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FIRST RESULTS FROM THE BUNCH ARRIVAL-TIME MONITORS AT SwissFEL

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Abstract

Two Bunch Arrival-Time Monitors (BAMs) based on fiber optical Mach-Zehnder intensity modulators have been commissioned at SwissFEL. Both operate simultaneously up to 100 Hz with a resolution <5 fs at 200 pC. We have developed concepts and tested hardware, which enhance the BAM commissioning and user operation.

INTRODUCTION

Two Bunch Arrival-Time Monitors (BAMs) based on fiber optical Mach-Zehnder intensity modulators [1], operating simultaneously up to 100 Hz with a resolution <5 fs at 200 pC, have been commissioned at SwissFEL. They derive their high stability from a pulsed optical reference distribution system in which the length of the single-mode optical fibers is stabilized for drift and jitter. For commissioning, instead of using a balanced optical cross-correlator as a phase detector we use a technically less demanding approach based on low drift and jitter laser-to-RF direct conversion, which delivers few tens of fs stability [2, 3]. In order that all BAMs measure simultaneously, it is necessary that a reference laser (OMO) pulse overlaps with the bunch at the given location. In addition, an integer number of pulses should fit in the link. To meet the above two requirements during commissioning multiple timing scans of the OMO pulses should be made. A complete scan may require a time-shift over an entire pulse train period, i.e., 7 ns. To speed up commissioning and allow adding of further BAM stations we have developed a concept for fast OMO pulse timing scan.

BAM REFERENCE DISTRIBUTION AND READOUT

BAM Optical Master Oscillator (OMO2)

The core of the SwissFEL reference distribution is a mode-locked laser oscillator (Origami 15, NKT Photonics) with pulse repetition rate of 142.8 MHz, phase-locked to a stable microwave reference at 2998.8 MHz (SMA100A, Rohde & Schwarz), which is locked to a 10 MHz Rb standard (FS725, SRS) [4]. All machine relevant frequencies are derived via harmonic extraction and delivered to the remote locations by single-mode fiber optical links, stabilized according to the client's specific requirements. Among others, BAM has the most stringent stability requirements for sub-10 fs drift, which is achieved via balanced optical cross-correlation [1]. In the general case the fiber optical link length is arbitrary and does not necessarily provide an overlap of a reference OMO pulse with the electron bunch. To secure a timing overlap, it is necessary to phase shift the OMO pulses over a pulse train period. Since at SwissFEL the OMO is the source of the entire reference distribution, such shifting will not effectively result in an overlap with the bunch, because the effect is a common mode. The alternative is either to have an optical delay line for each individual pulsed link, or to use a second OMO dedicated only for BAM commissioning (OMO2). We chose the second approach (Fig. 1). As in the case of the machine OMO, the one for BAM is locked to the same stable microwave reference. In addition, there is a bucket synchronization at 1.9833 MHz (super period). The advantage is, that any machine component with corresponding bucket synchronization, e.g., the gun and the experimental lasers, have also a common timing origin. The bucket synchronization is obtained by phase locking of one of the 3 GHz slopes to the slope of the super period at the zero crossing. The overlap is achieved with an IQ modulator (aka. vector modulator, shortly VM), which has a 12 bit DAC.

BAM Pulsed Optical Front End

The pulsed link synchronization used for BAM commissioning is based on low drift stabilized phase detector [2, 3]. The set-up is all-fiber and the phase detection principle doesn't require a dispersion compensation. The good drift stability (~10 fs pk-pk) is achieved by temperature stabilization of the basic components within the package, proper choice of the working point of the two photo diodes (2651E, Emcore), as well as careful balance of the forward and backward branches and the corresponding optical pulse powers. Dispersion compensation to reduce the pulse width to ~250 fs is nevertheless made to preserve the BAM resolution. A combination of a piezo-stretcher (PZ2, Optiphase) and a delay stage (MDL-02, General Photonics) is used to compensate for jitter and drift (Fig. 1). The naked fibers are housed in a hermetic package to minimize the environmental influence. The system is located in the temperature and humidity regulated synchronization (T&S) room.

BAM Readout Electronics

The BAM photoreceiver, the 7-slot VME crate with the pulse-forming front-end and readout cards are located in a separate 19" rack in the technical gallery (Fig. 1).

