ISBN: 978-3-95450-230-1 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2021-WEPP19

BUNCH ARRIVAL-TIME MEASUREMENT WITH ROD-SHAPED PICKUPS ON A PRINTED CIRCUIT BOARD FOR X-RAY FREE-ELECTRON LASERS*

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Abstract

The all-optical synchronization system implemented in the European X-ray free-electron laser (EuXFEL) is to receive an upgrade. The modifications are intended to allow operation with consistently high accuracy in a 1 pC mode, which is required for various user experiments. The lower charges, e.g. a factor of 20, lead to a reduced signal strength at the pickups and thus to a decreased resolution. A significant potential for improvement has been identified in a modified pickup structure and transmission network, which provide the transient voltage signal to subsequent parts of the synchronization system. One solution for a broadband pickup structure with short signal paths, large active surfaces and minimum aperture diameter could be achieved by connecting rod-shaped pickups to a combination network on a printed circuit board, which will be mounted in the beamline. In this contribution the proposed design is introduced and analyzed by electromagnetic field simulations.

INTRODUCTION

A stable high-resolution synchronization system is indispensable in fourth generation light sources, specifically linac-based free-electron lasers (FELs). To exploit their potential, it is necessary to synchronize various subsystems, distributed in the km-long facilities, with fs precision [1, 2].

There are two commonly used approaches for synchronization systems in FELs. The first is based on resonant cavities synchronized to the low-level rf, for example implemented at the LCLS [3]. In contrast the second uses a train of laser pulses, synchronized to the main rf clock, as an optical reference, which is correlated to the transient signal induced by the coasting bunch [4]. Though the additional installation of an optical distribution as well as a laser oscillator with sufficient rate, timing stability and short pulse duration is costly, these systems have advantages for high resolution synchronization in large facilities [2, 4]. The European X-ray free-electron laser (EuXFEL) [5], FERMI@Elettra [6] and the SwissFEL [7] are some of the notable examples, where the optical scheme is in operation. Furthermore, such a synchronization system will be used for SHINE [8].

One substantial criterion for the classification of light-sources is the pulse duration [9]. For many experiments it is favorable to have short pulses in atomic time scales, which can be achieved when the bunch charges are reduced [10]. Yet the non-invasive electro-optical arrival-time measurement, a key challenge in synchronization, depends on transient fields of the electron beam [1, 4] and thus is a limiting factor for a reliable low charge operation of current FELs.

To extend the EuXFEL parameter range towards low charges, the bunch arrival-time monitors (BAMs) need to be improved. Following a former design upgrade, the EuXFEL's operating synchronization system is capable to operate with 20 pC bunches and with resolution well below 6 fs r.m.s. for higher charges [11, 12]. After the successful completion of the ongoing design update, the BAM is planned to achieve a consistently high accuracy with 1 pC bunches.

In this paper a possible design and intermediate stages are presented after a brief introduction to the current BAMs.

ELECTRO-OPTICAL BAM

The arrival time of a single bunch is measured relative to an optical reference in the BAM, which is one end-station of the all-optical synchronization system. As a reference, 1 ps short laser pulses [13] are emitted from an optical laser oscillator synchronized to the master rf oscillator [2]. The laser pulse distribution system is actively stabilized by piezo fibre stretchers and free-space delay stations [2, 5].

The operation principle of electro-optical BAM, introduced in [4], can be divided into the rf part and the electro-optical correlation to the reference laser pulse.

In the rf part, the transient electric fields of coasting bunches couple with button-type pickups and induce a bipolar voltage signal [4]. State-of-the-art BAMs are equipped with four cone-shaped pickups [14] evenly distributed around the beam pipe. The signals are transmitted via coaxial cables [14] while each pair of opposite pickups is combined to compensate for the beam position [13].

Afterwards, the voltage signal is applied to a Mach-Zehnder-type electro-optical modulator (EOM), where the signal is probed by the optical reference [4]. By another free-space delay station the working point is set exactly to the voltage signal's zero crossing (ZC) for a perfectly timed bunch [4, 13]. Any temporal deviation causes a modulation voltage that effects the amplitude of the probing reference pulse [4]. In the operating range the amplitude difference is proportional to the arrival time [5] and therefore the relative timing can be determined by comparing the modulated pulse to unaltered reference pulses [4]. The information is retrieved and digitized in the data acquisition and the results are used to stabilize the operation by a feedback-loop [4, 5, 13].

