Wakefield Simulations for the Laser Acceleration Experiment at SLAC

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Abstract. Laser-driven acceleration in dielectric photonic band gap structures can provide gradients on the order of GeV/m. The small transverse dimension of the structure, on the order of the laser wavelength, presents interesting wakefield-related issues. Higher order modes can seriously degrade beam quality, and a detailed understanding is needed to mitigate such effects. On the other hand, wakefields also provide a direct way to probe the interaction of a relativistic bunch with the synchronous modes supported by the structure. Simulation studies have been carried out as part of the effort to understand the impact on beam dynamics, and to compare with data from beam experiments designed to characterize candidate structures. In this paper, we present simulation results of wakefields excited by a sub-wavelength bunch in optical photonic band gap structures.

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INTRODUCTION

It has long been realized that a laser-driven accelerator would benefit from a commercially available high repetition rate power source that can provide a strong field gradient. Accelerator structures based on dielectric materials are known to have a high breakdown threshold. Photonic band gap (PBG) structures made from dielectrics also benefit from deep industry experience because of telecommunication applications in case of the fiber, and lithographic fabrications in case of the woodpile. Many computer codes are available for detailed calculations of the electromagnetic modes in these structures. An experimental program (E163) is underway at SLAC's NLCTA test facility to investigate several candidate fibers available commercially as well as the woodpile structure under development [1, 2, 3, 4].

Optical PBG structures consist of a periodic lattice of dielectric material surrounding a central "defect" channel with typical transverse dimension on the order of microns. Electromagnetic wave modes, except those in the band-gap region, can propagate freely through the structure. An efficient structure would support a speed-of-the-light mode in the band gap with accelerating fields concentrated in the beam channel.

Wakefields are electromagnetic radiation caused by the interaction between a charged particle beam and its surrounding environment, and are generally left behind the radiating charge, especially for relativistic beams considered here. As the beam traverses an optical PBG structure, the wakefields excited can be severe since the loss of the energy stored in the beam fields is inversely proportional to the channel's radial dimension. The wakefield can act on the bunch itself because of the finite bunch length, or on a nearby trailing bunch. Wakefields polarized in the transverse direction can cause momentum kicks leading to deflection of a trailing particle's trajectory. It is a common cause for head-tail instability and it makes emittance preservation in a long linac a difficult task [1]. Longitudinal wakefields, on the other hand, can lead to change in the beam energy that affects longitudinal dynamics. It is also a factor that limits the amount of charge per bunch that can be accelerated, and must be taken into consideration in the design of an energy-efficient intra-cavity coupled accelerator system [5].

But the wakefield effect can also be exploited to investigate the nature of the accelerating mode, which otherwise would be difficult to access. It is one of the goals of the E163 experiment to measure the spectral properties of the wakefields excited either stochastically by single electrons in long bunches or coherently by sub-wavelength attosecond bunches.

Wakefields in dielectric structures in general, and optical scale structures in particular, have been investigated by many authors. The effects of the short-range wake in a laser-driven dielectric tube have been analyzed using a single resonance dielectric model [6]. The low-frequency component of the impedance was found to be dominant, and that the dielectric constant can be characterized as frequency-independent to a good approximation. Initial wakefield simulations in optical photonic band gap fibers have also been carried out [7]. The aim was to determine the signal-to-noise parameters for experiments designed to probe PBG fiber structures. Studies in the microwave regime have been

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done experimentally [8] and theoretically [9]. The goals of this work are to obtain detailed simulations of wakefields in PBG fiber structures operating in the optical regime to understand the impact on beam dynamics and structure design, and to provide comparisons with E163 measurements.

WAKEFIELD SIMULATIONS USING MAFIA

Wakefield radiation commonly occurs when the shape or the dimension of the conducting beam pipe changes. In the case of a PBG fiber, the dielectric boundary at the inner radius presents a discontinuity to the traveling beam fields, resulting in "Cerenkov" wakes being radiated, even though the beam channel is smooth and continuous. Furthermore, the interaction between the Cerenkov wake and the photonic band gap structure itself results in both an outgoing and a reflected, incoming wave. Wakefields are generally quantified by "wake functions", defined as the energy change or momentum kicks normalized to the bunch charge. Further discussions on the physics of wakefields can be found in [10, 11].

