PYTHON BASED CONTROL AND DIAGNOSTIC SYSTEMS FOR AREAL LINEAR ACCELERATOR

G. Amatuni, M. Yazichyan*, A. Grigoryan[1,] B. Grigoryan, A. Hovakimyan[1], H. Sargsyan[1], L. Aleksanyan, E. Mnatsakanyan[1], H. Davtyan, A. Otarov, A. Vardanyan grigoryan@asls.candle.am, Center for the Advancement of Natural Discoveries using Light Emission (CANDLE SRI Yerevan, Armenia)

[1]also at Yerevan State University (YSU Yerevan, Armenia)

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

Modern accelerator facilities require reliable control systems capable of providing stable machine operation, real-time diagnostics, and automated optimization of beam parameters. The increasing complexity of accelerator subsystems and the growing demand for high beam quality have stimulated the integration of advanced software technologies, data acquisition frameworks, and artificial intelligence (AI) methods into accelerator control environments. The control system of the AREAL linear accelerator [1-4] is designed according to a hierarchical client–server architecture and integrates all major accelerator subsystems, including vacuum [5-7], radio-frequency (RF) [8,9], magnets [10,11], cooling [12,13], diagnostic [14-17], laser [18], radiation, machine-protection, and personnel-safety systems [19]. Devices are connected through RS-232/485, USB, and data-acquisition interfaces (DAQ), while operational parameters and measurement data are stored in a centralized MySQL database and distributed to operator workstations via TCP/IP communication [14,15]. Python was selected as the primary programming language for server and client applications due to its extensive ecosystem of scientific libraries, hardware communication interfaces, database support, and capabilities for advanced data analysis and automation. Recent advances in machine learning have created new opportunities for accelerator diagnostics and control. In particular, deep-learning-based computer vision methods enable rapid extraction of beam characteristics from diagnostic images, providing information that can be used for automated feedback and optimization. Among these approaches, the YOLO (You Only Look Once) object-detection framework offers an attractive combination of detection accuracy and computational efficiency, making it suitable for real-time accelerator applications.

In this work, an AI-based beam detection and control system is developed and integrated into the AREAL accelerator control infrastructure. The detector is trained using thousands of labeled beam images acquired from YAG-screen diagnostic stations under a wide range of operating conditions. The trained model automatically identifies the beam region and extracts key beam parameters, including beam centroid coordinates and transverse beam dimensions. These quantities are transmitted in real time to the accelerator control system and used for automated beam alignment, steering, and beam-quality monitoring through closed-loop feedback algorithms.

To ensure reliable operation, the developed system incorporates communication monitoring, automatic device reconnection, error logging, parameter validation, and safe-state protection mechanisms. The combination of AI-driven beam diagnostics with robust Python based control-system architecture provides a foundation for intelligent accelerator operation, reducing operator workload, improving beam stability, and enabling future implementation of advanced autonomous control strategies.

LLRF CONTROL

The LLRF system is based on the LIBERA digital stabilization platform, whose server-side software is implemented within the EPICS framework. Manufacturer-provided IOCs enable seamless integration with operator interfaces developed according to accelerator RF requirements. In addition to LIBERA, a Micro Telecommunications Computing Architecture (μTCA) platform is employed for timing distribution and advanced LLRF control. μTCA provides a modular and scalable architecture with high-speed backplane communication, deterministic timing, precise synchronization, and hot-swap capability, making it well suited for accelerator applications such as LLRF regulation, timing distribution, data acquisition, and real-time feedback control. Precise timing synchronization is achieved through a μTCA-based timing system that distributes clock and trigger signals to RF, laser, magnet, and diagnostic subsystems. This ensures deterministic operation and accurate synchronization of RF pulses with beam generation and diagnostics. The µTCA hardware combines FPGA-based real-time processing with high-speed communication. RF signals are digitized by high-speed ADCs and processed in FPGAs, where IQ demodulation, amplitude and phase detection, and feedback control algorithms are executed. The resulting control signals are generated through DACs and applied to RF amplifiers and modulators. A Python-based software layer provides system configuration, monitoring, data visualization, and diagnostics. A key feature of the system is an AI-based pulse tracking and alignment framework for automatic RF pulse analysis and synchronization. The system performs real-time pulse amplitude and timing measurements and uses these data to optimize accelerator operation. Adaptive control algorithms adjust solenoid, dipole, corrector, and quadrupole magnet settings to improve beam transport and stability. Machine-learning techniques ensure robust operation under noise and signal fluctuations, reducing manual tuning requirements while improving beam reproducibility and operational efficiency. This approach represents an important step toward autonomous accelerator control (Fig. 1).

