ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-TUPHA125

THE BUNCH ARRIVAL TIME MONITOR AT FLASH AND EUROPEAN XFEL

M. Viti†, M.K. Czwalinna, H. Dinter, Ch. Gerth, K. Przygoda,
R. Rybaniec, H. Schlarb, DESY, Hamburg, Germany

Abstract

In modern free electron laser facilities like FLASH I/II and European XFEL at DESY a high resolution intra bunch train arrival time measurement is mandatory, providing a crucial information for the beam based feedback system. For this purpose a Bunch Arrival Time Monitor (BAM) was developed, based on an electro-optical scheme where an ultra-short pulsed laser is employed. A BAM is composed of several subsystems, including stepper motors, power management, dedicated readout board, management board for voltage settings, temperature sensors and temperature controller and optical amplifier. Part of the electronics is developed using the MicroTCA standard. We will present in this poster the basic requirements for the BAM, software design and implementation developed to manage the subsystems and their interactions.

INTRODUCTION

At the FLASH and European XFEL a beam based feedback for the electron bunch is mandatory to ensure the expected photon beam quality delivered at the experimental stations. Crucial information for the feedback system is provided by the Bunch Arrival Time Monitors (BAMs) which measure along the acceleration section of the machine the timing of the electron bunch with respect to a pulsed laser provided by a central Master Laser Oscillator (MLO), which is synchronized with the RF signal [1].

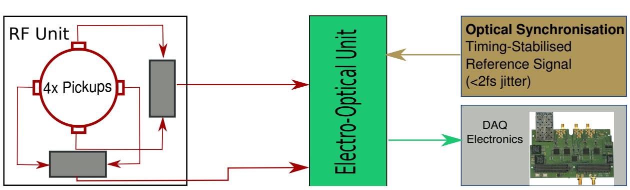

Figure 1: Basic Layout of the three BAM main components. The reference signal is provided by an external source, the laser-based synchronization system.

BASIC LAYOUT OF THE BAM

In this section we describe shortly the main components of the BAM system and their working principles. As Fig. 1 shows, the BAM system is composed of three parts, the RF unit, the electro-optical unit and the data acquisition system. The electro-optical unit is the core of the system. It combines the signals from the RF unit and a reference signal provided by an external source to perform the arrival time measurement. The result of this combination is then sent to the Data Acquisition System (DAQ).

- **The RF Unit** The electromagnetic field induced by the electron bunch is captured by four broadband pickups. Two opposite pickups are combined to reduce the dependence of the signal on the bunch transversal position [2].
- **The Electro-Optical Unit** Timing-stabilized laser pulses are provided as a reference signal to this unit. This signal serves also as clock for the DAQ electronics. The peak height of the pulses is modulated upon cross-correlation with an RF-signal, thus providing a temporal response from which the arrival time can be detected [3].
- **DAQ and Control** Dedicated electronics, firmware and software were developed to configure and control the single subsystems and for data acquisition [4]. Part of the electronics was developed using Micro Telecommunications Computing Architecture (MTCA) standard [5].

THE RF UNIT

Dependency on the transversal beam position is reduced by combining the signal of two opposite pickups. We will refer as RF signal the result of this combination. The RF signal amplitude is still function of the bunch charge as shown in Fig. 2. Higher bunch charge generates a higher amplitude, so bunch charges of several hundreds of picocoulomb can drive the bias voltage in the non monotonic region of the Electro-Optical Unit. To avoid that, one RF signal is filtered by a low-pass filter with a cut-off frequency of ca. 20 GHz and the maximal amplitude is also limited, thus allowing the measurement for higher bunch charges. This RF signal is called high charge channel, while the other is the low charge channel. The low charge channel has a cut-off frequency of ca. 40 GHz and has a theoretical resolution of 5-10 fs, while the high charge channel has a resolution of only 10-20 fs.

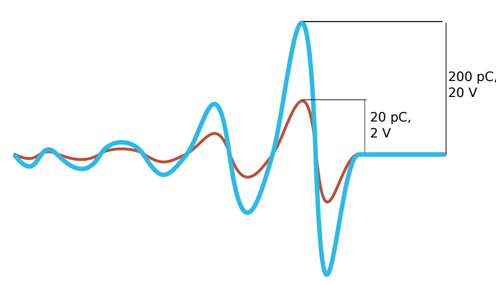

Figure 2: Dependency of the signal amplitude on the bunch charge. The amplitude increases with the bunch charge.

