PYTHON-EPICS RF CONDITIONING AUTOMATIC CONTROL SYSTEM AT THE SPALLATION NEUTRON SOURCE *

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Abstract

The RF Test Facility (RFTF) at the Spallation Neutron Source (SNS) is used for the conditioning of RF components such as ceramic vacuum windows and power couplers prior to their installation in the H^- ion linear accelerator. This process exposes components to high-power RF fields and thermal cycling to improve performance and remove surface impurities. To automate and optimize this process, a Python-based EPICS control system was developed alongside targeted hardware upgrades. The system enables real-time monitoring and control of RF power levels, temperature, and vacuum pressure. A user-friendly graphical interface was implemented using CS-Studio (Phoebus), allowing operators to adjust parameters and collect data efficiently. The system integrates a High-Power Protection Module (HPM) for interlocks based on vacuum and arc detection, ensuring safe operation. These upgrades have significantly improved the efficiency, accuracy, and safety of RF conditioning at the SNS RFTF. This paper describes the updated RF conditioning system, highlighting the software and hardware developments and their application in support of the Proton Power Upgrade (PPU) project.

INTRODUCTION

The Spallation Neutron Source (SNS) at Oak Ridge National Laboratory is a pulsed proton driver facility whose linear accelerator delivers beam to a liquid-mercury target for neutron production. High-power RF components, including ceramic vacuum windows, waveguide couplers, and klystron amplifiers are conditioned off-line to their full operational duty cycle and power levels at the RFTF before accelerator installation. This conditioning progressively exposes components to increasing RF fields and temperatures which aids in the outgassing of surface contaminants and suppresses multipacting [1].

The nearly completed Proton Power Upgrade (PPU) aims to increase the SNS beam power capability from 1.4 MW to 2.8 MW by raising the beam energy by 30% and the beam current by 50% [2]. Meeting the PPU schedule required conditioning substantially more RF components and spares, including new PPU superconducting couplers and klystrons which placed significant demands on RFTF. To address these requirements, the RFTF control system was modernized from a legacy EPICS sequencer program to a Python-based EPICS state machine; the operator interface was updated to CSS-Phoebus; and coordinated hardware upgrades were implemented for the High-Power RF (HPRF) and Low-Level RF (LLRF) systems. This paper describes the updated system architecture, the end-to-end conditioning workflow, and the upgrades and conditioning results achieved in support of the PPU project.

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RFTF SYSTEM OVERVIEW

The RFTF at the SNS consists of two independent HPRF test stands that operate at 402.5 MHz and 805 MHz. The 402.5 MHz test stand utilizes a WR2100 waveguide system and supports klystrons rated for up to 3 MW of RF peak power. The 805 MHz test stand uses WR1150 and WR975 waveguide sections and incorporates klystrons capable of providing 5 MW of RF peak power. Both test stands are powered by High-Voltage Converter Modulators (HVCM) with a maximum output of 11 MW at an 8% duty cycle and 60 Hz.

Each stand integrates three subsystems: An HPRF transmitter, which includes the klystron, circulator, waveguide system, and associated components; a LLRF system, which provides precise control of the RF power; and vacuum diagnostics, which include cold cathode gauges, roughing and turbo pumps and a residual gas analyzer. Fast protection against vacuum faults, arcing, and RF faults is provided by the LLRF system through a VXI-based LLRF High-Power Protection Module (HPM). Directional couplers at the input and output of the test assembly provide forward and reflected power measurements to the HPM and RF power meters used by the conditioning program. Fig. 1 shows a schematic of the system during RF vacuum window conditioning.

