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SIMULATIONS OF THE COMPACT TRANSVERSE-DEFLECTING SYSTEM FOR ULTRA-SHORT ELECTRON BUNCH DIAGNOSTIC

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Abstract

A compact TDS (transverse-deflecting system) has been proposed for diagnostics of extremely short electron bunches (up to single-digit femtosecond range). The main idea is to use terahertz radiation, produced from optical rectification of the facility's electron gun laser pulse. This provides an intrinsic synchronization between the electron bunch and the laser pulse. The proposed system is to be constructed at the test facility FLUTE (Ferninfrarot Linac- und Test-Experiment) at Karlsruhe Institute of Technology (KIT) [1], which provides the opportunity to create electron bunches of variable length and at medium energy (7 MeV up to 41 MeV). Simulations in CST MICROWAVE STUDIO are carried out in parallel with the experimental activities to optimize the design of the system. In the present paper the simulation results for several possible designs will be presented.

INTRODUCTION

The quest for ultra-short high brightness and high-energy electron bunches to produce coherent X-ray radiation in large-scale free electron lasers (FELs) is abundant. These bunches need to be verified in their length and shape, at multiple positions of the accelerator. Currently, this is mostly done by radio-frequency (RF) cavities, which use a dipole mode to deflect the electron beam and map its longitudinal profile on one of the transverse axes of a screen. These RF transverse deflecting systems (TDS) are however bulky, costly, and have synchronization issues for example due to RF jitter.

The compression of high-energy electron bunches has been driven to the extreme lately, with bunch lengths reaching the single-digit femtosecond realm. In large linear accelerators (LINACs) this usually works by alternating acceleration and compression, in order not to run into limitations due to space charge, which scales inversely squared with the beam energy.

The objective of the current project is to create a new innovative diagnostics system based on terahertz (THz) radiation, produced from optical rectification of the facility's electron gun laser pulse (see Fig. 1) [2]. This provides intrinsic synchronization only to be tuned by the laser and THz path lengths. Moreover, the high THz frequency and the high amplitudes improve on the temporal resolution, which is the key property of the system. The diagnostic structures, methods, and the overall system can then be transferred to larger facilities, such as FELBE, FLASH, or European XFEL to be used multiple times along the large LINACs.

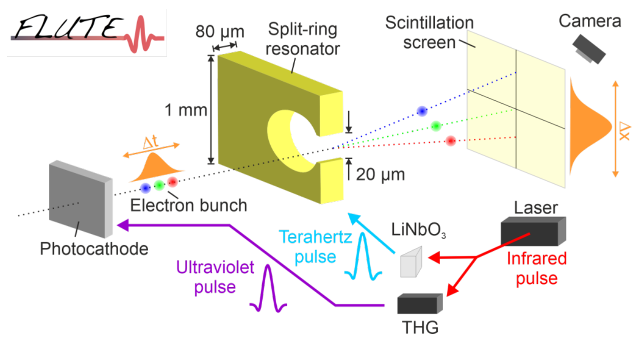

Figure 1: Scheme of the compact transverse-deflecting system (TDS).

The experimental optics setup is shown in Fig. 2. From the near-infrared (IR) laser pulse train a pulse is picked, split into two parts and compressed. One part is converted by third harmonic generation (THG) into a UV pulse to emit electrons at the copper photocathode. The other part is directed to a lithium-niobate (LiN) crystal, which generates a THz pulse to excite the split-ring resonator (SRR) within the vacuum chamber. The inset photo shows the optical table and the SRR vacuum chamber in the low-energy section of FLUTE [2].

