

Development of 3.9 GHz fundamental power couplers for the XFEL third harmonic cryomodules

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The Shanghai high repetition rate XFEL and extreme light facility linear accelerator employs two 3.9 GHz third harmonic cryomodules. The 3.9 GHz fundamental power coupler is one of the key components of the cryomodule and is designed to handle 2 kW of continuous-wave rf power, meeting operational requirements with a beam current of 0.3 mA and cavity gradient of 13.1 MV/m. A key innovation of the 3.9 GHz coupler is the incorporation of an adjustable antenna insertion depth, which enables online external quality factor (Q_{ext}) tuning and eliminates the need for a three-stub tuner, reducing system complexity and cost. Two 3.9 GHz coupler prototypes were fabricated and underwent comprehensive rf testing. The couplers achieved excellent performance with an insertion loss of -0.16 dB and return loss of -43.22 dB at 3.9 GHz after structural optimization. High-power rf conditioning demonstrated stable operation at 2 kW in traveling wave mode and 1 kW in standing wave mode. Sixteen production 3.9 GHz couplers were manufactured and integrated into two third harmonic cryomodules, which achieved maximum total cavity voltages of 63.6 and 59.8 MV, respectively, with average usable accelerating gradients of 23.0 and 21.6 MV/m. The cryomodules have been installed in the tunnel and initial beam commissioning has been completed successfully.

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I. INTRODUCTION

The Shanghai high repetition rate XFEL and extreme light facility (SHINE) consists of a continuous-wave (cw) superconducting linear accelerator (linac), two undulator lines covering the photon energy range from 0.2–15 keV, two x-ray beamlines, and six experimental end-stations [1–5]. The SHINE accelerator consists of an injector section, a laser heater section, four sections of 1.3 GHz standard superconducting cryomodules (CMs), one section of 3.9 GHz third harmonic superconducting cryomodules, three magnetic bunch compression sections, and a dechirper section at the end. The schematic layout diagram

of the SHINE facility is shown in Fig. 1. A total beam energy of 8 GeV is expected from the main linac by utilizing 54 primary 1.3 GHz cryomodules (with 4 spares) at a higher superconducting cavity gradient (~ 20 MV/m), in combination with two 3.9 GHz third harmonic cryomodules. The third harmonic cryomodules are intended to increase the peak bunch current and linearize the accelerating voltage for electrons within a bunch in the longitudinal phase space [6–8].

The 3.9 GHz fundamental power coupler (FPC) is a critical component of the third harmonic cryomodule. It is responsible for transferring radio frequency (rf) power into the cavity while isolating the ultrahigh vacuum of the cavity from the atmosphere [9,10]. Unlike the 1.3 GHz accelerating cavity, the 3.9 GHz cavity operates with a beam-to-rf phase close to 153° . In this configuration, the beam-induced rf power flows from the cavity back toward the coupler, which significantly reduces the power demand from the external source. Fermilab designed and built 3.9 GHz FPCs for the free electron laser user facility FLASH at DESY, which operated in a pulse regime

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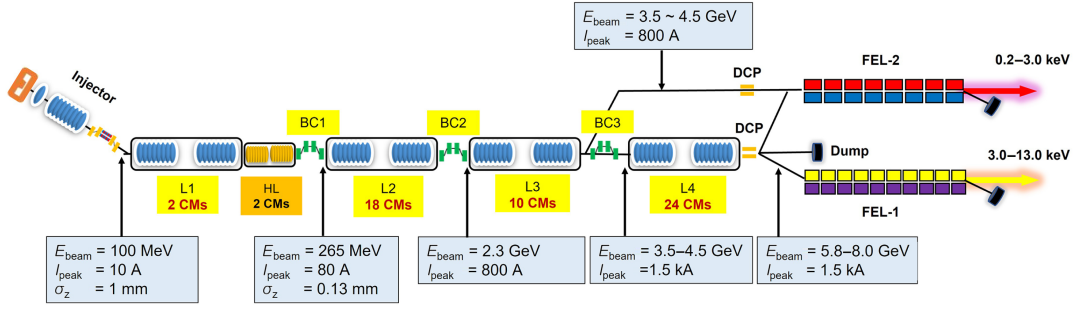


FIG. 1. Schematic layout diagram of the SHINE facility.

(1.3 ms $\times$ 10 Hz $\times$ 45 kW; maximal average power $\sim$ 600 W). This same design was subsequently used for the European x-ray free electron laser (Eu-XFEL) project [11]. The 3.9 GHz FPCs for the Linac Coherent Light Source facility (LCLS-II) with cw operation were based on the existing Eu-XFEL design but were redesigned with a few modifications to handle 2 kW of average power. The modifications include reducing the length of two inner bellows from 20 convolutions to 10 convolutions, increasing the thickness of the copper plating on the inner conductor from 30 to 150 microns, and changing the antenna length to fulfill the LCLS-II coupling requirement [12,13]. Based on the foundation established by the 3.9 GHz couplers for the Eu-XFEL and LCLS-II projects, a new 3.9 GHz FPC has been designed for the SHINE third harmonic cryomodule. This coupler is capable of handling 2 kW of cw rf power, meeting the operational requirements under a beam current of 0.3 mA and a cavity gradient of 13.1 MV/m.

The 3.9 GHz FPCs used in both the Eu-XFEL and LCLS-II projects employ a fixed antenna length, a design that offers simplicity in both construction and installation. However, the Eu-XFEL team reported that measurements of the external quality factor (Q_{ext}) on the first 3.9 GHz cryomodule (containing eight cavities) revealed variations of up to a factor of 2 among individual cavities [14]. To meet the Q_{ext} specification as closely as possible, the antenna tip of the coupler can be precision-cut and polished in a cleanroom to adjust its length, based on the measured Q_{ext} obtained after the coupler is installed on the superconducting cavity. Fine-tuning of the Q_{ext} can also be subsequently achieved using a three-stub tuner. A key innovation in the SHINE 3.9 GHz coupler design is the incorporation of an adjustable antenna insertion depth. This design approach effectively addresses the Q_{ext} variability issue encountered in fixed-length couplers. This feature enables online Q_{ext} tuning to meet the specific beam operation requirements of the accelerator. Moreover, this adjustability eliminates the need for a three-stub tuner within the accelerator system, thereby reducing both system complexity and cost. The main technical parameters of the SHINE 3.9 GHz FPC are listed in Table I. A 180° rotational layout is adopted for the 3.9 GHz couplers

between adjacent cavities in the third harmonic cryomodule design, thereby minimizing the transverse rf kick induced by the power couplers [15].

This paper is organized as follows. Section II presents the structural design, manufacturing process, and rf tests of the first two 3.9 GHz coupler prototypes, followed by the structural optimizations based on the test results. Section III describes the cooling strategy implemented for the 3.9 GHz coupler within the cryomodule and presents the test results of the single-cavity cryomodule. Section IV covers the assembly and horizontal testing of the SHINE 3.9 GHz third harmonic cryomodule, focusing on coupler performance. Finally, Sec. V provides the conclusions and outlook.

II. COUPLER DESIGN, MANUFACTURING, AND RF TESTS

A. Coupler design

As shown in Fig. 2, the 3.9 GHz coupler for the SHINE third harmonic cryomodule comprises four major sections: the cold section, the warm inner and outer conductor assembly, the warm rf window waveguide assembly, and the tuning mechanism. It features dual rf ceramic windows and a 50- Ω characteristic impedance coaxial line design. Leveraging proven designs, the cold rf window's design is similar to that of the SHINE 1.3 GHz coupler, while the

TABLE I. Main technical parameters of the SHINE 3.9 GHz FPC.

Parameters	Specification
Frequency	3.9 GHz
Type	Coaxial, dual windows
Window type	Cylindrical (cold) + planar (warm)
Coupler power capability	1.8 kW (0.3 mA beam current)
rf conditioning power, TW mode	2 kW (test bench)
External quality factor, Q_{ext}	2.13×10^7
Q_{ext} adjustment range	$1.0 \times 10^7 \sim 5.0 \times 10^7$
Antenna adjustment range	± 3 mm

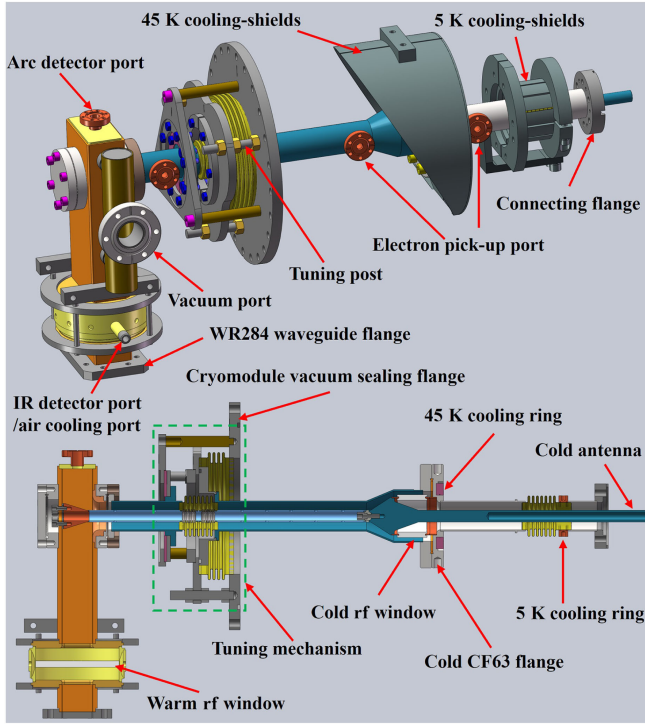


FIG. 2. Mechanical design of the SHINE 3.9 GHz FPC.