* This work is supported by the German Federal Ministry of Education and Research (BMBF) under contract no. 05K19RO1
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ISBN: 978-3-95450-230-1 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2021-WEPP19

Design Upgrade

A low charge mode with 1 pC bunches is demanded for the EuXFEL. To achieve the desired resolution, the BAM must receive an upgrade, increasing the sensitivity approximately by a factor of 20. Out of potential candidates for improvement, it is foreseen to update the EOMs and the rf part, aiming for at least a factor of 10 in the latter. By the function principle of the electro-optical BAM the sensitivity is directly proportional to the signal slope at ZC, which is depending on the signal yield and the bandwidth. The targeted slope normalized to the bunch charge is 150 mV ps^{-1} pC^{-1}.

To accomplish these improvements by decrease of the distance to the bunch or reduction of losses in the rf path, two designs were proposed in [15] and compared with a scaled version of the cone-shaped pickups. Despite some advantages, both did not meet the required signal strength and further development is necessary. In the following section an alternative is presented, which afterwards is combined with the printed circuit board (PCB) approach from [15].

ROD-SHAPED PICKUPS

A small protrusion of the pickup into the beamline was introduced in the second generation of cone-shaped pickups presented in [14]. The authors of [14] expected that the positive effect would be limited to a small protrusion. In this contribution a rod inserted into the beamline is adopted as a possible design basis, because a preliminary series of simulations with increasing protrusion showed a consistent rise of the signal slope at ZC. In the CST model, pictured in Fig. 1, the tapering was omitted for simplicity of the manufacturing process and for mechanical stability, but a small tapering of the tip might be beneficial if the radius does not significantly exceed the bunch length [14–16].

The resulting pickup is similar to an open coax-line electrode BAM as presented in [17] and an antenna on coaxial high power coupler [18], which is an open coaxial with substantial penetration depth of the inner conductor. The adopted BAM design is less complex, since the subsequent transmission line is likewise coaxial and not waveguide based as in the high power coupling case.

The rod-shaped pickup design allows for a reduced distance to the beam with minimal coverage of the transverse plane, which in turn reduces the cross-section for beam incidents and the potential halo disturbance. Furthermore the beamline wall needs a hole considerably smaller than that of the second generation pickup, thus desired wall currents are expected to be less disturbed.

Ideally the vacuum feedthroughs are placed flush with the beamline surface to reduce the number of transitions.

The greatest advantage of a rod-shaped pickup is the large active area. While the interaction is mainly limited to the circular top of the cone-shaped pickup, a protruding rod senses electric fields at its top as well as on a substantial part of the lateral surface.

