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RESONATOR DESIGN OPTIMIZATION FOR A COMPACT TRANSVERSE-DEFLECTING SYSTEM

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Abstract

Various design options have been studied and simulated using CST MICROWAVE STUDIO for a compact transverse-deflecting system (TDS) proposed for diagnostics of extremely short electron bunches. The idea of the method is to use terahertz (THz) radiation, produced from optical rectification of the facility's photoinjector laser. The proposed system is being commissioned at the test facility FLUTE (Ferninfrarot Linac- und Test-Experiment) at the Karlsruhe Institute of Technology (KIT).

The present work is focused on the simulations of the resonator used to amplify the streaking electric field. Two types of resonators and their arrays have been studied for this purpose: inverse split-ring and tilted slit resonator. Different types of THz pulse structure have been studied, including plane wave and transversally focused (Gaussian) beam. Useful analytical models have been proposed to systematize the results of the simulations.

INTRODUCTION

The main goal of the Compact TDS experiment at FLUTE [1, 2] is to develop an instrumentation for studying the longitudinal profile of ultrashort electron bunches. This will be implemented using streaking (transforming a longitudinal particle distribution into a transversal one). Conventional streaking devices are based on cavities with an externally generated streaking field. One advantage of the present experiment is to use the same laser pulse both for the generation of the electron bunch and the streaking field. For this purpose, 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 (LiN) crystal and used as the streaking pulse. This scheme allows usage of much more compact devices to provide an interaction between the electron bunch and the streaking pulse. The interaction is organized using a resonator structure of ~1 mm size (see Fig. 1). The detailed scheme together with the optical table design is presented in Ref. [3].

Such a technique allows studying longitudinal structure of ultrashort electron bunches of down to single-digit femtosecond length. Moreover, it provides an intrinsic synchronization between the electron beam and the THz pulse because they use the same source. After development of a working setup, it can be of interest for other linear facilities such as FELBE, FLASH, or European XFEL.

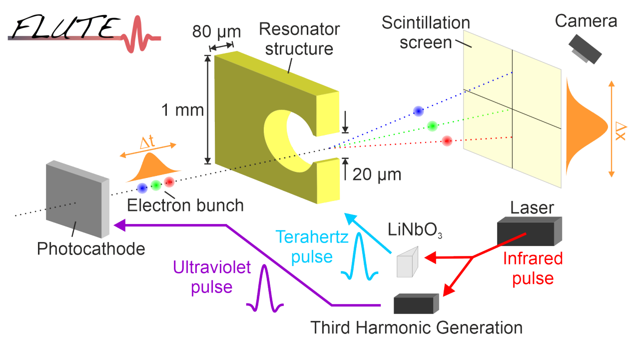

Figure 1: Scheme of the compact transverse-deflecting system (TDS) at the FLUTE facility.

RESONATOR GEOMETRY AND MATERIAL

Two different resonator design options have been used in simulations [4]: inverse split-ring resonator (ISRR) and tilted-slit resonator (TSR). The former had been initially proposed in Refs. [5, 6], the latter in Ref. [7]. Their shape and basic geometrical parameters are presented in Figs. 2 and 3, respectively.

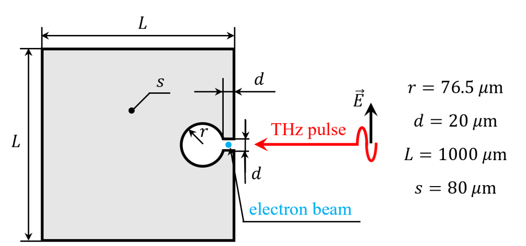

Figure 2: Inverse split-ring resonator (ISRR) geometry.

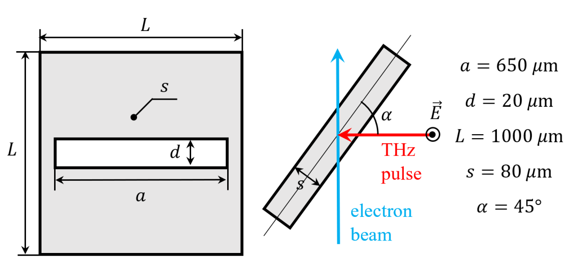

Figure 3: Tilted slit resonator (TSR) geometry.

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The resonator geometry defines two properties important for the experiment: resonance frequency f_{res} (corresponding to the spectral maximum of the response signal in the center of the resonator gap) and amplification coefficient K (a ratio between the maximal field of the response signal and excitation pulse). In Ref. [4] we derived their dependencies on the geometrical parameters and the following scaling laws have been found:

$$f_{res}[\mathrm{THz}] \approx 15\,/\,r[\mu\mathrm{m}]\,, \quad K \approx 140\,/\,d[\mu\mathrm{m}] \qquad (1)$$

for ISRR, and

$$f_{res}[\mathrm{THz}] \approx 145\,/\,a[\mu\mathrm{m}]\,, \quad K \approx 50\,/\,d[\mu\mathrm{m}] \qquad (2)$$

for TSR. They allow adjustment of the resonance frequency to the spectral maximum of the excitation signal, as well as finding a compromise between streaking efficiency and electron beam losses. A TSR provides lower K for the same gap height, but it has the advantage of a natural aperture, which blocks non-streaked electrons.

