DEVELOPMENT OF LASER ACCELERATOR CONTROL SYSTEM BASED ON EPICS

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Abstract

A proton radiotherapy device based on a petawatt (PW) laser accelerator is under constructing in Peking University, supported by the China's Ministry of Science and Technology. The control system's functionality and performance are vital for the accelerator's reliability, stability, and efficiency. The PW laser accelerator control system adopts a three-layer distributed architecture, including device control, front-end (input/output) control and central control (data management, and human-machine interface) layers. The software platform primarily uses EPICS, supplemented by PLC, Python, and Java, while the hardware platform comprises industrial control computers, servers, and private cloud configurations. The control system incorporates various subsystems that manage the laser, target field, beamline, safety interlocks, environment, synchronization, and functionalities related to data storage, display, and more. This paper presents a control system implementation suitable for laser accelerators, providing valuable insights for future laser accelerator control system development.

INTRODUCTION

The laser accelerator is a novel mechanism that harnesses the intense interaction between ultra-powerful lasers and specific targets, driving a profusion of electrons within the target, thereby generating a potent longitudinal electric field to accelerate ions. This acceleration gradient can reach levels of 10^3 to 10^6 times that of traditional accelerators. This method has the capability to accelerate charged particles to velocities nearing the speed of light within the microscopic temporal scales of femtoseconds and spatial dimensions of micrometers. Such groundbreaking particle acceleration showcases vast potential. Compared to traditional accelerators, laser proton accelerators boast significant prospective advantages in aspects like spatial equipment requirements, installation intricacies, operational and maintenance costs, radiation protection challenges, and overall system complexity. Among the myriad applications of laser accelerators, one of the most captivating prospects is employing laser-accelerated protons for tumor radiation therapy. Peking University is in the midst of constructing a proton beam therapy system based on the petawatt (PW) laser accelerator (CLAPA-II) [1–4], which will deliver protons at an energy level of hundreds of MeVs.

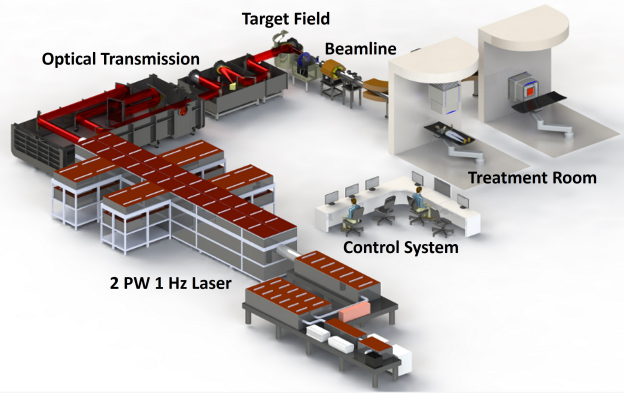

Figure 1: Schematic Diagram of the Overall Layout of the CLAPA-II.

This project aims to cater to the needs of tumor treatments by pioneering a slew of key technological advancements in laser systems, target material preparation, and proton therapy systems. The primary objective is to develop an advanced apparatus for proton radiotherapy and promote its wider use worldwide.

The control system for the CLAPA-II adopts a standard distributed framework based on EPICS [5]. Specific research objectives encompass an operator interface to facilitate control, monitoring, and protection of various equipment distributed across subsystems like the laser, the optical transmission, the target field, the beamline, and the treatment room (as depicted in Fig. 1). Adhering to the designed physical objectives, the system will produce and transmit the beam, ensuring the beam parameters meet the high repetition-rate proton irradiation requirements at the terminal. Furthermore, the control system, even under extensive integration and automation, should exhibit high reliability, swift real-time responsiveness, user-friendly human-machine interfaces, holistic safety interlock protection, a database-centric information management system, comprehensive electromagnetic radiation protection, and a network-based communication system. After progressing through stages like prototype preparation, experimental prototyping, engineering prototype, and product prototype, the final system should meet medical software standards, testing requirements, and performance criteria for proton therapy equipment in terms of reliability, stability, maintainability, and interactivity. Building on this, the project aims to finalize the laser platform and its applications, transforming it into an open-access user platform.

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This paper delves into detailing the hardware and software architectures of the control system for the laser accelerator, elucidating the control logic of principal subsystems and offering a visual depiction of the main control interface, hoping as a reference to readers and related professionals.

