ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-MOAPL01

THE CONTROL SYSTEM FOR THE LINEAR ACCELERATOR AT THE EUROPEAN XFEL - STATUS AND FIRST EXPERIENCES

T. Wilksen†, A. Aghababyan, R. Bacher, P. Bartkiewicz, C. Behrens, T. Delfs, P. Duval, L. Fröhlich, W. Gerhardt, C. Gindler, O. Hensler, J. M. Jäger, R. Kammering, S. Karstensen, H. Kay, V. Kocharyan, A. Labudda, T. Limberg, S. Meykopff, A. Petrosyan, G. Petrosyan, L. Petrosyan, V. Petrosyan, P. Pototzki, K. Rehlich, G. Schleßelmann, E. Sombrowski, M. Staack, J. Szczesny, M. Walla, J. Wilgen, H.-G. Wu, DESY, Hamburg, Germany
S. Abeghyan, S. Karabekyan, European XFEL GmbH, Hamburg, Germany

Abstract

The European XFEL is a 3.4 km long X-ray Free-Electron Laser facility with a superconducting, linear accelerator and initially three undulator beam lines. First user run with two experiments has started in September this year at the first photon beamline while the final installation and commissioning of the other, two photon beam lines is well underway. This paper will focus on control system parts of the linear accelerator and highlight briefly its design and implementation. Namely the hardware framework based on the MTCA.4 standard, testing software concepts and components at real and virtual accelerator facilities. A well-established method for integrating high-level controls into the middle layer by means of a shot-synchronized data acquisition allows for rapid deployment and commissioning of the accelerator controls. Status of the final installations, of the commissioning phase and some first experiences from a technical and an operational point-of-view will be presented.

INTRODUCTION

The European XFEL (EuXFEL) is a 3.4 km long X-ray Free-Electron Laser starting in Hamburg, Germany, and ending south of Schenefeld, a city in the neighbourhood of Hamburg. It comprises of an injector, a linear accelerator section, a beam distribution system, undulators, photon beam lines and experimental stations. The geometry of the facility is basically a straight line with a northern and a southern branch in the last third for the undulator sections and photon beam lines. The injector produces an electron beam by extracting electron bunches with a laser beam from a photo cathode, which is focused and accelerated by a normal-conducting RF gun to beam energies of 5 MeV. The accelerator will provide up to 2700 electron bunches at repetition rates varying from 1 Hz to 10 Hz with 10 Hz being the default rate. The RF pulse length (flat top) is 600 µs long and the bunch charge can be chosen within a range of 0.02 – 1 nC.

A first cryogenic 1.3 GHz RF module accelerates the beam to 150 MeV followed by a 3.9 GHz module linearizing the energy profile. The beam is fed at a beam energy of 130 MeV into a 1.6 km long linear accelerator section with 96 cryogenic modules installed. These modules are utilizing superconducting RF-technology and accelerate the electron bunches up to 14 GeV and with four more modules installed eventually up to 17.5 GeV. Additionally, the linear accelerator section has two bunch compressor sections installed at locations corresponding to energies of 0.7 GeV and 2.4 GeV for maximizing peak currents. A collimation section followed by a flexible kicker system at the end of the linear accelerator section can distribute configurable bunch trains into two electron beam lines with undulator systems. On the northern branch two undulator sections with a tunable, planar undulator system and second tunable, helical undulator system will provide two different hard X-ray photon beams produced by the self-amplified spontaneous emission process (SASE). On the southern branch only one tunable, planar undulator system has been installed for now. Each of the three undulator sections will provide a photon beam for two experiments, serving six stations in total. The undulator sections are supposed to deliver photon pulses within a wavelength range of 0.05 – 0.4 nm, resp. 0.4 – 4.7 nm, a pulse length between 10 – 100 fs and a peak brilliance of 10^{32} – 10^{34} photons/s/mm^2/mrad^2/0.1% bandwidth. The schematic overview of the European XFEL accelerator is shown in Fig. 1.

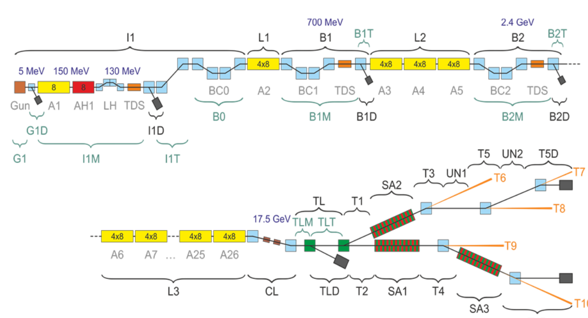

Figure 1: Schematic overview of the overall European XFEL accelerator with injector (I1), linear accelerator tunnel (L1 – L3), the collimation and distribution section (CL and TL) and the various SASE beam lines with its undulators (T1 – T10, SA1 – SA3).

