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POSSIBILITIES FOR PERFORMANCE ENHANCEMENT OF A COMPACT TDS AT FLUTE

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Abstract

A compact transverse-deflecting system (TDS) is being explored at the test facility FLUTE (Ferninfrarot Linac- und Test-Experiment) located at the Karlsruhe Institute of Technology (KIT). It has been proposed for diagnostics of short electron bunches. The idea of the technique is to use terahertz (THz) radiation, produced by the tilted-pulse front method using a part of the facility's photoinjector laser, amplified by a sub-mm scale resonator for streaking of the electron bunch. Two types of resonators and their arrays have been studied: inverse split-ring (ISRR) and tilted slit resonator (TSR).

Since the temporal resolution of this technique depends strongly on the electric field strength in the resonator gap, it would be desirable to increase this field strength. A horn-antenna-like device placed near the resonator has been proposed and simulated for this purpose. Simulations and geometrical parameter optimizations have been performed using CST MICROWAVE STUDIO and will be presented in this contribution.

INTRODUCTION

The goal of the Compact TDS experiment at FLUTE is to develop a method for studying the longitudinal profile of ultrashort electron bunches [1]. For this method, the longitudinal particle distribution is streaked. This means a time-varying transverse electric field is applied, transferring the longitudinal distribution to a transversal direction, where it can be recorded on a screen [2]. The approach does not involve any cavity-based devices which are used in conventional streaking systems. Instead, the same laser pulse is used both for the generation of the electron bunch and the streaking field. The laser pulse is split into two parts: one is converted by third harmonic generation into an UV pulse and directed at the copper photocathode in the electron source, while the other is transformed into a THz-range pulse using a lithium-niobate crystal and used as the streaking pulse. Compact devices can be used in this scheme to provide an interaction between the electron bunch and the streaking pulse. The interaction takes place in a resonator structure of ~1 mm size (see Fig. 1). The detailed scheme together with the optical table design is given in [3].

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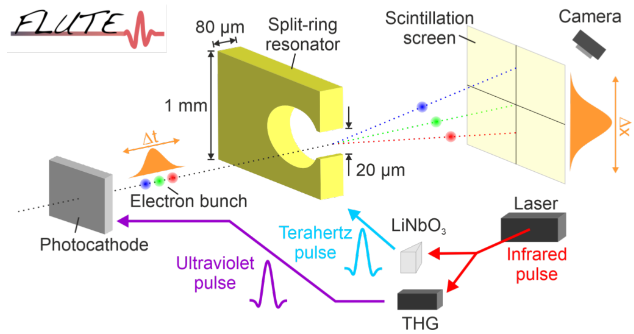

Figure 1: Scheme of the compact transverse-deflecting system (TDS) at the FLUTE facility.

RESONATOR GEOMETRIES AND EXCITATION SIGNALS

Two basic resonator design options have been used in simulations [4]: inverse split-ring resonator (initially proposed in [5] and [6]) and tilted-slit resonator (initially proposed in [7]). Their shapes are presented in Fig. 2.

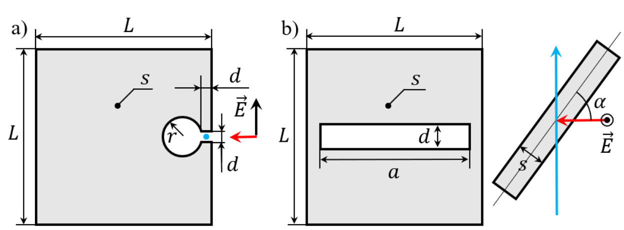

Figure 2: Inverse split-ring resonator (a) and tilted-slit resonator (b) geometry. THz pulse direction is shown in red, electron beam in blue.

It has been shown in [4] that their resonance frequencies are inversely proportional to the cutout radius for ISRR and horisontal slit size for TSR, respectively. The amplification coefficient (ratio between the maximal field of the response signal and excitation pulse) is inversely proportional to the vertical gap size for both schemes. In [8], it has also been shown that the resonator properties do not depend on its material (it can be made of any metal).

The THz pulse spectrum measured using THz bandpass filters is shown in Fig. 3(a). Figure 3(b) demonstrates the temporal structure of an exponentially modified Gaussian pulse, which has been used to approximate it. Transverse distribution of the excitation signal has been studied in [8]. In the present paper, vertically polarized plane waves have

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been used to clearly see the effect of all geometric parameters in the proposed enhancement schemes described in the following sections.

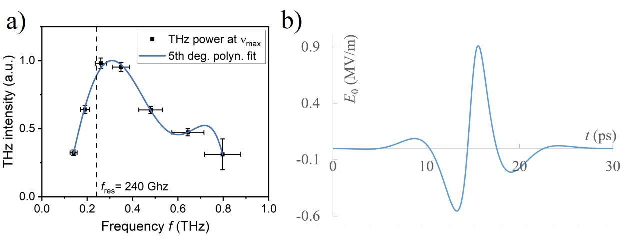

Figure 3: Measured THz pulse spectrum (a) and temporal structure of an exponentially modified Gaussian excitation pulse used in simulations (b).