The results presented here were obtained on a desktop computer using the 2D time domain solver "T2" of the MAFIA simulation code [12]. A cylindrically symmetric 1-dimensional PBG dielectric structure was chosen to simplify the computational requirements. Solutions to Maxwell's equations were evaluated numerically on a finite difference lattice. The beam bunch at a given radial offset was modeled as a thin charge ring, which was in turn represented as an infinite sum of multipole moments with cos $m\theta$ angular dependence. It traverses the structure as a rigid, longitudinally Gaussian, charge bunch. In general, the lowest order modes dominate. The longitudinal wakefield is given by the $m = 0$ (monopole) term, and the transverse wakefield is given by the $m = 1$ (dipole) term.

The PBG structure consisted of 24 concentric layers of two types of alternating dielectric materials designed to have the accelerating mode satisfy the Bragg condition [13]. Ideally, with a sufficiently large number of layers, only the accelerating mode is confined in the structure, and all other modes, including the unwanted higher-order modes, can freely propagate out without significant interaction with the beam. The parameters chosen were the dielectric constants ($\varepsilon_1 = 4$, $\varepsilon_2 = 2.1$), the fundamental mode wavelength $\lambda_0 = 1.5\ \mu m$, and the radius of the beam channel $\mathrm{R_{int}} = \lambda_0$. The thicknesses of the inner-most layer, and those of the two alternating layers, were then calculated numerically to generate the cylindrical Bragg structure. The Bragg layers were surrounded by an outer dielectric cladding; the structure is uniform along the beam direction.

The bunch length was chosen to be short enough to excite the fundamental accelerating mode: $\sigma_b = \lambda_0/10$. A single mesh size Δz was used in each simulation run. Even though it was recommended that the mesh size be selected according to the scaling $\Delta z = \sqrt{\sigma_b^3/\mathrm{L_z}}$ for numerical accuracy [14], it would result in a prohibitively large number of grid points. Instead, the simulation was repeated with the mesh size varied, $\Delta z = \sigma_b/10 - \sigma_b/40$, to verify convergence. The structure length was also varied, $\mathrm{L_z} = 30\lambda_0 - 100\lambda_0$, to verify numerical convergence and check for physical effects caused by the finite length. Furthermore, a reference structure, the dielectric waveguide (DWG), was used to check the reliability of the simulation by comparing with analytical calculations.

Wakefields in a Dielectric Waveguide

The transverse (dipole) wake function for an infinitely long DWG with a conducting outer-boundary layer was calculated using the steady-state solution of Ref. [15]. The result was compared to MAFIA simulation of a similar structure, with finite length ($\mathrm{L_z} = 30\lambda_0$) and a short section of conducting beam pipe required for launching the charged beam. Note that MAFIA yields not only the steady-state solution, but also the transient radiation produced as the beam travels from the conducting beam pipe into the dielectric waveguide structure.

The results of transverse wakes normalized to structure length are shown in Figure 1. The analytical result shows the steady-state periodic solution given by a sum of Bessel functions determined by the geometry and boundary condition of the DWG structure. The MAFIA result shows a sharp transient spike rising immediately behind the head of the bunch ($s = 0$). This corresponds to radiative energy loss as the bunch enters the DWG. The transient wake radiates out and travels through the dielectric material at the Cerenkov angle. Trailing particles positioned far behind the bunch, at $s \sim 5\ \mu m$ to $8\ \mu m$ for example, would experience predominantly the steady-state wakefield. Here, in the steady-state regime, the wake functions calculated by these two different methods show excellent agreement in absolute units (V/pC normalized to structure length). At $s \sim 9\ \mu m$, trailing particles would experience a wakefield dominated by the transient wake reflected back from the outer conducting boundary. The separation between the initial and reflected

