FIRST RESULTS FROM THE BUNCH ARRIVAL-TIME MONITOR AT THE SwissFEL TEST INJECTOR

V. Arsov#, M. Dehler, S. Hunziker, M. Kaiser, V. Schlott, Paul-Scherrer-Institute (PSI), Switzerland

Abstract

A bunch arrival-time monitor (BAM) based on a Mach-Zehnder type electro-optical intensity modulator is under development at PSI to meet the high requirements for stable SwissFEL operation. The timing precision is derived by a stable pulsed optical reference system. The first BAM is located upstream of the bunch compressor where the bunch energy is 250 MeV and the pulse length is approximately 3 ps. At this position, the bunch arrival time is sensitive to the laser- and gun timing. In this paper, we report on the commissioning of the RF- and optical front ends, the first arrival-time jitter and drift measurements.

INTRODUCTION

SwissFEL is planned to start user operation in 2016 with its hard X-ray beamline for tunable high briliance photon pulses with wavelengths 0.1-0.7 nm and pulse duration <10 fs [1]. This requires low charge operation in the range 10 pC - 200 pC for the driving linac with bunch lengths <10 fs. To guarantee the machine longitudinal stability by applying feedbacks, it is necessary to measure non-destructively the electron bunch arrival-time with resolution <10 fs at low charge at several locations. Such diagnostic instrument, called Bunch Arrival-Time Monitor, based on Mach-Zehnder electro-optical intensity modulator (EOM), an integral part of a highly stable (<10fs drift over days) pulsed optical reference system, is already in use at several institutes [2-6].

In the SwissFEL Injector Test Facility (SITF) the first such BAM prototype has been installed upstream of the bunch compressor. During the commissioning phase the goal is not to cover the SwissFEL specifications, but to demonstrate the proof of principle, gain know-how and outline the way to improve performance. In this paper, we describe the design of the system and report on the first experimental results.

MEASUREMENT SETUP

Optical Link Phase Detector and Stabilization

Our base-line to achieving <10fs drift stability over days is the use of a mode-locked laser oscillator with low intrinsic phase and amplitude jitter, locked to a low-drift RF master oscillator [1]. The laser pulses with duration of ~200 fs are distributed over length-stabilized dispersion compensated optical fiber links, with a balanced optical cross-correlator using non-linear optical crystal as a phase detector [7].

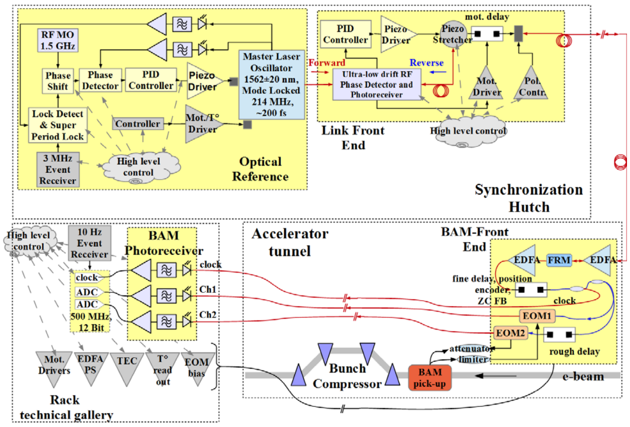

Figure 1: Layout of BAM and its stabilized pulsed optical reference.

For the commissioning of BAM upstream of the bunch compressor (Fig. 1), where the stability requirements are not as stringent, we use a simpler phase detection method to stabilize the optical link [8], based on low drift and jitter laser-to-RF direct conversion [9]. The set-up (Fig. 2) does not have free-space components and does not require dispersion compensation.

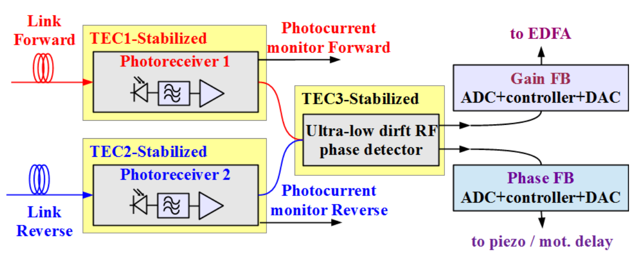

Figure 2: Block diagram of the low drift RF phase detector, used for stabilization of the pulsed BAM link.

