

IMPLEMENTATION OF MTCA.4-BASED CONTROLS FOR THE PULSED OPTICAL SYNCHRONIZATION SYSTEMS AT DESY*

M. Felber[#], L. Butkowski, M. K. Czwalińska, M. Fenner, C. Gerth, M. Heuer, M. Killenberg, T. Lamb, U. Mavrič, J. Mueller, P. Peier, K. Przygoda, S. Ruzin, H. Schlarb, C. Sydlo, M. Titberidze, F. Zummack, DESY, Hamburg, Germany
T. Kozak, P. Prędko, TUL-DMCS, Łódź, Poland
E. Janas, ISE-WUT, Warsaw, Poland

Abstract

With the current state of the synchronization system at FLASH (Free-electron Laser in Hamburg) the arrival time between electron bunches and optical laser pulses can be synchronized to a level of 30 fs rms, e.g. for pump-probe experiments. In the course of the development of an up-scaled system for the European XFEL and the migration of control hardware to the modern MTCA.4 (Micro Telecommunications Computing Architecture) platform, all involved components of the system will be replaced with new developments. The front-end devices are upgraded. FPGAs (Field Programmable Gate Arrays) are performing the data processing and feedback calculations. In order to facilitate the firmware development, a toolset (Rapid-X) was established which allows application engineers to develop, simulate, and generate their code without help from FPGA experts in a simple and efficient way. A software tool kit (MTCA4U) provides drivers and tools for direct register access e.g. via Matlab or Python and a control system adapter, which allows the server applications to be written control system independent. In this paper, an overview on the synchronization setups and their upgrades as well as an introduction to the new hardware is given. The Rapid-X and MTCA4U tool kits are presented followed by a status report on the implementation of the new developments.

INTRODUCTION

Like most other accelerator sub-systems the various setups of which the optical synchronization systems at FLASH and the European XFEL are constructed can be divided in four layers:

- 1) The front-end device, usually an electro-optic and/or an opto-mechanic setup connecting another component of the accelerator with the signals from the synchronization system.
- 2) The electronic hardware which is the platform for readout and processing of signals generated by the front-end device and actuating on it. It also connects to a CPU providing a physical interface to the external world. For the computation usually FPGAs are used.
- 3) The firmware running on an FPGA which can be divided in two layers. The base is the hardware specific

part which provides access to the peripherals like ADCs (Analog to Digital Converters), DACs (Digital to Analog Converters), and memory. The second part is application specific and can incorporate algorithms for the computation of physically meaningful numbers from the front-end signals and - in many cases - a feedback control loop.

4) The software layer which can also be separated in at least two parts. One is that it provides a framework for connecting to the firmware registers via specific drivers, e.g. to set and read parameters. The other is to process this data e.g. for displaying or performing supervision in an application code. The latter can also calculate algorithms and perform feedback control but opposed to the firmware the higher latency only allows for slower (low bandwidth) control loops. Usually the application software is integrated in the accelerator control system, in this case it is called server but it can also be an independent program or script.

Growing demands for the synchronization of FELs in number of setups and their performance triggers continuous upgrades on all four of the mentioned aspects which will be described in the following chapters.

FRONT-END DEVICES

The optical synchronization system has been operated at FLASH since 2009 [1]. It is based on the distribution of 200 fs long laser pulses at 1550 nm with a repetition rate of 216.7 MHz, 1/6 of the main 1.3 GHz RF. This reference signal can be used at remote locations in the accelerator for bunch arrival time monitors (BAMs) [2], RF reference stabilization (REFM-opt) [3] or laser synchronization (L2L) [4]. In a recent publication, a synchronization of 30 fs rms between the FEL and the Pump-Probe was experimentally shown [5]. In order to achieve this level of performance an active beam-based feedback (BBFB) stabilization [6] of the electron bunch arrival time with help of the fs-precise BAM measurements has to be applied as well as optical lock of the pump-probe laser to the reference with the scheme of two-color balanced optical cross-correlation. For attaining even better stability in future and to cope with the growing number of clients, all sub-systems of the optical synchronization are being improved. The European XFEL is being equipped with the improved designs from the start while FLASH is being upgraded and extended step by step.

