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STATUS OF THE THZ STREAKING EXPERIMENT WITH SPLIT RING RESONATORS AT FLUTE

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Abstract

THz streaking with split ring resonators (SRR) promise ultra-high (sub-femtosecond) temporal resolution even for relativistic electron bunches. A proof-of-principle experiment in collaboration between the University of Bern, the Paul Scherrer Institute (PSI) and the Karlsruhe Institute of Technology (KIT) is currently prepared at the FLUTE facility (Ferninfrarot Linac und Test Experiment) at KIT. Most of the critical components have been designed, tested and set-up in the 7 MeV diagnostics part of FLUTE. In this contribution we will present an update on the experimental set-up and report on SRR configurations which have been optimized for highest THz deflection, while simultaneously accounting for the restrictions of the manufacturing process. Test measurements characterizing the SRR samples and the THz source, which has been matched to the FLUTE gun laser, will also be presented.

INTRODUCTION

Low charge operation of electron accelerators opens up the possibility of generating highly brilliant beams with micrometre transverse sizes and femto-second bunch length. Beam instrumentation for single-shot measurement of such ultra-short electron bunches is either limited in time resolution to some tens of femto-seconds for electro-optical methods [1, 2] or requires quite complex and expensive infrastructure as in case of RF deflectors, which are capable of providing the desired time resolution even for highly relativistic beams [3].

The test accelerator for far-infrared experiments (FLUTE) at the Karlsruhe Institute of Technology [4] is presently being set-up and commissioned to generate ultra-short and intense THz pulses and to provide a test infrastructure for femto-second electron beam studies aiming for the development of advanced diagnostics. Based on the proposal of using high frequency THz fields, which are enhanced in a split ring resonator (SRR), to streak an electron beam for its temporal characterization [5], a proof-of-principle experiment is presently prepared at FLUTE, intending to make use of the 7 MeV beam from the RF photo-injector gun in order to demonstrate the applicability of this method in a real accelerator facility [6, 7]. The tasks in this research collaboration between the University of Berne, KIT and PSI are distributed in the following way:

- KIT provides the FLUTE accelerator, the photo-injector laser system to generate the electron beam and the THz radiation as well as beam optics simulations for ultra-low charge operation.
- The University of Berne provides the SRR and the THz pulse generation.
- PSI participates in the design optimizations of the SRR and provides the beam diagnostics for the FLUTE experiment.

STATUS OF THE SRR EXPERIMENTAL SET-UP AT FLUTE

The UHV-chamber for the SRR experiment has been installed at about 1.7 m behind the photo-cathode, where ASTRA simulations indicate, that transverse rms beam sizes of $\leq 10\ \mu m$ can be achieved at low ($\leq$ 100 fC) bunch charges [7]. In the experimental chamber, a set of SRRs can be accurately positioned to the electron beam path by means of UHV-compatible translation stages. A scintillator screen in combination with a high resolution optical telescope allows matching of the beam through the SRRs. Presently all components are interfaced to the FLUTE control system. The Ti:Sa FLUTE laser system, which provides the ps long UV (266 nm) pulses for the RF photo-injector gun and which is used to generate the short and intense THz pulses for exciting the SRRs, is in operation and the laser transfer line from the optics hutch to the FLUTE accelerator bunker is presently under commissioning. The THz pulse generation is set-up on an optical breadboard outside of the experimental chamber, from which the THz radiation is imaged through a CF-40 z-cut crystalline quartz UHV-window onto the SRRs by using an off-axis parabolic mirror. Overlap of the electron bunches with the sub-ps rise times of the THz streaking field is achieved with a motorized delay stage, while the synchronization is inherently provided through the use of the same laser for the electron beam and THz pulse generation. RF conditioning of the FLUTE gun is ongoing so that first acceleration of electrons is expected by October 2017.

THZ PULSE GENERATION

The intense single-cycle THz pulses for exciting the SRRs are generated by optical rectification [8-10] of the ultrashort FLUTE gun laser pulses (Coherent Astrella provides pulse energies of 6 mJ at a wavelength of 800 nm and a FWHM pulse length of < 35 fs with 1 kHz repetition rate) in a $LiNbO_3$ crystal.

Tilted Pulse Front Generation

Optical rectification, as any other nonlinear frequency conversion process, requires excellent phase matching in order to be efficient. Proper phase matching in $LiNbO_3$

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needs special geometries because the refractive index mismatch between the optical pump and the generated THz pulse is comparatively large. A viable and widely used geometry is the tilted pulse front pumping technique. The implementation, which has been chosen for the THz source of the SRR experiment at FLUTE, is depicted in Figure 1, where the pulse front tilt of the pump laser beam is created by the combination of a diffraction grating and an imaging system.

Optimal THz imaging was provided by a 4f imaging system consisting of a 200 mm focal length (SL1) and a 50 mm (SL2) focal length UHMWPE lens (see inset of Figure 3). The measured THz spot is shown in Figure 3. It was measured with a pyroelectric beam profiling THz camera (Spiricon Pyrocam IV). The FWHM THz spot dimensions are 0.92 mm in horizontal direction and 1.15 mm in vertical direction. From these measurements we deduce maximum electric field strengths of 14 MV/m for the FLUTE THz pulse set-up.