Prerequisites for low drift phase detection are the good temperature stability, the use of low drift components, symmetric path lengths for their connection, constant amplitudes of the mixed signals. The latter is achieved by an amplitude gain feedback with the first BAM EDFA as an actuator, thus minimizing AM-to-PM effects, especially in the phase detector. All sub-components are individually temperature stabilized with an accuracy of 10 mK. The optical powers on the photodiodes are set for low AM-to-PM conversion. The working point is close to a so called „sweet spot“, determined experimentally with an SSA.

Pickup and RF Front-End

In our initial approach we have developed two types of pickups: a button and a ridge wave guide (RWG), mounted on a common 38 mm vacuum chamber. The button pickup has 80 MHz intrinsic bandwidth. The used

#vladimir.arsov@psi.ch

ISBN 978-3-95450-127-4

feedthru (Meggit #8538972) limits effectivly the BW to 20 GHz. The RWG pickup with higher coupling strength, but lower BW (16GHz) was developed for bunch charges of few pC. Beam tests showed, that the RWG dynamic range concerning charge is small which makes it impractical for use at SwissFEL. Therefore its optimization will be discontinued. The current measurements are made with the button pickup.

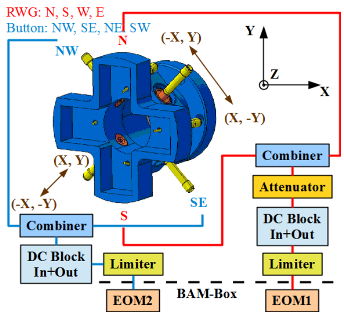

Figure 3: Layout of the pickup and RF-Front-End. Map for the orbit scans.

In order to minimize the orbit dependence of the pickup signal, two opposite ports are combined with phase-matched RF-Cables (350 mm SucoFlex404 from Huber+Suhner, K(male) connectors). Typical IL for the SucoFlex404 cables is S_{21}=-0.6 dB at 26 GHz and RL S_{11}=-25.2 dB at 26 GH. The combiner is of type P213H, ATM (1-18 GHz). The group delay difference of the cables and the combiner have been measured and compensated with 50fs precision (sweep range 1.0-1.5 GHz, bandwidth 1kHz, averaging over 64 sweeps). The cable from the combiner to the front panel of the BAM-Box is 800 mm SucoFlex404. A double DC-Block (Inmet 8039, 0.01-18GHz) decouples ground loops from the beam pipe. A limiter N9356C (5.6 V RF amplitude, 26.5GHz BW) protect the EOM but preserves the pickup steep slew rate. Inside the BAM-Box a 350 mm long Sucoflex404 cable connects the front panel and the EOM.

Electro-Optical Front-End (BAM-Box)

The electro-optical front end, is located near the pickup to ensure minimum BW losses through RF cables towards the EOM. Presently two EOM of type Mach10-056 from Covega (3dB BW at 12 GHz, zero-chirp, V_π=5.6V) are installed. Thus the BAM has two channels, allowing realization of high sensitivity and high dynamic range configurations [2]. The present measurements are with one channel only, realized with the button pickup and a limiter. Further, the box houses the end of the fiber link: two commercial EDFAs with 1.5 m Er-gain fiber from Photop [10] and a Faraday rotating mirror (FRM). The EDFA preceding the FRM is part of the optical link and is used as an actuator for the link amplitude feedback loop. The second EDFA is out of loop and serves for power management of the BAM photoreceiver. For near zero crossing BAM acquisition, a feedback loop with a non-contact linear servo motor is used [11]. The motor precedes the first EOM and the splitter for the optical clock signal. Thus the optical pulses carrying the arrival-time information and the clock signals for the ADC have always the same relative delay, ensuring clock synchronicity with the BAM acquisition. The motor movement is frictionless and back lash free. A position encoder with 10 nm accuracy provides an uni-directional repeatability of 18 nm (61 as) and a bi-directional repeatability of 16 nm (54 as), both confirmed by a measurement [12]. The position jitter added by the motor holding current was measured to be 8 nm (26 as) rms. The entire base plate of the box is uniformly temperature stabilized at 28°C with long term stability over weeks of 10 mK. The box has an inner shielding of 5 mm thick hard polyethylene doped with boron carbide against neutrons. On the outside there are 10 mm thick lead tiles against x-rays.