CONTROL SYSTEM ARCHITECTURES

Hardware Architecture

The control system of CLAPA-II adopts a standard distributed architecture based on EPICS, integrated with an auxiliary equipment control solution using WinCC + PLC. Figure **??** represents the hardware architecture of the control system, which is divided into three levels according to the standard model, including: device control, front-end or input/output control (IOC), and central control (data management, and human-machine interface) layers. The main hardware are listed in Table 1.

Table 1: Main Hardware

Device	Brand	Model
IPC	Advantech	APC-2010
Core Switch	H3C	S7506E-NP
Serial Port Server	MOXA	NPORT6650-16/32
USB Hub	MOXA	Uport 407
Server	H3C	R4900 G5

The Central Control Layer is mainly user-oriented, serving as the human-machine interface composed of system hosts and servers. Both the central control room and the subsystem control stations are equipped with operator consoles. These consoles display equipment status parameters and feature graphical user interfaces, enabling real-time data processing, image processing, user management, and control feedback. Through the operation of terminal equipment, operators can view and modify control displays and have access to various applications and other tools within the system, allowing convenient adjustment and control of equipment. This layer primarily consists of 21 matrix screens and 10 workstations. Additionally, the layer integrates a data management system that encompasses functionalities like database administration, data storage, data application, visualization, and data logic processing. The main hardware includes 12 servers, one set of UPS equipment, two 64-port core switches, and one 28-port access switch, all housed within the data center.

The IOC Layer serves as the front end of the system, consisting of industrial PCs (IPCs). Its primary task is to run EPICS IOC programs, PLC programs, and Python programs, executing specific transformation processes for data from various interface devices. In this layer, control signal variables from different interface devices initially use RS232/RS485/USB/OPCUA communication protocols and are then converted into Process Variables (PVs) using software drivers (S7-nodave) and specific hardware components, such as USB-Hub and Serial Port Server. These converted PVs are communicated using the EPICS CA (Channel Access) protocol for real-time data exchange and are then transmitted to the central control layer through the network. The main hardware in this layer includes 17 IPCs, two 48-port access switches, four 24-port access switches, five 16-port serial port servers, and five USB hubs.

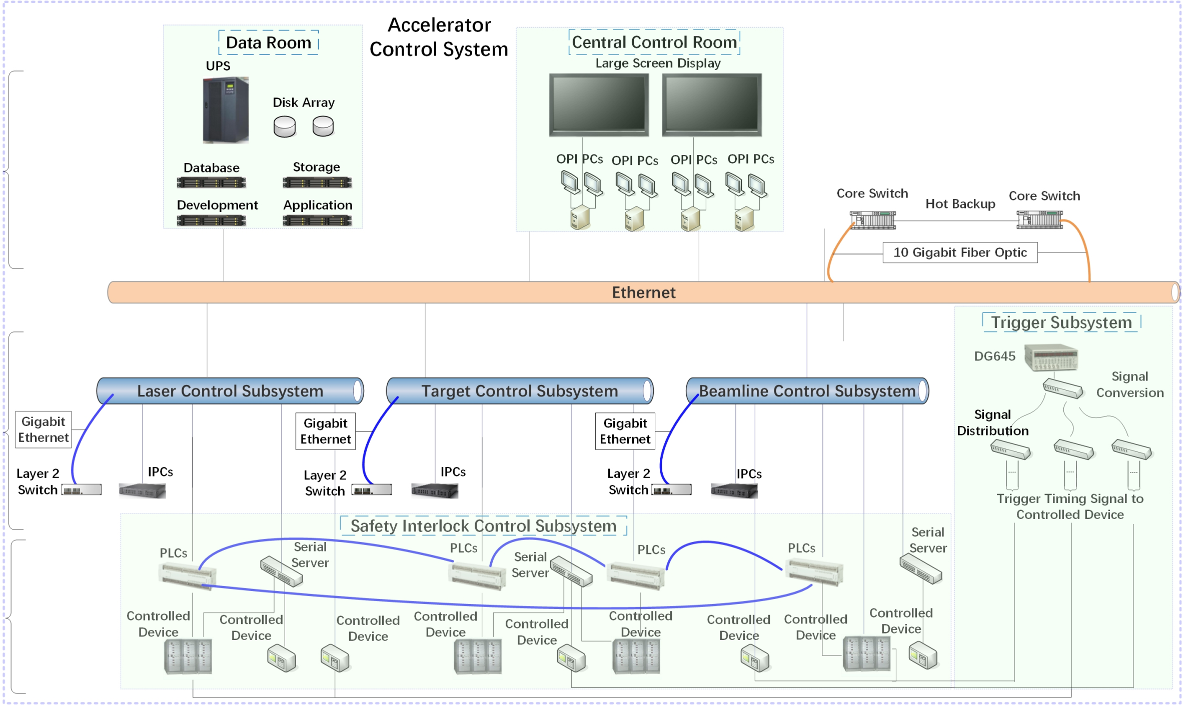

Figure 2: Hardware Architecture of the Control System.

