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OPTIMIZATION OF DIELECTRIC LASER-DRIVEN ACCELERATORS*

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Abstract

Dielectric laser-driven accelerators (DLAs) utilizing large electric fields from commercial laser system to accelerate particles with high gradients in the range of GV/m have the potential to realize a first particle accelerator 'on a chip'. Dual-grating structures are one of the candidates for DLAs. They can be mass-produced using available nanofabrication techniques due to their simpler structural geometry compared to other types of DLAs. Apart from the results from optimization studies that indicate the best structures, this contribution also introduces two new schemes that can help further improve the accelerating efficiency in dual-grating structures. One is to introduce a Bragg reflector that can boost the accelerating field in the channel, the other applies pulse-front-tilted (PFT) operation for a laser beam to help extend the interaction length. The combination of both schemes is also studied to improve the efficiency.

INTRODUCTION

Dielectrics can withstand electric fields roughly 2 orders of magnitude larger than metals at optical frequencies, and together with large fields from ultra-short laser pulses, they enable the development of dielectric laser-driven accelerators (DLAs) [1-3]. These DLAs can offer high accelerating gradients in the range of GV/m, and have the potential to reduce the size and cost of future particle accelerators. The dual-grating structures proposed by Plettner *et al.* [1] are of particular interest because they have a simpler geometry than other types of DLA, which reduces the complexity and expense of the fabrication process. To date, proof-of-principle experiments have demonstrated accelerating gradients of 300 MV/m [4], 690 MV/m [5], and 1.8 GV/m [6] for relativistic electrons, and gradients of 220 MV/m [7] and 370 MV/m [8] for non-relativistic electrons in dual-grating DLAs. These demonstrations pave the way for implementing an on-chip particle accelerator in the future.

In order to increase the energy efficiency, geometry optimization studies have been carried out for dual-grating DLAs [9-11]. In addition to this, two new kinds of scheme are proposed and studied in this paper to improve the energy efficiency for dual-grating DLAs. Firstly, the scheme of adding a Bragg reflector into bare dual-grating structures is described. This scheme boosts the accelerating field in the channel and thereby increases the energy efficiency compared to bare dual-gratings. Then a second scheme using PFT laser illumination is presented to extend the interaction length, thereby increasing the energy efficiency. Finally, particle-in-cell (PIC) simulations studying a combination of both schemes (see Fig. 1) are described.

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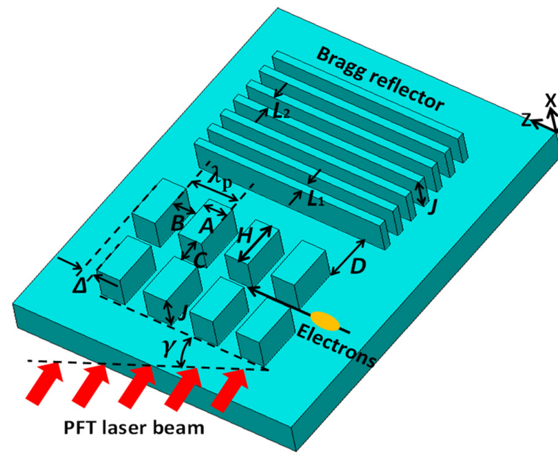

Figure 1: Schematic of the dual-gratings with a 7-layer Bragg reflector driven by a PFT laser beam with a tilt angle of γ. λ_p, A, B, C, D, H, J, L_1, L_2 and Δ represent grating period, pillar width, pillar trench, vacuum channel gap, distance between dual-gratings and Bragg reflector, pillar height, vertical size, dielectric-layer thickness, vacuum-layer thickness and longitudinal shift, respectively. The condition $A + B = \lambda_p$ is selected for all simulations to ensure synchronicity.

DUAL-GRATINGS WITH A BRAGG REFLECTOR

In this section, a Bragg reflector consisting of many layers of dielectrics is proposed as the first scheme to realise an efficient dielectric laser-driven accelerating structure, which is called 'dual-gratings with a Bragg reflector'. This design reflects back the laser power to enhance the accelerating field in the vacuum channel, thereby increasing the electrons' energy gain. Compared to the dual-grating structures reported in Refs [1, 9-11], it has extra geometry at distance D between dual-gratings and Bragg reflector, as seen in Fig. 1. It can be optimized to generate the maximum accelerating field by creating constructive interference in the channel centre. Considering quartz with a refractive index $n = 1.5$ as the dielectric material, a 7-layer Bragg reflector is chosen, following an optimization study in Ref. [12]. Moreover mature lithographic techniques allow the dual-gratings to be integrated with a Bragg reflector into a single wafer, with nanometre precision and at low cost [13].