warm rf window incorporates a robust design derived from a commercial klystron window and integrates an air-cooling system. A bellows in the cold section's outer conductor accommodates thermal contraction and mechanical tolerances during cryomodule thermal cycles. The cold antenna is fabricated from oxygen-free copper with a hollow tip to effectively mitigate mechanical stress on the cold rf ceramic window during thermal cycles. Meanwhile, the warm inner conductor's copper film thickness is increased to 150 μm specifically to reduce ohmic heating and lower the bellows' temperature, while a 30 μm copper film is applied to all outer conductor surfaces. The tuning mechanism, located on the atmospheric side of the cryomodule, adjusts the antenna's insertion depth via three tuning posts to vary the coupling strength. For

comprehensive performance monitoring, three electron pickup probes are installed in both the cold and warm sections to detect multipacting and field emission. Simultaneously, an arc detector on the waveguide box provides monitoring for arcing events. Two ports are located near the warm rf window. The first port facilitates warm rf ceramic window noncontact temperature monitoring via an infrared sensor. The second port serves as an air-cooling interface that provides active thermal management to maintain the rf window within a safe operating temperature range, if required. Additionally, a vacuum pump port on the waveguide box evacuates the warm section and the desorbed gases near the warm rf window. The cryogenic cooling strategy of the 3.9 GHz coupler follows the SHINE 1.3 GHz coupler, incorporating 5 and 45 K thermal intercepts at the cold bellows and cold CF63 flange, respectively. The 45 K cooling ring is brazed into a groove on the cold CF63 flange, enhancing thermal conduction compared to traditional fastening methods. WR284 waveguide is selected as the interface with a solid-state amplifier (SSA).

The design of the SHINE 3.9 GHz FPC has been completed. The work encompassed rf optimization, multipacting (secondary electron multiplication) simulations, and thermal analysis, and the results have been published [16].

B. Coupler manufacturing process

One set of SHINE 3.9 GHz FPC consists of 68 parts. The manufacturing processes of the 3.9 GHz couplers include parts machining, vacuum brazing of subassemblies, copper plating of rf surfaces, TiN coating of ceramic windows, electron beam welding (EBW), etc. [17]. The flow chart of 3.9 GHz coupler manufacturing processes is shown in Fig. 3. Most subassemblies of the couplers were fabricated using vacuum brazing technology, which offers better reproducibility and is less operator-dependent than welding. All brazed joints underwent 100% leak checking, with a required helium leak rate below 1.0×10^{-12} Pa m³/s. The cold antenna and the waveguide box were made of

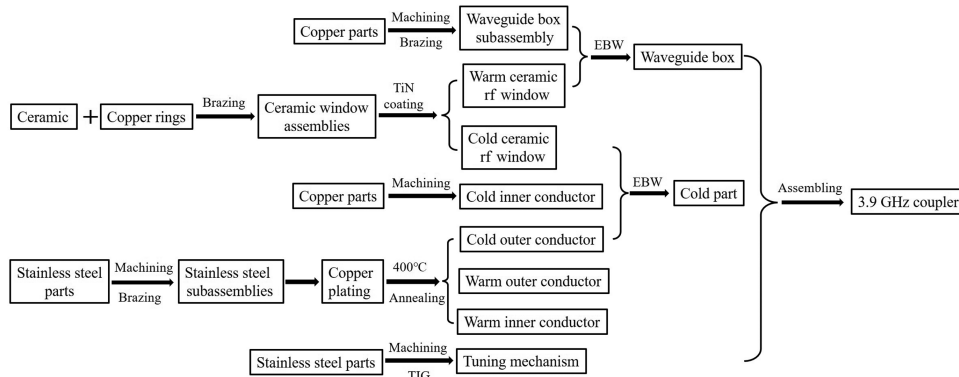


FIG. 3. Flow chart of the 3.9 GHz coupler manufacturing processes.

oxygen-free copper, while the others were made of stainless steel. To reduce rf loss, all stainless-steel rf surfaces were electroplated with copper films. The copper film thickness on the outer conductor was 30 μm . However, on the warm inner conductor, the thickness was increased to 150 μm to mitigate overheating, particularly on the bellows. To suppress secondary electron emission, the vacuum-side surfaces of the rf ceramic windows were coated with a TiN film. The target thickness of the TiN coating was 10 nm, with an acceptable range of 7 to 15 nm. EBW served as the final manufacturing step for integrating the ceramic window, inner conductor, and outer conductor of the cold section, and the waveguide assembly. This process required special care. Sophisticated fixtures were designed to protect the ceramic windows from metallization by welding vapor during EBW. These fixtures could be easily disassembled without damaging the coupler's copper films. No weld beads were permitted inside the coupler, and smooth electron beam welds were essential for optimal performance.

Two SHINE 3.9 GHz coupler prototypes have been fabricated, as shown in Fig. 4. Surface treatments and assembly procedures are critical steps that significantly influence the efficiency and speed of the subsequent high-power rf conditioning. These handling procedures essentially follow those established for the SHINE 1.3 GHz couplers [18]. All coupler parts were initially cleaned in an ultrasonic bath with a detergent solution in a class 100 cleanroom. They were then rinsed with ultrapure water until the resistivity of the effluent reached 14 $\text{M}\Omega\text{cm}$. After rinsing, the parts were dried with filtered high-purity nitrogen gas and left overnight under a laminar flow in a class 10 cleanroom. Immediately before assembly, each part was again blown with filtered nitrogen gas. A particle counter monitored the environment, requiring a count of fewer than 10 particles (size $> 0.3 \mu\text{m}$) per cubic foot. Parts failing this check were returned for ultrasonic cleaning. Pumping groups (including ion pumps, metal angle valves, and gauges) were mounted on each warm section and the

cold assembly, which included the rectangular waveguide. A leak test was then performed on both. After verifying hermeticity, the coupler test bench was baked in a modified vacuum furnace at 150°C for 72 h. Following the bakeout, the achieved vacuum levels were better than 5×10^{-7} Pa for the cold assembly and better than 5×10^{-6} Pa for the warm sections. The overall leakage rate for the entire system was below 1.0×10^{-12} $\text{Pa m}^3/\text{s}$. Meanwhile, residual gas analyzer measurements confirmed that the ratio of the total current for species with a mass-to-charge ratio greater than 44 atomic mass units (AMU) to the total ion current ($I_{\text{amu} > 44} / I_{\text{total}}$) was less than 1/1000.

C. Coupler rf tests

Prior to their installation in the cryomodules alongside the superconducting cavities, the FPCs must undergo full high-power rf conditioning on a room-temperature test bench. This rf conditioning process is critical for validating the coupler's design and rf performance. Moreover, it helps to desorb residual gases and eliminate microscopic surface contaminants, since any remaining flaws or contamination could otherwise degrade the performance of the associated superconducting cavity.

1. rf design of 3.9 GHz couplers test bench

The test bench includes a pair of back-to-back couplers and a rectangular connecting waveguide. Its rf design requires good impedance matching to minimize the reflection coefficient and maximize the transmission coefficient at the operating frequency of 3.9 GHz [19–21]. As shown in Fig. 5(a), the rectangular waveguide follows the WR284 standard, with a width of 72.14 mm and a height of 34.04 mm. The rf optimization focuses on three critical structural parameters [defined in Fig. 5(b)]: the insertion depth of the cold antenna (h), the distance between the antenna and the short-circuit surface ($d1$), and the distance between the two antennas ($d2$). A series of simulations are

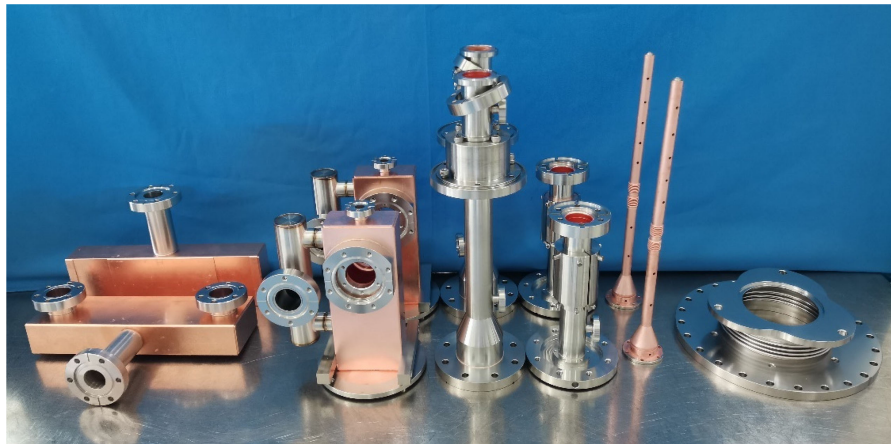


FIG. 4. Fabricated subassemblies of the 3.9 GHz coupler prototypes.

