DESIGN AND OPTIMISATION OF DIELECTRIC LASER DEFLECTING STRUCTURES*

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Abstract

Recent experimental demonstrations of dielectric laser-driven accelerator structures offer a path to the miniaturisation of accelerators. In order to accelerate particles to higher energies using a staged sequence of accelerating structures, integrating compatible micrometre-scale transverse deflecting structures into these accelerators is necessary. Using simulations, the present work outlines the design and optimisation of a fused-silica laser-driven grating deflecting structure for relativistic electron beams. Implications for device fabrication and experiments are outlined.

INTRODUCTION

The design of conventional particle accelerators is motivated by the Lorentz force, with magnetic fields for the efficient deflection of high energy particles. However, the possibility of transverse electric field gradient of the order 1 GV m^{-1} bypasses the need for magnetic fields for deflecting beams, and opens new options and length scales for accelerator design.

Recent experimental demonstrations of dielectric laser acceleration with electric fields exceeding 300 MeV m^{-1} are presented in Refs. [1–3]. Using ultrafast laser pulses of the order of 100 fs, this can be extended to electric field gradients of 1 GV m^{-1} [4].

The present work outlines electromagnetic simulations of a laser-driven dielectric deflecting structure. An experiment is proposed to demonstrate laser-driven dielectric deflecting structures with relativistic electron beams in a compact undulator.

THEORY

The theory of dielectric grating deflecting structures for relativistic electron beams is described in the previous work of Plettner, et al. [5–7]. Several key parameters can be used to compare dielectric accelerators of differing geometry. The accelerating gradient, denoted by G_0 is given by [8],

$$G_0 = \frac{q}{\lambda} \int_0^{\lambda} E_z[z(t), t] dz, \tag{1}$$

where q is the particle charge, λ is the laser wavelength, and the electric field E_z represents the electric field in the direction of travel of the electron. Similarly, a deflecting field can be denoted by D_0, defined by,

$$D_0 = \frac{q}{\lambda} \int_0^{\lambda} \left[\left(E_x[z(t), t] - cB_y[z(t), t] \right)^2 + \left(E_y[z(t), t] + cB_x[z(t), t] \right)^2 \right]^{\frac{1}{2}} dz, \tag{2}$$

where the electric and magnetic fields of the laser are decomposed into the directions x and y of Fig. 1.

The purpose of the dielectric grating structure is to generate periodic, local oscillations to the incident the electric field. The amplitude of the electric field therefore varies within the structure, with the maximum electric field anywhere in the structure defined as E_{max}. The maximum electric field in the structure determines the maximum incident electric field that the structure will sustain without damage.

One can define the field enhancement factor of a structure as $\eta = E_{\text{max}}/E_0$ [9]. Hence, the acceleration factor f_A (denoted by Plettner, et al. as the damage factor [8]) is given by,

$$f_A = \frac{G_0}{E_{\text{max}}}, \tag{3}$$

and the deflection factor by [9]

$$f_D = \frac{D_0}{E_{\text{max}}}. \tag{4}$$

Given a material with a known damage threshold electric field E_{dam}, the structure accelerating and deflecting fields can be scaled based upon the incident electric field E_0.

STRUCTURE AND LASER

The geometry of the structure simulated in the present work is presented in Fig. 1 below. The structure coordinates are defined in rectangular Cartesian coordinates, with the electron beam propagating in the z direction. The grating is rotated at an angle α about the y axis.

The structure is assumed to be illuminated by a single plane wave source of wavelength λ, propagating with wavevector k in the $-y$ direction, linear polarisation axis perpendicular to the grating and incident electric field E_0. Assuming a relativistic electron beam ($v \approx c$), the grating period in the direction of the electron beam trajectory should satisfy $\lambda_p = \lambda \cos \alpha$ [5].

At the photon wavelength of interest $\lambda = 800$ nm, the index of refraction of fused silica is approximately $n = 1.5$, and the relative permittivity $\varepsilon_r = n^2 = 2.25$ [10].

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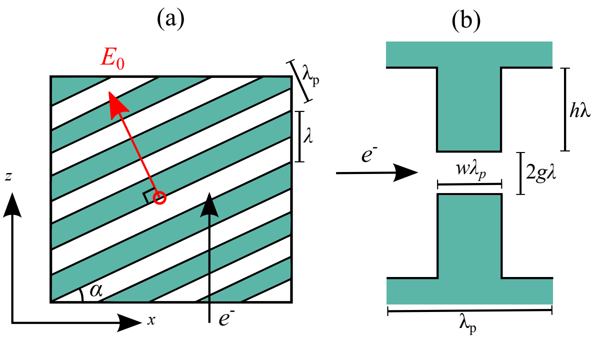

Figure 1: Dielectric grating structure. (a) Grating structure viewed from above. The electron beam travels in z, and the laser wavefront vector is incident in the $-y$ direction. (b) Grating profile, highlighting dimensions varied in these simulations.

