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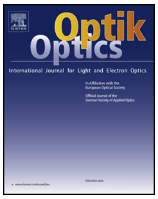

Original research article

Optimization of electron bunch injection in dielectric laser acceleration

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ABSTRACT

Dielectric laser acceleration (DLA) is new cheap and miniature laser acceleration scheme for acceleration of charged particles in the vicinity of the dielectric grating. In this paper injection characteristics of the electron bunch in a single fused silica grating based-structure with period $\lambda_g = 260\,nm$ is analyzed. Optimum aspect ratios of the grating width $d/\lambda g$ and height $h/\lambda g$ are obtained for the first surface mode harmonic. Simulation results of the injected electron dynamics show that there are two lateral positions ($y = 1.75$ and $y = 2.6\,\mu m$) that the final electron energy is maximized. Existence of these two lateral positions increases flexibility of the injection process. In other words, injection can be made in the range of $1.4 < y(\mu m) < 2.8$ with two peaks of energy. Finally, injection of Gaussian electron bunch at each two optimum transverse positions is investigated by a numerical simulation. The initial momentum distribution is assumed to be Gaussian around the mean resonance velocity ($\beta = \lambda g/\lambda = 0.33$). The initial longitudinal and transverse emittance of the electron bunch are selected as $\varepsilon_{||} = (\delta E/E) = 0.01$ and, $\varepsilon_{\perp} = 3\mu mmrad$ respectively. The net energy gain in the fifty grating periods is $2.03\,keV$ ($2.225\,keV$) and acceleration gradient for each injection position is about $160\,MeV/m$.

1. Introduction

Nowadays, the generation of high-energy physics experiments and high-brightness light sources induce an urgent need to develop new acceleration mechanics. The common electron accelerator technologies present several important limitations which attribute to the low acceleration gradients in conventional radiofrequency (RF) structures. Direct laser acceleration in a vacuum with the longitudinal field component inside of the laser beam is possible and has recently been reported [1], but due to the mismatch of the phase velocity of the accelerating field and the particle's velocity, the acceleration is confined to the Rayleigh length of the laser beam [2,3]. Some authors try to overcome this difficulty by new synchronization scheme in direct laser acceleration in vacuum [4,5]. Takeda et al. [6] suggested that the higher gradients could be achieved by use of optical near-field of a periodic metal grating structure for particle acceleration instead of RF driving fields. The charged particles are accelerated in the vicinity of periodic structures via the inverse Smith-Purcell effect (ISP) [7]. However, the measured optical acceleration gradients were too small (~10 keV/m) in contrast to the RF accelerators (~100 MeV/m). The maximum accessible gradient in metal structures is ultimately limited by the breakdown of the metallic accelerating structure (~100 MeV/m). Due to higher break down threshold of dielectric materials than metals, dielectric microstructures at optical frequencies withstand up to two orders of magnitude larger fields, so, higher acceleration gradients can be attained with regard to conventional microwave accelerators [8–13]. Recent advances in the generation and characterization techniques of ultra-short laser pulses over the last two decades [14], dielectric laser accelerators have

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been suggested both to miniaturize particle accelerators capable of producing relativistic high brightness beams of charged particles and laser-driven acceleration of relativistic electrons with acceleration gradients over 1 GeV/m [15,16].

The first demonstration of laser-driven acceleration in the vicinity of a dielectric material has been reported in 2005 [17,18]. Dielectric laser acceleration (DLA) adverts to the use of a laser to accelerate charged particles by periodic dielectric structures operating in the near field must have dimensions on the scale of the wavelength of radiation. The structure acts as a longitudinally periodic phase mask, ensuring a phase synchronicity between the electromagnetic field and the moving particles. This produces the desired periodic modulation of the electric field in the vicinity of the dielectric surface from an incoming plane wave. To achieve acceleration it is required to electric field propagates parallel to the direction of charged particles motion and electrons launch at the correct optical phase (laser-electron timing). The phase velocity of electromagnetic fields must be equivalent to the charged particles velocity which continuously imparts energy to the particle, hence the particles experience accelerating longitudinal component electric field and gain net energy. The high refractive index of silicon enables efficient optical coupling to both sub-relativistic and relativistic electrons [19]. Furthermore, DLA structures are manufactured by available lithographic fabrication methods. Therefore many DLA structures for single electron acceleration have been proposed so far: grating-based structures [20,21], photonic crystal structures [22,23] and woodpile structures [24]. Recently, acceleration gradients of nonrelativistic electron up to 300 MeV/m in dual gratings and up to 250 MeV/m in single gratings were demonstrated [25–27]. The other experiment was demonstrated in a micro-fabricated fused silica grating in excess of 200Mev/m [19]. Recently, dielectric laser acceleration of relativistic electrons by femtosecond duration laser pulses has been observed at SLAC and the electron accelerating gradient of 690 - 100 MV m^{-1} was measured [28].

