# Full-scale simulations of dielectric laser-driven accelerators

B. M. Cowan and G. I. Bell
Tech-X Corporation
Boulder, Colorado 80303, USA
Email: benc@txcorp.com

R. J. England, R. J. Noble, E. A. Peralta, and K. Soong
SLAC National Accelerator Laboratory
Menlo Park, California 94025, USA

***Abstract*—Dielectric laser acceleration (DLA) holds great promise for a new class of high-energy charged particle accelerators. Taking advantage of the high field intensities available from laser sources as well as the high damage threshold of dielectric materials, DLAs can attain more than an order of magnitude higher field gradient—energy gain per unit length—than conventional, microwave cavity-based accelerators. However, the design considerations for DLAs have notable differences from those of conventional accelerators. In this presentation, we first present the physics and requirements of DLAs, illustrating many of the principles through designs of photonic crystal waveguide accelerators. We then describe recent results on simulations of grating structures, discussing the simulation techniques and comparison with experiments.**

## I. Introduction

The extraordinary electric fields available from laser systems make laser-driven charged particle acceleration an exciting possibility. However, exploiting these fields requires careful design of accelerating structures. There are several broad requirements for achieving acceleration: First, there must be an electric field parallel to the direction of particle motion; second, the electromagnetic fields must propagate with a phase velocity equal to the particle velocity; and third, the particles must be separated into longitudinal bunches small compared to an optical wavelength, so that the particles all experience an accelerating electric field. The Lawson-Woodward theorem prohibits net energy exchange between a free-space mode and a charged particle, and thus some boundary or other structure is required for particle acceleration. Conventional electromagnetic cavities, simply scaled down from microwave frequencies to the optical regime, would not make effective laser-driven accelerators. One reason is that it is desirable to use dielectric materials rather than metals because of the higher breakdown threshold at optical frequencies. Another is that DLA structures are constrained by the available fabrication methods, which cannot replicate microwave cavity geometries at such a small scale.

Thus, DLA structure design and experimentation has been a major research effort over the last several decades. In an early series of experiments, a free-space mode with a single boundary was used to modulate an unbunched electron beam [1]. The experiment demonstrated the expected linear scaling of energy modulation with laser electric field as well as the expected polarization dependence. In the next phase of that program, an inverse free electron laser (IFEL) was used to optically modulate an electron bunch, and was followed by a chicane to translate the energy modulation into longitudinal modulation [2]. Once the electrons were optically bunched, the boundary used in [1] was placed downstream of the IFEL and chicane. Net acceleration or deceleration was observed, depending on the relative optical phase between the laser pulses driving the IFEL and boundary structure [3].

## II. Photonic crystal structures

Following those successful demonstrations, research turned toward design of structures that could attain acceleration over many Rayleigh lengths of the laser field. Conventional accelerators use coupled-cavity (or disk-loaded) waveguides to control the phase velocity of the EM field and provide the longitudinal electric component. An analogous approach to DLA would employ optical waveguides. Because it is desirable to accelerate highly relativistic particles, index-guided fibers do not suffice because their modes have sub-luminal phase velocity. However, photonic crystals provide a mechanism for confining a speed-of-light mode in an all-dielectric waveguide.

A photonic crystal-based DLA was first proposed and simulated in 2001, employing a photonic crystal fiber [4]. Following that, work was done to design structures amenable to lithographic fabrication, resulting in designs for two-dimensional [5] and three-dimensional [6] structures. The three-dimensional structure is shown with the accelerating mode profile in Fig. 1. For that structure, the geometry was modified to provide a periodic optical focusing scheme for the particle beam; this was shown through particle tracking simulations to be stable over millions of wavelengths.

## III. Grating structures

### A. *Design and experiment*

Several years ago, another broad class of DLA structures was proposed. This class involves a pair of dielectric gratings to shift the phase of an incident transverse pulse with a period of one optical wavelength, providing phase matching to a relativistic particle beam [7]. While this structure does not confine a mode co-propagating with the beam, it has the advantage that it requires fabrication of only a single microstructured layer and a single alignment between the two gratings; in addition, it provides a large aperture in one direction, allowing for