The Device Control Layer is the lowest level responsible for device control and monitoring. The controlled devices include various lasers, vacuum systems, multi-axis motors, spectrometers, switch valves, magnet power supplies, radiation detection equipment, cryogenic system equipment, and various beam detectors and instruments. The responsibilities for the implemented control functions include synchronous trigger control, digital and image display, data sampling, processing and storage, equipment status patrol, and alarm, etc. For key equipment that may cause accidents, multiple redundant or diverse control methods are configured. Since control equipment operates in a strong electromagnetic interference environment, the control system adopts anti-interference measures such as isolation, shielding, and rational grounding to minimize the interference of strong electromagnetic fields on the weak electric signals of the control system, enabling the system to work normally.

In addition, the establishment of a ZStack private cloud platform has enhanced our project with robust computational and data storage capabilities. Within this cloud environment, we've set up virtual machines running on both Windows and Ubuntu operating systems. These machines are essential for constructing, debugging virtual device IOCs, OPIs, and their associated business logic layer. This approach not only improves our working efficiency but also provides our project with a flexible and scalable infrastructure, fostering dynamic and adaptable progress in our research and development efforts.

Software Architecture

The software architecture of the control system is also divided into three levels, as shown in Fig. 3, with the main software listed in Table 2.

Table 2: Main Softwares

Software	Version	Software	Version
EPICS Base	7.0.4	Asyn	4-38
Stream Device	2.8.9	Auto Save	R5-10
MySQL	8.0.21	MongoDB	5.0.3
Phoebus	4.6.6	SNL	8.0
BEAST	3.2.1	Python	3.8
Data Browser	5.3.2.13	Archiver	1.1.0
WinCC	7.5	CA Gateway	2.1.2
Kafka	2.12	O-log	1.0.0

Operator Interface Layer This layer, pivotal in its role, bridges the communication between users and the accelerator system, ensuring real-time responses and facilitating efficient operations. Primarily, we meticulously implemented EPICS OPIs through CSS (Control System Studio)/Phoebus, granting users intuitive control over the majority of subsystems. Recognizing the need for immediate access to data, we designed user-friendly web-based data visualization interfaces using advanced JavaScript techniques. These interfaces not only allow seamless data browsing but also simplify the downloading process. Furthermore, given the importance of safety in such systems, we prioritized and employed WinCC [6] for the safety interlock system, thereby bolstering system reliability and security.

The Logic Operation Layer consists of various software components and specific functional modules, serving as the implementation layer for business and functional logic within the control system. For instance, it comprises state machines developed using State Notation Language (SNL), optimization of the beamline transmission system implemented with OpenXAL, and data storage (utilizing MySQL [7], MongoDB [8], Archive [9], and Python). It also involves safety interlock logic (WinCC and Python) and other applications, including authority management (CA Gateway), alarm management (BEAST), message service for alarms (Kafka), log management (O-Log), and FTP file transfer (FTP Server). These services offer comprehensive data processing capabilities, supporting the collection, storage, management, and processing of system data.

The Device Control Layer is the lowest layer of the architecture, directly interacting with device hardware, enabling device control and data acquisition. This layer runs various software programs, such as those developed for EPICS, PLC and Python scripts. The EPICS programs are responsible for transmitting most of the interaction data generated by the devices to the LANs, while the PLC programs control the real-time operations of safety interlock devices. The Python programs implement specific functional modules, such as conversion, storage, and processing of data. Operating these programs requires the support of numerous driver programs or other software packages, such as the S7-nodave driver for soft IOC communication with PLCs, the Device Control driver for the safety interlock PLCs used to control safety interlock system devices, and the Stream Device and Asyn drivers for the trigger system. Other subsystem IOCs also use various drivers, such as the areaDetector, Motor, Stream Device and Asyn for the beamline system, and the EPICS-Tango bridge for the laser system. Through the operation of this layer, the system can achieve unified control and management of device interfaces, as well as data acquisition and transmission, laying the foundation for efficient control system operation and management.

