NEW MTCA.4-BASED HARDWARE DEVELOPMENTS FOR THE CONTROL OF THE OPTICAL SYNCHRONIZATION SYSTEMS AT DESY*

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Abstract

The optical synchronization group at DESY is operating and continuously enhancing their laser-based synchronization systems for various facilities which need femtosecond-stable timing. These include the free-electron lasers FLASH and the upcoming European XFEL as well as the electron diffraction machine REGAE (Relativistic Electron Gun for Atomic Exploration) and the future plasma acceleration test facilities (LAOLA and FLASHforward). One of the major upgrades under development is the migration of the entire electronic control hardware to the new MTCA.4 platform which was introduced as the new standard for accelerator control in many facilities worldwide. In this paper we present the applied modules and the topology of the new systems. Main advantages are a compact design with higher performance, redundancy, and remote management.

INTRODUCTION TO MTCA.4

MTCA is a novel electronic framework derived from the Advanced Telecommunication Computing Architecture (ATCA) [1]. MTCA.4 was released as an official standard by the PCI Industrial Manufacturers Group (PICMG [2]) in 2011 and is supported by the xTCA for physics group, a network of physics research institutes and electronics manufacturers. Its main improvements over the preceding standards are enhanced rear I/O connectivity and provisions for improved precision timing. MTCA.4 has inherited many of the advantages of ATCA including capabilities for remote monitoring, remote maintenance, hot-swap of components, and the option to duplicate critical components, making the standard highly modular and flexible. It also made the outstanding signal processing performance of ATCA systems more affordable and less demanding in terms of space requirements and energy consumption.

Major accelerator facilities worldwide currently evaluate the deployment of MTCA.4-based Low-Level Radio Frequency (LLRF) systems, either for extensions or upgrades of existing infrastructure or for the initial equipment of new facilities.

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MTCA.4 System Architecture

A picture of an equipped MTCA.4 system is shown in Figure1. Fundamental components are the chassis which is available in different form factors and sizes, the power supply, a crate management controller (MCH), and CPU and hard drive.

For user applications specific analog and digital processing cards are used. From the front Advanced Mezzanine Cards (AMC) are inserted to the crate. There are various connections on the backplane which provide e.g. Gigabit Ethernet and PCI Express links between the slots and the MCH, dedicated clock and trigger distribution lines, and point to point links between the slots for fast real time communication between the cards. Additionally, there is the possibility to insert cards from the rear of the crate, so-called Rear Transition Modules (RTM) which connect to the according AMC board via the Zone 3 connector. This connection provides 60 differential pairs for analog or digital signals, which will be defined in the standard [3]. Often the cards have connectors for additional industrial standard piggy back boards like FPGA Mezzanine Cards (FMC) or IndustryPack (IP) modules.

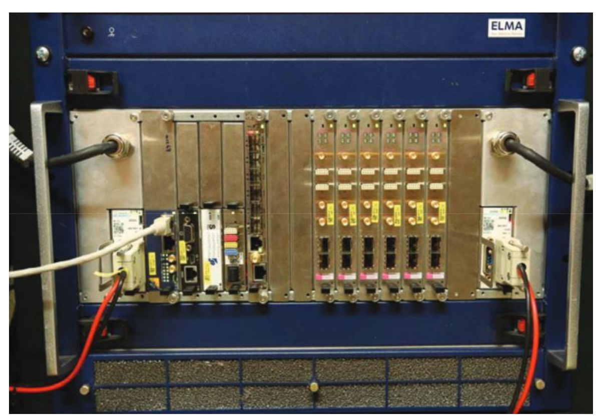

Figure 1: MTCA.4 crate equipped with AMC cards.

MTCA.4 AT DESY

In broad agreement between the involved groups, it was decided to use the MTCA.4 standard for the control electronics of the European XFEL. This involves the LLRF field control [4], timing system, diagnostics like beam position monitors [5] and camera readouts, and the optical synchronization system [6].