Photoreceiver. The device is an in-house development with three channels - "fine" BAM, "coarse" BAM and ADC clock. The photodiodes (2651E, Emcore) have 3 GHz bandwidth. The optical pulses for the two BAM-

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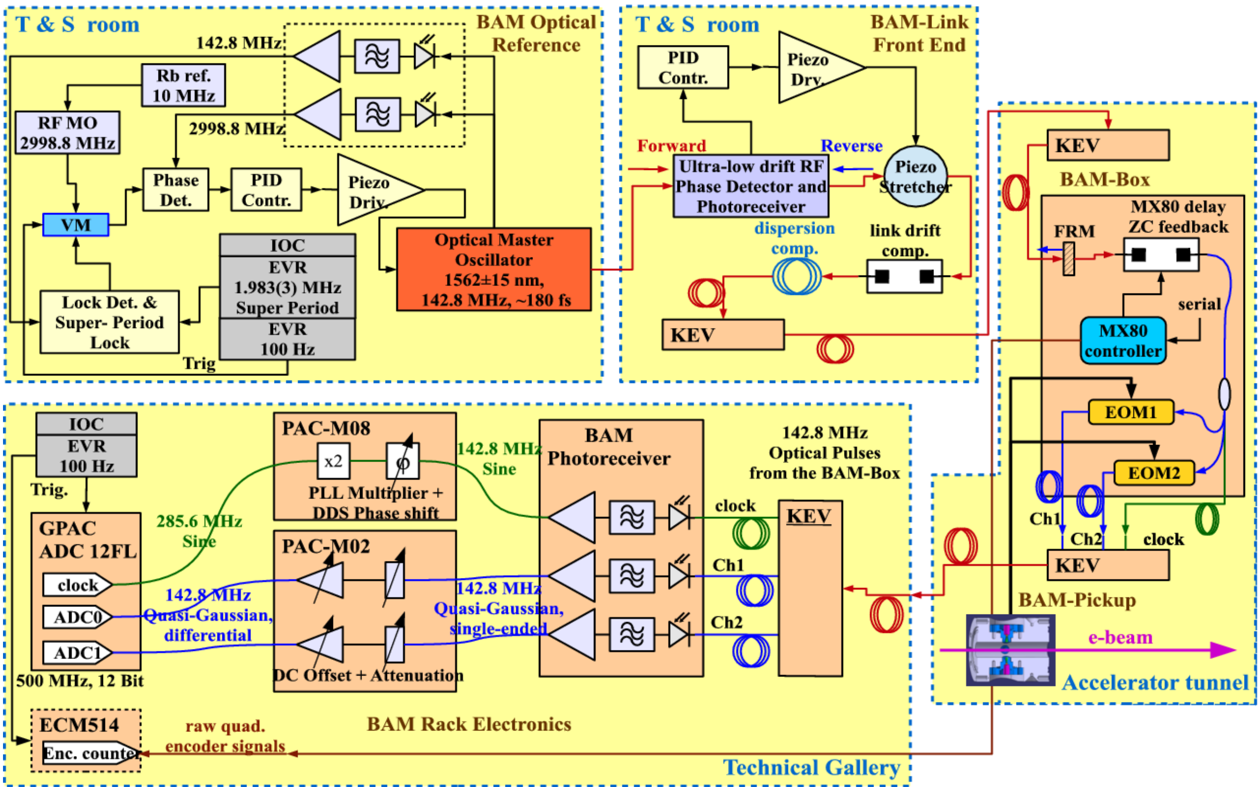

Figure 1: BAM pulsed optical reference and readout.

channels are Gauss-filtered to obtain flat tops and minimal pulse-to-pulse cross-talk at 142.8 MHz. This reduces the ADC sampling jitter sensitivity and improves the BAM resolution. The optical clock at 142.8 MHz has a sine shape. The photodiodes are operated close to saturation at ~1.5 mW. The output stage is a broadband trans-impedance amplifier with typical outputs of ~0.7 V pk-pk.

The triple photoreceiver is followed by a triple amplifier stage with flexible user adjustable input levels. The typical output is ~3 V pk-pk single-ended signal.

