DESIGN AND IMPLEMENTATION OF AN AUTOMATED HIGH-PRESSURE WATER RINSE SYSTEM FOR FRIB SRF CAVITY PROCESSING*

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Abstract

Traditionally, high-pressure water rinse (HPR) systems have consisted of relatively simple pump and rinse wand actuator systems intended to clean superconducting radio frequency (SRF) cavities during processing prior to test assembly. While these types of systems have proven effective at achieving satisfactory levels of cleanliness, large amounts of operator touch-labor are involved, especially in SRF cavities with complex geometries, where several fixture changes and cavity manipulations may be required. With this labor comes the risk of cavity damage or contamination, and the expense of the operator's time. To reduce this operator intervention and maximize cavity cleanliness and process throughput, a new, fully-automated, robotic HPR system has been commissioned in the Facility for Rare Isotope Beams (FRIB) cavity processing facility. This paper summarizes the design and commissioning process of the HPR system, and demonstrates improvements to the FRIB processing facility through the minimization of cavity contamination risk and reduction of technician labor through system automation. Comparative cavity RF test results are presented to further demonstrate system effectiveness.

INTRODUCTION

High-pressure rinsing (HPR) has been performed successfully at FRIB for many years on a research and development scale. The simple rinse system used previously, consisting of a rotary table and a rinse wand attached to a linear actuator, could be adapted for use with a wide variety of cavities, and served its purpose well. However, though flexible, this system required a large amount of fixtures to be used to support and align the cavities.

This reliance on fixtures was detrimental in two ways. First, the need to frequently change and manipulate fixtures during the rinse cycles increased the possibility of damage and contamination to the cavity. Operator error in fixture assembly and/or improper alignment could easily have caused cavity damage due to impact from the wand, and the repeated fastening and unfastening of bolts, dowel pins, and locking levers, as well as the rotating sprockets, bearings, and chains were a source of particulate contamination risk.

The second concern was the high labor cost associated with the operation of this system. The heaviest of the FRIB cavities weighs more than 90 kg, and, as such, requires more than one operator to manipulate in the fixture. The large amount of operator touch labor associated with these manipulations was not sustainable for the high-volume of processing required for the FRIB project. For these reasons, an automated rinse system was procured and installed to improve the efficiency and quality of the cavity rinsing process. The use of this system is anticipated to save more than 2500 person-hours of labor over the course of the project, as shown in Table 1 below.

Table 1: Labor Savings from New HPR System

Cavity Type	FRIB Production Cavity Quantity	R&D HPR Hours per Cycle	Robot HPR Hours per Cycle	Total Hours Saved
β=0.041	12	4	1	36
β=0.085	100	4	1	300
β=0.29	72	9	1	576
β=0.53	148	9	1	1184

Net Labor Savings (hrs)	2096
20% Reprocessing Labor (hrs)	419.2
Total Labor Savings (hrs)	**2515.2**

DESIGN AND INSTALLATION

Design and Procurement Process

While proposing designs, three primary concepts were focused on safety, quality, and efficiency. The most important of these, safety, would be achieved by minimizing the handling of the cavities required by the operator, and by barring the operator from entering any areas containing stored energy hazards. Quality would be achieved by analyzing the design for its ability to clean the cavities thoroughly, and efficiency by minimizing the amount of operator labor required to run a rinse cycle.

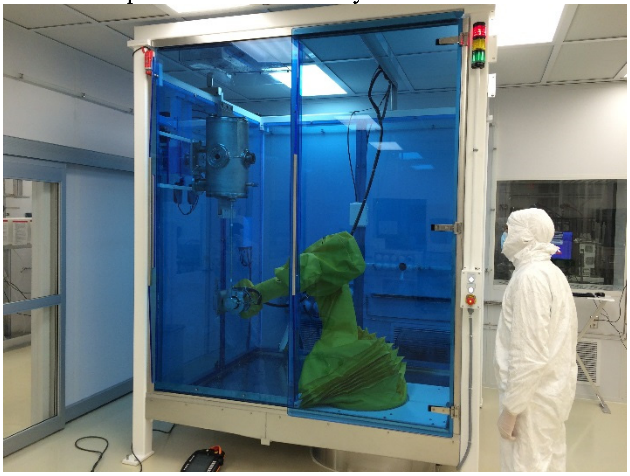

Figure 1: Robotic high-pressure rinse system, installed.

The HPR system went through several design iterations before the design was finalized. The initial designs were all

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variations on existing HPR systems used in other SRF facilities throughout the world. However, these systems were all cost-prohibitive due to the significant amount of automation required to accommodate the complex geometries of the FRIB SRF cavities. Following an unsuccessful round of vendor bidding, the design was changed significantly. The newly proposed and, ultimately, adopted, design (Fig. 1) relied on a six-axis cleanroom certified robotic arm along with a rotary seventh-axis cavity support fixture, rather than linear actuators, to move and align the wand with the ports being rinsed.

This shift in design allowed a different cohort of vendors to be selected. The initial bidding process focused on specialty manufacturers experienced in cleanroom equipment, whereas the second round took advantage of well-established general industrial automation equipment manufacturers. These vendors provided bids that were on the order of 40% less expensive, which made the project much more justifiable financially.

