14th International Beam Instrumentation Conference,Liverpool, UK JACoW Publishing
ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-WEPMO13

SINGLE-SHOT DETECTION OF SHORT ELECTRON BUNCH SHAPES AT MHz REPETITION RATES USING DIVERSITY ELECTRO-OPTIC SCHEME WITH ADVANCED RECONSTRUCTION ALGORITHMS AT EuXFEL AND FLASH

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Abstract

Real-time diagnostic of sub-picosecond relativistic electron bunches remains a significant challenge for accelerator facilities. While single-shot spectral decoding techniques are well-suited for high-repetition-rate operations, they introduce inherent limitations, compromising both temporal resolution and signal fidelity, especially for sub-ps signals. To overcome this fundamental trade-off, we propose a multi-channel measurement approach based on the diversity concept. By utilizing a multi-output electro-optic setup combined with a novel self-adaptive reconstruction algorithm, we enable the accurate retrieval of electron bunch shapes from distorted measurements. This new algorithm compensates for imperfections in the laser chirp, such as higher-order dispersion, enabling high-fidelity bunch shapes measurements over an extended temporal window. This paper details the underlying principles of our method, presents numerical results, and provides an update on the ongoing experimental implementations at the European XFEL and FLASH facilities. These advancements represent a significant step toward a robust, high-resolution, real-time bunch shape monitor.

INTRODUCTION

Accurate, real-time diagnostics of ultra-short electron bunches is a critical requirement for accelerators and Free-Electron Lasers (FELs) [1]. These facilities generate highly relativistic electron bunches with sub-picosecond durations at MHz repetition rate. The precise measurement of their time-domain profile is indispensable for optimizing machine performance, as it provides crucial information on key parameters such as bunch length, arrival time jitter, and bunch shapes. A common method for single-shot characterization of these profiles is spectral decoding [2, 3]. This technique uses the THz electric field from the electron bunch to modulate a chirped laser probe pulse, and the resulting spectral changes are captured in a single shot using an optical spectrum analyzer.

However, this method has long been considered fundamentally limited in its temporal resolution. This intrinsic constraint has been defined by the minimum resolvable duration, τ_R, which is expressed by the relationship [3]:

$$\tau_R = \sqrt{\tau_W \tau_L}\,, \qquad (1)$$

where τ_W is the compressed laser pulse duration, and τ_L is the stretched pulse duration. This limitation leads to significant distortions in the measured waveforms, which often fail to faithfully represent the actual bunch profile (see Fig. 1). This work addresses the key challenge of accurately recovering the true bunch shape from these distorted measurements.

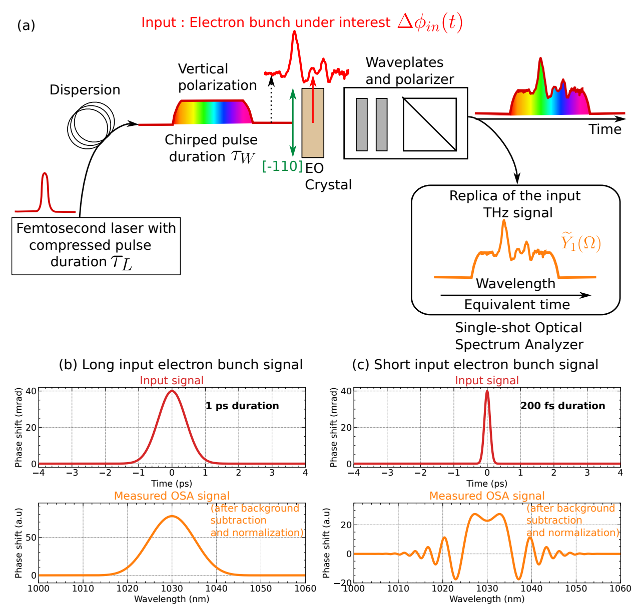

Figure 1: Inherent limitations of conventional electro-optic bunch diagnostics.

