ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPA079

CHARACTERIZATION AND OPTIMIZATION OF LASER-GENERATED THz BEAM FOR THz BASED STREAKING

M. Nabinger*, M. J. Nasse, J. Schäfer, A. Schmidt, J. L. Steinmann, C. Widmann, E. Bründermann and A.-S. Müller, Karlsruhe Institute of Technology, Karlsruhe, Germany
Z. Ollmann, University of Berne, Berne, Switzerland

Abstract

At the Ferninfrarot Linac- Und Test-Experiment (FLUTE) at the Karlsruhe Institute of Technology (KIT) a new and compact method for longitudinal diagnostics of ultrashort electron bunches is being developed. For this technique, which is based on THz streaking, strong electromagnetic pulses with frequencies around 240 GHz are required. Therefore, a setup for laser-generated THz radiation using tilted-pulse-front pumping in lithium niobate (LiN) was designed, delivering up to 1 µJ of THz pulse energy with a conversion efficiency of up to 0.03 %. In this contribution we study the optimization of the THz beam transport and environment.

INTRODUCTION

The demand for ultra-short electron bunches is increasing in accelerator facilities worldwide. For instance, free-electron laser experiments such as FLASH or SwissFEL require bunch lengths down to the single femtosecond (fs) level [1, 2], which need to be reliably diagnosed, often at several positions along the accelerator. However, longitudinal diagnostics of particle distributions in this regime is a feasible, but still challenging task that currently requires cost- and space-intensive methods such as large GHz-driven transverse deflecting RF-cavities [3]. Therefore, at the linac-based test facility FLUTE at KIT a new, compact and more cost-efficient approach for longitudinal single-fs diagnostics based on THz streaking is being investigated - the Split-Ring Resonator Compact Transverse-Deflecting System (SRR Compact-TDS).

SRR Compact-TDS

The general idea of the system is to push the conventionally used GHz to THz frequencies while using a small antenna-based resonator as amplification for the electrical streaking field after excitation by a strong THz pulse. As we use one laser system for both electron and THz generation, electron bunch and THz pulse are intrinsically synchronized. For a detailed explanation of the working principle, that is shown in Fig. 1, we refer to [4].

The temporal resolution R_z of the SRR compact-TDS is inversely proportional to the integrated field strength inside the gap and the frequency of the resonant THz field [5]. As the resonance frequency and field amplification factor are fixed by the geometry of the SRR, a decisive parameter for R_z to reach the single-fs level is the amplitude of the incident THz wave, or more general the THz pulse energy.

* matthias.nabinger@kit.edu

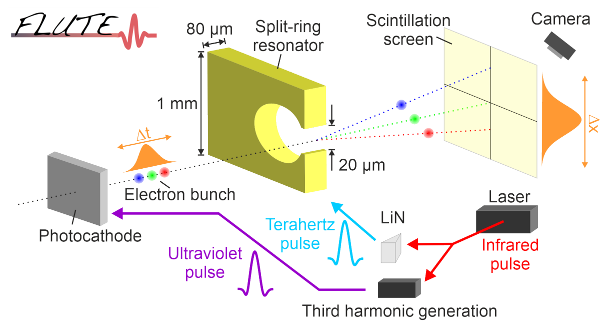

Figure 1: Working principle of the SRR Compact-TDS diagnostics THz-based streaking experiment at FLUTE.

Tilted-pulse-front Pumping

One of the most efficient methods for laser-based generation of intense THz pulses by optical rectification is the Tilted-Pulse-Front (TPF) pumping in LiN [6, 7]. Although LiN offers comparably high electro-optical coefficients, the difference of the refractive index for pump and THz wave prevents a collinear matching of the phase velocities involved in the process. Therefore, in the TPF technique, the laser wavefront is tilted to overcome the problem of phase mismatch between pump laser and emitted THz wave.

Experimental Setup

For the experimental SRR Compact-TDS setup, a TPF THz generation setup was designed and aligned on a portable module [4] as illustrated in Fig. 2. Here, the input infrared beam wavefront is tilted via a diffraction grating and imaged into the LiN crystal by a 4-*f*-telescope system consisting of two cylindrical lenses. After generation, the divergent THz beam is transported achromatically via flat metal mirrors and three THz lenses. Once the THz radiation leaves the module as collimated beam, it then passes a z-cut quartz vacuum window and is finally focused by an off-axis parabolic mirror to the interaction point. Only the last quarter of this beam path of approximately 1 m length is inside vacuum (Fig. 2c).

