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TERAHERTZ STREAKING DETECTION FOR LONGITUDINAL BUNCH DIAGNOSTICS AT FLUTE

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Abstract

The Karlsruhe Institute of Technology is exploring a compact method of longitudinal electron bunch diagnostics with femtosecond resolution that has recently been demonstrated for other parameter ranges. The experimental setup utilizes a THz-based streaking approach with resonator structures, achieving both high compactness and efficiency. In this paper, we report on the experimental observation of streaking signals with our Compact Transverse Deflecting System, which has been successfully tested using two different resonators, an Inverse Split-Ring Resonator and a Tilted-Slit-Resonator.

INTRODUCTION

While the potential construction of the largest particle accelerator in history is currently under discussion [1–3], the development of smaller and more compact components remains a central challenge across all areas of accelerator technology. The gold standard in longitudinal diagnostics for ultra-short electron bunches are streaking techniques, which require transverse deflecting structures measuring up to several meters in the beam pipe as well as seperate dedicated GHz RF amplifiers [4]. An unconventional approach to measuring femtosecond-scale electron bunch profiles is based on THz streaking. The general feasibility of the method has already been demonstrated in recent studies for different electron bunch duration and energy regimes [5, 6]. In this work, we confirm the applicability of the THz-streaking technique in a complementary parameter regime, employing the proposed Compact Transverse Deflecting System (Compact-TDS) realized at the Karlsruhe Institute of Technology (KIT).

The Compact-TDS utilizes one of two available resonator structures to enhance the electrical field component of a laser-generated THz pulse. This amplification as well as the transition from GHz to THz frequencies enables a single-digit femtosecond resolution [7] while maintaining a compact and efficient design. As a result, the diagnostic structure itself is on the order of millimeters with a streaking field created over a distance of less than 100 µm. For amplification of the streaking effect, different resonator structures can be considered. Using CST simulations [8], we studied various geometries [9] that can lead to increased field strengths of up to several MV/m [10]. A more detailed explanation of the Compact-TDS working principle illustrated in Fig. 1 can be found in [11].

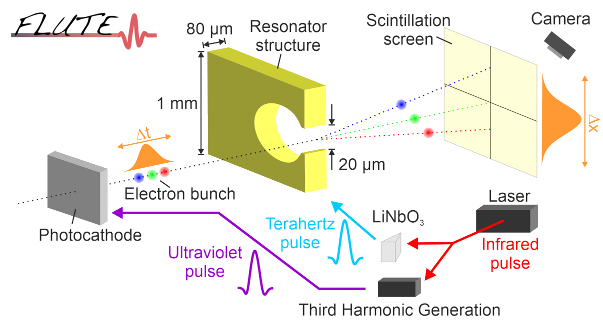

Figure 1: Working principle of the Compact-TDS diagnostics: A resonator structure amplifies the electric field of an incoming laser-generated THz pulse. The electron bunch passes through the resonator gap, where the enhanced streaking field maps its longitudinal profile onto the vertical plane.

Despite its high compactness and efficiency, achieving the required spatial-temporal overlap of the electron bunch and the THz pulse at the interaction point remains experimentally challenging. This places high demands on the design and alignment of the experimental setup.

EXPERIMENTAL SETUP

The Compact-TDS is being tested at the Ferninfrarot Linac- Und Test-Experiment (FLUTE), a linac-based test facility at KIT [12]. FLUTE accelerates electrons to energies of up to 90 MeV and is designed to compress electron bunches to the femtosecond level, enabling the generation of high-intensity THz radiation. For a first proof of principle, the experiment is currently located at the low-energy section of the facility, where the electron bunch energy is about 5.5 MeV and the bunch length is still in the order of a few picoseconds. The experiments were conducted with a bunch charge of 5 pC.

For photoinjection, we use a 7 mJ Ti:Sa-laser system generating electrons from a copper photocathode. The laser pulse is split and simultaneously used for THz generation via tilted-pulse-front pumping in lithium niobate [11], making both electron bunch and THz pulse intrinsically synchronized.

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Our setup includes two different resonator structures: an Inverse Split-Ring Resonator (ISRR) with dimensions of 1 mm × 1 mm × 80 µm and a gap size of 20 µm, as well as a Tilted-Slit Resonator (TSR) featuring a slit of 650 µm x 30 µm and a thickness of 100 µm (for sketches and a detailed analysis of the resonator geometries and their properties, see [9, 10]). Compared to our previous setup described in [13], we modified the resonator mount to accommodate the TSR via a clamping mechanism. Additionally, we completed the installation of a THz detector array, which primarily allows for verification of the THz pulse position at the interaction point.