HORN ANTENNA

One possible improvement, which may enhance the streaking efficiency of the resonator is to concentrate the electric field of the THz pulse on the resonator gap with a horn antenna. Although this type of antenna is well-known and had been widely studied, its usage in the TDS experiment differs from the convenient scheme. It will be used only to concentrate the electric field of the incoming THz pulse on the resonator gap. Since a waveguide region coupled to the horn is not used in this scheme, the term *horn concentrator* will be used.

First, an analytical estimation has been used to determine the limits of the spatial horn dimensions. Using a simple wave reflection rule one can easily find how deep a plane wave can enter into an angle formed by two conducting plates (see Fig. 4). If h_{in} is the distance between the plates measured in the input plane of the wave, then the wave will be reflected at the point where this distance reaches h_{out}:

$$\frac{h_{\text{out}}}{h_{\text{in}}} = f(\alpha) = \prod_{n=1}^{\lfloor \frac{\pi}{2\alpha} \rfloor} \frac{\tan n\alpha - \tan \alpha/2}{\tan n\alpha + \tan \alpha/2},$$

where α is the opening angle. Smaller ratios lead to better horn efficiency in concentrating the electric field, this will be proven in simulations. The main feature is that the ratio goes down to zero for small opening angles, therefore the horn efficiency theoretically can be infinitely increased. The only limitation in this case is the horn length. For a given α, there is an optimal length, above which further increase does not make sense, since all additional incoming field will be reflected back:

$$L_{\text{horn}}(\alpha) = \frac{1 - f(\alpha)}{2f(\alpha)\tan \alpha/2} h_{\text{out}}.$$

This dependency for $h_{\text{out}} = 1$mm is shown in Fig. 4, along with the geometric reflection scheme. Deviations from the simulation results are explained later.

This analytical estimation only gives a hint for the optimal horn concentrator dimensions and does not take into account

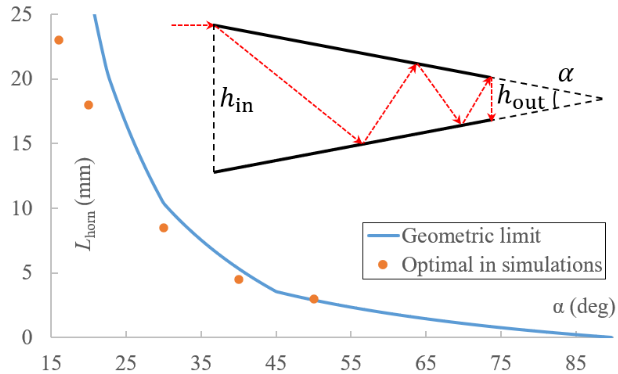

Figure 4: Optimal length of a horn concentrator for different opening angles and geometric reflection scheme.

the actual electric field vector directions in all the reflected waves. CST MICROWAVE STUDIO [9] simulations have been performed to calculate an amplification coefficient and to define how far the output plane of the horn may be moved from the electron beam. Amplification coefficient dependencies on the distance from the output plane are shown in Fig. 5 for different horn opening angles. They show maxima at the distance of 200—250 μm for opening angles smaller than 30° which is enough to move the horn out of the electron beam. According to the analytical estimation and simulations, smaller opening angles lead to better performance but also to larger horn length. This can be problematic because of lack of free space in front of the resonator. So, 20° opening angle seems to be a good compromise.

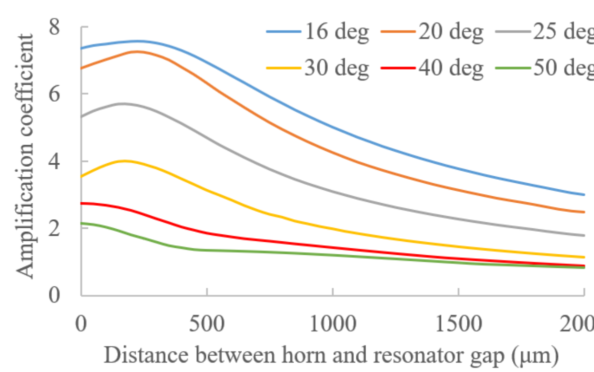

Figure 5: Horn concentrator amplification coefficient as a function of the distance from the horn output plane for different opening angles (horn length is optimized at each point).

VIVALDI ANTENNA

Another possible improvement is to transform ISRR into an exponentially shaped Vivaldi antenna [10]. Its shape and geometrical parameters are given in Fig. 6 (the exponential profile is defined by the λ_{v} parameter). The TSR resonator on the other hand does not have a similar option.

Streaking efficiency dependencies on the λ_{v} parameter for different L dimension (see Fig. 2) values are shown in Fig. 7.