SUBSYSTEMS DEVELOPMENT AND SOFTWARE INTEGRATION

Synchronized Trigger Control System

Clock Trigger The synchronous trigger system predominantly manages the DG645 [10] delay trigger device and acts as a globally interconnected system within the laser accelerator apparatus, designed to create the required timing triggers and synchronization clocks essential for operating the laser accelerator and beamline equipment. This system formulates a sequence of timed trigger signals, delivering

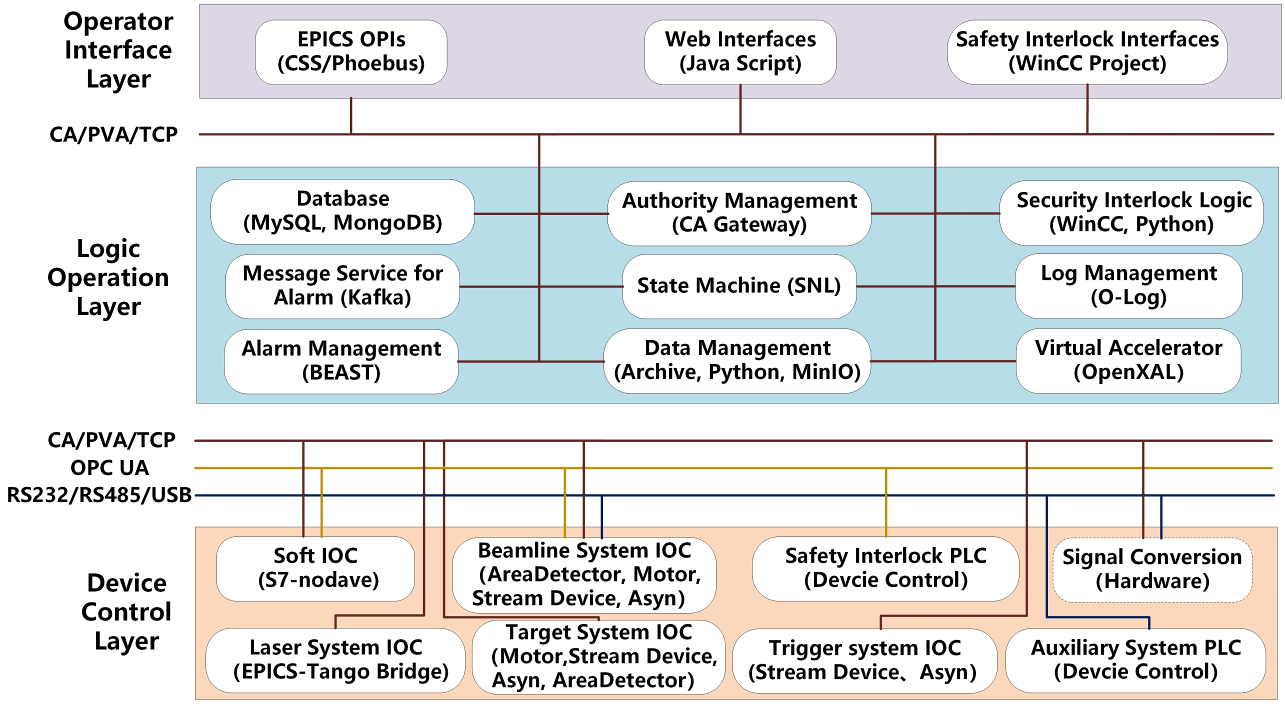

Figure 3: Software Architecture of the Control System.

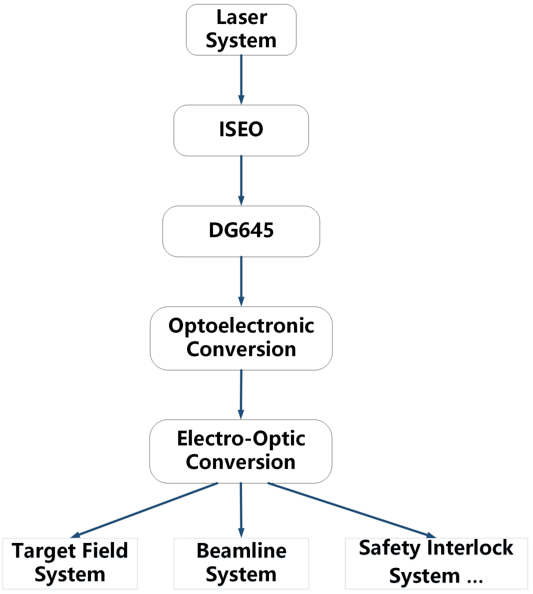

Figure 4: Synchronized Trigger Control System Structure Diagram.