The overall control system used at the EuXFEL facility is a common effort by of various groups at DESY

† Tim.Wilksen@desy.de

ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-MOAPL01

and the European XFEL GmbH. While the cryogenic and utility controls, the photon beam line and experiment controls are based on different approaches the interoperability of all the systems with the accelerator controls has been established and discussed here [1].

This paper is focusing on the electron beam controls for the linear accelerator, its design and implementation. The status of the final installation work, the commissioning of the controls and experiences from commissioning and first operations delivering photon beam to user experiments will be presented in the following sections.

ACCELERATOR CONTROL SYSTEM

The design of the accelerator control system for the European XFEL was highly driven by the existence of the smaller but technically similar accelerator facility FLASH, the Free-Electron Laser in Hamburg. FLASH is a 260 m long Free-Electron Laser in the ultraviolet vacuum (VUV) regime located on the DESY campus in Hamburg, Germany. It is based on the same superconducting RF-technology used for the cryogenic modules at the European XFEL and covers similar concepts for the machine layout. Specifically, the control system architecture and software framework had been proven to be a very suitable solution for a linear accelerator driving a free-electron laser. New technologies like the MicroTCA.4 standard [2] and the MicroTCA-based timing system [3] had been introduced to the FLASH accelerator already and tested successfully.

Concepts and Layout

For the European XFEL project the following key components had been determined to be essential to the accelerator control system layout:

- Using a standard hardware platform for fast front-end device controls. Here the new embedded system technology based on the MicroTCA.4 standard was chosen. Key requirements had to be a simple and remote management of a large number of devices as well as hot-swap capabilities of electronic components.

- A well supported open-source based operating system as standard for front-end computing nodes i.e. MicroTCA systems, embedded systems as well as for server and computing nodes for the backbone of the control system infrastructure.

- A software framework suitable for a linear accelerator driving a free-electron laser. For this both DOOCS [4] and TINE [5] have been chosen since both frameworks had been deployed successfully already at FLASH. DOOCS has TINE integrated by default so that interoperability works seamlessly for all standard solutions. Furthermore, both frameworks are able to connect to EPICS [6] easily, which made interfacing the cryogenic and utility controls system for the European XFEL accelerator possible. While DOOCS is used as the basic software framework for the accelerator controls, all vacuum and magnet controls are implemented with TINE. For high-level application libraries TINE is used as internal communication protocol.

- Synchronization of all accelerator beam diagnostics data and RF- resp. LLRF information for diagnostic displays and higher physics applications. A shot-synchronized bunch-resolved data acquisition had been successfully deployed in the past at FLASH [7]. Because of the experience with this system at FLASH and the scalability of this approach, the decision to use it for the European XFEL accelerator control system had been made early on in the conceptual design phase. The tight integration of the acquisition system directly into the middle layer allows for an efficient online access to all shot-related data, process it and feed it back into the middle layer for other applications like software-based feedbacks or online measurement programs. This layout is shown in Fig. 2.

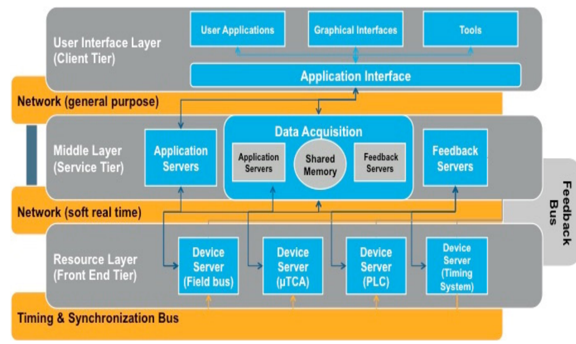

Figure 2: Accelerator control system layout with three layers and integrated data acquisition system on the middle layer.