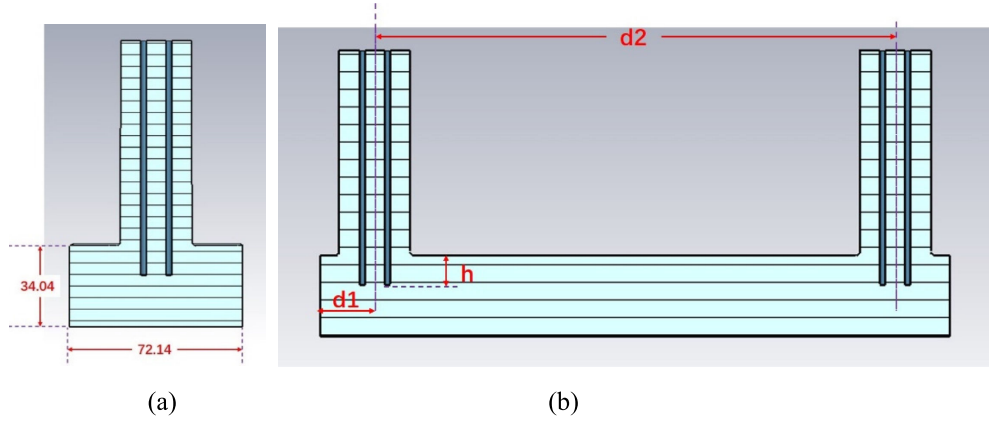


FIG. 5. (a) Structural dimensions of the WR284 waveguide and (b) parameters of the 3.9 GHz FPCs test bench.

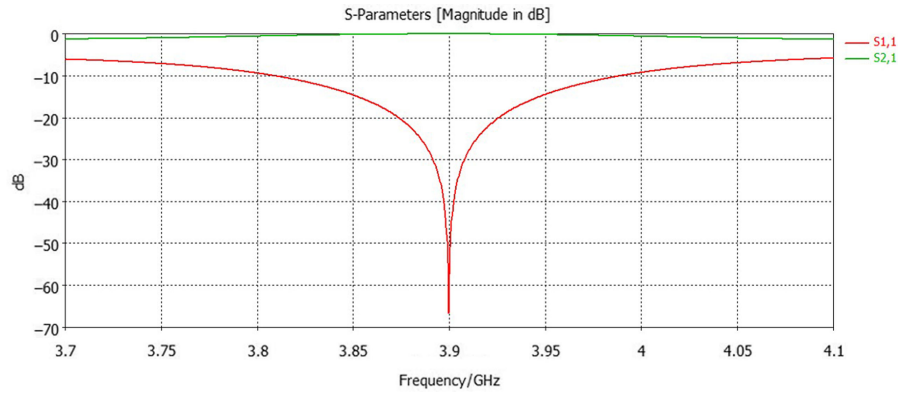


FIG. 6. S-parameter curves of the optimized 3.9 GHz coupler test bench versus frequency.

performed to identify the best combination of these parameters for achieving optimal transmission at 3.9 GHz.

The S-parameters of the 3.9 GHz coupler test bench were simulated using the high-frequency simulation software CST [22]. An optimal set of structural parameters was determined through parameter optimization: the insertion depth of the cold antenna (h) = 12.5 mm, the distance to the short-circuit surface ($d1$) = 23 mm, and the distance between the two antennas ($d2$) = 218.4 mm. Figure 6 presents the simulated S-parameter curves within the frequency range of 3.7 to 4.1 GHz. At the operating frequency of 3.9 GHz, the optimized results show a reflection coefficient (S_{11}) as low as -57.46 dB and a transmission coefficient (S_{21}) of -0.0033 dB, indicating excellent impedance matching and very low insertion loss.

2. S-parameter measurements of test bench

Two 3.9 GHz coupler prototypes were installed on the test bench, along with various vacuum tubes and ion pumps. Before conducting high-power rf conditioning, S-parameter measurements were conducted to verify the

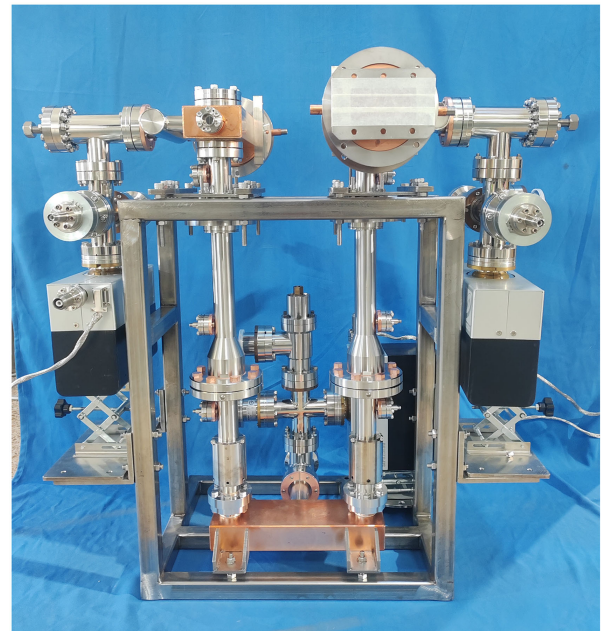


FIG. 7. 3.9 GHz couplers test bench.

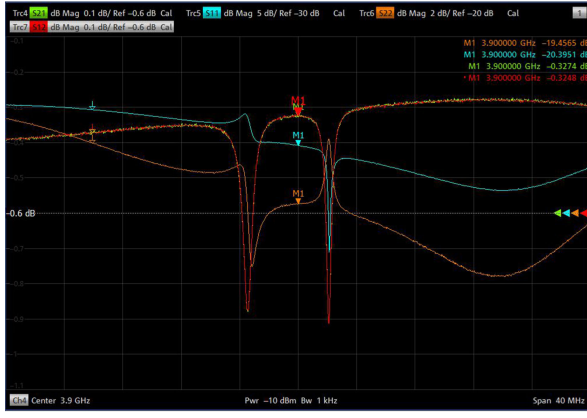


FIG. 8. Preliminary S-parameter measurements of the 3.9 GHz coupler prototypes.

overall impedance matching of the test bench. Figure 7 shows the assembled test bench for the 3.9 GHz couplers. After calibration, the network analyzer was used to measure the S-parameters at the input and output ports of the couplers.

As shown in Fig. 8, the measured S-parameters exhibit unexpected characteristics, including anomalous peaks at 3.89 and 3.915 GHz, which degrade the overall performance; this is suspected to arise from multiple signal reflections caused by impedance mismatch at discontinuities such as slits.

Based on transmission line theory, any discontinuity at a connection point will cause impedance variations, leading to signal reflection and potential microwave leakage. Inspection of the 3.9 GHz coupler model revealed that the area in the structural design most likely to cause impedance changes is the connection point of the warm inner conductor to the waveguide box, as shown in Fig. 9(a). The conical inner conductor is plug-installed into the waveguide box. To prevent microwave leakage, grooves are machined into the warm inner conductor to

accommodate shielding springs. Experiments were conducted by (1) leaving the grooves empty [no shielding spring, Fig. 10(a)], (2) placing two shielding springs [Fig. 10(b)], and (3) winding copper wire [Fig. 10(c)]. The test results yielded the following conclusions: (i) Abnormal peaks occur near 3.89 GHz in all cases. (ii) Without the shielding spring, the insertion loss is greatest, with S21 measuring -0.98 dB at 3.9 GHz. (iii) With two shielding springs or wound copper wire, the peaks become more pronounced, but the insertion loss decreases, resulting in an S21 of approximately -0.27 dB at 3.9 GHz. (iv) The shielding springs or copper wire serve to form a continuous conductive interface, thereby reducing the impedance discontinuity at the connection point. (v) The experimental results indicate that good electrical contact can effectively reduce insertion loss. However, the enhancement of the abnormal peak suggests that this connection structure might still introduce certain resonances or higher-order modes at specific frequencies (e.g., 3.89 GHz). To resolve this issue thoroughly, further optimization of the mechanical structure design at this connection point is required.

