ISBN: 978-3-95450-192-2 doi:10.18429/JACoW-IBIC2017-TUPCC15

DESIGN AND COMMISSIONING OF THE BUNCH ARRIVAL-TIME MONITOR FOR SwissFEL

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Abstract

The Bunch Arrival-Time Monitor for SwissFEL (BAM) is based on the concept which was successfully tested at the SwissFEL Test Facility (SITF). During the gap between the SITF decommissioning and the start of SwissFEL, all key components underwent design improvement. In this paper, we report on some of these new developments and on the commissioning progress.

INTRODUCTION

SwissFEL is an X-ray free-electron laser user facility with two beamlines. The first one, Aramis, designed for electron energies between 2.1 and 5.8 GeV and for hard X-rays in the range 1.8 to 12 keV, has been inaugurated in December 2016 [1] and is presently under commissioning to reach its final design parameters. The second beamline, Athos, designed for energies between 2.65 and 3.4 GeV and for soft X-rays between 0.2 and 2 keV, is scheduled for commissioning in 2018-20.

According to the initial concept, totally five BAMs had been foreseen for the Aramis and two more BAMs for the Athos beam lines. These BAMs are capable for two bunch operation with 28 ns bunch separation at 100 Hz with <10 fs resolution in the charge range of 10 to 200 pC (simultaneous, single-shot non-destructive measurement).

Presently all pick-ups, most of the electronics and cabling, including the optical fibres, have been installed. Two stations, BAM1 at the laser heater and BAM3 after LINAC1 between the two bunch compressors, are fully equipped and presently under commissioning.

DESIGN OVERVIEW AND IMPROVEMENTS

The BAM concept was successfully demonstrated with two stations in SITF [2,3]. In view of the different girder and space limitations, for SwissFEL the BAM-box underwent a redesign. In SwissFEL the boxes are located under the granite girder, which serves as a radiation shield. Lead and boron-doped polyethylene sheaths are used for additional shielding. For servicing the box can be lifted up on wheels and pulled from below the girder. The last few meters of the cable tree and the optical fibres are laid in a flexible cable chain and are retracted together with the box. The housing lids provide additional isolation against acoustical noise and radiation. They are easily removable to allow servicing.

Pick-up and RF-Front End

The BAM pick-ups are cone-shaped buttons with 2.39 mm base (DESY design [4]), but modified for the SwissFEL beam pipe, 8 mm behind the undullator lines (BAM5 and 7) and 16 mm for the rest of the BAMs. The vacuum chamber mounts have five micrometer screws for vertical and lateral fine centring of the chamber axis to the beam.

The button pairs in each of the two orthogonal axis are combined together to minimize the orbit dependence. The 20 mm long PhaseMaster160 cables (Teledyne) and the couplers, type PS2-55-450/17S, Pulsar Microwave, are fixed in dedicated mounts close to the pick-up chamber. The output of the coupler is connected to the EOMs with armoured PM160 cables, 0.7 m for the EOM1 (high resolution branch) and 1.2 m for the EOM2.

To prevent orbit dependence and spoiling of the pick-up RF-transient quality, the relative group delay of the two branches from the pickup to the combiner has to be minimized. Initially the combiners were measured separately and then matched to a cable pair, which best compensated the relative group delay of the two combiner ports. An example from BAM4, located after LINAC3, is shown on Fig. 1. Up to 40 GHz the pk-pk relative phase between the combiner inputs is 5.5 deg (380 fs mean group delay difference), red curve. A cable pair from many samples has been selected to have 5.4 deg relative phase difference (384 fs mean group delay), blue curve. The entire package has 3.0 deg pk-pk relative phase difference (103 fs mean group delay), green curve. This best possible match is not perfect. The reason is the amplitude and phase relations at higher frequencies for the high bandwidth PS2-55-450 combiners (1 - 40 GHz).

