ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-THAN03



# ULTRAFAST THz DETECTION AND ENHANCED ELECTRO-OPTICAL TIMING FOR LONGITUDINAL BEAM DIAGNOSTICS AT FREE ELECTRON LASERS*

Andreas Penirschke†,1, Bernhard Scheible[1], Rahul Yadav[1], Michael Kuntzsch[2], Marie Kristin Czwalinna[3], Holger Schlarb[3]
[1] Technische Hochschule Mittelhessen, Friedberg, Germany
[2] Helmholtz-Zentrum Dresden Rossendorf HZDR, Dresden, Germany
[3] Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

## *Abstract*

This work presents recent advancements in precision longitudinal beam diagnostics for Free Electron Lasers (FELs), focusing on the integration of ultra-fast, zero-bias Schottky diode-based terahertz (THz) detectors and enhanced electro-optical bunch arrival-time monitors (EO-BAMs). These innovations are vital for both currently operating and forthcoming FEL facilities, where achieving sub-picosecond timing accuracy and reliable low-charge diagnostics is critical for optimal machine performance and experimental success.

The THz detectors enable broadband, single-shot detection with picosecond time resolution, which is crucial for diagnostics such as real-time bunch compression monitoring at high repetition rates. Concurrently, the upgraded EO-BAM systems incorporate novel printed circuit board (PCB) pickup architectures optimized for ultra-low charge operation down to the sub-picocoulomb range, achieving femtosecond-level timing precision.

Together, these complementary technologies address the growing demands in FEL facilities for non-invasive, high-speed, and high-accuracy beam characterization, enabling improved synchronization, diagnostics, and accelerator performance optimization.

## ULTRAFAST THz DETECTORS

Recent advances in semiconductor terahertz (THz) detection technology have innovated beam diagnostics across the accelerator community, establishing THz detectors asversatile, multi-purpose diagnostic tools deployed at numerous accelerators for diverse longitudinal and transverse beam characterization applications. The widespread adoption of THz diagnostic systems spans numerous accelerator facilities worldwide, including European XFEL and FLASH @ DESY (Germany), LCLS @ SLAC (USA), SwissFEL @ PSI, (Switzerland), TELBE and ELBE @ HZDR (Germany), ALICE @ Daresbury Laboratory (UK), KARA and FLUTE @ KIT (Germany), the Advanced Photon Source (USA), and KAERI THz FEL (South Korea). The developed THz technology covers diverse detector architectures including zero-bias Schottky diodes [1], GaAs field-effect transistors with ultra-broadband coverage (0.2 - 29.8 THz) [2], antenna-coupled detector arrays [3], electro-optical sampling systems [4], and specialized cavity-type beam position monitors [5]. These systems operate across frequency ranges from sub-THz to far-infrared (> 50 THz), enabling comprehensive spectroscopic analysis of accelerator-generated coherent radiation.

In this work, we focus on zero-bias Schottky diodes (ZBSDs) that provide compact, cryogen-free, real-time monitoring of bunch profiles at facilities such as TELBE and FLASH. Operable across a frequency range from approximately ~ 0.05 to over 5 THz, these room-temperature devices suppress shot noise by eliminating the need for external bias and achieve an impulse response on the order of ~ 100 ps, a noise-equivalent power (NEP) close to $10\,\mathrm{pW}\,\sqrt{\mathrm{Hz}}^{-1}$ and voltage responsivities approaching $500\,\mathrm{kV\,W^{-1}}$ (see Fig. 1). The detector was tested using both a table-top setup for frequencies up to 1.2 THz and a Free Electron Laser (FEL) facility for extended characterization up to 5.56 THz [1]. Saturation characteristics at selected frequencies as well as the voltage responsivity compared on picosecond and millisecond timescales were investigated.