Figure 1(a) details the operating principle and shortcomings of a classical electro-optic beam diagnostic. A chirped laser pulse acts as a probe, getting modulated by the Coulomb electric field from an electron bunch, with the resulting spectrum recorded in a single shot. "Long Bunch Durations" (Fig. 1(b)): This method provides a reasonably accurate diagnostic of the bunch profile, but this only works for relatively low-bandwidth THz pulses from long electron bunches. "Short Bunch Durations" (Fig. 1(c)): For the sub-picosecond electron bunches required by modern facilities, the method fundamentally fails. The recorded spectrum shows significant distortions that do not accurately represent the true bunch shape, leading to a loss of critical diagnostic information and underscoring the urgent need for more advanced techniques.

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LIMITATIONS OF SINGLE-CHANNEL ELECTRO-OPTIC DIAGNOSTICS

A major drawback of conventional single-output electro-optic sampling is its inherent information limitation, which prevents the accurate reconstruction of the complete electron bunch profile. The recorded output signal, $Y_1(t)$ is connected to the input signal (i.e., the electron bunch profile), $\Delta\phi_{in}(t)$, by a transfer function :

$$\widetilde{Y}_1(\Omega) = H_1(\Omega)\Delta\widetilde{\phi}_{in}(\Omega) , \tag{2}$$

where the tilde indicates the Fourier transform. The transfer function $H_1(\Omega)$ is defined as:

$$H_1(\Omega) = \cos\left(\frac{\Omega^2}{2C}\right) , \tag{3}$$

with C representing the probe laser's chirp.

This transfer function has nulls where $H_1(\Omega) = 0$, meaning that no signal can be transferred to the output at those frequencies. This leads to a loss of information about specific frequency components of the electron bunch's profile. Because of these information gaps, the mathematical inversion becomes an ill-posed problem. Therefore, a single-output measurement cannot fully capture or reconstruct the complete broadband THz electric field of an electron bunch, $\Delta\phi_{in}(t)$, from a single distorted measurement $Y_1(t)$.

DIVERSITY ENHANCED ELECTRO-OPTIC SAMPLING (DEOS) AT EuXFEL AND FLASH

To overcome the inherent limitations of single-output electro-optic detection systems, a dual-channel diversity electro-optic sampling (DEOS) system for single-shot measurements, validated by table-top proof of principle experiments, has been developed for EuXFEL and FLASH [4]. The conceptual design and numerical test of this system, under conditions of a perfect linear laser chirp and small electro-optic modulation, are illustrated in Fig. 2.

The experimental setup at EuXFEL and FLASH, depicted in Fig. 3, incorporates several key modifications to enhance performance and enable the accurate characterization of electron bunches shapes. These enhancements include:

- **Optimized EO crystal orientation**: The electro-optic crystal is rotated by 90 degrees to align its [-110] axis perpendicular to the electron bunch's electric field, maximizing the modulation signal. This modification was integrated directly into the vacuum chamber.
- **Polarization control:** Waveplates and a polarizer (purple ellipses, Fig. 3) are used to precisely set the laser's polarization at 45 degrees relative to the Coulomb electric field.
- **Dual-channel acquisition**: A polarizing beam-splitter extracts two orthogonal polarization outputs, which are then acquired simultaneously in a single shot by a dual-channel optical spectrum analyzer that uses the high-speed KALYPSO linear array detector [5].

This multi-output configuration provides the essential redundant information to overcome the ill-posed nature of the single-channel measurement and to solve the reconstruction problem. While standard algorithms, such as the Maximum Ratio Combining (MRC) algorithm [6, 7], have shown some success, they are highly sensitive to non-ideal conditions, particularly the higher-order dispersion common in real-world chirped laser systems used for diagnostics. This sensitivity can lead to significant errors in the reconstructed bunch profile, compromising the accuracy of the diagnostic. To address this critical issue, we developed a novel retrieval algorithm that self-adapts to these laser imperfections. This approach moves beyond the simplistic assumption of a perfect linear chirp, enabling a more robust and accurate characterization of the electron bunch profile. Following successful initial tests at FLASH, the system at EuXFEL has been upgraded to support a 1 MHz acquisition rate, demonstrating the method's viability as a reliable, high-speed diagnostic tool in an operational accelerator environment. This capability is crucial for real-time monitoring and feedback control of high-repetition-rate electron beams.

