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FIRST MEASUREMENTS OF AN ELECTRO-OPTICAL BUNCH ARRIVAL-TIME MONITOR PROTOTYPE WITH PCB-BASED PICKUPS FOR ELBE

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Abstract

A vacuum-sealed prototype of an electro-optical bunch-arrival-time monitor has been commissioned in 2023. It consists of a pickup structure and a low-π-voltage ultra-wideband traveling-wave electro-optical modulator. The stainless-steel body of the pickup structure is partially produced by additive manufacturing and includes four pickups as well as an integrated combination network on a printed circuit board. This novel design aims to enable single-shot bunch-arrival-time measurements for electron beams in free-electron lasers with single-digit fs precision for low bunch charges down to 1 pC. The theoretical jitter-charge-product has been estimated by simulation and modeling to be in the order of 9 fs pC. The new prototype is tailored for validation experiments at the ELBE accelerator beamline. In this contribution first measurement results are presented.

INTRODUCTION

For synchronizing many subsystems and for stabilizing the arrival time of electron bunches an all-optical approach is used in several large free-electron-laser (FEL) facilities [1], where the arrival time is particularly critical for applications like pump-probe experiments [2]. The system requires a master laser oscillator phase-locked to the main RF oscillator, which emits picosecond laser pulses as timing reference [1, 3]. Furthermore, an actively stabilized distribution system must be established to transfer these pulses along the facility with minimal drift [1]. The electro-optical (EO) bunch arrival-time monitor (BAM) [1] is one of various end-stations in the all-optical synchronization system.

EO-BAM Operating Principle

In contrast to cavity-based BAM in radio-frequency (RF) synchronization [4], where the electron bunch excites a rather slowly decaying resonance, the EO-BAM detects an evanescent bipolar voltage signal [1]. The voltage is induced by the co-moving electric field of a bunch as the surface currents are disturbed by the pickup. The transient voltage leads to a current, which is transmitted via coaxial cables to a Mach-Zehnder-type electro-optical modulator (EOM) [1]. Usually the signals of two or more angular distributed pickups are combined to compensate for orbit variations [5]. The voltage signal serves as input for the EOM, where the intensity of the reference laser pulse is modulated accordingly [1]. The EOM bias voltage is set to a value such that the laser pulse amplitude is reduced to 50 % of the maximum value in order to make use of the bipolar pickup signal. By adjustable delay lines the system is tuned to perfect timing, so that the reference pulse and the zero crossing (ZC) of the voltage signal coincide at nominal bunch arrival time without additional modulation [6]. Early or late bunches result in a positive or negative signal, which causes an intensity modulation [1]. The laser-intensity modulation is processed by dedicated receiver electronics [3, 6]. A calibration curve is used to deduce the arrival time for every electron bunch [3, 6].

For future applications it is desirable to reach lower bunch charges, while at the same time the demands for synchronization accuracy rise as well. The current BAMs are equipped with 40 GHz cone-shaped pickups designed for bunch charges down to 20 pC [5], which achieve an overall resolution of 3.5 fs with 250 pC nominal bunch charge in the synchronization system of the European XFEL [7]. For low charges the signal strength and therefore also the BAM sensitivity decreases rapidly.

EO-BAM Upgrade

To pave the way for 1 pC operation of the European XFEL, an upgrade of the arrival-time diagnostics is mandatory. To reach the goal of maintaining a resolution below 10 fs even at this low-charge operation, an upgrade of the main BAM components is necessary. First the RF part, comprising of the pickup structure and the signal transmission, and second, the EOM must be redesigned. The bandwidth of both components should be increased up to 100 GHz and the length of the transmission line has to be reduced [8].

The EOM's half-wave voltage V_π needs to be lowered in order to reach a high modulation with the low expected signal strength. To reduce cable losses especially at high frequencies, the EOM will be placed closer to the beamline and thus the radiation hardness has been examined. In a future upgrade it might even be integrated in the RF structure.

