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BUNCH ARRIVAL TIME MONITOR CONTROL SETUP FOR SwissFEL APPLICATIONS

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Abstract

Based on a Mach-Zehnder intensity modulator, Bunch Arrival time Monitor (BAM) is a single-shot non-destructive multi-bunch diagnostic instrument, which measures the arrival time with <10 fs precision in the range of 10-200 pC at 100 Hz repetition rate. Being directly coupled to a length stabilized fiber optical link, it has intrinsically low drift (<10 fs/day) and is thus a useful instrument for the machine feedback. The overall monitor complexity demands the development of an extremely reliable control system that handles basic BAM operations. Two BAM prototypes were successfully used in the SwissFEL Injector Test Facility and further two are being presently commissioned at the SwissFEL. The system is very flexible. It provides a set of tools allowing one to implement a number of advanced control features such as tagging experimental data with a SwissFEL machine pulse number or embedding high level control applications into the process controllers (IOC). The paper presents the structure of the BAM control setup. The operational experience with this setup is also discussed.

INTRODUCTION

SwissFEL is a compact X-ray Free Electron Laser (FEL) newly built at Paul Scherrer Institute (PSI). With total length of ~750 m, optimized to produce extremely bright and short X-rays in the range from 1 to 70 A and pulse duration in the order of 20 fs, it poses challenging demands on the diagnostic instruments regarding stability and sensitivity. The advanced SwissFEL characteristics open unique research opportunities in many disciplines such as medicine, biology, chemistry, electronics and nanotechnology.

SwissFEL is driven by a warm electron linac, which generates electron bunches with a repetition rate of 100 Hz and charges in the range of 10 pC to 200 pC. The longitudinal bunch stability of the machine is critical for user experiments. To monitor and control this stability, among other longitudinal and transverse beam diagnostics, the facility is equipped with several stations that provide non-destructive, shot-to-shot electron bunch arrival-time information relative to the extremely stable pulsed optical reference system [1]. Such Bunch Arrival time Monitor (BAM) stations [2] are valuable longitudinal diagnostics tools for SwissFEL operations.

BAM DATA ACQUISITION AND PROCESSING MODEL

The basic BAM detection principle is shown in Fig. 1. A pulse train from a mode locked laser at 1560 nm and 142.8 MHz repetition rate is sent to the BAM front end ("Box") via length stabilized single mode optical fiber links. In the BAM front end the amplitude of all reference laser pulses is modulated to the half with a Mach-Zehnder intensity modulator, biased at quadrature for maximum linearity. One reference laser pulse coincides with the zero-crossing of the S-shaped RF transient from the button pickup. With such an overlap there is no amplitude modulation, but any arrival-time change causes modulation by the non-zero voltage from the RF transient. Thus the arrival time information is encoded in the amplitude modulation with a fs precision. In view of the active fiber link stabilization, BAM has also a very low intrinsic drift.

To minimize any orbit offset influence, the signals from two opposite buttons (horizontal or vertical) are combined and fed in the RF port of the EOM.

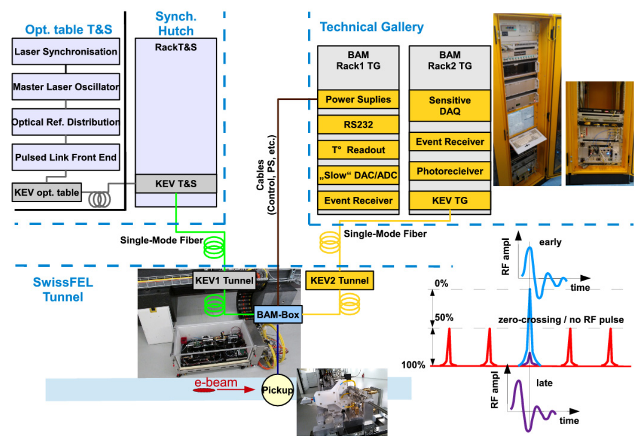

Figure 1: BAM topology and detection principle.

Each BAM station has the following components (see Fig. 2).

- An RF vacuum pickup consisting of four cone-shaped buttons, tapered to 50 Ohm vacuum feedthroughs with 40 GHz bandwidth. They are rotationally symmetrically mounted in the vacuum chamber with 16 mm diameter. Usually, two buttons are arranged horizontally and the other two vertically.
- Two Mach–Zehnder type electro-optic intensity modulators (EOM).
- Two erbium-doped fiber amplifiers (EDFA) with their controllers from Photop (II-VI).
- Reference laser pulse polarization control components (PCC), which include a Faraday rotating mirror, a polarization scanner, and a fiber polarizing beam cube.
- A high precision linear servo motor positioner MX80 from Parker with a controller from Copley Controls. The MX80 has a built-in incremental encoder with 10 nm

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resolution. The controller actively uses the readouts of this encoder, but can also output raw quadrature signals to external electronics for further processing.

