RF Backplane for MTCA.4-Based LLRF Control System

Krzysztof Czuba, Tomasz Jezynski, Matthias Hoffmann, Frank Ludwig, and Holger Schlarb

***Abstract*—Low-level RF (LLRF) control systems developed for linear accelerator-based free electron lasers (FELs) require real-time processing of thousands of RF signals with very challenging RF field detection precision. To provide a reliable, maintainable, and scalable system, a new generation of LLRF control based on MTCA.4 architecture was started at DESY for the FLASH and European-XFEL facilities. In contrast to previous RF control systems realized in 19-in modules, we could demonstrate field detection, RF generation, RF distribution, DAQ system, and the high-speed real-time processing entirely embedded in the MTCA.4 crate system. This unique scheme embeds ultra-high-precision analog electronics for detection on the rear transition module (RTM) with powerful digital processing units on the advanced mezzanine card (AMC). To increase system reliability and maintainability and to reduce performance limitations arising through RF cabling, we developed and embedded in the MTCA.4 crate, a unique RF backplane for RTM cards. This backplane is used for distribution of high-performance local oscillator (LO), RF, and low-jitter clock signals together with low-noise analog power supply to analog RTM cards in the system. In this paper, we present the design and architecture of the MTCA.4 crate with the RF backplane and successful test results of the LLRF control system.**

***Index Terms*—Accelerator control systems, accelerator instrumentation, free electron lasers, front-end electronics.**

I. Introduction

THE MODERN superconducting linear accelerator-based coherent light sources, such as FLASH [1], [2] and the European-XFEL (E-XFEL) [3], use precisely controlled RF field for electron beam acceleration. Real-time field stabilization is performed by a low-level radio frequency (LLRF) control system [4]–[6] that should assure up to 10^{-5} of amplitude and 0.01° of phase regulation accuracy. Such a challenging performance must be achieved while processing almost 100 RF signals from superconducting cavities at each of the 25 RF stations of the E-XFEL project. The control system must also fulfill stringent reliability and maintainability requirements. Only one service day per month is foreseen during regular operation of the E-XFEL. Prolonged machine downtime forces complications for the user run schedule and may be very expensive for the X-FEL consortium. Therefore, it is required to assure the maintenance time to be as short as possible. Those requirements forced the LLRF system designers to select a modular hardware platform supporting hot-swap and crate management system and build a compact hardware capable to integrate powerful digital processing units together with high-precision RF and analog circuits within one crate.

Currently, several crate standards (e.g., xTCA, VME, or PXI [7]) are used in research and the instrumentation field. The new hardware standard (Micro-TCA), adapted to physics experiments requirements by the MTCA.4 specifications [8], has been selected as a hardware platform for the FLASH and E-XFEL control systems. Two of many possible criteria for platform characterization were considered while selecting hardware for the E-XFEL project: a chassis/board size and the backplane connectivity.

Comparing a board size, the MTCA.4 offers more space (150×340 mm^2) for designers than VME, CompactPCI, or PXI, but less than VXI or ATCA. The advantage of MTCA.4 is that the offered space is split almost equally into two boards: AMC (in the front of the crate) and back-to-back compatible μRTM (located on the back side of the MTCA crate). It was decided that high-computational-power digital devices would be located on AMC modules, and the precise analog components of the control systems should be placed on the μRTM cards. In this way, physical separation of digital and analog domains can be achieved. This allows for noise reduction and also easy upgrade or exchange of a signal conditioner board when it is located on μRTM, while keeping standard, off-the-shelf, AMC computational boards.

Comparing the backplane connectivity, the MTCA.4 backplane offers four lanes from each AMC slot to a system slot (MCH, PCIe, or Ethernet switch) that are capable to provide up to $\sim$ 1000 MB/s transfer speed (PCIe Gen.2). In addition, several high-speed (gigalinks) are available for communication between neighbor slots. Compared to other standards, only ATCA offers higher bandwidth. There is no bus structure on the MTCA backplane, so a single board cannot block data transfer.