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#matthias.felber@desy.de

Master Laser Oscillator (MLO)

As the source of each synchronization reference signal for the whole accelerator, the phase stability of the MLO is especially crucial. Up to now it is locked to the RF master oscillator using conventional methods [7] but in future a more sophisticated MZI (Mach Zehnder Interferometer) setup will be used which is very similar to the one in the optical-RF reference modules [3], described later. The performance is expected to be sub-5 fs rms short-term [1 kHz–10 MHz] and sub-5 fs peak-peak long-term.

Link Stabilization Units (LSUs)

The fiber link stabilization from the MLO to the client was and will be based on balanced optical cross-correlation (OXC) between a reference and a reflected pulse but the opto-mechanic design of the LSU has completely changed. The footprint decreased by more than a factor of two while providing more flexibility e.g. for the implementation of polarization-maintaining fiber. This way it is possible to supply additional end-stations at FLASH, e.g. the plasma acceleration experiment FLASHForward [8] or the new beamline FLASH2 [9] which would not have been possible with the old design. An in-house developed balanced detector for the OXC provides superior low-noise performance compared to available commercial products. In a realistic scenario of environmental accelerator conditions the a 3.6 km fiber link was stabilized to 3.3 fs rms over 24 hours [10].

Synchronization of External Lasers (L2L)

Besides an RF-based pre-locking [11] the ultimate performance of sub-5 fs rms between the synchronization reference and an external laser (usually Yb @ 1030 nm or TiSa @ 800 nm) a two-color OXC is used. In the past only individual bread-board assemblies were applied. Now we designed a versatile applicable engineered version which is more compact and robust [4].

Bunch Arrival Time Monitor (BAM)

With the current design it is possible to measure the arrival time with <10 fs rms accuracy [2]. The redesign [12] of the complete BAM front-end is prepared for low-charge operation by providing the possibility to exploit the bandwidth of the new 40 GHz pickups [13].

RF Reference Module (REFM-opt)

The REFM-opt [3] stabilizes the reference signal for the LLRF (Low-Level Radio Frequency) detection used for regulating the accelerating field. By synchronizing to the optical reference residual drifts are avoided and load is taken from the BBFB which increases performance and robustness. The stability was shown to be better than 5 fs.

HARDWARE UPGRADES TO MTCA.4

MTCA is a novel electronic framework for analog and digital signal processing. MTCA.4 [14] was released as an official standard by the PCI Industrial Manufacturers

Group (PICMG [15]) 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 like VME (Versa Module Europa) are enhanced rear I/O connectivity and provisions for improved precision timing. MTCA.4 has many advantages 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.

MTCA.4 at DESY

In agreement between the involved groups, it was decided to use the MTCA.4 standard for the control electronics of the European XFEL and FLASH. This involves the LLRF field control [16], timing system, diagnostics like beam position monitors [17] and camera readouts, and the optical synchronization system [18].

Various boards were developed at DESY with collaboration partners in order to fulfil the different application tasks. In this paper we only provide a short summary of the boards developed and used for the synchronization system, because a detailed description of the modules is given already in [18]. The portfolio includes two AMCs (Advanced Mezzanine Cards) with Virtex FPGAs. One is built as a 10 Channel 125 MSPS digitizer card [19] and is used for laser synchronization while the other one has two FMC (FPGA Mezzanine Card) slots and is used for LSU control and BAM data processing. Another low-cost AMC is used as carrier board for stepper motor drivers, monitoring ADCs, or general purpose IO boards. In most cases the AMC is connected to an RTM (Rear Transition Module) which usually provides the interface to analog signals and e.g. analog processing for laser synchronization [20], ADCs and DACs for the LSU signals or a four channel piezo driver to drive the piezos that act as fast actuators in the control loop for lasers and fiber links.