- A motorized variable optical delay stage MDL-002 and its controller from General Photonics.
- Eight Peltier elements driven by a PTC10K controller (TEC) from Wavelength Electronics.
- A set of temperature, humidity, and air pressure measurement sensors.
- An in-house designed triple photo-receiver (PRX).
- Fast ADC bunch synchronous readout with an RF front end for pulse shaping, DC offsetting and clock shifting.

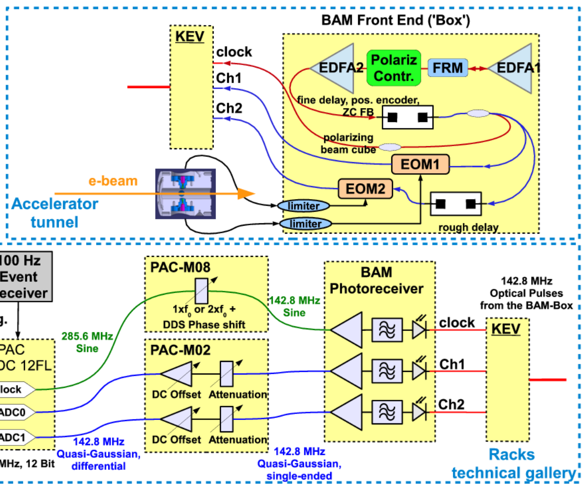

Figure 2: BAM frontend and acquisition electronics.

These components and their operational conditions define the SwissFEL BAM data acquisition and processing model.

By the use of a delay line with a high-accuracy position sensor, the amplitude modulation can be calibrated with time. The achievable time resolution is proportional to the slope of the RF pickup signal at zero crossing and the amplitude jitter of the laser pulses preceding the modulation, which are detected simultaneously in a single shot. Two EOMs define the high sensitivity and the high dynamic range BAM channels.

The BAM-box is temperature stabilized to 3 mK pk-pk over 1 hour and is located close to the beam pipe in order to reduce losses and drifts in the RF cables. The box also accommodates the end of the optical fiber link and two EDFAs. The first EDFA is used as an actuator for fiber link amplitude feedback loops. The second EDFA, which is out-of-loop, controls the power of the signal sent to the PRX. The first delay stage in the BAM box is used for zero-crossing feedback: each time the bunch arrival time exceeds a predefined limit determined by the slope of the RF transient signal, the reference pulse is shifted back to the zero-crossing, thereby keeping the BAM acquisition within the proper dynamic range of the transient. The second delay stage matches the zero crossing of the second BAM channel with the first one.

The modulated optical pulses from two BAM channels are transferred to a data acquisition back-end located in the technical gallery outside the accelerator tunnel. They are conditioned in the BAM PRX and read out by the in-house developed fast (500 MHz) 12-bit analog-to-digital converter (ADC) unit. The unit is a Generic PSI Analogue Carrier (GPAC) board [3] that is clocked with a signal generated from the same optical pulses. The optimal ADC dynamic range in view of a better time resolution is ensured by the use of a complementary PSI Analogue Carrier (PAC) module, which provides additional DC offset, amplitude control, and clock shifting functions.

The ADC data are processed by the GPAC FPGA software and then read out by a BAM control computers. Based on this information, the electron bunch arrival time is calculated and used for SwissFEL operations tasks.

Each of the three PRX channels has DC photocurrent outputs, which are actively used in the polarization and bias control feedbacks [2].

The above formulated data acquisition and processing model demands the development of a very efficient data acquisition and control system.

BAM DATA ACQUISITION AND CONTROL SYSTEM

The SwissFEL BAM data acquisition and control system is integrated into the facility controls [4], which is based on EPICS. The system is implemented as a generic BAM Control Setup (BCS), which can easily be extended to include any additional functionality, if needed. The BCS consists of the next components.

- Process control computers running EPICS Channel Access servers (IOCs, in terms of EPICS) and control hardware interfacing BAM equipment.
- Equipment control software which allows remote readout and control.
- Data acquisition and processing software.
- BAM beam synchronous data readout.

BAM Control Hardware and IOCs

All equipment which is outside the BAM box, is placed into two 19” standard PSI electronics racks located in the SwissFEL technical gallery. The same racks accommodate the IOCs and control hardware. This arrangement separates electromagnetic noise sensitive and not sensitive components into different racks, which minimizes the noise impact on BAM operations.

In each rack, there is one standard SwissFEL 7-slot Trenew VME-64x crate with external monitoring capabilities and remotely controlled mains power switches from Gude.