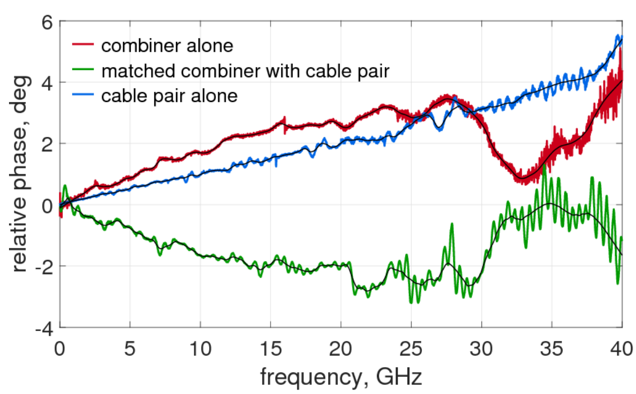

Figure 1: Phase match of the RF combiner and cables (BAM4).

Optomechanical Front End (BAM-Box)

The BAM-box is temperature stabilized with 8 large surface Peltiers. The mechanical design was improved to reduce the shear stress between the regulated base plate and the heat sinks by using flexible fixtures. Typical temperature stability for the components in contact with

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the regulated base is <5 mK over 1 h and <10 mK over 12 h. The typical box volume stability is 20 mK.

The EDFAs are commercial components from Photop, customized for PSI. They are bidirectional, high gain (>10 dB), operated either in constant current or constant power mode. The fibre length from the input to the output is 2 m (excluding the gain fibre, 0.8 m Liekki ER-80/125). The controller board is mounted directly on the housing and is interfaced to EPICS via RS232. Four diodes monitor the optical power in the forward and the backward directions. EDFA1 is set for optimum power in the link, EDFA2 optimizes the power for the readout electronics. Its output power is actively used in the user applications, described below.

The polarization scanner (PSC-15-2-1, Fig. 2) is a commercial component from Phoenix Photonics. The polarization is controlled with EPICS. The DC voltages for the three quarter waveplates are delivered from a DAC in the technical gallery. The signals are low pass filtered. PSC-15 is modified such that to be constantly enabled by the supply voltage. PSC precedes the Faraday rotating mirror (reflection/transmission = 10/90, PN: 500-25290-12-1, Lightel) and is thus part of the fibre optical link.

Two EOMs are used for BAM detection. The one for high BAM resolution, Power Bit SD40, II-VI company, has 40 Gb/s bandwidth and 4.5 V half-wave voltage. The one for the large dynamic range, MXAN-LN10, Photline, has 10 GHz bandwidth and 6.5 V half-wave voltage. To reduce the distance to the pickups, the EOMs are mounted on a 165 mm high holder. The so increased distance to the temperature stabilized base plate is a trade off for the reduced drift and attenuation in the RF cables from the pick-up. When the box reaches thermal equilibrium, the EOM temperature equals the one of the regulated base plate, namely few mK over 12 h.

To reduce the length of the out-of-loop fibres in the BAM-box, no bias controllers are implemented. The EOM bias working point setting and the bias stabilization are made with EPICS by using the available rack electronics in the technical gallery.

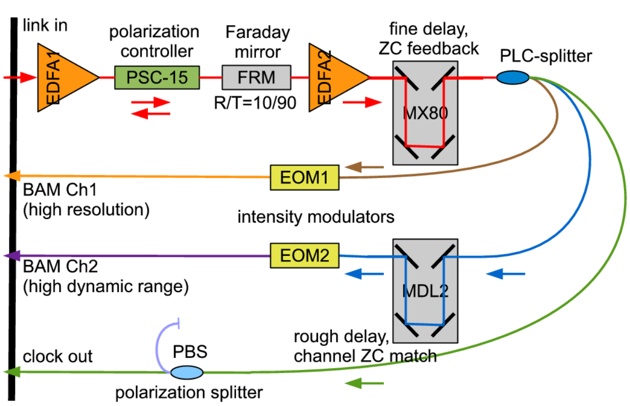

Figure 2: Layout of the BAM-box components.

The core of the BAM front end is a high-end precision linear servo motor positioner, 3 phase, 8 poles, 100 mm travel range, Type MX80, Parker, with a built-in digital incremental encoder and resolution of 10 nm (Renishaw RGH24O). This stage is used for zero crossing feedback of the arrival time signal and for calibration of the BAM slopes. Because the feedback requires frequent movement within few mm, no piezo-driven or spindle positioners can hold. The MX80 stage was used already in the SITF BAM prototypes with no failure due to radiation or a mechanical wear off.