For the pickup system, it was proposed to have pickups and combination network integrated on a printed circuit board (PCB) [8, 9]. This idea was first combined with rod-shaped

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pickups mounted on top of this PCB (rPCB) to maximize the effective pickup surface and reduce the wake loss while minimizing the distance between pickup and beam [10]. The reported slew rate at ZC was 171.6 mV ps^{-1} pC^{-1}, exceeding the project goal by 14 % [10]. For the construction of a first vacuum-sealed prototype, it was decided to use a planar version of the rod-shaped pickups, for simplified manufacturing with a slight improvement of the signal [11].

The potential resolution of the upgraded BAM was estimated using the simulation results of rPCB pickups, the measured response of a new EOM prototype and typical noise contribution. With the assumptions made in [12] a jitter-charge product of about 9 fs pC is expected, which reaches the project goal.

PROTOTYPE DESIGN

The first vacuum-sealed prototype of an EO-BAM based on planar pickups with integrated combination network, shown in Fig. 1, has been tailored for tests at the ELBE accelerator in the Helmholtz-Zentrum Dresden Rossendorf (HZDR). Vacuum compatibility of the prototype was realized in close cooperation with DESY and HZDR. It is connected with a DN40 ConFlat (CF) flange to an inner beamline diameter of 36 mm, while the minimal clearing between the pickups is 10 mm. The feedthrough module can be attached to the side with a DN25 CF flange. A sliding contact is used for the connection between the feedthroughs inner conductor and the end of the two stage combination network, which is integrated on a substrate. The V-type RF connector is limited to a bandwidth from DC to 65 GHz according to the manufacturer's specification.

The layout of the PCB was chosen similar to the PCB presented in [11] and shown in Fig. 1, but adapted for the mechanical and electrical material properties. As substrate a Rogers TMM® 10i laminate with dielectric constant Dk of 9.8 ± 0.245, a thickness of 380 µm and 35 µm of copper cladding was chosen [13]. The short-term vacuum compatibility has been tested at HZDR in a single batch of four different 20×40 mm substrate samples at once. The baseline pressure in the test chamber was 3×10^{-9} mbar. Due to the raw samples the pressure did not drop below 2×10^{-7} mbar. After the samples were baked at up to 105 °C for a total of almost three days, the pressure dropped to 7×10^{-9} mbar. The baseline could presumably be reached after some time, so that the test is considered successful.

The position of the PCB relative to the feedthrough is a critical dimension. The PCB rests on a ledge in the body and fits into a notch cut into a bulge at the feedthrough-module's surface to ensure that a good electrical contact is provided between inner conductor and trace, as well as between the ground plate and the outer conductor. On the opposite side two dowel pins jam the PCB in position, because a tilt out of the transverse axis was also identified as a critical defect in the tolerance analysis [11].

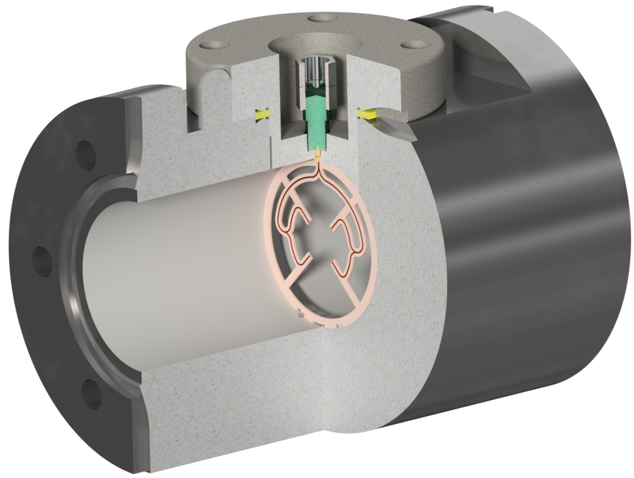

Figure 1: Rendering of the PCB-based BAM prototype.

