Geometric optimization study for a Dielectric Laser Accelerator

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Abstract. The quest to realize a particle accelerator on a chip has led to the emergence of dielectric laser accelerators (DLAs). DLAs have the capability for sustaining accelerating gradients in the GV/m regime using grating-shaped dielectric microstructures. The geometry of these microstructures is one of the decisive features affecting the accelerating gradient and energy gain. Here we present an optimization study comparing the performance of different geometrical configurations of dielectric microstructures through particle in cell (PIC) simulations, for both non-relativistic and relativistic regimes. Assuming electron beams with energies of 28 keV and 1 MeV, excited by a laser with a wavelength of 2 μm, pulse length of 100 fs and electric field of 1.5 GV/m, we show that even when grating parameters are the same, the design of the shape/structure plays a crucial role in the enhancement of energy gain and efficiency.

1. Introduction

Dielectric materials have a higher damage threshold than metals, making them a fitting choice for an accelerator which utilizes the near field produced by the interaction of ultrafast lasers with dielectric grating structures [1,2]. Structures with periodicity along the direction of motion of charged particles have been proposed to enable operation with high peak power pulse lasers [3]. Advancement in optical lithographic techniques has enabled the use of variously-shaped grating-based dielectric structures for DLAs [3-7]. Recently, enhancement in energy gain has been shown after the addition of Bragg reflectors (BRs) along with cylindrical [8] and rectangular [9] shaped grating structures. Motivated by the significance of dielectric configuration in achieving higher energy gain, we present a comparative study depicting the performance of two differently-shaped grating structures under the same electron beam, laser pulse and grating parameters. Additionally, we have explored the variation in performance of structures between non-relativistic and relativistic electron beam energies.

2. Simulation studies for geometry optimization

We used CST Studio Suite as the simulation code for this study [10]. This code was prominently used in recent numerical simulations for DLA [5,6]. The inbuilt time domain solver is used to obtain electric field distributions in the whole geometric domain. The PIC solver is used for calculating the dynamics of charged particles. The simulation depicts a working model of a

widely used dielectric laser accelerator, in which intense laser pulses are shone over periodic grating-shaped dielectric micro structures, and an electron beam moving perpendicularly can be accelerated significantly by matching the phase velocity [1].

Figure 1 presents the dielectric structures used for this comparative simulation study. We have designed two grating structures, one with cuboid shaped periodic dual pillars and another with cylindrical shaped periodic dual pillars. In order to mimic double-sided laser illumination [8,9], four BRs are added to each structure. The BRs are made up of the same material as the grating structures and increase the accelerating fields by providing greater coupling between the laser and the electron beam. An electron beam travels in the x direction, in the narrow channel formed between the dual pillar structures. A linearly polarized plane Electromagnetic (EM) wave, having a Gaussian envelope, is shone in the y direction, over the structures. A light beam travelling through vacuum and dielectric will be delayed by a phase of π, and produces a standing wave-like pattern for the electric field which provides an accelerating force on electrons. Simulation studies are carried out for electron beam energies in both the non-relativistic and relativistic regimes.
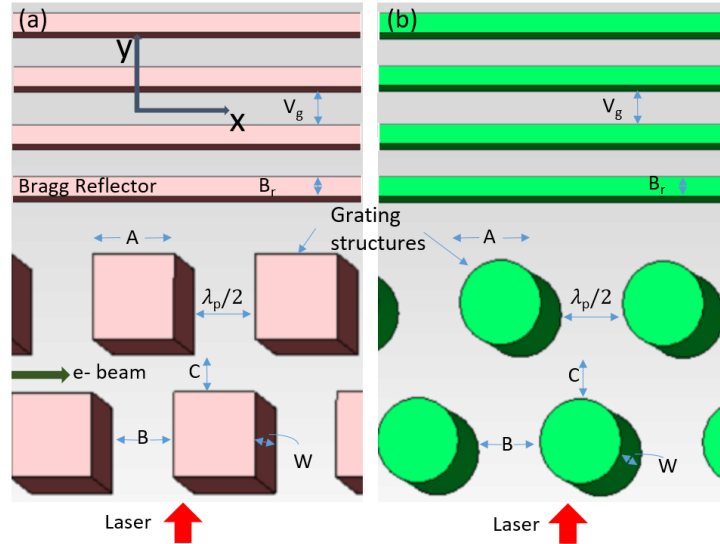

Figure 1. Dielectric structures used for the study: (a) cuboid-shaped structures; and (b) cylindrical-shaped structures.

2.1. Synchronicity condition

In order to achieve significant acceleration of the electrons, the phase velocity of the incident EM wave should be matched with that of the electron beam. To achieve this we have designed the dielectric structures according to the synchronicity condition:

$$mk_g + k/(\beta \cos \alpha) = 0, \tag{1}$$

where m is the order of the harmonic, k_g is the wavevector related to the grating period, k is the wavevector of the incident EM wave, β is the relativistic velocity factor and α is the angle between the incident laser and the normal to the grating periodicity direction (y direction). [11].

