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EVALUATION OF A NOVEL PICKUP CONCEPT FOR ULTRA-LOW CHARGED SHORT BUNCHES IN X-RAY FREE-ELECTRON LASERS*

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Abstract

The all-optical synchronization systems used in various X-ray free-electron lasers (XFEL) such as the European XFEL depend on transient fields of passing electron bunches coupled into one or more pickups in the Bunch Arrival Time Monitors (BAM). The extracted signal is then amplitude modulated on reference laser pulses in a Mach-Zehnder type electro-optical modulator. With the emerging demand of the experimenters for future experiments with ultra-short FEL shots, fs precision is required for the synchronization systems even with 1 pC bunches. Since the sensitivity of the BAM depends in particular on the slope of the bipolar signal at the zero crossing and thus, also on the bunch charge, a redesign with the aim of a significant increase by optimized geometry and bandwidth is inevitable. In this contribution a possible new pickup concept is simulated and its performance is compared to the previous concept. A significant improvement of slope and voltage is found. The improvement is mainly achieved by the reduced distance to the beam and a higher bandwidth.

INTRODUCTION

Free-electron lasers (FEL) became an important light source for experiments in various fields since they provide ultra-short pulses with extreme brilliance in atomic length and time scales [1]. FEL are well suited for applications in pump-probe experiments [1], where the timing jitter is specifically critical [2], as well as for capturing image sequences with atomic resolution on fs-time-scales, even below the FEL repetition rate [1, 3, 4].

For the generation of ultra-short X-ray pulses, FEL with short and ultra-low charge electron bunches (≤1 pC) have been found as a favorable option [5, 6]. Short bunches may shorten the X-ray pulse, reduce timing jitter and lead to single-spike operation, if sufficiently small compared to the cooperation length of the SASE process [2, 5, 6]. The European XFEL (EuXFEL) was upgraded from initially 1 nC electron bunches to cover a range from 0.02 nC to 1 nC [7] with a possible bunch length below 3 fs in the undulator section [8]. Moreover, a decrease to ultra-low charges of 1 pC is targeted.

The application in time-resolved experiments entails tight requirements for the overall machine synchronization in order to reduce the timing jitter [2]. The timing information is also used for post-processing experimental data [1]. The synchronization concerns all critical subsystems, specifically in the injector and if present the seeding and the pump laser [1]. Furthermore, the instrumentation must be suited for a broad spectrum of operation modes with different bunch properties even in a single bunch train [9, 10]. Besides, bunch arrival time monitors (BAM) are installed throughout the whole facility, thus experiencing different bunch properties.

A tremendous improvement in synchronization, exceeding RF techniques, and reduction of arrival time as well as energy jitter was achieved by the implementation of an all-optical synchronization system with two different feedback loops [11]. Though some updates have been introduced [12, 13], the basic scheme in use by the Deutsches Elektronen-Synchrotron (DESY) remained unchanged.

In this contribution the all-optical synchronization system will be briefly introduced with special attention on the state-of-the-art cone-shaped pickups, followed by a analytical discussion of the principal parameters determining the BAM resolution. These are the basis for three designs, which are presented at the end of this paper.

ALL-OPTICAL SYNCHRONIZATION SYSTEM

The all-optical synchronization system, as successfully tested at the free-electron laser in Hamburg (FLASH) by Löhl [11], mainly comprises of a mode-locked reference laser, length stabilized fiber links and different end-stations for synchronization and arrival time measurement [10–15]. The arrival time is non-destructively measured with respect to the reference laser in the BAM, which include high-bandwidth pickup electrodes in the RF unit, a Mach-Zehnder type electro-optical modulator (EOM) and the data acquisition system (DAQ) [10, 15].

Basic Working Principle of BAM

The transient electric fields of passing electron bunches are extracted in the RF unit and, if foreseen, initially processed with analogue components like RF combiners, limiters or attenuators [11, 12]. The received bipolar signal is transmitted over radiation hard silicon dioxide coaxial cables to the EOM [12], there it is probed at its zero-crossing by the reference laser [11]. Any temporal deviation will lead to an additional voltage, which the EOM turns into an amplitude modulation of the laser pulse. Therefore, the laser amplitude holds the timing information, which can be retrieved in the DAQ [11]. The signal slope at its zero crossing strongly influences the BAMs temporal resolution.

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The minimum design requirement for the currently installed BAM was ≥ 300 mV ps^{-1} with 20 pC bunches [12].