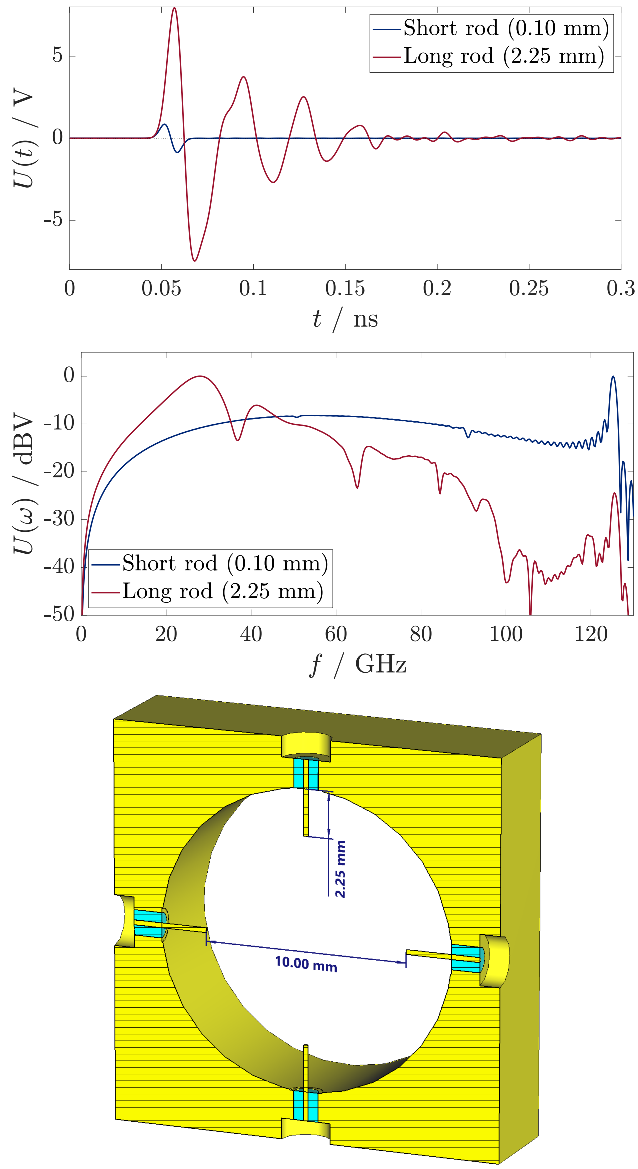

Figure 1: Simulated signal after the feedthrough in time domain (top) and its normalized shifted spectrum (bottom) with two different pickup lengths and constant tip-to-tip distance (10 mm) as well as a cross-section of the CST model of the simulated BAM structure containing four 2.25 mm long rod-shaped pickups with 10 mm tip-to-tip distance on v-type feedthroughs. The bunch is simulated as a Gaussian line charge with Q_b = 20 pC and σ_b = 1 mm.

A low stray capacity may ensure bipolarity of the signal as determined for the so called inductive limit [15, 16], though some assumptions of these analytic solutions are violated.

Negative aspects, like cross-talk and strong resonances, have to be investigated. The latter are caused by reflections at the feedthrough and the open end of the rod, hence the signal travels back and forth. The pickup will act as a dipole antenna, radiating part of the energy back into the beamline. Both problems must be addressed regarding long-range wakefields and head-tail instabilities.

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Simulation Results

First simulations of the rod-shaped design with the wakefield solver of CST PARTICLE STUDIO™ using a Gaussian current distribution with charge $Q_\mathrm{b} = 20\,\mathrm{pC}$ and standard deviation $\sigma_\mathrm{b} = 1\,\mathrm{mm}$ are promising. The influence of the rod length, a crucial parameter, was analyzed in two series of simulations. To assess the optimal length maximizing the signal slope at ZC, the first series used a fixed beamline diameter of 41 mm and the second a fixed distance between opposite pickup tips of 10 mm.

The second series gave an optimum length of approximately 2.25 mm while the first showed a non-linear relation. For short stubs the slope strongly depends on the length, but after about 2 mm a saturation effect is observed, which holds until an exponential growth is seen for unfeasibly long rods.

A design in accordance to the EuXFEL facility parameters achieved $120\,\mathrm{mV\,ps^{-1}\,pC^{-1}}$, which is 80 % of the objective. Further optimization, e.g. by using other feedthroughs and tapering or widening the rod, have not been fully exploited.

Non-hermetic Demonstrator

The simulation model was adapted to allow machining of a non-hermetic normal conducting demonstrator with short rods as pictured in Fig. 2. The brass body with 7.5 mm inner diameter was manufactured in-house by a turn and mill complete machining center DMC CTX alpha 300. A glass bead has been inserted in each of four milling pockets angular separated by 90°. The beads are fixed by pressure using Anritsu V102F connectors screwed into the brass body.

The scattering parameters were measured with a 40 GHz vector network analyzer (VNA) in free space under room conditions. While two ports have been attached to the VNA the other were terminated with 50 Ω.

All ports are highly reflective and in good agreement indicating that there are no significant variations due to production errors. Differences occur between port 1 and 2 of the VNA, furthermore some values are surpassing 0 dB and the reflective parameters do not match the simulation. Supposedly this is caused by calibration uncertainties.

The high reflection indicates low cross talk between the pickups and therefore the reflections occurring downstream of the rf path will have a minor influence on the other ports or the beamline.

Measured transmission spectra are shown in Fig. 3 alongside the corresponding simulation results. Common peaks indicate transmission between neighboring or opposite pickups. By evaluating the simulated fields they have been attributed to different TE-modes excited in the circular waveguide. This is confirmed by calculation of the related analytical frequencies of TE_{11}, TE_{21}, TE_{31} and TE_{41}.

It is planned to measure a demonstrator with elongated pins with a 67 GHz VNA in order to analyze the complete spectrum. Afterwards the response to a bunch will be measured by sending a short pulse through the beamline on a central wire or by building a hermetic body for tests, e.g. at the Accelerator Research Experiment at SINBAD (ARES).