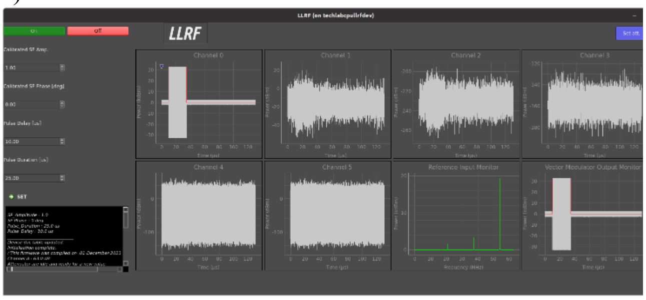

Figure 1: GUI for RF signal regulation and monitoring.

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.

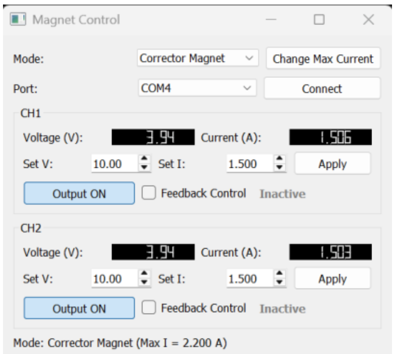

Figure 3: GUI for quadrupole and corrector magnets remote control.

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).

BEAM DIAGNOSTICS EQUIPMENT

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 WITH MAGNET CONTROL SYSTEM

To enable real-time beam diagnostics and automated accelerator control, an artificial intelligence (AI)-based beam detection system was developed using the YOLO (You Only Look Once) object detection architecture. Approximately 6,000 labeled beam images acquired from YAG-screen diagnostic cameras were used for training. The dataset covered a wide range of beam positions, sizes, intensities, and operating conditions. Data augmentation, including geometric transformations, brightness variations, and noise injection, was applied to improve model robustness. The trained model performs real-time beam localization and extracts key beam parameters, including centroid coordinates (x, y) and beam dimensions (w, h). These parameters are transmitted directly to the accelerator control system for online monitoring and feedback. The beam alignment system uses AI-derived centroid coordinates to implement closed-loop beam steering. The measured beam position is continuously compared with a predefined reference position (x0, y0), and correction signals are applied to horizontal and vertical steering magnets to minimize the position error. The feedback loop consists of image acquisition, AI-based beam detection, error calculation, steering correction, and position re-evaluation. The process is repeated until the beam satisfies the alignment criteria $|x - x_0| < \Delta x$ and $|y - y_0| < \Delta y$.

Beam dimensions (w, h) are simultaneously monitored to evaluate focusing quality. If the beam is correctly centered but exceeds predefined size limits, the system identifies inadequate focusing and initiates corrective adjustments of the solenoid settings. This integrated approach enables continuous beam stabilization and reduced operator intervention. The system was evaluated by comparing two operating modes: Baseline configuration and Iterative Learning Control (ILC) with pulse-to-pulse waveform optimization. Measurements were performed over 1200 pulses acquired at 20 Hz (Fig. 4).

