PROTOTYPE OF THE IMPROVED ELECTRO-OPTICAL UNIT FOR THE BUNCH ARRIVAL TIME MONITORS AT FLASH AND EUROPEAN XFEL

H. Dinter*, M.K. Czwalinna, C. Gerth, K. Przygoda, R. Rybaniec, H. Schlarb, C. Sydlo
DESY, Hamburg, Germany

Abstract

At today's free-electron lasers, high-resolution electron bunch arrival time measurements have become increasingly more important in fast feedback systems providing accurate timing stability for time-resolved pump-probe experiments and seeding schemes. At FLASH and the upcoming European XFEL a reliable and precise arrival time detection down to the femtosecond level has to cover a broad range of bunch charges, which may even change from 1 nC down to 20 pC within a bunch train. This is fulfilled by arrival time monitors which employ an electro-optical detection scheme by means of synchronised ultra-short laser pulses. At both facilities, the new bunch arrival time monitor has to cope with the special operation mode where the MHz repetition rate bunch train is separated into several segments for different SASE beam lines. Each of the segments will exhibit individual timing jitter characteristics since they are generated from different injector lasers and can be accelerated with individual energy gain settings. In this paper, we describe the recent improvements of the electro-optical unit developed for the bunch arrival time monitors to be installed in both facilities.

INTRODUCTION

The signal creation, detection and analysis in the electron bunch arrival time monitor is split into several subsystems, each fulfilling a particular task at their respective position in the signal processing chain. These include:

- The **RF unit** comprising four broadband pickups mounted in the beam tube in order to capture the electric field induced by the passing electron bunches [1]. The signals of opposite pickups are combined for a reduced position dependence of the measurement, resulting in two independent RF channels for the arrival time detection: Left + Right and Top + Bottom [2].
- The **electro-optical (EO) unit** converting the RF signal into an amplitude modulation of time-stabilised, ultra-short laser pulses provided by the optical synchronisation system [3,4] in order to achieve a high temporal sensitivity.
- **Electronics** for signal readout and control of the individual subsystems [5]. This part also performs communication with high-level control systems.

The general layout of the signal processing chain is illustrated in Fig. 1.

ELECTRO-OPTICAL UNIT

In this paper, we focus on the recent developments for the electro-optical part of the detection system. A schematic of the optical signal chain is shown in Fig. 2. Synchronised laser pulses enter the optical circulator at the top left and exit it on the right. A subsequent fast bidirectional fibre-optical switch acts as a selector which optical delay line is to be used for the current electron bunch subtrain.

After passing the delay stage and travelling back through the optical switch, the laser pulses are directed to the downward facing port of the circulator. An optical amplifier increases the signal level before it is split into three branches: one clock channel used as a trigger input for the sampling electronics and two channels leading to electro-optical modulators (EOM) corresponding to the two RF signal channels.

One of the signal paths leading to the EOMs provides the possibility of introducing an additional time delay through a separate optical delay stage. This can be used for adjusting the relative timing between the two channels, which might be necessary due to different RF cable lengths.

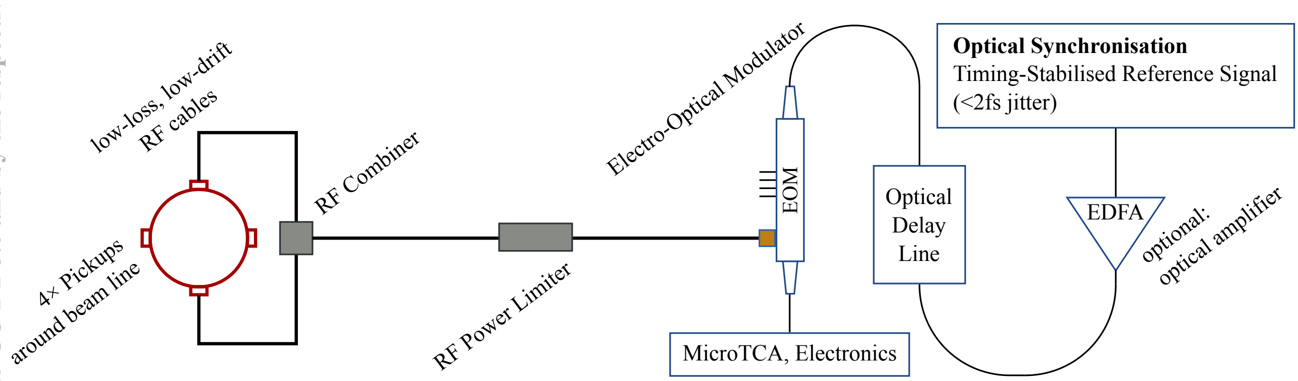

Figure 1: Basic layout of the cabling scheme (only one detection channel is shown).

