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EFFICIENT, HIGH POWER TERAHERTZ RADIATION OUTCOUPLING FROM A BEAM DRIVEN DIELECTRIC WAKEFIELD ACCELERATOR

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Abstract

Wakefields generated from dielectric structures driven by relativistic beams have demonstrated utility for high-gradient acceleration, phase space manipulation, and generation of THz radiation. The produced THz radiation is also useful to probe the electromagnetic fields during the dielectric wakefield acceleration (DWA) interaction. However, effective diagnostics requires effectively out-coupling of the radiation into free space for transport to appropriate interferometry diagnostics. We conducted simulations using CST Studio for a 10 GeV electron beam with FACET-II parameters in a slab-symmetric dielectric waveguide with the goal of optimizing the collected radiation signal. We studied various termination geometries including unperturbed, top-bottom offset, metallic horn antenna, and Vlasov-style antenna. Simulations indicate that the Vlasov-style antenna geometry, defined by an angled termination of bare material, is optimal. Detailed parametric studies were conducted on a variety of dielectric materials including quartz, diamond, and silicon. The coherent Cherenkov radiation (CCR) for the various cases was also computed as a function of beam ellipticity, for both symmetric and asymmetric drive beams.

INTRODUCTION

Dielectric wakefield acceleration (DWA) is a promising candidate for next generation high-gradient accelerators. In DWA, a relativistic electron bunch drives wakefields in a dielectric material which are used to accelerate a second trailing bunch. The acceleration gradient and frequency are dependent on the structure geometry, dielectric material, and drive beam parameters. DWA provides a unique approach to achieving the luminosity, efficiency, and cost requirements of future linear colliders and x-ray light sources. Novel THz driven structures are a promising alternative to conventional radio frequency accelerating structures due to their ability to achieve high gradients in simple form factors [1].

In practical implementations, planar (or Cartesian) geometries provide advantages over cylindrical structures in terms of tunability of modal content, albeit at reduced fields. In this regard, highly asymmetric emittance ratios, or flat beams, are important as they couple less favorably to higher-order modes and thus lead to fewer instabilities during the acceleration process [2, 3]. The proper outcoupling and detection of the emitted radiation spectrum is vital to understanding the finer details of accelerating and deflecting modes in a structure. Further, the discovery of high-field induced conductivity in dielectrics, also explored at FACET [1], suggests the use of advanced structure geometries and materials to enhance modal confinement. Investigations in this regard rely on precise measurement and analysis of the emitted radiation spectrum.

In this paper, we review various methods for outcoupling the radiation to external diagnostics. The optimization of radiation capture is also critical for future applications in dielectric-based, high-power THz sources [4]. A Vlasov-style antenna is a commonly used mode converter that is composed of a cylindrical waveguide with a shaped end [5]. The sidelobe generation, gain reduction, and inefficient power loading in Vlasov antennas make these modes unsuitable for driving conventional antennas. The wakefields of an ultra-relativistic electron bunch excite electromagnetic modes in a dielectric material that are classified as Coherent Cerenkov radiation (CCR). These modes depend on the index of refraction, $n = \sqrt{\epsilon_r}$, where ϵ_r is the relative permittivity. Because of the near-zero refractive index of dielectric materials used in DWAs, highly-directive beams can be realized.

We simulated DWA structures based on various materials including diamond, silicon, and quartz, all of which are coated with an outer metal layer to form dielectric lined waveguides. Diamond is an attractive material in DWA research because it has a low loss-tangent in the THz frequencies, a high thermal diffusivity, and also exhibits high breakdown thresholds. We report the results of the simulation studies of the radiation generated by electron beams for different structures and materials with particular attention to the scenario of the FACET-II E-321 DWA experiment [6, 7].

SIMULATION SETUP

In this computational study employing CST MWS [8] we considered a planar structure model, which consists of an ideally conductive external wall and a lossless internal dielectric coating. The waveguide is a rectangular metallic waveguide with two identical quartz, diamond and silicon slabs loaded on the top and bottom with a metal layering on

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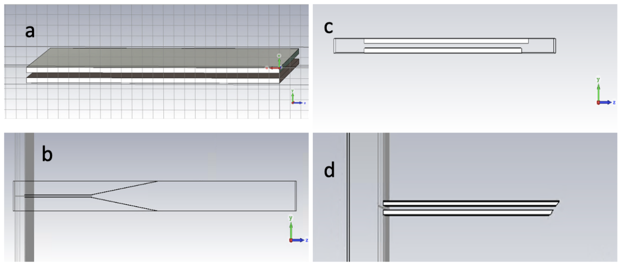

Figure 1: (a) is the uncut structure with parameters as shown in Table 1. (b) is the metal horn structure. (c) is the top-bottom offset structure. (d) is the Vlasov-style angled cut.