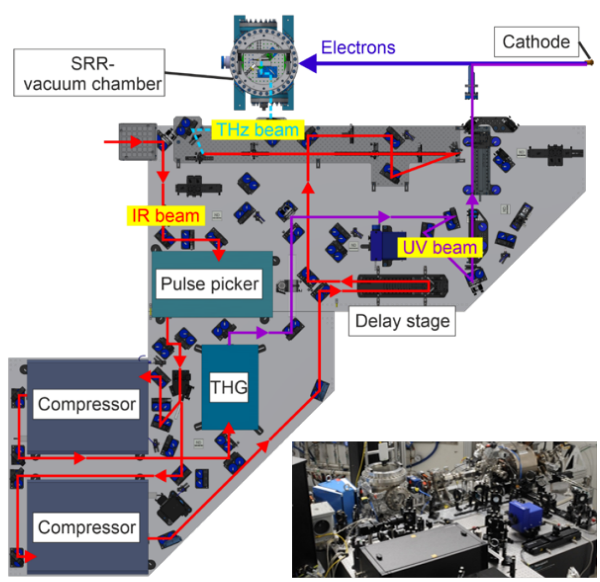

Figure 2: Optical scheme of the TDS experiment.

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BASIC PARAMETERS

THz Pulse Spectrum

The THz pulse spectrum has been measured using THz bandpass filters. Measurement results are shown in Fig. 3(a). The spectral maximum is located between 0.2 THz and 0.3 THz. Measurements of the high-frequency range are not sufficiently detailed. Therefore, a Gaussian pulse shape has been used in simulations as an excitation signal, the frequency is ranging from 0.1 THz to 1.0, 0.8, 0.6 and 0.4 THz, respectively (see Fig. 3(b)).

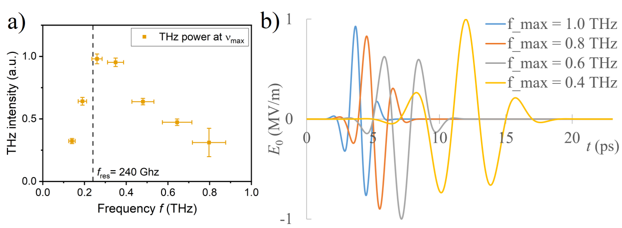

Figure 3: Measured THz pulse spectrum (a) and Gaussian excitation pulse (frequency range from 0.1 THz to f_{max}) for various f_{max} values (b).

Resonator Geometry

The initial resonator design used in the experiment and simulations is described in [3] and [4] (see Fig. 4). Also in [4] the term «inverse split-ring resonator» (ISRR) is proposed because the resonator is cut out of a solid metallic plate, which simultaneously serves as a mount.

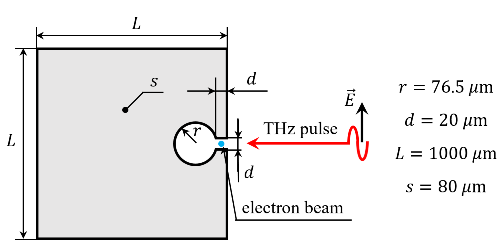

Figure 4: Inverse split-ring resonator (ISRR) geometry.

An alternative scheme is proposed in [5], where the electron bunch and THz pulse directions are still perpendicular, but the resonator plane is tilted to provide passage of both beams through the aperture (see Fig. 5). In the present paper this scheme is called «tilted-slit resonator» (TSR).

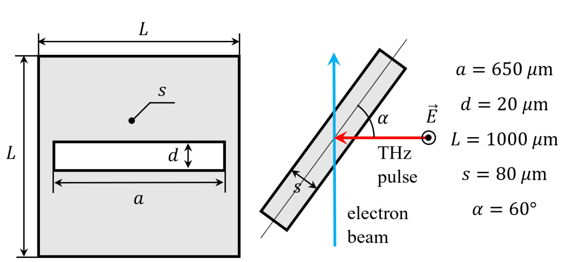

Figure 5: Tilted slit resonator (TSR) geometry.

FIGURES OF MERIT

Simulations of both resonator geometries with CST MICROWAVE STUDIO [6] show that the region of strong electric field induced by the incident THz pulse is located either in the gap or in the central part of the slit, respectively ($d \times d \times s$ volume). Moreover, the field in those regions can be treated as homogeneous and vertically oriented with good accuracy, and evolving synchronously in time.