precise delayed trigger signals to correlated devices within the accelerator, such as shutters, cameras, motors, and magnet power supplies. This ensures the harmonious operation of the laser system, target field system, and beamline system, accomplishing precise control over laser and proton pulses. The operational diagram of the synchronous system is displayed in Fig. 4. The T0 trigger signal is furnished by the Intelligence Synchronisation Electronics for Optics (ISEO) system [11] of the laser. The T0 signal from the ISEO system is connected to the DG645, which receives the T0 signal and outputs trigger pulses with specified delays. The timed trigger signal is converted into an optical signal through electrical/optical conversion and is transmitted to various subsystems to meet the synchronous triggering requirements of the subsystem devices. Employing electrical/optical conversion for trigger signal transmission not only minimizes trigger delay but also reduces the susceptibility of the trigger signal to Electromagnetic Pulse (EMP) [12, 13] interference, guaranteeing the stable operation of the subsystems.

Event Trigger In our exploration beyond the traditional DG645-based system, we've investigated an alternative triggering mechanism using the EVG/EVR Event Timing System. This method is designed for laser accelerators and is compatible with both single-shot and multi-shot firing modes. The system boasts a short-term jitter of 6.3 ps and a long-term jitter of 8.3 ps over 20 hours. It features an EVG cascading function, a versatile EVO adaptable as EVG, FANOUT, or EVR, and offers robust support for timing trigger, delay compensation, time stamp, fault interrupt, and status latch. Furthermore, it ensures synchronization of all equipment with the laser through inputs of 80 MHz and 1 Hz from ISEO to EVG. Given its versatility and precision, this system provides an effective counterpart to the DG645-based method, meeting varied synchronization and triggering requirements in laser accelerator operations.

Laser Control System

The laser system is pivotal for generating and overseeing the laser's operation. This module consists of various devices that collaboratively generate the essential laser energy and wavelength while also adjusting key laser parameters, including its pulse width and frequency. Fundamental to our experiments, this system delivers the laser energy necessary to power other systems. We source our 2 PW laser directly from France's THALES company, which operates on the Tango control system. To harmonize this with our EPICS setup, we've harnessed the EPICS-Tango bridge method, seamlessly transitioning Tango's control variables into EPICS counterparts. Our assessments indicate that PVs derived from the EPICS-Tango bridge exhibit comparable performance to the native EPICS PVs. The system offers real-time monitoring of laser parameters and operational status, integrating them into the safety interlock and conditional control systems. Subsequently, laser data is archived in the database, facilitating long-term storage and in-depth analysis.

Target Field Control System

On this accelerator, the laser interacts with the plasma, transferring energy to the proton beam through various mechanisms. This interaction takes place within the target field. Given that the temporal and spatial scales of the interaction are at the femtosecond and micrometer levels respectively, the demands for precision in temporal and spatial control are exceptionally high. We utilize lasers with microscale focus, supported by high-precision motors to adjust optical frames, facilitating efficient and precise focusing. To record the outcomes, advanced cameras are used, followed by a spectroscopic analysis to assess the optical setup. Meanwhile, the target system comprises a coordinated set of high-precision motors. Their movements are closely monitored by scientific cameras to verify accurate positioning. Every aspect of our approach emphasizes the importance of precision in our operations. The devices of the system are mainly controlled through the Motor, Asyn, Stream Device, and areaDetector modules in EPICS for input/output control of the devices.

Beamline Control System

The beamline consists of both horizontal and vertical sections [1, 3]. Currently, the foundational construction of the horizontal beamline has been completed. It primarily comprises 3 superconducting solenoids, 10 quadrupole magnets, and 2 bending magnets. The beamline system primarily achieves precise control of the proton beam energy, charge, and beam spot shape, making the more extensive application research of laser-accelerated ions possible. Its controlled devices mainly include the magnet power supply, primarily responsible for the adjustment and control of the beamline; and the beamline ionization chamber is used to observe the situation where the beamline is controlled. Apart from utilizing modules like areaDetector, Motor, Stream Device and Asyn, this system also incorporates rapid energy switching, which is achieved using the 'event codes' from the trigger system.