† michele.viti@desy.de

ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-TUPHA125

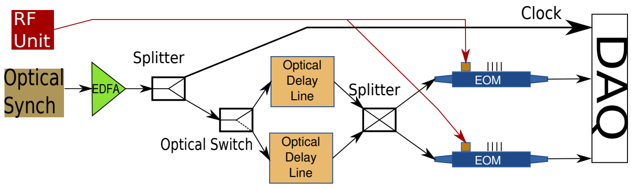

Figure 3: Basic Layout of the Electro-Optical Unit.

THE ELECTRO-OPTICAL UNIT

Figure 3 shows a schematic of the electro-optical unit and its parts. Each laser pulse provided by the MLO is split after being amplified and part of it (10%) sent to DAQ as clock signal. An optical switch sends the other part to an optical delay stage and after being split again, the laser pulses are combined in the electro-optical modulator with the two RF signals coming from the pickups. There are two optical delay stages (planned to become three in the future), one for each sub-macropulse (related to different SASE beamlines), in order to be able to set different delays to each of them. After the laser pulses being modulated, these are sent to the DAQ electronics.

Electro-Optical Modulator

The distance between 2 peaks of a RF signal is in the order of 10 ps while the ringing can take up to several 10 ns. The laser pulses have a FWHM of ~ 1 ps and a period of 4.6 ns. As already mentioned both signals are fed to an Electro-Optical Modulator (EOM). If a laser pulse encounters no RF signal, it experiences no modulation so its pulse height remains unaltered. If a RF signal is encountered, but laser pulse and RF signal are synchronized, still no modulation is observed. On the other hand if a RF signal is encountered but the two signals are not synchronized in time the pulse height is altered, i.e. modulated (Fig. 4) [6]. The modulation occurs via a Mach-Zehnder-type interferometer where the transmission factor for the laser light depends on the applied voltage through a non monotonic function (see Fig. 5). The applied voltage is the sum of a bias voltage and the external RF voltage. The bias voltage is usually chosen in such a way that the transmission is 50% when the RF voltage is equal to zero. The arrival time is defined as the distance in time to the position with both signals synchronized. The electro-optical unit is equipped with two EOMs, one for the high charge and the other for the low charge channel.

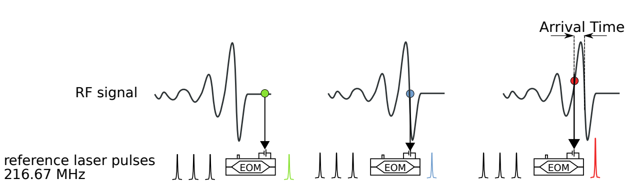

Figure 4: Working principle of the EOM. If no RF signal is encountered by the laser pulse or the laser pulse is perfectly synchronized with it, no change in the laser pulse height is observed (left and middle figure). if the two signal are not synchronized the pulse height is modulated (right figure).

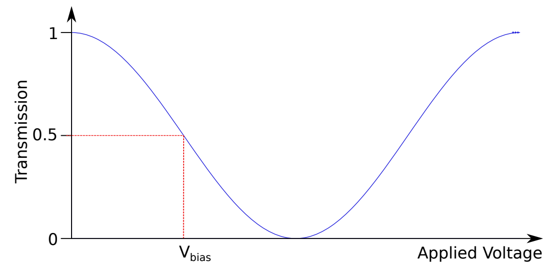

Figure 5: Transmission function for laser pulses in function of the applied voltage for the electro-optical modulator. The applied voltage is the sum of the RF voltage and a bias voltage chosen in such a way that the transmission is 50% for RF voltage equal to zero.