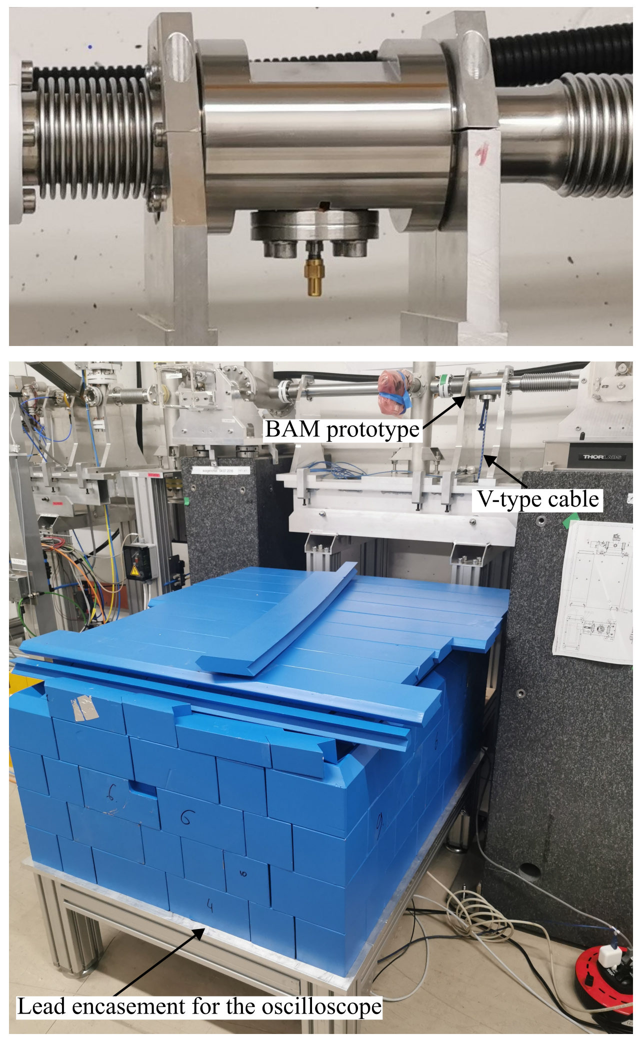

Figure 2: Close-up of the prototype installed between two bellows in the THz beamline of ELBE (top) and measurement setup in the beamline cave, before installing additional fans and α-radiation absorber (bottom).

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RF MEASUREMENT AT ELBE

In the course of a dedicated machine development shift at ELBE, two 2-day shifts were allocated for RF measurements with the novel EO-PCB-BAM prototype. A third shift is scheduled for December 2023, to measure the performance of the system with EOM.

Measurement Setup

Figure 2 (top) shows a close-up to the prototype between two bellows in the ELBE THz beamline. Off measurement time, the output was terminated with 50 Ω as shown in the picture. For measuring the RF signal, a two-port real-time oscilloscope, the Keysight UXR1102A, with maximum bandwidth of 110 GHz was used. To protect the oscilloscope against radiation, it has been encased in the custom lead crate shown in Fig. 2 (bottom), which was afterwards covered in an absorber to moderate the α-radiation stemming from the beam dump. The oscilloscope was remotely operated from the control room during measurements. Due to the distance between the oscilloscope and the BAM, two coaxial v-cable had to be used. A 121.9 mm Huber+Suhner SUCOFLEX® 570S and a 20.3 mm Rosenberger 70W-08S1-08S1-00203 extended by a v-female-female connector.

Measurement Results

Figure 3 shows an exemplary result of the first measurement shift. The full bandwidth of the Keysight UXR1102A oscilloscope was utilized in this case, with a brick-wall filter with roll-off at 113 GHz. The charge measurement was unreliable in this charge regime, but with a cathode current of (1.4 ± 0.2) µA and a repetition rate of 0.41 MHz in CW-mode, the mean bunch charge at the source is approximately 3.45 pC. Since a strong fluctuation was observed during the measurement, the segmented mode was used to save a batch of 1024 pulses for averaging.

The decisive slew rate is $(99.27 \pm 10.62)\,\mathrm{mV\,ps^{-1}}$ in this measurement. The error is expected to be mainly a consequence of charge fluctuations, thus the average slew rate should match the average charge with significantly lower uncertainty. The peak-to-peak voltage and rise time are (1.52 ± 0.11) V respectively (24.52 ± 1.09) ps.

