ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPG52

COMMISSIONING AND EXPERIMENTS WITH A COMPACT TRANSVERSE DEFLECTING SYSTEM AT FLUTE

M. Nabinger*, E. Bründermann, M. Fuchs, A. Malygin, K. Mayer, M. J. Nasse, M.-D. Noll, R. Ruprecht, J. Schäfer, T. Schmelzer, N. J. Smale, J. L. Steinmann, A.-S. Müller
Karlsruhe Institute of Technology, Karlsruhe, Germany
M. M. Dehler, R. Ischebeck, M. Moser, V. Schlott, Paul Scherrer Institute, Villigen, Switzerland
T. Feurer, M. Hayati, Z. Ollmann, University of Berne, Berne, Switzerland
S. Glukhov, O. Boine-Frankenheim, Technical University of Darmstadt, Darmstadt, Germany
M. Fritzsche, M. Laabs, Dresden University of Technology, Dresden, Germany

Abstract

A Compact Transverse Deflecting System (Compact-TDS) designed for longitudinal electron bunch diagnostics in the femtosecond regime is presently undergoing commissioning at the Karlsruhe Institute of Technology (KIT). This technique, based on THz streaking using a resonator structure, demands a high level of electron beam controllability and stability at the micrometer scale. To meet these requirements, the linear accelerator FLUTE (Ferninfrarot Linac- Und Test-Experiment) has undergone major upgrades in 2023, incorporating a new RF system equipped with a klystron, RF photoinjector and solenoid magnet.

In this contribution, we present first experiments conducted with the Compact-TDS at FLUTE, utilizing the upgraded RF setup.

INTRODUCTION

Last year's Nobel Prize in Physics was awarded for the establishment of attosecond physics [1], which clearly highlights the current relevance of deeper understanding and applications on ultra-short time scales. Many accelerator facilities worldwide are also extensively active in various fields using bunch lengths in the femtosecond range and below [2, 3]. Reliable, yet space- and cost-saving diagnostics of particle distributions on such time scales play a crucial role in this endeavor.

Therefore, a novel method for determining the longitudinal bunch profile of sub-10 femtoseconds is being investigated at KIT. It is intended to serve as a cost-effective and compact alternative to conventionally applied streaking methods [4]. The proposed Compact-TDS is currently being tested and commissioned at the LINAC-based test facility FLUTE. Its concept aims to elevate the standard streaking frequencies from GHz to the THz range, while employing a resonator structure to amplify the electric field. As illustrated in Fig. 1, an example of such a resonator structure could be an Inverse Split-Ring Resonator (ISRR), which holds the promise of achieving streaking field strengths of several MV/m [5]. For a detailed explanation of the working principle shown in Fig. 1, we direct readers to [6].

The Compact-TDS offers several advantages: One example is, since the same laser can be used for generating both the electrons, as well as the THz pulse driving the resonator structure, a synchronization between the bunch and the streaking field is intrinsically given. Moreover, the used THz frequencies enable resonance structures with dimensions in the order of millimeters and less, thus making the system extremely compact compared to other methods. However, due to the small structures, the method requires a very precise control and stability of the electron beam. For instance, in case of the ISRR used at FLUTE, the beam has to pass a gap size of only 20 µm, where it can interact with the oscillating streaking field. In order to meet these demands of machine stability, the entire FLUTE RF system has been upgraded recently.

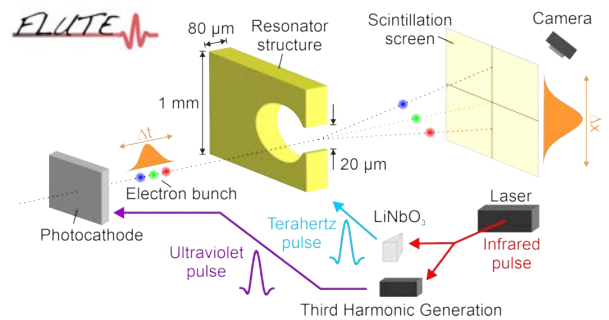

Figure 1: Working principle of the Compact-TDS diagnostics THz-based streaking experiment at FLUTE. The sketch illustrates an ISRR used as the resonator structure.

