

Research Article

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Design and Implementation of An EPICS-Based Automatic Superconducting Module Test System for SHINE

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Abstract

The Shanghai High Repetition Rate XFEL and Extreme Light Facility (SHINE) is a high-frequency hard X-ray free-electron laser (FEL) facility with a maximum repetition rate of 1 MHz, delivering photon energy from 0.4 to 25 keV. A critical component of SHINE is the superconducting module. Given the inherent complexity of its internal structure, a rigorous and precise performance evaluation is essential before beam operation. To evaluate its performance, we developed an automated module test system based on the Experimental Physics and Industrial Control System (EPICS). This comprehensive test system integrates various key technical domains, including radio frequency (RF), cryogenics, vacuum, electronics, radiation, and control. The test control framework employs Simple Network Management Protocol (SNMP) for software architecture, Stream Device for standardized device driver access, PyDM for user interface, Network Time Protocol (NTP) for timing synchronization, and Python scripting for test automation. The test system has been successfully applied to test multiple superconducting modules at our institute. This automation significantly reduces testing time and simplifies procedures, standardizes procedural execution, and ultimately enhances the overall test consistency and efficiency, while also providing a comprehensive data acquisition scheme essential for future beam operation analysis.

Keywords: SHINE, EPICS, Module Test, RF Test, Automation

1. Introduction

SHINE, a high repetition rate hard X-ray facility currently under construction, is comprised of a linear accelerator section, two undulators, two beamlines, four cryogenic stations, and essential infrastructures. The linear accelerator is divided into five sections (L0–L4). The beamline FEL-1 provides photon energy from 3.0–15.0 keV, and the beamline FEL-2 delivers photon energy from 0.2–3.0 keV. The cryogenic station incorporates three 4 kW cryogenic plants providing cooling capacity at 2 K (Kelvin) for the SHINE tunnel, in addition to a 1 kW capacity at 2 K dedicated to the test halls. The general layout of SHINE is shown in Figure 1. The superconducting module is a critical component used in large quantities throughout the SHINE linear accelerator. The injector

section (L0) comprises one twin-FPC cavity module (i1CM) and one nine-cell cavity module (i8CM). The L1 section includes two 1.3 GHz modules and two 3.9 GHz modules, while L2–L4 sections comprise 52 1.3 GHz modules [1,2].

Central to its design is the accelerator based on superconducting radio-frequency (SRF) technology, requiring the mass production and precise evaluation of numerous superconducting cryomodules. Every module includes eight superconducting cavities, eight fundamental power couplers (FPC), eight tuning devices, sixteen Higher Order Mode (HOM) couplers, one cryomodule system (including thermostat, vacuum pipe, and vacuum vessel), a beam position monitor (BPM), a superconducting magnet and

support system [3,4]. The layout of the module is presented in Figure 2. Before assembly, cavities are tested in both bare and dressed states through vertical tests (VT), and only qualified

cavities are assembled to modules. One module is tested over 20 days when strict adherence to specifications is required for tunnel installation.