Total streaking angle of an electron bunch of a unit length was taken as a measure of the streaking efficiency in the subsequent plots. A Python script has been developed to calculate the streaking efficiency using the results of the CST MICROWAVE STUDIO simulations [8].

To check the effect of the resonator material, the streaking efficiency for an ISRR with variable thickness and material has been calculated (see Fig. 4). The effect of the resonator material turned out to be negligible, as long as its conductivity is much higher than that of the surrounding vacuum.

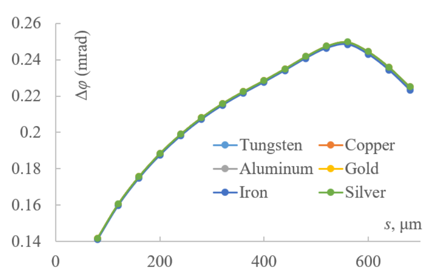

Figure 4: Effect of an ISRR material.

EXCITATION SIGNALS

Measured Spectrum and Gaussian Pulses

The THz pulse spectrum measured using THz bandpass filters is shown in Fig. 5(a). The spectral maximum can be seen at 0.2–0.3 THz. Even though this is only a preliminary, coarse measurement of the spectrum, it shows that the spectrum is asymmetric. Initially a Gaussian pulse shape has been used as an excitation signal with the frequency ranging from 0.1 THz to 1.0, 0.8, 0.6 and 0.4 THz, respectively (see Fig. 5(b)) [4].

To take the asymmetry into account we used a polynomial fit of the measured excitation pulse. However, this lead only to an increased number of periods with non-negligible amplitude in the response signal in the center of the resonator gap. During the parameter optimization this lead to an additional adjustment step (to choose which zero-crossing of the response signal meets the center of the electron bunch).

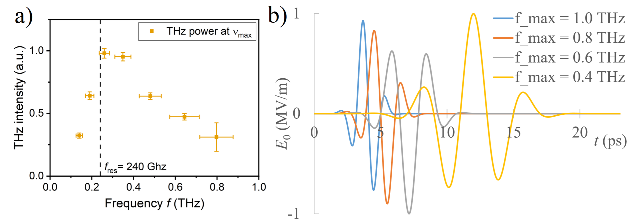

Figure 5: Measured excitation pulse spectrum (a) and Gaussian excitation pulses in time domain (b).

In Fig. 6 the results of the ISRR thickness optimization [4] are shown (for a Gaussian excitation pulse), together with the same results for the measured pulse (dotted lines). It can be seen that different zero-crossings should be chosen for different thickness values. However, the envelope of the dotted lines is close to the one which would correspond to a Gaussian excitation pulse with frequencies from 0.1 THz to ~0.5 THz. Therefore, usage of a Gaussian excitation pulse is acceptable in simulations.

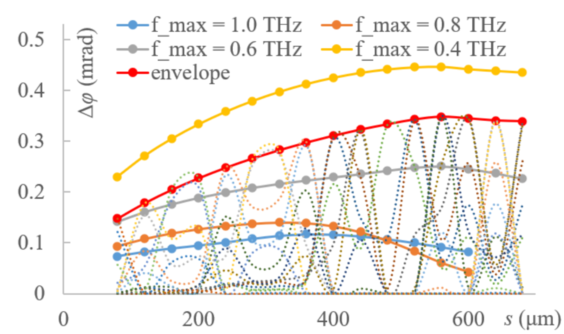

Figure 6: Streaking efficiency $\Delta\varphi$ vs ISRR thickness for various excitation pulse shapes. Solid lines correspond to Gaussian pulses. Dotted lines correspond to different timing values of the electron bunch w.r.t. the measured excitation pulse.

Multi-Period Excitation Signals

To efficiently streak an electron beam with a single resonator, only one slope of the excitation field can be used. However, one idea to improve the streaking efficiency is using an array of multiple resonators, it has been already proposed in Ref. [6]. However, a different generation technique of the initial laser pulse (before splitting it into photoinjector- and THz-arm) is needed for efficient usage of a resonator array. A technique utilizing large-area periodically-poled lithium niobate wafer stacks described in Ref. [9] can be used for this purpose.

According to the example signal shapes presented in Ref. [9], a reference multi-period excitation signal shape has been defined for further simulations of resonator arrays (see Fig. 7). It is a sine wave weighted by a trapezoidal pulse.

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It has the following parameters: frequency, amplitude and the number of periods.

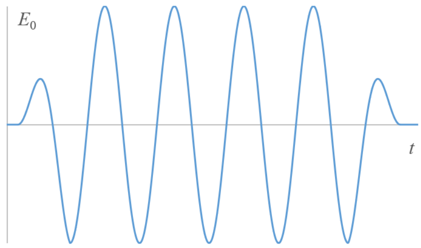

Figure 7: An example of a multi-period excitation signal.