Optical Delay Line

Ideally the working point of the BAM is where the laser pulses remain unmodulated, i.e. perfectly synchronized with the electron bunches. In order to calculate the arrival time properly and with high resolution, any deviation from the ideal working point has to stay in the region where the relation modulation - arrival time is monotone. Slow drift in the accelerator machine can move the working point outside the dynamic range for which the measurement gives meaningful results. For this reason a proper delay (negative or positive) must be applied in order to keep the working point in this region. Figure 6 shows an optical delay stage developed for this purpose. The timing is adjusted by a retro-reflector mounted on the a commercially available stepper motor. The laser pulse, entering the stage in the bottom right side, is coupled out from the fiber through a collimator and by means of two mirrors sent to the reflector, then being sent back to a second collimator which couples the laser pulse in the output fiber. A stepper motor from the company OWIS allows to apply a maximum delay of ±130 ps, where the size of the monotone region is around 7 ps. The motors are equipped with hall reference switch, which can be used as end switches to prevent mechanical damage. The dynamic range of the two channels, i.e. where the relation modulation - arrival time is monotonic, is 4-6 ps for the low charge channel and 10-12 ps for the high charge channel.

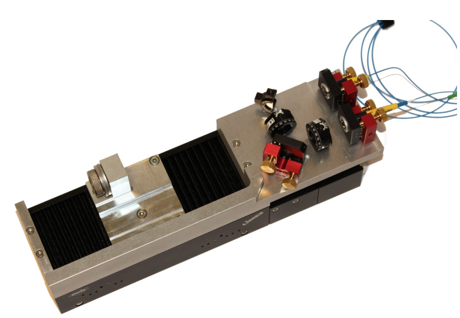

Figure 6: The delay stage is mounted on the linear stepper motor. For calibration purpose an encoder can be attached to the stepper motor as well (not shown in the photo).

ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-TUPHA125

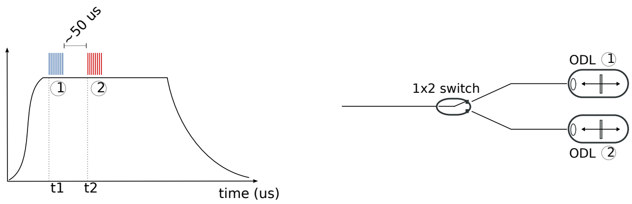

Figure 7: The bunch train at FLASH and European XFEL can be divided in two or more groups of bunches, each with different characteristics. This implies the necessity to set the delay time individually for each group of bunches and thus to have two or more ODLs.

Optical Switch

Modern X-Ray sources such as FLASH and European XFEL have the capability to drive multiple SASE beam lines, providing individually to the end user photon beams with different properties like wavelength, pulse length and intensity [7]. This involves to have bunches with different energies and charge inside the same bunch train. The bunch train for both facilities is divided in two parts which can have different properties (see Fig. 7). Since different energies and different charges imply different jitter and arrival time, we must have the possibility to set different delays, so multiple ODLs have to be employed. In order to select the proper ODL an optical switch is used. The shape of the laser pulses are preserved and a maximum amplitude loss of $\approx 15\%$ was measured. Moreover, the switching time was estimated to be in order of ≈ 100 ns, much smaller than 50 µs, i.e. the distances between the two bunch groups in a bunch train.

Electronics

In this section we describe the main electronic boards used to control and monitor all the subsystems in the electro-optical unit. The dedicated electronics for the DAQ will be described in a separate section. All boards described in this and next section were developed in DESY [5].

Temperature Monitoring and Control Board (TMCB) This board provides 14 ADC, 10 DAC channels and 20 configurable General Purpose Inputs and Outputs (GPIOs). The board provides thus the possibility to set the bias voltage for the EOMs, to read several temperature and humidity sensors as well as the interface to 2 temperature controllers. The board works in a stand alone mode and communication occurs via Ethernet or optical fiber.

Laser Diode Driver (LDD) This board is composed of a carrier and up to 8 mezzanines (only one in case of BAM), each providing a current source for a laser diode used for laser pulse amplification. Each mezzanine provides an Ethernet and a CAN bus interface and it can operate stand-alone. Features include thermal stabilization and two operation modes, namely with constant current or with constant output power.

Fuse Relay Board (FRED) The board allows control and monitor of up to 8 DC voltage channels, with individual fuses and current limitations for each channel. It has an Ethernet interface and it is suitable for stand-alone operation.

FMC20 with DFMC-MD22 The FMC20 carrier board can be equipped with two MD22 mezzanine boards. Each mezzanine can control up to two-phase bipolar stepper motors, operating in a MTCA crate. The mezzanine is equipped with a controller and a driver chip from the company Trinamic. The driver chip provides the current sources for the motor with the possibility to have up to 256 microsteps pro full steps (it is foreseen for BAM to have 64 microsteps for full steps). Particular feature like load detection and load dependent current are also implemented. The other chip is a controller chip which provides step signals to the driver chip determining thus position and velocity. The carrier board has a PCIe connection to allow high level software to access the firmware registers and communicates with controller and driver chips via SPI interface.