FLUTE RF SYSTEM UPGRADE

Over the course of 2023, the entire FLUTE RF system has undergone a major upgrade. The main changes for the

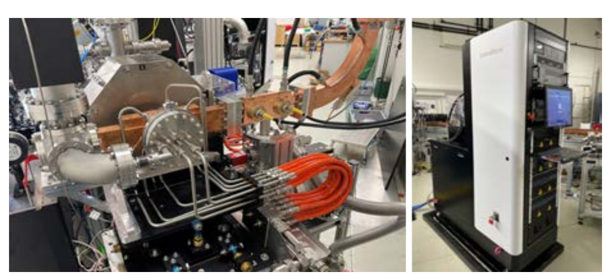

Figure 2: Photographs of the new RF photoinjector (left) and 10 MW RF unit (right) installed at FLUTE.

* matthias.nabinger@kit.edu

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPG52

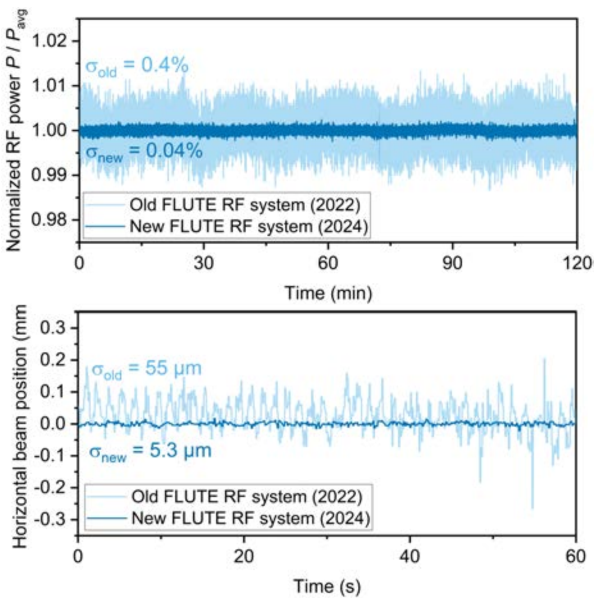

Figure 3: Comparison of RF stability performance for the old (up to 2022) and new (2024) FLUTE RF system (light and dark blue, respectively). Top: Normalized RF power P/P_{avg} versus time for an interval of 2 hours. The measurements were taken directly at the output of the specified RF unit. Bottom: Horizontal electron beam position versus time for an interval of one minute. The beam position was evaluated from the camera image of a YAG screen in the resonator plane with comparable machine settings.

5 MeV-section of FLUTE, where the Compact-TDS experiment is currently installed, are shown in Fig. 2: a new RF photoinjector with a new solenoid magnet, as well as a new 10 MW RF unit consisting of a klystron and modulator driving the RF photoinjector have been successfully installed. In October 2023, the first electron beam was measured using the new setup. Also, the RF system upgrade includes the integration of an additional 37 MW RF unit driving the LINAC of FLUTE and the possibility to operate at repetition rates up to 50 Hz. For more details of the RF system design, we refer to [7].

Figure 3 illustrates a comparison of the RF stability performance for the old and new FLUTE RF systems, with measurements taken in 2022 and 2024, respectively. The top diagram shows a 2-hour-measurement of the RF power at the directional coupler directly after the RF unit used at the time. To observe the percentage fluctuation, the power is normalized by the average power over that time interval, which was approximately 9.5 MW in both cases. The comparison demonstrates that the 1-σ-fluctuation of the RF power was reduced by roughly a factor of 10 from the old ($\sigma_{\mathrm{old}} = 0.36\,\%$) to the new system ($\sigma_{\mathrm{new}} = 0.04\,\%$).

