RF COMMISSIONING RESULTS IN THE SHINE

Y.B.Zhao *, X.Zheng, K.Xu, Z.G.Zhang, Q.Chang, S.J.Zhao
X.F.Huang, X.Y.Li, D.Gu, M.Zhang†, J.F.Chen, B.Liu ‡, Z.T.Zhao
Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai, China

Abstract

SHINE is an 8 GeV continuous-wave (CW) free-electron laser (FEL) facility, mainly composed of an injector, LINAC, an undulator segment, and experimental beamlines. Currently, for the accelerator section, the commissioning of the injector and the L1 segment of the LINAC has been completed. The RF structures in these two segments include a VHF electron gun, an L-band buncher, a dual-feed superconducting cavity, an injection eight-cavity module, two standard 1.3 GHz cryo-modules, and two 3.9 GHz cryo-modules. The RF specification of these accelerating structures have all met the design requirements. This paper will introduce the final parameters achieved through the commissioning of these accelerating structures and some problems encountered during the commissioning process.

INTRODUCTION

Currently, there are three hard X-ray free-electron laser facilities based on superconducting acceleration structures: the European XFEL [1], LCLS-II [2] in the United States, and the Shanghai HIgh repetition rate XFEL aNd Extreme light facility (SHINE) [3]. The first two are already in operation, while SHINE is under construction.

The LINAC of SHINE has a maximum design energy of 8 GeV and operates in continuous-wave (CW) mode. It consists of an injector and four linac sections (L1–L4), as shown in Figure 1. The injector includes a VHF electron gun, an S-band deflecting cavity, a 1.3 GHz buncher cavity, a single-cavity cryomodule, and an ABBA-type 8-cavities cryomodule. Section L1 comprises two standard 1.3 GHz 8-cavities cryomodules and two 3.9 GHz harmonic cryomodules, totaling 16 harmonic cavities. Section L2 has 18 standard 1.3 GHz 8-cavities cryomodules, L3 has 10, and L4 has 24. The total length of the accelerator is approximately 1.4 km. Commissioning of the injector and L1 segment has been completed. The injector output energy is 100 MeV, and the L1 output energy is 270 MeV with normalized emittances of 0.5/0.5 μm in the x/y directions.

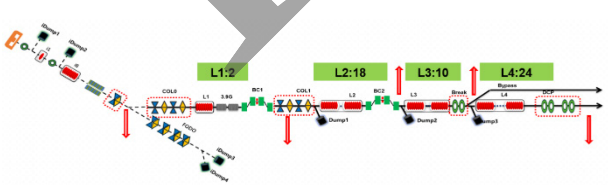

Figure 1: Layout of SHINE Facility

*zhaoyubin@sari.ac.cn, †bo.liu@ari.ac.cn, ‡zhangmeng@sari.ac.cn

INJECTOR

The main parameters of the injector are listed in Table 1. Figure 2 shows a photograph of the injector front-end. The injector mainly includes a VHF electron gun, a buncher cavity, a single-cavity cryomodule, and an 8-cavities cryomodule.

Table 1: Main Parameters of the Injector

Parameter	Value	Unit
Bunch charge	100	pC
Beam energy	100	MeV
Normalized slice Emittance	≤0.45	μm
Peak current	≥10	A
Bunch repetition rate	0–1	MHz

Figure 2: SHINE injector front-end

VHF Gun

The injector electron gun adopts a VHF gun [4] which operates at 216 MHz, powered by two 60 kW solid-state amplifiers, the gun output voltage is 750kV. The low-level RF (LLRF) system features two up-conversion channels driving the two amplifiers independently. Amplitude and phase balance between the two sources are adjusted online via FPGA algorithms. Since the VHF gun is made of copper and requires high power, significant frequency shifts occur between cold and warm states, leading to a long thermal settling time. An automatic power-up procedure is implemented: first, find resonance at low power in DDS mode with 1% duty cycle; then ramp power to 70 kW while tracking cavity frequency; gradually extend pulse width to CW and wait for thermal equilibrium; close the frequency control loop and switch to fixed-frequency output; align GDR phase with DDS phase, switch to GDR mode; and finally close amplitude and phase loops.