2.2. Simulation parameters

For a given electron beam energy, the simulation parameters for cuboid and cylindrical structures were kept the same. The value of the non-relativistic electron beam energy, thickness of BR

and grating period for cylindrical structures were as previously used in [8]. All other grating parameters were deduced by following Eq. (1) and were optimized by performing a parameter sweep in CST. Silicon was used as the dielectric material. The same EM wave parameters were considered in both non relativistic and relativistic regimes. Table 1 summarizes the simulation parameters. For the non-relativistic case, the upper pillars were shifted by half the grating period, to achieve a higher energy gain [8].

Table 1. Beam parameters, geometric parameters of the dielectric structures and driving laser parameters.

Parameter	Value (non-relativistic)	Value (relativistic)
Electron beam initial energy [MeV]	0.0284	1
Relativistic velocity factor, β	0.3	0.94
Length/width of the pillars, A [nm]	320	900
Vacuum gap between two pillars, B [nm]	320	900
Channel width, C [nm]	200	200
Height of the structures, W [nm]	1000	1000
Thickness of a BR, B_r [nm]	145	147
Vacuum gap between BRs, V_g [nm]	250	500
Grating period, λ_p [nm]	640	1800
Laser parameters		
EM wavelength [nm]	2000	
Pulse duration [fs]	100	
Electric field amplitude [GV/m]	1.5	

Figure 2 shows a 2-D (x-y plane) cut of the electric field distribution in the structure domain. Red and blue colours represent high and low field amplitudes respectively. For the non-relativistic case, we achieved higher field values in cuboid than in cylindrical shaped structures.
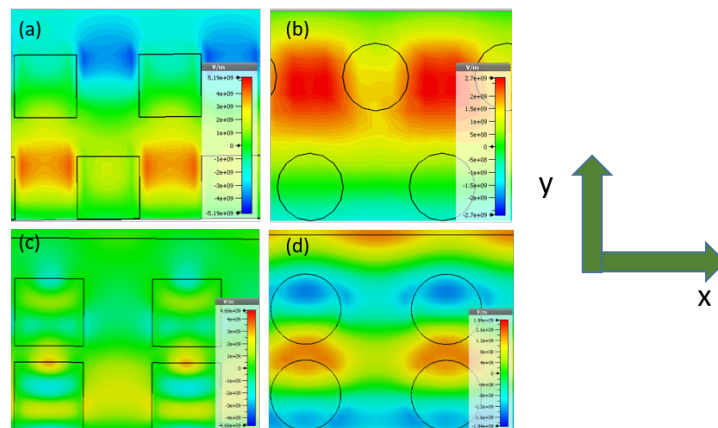

Figure 2. Electric field amplitude obtained in the structures: (a) cuboid, non-relativistic, max. field amplitude = 5.19 GV/m; (b) cylindrical, non-relativistic, max. field amplitude = 2.7 GV/m; (c) cuboid, relativistic, max. field amplitude = 4.66 GV/m; and (d) cylindrical, relativistic, max. field amplitude = 2.91 GV/m.

Figure 3 depicts the energy of the electrons with respect to the beam propagation direction. In the non relativistic regime (Fig. 3 (a)), the energy gain and accelerating gradient are 2.5 keV and 426 MeV/m respectively for the cuboid structures, and 0.6 keV and 97 MeV/m for the cylindrical structures. In the relativistic regime (Fig. 3 (b)), the energy gain and accelerating gradient are 5 keV and 308 MeV/m respectively for the cuboid structures, and 6 keV and 370 MeV/m for the cylindrical structures. This indicates that in choosing structures, β values must be taken into consideration. The total number of particles finally detected are $> 7 \times 10^4$ for cuboid shaped structures, but $> 3 \times 10^4$ for cylindrical shaped structures; cuboid structures are therefore better in terms of particle transmission efficiency.
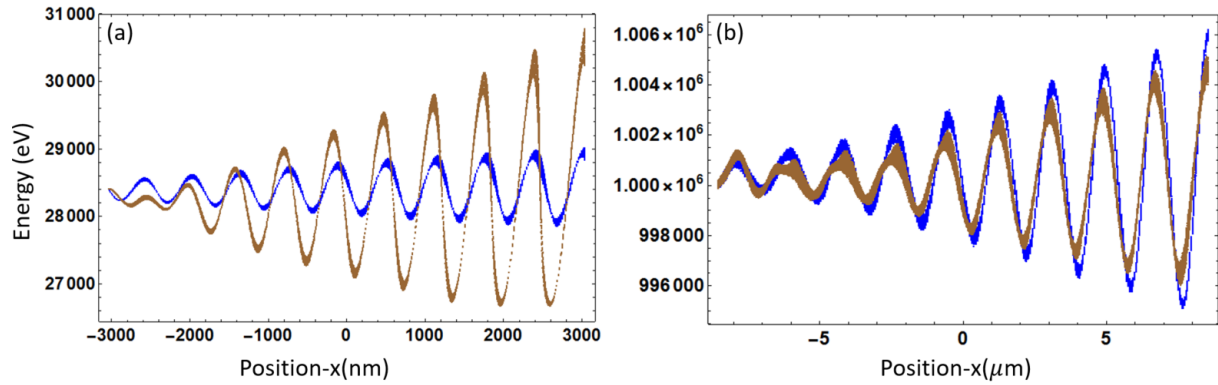