Transverse Signal Structure

The first simulations have been performed for a transversely infinite plane wave taken as an excitation signal, where only the temporal structure of the pulse has been studied [4]. However, in the experiment the excitation THz pulse has a round shape with a Gaussian profile and transverse size about 1 mm at the resonator position. CST MICROWAVE STUDIO allows simulating Gaussian beam sources with adjustable parameters. This feature becomes extremely important for simulation of the resonator arrays, which is described in the next section.

RESONATOR ARRAYS

If the excitation signal has enough number of periods with steep slopes of sufficient amplitude, then it may make sense to use an array of resonators to amplify streaking efficiency. In case of N ISRR's of thickness s and spacing A between centers, the streaking field along the electron beam path can be expressed in the following way (ISRR array is excited with a plane wave of frequency $\omega = 2\pi f$ and amplitude E_0):

$$E(t,z) = \begin{cases} E_0 \sin \omega t, & z \in [nA - s/2; nA + s/2]\,,\ n = 1 \ldots N, \\ 0, & \text{otherwise}\,. \end{cases} \tag{3}$$

Then the streaking efficiency $\Delta\varphi_N$ for an array of N ISRR's can be expressed as follows:

$$\begin{aligned} \Delta\varphi_1 &= \frac{4E_0}{\omega} \left| \sin \frac{\omega s}{2c} \sin \frac{\omega l}{2c} \right|, \\ \Delta\varphi_2 &= \frac{4E_0}{\omega} \left| \sin \frac{\omega s}{2c} \sin \frac{\omega l}{2c} \left(2\cos \frac{\omega A}{2c} + 1 \right) \right|, \\ \Delta\varphi_3 &= \frac{4E_0}{\omega} \left| \sin \frac{\omega s}{2c} \sin \frac{\omega l}{2c} \left(4\cos^2 \frac{\omega A}{2c} + 2\cos \frac{\omega A}{2c} - 1 \right) \right|, \\ &\ldots \\ \Delta\varphi_N &= \frac{4E_0}{\omega} \left| \sin \frac{\omega s}{2c} \sin \frac{\omega l}{2c} \right| F_N\left(\frac{\omega A}{2c} \right), \end{aligned} \tag{4}$$

where l is the electron bunch length, c is the speed of light. The form factor F_N is shown in Fig. 8 together with the envelope F_{env}:

$$F_{\mathrm{env}}(x) = \left| \frac{1}{\sin(x/2)} \right|, \quad x = \frac{\omega A}{2c}\,. \tag{5}$$

Then the position and the amplitude of the first side maximum can be found as follows:

$$A_* = c/f \approx 865\,\mu\text{m}, \quad (F_N)_{\max} = N\,. \tag{6}$$

This means that, in case of an optimal spacing between the resonators, their effect is additive, as expected. The optimal spacing value A_* is given for the spectral maximum of the measured THz pulse spectrum.

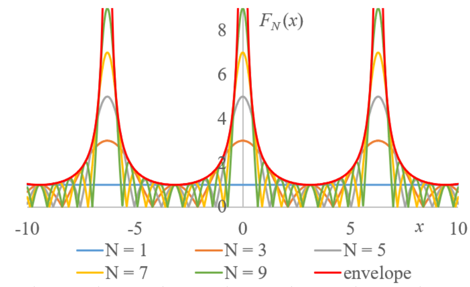

Figure 8: Streaking efficiency form factor F_N for various ISRR number N in an array.

The calculations above have been performed for a plane wave excitation pulse. However, for the case of a Gaussian beam its transverse size w at the focus plane plays an important role. The streaking efficiency for a 5-ISRR array and transversally focused excitation pulse as a function of w is shown in Fig. 9. The optimal w value is around 700 µm,

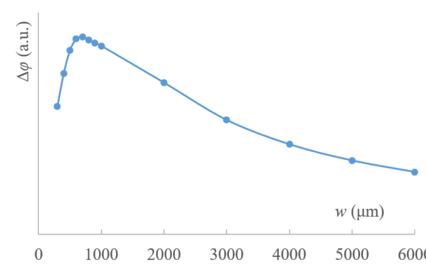

Figure 9: Streaking efficiency $\Delta\varphi$ for various transverse excitation pulse size.

which is close to the optimal resonator spacing A_*, as well as to the measured THz beam diameter. It is therefore difficult to excite several resonators with one THz beam of the size currently used at FLUTE simultaneously. In this case, a single resonator is more efficient than an array.

CONCLUSION AND OUTLOOK

The next optimization step of the resonator design for the Compact TDS experiment at FLUTE has been carried out. A compromise solution has been found between increasing the streaking efficiency and minimizing electron beam losses. The planned experimental strategy has been updated to utilize both main design options (ISRR and TSR).

Choice of metal for resonator production does not affect the streaking properties. Also, in case of a single excitation THz beam with the size currently used at FLUTE, an array of resonators does not lead to an increase in the streaking efficiency due to the required minimal spacing between the resonators.

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