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LLRF CONTORL SYSTEM FOR RF GUN AT SXFEL TEST FACILITY

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Abstract

A Soft X-ray Free Electron Laser Test Facility (SXFEL-TF) based on normal conducting linear accelerator was constructed at the Shanghai Synchrotron Radiation Facility (SSRF) campus by a joint team of Shanghai Institute of Applied Physics and Tsinghua University. It consists of multiple Radio Frequency (RF) stations with standing wave cavity (RF Gun) and traveling wave accelerating structures working at different frequencies. Low Level Radio Frequency (LLRF) system measures the RF field in the cavities or structures and corrects the fluctuations of the RF fields with the pulse-to-pulse feedback controllers.

This paper describes the hardware and architecture of the LLRF system for electromagnetic filed stabilization inside the RF electron gun of the SXFEL-TF. A complete control path, including the RF front-end board, I/Q detector and the feedback controller, is presented. Algorithms used to stabilize the RF field are presented as well as the software environment used to provide remote access to the control device.

Finally, the performance of the LLRF system that was measured under beam commissioning is presented. The LLRF system that meets the high accuracy requirements is also introduced.

INTRODUCTION

SXFEL-TF [1-2] is a prototype machine that was developed for the soft X-ray Free Electron Lase User Facility (SXFEL-UF) project. The SXFEL-TF Linac consists of an injector including an S-band photo-cathode Radio Frequency (RF) gun [3], two S-band accelerating sections, an X-band linearizer [4] and one main accelerator including one S-band accelerating section and six C-band accelerating sections, as shown in Fig.1. The repetition rate is 10 Hz. A high brilliant coherent light is emitted from electron bunches passing undulator [5-6]. SXFEL-TF accelerator accelerates electrons up to 840 MeV energy. Electron bunches are produced in a RF gun. Inside the RF gun they are accelerated close to the light velocity. Further acceleration in the traveling accelerating structure [7] increases only energy. The electron bunches after the injector go through the first dispersive magnetic chicane called bunch compressor [8]. In the bunch compressor they are compressed to 1 ps at the end. After the first bunch compressor the electron bunches pass several C-band traveling accelerating structures and finally reaches the undulator where the coherent light is generated. The more stable is the field inside the cavity or structure during the beam transport the more stable is the electron bunches which pass them and the less the energy spread.

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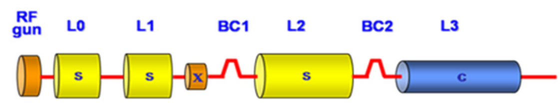

Figure 1: The schematic layout of SXFEL-TF LINAC.

With the development of microelectronic technology, especially the high performance Field Programmable Gate Array (FPGA), the digital LLRF [9-10] systems are widely used to control the RF stations. Before the RF signals sampled by fast Analog-to-Digital Converters (ADC), the RF signals are down converted to Intermediate Frequency (IF) signals. The FPGA processes the ADC sampling data with demodulation algorithms.

Table 1: Main Parameters and RF Tolerances of RF Gun

Parameters	Value
RF frequency (MHz)	2856
Repetition rate (Hz)	1~10
RF pulse length (μs)	3
Amplitude stability (%)	<0.04
Phase stability (Deg.)	<0.09

For the SXFEL-TF RF gun LLRF system, the main parameters and RF tolerances are listed in Table 1. The RF pulse length is 3 μs and the filling time of the RF gun is about 1.5 μs, only the pulse-to-pulse feedback [11] is used. Figure 2 presents the setup of RF Gun and control system based on Micro Telecom Computing Architecture (MicroTCA) platform in SXFEL. The RF gun is an one and a half cell copper, normal conducting, resonant cavity cooled by water. The resonance frequency of RF gun can be tuned by changing the gun water temperature. In order to correct the amplitude and phase of the RF gun, the controller needs information about current level of the field to regulate the power going into the RF gun. The cavity used for the RF gun at SXFEL-TF has one probe as field detector. A directional coupler placed just in the front of RF gun provides two signals: power going to the RF gun and power reflected from it. Firstly, all of these signals are down-converted to IF in the RF front-end board, sampled by high speed ADCs and sent to the main processing unit - FPGA. The baseband in-phase and quadrature components are extracted from the digitalized signals.