PAC-M02. The PSI Analogue Carrier Board (PAC) is developed in house for diagnostics applications. It allows plugging of up to four mezzanine-boards, each with two channels. It supports up to 8 remotely controlled DACs, stabilized low-noise supply voltages and four differential digital I/Os.

The PAC-M02 mezzanine board is used for photoreceiver signal conditioning and is controlled from the PAC DACs. At the input of each of the two channels there is a digital step attenuator (DAT-31A-PP+, Mini-Circuits) providing attenuation with 0.5 dB steps. At maximum signal the input to the ADC is 2 V pk-pk. The following step contains single-ended differential amplifier with 700 MHz bandwidth. Its purpose is to DC-shift the signal baseline, so that to fully utilize the ADC dynamic range, thus improving the BAM resolution.

PAC-M08 is a full DDS clock phase shifter, used to provide stable and adjustable clock signal with 425 fs timing resolution for the GPAC ADC. It has two outputs for 142.8 MHz and 285.6 MHz. The absolute phase is not recoverable. The design includes a VCXO (KVG V-7213-LF-571.2MHz), locked to the 142.8 MHz reference by a narrow band PLL (ADF4106). The phase shifting is done by a DDS Chip (AD9912). A separate diode multiplier is used for the 285.6 MHz output, which has a substantially lower added jitter (<60 fs) than the one integrated in the DDS chip. The integrated timing jitter of the 285.6 MHz output used for the BAM clock is <240 fs in the bandwidth of 10 Hz-10 MHz, which is sufficiently low for sampling of the photoreceiver pulses.

The much better phase step accuracy (425 fs) and low added phase noise achieved with the PAC-M08 clock shifter improves substantially the BAM resolution, which was earlier limited by the ability to effectively sample the OMO amplitudes at the peak and not at the slope.

GPAC. BAM uses the Generic PSI ADC Carrier board (GPAC), originally developed for the European XFEL button BPM [5]. The firmware is modified and kept generic for most of the diagnostics applications. The specific BAM-processing, e.g., normalization of the waveforms, detection of the sample number with the first modulation (electron bunch interaction), bunch ID stamping, calculation of the laser amplitude jitter, is done at the IOC side. The ADCs (KAD5512P-50, Intersil) are 12 bit, 500 MSa/s. The sampling clock is at 285.6 MHz, provided by the PAC-M08 card, allowing sampling of one peak and one baseline points for multiple OMO pulses. Digitized is not the form of a single pulse, but multiple OMO pulse amplitudes, which are then normalized by dividing each next one by the amplitude of the previous pulse [1]. This allows simultaneous detection of two

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bunches, as well as multiple pulses preceding the bunch modulation and thus measure *in situ* the amplitude jitter, which contains the shot-to-shot measurement error and which limits the BAM resolution. Since the clock signals are generated from the same optical pulse train as the BAM signals, the sampling is independent on phase shifts, e.g., caused by the delay stage for zero-crossing (ZC) feedback. The GPAC is triggered by the event receiver. The firmware provides a VME bus interrupt for the IOC and allows data processing between the events at 100 Hz.

ECM514 is an encoder counting VME card for readout of incremental encoder signals. It is triggered by the event receiver. The positions are read in two 32 bit registers - "live" and "latched". The card allows bunch synchronous position read-out of the linear servo motor MX80 in the BAM-Box used for ZC feedback (Fig. 1). The EPICS communication with MX80 is serial, but the controller outputs the raw quad encoder signals, which are counted bunch synchronously by the "latched" register. The processing is done on the IOC side. With each trigger the last motor position is kept and passed to the IOC, where a bunch ID is assigned, together with the processed ADC traces.

Event receiver. The EVR-VME-330 (Micro Research Finland) event receiver is served by the machine timing event master. Two events are dedicated for BAM - EV10 with 3.0 ms delay and EV12 with 5.7 ms delay with respect to the sequence start (EV38). EV10 is used for masking, i.e., when this event is active, the hardware triggers for the subsequent events, e.g., EV12 are suppressed (Fig. 2). This feature, developed initially for the MPS, is used to initiate triggers simultaneously to remote IOCs, e.g., the one for the VM in the T&S room and the BAM IOC in the technical gallery.

