THE EUROPEAN XFEL LLRF SYSTEM

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Abstract

The European X-Ray free electron laser accelerator consists of 808 superconducting cavities grouped in 25 RF stations. The challenges associated with the size and complexity of this accelerator require a high-precision, modular and scalable low level RF (LLRF) system. The Micro TCA technology (MTCA.4) was chosen to support this system and adapted for RF standards. State-of-the-art hardware development in close collaboration with the industry allowed for the system continuity and maintainability. The complete LLRF system design is now in its final phase and the designed hardware was installed and commissioned at FLASH. The MTCA.4 LLRF architecture and system performance results will be shown. Operation strategies and future automation algorithms for performance optimization will also be presented in this paper.

THE XFEL

The European X-Ray Free Electron Laser (XFEL) [1] is a 17.5 GeV coherent light source providing 27,000 flashes per second with a wavelength as low as 0.05 nm and a peak brilliance of 5×10^{33} photon/s/mm^2/mrad^2/0.1% bandwidth. It consists of 808 superconducting TESLA 1.3 GHz cavities, housed in 101 8-cavity cryomodules, organized in 25 RF stations. In the main linacs, each RF station, consisting of four cryomodules (32 cavities), is powered by a 10 MW klystron; every three RF stations correspond to an independent cryogenic string. The main components of the accelerator chain are depicted in Fig. 1. The requirements for accelerating field stability, accelerator up-time, modularity and reliability, coupled with the size of the accelerator, high channel count and the limited rack space for electronics inside the tunnel present an interesting challenge for the LLRF system.

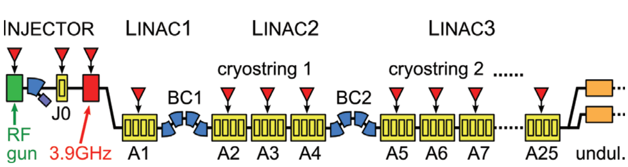

Figure 1: XFEL accelerator overview.

System Requirements

The LLRF system should set and maintain stable voltage and phase of the high-precision calibrated vector-sum of individual RF stations. The overall required RMS field stability should be better than 0.01% in amplitude and 0.01° in phase at the 1.3 GHz cavity operating frequency. The LLRF system should also provide a highly stable RF reference along the accelerator tunnel used to calibrate signals. Due to the large scale of the accelerator, a high degree of automation is expected to assist operators and system experts, including exception detection and handling. The LLRF should optimize operational and internal system parameters so that the field stability, accelerator availability and component lifetime are maximized. Finally, the responsibilities of the LLRF system is to provide an adequate interface to other accelerator subsystems, including support of RF systems conditioning and commissioning procedures.

The LLRF racks are located inside the XFEL tunnel, below the cryomodules (CM). To limit the degradation of electronics due to radiation and single event upsets, shielding panels are mounted above the racks. In the main linacs (L2 and L3), the usable rack height is 28 rack units (U) while only 16U are available in the injector section. This limited space coupled with the need for complete redundancy of the LLRF system in the critical section of the injector poses a real challenge and was a prime factor in the decision to host the LLRF system in a MTCA.4 chassis [2].

LLRF ARCHITECTURE

The master oscillator for the XFEL [3] provides a stable 1.3 GHz RF signal. For redundancy purposes, two identical master oscillators are installed and can be remotely selected. This RF signal is distributed along the accelerator tunnel and, combined with an optical synchronization system, provides a calibration reference for every LLRF station [4]. The LLRF system is organized following a semi-distributed architecture. Each RF station, (one klystron and four 8-cavity cryomodules) has a dedicated LLRF system, split into master and slave, as illustrated in Fig. 2. A detailed description of the different components composing the RF station LLRF system is given in the next section.

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Rack Modules

Each LLRF system is installed in a water-cooled, temperature-controlled rack. The main components of a typical LLRF station are: a drift compensation module (DCM), a reference module (REFM), a local oscillator generation module (LOGM), a MTCA.4 crate, a piezo controller module (PZ16M) and a power supply module PSM.

