EXPERIMENT DESIGN FOR BEAM-BASED CHARACTERIZATION OF A SUB-THZ DOUBLE BEND MODE CONVERTER

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Abstract

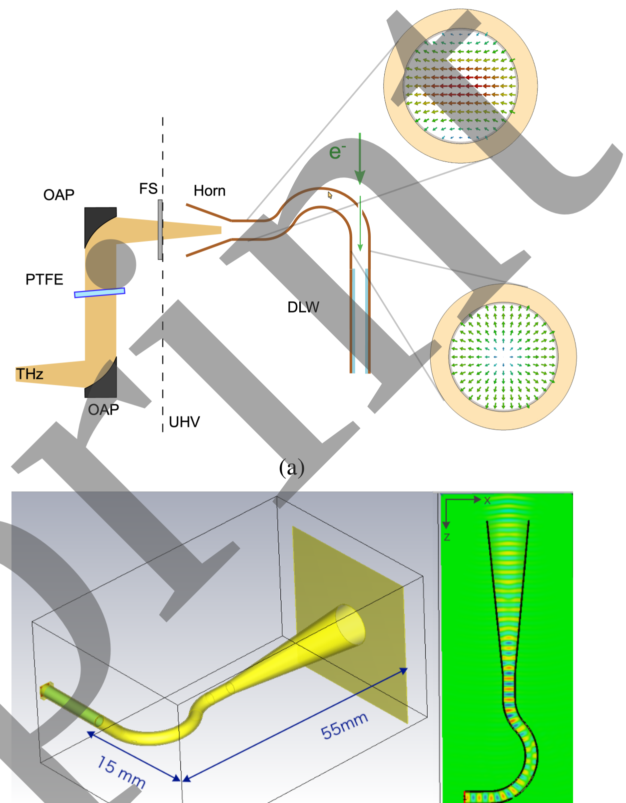
Laser-based high power THz generation advances rapidly, enabling THz-driven electron acceleration beyond the breakdown limits of conventional RF-driven structures. For this purpose the polarization of the externally coupled THz pulse has to match the required TM_{01} mode. Vice versa, beam-driven high power THz generation also relies on the TM_{01} mode and requires efficient out-coupling and transport. A crucial step in both applications is the conversion between the fundamental mode, and the TM_{01} in a compact manner, which can be achieved efficiently in a double bend geometry.

However, the double bend mode converter is fully integrated with the chained neighbouring devices. The embedding imposes challenges on the independent characterization of the converter, especially due to the strict tolerances. Utilising the wake field excited by an externally injected electron beam reduces the de-embedding complexity due to the requirements for THz in-coupling. Following tolerance studies, a beam-based experiment at ARES at DESY is proposed to study the conversion quality of the mode converter at 165 GHz, the design frequency envisioned for the TWAC project. The wake-driven excitation enables a wideband characterization around the design frequency.

A gently compressed (≈1 ps rms) high charge (≈50 pC) electron bunch is passed through a dielectric loaded waveguide, thereby exciting the TM_{01} mode. The out-coupled, sub-μJ THz pulse will be polarization filtered to determine the relative mode content between the residual unconverted TM_{01} and the expected TE_{11}.

INTRODUCTION

Cylindrical dielectric loaded waveguides (DLW) are of major interest for both externally driven THz structures for acceleration and manipulation of electron bunches, as well as for beam-driven THz generation for external applications [1]. While the fundamental TE_{11}-like hybrid mode enables transverse deflecting structures for current profile characterization [2], the TM_{01} mode is utilized for acceleration and compression, and predominantly excited by the wake. In both cases coupling of the THz pulse between freespace and waveguide is preferably done with a fundamental linearly polarized Gaussian to lower the requirements for the THz radiation transport in comparison to higher order Gaussians. An integrated mode converter has been proposed [3] which converts the TE_{11} mode to the TM_{01} by curvature of the waveguide. However, the mechanical tolerances require a detailed characterization of the mode conversion performance to potentially correct or compensate for design mismatches.



(a) (b)

Figure 1: (a) Schematic of in-coupling from a free space THz beam into a metallic waveguide, followed by the mode converter and finally the dielectric loaded waveguide for THz acceleration. (b) Corresponding CAD representation for time-domain electromagnetic simulations in CST Studio Suite, and in-plane field pattern E_x at 165 GHz.

Here, the double bend mode converter is scaled to 165 GHz [4] to match the expected frequency for the TWAC project [5], and embedded with the horn antenna for free-space coupling and the dielectric loaded waveguide as linac, as shown in Fig. 1a. To study the mode conversion a beam-driven experiment is proposed at ARES [6] which is based on the excitation, out-coupling and detection of the THz wake. A preliminary working point has been set up to estimate the detectable THz pulse energy.

