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RECENT PROGRESS OF FUNDAMENTAL POWER COUPLERS FOR THE SHINE PROJECT

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Abstract

The superconducting radio-frequency electron linear accelerator of the Shanghai HIgh repetition rate XFEL aNd Extreme light facility contains 610 1.3 GHz fundamental power couplers which are assembled in 77 superconducting cryomodules used for beam acceleration, and 16 3.9 GHz fundamental power couplers, which are assembled in two third harmonic superconducting cryomodules used for linearizing the longitudinal phase space. The first batch of 26 1.3 GHz coupler prototypes and two 3.9 GHz coupler prototypes have been manufactured from three domestic manufacturers for basic research. Several key manufacturing processes have been developed and qualified, including high residual resistivity ratio copper plating, vacuum brazing of ceramic windows, electron beam welding and titanium nitride coating. All the 1.3 GHz coupler prototypes have been power conditioned with 14 kW travelling wave (TW) and 7 kW standing wave (SW) RF in continuous-wave (CW) mode. Even higher power levels have been demonstrated with 20 kW TW and 10 kW SW RF, which indicates their robustness. Both 3.9 GHz coupler prototypes have been power conditioned with 2.2 kW TW and 2 kW SW RF in CW mode.

INTRODUCTION

The Shanghai HIgh repetition rate XFEL aNd Extreme light facility (SHINE) is a new continuous-wave (CW) hard X-ray free electron laser (FEL) currently under construction in China [1-2]. The SHINE facility includes an 8 GeV superconducting linear accelerator (Linac), three undulator lines, three FEL beamlines, and the first ten experimental stations. The total facility length is 3110 meters, and the tunnels are buried 29 meters underground. Its goal is to be become one of the most efficient and advanced FEL user facilities in the world, providing high-resolution imaging and other X-ray methods for cutting-edge research in diverse fields, including physics, chemistry, life science, materials science, and energy science.

The fundamental power coupler (FPC), which is used to transmit a high radio-frequency (RF) power to the beam and providing isolation between atmospheric pressure and ultrahigh vacuum in the superconducting cavity through ceramic windows, is a crucial component of the superconducting cryomodules in the superconducting Linac [3]. The SHINE Linac contains 610 1.3 GHz FPCs which are assembled in 77 1.3 GHz superconducting cryomodules used for beam acceleration, and 16 3.9 GHz FPCs, which are assembled in two third harmonic superconducting cryomodules used for linearizing the longitudinal phase space before bunch compression [4, 5]. The SHINE 1.3 GHz FPCs, which are used for CW operation, are modified, and optimized based on the TTF-III coupler design developed at DESY for high power pulsed operation [6, 7]. The main technical parameters of the SHINE 1.3 GHz FPC are listed in Table 1, and the mechanical design of the SHINE 1.3 GHz FPC is shown in Fig. 1a.

Table 1: Main Technical Parameters of the SHINE 1.3 GHz and 3.9 GHz FPC

Parameters	1.3 GHz FPC Specification	3.9 GHz FPC Specification
Operating Frequency (GHz)	1.3	3.9
Type	Coaxial, Double-RF-window	Coaxial, Double-RF-window
Ceramic RF Window type	Cylindrical (cold) + Cylindrical (warm)	Cylindrical (cold) + Planar (warm)
Maximum power (kW)	7	1.8
External quality factor, Q_{ext}	4.12×10^7	2.13×10^7
Q_{ext} adjustment range	$4.0 \times 10^6 \sim 1.1 \times 10^8$	$1.0 \times 10^7 \sim 5.0 \times 10^7$
Antenna adjustment range (mm)	± 7.5	± 3