With ILC enabled, reflected RF energy decreased by approximately 9%, indicating improved matching and accelerator efficiency. Independent Energy BPM measurements showed an increase in mean beam energy from 3.7002 MeV to 3.7502 MeV (≈50 keV gain). The energy spread was reduced from 0.01557 MeV to 0.00423 MeV, corresponding to an improvement factor of approximately 3.7. Similarly, the beam energy distribution width decreased from 0.0726 MeV to 0.0195 MeV. These results demonstrate enhanced beam quality, stability, and operational efficiency under ILC control. System reliability is ensured through communication timeouts, heartbeat monitoring, and clear GUI status indicators. Automatic reconnection mechanisms are implemented for serial and USB devices, while all communication errors are logged in a centralized database with timestamps.

Time-critical subsystems, including EPICS and low-level RF controls, operate independently from higher-level Python services, ensuring deterministic performance. Additional safeguards include parameter bounds checking, safe-state transitions in response to abnormal conditions, and integration with existing hardware protection systems such as interlocks, watchdogs, and current-limit circuits. Together, these measures provide a robust and fail-safe environment for accelerator operation.

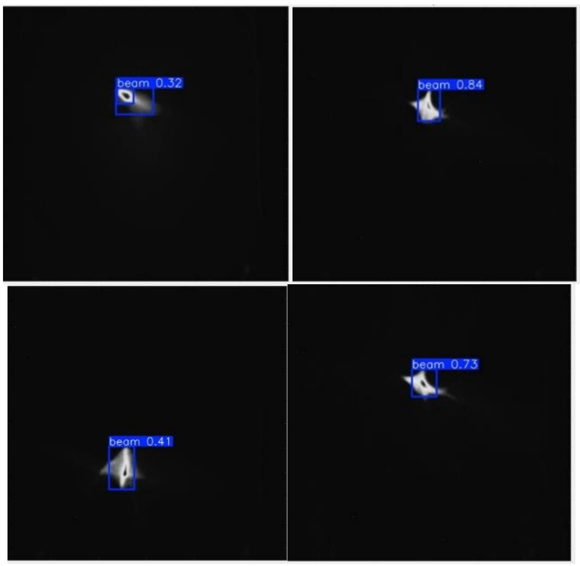

Figure 4: AI beam-based adjusted beam profile.

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. μTCA-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.

REFERENCES

[1] V.M. Tsakanov, et al., "AREAL test facility for advanced accelerator and radiation source concepts", Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, volume 829, 2016, pp. 284-290. doi: 10.1016/j.nima.2016.03.062

[2] V. M. Tsakanov, R. M. Aroutiounian, G. A. Amatuni, et al., "AREAL Low Energy Electron Beam Applications in Life and Materials Sciences", Nuclear Instruments and Methods in Physics Research A, v.829, pp. 248-253, 2016.

[3] G.A. Amatuni et al., "AREAL 50 MeV Electron Accelerator Project for THz and Middle IR FEL", in Proc. 8th Int. Particle Accelerator Conf. (IPAC'17), Copenhagen, Denmark, May 2017, pp. 1355-1357. doi:0.18429/JACoW-IPAC2017-TUPAB020

[4] B. Grigoryan, G. Amatuni, V. Avagyan, A. Grigoryan, M. Ivanyan et al., "Advanced research electron accelerator laboratory based on photocathode rf gun", IPAC11-2nd International Particle Accelerator Conference, 1066-1068, Kursaal, San Sebastian, 2011.

[5] V. Avagyan, V. Danielyan, A. Gevorgyan, V. Vardanyan, T. Mkrtchyan, et al., "Vacuum Apparatus for Thermal Testing of Electronic Equipment" Proceedings of IVESC-ICEE-2014, Saint-Petersburg, Russia, June 30-July04, 2014, ISBN 978-1-4799-5770-5, p 25

[6] A.Gevorgyan, V. Avagyan, V. Vardanyan, T. Mkrtchyan, et al., "An UHV Vacuum System for AREAL Linear Accelerator" Proceedings of IVESC-ICEE-2014, Saint-Petersburg, Russia, June 30-July 04, 2014, ISBN 978-1-4799-5770-5, p 87-89

[7] A.A. Gevorgyan, V.S. Avagyan, B. Grigoryan, T.H. Mkrtchyan, A.S. Simonyan, V. V. Vardanyan, "Design and Performance of Ultimate Vacuum System for the AREAL Test Facility" Proceedings of IPAC2014, pp., 2311-2313, Dresden, Germany 2014.