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Table 1: Structure Parameters of the Integrated Components

Mode Converter		
Waveguide radius	b_{metal}	1.091 mm
1st bend radius	R_1	8.0 mm
angle	θ_1	43°
2nd bend radius	R_2	8.182 mm
Pinhole	r_p	0.37 mm
DLW		
Inner radius	a_{dlw}	0.913 mm
Outer radius	b_{dlw}	1.091 mm
Dielectric Permittivity	ε_r	3.81
Length	l_{dlw}	50 mm
Horn antenna		
Horn axial length	l_h	30 mm
Flare angle	θ_h	5.5°
Horn aperture radius	a_h	4 mm

TOLERANCES AND FULL STRUCTURE DESIGN

To quantify critical parameters for mechanical tolerances a sensitivity study in CST Studio Suite [7] is conducted with respect to the geometrical parameters of the double bend. The nominal design values are listed in Table 1. Waveguide radius b, radii of curvature R_1 and R_2 of the two bends, the bending angle θ_1 and pinhole size r_p are varied relative to their design value, and their influence of the unconverted transmission S-parameter $|S_{21}^{(\text{TE}_{11})}|$ at the design frequency is studied. Figure 2 shows the local dependence on the five geometrical parameters, revealing that b_{metal} is the most sensitive parameter, assuming a variation of ±10 µm. The dependence is asymmetric, restricting toleration towards smaller b_{metal}. While this tolerance can easily be met with modern CNC milling, potential drilling and bending methods have to be discarded. The second most sensitive parameter is the bending angle θ_1 which is varied by ±1°. A variation to larger θ_1 is more tolerable than to smaller values. Over the full sensitivity parameter range the transmission in the converted mode $|S_{21}^{(\text{TM}_{01})}|$ varies only −0.45 dB and −0.45 dB, showing that THz-electron interaction in the TM_{01} is barely affected. Only deteriorative interaction with the TE_{11} mode is critical with respect to machining tolerances.

Figure 1b shows the electromagnetic model of the full structure, including horn antenna and the DLW, which is simulated with the time domain finite-integration method in CST Studio Suite. An external linearly polarized Gaussian beam is excited which propagates towards the horn antenna. The full structure covers free space-to-waveguide coupling, TE_{11}-to-TM_{01} mode conversion, dissipation in Copper, losses at the pinhole, and propagation through the DLW. The Gaussian beam and antenna parameters have been chosen based on the optimal coupling condition [8] (beam radius $w(z)$ to horn aperture radius a_h ratio of 0.768). The transmission F-parameter in TM_{01} reaches −1.30 dB (74 %) at the outgoing port. Preliminary studies on the Gaussian beam parameters result in little variation in the transmission coefficient, but require more in-depth analysis, currently limited due to the high computational effort.

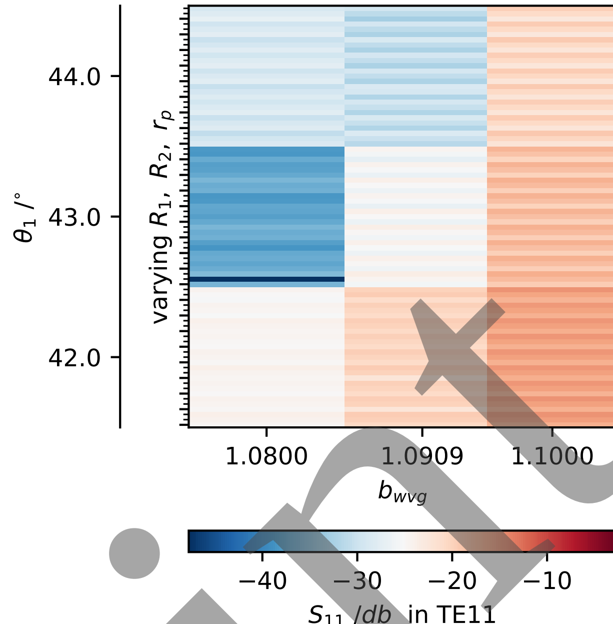

Figure 2: Sensitivity in the unconverted transmission S_{21} in TE_{11} at 165 GHz with respect to geometrical parameters. The design value is −30 dB. r_p, R_1, R_2 were varied around the nominal value by ±0.01 mm, ±0.02 mm, ±0.01 mm, respectively.

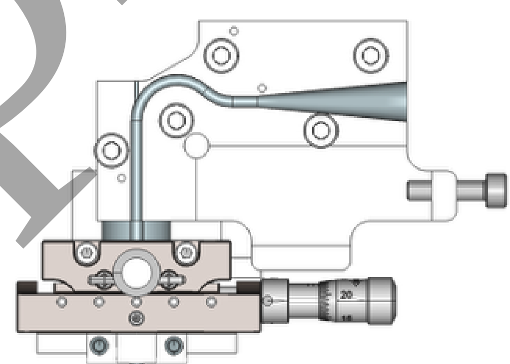

Figure 3: CAD view onto the bottom split-block, embedding the lower half waveguide-like structure.