Following a geometry study in Ref. [12], a dual-grating structure with a 7-layer Bragg reflector, with $C = 0.5\lambda_p$, $H = \lambda_p$, $A = 0.5\lambda_p$, $\Delta = 0$, $D = 0.8\lambda_p$, $\lambda_p = 2.0$ μm, is chosen as the optimum for our 2-dimensional PIC simulations. The

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electron bunch employed in our simulations has a mean energy of 50 MeV, bunch charge of 0.1 pC, RMS length of 9 μm, RMS radius of 10 μm, normalised emittance of 0.2 mm·mrad, and energy spread of 0.03%. Such an electron bunch can be produced by the future CLARA [14]. A linearly polarized Gaussian laser pulse with wavelength λ_0 = 2.0 μm, pulse energy ΔP = 2.1 μJ, pulse duration τ_0= 100 fs, and waist radii w_x = 50 μm, w_z = 50 μm would generate a field E_0 = 2.0 GV/m. When such a field is used for illumination, the maximum field is still below the damage threshold for quartz structures. In a co-moving frame of the laser pulse, the electrons experience a temporal electric field $E_t = G_p e^{-\left(\frac{z}{w_{\rm int}}\right)^2}$ with a characteristic interaction length $w_{\rm int} = \left(\frac{1}{w_z^2} + \frac{2\ln 2}{(c\tau_0)^2}\right)^{-0.5}$ = 22.7 μm, as described in Ref. [15], where c is the speed of light. Integration of this field E_t with a peak gradient of G_p = 1.0 GV/m results in a maximum energy gain of ΔE_m = 40 keV, which can be used to calculate the loaded gradient for subsequent simulations. Due to limitations in our computing hardware, a 100-period optimum structure with a length of LZ = 200 μm is chosen for our simulations.

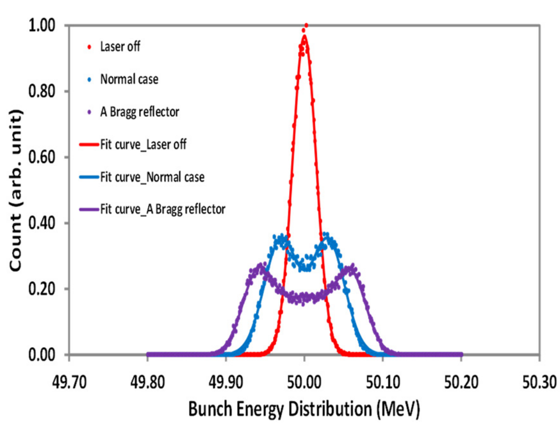

Figure 2: Bunch energy distribution for the cases of laser-off (red dots and fit curve), laser-on without a Bragg reflector (blue dots and fit curve), and laser-on with a Bragg reflector (purple dots and fit curve).

Figure 2 shows the bunch energy distribution for the modulated electrons, with the laser off and on. It can be seen that the energy sprectrum has a double-peaked profile after laser-bunch interaction, due to the RMS bunch length of 9.0 μm being longer than the laser wavelength of 2.0 μm, which agrees well with the reported results [4, 5, 11]. Using the Gaussian fits to these energy spectra, the maximum energy gain is calculated from the difference between the abscissa of the half-width at half-maximum (HWHM) point for a laser-on spectrum and a laser-off spectrum [4, 5]. The maximum energy gain is ΔE_2 = 63 keV for optimized dual-gratings with a Bragg reflector, while it is ΔE_1 = 37 keV for bare dual-gratings. This corresponds to loaded gradients of 1.575 GV/m and 0.925 GV/m, respectively. The loaded gradient is therefore increased by 70% when a Bragg reflector is added, for optimized dual-gratings. This indicates that the energy efficiency is improved by 70% when a 7-layer Bragg reflector is used.

DUAL-GRATINGS DRIVEN BY A PFT LASER

In this section, the same laser parameters are used for the optical system, as shown in Fig. 3, to generate a PFT laser beam with an ultrashort pulse duration τ_0 = 100 fs and a tilt angle $\gamma = 45^0$. As calculated in Ref. [16], an interaction length of $L_{\rm int}$ = 51 μm is obtained for an incident laser waist radius w_z = 50 μm. When such a front-tilted pulse propagates through the structure to interact with the electron bunch within it, the maximum energy gain is calculated to be $\Delta E_{\rm PFT} \approx qG_p\sqrt{\pi}L_{\rm int}$ = 90 keV with LZ = 200 μm and G_p = 1.0 GV/m. This is also used to calculate the loaded gradient for subsequent simulations of PFT laser illumination.

