RECENT DEVELOPMENTS OF THE EUROPEAN XFEL LLRF SYSTEM

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Abstract

The European X-ray free electron laser (XFEL) [1] comprised more than 800 TESLA-type super-conducting accelerator cavities which are driven by 25 high-power multibeam klystrons. For reliable, reproducible and maintainable operation of the linear accelerator (linac), the low-level radio frequency (LLRF) system will process more than 3000 RF channels. Furthermore, stable FEL operation demands field stability better than 0.01 deg. in phase and 0.01 % in amplitude. To cope with these challenges, the LLRF system is developed on a MTCA.4 [2] platform. In this paper, we give an update on the latest electronics developments, improvements of the feedback controller algorithm and measurement results at FLASH.

THE MTCA.4-BASED LLRF SYSTEM

The XFEL is a free electron laser generating X-ray laser pulses of tunable wavelength by the SASE process, using an electron beam accelerated to 17.5 GeV, in a pulsed operation mode. Providing users with stable and reproducible laser pulse properties requires a very precise control of acceleration fields, over the 25 RF stations distributed along the 2 km linac. One XFEL RF station spans 50 m, containing 4 cryogenic acceleration modules with eight 1 m long cavity each. The RF signals are processed in two MTCA.4 crates located between module $1-2$ and $3-4$. A direct optical connection links master and slave subsystems while a fiber daisy-chained topology ensures communication among neighbor RF stations. An overview of the MTCA.4 LLRF system for the XFEL and a description of its main components is found in [3]. Most of the hardware and control strategies for the XFEL are implemented and tested at the Free Electron LASer in Hamburg (FLASH), providing a commissioning test bench of the XFEL LLRF system prior to its tunnel installation. Automation and operation concepts are evaluated at FLASH and later scaled up for the XFEL. Since 2011, a MTCA.4 LLRF system has been permanently installed and its performance has been evaluated. Recently a second system was installed in the accelerator tunnel at FLASH, to gain experience in an XFEL-like environment including accessibility restrictions, influence of radiation and limited rack space for in-tunnel installations. A picture of the LLRF system hosted in a MTCA.4 crate and equipped for 2 cryogenic acceleration modules (cryomodules) is shown in Fig. 1.

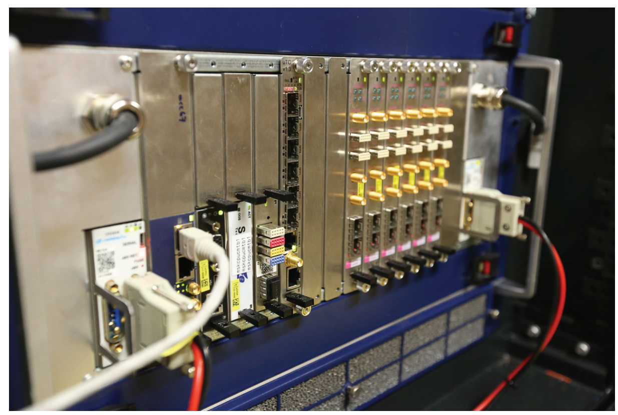

Figure 1: MTCA.4 LLRF installation at FLASH.

Preliminary results of radiation measurements inside the shielded LLRF racks show 0.45 mGy/h and an average of 2 single event upsets per hour. This radiation level had no detected influence on the CPU and memory but the impact on the FPGA code still remains to be investigated. The amplitude and phase regulation over the RF flattop while controlling one cryomodule in closed loop was measured to be 0.008 % (rms) and 0.007 deg. (rms), Fig. 2. The controller performance was validated using beam-based measurements and meets the XFEL specifications.

RECENT HARDWARE DEVELOPMENT

While the architecture and the design of the XFEL LLRF system is finalized, some of its subcomponents are still undergoing revisions and upgrades, adding functionality, performance and versatility to the overall system. Some MTCA.4 modules went through minor revisions and are now ready for mass productions (down-converters, vector-modulators, power supplies), others like the main LLRF controller (uTC) and digitizers (uADC) were upgraded to a more powerful FPGA, with larger and faster memory and increased functionality by adding output DACs

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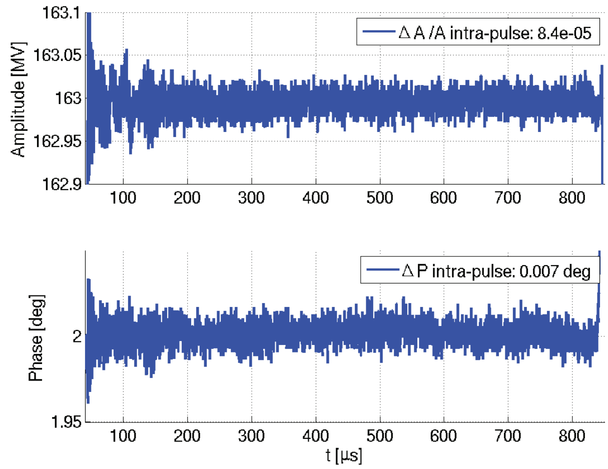