FIRMWARE AND RAPID-X

The implementation of algorithms and procedures on a FPGA requires a hardware description language such as VHDL. Therefore application engineers are usually dependent on the availability of FPGA experts which implement their schemes. During debugging or when a change is required this can result in an ineffective and time-consuming iterative process between VHDL programming and testing. In order to overcome this challenge a toolset called Rapid-X [21] was developed. The idea is that the hardware specific part of the firmware is separated from the application algorithms. While the first is developed by the FPGA expert, the latter can be easily designed by a user who does not need deep knowledge of the underlying processes. Additionally, this approach makes it easy to reuse the algorithms developed for a certain application in projects that use other boards or to migrate a given project to a different board by simply substituting the hardware-specific VHDL code.

The platform for Rapid-X is the software Matlab/Simulink [22] which is used to describe complex systems and algorithms with block diagrams. The Xilinx System Generator tool already offers the possibility to design, simulate and test standard Simulink models with data processing in the FPGA. However, the model still needs to be connected to other parts of the HDL project, which includes elements such as clock distribution, external memories, signal sources and sinks (also from and to other boards), ADCs, DACs, etc. This becomes increasingly difficult, the more complex the hardware architecture and the entire system is. With the custom Simulink library Rapid-X the designer can directly integrate these peripherals in the design and compile it to a complete VHDL project without any more help from the expert.

Rapid-X was already extensively used e.g. to generate firmware for data acquisition or to develop, implement, and test advanced feedback control algorithms [23].

SOFTWARE TOOL KIT MTCA4U

At DESY a tool kit was developed in order to ease the development, debugging, and distribution of application software. It is the DESY MicroTCA.4 User Tool Kit (MTCA4U) which basically consists of three tools [24].

1) A PCI-express driver (Linux kernel module) which is universal for basic access to all devices developed at DESY. Modularity and expandability allow generating device-specific drivers with a minimum of code, inheriting the functionality of the base driver.

2) A C++ API (Application Programming Interface) which allows convenient access to all device registers by name, using mapping information which is automatically generated when building the firmware. A graphical user interface (Qt Hardware Monitor) allows direct read and write access to the device, including plotting functionality for recorded raw data. The API is also used to provide Matlab- and Python-bindings and command line tools which all use the same syntax.

3) The third tool is an adapter for easy integration of independent application code into a control system, e.g. DOOCS [25] at FLASH and the European XFEL. When the application is integrated to the control system with the adapter it becomes a server for a device or task. The idea is that the control system adapter makes it easy to reuse the developed code at facilities using other control systems e.g. EPICS or TANGO.

STATUS AND CONCLUSION

The implementation of MTCA.4-based controls and the redesign of all front-end devices for the synchronization systems at FASH and the European XFEL promise to improve the performance, increase flexibility and maintainability and reduce the space requirements. However, for a small team like ours this effort on all four presented aspects of the system is a big challenge. As a matter of fact, the migration is not as advanced as anticipated in the project plans.

The design for all of the front-end devices is finished, some are still in the prototyping phase and some are already in operation in the facilities.

Most of the MTCA hardware components which were developed in our group at DESY are available from industry partners due to licensing agreements thus making them available for the accelerator community and beyond. Only a few FMC modules still need to be revised.

The Rapid-X framework supports all AMC modules used by us and is continuously extended. After a rather long debugging phase it has proven to be an extremely valuable tool for our feedback algorithm development. Yet, the firmware for the three main applications laser synchronization, fiber link stabilization, and bunch arrival time monitors is not completed.

The MicroTCA.4 User Tool Kit is meanwhile in a mature state and its tools are widely used. However, none of the needed servers, meaning control system independent software connected to a DOOCS adapter have been programmed yet. For the development phase usually Matlab scripts making use of the MTCA4U tools to access data from the FPGAs are applied. For the laser synchronization which is the first setup needed in operation at several locations a Python script is being prepared to temporarily substitute for the missing server.

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