RF Unit and Pickups

The RF unit so far comprises four identical pickups mounted circularly around the beam line. The combination of opposite pickup signals compensates for the orbit dependency [16]. The original pickups used at FLASH were of button-type and designed for a 10 GHz bandwidth [17]. This pickup struggled with ringing and strong signal reflections at the alumina vacuum feedthrough [17] degrading the signal strength and resolution for charges below 150 pC [18]. Hence, a new design was required [18].

A novel pickup (Fig. 1, left), similar to those designed for the CERN linear collider test facility [19], was proposed as a solution in FEL applications [20]. The cone-shaped design, finalized in [12], with 40 GHz bandwidth became a new standard device used at the EuXFEL and other FEL.

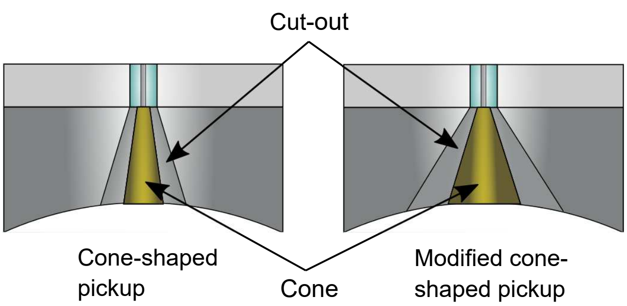

Figure 1: Cross section of the 1st gen. cone-shaped pickup (left) and the modified 2nd gen. cone-shaped pickup for high peak-to-peak voltage (right) adapted from [13].

Due to high losses in the RF path a design update was necessary (Fig. 1, right). The second generation of cone shaped pickups were optimized towards a maximum signal voltage at the cost of its slope by increasing the active surface and letting the cone slightly protrude into the beam pipe [13]. A limit was reached, where a larger surface, e.g., more than a few bunch lengths, further decreases the slope without an increase in peak-to-peak voltage [13]. The protrusion increases the inductance, which unfavorably deforms the signal shape [13]. Nonetheless, a combination of both modifications increased the peak-to-peak voltage sufficiently for 20 pC bunches while maintaining an acceptable slope [13].

Recently the performance of the state-of-the-art system was evaluated at the EuXFEL. The correlation of two adjacent monitors with less than 1 m distance was analyzed. Examining the measured arrival-times for a period of 1 min gave a timing jitter of approximately 6 fs r.m.s. caused by the BAM resolution and critical parts of the reference laser distribution system [21].

RF Signal

The limitations of current pickup structures are evident in the theoretical consideration of the time domain voltage signal. The calculations can be simplified by assuming a Gaussian bunch and a rectangular pickup surface. Depending on the frequency range, the signal looks like a charge source, a current source or intermediate [22]. The image charge on the pickup surface is calculated by

$$Q_{\text{im}} = \int_{-\infty}^{\infty} \frac{\varrho(z - c_0 t) w(z)}{2\pi r_{\text{pickup}}} \mathrm{d}z, \qquad (1)$$

with the linear charge density ϱ of the ultra-relativistic bunch, pickup width $w(z)$ and the distance between pickup surface and bunch r_{pickup} [23]. Fringing fields at the gap between flush mounted pickup and beam pipe may be introduced in a constant factor. The maximum voltage is proportional to the bunch charge, Q_{bunch}. This is also true for the signal slope of the cone shaped pickups, as empirically shown at FLASH [16]. Furthermore, the maximum voltage is inversely proportional to r_{pickup} and is depending on the ratio of pickup and bunch lengths as well. The function approaches the maximum value asymptotically and deviates only slightly from the value for a pickup longer than a few bunch lengths [13, 22]. This also effects the signal slope, as the maximum voltage barely changes in this region while both extrema drift apart, leading to a decreasing slope [13].

Additionally, the signal width is limited by the bandwidth. The product of a signal's rise time τ as response to a step function and the frequency bandwidth Δf satisfies[1]

$$\tau \Delta f = 1. \qquad (2)$$

This rise time serves as an upper limit and can be expressed by the maximum slope S_{max} and the peak-to-peak voltage U_{PP} with $\tau = U_{\text{PP}} \cdot S_{\text{max}}^{-1}$ giving

$$S_{\text{max}} \leq V_{\text{pp}} \cdot \Delta f. \qquad (3)$$

ULTRA-LOW CHARGE MODE

For new experiments in the EuXFEL, with an ultra-low charge mode (≤1 pC), the 2nd generation pickups are incapable of providing the required signal for fs resolution. Therefore, the BAM will be upgraded with a novel pickup structure and new EOM.