Figure 2: MTCA.4 LLRF system flattop regulation.

or optical link connections for future accelerator developments. The measurement accuracy of single RF channels has been improved to 0.003 % in amplitude and 3 mdeg. in phase. An improved MTCA.4 module (uDWC-VM) was developed for single-cavity single-klystron regulation, combining the analog signal processing functionalities of the down-converter and of the vector modulator. This module paired with the new digitizer (SIS8300L) offers the full controller functionality within a compact form factor and will be used for the XFEL gun, among other single-cavity applications. The MTCA.4 crates have been undergoing various mechanical and technical revisions, in collaboration with several industrial partners. The benefits are a better cooling capability in the electronic crate and compatible with the RF backplane (uRFB) [4]. The uRFB distributes the reference RF signal, the local oscillator and the clock signals to all rear MTCA.4 modules and reduces hereby the RF cabling efforts. The RF signals are generated and conditioned by the local oscillator generation module (uLOG), currently in production. The RF reference distribution design is finalized for the accelerator and the undulator section. A combination of point-to-point and daisy-chained distributions, laser-to-RF synchronization and interferometer-line distribution are used. Design details and challenges are presented in [5].

Other external modules supporting the MTCA.4 LLRF system have also been improved, such as the power supply module (PSM), providing power to all other external modules, the drift compensation module (DCM) and the piezo control module (PZ16M).

In preparation for the mass production of LLRF modules, test stands were designed for the quality control of incoming components. While the basic functionality of the modules is tested by vendors, the advanced performance tests are carried at DESY. A global integration test, including all modules installed in the crate is planned before the racks are lowered into the XFEL tunnel. One key advantage of the MTCA.4 framework is the advanced management of its modules but it requires full compliance and inter-module compatibility. The MTCA.4 installation at FLASH also provided the opportunity to identify early-on the challenges associated with system integration.

TOOLS AND SYSTEM DEVELOPMENT

The scale of the XFEL requires a high degree of automation and global control, which should be implemented starting at the subsystem level. Automated cavity resonance control, including stepper motor tuner and piezo actuators is necessary. Cavity quenches introducing strong heat load fluctuations should be avoided to protect the cryogenic system. Automated prevention and detection of possible quenches is realized through measurement routines and gradient limiters implemented inside the control loop. A detailed description of LLRF-specific automated tools can be found in [6]. A key automated feature of the LLRF system is the beam loading compensation; its concept for the XFEL is presented below.

Beam Loading Measurement and Compensation

A typical measurement of an uncompensated beam loading pattern is shown in Fig. 3. Due to the higher measurement accuracy, even single bunch transients for moderate charges can be detected.

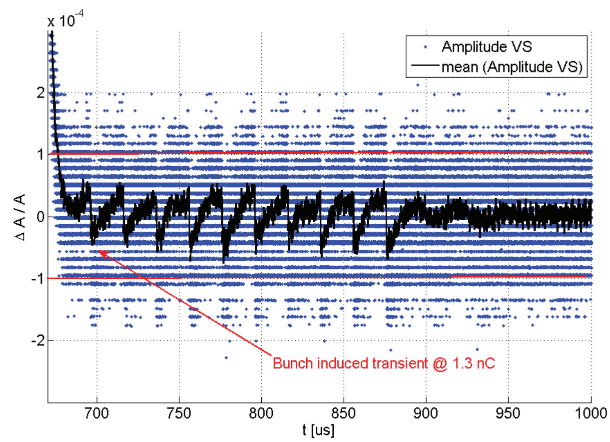

Figure 3: Uncompensated beam loading measurement of 10 bunches at 1.3 nC and repetition rate of 50 kHz (0.065 mA).

The XFEL general operation bunch pattern consists of up to 2700 bunches at a repetition rate of 4.5 MHz and with a variable charge distribution. This multi-pattern beam scheme will be implemented at FLASH, when the second undulator line (FLASH II) comes in operation, end of 2013. Overall, this demands a highly flexible and accurate beam loading compensation within the LLRF system, to meet the LLRF performance specifications. The bunch charge is measured to increase the RF power for beam loading compensation. This prevents to accidentally overfill the cavity, potentially causing a cavity quench in case of fast (μs) beam inhibits. In addition, information about the expected