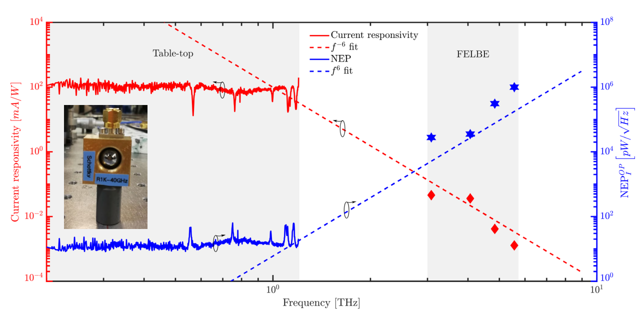


Figure 1: Responsivity and noise equivalent power of the log-spiral antenna-coupled broadband zero-bias Schottky detector [1].

### *Selected THz Application within a BCM Monitor*

A study of a high-speed detector system for longitudinal bunch diagnostics in the terahertz domain at TELBE was presented, in which fast, room-temperature operable zero-bias Schottky diodes were used to measure electron bunch lengths via coherent transition radiation (CTR) [6].

* This work is supported by the German Federal Ministry of Research, Technology and Space (BMFTR) under contract no. 05K22RO1 and 05K22RO2.
† andreas.penirschke@iem.thm.de

ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-THAN03

The primary goal was the precise detection of ultrashort electron bunch longitudinal structure, typically in the sub-picosecond range. At TELBE, electron bunches emit coherent THz pulses via transition radiation from thin metal foils, directly encoding their temporal charge distribution. The emitted THz radiation is collected and focused onto a THz detector using optimized free-space optics. Compared to a pyro-electric detector, zero-bias Schottky diodes offer wide bandwidth and fast response times. Figure 2 illustrates the ZBSD detector's high linearity across various bunch charges, with a consistent proportional response from 18 pC to 45 pC, which confirms its quantitative reliability for charge measurement [2]. This linearity is crucial for accurate charge and bunch length assessments in accelerator operations.

The performance of the ZBSD detector was evaluated through systematic bunch charge variation measurements. Bunch charges were varied from 18 pC to 45 pC, directly modulating the THz power emitted by transition radiation. As can be seen in Fig. 2(a) the ZBSD demonstrated an almost linear response throughout the entire charge range. Simultaneous measurements with a reference pyroelectric detector confirms the correlation. According to theory, a quadratic relationship should be expected; however, neither detector observes this. It is assumed that the shape of the bunch also changes when the bunch charge increases. Figure 2(b) shows the result of bunch compression measurements performed at 45 pC bunch charge using both, a ZBSD and a pyroelectric detector. Compression was achieved by adjusting the acceleration cavities to introduce a longitudinal energy chirp, with the LA2 parameter serving as the offset phase reference. At negative LA2 phases, where the THz power remained low, both detectors showed excellent agreement. However, approaching phase matching conditions where the THz power increased dramatically, the ZBSD detector entered saturation earlier than the pyroelectric detector, indicating maximum bunch compression. This early saturation behavior demonstrates the superior sensitivity of the ZBSD system to detect critical machine parameters and provides a clear diagnostic signature for optimal compression settings [2].

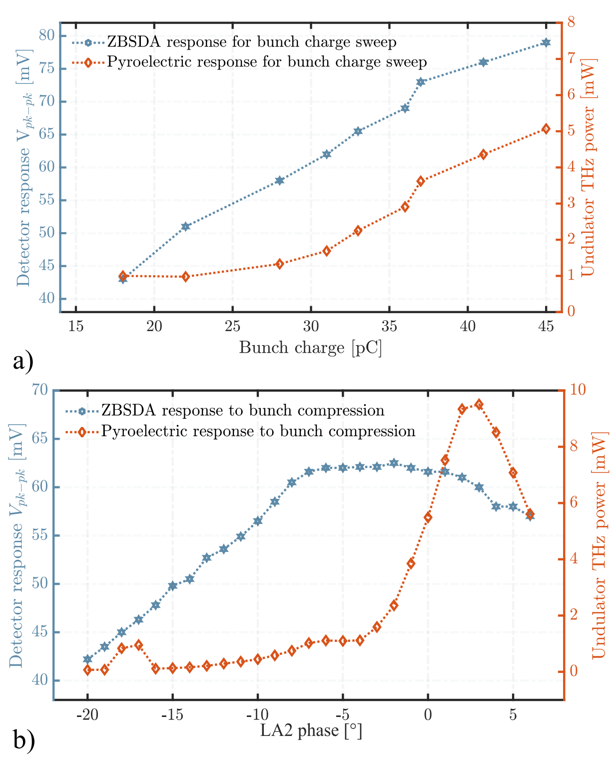


Figure 2: a) Linearity measurement result by varying the THz power by bunch charge sweep and b) Bunch compression measurement results at 45 pC (LA2 is the offset phase). [6]