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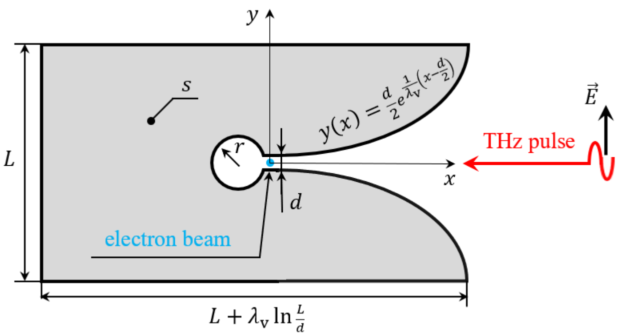

Figure 6: Vivaldi antenna dimensions.

Streaking power increases with λ_v and L as well. However, above $L \approx 4000\ \mu$m the gain becomes insignificant. λ_v is limited by the maximal admissible resonator length, similar to the horn antenna case.

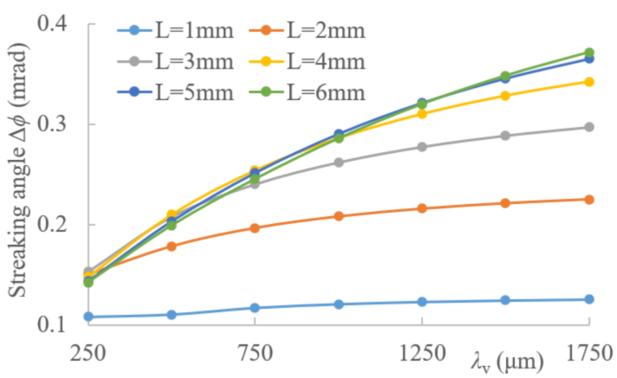

Figure 7: Streaking power dependencies on the λ_v parameter for different L dimension values of a Vivaldi antenna.

An exponentially shaped Vivaldi antenna shows up to 3 times better performance in terms of the streaking efficiency than a simple ISRR. It can be produced by laser cutting. On the one hand, for this type of resonator the small gap region requires more precise manufacturing. On the other hand, a Vivaldi antenna forms an electron beam aperture (similar to the TSR case) at least from one side, mostly blocking non-streaked electrons.

SCHEME COMPARISON

The idea to combine both techniques considered above has been proposed in [11]. This gives four improvement options for the ISRR scheme: with and without Vivaldi and horn concentrator (see Fig. 8), additionally a round horn concentrator with the same opening angle can be studied. Having in mind that in the real experiment the transverse size of the THz pulse is limited, streaking efficiency dependencies on the transverse resonator structure size L for these options are shown in Fig. 9. Tere, the horn opening angle equals to 20° and the Vivaldi antenna parameters are adjusted to obtain the same length.

As it had been shown in [4], for the basic ISRR option there is almost no efficiency dependence on L. At

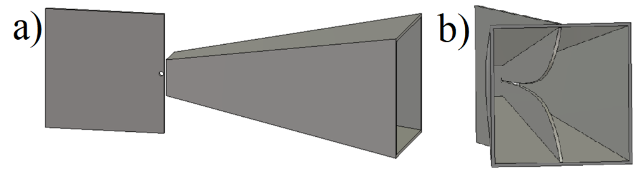

Figure 8: ISRR modifications: horn concentrator (a); integrated Vivaldi antenna and horn concentrator (b).

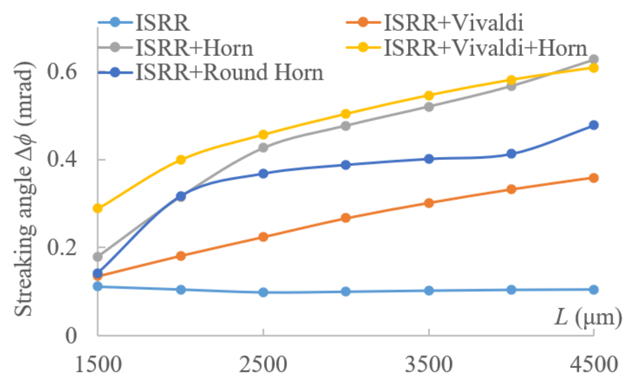

Figure 9: Streaking power dependencies on the transverse dimension L for different improvement options.

$L \approx 4500\ \mu$m Vivaldi antenna provides up to 3 times enhancement, while horn antenna up to 6 times and almost the same amount for the combined option. The latter one is the most difficult to manufacture, therefore its usage is not reasonable.

CONCLUSION AND OUTLOOK

Two different resonator design options for the TDS experiment have been investigated in the previous papers (ISRR and TSR) [4, 8]. In the present paper two improvement options for the ISRR scheme have been studied (Vivaldi antenna and horn concentrator, as well as their combination). The former option may provide up to 3 times streaking efficiency enhancement and has the advantage that the Vivaldi antenna can be produced by laser cutting similarly to a simple ISRR. The latter option may provide up to 6 times enhancement (and potentially even more because the efficiency is limited only by admissible horn length). The combination of both schemes does not provide a significant advantage over the horn concentrator alone.

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