ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-WEPMO36

CONCEPTS FOR BEAM DIAGNOSTICS BASED ON PLANAR PICKUPS ON A PRINTED CIRCUIT BOARD*

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Abstract

For the upgrade of the electro-optical bunch arrival-time monitors (EO-BAMs) employed at several free-electron laser (FEL) facilities, a novel pickup structure has been proposed. Its feasibility was successfully tested at the ELBE accelerator. The design comprises planar pickups on a printed circuit board (PCB) with an integrated combination network. It delivers a significantly stronger signal compared to established pickups. Applying the upgrade to existing machines enables two key capabilities: Reliable operation at 1 pC charge levels for FELs and ultrafast electron diffraction facilities, and enhanced arrival-time resolution for standard operational modes. Furthermore, the PCB implementation enables unprecedented flexibility in planar pickup design, facilitating multi-functional diagnostic capabilities. This work presents a compact implementation strategy for integrating high- and low-resolution channels for EO-BAMs on a single substrate through a dual-functionality layout, and conceptual advancements in beam diagnostics using a PCB architecture for measuring other beam properties.

INTRODUCTION

The electro-optical bunch arrival-time monitor (BAM) implemented in the all-optical synchronization of several free-electron laser (FEL) facilities [1–4] typically uses cone-shape pickups developed for 20 pC bunch charges [5, 6]. The transient bipolar voltage signals induced in two opposite pickups are combined and applied to the electrical input of an electro-optical modulator (EOM) of Mach-Zehnder type [6]. A laser oscillator in a phase-locked loop with the accelerator's main RF oscillator provides short laser pulses as a timing reference [7]. These pulses overlap with the voltage signal in the EOM, leading to an amplitude modulation, which imprints the arrival-time information on the pulse intensity [7]. The intensity modulation is measured and digitized to determine the arrival time [8, 9].

A redesign was proposed to improve the arrival-time resolution and to allow reliable operation with 1 pC bunches [10]. The new design comprises 4 planar pickups in a printed circuit board (PCB) with an integrated combination network [10, 11]. A first demonstrator showed the viability of this approach in beam-based measurements at ELBE [12, 13].

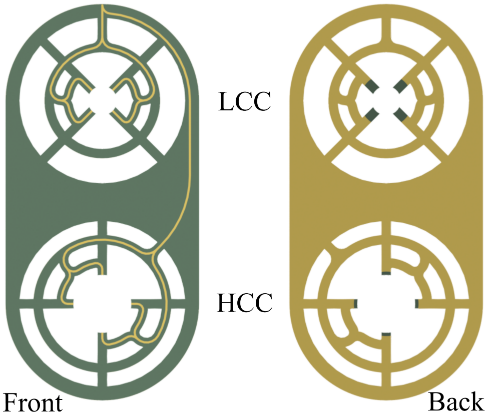

Figure 1: Heuristic PCB layout for a 2-channel BAM. Green indicates the dielectric, yellow shows the conducting layer.

ARRIVAL-TIME MONITORING WITH DUAL-CHANNEL LAYOUT

FELs can facilitate a wide range of bunch charges, e.g. 20 pC to 1 nC at the European XFEL [14]. Since the signal generated by the EO-BAM pickups scales linearly with the bunch charge, a design optimized for 1 pC experiencing a 1 nC bunch might damage the subsequent components. A multi-channel design may mitigate this problem and provide a robust system capable of operating with a wide range of beam properties. This design has a low-charge channel (LCC) and a high-charge channel (HCC) implemented on a single PCB. To save the investment in a second evaluation chain, it may use a single connector fed with both signals.

This idea can be tested with a simulation model based on some heuristic assumptions. Many design parameters influence the shape and scale of the RF signal induced in planar pickups, but an implementation on a single PCB reduces the number of individually configurable parameters. Both channels will share the same laminate, thus substrate thickness, permittivity, loss tangent and cladding are identical. The sensitivity must be adjusted by the PCB layout. In simulations, we found that a shorter pickup has a decreased signal level and slew rate, reducing the EO-BAM's sensitivity and the voltage experienced by subsequent components. The effect can be increased by a larger aperture and therefore distance from the pickup to the bunch. The first concept is shown in Fig. 1. The pickups were set to lengths of 2.5 mm (LCC) and 0.75 mm (HCC) with a distance to the beam of 3 mm, respectively 6 mm.