The transition to a more unified design also helped to simplify the process of automating the system, and to expand its flexibility for other cavity configurations. Only a single end effector alignment step is required with this system, as opposed to multiple steps and/or fixture adjustments required for a multi-wand or rotary-table based system. Programming the wand sweep is as simple as marking off points with the integrated teach-pendant, defining the rotation of the robot wrist to adjust nozzle spin, and allowing the automation software to turn these data into a cohesive rinsing program. This also simplifies the expansion of this system's use with experimental cavities for R&D with minimal modifications needed for the HPR fixtures.

Equipment Installation and Validation

Prior to installation of the robotic HPR cell, the existing HPR system was disassembled and moved to another area of the cleanroom for recommissioning and use as a redundant system. A large wall of plastic sheeting was hung from the ceiling in the HPR bay of the cleanroom to minimize particulate cross-contamination, and to allow work to continue in other work centers during the installation and commissioning period.

Figure 2: Installation of the robot and frame.

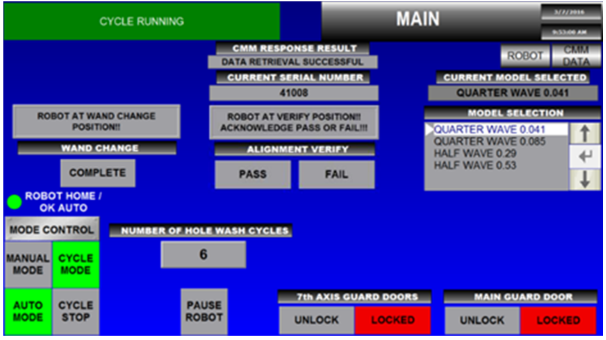
The robot was moved into position, and the cell enclosure frame was assembled around it. Once the position of the cell was established, both the frame and robot were attached to the floor with concrete expansion anchors (Fig. 2). Next, the floor pan, drainage system, walls, and doors were bolted to the frame. Once all structural and mechanical components were installed, the robot and control wiring was completed, and, finally, the waterproof robot jacket was installed to the arm.

With all mechanical assembly complete, each of the rinse programs were verified with the master cavities, final points were touched up, and minor modifications were made to the rinse programs. The water pumping system was purged with ultrapure water (UPW) for several hours, and water quality checks were performed periodically. The walls and floor of the cleanroom and cell were mopped and wiped with cleanroom-grade ethanol to remove particulate contaminants from the installation process, then air particle counts were taken to re-validate the cleanliness of the installation area.

OPERATIONS

Rinse Process Description

A universal mounting plate, which is compatible with all four FRIB cavity types, is bolted to the mounting flange of the cavity. The cavity is then raised into the rinse cell and is bolted to the seventh-axis rotational fixture adapter plate. Two precision locating pins ensure proper alignment of the cavity on the plate. The safety-interlocked cell doors are closed and latched to allow the process to begin.



CYCLE RUNNING

CMM RESPONSE RESULT: DATA RETRIEVAL SUCCESSFUL

CURRENT SERIAL NUMBER: 41008

CURRENT MODEL SELECTED: QUARTER WAVE 0.041

ROBOT AT WAND CHANGE POSITION!!

ROBOT AT VERIFY POSITION!! ACKNOWLEDGE PASS OR FAIL!!!

NUMBER OF HOLE WASH CYCLES: 6

Figure 3: Robot HMI control screen.

The cavity rinse recipe and duration of the rinse is defined by the operator on the human-machine interface (HMI) screen (Fig. 3). Cavity alignment data, taken from the coordinate-measuring machine (CMM) for the cavity being rinsed, is uploaded to the PLC via EPICS to establish offset positions for the wand, and to counteract any deviations in port location from the manufacturing process. Next, the wand moves in front of the enclosure door to allow the operator to validate that the correct wand is assembled to the robot arm. Once verified, the robot begins its alignment check.

For half-wave cavities, the wand moves to within a centimeter of each of the ports, and pauses so that the operator may verify visually and confirm on the HMI that the wand is properly aligned. For quarter-wave cavities, a laser reticule is projected from the end of the robot arm onto the inner conductor and bottom flange of the cavity. Alignment of the wand is determined by the position of the laser crosshair on the tip of the inner conductor [1].

Once alignment is verified, the wand enters a spray deflector tube and purges with UPW for five minutes to remove any stagnant water from the pump, hoses, filter housing, and wand. The operational pressure of the high-pressure water at the pump outlet is approximately 93 bar, being sprayed out of a nozzle with eight jets, all at different angles. After purging, the wand enters each of the cavity ports in a pre-programmed order at a rate of 100 cm/minute, rotating continuously to prevent the formation of oxidation spots on the cavity surface, and to maximize the cleaning area of the spray jets. The seventh-axis fixture automatically rotates the cavity as needed to allow all of the ports to be rinsed. Once the rinse cycle is complete, the cavity is unbolted from the adapter plate and is hung to dry in the cleanroom overnight prior to clean assembly for vertical testing.

