DESIGN CONCEPT FOR A THz DRIVEN STREAK CAMERA WITH ULTRA HIGH RESOLUTION

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Abstract

The resolution of streak camera systems strongly depends on the slew rate of the deflecting element, being proportional to the amplitude and the frequency of the deflector. An attractive approach to reach femto and even sub-femto second resolution are THz driven electron streak cameras, which have been only recently proposed. Here, the ultra fast streaking field is generated by exciting a suitable resonant THz antenna, e.g. a split ring resonator with an intense THz pulse [1]. With today's THz sources streak field amplitudes in excess of 1 GV/m are within reach. Here, we present the concept for a proof of principle system. The THz pulse will be generated by rectifying the pulse from an existing 800 nm laser system in a suitable crystal as LiNbO3 [2]. For the source of the electron beam to be streaked, we plan to use an RF photo gun yielding a relativistic 6.5 MeV beam. We describe the setup of the system and present simulations of the beam dynamics.

INTRODUCTION

Pulsed electron sources are capable of emitting electron bunches with durations in the few hundred femto second regime and, using bunch compressor chicanes, these can be further shortened reaching the few femto second regime. Full temporal characterization of such electron bunches is a prerequisite for their use, for example in seeding of X-ray Free Electron Lasers. This issue is complicated by the non negligible pulse-to-pulse fluctuations of such machines requiring single-shot characterization techniques.

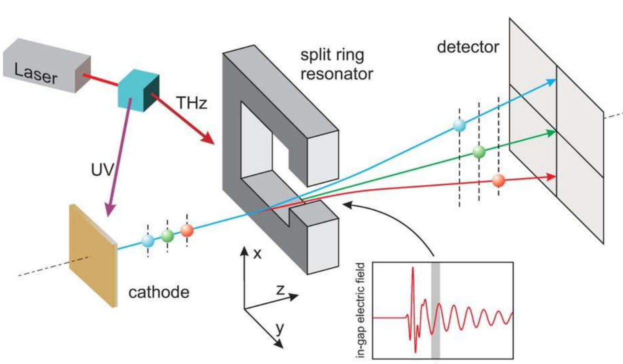

Figure 1: Measurement principle.

In the field of ultra fast electron diffraction, streak cameras have been shown to allow for sub-picosecond bunch duration measurements. Even streak cameras based on deflection mode RF cavities have been demonstrated to operate with sub-100 fs resolution for keV to MeV electron energies [3], yet the issue of phase jitter in RF cavities is a challenge. While obtaining temporal resolutions in the 10-100 fs regime is conceivable with current technologies, few-femtosecond or even sub-femtosecond resolutions seem out of reach. Here, we propose an approach with the potential to achieve a resolution around a femtosecond for electron bunches in the 10 kV to MV energy range [4]. The methodology relies on a resonant THz sub-wavelength structures irradiated with an intense single-cycle THz pulse. The design is reminiscent of a classic streak camera. The deflecting electrodes and the RF streaking field of a standard streak camera are replaced by a split-ring resonator (SRR) and the electric near-field in its gap, respectively. The SRR's resonance frequency can be varied between 100 GHz and several THz simply by changing its geometry, allowing for THz streak field rise times between hundreds of femtoseconds to several picoseconds. The electron bunch passing through the SRR's gap experiences a transverse momentum transfer which sign and magnitude depend on the longitudinal bunch position. Thus, the longitudinal bunch density is mapped onto the transverse axis and can be easily measured with a spatially resolved electron detector. THz-driven streaking should be well adapted to measure ultra short electron bunches, even on a single-shot basis. Ideally, the electron bunches and the THz pulses are generated with the same laser system, that is to say, synchronization between the two is inherently guaranteed.

The planned research builds on the extensive recent work in the field of laser-driven particle acceleration (see e.g. [5]). Particle beams have been accelerated from rest using infrared fields of lasers [6,7]. Due to the small wavelength and corresponding structure size, only low-charge beams could be generated. An acceleration by a field of a few terahertz is described in [8], showing an energy gain of about 7 keV [9]. In the present case, the effective accelerating field is transverse to the direction of motion of the particles, such that particle bunches are streaked rather than accelerated. While the final goal is different, the methods are similar, and we expect to build on the rapid progress made in the field of laser acceleration.

In the following, we describe the principle behind the measurement system, present simulation results for the deflector as well the required electron source and give a first layout of deflector and diagnostics station.