DAQ AND CONTROL

The DAQ receives clock and modulated laser pulses through three photo-diodes. Onboard attenuator for the laser pulses are available which can be set via FPGA registers. The trigger is provided by the X2Timer board via the back-plane of the MTCA crate. Each channel has two 16 bit ADCs, one sampling the peak of the laser pulse and the other the base. The pulse height is define as the difference peak - base. A clock distribution chip performs clock synchronization as well as application of a delay to the clock to allow the ADCs to sample any desired point along the laser pulse. After sampling the data of each ADC are filtered in order to acquire only the modulated laser pulse and specific unmodulated ones, used later for normalization. Figure 8 shows the schematics of the data acquisition system for one ADC of one channel. The ADC is sampling with a rate of the 216 MHz, the rate of the laser pulses, and 1024 of the unfiltered samples are stored for each macropulse. Usually the samples are stored starting from trigger, but an arbitrary delay can be applied. We refer to these data as raw data. A filter selects the pulses according to the settings of the macropulse like the bunch repetition rate and bunch number (filtered data).

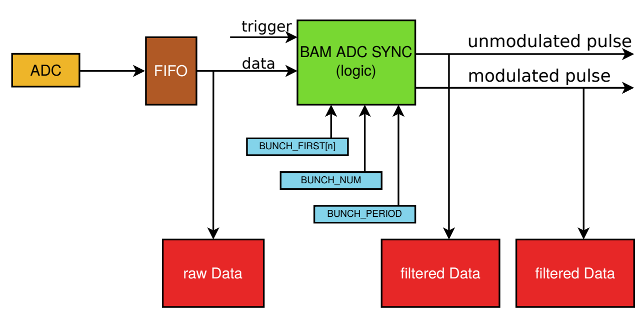

Figure 8: Schematic of the data acquisition scheme in the firmware for one ADC. Data are stored before and after having been filtered.

ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-TUPHA125

The firmware in the FPGA performs some mathematical operations on the filtered data, among them a division. The filtered and the raw data are stored in an internal RAM and then transferred through DMA to the DAQ Computer. Mathematical operations in the firmware are necessary because a raw (non calibrated) value of the arrival time must be calculated and sent via optical link to the Low Level RF System for the fast beam based feedback [8]. This operation is time critical and thus it must be performed at the firmware level.

Electronics

The DAMC-FMC25 carrier board provides the FPGA for basic data processing, a second FPGA for board management as well as some additional diagnostics. The dual mezzanine DFMC-DSBAM contains three photo diodes to couple the electronics with the laser pulses, attenuators for the low and high charge channel, the clock distribution chip and four 16 bit ADCs [5, 8].

SOFTWARE

The software for slow-control and data acquisition is written in C++11 and it consists of specific libraries and servers for Control Systems, e.g. DOOCS in the case of FLASH I/II and XFEL [9]. The ChimeraTK package [10] was used to access the PCIe registers and to write DOOCS clients. The current software for the readout is undergoing to a major restructuring, which changes completely the implementation but leaves the API and the functionalities mostly intact. In the paper we concentrate and describe the new implementation. From a logical point view, one can identify five independent units which corresponds basically to the five boards described in the previous sections. Dedicated DOOCS servers were implemented for each of them: the laser diode driver, the BAM box management, the power management, the readout and the stepper motor server. All of these units operate independently from each other, without interaction, except for the motor and the readout server, since the latest has a client to the motor server (Fig. 9).

Motor Server

The newest hardware is based on the FMC20 with a MD22 board. Older versions of the BAM system use a Beckhoff-based front-end for stepper motors. An additional DOOCS server provides access to the front-end. This older version will still be in use for at least one year, so the new software must be transparent and provide one interface for the two systems, namely the one based on the FMC carrier board with the MD22 mezzanine and the one using a DOOCS server for the Beckhoff-based front-end. Figure 10 shows the scheme with an UML-like diagram.

