

PYTHON BASED CONTROL AND DIAGNOSTIC SYSTEMS FOR AREAL LINEAR ACCELERATOR

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Abstract

The AREAL linear accelerator, constructed in Yerevan, Armenia, is designed to generate low-emittance, ultra-short electron beam pulses for advanced research in novel accelerator technologies, coherent radiation sources, and the dynamics of atomic and molecular processes.

This paper presents an overview of the Python-based control system developed for the AREAL accelerator. The system architecture, associated hardware components, and supporting software infrastructure are described in detail. Particular attention is given to the client-server design, database integration, and hardware interfacing solutions. In addition, auxiliary applications that support operation, monitoring, and data management are discussed. Finally, future development directions of the control system, including its adaptation to planned AREAL upgrades, are outlined.

INTRODUCTION

From the control system point of view the AREAL linear accelerator [1-4] components are categorized as follows: vacuum system (ion pumps, vacuum gauges, gate valve and fast closing valve) [5-7], RF system (low-level radio frequency: LLRF) [8, 9], magnet system (solenoid, dipole, corrector and quadrupole magnets) [10, 11], cooling system [12, 13], diagnostic system (CCD cameras for YAG stations, movers and Faraday cups) [14-17], laser system [18], radiation, machine and personal safety systems [19]. The AREAL linear accelerator control system is based on “client/server” model and has three layers of hierarchy. The first layer is an interface to which the devices are connected via RS-232/485, USB and DAQ (Data acquisition), depending on a device type and specifications. The second - middle layer is a MySQL database for parameter and measurement data storage. The third layer is operator interface computers which are located in the control room. The connection between these three layers is performed via TCP/IP protocol [14, 15]. The main programming language for the server and client parts is a Python. The server software allows to get and save the readings of vacuum gauges, ion pumps and dosimeter devices, as well as the last actual positions and values of optical and optoelectronics elements on a laser table in a database. Then they are send to clients for monitoring and also for a reset of positions if necessary.

For implementation of AREAL accelerator control system servers and clients as well as for data analyses and

beam parameters measurement tools, Python programming language is selected. Python is an open-source programming language widely used by scientists today. It offers a rich ecosystem of open-source scientific libraries that implement modern algorithms, enabling advanced data analysis, optimization, machine learning, and high-performance computing. In addition, Python provides numerous libraries for interfacing with hardware, managing network communications, and working with databases, including robust support for systems such as MySQL, making it suitable for control and monitoring.

LLRF CONTROL

The LLRF control is performed via LIBERA device which is a digital low level RF stabilization system. The LIBERA device’s server part is programmed in a framework of the EPICS control system, so all required IOCs are installed on LIBERA by manufacturers. Channel accesses between IOCs and operator interface software is developed according to RF group requirements. Besides LIBERA device, a Micro Telecommunications Computing Architecture (μ TCA) is used for timing stabilization and LLRF control. μ TCA is a modular, high-performance hardware platform widely adopted in accelerator control systems, telecommunications, and experimental physics applications [20]. It provides a robust and flexible infrastructure for building scalable and reliable control and data acquisition systems. The key advantages of the μ TCA platform include high-speed data transfer through backplane communication, a modular architecture based on Advanced Mezzanine Cards (AMC), deterministic timing and precise synchronization capabilities, and scalability suitable for complex distributed systems. In addition, μ TCA systems are designed to meet the reliability requirements of continuous operation environments. It is also valuable with its hot-swap possibility, which allows to replace cards without interrupting device operation. In accelerator applications, μ TCA is particularly well suited for LLRF systems, timing distribution, data acquisition and processing, and real-time feedback control. The platform enables tight integration between FPGA-based hardware processing and high-level software control, providing an efficient framework for precise RF signal generation, regulation and monitoring.

Precise timing is a critical requirement in accelerator systems, where RF fields, beam injection, magnet and diagnostic devices operations must be synchronized with nanosecond and, in some cases, picosecond-level accuracy.

The timing system, implemented on μ TCA hardware, provides centralized clock distribution and trigger signal generation, ensuring synchronous operation across all subsystems. It enables synchronization of RF pulses with laser and delay generator systems and guarantees deterministic latency throughout all devices. As a result, RF pulses accurately aligned with laser pulse and the beam diagnostics are properly synchronized with acceleration cycles. Thus all subsystem operations are coordinated in a consistent and reproducible manner (Fig. 1).