We redesigned the installation structure at the connection point of the warm inner conductor to the waveguide box, replacing the original shielding spring seal with a bolted spring contact structure, as shown in Fig. 9(b). Following this modification, S-parameter measurements were conducted. The results demonstrated a significant improvement: the abnormal peaks were eliminated, yielding a smooth curve. At 3.9 GHz, the measured S21 and S11 parameters were -0.16 and -43.22 dB, respectively. These S-parameter measurement results are presented in Fig. 11. The measurement results confirm the considerable success of the structural redesign. An S21 value of -0.16 dB indicates extremely high signal transmission efficiency with very low insertion loss. Meanwhile, an S11 value as low as -43.22 dB signifies excellent port impedance matching, implying

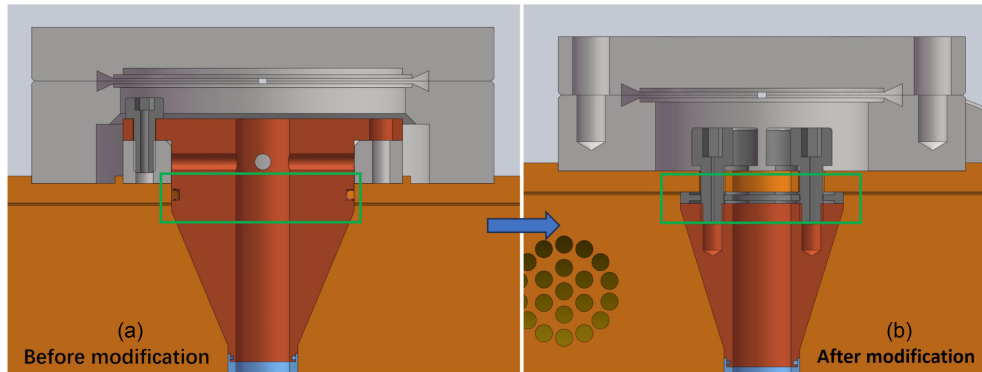


FIG. 9. Comparison of the installation structures for the warm inner conductor and waveguide box: (a) original and (b) redesigned configurations.



FIG. 10. S-parameter measurements for different installation configurations: (a) no shielding spring, (b) placing two shielding springs, and (c) winding copper wire.

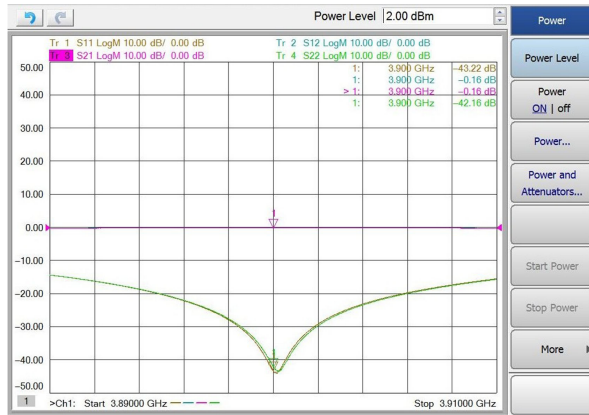


FIG. 11. S-parameter measurements after design optimization.

that the reflected signal energy is negligible. The elimination of abnormal peaks and the smoothing of the curve demonstrate that the new bolted spring contact structure effectively enhances impedance continuity and suppresses potential resonant modes at the connection point. In summary, these performance metrics affirm a fundamental optimization of the mechanical design.

3. High-power rf tests

Two modified 3.9 GHz coupler prototypes were reassembled and installed on the test bench for high-power

rf tests. Figure 12 shows the layout of the rf test system for the 3.9 GHz FPCs. The rf test system consists of four major subsystems: (1) a power source system, (2) a power transmission system, (3) a test bench, and (4) an interlock control and data acquisition system [23,24]. The power source system includes a solid-state amplifier (SSA) capable of outputting 2 kW of cw power. The power transmission system comprises various transmission waveguides, directional couplers, water-cooled rf-absorbing loads, and a sliding short circuit. Three ion pumps are used for vacuum extraction and maintenance in the warm part of the upstream coupler, the warm part of the downstream coupler, and the cold parts assembly. An interlock control and data acquisition system was developed to monitor and record parameters such as incident power, reflected power, temperature, vacuum level, electron current, and arc events, and to immediately cut off the power source when interlocking signals exceed preset thresholds to protect the couplers.

The high-power rf tests include two types of rf conditioning procedures: cw rf conditioning in the traveling wave (TW) mode and cw rf conditioning in the standing wave (SW) mode. In the TW mode, the terminal of the rf test system is connected to a water-cooled rf-absorbing load. The microwave power generated by the source travels through the upstream and downstream couplers and is ultimately absorbed by the terminal load. In the SW mode, the system terminal is connected to a sliding short circuit to reflect the microwave power almost entirely. The reflected wave then travels back through the downstream and upstream couplers. A circulator is used to protect the power source by directing the reflected power into a dedicated load.

The TW cw rf conditioning test was first conducted. The rf power was increased stepwise from 0 to 2 kW in increments of 0.2 kW, with a dwell time of 5 min at each step. The rf power was then maintained at the maximum level of 2 kW for 12 h. Figure 13 shows the temperature variations at various monitoring points for both the upstream and downstream couplers throughout the TW cw rf conditioning process. The layout of the temperature monitoring points on the couplers is illustrated in Fig. 14. Here, UT denotes the upstream coupler temperature, and DT denotes the downstream coupler temperature. Specifically, UT-1 and DT-1 represent the infrared temperatures of the warm rf windows for the upstream and downstream couplers, respectively. UT-4 and DT-4 correspond to the temperatures of the cold CF63 flanges on the upstream and downstream couplers, which are closest to the cold rf windows. The test results indicate that after approximately 4 h of rf power maintenance, the coupler temperatures remained stable. The temperatures at each monitoring point of the upstream and downstream couplers showed good consistency, and the maximum temperature measured on the couplers was about 67 °C. Figure 15 shows

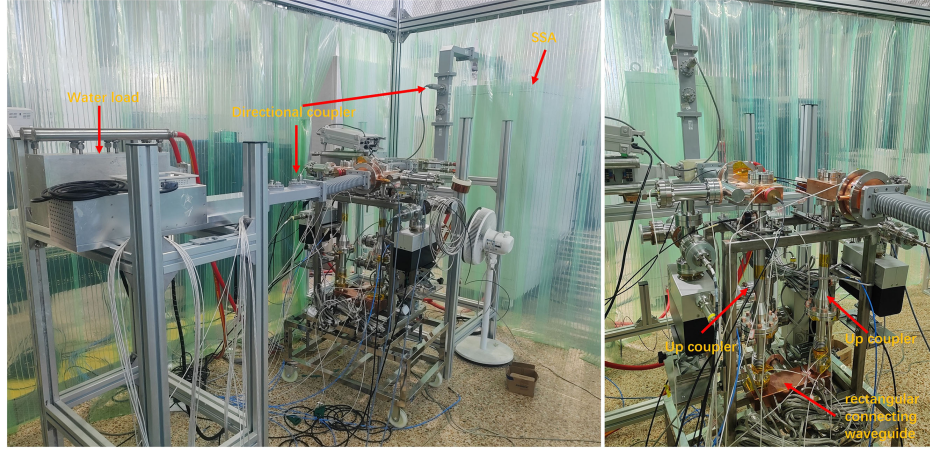


FIG. 12. Layout of the rf test system for 3.9 GHz FPCs.

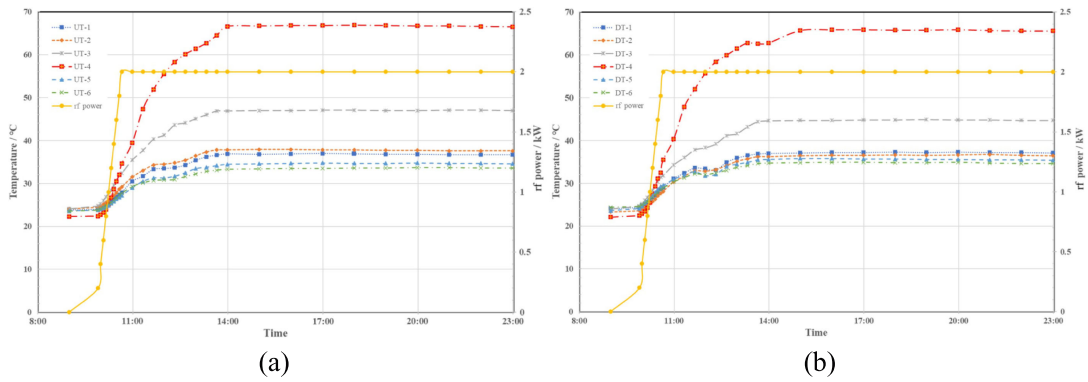


FIG. 13. (a) Upstream and (b) downstream coupler temperature variations during TW cw rf conditioning.