## ELECTRO-OPTICAL TIMING FOR FELs

All-optical synchronization systems are employed at several X-ray free-electron laser (XFEL) facilities relying on electro-optical bunch arrival-time monitors (EO-BAMs) for precise measurement of individual bunch arrival times relative to an optical reference. The main laser oscillator is phase-locked to the RF master oscillator via a phase-locked loop (PLL) that compares the laser's repetition rate and carrier-envelope phase with the RF reference, ensuring optical synchronization with sub-femtosecond stability. The RF master oscillator generates a highly stable signal that is distributed via a coaxial RF distribution system, which is resynchronized to the optical pulse to serve as a timing reference. Concurrently, the repetition rate of the laser pulse train, carrying timing information, is delivered through an electronically stabilized fiber-based laser distribution system. This system employs active feedback loops to compensate for phase drifts and environmental fluctuations, enabling precise timing synchronization at multiple stations, such as the electron injector and RF cavities. This ensures that the electronic, optical, and RF signals remain temporally synchronized over extended periods, maintaining phase coherence essential for precise beam and pulse generation. Consequently, the injected electron bunches and RF fields within the cavities are synchronized to the master oscillator through the master laser oscillator, enabling ultrashort pulse formation and stable operation of the XFEL. Figure 3 shows the layout of the synchronization system at the European XFEL.

### *Bunch Arrival-Time Monitoring*

An upgrade of the well-established EO-BAM technology is necessary to achieve sensitivity levels that enable stable XFEL operation with low bunch charges in the order of 1 pC or to significantly enhance temporal resolution during standard operation at double-digit pC bunch charges for future operation. This advancement requires a redesign of the RF signal path, including both pickup structures and electro-optical modulators. Starting from the general pickup development [8], a novel pickup concept employs planar pickup elements with bandwidths extending up to 100 GHz, integrated on a printed circuit board (PCB) featuring an embedded combination network, as shown in Fig. 4. Theo-

ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-THAN03



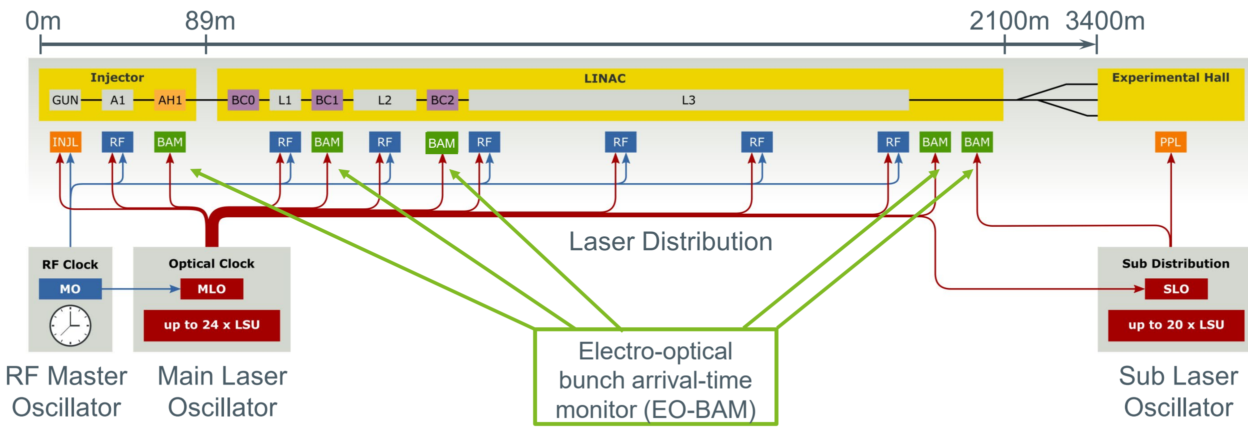


Figure 3: Layout of the synchronization system at the European XFEL (modified from Ref. [7]).