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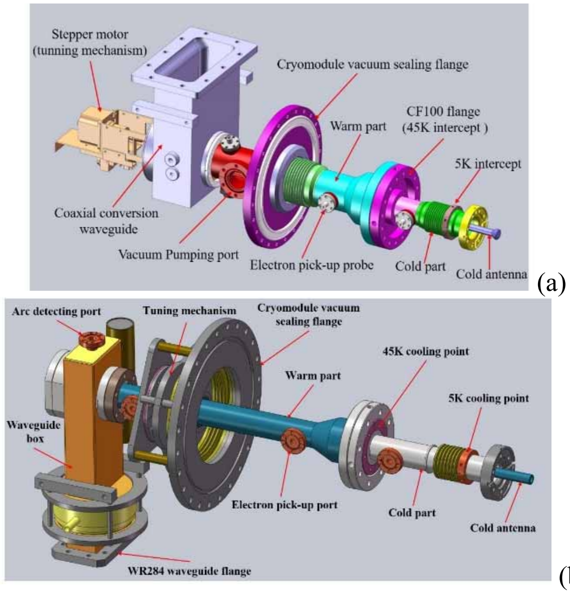

Figure 1: Mechanical design of the SHINE 1.3 GHz FPC (a) and 3.9 GHz FPC (b).

Different from the 1.3 GHz accelerating cavity, the 3.9 GHz third harmonic superconducting cavity operates close to 180° beam-to-RF phase, where the beam induced RF power is radiating from the cavity into the coupler, thus, the power fed by the power source is significantly reduced. The SHINE 3.9 GHz FPC must sustain up to 1.8 kW average RF power in the travelling-wave (TW) regime. A SHINE 3.9 GHz FPC to withstand 2 kW CW power and with an adjustment function has been designed. The main technical parameters of the SHINE 3.9 GHz FPC are listed in Table 1, and the mechanical design is shown in Fig. 1b. The optimal Q_{ext} of the SHINE third harmonic cavity was 2.13×10^7 and the adjustment range of Q_{ext} spans from 1.0×10^7 to 5.0×10^7 to compensate for the tolerance caused by the cryomodule assembling. In the design of the 3.9 GHz third harmonic cryomodule, a 180° rotation layout is adopted between the adjacent cavities for the 3.9 GHz FPCs to minimize transverse RF kick caused by power couplers [8].

MANUFACTURING OF FPCS

One SHINE 1.3 GHz or 3.9 GHz FPC consists of more than 60 parts and requires a dozen auxiliary tooling fixtures. The main steps in the coupler manufacturing are roughly the same as with other couplers or this type, such as the ones for the Eu-XFEL and the LCLS-II, including parts machining, brazing of sub-assemblies, copper plating of RF surfaces, TiN coating of ceramic windows, and electron beam welding (EBW) to form the final individual warm and cold parts [9]. The cold and warm sub-assemblies are vacuum brazed before electron-beam welding, which produces better reproducibility than just welding, allows more operator control and is better for mass production. Cleaning, assembling onto the RF test stand, and vacuum baking are also essential for efficient RF high power conditioning [10]. Validation of every key manufacturing step not only provides a thorough understanding of the process, but also improves product quality and reliability. Performance criteria and validation techniques have been established for monitoring and controlling of process parameters to ensure that the specified requirements continue to be met. Details about the qualification and validation of the key manufacturing processes are introduced in the published article [11]. To date, 26 SHINE 1.3 GHz and two 3.9 GHz FPC prototypes from three domestic manufacturers have been manufactured, as shown in Fig. 2.

