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ADVANCING CONDUCTION-COOLED 650 MHz SRF TECHNOLOGY FOR INDUSTRIAL ACCELERATORS AT FERMILAB'S IARC

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Abstract

The National Nuclear Security Administration (NNSA) funds the Illinois Accelerator Research Center (IARC) at Fermilab in developing a high-power, conduction-cooled Superconducting Radio Frequency (SRF) accelerator tailored for industrial applications requiring robust and efficient operation. A 650 MHz, 1.6 MeV, 20 kW SRF accelerator is currently under development, employing a conduction cooling approach to simplify cryogenic requirements and enhance accessibility for industrial use. The accelerator's control system is implemented on the Blinky Lite platform, selected for its open-source architecture, secure remote access capabilities, and operational flexibility—attributes advantageous for industrial deployment and sustained operation. A dedicated beamline is designed to measure essential beam parameters and test the integrated performance of the accelerator and control systems, thereby validating their operational readiness for intended applications.

MOTIVATION FOR THE COMPACT SRF ACCELERATORS

Cobalt-60 (Co-60) has long been the primary technology for sterilizing medical devices. However, growing safety, security, and environmental concerns are driving a global transition away from isotope-based sterilization. At the same time, existing X-ray and electron beam (e-beam) systems often fail to provide the beam power, reliability, or cost efficiency required for high-throughput industrial use.

The demand for deployable, U.S.-manufactured alternatives has intensified, with strong support from the Office of Radiological Security (ORS) for solutions that enhance both resilience and security. In response, Fermilab, in partnership with the National Nuclear Security Administration (NA-22), is developing a next-generation 20 kW, 1.6 MeV continuous e-beam system operating at 650 MHz (Fig. 1) [1].

This platform employs an Nb_3Sn superconducting cavity [2] cooled by commercial cryocoolers [3, 4], eliminating the need for complex cryogenic infrastructure and enabling push-button operation without specialized staff. Its compact and rugged design, with an integrated RF gun and efficient RF system, makes it suitable for large-scale industrial deployment. While optimized for medical device sterilization, the system also holds promise for environmental applications such as PFAS remediation and waste treatment [5]. This paper will focus on the control system architecture and

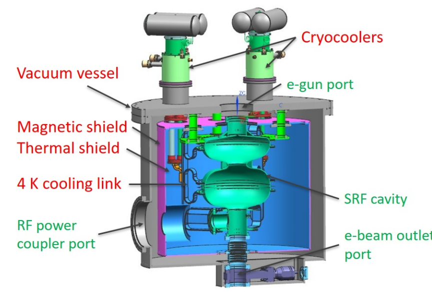

Figure 1: Section view of the 1.6 MeV 20 kW 650 MHz conduction-cooled SRF e-beam accelerator.

beamline design that enable reliable, high-throughput performance.

BLINKY LITE CONTROL SYSTEM

A reliable and fully integrated control system is essential for deploying compact accelerators in industrial environments. To meet this need, the project adopts the Blinky Lite control system, a lightweight, full-stack solution that includes all necessary features for efficient and secure operation. The system integrates device interfaces, communication protocols, configuration databases, alarm and notification systems, device viewers, plotting tools, as well as access and setting history, ensuring seamless operation and comprehensive oversight. The control system architecture is demonstrated in Fig. 2.

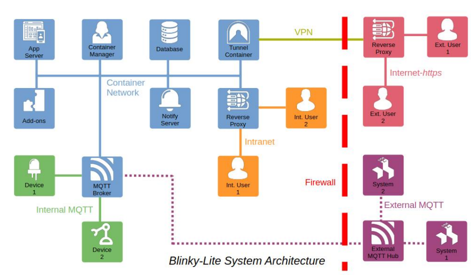

Figure 2: Blinky Lite Architecture.

Because industrial facilities often operate continuously, unexpected issues can arise at any time, including during overnight shifts when experts may be off-site. The Blinky Lite [6] system addresses this challenge by providing secure remote access, allowing engineers to monitor and intervene in real time from the field. This capability enhances both reliability and responsiveness, which are critical for high-throughput applications. Ultimately, the control system supports the project's goal of delivering a compact, rugged accelerator that can be reliably operated in industrial settings without the constant presence of specialized personnel.

