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EFFICIENT TERAHERTZ GENERATION BY TILTED-PULSE-FRONT PUMPING IN LITHIUM NIOBATE FOR THE SPLIT-RING RESONATOR EXPERIMENT AT FLUTE

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Abstract

A compact, longitudinal diagnostics for fs-scale electron bunches using a terahertz (THz) electric-field transient in a split-ring resonator (SRR) for streaking will be tested at the Ferninfrarot Linac- Und Test- Experiment (FLUTE). For this new streaking technique, intensive THz pulses are required, which will be generated by laser-based optical rectification. We present the setup for generating THz pulses using tilted-pulse-front pumping in lithium niobate at room temperature used at FLUTE. Excited by an 800 nm Ti:Sa pump laser with 35 fs bandwidth limited pulse length, conversion efficiencies up to 0.027% were achieved. Furthermore, the status of the SRR experiment is shown.

INTRODUCTION

Ultrashort electron bunches down to the range of a few, or even sub-femtoseconds, have become increasingly important in accelerator physics for several years [1–3]. Longitudinal diagnostics of such short bunches is not only necessary for a better understanding of charge-limiting effects such as bunch instabilities, but it also presents a challenging task that so far can only be accomplished with a few reliable methods. At present, transverse deflecting structures such as RF streaking cavities are used as the gold standard to provide the required temporal resolution [4]. However, they have the disadvantages of comparatively high space and cost requirements. Therefore, a compact and promising advancement of time-resolved electron streaking via THz fields excited in a split-ring resonator (SRR) is currently studied at the accelerator test facility FLUTE at the Karlsruhe Institute of Technology (KIT). Figure 1 shows the principle of the SRR diagnostics [5]: The infrared (IR) pulses of the FLUTE laser system are split in two and used to generate the electron bunches via third harmonic generation (THG) and simultaneously for laser-based THz generation in lithium niobate (LiN). After coupling the THz pulses into the SRR antenna structure, a high-frequency electric field is generated within the $(10 \times 20 \times 20)\ \mu\mathrm{m}^3$ gap. For a successful streaking the electric field has to be synchronized to the bunch such that the field has a zero-transition when the center of the bunch passes the center of the SRR gap. Due to the interaction of the field with the electron bunch passing through the gap, the electrons in the head of the bunch are then accelerated

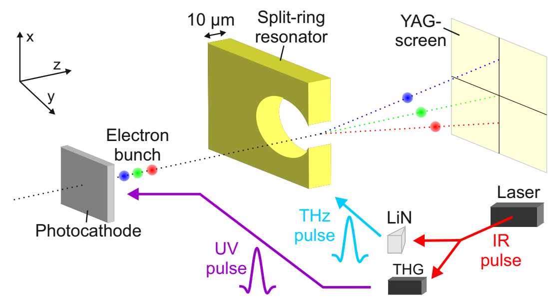

Figure 1: Principle of the SRR experiment at FLUTE (not to scale). By coupling laser-generated THz pulses into the antenna structure of the SRR, a strong and high-frequent E-field is generated that can be used to streak the photoinjected electrons.

transversely in one direction whereas the electrons in the tail of the bunch are accelerated in the opposite direction. This streaking maps the longitudinal density profile into the transverse plane, which can be read out on a YAG screen after an appropriate drift space. If the path length after the interaction point is additionally combined with a spectrometer dipole, the applicability of the method can be even extended to longer bunches in the ps range, as shown by recent simulation results [6]. The achievable temporal resolution for the shortest possible bunch lengths also depends primarily on the strength of the electric field and therefore on the total energy of the THz pulse [7].

