LLRF PROTOTYPE DESIGN FOR THE 1.3 GHZ CRYOMODULE OF THE SHENZHEN SUPER-CONDUCTING SOFT X-RAY FEL *

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Abstract

This paper presents the design and preliminary test results of a Low-Level Radio Frequency (LLRF) prototype system developed for the 1.3 GHz standard cryomodule of the Shenzhen Superconducting Soft X-ray Free Electron Laser (S^3FEL). The system is implemented within an MTCA.4 platform, integrating eight RF controller boards for superconducting cavity field acquisition and microwave excitation control to stabilize the RF field and ensure steady electron beam acceleration, alongside two tuner controller boards for driving eight coupler motors, eight cavity tuner motors, and sixteen piezoelectric actuators (PZTs). A high-speed peer-to-peer (P2P) backplane bus enables real-time communication between RF and tuner control boards. The report outlines the hardware architecture of this modular LLRF system and discusses initial functional and performance tests, demonstrating its suitability for meeting the precise stability requirements of the S^3FEL project.

INTRODUCTION

Free-electron lasers (FELs) are among the most important high-brightness X-ray sources for advanced scientific research. The Shenzhen Superconducting Soft X-ray Free Electron Laser (S^3FEL) project adopts a superconducting linear accelerator operating with 1.3 GHz superconducting cavities, targeting an electron beam energy of up to 2.5 GeV and a pulse repetition rate of up to 1 MHz [1]. Such demanding operating conditions impose stringent requirements on the stability of the RF field amplitude and phase within the accelerating cavities.

To maintain stable accelerator operation under high repetition-rate conditions and external perturbations such as microphonics and Lorentz force detuning, a high-performance low-level RF (LLRF) control system is essential. Conventional architectures, such as CompactPCI (CPCI)-based systems, often suffer from limited bandwidth, fixed slot configurations, insufficient scalability, and relatively high latency, making them inadequate for the precision microwave measurement and control requirements of S^3FEL.

To address these challenges, this work proposes an MTCA.4-based LLRF prototype system for the S^3FEL standard superconducting cavity module. The system is capable of RF field acquisition, microwave drive generation, and cavity resonance tuning through feedback control, thereby meeting the strict stability requirements of the accelerator.

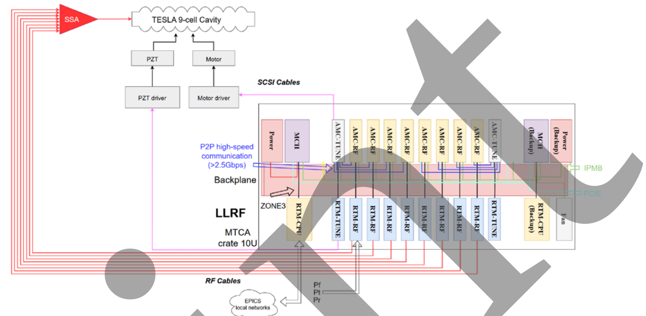

Figure 1: Topology of the MTCA.4-Based LLRF system.

SYSTEM DESIGN AND ARCHITECTURE

The proposed LLRF system is implemented using a standard MTCA.4 chassis, as illustrated in Fig. 1. The prototype microwave measurement and control system for the 1.3 GHz superconducting accelerator module consists of eight RF control boards, two tuning control boards, a power supply module, a MicroTCA Carrier Hub (MCH), and a CPU board. All boards are installed through the MTCA.4 backplane, which provides both power distribution and high-speed signal interconnections.

Each control module consists of an Advanced Mezzanine Card (AMC) and a Rear Transition Module (RTM) [2]. Figure 2 shows the RF control board. The RF AMC card performs microwave drive regulation and digital signal processing, while the RF RTM card is responsible for RF signal acquisition and transmission. The acquired signals include the forward power signal (Pf), reflected power signal (Pr), cavity probe signal (Pt), reference signal (REF), and local oscillator signal (LO). The AMC and RTM communicate through the Zone-3 connector compliant with the MTCA.4 D1.0 specification, jointly enabling RF field stabilization and reliable beam acceleration [3].

Each 1.3 GHz superconducting cavity module contains eight cavities. For each cavity, one slow tuner motor control channel, two piezoelectric actuator (PZT) control channels, and one coupler motor control channel are required [4]. To fulfill these requirements, the system integrates two pairs of MTCA.4 tuning control boards, each consisting of one AMC and one RTM module, with each pair responsible for four cavities. Figure 3 presents the tuning control board.

The tuning AMC card performs signal processing and generates control signals for the motor drivers, while the tuning RTM card outputs control signals for the PZT drivers. Each AMC board provides 16 electrically isolated digital outputs through an FMC expansion module for motor

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control, whereas each RTM board provides eight 16-bit DAC channels for high-precision PZT actuation.

The coupler motor is used to adjust the external coupling strength of the cavity, thereby regulating the cavity quality factor. Both the tuning motors and the piezoelectric actuators are employed for cavity resonance tuning, enabling precise control of the cavity resonant frequency.

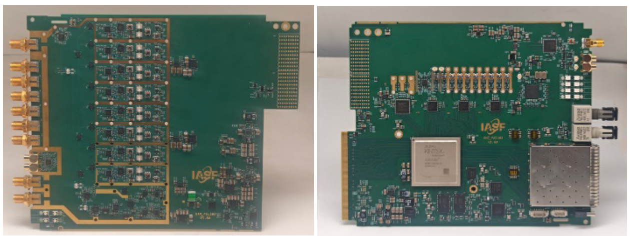

Figure 2: RF control board including AMC and RTM modules.