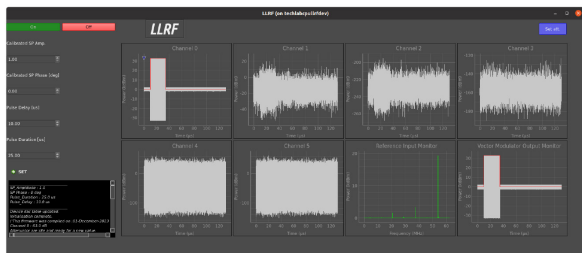


Figure 1: GUI for RF signal regulation and monitoring.

The μ TCA-based hardware system operates through a combination of FPGA-based real-time processing and high-speed data communication, enabling low-latency and high-precision control required for LLRF applications.

RF signal acquisition is performed using high-speed analog-to-digital converters (ADCs) integrated on Advanced Mezzanine Card (AMC) modules. The digitized signals are processed in real time by field-programmable gate arrays (FPGAs), where key operations include in-phase and quadrature (IQ) demodulation, amplitude and phase detection, and execution of feedback control loops.

The processed data are subsequently used to generate control outputs via digital-to-analog converters (DACs), which drive RF elements such as amplifiers and modulators. A Python-based software layer interfaces with the hardware, providing system configuration, real-time data visualization, as well as logging and diagnostic capabilities. This tightly integrated architecture ensures deterministic behaviour and high performance in demanding accelerator environments.

The key innovation is the development of an AI-based pulse tracking and alignment system, designed to automatically analyse RF pulses and optimize their synchronization with major systems.

The system performs real-time pulse amplitude estimation and temporal position detection, enabling precise characterization of pulse size and timing, including observation on beam diagnostics. Based on these measurements, adaptive control algorithms adjust the currents of solenoid, dipole, corrector, and quadrupole magnets to optimize beam parameters.

To ensure robust performance, machine learning techniques are employed to maintain accurate detection and alignment even in the presence of noise and signal fluctuations.

This approach significantly reduces the need for manual tuning of pulse parameters, enhances beam stability and reproducibility, and lowers operator workload. Overall, the

proposed AI-driven methodology represents a step toward autonomous accelerator control systems.

MAGNETS CONTROL

Two complementary magnet control systems were developed using Python and tailored hardware platforms. The first system targets solenoid and dipole magnets, utilizing National Instruments (NI) data acquisition (DAQ) hardware and incorporating machine learning algorithms for advanced hysteresis compensation and automated degaussing. The second system addresses quadrupole and corrector magnets, implemented on a Raspberry Pi-based architecture to provide flexible, distributed, and cost-effective control. Together, these systems form a modular and scalable solution, combining real-time hardware interfacing, intelligent control algorithms, and user-friendly graphical interfaces.

Solenoid and dipole magnets are primarily responsible for beam steering and longitudinal focusing, as well as for beam energy spectrometry. Their magnetic behaviour is strongly affected by hysteresis, introducing nonlinearity and history dependence. To mitigate these effects, the Python-based control software interfaces with NI DAQ hardware to provide high-resolution analog outputs for current and voltage control, real-time analog input for feedback acquisition, and stable, deterministic signal generation. Machine learning algorithms predict magnet response from historical data, enabling hysteresis compensation, reducing field errors during ramping, and improving reproducibility of magnetic states. An automated degaussing procedure applies controlled current oscillations with decreasing amplitude to eliminate residual magnetization, ensuring consistent initial conditions. The graphical user interface (GUI) allows real-time monitoring, setpoint control, visualization of magnet state, and both manual and automated operation (Fig. 2).

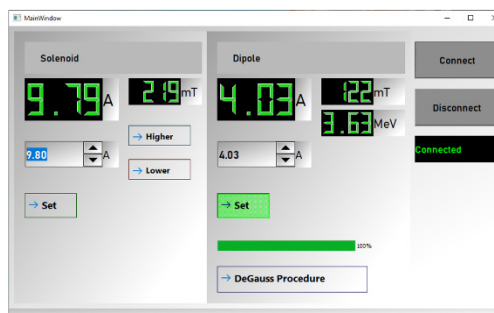


Figure 2: GUI for Solenoid and dipole magnets remote control.

Quadrupole and corrector magnets, used for beam focusing and fine trajectory correction, require multi-channel synchronized control, high-precision low-current operation and distributed deployment. A Python-based control system on a Raspberry Pi platform meets these requirements, providing serial or GPIO communication with power supplies, multi-channel control, and lightweight, responsive logic. The GUI allows independent control of

multiple channels, real-time current and voltage monitoring, easy switching between control modes, activation of feedback loops. This approach emphasizes modularity and scalability, supporting expansion to additional magnets and integration into broader control frameworks.