As a first step stray fields may be neglected. As a reasonable figure of merit characterizing the streaking power of the system one may choose a vertical opening angle $\Delta\varphi$ received by the bunch after passage of the resonator. Consider an electron bunch of length l at momentum p and corresponding velocity v (momentum spread is neglected) passing through a gap of length s filled with a homogeneous vertical electric field varying harmonically: $E_y(t) = E_0 \sin \omega t$, where $\omega = 2\pi f$. The entrance time is adjusted in such a way that the bunch passes the center of the gap at zero field (see Fig. 6, where $t_* = (s + l)/(2v)$).

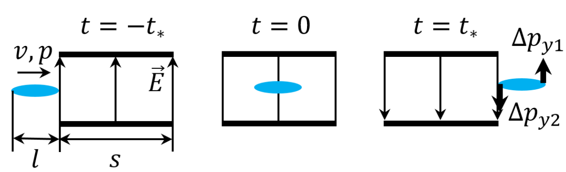

Figure 6: Streaking power integration scheme.

Then for sufficiently short ($l \ll v/\omega$) bunches $\Delta\varphi$ can be calculated as follows:

$$\Delta\varphi \approx \frac{|\Delta p_2 - \Delta p_1|}{p} = \left|\frac{4eE_0}{\omega p} \sin\frac{\omega l}{v} \sin\frac{\omega s}{v}\right| \approx \frac{4eE_0}{vp} l \left|\sin\frac{\omega s}{v}\right|.$$

For relativistic bunches a maximal effect will be obtained at $s \approx \frac{c}{4f}$ which corresponds to 250 μm at $f = 0.3$ THz and 375 μm at $f = 0.2$ THz.

As expected, the streaking angle $\Delta\varphi$ is proportional to the amplitude value E_c of the field in the center of the region. In the real experiment the field is pulsed and it is more convenient to introduce the amplification coefficient K as the ratio between maximal field in the center of the region and maximal field of the incident THz pulse.

The inner (cut out) part of the resonator behaves like an «open cavity» with its own electromagnetic modes which can be excited if the incident THz pulse contains corresponding frequencies and has a matching field pattern. The maximum of these eigen-frequencies is the resonant frequency f_{res}. This is the frequency where the resonator can be excited most efficiently.

GEOMETRIC PARAMETER SWEEP

In this section, the dependencies of the figures of merit on the main geometric parameters are studied. Simulations show that the effect of the overall resonator dimensions is small and the geometry of the cut out part is much more important.

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Resonant Frequency

Figure 7 shows a schematic view of the electric field in the middle cross-section of a cut-out part of an ISRR (a) and a TSR (b). They resemble the field pattern of the TE_{111} mode in a pillbox cavity and of a TE_{101} in a rectangular cavity, respectively. Therefore, parameters affecting the resonant frequency will be the resonator thickness as well as the cutout radius for ISRR and the horizontal slit size for TSR. Figure 8 shows that the thickness dependency on the other hand is negligible.

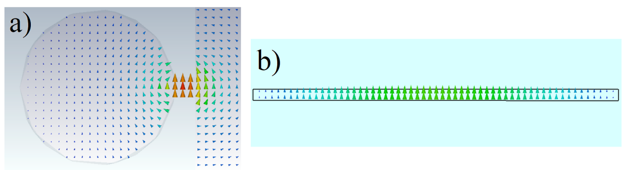

Figure 7: Field pattern in the middle cross-section of a cut out part of an ISRR (a) and a TSR (b).

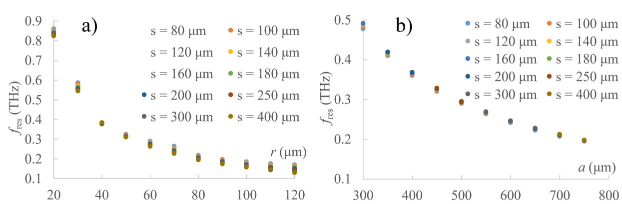

Figure 8: Dependency of the resonant frequency f_{res} on the geometric parameter r for the ISRR (a) and a for the TSR (b).