Moreover, we have employed OpenXAL, a virtual accelerator, to meticulously simulate and optimize beam trajectories. This tool empowers us to analyze and forecast precise modulations, evaluate the impact of operational parameters and configurations, and pinpoint potential optimizations, all without having to engage our actual accelerator, thereby ensuring a blend of maximal efficiency and stability during live operations.

Treatment Control System

Distinct from previous laser accelerators, our system is pioneering as it will be the inaugural apparatus dedicated to irradiation therapy. Given this novelty and the profound implications, the role of our Treatment Control System (TCS, as shown in Fig. 5) becomes even more pivotal. At its core, the "TCS CORE" functions as the central nervous system, orchestrating seamless communication with other integral components via a series of adapters. The Treatment Planning System (TPS) is meticulously integrated with the Oncology Information System (OIS), ensuring unmatched precision and consistency in treatments. Meanwhile, the Interlock System stands guard, providing a robust safety mechanism, and ensuring unyielding stability throughout the therapeutic process.

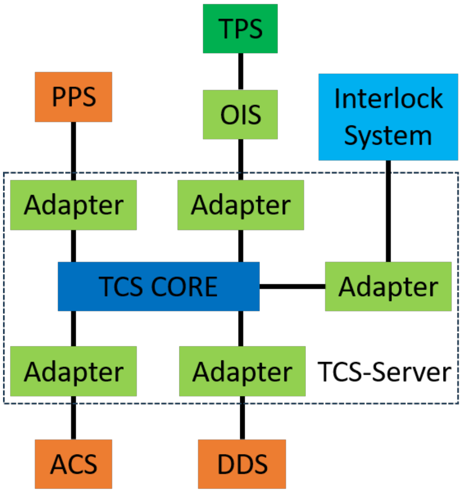

Figure 5: Integrated Architecture of the Advanced TCS.

On the left side of Fig. 5, the Patient Positioning System (PPS) collaborates seamlessly with the Accelerator Control System (ACS), guaranteeing fluidity during therapy sessions. Simultaneously, the Dose Delivery System (DDS) directly connects with the TCS CORE, ensuring the accurate and consistent delivery of radiation doses to patients. The TCS-Server, as a distinct module, offers necessary backend support and data exchange functionalities to the TCS CORE.

This architectural design aims to ensure accuracy, efficiency and safety in the overall therapeutic workflow, reflecting our dual commitment to technological innovation and therapeutic efficacy.

Safety Interlock System

Figure 6 showcases three primary safety interlock systems: Personal Safety, Equipment Safety, and Medical Safety.

The Personal Safety Interlock System uses access control, infrared detection, and image recognition to manage personnel access. Concurrently, radiation detectors monitor

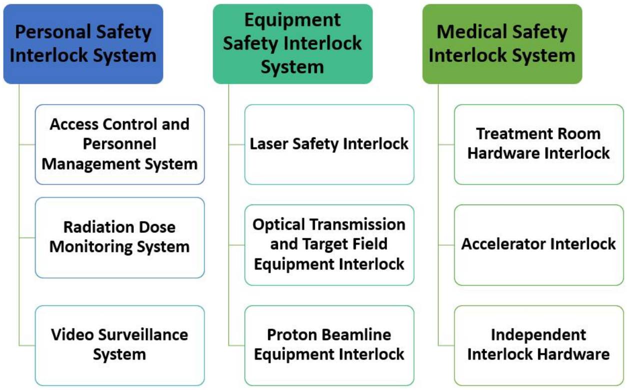

Figure 6: Three-Tier Safety Interlock System Overview.

neutron and gamma doses in real-time. The system also incorporates video surveillance for additional monitoring.

The Equipment Safety Interlock System oversees the operation of key apparatuses through specific interlock mechanisms. It manages the operation of laser equipment, optical transmissions, and proton beamline equipment to reduce potential risks.

The Medical Safety Interlock System is designed for the safe operation of medical equipment and procedures. It utilizes hardware interlocks to ensure the safe functioning of devices in treatment rooms and integrates an accelerator interlock for added security.

Data System

The CLAPA-II control system consolidates both real-time and historical data into its database, allowing users network-wide to access, analyze, and even leverage machine learning techniques to optimize beam performance. To accommodate the diverse data needs, we utilize both MySQL and MongoDB.

MySQL, chosen for its open-source nature and compatibility with popular operating systems, excels in intricate data query transactions. However, its limitations with extensive data writing and swift simple query responses necessitate a complementary solution for handling vast files and rapid retrievals.