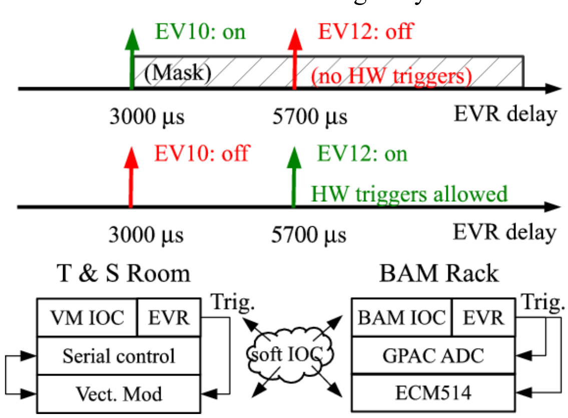

Figure 2: Trigger masking and synchronization.

I/O Controller, type IFC1210 VME from IOxOS Technologies [6], runs real-time Linux and is responsible for the EPICS record processing and linking with the machine network. The 100 Hz communication with the rest of the VME boards (GPAC, PAC, ECM) is done through the VME bus. Data processing is done sequentially through the VME interrupt generated by the GPAC card and includes normalization of the raw ADC waveforms, extraction of the BAM relevant data (see subsection GPAC), MX80 encoder position readout, bunch-ID stamping and structured waveform processing for client applications.

FAST TIMING SCAN CONCEPT

The "fast" scan refers to a method for bunch synchronous delay-shifting of the OMO pulses over a large interval with a high resolution. The goal is to establish an overlap between the OMO pulse and the electron bunch. Such scans provide information on the BAM pickup transients, e.g., charge or orbit dependence. The method enhances commissioning by speeding up the work on matching the zero crossings of the "fine" and "coarse" channels of a single BAM station, as well as the zero-crossing overlap for all BAMs. It provides also a rough estimate of the BAM resolution.

The method uses the VM in the OMO2 reference path as an actuator (Fig. 1). Up to 7 BAM stations can be included simultaneously in a single run.

The VM is primarily used for super-period lock. It communicates with EPICS over a slow serial port. To allow fast bunch synchronous scans at up to 100 Hz step rate the VM hardware and firmware were modified to support triggering by the event receiver. In VM triggered mode its phase advances by a predefined step on receiving of an external trigger pulse. The 100 Hz scan is much slower than the bandwidth of the OMO2 PLL, therefore the laser remains in lock, but its phase is effectively delayed relative to the origin determined by the bucket synchronization.

A technical challenge was to provide simultaneous trigger start of the VM IOC in the synchronization room and the BAM IOC in the technical gallery. The solution was provided by the trigger masking concept (Fig. 2). The remote clients are normally triggered by the BAM EV12. The trigger masking allows a preceding event, i.e., EV10, when active, to suppress the EV12 controlled triggers for the given client. The trigger sequence by event masking is managed by the fast scan EPICS soft IOC server. During the scan the serial communication with the VM is temporarily interrupted to prevent loss of phase steps.

On the BAM crate side, there is a buffer, which stores the GPAC ADC traces for each individual trigger and a trigger counter. For practical reasons the buffer size is 7170 elements, allowing storage of two ADC traces with 1024 elements (normalized trace). The mechanism allows scans from 0 to 7 ns with 1 ps step or within arbitrarily smaller interval with >80 fs step size. The interval limits are adjusted automatically to the user defined step size, so that the maximum buffer size of 7170 elements is not exceeded.

At the end of the scan the serial communication with the VM is restored and the final VM position is compared to the expected one for the given counter and step size. A warning message is given, if scan steps were lost.

The fast scan tool is fully automated and accessible form the SwissFEL BAM-expert launcher. A typical fast scan with 1 ps step size over a pulse train period lasts

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~70 s at 100 Hz and ~12 min at 10 Hz. For comparison, the Matlab VM scan tool used during the Test Injector phase some years ago required 1.5-2 hours.

The buffered traces are stored in Matlab binary files. They can be displayed as a function of the phase delay either during the scan for an arbitrary sample number (online monitoring of the scan quality), or saved for post processing, e.g., with a dedicated expert user tool for slope fitting, which is also accessible form the launcher.