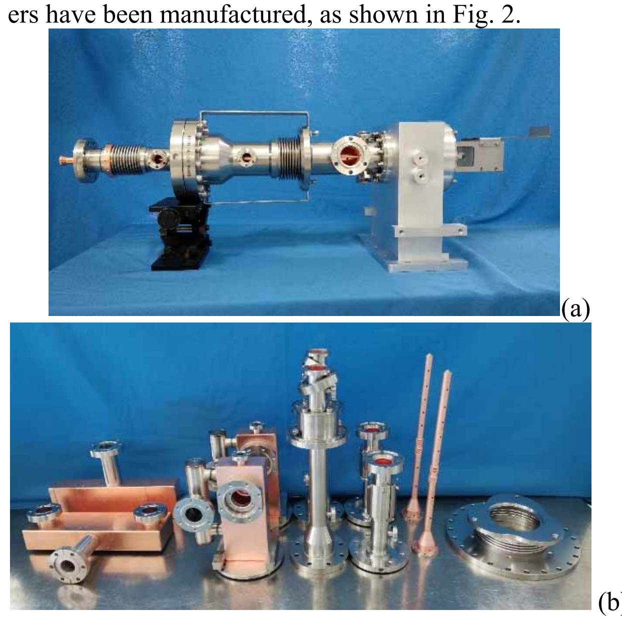

Figure 2: The fabricated 1.3 GHz (a) and 3.9 GHz (b) coupler prototypes.

RF HIGH POWER TESTS

An RF high power test is the most direct and effective means to verify whether the manufacturing processes of the FPCs and their performance meets the design targets. Also, the conditioning removes residual absorbed gases and burns-off microscopic surface imperfections. The surface treatments and assembling of the FPCs need to be done correctly to make the RF conditioning faster and more efficient. SHINE has established a set of standard process specifications for coupler clean cleaning, clean assembling, and vacuum baking operation. Before assembling, each coupler part was blown with filtered high-purity nitrogen gas and the particle counter was satisfied to be less than 10 particles of size > 0.3 microns per cubic foot. After 72 hours @ 150 °C vacuum baking, the vacuum pressure of the cold assembly and warm assembly were to be less than 1×10^{-8} mbar. Also, a residual gas analyzer (RGA) was used to verify that the H partial pressure was less than 5×10^{-9} mbar, the H_2O partial pressure was less than 5×10^{-10} mbar, and the partial pressure of each gas with mass number greater than 44 was less than 5×10^{-12} mbar.

An automatic RF test bench for 1.3 GHz and 3.9 GHz FPCs have been installed and are currently being used. The RF test system consists of four major subsystems: (1) power source system, (2) power transmission system,

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(3) test bench, and (4) interlock control and data acquisition system. The layout of 1.3 GHz and 3.9 GHz RF test systems is shown in Fig. 3.


(a)
(b)

Figure 3: The layout of RF test system for 1.3 GHz (a) and 3.9 GHz (b) FPCs.

To date, 26 1.3 GHz FPC prototypes have been RF high power conditioned. All of them have successfully passed the RF high power tests on the room temperature test bench, including CW operation at 14 kW for 6 hours in TW mode and CW operation at 7 kW for 12 hours in SW mode. Even higher power levels were demonstrated at 20 kW CW TW and 10 kW CW SW keeping at this level for twelve hours through two 1.3 GHz FPC prototypes. Figure 4 shows the history curves of vacuum pressure versus RF power throughout the RF tests [12].

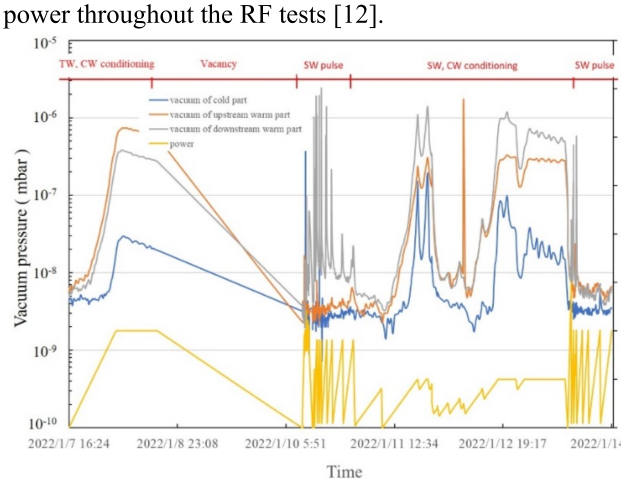

Figure 4: The RF power test history curves for a pair of 1.3 GHz coupler prototypes.