Table 1: Parameters Relevant to DWA Experiments at FACET-II

Parameter	Value	Unit
Structure		
Structure length	12	mm
$\text{Length}_{\text{horn}}$	12	mm
Metal thickness	0.01	mm
Dielectric Gap	0.24	mm
Dielectric thickness	0.24/0.1/0.076/0.05	mm
Width	12	mm
Sim. duration	100	ps
Flat/Spherical Beam		
Q	2	nC
E	10	GeV
$\sigma_{x,y}$	300, 10/100, 100	µm
σ_z	10/100	µm
$\epsilon_{nx,ny}$	3.8	µm

the outer sides of the dielectrics. An electron beam of energy 10 GeV was injected parallel to the structure, through the center, and propagated for 100 ps. The termination reference geometries are shown in Fig. 1 and the parameters of the structures and beam are in Table 1.

In CST MWS the time domain solver is used to obtain electric field distributions in the whole geometric domain. We used the Particle-in-cell solver for calculating the dynamics of charged particles. Our simulation used a working model of a widely used dielectric wakefield accelerator. With this model, we calculated the radiation for various terminations of the structure including metallic horns, Vlasov-style antennae, top-bottom offset, and without termination (i.e. uncut).

The simulations were performed for both flat and spherical beams parameters given in Table 1. A series of Vlasov-type, high-power microwave launchers were investigated with several slant cut angles. This study was repeated for different angles of the horn and the radiation pattern and gain were recorded.

ANALYSIS

The electric field was calculated using the probes feature in CST. The simulated electric field was resolved spatially and temporally. The fundamental frequencies for different thicknesses were calculated by performing a fast Fourier transform on the electric field. Simulations were performed for flat beams in planar structure with the results are shown in Fig. 2. The dielectric material used for this study was quartz with dielectrics gap of 240 µm. The reference structure chosen had a Vlasov cut of $\theta = 50°$ at the termination. These results show that more modes were excited when beams with smaller σ_z passed through the same structure. The greatest value for σ_z chosen was 100 µm and smallest was 10 µm, while all other parameters are shown in Table 1. More directed farfield radiation was generated for the Vlasov-style cut and top-bottom offset structures than for the metal horn or uncut structures as shown in Fig. 3.

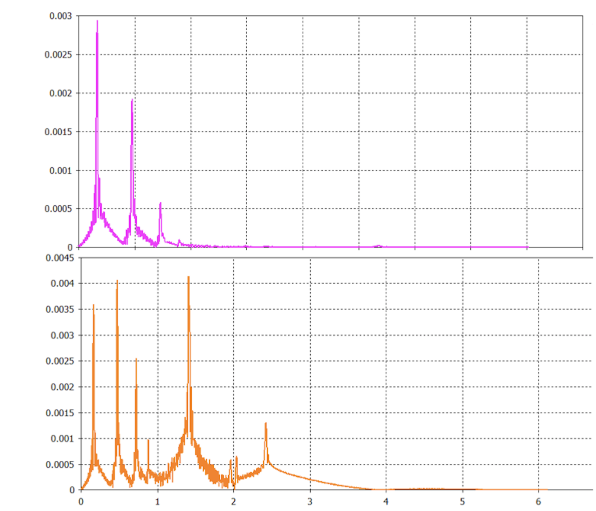

Figure 2: (Top): Spectral gain curve for σ_z was 100 µm, (Bottom): Spectral gain curve for σ_z was 10 µm.

Transverse mode coupling can lead to beam breakup (BBU) effects [9]. We studied both symmetric and asymmetric beams in slab structures and found that while the symmetric beam deteriorated significantly over a distance of 30 cm, the asymmetric beam was relatively stable, with the transverse spot size σ growing to 11.2 µm from 10.4 µm at the beginning [10].