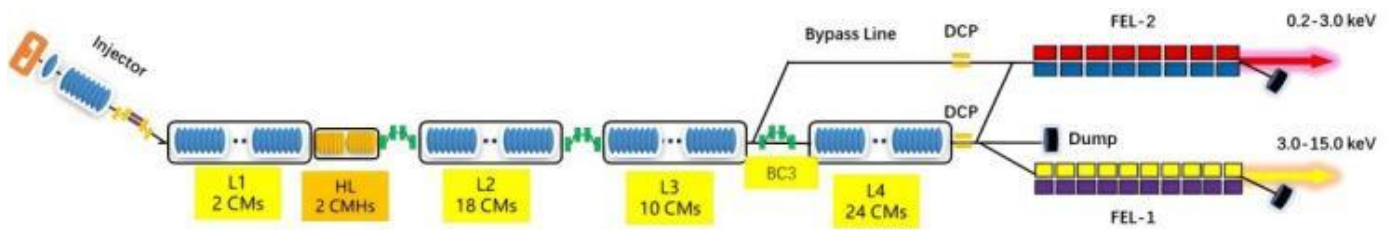


Figure 1: The Layout of SHINE

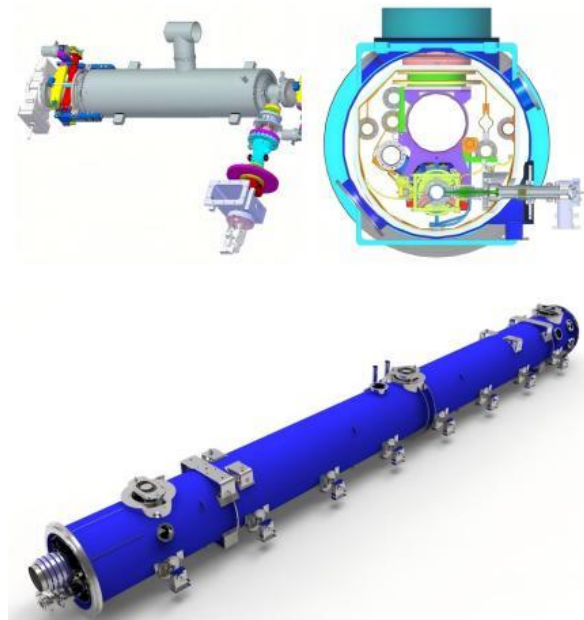


Figure 2: The Layout of The Superconducting Module

The assembly and testing of modules are conducted in two halls on the campus of the Shanghai Advanced Research Institute occupying a combined area of 3,000 square meters. The two halls are equipped with four vertical test platforms (VTF1-2 in ATF1, VTF3-4 in ATF2) and four horizontal test platforms (HTF1-2 in ATF1, HTF3-4 in ATF2). The layout of the halls is shown in Figure 3. EPICS is a control system developed by Los Alamos National Laboratory (LANL) and Argonne National Laboratory (ANL) [5,6].

EPICS is a standard model known for portability, expansion, and reusability. It has been applied in hundreds of physics experimental facilities, such as Beijing Electron-Positron Collider (BEPC), Shanghai Synchrotron Radiation Facility (SSRF), Linac Coherent Light Source (LCLS), European X-ray Free Electron Laser (XFEL), and others.

SHINE relies on the mass production of superconducting modules that must operate within extremely tight tolerances to support its 1 MHz repetition rate. While manual testing procedures are inherently time-consuming and prone to error, the primary driver for automation lies in the strict requirements for performance consistency and data traceability. Specifically, manual operations introduce operator-dependent variations that degrade the uniformity required, while manual data logging creates fragmented datasets that impede future root-cause analysis. Therefore, an automated framework is not merely a tool for efficiency, but a critical requirement to enforce standardized execution protocols over the entire lifecycle of the modules. To address these requirements, we developed an EPICS-based control system capable of integrating standardized device drivers, executing automated testing, and establishing a robust data archiving pipeline.

This paper describes the design and implementation of an EPICS-based control system developed specifically for module testing.

The system adopts reliable scripting to achieve standardized device access, automated test execution, and real-time data archiving.

2. Module Test Requirements and Implementation

2.1. Module Test Requirements

Module test objectives are defined by SHINE acceptance criteria, covering accelerating gradient, heat load, HOM, tuner performance,

quadrupole magnet, BPM, cryomodule, dark current and vacuum [7,8]. The acceptance criteria are illustrated in the following table1 [9]. Key measurement requirements include:

- Measurement of the superconducting cavity spectrum and Π mode frequency;
- Characterization of FPC conditions at room temperature and 2 K [10].

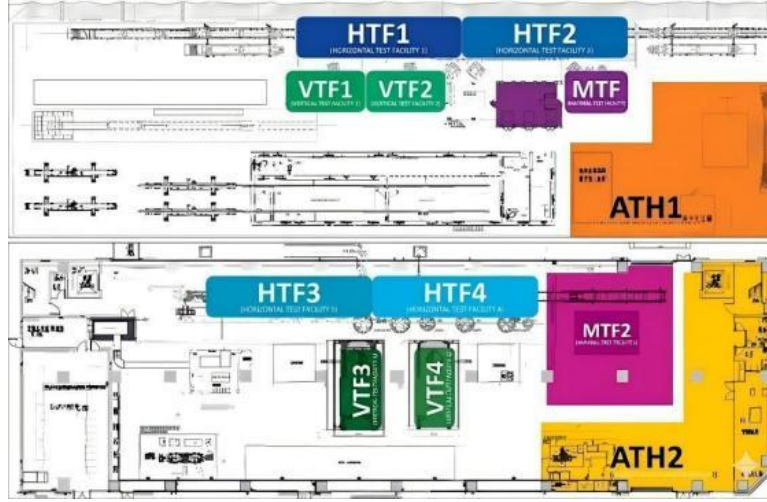


Figure 3: The Layout of Halls

- Determination of the external quality factor of the FPC (Q_e)
- Cavity performance tests: E_{acc} vs Q_0 , E_{acc} vs $X-ray$, E_{acc} vs I_{dc} .

2.2. Implementation of the Module Test Platform

There are many systems involved in the module test platform. The module test diagram is illustrated in Figure 4. The module test platform integrates:

- The solid-state power amplifier (SSPA) delivers up to 5.2 kW of the cavity, coupled to FPC via a waveguide.
- The LLRF controls the forward signals and the feedback signals of the cavity via an FPGA-based loop, enabling the cavity to achieve resonance through the Self-Excited Loop (SEL) [11].
- The RF interlock protects the cavity and FPC by monitoring quench, temperature, electronics, and other protection signals to shut down the SSPA when a fault signal is detected.
- Radiation dose is monitored using a Geiger-Müller counter positioned two meters from the center of the cavity.
- Dark current is measured with Faraday cups at both ends of the module (feed cap and endcap), capable of detecting nanoampere-scale currents generated by radiation.
- The cryomodule is regulated by valves and heaters to control the levels of liquid helium and pressure. The static load is calculated from heater power and flowmeter rate, while the dynamic load is derived from applied RF power and flowmeter measurements [12,13].
- During the module test, RF test is the primary task. It takes a