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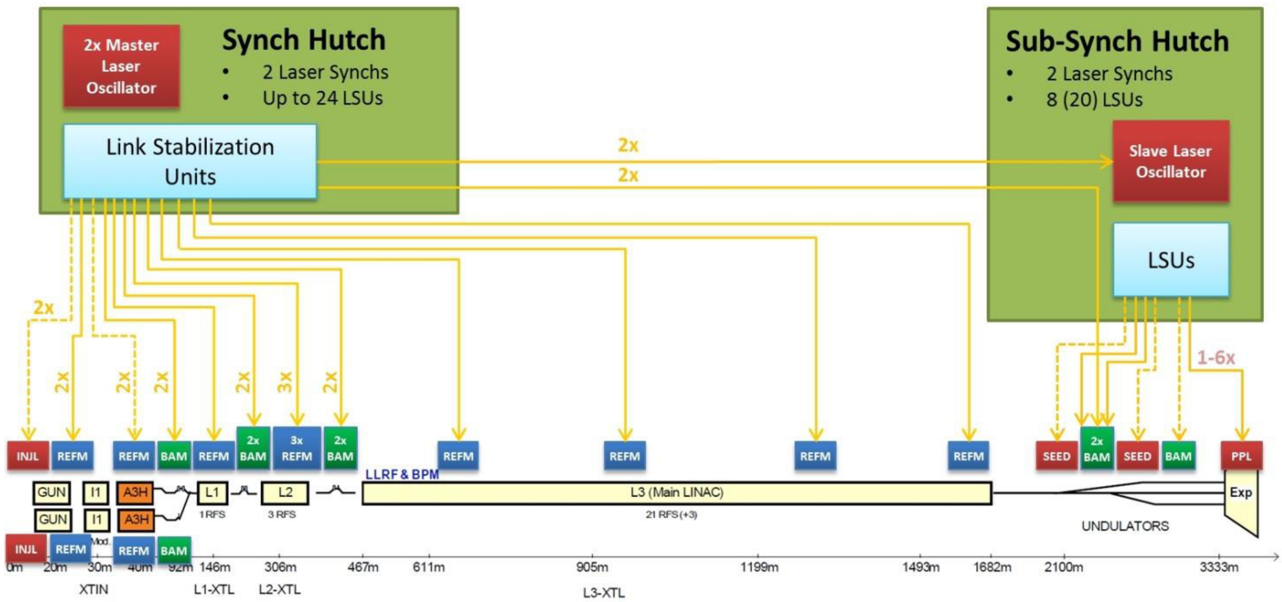

Figure 2: Schematic view on the optical synchronization system at the European XFEL.Up to 24 stabilized fiber links serve for laser synchronization, bunch arrival time monitor stations and RF reference generation modules. The sub-synch hutch located in the experimental hall serves further end stations.

In the course of the developments required for fulfilling the demanding tasks, the standard was further adapted and improved. Naturally also other facilities at DESY like for example the free-electron laser FLASH and the electron diffraction machine REGAE [7] migrate to MTCA.4.

In order to facilitate the development of new boards for extending the portfolio of applications and to ensure the availability of spare parts, DESY took the initiative for a better establishment of the MTCA.4 standard in industry. With substantial funding from the Helmholtz Association for a two-year validation project, DESY has developed novel, fully MTCA.4-compliant components to lower the barriers to adoption in a wide range of industrial and research use scenarios [8].

Most designs are licensed to industry partners who offer those components to their customers. This way it is easy for other institutes and companies to make use of the sophisticated designs (e.g. high speed digital or low noise analog cards) without the need for own developments or additional agreements.

THE OPTICAL SYNCHRONIZATION SYSTEMS AT DESY

FLASH was the first large scale accelerator facility worldwide using a laser-based synchronization system which was deployed in 2008/2009 [9, 10]. For the upcoming European XFEL a similar system is foreseen, scaled to the larger distances and incorporating major improvements. In both cases it provides a reference distribution on a femtosecond level in order to allow time resolution of pump-probe experiments with ultra-short FEL pulses [6].

The main applications of the optical synchronization system are precise bunch arrival time monitors (BAMs), synchronization of external lasers like the pump-probe laser or for FEL seeding, and provision of a precise reference for the LLRF system.

In smaller facilities like REGAE such a complex laser-based reference distribution is not applicable. Nevertheless they benefit from the developments e.g. for laser synchronization and especially the MTCA.4 hardware progress [7].