TERAHERTZ GENERATION

The optical rectification (OR) approach has emerged as one of the most efficient methods for laser-based generation of intense THz pulses [8]. Crucial for high efficiencies is the fulfilling of phase matching, which in our case can be expressed as

$$v_{\mathrm{THz}}^{\mathrm{ph}} = v_{\mathrm{opt}}^{\mathrm{gr}}, \tag{1}$$

where $v_{\mathrm{THz}}^{\mathrm{ph}}$ and $v_{\mathrm{opt}}^{\mathrm{gr}}$ denote the phase and group velocity of the emitted THz and optical pump wave, respectively. In contrast to the nonlinear crystals zinc telluride and gallium phosphide, which are widely used for OR, the phase matching given by Eq. (1) cannot be achieved collinearly for LiN, although the material exhibits excellent optical properties due to high electro-optical coefficients.

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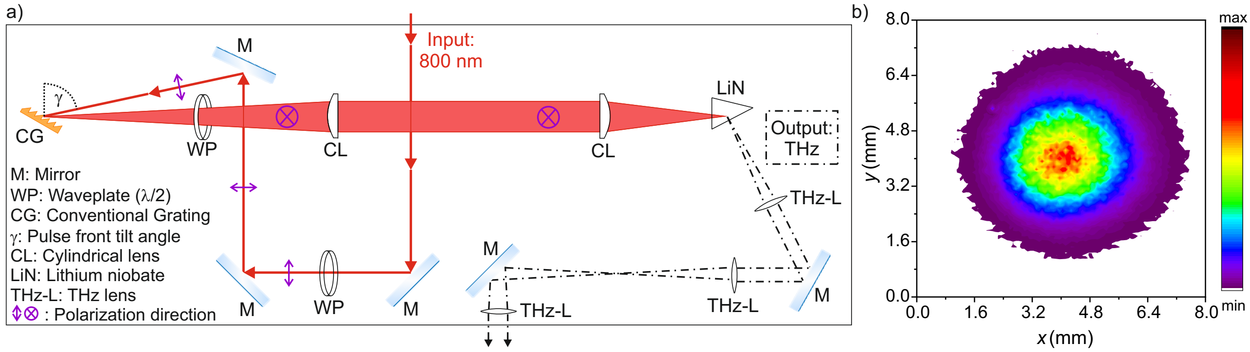

Figure 2: a) Design of the laser-based THz generation setup at FLUTE. A conventional grating (CG) induces the pulse front tilt angle γ, so that phase matching and as a consequence efficient THz generation can be achieved by pumping the LiN crystal. b) THz intensity beam profile at the crystal, measured with a pyroelectric camera.

Tilted-Pulse-Front Pumping

With use of tilted-pulse-front (TPF) pumping, phase matching can also be achieved for LiN by tilting the THz pulse front by an angle γ with respect to its propagation direction [9]. Then Eq. (1) changes to

$$v_{\mathrm{THz}}^{\mathrm{ph}} = v_{\mathrm{opt}}^{\mathrm{gr}} \cdot \cos\gamma . \tag{2}$$

As a consequence, phase matching can be achieved, if the pulse front tilt angle γ is selected appropriately.

Figure 2 a) shows the design of the laser-generated THz setup using TPF pumping as it is currently used at FLUTE. For pumping, the titanium-sapphire (Ti:Sa) photoinjector laser system with a center wavelength of 800 nm, a bandwith-limited pulse length of 35 fs, and a repetition rate of 1 kHz is used. Initially the pulses coupled into the setup are polarized horizontally before being reflected onto a conventional diffraction grating. This polarization-dependent grating induces the pulse front tilt angle γ. Since the LiN crystal requires vertical polarization, a half-wave plate is used before the TPF beam is imaged from the grating into the LiN crystal by a 4*f*-telescope system consisting of two cylindrical lenses.

The beam profile of the THz pulses being emitted is illustrated in Fig. 2 b), where the measurement was performed with a pyroelectric camera about 1 cm after the crystal. The generated THz beam is then guided to the SRR by three THz lenses and an off-axis parabola in 4*f*-configuration. The setup was conceived as a portable module in order to be able to perform the alignment at a suitable location, since space on the optical table in the experimental hall is limited and offers only restricted access.