whole process during the test period. One cavity has four ports: one input power port, one extraction power port, two HOM ports. It measures power values from these eight cavities: PF, PR, PT, $P_{hom,C}$, $P_{hom,pu}$ totaling 40 values for one module. The acceleration gradient and the loaded quality factor are calculated. To evaluate the long-term operation and heating effect of the FPC, is calculated using Equation (2) based on the measured PF and PT values in this test system. Prior to this, must be calibrated using $PF \approx 50W$ according to formulas (2) and (1). The following equations are obtained for Equation (2) and (1) [14,15];

$$E_{acc} = \frac{1}{L} \sqrt{4 \left(\frac{r}{Q} \right) P_f Q_e} \quad (1)$$

L is the effective acceleration length of the cavity, r/Q is the cavity geometric factor, while the loaded quality factor according to Equations. (5)(6)

$$E_{acc} = \frac{1}{L} \sqrt{\left(\frac{r}{Q} \right) P_t Q_t} \quad (2)$$

$$\frac{1}{Q_L} = \frac{1}{Q_e} + \frac{1}{Q_0} + \frac{1}{Q_t} + \frac{1}{Q_{ext,hom}} + \frac{1}{Q_{pu,hom}} \quad (3)$$

For the strongly coupled cavity, according to Equations. (4), (5):

(4)

(5)

(6)

The total voltage is calculated using Eq. (7):

(7)

The power value of each cavity is measured by the power meters. The decay time is derived of the cavity PT, which is measured by the LLRF. To reduce the number of power meters and frequency counters, a seven one-eighths RF switch controller is used to switch the power of the home port, as well as the cavity PF/PT frequency, spectrum, and oscilloscope. The 1.3 GHz module inHTF4 is shown in Figure 6.