Facing experimental difficulties (e.g. instabilities of the laser and RF systems) most recent measurement campaigns have not revealed any obvious streaking effects so far [8]. While new simulation studies investigate possible improvements of the system design [9], one other possible reason for the missing streaking observation might be an insufficient THz pulse energy reaching the resonator. Thus, in this contribution the THz transport and environment is studied to increase the resulting streaking strength of the SRR Compact-TDS.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPA079

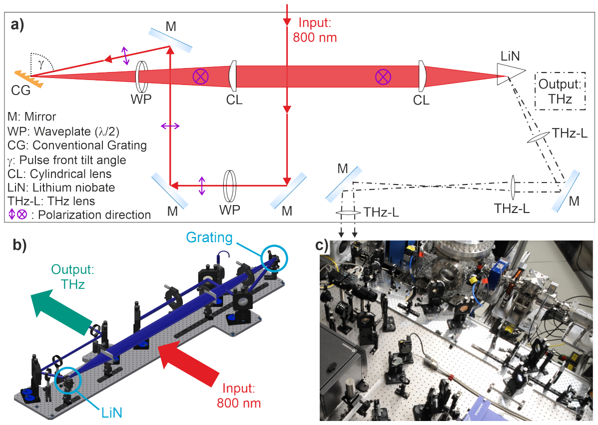

Figure 2: a) Sketch and b) technical drawing of the TPF setup. c) Photograph of the module installed at the accelerator.

TERAHERTZ CHARACTERIZATION

With the TPF module a THz pulse energy of up to 1.08(5) µJ with a pump pulse energy of 3.56(1) mJ could be achieved (Fig. 3, top). This corresponds to a conversion efficiency of 0.030(3) %. The measurement was done at room temperature and with a bandwidth limited pump pulse length of 35 fs, using a pyroelectric power meter calibrated by the PTB (Physikalisch-Technische Bundesanstalt).

In addition, we coarsely determined the laser-generated THz spectrum by using metal mesh THz bandpass filters and measuring the relative share of transmitted THz power (Fig. 3, bottom). We used seven bandpass filters with central frequencies ν_{max} ranging from 0.14 THz to 0.8 THz. For comparison, the dashed line indicates the resonance frequency of the SRR Compact-TDS, which by design is located at f_{res} = 240 GHz.

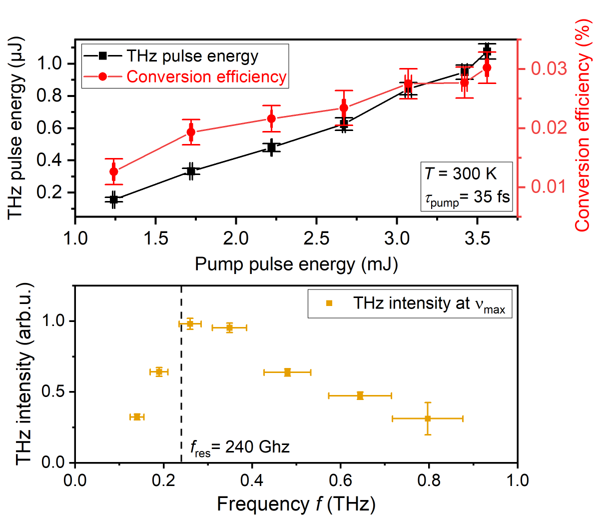

Figure 3: Top: THz pulse energy and conversion efficiency as a function of pump energy. Bottom: THz spectrum measured using THz bandpass filters. The horizontal uncertainty bars correspond to the FWHM filter bandwidths. The dashed line indicates the resonance frequency of the used SRR.

BEAM TRANSPORT OPTIMIZATION

In order to increase the THz pulse energy coupled into the resonator, the THz beam transport from crystal to the interaction point was improved.

Terahertz Optics

In the previous design of the TPF module, ZEONEX was chosen as THz lens material, because it exhibits high transmittance and a similar refraction index both in the THz and the visible spectral range. This permits an alignment of the THz beam using a visible alignment laser. However, for a 20 mm thick lens (f = 75 mm) a transmittance of only 81.8 ± 1.4 % was measured using our TPF THz source, indicating an absorption coefficient of ≈ 0.1 cm^{-1} (see Table 1).

Table 1: Comparison of ZEONEX and UHMWPE for THz optics. The absorption coefficient was derived by a transmittance measurement of 20 mm thick lenses.