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[*] This work is supported by the German Federal Ministry of Research, Technology and Space (BMFTR) under contract No. 05K22RO2.

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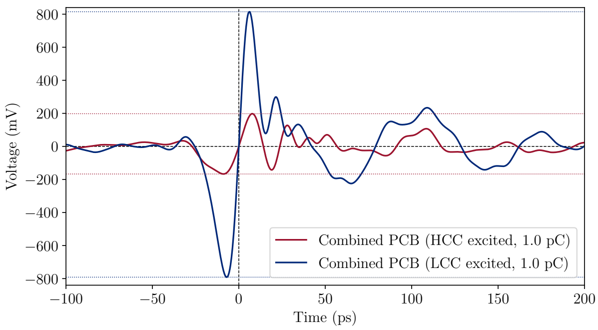

Figure 2: Simulated voltage signals from the 2 BAM channels in the combined topography.

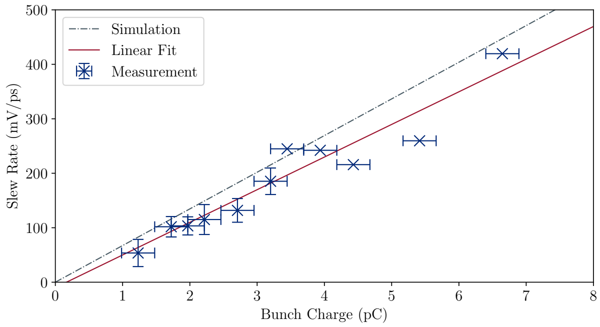

Figure 4: Slope at the ZC of the signal measured at HZDR for the first PCB-based demonstrator vs bunch charge.

Simulations of LCC and HCC on circular standalone PCBs gave a signal ratio of 3.0 determined by peak-to-peak voltages. Integration in a single PCB with a non-optimized signal combination does increases the ratio to around 4.4, which is likely caused by losses and dispersion in long transmission from the HCC to the port. If the signal slew rate, which is more prone to dispersive effects, is used as a comparative measure, the difference is even more pronounced. In addition to the long transmission losses, the combination causes signal reflections for both channels.

The resulting signals induced by an 1 pC bunch are shown in Fig. 2. It is apparent that the HCC channel gives a distorted signal. However, both signals seem to be sufficient for arrival-time measurements, although an optimization of the combination is necessary. A simple solution to reduce the effects of dispersion on the HCC signal would be a 135° rotation of the LCC and having the combination in the center with the feedthrough leaving the beamline to the right. This, on the other hand, would reduce the losses of the HCC and, therefore, its maximum charge.

CONCEPTS FOR MEASURING OTHER BUNCH PROPERTIES

The voltage signal induced in a pickup structure on a PCB depends on its geometry as well as on many bunch parameters. This might be a drawback in the BAM because jitter of the beam properties would translate into jitter in the measured arrival time. However, it would be possible to use this dependency to monitor other beam parameters such as beam position, bunch length, or charge.

In some cases, it might be possible to realize the monitoring on the same board by an extended evaluation chain, in other cases the versatility of the PCB-based approach has to be utilized by a new layout. Different concepts will be proposed in this section.

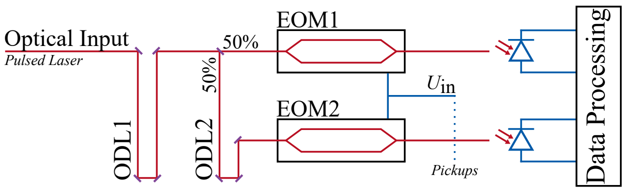

Figure 3: Optical unit to measure the signal slope.

