

# CONCEPT OF A NOVEL HIGH-BANDWIDTH ARRIVAL TIME MONITOR FOR VERY LOW CHARGES AS A PART OF THE ALL-OPTICAL SYNCHRONIZATION SYSTEM AT ELBE\*

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## Abstract

Numerous advanced applications of X-ray free-electron lasers require pulse durations and time resolutions in the order of only a few femtoseconds or better. The generation of these pulses to be used in time-resolved experiments require synchronization techniques that can simultaneously lock all necessary components to a precision in the range of a few fs only. The CW operated electron accelerator ELBE at the Helmholtz-Zentrum Dresden-Rossendorf uses an all-optical synchronization system to ensure a timing stability on the 10-fs scale of the reference signal.

ELBE requires a minimum beam pipe diameter of 43mm that limits the achievable output voltage of the pickup structure to drive the attached electro-optical modulator.

This contribution presents a concept for a novel high-bandwidth arrival time monitor with sufficient output signal for the attached EOMs for very low charges as a part of the all-optical synchronization system at ELBE.

## INTRODUCTION

In order to investigate dynamical processes down to the femtosecond time scale, free electron lasers (FELs) are conducted to deliver ultrashort x-ray pulses for pump-probe experiments [1,2]. These time-resolved measurements require synchronization between an external pumping laser and the FEL pulse for probing lower than the pulse duration, i.e., a few femtoseconds. The FEL pulse timing can be determined by high-resolution arrival-time measurements of electron bunches at the undulators [3].

In recent years, the interest for ultrashort x-ray pulses is continuously rising which requires for the accelerator an ultra-low bunch charge operation down to a few pC only [4,5]. Different schemes for bunch arrival time measurements have been implemented so far allowing for single-shot detection with a resolution of a few fs and below [6-10].

At the free-electron lasers European XFEL and FLASH in Hamburg, pickup-based bunch arrival-time monitors (BAM) with electro-optical detection schemes have been implemented.

As part of a laser-based synchronization system, bunch arrival-time monitors (BAMs) measure the arrival time with a sub-10 fs time resolution for bunch charges higher

than 500 pC [11]. A beam-induced signal modulates the amplitude of an external laser pulse in a Mach-Zehnder type electro-optic modulator (EOM). This laser pulse is delivered through a stabilized optical fiber link with a drift stability of around 10 fs per day. Thus, as a direct client of this highly stable optical reference, the current BAM, based on standard telecom EOMs at 1550 nm has an intrinsic low drift feature, in addition to the high resolution. The reference timing is the zero crossing of the pickup signal, where the sampling laser pulse has no modulation. The EOM DC bias is chosen in such a way that without an external RF modulation the amplitude of the sampling laser pulses is halved. Any deviation from the zero crossing of the pickup transient, i.e. bunch arrival-time jitter, results in an amplitude modulation of the reference laser pulse. With a proper calibration with a precession delay line, this amplitude modulation is directly converted to arrival-time information with a dynamic range corresponding to the linear part of the pickup slope. More details are given in [11-12]. The slope steepness at the zero crossing defines the modulation voltage which the laser pulse experiences in the presence of an arrival-time jitter. This determines the time resolution as well as the sensitivity of the BAMs. The slope steepness reduces proportionally with the bunch charge leading to a BAM performance degradation for charges lower than 200 pC [3,13].

The cone shaped pickups are part of the synchronization systems at European XFEL, FLASH and ELBE (Helmholtz-Zentrum Dresden- Rossendorf) [14-16].

The first facility-wide evaluation of the optical synchronization system at the European XFEL demonstrated a performance of the optical synchronization infrastructure on the single-digit femtosecond timescale with the existing BAMs [17].

In order to achieve a time resolution down to a few pC for a low charge operation mode, the bandwidth of the current BAMs need to be increased from 40 GHz up to 80 GHz or higher.

This paper presents a concept of an ultra-wideband pickup structure frequencies up to 80 GHz or higher with sufficient output signal for driving the attached EOMs.

## CONE SHAPED PICKUP DESIGN

The RF properties of the pickup are defined by its shape, the material, the used connectors, and the cables connected to the pickup. However, the pickup shape has the largest influence on the performance of the system.

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In [14] a tapered coaxial structure was proposed, which comprises a cone-shaped pickup electrode with the corresponding cut-out, as shown in Figure 1. Unlike the classical button-type pickup, the cone-shaped pickup avoids resonances within the pickup due to the tapered transition from the beam pipe to the connector having a constant line impedance of  $50 \Omega$ .