In Fig. 3, we see that there is side lobe radiation generation only in the case of the Vlasov cut and offset structures. In the other two geometries, metal horn and uncut, radiation is not directional due to abundant reflection, i.e. impedance mismatch. This is an issue when trying to capture the radiation using waveguides.

For all the structures, we calculated the farfield radiation at their fundamental frequencies. One goal of research at FACET-II is to study the effects of deflection modes. The optimization study was done at different angles for all the structures. We noticed that the gain increases as we de-

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Table 2: Gain in dB at Different Angles for Different Structures

Thickness	**Uncut (45°)**	**Offset (45°)**	**Horn (8.5°)**	**Horn (5°)**	**Horn (10°)**	**Horn (2°)**
240 µm	3.26	3.05	6	3	2	1.7
100 µm	6.25	8.58	11	6.4	6	6.1
76 µm	7.82	11.8	14	40	18.6	10
50 µm	11.5	24.3	17	15	30	15
			Vlasov cut			
Thickness	59.33°	30.67°	50°	40°	70°	45°
240 µm	5.2	6	10.2	7.8	4	5.4
100 µm	18.9	14	20.1	16.1	17.5	16
76 µm	29.6	22.1	27.1	22	25	25
50 µm	38.4	36	44.7	40	35	47

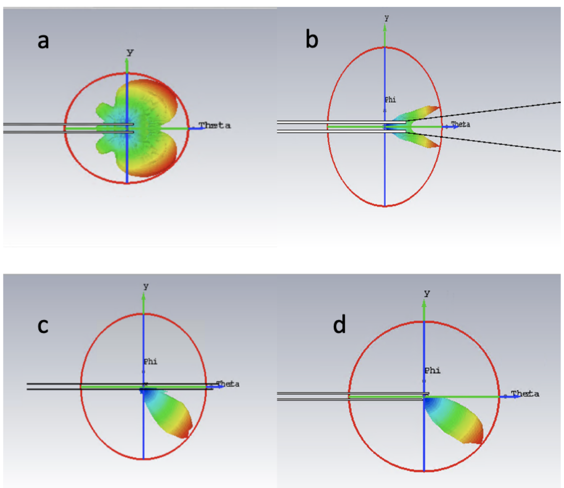

Figure 3: Farfield radiation angular distribution (a): metal horn structure, (b): uncut structure, (c): offset structure, (d): Vlasov cut structure.

crease the thickness of the dielectric from 240 microns to 50 microns.

The proposed antenna results in increased antenna gain. The electric field is more directional, in the direction of the cut, and radiation decreases for cut angles going from 55 degrees to 35 degrees. Table 2 shows radiation plots for the different frequencies, giving an easy reference of the angles and gain. The specific angle cut for the dielectric structure aids in the control of the diverging THz beam and ultimately directs the radiation forward [5]. The produced THz radiation is useful to probe the electromagnetic fields during the dielectric wakefield acceleration (DWA) interaction because the electric fields that actually are the wakefield leak out the end of the tube as THz radiation. By measuring them and reconstructing the temporal profile of these THz waves, we can infer the longitudinal wakefield profile. The outcoupling only changes the spatial distribution so we don't waste energy going to places that aren't our detector. The temporal profile should be basically unchanged by any "antenna".

One of the planned experiments for FACET-II involves testing DWA structures with the goals of characterizing the emitted CCR, determining achievable field gradients, and demonstrating high gradient acceleration [11]. We will perform CCR autocorrelation, after extraction and transport to the interferometer, to determine the spectral content and reconstruct the wakefield. At FACET-II E-321 this will be achieved using a THz interferometer and pyro-electric detector setup [12].

CONCLUSION

DWA is already a useful tool for accelerator applications such as THz sources, beam phase space manipulation [13, 14], and diagnostics. Demonstration of GV/m fields at FACET using DWA raised new questions such as wakefield damping, BBU control, photonic structures and new materials [15]. FACET-II will represent a significant advance in DWA research with its high quality beams permitting tests on long structures, staged acceleration, bunch shaping, and bunch train operation.

In this paper, different ways of outcoupling radiation were investigated. The proposed antenna resulted in increased antenna gain and good performance in terms of sidelobe level. Electric fields of GV/m can be produced by the passage of electron beams through these structures, which have transverse dimensions on the order of a few millimeters. This optimization will prove useful for the practical design of the experimental diagnostics. After studying the four structures, we concluded that a Vlasov antenna is most optimal for high power radiation collection.

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