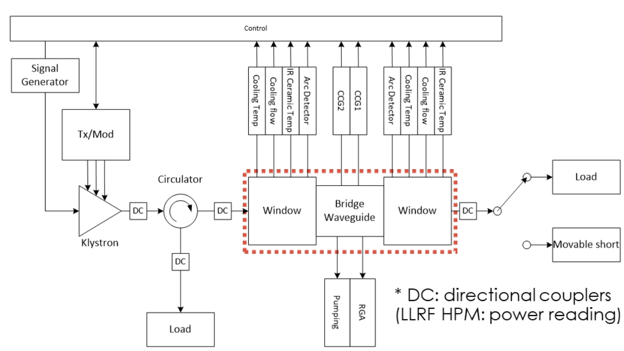

Figure 1: Schematic of the SNS RFTF test stand showing the back-to-back bridge waveguide (BWG) assembly, directional couplers, vacuum instrumentation, and HPM interlock signal path. The water load is replaced by a movable short for standing-wave conditioning.

RF CONDITIONING WORKFLOW

The RFTF conditioning process follows five sequential steps:

1. Assembly: In a clean room, bridge waveguides and gate valves are ultrasonically cleaned, vacuum leak integrity is verified to better than 1×10^{-9} Torr·L/s, and a baseline VNA S-parameter measurement is recorded.
2. Baking: Assemblies are baked at 120–200 °C for a minimum of 72 hours under 10^{-9} Torr vacuum using resistive heat tapes and RTDs managed by a temperature controller. RGA partial pressures are logged throughout. (Fig. 2)
3. Installation: After baking, the assembly is installed in the appropriate test stand and all protection interlock channels-HPM, vacuum CCGs, arc detectors, and water flow-are verified.
4. Conditioning: High-power RF processing proceeds using the automated conditioning modes described in following section. (Fig. 4)
5. Storage: Conditioned components are subsequently stored under dry nitrogen or vacuum using an actively pumped manifold.
6. Inventory Update: The component inventory database is updated and a report is generated. This report summarizes the conditioning and includes conditioning steps, plots and RGA records.

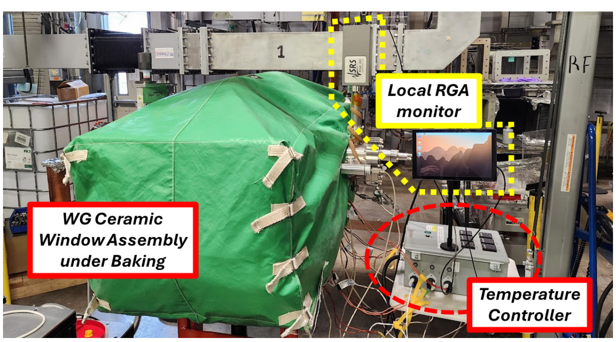

Figure 2: Waveguide ceramic window assembly baking in progress prior to high-power RF conditioning at the SNS RFTF. The green thermal insulation blanket covers the baking assembly; heat tapes and RTDs (not visible) are managed by an automated temperature controller following a 12-hour ramp-up, soak, and ramp-down profile.

PYTHON-EPICS CONTROL SYSTEM

The EPICS conditioning sequencer originally implemented in State Notation Language (SNL) has been replaced with a Python-EPICS state machine running on a soft IOC. Python was selected for its flexibility, maintainability, and access to third-party libraries that simplify logging, analysis, and future feature expansion. The control logic evaluates relevant EPICS process variables (PVs) on each execution cycle and updates RF power and pulse parameters accordingly. State transitions, parameter changes, and fault events are archived in a timestamped, plain-text elog, and a separate log records RGA partial pressures at user-programmable intervals to preserve the conditioning history for each component. The controller interfaces with EPICS using common Python EPICS modules, namely PCASpy [3] for exposing a small set of application PVs (setpoints, limits, mode/status flags) and PyEPICS [4] for reading and writing existing IOC PVs associated with the signal generator (SG), LLRF/RF permit chain, vacuum instrumentation (CCG), and RF power readbacks. This software-based approach integrates cleanly with the existing EPICS infrastructure while keeping the conditioning logic easy to modify and extend.