* hannes.dinter@desy.de

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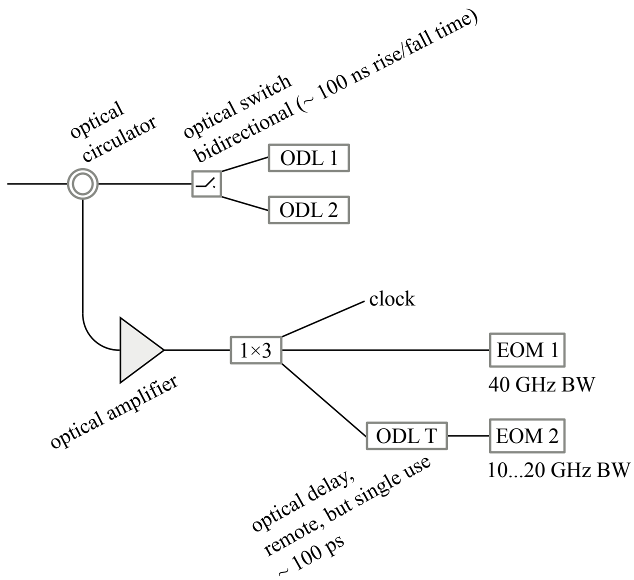

Figure 2: Optical signal processing chain.

In the EOMs, the laser pulses undergo an amplitude modulation depending on the arrival time of the electric signals coming from the RF pickups in the beam tube [6]. Changes in the timing of the electron bunches and thus of the electric signals result in a different modulation of the laser intensity, which is then detected by the readout electronics. By making use of the ultra-short, time-stabilised pulses from the optical synchronisation system, this detection scheme provides a high resolution combined with a timing accuracy in the range of a few femtoseconds [3].

OPTICAL DELAY STAGE

In order to achieve a high timing resolution, the EOMs are operated at a working point where the modulation of the laser pulses depends linearly with a steep slope on the arrival time of the electric signal. If the timing of the electron bunches and thus of the pickup signals changes by a large amount, the EOM is not longer driven in its linear regime, leading to measurement errors. In order for the system to stay within the working range, it is in such cases necessary to adjust the relative timing between the reference pulses and the electron bunches.

Figure 3 shows a photograph of the newly developed optical delay stage designed for this task. The adjustable timing delay is introduced by a retroreflector mounted on a commercially available motorised stage.[1] The laser pulses entering the setup through the optical fibre at the bottom right are coupled out by a collimator, directed to the retroreflector by two mirrors and coupled back into fibre by a second collimator. On its way, the free-space beam passes two wave plates which can be used for adjusting the polarisation.

By driving the motor stage, the optical path between the collimators and thus the transit time of the laser pulses is changed. The stage has a travelling distance of $\Delta z = 70$ mm, leading to a dynamic range of $2\Delta z = 140$ mm, or 467 ps, as the light passes this path twice on its way to the retroreflector and reverse. The optical power variation at the output is less than 10%, measured over the whole travelling distance.

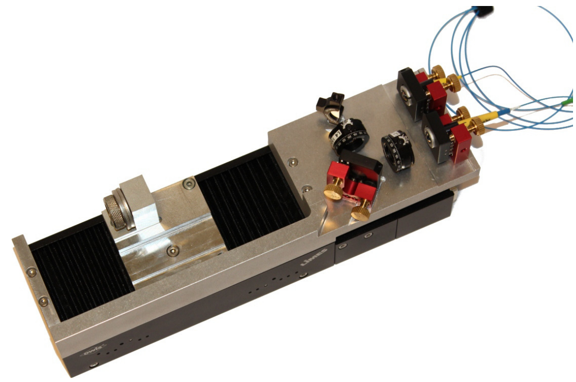

Figure 3: Optical delay stage.

