STANDING WAKEFIELD ACCELERATOR BASED ON PERIODIC DIELECTRIC STRUCTURES

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Abstract

In recent years dielectric wakefield accelerators (DWA) have attracted significant attention for applications in high energy physics and THz radiation sources. However, one needs sufficiently short driving bunches in order to take advantage of the DWA's scaling characteristics to achieve high gradient and high frequency accelerating fields. Since a single large charge (Q) driving bunch is difficult to be compressed to the needed rms bunch length (σ_z), a driving bunch train with smaller Q and small emittance, should be used instead for the DWA. In view of this senario, the group velocity of the excited wakefields needs to be decreased to nearly zero, so the electromagnetic energy does not vacate the structure during the bunch train. In this paper we propose a standing wakefield accelerator based on periodic dielectric structures, and address the difference between the proposed structure and the conventional DWA.

INTRODUCTION

Acceleration of electrons in wakefields set up by a train of drive bunches in a dielectric structure has shown promise as the basis for a linear accelerator in which large accelerating gradients can be achieved [1-2]. In a conventional DWA, an ultrarelativistic electron bunch travels through the vacuum channel surrounded by an uniform dielectric layer. The electric field of the bunch interacts with the dielectric material to excite Cerenkov wakefields in the structure, shown in Fig. 1. By placing a Gaussian pillbox just inside

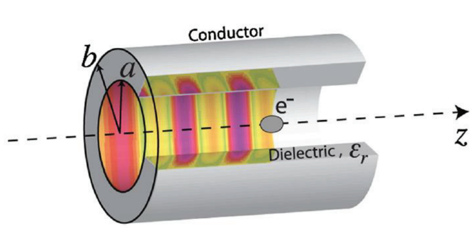

Figure 1: Illustration of a cylindrical DWA. A "driving" bunch excites the wakefields in the dielectric layer, while a following "witness" bunch (not shown) would be accelerated by the wakefields (color bands).

the dielectric layer and enclosing the drive bunch, one can approximate the decelerating field by [3]

$$E_{z,dec} \approx \frac{eN_b}{\pi a \epsilon_0 \left(a + \sqrt{\frac{8\pi}{\epsilon_r - 1}} \epsilon_r \sigma_z \right)} \tag{1}$$

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where a is the inner radius of the dielectric layer, and ϵ_r is the relative dielectric constant. From Eq. (1) we see that for very small σ_z the decelerating field scales approximately with $1/a^2$. This is a powerful scaling characteristic that enables DWA to achieve high gradient fields (GV/m). Resonant excitation of coherent Cerenkov wakefields [4] and breakdown limits [5] in a uniform DWA has been explored experimentally at BNL and UCLA respectively. The eigenmodes excited by an on-axis driving bunch are azumuthally symmetric TM_{0n} modes. The resonant frequencies at which the electron bunch excites are found by solving dispersion relation of the electron bunch, given by

$$\omega = v_b k \tag{2}$$

along with the transcendental dispersion relation for the structure, namely [6]

$$\frac{I_1(k_n a)}{I_0(k_n a)} = \frac{\epsilon_r k_n}{\kappa_n} \frac{J_0(\kappa_n b) Y_1(\kappa_n a) - Y_0(\kappa_n b) J_1(\kappa_n a)}{J_0(\kappa_n b) Y_0(\kappa_n a) - Y_0(\kappa_n b) J_0(\kappa_n a)} \tag{3}$$

where k_n and κ_n are the radial wave numbers in the beam channel and dielectric regions, respectively. The group velocity (v_g) of the wakefield is much slower than the phase velocity ($v_\phi = v_b \approx c$), and it can be computed numerically from

$$v_g = \frac{P}{U_{em}} \tag{4}$$

where P is the total power and U_{em} is the total electromagnetic field energy per unit length. We can visually compare v_g and v_ϕ of the wakefields from the dispersion relation, shown in Fig. 2. The group velocities of the res-

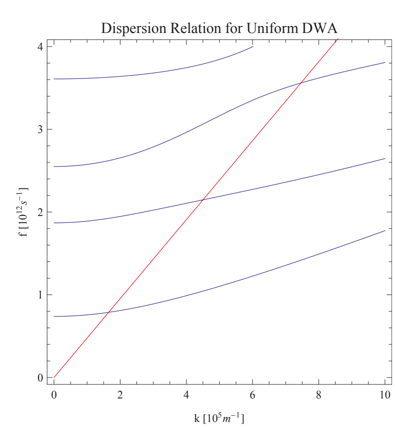

Figure 2: Eq. (2) and the first three modes (TM_{01}, TM_{02}, and TM_{03}) from Eq. (3) are plotted for an uniform DWA.