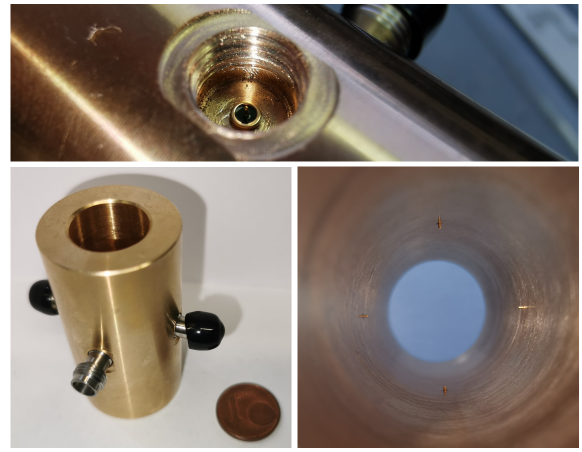

Figure 2: Photographs of the non-hermetic brass demonstrator. The images show a glass bead before final assembly of the v-type connector (top), the finished demonstrator (bottom left) and the protruding pins (bottom right).

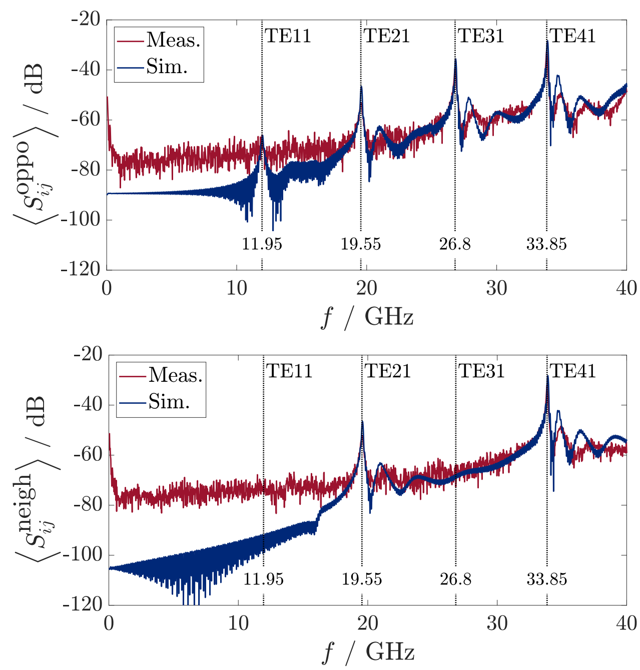

Figure 3: Measured (red) and simulated (blue) transmission parameters between opposite (top) and neighboring (bottom) pickups. The spectra are the mean of according S_{ij} parameter (note that only $j = 1$ was simulated). Dashed vertical lines mark resonances in the filtered measurement data.

ROD-SHAPED PICKUPS ON A PCB

A stripline pickup had been proposed in [15]. Though it achieved promising results and potential for optimization is left, the rod-shape yields a stronger signal and has been adopted. Nonetheless, the PCB could fulfil the requirements for a short high bandwidth combination network and offer the opportunity to get close to the beam without a reduction of the beampipe radius. For this purpose, the PCB is mounted inside the beamline vacuum.

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A PCB equipped with four rod-shaped pickups is expected to merge the benefits of both approaches. The rods couple to the electric field of the coasting bunch and a microstrip line joins the four channels to a common exit. The combined signal is coupled out of the beamline through a single v-type connector.

The first draft and the simulation result are pictured in Fig. 4. It achieved a normalized signal slope at ZC of 171.6 mV ps^{-1} pC^{-1}, which exceeds 114 % of the required design value. With a 20 pC bunch the peak-to-peak voltage is 27.9 V, presumably leaving only 1.4 V for 1 pC operation at the end of the combination network. A duration of 13.5 ps peak-to-peak is the upper limit of the dynamic range.

Optimization can be achieved by reducing the angle between each of the pickup pairs. This reduces the lossy transition line, but the BAM capability to compensate for beam position will be narrowed in one direction. Furthermore the junctions offer little signal enhancement, mainly compensating for losses on the path. Rod diameter, length and tapering are less constrained by the proposed design, thus leaving additional room for optimization.