Key Components

MTCA.4 Systems About 220 MicroTCA systems adhering to the MTCA.4 standard are installed at the European XFEL accelerator und used to perform various read-out tasks for standard beam diagnostics like beam position, charge readings or beam losses, to run low-level RF control algorithms, to process camera images for screens, perform wire-scanner measurements and many other special diagnostics tasks. All MicroTCA systems are equipped with the same basic MTCA.4 modules as there are a power-supply, a Management-Controller Hub (MCH), CPU as an Advanced Mezzanine Card (AMC), a Timing System AMC, optionally a Timing System Rear Transition Module (RTM) if required and Machine Protection System modules (AMC/RTM pair). This forms the base for a standard MicroTCA system as used for the linear accelerator control system. Further MTCA.4 modules equipped with more than 2500 FPGA devices for read-out, measurement and control tasks are installed depending on the required subsystem support at a given location in the accelerator. All of these modules can be managed remotely via Intelligent Platform Management Interface (IPMI) interfaces and the MCH. Linux drivers with hot-swap support allow for PCIe access of the various AMC and RTM modules from applications running on the CPU AMC. DOOCS servers provide the data via those drivers to the higher control system layers, triggered by an interrupt provided by the timing system via

ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-MOAPL01

ZeroMQ [8]. The data is attributed with a unique event identification number, which is essentially the shot or RF pulse number of the linear accelerator.

Timing System The timing system has been developed with a strong focus on pulsed, linear accelerators. With the repetition rate of the RF pulse at 10 Hz the timing system distributes information to all front-end modules via a dedicated optical fibre system. It is drift-compensated to minimize temperature-related variations in traveling times and allows for a precision of 10 ps RMS jitter. Next to clock signals, event trigger, the unique shot number, the timing system provides bunch-related information as a so-called "bunch pattern". It defines the number of bunches and the bunch spacing of the bunch train at a given section. It is sent out before the first bunch arrives there. The timing system synchronizes the 50 Hz mains frequency with the base frequency of 1.3 GHz as delivered by the RF system master oscillator. Clock signals with several synchronized, frequencies are provided for the various subsystems.

Machine Protection System The Machine Protection System (MPS) is tightly linked with the timing system. While the operator asks for desired beam parameters the MPS evaluates continuously all status signals provided by MPS relevant components and sends the resulting beam limits to the timing system. The timing system combines these limits with the requested beam parameters and creates section-wise bunch patterns to be distributed. A direct connection to the laser controller and dump kicker allows an immediate response.

The MPS has been implemented using MTCA.4 modules developed in-house at DESY. About 150 modules have been installed along the accelerator beam line and are connected via a dedicated fibre optic network.

Data Acquisition System The data acquisition system (DAQ) is designed to collect all front-end data via UDP-based multicast-enabled push protocol. The front-ends receive an interrupt from the timing system and send the data together with the timing system information i.e. the shot number to the data acquisition instance. The data is collected in event structures synchronized by the shot number and stored in a large shared memory area. From there it is available for immediate online processing by middle layer servers through a dedicated interface. Results of this processing are not only available for standard DOOCS client processes for display but can be written back to shared memory and therefore included into the corresponding event structure. Once the event structure is considered to be complete, it is written to disk for later offline analysis and can be saved on tape by request.

For test purposes a test data acquisition instance had been available for quite some time. When the software development started for the European XFEL accelerator control system software, not only the need for testing the basics of the acquisition framework arose but also testing high-level controls applications using the DAQ framework. Therefore an additional virtual DAQ instance was setup using simulated data and real data from test equipment. This "Virtual XFEL" instance functions as a test-bed for the general control system framework and to evaluate new concepts and paradigms. Furthermore, it allowed testing tools - like higher-level physics applications and other software required for operations - prior to the first commissioning stages [8].

Graphical User Interface For accelerator operations and expert usage several options for a graphical user interface to the accelerator control system exists. While MATLAB- and Python-based applications are used primarily for dedicated purposes like machine studies or experiments, the standard interface was chosen to be the Java DOOCS Data Display, in short JDDD [9]. This tool is an editor for creating graphical user interfaces, also called panels, to the control system without having to use a programming language. At the same time it can function as a runtime to start and run panels. The control systems group usually provides generic panels while the experts themselves create subsystem panels. Operators contribute to the panel design for operation-specific purposes. The runtime can be either launched via Java Webstart as a Java application or started as an HTML5-based interface remotely through a secured web server access. Status panels as used for operations in the central control room for the accelerator at DESY are made with JDDD. An example is shown in Fig. 3.

Figure 3: Status screen for the injector section of the European XFEL linear accelerator created with JDDD.

The panels are stored as XML files on a central repository for general availability but can be saved for individual use also locally.

