LOW LEVEL RF FOR SRF ACCELERATORS

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Abstract

Low level radio frequency (LLRF) systems are a fundamental component of superconducting RF accelerators. Since the release of the MicroTCA standard (MTCA.4), major developments in MTCA.4-based LLRF systems have taken place. State-of-the-art LLRF designs deliver better than 10^{-4} relative amplitude and 10 mdeg phase stability for the vector sum control of SRF cavities. These developments in LLRF systems architecture and technology, driven by research institutes and supported by the industry are of highest importance for the European XFEL, but also for other SRF-based projects such as LCLS-II and the ESS, as well as for the next generation accelerators with 10^{-5} and mdeg regulation requirements.

INTRODUCTION

Low level radio frequency (LLRF) control and systems have been around for as long as particle accelerators have existed, so one can legitimately ask if there is something left to be demonstrated in this field. The final goal has not changed since the early days: control the accelerating field in amplitude and phase with the required precision and stability. With the advent of FPGAs, digital LLRF systems have gradually replaced their analog counterpart. The evolution of technology has changed the implementation of LLRF systems and opened new doors, in effect spreading the field of applications. Increasing FPGA capabilities and very fast analog-to-digital converters have changed the way designers approach LLRF systems, always pushing further and extending its role within the accelerator control. Every new generation accelerator pushes the limit of the beam control stability requirements. State of the art accelerators require RMS amplitude and phase stability of 0.01% and 0.01 deg. LLRF systems should prepare for the next challenge: 10^{-5} amplitude and millidegree phase stability requirements.

Details on the architecture of the XFEL LLRF system can be found in [1–3]. This paper presents instead an overview of some of the many facets of a LLRF system for superconducting RF (SRF) accelerators, with examples taken from the LLRF system developed using the micro telecommunications computing architecture (MTCA.4) [4] for the European X-ray free electron laser (XFEL) accelerator. In particular, the interface and contributions of the LLRF to other sub-systems are presented. The second part of this contribution focuses on special challenges posed to the LLRF system, relevant for large scale SRF accelerators.

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INTERFACES TO LLRF

RF Power Sources

The very next component in the RF signal chain at the output of the LLRF system is the high power RF amplification and distribution: pre-amplifiers, klystrons, solid state amplifiers or inductive output tubes followed by a waveguide distribution including power directional couplers, circulators and phase shifters. While the responsibility of the LLRF system lies in delivering the proper accelerating drive signal, the impact of all down stream subcomponents should be taken into account. In most cases, amplitude and phase klystron linearization is necessary to optimize the controller performance, implemented as look up tables [5] or by polynomial interpolation [6], as a middle layer server or directly in the FPGA of the LLRF controller.

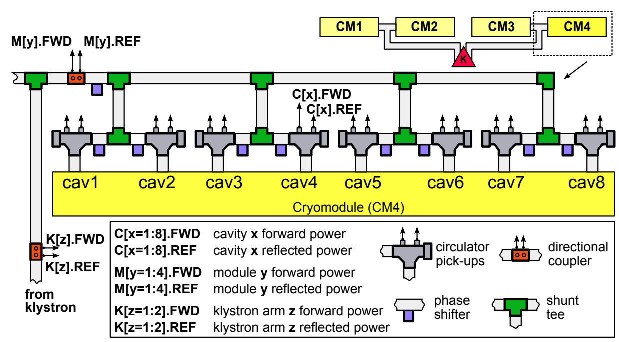

Figure 1: XFEL waveguide distribution showing forward and reflected power pick-ups.