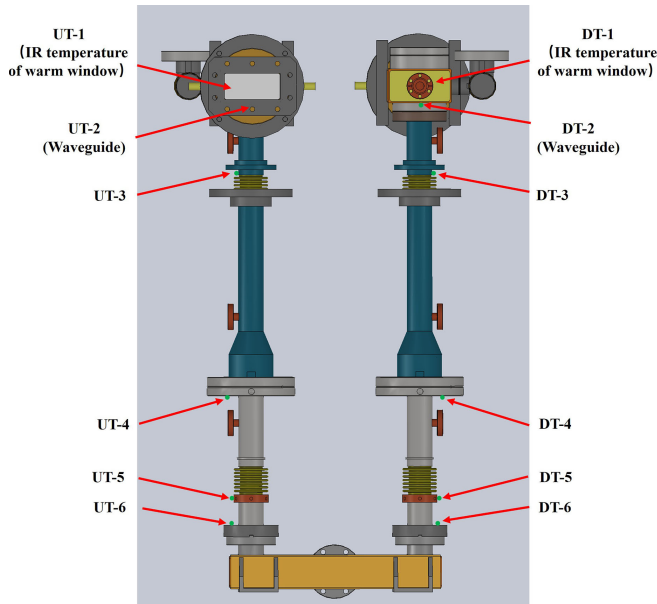


FIG. 14. Layout of the temperature monitoring points on the 3.9 GHz couplers test bench.

the vacuum variation during the TW cw rf conditioning process. The vacuum level deteriorated as the rf power increased, but it gradually improved during the rf power maintenance period. Throughout the entire TW cw test, no interlock events occurred. The measured electron current activity remained essentially at background levels.

The water-cooled rf-absorbing load of the rf test system was then replaced with a sliding short circuit to commence SW cw rf conditioning. The rf power was incrementally increased from 0 to 1 kW in steps of 0.15 kW, with a dwell time of 5 min at each step. The rf power was then maintained at the maximum level of 1 kW for 12 h. By adjusting the position of the sliding short, both the amplitude of the standing wave and the location of the wave nodes could be altered. This ensured thorough rf conditioning along the entire length of the couplers. As shown in Fig. 16, after approximately 4 h of rf power maintenance, the temperatures at various monitoring points of the couplers stabilized. The highest temperature, approximately 67°C, was observed on the cold CF63 flange. Owing to the outgassing achieved during the prior TW cw rf conditioning, the initial vacuum level of the couplers was

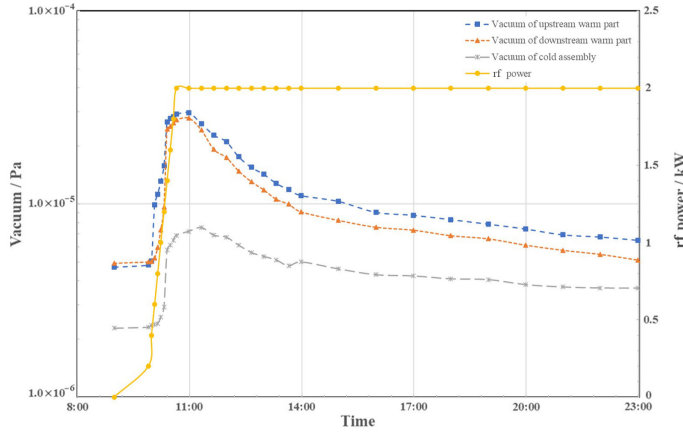


FIG. 15. Vacuum curves of the warm parts and the cold assembly during TW cw rf conditioning.

significantly improved, reaching the 10^{-7} Pa range. As the rf power increased, the vacuum level deteriorated; however, this degradation was relatively moderate, which can be attributed to the improved initial vacuum level achieved during the prior TW rf conditioning. As shown in Fig. 17, after 4 h of rf conditioning at the maintained power of 1 kW, the vacuum tended to improve, stabilizing within the range of 1×10^{-6} Pa to 5×10^{-6} Pa.

Both 3.9 GHz coupler prototypes were rf conditioned under the TW and SW modes, respectively. The test results demonstrate that their performance meets the specified power requirements. The successful rf conditioning of both prototypes can be primarily attributed to the advanced manufacturing and surface treatment processes developed for the SHINE FPCs, in addition to the optimized structural design [18]. Specifically, the stringent clean assembly procedures and effective vacuum baking process were key to reducing contamination and improving rf conditioning efficiency.

The FLASH 3.9 GHz couplers underwent rf power conditioning in TW mode using 10 Hz pulsed power at

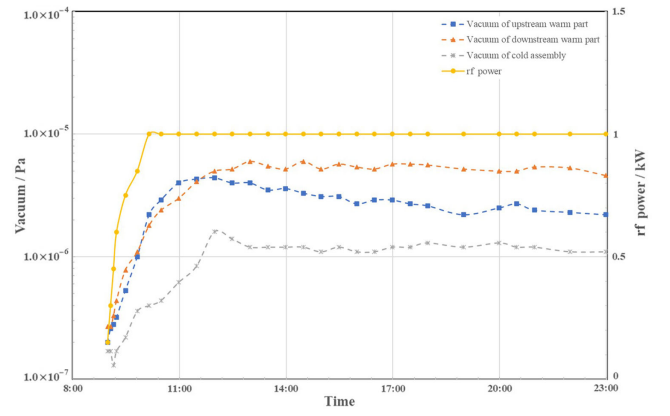
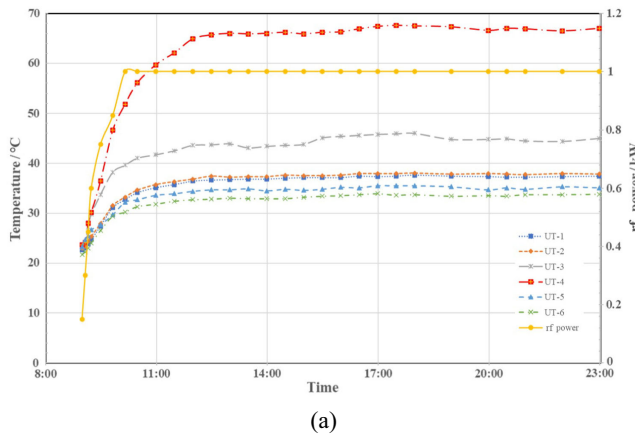


FIG. 17. Vacuum curves of the warm parts and the cold assembly during SW cw rf conditioning.

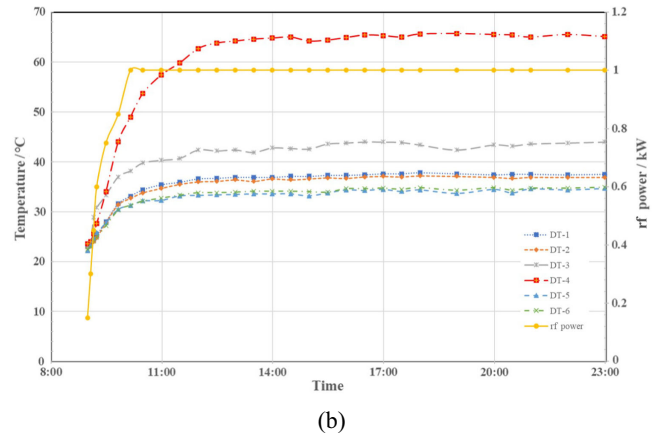
room temperature test bench. The maximum peak power was 61 kW with a pulse length of 1.3 ms, corresponding to an average power of approximately 0.8 kW [25]. Separately, two LCLS-II 3.9 GHz coupler prototypes were rf conditioned to 2 kW of cw power in TW mode [14]. Table II presents a comparison of the rf test results and Q_{ext} specification for the 3.9 GHz couplers from three international FEL facilities (FLASH, LCLS-II, and SHINE). The results demonstrate that the SHINE 3.9 GHz coupler, benefiting from specific design optimizations such as a new bolted spring contact structure, achieved superior performance in terms of insertion loss and return loss.

III. SINGLE-CAVITY CRYOMODULE INTEGRATION AND HORIZONTAL TEST

A preassembly horizontal test has been conducted on a single 3.9 GHz cavity cryomodule. The primary goal of this test is to mitigate technical risks associated with the assembly and commissioning process, thereby ensuring the success of the full third harmonic cryomodule series for the SHINE project. The test cryomodule integrates key



(a)



(b)

FIG. 16. (a) Upstream and (b) downstream coupler temperature variations during SW cw rf conditioning.

TABLE II. Comparison of the rf test results for the 3.9 GHz couplers from three international FEL facilities.

	S11	S21	rf power	Q_{ext}
FLASH/Eu-XFEL	−18 dB	−0.6 dB	Pulse TW: 1.3 ms × 10 Hz × 61 kW (Average power ~0.8 kW)	$\sim 1.0 \times 10^6$
LCLS-II	...	...	cw TW: 2 kW	2.5×10^7
SHINE	−43 dB	−0.16 dB	cw TW: 2 kW cw SW: 1 kW	2.1×10^7

components, including a 3.9 GHz superconducting cavity, a 3.9 GHz coupler, a tuner, and a magnetic shielding assembly. The main objectives of this test are twofold: first, to develop and validate the integrated assembly procedures for the 3.9 GHz cryomodule; and second, to verify the performance of both individual components and the cryomodule as a whole. Specifically, for the 3.9 GHz coupler, the tests focus on three critical aspects: (1) verifying its cooling performance within the cryomodule, (2) validating its Q_{ext} adjustment function, and (3) examining its rf power handling capabilities.