PROJECT STATUS

Staging the Commissioning

One of the challenges while the installation stage of the European XFEL accelerator still went on was to put a completed section into operation as soon as possible to allow for an early commissioning. This plan was actually followed upon for the RF-gun, the injector beam line with its first cryogenic RF-module, the superconducting linear accelerator section and the first photon beam line SASE1. For the linear accelerator control system this required in consequence to have the basic control system components and infrastructure in place and working long before the actual installation and commissioning of all subsystems was done. Furthermore it had to be available and operable

ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-MOAPL01

for commissioning while sections downstream still had to be integrated into the overall structure.

Status of the Installation and Commissioning

The RF-gun had been taken into operation for first tests and conditioning end of December 2013. At that time the initial control system infrastructure as well as the timing system were already operational. In the following two years the installation of the injector took place including the first accelerating 1.3 GHz module and the third-harmonic 3.9 GHz linearizer module.

At the end of 2015 first beam was transported through the complete injector beamline up to the injector dump. All basic components of the control system existed already in one or the other kind in the injector area. Therefore operating the injector allowed for testing and operating all relevant components to prepare for the later commissioning of the linear accelerator section. This was done throughout 2016 while the installation in the linear accelerator tunnel was proceeding. In 2016 the accelerator control system infrastructure was completed by adding more DAQ instances to the system, setting up and configuring tools for remote managing of the over 300 systems and implementing first high-level controls applications. At the same time the installation in the northern tunnels was progressing well covering both undulator sections SASE1 and SASE3. The commissioning of the injector proved to be able to deliver 2700 electron bunches at a repetition rate of 10 Hz using the 4 kW high-power beam absorber at the end of the injector. In total, a beam charge of about 3 C was produced during the injector commissioning.

In April 2017 first beam was successfully transported at 6 GeV through the full linear accelerator and collimation beam line. In the meantime the photon diagnostics for SASE1 was integrated into the control system and the installation for the northern tunnels completed.

Only two months later in June 2017 the first production of photon light was seen at the end of the first photon beam line and shortly after photon beam production be means of SASE. Commissioning of the undulators and photon diagnostics took place late this summer together with experts from the XFEL GmbH responsible for the photon diagnostics systems.

Figure 4: Accelerator control room on DESY campus showing the European XFEL accelerator area with its consoles and status displays.

The first undulator beam line SASE1 is now in production mode since September this year and provides up to 30 bunches with photon pulse energies of 9.3 keV and typically 500 µJ to 700 µJ for two individual experiments. That is, the first undulator beam line is running successfully now for the first users only after less than half a year the linear accelerator sections had been taken into operation the first time. Operations of the European XFEL are now on a regular schedule and headed from the accelerator control room on the DESY site as shown in Fig. 4.

The current controls system status for the linear accelerator (without photon diagnostics as it is the responsibility of the European XFEL GmbH) comprises more than 300 UNIX-based systems, embedded ones, MicroTCA and server nodes. Almost 9 million control system parameters[1] are visible within the European XFEL accelerator control system namespace and about 600 k DOOCS archives – histories of parameters – are online to date. More than 800 different device types are registered and about 38 k locations are known to the system.

The data acquisition with its three instances i.e. without the virtual XFEL instance operates at a sustained input rate of about 1.5 GB/s collecting more than 40 k of individual parameters, mainly form standard diagnostics, LLRF controllers and coupler interlock systems. The compressed data files are archived at a rate of up to 30 TB per day. About one week worth of data is kept online on disk retrievable through various tools after which it is either being removed or taped on request. Subsets of the archived data can be extracted by users and stored locally. The graphical user interface JDDD keeps about 11 k of different panels i.e. XML files in a central repository and has about 200 different users. User interfaces created with JDDD can be quite elaborate. The overview and controls panel e.g. for all magnet power supplies of the European XFEL linear accelerator counts more than 26 k widget components and makes more than 4 k calls per second to device server. This is shown in Fig. 5.

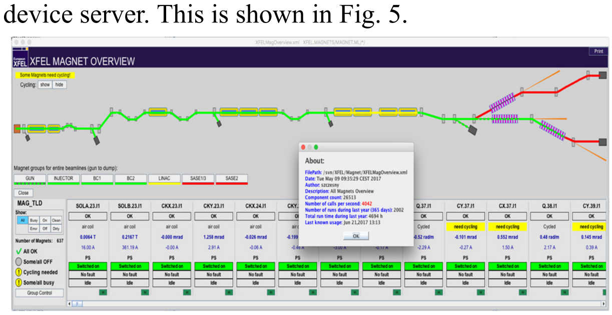

Figure 5: Example of a complex JDDD panel as used for magnet controls at the European XFEL linear accelerator.