Wakefields and Ringing

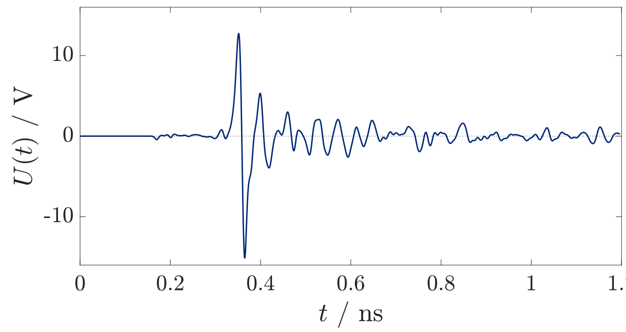
The design contains various sources for wakefields and ringing, which have to be addressed. The coasting beam inside the substrate aperture is a source of Cherenkov diffraction radiation (ChDR) as well as transition diffraction radiation (TDR) [19] and the PCB ground plate also causes TDR. Furthermore the transmission line includes many transitions which cause field reflections. Part of the energy is lost in the transmission line and part will be radiated from the rod-shaped pickup antenna.

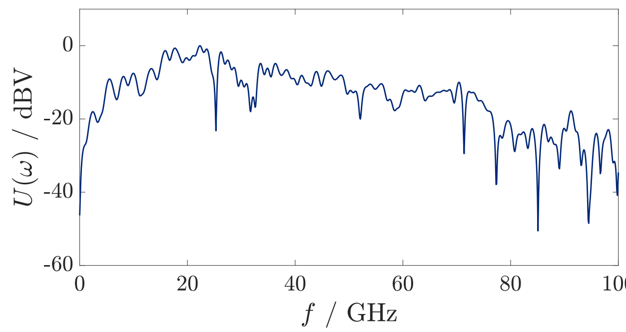
It is necessary to prevent an effect on the bunch tail, to subsequent bunches and to the voltage signal. A potential solution to reduce the effect of radiation on the signal is the use of a shielded quasi-coaxial transmission line. According to simulations, TDR contributes most to the perturbative fields. Supposedly it could be limited at expense of the cylindrical symmetry by clipping the ground to the significant area which would be efficiently restricted by using a quasi-coaxial design.

CONCLUSION

In simulations the use of rod-shaped pickups showed clear advantages compared to the cone-shape and became the basis for further developments. In addition, measurements on a non-hermetic demonstrator were in accordance with the simulation, but further measurements are necessary to prove viability of the concept in a use-case scenario.

A set of four rod-shaped pickups on a PCB is a promising design for a low charge BAM. In simulations the signal slope after combination surpassed the project goal about 14 %. The design offers a good starting point for optimization, with many variable geometry parameters and a preliminary combination network. Another demonstration experiment and a manufacturable design for the pickups on a PCB are foreseen after the optimization phase.





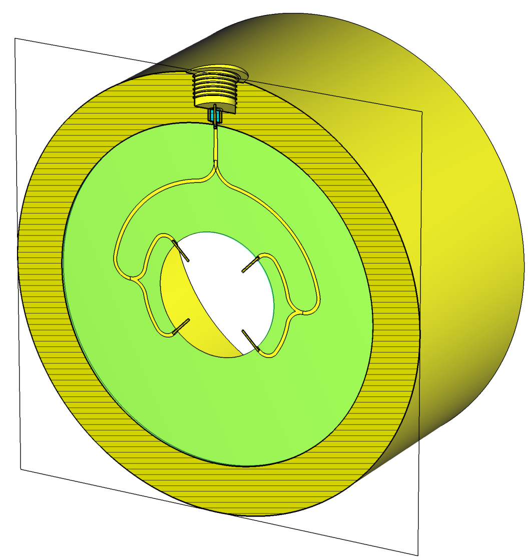


Figure 4: Simulated signal in time domain (top) and its normalized spectrum shifted to max(U) = 0 (center) taken at the end of the vacuum feedthrough (v-type) as well as the simulation model of rod-shaped pickups on a PCB (bottom) cut at the center of the feedthrough. The bunch is simulated as a Gaussian line charge with $Q_b = 20$ pC and $\sigma_b = 1$ mm.

ACKNOWLEDGEMENTS

Our thanks go to the laboratory of production engineering under the lead of Prof. Udo Fiedler associated to the faculty of *Engineering Management - Industry* at *Technische Hochschule Mittelhessen* (Friedberg, Germany) for the manufacturing of the demonstrator's brass body and in particular to Harald Jung for his dedication and excellent work.

ISBN: 978-3-95450-230-1 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2021-WEPP19

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