The MTCA.4 standard also offers scalability and remote diagnostics capabilities, which improve maintainability—crucial features for large scientific machines.

Most digital interfacing and connections in the E-XFEL LLRF system are performed by the MTCA standard AMC backplane and through fiber-optic and Ethernet cables connected to AMC card front panels. Most of the RF and analog board-to-board and outside system connections are realized by cables with SMA connectors at the back side of the crate. There

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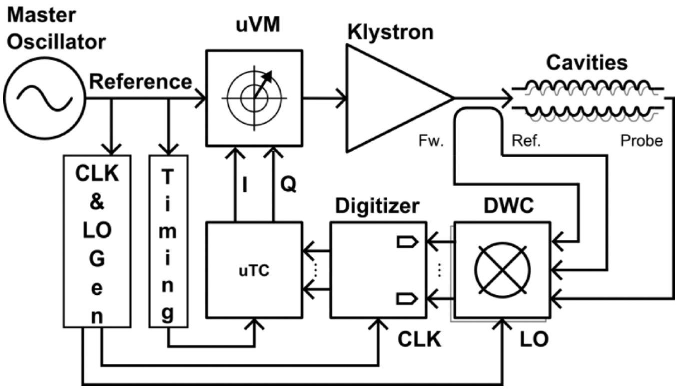

Fig. 1. LLRF system architecture and signal flow.

are more than 30 RF and clock connections necessary for one crate. In case of crate failure, disconnecting and reconnecting all those cables lasted about 2 h. Installation was sensitive to human errors like flipped channels or loose connector. Finding mistakes took sometimes a few days of faulty system operation. The former system design did not support hot-swap of modules. Therefore, in case of any board failure, the entire crate had to be shut down. Running it again required laborious restarting of software and tuning of the system.

This paper presents a concept and design of the μRTM RF Backplane (μRFB), for which a patent is pending, that allows for the replacement of most of the internal LLRF RF cable interconnections, leading to improvement of the system's performance and reliability. Maintenance time in case of board failure can be shortened from several hours or days down to about 10 min.

II. RF Signal Distribution Within the LLRF System

The E-XFEL LLRF system architecture and physical realization in the MTCA crate is shown in Fig. 1. The forward, reflected, and probe signals (all at frequency of 1.3 GHz) from superconducting cavities are converted down to an IF frequency by multichannel downconverter modules (DWC) designed as μRTM cards. IF signals are digital-to-analog converted by an AMC digitizer module . Data from up to eight digitizer modules are collected by the main LLRF MTCA controller module (AMC card called uTC) [9] with the use of low-latency links (LLLs) available on the MTCA AMC backplane [10]. The uTC uses the acquired data to calculate the output signal that is used to drive a μRTM vector modulator card [11]. The LLRF system feedback loop is closed by a klystron that supplies the accelerator cavities. More details on realization of the E-XFEL LLRF system are given in [12].

Besides cavity signals provided to DWC card inputs, there are up to 18 LO and RF reference signals (1.354 and 1.3 GHz, respectively) and up to 18 high-performance clock signals that must be delivered to the rear panels of the LLRF MTCA crate. Due to the high frequency, those connections must be realized by coaxial cables with RF connectors. Such a large number of RF cables on a relatively small area of μRTM front panels significantly complicates system installation and affects maintainability and reliability of the hardware. To improve this issue, the idea of the μRFB was developed that eliminates cable interconnections between μRTM boards and LO, CLK, and RF reference signal sources.

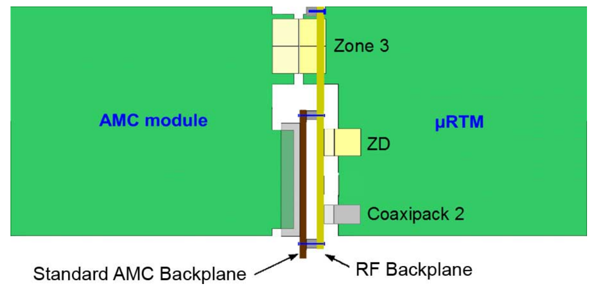

Fig. 2. RF backplane position in the MTCA crate.

