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REAL-TIME MEASUREMENTS OF THE RF-PATH OF AN ELECTRO-OPTICAL BUNCH ARRIVAL-TIME MONITOR WITH INTEGRATED PLANAR PICKUP STRUCTURE WITH LOW-CHARGE ELECTRON BEAMS AT ELBE

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Abstract

Ultra-low-charge operation of free-electron lasers down to 1 pC or even lower, requires adequate diagnostics for both, the users and the operators. For the electro-optical bunch-arrival time monitor a fundamental design update is necessary to yield single-digit fs precision with such low charges. In 2023 a vacuum sealed demonstrator for a novel pickup structure with integrated combination network on a printed circuit board was built for operation at the free-electron laser ELBE at HZDR. Together with a new low-pi-voltage ultra-wideband traveling wave electro-optical modulator, this concept reaches an estimated theoretical jitter charge product of 9 fs pC. Proof-of-concept measurements with the pickup demonstrator were carried out at ELBE.

INTRODUCTION

Many X-ray free-electron laser (XFEL) facilities, such as the European XFEL and FLASH at DESY, ELBE at the HZDR and the SwissFEL at PSI, use an electro-optical (EO) synchronization scheme [1–4]. For this scheme a pulsed laser is locked to the main oscillator in a phase-locked loop and emits short laser pulses as timing reference [5]. They are distributed along the accelerator and to the experimental hall through actively length-stabilized optical fibres. The link to the substation in the experimental hall at the European XFEL is 3.5 km long [2, 5, 6]. The pulses are used for synchronization of various subsystems and also as reference for relative arrival-time measurements in the electro-optical bunch arrival-time monitors (EO-BAM) [2]. This method allows unprecedented accuracy for the electron bunch arrival time measurement important for arrival-time stabilization and various experiments.

In the EO-BAM an evanescent voltage pulse, induced by the bunch's self-field, is matched with the laser reference in a Mach-Zehnder-type electro-optical modulator (MZM) [5]. Thus the voltage translates into a modulation of the laser amplitude [5]. In case of the EO-BAM a bias voltage is used at the MZM to reduce the amplitude to 50% by default [7].

In the RF part of the state-of-the-art EO-BAM, high bandwidth cone-shaped pickups [8] couple to the self-fields of each passing electron bunch. Usually an array of four pickups is used and the induced bipolar signal of two opposite pickups combined, before transmission to the MZM's signal port for beam position compensation [9].

For a bunch arriving on time, a perfect overlap between the zero-crossing (ZC) of the bipolar voltage signal and the reference laser pulse is ensured by adjustable delay stages in the optical path, leaving only the effect of the bias voltage [5, 10]. The applied voltage is not zero if the bunch arrives early or late compared to the reference. The signal can be viewed as linear for small arrival-time deviations, leading to a linear dependence of the arrival-time mismatch to the laser amplitude modulation [11]. The modulated optical signal is measured by photodiodes, digitized and finally converted into timing information [10, 12].

Due to this operating principle, it is clear that two of the key parameters for the arrival-time resolution are the slew rate (SR) of the voltage signal at its ZC and the half-wave voltage U_π of the MZM.

EO-BAM Upgrade

The state-of-the-art EO-BAM was developed for bunch charges ranging from 20 pC to 1 nC. At the European XFEL the EO-BAM achieved a resolution of 3.5 fs with 250 pC nominal bunch charge [6]. It is planned to upgrade the MZM and pickup structure in order to achieve a higher resolution and allow for single-digit fs resolution with lower bunch charges, down to ≤1 pC. For the desired improvement, it is necessary to increase the bandwidth of all components to up to 100 GHz and reduce the length of the lossy signal transmission line between pickup and MZM [13]. Additionally the distance between electron bunch and pickup could be reduced to increase the coupling. For the MZM, besides the increase in bandwidth, a lower U_π is needed [7].

BAM Demonstrator

In 2023 a first vacuum-sealed demonstrator was built as a proof-of-concept comprising a printed circuit board (PCB) integrated pickup structure [14]. Simulation results of this concept showed the potential to reach a jitter-charge-product of 9 fs pC, when combined with a new low-pi-voltage ultra-wideband traveling wave electro-optical modulator developed at Karlsruhe Institute of Technology (KIT) [7].

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For the demonstrator, 35 µm thick planar copper pickups and a microstrip transmission line with combining network for four pickups are realized on a 380 µm Rogers TMM® 10i laminate [15] with dielectric constant Dk of 9.80 ± 0.245 and dissipation factor 0.0020 [14]. The PCB is inserted into a DN40 ConFlat flange with a diameter of 36 mm and leaves a minimum aperture of 10 mm for the beam [14]. A commercial V-type connector is used as vacuum-feedthrough, which limits the bandwidth to 65 GHz [14]. A rendering of the demonstrator is shown in Fig. 1.