Thus, MongoDB, a non-relational database, complements MySQL in our system. Its capacity to seamlessly handle large-scale data, especially when data surpasses 50 GB, makes it our choice for storing substantial data like camera-captured images. Moreover, we employ MinIO specifically for large file storage, while only indexing these files in our experimental metadata for efficiency. Augmenting this, we've introduced a web service, crafted using Vue and Flask, dedicated to managing experimental metadata.

Additionally, machine learning has become vital in our operations. By applying machine learning to historical data, we can predict beam trends and equipment failures. This helps us anticipate and address issues earlier, reducing downtime and improving beam quality for more reliable experiments. In summary, we've developed an integrated data system for CLAPA-II, covering acquisition to utilization.

Main Control System OPI Display

In Fig. 7, the main control interface serves as the control and monitoring nexus, enabling users to access real-time experimental data and interact with all pertinent subsystems. Its primary modules are listed below.

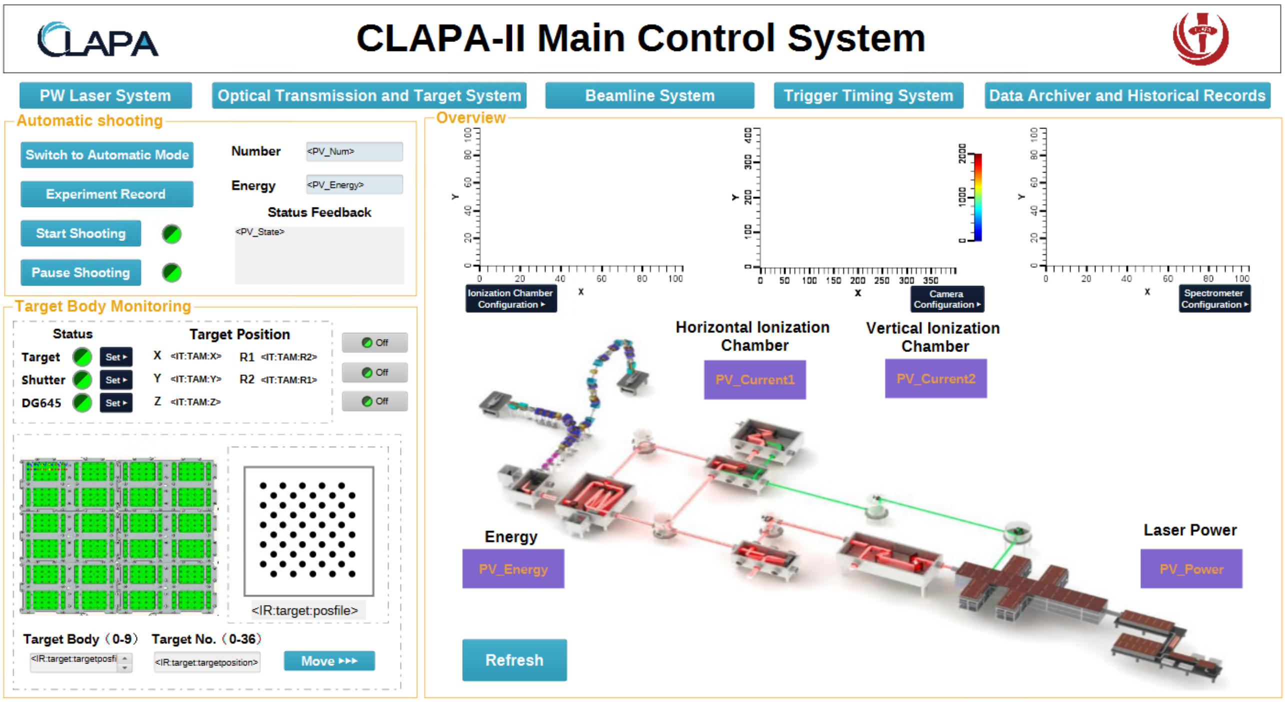

Figure 7: Main Control System OPI.

Subsystem Jump Buttons This module provides detailed interaction interfaces for distinct subsystems, allowing precise control, monitoring, and configuration of each. It serves as an integral connector to various systems such as the PW laser system, optical transmission and target field system, beamline system, trigger timing system, and the data archiver and historical records. By facilitating direct engagement with each subsystem's specific controls and settings, it ensures seamless integration and coordination among various experimental components.

Automatic Shooting Parameter Settings This component focuses on automating and controlling the shooting parameters of the experiment. It is vital for initiating and pausing shooting sequences and adjusting the recording parameters, thus enhancing the precision and repeatability of the experimental shots. The real-time status feedback feature in this module is crucial for instant anomaly detection and response, ensuring the smooth progression of the experiments.