Synchronization System Architecture

A schematic representation of the synchronization system is shown in Figure 2. The master-oscillator (MO, not shown in the figure) distributes a stabilized 1.3 GHz reference to which the master laser oscillator (MLO), with a repetition rate of 216.7MHz (a sixth of the MO frequency), is locked. The MLO is a passively mode-locked erbium laser oscillator, emitting 200 fs long pulses at the telecom wavelength of 1.55 um. The stabilized pulse train from the MLO is split into multiple channels and guided to the individual link stabilization units (LSUs) through the free-space distribution (FSD). Each LSU actively stabilizes the effective length and therefore the transit time of its assigned optical link fiber, which can be conveniently guided through the entire FEL to stations obliged to femtosecond timing stability. Recently the stabilization of a 3.6 km long fiber link to 3.3 fs rms and 15 fs peak to peak (measured with an independent out-of-loop detector) was demonstrated over 25 hours. The link was operated under realistic conditions, laid out in an uncontrolled ambient environment [6].

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Bunch Arrival Time Monitor

The BAM uses a broadband pickup signal induced by the electron bunch which is sampled by the optical pulses of the synchronization system in an electro-optic modulator (EOM). Arrival time deviations modulate the amplitude of the optical pulse train. This amplitude modulation is converted to an electrical signal and read out with fast ADCs for further processing. This information can be used directly by the FEL experiments and it is used for a fast feedback to the LLRF system for correcting the amplitude of the accelerating modules with a low latency of only a few microseconds. The resolution of the BAM is charge dependent but typically in the order of a few femtoseconds even for bunch charges < 100 pC [11]. By this means the relative arrival time jitter of the FEL is reduced to 20 fs rms [12].

Laser Synchronization

The output of a stabilized fiber link serves as a reference for the synchronization of remote mode-locked laser oscillators. This happens usually in two steps: In the first step an RF signal is generated from each of both pulse trains of the reference and the oscillator. These are compared in an RF mixer (down converter) which provides an error signal proportional to the phase difference of the two inputs. A digital feedback controller stabilizes this phase difference by acting on the frequency/phase of the oscillator [13]. In a second step the two optical pulse trains are compared in a balanced optical cross correlator (OXC). This device combines the pulses in a non-linear crystal to generate second harmonic light whose amplitude is proportional to the timing difference. This information is then again used to stabilize the timing of the oscillator with respect to the reference. While the RF lock provides maximum flexibility and robustness it suffers from limited performance due to the noise and drift of components like the photo detector. The OXC provides maximum sensitivity and therefore the lowest achievable jitter but has the disadvantage of limited operating range and is therefore more sensitive to disturbances. Preliminary measurements show that sub-10 fs rms stability can be sustained over long time periods [10].

RF Reference

The beam-based longitudinal feedback for the stabilization of the bunch train with the help of the BAMs can provide only small corrections and therefore relies on an intrinsically stable LLRF control. For this reason the reference to which the LLRF system compares the field probe signals from the accelerating cavities must be as stable as possible. Coaxial RF distribution or a simple photo detector conversion from the optical reference is not sufficient in terms of noise and drift. Therefore a new approach was developed at DESY which resulted in the design of so-called REFM-OPT modules [14, 15]. In these modules the stabilized optical reference is compared with the local LLRF reference in an EOM. Phase deviations between the two are converted to an RF signal amplitude. This is further processed with analog electronics such that only a baseband signal is read out by the digital feedback controller. The feedback loop acts on a vector modulator or phase shifter to stabilize the RF reference with respect to the optical reference. The control takes place in the so-called TMCB board which is not a MTCA.4 module. The long-term stability is below 4 fs peak-to-peak [15].

Laser Synchronization at REGAE and LAOLA

As the REFM-OPT module incorporates a low jitter and low drift “Microwave vs. Optical PhasE Detector” (MOPED) between an optical and an RF signal the scheme can be as well used to stabilize a mode-locked laser oscillator with respect to an RF reference when an optical reference is not available and therefore the OXC is not applicable. Several challenges have to be overcome in the redesign of the setup to adapt it from the convenient telecommunication wavelength to the Titan:Sapphire laser wavelength of 800 nm [16].

INTRODUCTION OF USED MTCA.4 MODULES

The hardware modules required for the different tasks in the optical synchronization systems like signal detection, sampling, processing, and actuating are mostly generic and applicable in different setups and configurations. Only for a few very specific tasks individual boards were designed.