Planned Signal Improvement

New layouts are restrained in each facility by design regulations and previous design choices. For the next BAM upgrade in the European XFEL a smaller pipe diameter is now permitted. The possible reduction from 40.5 mm [12] to 10 mm gives a potential fourfold signal increase. When additionally the bandwidth is raised one can expect an improvement by one order of magnitude. Moreover, it is possible to combine multiple signals and to shorten the lossy RF path for further improvement.

The downside of these changes is a shorter dynamical range and a higher damage risk due to increased likeliness of direct beam impacts and high voltages at high charge mode. Special attention must be given to machine protection for all subsequent components.

[1] Denote that the right-hand side of the related uncertainty inequalities by Küpfmüller [24] and Gabor [25] depend on the definitions of bandwidth and duration.

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Aperture Reduction

A straightforward option for improvement is the sole reduction of the beam pipe aperture. A diameter of 10 mm is possible in combination with the smaller first-generation cone-shaped pickup. The second-generation pickups cannot be installed in a four-pickup configuration with this diameter due to its dimensions, as the cut-outs would overlap. A simulation with the wakefield solver of CST PARTICLE STUDIO™ yields a slope of 1746 mV ps^{-1} with 13.7 V peak-to-peak voltage and a dynamical range of 12.4 ps at the nominal 20 pC. The ringing of the signal pictured in Fig. 2 initially is significantly higher but rapidly decreases during the first 0.3 ns.

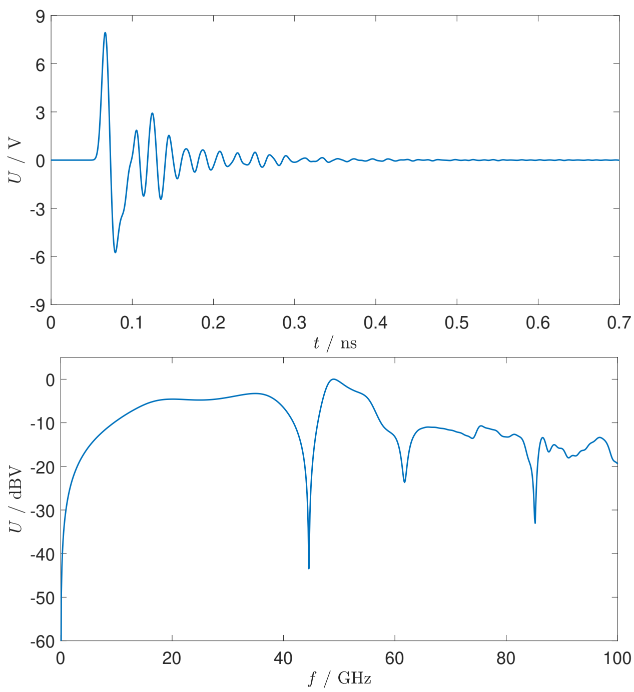

Figure 2: Simulated signal in time domain (top) and its normalized spectrum (bottom) taken at the end of the vacuum feedthrough of a single pickup with 10 mm minimum distance.

90-GHz Cone Shaped Pickup

We proposed a new concept with pickups scaled to support up to 90 GHz 2019 with the dimensions specified in Table 1 [26]. This pickup was simulated afterwards in a BAM like setup, with four identical pickups equally distributed around a pipe section, omitting the proposed signal combination. In addition, the former bunch parameters have been initially used. These are a super relativistic ($v = c_0$) Gaussian bunch with $\sigma = 1$ mm and charge of 20 pC. Therefore, the voltage can be compared to the well-described state-of-the-art pickups according to Angelovski et al. [13, 16].