The state machine implements three automatic operation modes - ***AutoRun***, ***AutoPW***, and ***AutoCycle*** - with supervisory vacuum and trip handling (Fig. 3). In ***AutoRun***, RF power is increased by stepping the SG output at a configurable interval until a user-defined forward-power goal is reached. When a trip occurs, the software classifies the fault and applies the configured recovery behavior: for recoverable permit/interlock trips, it can either automatically ramp back to the goal after the permit is restored, or hold and wait for an operator reset. An arc-fault trip is treated as a non-recoverable event. The controller stops immediately, exits automatic operation, and remains idle until the user intervenes and resets the system.

When the forward-power goal is reached, the controller can transition to ***AutoPW***. This mode increases the pulse width in discrete steps up to a programmable maximum using a countdown timer and automatically disables once the maximum pulse width is reached. Alternatively, the ***AutoCycle*** mode varies the forward power between adjustable minimum and maximum bounds with a programmable soak time, executing cycle-up and cycle-down phases. Vacuum protection is handled via the CCG. When the CCG pressure exceeds a user-defined limit, the controller rapidly suppresses RF power by backing off the SG level. This limit can be adjusted during operation and normal ramping/cycling resumes automatically after pressure recovers. The operator interface has been migrated from EDM to CSS-Phoebus [5, 6], providing a consolidated view of key readbacks (HVCM/klystron status, forward/reflected power, vacuum, interlocks, and trip counters) and allowing conditioning parameters to be adjusted online without stopping the program.

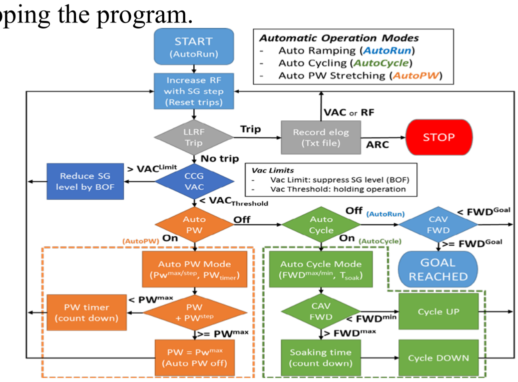

Figure 3: Python-EPICS conditioning state diagram: AutoRun (auto ramping), AutoPW (pulse-width stretching), AutoCycle (power cycling with soak time), and vacuum/permit-trip handling and fault logging.

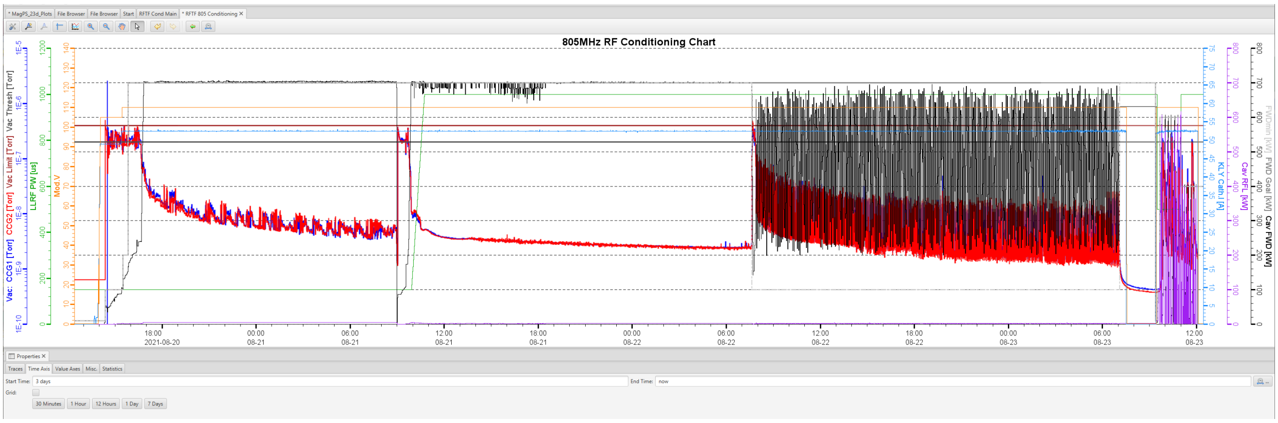

Figure 4: Typical SNS RFTF RF-conditioning sequence (~2 weeks): ramp power, step up pulse width/duty cycle, hold at full power, and optionally power-cycle; SCL couplers may use a movable short for standing-wave conditioning.

