SLAC−PUB−16887

# Dielectric Laser Acceleration and Focusing Using Short-Pulse Lasers with an Arbitrary Laser Phase Distribution

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**Abstract.** Femtosecond laser pulses can be used to achieve desired $\mathrm{GV\,m^{-1}}$ electron accelerating gradients in dielectric laser accelerator structures. Extending this interaction over a distance exceeding 1 mm may require the use of focusing structures. Using simulations, we motivate a new dielectric laser focusing structure driven by short laser pulses. In contrast to previous dielectric laser accelerator microstructures, the surface of this structure has three heights. Using simulation, we show that this structure has a peak focusing field gradient equivalent to $2.9\ \mathrm{MT\,m^{-1}}$.

## INTRODUCTION

A fundamental feature of modern particle accelerators is the design of periodic lattices incorporating strong focusing elements. Such a scheme enables compact accelerator apertures. Dielectric laser accelerators (DLAs) are one technology for compact, high gradient accelerators, with very compact transverse apertures on the order of $\sim 1\ \mu\mathrm{m}$ [1, 2]. In order to transport charge efficiently through a DLA accelerator longer than 1 mm, transverse focusing elements will be required. Such focusing elements should ideally be compatible with existing laser-driven microaccelerator architectures.

Several conventional schemes could be employed to provide transverse focusing. At subrelativistic energies, Einzel lenses using electrostatic focusing could be employed [3]. Conventional magnetic quadrupoles could either be fabricated from permanent magnets [4] or compact electromagnetic quadrupoles [5] with transverse gradients of order $\sim 1\ \mathrm{kT\,m^{-1}}$. However, since the transverse apertures of DLAs are $\sim 1\ \mu\mathrm{m}$, strong transverse focusing forces of order $\sim 1\ \mathrm{MT\,m^{-1}}$ are required to confine electron beams [3].

The high electric fields of femtosecond laser pulses can be used to power dielectric focusing structures. A focusing method of this type is ideal, from the perspective of making a truly integrated DLA accelerator, owing to its compactness, laser-driven compatibility, and amenability to integrated nanofabrication. In previous work, several focusing structures have been proposed based on laser-driven structures [6, 7, 8] and ponderomotive focusing [9]. In this work, a new laser-driven dielectric focusing structure is proposed. Using simulations, the focusing strength of such a structure is calculated.

## CHECKERBOARD FOCUSING STRUCTURE

A new focusing structure is proposed. The structure is based on a previously proposed deflecting structure [6, 10], with microstructures in dielectric surfaces illuminated symmetrically by two laser beams propagating perpendicular to the electron beam. In contrast to previous DLA structures, this surface has three heights. The structure layout and scale are illustrated in Fig. 1.

*This material is based upon work supported by the U.S. Department of Energy, Office of Science, under Contract No. DE-AC02-76SF00515.*

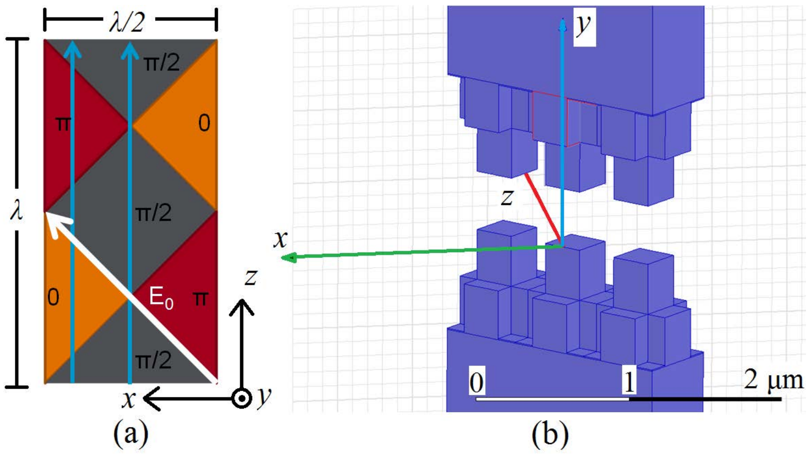


**FIGURE 1.** Checkerboard focusing structure. (a) Schematic of focusing structure, viewed from the direction of propagation of one of the incident laser beams, $-y$. Electron trajectories ($z$-direction) are indicated by the blue vectors. (b) Model of the proposed structure in Ansoft HFSS. Laser wavevectors $k$ are incident in both the $-y$ and $y$ directions (blue vector), and electron trajectories are in the $z$-direction (red vector).