The waveguide power distribution can be fixed or dynamically adjustable, for optimal cavity field control. Phase shifters are typically mounted along the waveguides, to control the incoming waveform phase, for individual cavities, or for group of cavities. Motorized phase shifters and motorized hybrid splitters allow for a tunable power distribution, providing an additional knob to control the cavity forward power (slow control). This also has a direct impact on the reflections and cross talks between cavities which can clearly be seen from the LLRF system. Directional couplers used along the waveguide distribution are important monitoring points (Fig. 1). The directivity of these couplers affects the waveform detection. Forward and reflected power signals can then be efficiently decoupled within the LLRF system. For the XFEL, the forward and reflected power waveforms (P_{FWD} and P_{REF}) are digitized by dedicated MTCA.4 boards and then centralized into the main LLRF controller [7]. The main controller then performs a complex linear combination of P_{FWD} and P_{REF} to decouple the waveforms, effectively removing the cross-coupling induced by the directivity of the circulator pick-ups. These calibrated P_{FWD} and

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P_{REF} waveforms can in turn be used to compute a *virtual probe*, as demonstrated experimentally at the free electron laser in Hamburg (FLASH) in Fig. 2. Deviation from the detected cavity probe signal can then be used to diagnose problems in the signal chain.

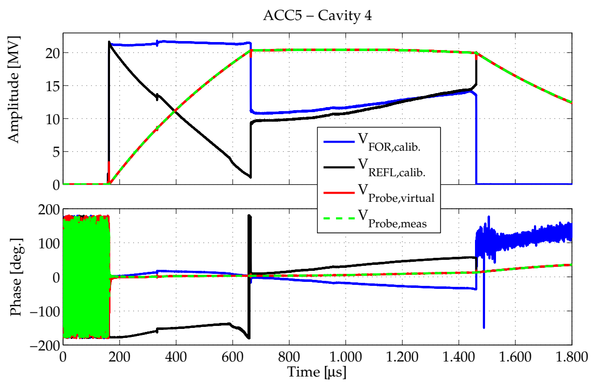

Figure 2: Cavity probe measured and calculated using the calibrated P_{FWD} and P_{REF} signals.

Klystrons are a significant cost driver for pulsed SRF accelerators, every action should be taken to optimize their lifetime. The LLRF system can contribute in that aspect by closely monitoring the forward and reflected power directly at the output of the two klystron arms. Any deviation from nominal output power waveforms or sudden fluctuations of the reflected power are a strong indication that something is amiss. A special direct sampling MTCA.4 board was developed for this purposed [8]. Combined with a dedicated rear transition module (RTM), it monitors the klystron input and output signals, triggers an alert and interrupts the LLRF drive signal within 200 nsec of an unexpected event, which in turn, may help extend the lifetime of the klystron [9].

Cryogenic Plant

For superconducting accelerators, the cryogenic subsystem keeps the liquid Helium bath at 2K, and maintains the He pressure stable to better than ±1 mBar. The relationship with the LLRF system becomes obvious for large scale machines, where the dynamic heat load fluctuates largely with RF operation scenarios. This inter-dependence between RF controls and cryogenics is essential in the case of the XFEL where cold compressors are used [10], which are more sensitive to helium flow fluctuations than warm compressors. As a consequence, planned RF operation changes such as ramping up or down an RF station should be negotiated with the cryogenics group, so that counter measures (stopping or starting heaters) can be taken in time, in order to minimize cryoload fluctuations. Based on the Q_0 versus gradient profile typically determined during vertical testing of SRF cavities, an online dynamic heat load estimation can be computed and used to estimate the heat dissipated into the cryogenics system at the scale of a cavity, cryomodule or cryosection.

Unplanned dynamic heat load events, such as cavity quenches should be detected as early as possible and counter acting measures should be taken. Here again, the LLRF system has all elements at hands to best detect and react on a cavity quench. Details on automatic quench detection for the XFEL are found in [11]. Figure 3 illustrates the importance of detecting and stopping a cavity quench, from the point of view of cryogenic stability.

Communication with the cryogenic system takes place on different levels. A *cryo OK* signal is also crucial for piezo operation, as piezos should not be operated unless the cryomodule is cold. For the XFEL, such a signal is distributed on the MTCA.4 crate backplane to LLRF modules, and sent externally to the piezo driver module, acting as a cryogenic interlock for piezo operations.