Buncher Cavity

The buncher cavity shapes the continuous beam into short bunches synchronized with the RF field via velocity modulation and drift bunching, significantly improving capture efficiency, peak current, and beam quality. SHINE uses a 1.3 GHz two-cell copper buncher cavity, designed to provide 275 kV cavity voltage, powered by a 15 kW 1.3 GHz solid-state amplifier. In order to enable immediate commissioning and put into operation as soon as possible, each cavity is equipped with a dedicated tuning rod in the design. Coaxial insertion/retraction and counter-motion adjust the cavity's resonant frequency and field flatness, respectively, controlled by the buncher LLRF system [5].

Single-Cavity Cryomodule

The single-cavity cryomodule (Inj-s) [6] operates at 1.3 GHz. To preserve emittance, dual-feed coupling is used. To minimize power-source types, two 5.2 kW amplifiers identical to those for the standard 8-cavity module are employed. Similar to the electron gun, one LLRF system drives two amplifiers via internal amplitude and phase regulation, enabling precise field control. Although the maximum achievable voltage is 15 MV, physics optimization sets the operating voltage at 6 MV.

8-Cavity Cryomodule

The 8-cavities injector cryomodule (Inj-8) [6] also operates at 1.3 GHz, using ABBA coupler arrangement to minimize emittance growth, powered by 5.2 kW amplifiers. The design voltage is 90 MV, with individual cavity voltages listed in Table 2. Horizontal tests show that the 8th cavity exhibits increased HOM signal and quenches above 12 MV.

Table 2: Cavity Voltages of the Inj-8 Cryomodule

Cavity No.	1	2	3	4	5	6	7	8	total
Voltage (MV)	15	14	13	13	10	9	6	10	90

During commissioning, radiation from the 6th cavity increased significantly at 12.5 MV during the second phase of commissioning. Voltage was reduced to 6 MV for safe operation.

TDS

The injector TDS operates at 2997.2 MHz with a 0.5 m accelerating structure. Maximum repetition rate is 50 Hz, powered by a 10 MW klystron with 3 μs pulse width. Required amplitude and phase stability (RMS) are 0.04% and 0.1°, respectively.

LINAC L1 SEGMENT

All L1 equipment is installed in the tunnel: cryomodules are suspended from the ceiling, control racks and power sources are on the floor, separated by a 30 cm shield. Circulators, dry loads, etc., are mounted on this shield. Figure 3 shows the L1 segment. L1 houses two 1.3 GHz standard 8-cavities cryomodules [7], two 3.9 GHz 8-cavities harmonic cryomodules [8], and one S-band TDS.

The two 1.3 GHz cryomodules provide >230 MeV gain; the two 3.9 GHz modules provide ~60 MeV deceleration. When 3.9 GHz cavities are in acceleration mode, maximum L1 output energy reaches 430 MeV; under normal operation, output energy is 270 MeV.

Figure 3: L1 section of SHINE Linac

1.3 GHz Cryomodules

Based on requirements and horizontal tests, L1 first 1.3 GHz module (CM1) operates at 120 MV (peak), second (CM2) at 110 MV (peak). Among 16 superconducting cavities, 8 showed radiation in horizontal tests; after cooldown in tunnel, radiation levels were consistent, confirming proper installation.

3.9 GHz Cryomodules3

Designed for 60 MV total voltage (≈4 MV per cavity), actual commissioning uses 40 MV (peak). Among 16 cavities, six cavities showed radiation in horizontal tests; in tunnel, only the 8^{th} cavities of the first module showed measurable radiation, consistent with horizontal test performance. The reason why no radiation has been detected in the other cavities is still under investigation.

Cryogenic Losses

During L1 commissioning, a lot of quenches caused by LLRF loop unlocks degraded Q_0 significantly. Dynamic loss measurements were attempted under operation with a 4 kW cryogenic system, which was under-sized for total dissipation; accurate data were not obtained.

TDS

An S-band TDS is installed in the L1 room-temperature section, powered by a 20 MW klystron in pulsed mode for bunch-length measurement. It operates at 2997.2 MHz with a 1.5 m structure, 50 Hz max repetition rate, 1.2 μs pulse width. Amplitude and phase stability (RMS) are 0.04% and 0.1°, respectively.