PRINCIPLE

The principle used in the measurement is shown in Figure 1. The photon beam to be measured modulates a photo cathodes and creates an electron beam, which is accelerated

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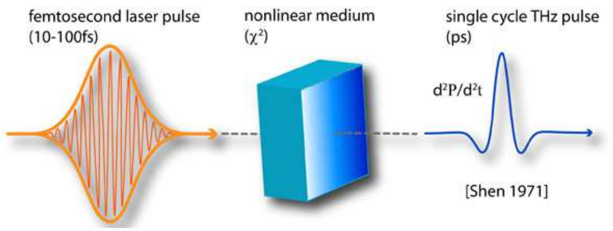

Figure 2: THz generation through optical rectification of laser pulses.

either in a DC or an RF gun. Using optical rectification a plane wave pulse is excited from a second laser pulse, which excites the fundamental mode in a split ring resonator and generates a deflecting field. By letting the electron bunch pass through the zero crossing of the deflecting mode, we obtain a correlation between longitudinal current density and the vertical beam offset. The read out is done via a following transverse electron beam profile monitor.

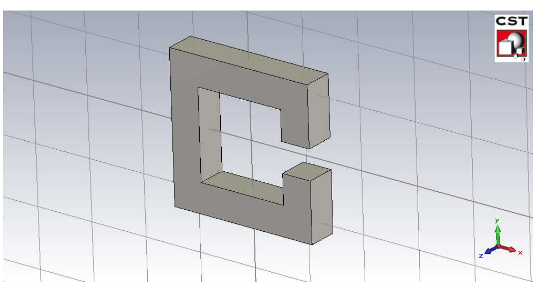

Figure 3: Ring resonator for 1000 GHz resonance frequency.

A first, initial experiment is planned, which will give a proof of principle and will generate both the measurement beam and the THz pulse from the same laser source. By observing the vertical blow up of the beam due to the streaking, laser pulse lengths in the order of a picosecond are sufficient, avoiding major synchronization problems.

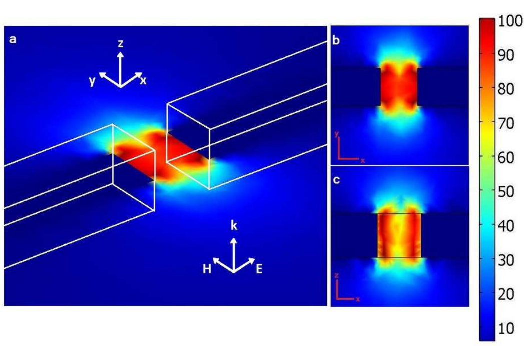

Figure 4: Transverse electric field distribution in the gap.

THz Generation

Currently, high-field single-cycle THz pulses are mostly generated by optical rectification of approximately 100 fs laser pulses in inorganic crystals, such as ZnTe or $LiNbO_3$,

Table 1: Mechanical and Electrical Parameters of the Split Ring Resonators

f (THz)	0.1	0.3	1
width (µm)	370	130	50
deflector gap (µm)	10	10	10
kick (eV/c), 1 MV/m in gap	43.0	27.7	26.5
Q factor	10.8	10.3	11.8

or in organic crystals, such as DAST or OH1 (Fig. 2). Optical rectification is a second order nonlinear frequency mixing process and as such the THz generation efficiency is dominated primarily by three factors, the pump laser intensity, the nonlinear material coefficient, and phase matching. The highest fields to date have been obtained from $LiNbO_3$, DAST and OH1 with electric field strengths in excess of MV/cm.

Split Ring Resonator

For different resolutions and ranges, we are planning to work with three different resonator types, having resonance frequencies of each 100, 300 and 1000 GHz. They have a quadratic shape using a rectangular metallic conductor of 10 µm thickness. As an example, Figure 3 shows the geometry of the 1000 GHz type. The width of the gap, where the beam is passing was chosen at 10 µ for all frequencies.

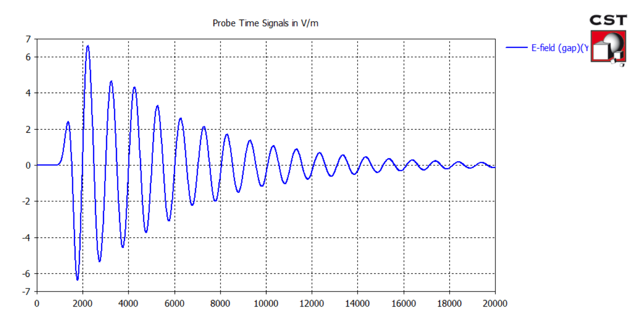

Figure 5: Electric field inside gap of 1000 GHz resonator excited with plane wave pulse of 400 fs FWHM.

