

AUTOMATED CONTROL AND MONITORING INFRASTRUCTURE FOR THE CROCKER NUCLEAR LABORATORY CYCLOTRON

C. López, M. Backfish, H. Berns, M. Novotny, R. Sahebzada, E. Prebys*
Crocker Nuclear Laboratory, University of California, Davis, CA, USA

Abstract

The Crocker Nuclear Laboratory (CNL) is advancing a next-generation control system architecture tailored for scalable, high-speed, and AI-integrated Cyclotron operations. The platform adopts a hybrid approach: LabVIEW® and CompactRIO (cRIO) provide deterministic device-layer control, while a modular Python-based supervisory and application layer enables high-level coordination, responsive visualization, structured data, and logging. Communication protocols were benchmarked to guide system design, revealing that ZeroMQ achieves sub-millisecond latency—over ten times faster than standard TCP/IP implementations (100 ms). This performance difference is critical for real-time responsiveness and the future deployment of autonomous control strategies. The architecture is designed to operate in parallel with existing infrastructure. While the system has been tested on the main Cyclotron Magnet, it is readily extendable to other subsystems, including the beam source, extraction beam, and beamline transport elements. It establishes a robust foundation for adaptive optimization, predictive fault detection, and fully AI-native accelerator control, in line with recent trends in modern control architectures.

INTRODUCTION

The CNL at UC Davis operates a 76-inch isochronous cyclotron for proton therapy, aerospace testing, and nuclear science [1]. To enable AI-driven control and high-precision beam diagnostics, we present a hybrid control architecture that combines deterministic LabVIEW® (1 kHz real-time I/O) [2], Python-based analytics [3], and custom electronics—achieving picoamp-level current sensitivity and over tenfold lower latency than TCP/IP via ZeroMQ.

While LabVIEW and NI hardware ensure safety-critical control [2], Python orchestrates high-rate telemetry logging (via SQLite), machine learning workflows [4], and responsive operator interfaces. This modular design operates in parallel with the legacy control system, allowing seamless commissioning without system downtime. To overcome limitations in low-current measurement, we developed a high-dynamic-range ammeter (pA– μ A) [5] and galvanically isolated [6] readouts to extract signals from existing analog meters without introducing interference.

The benchmarks demonstrate ZeroMQ's submillisecond round-trip latency [3], facilitating real-time feedback for autonomous tuning. The architecture provides a scalable framework for predictive maintenance and optimization across cyclotron subsystems, with immediate applications in beamline stability. Figure. 1 shows a labeled cutaway view of the CNL

cyclotron, highlighting key magnetic elements controlled by the system.

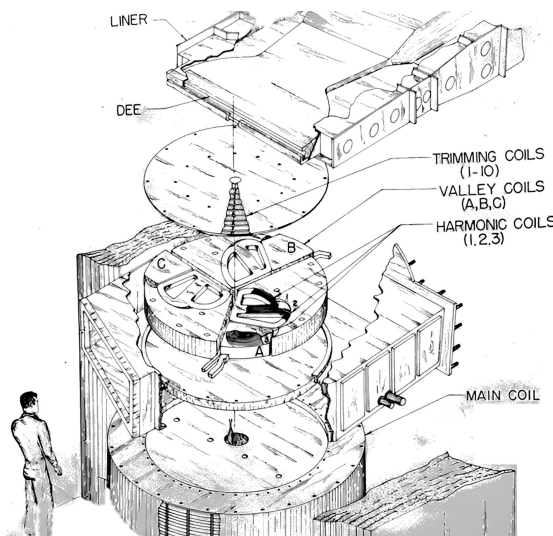


Figure 1: Schematic of the CNL 76-inch isochronous cyclotron.

DEVICE LAYER: HARDWARE INTEGRATION AND BEAM DIAGNOSTICS

The device layer, shown at the base of the system architecture in Fig.2, interfaces directly with the cyclotron's analog and digital signals via National Instruments (NI) cRIO. This layer acquires over 50 real-time inputs/outputs—including actuator voltages, interlock states, and beamline diagnostics—at deterministic 1 kHz rates using LabVIEW® [2]. To support high-sensitivity feedback, CNL developed a custom analog front-end for beam current monitoring. The circuit integrates multiple gain stages and a logarithmic amplifier topology based on the LT1012 precision operational amplifier [5], achieving a dynamic range spanning from picoamps to over 100 μ A. To ensure compatibility with the existing analog monitoring infrastructure, galvanic isolation was implemented using precision isolated amplifiers [6]—allowing accurate current measurements without introducing electrical interference or compromising legacy systems. This design eliminates switching artifacts common in range-selectable instruments and enables precise, continuous diagnostics across wide current levels. In combination with high-current actuator telemetry, the device layer provides full-spectrum observability of the cyclotron's physical state—forming the foundation for AI-based feedback, real-time beam stabilization, and predictive anomaly detection.

