COMMISSIONING AND RESULTS FROM THE BUNCH ARRIVAL-TIME MONITOR DOWNSTREAM THE BUNCH COMPRESSOR AT THE SwissFEL INJECTOR TEST FACILITY

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Abstract

A high bandwidth Bunch Arrival-Time Monitor (BAM) has been commissioned downstream the bunch compressor at the SwissFEL Injector Test Facility (SITF). A new acquisition front end allowing utilization of the ADC full dynamic range was implemented. The resolution was measured as a function of the bunch charge for two different electro-optical intensity modulators (EOM). BAM measurements of machine relevant parameters were made. A comparison with the results from other diagnostics shows good agreement.

INTRODUCTION

SwissFEL is planned to start user operation in 2017 at charges between 10 pC - 200 pC [1]. To secure stable machine operation by applying feedbacks, as well as for decoupling of error sources manifested as bunch arrival time jitter, the latter should be measured non-destructively with resolution of 10 fs. In addition, BAM should have a low drift in the order of 10 fs/day. Such requirements are fulfilled for a scheme based on Mach-Zehnder type electro-optical modulator (EOM) [2], interfaced to a single-mode optical fiber link, through which reference laser pulses from a mode locked laser (few 100 fs pulse duration) are distributed [3]. These fiber links are stabilized in length via optical cross-correlation. A pick-up signal generated from the electron bunch is sampled at zero crossing with one of the reference laser pulses. At zero crossing this pulse is not modulated, but any temporal-offset of the beam produces a modulation voltage, which is converted in the EOM to amplitude modulation. With proper calibration, this amplitude modulation is interpreted in terms of arrival-time. An advantage of the method is that when acquiring the BAM signal with a fast ADC by sampling the amplitude and baseline points of the laser pulse-train, not only the pulse which interacts with the electron bunch is measured, but also multiple pulses preceding it, thus obtaining online information about the instantaneous BAM resolution. The technical difficulty is, that for the low charges foreseen for Swiss FEL, the pick-up response is small, thus limiting the resolution, as demonstrated with the first BAM prototype installed in SITF upstream the bunch compressor [4]. This paper describes the commissioning of a second BAM downstream the bunch compressor, for which several improvements were implemented, aiming for higher resolution at low charge.

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IMPROVEMENTS IN THE BAM SETUP

The general system topology and schematic layout was already described in [4]. The new BAM front-end is located close after the last dipole of the SITF bunch compressor. Among the improvements aiming to increase the resolution is the use of higher bandwidth components. The EOMs are 40 GB/s (33 GHz), PowerBit SD40 (Oclaro) and MXAN-LN40 (Photline) installed in the first and the second BAM channels. All the RF cables are PhaseMaster160 from Teledyne with 40 GHz band width, low-drift at 24°C and with low sensitivity to radiation [5]. The pick-up Type KX00-0258 with cone-shaped buttons and 40 GHz bandwidth was developed by DESY and TU-Darmstadt for the European XFEL and produced by Orient Microwave [6]. The design is for the European XFEL beam pipe diameter of 40.5 mm. The vacuum chamber is adapted on both sides to the 38 mm beam pipe of the SITF with 20 cm long tapers. For SwissFEL the same cone-shaped button pick-up feedthroughs were adapted for 16 mm beam pipe diameter. A prototype KX00-0293 has been ordered at Orient Microwave and is expected to arrive for test at PSI at the beginning of September. It is expected that the smaller beam pipe diameter of SwissFEL will provide for stronger RF signals, thus improving the resolution at low charge.

The only low bandwidth components inherited from the first BAM are the limiters N9356C (25dBm threshold, 26.6 GHz bandwidth, Agilent), which allow higher voltages and full utilization of the EOM half-wave voltage range. A higher bandwidth limiter Type N9355F (50 GHz, 10 dBm) was also tested, but for higher input voltages than the nominal 10 dBm it starts to distort the signal, thus spoiling the resolution.

The next modification aiming the achievement of higher resolution at low charge is the combination of a photoreceiver and an offset-DAC. The photoreceiver accepts higher input optical powers (~2mW) and has 3V pk-pk output at 0.5mW optical input. The amplification stage is externally accessible, allowing optimal adjustment of the RF signal thresholds, thus preventing saturation. The offset-DAC shifts the RF signal by a DC voltage to optimally match it to the acquisition ADC input thus utilize the full resolution (presently 12 bit). The use of this combination showed considerable improvement in the BAM resolution, which otherwise was unsatisfactory despite the high bandwidth components [7]. A 16 bit ADC which is expected to further improve the resolution was recently installed and beam tests are pending.