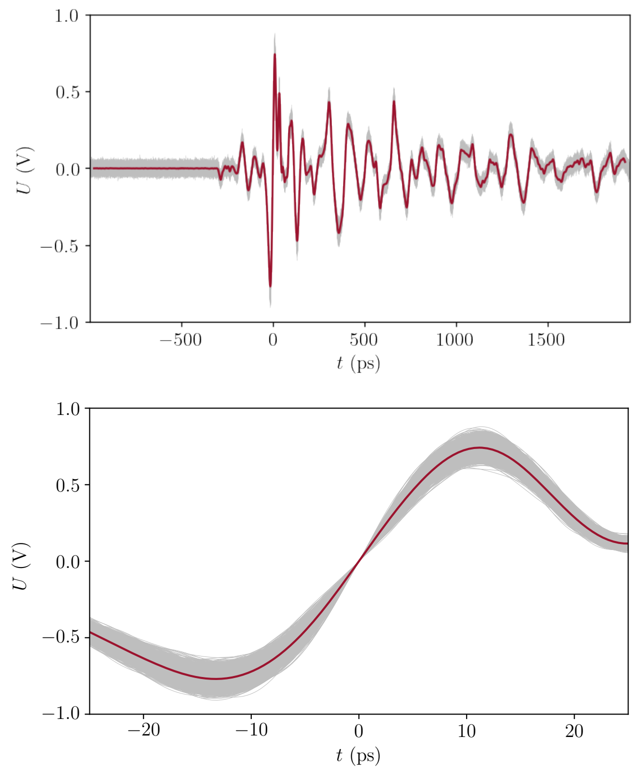

Figure 3: Measurement #34 (2023-07-27) with a total bunch charge of approximately 3.45 pC. A set of 1024 pulses is plotted in gray and the average signal in red. The top figure includes about 2 ns of ringing and the bottom is zoomed to the main pulse.

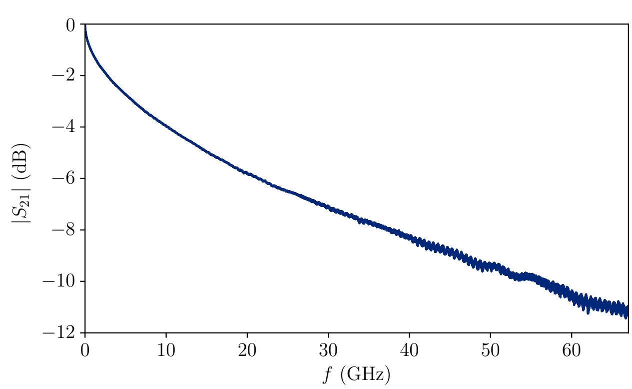

Figure 4: Scattering parameter of the 20.3 mm Rosenberger and 121.9 mm Huber+Suhner cables with the connector as used in the measurements.

Discussion

The measurements were carried out using a combined transmission line length of more than 1.4 m with high attenuation above 11 dB at 67 GHz. For the final EOM-integrated BAM it is planned to omit the external cable completely. Furthermore, the simulated signal was also taken directly at the feedthrough port. The scattering parameters of the assembly of the two cables and the v-female-female connector, shown in Fig. 4, have been measured for de-embedding.

The transmission line is modeled with a two-port network as shown in Fig. 5. The outgoing signal at port 2 in a two-port network is defined as

$$V_2^- = |S_{21}|\, V_1^+ + |S_{22}|\, V_2^+ \,, \tag{1}$$

where + denotes the incident and − the reflected wave [14]. In these measurements it will be assumed that no wave will be reflected in the oscilloscope, leading to $V_2^+ \approx 0$. With $S_{21} \neq 0$ in the whole signal spectrum, it is possible to get the simplified input signal by

$$V_1^+ = \frac{V_2^-}{|S_{21}|} \tag{2}$$

in frequency domain. The measured time-domain signal must be transformed by fast Fourier transform before this