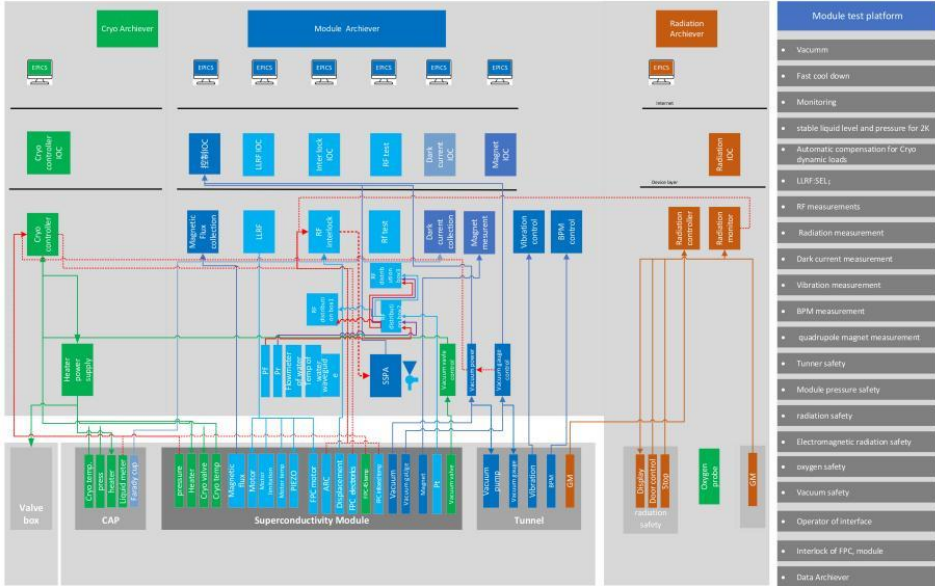


Figure 4: The Schematic Diagram of Module Test

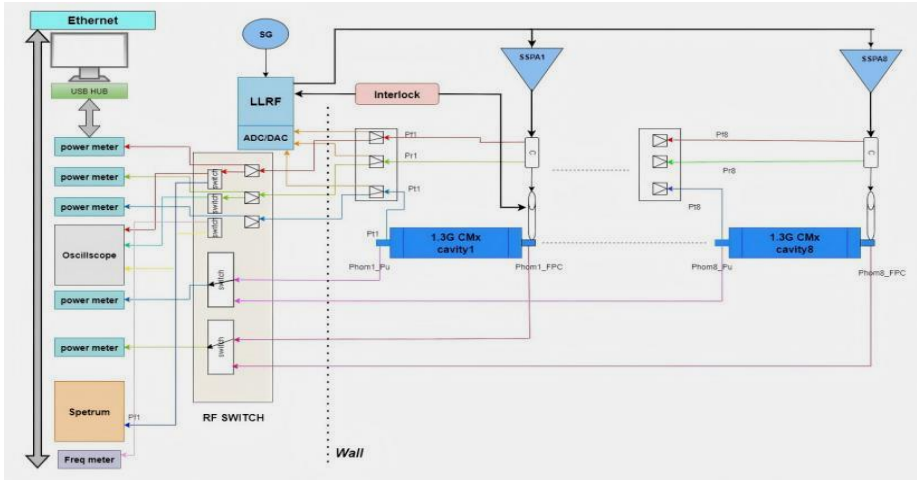


Figure 5: The Schematic Diagram of Rf Test

Item	Parameter	Acceptance Criteria
Gradient	E_{acc}	$\geq 20 \text{ MV/m}$
	$V_{c,total}$	$\geq 166 \text{ MV}$
	$I_{dc}@V_{c,total} = 166 \text{ MV}$	$< 30 \text{ nA}$
Heat Load	$Q_0@V_{c,total} = 166 \text{ MV}$	$\geq 3.0 \times 10^{10}$
	Stability Test	10 h or FPC Temp. achieves equilibrium
	2 K Load (Static)	$< 20 \text{ W}$
	2 K Load (Dynamic @ 166 MV)	$< 120 \text{ W}$
	2 K Load (Total)	$< 140 \text{ W}$
	FPC Cold-end Temp. Infrared Temp.	$< 150 \text{ K}$ $< 80^\circ \text{ C}$
Residual Magnetic	Magnetic flux	$< 0.2 \text{ mG}@300 \text{ K}$
Higher Order Mode (HOM)	Q_e	$> 3.0 \times 10^{11}$
	P_{hom}	$< 1.4 \text{ W}@20 \text{ MV/m}$
Tuner	Slow tuner range	$1300 \text{ MHz} \pm 0.02 \text{ MHz}$
	Piezo range	$0 - 500 \text{ Hz}$
BPM	Impedance	$50 \Omega \pm 3 \Omega$
	S_{21}	$< -55 \text{ dB}@0 - 2 \text{ GHz}$
Vacuum	Beam vacuum (2 K / Room Temp)	$< 1.3 \times 10^{-7} \text{ Pa} / < 1.3 \times 10^{-5} \text{ Pa}$
	Coupler vacuum (2 K / Room Temp)	$< 6.5 \times 10^{-6} \text{ Pa} / < 1.3 \times 10^{-5} \text{ Pa}$
	Isolation vacuum (2 K / Room Temp)	$< 5 \times 10^{-4} \text{ Pa} / < 5 \times 10^{-1} \text{ Pa}$
Radiation	GM	$< 1 \text{ mSv/h}$, 2 m from cavity center

Table 1: SHINE Acceptance Criteria



Figure 6: The First 1.3 GHz Module in the HTF4

3. Software Implementation

3.1. Software Architecture

In this system, an SNMP agent is applied on each device to collect data and respond to requests from the SNMP manager that runs on both the device and the IOC server [16]. Time synchronization

is achieved using the NTP, while management information bases (MIB) are used to query device status information, which is then returned to the SNMP manager [17]. The SNMP acquires these response data and maps them to process variables (PV) in the real-time database (db) file. These PVs are accessed and visualized

through the operator interface (OPI), developed with PyDM and connected via the channel access (CA) protocol [18]. In addition, PV data can be retrieved from the Archiver appliance through its HTTP interface for historical data storage and retrieval. The software architecture of the RF test system is illustrated in Figure 7. The SHINE archiver is shown in Figure 8.

3.2. Device Control

Stream Device is an EPICS support module designed for devices with byte-stream communication interfaces. It incorporates an a syn Driver interface to handle underlying communication protocols and can be extended to support additional bus drivers [19,20]. In the RF test system, multiple devices are integrated, including:

- ROHDE&SCHWARZ N8PRS power meter (usb 3.0 interface)
 - KEYSIGHT 53230A frequency counter (ethernet interface)
 - RF switch controller (ethernet interface)
 - KEYSIGHT EXA spectrum analyzer (VNC server interface)
- Except for the spectrum analyzer, which uses VNC for

communication, the other devices are controlled through the Stream Device. The Stream Device protocol uses plain ASCII text to execute commands during IOC startup. Protocol files are written based on hardware control commands. An example of a power meter driver is as follows:

```
terminator = CRLF;
Reply Timeout = 1000;
ReadTimeout = 1000;
Separator = ",";
reset{
  out "*rst";
}start
{out "INIT: CONT %d";
}getpower{
  ExtraInput=Ignore;
  Out "FETCH?";
  in "%f";
```

