A SLAB DIELECTRIC STRUCTURE AS A SOURCE OF WAKEFIELD ACCELERATION AND THZ CHERENKOV RADIATION GENERATION

Diktys Stratakis#, Gerard Andonian, Xuan Wei, James B. Rosenzweig, University of California, Los Angeles, CA 90095, U.S.A.

Abstract

Acceleration of electrons in wakefields set up by a series of drive bunches in a dielectric structure has been proposed as a possible component of next-generation accelerators. Here, we discuss future experimental work with a slab sub-millimeter dielectric loaded accelerator structure that in contrast to conventional dielectric tubes should diminish the effects of transverse wakes and will permit higher total charge to be accelerated. The proposed experiment will allow the generation of unprecedented peak power at THz frequencies. In addition, it can generate ~50-150 MV/m drive fields and thus will allow the testing of acceleration using witness and drive beams. We examine details of the geometry and composition of the structures to be used in the experiment.

INTRODUCTION

Conventional accelerators, based on metallic resonant cavities scale unfavorably to high gradients due to the need of simultaneously scale the power sources to higher frequencies. As the resonant structures are scaled to higher gradients/ frequencies and hence smaller dimensions, the fabrication tolerances become increasingly smaller and beyond state-of-the-art. On the other hand, acceleration of electrons in wakefields set up by a series of drive bunches in a dielectric structure has shown promise as the basis for a linear accelerator in which large acceleration gradients can be achieved [1-3]. This concept is attractive since it would not require rf power to be injected into the structure from an external source, but rather would use wakefields set up by injected bunches obtained from a conventional low energy rf linac. In addition, dielectric wakefield accelerators (DWA) have attracted significant attention to applications as advanced THz light sources, in either single or multi-mode. This method for generating coherent THz pulses, known as coherent Cerenkov radiation (CCR) yields not only quite high peak power, but can also give very narrow line widths [4].

The dielectric structure considered under the present study is shown in Fig. 1. It consists of a planar hollow dielectric slab coated on the outer surface with metal to form a dielectric lined waveguide. As a high energy electron beam is passing through the slab it generates CCR that is confined to a discrete set of modes due to the waveguide boundaries. As we will demonstrate numerically later this coherent excitation process offers a simple and effective energy conversion scheme, allowing creation of sources producing unprecedented peak power at THz frequencies.

A planar dielectric structure [5, 6] is attractive because of the following aspects:

- Tuning: the operating parameters of the dielectric slab can be easily adjusted by moving the side walls inwards/outwards, if clearance is provided between each dielectric slab and the adjacent side wall.
- Stored energy: at a certain frequency for a given gradient the rectangular waveguide can store more energy than a cylindrical one, thus beam loading can be reduced;
- Focusing: in the beam channel, the EM field is not uniform transversely, so there exist transverse forces on a relativistic beam, which is able to provide a focusing force that acts on the beam, serving as a magnetic quadruple, while the beam is being accelerated or decelerated.

The primary motivation of our proposed experimental work is to investigate the possibility of using a sub-millimeter dielectric slab as wakefield accelerator and as a source of coherent Cherenkov radiation in the terahertz regime. We plan to use the beam currently available at the ATF at BNL. The nominal beam parameters for ATF are the ones used in our simulation and are shown in Table 1.

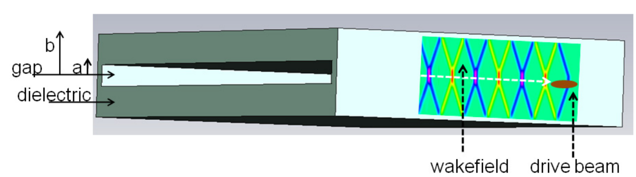

Figure 1: Conceptual drawing of the dielectric wakefield accelerator. A “drive” beam excites wakefields in the slab, while a subsequent “witness” beam (not shown) would be accelerated by the reflected wakefields (band of color).

THEORY AND SIMULATION

An ultravistic electron beam bunch travels in the hollow channel along the axis of the slab, exciting modes in the structure via Cherenkov radiation that superimpose to create a wakefield traveling with a phase velocity equal to the velocity of the bunch. The wakefield of the n th mode excited in the structure can be approximated by [7]

$$\cot[\frac{2\pi}{\lambda_n}\sqrt{\varepsilon-1}(b-a)] = \frac{2\pi}{\lambda_n}a\frac{\sqrt{\varepsilon-1}}{\varepsilon} \qquad (1)$$

where n is the mode number and a and b are the half width of the gap and the height of the structure. For simplicity we assume that the slab is infinite in the other direction. The dielectric constant is defined by ε. The magnitude of the decelerating field produced in the

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#diktys@physics.ucla.edu

dielectric structure is given approximately by the simple formula

$$E_{z,dec} = \frac{Q_l}{2\varepsilon_0\left(a + 2\pi\sigma_z \dfrac{\varepsilon_r}{\sqrt{\varepsilon_r - 1}}\right)} \qquad (2)$$

where σ_z is the rms bunch size, a is the half-width of the gap size, Q_l is beam line-charge (along the "infinite" direction) and ε_r is the relative permittivity.