The bipolar signal pictured in Fig. 3 has a peak-to-peak voltage of 3.52 V and the peaks are separated by 8.01 ps, more than doubling the slope to 722.4 mV ps^{-1}. Though the pipe radius was decreased nearly by a factor of four,

Table 1: Specifications of the 90 GHz-Pickup in [26], the Modified Pickup (Gen. 2) from [16] and the Original (Gen. 1) from [12]

	Draft'19	**Gen. 2**	**Gen. 1**
Cut-out dia.	1.00 mm	1.62 mm	1.62 mm
Tapered cut-out dia.	2.26 mm	13.6 mm	5.60 mm
Cone dia.	0.45 mm	0.70 mm	0.70 mm
Tapered cone dia.	1.02 mm	6 mm	2.42 mm
Cone height		6 mm	6 mm
Protrusion		1 mm	0 mm
Relative permittivity	3.75	4.1	4.1
Line impedance	50 Ω	50 Ω	50 Ω

the gain is only 2.4. The increased bandwidth leads to a reduced rise time of 7.9 ps but it cannot compensate for the missing protrusion and the smaller active area. Thus, the pickup cannot outperform the 1st generation, but a smaller peak-to-peak voltage gives advantages in machine protection. Reducing the bunch charge to 1 pC accordingly gives a slope of 36.2 mV ps^{-1}, which undershoots the minimum target by about a factor of 4. For a further increase the combination of more than two signals is planned. By the combination of 8 pickups, without any phase shift and 3 dB attenuation at each stage, a factor of 2.8 might be possible. Eight pickups has been determined as the limit, because 400 Ω pickups would be necessary due to the impedance change at a T junction type combiner, to have a 50 Ω connection to the EOM. This is well above the vacuum impedance and requires tiny components. A less radical option is the combination of 4 pickups for a potential improvement of factor 2.

Compared to both preceding pickup generations, the voltage is approximately proportional to the radius of the circular pickup surface. This may indicate a bunch-pickup ratio where only the pickup width, but not its length is relevant.

Printed Circuit Board BAM

For ultra-short bunches the transition to a short rectangular pickup on a printed circuit board (PCB) with a trace thickness still larger than the bunch length appears possible. This concept possibly allows for a 100 GHz pickup without the drawback of smaller dimensions. Further benefits are the possibility to use well-known components with precise production methods and well-described materials. The transmission lines (TL) and combination network may be realized on the PCB reducing the RF path, which is specifically important to prevent dispersion effects in broadband quasi-TEM TLs. A microstrip is favorable for its width, but entails dispersion and is less shielded. Therefore, it is planned to use a microstrip (MS) for coupling to the field and a stripline (SL) for the combination network. A preliminary simulation, shown in Fig. 4, of a PCB based pickup was done with a 1.55 mm wide and about 15 mm long 50 Ω SL in a $\epsilon_r = 4.03$ substrate disc with 10 mm aperture inside. For a 20 pC bunch the simulation returns a slope of

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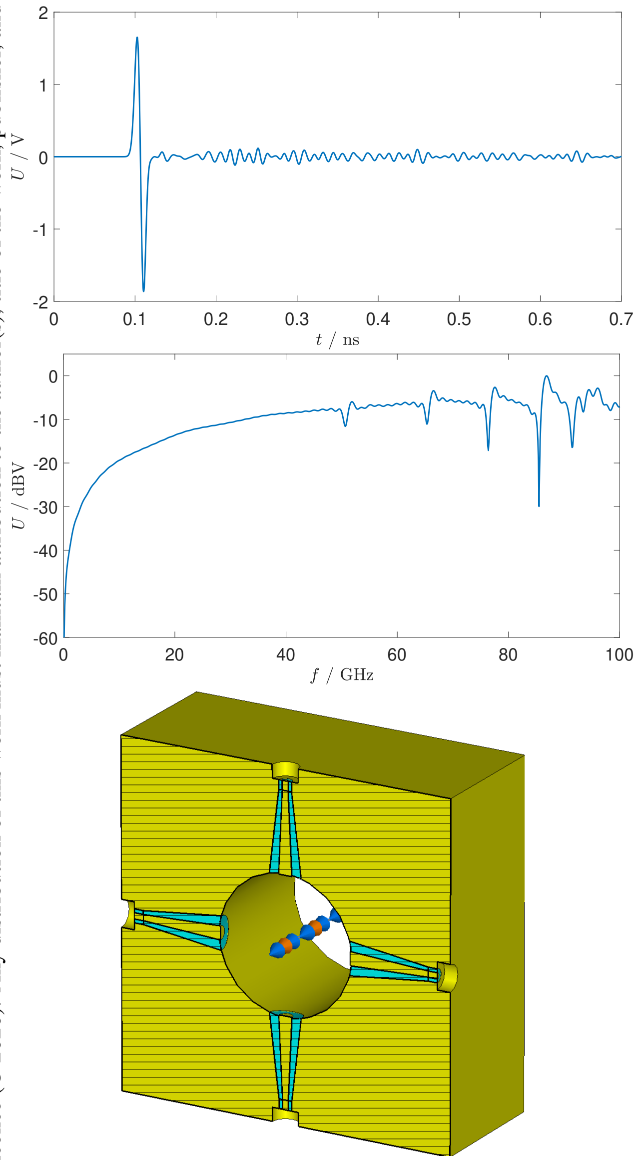