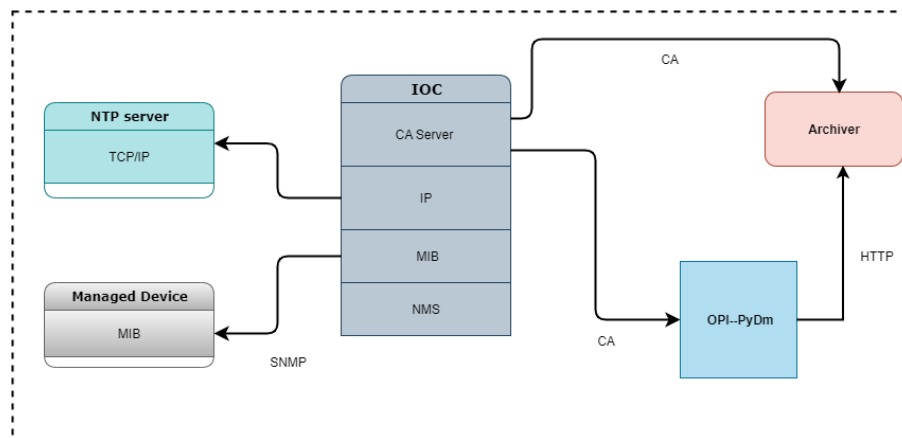


Figure 7: The Software Architecture of RF Test System

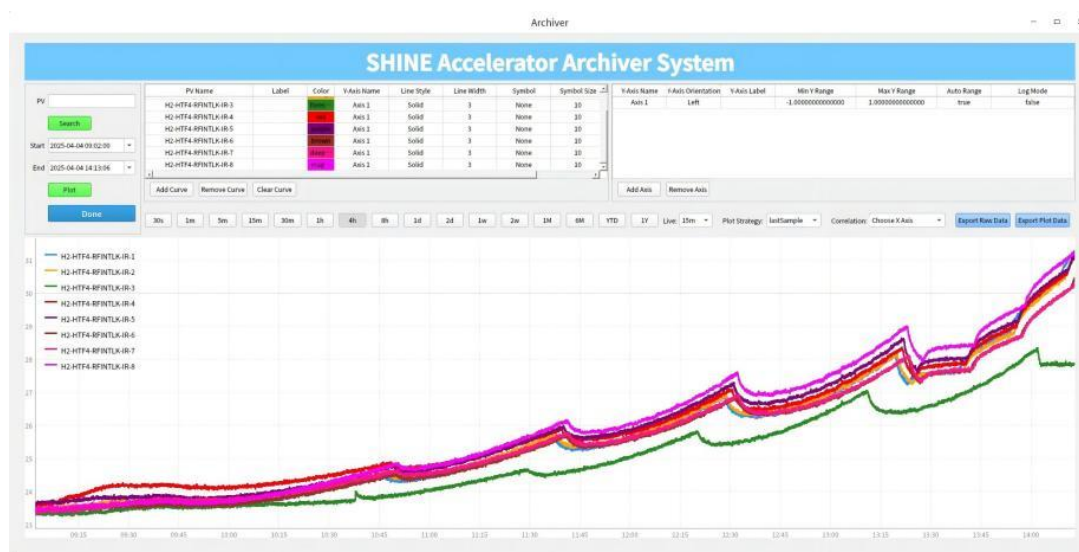


Figure 8: The Archiver in SHINE

3.3. Data Acquisition and Storage

Data acquisition is carried out using the EPICS real-time database, which communicates with the device layer over the network to enable data collection and storage. Upon request from the OPI client, real-time data are transmitted and displayed. The data are stored in the database file [21,22]. An example of a real-time database record file is shown below:

```
{record (ao "(DEV) power meter")
field (DESC, "set value")
field (EGU, "W")
field (SCAN, "Passive")
field (DTYP, "stream")field (VAL, "1")
field (OUT, "@simple. proto set offset (POW-port)")
}
```

The DESC field describes the signal name. The EGU field specifies the engineering unit. The DTYP field declares the device type, and the SCAN field determines the scanning interval. The minimum period is set to 0.1 seconds to ensure accurate data acquisition and display. To improve reusability, the database file employs macro replacement. For example, DEV identifies the device, and POW-port loads specific parameters through the db Load Records command in the IOC startup script. Historical data storage is implemented using the Archiver appliance, which archives millions of PV from all integrated systems. During the module tests, real-time PV data is archived by PV name, ensuring long-term accessibility and enabling test reports to be generated from stored data.

3.4. User Interface

PyDM is a PyQt-based framework for developing user interfaces in control systems. It supports both a drag-and-drop screen builder for simple applications and a Python-based framework

for building complex interfaces [23]. The combination of PyQt's cross-platform features and Python's flexibility makes PyDM effective for operator interfaces in EPICS environments. All sub-system operational interfaces are centralized on the main screen developed by the SHINE controls team. The OPI of test HALL1 is presented in Figure 9. The user interface of the RF test system is divided into four sub-interfaces based on their functions for operation and display. The OPI of the RF test is shown in Figure 10. The OPI for the RF test is the following:

- Sub-interface 1: Displays cryogenic parameters, RF parameters, radiation parameters, vacuum parameters, dark current parameters.
- Sub-interface 2: Provides tools for superconducting cavity calibration.
- Sub-interface 3: Supports channel selection on the 1-in-8 RF switch, oscilloscope monitoring, data saving for cavities and couplers, and calibration of the power meter.
- Sub-interface 4: Configures measurement settings such as power meter functions, time and pulse points, startup, shutdown control of devices.

3.5. Time Synchronization

The time synchronization requirements depend on the experiment requirement [24]. High precision facility require nanosecond accuracy, whereas millisecond precision is sufficient for our module test. The NTP a TCP/IP application layer protocol, is widely used to synchronize clocks between clients and servers [25]. A dedicated NTP server provides synchronized system time. Times yncd is adopted instead of NTP in the RF test system. Time syncd connects to the same time server within the Ubuntu system, offering a lightweight and well-integrated solution for millisecond-level synchronization. The NTP server configuration for times yncd is located at: /etc/systemd/timesyncd.conf [26].