The spatial overlap of the electron bunch and THz focus at one of our resonator structures was improved by upgrading the entire RF system of FLUTE (photoinjector, solenoid, two klystrons, waveguides, linac module) over the last 2 years [14]. Additionally, we increased the beam stability even further with, for example, the installation of a pinhole aperture. For details on the experiments prior to the hardware upgrade, and for a discussion of the electron beam dynamics enabling a visible streaking effekt, we refer readers to [15].

Regarding the temporal overlap, we can adjust the path length of the THz generation beam with a motorized delay stage. We coarsely pre-adjusted the temporal overlap by performing the experiment described in [16], where a temporal overlap was predicted for a delay stage position of 110 mm.

DATA ACQUISITION AND ANALYSIS

After aligning the electron beam and THz pulse to one of our resonator structures, the electron beam passing the resonator was recorded using a camera observing a beam screen located around 1.5 m downstream of the interaction point. The beam profile was averaged over 50 shots and acquired twice: once with the THz beam coupled into the vacuum chamber, and once with the THz beam blocked. This procedure was repeated while scanning the delay stage around the expected temporal overlap.

To quantify the effect of the THz interaction, a difference image was calculated by subtracting the THz-off image from the THz-on image and computing the mean absolute deviation (MAD) [17]:

$$\mathrm{MAD} = \frac{1}{N}\sum_{i=1}^{N} |x_i - \bar{x}| \ , \quad (1)$$

where x_i denotes the intensity of the i-th pixel, $\bar{x}$ is the mean intensity, and N is the total number of pixels considered. A high MAD value indicates a large deviation between the two images, suggesting an influence of the THz pulse on the electron bunch.

EXPERIMENTAL RESULTS

The computed MAD value of the difference images with and without THz influence in dependence of the delay stage position is illustrated in Fig. 2. Here, six independent datasets slightly differing in the spatial position of the resonator relative to the THz beam are shown. The MAD value was normalized to the arithmetic mean of all MAD values between 90 and 100 mm. For all datasets, we can observe a systematic increase in the measured signal between approximately 104.5 and 106.5 mm, highlighted in light gray.

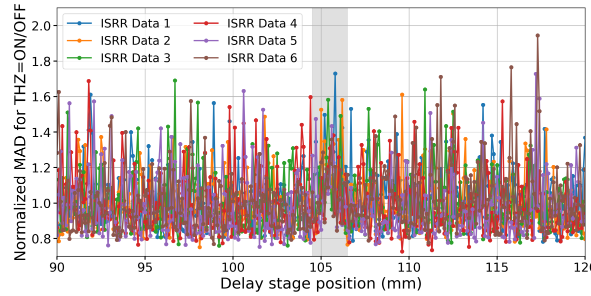

Figure 2: Delay-dependent normalized MAD values for six ISRR datasets, each with a slightly different resonator position. A consistent signal increase is observed between approximately 104.5 and 106.5 mm, marked in light gray, indicating a THz-induced interaction.

A more pronounced signal is observed in the normalized MAD as a function of delay stage position for a representative TSR dataset, as shown in Fig. 3. The significantly improved signal-to-noise ratio compared to the ISRR measurements is attributed to the resonator geometry: In the ISRR, the streaking field is confined to the gap region, and only a part of the electron bunch traverses this area because of limited beam focusing. Consequently, only a subset of electrons receives a vertical kick, with the rest forming an unstreaked background that reduces the MAD value. In contrast, the TSR generates the streaking field across the entire slit, with peak strength at the center, effectively acting as an aperture. This ensures that primarily electrons affected by the field reach the screen, enhancing the visibility of the streaking effect.

Considering that the THz pulse arrives later with increasing delay stage positions, Fig. 3 shows a relative steep rising edge in the signal, indicating the initial overlap between the bunch and the leading part of the THz streaking field. This is followed by a more gradual decline, as the bunch increasingly interacts only with the decaying tail of the streaking field.

To model this behavior, an exponentially modified Gaussian (EMG) function [18] was fitted to the signal. The functional form of the fit is given by

$$f(x) = A \cdot e^{\frac{1}{2}(\sigma\lambda)^2 - \lambda(x-\mu)} \cdot \mathrm{erfc}\left(\frac{\sigma\lambda - \frac{x-\mu}{\sigma}}{\sqrt{2}}\right) + C \, , \quad (2)$$

where A denotes the amplitude, μ the Gaussian center, σ its standard deviation, λ the exponential decay rate, and C a constant offset. The function $\mathrm{erfc}(\cdot)$ is the complementary error function.