The controller, ACJ-055-18, Coupley Controls, is also mounted in the BAM-box. There are fully implemented digital current, velocity and position loops, which are pre-programmed on the controller. The control is made with ASCII commands from a RS232 server in the technical gallery, providing the travel trajectory, homing, velocity, acceleration, position, etc. The maximum velocity is 30 mm/s and the accelerations are 60 mm/s^2.

The controller actively uses the readouts of the digital incremental encoder and in addition also outputs the raw quadrature signals, thus allowing independent (deterministic) position readout and bunch ID stamping.

After SITF decommissioning, a VME encoder counter counter card, type ECM514, was successfully tested for bunch ID stamping and is presently installed for all BAM stations in SwissFEL. The standard firmware was changed such, that a dedicated index register holding the motor encoder positions is triggered by the event system and the value is latched until the next cycle, during which EPICS assigns the bunch number and the event valid flag.

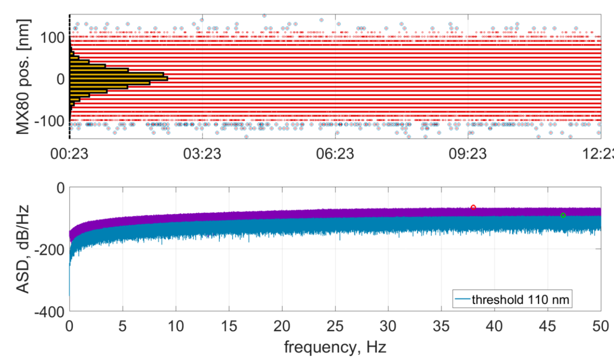

Figure 3: BAM3 delay stage position jitter.

Without a holding current the MX80 stage is loose, but when operational, the three loops keep it rigidly in place. Depending on the loop settings, when not moved, the motor performs small oscillations around the set values. The amplitude is < 1 fs, which is well below the required BAM sensitivity. Potentially the stage is susceptible to vibrations, but long term observations with the two BAM stations installed in SwissFEL show no significant disturbances even during heavy instillation work on the site. Presently there is an EPICS application and a Matlab tool with which large deviations of the motor positions are captured and the expert is informed via Email or SMS. Also there is a dedicated buffer, which captures the motor positions at 100 Hz and from which the acceleration spectral density (ASD) is calculated. Thus potential disturbances up to 50 Hz can be identified. So far on very rare occasions specific peaks were detected. An example from BAM3 for a typical undisturbed operation is shown

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on Fig. 3. The rms jitter is 24 nm (80 as) and the pk-pk value is 290 nm (1 fs). Only few positions (blue circles on Fig. 3) exceed the alarm threshold set at 110 nm (366 as).

The free space defined by the MX80 stage marks the border between the single mode and the polarization maintaining fibres in the BOX (Fig. 2). The sender and the receiver collimators, Type CLB-155-28 (SMF28) and CLB-155-15 (Panda PM), Princetel, have a focal length of 11 mm, divergence of 0.5 mrad and beam size of 2 mm.

A typical coupling efficiency profile over the travel range is shown on Fig. 4. for measurements on different days at circumstances explained in the legend. The example is from BAM1. The coupling efficiency is normalized to the peak power. It varies between 0.2 dB and 0.27 dB, but the profile shapes remain similar. The largest deviation was measured when the BAM-box was transported from the lab to the SwissFEL tunnel before re-alignment. After that the stability of the coupling efficiency remained constant over months without the necessity for realignment.

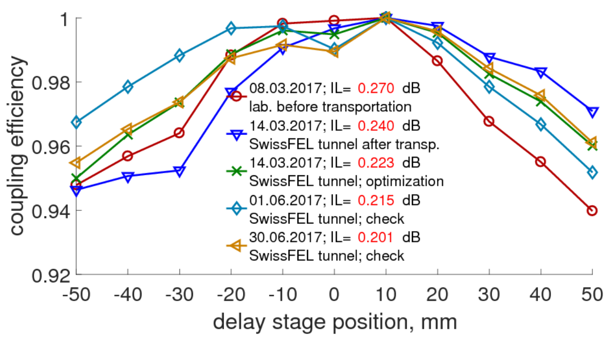

Figure 4: BAM1 delay stage collimator alignment.