Readout

The software for the readout and slow control part is developed to be as independent as possible from any Control System. It is planned to integrate this interface in the application core for the control system adapter of the ChimeraTK

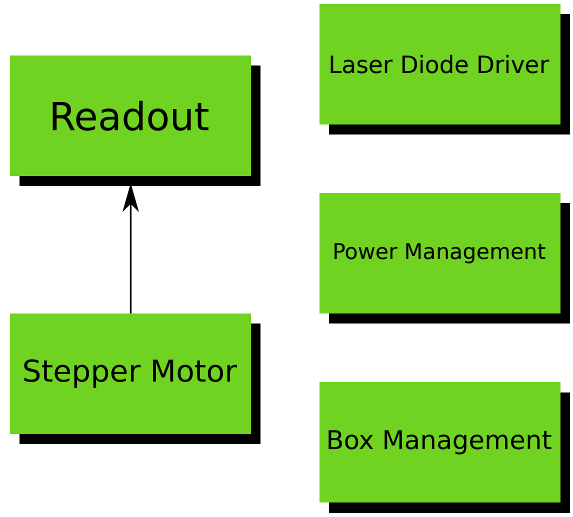

Figure 9: Independent software unit for the BAM system. Each block represents a separate DOOCS server.

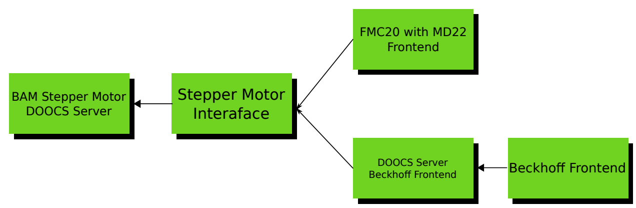

Figure 10: Schematic of the software structure for stepper motor library and DOOCS server.

framework [11]. The State Machine runs in a singleton and an interface is implemented to emit the proper events, to provide the needed information for internal calculation during transition (like calibration or slow feedback) and to retrieve the data. In the DOOCS Control System the interface is provided by the so called location, which is an instance of a particular class. A server can have more than one location in order to access one or more devices. The present implementation for the DOOCS server forsees two location instances which through the interface interact with the state machine. One location is used to set the firmware registers, to run the algorithms for the setting of the ADCs and filter and download the raw data. The second location has the task to download and process the filtered data, perform calibration and slow feedback. Calibration is necessary in order to transform the value of the normalized modulation in time unit (e.g. femtosecond or picosecond). The slow feedback is necessary because the transformation function modulation-time unit is not monotonic. In case of a drift of the arrival time, the value of the modulation can move outside of the monotonic region, so a suitable correction must be applied through the optical delay line. The transformation function is not linear and its non-linearity increases with the bunch charge. While for 50 pC bunch charge, a straight line may still be a good approximation, for a bunch charge of 200 pC or higher, a polynomial of 4th or even 5th degree is needed. The degree of the polynomial is determined is such a way

ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-TUPHA125

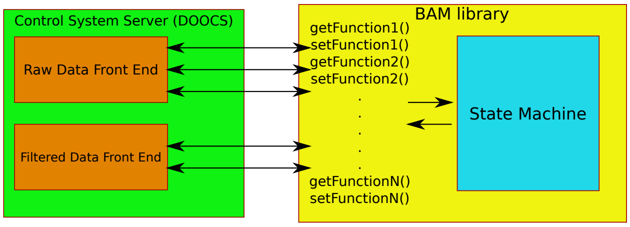

Figure 11: Schematic of the software structure for readout library and DOOCS server.

that the residuals of the fit function are in the order of 10-20 fs. The polynomial parameters and the corresponding charge are saved in a look up table, and then selected during run time, according to the value of the charge measured by the toroids along the beam line. The bunch charge measured by the toroids determines also which channel is used for slow feedback according to a threshold value set by the operator. The operator also has the possibility to select manually which channel has to be used.

Laser Diode Driver, Box and Power Management

Dedicated library and protocols were developed to allow communication with the LDD and FRED boards. The LDD protocol is based on binary packages and TCP/IP to access the register in the microcontroller on the boards. The software is standalone and command line tools and QT user interface are also available.