Table 1: Beam Parameters

	σ_z (μm)	σ_r (μm)	Q(pC)	E (MeV)
ATF	50-250	40	50	60

The use of simulations gives us a variety of tools for understanding the physics of designing and analyzing the proposed DWA experiments. For this task we will use the particle-in-cell code OOPIC Pro. The beam parameters used in our simulation are shown in Table 1.We also note that for all our studies the dielectric material is assumed to be quartz (SiO_2) with ε_r=3.8.

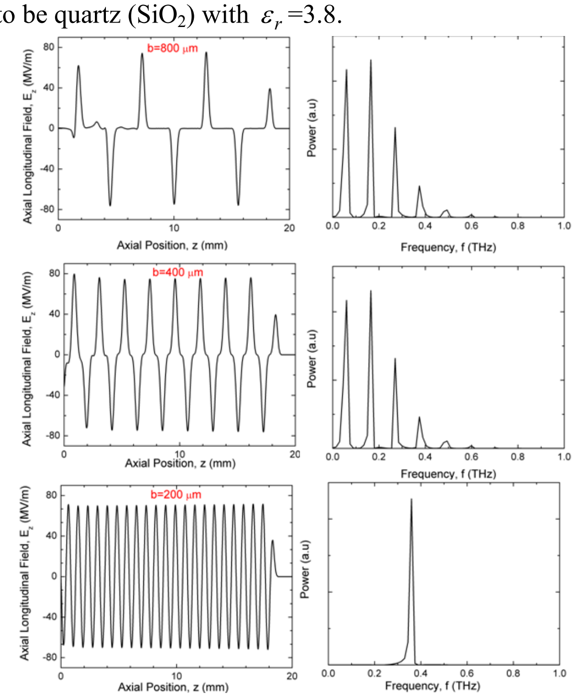

Figure 2: OOPIC simulation of a slab DWA for different dielectric thicknesses: Left: Longitudinal accelerating field. Right: corresponding frequency spectrum.

Parametric scans where conducted with OOPIC with the purpose of gaining a picture of how the peak accelerating field and wakefield of the emitted radiation change as the slab dimensions and beam properties are varied. An example is shown in Fig. 2 where a design study of the slab structure is illustrated, taking as free parameter the thickness of the dielectric. In the simulation, the slab half-width of the gap is kept fixed at a=100 μm. The left column displays the longitudinal field. For b=200 μm it becomes perfectly sinusoidal indicating that a single mode frequency mode is excited in the structure. This fact is confirmed in the right column where the power spectra is calculated from the field plots.

The axial electric field is shown for varying values of the pulse width in Fig. 3. For the simulation we assume a=100 μm and b=400 μm and Eq. (1) predicts a TM_{01} mode for λ=2190 μm. The loss of coherence is clearly seen as the bunch length $\sigma_z \leq \lambda / 2\pi$. Another interesting fact is that the accelerating field scales as $1/\sigma_z$. This fact is in agreement with Eq. (2) and suggests that the pulse width can significantly influence the acceleration of the beam.

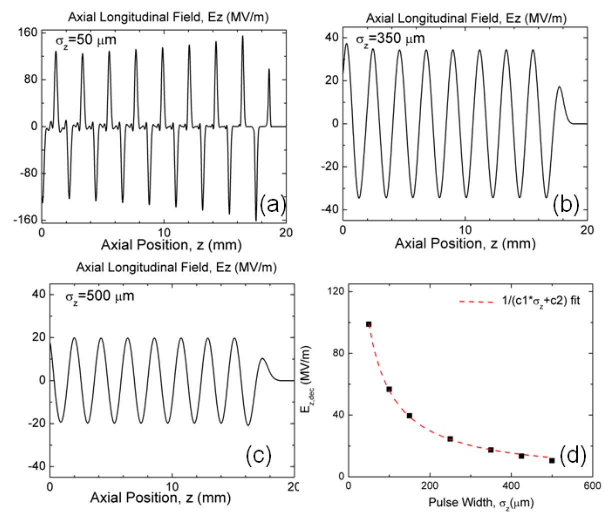

Figure 3: OOPIC simulation of the longitudinal axial accelerating field for a slab DWA for different pulse width,σ_z. The parameters a and b are set fixed at 100 μm and 400 μm respectively.

In Fig. 4(a) we plot the wavelength of the excited fundamental mode for different slab heights, b. The squares are data obtained by taking the discrete Fourier transform of the longitudinal axial electric field while the solid lines are obtained from Eq. (1). As in Fig. 2 the half width of the gap is kept fixed at a=100 μm. Figure 4(b) displays the decelerating field seen by the driving electron bunch with the half-width of the gap. Interestingly, and in contrast to tube geometries, there is a weak dependence with that width.