A. Cooling performance test of the 3.9 GHz coupler prototype

Figure 18 illustrates the 3.9 GHz single-cavity test cryomodule and the conductive cooling structure for its coupler within the cryomodule. The cooling structure for the SHINE 3.9 GHz coupler within the cryomodule follows the design principle of the SHINE 1.3 GHz coupler. Flexible copper-braids are used for effective heat removal: two copper braids connect the coupler's 5 K thermal intercept to the 5 K helium pipe, while another two connect its 45 K intercept (specifically, the cold CF63 flange) to the

45 K cooling shield of the cryomodule. In contrast, the 3.9 GHz coupler for the Eu-XFEL employs a different strategy, which uses 5 and 80 K (liquid nitrogen) temperature stages. Specifically, the coupler's cold end flange (connected to the cavity) is connected to the 5 K helium pipe, and the cold CF63 flange is connected to the 80 K cooling shield.

The experimental results demonstrate that using double copper-braid significantly reduces the temperature of the coupler. Table III presents a comparison of the measured static and dynamic (under 1 kW rf power) temperatures for the 3.9 GHz coupler employing single and double copper-braid cooling configurations. Figure 19 shows the measured temperature curves of the 3.9 GHz coupler under double copper-braid configuration. The data confirm a substantial temperature decrease at key locations; for instance, under 1 kW power transmission, the temperature at CP1-T1 decreases from 22 to 15.2 K, and at CP1-T2 from 248.9 to 121.4 K. The static and dynamic heat loads on the coupler's 5 and 45 K stages were estimated from the temperature drop across the thermal copper-braids. The 5 K static heat load of the 3.9 GHz coupler is approximately 0.8 W, and the 45 K static heat load is approximately 7.1 W. Under 1 kW cw rf power, the 5 K dynamic heat load is

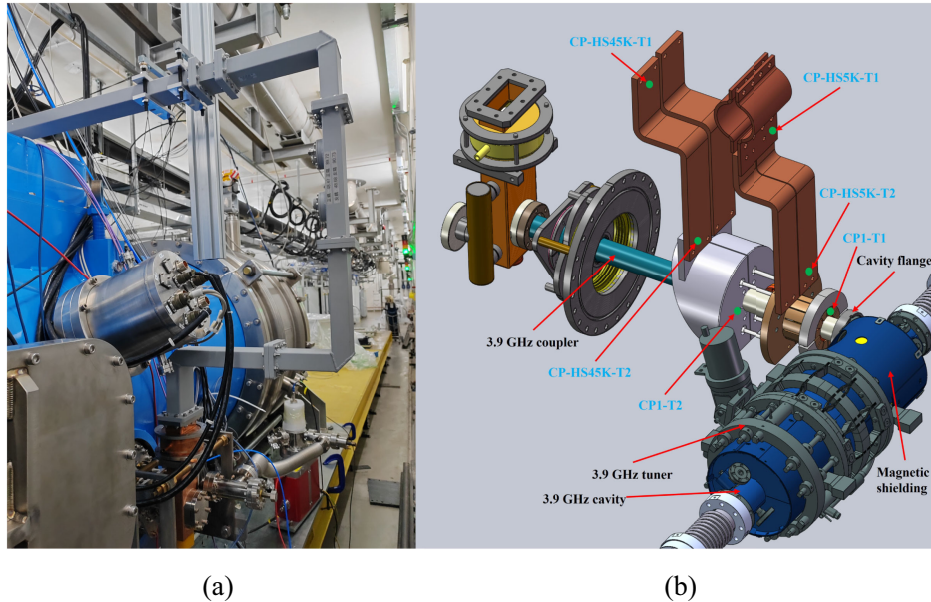


FIG. 18. (a) 3.9 GHz single-cavity test cryomodule and (b) conductive cooling structure of its coupler.

TABLE III. Comparison of measured static and dynamic temperatures for the 3.9 GHz coupler with single and double copper-braid configurations.

	Single copper-braid		Double copper-braids	
	Static (K)	Dynamic (K)	Static (K)	Dynamic (K)
CP1-T1	13.43	22.07	9.28	15.18
CP1-T2	66.77	248.94	67.14	121.37
CP-HS45K-T1	52.96	81.46	57.52	67.78
CP-HS45K-T2	61.74	211.62	63.3	101.70
CP-HS5K-T1	6.02	7.32	6.01	7.04
CP-HS5K-T2	8.76	13.25	6.31	7.74

about 2.2 W, and the 45 K dynamic heat load is approximately 29.4 W. These results demonstrate that the thermal performance of the coupler could meet the operational requirements for the 3.9 GHz third harmonic cryomodule.

B. rf tests of 3.9 GHz coupler and cavity prototypes

High-power rf conditioning of the 3.9 GHz coupler was first conducted online prior to the cooldown of the single-cavity cryomodule. This process utilized the coupler's rf power dissipation for outgassing, thereby preventing gas adsorption by the superconducting cavity at cryogenic temperatures. The rf conditioning procedure comprised two main steps: (1) Pulsed rf conditioning: The process began in pulsed mode with a pulse repetition rate of 10 Hz. The pulse width was sequentially increased through 5%, 10%, 15%, and 20% duty cycle at a fixed peak power of 1 kW. The incident power was increased stepwise from 0.1 to 1 kW in 0.2 kW increments. The couplers were rf conditioned at each power level for 5 min. This pulsed conditioning step verified the stability of both the coupler and the test system, ensuring the safety of the cryomodule. (2) cw conditioning: Following the pulsed conditioning, the couplers underwent cw rf conditioning. The cw power was

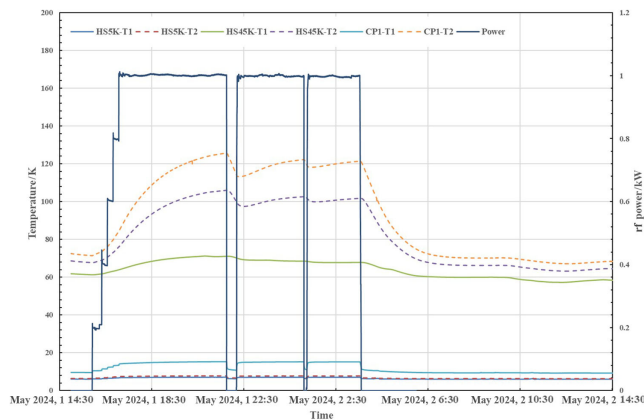


FIG. 19. Temperature curves of the 3.9 GHz coupler measured under double copper-braid configuration.

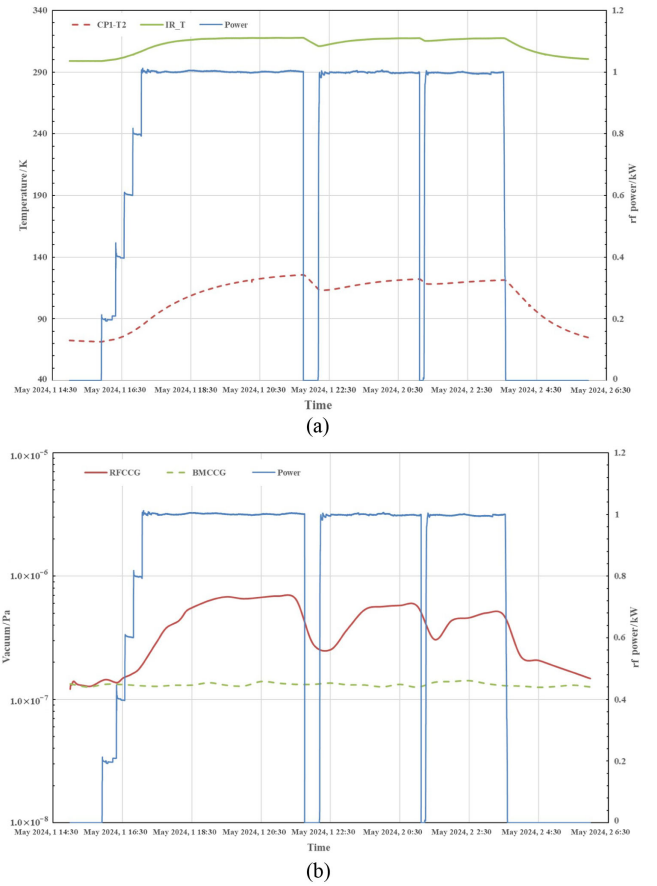


FIG. 20. (a) Temperature and (b) vacuum evolution during the cryogenic high-power rf conditioning of the 3.9 GHz coupler prototype.

ramped from 0.1 to 1 kW in 0.1 kW steps, with a 10-min dwell time at each step.