III. RF Backplane Concept

A. High-Performance Power Supply for μRTM

The MTCA.4 standard μRTM card power supply is specified as single +12 V provided over the AMC module from the AMC backplane. The total payload power for each AMC $-\mu$RTM pair is limited to 80 W with the assumption that μRTM will not consume more than 30 W. Such power may not be sufficient for all μRTM applications. Additional power delivered over the μRFB may solve this problem, but care must be taken to provide the necessary μRTM cooling capabilities of the crate. This should, therefore, be treated as a special usage of the RF backplane.

It is important that the AMC power supply is treated as a noise source since it was designed for powering digital modules. Selected RF modules located on the μRTM may require negative power supply voltages, and these can be taken from +12 V with dc/dc converters, but those are noisy voltage sources and may cause unwanted interferences for sensitive analog electronics. In contrast, the RFB offers a unique opportunity to deliver high-performance positive and negative power to μRTM cards and separate this power supply from noisy AMC sources.

B. Connectors

There are two types of connectors required for the μRFB: coaxial for LO and RF reference signals, and differential for clocks. A Coaxipack 2 type connector [13] with up to six interfaces was selected. It was placed in the lower area of the backplane for physical separation with CLK signals and with Zone 3 area conducting fast digital interfaces (see Fig. 2).

For CLK signals, a 30-differential-pair ZD connector [14] was selected. It offers enough pins to cover clock connection, the analog power supply, and a good grounding connection between μRFB and μRTMs.

C. Crate Mechanics and RF Backplane Area

The MTCA.4 standard did not foresee the RF backplane, but provided a space between the AMC backplane and μRTM area for optional AMC backplane extensions. It was found that this area can be used for placing the μRFB as shown in Fig. 2. There

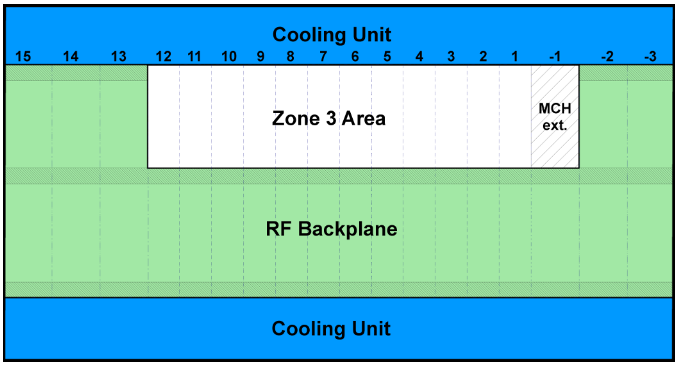

Fig. 3. Area available for μRFB in the MTCA.4 crate (rear view).

is enough space to place both ZD and miniature coaxial connectors for transmitting signals from μRFB to μRTMs.

It was important to find that the μRFB can be placed at such distance from the μRTM edge that connectors would not collide with standard MTCA.4 μRTM cards not supporting the RF Backplane. Therefore, compatibility of commercial μRTM boards to the LLRF crate is not affected, and the μRFB can be treated as a useful extension for the MTCA.4 crate.

It was achieved by making the distance of the AMC backplane front to the front of the RF backplane equal to 9.5 mm and the μRFB thickness equal to 4 mm. This yields a very short distance between both backplanes of about 5 mm (depending on AMC backplane design). Nevertheless, it was verified with crate vendors that there will be no mechanical collisions. It was also confirmed that the RF backplane can be mounted after adding simple mechanical fixtures to a standard MTCA.4 crate. In case the extended payload power is used by μRTM cards, the crate cooling capacity has to be increased. Crate vendors confirmed that it is feasible.

The rear view of the MTCA.4 crate (not to scale) is shown in Fig. 3. Standard μRTM slot numbers are given (1–12). For simplifying the μRFB description, slots used for MCH and MTCA power supplies were numbered also (-1 to -3 and 13 to 15).