Target Body Monitoring This segment is crucial for the meticulous monitoring and control of the target body and its interaction with beams or lasers. It provides accurate controls over the target's position, the shutter's operations, and the triggering time via the DG645, impacting the overall accuracy and stability of the experiments. This module is vital for regulating the interaction between light and target, ensuring precise and successful experimental outcomes.

Primary Data Overview This module is pivotal for the real-time observation and analysis of the primary data including ionization levels, visual feedback, spectral properties, and energy levels of the interactions. It consolidates data from the Ionization Chamber, Camera, Spectrometer, and Energy monitors, offering crucial insights and correlations, which are indispensable for analyzing and interpreting the results of the laser acceleration experiments.

CONCLUSION

The overall structure of the CLAPA-II adheres to a distributed control system SCADA structure; the main integrated tools are EPICS and WinCC. IPCs, servers, or PLCs provide the environment for running IOC and related programs. Gigabit Ethernet backbone, fieldbus, industrial Ethernet, serial port, etc., constitute the comprehensive environment for system communication, wherein the communication protocols primarily include TCP/IP, OPC UA, Modbus, and RS232/485, among others. Currently, the development of the control system is proceeding as planned, having completed the detailed design of the scheme. Leveraging Peking University's CLAPA-I [14, 15] accelerator experimental platform, the development of the IOC and OPI for key devices has been initiated; furthermore, related works, such as the research on the PW laser target radiation EMP and its shielding solutions, have also been concluded. As the project progresses and the control system is refined, we are confident in our ability to explore a more comprehensive EPICS control system solution based on laser accelerators, and to offer valuable recommendations for developments in related fields.

ACKNOWLEDGEMENTS

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REFERENCES

[1] K. D. Wang *et al.*, "Achromatic beamline design for a laser-driven proton therapy accelerator", *Phys. Rev. Accel. Beams*, vol. 23, no. 11, p. 111302, Nov. 2020. `doi:10.1103/PhysRevAccelBeams.23.111302`

[2] D. Li *et al.*, "Introduction of research work on laser proton acceleration and its application carried out on compact laser–plasma accelerator at Peking University", *Photonics*, vol. 10, no. 2, p. 132, Jan. 2023. `doi:10.3390/photonics10020132`

[3] K. D. Wang *et al.*, "Beam distribution homogenization design for laser-driven proton therapy accelerator", *Nucl. Instrum. Methods Phys. Res. Sect. A*, vol. 1040, p. 167196, Oct. 2022. `doi:10.1016/j.nima.2022.167196`

[4] H. Ge *et al.*, "Design of Ionization Chamber for CLAPA II", *Mechatron. Autom. Technol.: Proc. ICMAT'22*, vol. 33, p. 202, 2023. `doi:10.3233/ATDE221167`

[5] EPICS, `https://epics-controls.org`

[6] WinCC, `http://www.wincc.com.cn`

[7] MySQL, `https://www.mysql.com`

[8] MongoDB, `https://www.mongodb.com`

[9] EPICS Archiver Appliance, `http://slacmshankar.github.io/epicsarchiver_docs/details.html`

[10] Digital Delay Generator, `https://www.thinksrs.com/products/dg645.html`

[11] ISEO, `https://pdf.directindustry.com/pdf/thales/iseo/34770-235492.html`

[12] Y. Xu *et al.*, "Analysis of electromagnetic pulses generated from ultrashort laser irradiation of solid targets at CLAPA", *Chin. Phys. B*, vol. 31, no. 2, p. 025205, Nov. 2021. `doi:10.1088/1674-1056/ac3735`

[13] Y. Xia *et al.*, "Enhancing electromagnetic radiations by a pre-ablation laser during laser interaction with solid target", *Phys. Plasma*, vol. 27, no. 3, pp. 032705, Mar. 2020. `doi:10.1063/1.5140585`

[14] X. Yan, *et al.*, "Recent progress of laser driven particle acceleration at Peking University", *Front. Phys.*, vol. 8, no. 5, pp. 577–584, Aug. 2013. `doi:10.1007/s11467-013-0372-2`

[15] X. Yan *et al.*, "From laser acceleration to a laser proton accelerator", *Laser Acceleration of Electrons, Protons, and Ions V, SPIE*, vol. 11037, p. 1103706, May 2019. `doi:10.1117/12.2521023`