EXPERT USER APPLICATIONS

During the SITF phase multiple expert applications ran with Matlab on PC consoles in the control network. After the decommissioning at the end of 2014 one station was kept as a development platform for a variety of new advanced techniques, including a method for embedding MATLAB programs into the EPICS IOCs.

EOM Bias Scan Tool

The tool allows determining of the EOM transmission curves, and setting of the working point. There are two user selectable modes - setting for the maximum and for quadrature. The first one is used for system tuning, the second one is the standard BAM acquisition mode. The tool outputs parameters, which are used by other routines, such as the bias slope, the insertion loss at the working point, the half-wave voltage, etc. The actuator for the bias scan is a "slow" DAC (20 kHz, 16 bit Hytec 8402), the detectors are "slow" ADCs (100 kHz 16 bit Hytec 8401), which measure the DC photocurrents from the EOM1 and EOM2 channels of the BAM photoreceiver (PRX). All the electronics is located in the BAM racks in the technical gallery.

With proper range setting, the embedded script which runs with EPICS, finishes the scan in approximately 15 s, 5 times faster than the previous Matlab script deployed on a remote console.

Polarization Stabilization Tool

The BAM fibre links are standard single mode fibres. The EOM transmission is polarization dependent, therefore for stable BAM detection the polarization has to be stabilized.

The polarization variation is slow, therefore the network speed is not a limiting factor. The stabilization tool is made with onboard HW components and by using EPICS. The actuators are the three quartar-waveplates of the polarization scanner, controlled by DACs in the technical gallery (Fig. 2). The fibre polarization beam combiner is the analyser. The polarization dependent insertion loss (IL) is defined by the EDFA2 output power, provided to EPICS by the EDFA controller via RS232, and the DC photocurrent of the PRX clock channel, measured with an ADC.

The routine follows a standard optimization logic, which applies also for manual polarization adjustment. First, waveplate one (WP1) is toggled in small steps until the insertion loss in the PRX clock channel is minimized. Then, after a certain delay, the second and finally the third waveplates (WP2 and 3) are changed. The scanning steps and the delays are selectable from the expert panel. Also, if desired, any waveplate can be excluded from the cycle. A safety feature disables the script if the EDFA2 output is low.

From the GUI there is a possibility to visualize the polarization stability for 1 h and for 12 h (buffers on softioc). The tool opens five strip charts, which display the buffers for the insertion loss (IL), the absolute power of the PRX clock channel and the variation of the three waveplates. The sampling rate is 1 s. In addition the statistics on all curves is calculated - minimum, maximum, peak-peak, average and standard deviation values. For all these there are dedicated EPICS channels which can be extracted for processing and archiving, e.g. with Matlab. An example from the BAM3 station, placed after LINAC1 between the two bunch compressors, is shown on Fig. 5.

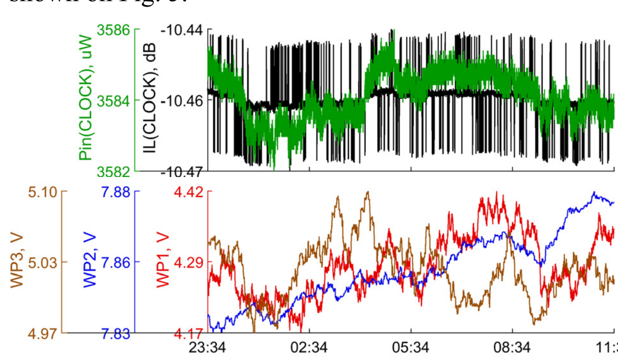

Figure 5: BAM3 polarization stability over 12 hours.

The peak-peak stability of the insertion loss over 12 h is 0.02 dB. The absolute pk-pk power variation is 4 µW. At stable conditions the variation of the waveplates is small, in the order of few hundreds of mV.

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EOM Bias Stabilization Tool

The experience from SITF showed that after a bias scan, when the working point for BAM measurement was set, the EOM transmission would drift. The smaller the EOM half-wave voltage, the bigger the drift. After few iterations for readjusting of the bias manually, the drift became small. One explanation for the effect is the building up of space charge in the EOM crystal with the changing laser power (short pulses).