The focusing structure is designed such that an electron traversing the structure experiences a transverse deflecting force proportional to its transverse position in the channel. For relativistic electrons ($\beta \approx 1$), the length of the structure is designed to match the incident laser wavelength. The structure has three pillar heights, dimensioned to impose phase changes of 0 rad, $\pi/2$ rad, and $\pi$ rad at the center of the electron beam channel. The structure is illuminated symmetrically by two laser fields incident in the $y$ direction (from above and below), with linear polarization $E_0$ oriented in the direction indicated by the white vector in Fig. 1(a). The structure was assumed to be fabricated from fused silica ($n \approx 1.5$), with a laser wavelength $\lambda = 800$ nm [11]. Previous work on deflecting structures identified that the deflection force was maximum for a pillar height of $0.85\lambda$ [10]. Hence, in order to impose phase changes of $\pi/2$ and $\pi$, pillar heights of $0.42\lambda$ and $0.85\lambda$, respectively, were selected. An analytical estimate for the pillar height $h$ resulting in a phase change of $\pi$ is given by [12]:

$$h = \frac{\lambda}{2\,(n-1)}, \tag{1}$$

which for the selected wavelength and refractive index yields an optimum pillar height of $h = 1\lambda$. The selected pillar height of $0.85\lambda$ is close to this analytical estimate for optimum pillar height.

## SIMULATIONS

Initial electromagnetic simulations of the focusing structure were performed in Ansoft HFSS [13]. The electron velocity was assumed to be relativistic ($\beta \approx 1$). The transverse force on an electron was evaluated by integrating the electromagnetic fields on an electron across a single period of the structure. At a particular phase of the incident laser, the force on an electron is presented in Fig. 2.

For the phase illustrated in Fig. 2, several limitations on DLA structures can give an estimate on the focusing gradient provided by the structure. Using femtosecond laser pulses, an incident laser field of $E_0 = 1\ \mathrm{GV\,m^{-1}}$ can conservatively be used, below the damage threshold of the fused silica structures, which has been demonstrated for similar accelerating structures to be of the order $\sim 0.8\ \mathrm{J\,cm^{-2}}$ [14]. Evaluating the HFSS simulations, the focusing structure was found to have a peak enhancement factor of $\eta = E_{\mathrm{max}}/E_0 = 1.79$ (ratio of peak electric field in the dielectric material to the incident electric field). The peak focusing gradient $K$ can be estimated as [3]:

$$K = f'\eta E_0, \quad f' = \frac{\mathrm{d}D_0(r)}{\mathrm{d}r}, \tag{2}$$

where $D_0(r) = \langle F_\perp(r)\rangle / E_{\mathrm{max}}$ is the transverse deflection factor evaluated at position $r$ from the device center, and $\langle F_\perp(r)\rangle$ is the average transverse force at position $r$. Inspection of the present simulations yields $f' = 4.9 \times 10^5\ \mathrm{m^{-1}}$,