The wide band THz pulse can feed only energy into the resonator within its bandwidth. Nonetheless the geometric field enhancement due to the resonator shape gives enhancement factors between 6 and 20 for the deflecting field inside the gap. Figure 5 shows the response of the 1 THz type.

Table 1 gives an overview of the various resonators. The effective kick seen by a relativistic beam passing the gap is given by the electric and magnetic field taken into account the transit time factor. These were calculated for a reference gap gradient of 1 MV/m with CST Particle Studio and are also given in this table. The maximum field inside the resonator is limited by thermal effects due to conductive losses and field emission effects – we assume to be able to reach 500 MV/m peak, which would give us, depending on the frequency, deflections between 13 and 21 keV/c, which are sufficient to work even with low relativistic beams. For

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highly relativistic beams as e.g. a spent FEL beam at several GeV, a phased array of SRRs would be required.

In the simulations, we also looked at secondary effects in the resonators. Even with this high frequencies, conduction effects were not yet visible. Also the variation of the kick over the gap aperture is below 10%.

Generating the Electron Beam

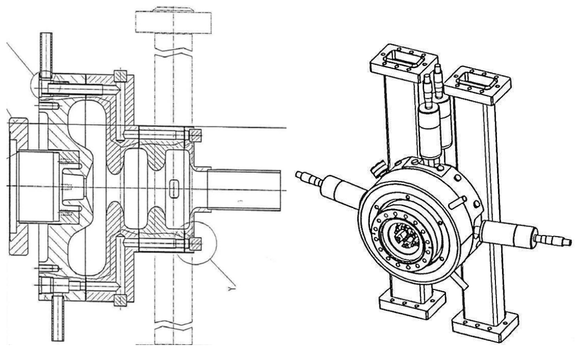

Figure 6: Geometry of the RF gun.

The electron beam generated on the photo cathode should be a faithful replica of the photon signal, this property should be conserved during acceleration and transport through the deflector. Furthermore there is an inherent conflict in choosing the value of the beam current between getting a good detection signal and avoiding space charge effects while focusing the beam through the 10 µm deflector gap.

For a non accelerator, lab based applications, using a compact DC based gun would be preferable. The lower beam energy, 30-100 keV, would be deflected stronger giving a higher resolution. But space charge forces are more visible, making the beam optics even at the design current of 10 mA in such a device quite challenging. A design based on that approach is in development, but not shown here.

The alternative used here is an RF gun. The emitted electrons get rapidly accelerated at gradients up to 100 MV/m, reducing strongly space charge effects. Longitudinal information in the intra bunch density are much better conserved and the dramatically improved transverse emittance allows an efficients focusing of the beam into the 10 µm deflector gap.

The split ring resonator experiment (SRR) was originally planned to be performed using existing equipment at PSI as the RF gun and the solenoid from the SwissFEL Injector Test Facility SITF [10]. But resent discussion with the THz group at KIT centered on doing the setup inside the FLUTE test stand [11], which uses a similar setup. The RF gun is also a 2 1/2 cell gun [12] and solenoid has the same dimensions, so we should expect quite similar behavior concerning the beam dynamics. So the results should apply to both cases.

We modeled the beam dynamics using the geometry of the 2 1/2 cell RF gun, which we had in use in the SwissFEL test injector facility SITF [10]. The gun was originally developed for high current operation in the CLIC test facility CTF-2 [13]. The general geometry is shown in Fig. 6. A specialty

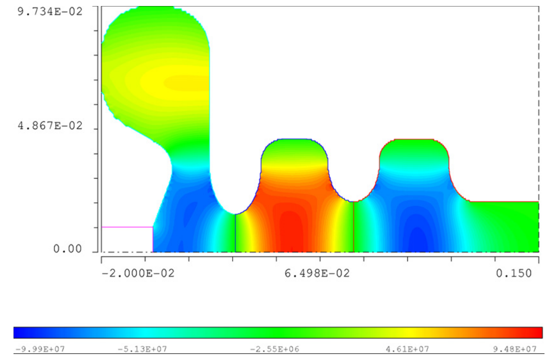

Figure 7: Accelerating mode - contour plot of longitudinal electric field.

compared to other design is the large diameter first half cell, where the TM_{02}resonance is used for the main accelerating mode (Fig. 7). The original reason for this choice is, that this resonance is particularly well suited to generate a bunch train with extremely high beam charges and currents. For the operation at the extremely low currents required this feature has no influence. A second feature, more useful, is the use of large irises between cells minimizing the non-linearity of the RF fields.

