuum control systems in proton accelerator projects, we have further optimized and implemented the vacuum control system. During operation of the proton cyclotron, the vacuum control system has demonstrated excellent, reliable, and stable performance. The successful application of this control system provides valuable experience for the design and optimization of similar proton cyclotron vacuum control systems.

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