Optionally, the second collimator can be replaced by a plane mirror, doubling the optical path length and the dynamic range of the system at the cost of reducing the positioning accuracy. In this case, the maximum delay is 934 ps. It is still to be investigated which of the two options provides better performance in terms of operating range vs. positioning precision and reproducibility.

BIDIRECTIONAL OPTICAL SWITCH

A key feature of FLASH and the European XFEL is the operation mode of a common linear accelerator driving multiple SASE beam lines [7]. The separate experimental end stations pose individual requirements on photon wavelength, spectral profile and pulse duration, raising the necessity of accelerating different parts of the electron bunch train with differing energies as well as unequal charges (see Fig. 4). This results in individual and varying timing characteristics among the separate bunch subtrains.

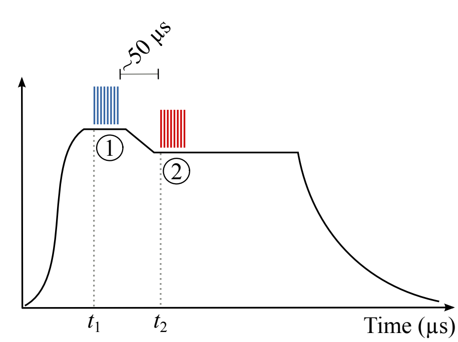

Figure 4: Electron bunch subtrains for different SASE beam lines.

The linear range of the modulated output signal of the EOMs is typically 2 ps to 4 ps. This is a consequence of the high sensitivity of the detection scheme. The timing between the electron bunches and the optical reference pulses needs

[1] OWIS LIMES 60-70 HSM

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to be adjusted for each subtrain individually as soon as it leaves the linear region.

The transition time between the different parts of the bunch train lies in the range of a few tens of microseconds, which exceeds the feasible driving speed of the optical delay stage. Instead, the different timings are realised by using a separate optical delay stage per subtrain.

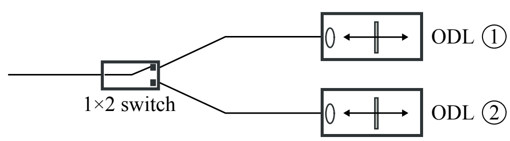

Figure 5: Individual optical delay stages for different electron bunch subtrains.

The toggling of the laser pulses' path between the different delay stages is carried out by a fast optical switch, as indicated in Fig. 5. The light passes the switch in both directions, therefore the use of a bidirectional device is necessary. An extension of this scheme to three or more optical delay lines is possible by using multiple switches in series or a switch with more than two outputs.

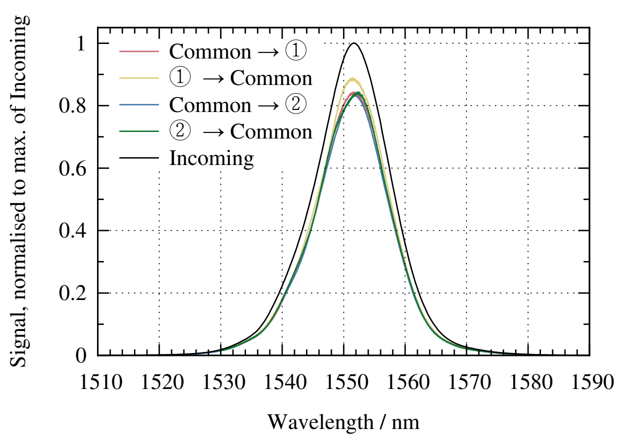

Figure 6: Optical spectrum of laser pulses after travelling in different directions through different ports of a bidirectional optical switch, compared to the spectrum of the incoming light.