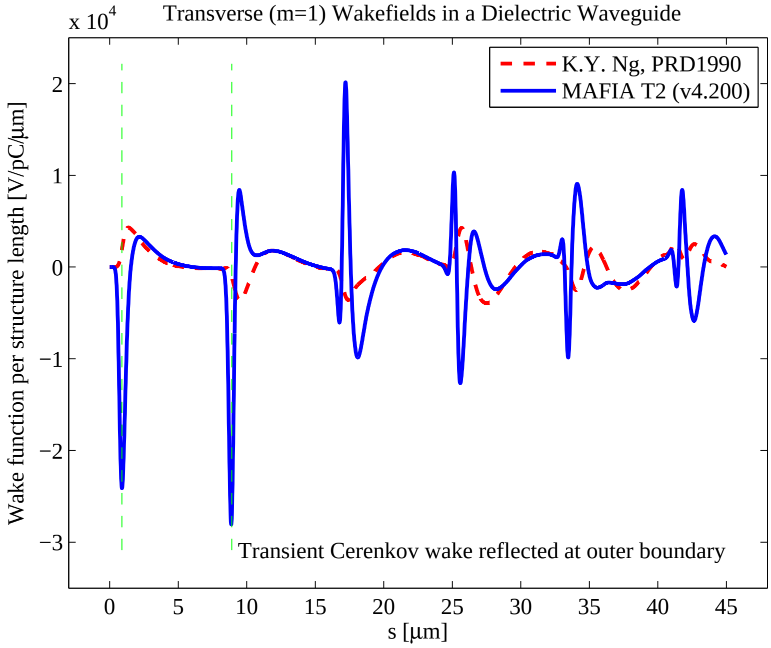

FIGURE 1. Wake functions for a dielectric waveguide, normalized to structure length, as a function of the distance behind the bunch-head: MAFIA vs. analytical calculation. The vertical dashed lines indicate the expected separation between the initial transient pulse and its reflection at the outer conducting boundary.

transient pulses is consistent with expectation given the geometry and the Cerenkov angle. At a distance of the structure length behind the bunch, discrepancy is expected due to wakefields leaking out of the fiber. This effect was included in MAFIA but not in the analytical calculation. Similar results are obtained for an $L_z = 100\lambda_0$ long structure.

Wakefields in a Bragg Fiber

The wakefields in a photonic band gap structure were investigated by simulating a bunched beam traveling through a Bragg fiber. Absorbing boundaries were imposed at the outer radius and at the ends of the fiber. A short conducting beam tube section was required at the entrance to launch the charged beam.

Results of the MAFIA simulations of an $L_z = 30\lambda_0$ Bragg fiber are shown in Figure 2. For the longitudinal (monopole) wakefield calculation, the drive bunch was positioned on axis, and the grid size was chosen to be $\Delta z = \sigma_b/30$. The transverse (dipole) wakefields were obtained with the drive bunch offset radially at the beampipe radius R_{int}, and the grid size was chosen to be $\Delta z = \sigma_b/20$. The transverse wake function for an arbitrary offset r_0 can be obtained using the scaling factor r_0/R_{int}. The wake functions show a transient spike followed by periodic oscillations. For both the longitudinal and transverse wakes, the frequency spectrum show a sharp peak at the design fundamental wavelength. It is superimposed on a broad spectrum associated with beam excitation with a short wavelength cut-off characterized by the bunch length.

It remains to be seen whether this degeneracy is a general feature of the Bragg fiber. It is worth pointing out that a similar degeneracy is observed in a dielectric waveguide when the dielectric layer thickness becomes very small relative to the radial dimensions [15]. The inner most layer of this Bragg structure is very thin, so this degeneracy could be due to the particular set of parameters chosen.

To check for systematic effects in the calculation, the simulation was repeated varying the structure length and/or the mesh size until the results converge. In MAFIA, a separate calculation was needed for each multipole term. Convergence for the transverse (dipole) wakefield calculations was readily achieved. Results for $L_z = 30\lambda_0$ and $L_z = 100\lambda_0$ structures differ only near the end of the fiber when leakage occurred for the shorter structure. Also, the longer structure allowed reflected wake to be included. When the mesh size was varied, no difference was observed