FRED uses a telnet section and string commands to control and set the board. As for LDD, the software is standalone and a QT interface is also available. The software for the Box Management is shared by two projects, namely the BAM project and the EOD project [12]. Both projects share the same mechanical box and use TMCB for the control management. The difference is how the TMCB is accessed: the board for BAM is connect via optical link to a FMC25 and the register of the TMCB are mapped on the FMC25 FPGA thus making them accessible via PCIe while the TMCB board for EOD is reachable directly via Ethernet using the protocol Rebot. The ChimeraTK library provided a common interface for PCIe register and Rebot register, thus only one server was developed for both hardware configurations.

INSTALLATION AND COMMISSIONING

At the moment three BAM systems are fully employed at FLASH and five at XFEL. The systems at FLASH and XFEL share the same DAQ system, including firmware and high level software for readout, while the XFEL has the newest generation of the RF and Electro-Optical Unit. An upgrade at FLASH is foreseen by the end of 2017 as well as the installation of new systems in both machines (Fig. 12) [13].

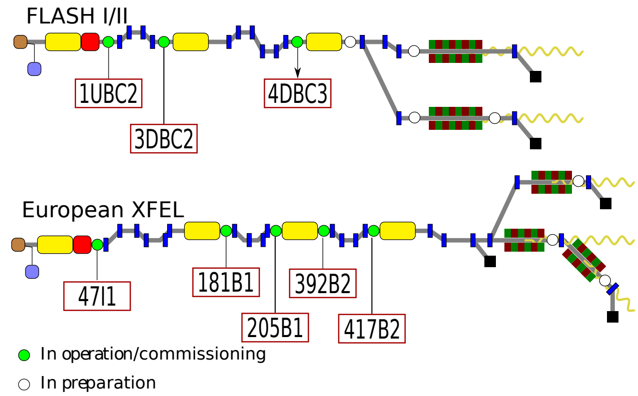

Figure 12: Positions and labels of the installed BAM systems along the beamline at FLASH and European XFEL.

REFERENCES

[1] H. Dinter *et al.*, "RFTweak 5 - An Efficient Longitudinal Beam Dynamics Code", in *Proc. FEL'15*, `https://doi.org/10.18429/JACoW-FEL2015-MOP060`

[2] A. Angelovski *et al.*, "Evaluation of the cone-shaped pickup performance for low charge sub-10 fs arrival-time measurements at free electron laser facilities", *Phys. Rev. ST Accel. Beams* 18, 012801 (2015).

[3] S. Schulz *et al.*, "Femtosecond all-optical synchronization of an X-ray free-electron laser", *Nature Communications* 6, 5938 (2014).

[4] M.K. Czwalinna *et al.*, "New Design of the 40 GHz Bunch Arrival Time Monitor Using MTCA.4 Electronics at FLASH and for the European XFEL", in *Proc. IBIC'13*, paper WEPC31.

[5] MicroTCA, `http://mtca.desy.de`

[6] A. Kuhl *et al.*, "Comparative Analysis of Different Electro-Optical Intensity Modulator Candidates for the New 40 GHz Bunch Arrival Time Monitor System for FLASH and European XFEL", in *Proc. IBIC'13*, paper WEPC41.

[7] K. Honkavaara *et al.*, "FLASH: First Soft X-ray FEL Operating Two Undulator Beamlines Simultaneously", in *Proc. FEL'14*, paper WEB05.

[8] K. Przygoda *et al.*, "MicroTCA.4 Based Optical Frontend Readout Electronics and its Applications", in *Proc. IBIC'16*, `https://doi.org/10.18429/JACoW-IBIC2016-MOPG13`

[9] DOOCS, `http://tesla.desy.de/doocs/index.html`

[10] G. Varghese *et al.*, "ChimeraTK - A Software Tool Kit for Control Applications", in *Proc. IPAC17*, `https://doi.org/10.18429/JACoW-IPAC2017-TUPIK049`

[11] M. Killenberg *et al.*, "Abstracted Hardware and Middleware Access in Control Applications", presented at ICALEPCS 2017, Barcelona, Spain, October 2017, paper TUPHA178, this conference.

[12] B. Steffen, "Electro-Optic Methods for Longitudinal Bunch Diagnostics at FLASH", Ph.D. thesis, Phys. Dept., Hamburg University, Hamburg, Germany, 2007.

[13] H. Dinter, "Longitudinal Diagnostics for Beam-Based Intra Bunch-Train Feedback", Ph.D. thesis, Phys. Dept., Hamburg University, Hamburg, Germany, in preparation.