Conversion Efficiency

We used a pyroelectric power meter calibrated by the Physikalisch-Technische Bundesanstalt (PTB), Germany's national metrology institute, to derive the THz pulse energy just behind the LiN crystal. Figure 3 shows the resulting THz pulse energy, as well as the calculated corresponding THz conversion efficiency, as a function of the pump pulse energy. The nonlinear behavior of the THz generation process is clearly visible from the curvature of the THz pulse energy

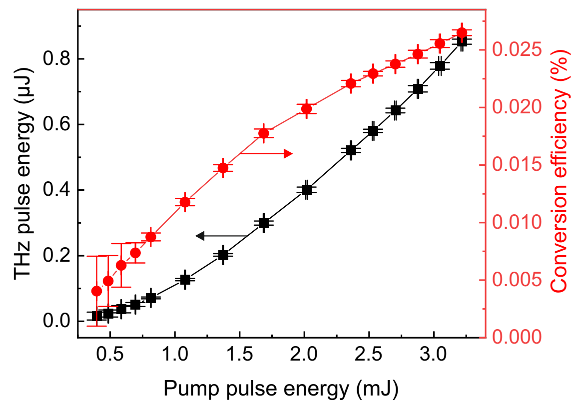

Figure 3: THz pulse energy (black squares) and corresponding conversion efficiency (red dots) as a function of 800 nm pump pulse energy with 35 fs pump pulse length at room temperature. The connecting lines are guides to the eye.

data. For the conversion efficiency, a highest value of 0.027% was achieved for a pump pulse energy of 3.22 mJ. If we follow [10] and assume that the conversion efficiency scales linearly with the pump pulse length up to about 200 fs, the efficiency achieved here is similar to previously reported highest efficiencies for TPF pumping with Ti:Sa pulses in LiN at room temperature [11].

SRR EXPERIMENT - STATUS

In the following, an overview of the status in the SRR experiment is given.

Experimental Setup

After adjusting the portable THz setup and optimizing the conversion efficiency, the module was installed on the optical table in the experimental hall at FLUTE. At the same time, the layout of all optical components was adapted to the principle explained in Fig. 1 using 3D-CAD drawings. All optical elements were set up on the optical table next to the photoinjector and aligned. The design goal of this setup is to match the laser path lengths for both, the photoinjection and the THz generation, so that there is a temporal overlap between electron bunch and THz pulse or streaking field at

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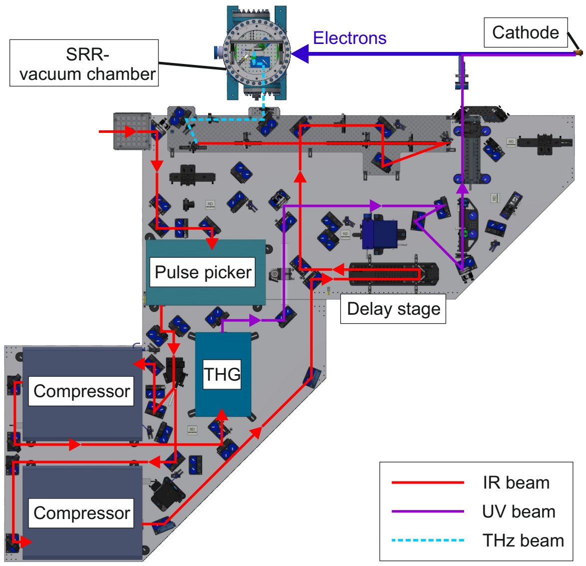

Figure 4: Overview of the setup on the optical table in the experimental hall at FLUTE. Illustrated are both laser paths for photoinjection and THz generation with their key elements.

the SRR position in the vacuum chamber. An overview of the optical setup is shown in Fig. 4, where the uncompressed pulses are directed to the optical table and split after the pulse picker into the two paths for photoinjection as well as for THz generation. For temporal fine tuning, a delay stage was installed, which allows an effective change of the laser path length for THz generation by 75 cm corresponding to a time difference of 2.5 ns.