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Another improvement for BAM is the implementation of continuous bunch synchronous acquisition. The concept is described in [8], therefore it will only be summarized shortly here. The raw BAM traces from the two BAM channels are stamped with the bunch ID within the 10 Hz cycle and passed to the server as a single EPICS structured record. On the server side there are two buffers, which continuously exchange – while the first one is filled with data, the second one is slowly read at about 1 Hz with a high level application, e.g. Matlab. There the traces are split back and converted to bunch stamped arrival-time and instantaneous BAM resolution values. The continuous stamping has 100% reliability (no invalid events) with occasional slippage, i.e. omission of a following event (<0.1 ‰ occurrence).

BAM MEASUREMENTS

BAM Charge Sensitivity

Figure 1 shows the pick-up charge response of the first BAM channel when the reference laser pulse is swept across the RF transient with a vector modulator.

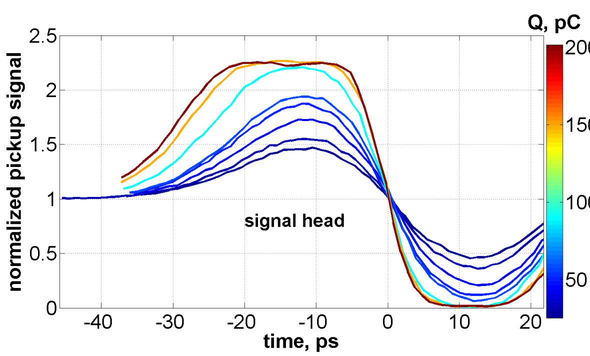

Figure 1: BAM pick-up signal sensitivity on the charge for the EOM1: PowerBit SD40 (Oclaro).

In the range 90pC – 200 pC the pick-up response was strong enough to engage the limiter and to completely utilize the EOM half-wave voltage range ($V\pi = 4.6$ V). In this charge range the measured BAM resolution was 10 fs – 13 fs (Figure 2, red circles), which at these conditions is solely limited by the 12 bit ADC. For lower charges the pick-up response was weaker and 100% modulation could not be achieved. The resolution was correspondingly lower, reaching 40 fs at 25 pC (Figure 2, red circles).

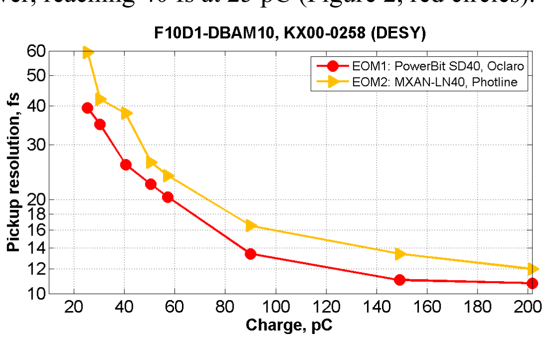

Figure 2: BAM resolution for the two EOM channels as a function of the bunch charge.

The EOM of the second BAM channel (MXAN-LN40, Photline) has a halve-wave voltage in the order of 9 V. The pick-up response was similar to the one of Figure 1 (same type of pick-up), but due to the larger $V\pi$ the slope steepness is smaller and so is the measured resolution (Figure 2, yellow triangle) . For EOM2 the resolution in the range 90 pC - 200 pC varied between 12 fs -16 fs and for 25 pC was reduced to 60 fs.

Measurement of the Bunch Compressor Dispersion Parameter R_{56} with BAM

The bunch compressor (BC) dispersion parameter R_{56} was measured in two ways. An established method is to use a transverse deflecting structure (TDS) and measure the position offset on a BPM when the energy is varied in a small range ΔE. This method is destructive for the beam. The alternative non-destructive method is to measure the arrival time offset δt with BAM for the same small energy change. All cavities were operated on-crest (no compression), including the one used normally to produce an energy chirp on the beam for compression. This cavity will be called FINSB03 further in the text.

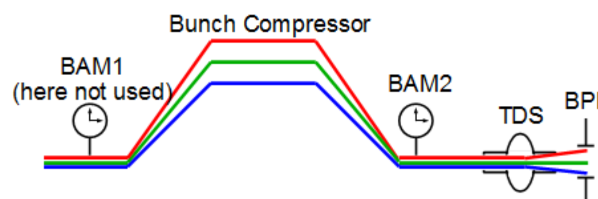

Figure 3: Scheme of the R56 measurement with the TDS and BAM. Beam energy E_1(red) < E_2(green) < E_3(blue).