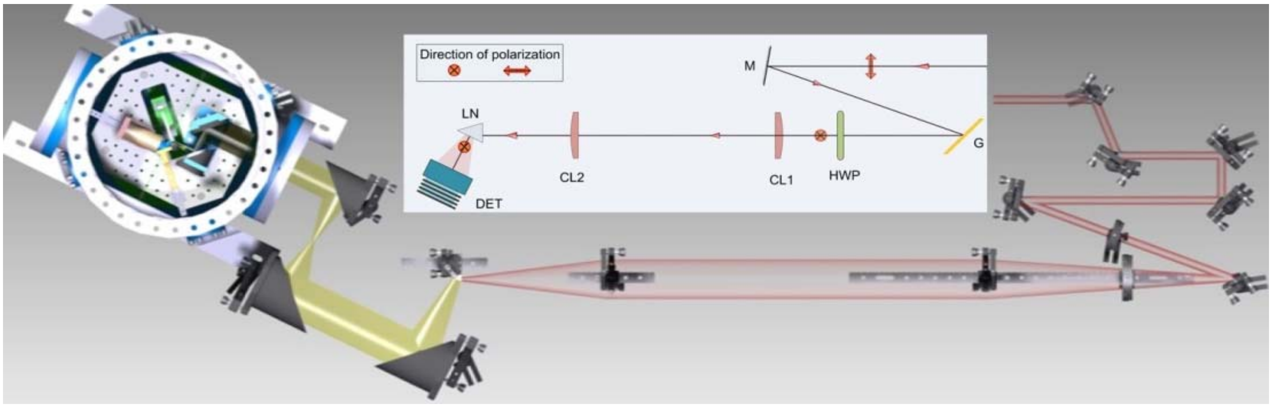

Figure 1: Layout of the THz source at FLUTE (shown in red and schematically in the inlet). M: dielectric mirror; G: reflection grating; HWP: λ/2 retardation plate; CL1: plane convex cylindrical lens (f = 421 mm); CL2: plane convex cylindrical lens (f = 250 mm); LN: MgO doped stoichiometric $LiNbO_3$ prism. The THz-transport to the SRR in the vacuum chamber is also shown (yellow beam path).

Experimental Results

The main challenge was the optimization of the source geometry to the FLUTE gun laser, which provides pulse durations of only 35 fs (FWHM) and a maximum pump pulse energy of 3.35 mJ that is allocated for the THz pulse generation. A calibrated SLT THz 20 type pyroelectric THz energy meter (DET) was used to measure the energy of the THz pulses and the results are shown in Figure 2 (black dots) as function of the pump laser energy. We find a monotonic increase of THz energy with pump energy up to the highest pump energies used. The maximum THz pulse energy was 0.8 µJ resulting in a laser-to-THz conversion efficiency of up to 0.024 % as also shown in Figure 2 (blue stars).

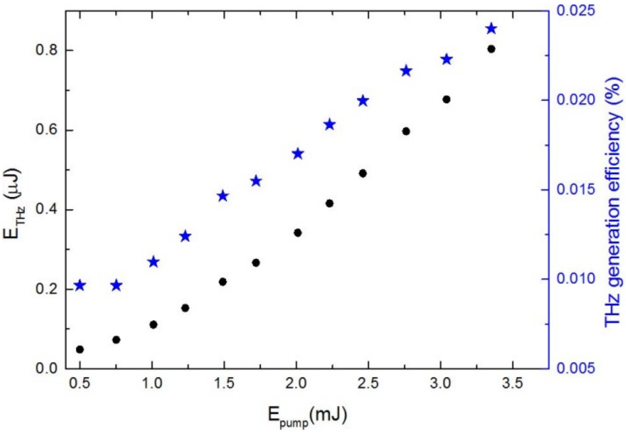

Figure 2: THz pulse energy (black dots) and conversion efficiency (blue stars) as a function of pump energy.

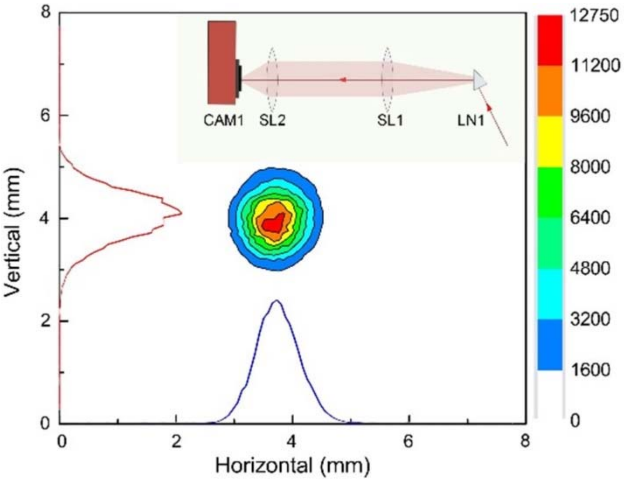

Figure 3: Camera image of the THz beam at the image plane of a 4f THz imaging system. A schematic of the 4f imaging system is seen in the inset.