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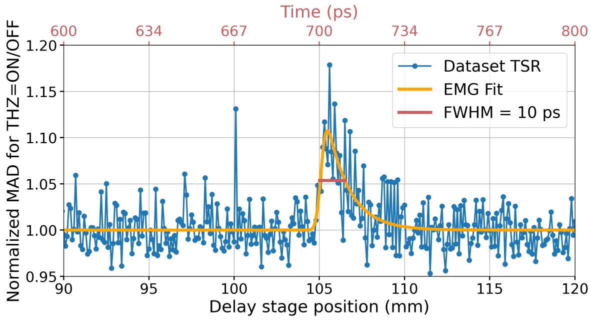

Figure 3: Delay-dependent normalized MAD values for a single TSR dataset. A distinct signal is observed around 105.5 mm and is fitted with an EMG function (orange), resulting in a FWHM of 1.52 mm or 10 ps (red). Assuming a Gaussian bunch profile, this corresponds to an electron bunch length of 4 ps FWHM (cf. Fig. 4).

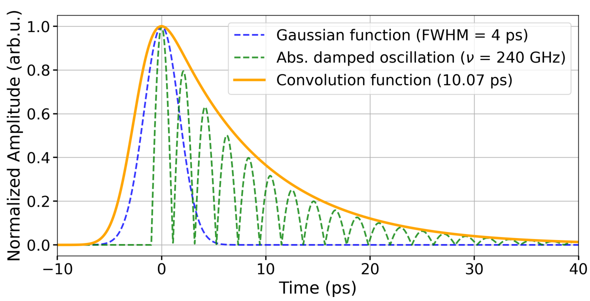

Figure 4: Convolution (green) of a Gaussian function (width of 7 ps, dashed blue line) with an absolute damped oscillation (frequency of 240 GHz, dotted orange line).

The fit result shows a signal peak at 105.5 mm, consistent with the measurement using the ISRR and close to the predicted overlap position of 110 mm, as discussed earlier. The full width at half maximum (FWHM) of the signal is determined to be 1.52 mm. Taking into account that the delay corresponds to a round trip of the optical path on the delay stage, this translates to a temporal signal width of approximately $\tau = 10$ ps.

If we assume the measured signal to result from the convolution of a Gaussian bunch profile with a damped oscillation, a numerical approximation can be done: If we consider the oscillation of the streaking field at the TSR's resonance frequency of 240 GHz to be effectively damped (1% of the peak value) after 10 oscillation cycles (based on simulations similar to results for ISRR in [10]), the convolution function yields a width of 10.07 ps (FWHM) for a Gaussian bunch length of 4 ps (FWHM), as illustrated in Fig. 4. Given all the assumptions, this can be seen as an upper limit, which is consistent with independent measurements of the photoinjection laser pulse duration of around 2.5 ps (FWHM).

Figure 5 shows a false-color representation of the electron beam intensity using the TSR, recorded at a delay stage position where temporal overlap between the electron bunch and the THz pulse was found. In the presence of the THz field (right) a vertically broadened charge distribution can be seen

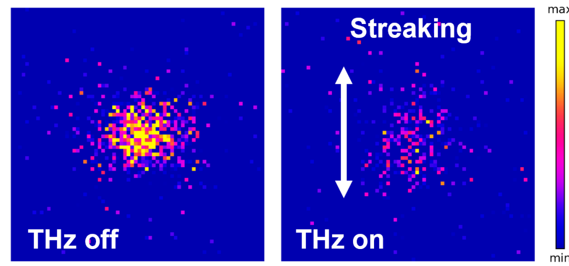

Figure 5: False-color representation of the electron beam intensity on a beam screen located 1.5 m downstream of the interaction point using the TSR, shown for a delay stage position where electrons and the THz pulse overlap. The vertical streaking induced by THz excitation (right) causes a vertical redistribution of the charge and a lower charge density compared to the case without THz (left).

compared to the non-excited case (left). Although the overall vertical streaking is still relatively weak, primarily leading to a reduction in charge density, it confirms successful overlap of electron bunch and THz pulse and demonstrates a THz-induced transverse momentum transfer to the electron bunch.

CONCLUSION AND OUTLOOK

THz streaking signals were successfully detected in the Compact-TDS at FLUTE (KIT), confirming the general feasibility of the proposed diagnostic method. Both available resonator structures, ISRR and TSR, demonstrated a measurable influence of the THz field on the electron bunch. From the delay-dependent measurements using the TSR, an upper limit for the bunch length of approximately 4 ps was estimated, which is in good agreement with prior estimations.