Amplification Coefficient

The amplification coefficient K is affected mostly by the gap size for ISRR and vertical slit size for TSR (see Fig. 9).

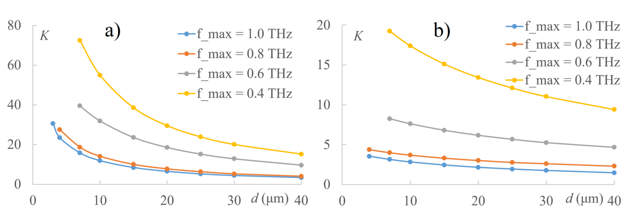

Figure 9: Dependency of the amplification coefficient K on the geometric parameter d for the ISRR (a) and the TSR (b).

Optimal Resonator Thickness

The calculation scheme shown in Fig. 6 can be improved to take stray fields into account. For this purpose a sufficient number of E-field probes should be placed along the electron beam path in the strong field region, then the field seen by an electron can be integrated. Figure 10 shows the $\Delta\varphi$ dependencies on the resonator thickness for various upper frequency limits of the incident THz pulse (electron beam energy is 7 MeV, bunch length is 520 fs).

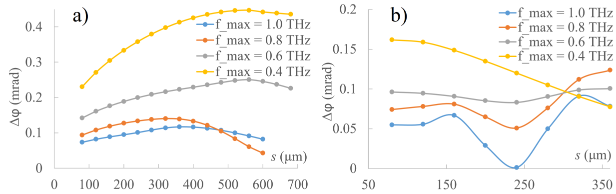

Figure 10: Streaking efficiency $\Delta\varphi$ for various thicknesses of the ISRR (a) and the TSR (b).

In the TSR case the dependency is more complicated because above 0.4 THz higher electromagnetic modes, which can be excited in the cut out resonator part, come into play. However, the ISRR geometry seems to be more effective for the purposes of the experiment due to a more concentrated field in the strong field region.

Additional Options

An ISRR with an elliptic cutout shape with semiaxes r_x and r_y has also been simulated (see Fig. 11(a)). This option offers an additional degree of freedom in adjusting the resonant frequency but no qualitatively new features in comparison to the circular cutout shape (dashed line).

An ISRR rotation angle α around the y-axis (see Fig. 5) has been introduced to study the possibility of an increasing the THz pulse energy acceptance of the resonator. Figure 11(b) shows almost no dependency of the field in the gap center on α. This means that the energy acceptance depends only on the gap volume but not on its orientation. Therefore, tilting the resonator may only decrease the streaking power due to a shorter electron path in the strong field region.

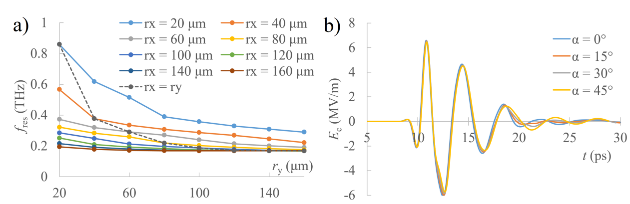

Figure 11: Resonant frequency of an ISRR with an elliptic cutout (a) and E-field in the gap center of a tilted ISRR (b).

CONCLUSION AND OUTLOOK

Two different resonator geometries were simulated as a core part of a compact transverse-deflecting system at FLUTE (KIT): inverse split-ring resonator [3], [4], and tilted slit resonator [5]. Taking into account the properties of the excitation THz pulse, the former option is preferable. Also it makes sense to prepare several ISRR samples of different thicknesses to achieve optimal streaking efficiency. However, the TSR option is also planned for study because electrons observed on the downstream screen have for sure gone through the resonator and missing the gap as is the case with an ISRR is not possible.

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