Process Data

More than fifty cavities have been successfully rinsed in the nine months since the cell was installed. Liquid particle counts (LPCs) are systematically collected at the completion of each rinse cycle to verify that the cavity has been sufficiently cleaned. Comparing these measurements has shown that the cavities rinsed with the robotic HPR reach the same level of cleanliness or better than the cavities rinsed on the old HPR system were able to achieve. The average final LPC measurement for the robotic HPR is 125 particles of 0.3 microns in size per milliliter of sample collected, compared to 147 counts per milliliter for the R&D HPR system (Fig. 4).

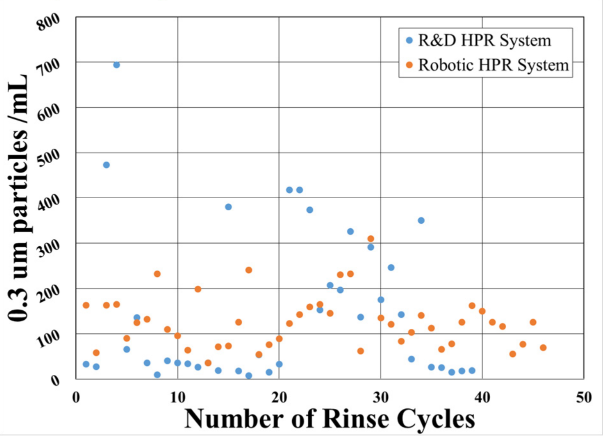


Figure 4: R&D vs. Robotic HPR LPC comparison.

Periodic air particle count measurement has shown that the inside of the robotic HPR enclosure remains at ISO 5 classification (the same as the cleanroom that it is installed inside) or better, both while the robot is moving, and while it is idle. This high level of cleanliness, especially during operation, is instrumental in preventing airborne particles from contaminating the cavity and causing performance issues during RF testing.

Cavity Performance Comparison

Dozens of cavity tests have been performed since the installation of the robotic HPR system, and satisfactory results have been obtained for all four FRIB cavity configurations. The most abundant and readily comparable cavity test data for the HPR systems is for beta = 0.29 half-wave resonator (HWR) cavities. As can be seen in Fig. 5, the Q_0 vs. E_{acc} curves for these cavity tests are very similar, demonstrating a high level of cleanliness and no marked degradation in performance as a result of the transition from the old to the new HPR system. This pattern is observed for all cavity types. Field emission onset levels are also comparable between certified cavities rinsed on each of these rinse systems, as well (Fig. 6), further emphasizing the efficacy of the robot.

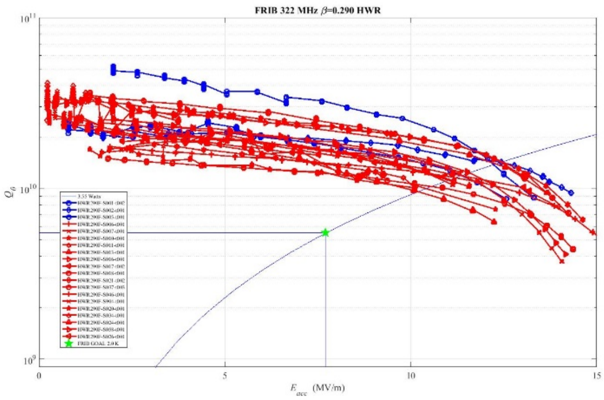


Figure 5: β=0.29 HWR Q_0 vs. E_{acc} Comparison between Robotic System (Red) and R&D System (Blue).

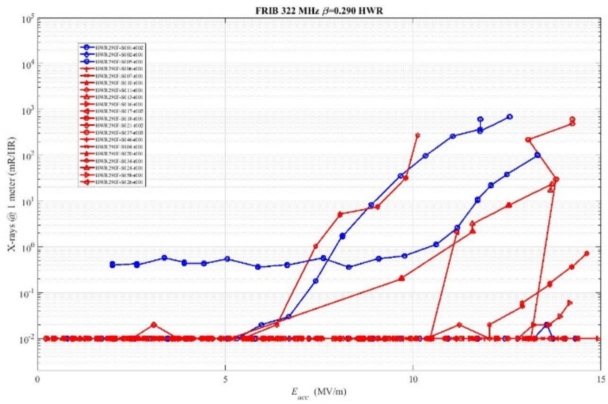


Figure 6: β=0.29 HWR X-rays vs. E_{acc} Comparison between Robotic System (Red) and R&D System (Blue).

CONCLUSION

The robotic HPR system installed for the processing of FRIB SRF cavities is just as effective as the R&D HPR system at achieving excellent cleaning and satisfactory RF test results. The added benefit of the reduced labor costs and minimization of risk to safety and cleanliness make the new system essential for delivering FRIB cavities.

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[1] L. Popielarski, *et al.*, "Low-Beta SRF Cavity Processing and Testing Facility for the Facility for Rare Isotope Beams at Michigan State University", in *Proc. 17th International Conference on RF Superconductivity*, Whistler, BC, Canada, Sept. 2015, paper TUPB022, p. 597.