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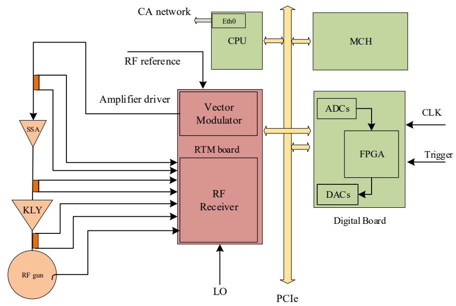

Figure 2: The block diagram of RF gun setup in SXFEL.

HARDWARE

The main components of a LLRF station contain one Clock and LO module, one MicroTCA crate, one Power Supply Unit, one MicroTCA Controller and Hub (MCH), one Central Processing Unit (CPU), one RF down-converter module and one digital processing board.

The clock and LO module is a product of Hebei Signalmicrowave technology Co.,LTD. It receives a 2856 MHz reference signal from master oscillator (MO) and provides clock, Local Oscillator (LO) signals for downconverter and digitizer after divided and mixed. The clock frequency is 102 MHz, and local oscillator frequency is 2830.5 MHz. The phase noises of MO, LO and clock are measured using the Agilent signal source analyzer E5052B. The diagram and test results are shown in Fig.3.

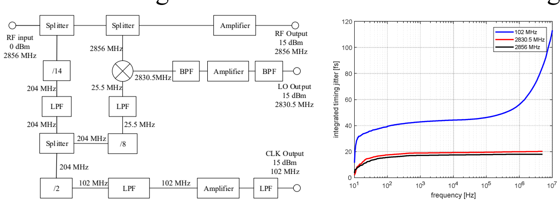

Figure 3: The diagram (left) and test results (right) of Clock & LO module.

All the signals condition is processed in the analog frontend DRTM-DWC8VM1 [12] which is an eight channel high frequency down-converter and one channel vector-modulator RTM module in compliance with the MicroTCA specification. The short-term amplitude and phase stabilities are 0.005% and 10 fs (rms) at [10 Hz and 1 MHz]. The digital board adopts the SIS8300L2 Advanced Mezzanine Cards (AMC) board which is a 10 channel digitizer. The core of the digital board is a VIRTEX 6 FPGA. The communication between Rear-Transition Module (RTM) and AMC take place via ZONE 3 connector.

SOFTWARE AND FIRMWARE ARCHITECTUTE OF PULSE-TO-PULSE FEEDBACK LOOPS

For intrapulse feedback, the RF pulse of the RF gun which is about 3 µs is too short and the 1.5 µs loop latency of the waveguide and coaxial-cable is too large. So we only use the pulse-to-pulse feedback loop to reduce the slow fluctuations of the RF field. The software and firmware architecture for the RF gun amplitude and phase feedback loop is depicted in Fig.4.

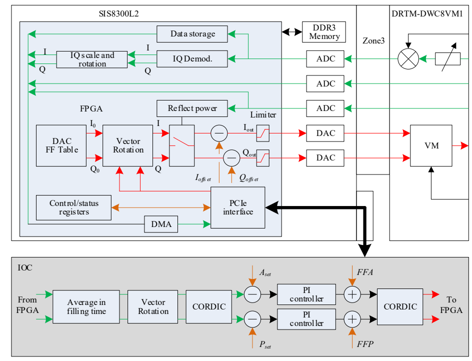

Figure 4: A software and firmware architecture of pulse-to-pule feedback loops for SXFEL RF gun LLRF.

The real-time functions of the LLRF control system are implemented in FPGA, such as raw data of waveform acquisition, IQ detection of RF signals and interlock protection. The IF signals down-converted in the DRTM_DWC8VM1 go through ZONE 3 connector to SIS8300L2, then sampled by ADCs. A 2 GByte Double-Data-Rate Three Synchronous Dynamic Random Access Memory (DDR3 SDRAM) is used to store the raw data sampled by ADCs and the IQ waveforms after IQ demodulation and eventually read out from PCI-express.