The RF high power tests of 3.9 GHz FPC prototypes include three types of conditioning procedures: pulse RF conditioning, CW RF conditioning in TW mode and CW RF conditioning in SW mode. The power was increased up to CW 2 kW in TW mode, and the power at final power level was maintained for 22 hours. Even higher power 2.2 kW was tried and kept for two hours, which was the maximum output power of the Solid-State Amplifier. Figure 5 shows the temperature distribution for the upstream coupler and downstream coupler during the whole CW conditioning process respectively. Finally, we tried the RF conditioning test in the SW mode. The power was increased up to 2 kW and maintained for two hours. The temperature and vacuum of the two coupler prototypes were kept under reasonable thresholds.

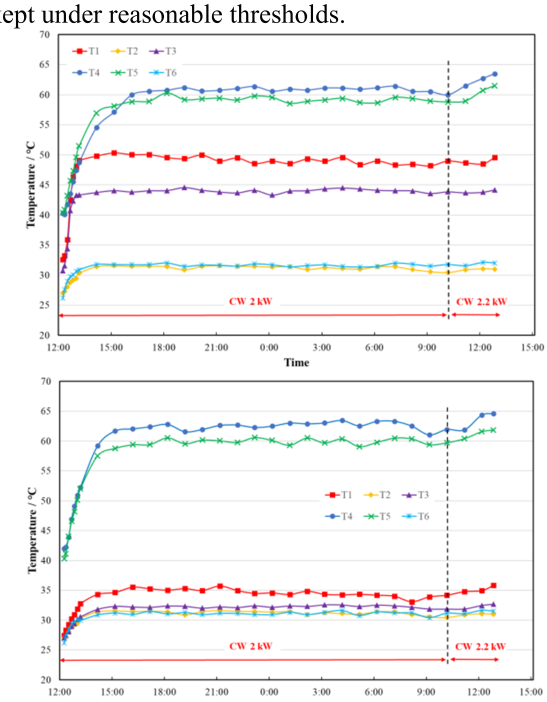

Figure 5: Temperature distribution for the upstream coupler (a) and the downstream coupler (b) during the CW conditioning in TW mode for 3.9 GHz FPC prototypes.

CONCLUSIONS AND OUTLOOKS

The SHINE 8 GeV superconducting RF electron Linac will use 610 1.3 GHz FPCs that are based on the TTF-III 1.3 GHz coupler design with some modifications for CW operation with input power up to 7 kW, and 16 3.9 GHz FPCs with handle power up to 2 kW. The first batch 26 1.3 GHz and two 3.9 GHz coupler prototypes from three domestic manufacturers were manufactured and RF high power tested at room temperature. Prior to manufacturing of the prototypes, key processes were qualified including high residual resistivity ratio (RRR) copper plating, vacuum brazing of the ceramic RF windows, EBW and TiN coating, and both the clean surface treatment processes and the high-power testing procedures have been established.

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All the 1.3 GHz coupler prototypes passed the RF high power conditioning requirements at 14 kW CW TW and 7 kW CW SW. Even higher power levels were demonstrated at 20 kW CW TW and 10 kW CW SW, which is a good validation of the manufacturing process. Some 1.3 GHz FPC prototypes have been assembled into the cryomodule prototypes, and the first cryogenic horizontal test was also successful, validating the superconducting accelerating unit: 1.3 GHz superconducting cavities equipped with a helium tank, with FPCs and tuners in the final cryomodule configuration. A nominal accelerating field of 16 MV/m was achieved with an input power of 1.6 kW.

Both 3.9 GHz coupler prototypes have successfully passed the RF high power conditioning of CW 2.2 kW in TW mode and CW 1 kW in SW mode. Even higher power levels have been demonstrated with CW 2 kW in SW mode, which means that the SHINE 3.9 GHz coupler can withstand at least 3 kW CW power in the TW mode, and even 4 kW is also feasible under enough cooling condition. Next step, the 3.9 GHz coupler prototype will be assembled with 3.9 GHz superconducting cavity, magnetic shielding, and tuner, and tested in the horizontal cryostat as integrated unit to demonstrate the performance and define if any further modification required before starting serial production of two SHINE 3.9 GHz cryomodules.

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