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Numerical study of a multi-stage dielectric laser-driven accelerator

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Abstract

In order to overcome the limits of commonly used radiofrequency accelerators, it is highly desirable to reduce the unit cost and increase the maximum achievable accelerating gradient. Dielectric laser-driven accelerators (DLAs) based on grating structures have received considerable attention due to maximum acceleration gradients of several GV/m and mature lithographic techniques for structure fabrication. This paper explores different spatial harmonics excited by an incident laser pulse and their interaction with the electron beam from the non-relativistic (25 keV) to the highly relativistic regime in double-grating silica structures. The achievable acceleration gradient for different spatial harmonics and the optimal compromise between maximum acceleration gradient and simplicity of structure fabrication are discussed. Finally, the suitability of a multi-stage DLA which would enable the acceleration of electrons from 25 keV to relativistic energies is discussed.

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Keywords: Dielectric laser-driven accelerator (DLA); micro accelerators; electron beam; compact radiation source; multi-stage acceleration; high acceleration gradient; relativistic particle beam.

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1. Introduction

Dielectric laser-driven accelerators (DLA) are strong potential candidates for ultra-compact electron accelerators and might even open up new avenues for future high energy physics accelerators and free-electron lasers. Due to a much higher damage threshold (0.2-2 J/cm^2) than metals, dielectric microstructures can support accelerating fields that are orders of magnitude higher than what can be achieved in conventional radio-frequency cavity-based accelerators. They can therefore support acceleration gradients up to several GV/m. Many candidates for DLAs have been proposed so far: Grating-based structures [1]-[6], photonic crystal structures [7][9] and woodpile structures [10]. A proof-of-principle experiment has successfully demonstrated acceleration of relativistic electrons with an accelerating gradient of 250 MeV/m [11] in a fused silica double-grating structure and the acceleration of non-relativistic 28 keV electrons through a single-grating structure was also observed [12]. These two experiments demonstrate the possibility of an all-optical DLA for full energy acceleration in the future.

The geometry with two gratings facing each other is called a double-grating structure, which was originally proposed by Plettner [1] as shown in Fig. 1. Initial studies into these double-grating structures have already been performed by the authors with the aim to increase the acceleration efficiency for highly relativistic and non-relativistic electrons [13]. This paper investigates a grating-based multi-stage DLA from 25 keV ($\beta = v/c$=0.3, where v is the electron velocity and c the speed of light) to the highly relativistic regime where $\beta \approx 1$. In particular, the different spatial harmonics excited by the diffraction of an incident laser pulse are analysed. In a second step the achievable acceleration gradient, as identified through simulations for different spatial harmonics, will be discussed. On this basis, an optimal compromise between maximum acceleration gradient and simplicity of structure fabrication is proposed for a novel structure that would be suitable to accelerate electrons from 25 keV to highly relativistic energies.

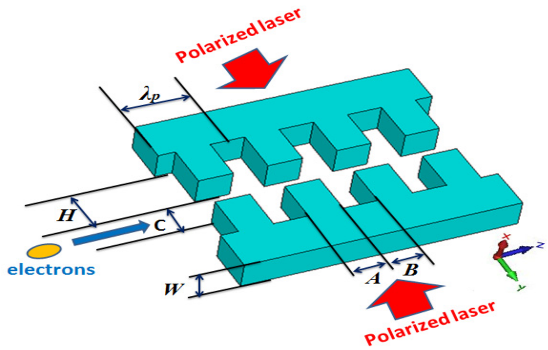

Fig. 1. Schematics of a dielectric double-grating structure excited symmetrically by laser beams. λ_p, C, H and W represent grating period, vacuum channel width, pillar height and dielectric wall width.

2. Accelerating Field Simulation

The VSIM code [14] based on the finite-difference time domain (FDTD) method has been used to precisely calculate the electric field distribution in the 2-dimensional geometry of the double-grating structure. The acceleration gradient G_0 was evaluated by $E[z(t),t]$ which is the electric field distribution along the vacuum channel center as shown in Fig. 2 (c) using

$$G_0 = \frac{1}{\lambda p}\int_0^{\lambda p} E[z(t),t]dz, \quad (1)$$

where λ_p is the grating period and, $z(t)$ is the position of electrons at time t. Silica-grating structures generating G_0=0.5 E_0 [1] , where E_0 is the input laser electric field, have been reported. This value can be doubled [4],[5] by illuminating the structure from both sides. The other important factor is the acceleration efficiency, given by $\eta = G_0/E_{max}$ and is used to evaluate the maximum achievable acceleration gradient, where E_{max} is the maximum electric field generated by the laser electric field E_0 in the material.