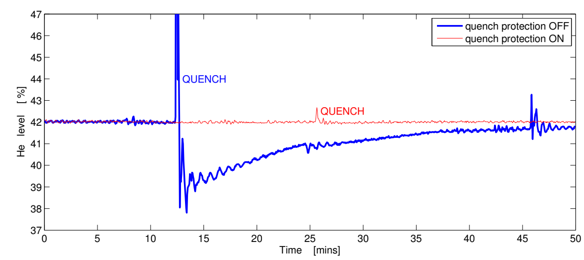

Figure 3: Influence of a cavity quench on the cryogenic system.

SRF Cavities and Couplers

The LLRF system disposes of multiple actuators to regulate the accelerating voltage accurately and efficiently. The cavity bandwidth is precisely controlled using adjustable input power couplers. In the case of large scale SRF accelerators, motorized couplers offer the flexibility to remotely change the cavity bandwidth. The LLRF should include an online calculation of cavity bandwidth and loaded quality factor Q_L, as well as a software to set and keep the Q_L to its target value [12]. It was also shown that adjusting Q_L can be an efficient way to maintain flat accelerating profiles when operating cavities at different gradients in a vector sum configuration with high beam loading [13].

While SRF cavities are often presented as the key element of a cryomodule, RF input power couplers are probably its most complex structures, and deserve special care at all levels of the cryomodule life time. Before operation, special care must be taken to commission the couplers, for different input power, but also for different coupling ratios (Q_L). During operation, it is essential for the LLRF system to monitor closely the status of the input coupler, in particular thermal effects, visible as Q_L fluctuations, or interlock events due to sparking or light emission.

Equally important is the cavity resonance control. For TESLA cavities, this is typically broken down into slow and fast tuning, namely using cold stepper motors and piezo electric actuators respectively. The LLRF system relies on piezos to compensate for Lorentz force detuning but also for

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microphonics regulation and cavity resonance control. The LLRF system needs to provide online detuning monitoring and several level of tuning automatisms. Automatic Lorentz force detuning compensation is routinely used in SRF accelerators. For the XFEL, a combined action of the frequency tuners and the piezo is also required during normal operation. A re-tuning of the cavity using the stepper motor is required when the fine tuning using the piezo reaches the limit of the DC bias. This so-called *piezo relaxation* automation server ensures cavity resonance control, while minimizing usage of the stepper motors to optimize their lifetime.

The special case of normal conducting cavities can also be evoked here (RF gun or transverse deflecting structures). Cavity resonance control can be achieved by adjusting the RF pulse length, to fine tune the temperature regulation, hence keeping the cavity on resonance and minimizing its reflected power. Furthermore, control of the gas pressure inside the waveguide has an impact on the phase of the incoming RF wave and can also be handled by a slow feedback controller, within the LLRF system.

Beam and Diagnostics

Regardless of the RF field regulation, the beam is the ultimate judge of the LLRF system performance. Numerous applications have been developed to improve the LLRF system using beam information. Cavity detuning calculation should include beam loading [14], beam loading compensation is scaled by the toroid information, beam-based feedback modulates the set point amplitude and phase based on beam arrival time and beam compression monitors (BAM, BCM) [15]. Beam loading transients are used to temporally align individual cavity channels (Fig. 4), and the information from the final beam energy monitor is essential to calibrate the vector sum absolute gradient. While its true performance evaluation can only be assessed using outer-loop measurements, the LLRF system should nonetheless have its own diagnostic server to monitor and check on its regulation and control performance. Intra-pulse and inter-pulse RMS and peak-to-peak stability should be logged and trigger an alert when out of range. The LLRF system should also monitor and react on abnormal growth of iterative feed-forward tables, or controller output signal.

Operation

The interface between LLRF and operations becomes clear as soon as RF commissioning starts. The controls of the LLRF system must be clearly presented to operators, by means of intuitive graphical interface, layered complexity, and explicit alerts and alarms. An alteration of the RF drive due to a cavity quench or due to the internal triggering of a limiter should be immediately communicated to the operator. Automation tools should be functional, but before all, usable by non-experts or they fail their purpose. User panel design is often left as the last step and the time allocated for their realization ofter underestimated. Navigation from panel to panel, abstraction of complexity, concentration of relevant data into one panel, and the option to look at the same data from different angles are key concepts for panel design.