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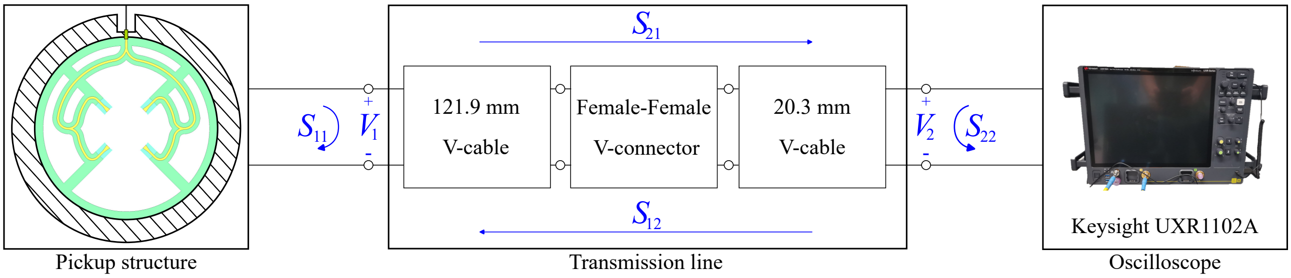

Figure 5: Block diagram of the electrical setup with scattering parameter for de-embedding.

step. With inverse fast Fourier transform, the de-embedded time-domain signal is retrieved afterwards.

After de-embedding the whole RF transmission line, the slew rate at main zero-crossing is (275.71 ± 34.64) mV ps^{-1} with a peak-to-peak voltage and rise time of (4.16 ± 0.31) V respectively (24.08 ± 1.34) ps. Supposing a linear dependency on the bunch charge [15, 16], the measured slew rate is normalized to 79.9 mV ps^{-1} pC^{-1} and just above half of the project goal. This could potentially allow for the desired BAM resolution down to 2 pC.

Figure 6 shows the simulated signal compared to the mean of 1024 measured pulses after de-embedding. For the simulation the bunch-charge was set to 3.5 pC for comparable results. The measured and the simulated signals coincide very well in the vicinity of the bunch and deviate otherwise. The slew rate is even lower, at 235.50 mV ps^{-1}, which is significantly worse than in the previously proposed design with a thin glass substrate. This indicates that the TMM® 10i substrate is not optimal.

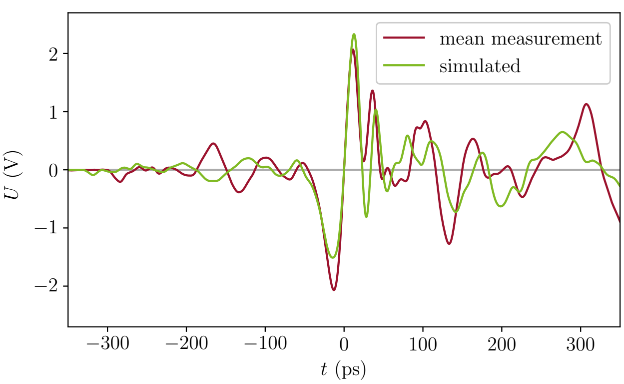

Figure 6: Comparison of the simulated signal and the average measured signal given in Fig. 3 after simplified de-embedding.

CONCLUSION AND OUTLOOK

The first prototype led to promising results and showed that a PCB-based BAM with planar implementation of rod-shaped pickups is viable. It must be emphasized that the prototype was not built to exploit its full potential. In particular, the use of a thinner fused-silica substrate should provide for further improvements. This is also advisable, since the current substrate might suffer radiation damage in long-term use due to its hydrocarbon content. After disassembling, the BAM must also be analyzed for defects caused by beam incidence and radiation.

Although the first prototype could not reach the project goal in accordance with simulations using the same materials, it already exceeds the performance reported for the current pickups [15, 17]. Since not all relevant data was reported with the results, the comparison must be treated with caution and ideally a comparative study should follow for a robust validation.

In summary, the preliminary review suggests that the novel design approach is operational and provides a significant improvement. By simulation it is likely that a different substrate will considerably improve the signal. Furthermore, the principle is expected to be transferable to other applications. If the in-depth analysis confirms the positive result and the measurements with an EOM, planned for December 2023, are successful, an improved prototype will be built. If possible, a W-type connector should be used, to extend the bandwidth limit to more than 100 GHz. In addition, it is reasonable to explore different PCB topologies in a non-vacuum structure, in a test chamber or with a free-space beam. Finally, it is foreseen to build a new BAM for FLASH and for the European XFEL.

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