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Investigations into dual-grating THz-driven accelerators

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ABSTRACT

Advanced acceleration technologies are receiving considerable interest in order to miniaturize future particle accelerators. One such technology is the dual-grating dielectric structures, which can support accelerating fields one to two orders of magnitude higher than the metal RF cavities in conventional accelerators. This opens up the possibility of enabling high accelerating gradients of up to several GV/m. This paper investigates numerically a quartz dual-grating structure which is driven by THz pulses to accelerate electrons. Geometry optimizations are carried out to achieve the trade-offs between accelerating gradient and vacuum channel gap. A realistic electron bunch available from the future Compact Linear Accelerator for Research and Applications (CLARA) is loaded into an optimized 100-period dual-grating structure for a detailed wakefield study. A THz pulse is then employed to interact with this CLARA bunch in the optimized structure. The computed beam quality is analyzed in terms of emittance, energy spread and loaded accelerating gradient. The simulations show that an accelerating gradient of 348 ± 12 MV/m with an emittance growth of 3.0% can be obtained.

1. Introduction

Dielectric structures have been found to withstand electric fields one to two orders of magnitude larger than metals at optical frequencies, thereby sustaining high accelerating gradients in the range of GV/m. These dielectric structures can be driven either by infrared optical or by THz pulses, enabling dielectric laser-driven accelerators (DLAs) and dielectric THz-driven accelerators (DTAs). Empirically, it is found that the RF-induced breakdown threshold E_s scales with frequency as $f^{1/2}$ and pulse duration as $\tau^{-1/4}$, as described in $E_s \propto f^{1/2}\tau^{-1/4}$ [1,2]. This indicates that in principle, DLAs can generate accelerating gradients higher than DTAs. DLAs have successfully demonstrated accelerating gradients of 300 MV/m [3] and 690 MV/m [4] for relativistic electron acceleration, and gradients of 25 MV/m [5], 220 MV/m [6] and 370 MV/m [7] for non-relativistic electron acceleration. However, DLAs suffer from low bunch charge and sub-femtosecond timing requirements due to the short wavelength of operation. In a DLA, a laser beam is used to accelerate particles through a microscopic channel in an artfully-crafted glass chip. Such a channel gap can be no wider than several μm [3,4,8–12] in order to generate a high gradient of GV/m, which limits the transverse size and hence the bunch charge. Furthermore, for a laser wavelength of 2 μm, the particle bunch has to occupy only a small fraction of the optical cycle in order to maintain good beam quality in terms of emittance and energy spread. If 1^0 of optical cycle is used, the total bunch length is only 5.6 nm, which also limits the particle bunch charge. In addition, the timing precision between the optical cycle and the arrival of the particle bunch is a practical concern. Using a laser wavelength of 2 μm, a 1^0 phase jitter requires a timing jitter of < 20 as between the optical pulse and the particle bunch, which is challenging to maintain over long distances.

THz frequencies provide wavelengths two orders of magnitude longer than optical sources. In this situation, DTAs can be fabricated with conventional machining techniques due to the long wavelength of operation. This accommodates particle bunches with larger sizes and charges, which is more beneficial for bending and focusing [13] compared to DLAs. DTAs also provide a more accurate timing jitter than DLAs. For a THz wavelength of 600 μm, 1^0 of optical cycle corresponds

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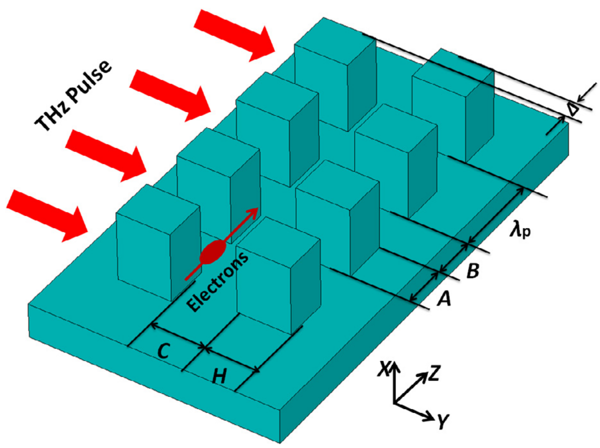

Fig. 1. Schematic of a dual-grating structure illuminated by a THz pulse. λ_p, A, B, C, H, and Δ represent grating period, pillar width, pillar trench, vacuum channel gap, pillar height and longitudinal shift, respectively; $A + B = \lambda_p$ is selected for all simulations.

to a 1.7 μm bunch length, while 1^0 of phase jitter requires a 5.6 fs timing jitter, which is readily achievable [14]. With recent advances in sources for the generation of THz, mJ pulse energy and extremely high electric fields in the GV/m have been achieved [15–17], which can boost the accelerating gradient up to GV/m for a DTA. Experiments have already demonstrated the acceleration of electrons in THz-driven dielectric structures [18–20]. Therefore, DTAs are holding great potential for reducing the size and cost of future particle accelerators.