* eprebys@ucdavis.edu

logged into an SQLite database on a dedicated thread, capturing actuator values and timestamps at 1 Hz. This ensures persistent data collection even during GUI outages and provides a rich dataset for trend analysis and machine learning.

By abstracting the interface between deterministic control and high-level application logic, the supervisory layer ensures robust, extensible operation while supporting high-speed feedback and future autonomous control.

HIGH-LEVEL APPLICATION LAYER

The application layer is implemented in Python and serves as the primary interface for operators and advanced computational modules. It connects to the supervisory layer via ZeroMQ, replacing an earlier TCP/IP-based implementation. Operating independently of the deterministic control loop, this layer supports responsive interaction and high-frequency data exchange with minimal latency.

A graphical interface provides real-time visualization of all actuator states, current feedback. Users can adjust set-points and toggle channels directly through the GUI, with updates transmitted every 10 ms. All incoming telemetry is parsed continuously and rendered with low latency for intuitive monitoring.

In parallel, the application layer logs all values—currents, digital states, and timestamps—into a local SQLite database at 1 Hz. The architecture supports integration of data-driven modules, including anomaly detection, predictive diagnostics, and reinforcement learning-based beam optimization [4,7]. Python's native compatibility with machine learning frameworks ensures autonomous control strategies.

This layer completes the separation between real-time control and supervisory intelligence, enabling modular extensions, remote operation, and AI-native optimization workflows.

CONCLUSION AND OUTLOOK

The control system developed at CNL establishes a modular AI-native foundation for real-time cyclotron operation. By combining deterministic LabVIEW® control with cRIO NI hardware and a Python-based supervisory and application layer, the architecture enables robust, scalable, and low-latency performance. Each layer is optimized for its function—fast, hardware-timed I/O at the device and control levels; flexible communication and logging at the supervisory layer; and extensible visualization and AI integration at the application level. ZeroMQ has been validated as the pre-

ferred messaging protocol, offering sub-millisecond responsiveness critical for autonomous feedback and optimization.

Initial commissioning tests demonstrated reliable system performance. The custom ammeter achieved stable beam current monitoring across a dynamic range spanning from picoamps to microamps. The SQLite logging infrastructure successfully handled more than 50 channels at rates exceeding 1 kHz without data loss, supporting future machine learning data set generation and long-term diagnostic traceability.

This infrastructure lays the foundation for closed-loop beam optimization, predictive fault mitigation, and intelligent system tuning powered by real-time feedback and AI. Future work will focus on integrating online learning agents, anomaly detection modules, and autonomous beamline coordination—advancing toward fully self-optimizing cyclotron operation.

ACKNOWLEDGMENTS

This work was supported by the Crocker Nuclear Laboratory and the University of California, Davis. Additional support was provided by the ANID Becas Chile scholarship [grant number 72160516].

REFERENCES

- [1] CNL, <https://crocker.ucdavis.edu>
- [2] E. Loftin *et al.*, “Magnet Mapping At LANSCE”, in *Proc. IEEE Pulsed Power Conf. (PPC)*, San Antonio, TX, USA, pp. 1–4, Jun. 2023. doi: 10.1109/PPC47928.2023.10310771
- [3] H. Chen, G. F. Liu, D. Zhang, T. Qin, and X. K. Sun, “A study of performance comparison of databases for HALF data archiving system”, *J. Instrum.*, vol. 18, no. 12, p. P12015, 2023. doi: 10.1088/1748-0221/18/12/P12015
- [4] A. Scheinker, “cDVAE: VAE-guided diffusion for particle accelerator beam 6D phase space projection diagnostics”, *Sci. Rep.*, vol. 14, p. 29303, 2024. doi: 10.1038/s41598-024-80751-1
- [5] Linear Technology, *LT1012 Precision input current, microvolt offset, low noise Op Amp*, 2018. <https://www.analog.com/media/en/technical-documentation/data-sheets/lt1012.pdf>
- [6] Texas Instruments, *AMC3301 Precision, Isolated Amplifier Datasheet*, May 2025. <https://www.ti.com/lit/ds/symlink/amc3301.pdf>
- [7] R. J. Shalloo *et al.*, “Automation and control of laser wakefield accelerators using Bayesian optimization”, *Nat. Commun.*, vol. 11, no. 1, p. 6355, 2020. doi: 10.1038/s41467-020-20245-6