Almost the entire area of the crate cross section (rear view) is available for the RF backplane, except for the Zone 3 area foreseen for AMC-to-μRTM connections. Only one MCH module was assumed to be used in the crate for the E-XFEL LLRF system. It is recently known that some MCH modules may be equipped with the RTM connection extension. The Zone 3 area of slot -1 was therefore also excluded from the RF backplane.

D. Assignment

The E-XFEL LLRF system architecture assumed that slots 1–3 of the crate will be occupied by CPU, timing, and interlock modules. Those modules do not require RF interconnections and are treated as noisy due to their usage of high-speed digital circuits. Therefore, the RF backplane signal entry will be placed in the left area of the crate (slots 12–15) to get a good physical separation from noisy modules. Since slots 13–15 on the RTM side are not occupied in the MTCA.4 specification, it creates an excellent opportunity for integrating an LO and clock generation subsystem in the crate. In case the volume of slots 13–15 is not sufficient or there is no need to integrate reference signal sources, a signal can be delivered to the RF backplane by a simple RTM adapter board with RF connectors at the front panel.

Slots -2 and -3 can successfully be used for installation of an analog power supply for μRTM cards. Development of such special power supply modules was discussed with selected manufacturers, and MTCA crate vendors confirmed that they can extend crate cooling capacity in this area.

IV. RF Backplane Prototype

The prototype of μRFB for the E-XFEL LLRF system was designed to prove the principle based on the following assumptions originating from the basic LLRF system prototype:

- slot 12 is devoted for signal entry;
- distribution of eight LO signals (1354 MHz) to slots 4–11;
- distribution of three RF reference (1300 MHz) signals to slots 4, 5, and 11;
- distribution of 18 CLK signals (81 MHz differential LVPECL) to slots 4–11, two clocks for each slot;
- distribution of $+7$ and -7 V analog power supply (PWS) to slots 4–12. Bus type distribution. PWS entry in slot 15.

The simplified block diagram of the RF backplane is shown in Fig. 4. There are power splitters on the left side of slot 12, where signals entering the μRFB are split and further distributed to all covered μRTM slots. Clocks are distributed from the CLK connector of slot 12 in star configuration. The PWS is connected from the entry connector to all μRTM slots of interest.

For saving material, the printed circuit board (PCB) was designed to cover the area between slots 15 and 4 of the crate. A 10-layer PCB was built with a low-loss RF substrate to minimize RF loss and assure proper impedance matching of RF and differential lines.

The Coaxipack 2 connector pins are solder-type and can be soldered to maximum 2-mm-thick PCBs. The total thickness available for the RF backplane is 4 mm.

An advantage was taken of this problem to split the μRFB design into two boards: a 2-mm-thick backplane and 2-mm-thick so-called "RF backplane shield," which is a PCB with cavities milled to cover soldered pins of the Coxipack 2 connectors and shield them from the AMC backplane EMI.

Both μRFB and the μRFB shield boards are edge-plated to reduce the interference from the AMC backplane and digital subsystems surrounding the μRFB.

The designed board prototype assembled in the crate is shown in Fig. 5.

V. Tests

RF backplane tests were performed both in laboratory conditions and with the backplane installed in the MTCA.4 crate. A number of adapter boards were designed and manufactured to make it possible to measure parameters of signals distributed over the backplane.

A. Laboratory Tests

In laboratory tests, the RF loss, return loss, and crosstalk were measured outside of the crate. The worst-case RF loss in the PCB was measured to be about 1 dB at 1.3 GHz (not including the power splitter), which is a very good result as expected for