[8] A. Vardanyan et al., "Travelling Wave Accelerating Structure for Areal 50 MeV Energy Upgrade", in Proc. 8th Int. Particle Accelerator Conf. (IPAC'17), Copenhagen, Denmark, May 2017, pp. 4130-4132. doi:10.18429/JACoW-IPAC2017-THPIK014

[9] A.Vardanyan, H. Avdishyan, H. Davtyan, B. Grigoryan, L.H. Hakobyan, H. Poladyan, "Design and Commissioning of S-Band RF Station for AREAL Test Facility" Proceedings of IPAC2014, pp., 3834-3436, Dresden, Germany 2014.

[10] A.Tsakanian, A. Simonyan, B. Grigoryan, et al., "AREAL Solenoid, Dipole and Steering Magnets Design and Performance" Proc. of IPAC2014, Dresden, Germany, p. 1223-1225

[11] H. Davtyan, G.A. Amatuni, A.A. Asoyan, A. Grigoryan, and M.G. Yazichyan, "The Influence of Solenoid Field on Off-Axis Travelling Beam in AREAL Accelerator", in Proc. IPAC'22, Bangkok, Thailand, Jun. 2022, pp. 422-424. doi:10.18429/JACoW-IPAC2022-MOPOTK001

[12] V. Vardanyan, G. Amatuni, et al., "Distributed Cooling System for the AREAL Test Facility" Proceedings of IPAC2014, pp., 4010-4012, Dresden, Germany 2014.

[13] V. Vardanyan, V. Avagyan, A. Gevorgyan, T. Mkrtchyan,et al., "Cooling Systems for Advanced Vacuum Electron Sources" Proceedings of IVESC-ICEE-2014, Saint-Petersburg, Russia, June 30-July04, 2014, ISBN 978-1-4799-5770-5, p 260-261.

[14] G. A. Amatuni, A. Sargsyan, V. V. Sahakyan, G. S. Zanyan, N. W. Martirosyan, V. V. Vardanyan and B.A. Grigoryan, "An Overview of Beam Diagnostic and Control Systems for 50 Mev AREAL Linac", Journal of Instrumentation, v. 12, pp. 1-9, 2017.

[15] V. Sahakyan, G. Amatuni, A. Azatyan, B. Grigoryan, N. Martirosyan, A. Sargsyan, V. Tsakanov, G. Zanyan, "Beam Diagnostic and Control Systems for AREAL 50 MeV Linac", Proceedings of IPAC'17, Copenhagen, Denmark, pp. 114-116, 2017.

[16] H. Tamoyan, G. Zanyan, H. Davtyan, "Low Energy Electron Beam Emittance Measurement at AREAL Accelerator ", Armenian Journal of Physics, vol. 12, issue 2, pp. 170-177, 2019.

[17] G. Amatuni et al., "Measurements of the transverse beam emittance at the AREAL linac", in Proc. IPAC'24, Nashville, TN, May 2024, pp. 2206-2209. doi:10.18429/JACoW-IPAC2024-WEPG12

[18] A. Lorsabyan, A. Gevorgyan, B. Grigoryan, A. Simonyan, V. Clet, A. Courjaud, T.K. Sargsyan, "Yb DOPED HIGH-ENERGY UV ULTRAFAST LASER FOR AREAL FACILITY" Proceedings of IPAC2014, pp., 2412-2414, Dresden, Germany 2014.

[19] V. Khachatryan, V.Petrosyan, A. Sargsyan, "Radiation Safety Considerations for Areal Electron Linac With Beam Diagnostic System" Proc. of IPAC2014, Dresden, Germany, p. 1647-1649.