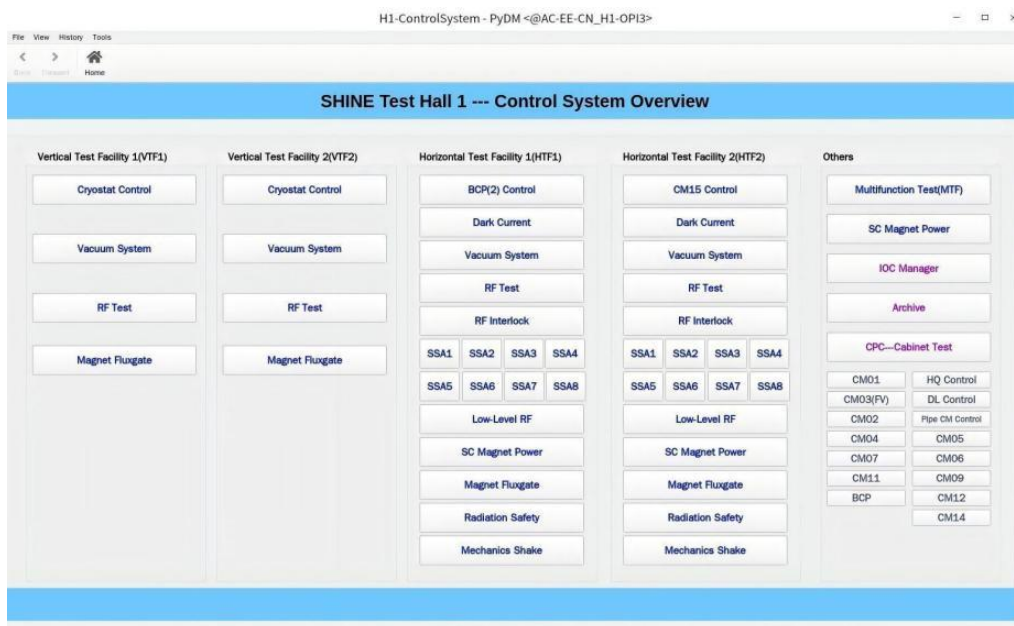


Figure 9: The OPI of Test Hall



(a)



(b)



(c)

Figure 10: The Interfaces of The RF Test System: (A) The Main RF Test Interface; (B) The Superconducting Cavity Calibration Interface; And (C) The RF Control Interface

4. Test Automation

The test schedule is divided into two primary categories: Task 1.0 focuses on the standard module performance evaluation based on acceptance criteria, while Task 2.0 is dedicated to the test schedule for automation upgrades and optimization of the testing process. The test schedule is illustrated in the table 2. Test automation is achieved through Python scripts, and PyDM-based user interfaces.

Cavity tuning automation: A two-step coarse-to-fine algorithm aligns all eight cavities in Π -mode. FPC conditioning automation:

Power ramping in both pulse and CW modes, integrated with an automated recovery framework, validates the power-handling capacity and stability of the FPC up to the required 5 kW threshold.

During the module test, automatic cavity conditioning addresses key aspects: (1) The multipacting (MP) region in the TESLA cavity type, between 17 and 24 MV/m requires CW conditioning of each cavity individually [27-29]. (2) Sporadic quenches occurring within the MP range are quickly recovered, resulting in a stable accelerating gradient(Eu).

Day	Task 1.0	Task 2.0
Day1	Assembly handover	1.Assembly handover; 2. Signal check; 3. BPM measurement; 4. Interlock safety check; 5.FPC conditioning; 6.Pre-cool down check;
Day2	1.Cable calibration at room Temp; 2.Demagnetization at room Temp; 3.adjustment.	cool down initiation
Day3	1.Spectrum measurement at room Temp; 2.BPM measurement; 3.Signal check.	Maintain at 45 K for 12 hours.
Day4	1.Coupler range; 2.Interlock safety check; 3.FPC conditioning.	1.Demagnetizationat 45 K; 2.fast cool down; 3.pumping to 2K; 4.FPC conditioning at 2K.
Day5	1.Pre-cool down check; 2.cool down initiation; 3.cool down to 160 K.	1.2K signal check; 2.FPC range measurement.
Day6	Maintain at 45 K for 12 hours	1.2 K spectrum measurement; 2.2 K signal measurement; 3.Tuner test (limitation).
Day7	1.fast cooldown; 2.pumping to 2 K.	1. Tuner test; 2 calibration; 3 CURVE 0.
Day8	1.2K signal check; 2. Safety check; 3. FPC CW conditioning.	Cavity conditioning