onant modes are the slopes ($2\pi\partial f/\partial k$) of the dispersion curve at the intersecting points. Fig. 3 illustrates the role of group velocity in the structure. For a given time t, the electron bunch has travelled a distance $v_b t$, exciting Cerenkov wakefield behind it. The total volume behind the driving bunch is not completely filled with radiation because during the same time the wakefield has travelled a distance $v_g t$. In the limit of zero group velocity, both region 1 and 2 will be filled with radiation. For nonzero v_g, region 1 is excluded, leaving only region 2 occupied by wakefields [7]. The primary motivation of our work is to investigate

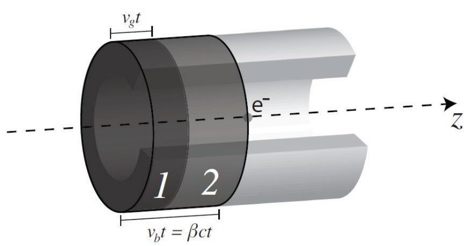

Figure 3: Illustration of the group velocity for a Cerenkov wakefield pulse excited by a relativistic electron bunch.

the possibility of designing a zero group velocity DWA by introducing a periodicity in the dielectric function.

THEORY AND SIMULATION

In order to completely fill the volume behind the driving bunch with wakefields, we introduce a longitudinal periodicity in the dielectric material, namely $\epsilon_r(z) = \epsilon_r(z+d)$, where d is the period. The wakefield will undergo multiple reflections and thereby lowering the group velocity. To treat this problem analytically, we need to solve the Maxwell equation in inhomogeneous media given by [8]

$$\left[\nabla^2 + \epsilon_r k^2\right] E + \nabla\left(E \cdot \nabla \ln \epsilon_r\right) = 0 \qquad (5)$$

the solution to Eq. (5) consists of an infinite sum of spatial harmonics, namely [9]

$$E_z = \sum_{n=-\infty}^{\infty} E_n(y) e^{i(k_z + nK)z} \qquad (6)$$

where $K = 2\pi/d$. A closed form dispersion relation is not possible in this case. High Frequency Structure Simulation (HFSS) was used to obtain an numerical dispersion relation for the case of two alternating layers of dielectric materials, namely

$$\epsilon_r(z) = \begin{cases} \epsilon_{r1} & 0 < z < d_1 \\ \epsilon_{r2} & d_1 < z < d \end{cases} \qquad (7)$$

where $d_1 = \delta d$, and δ is the duty cycle. One period of the simulation structure in HFSS is shown in Fig. 4. Only a fraction of the cylinder is needed for simulation because the TM_{0n} modes are azimuthally symmetric. Propagations in periodic structures exhibit pass bands and stop bands in the dispersion relation. The zero group velocity modes exist at the edge of the bands where the derivative of the dispersion

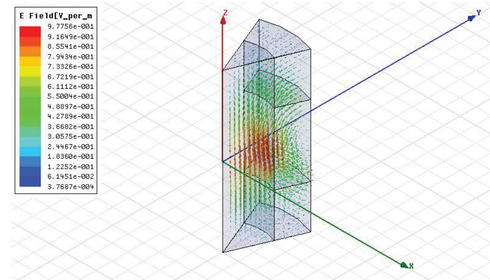

Figure 4: Simulation structure used in HFSS to numerically compute the dispersion relationship for electromagnetic propagation in a periodic dielectric lined waveguide.

curve vanishes. The Optimetrics feature in HFSS is used to vary the structure parameter in order to match the zero group velocity mode to Eq. (2); analytically, this resonant condition is given by

$$\frac{\omega d}{v_b} = kd = \mu \qquad (8)$$

where μ is the phase advance of the wakefield. A standing wave is excited when $\mu = \pi$, as shown in Fig. 5. The structure can be tuned to be single moded given the roll off wavelength condition ($\lambda \geq 2\pi\sigma_z$) for an ideal Gaussian charge distribution is satisfied. Resonant excitation of co-

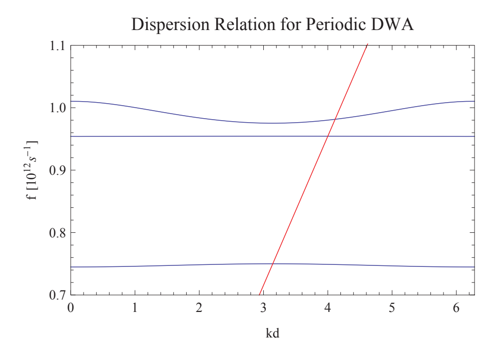

Figure 5: The dispersion relation of the first three TM modes and Eq. (2) are plotted for a periodic DWA.

herent Cerenkov wakefields by a bunch train is simulated for both uniform and periodic DWA using OOPIC. The two simulation senarios are both tuned to coherently radiate at 750 GHz, and the simulation parameters are summarized in Table 1. Fig. 6 and 7 shows the Cerenkov wakefields excited by a four bunch driving train in the uniform and periodic DWA respectively. In the case of the uniform DWA, we see a traveling Cerenkov wakefield only occupying region 2, while leaving region 1 vacant. In the case of periodic DWA, the entire volume behind the drive train is occupied by a standing wakefield oscillating in time with fixed nodes and antinodes. While both wakefields are radiating at the same frequency, we do see noticeable decrease in the field gradient for the case of periodic DWA (∼150 MeV/m as opposed to ∼220 MeV/m).