SPLIT RING RESONATOR DESIGN OPTIMIZATION

The original design concept of a THz-driven streak camera was based on a classical split ring resonator as shown in picture (a) of Figure 4, which poses quite a few challenges for use in an accelerator environment. Mounting the resonator without perturbing the field pattern of the resonance would require a dielectric holder attached to the SRR. This would cause two problems, one is the charging up of the SRR by halo electrons with subsequent breakdowns and the second a strong heat up of the resonator by halo electron bombardment (or by an accidental hit with the main beam). An alternative design has thus been followed, where the resonator is milled and drilled out of a solid 80 µm thick plate, which simultaneously serves as a mount for the SRR to be fixed on a motorized stage for precise (µm-level) and reproducible positioning. The new SRR configuration is shown in part (b) of Fig. 4, while parts (c) and (d) show images of the prototype, which was manufactured from glass and was gold coated subsequently.

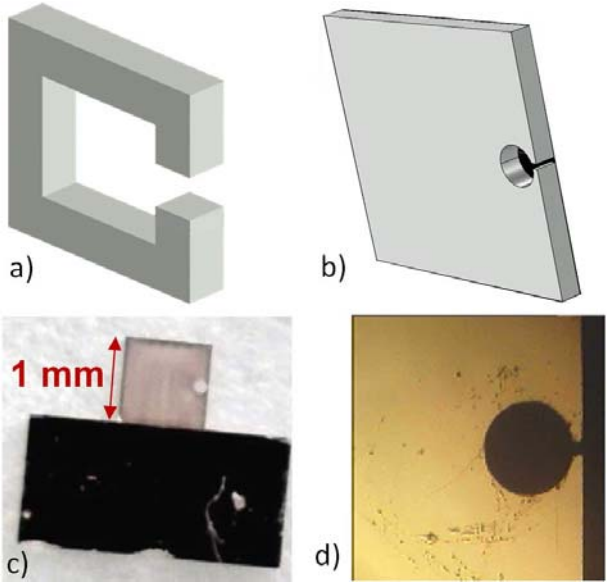

Figure 4: a) "Classical" SRR [5] with gap dimensions of 20 µm (height) x 20 µm (width) x 20 µm (length), b) manufacturing design with increased gap length / plate thickness of 20 µm x 20 µm x 80 µm, c) and d) images of the prototype SRR made from glass with gold coating.

In addition to the improved mechanical stability, the larger gap length of 80 µm for the new SRR design (b) increases the interaction region between the electron beam and the THz field, resulting in larger kick strength. With the measured THz field strength of 14 MV/m, a kick strength of 12 keV/c can be applied by the SRR to the 7 MeV beam at FLUTE. This provides a sufficiently large streaking (chirp) of the beam, clearly detectable on the downstream screen monitor in the gun spectrometer.

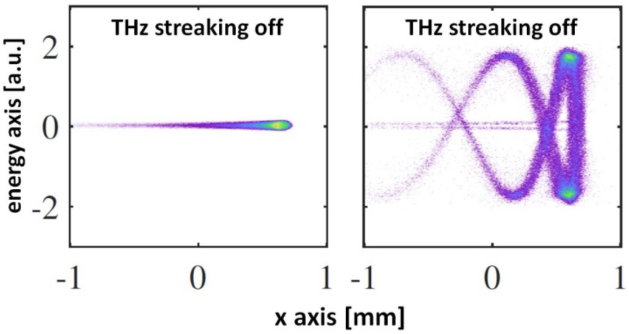

Figure 5: Simulated screen images on the FLUTE spectrometer showing the effect of 5 keV/c kick strength [7].

Figure 5 shows simulated screen images in the FLUTE low energy spectrometer calculated with the ASTRA code for conservatively assumed kick strengths of 5 keV/c where e.g. losses in the THz transport are taken into consideration. The resulting streaking structure of the ps long FLUTE beam is clearly visible.

SUMMARY AND OUTLOOK

The SRR chamber has been installed in the FLUTE beam line at 1.7 m behind the photo cathode. The THz pulses for exciting the SRR are generated by optical rectification in a $LiNbO_3$ crystal using the ultrashort FLUTE gun laser pulses. The experimental set-up has been tested and maximum field strengths of 14 MV/m have been achieved with the available pump pulse energy of 3.35 mJ. With the optimized SRR design, kick strengths of 12 keV/c are expected, which should result in a time resolution of ≤ 20 fs for the THz streaking experiment at FLUTE.

After RF conditioning of the photo-injector gun and control system integration of all sub-systems, first electrons are expected in the FLUTE facility by fall of this year, so that that it should be possible to execute the SRR experiment by the end of 2017.

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