EXPERIMENTAL RESULTS

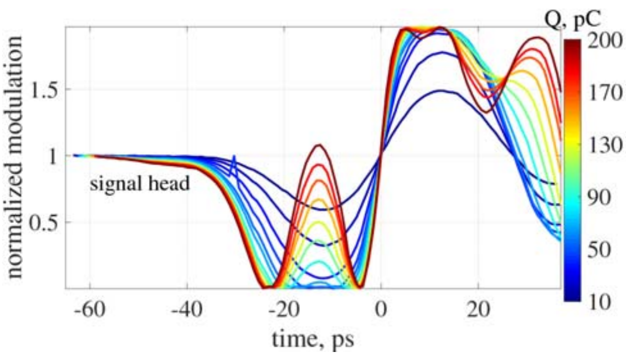

Figure 3: Normalized modulation as a function of the OMO pulse delay at different bunch charges.

The fast scan method was applied to measure the BAM pickup response at different charges (Fig. 3). Used is the 16 mm beam pipe diameter BAM-Pickup at the laser heater [7]. The results are similar to the ones measured earlier at the SwissFEL Test Injector (unpublished). The displayed waveforms are not the pickup voltages, but the normalized modulation of that single OMO pulse, which has interacted with the electron bunch, displayed as a function of the OMO pulse delay. The curves on Fig. 3 have been shifted at post processing to overlap the zero crossings. For high charge a typical "over-rotation" is observed. At higher coupling efficiency the pickup-voltage is higher than the EOM half-wave voltage, which leads to non-linear response and eventually swap to the adjacent EOM slope. The BAM measurement is made in the linear part of the EOM slope (near quadrature) and near the zero-crossing of the pickup-transient.

The quality of the pickup response is defined with the slew rate and the modulation depth. The latter is the ability to achieve 100 % modulation. At the pickup zero crossing the laser amplitudes are in quadrature (normalized modulation equal to 1). At higher amplitudes of the pickup transient the modulation becomes 100 % (normalized modulation equal to 0). The modulation depth is 100 % for a large range of bunch charges between 40 pC and 200 pC, and the dependence is flat (Fig. 4).

The BAM resolution is determined as a the product of the pickup slope [fs/% modulation] and laser amplitude jitter of the multiple laser pulses preceding the electron bunch modulation [% modulation]. Thus the resolution depends not only on the pickup response, but also on the noise of the entire reference distribution chain, BAM-Box and acquisition electronics. The amplitude jitter of the reference laser pulses is measured shot-to-shot simultaneously with the arrival-times for bunches 1 and 2 and is in the order of 0.15 %. The slew rate was measured with delay stage calibration close to the zero crossing.

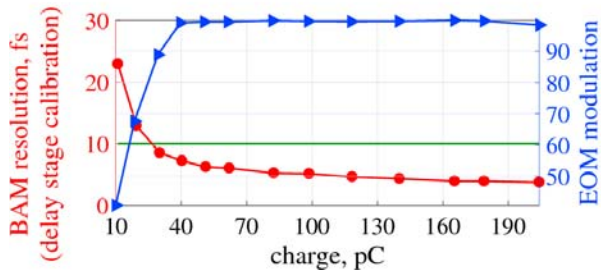

Figure 4: BAM resolution and EOM modulation depth as a function of the bunch charge.

For the 16 mm pickup the resolution is below 10 fs for the charge range 30 -200 pC. For lower charges the coupling efficiency is not sufficient. The improved electronics (photoreceiver, clock phase shifter, ADC input signal conditioning) contributed substantially to the improvement of the BAM resolution. For the BAMs after the undulators, 8 mm pickups are installed [7]. For those, twice as high coupling efficiency and better resolution at low charges is expected.

CONCLUSION

We have developed concepts for fast timing scan of the reference laser pulses over a larger interval with <80 fs accuracy using a VM in the synchronization path of the laser. Depending on the machine repetition rate the method shortens the time to obtain an overlap between the laser pulse and the electron bunch from initially more than an hour to a few minutes. The technique can be of practical interest not only for BAM, but also for the experimental lasers, where an overlap between the pump and the FEL beams is required. The advantage of the method is that no free space delay stages are involved, which avoids beam pointing instabilities and drifts.

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