Measuring the Signal Slew Rate

A single bunch measurement of the signal slew rate close to the zero crossing would provide useful information in many cases. This necessitates two values of the instantaneous voltage with a known delay. One of these could be at the supposed zero crossing, already measured for the arrival-time monitor. Assuming a delay of 1 ps, the voltage difference between both sampling points could be around $\geq$150 mV pC^{-1}. By adjusting the delay between the two laser pulses, it would be possible to tune the sensitivity based on the nominal bunch charge, but a larger delay would increase the importance of a polynomial fit of the signal edge.

If the laser repetition rate and the reading electronics were fast enough to sample many points on the voltage signal, this would already be enough to retrieve the information, but with the drawback of a fixed delay, which could exceed $1/2U_\pi$ of the EOM. By a fast switch to an optical delay line (ODL), the delay of the preceding pulse could be adjusted. An alternative compact implementation could be achieved by splitting a part of the reference laser pulse and sampling the voltage signal at an adjustable delay after the primary pulse for arrival-time measurement. The advantage of a more flexible delay comes at the expanse of laser intensity. A general layout of this concept is shown in Fig. 3.

Bunch Charge

The voltage signal induced in the pickups scales linearly with the bunch charge. Therefore, the maximum voltage as well as the signal's slew rate are directly proportional to the charge. This has been verified in measurements with a first demonstrator shown in Fig. 4, which gave 59.87(137) mV ps^{-1} pC^{-1} [12]. Simulations indicate that the final design will surpass 150 mV ps^{-1} pC^{-1} [13].

This dependency could be utilized to determine the bunch charge by either the peak voltage or the signal's slew rate. For absolute charge measurements, the proportionality constant must be known. Without it the effect of charge jitter on the arrival time could still be compensated for in data processing.

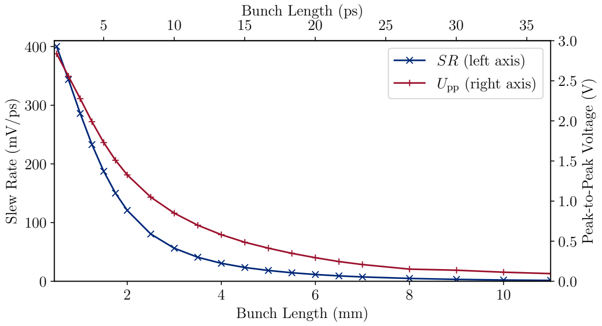

Figure 5: Simulated signal slew rate (blue, left axis) and peak-to-peak voltage (red, right axis) vs. bunch length.

Bunch Length

The proposed charge measurement assumes a constant bunch length σ. Under some assumptions [15], the signal can be approximated by the derivative of the longitudinal line charge density. Therefore, the gradient and maximum scale with σ^{-1} if the charge is constant and the signal is not limited by the bandwidth. A set of simulations shown in Fig. 5 gave a strong nonlinear decline with increasing bunch length in accordance with these expectations. This would spoil the bunch-charge measurement if a significant bunch-length jitter was present, but it also gives an opportunity to use the same principle to measure the bunch compression for a known bunch charge. However, this is not relevant for very short bunches found in X-ray FELs, which exceed the maximum bandwidth. Regarding the arrival-time measurement, bunch charge and length are both compensated simultaneously if the arrival-time measurement is normalized by the instantaneous slew rate.

Beam Position

A beam position monitor (BPM) can not be realized within the BAM, since only a sum signal is coupled out of the beamline. To determine the feasibility of a PCB-based BPM, a board with four pickups each having a straight transmission line to a feedthrough was simulated. The tip-to-tip distance of the pickups was set to 10 mm in a 40.5 mm beamline.