Day9	1.FPC range measurement; 2.BPM mearsurment.	1.Cavity conditioning; 2.CURVE2 verification; 3.Warm-up at 45 K.
Day10	1.Cryogenic cable calibration; 2.2 K spectrum measurement; 3.2 K signal measurement.	Re cool down
Day11	1.Tuner test (limitation); 2.Notch test; 3.calibration; 4.CURVE0 ;	1.BPM mearsuremet at 2 K; 2.HOM measurent at 2 K.
Day12	1.Cavity conditioning; 2.GDR/Microphonics test; 3.calibration.	1.Static heat load calibration; 2. Q_0 measurement.
Day13	Cavity conditioning	1.166 MV stability test; 2.Quadrupole magnet Powering and demagne- tization; 3.Microphonics.
Day14	Cavity conditioning	Transfer function measurement
Day15	Cavity conditioning	1.LLRF test; 2.Frequency reset; 3.Pre-warm-up inspection.
Day16	1.CURVE2 verification; 2.166 MV stability test; 3.Quadrupole magnet Powering and demagne- tization.	warm-up
Day17	warm-up at 45 K	warm-up
Day18	Re cool down	warm-up
Day19	1.HOM test; 2.Microphonics measurement.	1.warm-up; 2.Frequency re-verification.
Day20	Static heat load calibration	handover back to assembly
Day21	Static heat load calibration	
Day22	Single-cavity Q_0 measurement Average Q_0 measurement	
Day23	GDR/Microphonics test	
Day24	1.Frequency reset; 2.Pre-warm-up inspection.	
Day25	warm-up	
Day26	warm-up	
Day27	1.warm-up; 2.Frequency re-verification; 3.handover back to assembly.	

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Table 2: SHINE Test Schedule

4.1. Cavity Tuning Automation

The program is used to automatically determine the phase difference of the cavities, enabling the simultaneous tuning of eight cavities in Π -mode. The program is written in Python, with the user interface developed with PyDM. The cavity tuning procedure consists of two stages. First, coarse tuning is performed in 10° steps across 360° range to locate the region containing the higher value of transmitted power (PT). Then, fine-tuning is carried out in 0.1° increments within a $\pm 3^\circ$ range around the resonance point

to accurately confirm the resonance phase by identifying the maximum value of PT. The flowchart of the tuning process is shown in Figure 11. The user interface is presented in Figure 12.

4.2. FPC Automatic Conditioning System

Each FPC must be conditioned both at room temperature and at 2 K in the detuning cavity. Conditioning at room temperature is divided into two modes: pulse and CW. It needs to be finished in CW mode after 2 K conditioning. A Python script is developed to

automate this process, with the interface implemented in PyDM. For pulse conditioning, the power is increased from 500 W to 5 kW in 500 W steps, with a repetition rate (RR) of 10 Hz and duty from 5% to 20%.

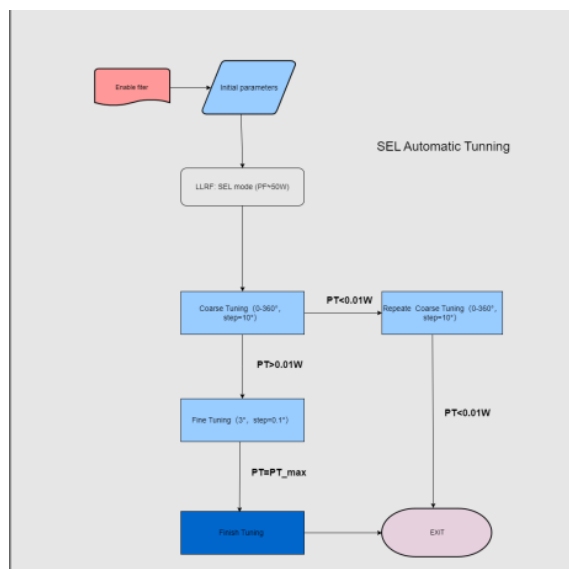


Figure 11: The Flowchart of Automatic Tuning



Figure 12: The OPI of Automatic Tuning System

For CW conditioning, the power is raised from 500 W to 5 kW in 500 W increments, with each step for 30 minutes. Once upon detecting a fault, it not only protects FPC by initiating a shutdown but also automatically recovers by resetting the interlock and reloading SSA to the pre-fault level power. Conditioning at 5 kW is completed when one of two criteria is met: either the coupler's cold section temperature reaches 323 K at room temperature, or the temperature rise of the cold section at 2 K is less than 0.1 K within one hour. Data logging for every power increase step is performed automatically and stored locally. The process flowchart is shown in Figure 13.

4.3. Cavity Automatic Conditioning System

The cavity conditioning process is carried out using a Python script, with the user interface built with PyDM. The cavity condition procedure starts at 16.5 MV/m and progresses to 26 MV/m in 0.1 MV/m increments. When the cavity quench appears, the cavity automation system resets the interlock and SSPA [30]. If other interlock occurs, the automatic program will terminate immediately, and an audible alert is triggered. The program remains terminated until operating personnel manually verify the interlock fault status and confirm that conditioning criteria are met for safe resumption. The process flowchart is shown in Figure 14. The automatic system achieves the usable accelerating gradient in less than two hours for most cavities. The data associated with each

increase in the accelerating gradient and the specific PVs involved in interlock protection events are automatically archived in local

storage. The user interface is presented in Figure 15. The result of the cavity automation conditioning is illustrated in Figure 16.