Following cryomodule cooldown, high-power rf conditioning was repeated to verify the coupler's thermal stability and vacuum integrity. Figure 20 shows the temperature and vacuum curves during high-power rf conditioning of the 3.9 GHz coupler under cryogenic conditions. After maintaining a cw power level of 1 kW for 6 h (despite two interruptions in rf transmission due to sensor equipment failures), the temperatures of the cold CF63 flange and the warm rf window (measured by infrared) reached equilibrium. The maximum cold CF63 flange temperature (CP1-T2) was 121 K, and the maximum warm rf window infrared temperature was 44 °C (317 K). Concurrently, the vacuum level improved, achieving a maximum vacuum of 5.0×10^{-5} Pa. The temperature of the cold CF63 flange, which is typically used for interlock controls, should be maintained below 150 K.

The Q_{ext} tuning capability of the 3.9 GHz coupler was validated following high-power rf conditioning. Figure 21 compares the simulated and measured Q_{ext} values versus the distance between the antenna tip and the cavity axis.

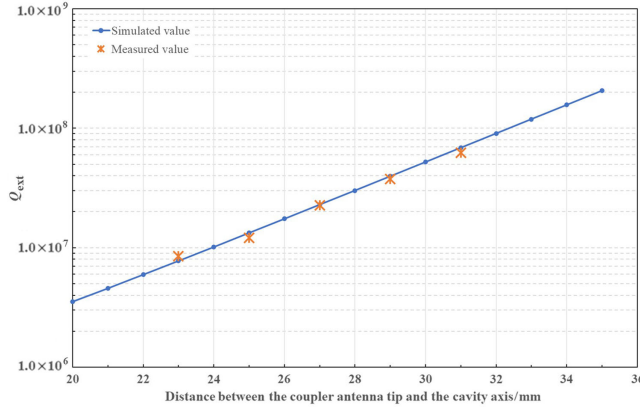


FIG. 21. Comparison between simulated and measured Q_{ext} as a function of the coupler antenna distance from the cavity axis.

Over a mechanical adjustment range of ± 4 mm, the Q_{ext} was tuned from 8.5×10^6 to 6.2×10^7 . This demonstrated operational range fully covers the coupler's designed adjustable range (1.0×10^7 to 5.0×10^7), confirming its wide tuning capability. The discrepancy between the measured and simulated Q_{ext} values is within 10%. Finally, the Q_{ext} was precisely tuned to the design value of 2.1×10^7 .

The superconducting cavities for the SHINE 3.9 GHz third harmonic cryomodule have required specifications of an operating gradient of 13.1 MV/m, a maximum operating gradient of 15 MV/m, and an unloaded quality factor (Q_0) of not less than 2.0×10^9 at 13.1 MV/m. These specifications were validated during the horizontal test of the single-cavity test cryomodule. The 3.9 GHz superconducting cavity achieved a maximum accelerating gradient of 20.3 MV/m, which is consistent with its vertical test results. The Q_0 value also showed good agreement with the vertical test data. A stability test was conducted at a cavity gradient of 18.0 MV/m to further verify the performance of the cavity and its coupler. To assess the coupler's temperature and vacuum stability under higher rf power, the cavity was deliberately detuned. This approach allowed the incident power on the coupler to be increased to 1.2 kW while maintaining the cavity gradient at 18.0 MV/m. This high-power state was sustained for 3.5 h, during which the temperatures of the coupler's warm rf ceramic window and the cold CF63 flange stabilized at safe levels, not exceeding 41 °C and remaining below 136 K, respectively. Despite four quenches triggered by significant helium pressure fluctuations, the cavity system maintained overall stable operation. Subsequently, the cavity was tuned back to resonance, reducing the incident power to 0.67 kW. The system continued to operate stably for an additional hour, with the coupler temperatures and vacuum levels gradually returning to their nominal values. Figure 22 illustrates the variation of the coupler temperature and vacuum level

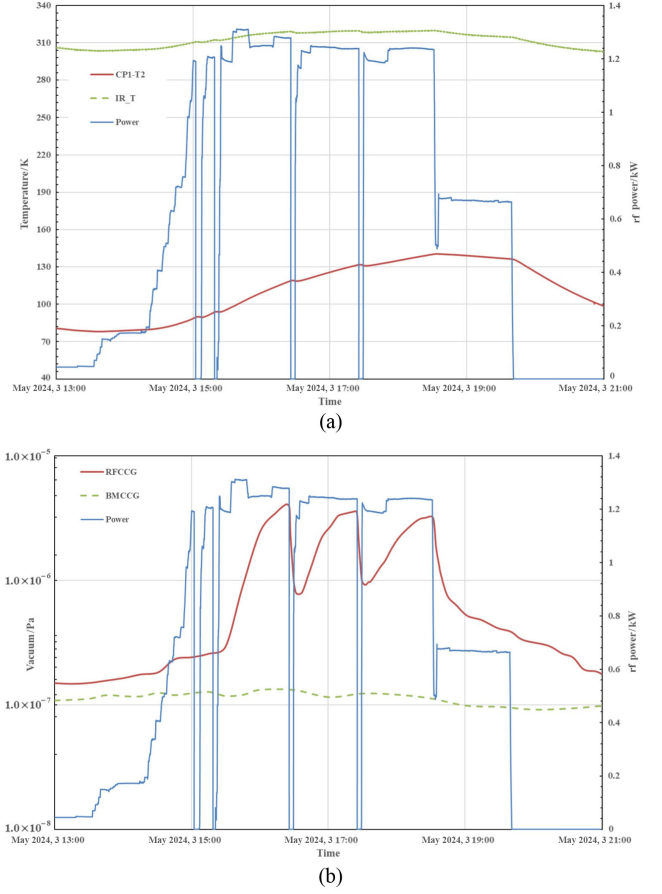


FIG. 22. (a) Temperature and (b) vacuum variation with incident power during the cavity gradient stability test.

with the incident power during this cavity gradient stability test.

IV. CRYOMODULE ASSEMBLY AND TESTS

The 3.9 GHz third harmonic cryomodule contains the following key components: eight superconducting cavities, eight couplers, eight tuners, eight magnetic shields, nine intercavity bellows, one superconducting quadrupole magnet, one beam position monitor, two gate valves, and a cryostat that houses the cold mass. The couplers on adjacent cavities are arranged in a 180° alternating (left-right) configuration along the beam axis. Following successful 3.9 GHz coupler prototype validation, batch production of the 3.9 GHz coupler commenced. Sixteen 3.9 GHz couplers have been manufactured and tested, all passing high-power rf conditioning on a room-temperature test bench under 2 kW TW cw and 1 kW SW cw conditions. These couplers were subsequently integrated into two SHINE 3.9 GHz third harmonic cryomodules and passed horizontal cryomodule testing. The total available cavity voltages for the two cryomodules reached 63.6 and 59.8 MV, respectively, corresponding to average usable accelerating gradients of 23.0 and 21.6 MV/m.

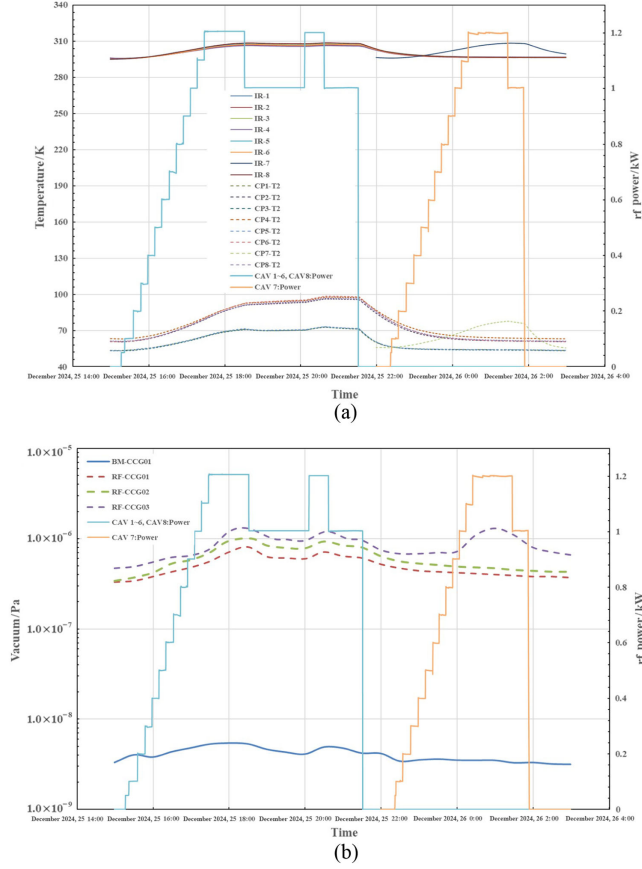


FIG. 23. (a) Temperatures and (b) vacuum evolution during cw rf conditioning of 3.9 GHz couplers in the H-CM2 Cryomodule.

The average Q_0 for both cryomodules was 3.4×10^9 , with 2 K static heat loads measured at 29.5 and 30.3 W, respectively. The cryomodules meet all key SHINE project requirements, apart from static heat loads. The detailed testing content of the cryomodules will be specifically addressed in a separate paper. This section focuses on the performance of the 3.9 GHz couplers, using the H-CM2 cryomodule (the second 3.9 GHz third harmonic cryomodule) as a case study.