The gun is followed by a solenoid focusing the beam into the aperture of the split ring resonator. The operating parameters gun and solenoid are listed in Table 2.

Table 2: Operating Parameters of Gun and Solenoid

RF Gun	
Gradient (MV/m)	100
Emission phase (deg.)	39
laser spot dia. (µm)	50
Beam energy (MeV)	6.5
Solenoid	
Length (mm)	260
Inner diameter (mm)	80
Outer diameter (mm)	385
Peak magnetic field (mT)	290
Beam parameters in focus	
r_{rms} (µm)	0.97
ϵ_n (nm rad)	1.05

Both gun and solenoid are rotationally symmetric, so the beam dynamics could be simulated using the 2 1/2D particle in cell code MAFIA TS2 [14]. To capture space charge forces accurately, grid resolutions down to 5 µm were used. To have reasonable computation times, the solenoid was set to a relatively high field to obtain beam focus already shortly after the solenoid at 520 mm instead having to track the particles in the drift between solenoid and deflector to the design location at 1700 mm.

Figure 8 shows the evolution of the rms beam radius from emission to the focal point for 10 and 20 mA current. The transverse beam parameters in the focal point are also listed in Table 2. As also the transverse phase space plot in Figure 9

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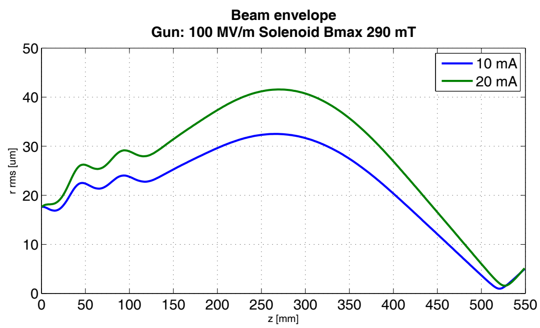

Figure 8: Beam envelope for 10 and 20 mA peak current for an artificially shortened focus position of 520 mm (Design: 1700mm).

shows, we should be able to propagate the beam though the 10 µm sized aperture of the split ring resonator.

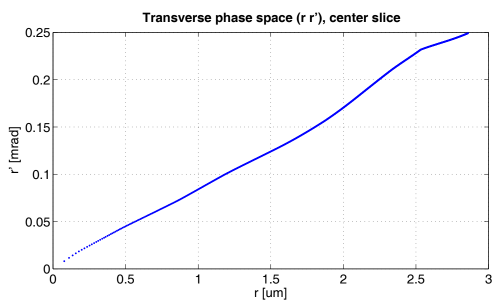

Figure 9: Transverse phase of the center slice of 10 mA beam near the beam focus.

EXPERIMENTAL SETUP

The split ring resonator (SRR) experiment will be performed in the FLUTE test beam line at Karlsruhe Institute of Technology (KIT). A layout of this beam line, indicating the location of the interaction chamber, is shown in Figure 10. The interaction chamber occupies the location of the future bunching cavity.

We only want to have a proof of the principle, showing a transverse blow up as a function due to the streaking action of the SRR. That allows us to avoid synchronization problems between measurement beam and the THz pulse, something, which need to be addressed in a later phase. Also, both the THz pulse and the electron beam can be generated from the same laser pulse with a rather standard optical delay stage to synchronize both.

Terahertz radiation enters the interaction chamber using a crystalline z-cut quartz window from the side. It will be focused onto the SRR with a remotely adjustable paraboloid mirror. A camera will be positioned at the opposite side, allowing for alignment and beam profile measurements.

The effect of the terahertz field on the beam will be measured with a transverse electron beam profile monitor, located 1.2 m behind the interaction zone. Beam profile measurements of 30 fC beams have been performed with such a monitor [15], and an optical resolution of 8 µm according to ISO 12233 has been determined [16].