In this chapter most of the used modules are introduced with a short description.

SIS8300 Versatile FPGA (Virtex 5) AMC board with 10 channel 125 MSPS 16 bit ADCs and 2 fast DACs, developed in co-operation between DESY and the industry partner Struck GmbH [17].

FMC25 Versatile FPGA (Virtex 5) AMC board for data processing and FMC carrier with two high pin count FMC slots [18]. The board was developed at DESY and licensed to the company CAEN ELS d.o.o. [19].

FMC20 Low-cost FPGA (Spartan6) AMC board for interfacing with actuator modules and FMC carrier with two FMC slots. The board was developed at DESY and licensed to the company eicSys GmbH [20].

AD84 Generic analog IO RTM board with 8 channel 10 MSPS 16 bit ADCs and 4 channel DACs. The board was developed at DESY, not yet licensed to an industry partner [1].

DWC8300 10 channel low-noise down converter RTM board (0.7 GHz – 4 GHz). The board was developed at DESY and licensed to the company Struck GmbH [17].

PZT4 Generic 4 channel piezo driver and piezo sensor RTM board with switchable output range (up to ±80 V), internal DAC or external input, and internal or

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external power supply [21]. The board was developed at DESY and licensed to the company eicSys GmbH [20].

MD22 2 channel stepper motor driver FMC board with end-switch and encoder readout. The board is capable of driving up to 1.8 A coil current and supports 256 micro steps. It was developed at DESY and is licensed to the company eicSys GmbH [20].

AD16 Generic ADC FMC board with 16 channels up to 200 kSPS and 18 bits resolution. The board was developed at DESY and is not yet licensed to an industry partner [1].

LASIO Versatile, general purpose, low-cost IO FMC board with 39 IO pins. Each pin can be assigned to digital IO, gnd or alternate function like ADC, DAC, power supply, or UART (12 V) via Xilinx CPLD. The board was developed at DESY, not yet licensed to an industry partner [1].

DSBAM FMC board specially designed for the BAM readout. It incorporates 4 ADCs for two channel interleaved sampling at up to 250 MSPS with 16 bit resolution, and has photo diodes and clock generation on board [18].

SFP4 Generic 2-4 channel SFP+ GbE or fiber transmission FMC board. Board was developed at DESY, not yet licensed to an industry partner [1].

LASY RTM board under development at DESY specially for laser synchronization purposes. It is based on the down converter design but incorporates many laser specific inputs and features.

TOPOLOGY OF THE SYSTEMS

Laser Synchronization Electronics

The laser synchronization development is the most advanced and already used permanently at REGAE and at the third FLASH injector laser albeit with limited features compared to the anticipated final setup [7].

The RF signal generated from the laser pulse train is down-converted in the DWC8300 to an intermediate frequency which is sampled by the SIS8300. Additionally the baseband signal from an OXC or MOPED setup is fed to a second ADC. After phase detection and signal processing the feedback controller output is digitally transferred to the next slot in the crate where it is received by the FMC20. From here the PZT4 is addressed to drive the piezo in the laser cavity. If the required tuning exceeds the piezo range a coarse tuning step has to be performed. For the MLOs and the pump-probe lasers of the European XFEL (tuned by internal temperature change) this is done via the LASIO board, in all other cases the coarse tuning is done with a delay stage within the laser cavity driven by a stepper motor via the MD22.

Additional inputs of the down converter and later the LASY are used for bucket detection to set the correct absolute timing and for some other required monitoring and control signals.

For remote control the LASIO additionally provides all needed features for monitoring and driving the MLO's controller unit and for driving beam shutters.

As the PZT4 is capable of driving more than one piezo also laser oscillators with two piezos and/or two lasers oscillators can be synchronized with no additional hardware.