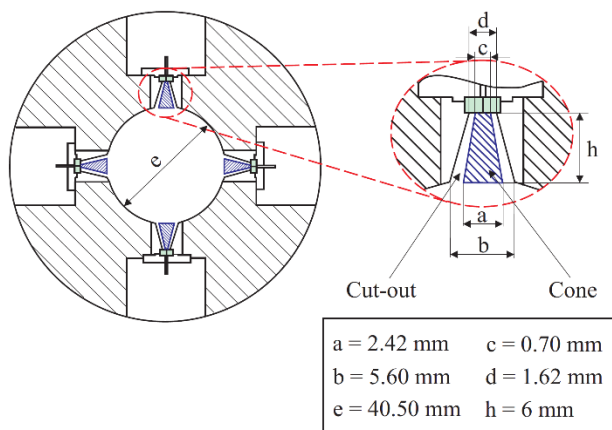


Figure 1: Cross-section of the current cone-shaped pickup with dimensions [14].

The cone shaped pickups allow for the detection of the arrival time with fs resolution for the low charge operation mode with low bunch charges at ELBE. Figure 1 shows a sketch of the cross-section of four cone shaped pickups integrated in the housing with corresponding dimensions for FLASH II, European XFEL and ELBE.

The simulation results of one pickup in time domain and the respective normalized frequency spectrum is shown in Figure 2.

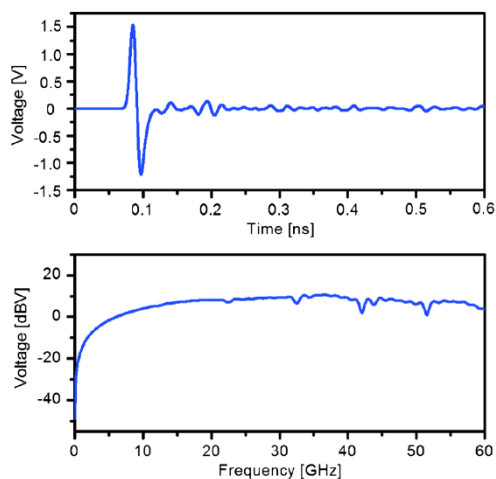


Figure 2: Simulation results of one pickup in time domain (top) and the respective frequency spectrum normalized by the spectrum of the particle beam (bottom) [14].

It can be seen that the spectrum of the voltage is resonance-free up to 60 GHz except small kinks in the spectrum around 23, 33 and 43 GHz.

The broadband pickup structure developed for FLASH (1<sup>st</sup> generation) was optimized to achieve the maximum slope for low bunch charges down to 20 pC. An upgrade to

the 2<sup>nd</sup> generation was necessary to overcome significant losses in the RF signal path from the pickup structures to the EOM that prevents maximum modulation and thus optimal operation of the EOMs. By constructive changes of the pickup structure to 2<sup>nd</sup> generation, the desired peak-to-peak voltage could be achieved with sufficient signal bandwidth. The achievable signal slope and the corresponding peak-to-peak voltage as a function of the cone angle at 20 pC bunch charge are shown in Figure 3.

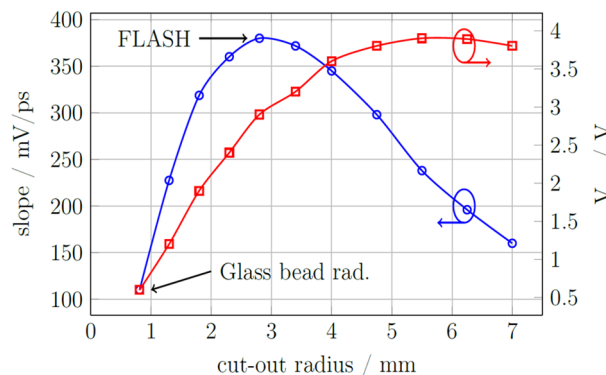


Figure 3: Simulated slope and voltage of a single pickup as a function of the cut-out radius for a bunch charge of 20 pC.

It can be seen clearly that the pickup structure 1<sup>st</sup> generation has been optimized to the maximum achievable signal slope, rather than to a maximum signal output voltage. Taking into account the signal losses in the RF path up to the electro-optical modulators, a maximum sensitivity for a cone radius of 4.8 mm is obtained. The maximum signal slope is still 300 mV / ps at a peak-to-peak voltage of 3.85 V.

In Figure 4 the signal slope for a bunch charge sweep from 5 pC up to 95 pC within a measurement campaign carried out at ELBE is shown [16].

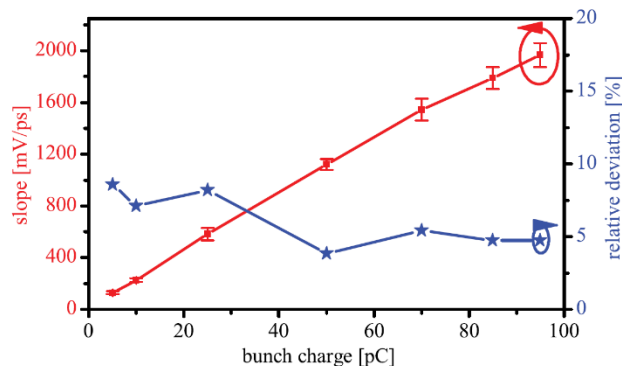


Figure 4: Measured pickup signal slope dependence of the bunch charge at ELBE. Blue curve shows the relative slope deviation for 128 shots (taken from [16]).