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The Compact Superconducting RF-Linear Accelerator Test Stand (CSRF-LATS)

The Compact Superconducting RF Linear Accelerator Test Stand (CSRF-LATS), originally developed to demonstrate conduction cooling, has been repurposed as the platform for commissioning and integrating the control system [4, 7].

The control system leverages the Blinky-Lite instrumentation suite (Fig. 3), which is built on the *Raspberry Pi PicoW* platform. A generic Blinky-Lite tray interface is used to connect with the PicoW, and the tray code is packaged within a Docker container for streamlined deployment on the control system server.

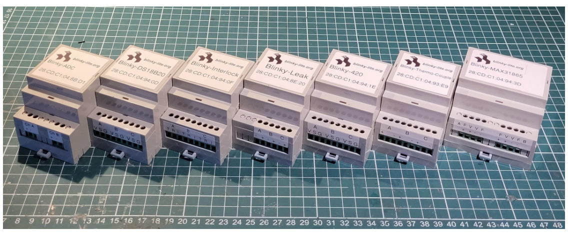

Figure 3: The Blinky Lite Instrumentation Suite.

Among the key components is the *Bl-Max31865 Cryogenic Temperature Measurement System*, a precision four-wire measurement system based on the *MAX31865* chip, as shown in Fig. 4. Each module provides two channels with 15-bit resolution, operates wirelessly without communication cables, and is optimized for low power consumption, requiring a 3.7–5.2 V supply with a maximum draw of 65 mA. Designed for efficient operation, it supports pulse-mode excitation with a minimum pulse length of 100 ms and is packaged in a compact four-module-wide DIN enclosure. These features make the system particularly well-suited for cryogenic accelerator environments, where minimizing cabling, reducing thermal load, and ensuring precise, reliable temperature monitoring are essential for stable operation.

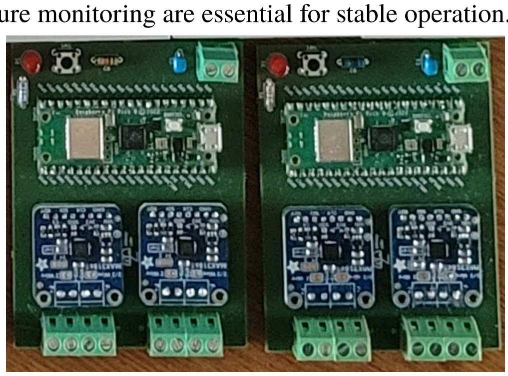

Figure 4: The MAX31865 chip enables wireless, high-precision temperature monitoring while minimizing thermal load, making it particularly advantageous for cryogenic applications.

The first stage of control system integration of external hardware focuses on the vacuum and cryogenic subsystems. The insulating vacuum of the cryostat is maintained using a *Leybold 450 i Turbocart*. While the vacuum cart offers limited remote control functionality, key operational parameters can be adjusted via the front panel. Remote capabilities include power control (on/off), vacuum pressure monitoring, and alarm status reporting, all accessible through a DB-15 interface. This interface is connected to a *CONTROLLINO MAXI Automation programmable logic controller (PLC)*, which enables integration with the broader control system.

For cryogenic cooling, the cavity is maintained at low temperature using a *CryoMech pulse tube cryocooler*, powered by the *CPA1114 Compressor Package*. The compressor supports communication via the Modbus protocol over an Ethernet interface, allowing for robust and flexible remote monitoring and control.

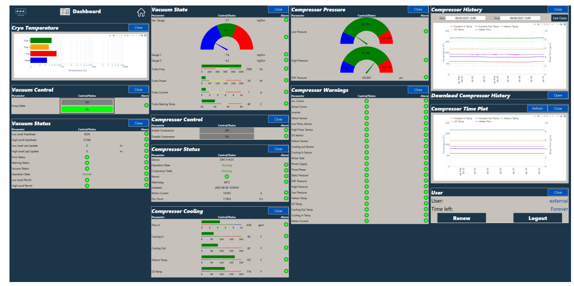

Figure 5: The Blinky Lite Dashboard monitoring the vacuum, cryo status, and establishing superconductivity for the SRF cavity.

With vacuum control, cryogenic control, and temperature monitoring fully integrated into the Blinky Lite system, a stable conduction-cooled cryogenic environment has been established. Figure 5 illustrates the vacuum and cryogenic monitoring dashboard implemented within the Blinky Lite interface.