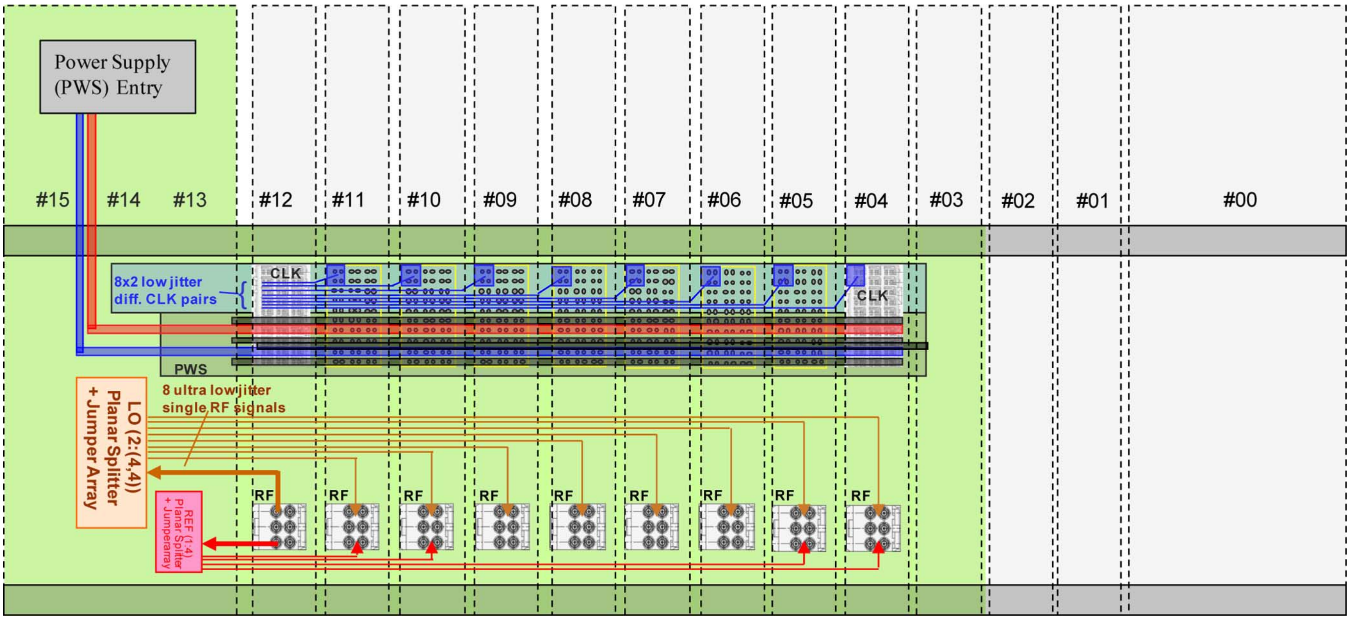

Fig. 4. RF backplane prototype block diagram.

Fig. 5. RF backplane prototype assembled in the MTCA.4 crate.

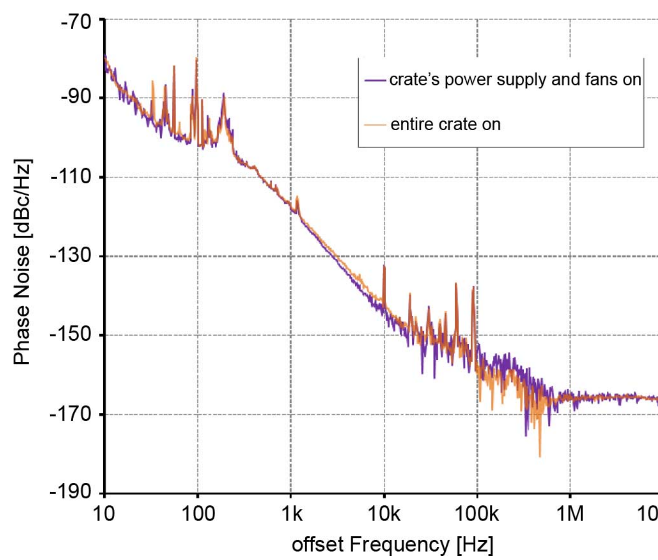

Fig. 6. Phase noise of 1.3-GHz signal distributed over the backplane inside of MTCA.4 crate equipped with fans and DSP subsystems.

a design with the chosen substrate. Crosstalk between CLK and RF or LO lines could not be measured with available equipment. It is estimated to be above 90 dB, which was also expected due to the significant physical distance separating the CLK and RF sections.