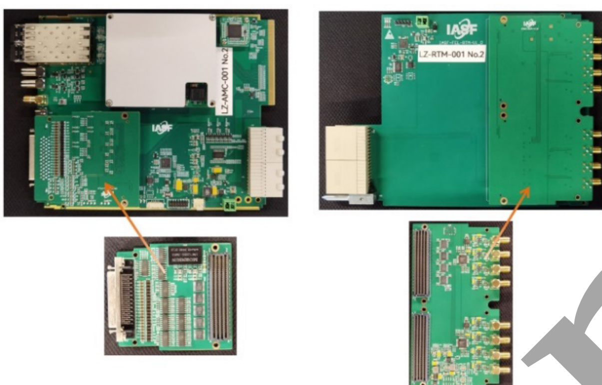

Figure 3: Tuning control board including AMC and RTM modules.

HARDWARE IMPLEMENTATION

Accurate cavity field regulation requires close coordination between the RF control boards and the tuning control boards. In the RF control subsystem, RF signals acquired from the cavity are first processed by the RTM through analog mixing and filtering stages before being transmitted to the AMC for analog-to-digital conversion. The FPGA implemented on the AMC performs IQ demodulation to extract the amplitude and phase information of the RF field.

Based on the acquired field signals, the FPGA dynamically regulates the RF drive signal delivered to the high-power RF source, thereby realizing closed-loop control of the cavity excitation field. The processed data are transmitted to the tuning control AMC through the high-speed backplane P2P communication link.

Within the tuning control AMC, dedicated control algorithms generate tuning commands according to the received cavity field error signals. The corresponding motor drivers are controlled through the 16 optically isolated FMC outputs. Meanwhile, the RTM outputs finely adjustable drive voltages to the PZT actuators through eight 16-bit DAC channels, enabling rapid compensation of cavity frequency deviations.

The entire hardware architecture adopts a highly modular MTCA.4 AMC/RTM design, facilitating system scalability, maintainability, and future upgrades [5].

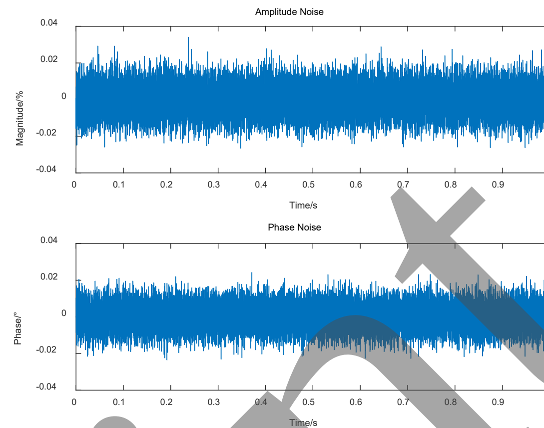

Figure 4: Measured amplitude noise and phase noise of the output RF signal.

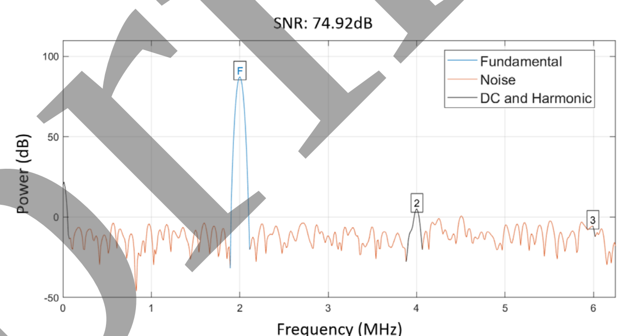

Figure 5: Signal-to-Noise ratio of the output signal.

PRELIMINARY TEST RESULTS

Laboratory tests were carried out to evaluate both the functionality and performance of the proposed LLRF system. Experimental results indicate that all channels operate correctly and reliably. The RF control board successfully acquired RF signals from a simulated cavity and generated the corresponding RF excitation signals.

Figure 4 shows the measured amplitude noise and phase noise of the output RF signal. The root mean square (RMS) amplitude noise was measured to be below 0.02%, while the RMS phase noise was below 0.02°. In addition, the measured signal-to-noise ratio (SNR) reached 74.92 dB, as shown in Fig. 5.

The tuning control boards were also verified to correctly operate both the motor drivers and the PZT drivers. The RF control boards and tuning control boards communicated through PCIe-based P2P links on the MTCA.4 backplane, enabling stable high-speed data transmission and real-time inter-board communication.

Furthermore, closed-loop experiments were performed based on the established functional platform. The results demonstrate that the system can rapidly respond to and compensate for injected frequency offset disturbances. The achieved RF amplitude and phase regulation accuracy satisfies the design specifications. These preliminary experimental results confirm that the proposed LLRF prototype is capable of meeting the stringent stability requirements of the S^3FEL accelerator.

CONCLUSION

An MTCA.4-based LLRF prototype system for the 1.3 GHz superconducting cavity module of S^3FEL has been presented in this paper. The proposed system integrates eight RF control boards and two tuning control boards within a single MTCA.4 chassis, enabling coordinated multi-cavity control and low-latency feedback through a high-speed P2P backplane communication architecture.

Preliminary experimental evaluations verify that the proposed system achieves the required functionality and performance for high-stability RF field regulation in the S^3FEL accelerator. Future work will focus on integrated testing with superconducting cavities and further optimization of both hardware architecture and control algorithms to enhance the overall performance of the LLRF system.

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