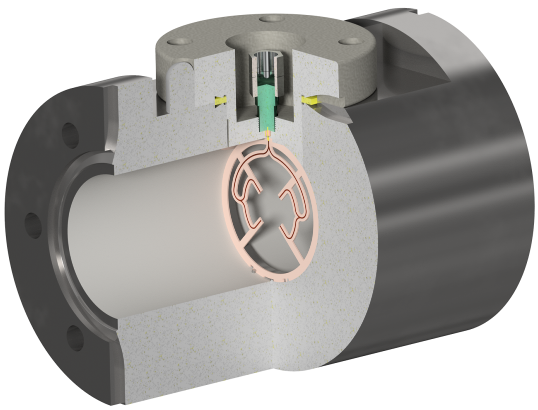

Figure 1: Rendering of the PCB-based demonstrator [14].

First results of the measurement done with ELBE at Helmholtz-Zentrum Dresden Rossendorf (HZDR) have been published on IBIC 2023 [14] and indicated, that a PCB-based BAM with planar pickups and combination network is a viable option [14]. For the analysis only one of over 200 measurements has been viewed so far. It contained a set of 1024 signals recorded in segmented mode with a bunch charge of 3.45 pC and supposedly centered beam. This contribution expands the analysis to include the dependency on beam charge and position, for which gate voltage of the thermionic electron gun and the steerer current were varied.

MEASUREMENT RESULTS

The measurements were done at HZDR during two beam shifts in July and August 2023. The V-type port of the PCB-based BAM demonstrator was connected to a Keysight UXR1102A real-time oscilloscope with two coaxial cables with a total length of 142.2 cm.

For evaluation of the large amount of measurement data a dedicated *python*™ script was written. This script is able to load the measurement data from a hdf5-file exported by the Keysight UXR1102A and evaluate the recorded waveforms. For each measurement all waveforms/segments are loaded and the algorithm detects relevant signals using SciPy's peak-finder. Some of the longest waveforms contain hundreds or thousands of bipolar pulses produced by subsequent electron bunches. The script determines a few key parameters, such as the maximum and minimum voltage, the SR at and the position of the ZC for each pulse. The SR is calculated by detecting the significant ZC and using two points before and after ZC to calculate the SR of three short intervals by linear approximation. The SR is then determined as the weighted average of these three segments. Thereby the weighting function is depending on the distance of the actual ZC to the data points. If desired, the script is able to use a provided scatter matrix for de-embedding the external transmission line by the algorithm described in [14].

Bunch Charge

During the measurements, the bunch charge was varied from about 1.2 pC to 6.7 pC. These conditions are not typical for the operation of ELBE and therefore below the specification for the existing beam diagnostics. Specifically for the integrating current transformers (ICTs) the resolution was not sufficient for reliable bunch charge measurements in the pC range. Thus, the charge had to be estimated by the electron-gun's cathode current I_c and repetition rate f_{rep} with

$$Q_B \approx \frac{I_c}{f_{rep}} = I_c T_B, \quad (1)$$

where T_B is the bunch spacing. The repetition rate was set to 406.3 kHz corresponding to a bunch spacing of 2.4612 µs. By a large number of measurements with two or more consecutive pulses, the bunch spacing could be estimated to 2.461 538 59(73) µs. The measured cathode current was in the order of 1 µA with a display resolution of 0.1 µA. The uncertainty of the bunch charge ΔQ_B, defined by

$$\Delta Q_B \approx \Delta T_B \, |I_c| + \Delta I_c \, |T_B|, \quad (2)$$

is dominated by the first term and also in the range of 10%.

The standard deviation of the calculated SR is based on 1 to 119 events per charge. Due to the pattern of the fluctuations of SR and peak-to-peak voltage in many measurements, this error is expected to be mainly a consequence of charge jitter. Though both errors are essentially the uncertainty of the bunch charge for each pulse, the x-error is a consequence of the display resolution, while the y-error is likely caused by jitter of the machine due to uncommon beam properties.

The slew rate as a function of the bunch charge is shown in Fig. 2. The two series only differ in the roll-off characteristics of the oscilloscope. For the green (dot) series a Bessel filter with f_c = 75.3 GHz and for the red (cross) series a Sinc filter with f_c = 113 GHz was used. Both exhibit similar results, which can be explained by the cable's and feedthrough's cut-off frequencies of about 67 GHz.

Both series show a linear dependency with similar slopes of 60.99(136) mV ps^{-1} pC^{-1} (Bessel filter) respectively 57.06(331) mV ps^{-1} pC^{-1} (Sinc filter) and a mean slope of 59.87(137) mV ps^{-1} pC^{-1}. If the SR is normalized for each of these pulses the average is 54.7(133) mV ps^{-1} pC^{-1}, which is reduced by the sets significantly undercutting the trend. A possible explanation is a charge error caused by the cathode current resolution.