Material	Refractive index	Abs. coeff. (cm^{-1})
ZEONEX	1.53 [10]	≈ 0.1
UHMWPE	1.54 ± 0.01 [11]	≈ 0.04

To increase the transmittance per THz lens we investigated UHMWPE (ultra-high-molecular-weight polyethylene) as an alternative material. Figure 4 shows a THz time-domain spectroscopic measurement [12] of a 10 mm thick plano-parallel UHMWPE sample in the time domain and the resulting transmittance over frequency. Since the experiment was conducted in air, the transmission spectrum shows distinct absorption lines caused by water in the air, as well as a somewhat noisy signal for lower frequencies. Nevertheless, it can be confirmed that UHMWPE shows very little transmittance losses for the relevant frequency range of a

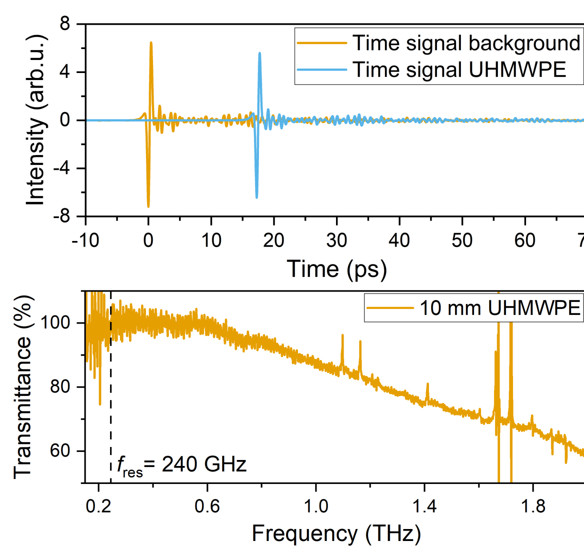

Figure 4: Top: Amplitude in the time domain of a THz-TDS signal without sample (orange) and with 10 mm UHMWPE (blue). Bottom: Transmittance in frequency domain.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPA079

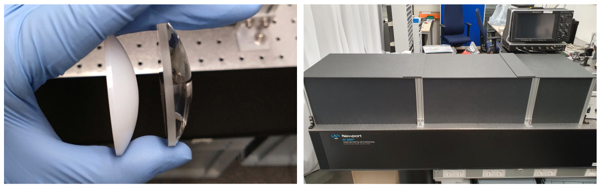

Figure 5: Left: Pictures of self-made UHMWPE (white) and commercial ZEONEX (transparent) THz lenses. Right: Optical enclosure with filtration system for the THz module.

few hundred GHz. From the measured delay in time-domain an average refractive index of $n = 1.52$ can be derived. Considering uncertainties regarding the sample thickness and the step size of the used delay stage, the value is in good agreement to [11].

Consequently, in contrast to the commercially acquired ZEONEX lenses, the UHMWPE THz lenses were self-made by turning in the institute's workshop. Figure 5 (left) shows a photograph of both lens types for comparison. The dimensions of the lenses were designed based on the commonly known lensmaker equation for a plano-convex lens. After manufacturing we observed a transmittance of $91.9 \pm 1.9\,\%$ for a 20 mm thick UHMWPE THz lens ($f = 75$ mm), i.e. about 10 % more than the comparable ZEONEX lens, resulting in an absorption coefficient of about half (see Table 1).

Also - as shown in Fig. 6 - the optics were tested as a 1-to-1 replacement in the exisiting THz TPF module and the THz beam intensity profile was measured in the focal point of the first 4-f-telescope after the first two THz lenses (distance $\approx$ 35 cm from the crystal). For the measurements, the THz camera MICROXCAM-384i-THz (384×288 pixels, based on uncooled microbolometer focal plane array [13]) was used. By directly comparing the two intensity profiles and marked 2D-gaussian contour lines (white dashed lines), one can state that the self-made UHMWPE lenses do not show any significant horizontal or vertical shift, while preserving focal length (equal spot sizes within uncertainties) and transmitting more light.

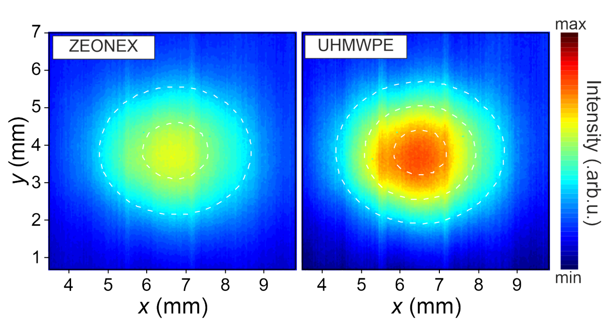

Figure 6: THz intensity profiles after the first two THz lenses seen by a THz camera. Left: ZEONEX; Right: UHMWPE. The false color scale applies to both plots. In addition, contour lines (white; 85 %, 62 % and 38 % of maximum intensity scale) of a 2D-gaussian fit function are shown.