The improved RF stability directly translates to a higher shot-to-shot electron beam stability: As an example, we present in the bottom diagram of Fig. 3 the standard deviation of the horizontal beam position measured over one minute. It clearly shows a decrease by one order of magnitude for the new system compared to the old one. It should be noted, that the beam position was observed at a scintillating YAG screen in the resonator plane for comparable machine settings, which were assumed to be optimal for experiments with the Compact-TDS setup at the particular time. As discussed in [8], the beam position fluctation with the old FLUTE RF system was in the order of hundreds of micrometers, which is one order of magnitude larger than the gap size of the ISRR. With the new system, however, the beam fluctuation could be improved to the extent that it is on the order of the resonator gap size (for Fig. 3, the peak-to-peak amplitude of the beam position measured with the new system is $\approx 40\,\mu$m). The increased electron beam stability allows for more precise handling of the experimental setup for its further enhancement.

EXPERIMENTAL SETUP

In order to decrease dark current and the electron bunch size at the resonator structure, a pinhole aperture was recently installed in the Compact-TDS experimental vacuum chamber in front of the resonator structure. The component was manufactured by LT Ultra Precision Technology [9] and comprises two 5 mm thick copper plates, each with one plane side of high flatness. On one side of one plate, three channels are milled and the plates are tightly screwed together (Fig. 4a). The resulting pinhole aperture features holes with 50, 100 and 200 µm diameter and was installed in a holder on two motor axes for horizontal and vertical position adjustments (Fig. 4b). Due to the improved electron beam stability, it was easily possible to get electrons through

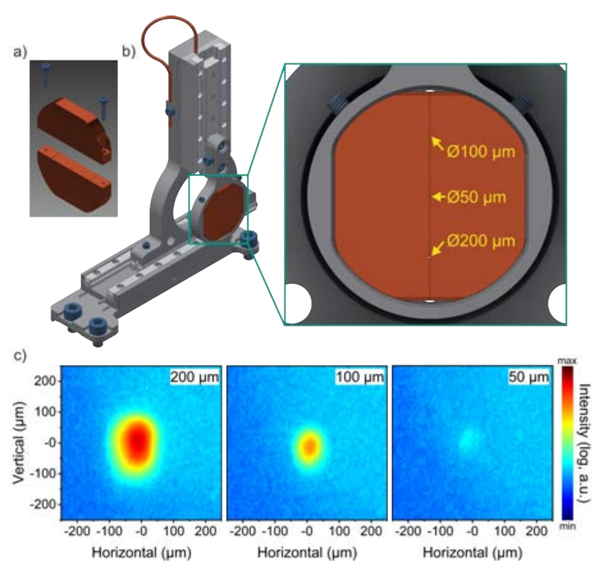

Figure 4: Top: CAD-drawings of the recently installed pinhole aperture. a) Manufacturing principle and b) the installation on two motor axes with close-up look on the 3 different available pinhole aperture sizes. c) Electron beam intensity as false-color representation measured on a YAG screen in the resonator plane for all pinholes.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPG52

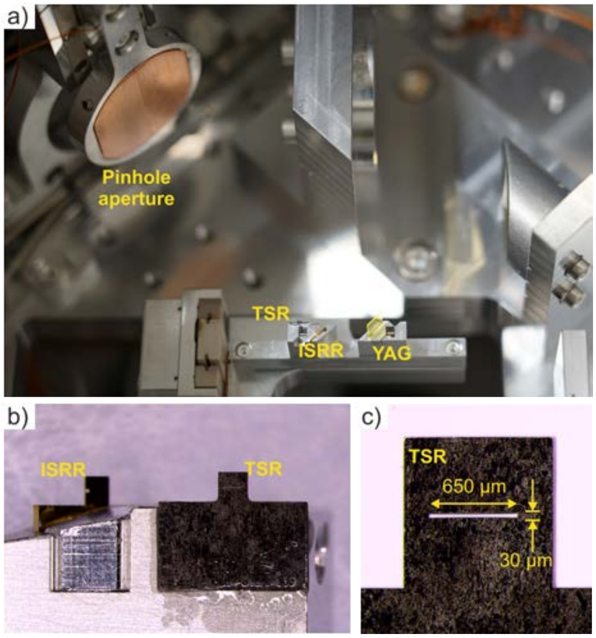

Figure 5: a) Photograph of the interior of the experimental chamber with the currently installed pinhole aperture and the holder for the two resonators (ISRR and TSR), as well as the diagnostics YAG screen. b) Microscope picture of the TSR glued onto the resonator holder with the ISRR in the background. c) Zoom of the TSR and dimensions of the slit.