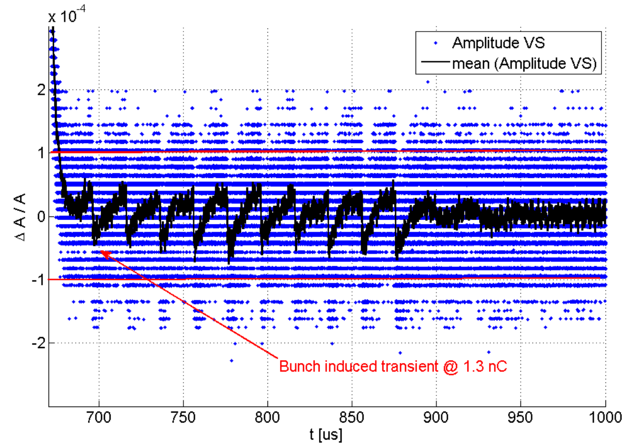

Figure 4: After aligning the delays of individual channel (81.25 MHz ADC clock increments), single bunch transients are clearly visible on the amplitude vector sum.

The LLRF system plays an important role when machine operation modes are changed: finite state machines are developed as top-level servers, to ramp up or down an RF station for example or to adjust machine settings when beam parameters are modified: beam current, wavelength or patterns for example.

Controls and other Subsystems

The controls system and the LLRF system must go hand in hand. Indeed, the software architecture of the LLRF system is linked to that of the control system: which LLRF functionality is pushed down to the firmware level, which is allowed on the front-end server, and which is relayed to middle-layer or high-level servers.

The software architecture of LLRF system is also bound to the data acquisition server (DAQ). How to transfer the data, through broadcasting, polling or using a subscriber-sender approach? How much and which data to send? State-of-the art LLRF crates can support up to several hundreds Gbps data throughput. In the case of the XFEL, the maximum bunch repetition rate of 4.5 MHz drives a 9 MHz accelerating field resolution for end-user experiments to correlate results with individual beam bunches. This imposes a 16k minimum buffer size for the DAQ channels per RF pulse. Storage capabilities and bandwidth are clear boundaries to the LLRF architecture designers.

Finally, real-time capabilities of the LLRF system is another key point. Not necessarily required for standard operation, this becomes essential for higher repetition rates, such as the proposed 25 Hz XFEL upgrade.

The list given above is not complete. The LLRF system has ramifications within the machine protection system, the personnel interlock, end-user experiments, beam optics and magnet controls, etc.

LARGE SCALE ACCELERATORS

Clearly, large scale SRF linear accelerators such as the XFEL, LCLS2 [16], the ESS [17] or the projected ILC [18] must be approached with mass production in mind. Often, for smaller scale projects in research laboratories, a prototype is produced, tested and installed into the accelerator. This approach fails as the size of the machine scales up. This section presents some insight on key elements relevant for the LLRF systems of large machines.

Production and Quality Control

The production of components is the first step where the scale of large machines is felt. Mass production of LLRF components must be outsourced to industry. While taking away the production effort, this approach also puts an additional burden for the preparation of documentation required for industrial production. Mechanical 3D models have to be produced, functional checks must be described and documented, complete specifications should be produced and published, some productions require licensing or certifications, calls for tender have to be launched and awarded, formal communication with the industrial partners through non-conformity reports have to be exchanged, etc... This represents a noticeable change in the work approach and habits, sometimes deviating from the traditional work culture of accelerator laboratories.

Quality control of the produced components is a crucial step for a successful deployment of the LLRF system. For example, the XFEL LLRF system comprises more than 300 down-converter MTCA.4 boards. Testing individual components before installing them in the tunnel saves a lot of commissioning time, often rare toward the end of the accelerator installation. Hence, test stands should be designed to automate functional tests for specific boards. The module manufacturer can be expected to check the basic functionality and electrical soundness of the components; more advanced test requiring specific firmware or system level integration tests can only be done on-site.