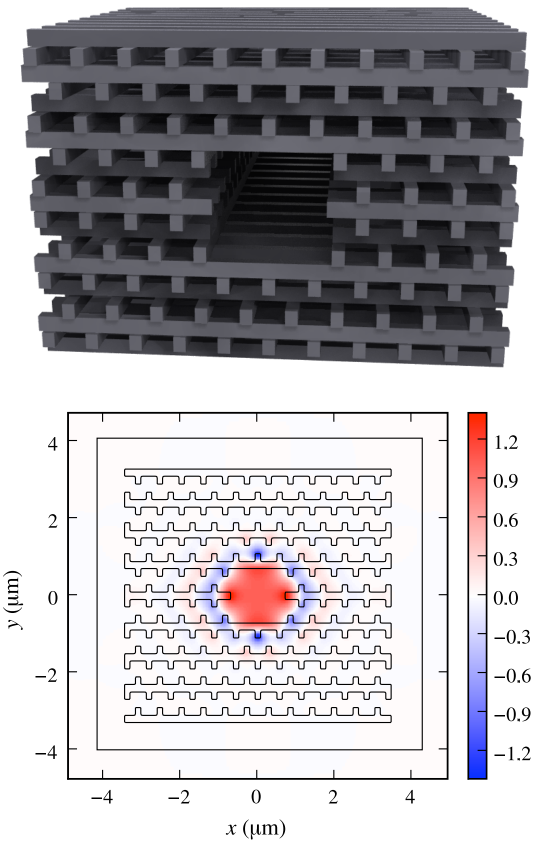


Fig. 1. Top: A schematic of the woodpile accelerating waveguide; bottom: The longitudinal electric field in the accelerating mode.

greater charge throughput than a photonic crystal waveguide. The parameters of this design were studied to optimize the average accelerating gradient.

Recently, experiments at SLAC demonstrated the effectiveness of this structure. Gratings fabricated out of fused silica with an 800 nm period were illuminated with a ps-scale Ti:Sapphire laser pulse. A 60 MeV electron pulse, not optically prebunched, was overlapped in time with the laser pulse. The laser fields in the grating modulated the electron energies, showing accelerating gradients in excess of 250 MeV/m [8].

### *B. Full-scale simulations*

We performed full-scale simulations of the laser fields and particle dynamics using the Vorpal engine in the VSim particle-in-cell code [9]. This technique self-consistently models electromagnetic fields and charged particles, following the particles in continuous phase space, and computing the fields on a Cartesian mesh using the finite-difference time-domain (FDTD) method. We enhanced this method to provide direct particle-material interactions present in this system. In the experiment, only a small fraction of the electrons in the incident bunch actually traverse the 400 nm gap between the gratings. The remainder pass through the silica of the structure; some can be deflected by the laser fields and pass through the structure for part of their trajectory and vacuum for the other

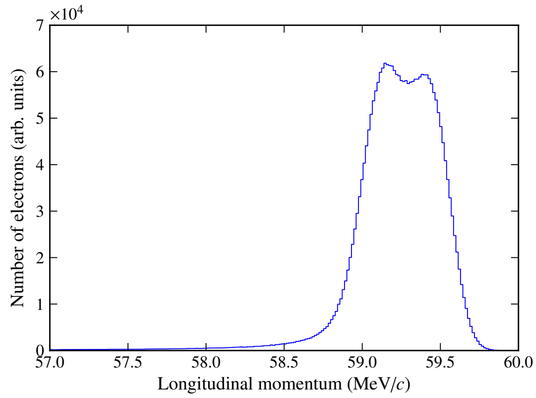


Fig. 2. The spectrum of electrons passing through the grating structure, after modulation by the laser field.

part. We implemented Monte-Carlo methods to model both the bremsstrahlung and the ionization interactions, achieving good agreement with the Geant4 particle interaction code.

Our simulations, covering 1 mm of particle and field interaction with the structure, agreed well with the experimental results; the final electron spectrum is shown in Fig. 2. We also observed that the fields in the structure could result in an optical density modulation of the particles. In this presentation, we discuss our methods and results in detail.

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## References

[1] T. Plettner *et al.*, “Visible-laser acceleration of relativistic electrons in a semi-infinite vacuum,” *Phys. Rev. Lett.*, vol. 95, no. 13, p. 134801, Sep 2005.
[2] C. M. S. Sears *et al.*, “Production and characterization of attosecond electron bunch trains,” *Phys. Rev. ST Accel. Beams*, vol. 11, no. 6, p. 061301, Jun 2008.
[3] ——, “Phase stable net acceleration of electrons from a two-stage optical accelerator,” *Phys. Rev. ST Accel. Beams*, vol. 11, no. 10, p. 101301, Oct 2008.
[4] X. E. Lin, “Photonic band gap fiber accelerator,” *Phys. Rev. ST Accel. Beams*, vol. 4, p. 051301, May 2001.
[5] B. M. Cowan, “Two-dimensional photonic crystal accelerator structures,” *Phys. Rev. ST Accel. Beams*, vol. 6, no. 10, p. 101301, Oct 2003.
[6] ——, “Three-dimensional dielectric photonic crystal structures for laser-driven acceleration,” *Phys. Rev. ST Accel. Beams*, vol. 11, no. 1, p. 011301, Jan 2008.
[7] T. Plettner, P. P. Lu, and R. L. Byer, “Proposed few-optical cycle laser-driven particle accelerator structure,” *Phys. Rev. ST Accel. Beams*, vol. 9, no. 11, p. 111301, Nov 2006.
[8] E. A. Peralta *et al.*, “Demonstration of electron acceleration in a laser-driven dielectric microstructure,” *Nature*, vol. 503, no. 7474, pp. 91–94, 11 2013. [Online]. Available: http://dx.doi.org/10.1038/nature12664
[9] C. Nieter and J. R. Cary, “VORPAL: A versatile plasma simulation code,” *J. Comput. Phys.*, vol. 196, p. 538, 2004.