all of the pinholes, reducing the electron spot size down to the dimensions of the resonator gap (Fig. 4c).

Furthermore, an alternative resonator structure was added to the Compact-TDS setup. This Tilted-Slit-Resonator (TSR) structure - proposed in [10] - was installed next to the existing ISRR resonator by gluing. The motorized holder allows to center either the TSR or the ISRR in the THz focus point, allowing to test the streaking effect from two different geometries. Figure 5a shows a picture of the inside of the experimental chamber, with microscopic views of the TSR in b and c. Besides the above mentioned pinhole aperture, the YAG screen and the ISRR, it can be seen that the added TSR is installed with a relative angle of 45° to both the electron and THz beam. A comparison of the properties and performance between both resonator geometries was studied by simulations in [11] and [12].

The TSR structure was made by laser microfabrication [13] and has a slit length of 650 µm and a slit or gap height of 30 µm. The main advantage of this alternative geometry is that it serves as an additional natural aperture for the electron beam: all electrons reaching the detection screen have experienced streaking field, the rest is blocked by the resonator (in our case 100 µm thick molybdenum foil) if the electron beam size is on the order of the slit dimensions. With the improved beam quality by the RF upgrade and pinhole aperture, the TSR geometry could be scanned with very high precision, significantly improving our knowledge of the electron beam position relative to the resonator. However, as a spatial overlap with the THz beam is needed for the generation of a streaking field, an additional enhancement of the setup is required to reduce the THz spot position uncertainty.

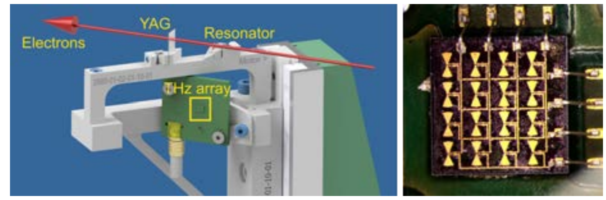

Figure 6: Left: CAD-drawing of the newly designed holder for resonator, YAG screen and THz detector array. Right: Microscopic picture of the 4x4 Schottky-diode based THz detector array prototype.

For this purpose, a THz detector array is currently being developed and installed in collaboration with the Dresden University of Technology. Figure 6 shows the new Compact-TDS resonator holder design with integrated THz detector array (left picture), which will allow an in-situ measurement of the THz spot location under vacuum. After calibration with a structurally identical THz generation setup [14], the array can also be used for an estimation of the present THz pulse energy. A prototype of the 900 µm × 900 µm array consisting of 4 × 4 antenna coupled Schottky-diodes is already fabricated (Fig. 6, right picture) and successfully tested for ultra high vacuum compatibility.

A recent experimental campaign to search for an overlap of electron and THz beam at the TSR leading to an observable streaking suffered from the large uncertainty of the THz spot location in the order of several millimeters. Therefore, the installation of the array is planned for the near future to enable more effective experiments with the Compact-TDS.

CONCLUSION AND OUTLOOK

First experiments were conducted for the longitudinal bunch diagnostics Compact-TDS at KIT, using the upgraded RF system at FLUTE. The enhancements significantly increased the electron beam quality by an order of magnitude, allowing for a precise alignment to a newly installed pinhole aperture and an alternative resonator structure. Experimental runs with the TSR revealed the need for an in-situ possibility to verify the THz spot location, which is planned to be realized by adding a THz detector array to the Compact-TDS setup in order to observe an electron bunch streaking.