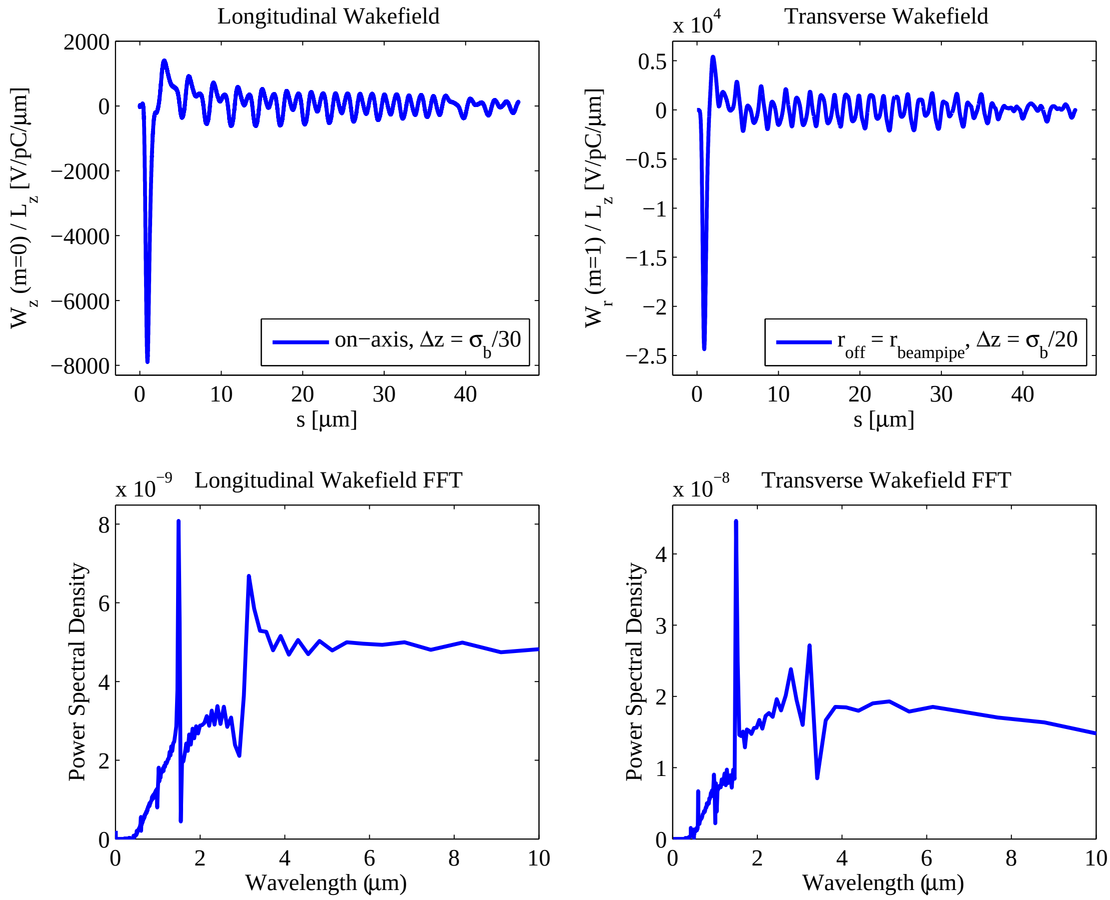

FIGURE 2. Wake functions in a Bragg fiber obtained using MAFIA. The top row shows the longitudinal (monopole) and transverse (dipole) wake functions, normalized to structure length ($L_z = 30\lambda_0$), while the bottom rows shows the corresponding Fourier transforms.

for $\Delta z = \sigma_b/10$ and $\Delta z = \sigma_b/20$.

For the longitudinal (monopole) wakefield, length convergence also occurred at $L_z = 30\lambda_0$. But the mesh size needed to be reduced to the range $\Delta z = \sigma_b/20 - \sigma_b/30$. Otherwise, numerical artefact can be seen in the transient pulse shape. Results of the longitudinal wake functions for $L_z = 30\lambda_0$ and $L_z = 100\lambda_0$ are shown in Figure 3. It appears that the reflected transient pulse decreases at large distance behind the bunch. This indicates that unwanted modes were being radiated away from the structure.

SUMMARY AND OUTLOOK

The presence of wakefields in laser-driven dielectric photonic band gap structures is an important problem considering its effect on beam dynamics and structure design. An initial set of detailed simulations has been completed for a cylindrical Bragg structure. The results indicate that the short-range wake appears manageable. More work is needed to understand long-range wakes and the attenuation of unwanted higher-order modes.