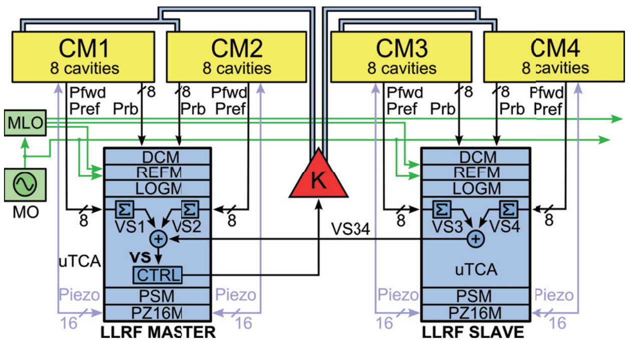

Figure 2: The RF station LLRF master-slave architecture.

REFM Critical RF stations (injector, L1 and L2) have a dedicated optical-RF synchronization unit [5], based on a Mach-Zehnder interferometer which phase locks the 1.3 GHz RF reference to the sub-10 femtosecond Master Laser Oscillator (MLO), distributed along the tunnel by the optical synchronization system.

DCM The Drift Calibration Module is directly connected to 16 cavity probe cables and to the laser synchronized 1.3 GHz reference signal. This module provides programmable attenuation, ranging from 0 to 30 dB, for each of the 16 cavity channels. Its second purpose is to compensate for any phase and amplitude drift taking place inside the mixers at the down conversion stage. A few 100 μsec preceding each RF pulse, the RF reference amplitude is measured in the DCM and injected into each of the 16 cavity channels. The amplitude measurement is sent and compared against the value measured for each channel in the ADC boards. Pulse to pulse drifts are hence tracked and compensated just before each RF pulse. This module is temperature-controlled; diagnostic data are monitored over its ethernet connection.

LOGM The LO Generation Module gets the 1.3 GHz reference signal from the REFM, internally divides and mixes the signal to produce a 1354 MHz local oscillator signal (LO) used by the down converters, and 81.25 MHz external clock (CLK) signals used by the digitizers. The reference signal is also split and distributed to the MTCA.4 modules. The 10 Hz-1 MHz integrated additive jitter for the LO is about 2 fs RMS. A reset signal coming from the MTCA.4 timing module is used to synchronize the phases of the divided signals after a system restart.

PZ16M This piezo driver module is designed to handle 16 cavities, each equipped with double stack piezo tuners. The first piezo tuner can be used as actuator (for Lorentz force detuning and microphonics compensation), and the second one as a mechanical sensor or as a spare part. The piezo module allows remote switching between piezo actuator and sensor functionality. It provides a bipolar +/- 70 VDC drive, with 20 kHz bandwidth per channel. Piezo waveforms and sensor data are processed inside the FPGA of the MTCA.4 LLRF controller.

PSM This power supply module provides power to the DCM, REFM, and LOGM. It follows a redundant and modular design; each unit is doubled and can be hot swapped. Power management and diagnostic data such as DC voltages, ripples, current consumption and fan speed are sent over an ethernet connection.

MTCA.4 Crate

The MTCA.4 crate follows the standards of the ATCA [2] architecture, where rear transition modules (RTM) in the back of the crate handle analog signal conditioning while most of the digital computation is taking place inside the advanced mezzanine cards (AMC) located at the front of the crate. Communication from the RTM to the AMC takes place through the so-called zone 3 area, while communication between AMC modules is covered by the AMC backplane.

DWC - SIS Through a 10-channel down converter (DWC) RTM, RF signals are down-converted to a 54 MHz intermediate frequency (IF). Each channel has a programmable attenuator (0-30 dB). IF signals are then sent over zone 3 to an ADC board (SIS) [6], designed in collaboration with one of DESY's industrial partners. The FPGA takes care of channel delay, drift compensation, IQ detection and rotation, filtering, partial vector sum and amplitude and phase calculation. The 81.25 MHz sampled IF signals are averaged using a sliding window scheme and the 16-bit calibrated partial vector sum IQ signals (8 cavities) are sent to the LLRF controller at a rate of 9.027 MHz.

uTC - VM The MTCA.4 LLRF controller (uTC) has a Virtex 6 FPGA where calculation and rotation of the total vector sum are performed. As shown in Fig. 2, the total vector sum for RF control is computed inside the master uTC. It comprises CM1 and CM2 partial vector sums from the master crate and the total vector sum of CM3 and CM4 from the slave crate. The set point error is calculated and the RF field control is performed using a second order MIMO scheme [7]. Feed forward tables are added, and after output rotation, the IQ drive signals are sent to the vector modulator (VM) RTM over zone 3. The VM performs single sideband modulation of the RF reference signal; input and output power levels of the RF chain are monitored. The FPGA also controls the output programmable attenuators, power amplifier and fast RF gates for the interlock system.