Prior to cryomodule cooldown, high-power rf conditioning of the 3.9 GHz couplers was routinely conducted on the cryomodule at room temperature. After the cryomodule was cooled down, high-power rf conditioning was repeated at cryogenic temperatures. The low-temperature rf conditioning procedure followed the same steps as the room-temperature rf conditioning. However, to promote

temperature stabilization of the couplers under cryogenic conditions, the maximum power was increased to 1.2 kW and maintained for approximately 1 h before being reduced back to 1.0 kW for the final conditioning step. As shown in Fig. 23, which depicts the variation curves of the infrared temperatures of the warm rf windows, the temperatures of the cold CF63 flanges, the vacuum conditions in the warm sections of the couplers (monitored in three groups: RF-CCG01 for couplers No. 1 and 3, RF-CCG02 for No. 5 and 7, and RF-CCG03 for No. 2, 4, 6, and 8), and the beam vacuum (BM-CCG01) during the cw rf conditioning at cryogenic temperatures, the coupler temperatures reached equilibrium after approximately 6 h of power maintenance. The vacuum levels showed a consistent improvement. The maximum infrared temperature of the warm windows was approximately 36°C (309 K), while the temperatures of the cold CF63 flanges remained below 100 K. The temperatures of the couplers on both sides of the cryomodule demonstrated excellent consistency, despite slight differences in the length of the thermal copper braids between the adjacent couplers due to the ABAB-type arrangement of the cavity string. All couplers completed the entire rf conditioning process without any interlock triggers. These results demonstrate that the couplers achieved thermal equilibrium and stable vacuum conditions under high-power load, indicating robust performance.

Following the high-power rf conditioning of the 3.9 GHz couplers, the adjustment ranges of the Q_{ext} were measured. Table IV summarizes the measured Q_{ext} adjustment range and the final adjusted values for each coupler. The Q_{ext} adjustment range spans approximately one order of magnitude, meeting the design specification. The value of Q_{ext} is determined by the insertion depth and position of the coupler's antenna relative to the cavity. The variation in Q_{ext} from coupler to coupler arises primarily from the following factors: (1) machining tolerances of the superconducting cavities, (2) machining tolerances of the couplers, (3) machining tolerances of the cryostat, (4) assembly alignment errors of the cryomodule, and (5) measurement uncertainties.

The cavity voltage stability test of the cryomodule was conducted in two phases. First, a stability test was performed at a total cavity voltage of 50 MV, corresponding to an accelerating gradient of 18 MV/m per superconducting cavity, with an incident power of approximately 0.66 kW. The cavity voltage remained stable for 2.5 h. Subsequently, a second stability test was carried out at a reduced total

TABLE IV. Measured Q_{ext} adjustment range and final adjusted operation values for each coupler.

	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8
Upper value	8.50×10^7	5.37×10^7	8.02×10^7	6.80×10^7	6.26×10^7	9.32×10^7	8.31×10^7	6.84×10^7
Lower value	3.67×10^6	1.61×10^6	3.08×10^6	2.27×10^6	3.14×10^6	2.02×10^6	3.38×10^6	2.92×10^6
Operation value	2.12×10^7	2.24×10^7	2.27×10^7	2.18×10^7	2.17×10^7	2.17×10^7	2.2×10^7	2.18×10^7

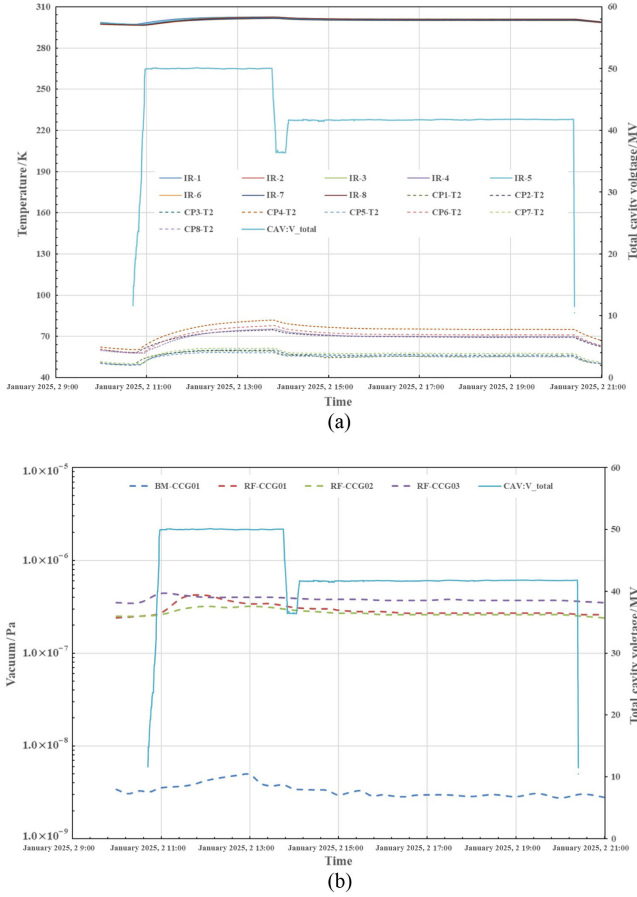


FIG. 24. (a) Temperatures and (b) vacuum variation during cryomodule cavity voltage stability test.

cavity voltage of 41.5 MV, equivalent to a gradient of 15 MV/m per cavity, and an incident power of about 0.46 kW. The cavity voltage was maintained stably for 6 h. During this period, the temperatures of the couplers and the vacuum levels stabilized, reaching equilibrium as illustrated in Fig. 24. The maximum infrared temperature of the coupler's warm rf ceramic windows did not exceed 30 °C, and the peak temperature of the cold CF63 flanges remained below 80 K. Throughout the test, no interlocks were triggered.

The total static heat load of the H-CM2 cryomodule measured at 2 K by the vapor boil-off method was 30.28 W. Under a total cavity voltage of 36 MV (corresponding to a field gradient of 13.1 MV/m per cavity), the dynamic heat load at 2 K reached 60.94 W. Based on the temperature gradients at the 5 and 45 K thermal copper-braid of the couplers and the material properties of the copper-braid, the eight 3.9 GHz couplers contributed a static heat load of 6.08 W at 5 K and 51.68 W at 45 K. These values represented a significant reduction in heat load compared to the single-cavity test cryomodule. The enhancement was primarily attributed to the stabilized manufacturing process from batch production, particularly the electroplated copper



(a)



(b)

FIG. 25. 3.9 GHz third harmonic cryomodule (a) ready for transportation and (b) after installation in the tunnel.

film technique, coupled with refined cryomodule assembly procedures that minimize thermal interconnections.

The two SHINE third harmonic cryomodules have passed all horizontal tests, meeting all performance standards, and have been delivered to the tunnel for accelerator installation. Figure 25 illustrates the 3.9 GHz cryomodule ready for transportation and after its installation in the tunnel.

V. CONCLUSIONS AND OUTLOOK

The core L1-BC1 segment of the SHINE superconducting linear accelerator incorporates two 3.9 GHz third harmonic cryomodules for linearizing the longitudinal energy distribution of the electron beam. The 3.9 GHz FPC, as a key component of the third harmonic cryomodule, has completed its design and prototype development phase. Subsequent optimization, informed by prototype testing, significantly improved its insertion loss and return loss. Furthermore, the coupler prototypes were validated under cw power conditions, achieving 2 kW in TW mode and 1 kW in SW mode, thereby meeting the design targets. A double thermal copper-braid cooling structure, implemented within a single-cavity test cryomodule, effectively managed the coupler's temperature rise. Based on these

successful prototypes, an engineering batch production was initiated. Sixteen formal 3.9 GHz couplers were manufactured and integrated into the two third harmonic cryomodules. These cryomodules subsequently passed all horizontal tests, achieving maximum total cavity voltages of 63.6 and 59.8 MV, respectively. Throughout the cavity voltage stability tests, critical coupler parameters, such as temperature and vacuum levels, remained stable. The entire L1-BC1 segment, including its two third harmonic cryomodules, was installed in the tunnel by early August 2025. Initial beam commissioning for the injector and L1-BC1 segment has been completed successfully. Key measured beam parameters include a bunch charge of 54.6 pC, a peak current of 56.4 A, a final beam energy of 273.5 MeV, and a bunch repetition rate of 1000 Hz. Both the overall beam performance and rf amplitude-phase stability have met the phase acceptance criteria, marking a significant step towards the realization of an 8 GeV cw superconducting linear accelerator. Current efforts are focused on installing and commissioning the SHINE linac's L2-BC2 and L3 segments, the beam distribution lines, and the FEL-II undulator line. The objective is to achieve a 4 GeV electron beam and realize first lasing in the soft x-ray range by August 2026.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available because they contain commercially sensitive information. The data are available from the authors upon reasonable request.

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