Although the streaking effect is already evident in beam screen images, it remains relatively weak, most likely due to limited THz pulse energy or coupling efficiency into the interaction region. A possible next step would be to optimize the THz injection scheme [19] or, alternatively, to take advantage of the recent commissioning of the magnetic bunch compressor at FLUTE [14, 20] and move the setup to the high-energy section. This would enable the characterization of ultrashort, femtosecond electron bunches in future experiments.

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REFERENCES

[1] M. Benedikt *et al.*, "Future Circular Collider Feasibility Study Report: Volume 1, Physics, Experiments, Detectors", *arXive*

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preprint, Apr. 2025.
doi:10.17181/CERN.9DKX.TDH9

[2] M. Benedikt *et al.*, “Future Circular Collider Feasibility Study Report: Volume 2, Accelerators, Technical Infrastructure and Safety”, *arXive preprint*, Apr. 2025.
doi:10.17181/CERN.EBAY.7W4X

[3] M. Benedikt *et al.*, “Future Circular Collider Feasibility Study Report: Volume 3, Civil Engineering, Implementation and Sustainability”, *arXive preprint*, Apr. 2025.
doi:10.17181/CERN.I26X.V4VF

[4] P. Krejcik, R. Akre, L. Bentson, and P. Emma, “A Transverse RF Deflecting Structure for Bunch Length and Phase Space Diagnostics”, in *Proc. PAC'01*, Chicago, IL, USA, Jun. 2001, paper WPAH116, pp. 2353–2355.

[5] X.L. Shen *et al.*, “A THz driven split-ring resonator based ultrafast relativistic electron streak camera”, *AIP Advances*, vol. 9, no. 8, p. 085209, Aug. 2019.
doi:10.1063/1.5080374

[6] X. He *et al.*, “Terahertz-driven Two-Dimensional Mapping for Electron Temporal Profile Measurement”, *arXive preprint*, Dec. 2024.
doi:10.48550/arXiv.2412.04108

[7] M. Yan *et al.*, “Design of a Time-resolved Electron Diagnostics Using THz Fields Excited in a Split Ring Resonator at FLUTE”, in *Proc. IBIC'16*, Barcelona, Spain, Sep. 2016, pp. 475–478.
doi:10.18429/JACoW-IBIC2016-TUPG56

[8] CST STUDIO SUITE, https://www.3ds.com/products/simulia.

[9] S. Glukhov *et al.*, “Resonator Design Optimization for a Compact Transverse-deflecting System”, in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, pp. 2343-2346.
doi:10.18429/JACoW-IPAC2024-WEPG53

[10] S. Glukhov *et al.*, “Simulations of the compact transverse-deflecting system for ultra-short electron bunch diagnostic”, in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 4887–4890.
doi:10.18429/JACoW-IPAC2023-THPL192

[11] M.. Nabinger *et al.*, “Characterization and optimization of laser-generated THz beam for THz based streaking”, in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 4149–4153.
doi:10.18429/JACoW-IPAC2023-THPA079

[12] M. J. Nasse *et al.*, "FLUTE: A versatile linac-based THz source", *Review of Scientific Instruments*, vol. 84, no. 2, p. 022705, Feb 2022.
doi:10.1063/1.4790431

[13] M. Nabinger *et al.*, “Commissioning and Experiments with a Compact Transverse Deflecting System at FLUTE”, in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, pp. 2339-2342.
doi:10.18429/JACoW-IPAC2024-WEPG52

[14] A. Malygin *et al.*, “Status of the FLUTE RF system upgrade”, in Proc. IPAC'25, Taipei, Taiwan, June 2025, paper MOPM083, this conference.

[15] J. Schäfer, “Feasibility studies for a Transverse Deflecting Structure measurement at FLUTE”, Ph.D. thesis at the Karlsruher Institut für Technologie (KIT), May 2024.
doi:10.5445/IR/1000170357

[16] M. Nabinger *et al.*, “Efficient terahertz generation by tilted-pulse-front pumping in lithium niobate for the split-ring resonator experiment at FLUTE”, in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 4299–4301.
doi:10.18429/JACoW-IPAC2021-THPAB251

[17] Wikipedia contributors, "Average absolute deviation," *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/wiki/Average_absolute_deviation

[18] Wikipedia contributors, "Exponentially modified Gaussian distribution," *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/wiki/Exponentially_modified_Gaussian_distribution

[19] S. Glukhov *et al.*, “Possibilities for performance enhancement of a compact TDS at FLUTE”, in Proc. IPAC'25, Taipei, Taiwan, June 2025, paper THPM087, this conference.

[20] M. Nasse *et al.*, “First THz light generated in high-energy section of FLUTE”, in Proc. IPAC'25, Taipei, Taiwan, June 2025, paper TUPM010, this conference.