The compensation for the phase loop in the LLRF path can be expressed as Eq. (1).

$$\begin{pmatrix} I \\ Q \end{pmatrix} = A \cdot \begin{pmatrix} cos(\theta) & -sin(\theta) \\ sin(\theta) & cos(\theta) \end{pmatrix} \cdot \begin{pmatrix} I_0 \\ Q_0 \end{pmatrix} \quad (1)$$

To prevent the klystron from damaging by overhead reflection power, there is a switch interlock implemented in FPGA for fast interlock. The detail implementation of the reflection power protection module is depicted in Fig. 5. The I and Q values of the input and reflected signals can be obtained after down-conversion [13], ADC sampling and Finite Impulse Response (FIR) filter. Then, their amplitude can be obtained by using the Coordinated Rotation Digital Computer (CORDIC) algorithm [14-15]. It detects the power of the reflected power in real-time inside the detection of breakdown module. When the reflect power exceeds the setting limiter reflect power (threshold), it generates a breakdown flag which serves as protection module input signal. Then it will generate the switch signal cutting off the input signals of DACs at the interlock time duration to protect the system from damage.

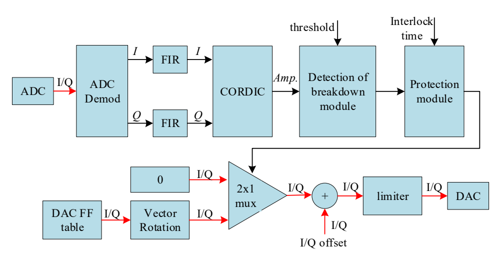

Figure 5: The block diagram of the reflection power protection module.

On the software layer, we use the Experimental Physics and Industrial Control System (EPICS) as the control platform for the LLRF system and establish a soft Input and

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Output Controller (IOC). The controller software handles: generation of set-point, feed-forward and feedback tables from the basic settings, start-up configuration files, feedback parameters and exception handler control parameters. The software also provides the user the opportunity to download/upload data into FPGA and upgrade the controller firmware. The data from FPGA is filtered and integrates over the accelerator filling time duration to get the efficient accelerating field. The loop phase and amplitude attenuation are compensated by rotation matrix. The final amplitude and phase are calculated by CORDIC algorithm. Then compared with set-point, the errors are fed into the Proportional and Integral (PI) controller. The controller output values plus the Feedforward value compensating the changing of amplitude and phase scale and rotate the desired table stored in DAC feedforward table in FPGA using the Eq. (1). The DC offset in DAC and the RF leakage in the Vector-modulator can be compensated using Eq. (2).

$$\begin{aligned} I_{out} &= I_{in} + I_{offset} \\ Q_{out} &= Q_{in} + Q_{offset} \end{aligned} \qquad (2)$$

MEASUREMENTS

The LLRF system based on MicroTCA has been installed in the RF gun station of the SXFEL test facility. The performance was measured under the beam commission with feedback on/off, as shown in fig. 6. The measurements were taken over 12 minutes. The top plot is the amplitude and the bottom plot is the phase of RF field in the RF gun. The RMS value of gun pickup amplitude is 0.018%, phase is 0.0487^0, which meet the requirements of SXFEL-TF RF gun.

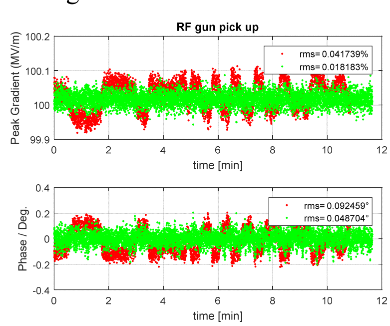

Figure 6: RF gun pick-up signal amplitude and phase stability measurement without and with feedback.

CONCLUSION

The LLRF system is a curial part for particle accelerator and has been widely studied in many accelerator laboratories, such as KEK, SLAC, CERN, IHEP, PSI and DESY et al. The performance of the component in the LLRF system, algorithms and procedures has determined the final beam stability. The clock and LO module has been designed, measured and installed in the RF gun LLRF station. A LLRF system based on MicroTCA has been developed and installed in RF gun of SXFEL. It works on pulse-to-pulse mode and provides better performance and increased compactness and maintenance. The characteristics of LLRF system have proven to satisfy the requirement of SXFEL RF gun. The architecture of the LLRF system is flexible to add more functions and upgrade.

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