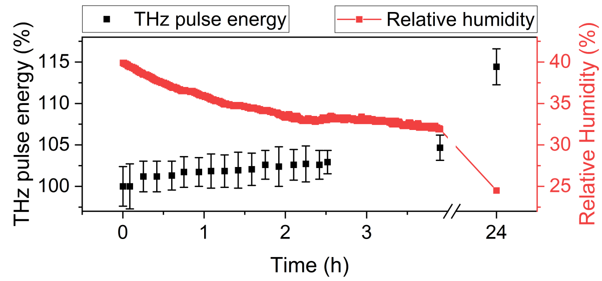

Figure 7: THz pulse energy (normalized to first measurement value) and relative humidity over time while using a drying system for removing moisture. The THz pulse energy was measured after a transport distance of $\approx$ 35 cm.

Ambient Conditions

Since three quarters of the THz beam path is outside of vacuum, we expect to have absorption of THz power by the water vapor in the ambient air. To quantify the amount of absorption loss, we built an optical enclosure (Fig. 5, right) around the THz module and used a dust and humidity filtration system [14] to decrease THz absorption by water in air and measure its impact on the THz transport.

Figure 7 shows the THz pulse energy normalized to the first measurement value as well as the relative humidity over time when the filtration system was turned on. It can be noted that after only about 4 hours, the relative humidity in the volume could be decreased by roughly 10 % resulting in a THz pulse energy gain of about 5 %. After filtering for 24 h an increase in THz power of nearly 15 % could be observed.

CONCLUSION AND OUTLOOK

In conclusion, crucial improvements for the THz pulse energy could be realized, which is a critical parameter for achieving single-fs resolution in the SRR Compact-TDS diagnostics experiment at FLUTE. By changing the material and manufacturing UHMWPE THz lenses, as well as enclosing and dehumidifying the THz TPF setup environment, the overall transport loss of THz radiation could be reduced significantly. Based on our measurements, at the SRR interaction point a THz pulse energy of $188\,\% \pm 40\,\%$ compared to the previous setup can be expected. This results in a factor of the order of two times the streaking strength, which will substantially facilitate the search for streaking in future experiments.

ACKNOWLEDGEMENTS

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

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPA079

REFERENCES

[1] J. Roensch-Schulenburg *et al.*, "Generation of Ultra-short Electron Bunches at FLASH", in *Proc. FEL'12*, Nara, Japan, Aug. 2012, paper THPD33, pp. 610–613.

[2] V. Schlott *et al.*, "Overview and Status of SwissFEL Diagnostics", in *Proc. IBIC'15*, Melbourne, Australia, Sep. 2015, pp. 12–16. doi:10.18429/JACoW-IBIC2015-MOBLA03

[3] 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.

[4] 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

[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. IBIC'16*, Barcelona, Spain, Sep. 2016, pp. 475–478. doi:10.18429/JACoW-IBIC2016-TUPG56

[6] J. Hebling, K.-L. Yeh, M. Hoffmann, B. Bartal and K. A. Nelson, "Generation of high-power terahertz pulses by tilted-pulse-front excitation and their application possibilities", *J. Opt. Soc. Am. B*, vol. 25, no. 7, pp. B6–B19, 2008. doi:10.1364/JOSAB.25.0000B6

[7] X. Wu *et al.*, "Half-percent terahertz generation efficiency from cryogenically cooled lithium niobate pumped by Ti:sapphire laser pulses", *arXiv preprint*, 2016. doi:10.48550/arxiv.1601.06921

[8] J. Schaefer *et al.*, "Split-ring resonator experiments and data analysis at FLUTE", presented at the IPAC'23, Venice, Italy, May 2023, paper THPL122, this conference.

[9] S. Glukhov *et al.*, "Simulations of the Compact Transverse-Deflecting System for Ultra-Short Electron Bunch Diagnostic", presented at the IPAC'23, Venice, Italy, May 2023, paper THPL192, this conference.

[10] Tydex, https://www.tydexoptics.com/products/thz_optics/thz_materials/.

[11] E. Bründermann, H.-W. Hübers and M. F. Kimmitt, "Optical Components", in *Terahertz Techniques*, Berlin, Heidelberg, Germany: Springer, 2012, pp. 51–102.

[12] Menlo Systems GmbH, TDS Spectrometer TERA K15 with emitter TERA15-FC, https://www.menlosystems.com/.

[13] L. Marchese *et al.*, "Overcoming the challenges of active THz/MM-wave imaging: an optics perspective", in *Proc. SPIE 10639, Micro- and Nanotechnology Sensors, Systems, and Applications X*, Orlando, FL, United States, May 2018, pp. 372–379. doi:10.1117/12.2305398

[14] Thorlabs, Inc., *PACU* https://www.thorlabs.com/thorproduct.cfm?partnumber=PACU/.