The hardware architecture reflects the differing requirements of the two systems. The NI DAQ-based setup provides high-precision analog I/O, stable signal generation, and PC-based computational capability for ML algorithms. The Raspberry Pi-based setup offers an embedded, low-power control unit with network connectivity suitable for distributed deployment. This hybrid design leverages the precision and computational power of NI DAQ for critical tasks, while employing Raspberry Pi systems for flexible, scalable, and cost-effective control.

The combined system offers several advantages: enhanced accuracy through ML-based hysteresis compensation, operational stability via automated degaussing, scalability for additional magnet types, cost efficiency through distributed Raspberry Pi deployment, and user-friendly operation enabled by intuitive graphical interfaces (Fig. 3).

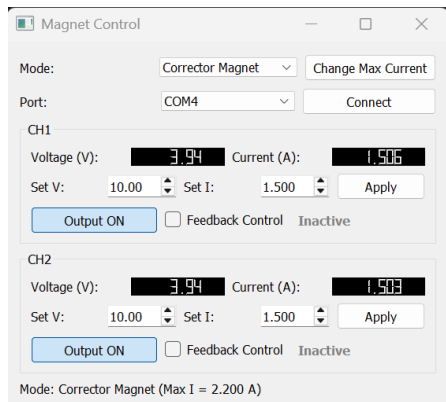


Figure 3: GUI for quadrupole and corrector magnets remote control.

BEAM DIAGNOSTICS EQUIPMENT AND OTHER APPLICATIONS

Remote connectivity between diagnostic equipment and operator interface computers has been established to enable centralized monitoring and control. Custom Python-based software was developed for CCD cameras, allowing users to capture beam images and extract key parameters, including transverse RMS size and beam center position.

On the AREAL accelerator, the charge of individual electron bunches is measured using two Faraday cups. One insertable Faraday cup, is installed in the gun section, while the second moveable is used for ‘in-air’ charge measurements at beam extraction windows on straight and bent spectrometer arms. Electrical connections from the Faraday cups are terminated by BNC connectors, and the output signals are integrated on an oscilloscope. The measured signal is mathematically transformed to obtain the corresponding bunch charge.

Python-based applications have also been implemented for remote control of all movers and vacuum shutters, as

well as for motion control of motorized stages. The software interfaces with Newport SMC100CC single-axis DC servo motor controllers and Thorlabs KDC101 K-Cube brushed DC servo motor controllers, providing precise and automated positioning capabilities.

LLRF CONTROL SYSTEM INTEGRATION WITH MAGNET CONTROL SYSTEM

The AI-based pulse tracking system is designed to operate in close integration with the developed control software, forming a unified and coordinated control framework.

Based on the results of pulse analysis, machine learning algorithms dynamically adjust the currents of accelerator magnets to achieve the desired beam parameters (Fig. 4). The AI-driven alignment mechanism ensures accurate temporal synchronization (jittering) of RF pulses, while continuous real-time tracking further improves system precision and stability.

This integrated approach establishes a cohesive control ecosystem in which key accelerator subsystems operate in a synchronized and optimized manner, contributing to enhanced performance, reproducibility, and operational efficiency.

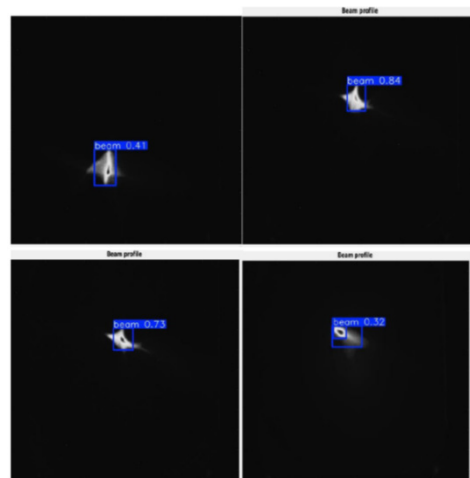


Figure 4: AI beam-based adjusted beam profile.

CONCLUSION

The AREAL linear accelerator control system integrates Python-based software with flexible hardware platforms to provide precise, scalable, and intelligent management of laser, RF systems, timing, magnets and diagnostics. Machine learning-enhanced magnet control and AI-driven pulse tracking enable automatic compensation, beam-based alignment, and reproducible operation with minimal manual intervention. μ TCA-based LLRF and timing systems ensure high-precision synchronization, while remote diagnostics and motion control enable centralized monitoring and feedback. This integrated framework demonstrates a robust and modular approach, establishing a foundation for future autonomous accelerator operation and advanced experimental capabilities.

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