Figure 3. Energy of the electrons while moving through structures: (a) non relativistic regime; and (b) relativistic regime. The brown and blue lines represent cuboid and cylindrical shapes.
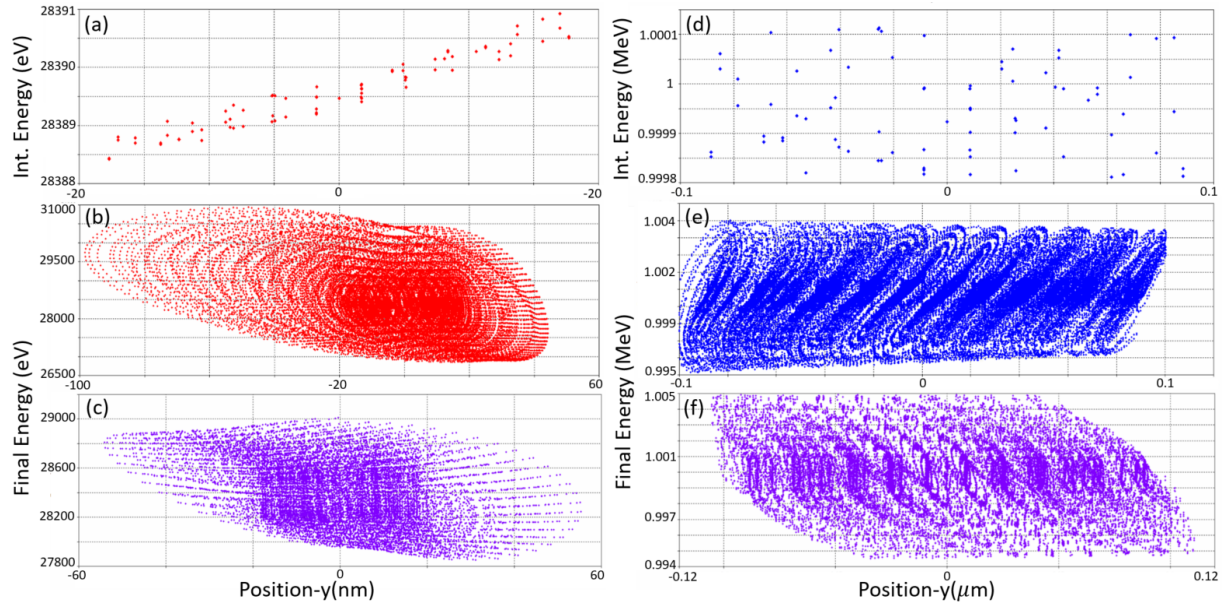

Figure 4. Energy spread of the electron beam. Non-relativistic case: (a) Initial spread = 2 eV; (b) cuboid, final spread = 4.05 keV; and (c) cylindrical, final spread = 1.15 keV. Relativistic case: (d) Initial spread = 0.0003 MeV; (e) cuboid, final spread = 0.009 MeV; and (f) cylindrical, final spread = 0.01 MeV.

Figure 4 shows a comparison of energy spread. Figure 4 (a) portrays a 2 eV energy spread

for an initial electron beam having non relativistic energy. This beam shows an energy spread of 4.05 keV after passing through cuboid shaped structures (Fig. 4 (b)) and 1.15 keV after passing through cylindrical shaped structures (Fig. 4 (c)). This suggests that the electron beam injected with non relativistic energy, experiences a lower energy spread in cylindrical structures than in cuboid ones.

Performing a similar comparison in the relativistic regime, and assuming an initial beam energy spread of 0.0003 MeV (Fig. 4 (d)), we find that the energy spread increases for both cuboid and cylindrical structures after passing through them. For the cuboid it results in a final energy spread of 0.009 MeV (Fig. 4 (e)), while for the cylindrical it results in a 0.01 MeV spread (Fig. 4 (f)).

3. Conclusions and outlook
In conclusion, we have numerically compared the electron beam acceleration through cuboid and through cylindrical shaped grating structures. The simulation shows that the performance of the structures differs between non-relativistic and relativistic electron beam energy. In the former case, cuboid structures show higher energy gain, accelerating gradient and energy spread, but in the latter case, cylindrical structures show this effect. Particle transmission efficiency is always higher in cuboid shaped structures. It is therefore extremely difficult to conclude that one particular shape performs better in all respects, but it is evident that the choice should be made on the basis of particular experimental conditions and according to the needs of the user. The study emphasizes the role of the geometry of the dielectric structures for a DLA; however, the experimental difficulties in producing structures of the desired shape also need to be addressed. In the future, with the help of parallel processing to speed up the simulations, we plan to increase the periodicity of the structures to achieve higher gain and address electron beam focusing effects, before seeking experimental validation.

4. Acknowledgments

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