The measured signal slope for bunch charge of 20 pC is around 360 mV / ps and corresponds to the simulated data. The uncertainty due to the absolute noise level, is obtained from a set of 128 consecutive shots and is increasing as the bunch charge increases. The relative deviation which is a combination of the relative precision of the detection and

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the bunch charge fluctuation remains below 10% for the entire range of the bunch charge sweep.

The ultra-low-charge mode down to a view pC requires a system bandwidth of at least 80 GHz to 100 GHz from the pickup to the attached EOM. In order to increase the bandwidth of the pickup for a constant line impedance, the pickup dimensions need to be reduced. Figure 5 shows the simulation results of a pickup structure filled with a glass ceramic having a relative permittivity of  $\epsilon_r = 3.75$  a radius of the inner conductor  $r_{in} = 0.226\text{mm}$  and the outer conductor radius  $r_{out} = 0.5\text{mm}$  tapered to a outer conductor radius of  $r_{out,cone} = 1.13\text{mm}$ .

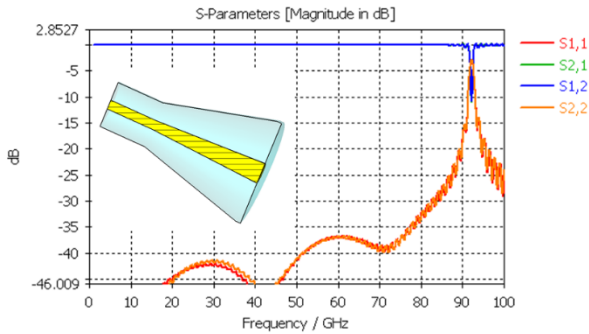


Figure 5: Cross section of the proposed pickup structure and corresponding s-parameter simulation result.

In Figure 5 it can be seen, that the pickup structure is resonance free up to 90-100 GHz can be reached by further reduction of the pickup diameter.

In order to increase the output voltage at the attached EOM and to reduce the orbit dependency, several pickups need to be arranged in a circle around the beamline. Figure 6 shows a sub-circuit of two pickups and an impedance matched combiner structure.

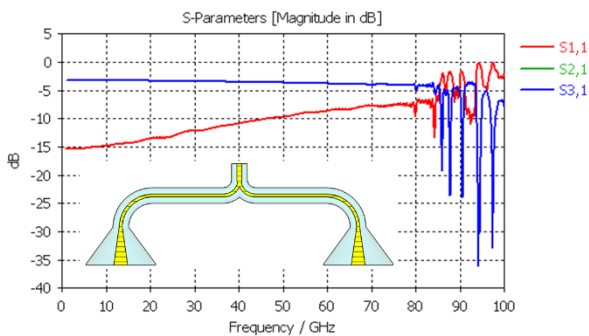


Figure 6: Combination of two pickup structures using an impedance matched combiner structure.

The simulated s-parameters exhibit resonances above 80 GHz that need to be improved within the project. A further combination is required to connect 4 pickups to a sub-circuit. Figure 7 shows a model of a pickup circuit containing 8 pickups equally spaced around the beamline.

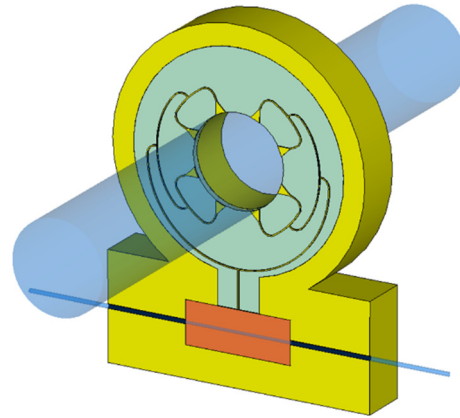


Figure 7: Exemplified pickup arrangement: 8 pickups, 4 pickups each were combined to an integrated sub-circuit with two connectors only.

Further research efforts need to be carried out to optimize the pickup circuit for the ultra-low-charge mode and to provide sufficient output voltage for subsequent EOMs.

## CONCLUSION

A high bandwidth cone-shaped pickup for the BAMs for free-electron lasers is introduced. A new concept of an ultra-wideband pickup structure for beampipe-diameters down to 10 mm for frequencies up to 80 GHz is presented.

This makes it suitable for enabling a sub- 10 fs time resolution for high and low bunch charge operation down to 1 pC of the FELs.

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