Particle acceleration at a grating is based on the diffraction of laser light. The diffracted light field is associated with spatial harmonics which can be used to accelerate electrons, in close of the dielectric grating surface. In conventional RF accelerators, the electron bunch length is typically much shorter than the wavelength of the accelerating electric field. In an optical accelerator for a focusing structure the beam envelope radius100 nm and normalized emittance 2 μm-mrad for a dual grating is used [29,30].

In the present work, we figure out an optimal electron bunch injection conditions. The electron optimum dimension and the injection position are achieved. We optimize electron bunch injection and find out the spatial electron bunch dimensions in order of micron and with ultra-low emittance. The chosen structure in this article is a single fused silica grating based-structure. In section II we investigate and analyze the spatial harmonics exited close to the single grating in the normal incidence of the laser beam. Then the grating dimensions are optimized for the first harmonic amplitude. In section III, we obtain the optimum size of the electron bunch with definite emittance with the correct synchronization with the first harmonic. In section IV we present the simulation results of electron bunch acceleration in the optimum injection conditions. Concluding remarks are made in section V.

2. Spatial harmonic analysis

The diffraction of the incident wave at the grating excites spatial harmonics close to the vicinity of the dielectric grating. We use finite difference time domain (FDTD) algorithm to calculate the harmonic TM mode of the grating. Harmonics travels with a phase velocity $v_{ph} = (\lambda_g/\lambda)\ c/n$, where λ_g is the grating period, λ the wavelength of the incident light, n the harmonic number and c the speed of light. If the n-th harmonic is synchronous with electrons with the velocity $v = v_{ph}$, the electrons can be trapped in that spatial harmonic and get energy. This yield a synchronicity condition $\lambda_g = n\lambda v/c$ where n is the order of the accelerating mode harmonic, v is electron velocity and λ is laser wavelength. The accelerator structure utilized is fused silica (refractive index $n = 1.47$) grating with period λ_g pillars of width d and height h as shown in Fig. 1. The structure is assumed to be illuminated normally by a plane wave source as shown in Fig. 1b. The propagation of plane wave through the grating is shown in Fig. 1a obtained from FDTD code for three

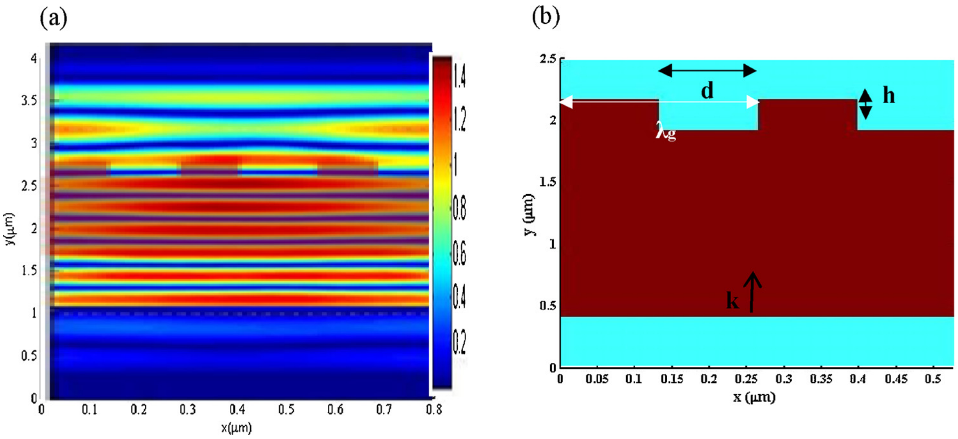

Fig. 1. (a) Snapshot of the grating and the calculated longitudinal field from FDTD simulation. Here red fields are accelerating and blue fields are decelerating zone. A laser pulse incident from bottom excites near fields with travelling wave modes. (b) Schematics of a dielectric single-grating structure by λg, d, and h represent the grating period, grating pillars of width and height respectively (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).