LOW-LEVEL RF SYSTEM

The LLRF system uses digital IQ modulation based on CPCI architecture. Hardware includes digital signal processing boards, RF front-ends, and auxiliary boards. The DSP chain uses high-speed ADC + FPGA + DAC, high-speed Ethernet, and ARM running IOC. The RF front-end down-converts high-frequency signals to IF for ADC sampling and up-converts processed IF signals to drive power sources. Auxiliary boards provide motor/PZT drive, interlock logic, and timing interfaces.

Figure 4: SHINE LLRF controller

Each RF structure is equipped with a dedicated LLRF controller. All IF signals use a common 19.67 MHz frequency for DSP board reuse. Both 1.3 GHz and 3.9 GHz systems run CW with identical control algorithms. Current operation uses GDR mode. For high-Q superconducting cavities, NANC [9] control mitigates microphonics. Achieved stability is listed in Table 3.

Table 3: Amplitude and Phase Stability of Cryomodules

Module	Inj-8	CM1	CM2	HCM1	HCM2
Amplitude (%)	0.002	0.007	0.005	0.006	0.003
Phase (deg)	0.009	0.009	0.01	0.008	0.007

Beam commissioning time is typically scheduled from 18:00 to 24:00, requiring daily warm-up and thermal equilibrium. When power is ramped from zero to normal operation power, water temperature stabilizes slowly. Since LLRF and power amplifiers share cooling water, reference phase drifts slowly: up to 1.6° at 1.3 GHz and 6° at 3.9 GHz from cold to equilibrium. Reference phase compensation is under study to reduce drift to <0.1°.

SUMMARY

The injector was commissioned from October to December 2024, achieving 100 MeV with energy stability <0.011%. All cryomodules and RF structures operated normally with required amplitude and phase precision.

Section L1 was commissioned from August to December 2025, achieving 270 MeV output energy with stability <0.011%. Two 1.3 GHz, two 3.9 GHz cryomodules, and S-band TDS performed reliably, meeting specifications.

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REFERENCES

[1] Altarelli, M., Brinkmann, R., Chergui, M., et al., "XFEL: The European X-Ray Free-Electron Laser - Technical Design Report," Hamburg, Germany, Rep. DESY 2006-097, July 2007, https://doi.org/10.3204/DESY_06-097

[2] LCLS-II Project Team, "Linac Coherent Light Source II (LCLS-II) Project Final Design Report," SLAC National Accelerator Laboratory, Menlo Park, CA, USA, Rep. LCLSII-1.1-DR-0251-R0, 2015.

[3] Z. Zhao and H. Ding, "Shanghai hard X-ray FEL facility progress status", in Proc. IPAC'24, Nashville, TN, USA, May 2024, pp. 967-972, doi:10.18429/JACoW-IPAC2024-TUZN1

[4] H. Chen, L. M. Zheng, B. Gao, et al., "Beam dynamics optimization of very-high-frequency gun photoinjector," Nucl. Sci. Tech., vol. 33, p. 116, 2022, doi:10.1007/s41365-022-01105-y

[5] Z. G. Zhang, W. F. Yang, H. R. Jiang, et al., "Study on low-level control of buncher in hard X-ray free electron laser facility," High Power Laser and Particle Beams, vol. 37, no. 9, p. 094001, 2025, doi:10.11884/HPLPB202537.250106

[6] J. Chen et al., "Cryomodules development for SHINE project", in Proc. IPAC'24, Nashville, TN, USA, May 2024, pp. 2788-2790, doi:10.18429/JACoW-IPAC2024-WEPS42

[7] J. F. Chen, Y. Zong, X. Y. Pu, S. W. Xiang, S. Xing, Z. Li, et al., "Ultra-high-quality factor and ultra-high accelerating gradient achievements in a 1.3 GHz continuous wave cryomodule," Nucl. Sci. Tech., vol. 36, no. 2, 2025, doi:10.1007/s41365-024-01630-y

[8] X. Wu et al., "Mass production of 3.9 GHz 9-cell cavities at SHINE", in Proc. IPAC'24, Nashville, TN, USA, May 2024, pp. 2006-2009. doi:10.18429/JACoW-IPAC2024-WEPC21

[9] N. Banerjee, G. Hoffstaetter, M. Liepe, P. Quigley, Z. Zhou, "Active suppression of microphonics detuning in high QL cavities," Phys. Rev. Accel. Beams, vol. 22, no. 5, p. 052002, 2019, doi:10.1103/PhysRevAccelBeams.22.052002.