Both VME crates contain one IOC, which is an intelligent FPGA controller IFC 1210 board from IOxOS running a real time Linux kernel, and a new generation EVent Receiver (EVR) card EVR-VME-300 from Micro-Research Finland talking to the advanced SwissFEL timing and event distribution system [5].

The other components of VME crates are different.

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The noise sensitive crate has a GPAC/PAC set and an incremental encoder counter card ECM514 (from Kramert GmbH), which interfaces the external encoder output of the MX80 controller unit.

In the second crate, there is an in-house designed VME transition board with DIO functionalities and a VICB8002 IP carrier board with two IP-ADC-8401 and two IP-DAC-8402 modules (from Newwood Solutions, a former Hytec) on it to deal with 16 bit "slow" ADC (100 kHz) and DAC (20 kHz) signals.

In addition, the noise not-sensitive rack accommodates a serial server unit from Moxa, which can handle up to 16 serial (e.g. RS232) ports, an in-house developed precise temperature/humidity/air pressure monitoring unit ToBaS [6], and the rest of the equipment, which is outside the BAM box. One notes that in the SwissFEL control system Moxa units are primary Linux IOCs directly talking to serial devices.

Equipment Control Software

BAM equipment control software is implemented as a set of equipment control software modules (ECSM) created and supported in the frames of the PSI application development environment (PADE). The environment uses Git for software revision controls and a powerful PSI inventory database together with its complementary application installation and loading tools [7].

The core of PADE is the EPICS toolkit. As an international collaboration project, with a wide variety of robust tools created and available for users, EPICS significantly simplifies any controls development.

For instance, serial (e.g. RS232) and network (TCP/IP) devices can easily be accessed with the use of the StreamDevice software module [8]. All that has to be done is to define device communication parameters (e.g. a baud rate), specify device commands in a standard protocol file, create an EPICS database with records referencing those commands, and run this database on any IOC that has a serial communication port.

Another example is the PSI VME bus memory handling software (VMHS) module, which is implemented as an extension of a generic device support package (regDev) on top of accessing memory mapped (mmap) registers and IOxOS FPGA (tosca) drivers [9]. Based on this module, the efficient handling of a variety of VME cards can be performed with the use of a relatively simple EPICS database containing standard records associated with registers and memory on those cards.

Since in the PADE framework each particular device type is handled by its dedicated device control software module, it was natural to implement each BAM equipment control software module as a combination of the device control software modules associated with this equipment and the EPICS database handling this equipment.

As a result, the next BAM equipment control software modules were created:

- MX80, MDL, and EDFA for handling their corresponding RS232 controllers. They all use generic StreamDevice setting components. In addition, the EDFA software includes a state machine program for keeping the device parameters in safe operational limits.
- Gude and VME crate monitoring, which also uses generic StreamDevice settings to talk to the related units.
- VME Slow Memory Access for interfacing ADC/DAC/DIO, Kramert encoder VME cards, and reference laser pulse polarization control components with the use of the VMHS package.
- GPAC/PAC for handling the corresponding set based on the VMHS package.
- ToBaS for monitoring BAM temperature, humidity and pressure sensors.

Furthermore, each serial or network equipment component is handled by a dedicated thread running on either a Moxa IOC or a so-called SoftIOC, which is usually deployed on one of PSI virtual Linux machines. It should be noted that such a single component oriented configuration, in particular, allows one to perform any equipment specific test or troubleshooting work without affecting the rest of the system.

Data Acquisition and Processing Software

The main tasks of BAM data acquisition and processing software are:

- to evaluate the bunch arrival time and jitter and
- to set up and maintain BAM equipment operational conditions, which are required by the data acquisition and processing model.

The first task is performed on a shot-to-shot basis by the used GPAC/PAC set and the IOC, which hosts it and communicates with it over the VME bus. As a part of the EPICS database, current bunch arrival time estimates are always available for users.

The second task is done by applications written in MATLAB and interfacing EPICS channels with the use of the PSI MOCHA/CAFE library [10]. By handling channels, which are in charge of particular BAM equipment components, these applications ensure that the parameters of such components do not introduce any distortions that make BAM data incompatible with the model. The applications are mostly implemented as classic closed control loops. For instance, to make sure that the EOM DC is biased in quadrature, one such application performs EOM bias scans. Based on BAM tuning signals, this application determines the EOM transmission curve by changing the EOM bias voltage by "slow" DAC and measuring the resulting DC photocurrent by "slow" ADC. When the scan is complete, the working point is defined in accordance with the BAM data acquisition and processing model.