Figure 3: The signal in time domain (top) and its normalized spectrum (center) taken at the end of the vacuum feedthrough of a single pickup as well as the simulation model with 90 GHz cone-shaped pickups (bottom).

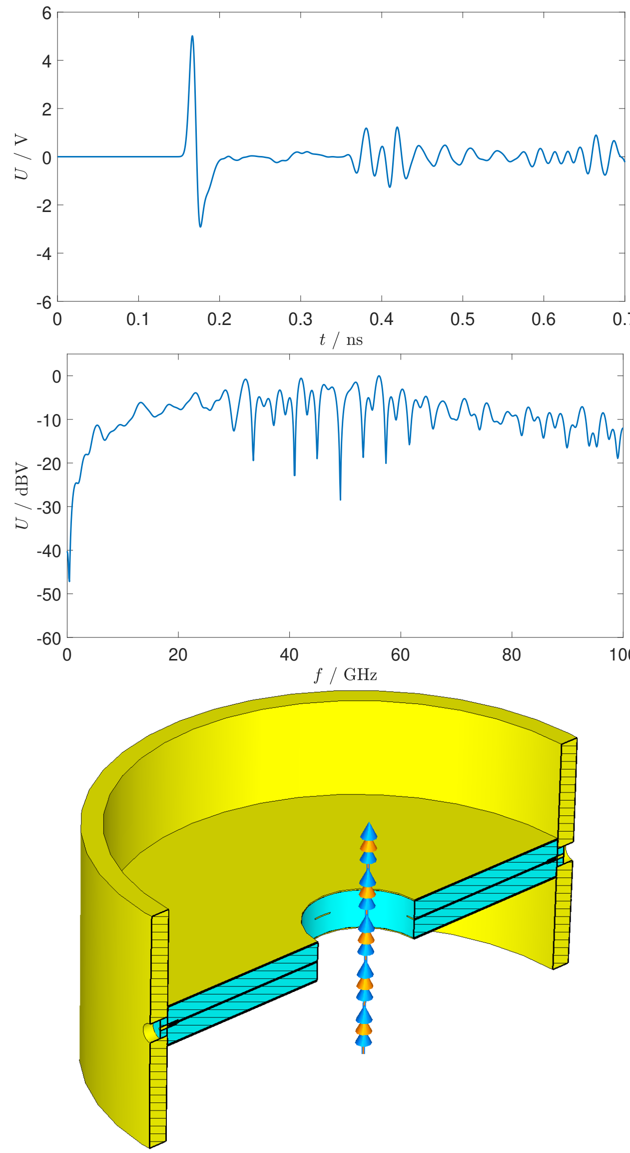

Figure 4: The signal in time domain (top) and its normalized spectrum (center) taken at the end of the vacuum feedthrough of a single pickup as well as the simulation model with 50 Ω stripline pickups (bottom).

about 1270 mV ps^{-1}. The SL pickup is exceeding the current as well as the 90 GHz cone-shaped pickups, but does not achieve the performance of a generation 1 pickup of equal aperture. Furthermore, crosstalk and reflections at the vacuum feedthrough as well as the open pickup end generate delayed but significant ringing.

CONCLUSION

A high bandwidth cone-shaped pickup with 10 mm aperture leads to a significant improvement by reduction of the distance and increase of the bandwidth. If a maximum voltage is of no concern, a configuration of 1st generation pickups in a 10 mm beam pipe is a simple solution estimated sufficient for bunch charges down to 4 pC. In case of ultra-short bunches a PCB-type BAM may be suited to support 100 GHz without the drawback of reduced dimensions. With the current design restrictions, a signal combination is inevitable. Further studies of an integrated combination network are required to reduce signal reflections and losses. Furthermore, it is necessary to investigate the properties of PCB boards regarding vacuum suitability and radiation hardness. Specifically, potential damages caused by beam incident need to be assessed.

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