Temporal Overlap

To preadjust the delay stage position for temporal overlap, we conducted an experiment shown in Fig. 5 a). By focusing the electron beam on the aluminum SRR holder, transition radiation in the THz range is generated. This radiation is then guided out of the vacuum chamber via the off-axis parabolic mirror and a flat metal mirror. Both THz pulses, laser- and electron-generated, are then spatially overlapped by a beam combiner and finally detected with the same fast broadband Schottky-barrier diode (manufacturer: Virginia Diodes, Inc., USA). The measurement result is shown in Fig. 5 b). The signal peaks of the laser-generated and electron-generated THz pulses measured with the Schottky diode and read out with a 6 GHz oscilloscope can be seen. For the double-peak structure of the electron-generated THz signal, which is most likely caused by a laser prepulse, the larger peak was assumed to be the valid signal. In addition, the delay stage was set, so that the time difference of the two pulses was 2.7 ns. This delay corresponds to twice the distance from the beam combiner to the SRR position, compensating for the additional beam path to the detector. Thus - within the accuracy of this measurement setup - the temporal overlap of both pulses at the SRR position should already be sufficient for bunch lengths of a few ps, although scanning will be required to improve the alignment for ultrashort bunches.

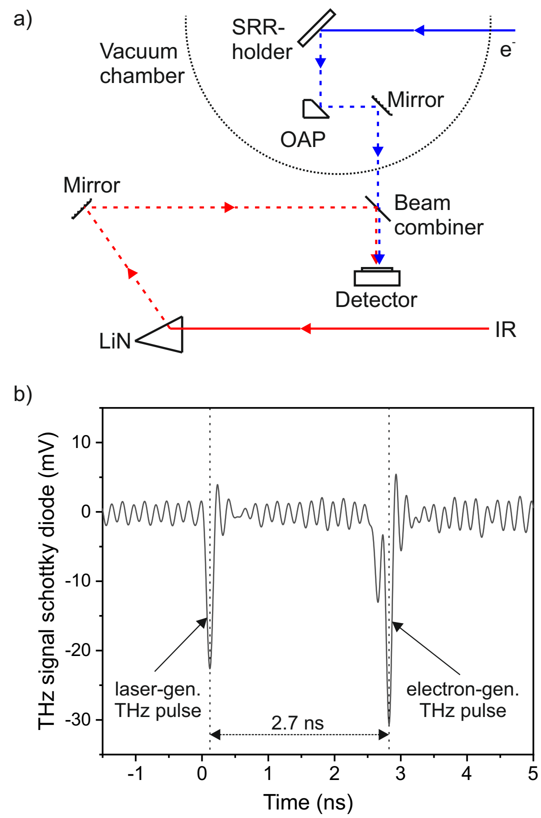

Figure 5: a) Sketch of the principle to measure the temporal overlap. b) Result of the simultaneous measurement of both laser- and electron-generated THz pulses with a Schottky-barrier diode and a 6 GHz oscilloscope. The spacing in time of 2.7 ns corresponds to the delay between the SRR and the beam combiner position ensuring a temporal overlap of electrons and laser-generated THz at the SRR position.

SUMMARY AND OUTLOOK

Currently, the SRR experiment is being tested as an advancement of longitudinal diagnostics for ultrashort electron bunches at FLUTE. For this purpose, intense THz pulses are needed, which are optically generated based on TPF pumping in LiN. The design of the setup for THz generation as well as measurements of the beam profile have been presented. A conversion efficiency up to 0.027% was achieved, comparable to the best results in the literature under the here used experimental conditions. Moreover, experimental results were shown to achieve the temporal overlap. In the near future we attempt to detect streaking with the SRR setup at FLUTE.

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