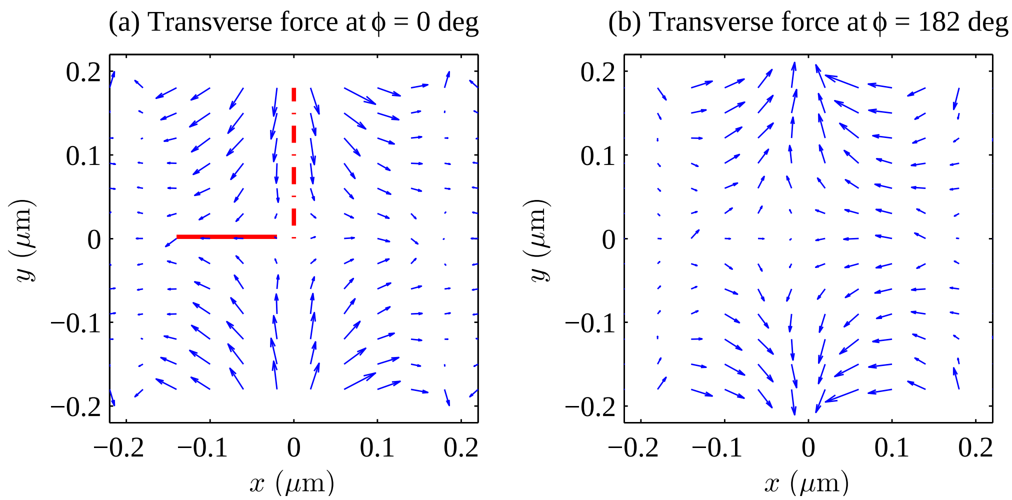


**FIGURE 2.** Calculated transverse force on an electron, arriving at positions in the horizontal coordinate $x$ and the vertical coordinate $y$. The force was determined by integrating the electromagnetic field over a single period of the structure, for an electron arriving at a particular laser wavefront phase. (a) Vertically focusing phase. The vertical focusing gradient evaluated along the red dot-dash line is summarized in Table 1, and the corresponding horizontal gradient evaluated along the solid red line. (b) Vertically defocusing optical phase, 180 deg out of phase with respect to (a).

and $K = 8.7 \times 10^{14}$ V m$^{-2}$. Analogously to the method in Ref. [3], the focusing gradient can be converted to an equivalent magnetic field gradient by $G = K/c = 2.9$ MT m$^{-1}$, where $c$ is the speed of light. This compares favorably with previous laser-driven focusing structures, with a peak focusing gradient of $G = 0.4$ MT m$^{-1}$ [8]. Subsequently, this focusing gradient can be normalized by the electron beam energy such that [3]:

$$G = T^2 \frac{\beta\gamma m_e c}{q_e}, \tag{3}$$

where $m_e$ is the electron rest mass and $q_e$ the electron elementary charge. Normalized values of the focusing gradient, $T^2$, are summarized in Table 1.

**TABLE 1.** Vertical focusing gradient corresponding to Fig. 2(a) (evaluated along dot-dash line), normalized for different electron beam kinetic energies.

| **Kinetic energy (MeV)** | $T^2$ ($10^7$ m$^{-2}$) |
|---|---|
| 4 | 19 |
| 8 | 10 |
| 60 | 1.4 |

Similarly to the vertical focusing gradient, the horizontal defocusing gradient of the structure was also evaluated along the solid red line in Fig. 2(a). Along this horizontal axis, the defocusing gradient was found to be $K = 4.9 \times 10^{14}$ V m$^{-2}$, or equivalently $G = 1.7$ MT m$^{-1}$. This asymmetry (less than a factor of two) between the horizontal and vertical planes is small, and, as such, the device still has horizontal focusing strength sufficient to confine short bunches in narrow DLA apertures [3].

## SUMMARY

In this work, a new dielectric focusing structure was proposed. Using electromagnetic simulations, it was demonstrated that such a structure can be expected to achieve significantly higher focusing gradients than either conventional electrostatic or electromagnetic focusing elements, or previously proposed dielectric focusing structures.

The structure proposed in the present work creates quadrupole-like transverse forces on an electron beam. One desirable feature of the structure is that it can be repeated along the transverse $x$ coordinate. In so doing, multiple electron beams could be accelerated in parallel. This could allow higher charge transport for DLAs.

The structure considered in the present conceptual work has not been thoroughly optimized. In this work, focusing forces were investigated for relativistic electrons. Future studies may consider optimizing the structure for subrelatvistic electron velocities. In addition, future work will consider a full parameter optimization of the proposed structure, including sensitivity of the structure to alignment tolerances.

## ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy under contract number DE-AC02-76SF00515, and by the Gordon and Betty Moore Foundation under grant GBMF4744.

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