RESULTS

Electromagnetic modelling of the deflecting structure was performed using the Ansoft High Frequency Structure Solver (HFSS) software package, version 13.0. Scans over different geometrical parameters (illustrated in Fig. 1) were made. As individual scan parameters were varied, the other parameters were kept at nominal values [5]: $\lambda = 800$ nm, $g = 0.2$, $\alpha = 25°$, $h = 0.85$, $w = 0.5$.

In the present work, simulations were performed with an incident electric field of unit amplitude $E_0 = 1$ V m^{-1}. However, the electric field within the structure can be greater than this. Plotted in Fig. 2 is the maximum electric field in the structure, for different gaps.

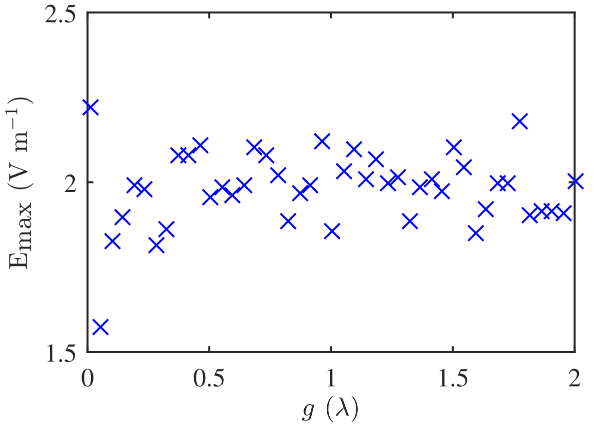

Figure 2: Maximum electric field in the structure, varying gap. For the dielectric grating structures analysed here, the maximum electric field $E_{\max}$ is found at the surface between the vacuum and the dielectric. The value of $E_{\max}$ rises sharply as g increases from zero, towards a constant value.

As noted by Peralta [9], interrogating the field along boundaries in finite-element simulations can lead to unpredictable output. It was found that observing the field 5 nm into the vacuum gave a conservative estimate for the field at the boundary, and $E_{\max}$. Fig. 3 illustrates the gap dependence. It is clear that minimising the half-gap g maximises both f_A, f_D.

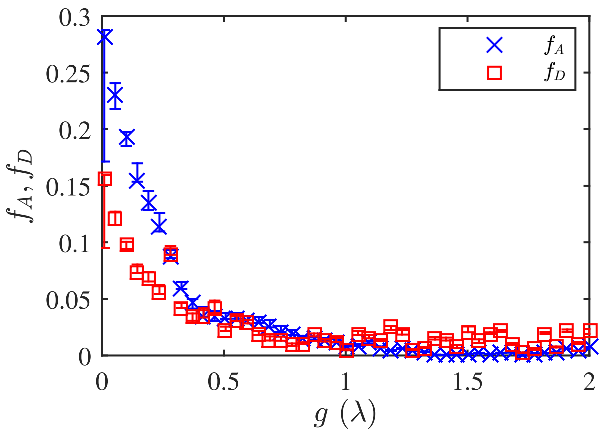

Figure 3: Acceleration and deflection factors, varying gap g. Minimising g optimises the field strength.

Figure 4 illustrates the dependence on rotation α. As the rotation angle α tends to zero, the deflection factor approaches zero, and the acceleration factor approaches a maximum. Likewise, as $\alpha \to 90°$, the opposite is observed. This however forces $\lambda_p \to 0$, which could make such geometries impractical.

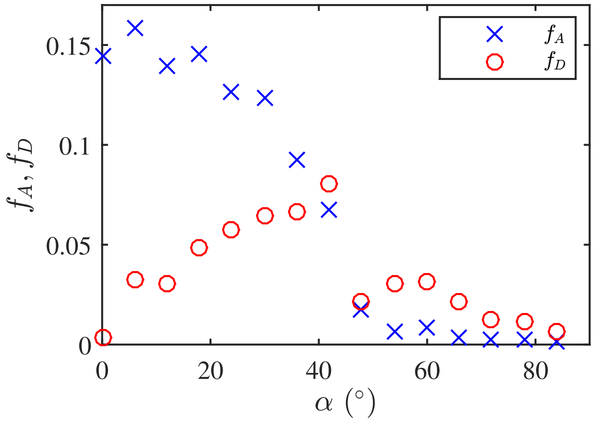

Figure 4: Acceleration and deflection factors, varying rotation angle α. As $\alpha \to 0$, the geometry approaches the grating accelerator without significant deflection.

Figure 5 illustrates the dependence on pillar height h. As the pillar height approaches zero, the amplitude of the phase modulation of the grating also approaches zero. Without this modulation, there is no net force on the particle.

Illustrated in Fig. 6 is the dependence on pillar width. There is a weak dependence on pillar width, with a broad maximum about $w = 0.5$.