B. MTCA.4 Crate Tests

In the next step, the μRFB was installed in the crate. Distributed signal performance was analyzed in various conditions, starting with crate power supply switched off and after subsequent switching on additional devices like MCH, fans, etc., and ending at crate equipped with several AMC and μRTM boards communicating with Gbit speed over the AMC backplane. Unfortunately, due to a lack of a sufficient number of devices, no fully loaded crate with 12 AMC $-\mu$RTM pairs could be tested, but only the MCH, CPU, three digitizer AMC, and three DWC μRTM boards were present in the crate. Signal spectra and phase noise of LO and RF reference signals were recorded, and clock jitter was measured.

Excellent results were achieved. In the frequency range from a few kilohertz to 6 GHz, no spectral lines coming from the MTCA crate and inserted cards were observed on the level of roughly -80 dB (spectrum analyzer measurement range). This is due to a good shielding of the μRFB.

Similar observations were made of phase noise spectra of distributed signals. An example of the measurement results is shown in Fig. 6, where 1.3 GHz signal phase noise is compared in the crate without and with digital subsystems. Only a very small, negligible phase noise level increase can be observed. The final test was performed through acquiring data by the digitizer board while the downconverter board

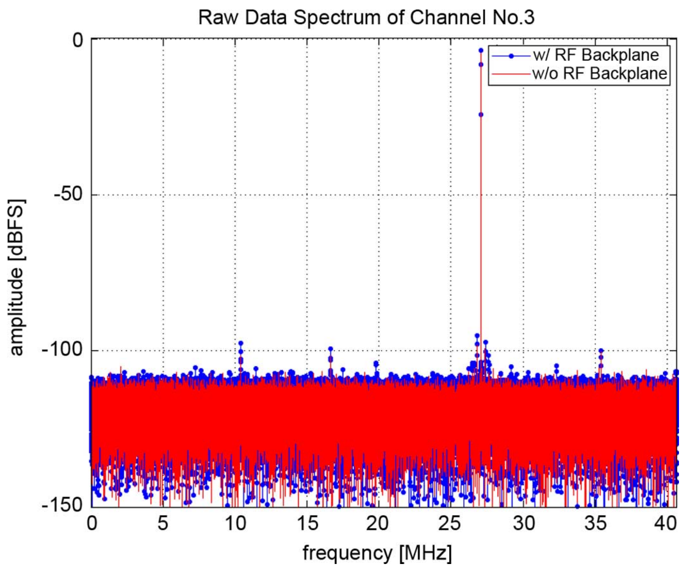

Fig. 7. Comparison of signal spectrum recorded by digitizer (AMC) supplied by the downconverter module (μRTM) when LO and CLK signals were provided via front panels (red) and via the μRFB (blue).

was receiving LO signals over the RF backplane. The fast Fourier transform (FFT) of the digitized signal was observed, and no spectrum degradation was recorded when compared to LO signal distribution over standard coax cable—see Fig. 7. Signal-to-noise ratio (SNR) values [1 MHz bandwidth (BW)] measured during no μRFB and μRFB operation are equal, respectively -82.2 and -82.4 dB. Difference is within measurement uncertainties.

The last test showing no degradation of the system performance confirmed fully that the RF backplane can be successfully used for reduction of external connections at the MTCA crate.

VI. Summary

The described RF backplane is a unique extension of the MTCA crate, allowing for RF and clock signal interconnections between μRTM boards and also providing a high-performance analog power supply to boards inside of the crate. This solution is compatible with standard μRTM boards and does not require significant modification of crate mechanics. Only three mounting bars must be added to the standard MTCA.4 crate to fix the μRFB.

The RF backplane allows for the reduction of external cabling of the MTCA crate, improves reliability and maintainability, and leads to a reduction of the system size and installation costs.

Tests demonstrated high performance of RF signal distribution over the μRFB. No significant jitter and phase noise degradation from crate and digital subsystems was detected after using the backplane in the operating system. Also, spectra of signals recorded by digitizers exhibit parameters comparable to ones achieved without the RF backplane. This result confirmed the envisioned benefits of the new RF backplane in the MTCA.4 crate.

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