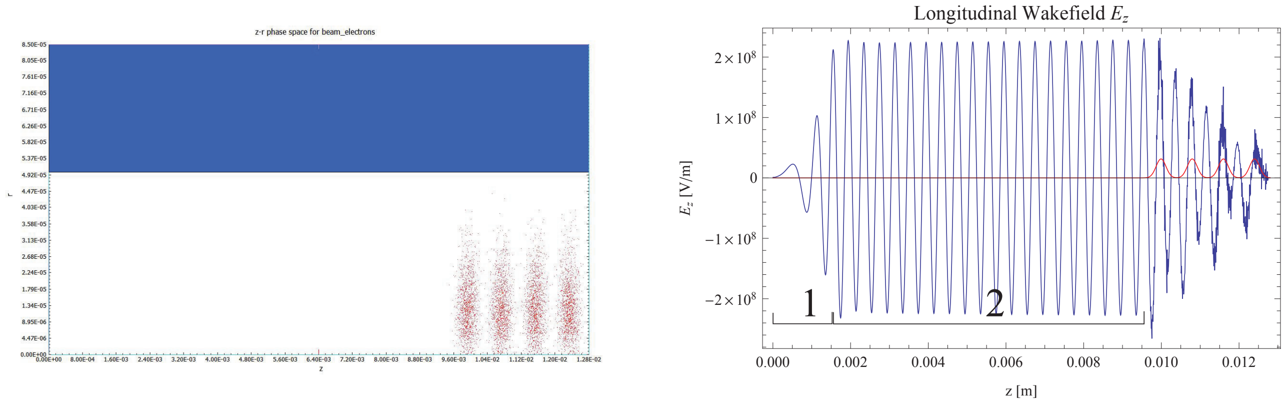

Figure 6: Cerenkov wakefields (blue) excited by a four bi-gaussian bunch train (red) in an uniform DWA.

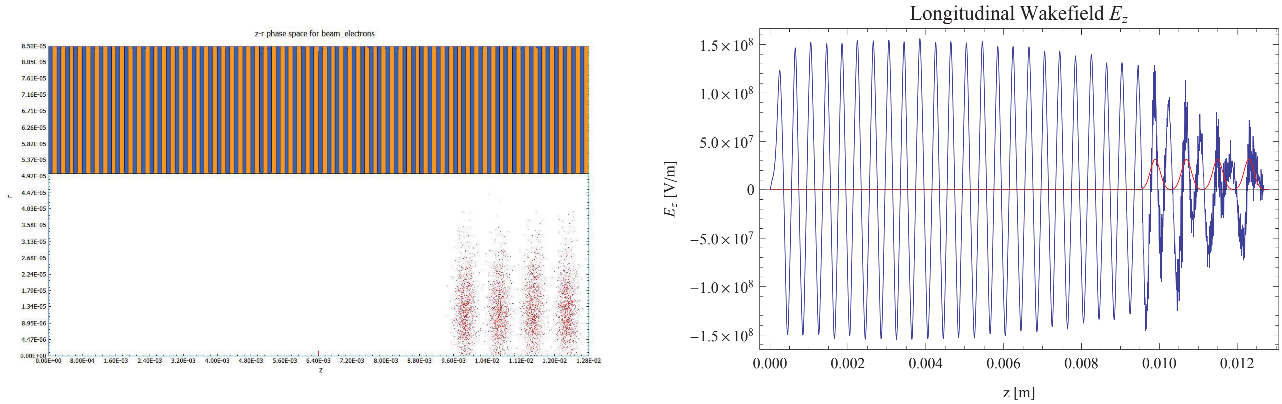

Figure 7: Cerenkov wakefields (blue) excited by a four bi-gaussian bunch train (red) in a periodic DWA.

Table 1: Simulation Parameters.

Bunch charge	Q	250 pC
rms bunch radius	σ_r	15 μm
rms bunch length	σ_z	125 μm
Dielectric inner radius	a	50 μm
Dielectric outer radius	b	85 μm
Bunching spacing	Δ	800 μm
Uniform dielectric constant	ϵ_r	9.8
Periodic dielectric constants	$\epsilon_{r1}, \epsilon_{r2}$	3, 13
Duty cycle	δ	0.45

CONCLUSION

A standing wave DWA based on periodic dielectric structure is proposed and simulated. The dispersion relation is computed numerically using the Optimetrics feature in HFSS, and a zero group velocity Cerenkov wakefield excited by a four bunch train is observed in OOPIC. Theoretical work is currently being done to explore the case of small dielectric contrast in the periodic region and the beam loading effects. For low dielectric contrast structures the fabrication process may be more feasible than a high dielectric contrast structure.

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