Fiber Link Stabilization Electronics

For serving the LSUs MTCA.4 offers a very compact and efficient solution because four links can be stabilized with only two slots in the crate. The heart of the LSU is an OXC whose signal is sampled by the AD84 (2 ADC channels per link). The processing is done with the FMC25 which computes the feedback controller output and, similar to the laser application, transmits the required actuator action to the FMC20. Again, this board addresses the piezo driver in the rear which drives a piezo-based fiber stretcher to compensate for the detected timing change in the link fiber by stretching a piece of it. Also here a delay stage is required for coarse tuning when the piezo stretcher reaches its limit. The delay stage is driven by the MD22. For a complete set of four LSUs all eight ADC inputs from the AD84, all four piezo driver outputs from the PZT4, and all four motor drivers on two MD22 FMCs mounted on the FMC20 are used.

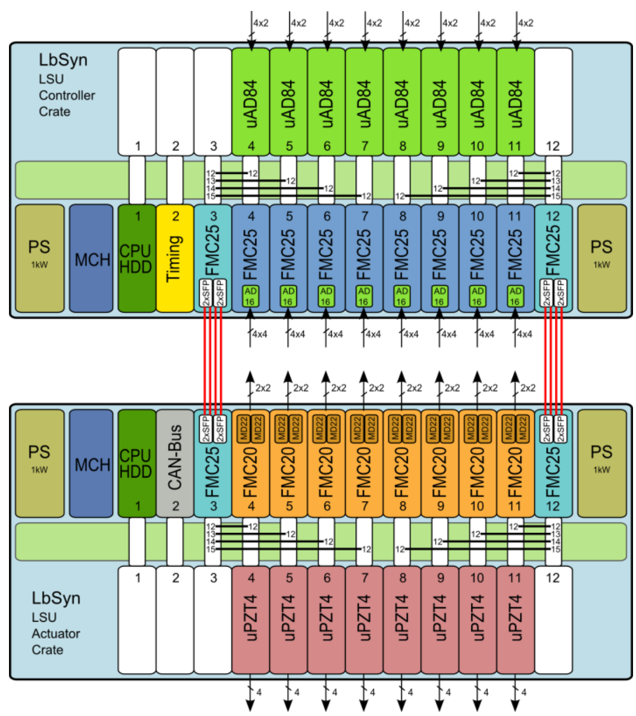

Figure 3: MTCA.4 setup for controlling up to 32 LSUs.

Additionally, the AD16 FMC mounted on the FMC25 carrier collects slow monitor signals like optical power levels and backup phase detector signals. Four slow ADC

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channels are available and used for one LSU, again fitting perfectly to the 16 channel ADC when controlling and monitoring four LSUs simultaneously.

In the baseline design of the European XFEL 23 LSUs are foreseen with the possibility for upgrades to more units. Despite the compact design this requires 12 crate slots which are not available as two slots are used by a timing module and the CPU. For this reason and to avoid distortions on the sensitive OXC detector signals by electromagnetic interference from the actuators (piezo = high voltage, stepper motor = sharp current spikes) the planned design foresees to physically separate the detector unit comprised of AD84 and FMC25+AD16 from the actuator unit comprised of FMC20+2xMD22 and PZT4. Figure 3 shows a schematic view of the complete setup ready for controlling max. 32 LSUs. The communication between the detector and the actuator crate is done via a FMC25 concentrator, collecting the signals from up to four FMC25 controller boards and sending them via a SFP4 module to the corresponding SFP4 on the FMC25 receiver board. From here the signals are distributed again to the FMC20 boards driving the actuators. To minimize the latency the complete communication happens via low latency point-to-point links on the crate backplane and direct fiber connections between the two SFP4s.

BAM Readout Electronics

The amplitude modulated laser pulses from the electro-optical BAM frontend setup are guided in fibers to the photo detectors placed on the DSBAM FMC module. Here, a sampling clock for the fast ADCs used for probing the pulse amplitudes is extracted. The FMC is placed on a FMC25 for processing the ADC data. Fast low-latency links are provided via SFP modules on the DSBAM to ship the arrival time information to the LLRF station for beam-based feedback correction.

Additionally, an FMC20 carrier with two MD22 motor driver cards is used to drive the delay stages in the BAM frontend.

CONCLUSION

The design topology of hardware modules required for signal detection, analog and digital processing and actuating in the optical synchronization systems was introduced. The systems are partly in the prototype state and partly already applied in the facilities. Further tests and the design and improvement of firmware and high level software i.e. control system servers is pursued in a couple of test setups. Within the next year the presented systems will be operational in FLASH, the European XFEL and other facilities.

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