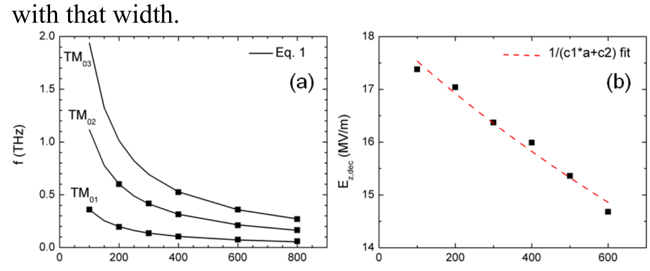

Figure 4: (a) Scaling of mode frequencies with outer radius b, for constant a=100 μm and σ_z=150 μm, and (b) Scaling of decelerating field, seen by the driving bunch with gap size, a.

By carefully examining Eq. (2) we can see that this result is anticipated since the $1/a$ dependence for tubes is replaced by a more complex relation which is more dominated by the pulse width rather the gap size.

EXPERIMENTAL PLANS

One of the preliminary experimental concerns is the geometry of the dielectric slab. This includes the choice of a and b as well as the length of the slab. As detailed in the analysis in the above section the gap size and the slab height determine the wavelength of the CCR emitted. This is central to our experimental goal of producing radiation in the terahertz regime. This requirement, along with our beam parameters and the signal apparatus, governs the possible combinations of gap and height sizes that we may choose. The thickness of the wall of the dielectric slab must be such that the wavelength corresponds to a terahertz frequency according to Eq. (1). At the same time the rms beam radius must be so that the beam can pass through it without damaging the dielectric tube. The slab will be coated at the outer surface by a thin layer of aluminum. Difficulty with this technique arose when it was observed that the electron beam vaporized the aluminum cladding in most cases [8]. We now believe that a dielectric cladding of different refractive index (a Bragg mirror) would provide the necessary reflection while withstanding higher fields than aluminum. Examination of this possibility though extends beyond the present work.

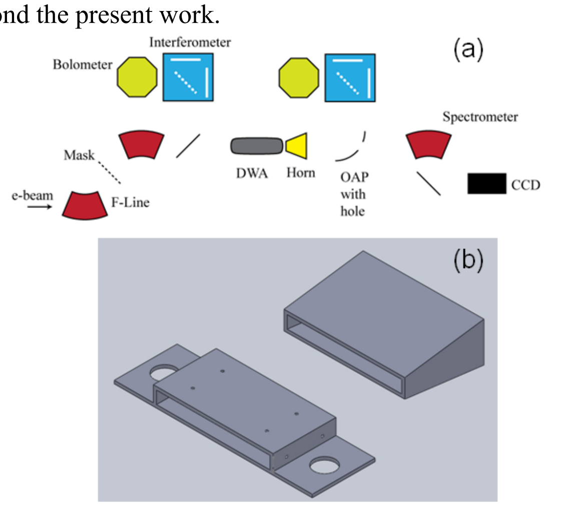

Figure 5: (a) Schematic of the experimental configuration for DWA planned experiment at BNL, and (b) holder and horn for the dielectric slab.

The experiment will be carried out at the ATF at BNL with typical beam parameters shown in Table 1 and Fig. 5 displays the set up. The ATF is a ideal facility as it allows to create pulse trains of adjustable spacing using a wire mask at high dispersion point to notch out portions of the beam. The compressed electron beam once it passes the DWA propagates collinearly with the emitted CCR to a 90 degree of parabolic axis mirror (OAP) where the electron beam is dumped and the radiation collimated out of the vacuum chamber into a detection apparatus. With the aid of a standard Michelson interferometer in conjuction with a cryogenic cooled bolometer measurement of the CCR power spectrum will be accomplished by autocorrelating the radiation pulse and applying discrete Fourier transform analysis to the data. In order to increase the amount of CCR arriving at the detector a launching horn will be placed immediately after the end of the dielectric slab.

Below we list the tasks this experiment wishes to accomplish:

- **Coherent Cherenkov radiation measurements**: Investigations of the THz CCR signal in spectral range will be excited to include harmonics, as an independent measure of the fields in the dielectric.
- **Materials**: A variety of different materials (quartz, diamond) will be studied.
- **Geometry**: Dependence of frequency with material properties
- **Two-beam experiments**: Direct observation of acceleration of witness beam

SUMMARY

The measurements from the ATF experiments would significantly advance the state of knowledge on dielectric wakefield acceleration. By having measured the coherent Cherenkov radiation and having shown direct energy exchange with the beam, these experiments would prove the viability of dielectric tube wakefield accelerators with GV/m accelerating gradients.

Next phase measurements if successful will demonstrate substantial high-gradient acceleration of beam thus opening the possibility of colliders and compact high energy machines based on slab dielectric wakefield structures.

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