Installation

The installation of the LLRF system for a large scale accelerator such as the XFEL is stretched over almost 2 years. A planed and systematic approach is required to install the LLRF system inside the tunnel. All devices must be labeled and the installation of components should be fully documented and saved into a database at the time of installation. One should be able to look up in a database and retrieve the serial number of a given board installed inside a crate for a given RF station. For the XFEL, such labeling and documentation is done using KDS (Kabel Dokumentations-System [19]). More details about the installation sequence and quality control can be found in [20]. The MTCA architecture proved useful for module bookkeeping as each MTCA.4 device is equipped with an electronic key, readable from the crate manager [21]. Hence, one can remotely cross check where each device is installed.

Remote Access and Management

For large scale accelerators, the LLRF system should be designed to minimize tunnel access. A first consequence is that all software and firmware versions must be remotely checkable and upgradeable. For consistency, the same *beta* firmware and software version must be used to commission all RF stations. This can be ensured during installation time, by loading firmware following an automated procedure. However, one should also have the option of checking and upgrading remotely the firmware version for all LLRF components such as crate backplanes, crate controller or CPU kernel version for example.

Furthermore, redundancy is implemented where possible to maximize the LLRF system availability. For the XFEL, the LLRF system is duplicated into main and spare subsystems in the injector and in the first linac. The redundant system is a hot-spare, meaning it is on at all times and expert operators can remotely switch between the main and the spare LLRF systems. To achieve this, all RF signals need to be split between the two sub-systems and a remote control switch module redirects the drive signal either from the main or from the spare system.

Redundancy is also a key element of the MTCA.4 architecture, which allows for redundant power supplies and redundant crate management controllers. Both power supplies are on at all times, both sharing the power load. If one power supply fails, the second one automatically takes over 100% of the load. The defective power supply can then be hot-swapped at later time; no shutting down of the crate is required.

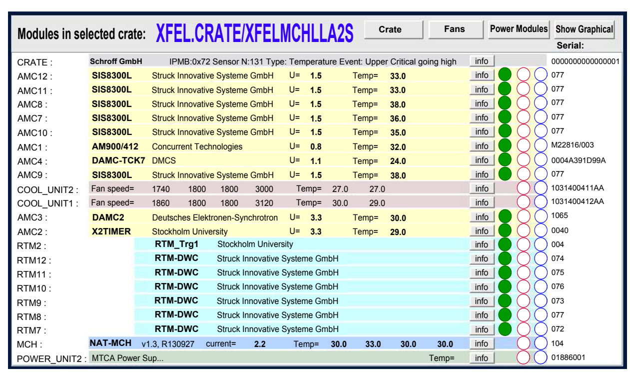

Figure 5: Overview diagnostic panel for a typical XFEL MTCA.4 LLRF crate.

For the European XFEL, the management capabilities of the MTCA.4 include online temperature monitoring at several key locations of individual boards within a crate. A high-level diagnostic server monitors the evolution of temperature for all boards. Fans speeds, CPU load, single event upsets due to radiation are also tracked and logged and contribute greatly to the system health monitoring and aging detection. The diagnostic overview panel for a typical XFEL crate is presented in Fig. 5, showing the crate slot allocation, general information and temperature readouts for all boards inside the crate.

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Automation

One can never emphasize enough the importance of software development required for SRF accelerators. In particular, a large part of this effort goes into automation for machine commissioning and operation, and becomes essential with large scale machines such as the XFEL. The following is only a partial list: automatic cavity frequency tuning and detuning, cavity bandwidth control, system performance and diagnostic server, system start-up and shutdown, quench detection and reaction, cavity sub-π mode identification and notch filter configuration, system identification and controller parameters update, vector-sum calibration, combined control of the first accelerating and the third harmonic modules, calibration of cavity probes, calibration of forward and reflected power, etc.

Many of these functions automate calibration steps which have otherwise to be performed manually by operators (for example: automatic cavity tuning during operation and detuning before cryomodule warm-up). Other functions are essential because one cannot visually monitor all signals (for example: quench detection and reaction or RF station start-up and shut-down). While the core algorithm is usually relatively simple (for example: cavity detuning), a lot of effort goes into exception handling (loss of RF, coupler interlock, piezo reaction, motor over heating prevention, etc.)