LOW LEVEL RF SYSTEM

The compact nature of the conduction-cooled accelerator necessitates that all supporting sub-systems be similarly compact and cost-effective. To address this, a novel low-level RF (LLRF) system was developed based on the *Red Pitaya STEMlab 125-14*, a credit-card-sized RF signal acquisition and generation platform available for under $700. The complete LLRF system consumes less than 8 W of wall-plug power and weighs under 1.2 kg, making it highly suitable for integration in space- and power-constrained environments. The system has been successfully tested on a superconducting 650 MHz cavity with a loaded quality factor exceeding 10^9, achieving accelerating gradients over 3 MV/m in the presence of microphonic vibrations exceeding 30 Hz with frequency content up to 300 Hz. Under these conditions, the system maintained amplitude regulation better than 0.5 % and phase stability within 0.2 degrees. (Figure 6)

The *Red Pitaya STEMlab 125-14* is a compact FPGA-based platform featuring dual 125 Msps, 14-bit ADCs and DACs, and is based on the *Xilinx Zynq 7010 SoC* architecture. The system operates on just 5 V DC and consumes approximately 1 W of power. Due to the limited clock rate of the FPGA, a single sideband (SSB) upconversion scheme was implemented to generate the required 650 MHz RF signal from a 25 MHz baseband signal. This upconversion uses a

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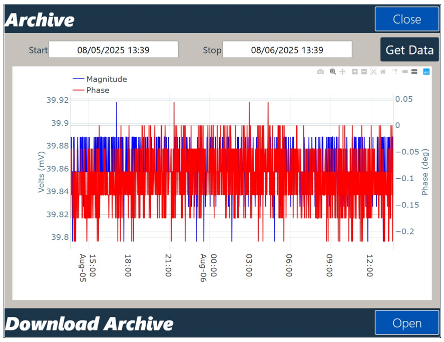

Figure 6: The phase and amplitude over a day.

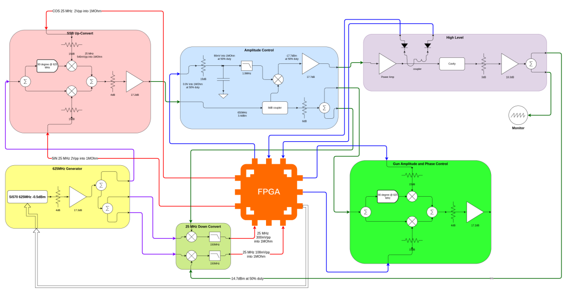

Figure 7: The block diagram of the LLRF system.

625 MHz low-phase-noise *Si570 voltage-controlled crystal oscillator (VCXO)*, programmable via I^2C, and thermally stabilized using a custom resistor-based heater bank regulated by a *Raspberry Pi PicoW* running a PI loop, all integrated within the Blinky Lite control system. The amplitude and phase of the cavity drive signal are controlled via mixer-based modulation and adjusted in real time by the FPGA. Cavity feedback is down-converted using the same 625 MHz reference to suppress DC offsets, enabling robust phase lock and amplitude regulation. Figure 7 shows the block diagram of the LLRF system.

BEAM LINE DESIGN

The beamline is designed to support the measurement of both beam current and energy while also ensuring safe deposition of the beam into the beam dump. Beam energy is determined through a combination of beam steering and position measurements using a beam position monitor (BPM). Beam current can be measured at the beam dump, and the BPM also provides an additional method for current estimation. To prevent thermal damage and avoid localized heating, the beam is deliberately spread across the surface of the beam dump, minimizing the formation of hot spots, as shown in Fig. 8. The beamline layout is shown in Fig. 9.

CONCLUSION

A compact, conduction-cooled superconducting electron accelerator platform has been developed with fully integrated control, RF, and diagnostics systems tailored for industrial deployment. The Blinky Lite control system provides full-stack instrumentation, secure remote access, and streamlined operation across vacuum, cryogenics, and beam diagnostics. A low-cost, low-power LLRF system enables stable