To minimize periods when bunch arrival time estimates become invalid, the second task must be performed as fast as possible. Usually MATLAB applications at PSI are deployed on PC consoles running Linux. The loop execution time of such high level applications is strongly affected by natural latencies introduced by the network and general purpose operating system. In some BAM related cases this time can reach one minute and more, which is

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certainly not a good performance for SwissFEL operations. To improve the situation, with the use of a special MATLAB conversion tool [11] developed at PSI all such applications were embedded into the IOCs directly handling the corresponding control equipment. The results are clearly noticeable. An average execution time of control loops was reduced by up to 5-10 times, which was especially impressive when dealing with the corresponding absolute time values. For instance, for the above mentioned EOM bias scan this time was reduced from 75 to 15 seconds.

BAM Beam Synchronous Data Collection

Each electron bunch produced by the SwissFEL machine is assigned a unique ID number, which is generated by the timing system and distributed by this system all over the facility. An in-house developed beam synchronous data acquisition system (BSDAQ) [12] provides a powerful mechanism for collecting and saving control system data, which are also associated with some EPICS records and referenced as channels, in the form of metadata tagged with such a bunch ID. This allows one to easily restore all facility parameters associated with each produced bunch sometimes later (off-line) and to use this information for a variety of applications, including tests and improvements of the BAM data acquisition and processing model.

The list of all channels, which have to be collected and saved by BSDAQ, is requested by control system users. Based on this list, each IOC is provided with those channels that are handled locally.

In its IOC default setting for 100 Hz, one bunch operations, the BSDAQ data collection software is activated in the last 1 millisecond of the available 10 millisecond interval between two produced bunches. It obtains the bunch ID number from the timing system (via a standard or embedded EVR card), collects the requested data and tags them with this number. This default setting assumes that all data processing associated with each particular bunch ID is done before the corresponding BSDAQ data collection starts. However, if this data processing is not done, then the data and bunch ID consistency will be violated. In case of BAM, such violations were observed on very rare occasions and were caused by extremely heavy simultaneous GPAC, IOC, and control network loads. To prevent such situations, BAM data collecting BSDAQ software was modified. After each successful data collection cycle, the ID of the following bunch is immediately saved in a local buffer, and the data collecting software waits until the data processing performed by GPAC and IOC is finished. As soon as this processing is done, the software collects all required data, tags them with the saved bunch ID, and gets ready for the next bunch. The overall SwissFEL beam synchronous data consistency is much more important for the facility than the existence of rare gaps in BAM beam synchronous data produced by the modified data collecting BSDAQ software.

CONCLUSION

The BAM control setup was designed by diagnostics and control system experts. As a result, all its components are highly optimized to do their jobs as efficient as possible. A very good performance of the setup was demonstrated during SwissFEL Injector Test Facility operations and commissioning of first SwissFEL BAM stations.

REFERENCES

[1] S. Hunziker *et al.*, “Reference distribution and synchronization systems for SwissFEL: concept and first results”, in *Proc. IBIC’14*, Monterey, CA, USA, Sep. 2014, pp. 29-33.

[2] V. Arsov *et al.*, “Design and commissioning of the bunch arrival time Monitor for SwissFEL”, in *Proc. IBIC’17*, Grand Rapids, MI, USA, Aug. 2017.

[3] W. Koprek *et. al.,* “Overview of applications and synergies of a generic FPGA based beam diagnostics electronics platform at SwissFEL”, in *Proc. IBIC’15*, Melbourne, Australia, Sep. 2015, pp. 165-169.

[4] E. Zimoch *et al.*, “SwissFEL control system overview, status, and lessons learned”, presented at ICALEPCS’17, paper MOAPL04, this conference.

[5] M. Janousch *et al.*, “Overview and status of the SwissFEL control system”, in *Proc. ICALEPCS’15*, Melbourne, Australia, Oct. 2015, pp. 1169-1172.

[6] M. Brönnimann *et al.*, “EtherCAT based RF interlock system for SwissFEL”, presented at LLRF’15, Shanghai, China, Nov. 2015.

[7] R. Krempaska *et al.*, “Control system configuration management at PSI Large Research Facilities”, in *Proc. ICALEPCS’13*, San Francisco, CA, USA, Oct. 2013, pp. 1125-1126.

[8] StreamDevice 2, `http://epics.web.psi.ch/software/streamdevice`

[9] regDev, mmap, tosca, `https://github.com/paulscherrerinstitute`

[10] J. Chrin, “An update on CAFE, a C++ channel access client library, and its scripting language extensions”, in *Proc. ICALEPCS'15*, Melbourne, Australia, Oct. 2015, pp. 1013-1016.

[11] P. Chevtsov *et al.*, “MATLAB control applications embedded into process control controllers (IOC) and their impact on facility operations at Paul Scherrer Institute”, presented at ICALEPCS’17, Barcelona, Spain, Oct. 2017, paper TUPHA020, this conference.

[12] S. Ebner *et al.*, “SwissFEL - beam synchronous data acquisition – the first year”, presented at ICALEPCS’17, Barcelona, Spain, Oct. 2017, paper TUCPA06, this conference.