SYSTEM UPGRADES IN SUPPORT OF THE PPU PROJECT

A second modulator (RFAX HVCM) was installed in 2015 to support the SNS Beam Test Facility (BTF) and the RFTF 402.5 MHz test stand. During routine operation, the RFAX HVCM primarily serves the 402.5 MHz test stand, while the original RFTF HVCM primarily supports the 805 MHz test stand. However, the flexibility of the RFTF HVCM to power either test stand was maintained. The LLRF signal generation and pulse timing for the two frequencies are fully separated, enabling the 402.5 MHz and 805 MHz stands to run independent conditioning campaigns in parallel. On the software side, the conditioning program evolved from the original JLAB LabVIEW system through an EPICS sequencer to the current Python-EPICS implementation, reducing maintenance burden and simplifying adaptation to new component types. The RFTF conditioned all RF components required for the PPU, including SCL couplers [7], as summarized in Table 1.

Table 1: RF Components Conditioned at the SNS RFTF Since 2019 in Support of the PPU Project

Component Type	Qty.	Notes
SCL Fundamental Power Couplers	46	805MHz, up to 700kW peak at 6% duty; includes all PPU couplers [7]
Klystrons (DC/RF conditioning)	23	Includes all PPU klystrons
PPU WG Circulators & Water Loads	Multiple	New PPU hardware qualification
NCL Windows & Couplers (RFQ/CCL/DTL)	Multiple	Ongoing spare preparation; 402.5 MHz

ONGOING DEVELOPMENTS

Several enhancements are underway to further improve conditioning efficiency and expand the capabilities of the RFTF. A camera-based thermal imaging system is being implemented for real time monitoring of the ceramic window during high-power processing, supplementing existing arc detectors and vacuum interlocks. This system provides direct temperature measurements of the ceramic window unlike the older system when relied on inlet and outlet temperatures of the cooling water. Software enhancements include tighter integration with the klystron modulator fault system and automated soft-limit selection to reduce operator input during routine conditioning.

CONCLUSION

A Python-EPICS automatic RF conditioning control system has been developed and deployed at the SNS RFTF, replacing the legacy EPICS sequencer with a more flexible state-machine implementation and updating the operator interface to CSS-Phoebus. Coordinated hardware upgrades-HVCM expansion and LLRF system separation-enabled simultaneous dual-frequency conditioning, substantially increasing throughput. These capabilities supported the PPU project, with 46 SCL FPCs and 23 klystrons among the components conditioned. Ongoing developments in ceramic monitoring and control software will sustain RFTF capabilities for future SNS operations.

ACKNOWLEDGEMENT

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REFERENCES

[1] S. M. Hasan *et al.*, "Development of an RF Conditioning System for Charged-Particle Accelerators," *IEEE Trans. Instrum. Meas.*, vol. 57, no. 4, pp. 743-750, Apr. 2008. doi:10.1109/TIM.2007.911638

[2] M. S. Champion et al., "Progress Towards the Completion of the Proton Power Upgrade Project," in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, pp. 1688-1691. doi:10.18429/JACoW-IPAC2024-TUPS27

[3] Portable Channel Access Server for Python (PCASpy), https://pypi.org/project/pcaspy/

[4] Channel Access Client for Python (PyEPICS), https://pyepics.github.io/pyepics/.

[5] EPICS Collaboration, "Experimental Physics and Industrial Control System.", https://epics-controls.gov/.

[6] Control System Studio (CS-Studio/Phoebus), https://controlsystemstudio.org/.

[7] J. Mammosser, "Recent experience with testing and operating RF couplers at SNS," presented at *WWFPC#6*, CERN, Jul. 2024.