A typical approach calculating the beam offset is the difference-over-sum method with

$$\Delta x = \frac{1}{S_{\mathrm{x}}} \frac{U_{\mathrm{right}} - U_{\mathrm{left}}}{U_{\mathrm{right}} + U_{\mathrm{left}}}, \quad \Delta y = \frac{1}{S_{\mathrm{y}}} \frac{U_{\mathrm{top}} - U_{\mathrm{bottom}}}{U_{\mathrm{top}} + U_{\mathrm{bottom}}}, \quad (1)$$

where $S_{\mathrm{x,y}}$ are the horizontal and vertical sensitivity [16]. In the following, the maximum voltage will be used for the U_{i} but it can also be substituted with the signal slew rate.

The sensitivity can be determined from the difference-over-sum as a function of the bunch offset, as shown in Fig. 6. A linear fit with fixed interception at 0 over the first mm gives a position sensitivity of $S_{\mathrm{x,y}} = 19.46\,\%\,\mathrm{mm}^{-1}$. If the sensitivity is calculated with the signal slew rate instead of the maximum voltage, the value degrades slightly to $S^{\mathrm{SR}}_{\mathrm{x,y}} = 18.14\,\%\,\mathrm{mm}^{-1}$. The difference between the horizontal and vertical position sensitivity is negligible, and both are sufficiently linear, but Fig. 7 reveals that the diagonals are highly nonlinear due to horizontal-vertical coupling.

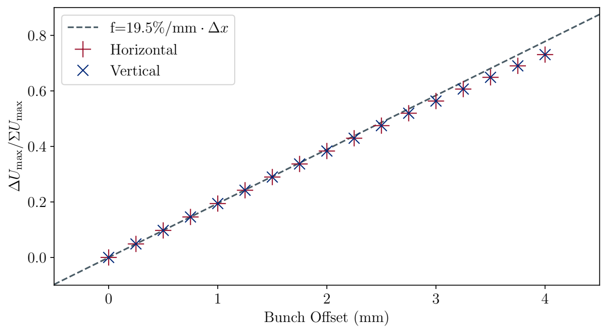

Figure 6: Simulated horizontal and vertical difference over sum for planar pickups on a PCB with four connectors.

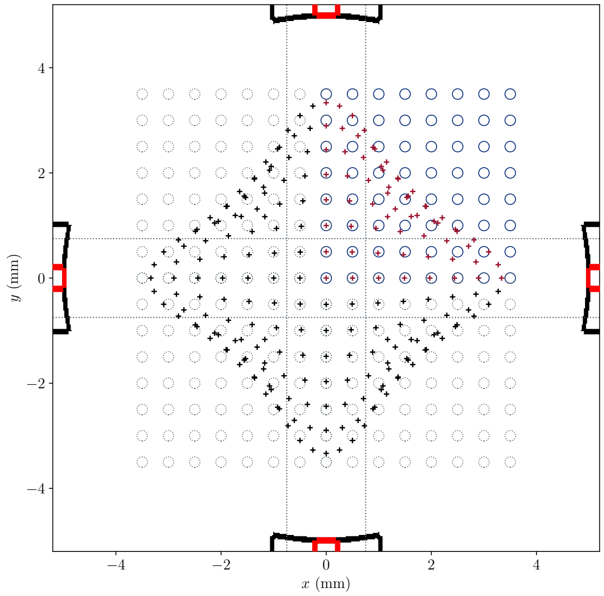

Figure 7: Actual beam position (circles, $r = 0.1$ mm) and expected reading (cross) calculated with $S_{\mathrm{x,y}} = 19.46\,\%\,\mathrm{mm}^{-1}$ and Eqs. (1). Only the top right quadrant was simulated, the rest has been mirrored for visualization. The pickup position is indicated in red/black.

CONCLUSION

In this paper, different concepts for the advancement of planar pickups on a PCB have been explored. A multichannel design can protect BAM components from overvoltages during high-charge operation. With a second EOM, it is possible to determine the signal slew rate at the zero crossing to normalize the arrival-time measurement and in some cases also to determine the bunch charge or length. Finally, a sensitive PCB-based BPM with high linearity but strong horizontal-vertical coupling is feasible. A narrow-band evaluation of the BPM signals has not been investigated, but would reduce the cost of such a system. All concepts need further development and optimization.

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