Photoreceiver and Data Acquisition Back-End

The optical pulses from the two BAM channels and the optical clock are conditioned prior to the ADC in a photoreceiver (PRX) module. The in-house design includes photodiodes with high intrinsic BW (3GHz, Ortel 2861E), followed by broad-band, low-noise and high dynamic range transimpedance amplifiers. The filters are optimized to minimize sampling jitter sensitivity. The resulting pulses have nearly Gaussian shape with broad flat top followed by a large flat inter-pulse interval. The clock signals, generated from the same optical pulse train are filtered to a sine signal. The input optical power levels are in the order of 450 µW. The photodiodes are operated close to saturation (prevent shot noise limited acquisition), but far enough to avoid clipping on modulation. After the pulse shaping the pulses are amplified and split differentially with an amplitude of 1 V, which allows use of the half of the ADC range (max 2.15 V) at full modulation by the electron beam. The ADC mezzanine board type ADC12FL (12 bit, 500 MHz, GPAC carrier board) has differential AC coupled inputs [13]. This prevents offsetting and stretching of the pulses at low signal regimes, having an impact on the BAM resolution. One ADC channel samples simultaneously both the pulse amplitude and the baseline with 428 MHz rate. This clock signal is derived from the optical pulses (214 MHz) synchronous with the ones modulated by the electron beam. Thus the modulation by the bunch is sampled always at the same sample position of the ADC. The optical pulses preceding the modulated one are used to detect the laser amplitude jitter, which determines the resolution. A typical number is 0.25%-0.3%, but the limit comes from the ADC resolution and not from the laser.

BAM MEASUREMENTS

To characterize charge and orbit dependence of the button pickup the reference laser pulses are shifted relative to the electron beam with a vector modulator with a step of 1 ps and positioning resolution of 166 fs. For each parameter, charge or orbit, the amplitude modulation

ISBN 978-3-95450-127-4

is recorded as a function of the vector modulator delay, from which dependence the slew rate is derived.

Pickup Characterization,Charge Dependence

The dependence of the button pickup resolution on the charge is shown on Fig. 4. Between 200 and 60 pC the resolution decreases slowly form 20 fs to 30 fs. Below 60 pC the degradation is faster and at 10 pC it reaches 170 fs.

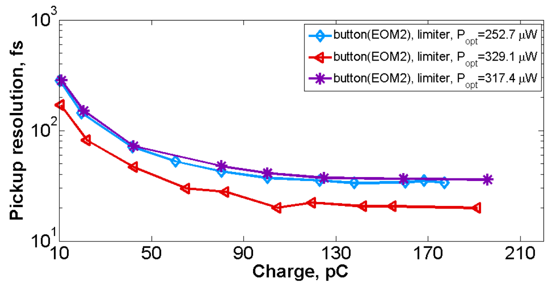

Figure 4: Pickup resolution dependence on the charge.

The main limitation on the BAM resolution with the present setup are the bandwidth of the feedthrus (20 GHz) and the EOMs (12 GHz). In addition, the AC input of the ADC card prevents offsetting the baseline and scaling of the amplitude of the laser pulses, so that to use its full 12 bit range independent on the charge. A 16 bit ADC and a signal conditioning DAC are in progress to improve the resolution and diminish the shot noise effect at low charge.

Pickup Characterization, Orbit Dependence

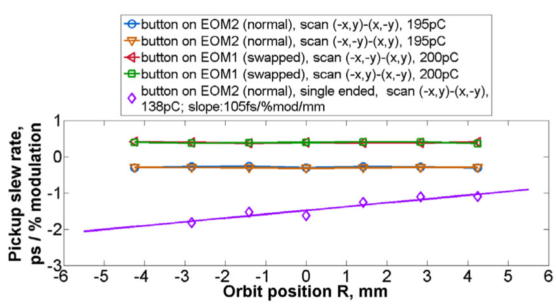

Figure 5: Orbit dependence of the button pickup slew rate.