Final Installation and Commissioning

The installation of the southern branches serving the second undulator beam line SASE2 will be finished by end of fall. Commissioning of this branch will not happen

[1] This number includes not only parameters used for controlling a device parameter but also "meta" properties required for e.g. user interfaces to the proper display the error state or engineering units.

ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-MOAPL01

until next year, while the already completed third undulator beam line, SASE3, will be commissioned later this fall. This beamline is located in the same electron beam branch as SASE1. Therefore the commissioning of control system components will be focusing on the additional undulator section, photon diagnostics and the parallel bunch train operations.

EXPERIENCES

Staging the installation and specifically the commissioning process was to some extent a challenge for getting the accelerator components deployed because it required to keep the backbone of the infrastructure always in a reliable operational state. Modifications could only be done during maintenance windows for the sections already in production mode. On the other hand this allowed for an early commissioning and testing at real conditions of almost all basic accelerator system components. Problems, missing features, design issues could be caught early on and improved or modified. This enabled a quite rapid deployment of accelerator diagnostics, tools and applications for the later stages and sections of the accelerator.

Decisions to use already well-known and proven software frameworks for accelerators like TINE and DOOCS enabled us to focus on the development of applications rather than debugging fundamental conceptual issues as it would have been likely the case with a framework started from scratch.

The FLASH facility not only acted as a prototype for the European XFEL but also served as an excellent testbed for hardware and the software framework. The similarity of this facility and the choice to use the same control system architecture with more than 10 years of experience proved to be of great benefit.

The Virtual XFEL framework has been shown to be very valuable, too. Accompanied by the guidance and expertise of a specifically for this purpose formed high-level controls team with machine physicists and control system experts, this idea has paid off well. Because it is available all the time, contrary to FLASH facility, it is used to test new concepts, enhancements or just modified and improved applications before they will be put into the field. That can potentially save significant machine studies time.

Using a hardware platform based on the MicroTCA.4 standard throughout all subsystems has been proven to be an excellent decision, too. Sharing common hardware modules among the various subsystems for diagnostics, RF-controls and regulation, vacuum and magnet controls allowed for standardized solutions in hardware as well as for software components. The hot-swap and remote management capabilities already came in very helpful when trying to keep the downtime of the machine as low as possible during all the commissioning runs because an access to the hardware and hence accelerator tunnel could be avoided.

For all commissioning stages, the control system for the European XFEL linear accelerator has been operable from day one without any trouble. Though it might not be feature-complete with respect to upcoming challenges prompted for by photon beam users and their experiments, all of the commissioning goals were fulfilled quite well by the control system so far.

OUTLOOK

It is expected that after mid next year the installation of the final four cryogenic modules the European XFEL accelerator will be finished. At that time the accelerator control system installation and commissioning for the last undulator beam line will be completed and supposed to be in full operation.

REFERENCES

[1] A. Aghababyan *et al.*, “The Large Scale European XFEL Control System: Overview and Status of Commissioning”, in *Proc. 15th Int. Conf. on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'15)*, Melbourne, Australia, Oct. 2015, paper MOA3O02.

[2] H. Schlarb *et al.*, “The Case of MTCA.4: Managing the Introduction of a New Crate Standard at Large Scale Facilities and Beyond“, in *Proc. 14th Int. Conf. on Accelerator and Large Experimental Physics Control System (ICALEPCS'13)*, San Francisco, USA, Oct. 2013, paper MOPPC081.

[3] XFEL Timing System, `http://ttfinfo2.desy.de/doocs/Timing/CDRv2.2short.pdf/`.

[4] Distributed Object-Oriented Control System, DOOCS, `http://doocs.desy.de/`.

[5] Three-fold Integrated Network Environment, TINE, `http://tine.desy.de/`.

[6] EPICS, `http://www.aps.anl.gov/epics/`.

[7] A. Aghababyan *et al.*, “Multi-Processor Based Fast Data Acquisition for a Free Electron Laser and Experiments”, in *IEEE Transactions on Nuclear Science*, vol. 55, No. 1, pp. 256-260, February 2008.

[8] W. Decking *et al.*, “The Virtual European XFEL Accelerator”, in *Proc. 15th Int. Conf. on Accelerator and Large Experimental Physics Control System (ICALEPCS'15)*, Melbourne, Australia, Oct. 2015, paper TUD3O04.

[9] A. Petrosyan *et al.*, “JDDD: A Tool for Operators and Experts to Design Control System Panels”, in *Proc. 14th Int. Conf. on Accelerator and Large Experimental Physics Control System (ICALEPCS'13)*, San Francisco, USA, Oct. 2013, paper TUMIB09.