ACKNOWLEDGMENTS

M. Nabinger acknowledges the support by the DFG-funded Doctoral School "Karlsruhe School of Elementary and Astroparticle Physics: Science and Technology" (KSETA), the IPAC Student Grant and funding by the BMBF ErUM-Pro project Compact TDS (FKZ 05K22VK3).

REFERENCES

[1] "Light as fast as electrons", *Nat. Phys.*, vol. 19, no. 11, p. 1520, Nov. 2023. doi:10.1038/s41567-023-02305-y

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPG52

[2] J. Roensch-Schulenburg *et al.*, "Generation of Ultra-short Electron Bunches at FLASH", in *Proc. 34th Int. Free-Electron Laser Conf. (FEL2012)*, Nara, Japan, Aug. 2012, pp. 610–613, paper THPD33.

[3] V. Schlott *et al.*, "Overview and Status of SwissFEL Diagnostics", in *Proc. 4th Int. Beam Instrumentation Conf. (IBIC'15)*, Melbourne, Australia, Sep. 2016, pp. 12–16, paper MOBLA03.

[4] P. Krejcik, R. Akre, L. Bentson, and P. Emma, "A Transverse RF Deflecting Structure for Bunch Length and Phase Space Diagnostics", in *Proc. 19th Particle Accelerator Conf. (PAC'01)*, Chicago, IL, USA, Jun. 2001, paper WPAH116, pp. 2353–2355.

[5] M. Yan *et al.*, "Design of a Time-resolved Electron Diagnostics Using THz Fields Excited in a Split Ring Resonator at FLUTE", in *Proc. 5th Int. Beam Instrumentation Conf. (IBIC'16)*, Barcelona, Spain, Sep. 2016, pp. 475–478. doi:10.18429/JACoW-IBIC2016-TUPG56

[6] 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. 12th International Particle Accelerator Conf. (IPAC'21)*, Campinas, Brazil, May 2021, pp. 4299–4301. doi:10.18429/JACoW-IPAC2021-THPAB251

[7] A. Malygin *et al.*, "Status of the FLUTE RF system upgrade", in *Proc. 13th International Particle Accelerator Conf. (IPAC'22)*, Bangkok, Thailand, May 2022, pp. 2452–2453. doi:10.18429/JACoW-IPAC2022-THPOST008

[8] J. Schäfer *et al.*, "Split-ring resonator experiments and data analysis at FLUTE", in *Proc. 14th International Particle Accelerator Conf. (IPAC'23)*, Venice, Italy, May 2023, pp. 4760–4763. doi:10.18429/JACoW-IPAC2023-THPL122

[9] LT Ultra-Precision Technology GmbH, Herdwangen-Schönach, Germany, https://www.lt-ultra.com/impressum/

[10] L. Zhao *et al.*, "Terahertz Streaking of Few-Femtosecond Relativistic Electron Beams", *Phys. Rev. X*, vol. 8, no. 2, pp. 021061, June 2018. doi:10.1103/PhysRevX.8.021061

[11] S. Glukhov *et al.*, "Simulations of the compact transverse-deflecting system for ultra-short electron bunch diagnostic", in *Proc. 14th International Particle Accelerator Conf. (IPAC'23)*, Venice, Italy, May 2023, pp. 4887–4890. doi:10.18429/JACoW-IPAC2023-THPL192

[12] S. Glukhov *et al.*, "Resonator Design Optimization for a Compact Transverse-deflecting System", presented at the 15th Int. Particle Accelerator Conf. (IPAC'24), Nashville, TN, USA, May 2024, WEPG53, this conference.

[13] Innotech Photonics GmbH, Kaiserslautern, Germany, https://innotech-photonics.de/

[14] M.. Nabinger *et al.*, "Characterization and optimization of laser-generated THz beam for THz based streaking", in *Proc. 14th International Particle Accelerator Conf. (IPAC'23)*, Venice, Italy, May 2023, pp. 4149–4153. doi:10.18429/JACoW-IPAC2023-THPA079