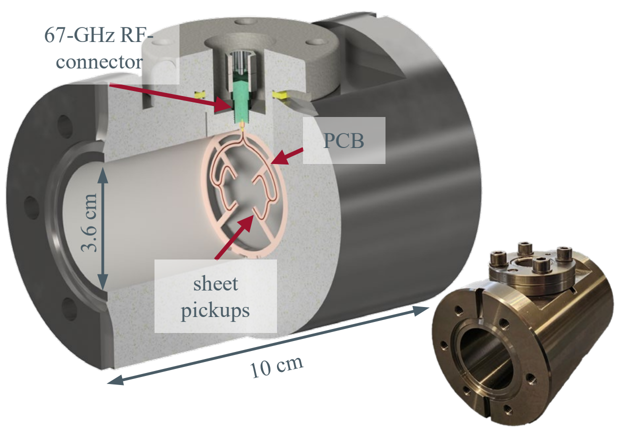


Figure 4: Rendering of the PCB-based demonstrator [11] and picture of the realized demonstrator [12].

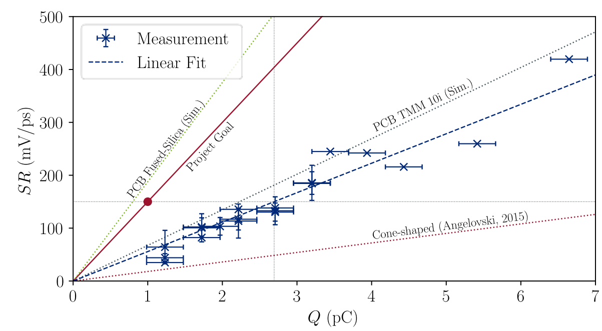


Figure 5: Charge-dependent zero-crossing slope of the voltage signal measured at HZDR for the first vacuum-compatible PCB-based pickup structure, including comparative data from Ref. [13] and simulation results from Ref. [11]. [14]

retical modeling and simulations estimate the jitter-charge product of this concept to be approximately 9 fs pC [9], with experimental validation achieved using a 67 GHz demonstrator at the ELBE facility (HZDR) [10].

Measurements of the first vacuum-compatible PCB-based BAM demonstrator were conducted with a V-type rf connector (up to 67 GHz bandwidth) connected to a Keysight UXR1102A oscilloscope. The bunch charge was varied from approximately 1.2 pC to 6.7 pC and estimated from cathode current $I_c$ and repetition rate $f_{rep}$ using $Q_B \approx I_c/f_{rep}$, with an uncertainty of approximately 10% dominated by timing variations and limited current resolution of 0.1 µA. The measured slew rate demonstrated linear dependency on bunch charge with slopes of 60.99(136) mV ps$^{-1}$ pC$^{-1}$ (Bessel filter) and 57.06(331) mV ps$^{-1}$ pC$^{-1}$ (Sinc filter), yielding a mean slope of 59.87(137) mV ps$^{-1}$ pC$^{-1}$, with performance limited by cable and feedthrough cutoff frequencies around 67 GHz.

Figure 5 shows the expected slope when using fused silica as a PCB material. A new demonstrator is presently under development that is designed to surpass the project goal of 150 mV ps$^{-1}$ pC$^{-1}$ by utilizing advanced substrate materials.

## CONCLUSION

The development of ultra-fast zero-bias Schottky diode THz detectors and enhanced electro-optical bunch arrival-time monitors represents a significant advancement in precision longitudinal beam diagnostics for FEL facilities. The demonstrated capabilities of broadband single-shot detection with picosecond resolution and femtosecond timing precision for sub-picocoulomb measurements and establish new benchmarks for non-invasive beam characterization. The integration of PCB-based EO-BAM architectures and room-temperature ZBSD operation addresses critical challenges in high-repetition-rate FEL facilities. These complementary technologies enable real-time bunch compression monitoring and precise synchronization control essential for advanced experimental programs. These performance characteristics position the technologies as essential components for future FEL facilities requiring sub-picosecond timing stability and ultra-low charge operation, establishing the foundation for next-generation high-precision beam diagnostics.

ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-THAN03

## REFERENCES


[1] R. Yadav *et al.*, "State-of-the-art room temperature operable zero-bias Schottky diode-based terahertz detector up to 5.56 THz", *Sensors*, vol. 23, no. 7, p. 3469, 2023. doi:10.3390/s23073469

[2] R. Yadav *et al.*, "GaAs-based antenna-coupled field effect transistors as direct THz detectors across a wide frequency range from 0.2 to 29.8 THz", *Opt. Express*, vol. 32, no. 24, p. 43 407, 2024. doi:10.1364/oe.534393

[3] J. Holstein *et al.*, "8×8 patch-antenna-coupled TeraFET detector array for terahertz quantum-cascade-laser applications", *IEEE Trans. Terahertz Sci. Technol.*, vol. 14, no. 6, pp. 799–807, 2024. doi:10.1109/TTHZ.2024.3438429

[4] G. Niehues *et al.*, "Electro-optical diagnostics at KARA and FLUTE - results and prospects", 2021. doi:10.18429/JACOW-IPAC2021-MOPAB293

[5] Y. Honda *et al.*, "High-efficiency broadband THz emission via diffraction-radiation cavity", *Phys. Rev. Accel. Beams*, vol. 22, no. 4, p. 040 703, 2019. doi:10.1103/PhysRevAccelBeams.22.040703

[6] R. Yadav, A. Penirschke, M. Kuntzsch, and S. Preu, "Longitudinal bunch diagnostics in the Terahertz domain at TELBE using fast room temperature operable zero-bias Schottky diodes", 2024. doi:10.18429/JACOW-IBIC2024-THP41

[7] S. Schulz *et al.*, "Few-femtosecond facility-wide synchronization of the European XFEL", p. Germany, 2019. doi:10.18429/JACOW-FEL2019-WEB04

[8] B. Scheible *et al.*, "Pickup development for short low-charge bunches in x-ray free-electron lasers", *Phys. Rev. Accel. Beams*, vol. 24, no. 7, p. 072 803, 2021. doi:10.1103/PhysRevAccelBeams.24.072803

[9] A. Kuzmin *et al.*, "Modeling and experimental evaluation of a bunch arrival-time monitor with rod-shaped pickups and a low-pi-voltage ultra-wideband traveling wave electro-optic modulator for x-ray free-electron lasers", Kraków, Poland, pp. 447–450, 2022. doi:10.18429/JACoW-IBIC2022-WEP24

[10] B. Scheible *et al.*, "Real-time measurements of the rf-path of an electro-optical bunch arrival-time monitor with integrated planar pickup structure with low-charge electron beams at ELBE", 2024. doi:10.18429/JACoW-IPAC2024-WEPG82

[11] B. Scheible *et al.*, "First measurements of an electro-optical bunch arrival-time monitor prototype with PCB-based pickups for ELBE", in *Proc. IBIC'23*, Saskatoon, Canada, pp. 214–218, 2023. doi:10.18429/JACoW-IBIC2023-TUP012

[12] B. Scheible, S. Vilcins, and A. Penirschke, "Pickups for high bandwidth applications", presented at the Button BPMs for Synchrotron Light Sources Workshop, Barcelona, Spain, Dec. 2024. https://indico.cells.es/event/1542/contributions/2937/

[13] A. Angelovski *et al.*, "Evaluation of the cone-shaped pickup performance for low charge sub-10 fs arrival-time measurements at free electron laser facilities", *Phys. Rev. Spec. Top. Accel. Beams*, vol. 18, no. 1, 2015. doi:10.1103/PhysRevSTAB.18.012801

[14] B. Scheible *et al.*, "First measurements of a demonstrator for the electro-optical bunch arrival-time monitor with PCB-based pickups", presented at the 12th MT ARD ST3 Meeting, Darmstadt, Germany, Jul. 2024. https://indico.desy.de/event/38690/contributions/171838/