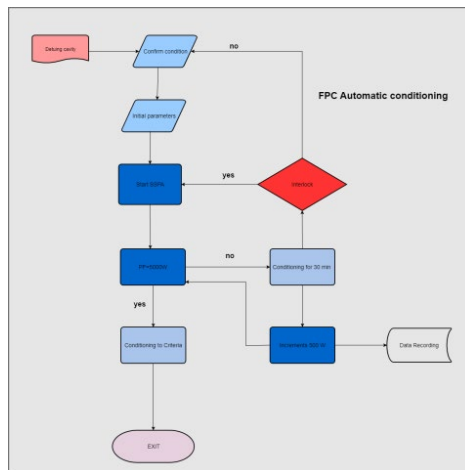


Figure 13: The Flowchart of Automatic FPC CW Conditioning

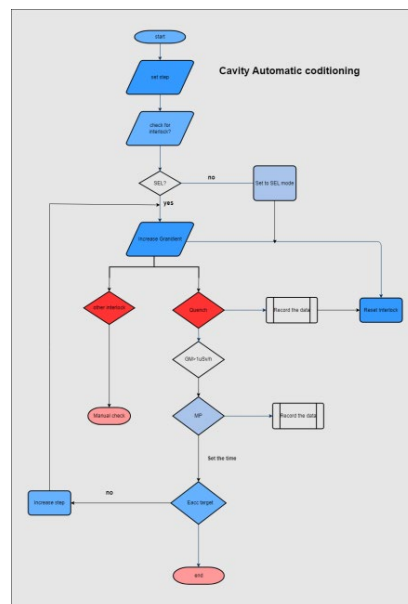


Figure 14: The Flowchart of Cavity Condition Automatic



Figure 15: The OPI for Cavity Condition Automating

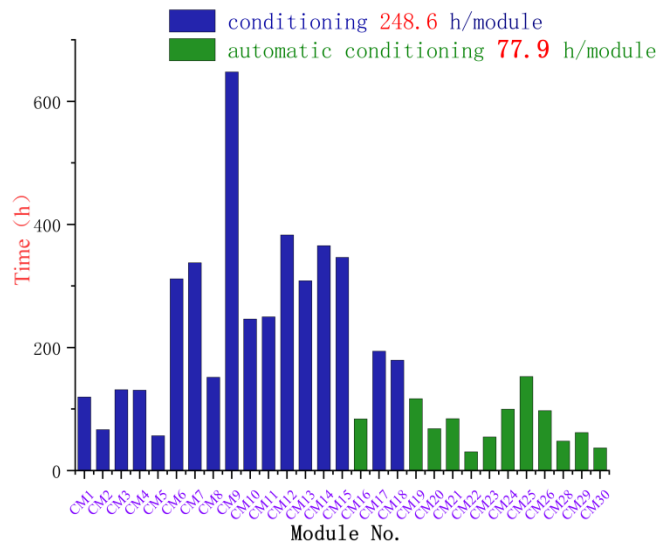


Figure 16: The Result of Automatic Cavity Conditioning Time

5. Conclusion

In this work, we presented the design and implementation of an EPICS-based automated test system for the superconducting modules. To date, more than 30 modules have been successfully evaluated using this platform. The test results confirm that the 3.9 GHz modules achieved a total voltage $V_c > 36$ MV and a quality factor $Q_0 > 2 \times 10^9$ at 36 MV. For the 1.3 GHz modules, the majority meet the acceptance criteria of $V_c > 166$ MV and $Q_0 > 3 \times 10^{10}$ at 166 MV. Notably, the injector section achieved 100 MeV beam acceleration on October 30, 2024 [31]. Beam performance testing has reached a critical milestone. From November 2nd to 3rd, 2025, at the linear accelerator L1/BC1 section, the system demonstrated exceptional stability and precision. The beam energy reached 273.5 MeV, with a peak current measured at 56.4 A. Regarding beam quality, the normalized projected emittance was recorded at 0.54/0.34 mm·mrad(horizontal/vertical), while the normalized slice emittance remained as low as 0.31 mm·mrad. Furthermore, the system exhibited robust high-frequency operational capacity, the bundle repetition frequency hit 1000 Hz with a bundle charge of 54.6 pC [32].

The implementation of automation has significantly enhanced the efficiency and standardization of the module testing procedures. Cavity conditioning tests demonstrate that the complete performance evaluation, which required 144 hours of continuous manual operation, is now executed autonomously in approximately 56 hours. This represents a 61% reduction in conditioning time, alongside a substantial decrease in operational labor costs. Through these systemic improvements, the total module test cycle has been successfully shortened from 27 days to 20 days. The upgraded automated system ensures superior accuracy and repeatability, which are critical for the quality control of SHINE's large-scale module deployment. Future work will focus on integrating advanced data analysis and predictive maintenance algorithms into the control loop to further optimize the operational efficiency and reliability of SHINE.

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Authorship contribution statement

Chen Luo: Software, Data Curation, Writing - Original draft preparation. **Kai Xu:** Software, Data Curation.

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