The measurement is schematically shown on Figure 3. The higher energy beams (blue) take the shorter path in the bunch compressor and arrive earlier at the detector (BAM2). On contrary, the lower energy beams (red) take the longer path in the bunch compressor and arrive later at BAM2. Similarly, the time-dependent transverse deflection from the TDS results in different beam positions on the BPM, which are proportional to the small relative energy variation. A measure for the strength of the effect is the BC dispersion parameter R_{56}. Equation (1) shows the dependence between the arrival time change and the energy change:

$$\delta t = \frac{R_{56}}{c_0} \cdot \frac{\Delta E}{E} \tag{1}$$

Prior to the R_{56} measurement, the beam energy was precisely measured as a function of the low-level RF input to FINSB03 with a dipole spectrometer situated at the end of the machine. A set value variation between 0.2584 and 0.2784 (a.u.) corresponded to bunch energy variation of (200.70 ± 2.95) MeV.

R_{56} was calculated from equation 1, where the arrival time was measured with BAM. For this particular measurement the charge was 45 pC for which the BAM resolution was 24 fs. An example for one such measurement is shown on Figure 4, where the arrival time

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is plotted as a function of the above mentioned FINSB03 set energy variation. R_{56} is determined from the slope of the linear fit by accounting of all calibration constants.

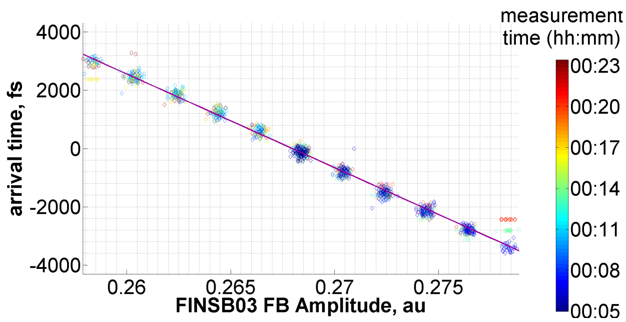

Figure 4: Example of the BAM sensitivity on FINSB03 amplitude change at on-crest operation corresponding to energy variation of (200.70 ± 2.95) MeV.

Several sets of such measurements were made for a fixed BC angle to evaluate the statistical errors. The BC angle was varied between 1° and 5°. The results are shown on Figure 5 for the TDS and BAM. The error bars are the rms values from the multiple measurements at a fixed angle. Both methods show good agreement with the theoretical curve (solid line).

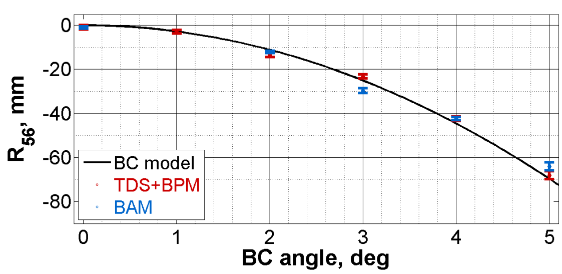

Figure 5: Measurement of the R56 for different BC angles with TDS and BAM.

Measurement of the Energy Jitter with BAM

For this measurement, the FINSB03 cavity, normally used to produce an energy chirp on the beam for compression, is operated at the negative zero-crossing, thus decompressing the beam. The principle is shown on Figure 6 schematically.

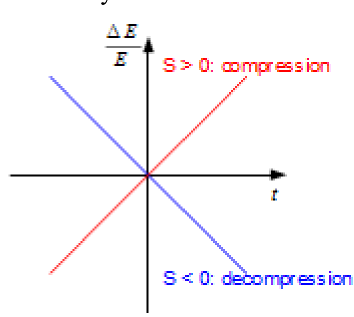

Figure 6: Arrival time dependence on the energy change ΔE/E caused by the RF field $U=\pm U_0 \sin(2\pi f t)$ at zero-crossing with a gradient slope $S=\frac{\Delta E}{E}\frac{1}{t}=\frac{1}{E}\frac{dU(t)}{dt}|_{t=0}$.

Usually for bunch compression, FINSB03 is set off-crest on the positive slope S to create an energy chirp, such that the beam head gains less energy than the beam tail, leading to compression in the magnetic chicane.

In the proposed measurement, FINSB03 was operated at zero-crossing at the negative slope, thus decompressing the beam. At these conditions, the initial arrival time jitter is enhanced. To quantify the effect, the reciprocal compression factor F_C is introduced:

$$F_C=\frac{t+\delta t}{t}=1+\frac{\delta t}{t} \qquad (2)$$

The compression factor is the ratio between the rms bunch lengths before and after the bunch compressor, with a larger compression factor meaning shorter bunch. In equation (2) the reciprocal compression factor F_C is expressed in terms of arrival time t and arrival time offset δt behind the bunch compressor and measured with respect to the bunch centre. $F_C > 1$ means bunch arrival-time delay and timing jitter increase (decompression), whereas $F_C < 1$ means earlier bunch arrival-time and timing jitter decrease (compression).