Tests of the performance of a commercially available fast, bidirectional, polarisation maintaining fibre-optical switch[2] have been conducted in order to evaluate the switching speed and the device's influence on the optical spectrum of the laser pulses. The rise and fall times of laser light travelling in different directions through different ports of the switch have been measured to be around 100 fs at a repetition rate of 100 kHz. This duration is well below the available switching time of ~ 50 µs needed for the transition of the RF field in the accelerating cavities. At the exit of the switch the laser pulse amplitude is reduced by approximately 15% compared to the incoming light. The spectral shape is preserved, as shown in Fig. 6.

[2] AGILTRON NanoSpeed™ 1 × 2 bidirectional fibre-optic switch with 100 kHz driver

ELECTRONICS

For the control and monitoring of all subsystems several supporting electronic components are included in the setup:

- **TMCB** (Temperature Monitoring and Controls Board), developed at DESY for general purpose use in stand-alone devices. It is a versatile FPGA (Spartan6) board with 14 diverse ADC channels, 10 DAC channels, 4 temperature read-outs and 20 configurable GPIOs. It provides interface via Ethernet (RJ45) or optical communication (SFP+).

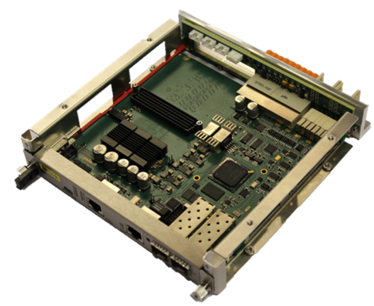

Figure 7: TMCB.

- **LDD** (Laser Diode Driver), developed at DESY. It is a high-precsion, low noise laser diode current driver and TEC controller. It has a compact mezzanine form factor with CAN and Ethernet interfaces and is suited for stand-alone operation.

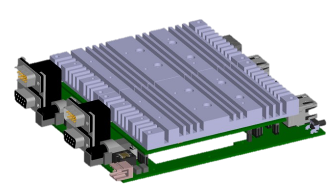

Figure 8: LDD.

- **FRED** (Fuse and Relay Board). This board was developed at DESY and is used in many 19" devices in electron diagnostics and beam control. It allows for remote monitoring and control of up to 8 DC voltage channels with individual fuses and current-limitations.

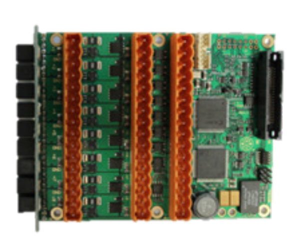

Figure 9: FRED3M.

- As temperature controller, a commercially available TEC controller[3] is used. It is remotely supervised using digital pins on the TMCB over the RS232 protocol.

[3] Meerstetter TEC-1091

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THERMAL CONCEPT

In order to maintain the high timing stability of all involved components, the environmental conditions inside the unit have to be kept as stable as possible. Temperature variations lead to timing drifts in optical fibres (typically 30 – 50 fs / (K · m)) and working point shifting, e.g. of the EOMs. For a reduced susceptibility to external changes, all timing-critical components are mounted inside a thermally insulated and actively temperature stabilised compartment.

The electro-optical unit is housed in a 19" box, accommodating all optics, fibre-optics, DC and RF electronic devices. Only the DC power supplies are assembled as an external device.

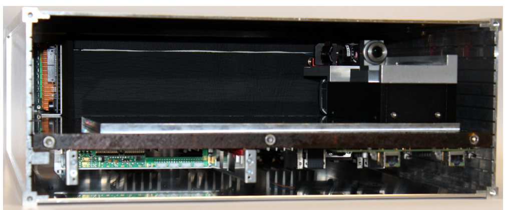

Figure 10: Front view of the 19" box housing the electro-optical unit. The middle plate separates the two temperature compartments.

The chassis is separated into two compartments, see Fig. 10. In the lower compartment (see Fig. 11), all components which introduce larger heat load, like TMCB, LDD, TEC controller and radiators of peltier elements, are mounted. The upper compartment (see Fig. 12) is thermally insulated from the lower part. In the front, a passively temperature stabilised area for the optical delay stages is located. In the rear, an actively temperature stabilised box with the sensitive fibre-optics and RF components is mounted.