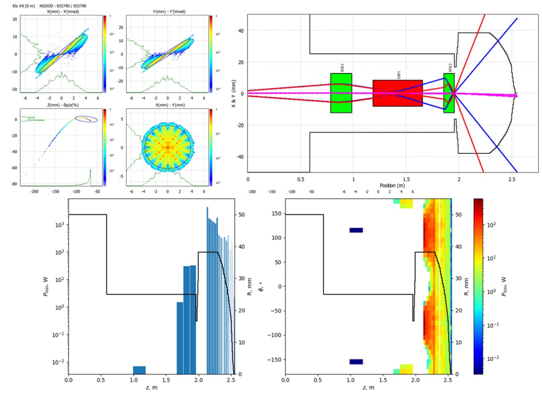

Figure 8: Simulated beam profile from MICHELLE [8, 9] based on the electron gun and cavity. Then propagated through the beam line with TraceWin [10, 11]. Beamline design minimizes hot spots on the dump; peak power loss is limited to 350 W/cm^2.

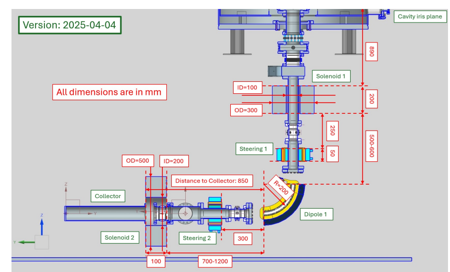

Figure 9: Beamline layout featuring a focusing solenoid, 90° dipole bend, and defocusing solenoid.

operation with sub-percent amplitude and sub-degree phase regulation. The beamline, designed to support energy and current measurements, incorporates thermal management strategies to absorb beam power safely.

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REFERENCES

[1] T. K. Kroc, J. C. Thangaraj, R. T. Penning, and R. D. Kephart, "Accelerator-driven medical sterilization to replace Co-60 sources", Fermi National Accelerator Lab., Batavia, IL, USA, Rep. FERMILAB-PUB-17-314-DI, 2017. `https://www.osti.gov/biblio/1394793`

[2] S. Posen and D. L. Hall, "Nb_3Sn superconducting radiofrequency cavities: fabrication, results, properties, and prospects", *Supercond. Sci. Technol.*, vol. 30, no. 3, p. 033004, 2017. `doi:10.1088/1361-6668/30/3/033004`

[3] R. C. Dhuley, S. Posen, M. Geelhoed, O. Prokofiev, and J. Thangaraj, "First demonstration of a cryocooler conduction cooled superconducting radiofrequency cavity operating at practical cw accelerating gradients", *Supercond. Sci. Technol.*, vol. 33, no. 6, 06LT01, 2020. `doi:10.1088/1361-6668/ab82f0`

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[4] R. C. Dhuley, S. Posen, M. Geelhoed, and J. Thangaraj, “Development of a cryocooler conduction-cooled 650 MHz SRF cavity operating at ~10 MV/m cw accelerating gradient”, in *IOP Conf. Ser.: Mater. Sci. Eng.*, p. 012147, 2022. doi:10.1088/1757-899x/1240/1/012147

[5] C. Lange and C. Cooper, “Degradation of Poly-and Perfluoroalkyl Substances (PFASs) in water via high power, energy-efficient electron beam accelerator”, 3M Company, Maplewood, MN, USA, Rep. FERMILAB-POSTER-23-058-ETD, 2024. doi:10.2172/1974706

[6] D. McGinnis, Blinky lite. https://blinky-lite.org/index.html

[7] Y. Ji *et al.*, “Experiments on a conduction cooled superconducting radio frequency cavity with field emission cathode”, *arXiv*, 2022. doi:10.48550/arXiv.2208.14905

[8] J. Petillo *et al.*, “The MICHELLE three-dimensional electron gun and collector modeling tool: theory and design”, *IEEE Trans. Plasma Sci.*, vol. 30, no. 3, pp. 1238–1264, 2002. doi:10.1109/TPS.2002.801659

[9] J. J. Petillo, E. M. Nelson, J. F. DeFord, N. J. Dionne, and B. Levush, “Recent developments to the MICHELLE 2-D/3-D electron gun and collector modeling code”, *IEEE Trans. Electron Devices*, vol. 52, no. 5, pp. 742–748, 2005. doi:10.1109/TED.2005.845800

[10] *TraceWin*, CEA Saclay, 2014.

[11] D. Uriot, N. Pichoff, *et al.*, “Status of TraceWin code”, in *Proc. IPAC’15*, Richmond, VA, USA, May 2015, pp. 92–94. doi:10.18429/JACoW-IPAC2015-MOPWA008