SYSTEM INTEGRATION

Each pair DWC-SIS consists of 10 channels: 1-8 are reserved for cavity RF signals, the remaining two are used for RF reference or VM output monitor. For each cryomodule, one DWC-SIS pair is dedicated to cavity probes, one to forward and one to reflected power signals. For one RF station, 6 DWC-SIS pairs are used to handle CM1 and CM2 in the master crate and 6 other pairs are used in the slave MTCA.4 crate to handle probe, forward and reflected signals of CM3 and CM4. Figure 3 shows the board distribution within the MTCA.4 master crate, including crate management modules: power supply (PS), MTCA controller hub (MCH), CPU and timing (TMG).

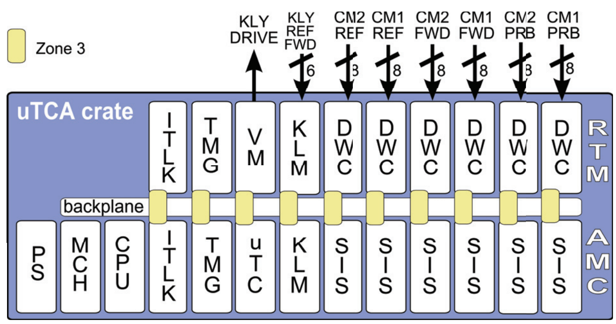

Figure 3: Top view of the MTCA.4 board distribution.

A fast ADC digitizer was also developed for klystron life time management (KLM) purposes. It consists of an RTM-AMC pair which down-converts and digitizes the forward and reflected power signals at the output of the preamplifier and at the output of each arm of the klystron. The fast digitizer and low latency communication to the LLRF controller allow to shut off the RF to protect the klystron with a 250 nsec reaction time, triggering on high reflected or sudden forward power drop. As part of the interlock system (ITLK), a radiation monitoring board based on radiation sensitive SRAM memories and RadFET dosimeters is placed in each crate, measuring photon and gamma radiations with a precision of 10^4 neutron.cm^{-2} and 10^{-3} Gy.

Software and Automation

Automation is essential due to the large scale of the accelerator. To this extend, a hierarchy of automatic systems is currently being developed and tested at FLASH, either implemented in firmware or as high-level servers. Different limiters act when a cavity gradient exceeds a near-quench threshold either by truncating the RF pulse or by gradually decreasing the set point within the pulse until the cavity gradient falls back to a safe zone. Cavity loaded Q (Q_L) can be automatically set and adjusted. A quench detection server monitors cavity Q_L's during the decay and shuts the RF off on the next pulse if a sudden drop in Q_L is detected. A piezo server performs dynamic Lorentz force detuning compensation. Learning feed forward automatically modifies the feed forward table to minimize repetitive controller errors. Beam-based feedback acts on the set point to flatten the energy profile. Cavity virtual probes are calculated inside the LLRF controller from forward and reflected power. They can then be injected into the vector sum calculation in place of actual probe signals, should the later be defective. More automation will certainly be required as operational experience is gained. From the preliminary tests performed at FLASH, it is also clear that hierarchy and precedence among automated actions is crucial.

System Performance

Several test setups based on the MTCA.4 LLRF system have already been installed at DESY: at the FLASH cryomodule test bench facility (CMTB), at the relativistic electron gun for atomic exploration (REGAE), at the klystron test facility and at FLASH electron beam position monitors. The first accelerating module at FLASH was also successfully driven in closed loop using the XFEL MTCA.4 LLRF design. In-loop and outer-loop performance measurements showed an RMS amplitude and phase regulation of $\Delta A/A = 5 \times 10^{-5}$ and $\Delta\Phi = 0.009°$, resulting in a beam energy stability lower than 0.005%, fulfilling the XFEL stability specifications [1]. Long term stability and system-level integration remain to be evaluated when all stations at FLASH are equipped with MTCA.4 systems, as scheduled for summer 2012.

SUMMARY

An overview of the XFEL LLRF system was presented. Although many implementation details have to be left out in such a system overview, the design decisions and system level concepts were described. A prototype version of the LLRF system was installed and successfully tested for one cryomodule at FLASH and showed promising results, meeting XFEL regulation specifications. Although the conceptual design is now already tested and verified, the full system integration when all 7 accelerating modules at FLASH are equipped with the XFEL LLRF system is key to understanding the intrications of scaling it to a full-size accelerator.

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