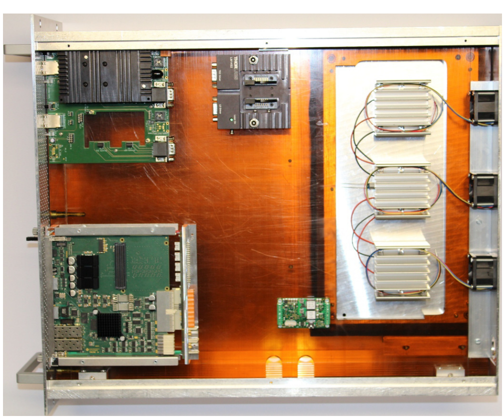

Figure 11: Lower compartment.

The temperature regulation by means of thermoelectric heating/cooling acts on a metallic base plate on which all parts are fixed. The thermally stabilised air volume is enclosed by a plastic box which is encased in heat insulation. A PID temperature controller is used for stabilising the base plate to $|\Delta T| < 0.01$ K.

Figure 12: Upper compartment.

Venting is achieved from front to rear with fans. This fits to the air conditioning concept of the 19" racks, which should deliver a stability of ±0.1 K by design.

SIGNAL READOUT

For sampling the modulated laser pulses exiting the EOMs a setup based on MicroTCA [8] electronics components is used. The digitalisation is done using an FMC board specially designed for the BAM readout (DFMC-DSBAM). It incorporates 4 ADCs for two channel interleaved sampling at up to 250 MSPS with 16 bit resolution, and has photo diodes and clock generation on board [9].

Figure 13: MicroTCA chassis equipped with x2timer, DAMC-FMC25 and DFMC-DSBAM modules.

Currently ongoing activities include circuit board design and evaluation, firmware development and high-level software programming. In Fig. 13, a photograph of a MicroTCA system used as a laboratory setup is shown. It is equipped with general-purpose timing and compute cards as well as the DFMC-DSBAM used for testing and development activities.

Figures 14a and 14b show test results from this setup. A series of laser pulses coming from a reference oscillator was scanned by changing the delay between the clock and sampling channels of the DFMC-DSBAM. The temporal

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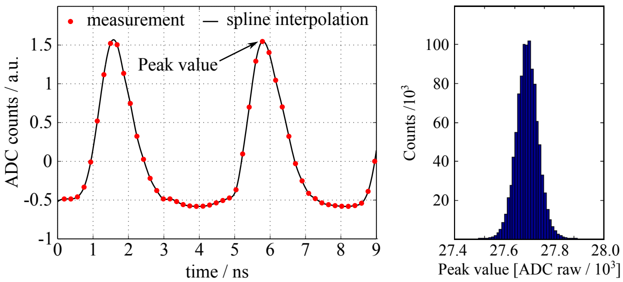
profile of the laser pulses is reproduced within the analogue bandwidth of 1 GHz.



(a) Laser pulse train sampled by scanning the ADC clock delay.

(b) Distribution of detected peak values (1000 pulses).

Figure 14: Readout of optical pulses using the direct sampling electronics of DFMC-DSBAM.

A peak detection accuracy with better than 0.3% (STD) (from Fig. 14b) gives an upper limit of the cumulative amplitude jitter including laser pulse input, clock jitter and ADC resolution. Developments are ongoing to improve the amplitude detection accuracy in hardware and firmware.

CONCLUSION

A prototype of the improved electro-optical unit for the bunch arrival time monitors at FLASH and the European XFEL has been developed and is currently under construction. All included as well as supporting external components have been assembled and have been or are presently being tested. First measurements using the new signal processing and acquisition electronics show promising results and are in agreement with the expectations.

Current activities include the finalisation of the unit's internal cabling, mounting of the optics and ongoing firmware and high-level software developments. Further tests and performance evaluations will be conducted as soon as the setup reaches its final state. After completion of these steps the device will be installed in the injector section of the European XFEL for testing and commissioning with electron beam.

In the long term, at FLASH, eight bunch arrival time monitors will be installed or upgraded to the improved design, while up to ten setups are planned for the European XFEL, yielding in total 18 diagnostics stations needing to be equipped with electro-optical units of this kind. Once the prototype has proven its functionality in operation with beam, further devices are planned to be series manufactured and commissioned at the respective locations. An installation and testing routine is currently being developed on the basis of the experience gained with the prototype unit.

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