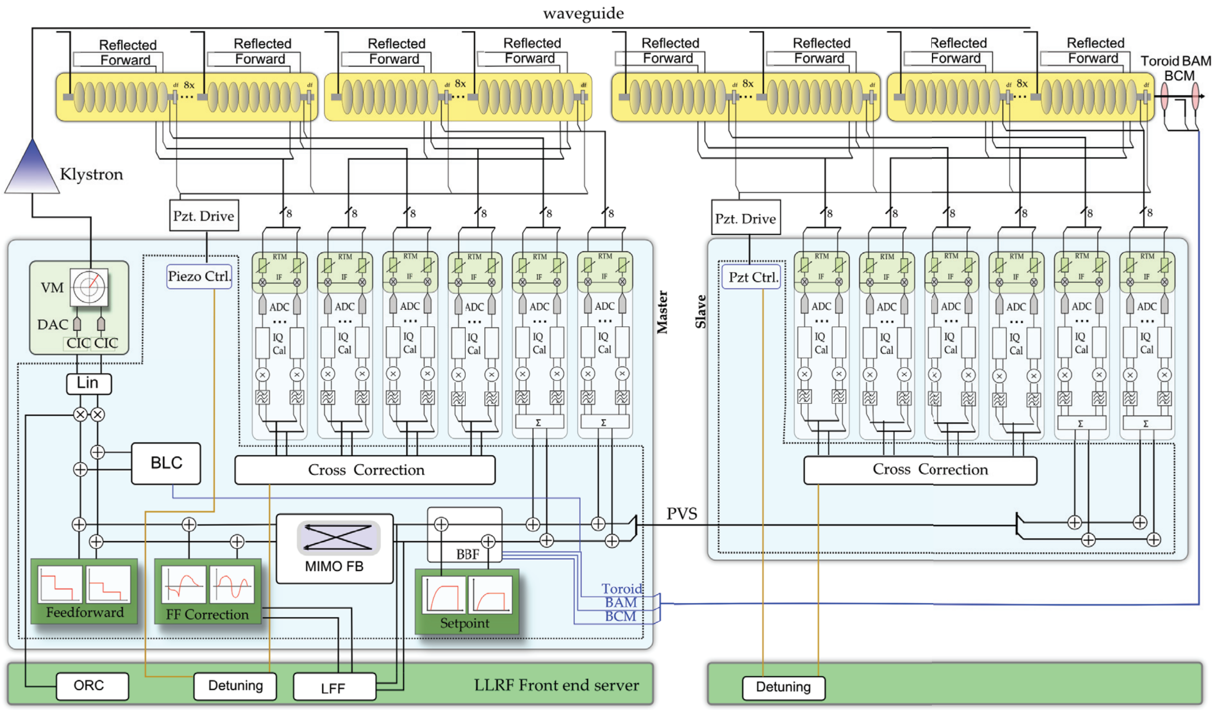

Figure 4: Functional block diagram for 32 cavity regulation.

bunch pattern is distributed in advance of the upcoming RF pulse.

Semi Distributed Controller Regulation

The functional block diagram of the LLRF regulation loop is shown in Fig. 4. The 16 cavity data acquisition and preprocessing section is identical for the master and the slave subsystems. The main controller sums up the two partial vector sum (PVS), resulting from the contribution of cryomodule (CM) 1 and 2 on the master LLRF system and CM 3 and 4 on the slave LLRF system. This global vector sum is then processed within the feedback controller to generate the klystron drive signal. The controller signal flow starts with beam-based signal correction followed by a multiple input, multiple output (MIMO) feedback controller [7]. Predictable and repetitive distortions are treated by an iterative learning feed-forward (LFF) and advanced beam loading compensation (BLC). Finally the klystron driving signal is scaled in amplitude and phase by loop parameter corrections (ORC) and the klystron linearization is applied before modulation to the operating frequency of 1.3 GHz. This regulation concept is permanently in operation in the FLASH LLRF system, suppressing the main disturbances during regular machine operation.

CONCLUSION AND OUTLOOK

An overview of the recent development for the XFEL LLRF system was presented. The designed hardware has been tested at FLASH and proved it can meet the tight XFEL regulation requirements. The complete system integration validation will happen this summer, when FLASH is fully equipped with the MTCA.4 LLRF system. Beam-based measurements and control algorithms have been developed and successfully tested at FLASH. Adapting the LLRF system to handle multi-pattern beam will take place at the end of this year, during the commissioning of FLASH II. More experience will also be gained with the MTCA.4 LLRF system during the commissioning phase of the first component of the XFEL accelerator chain, the RF gun, scheduled for fall 2013. Recent experiences show that on-going performance increase is necessary to meet stability requirements towards 0.001 % in amplitude and 1 mdeg. in phase, requested by state-of-art FEL experiments.

REFERENCES

[1] "The European X-Ray Free Electron Laser Technical Design Report," `http://xfel.desy.de`.

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

[3] J. Branlard *et al.*, "The European XFEL LLRF System," IPAC12, USA.

[4] K. Czuba *et al.*, "RF Backplane for MTCA.4 Based LLRF Control System," Real-time workshop 2012, USA.

[5] K. Czuba *et al.*, "Overview of the RF Synchronization System for the European XFEL," WEPME035, IPAC13, China.

[6] J. Branlard *et al.*, "LLRF Automation for the 9mA ILC Test at Flash," LINAC12, Israel.

[7] C. Schmidt *et al.*, "Precision Regulation of RF Fields with MIMO Controllers and Cavity-based Notch Filters," LINAC12, Israel.

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