For a second measurement, pictured in Fig. 3, the gate voltage was recorded, since it was still operated in a range with better resolution than the cathode current. Due to the fact that only one waveform was measured per voltage increment, the y-error was postulated to be close to the mean of

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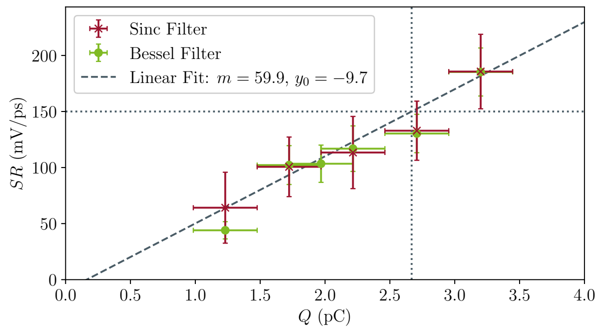

Figure 2: Slew rate vs bunch charge using two of the oscilloscope's filter types as well as the respective linear fits.

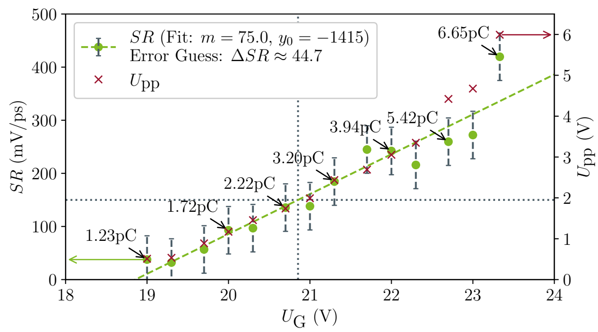

Figure 3: Slew rate and peak-to-peak voltage vs gate voltage. An estimate of the bunch charge is added as annotation.

the first measurements standard deviations. The error bar is set to twice this value to indicate the maximum error.

A linear trend is visible in a short scale for the SR as well as for the peak-to-peak voltage, but the readings deviate for low and high gate voltages. This is probably caused by a non-linear dependency of the bunch charge on the gate voltage, which should be determined by a modified Child's law [16].

Beam Position

Another measurement series was done by sweeping the current of two magnetic steerers, called TH2MSV02 (vertical) and TH2MDC01 (horizontal), while the bunch charge was kept constant at 2.22(25) pC. The deflection was done along the vertical and horizontal axis separately, to avoid hitting one of the four pickups, that are rotated by 45° with regards to these axes. The beam position was measured with two beam position monitors, TL1-DS-01 and TL1-DS-05, located just a few meters before respectively less than a meter behind the BAM demonstrator.

The slew rate is pictured in Fig. 4 as a function of the horizontal respective vertical beam displacement. For each steerer configuration 17 pulses have been measured and averaged, except for the nominal center with up to 34 pulses. No clear trend is visible, the linear fits have slopes of less than 5.1(26) mV ps^{-1} mm^{-1} and the maximum deviation of the averaged SR is 15.5%. Therefore, the combination of four pickups effectively compensates for the beam position.

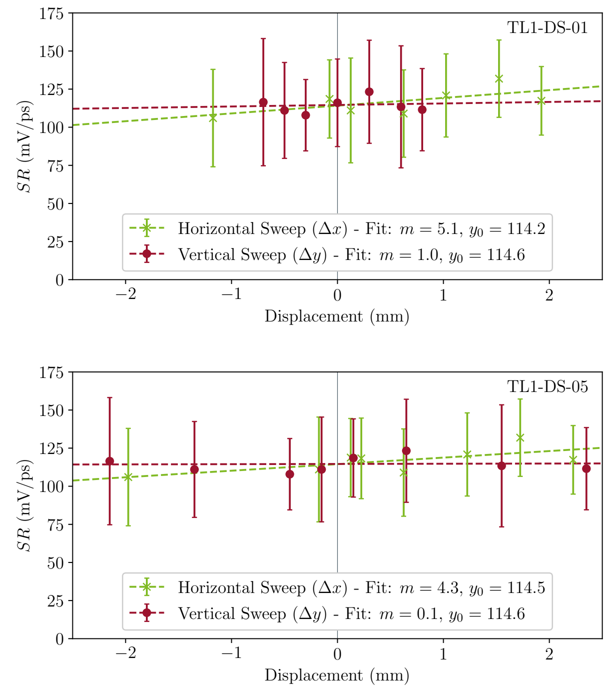

Figure 4: Slew rate vs beam position measured at TL1-DS-01 (top) and TL1-DS-05 (bottom). The vertical lines indicate the initial beam position (nominal center).

CONCLUSION AND OUTLOOK

The measurement series analyzed for this contribution exhibit the expected behavior. The slew rate is a linear function of the bunch charge and hardly depending on the beam position, since the combination of four pickups compensates for most of the effects caused by the displacement.

Measurements with an electro-optical modulator are still pending and it is planned to build a second demonstrator with a W-type connector and a glass substrate, which is expected to meet the requirements for ultra-low-charge operation. Finally, it is foreseen to build a new bunch arrival-time monitor for FLASH and for the European XFEL.

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