For the orbit dependence measurements of the BAM pickup the orbit feedback was set such to create a trapezoidal longitudinal offset with the pickup being in the middle. The orbit position was measured with a BPM next to the BAM pickup. All the measurements were made with the button pickups NW-SE which are at -45° relative to the horizontal. A layout of the used ports and a map for the orbit scans is shown on Fig. 3. The orbit variation was made either along the axis of the pickups or in perpendicular direction. In the last set of scans only the button at the SE position was connected (single ended). For it the slew rate has a clear orbit dependence with a slope of 105 fs/%mod/mm. Due to the lower signal intensity, the slew rate is also larger (lower resolution). To prevent such orbit dependence during BAM acquisitions the opposite pickups are combined and the group delay in the cables and combiners are matched with accuracy 50 fs. Thus the orbit dependence of the slew rate cancels, as evident from the other two pairs of curves. For each pair the working point on the EOM transmission curve was set on the opposite EOM slope (case "normal" and "swapped", Fig. 5). Thus the sign of the slew rate changes, but the absolute value remains the same. For each set no orbit dependence is observed.

BAM Drift Measurement

A long term bunch-arrival time measurement is shown on Figure 6. The average charge was 130 pC. The optical fiber link was stabilized with accuracy 21 fs with the link motor compensating 47 fs of fiber drift. A feedback loop with amplitude 40 fs and gain 0.4 ensures that the BAM acquisition is kept always near the zero crossing of the pickup slope, determined in a calibration run. The resolution is 20 fs.

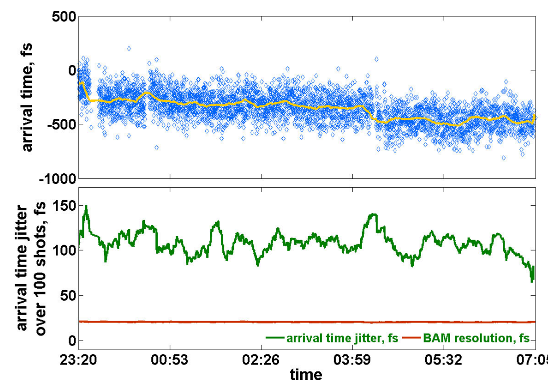

Figure 6: (upper plot) BAM drift measurement with the button pickup at mean charge 130 pC and with mean resolution 20 fs.
(lower plot) Arrival time jitter over 100 shots (~10 s) and instantaneous resolution.

The drift determined as a sliding average over 100 shots (approx 10 s) is 410 fs over 7 h 44 min. During the BAM measurement, there were several RF-interlocks when the bunch was interrupted (empty spaces on the drift plot). After recovery the BAM acquisition was resumed automatically. The lower plot shows the jitter, calculated as the deviation of the instantaneous arrival-time from the above smoothed average. The rms jitter is 110 fs and the peak is 150 fs. Jitter values of this order have been measured with BAM also earlier, before the commissioning of the optical fiber link. This jitter accumulates in the gun-laser amplifier and transfer line sections following the stabilized laser oscillator. To measure and minimize this influence, a dedicated laser arrival time monitor is under development.

The BAM ADC allows monitoring of the laser pulses preceding the modulated one, thus providing information about the instantaneous laser amplitude fluctuations (typically 0.25%) and thus the resolution (red curve on Fig. 6). The instantaneous resolution fluctuated between 19.8 fs and 21fs.

ISBN 978-3-95450-127-4

Bunch Arrival-Time Dependence on the Gun

Upstream of the bunch compressor the bunch arrival time jitter is dominated by fluctuations of the gun phase and the laser arrival time on the cathode [3]. By scanning of the gun phase it is possible to determine its partial influence on the arrival time, according to the equation:

$$G_{gun} = \frac{dt_{beam}}{dt_{gun}} = 2\pi f^{(S)} \frac{dt_{beam}}{d\phi_{gun}} \quad (1)$$

where $f^{(S)} = 2.9979$ GHz is the S-band gun frequency and the derivative can be determined experimentally, e.g. from the phase scan slope of Figure 7. At this particular run the BAM resolution was 17 fs, the bunch energy was 245 MeV with average charge 84 pC and length 3 ps.