Experimental Chamber

The split ring resonator will be installed on a hexapod in the experimental chamber. The hexapod allows for a full control of the position and orientation of the resonator, and will be used to align it to the electron beam. It is equipped with six piezo-electric motors, allowing for a nominal accuracy of better than 1 µm. The interaction will take place at the center of the chamber. A CAD model of this chamber is shown in Figure 11. The position and the transverse size of the electron beam will be determined on a scintillating crystal, which can be positioned at the same location as the split ring structure. A microscope lens with a long working distance will be installed to image the scintillator, through the center hole of the mirror, and to alternatively verify the location of the SRR. We aim for a projected pixel size of 650 nm. The resolution of the imaging setup, including vacuum window and mirror, will be determined experimentally.

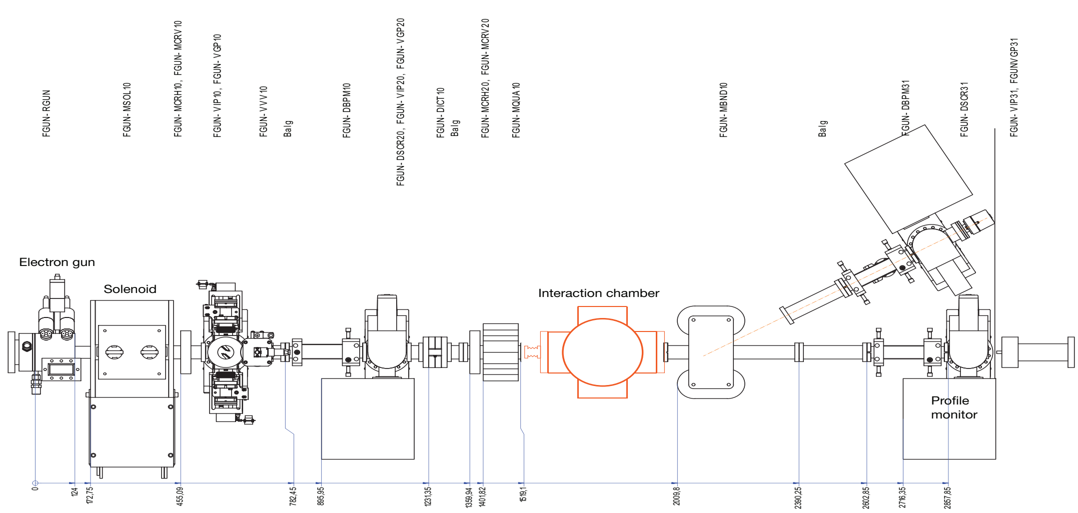

Figure 10: Planned installation in the FLUTE beam line.

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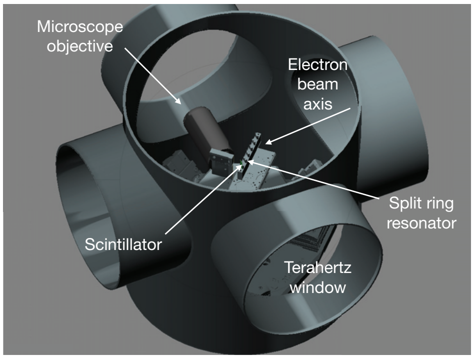

Figure 11: The planned experimental chamber, with the interaction zone for the split ring resonator.

The six-dimensional alignment structure will be equipped with an additional translation stage, mounted diagonally on top of the hexapod. This stage will allow to replace the structure quickly, and to test a series of structures without having to break the vacuum.

SUMMARY AND OUTLOOK

We propose a new concept for a femto to sub femto resolution streak camera. It is based on using micro structure type split ring resonator (SRR), which are fed by a single cycle THz pulse generated by optical rectification of a laser pulse. In order to vary range and resolution of the device, we are working with different designs in the range of 100-1000 GHz. Simulations show, that we can expect up to 20 keV/c maximum transverse kick from a single resonator. To generate the measurement beam, we plan to use a 2 1/2 cell RF gun, which offers the high beam quality to focus the electrons through the micron sized gap of the SRR while preserving the time domain resolution.

We are currently in the design phase for an initial experiment to be conducted at the FLUTE THz beam line at KIT using only the first stage containing the RF gun and the solenoid. Both the photo emission of the measurement beam as well as the THz pulse will be generated by the same laser pulse, that way avoiding synchronization problems. The goal is to prove the principle, by looking at the vertical beam blow up due to the streaking action of the SRR deflector.

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