In this paper a quartz dual-grating structure is investigated for accelerating electrons at THz frequencies. As shown schematically in Fig. 1, a short, intense THz pulse is used to illuminate a dual-grating structure, creating standing-wave-like electric field in the structure's channel gap where the electrons travel and are accelerated. In Section 2, geometry optimizations are performed in order to find the optimum dual-grating structure for the acceleration of relativistic electrons. It is then followed in Section 3 by a detailed wakefield study of an optimized 100-period dual-grating structure. Simulations are performed using the beam properties of the future Compact Linear Accelerator for Research and Applications (CLARA) [21] which is planned as an X-ray free electron laser (FEL) test facility located at the Daresbury laboratory in the UK. In Section 4, a linearly-polarized THz pulse is introduced to interact with the CLARA bunch in the optimized structure. The achievable beam quality is analyzed in terms of emittance, energy spread and loaded accelerating gradient. Finally the current challenges and limitations are discussed.

2. Geometry optimization

The dual-grating structure is a modification from the original design by Plettner et al. [8]. When a linearly-polarized THz pulse travels through the structure, the speed of the wave in vacuum is higher than that in the dielectric grating pillar. This produces the desired π phase difference in the vacuum channel for the wave front, resulting in periodic energy modulation for electrons traveling along the longitudinal z-axis.

In order to optimize such a dual-grating structure, VSim [22], based on a finite difference time domain (FDTD) method, is used to compute the electric and magnetic fields generated in the structure. The gratings are modeled as a 2-dimensional (y–z plane) structure to simplify our computations for the electric and magnetic fields. Periodic boundary conditions are applied along the electron channel in the z direction. Matched absorbing layers (MALs) are used along the laser propagation direction (y-axis) to absorb the transmitted wave. The mesh size is set to $\lambda_p/80$ so that the simulation results are converged to increase accuracy.

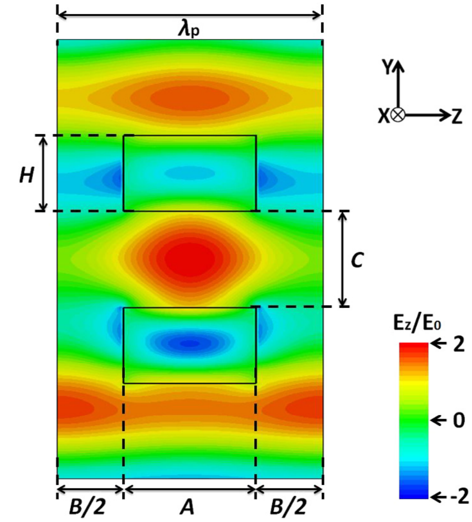

Fig. 2. Longitudinal electric field E_z distribution in a single unit dual-grating structure illuminated by a uniform plane wave with a field E_0 along y-axis.

A plane wave with a wavelength of $\lambda_0 = 150$ μm and a field amplitude E_0 propagates in $+y$ and illuminates a single unit dual-grating structure, as illustrated in Fig. 2. A grating period of $\lambda_p = 150$ μm is chosen so that the first spatial harmonic and relativistic electrons are synchronized [23]. The desired π phase difference for the wave front is achieved by setting pillar height $H = \frac{\lambda_0}{2(n-1)} = 0.50\lambda_0$, here quartz with a refractive index of $n = 2$ (Ref. [24]) is chosen due to its high damage threshold [18–20,25–27] and thermal conductivity.

The accelerating gradient G_0 is evaluated by $E_z[z(t), t]$ which is the longitudinal electric field integral along the vacuum channel center as shown in Fig. 2:

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

where λ_p is the grating period, $z(t)$ is the position of the electrons in the vacuum channel at time t. To find the maximum accelerating gradient, we need to maximize the electric field distributed in the structure, which should not exceed the material damage field. So an accelerating factor [28] ($AF = G_0/E_m$) is defined by the ratio of the accelerating gradient G_0 to the maximum electric field E_m in the structure.

A detailed geometry optimization is carried out to maximize the accelerating factor AF with the widest channel gap C. For an initial pillar height $H = 0.50\lambda_0$, a maximum accelerating factor $AF = 0.18$ can be achieved when the vacuum channel gap $C = 0.20\lambda_0$ as seen in Fig. 3(a). When C increases from $0.20\lambda_0$, the accelerating factor AF gradually decreases, which can be seen in Fig. 3(a). This means that the achievable gradient gradually drops with $C > 0.2\lambda_0$, so a channel gap of $C = 0.50\lambda_p$ is chosen as an acceptable parameter due to a trade-off between the accelerating gradient and available phase space in which high accelerating gradient occurs. As shown in Fig. 3(b), a maximum accelerating factor ($AF = 0.141$) appears at a pillar height of $H = 0.80\lambda_p$ for the structure with an optimum channel gap, $C = 0.50\lambda_p$. Fixing the grating structure, $C = 0.50\lambda_p$ and $H = 0.80\lambda_p$, we then set out to find the optimal pillar width A. Fig. 3(c) shows $AF = 0.141$ can be obtained for a pillar width $A = 0.50\lambda_p$. The longitudinal shift Δ between the gratings is also investigated. It can be seen from Fig. 3(d) that the maximum $AF = 0.141$ occurs when perfectly aligned ($\Delta = 0$ m). However, the worst shift can reduce the accelerating factor by a factor of 54% to $AF = 0.065$. The damage threshold for quartz at THz frequencies is found experimentally to be ~13.8 GV/m [25]. So a maximum accelerating factor of $AF = 0.141$ corresponds to a maximum achievable gradient of $0.141 \times 13.8 = 1.95$ GV/m for a quartz dual-grating structure.