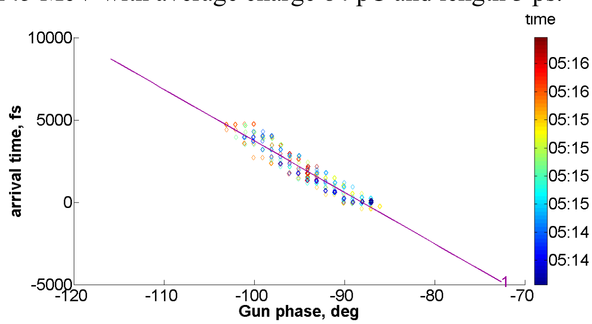

Figure 7: Bunch arrival-time as a function of the gun phase with slope 310 fs/deg.

A gun phase scan around a mean value of -94.3° with 4° (rms) deviation causes 1.9 ps bunch arrival time change (1.4 ps rms). The slope is 310 fs/deg. Thus, the partial contribution of the gun phase on the bunch arrival time upstream of the bunch compressor is 34%. This result is preliminary and demonstrates the sensitivity of the BAM on the gun phase.

SUMMARY AND OUTLOOK

A bunch arrival-time monitor based on a Mach Zehnder type electro-optical intensity modulator is installed and operational at the SwissFEL Test Injector upstream of the bunch compressor. The performance of the different subsystems has been investigated dependent on different environmental and machine parameters. The main limitation in view of the specifications for SwissFEL is the bandwidth of the pickup feedthrus and the one of the EOMs, which limit the performance at low charge below 60 pC. Development of a high bandwidth feedthru simultaneously having sufficient RF bandwidth (<40 GHz), mechanical robustness and vacuum compatibility is a challenge, which we are presently addressing with the support of industrial partners and institutes. Higher bandwidth and space-compatible EOMs are foreseen for tests with the BAM front-ends upstream the bunch compressor, which are to be installed in the winter shut down together with a new higher bandwidth pickup. In addition, we foresee tapered reduction of the beam pipe diameter for the pickup below the cut-off frequency of the X-Band cavity to suppress cross-talk. We foresee exchange of the ADC card with a 16 bit one. A remote controlled DAC front-end will allow dynamic signal conditioning for use of the entire ADC range, thus improving the performance at low charge.

REFERENCES

[1] SwissFEL CDR V20, (2012).
[2] F. Loehl et al., "A sub-50 fs bunch arrival-time monitor system for FLASH", DIPAC2007, Venice Italy, 23-25 May, (2007).
[3] F. Loehl, "Optical Synchronization of a Free-Electron Laser with fs Precission", DESY-THESIS-2009-031, (2009).
[4] M. K. Bock, et al., "Benchmarking the Performance of the Present BAMs at FLASH", TUPD28, DIPAC2011, (2011).
[5] M. K. Bock, "Measuring the Electron Bunch Timing with fs Resolution at FLASH", DESY-THESIS-2013-008, (2013).
[6] L. Pavlovic et al., "BAM at FERMI@ELETTRA", TUPSM086, BIW10, Santa Fe, NM, US, 15-19. April, (2010).
[7] J. Kim et al., "Drift-free fs timing synchronization of remote optical and microwave sources", Nature Photonics, vol. 2, pp.733-6, (2008).
[8] S.Hunziker, FEL-HS84-059-1, "RF Link Stabilization for BAM1", PSI-Memo, (2013).
[9] S. Hunziker et al., "Ultra-Low Drift and Jitter Laser-to-RF Direct Conversion Unit", IRUVX Report, WP8, Industrialization, (2011).
[10] Photop EDFA Specification, V90727 Vers. H, (2010).
[11] MX80 Precision Grade Prod. Manual-No.100-5326-01, Daedal Div., Parker Hannifin Corp., March 12, (2010).
[12] M. Dehler, V. Arsov, M. Kaiser, EuCard Grant Agreement-Nr.227579, Final Deliverable Report, D9.5.2, (2013).
[13] ADC12FL Manual, Rev. 1.1, PSI.

ISBN 978-3-95450-127-4