There are commercial EOM bias controllers on the market, some of them with a small footprint, e.g. MBC-DF-UC-U from Pharad. We have tested such controllers and considered their integration in the new BAM-box design, including the special fibre management.

The combination of an EOM and a bias controller requires a closed fibre loop between them. For the splicing, a minimum fibre length is necessary, which makes the handling difficult and in addition increases the length of the out-of-loop fibres in the Box. The new Box design solves the problem with the fibre handling, but in order to reduce the fibre drift, we decided initially not use the controllers. Instead the bias stabilization is done with EPICS in a similar way as the polarization control tool.

There are two versions of the script which differ in complexity, but deliver similar results. Both use the EOM insertion loss, defined by the EDFA2 output power and the DC photocurrent of the PRX EOM1 (or EOM2) channel, measured with an ADC

The first bias stabilization script compares the instantaneous EOM insertion loss with the set value and if the difference is larger than a certain preset value, a correcting bias is applied. The loop set point, the set point tolerance and the gain are selectable from an expert GUI. The values for the loop set point and the bias slope are automatically overtaken from the EOM bias scan script, but the expert can change them also by hand.

The script uses different step sizes depending on how far is the instantaneous insertion loss from the set value. Thus the required bias is achieved within seconds and then is slowly controlled over hours. It is possible to go to the working point form any initial value, e.g. starting from maximum. This is especially convenient, because the 3 dB offset between the maximum and quadrature can be easily set in the GUI.

From the GUI it is possible to display the bias stability for each of the two EOMs for 1 h and for 12 h (buffers running on softiocs). The tool opens three strip charts with the buffer values for the EOM insertion loss (IL), the absolute power of the PRX EOM channel and the EOM bias voltage. The sampling rate is 1 s. In addition the statistics on all curves is calculated. The script is automatically disabled, if the input optical power is low.

An example from the BAM3 station for the EOM bias stabilization with the "simple" script is shown on Fig. 6. The peak-peak stability of the EOM insertion loss over 12 h is 0.03 dB. The absolute pk-pk power variation is 7 µW. The lowest plot shows the correcting DC bias, which peak-peak value is 40 mV.

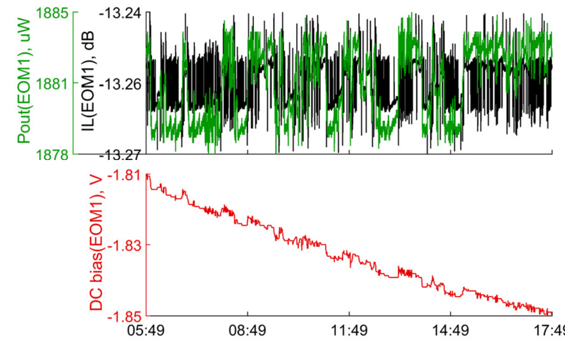

Figure 6: EOM1 bias stability over 12 hours for BAM3.

The second EOM bias stabilization script uses PID approach. In the expert GUI the user can select the insertion loss set point, the loop time constant, the P, I and D gains. The instantaneous insertion loss is measured in EPICS in a similar way as in the "simple" script, but the error signal is calculated according to the PID gains and the EOM bias slope, determined beforehand with the bias scan tool. The proper choice of the gain parameters requires expertise. Good results are obtained with the Ziegler-Nichols method [5] when initially the I and D gains are set to zero and the P gain is increased until the loop starts to oscillate. The period of oscillation is then used to set I and D. As with the other tools, the script was written initially in Matlab and then embedded into the IOCs. An example from the BAM test station after SITF decommissioning is shown on Fig. 7.

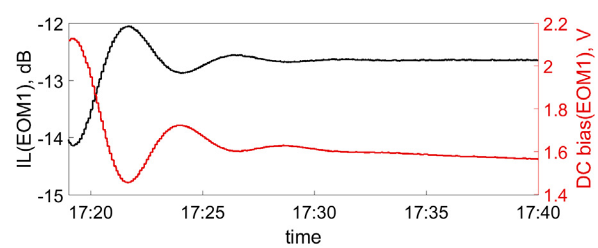

Figure 7: Settling of the EOM bias with the PID stabilization script.

CONCLUSION

The first two SwissFEL BAM stations have been taken into operation. Commissioning with beam is ongoing.

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