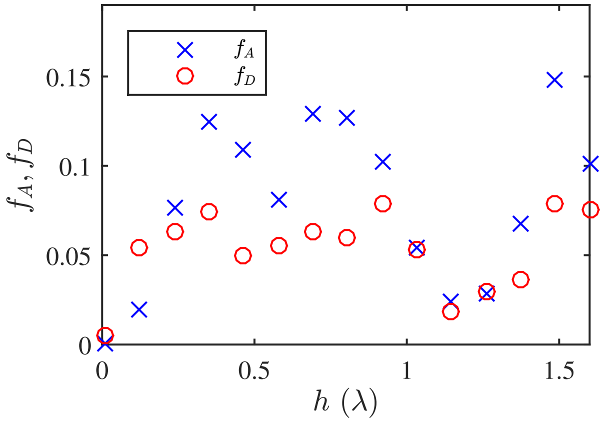

Figure 5: Acceleration and deflection factors, varying pillar height h. There is a weak dependence on pillar height, with minima at $h = 0$, $h = 1.2\lambda$.

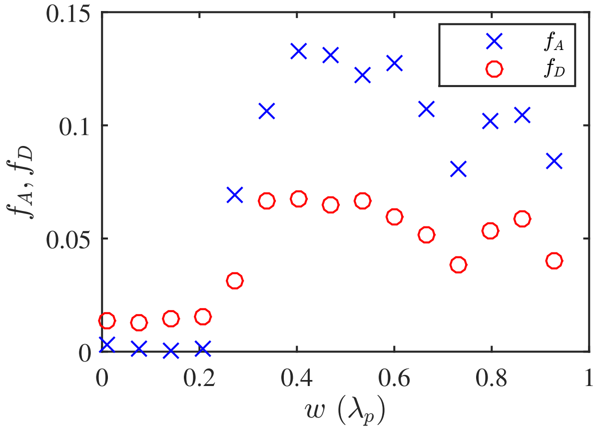

Figure 6: Acceleration and deflection factors, varying pillar width w. There is a weak dependence on w, with minima where $w = 0$, $w = 1$ (both cases have no pillars).

PROPOSED EXPERIMENT

Using the Next Linear Collider Test Facility, the E163 experiment at SLAC has demonstrated dielectric structures for laser acceleration and beam position monitors [1, 11]. A natural extension of this work is the experimental demonstration of proposed grating dielectric deflecting structures [5].

A key requirement of (planar) undulators is to provide a periodic transverse force of alternating direction. Previous dielectric laser undulator proposals assumed a sequence of laser beams incident from above and below the dielectric structure to provide the alternating sign of the deflecting force [5, 6, 12]. Instead, it is proposed to illuminate the structure from a single direction, and alternate the phase of the dielectric grating, as illustrated in Fig. 7. This can be defined lithographically, at the fabrication stage.

As a demonstration of the deflecting structures, it is proposed to construct a dielectric laser undulator of several periods. Using relativistic electrons of E = 60 MeV, with a modest undulator period of 20 dielectric laser gratings it should be possible to generate soft X-ray radiation. This is illustrated in Fig. 8 below.

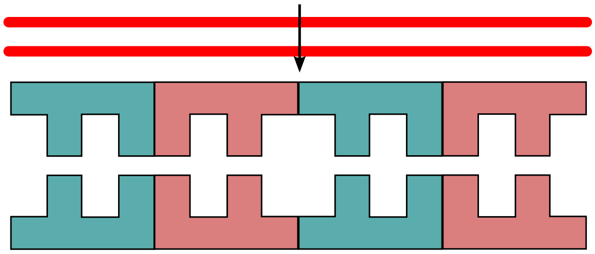

Figure 7: Schematic proposal of dielectric laser undulator, illuminated by a plane wave from a single face. Four undulator poles are illustrated, of two grating periods per pole. By alternating the grating pillar phase at each undulator pole, alternating polarity of deflecting forces is achieved.

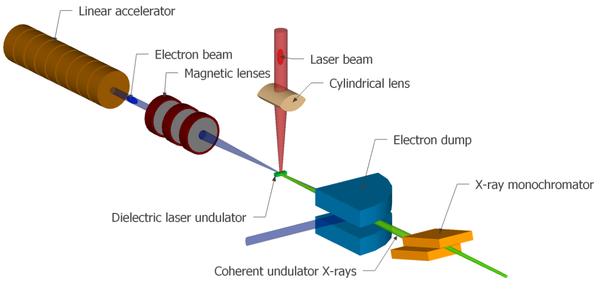

Figure 8: Proposed dielectric laser undulator experiment at NLCTA, SLAC.

DISCUSSION

The present work has considered the ideal alignment of the laser and deflecting structure. Future work should also outline the alignment tolerances of such devices, to further inform design.

CONCLUSION

Integration of micrometre-scale dielectric laser deflecting structures with dielectric laser accelerators is a key step in the realisation of miniaturised accelerators.

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