High-level server are currently being discussed and designed for the XFEL. An overall energy server, for example, monitoring the energy change of each RF station. When a problem arises in one RF station (quench, lowering of the accelerating gradient set-point), the energy server distributes the energy loss among neighboring stations. This action takes place on a high-level between RF pulses and at a lower-level, within the LLRF system for intra-RF pulse reactions. Fast fiber-link communication between neighboring LLRF stations transfer the energy gain information to adjacent stations (upstream and downstream), and counter measure actions can be taken within the RF pulse to minimize the overall energy loss.

The software automation work for the European XFEL has started since many years but is expected to go on way beyond beam operation of the facility.

CONCLUSION

Rather than a description of the LLRF system designed for the European XFEL, this contribution presents a survey of the plurality of applications involving the LLRF system for SRF accelerators, with implementation examples taken from the XFEL. Some of the features presented here are already developed and tested at FLASH or at the XFEL RF gun (installed last year). Others are still in the design process and their true impact or performance still needs to be evaluated. The installation and commissioning of the XFEL is scheduled from 2014 until 2016. Very valuable experience will be gathered during this time, and the lessons learned will be similarly reported.

REFERENCES

[1] J. Branlard *et al.* "The European XFEL LLRF System", IPAC 2012, New Orleans, LA, USA

[2] J. Branlard *et al.* "MTCA.4 LLRF System for the European XFEL", MIXDES 2013, Gdynia, Poland

[3] J. Branlard *et al.* "Recent Developments of the European XFEL LLRF System", IPAC 2013, Shanghai, China

[4] MicroTCA® is a trademark of PICMG, MTCA.4 specifications: http://www.picmg.org

[5] W. Chichalewski *et al.* "High-Power Amplifier Chain Nonlinearity Influence on the Accelerating Beam Stability in Free Electron Laser (FLASH)", MIXDES 2009, Łódź, Poland

[6] M. Omet *et al.* "Development of FPGA-based Predistortion-type Linearization Algorithms for Klystrons within Digital LLRF Control Systems for ILC-like Electron Accelerators", Real-time workshop 2014, Tsukuba, Japan

[7] D. Makowski *et al.* "High-Speed Data Processing Module for LLRF", Real-time workshop 2014, Tsukuba, Japan

[8] S. Bou Habib, "MTCA Fast Digitizer for Direct RF Measurements", MIXDES 2013, Gdynia, Poland

[9] L. Butkowski *et al.* "Klystron Measurement and Protection System for the XFEL on the MTCA.4 Architecture", ICALPECS 2013, San Francisco, CA, USA

[10] "The European X-Ray Free Electron Laser Technical Design Report", http://xfel.desy.de, Cryogenics p.544-553

[11] J. Branlard *et al.* "Superconducting Cavity Quench Detection and Prevention for the European XFEL", ICALEPCS 2013, San Francisco, CA, USA

[12] W. Cichalewski *et al.* "Feedback Control of Loaded Q Values of the Superconducting Cavities at FLASH", Real-time workshop, 2012, San Francisco, CA, USA

[13] J. Branlard *et al.* "LLRF Automation for the 9mA ILC Test at FLASH", LINAC 2012, Tel Aviv, Israel

[14] M. Grecki *et al.* "Resonance Control of Superconducting Cavities at Heavy Beam Loading Conditions", IPAC 2012, New Orleans, LA, USA

[15] S. Pfeiffer *et al.* "Fast Feedback Strategies for Longitudinal Beam Stabilization", IPAC 2012, New Orleans, LA, USA

[16] Linac Coherent Light Source II, http://lcls.slac.stanford.edu

[17] The European Spallation Source, http://europeanspallationsource.se

[18] The International Linear Collider, https://www.linearcollider.org

[19] DESY's Kabel Dokumentations- System (KDS) is the XFEL cable installation database: http://kds.desy.de

[20] J. Branlard *et al.* "European XFEL RF Gun Commissioning and LLRF LINAC Installation", IPAC 2014, Dresden, Germany

[21] D. Makowski *et al.* "Standardized Solution for Management Controller for MTCA.4", Real-time workshop 2014, Tsukuba, Japan