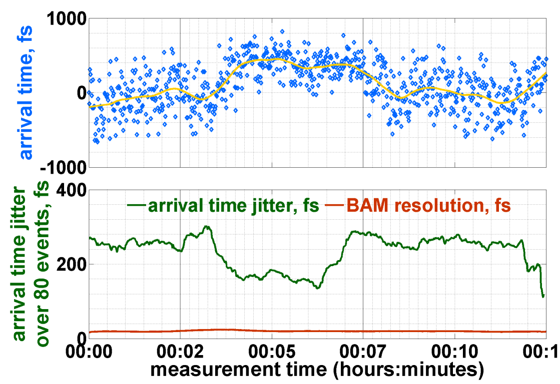

Figure 7: Arrival-Time jitter change when the FINSB03 cavity is cycled between on-off-on state. A clear decrease of the arrival time jitter (lower plot, green trace) to roughly 150 fs in the off-state is visible. The red curve on the lower plot is the instantaneous BAM resolution.

The effect of the timing jitter increase is illustrated in Figure 7, showing the arrival time (upper plot) and the arrival time jitter (lower plot). The lower plot shows also the instantaneous BAM resolution, measured online and simultaneously with the arrival time traces. The average BAM resolution was 20 fs at 50 pC.

Initially FINSB03 was turned on and set at the negative zero-crossing slope, leading to a large arrival time jitter band in the order of 250fs (rms). When FINSB03 was switched off, no additional energy chirp was induced to the beam and the jitter band shrunk to roughly 150 fs (rms). Eventually FINSB03 was turned on again, recovering the large jitter band.

F_C can be directly measured with BAM as a jitter enhancement at given RF settings compared to the jitter without compression. F_C can be also calculated from equations (1) and (2) with R_{56} = -46.9 mm.rad^2 (nominal

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BC angle 4.1°) and E = 130 MeV. The slope S of the field gradient (Figure 6) is calculated from the FINSB03 forward power P by using the calibration for the field amplitude U_0 from [9]:

$$U_0[MeV]=12.6\cdot\sqrt{P[MW]} \tag{3}$$

The measurements were made at three FINSB03 settings: 0 MW (FINSB03 was off), 4.5 MW and 9.4 MW. The timing jitter values were normalized to the one corresponding to FINSB03 switched off, at which the slope S was constant and the reciprocal compression factor F_C equals one. The results are shown on Figure 8.

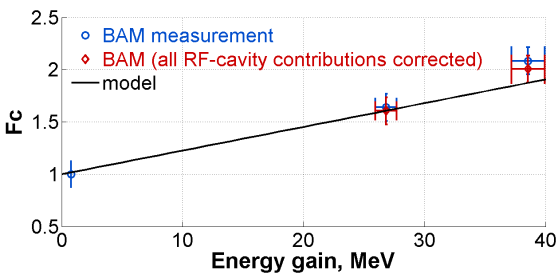

Figure 8: Beam decompression measured with BAM as rms arrival time jitter increase when the FINSB03 cavity is on (cavity powers 4.5 MW and 9.4 MW) at negative zero-crossing of the RF compared to the uncompressed state (FINSB03 RF-off).

The blue markers are the BAM measurements. The red markers are the arrival-time measurements corrected with the energy jitter contribution of all RF-cavities to the arrival-time. The error bars are calculated from the rms RF-cavity power change and the arrival-time resolution. The solid line is the model dependence. There is a good agreement between the measurement and the theoretical value. This measurement was dominated by the timing jitter upstream the bunch compressor, which was properly measured with BAM by accounting the influence of the RF-cavity phases and amplitudes.

Diagnostics Response Measurement

The diagnostics response measurements are thoroughly described in [10]. The BAM downstream the BC was among the used longitudinal diagnostics components. During runtime BAM was acquiring bunch ID stamped traces at 10 Hz simultaneously with the actuators used in the diagnostic response – bunch charge, cavity phases and amplitudes. After splitting and conversion into bunch-stamped arrival time the data were available for correlation with the other parameters. The measurements were made at 20 pC for which the BAM resolution was 50 fs, presently still limited by the ADC resolution and the insertion loss of the offset-DAC. With the new triple photoreceiver having more amplification and less saturation at high optical powers, a resolution of 40 fs was achieved at this charge (Figure 2).

CONCLUSION

10fs BAM resolution was demonstrated for 200 pC, thus meeting the specifications for the initial phase of SwissFEL at high charge. With the use of a 16 bit ADC card and a pick-up with 16 mm beam pipe diameter, it is expected to achieve an even better resolution. The measurements are pending before the decommissioning of SITF. The BAM downstream the bunch compressor was successfully used to measure SITF machine parameters. Presently the BAM server runs with Matlab, with the possibility to export the bunch stamped events in structured EPICS records. The goal is eventually the whole data processing to be done on the FPGA.

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