As the next step, 3D time domain calculations are needed to evaluate the wakefields in candidate PBG fibers, such as the HC-1050, to be used in the E163 experiment. Comparison with measurements will yield valuable information on the characteristics of the accelerating mode in photonic band gap structures.

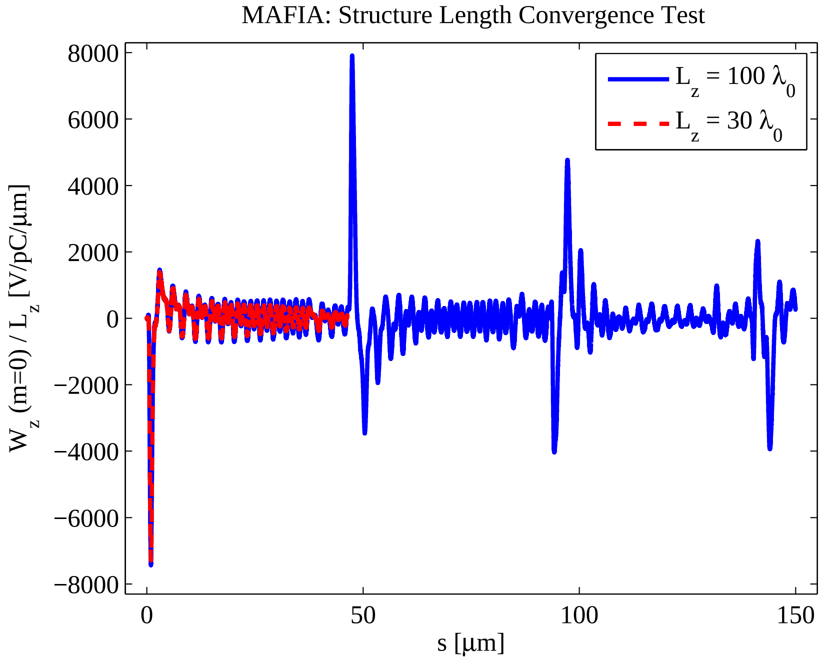

FIGURE 3. Longitudinal (monopole) wakefields in a Bragg fiber obtained using MAFIA for two structure lengths: $30\lambda_0$ and $100\lambda_0$. The reflected transient pulse appears to decrease with distance behind the bunch.

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REFERENCES

1. E. Colby, these proceedings.
2. C. McGuinness, these proceedings.
3. R. Noble, these proceedings.
4. J. England, these proceedings.
5. Y. C. N. Na *et al.*, *Phys. Rev. ST Accel. Beams*, **8**, 031301 (2005).
6. R. H. Siemann and A. W. Chao, in *Proc. 2005 Particle Accelerator Conference, Knoxville, Tennessee*, edited by C. Horak, pp. 1916 – 1918.
7. C. M. S. Sears *et al.*, in *Proc. 2007 Particle Accelerator Conference, Albuquerque, NM*, pp. 3106 – 3108.
8. C. Jing *et al.*, *Phys. Rev. ST Accel. Beams*, **12**, 121302 (2009).
9. G. R. Werner *et al.*, *Phys. Rev. ST Accel. Beams*, **12**, 071301 (2009).
10. A. W. Chao, *Physics of Collective Beam Instabilities in High Energy Accelerators*, John Wiley & Sons, Inc, New York, 1993. (Also available in PDF at http://www.slac.stanford.edu/~achao/wileybook.html.)
11. L. Palumbo *et al.*, *Wake Fields and Impedances*, in CAS Advanced School on Accelerator Physics, Rhodes, Greece, 1994.
12. T. Weiland and R. Wanzenberg, *Wake Fields and Impedances*, in Joint US-CERN Accelerator Course, Hilton Head, South Calorina, 1990. Also see MAFIA-Software, User Manual Version 4.2, CST AG, Darmstadt, Germany.
13. A. Mizrahi and L. Schachter, *Phys. Rev. E*, **70**, 016505 (2004).
14. T. Weiland, in *Handbook of Accelerator Physics and Engineering*, edited by A. W. Chao and M. Tigner, (2002).
15. K. Y. Ng, *Phys. Rev. D*, **42**, No. 5, 1819 (1990).