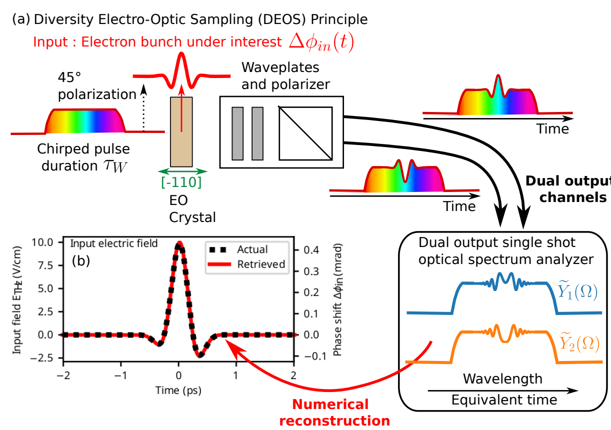

Figure 2: Conceptual validation of the DEOS strategy for electron beam diagnostics.

The DEOS experimental setup that enables the acquisition of two distinct signals in a single shot is shown in Fig. 2(a). This dual-channel approach is the key to overcoming the inherent information loss of conventional, single-output systems. The two outputs from the polarizing beam-splitter carry complementary information about the electron bunch's THz field, providing the redundant data needed for high-fidelity reconstruction. Figure 2(b): Numerical simulations showing the reconstruction of the input field, which confirms the DEOS method's effectiveness for accurately measuring electron bunch shapes (adapted from Ref. [4]).

The system shown in Fig. 3 overcomes the limitations of single-channel methods by acquiring two simultaneous outputs (Out1 and Out2) using the KALYPSO linear array detector. This configuration is essential for accurate reconstruction of the electron bunch's THz profile. The purple ellipses indicate critical upgrades over classical electro-optic diagnostics.

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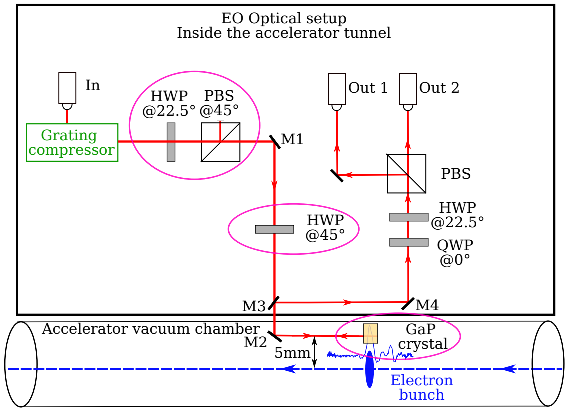

Figure 3: Advanced dual-channel DEOS setup for electron bunch diagnostics at FLASH and EuXFEL (PBS: Polarizing Beam Splitter, QWP: Quarter Wave Plates, HWP: Half Wave Plates, M: Mirrors)

SUMMARY

We have successfully demonstrated that diversity-enhanced electro-optic detection is a robust technique for high-fidelity measurement of sub-picosecond electron bunch shapes. This method offers both high resolution and an extended acquisition window at MHz+ repetition rates. Its utility extends beyond accelerator diagnostics, making it suitable for characterizing broadband THz radiation from various sources, including table-top systems, THz coherent transition radiation (CTR), and FELs. The system's successful validation at FLASH and its current operational status at the European XFEL confirm its readiness to meet the demanding diagnostic needs of next-generation accelerator facilities.

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