MECHANICAL DESIGN AND PLANNED CHARACTERIZATION EXPERIMENTS

Based on the tolerance study a split-block design is chosen for machining based on CNC milling. The waveguide cross section is split and each half is high-precision milled into the surface of a copper block. Figure 3 shows the bottom half block into which the hollow structure geometry is embedded.

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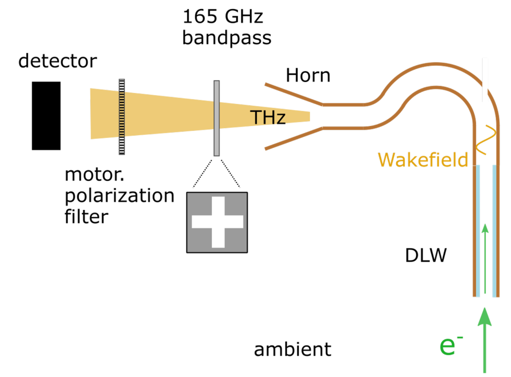

Figure 4: Schematic of the planned beam-based experiment for the structure characterization. (not to scale)

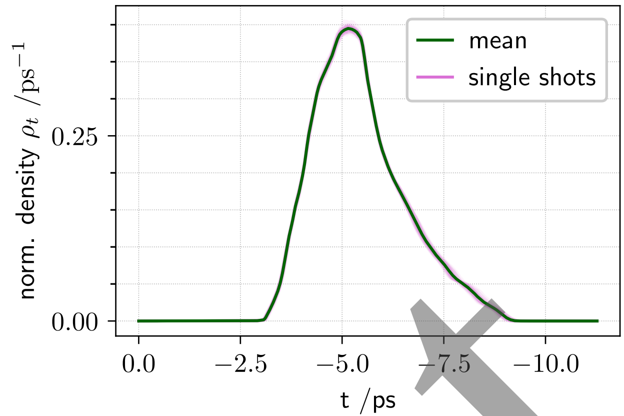

Figure 5: Longitudinal bunch profile measured with the PolariX TDS at one zero crossing.

The two half blocks are precision aligned by alignment pins. The DLW is mounted in a V-groove slot on a precision, open-aperture XY stage for alignment with the mode converter.

To study the mode conversion performance a beam-driven experiment is planned in the in-air experimental section at ARES [6]. ARES is a highly versatile R&D test facility at DESY, delivering up to 155 MeV/c bunches accelerated by an S-Band gun and two travelling wave structures, for the generation of ultra-short bunches with high stability to develop advanced diagnostics and explore new applications. Figure 4 outlines the experiment design planned at the in-air experimental station. Instead of injecting the electrons through the pinhole for co-propagation with an externally in-coupled THz pulse, a high charge bunch is injected from the opposite side, excites a significant wake whose spectral content is dominated by the TM_{01} mode, which is further converted to TE_{11} and out-coupled at the antenna. Remaining higher order spectral content is filtered out by a cross-bar type bandpass filter. A motorized polarization filter in front of the THz detector will enable the performance evaluation of the mode conversion.

A preliminary unoptimized high charge, compression working point is set up at ARES with 95 pC bunch charge at 105 MeV/c. The longitudinal profile is measured by the PolariX transverse deflecting structure [9, 10], reaching $\sigma_t = (1.0 \pm 0.1)$ ps rms, Fig. 5. The bunch is transported to and extracted at the Titanium foil at the in-air section where its transverse beam profile is measured. This indicates that roughly 50 % of the charge will be enclosed by the hollow aperture of the DLW from Table 1. Based on simulations using the wakefield solver in CST Studio Suite [7], and complementary *ECHO2D* [11], the wake carries ≈0.6 µJ. Applying the previous coupling study results and the transmission through the 165 GHz filter (40 GHz bandwidth at −3 dB), the conservatively estimated THz energy at the detector is ≈0.2 µJ, which is very well measurable with pyroelectric detectors, for instance Gentec-EO THZ9B-BL-DA-D0.

CONCLUSION AND OUTLOOK

The full coupling and conversion performance of the integrated mode converter structure has been simulated, and the tolerances for the mechanical design of the converter have been deduced from electromagnetic simulations. However, the expected conversion performance requires an experimental verification for which a beam-based experiment has been outlined. THz Detector requirements have been deduced from experimental beam parameters and structure geometry. The herein applied velocity bunching limits the achievable peak current due to strong space-charge forces. This will be mitigated by magnetic compression [12] which allows for higher peak current and, thereby, higher THz pulse energy. For proper quantification of the current profile at the structure potential bunch lengthening due to scattering has to be studied in simulations. Following the wake-based characterization a complementary measurement is planned on the basis of a CW THz spectroscopy setup. Tunability of the structure is also explored, firstly in simulations, and subsequently on the characterization experiment. Finally, the compact mode converter will replace a collinear coupling scheme on the final TWAC prototype [5], and support efficient THz-driven electron acceleration.

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