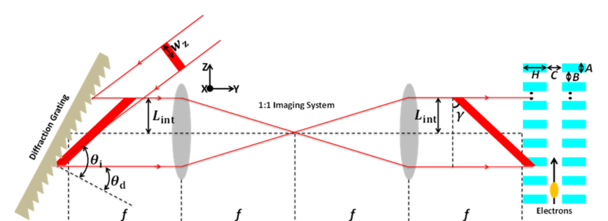

Figure 3: Diagram of a PFT laser generated by a dedicated optical system.

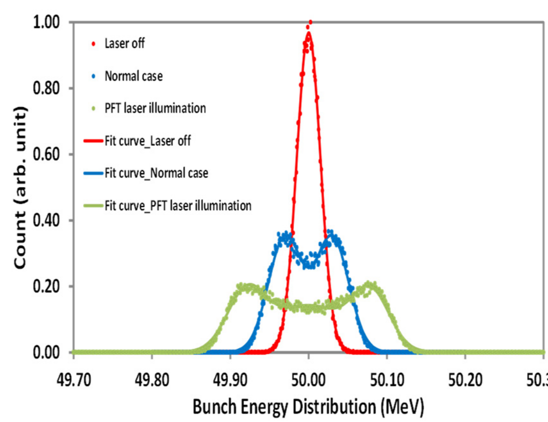

Figure 4: Bunch energy distribution for the cases of laser-off (red dots and fit curve), laser-on with a normal laser pulse (blue dots and fit curve), and laser-on with a front-tilted laser pulse (green dots and fit curve).

Using the Gaussian fitting lines and HWHM methods, Figure 4 shows that the maximum energy gain is ΔE_1 = 37 keV for normal laser illumination, whereas it is ΔE_3 = 88 keV for PFT laser illumination. This corresponds to maximum loaded gradients of 0.925 GV/m and 0.978 GV/m, respectively. It is found that both illuminations have similar loaded gradients, but illumination by the PFT laser generates an energy gain which is larger than the normal laser by 138%.

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DUAL-GRATINGS WITH A BRAGG REFLECTOR DRIVEN BY A PFT LASER

In this section, we set out to study the improvement of the energy efficiency for dual-grating DLAs through combining both schemes together. Here, a dual-grating structure with a 7-layer Bragg reflector has the same geometrical parameters as the first scheme. Such a structure will be explored, driven by a PFT laser beam; hence, an energy efficiency larger than either of the two schemes can be expected.

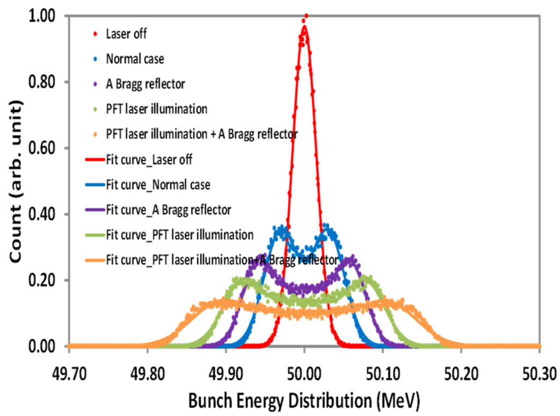

Figure 5: Bunch energy distribution for the cases of laser-off (red dots and fit curve), laser-on with a normal laser pulse for bare dual-gratings (blue dots and fit curve), laser-on with a normal laser pulse for dual-gratings with a Bragg reflector (purple dots and fit curve), laser-on with a front-tilted laser pulse for bare dual-gratings (green dots and fit curve), and laser-on with a front-tilted laser pulse for dual-gratings with a Bragg reflector (yellow dots and fit curve).

Figure 5 shows the results of the PIC simulations for different cases. Based on the Gaussian fits and HWHM methods, the maximum energy gain is $\Delta E_1 = 37$ keV for normal laser illumination on bare dual-gratings, $\Delta E_2 = 63$ keV for normal laser illumination on dual-gratings with a Bragg reflector, $\Delta E_3 = 88$ keV for PFT laser illumination on bare dual-gratings, and $\Delta E_4 = 131$ keV for PFT laser illumination on dual-gratings with a Bragg reflector. This corresponds to maximum loaded gradients of 0.925 GV/m, 1.575 GV/m, 0.978 GV/m, and 1.456 GV/m, respectively. These results are listed in Table 1.

As expected, while PFT laser illumination has a similar loaded gradient to the normal one, a Bragg reflector boosts the loaded gradient, and hence the energy efficiency, for dual-grating DLAs. The loaded gradients are increased by 70% and 49% for normal and PFT laser illumination respectively, when a Bragg reflector is added, for bare dual-grating structures. For dual-gratings with a Bragg reflector driven by a PFT laser beam, the energy gain is increased by 254% as compared to normal laser illumination on bare dual-gratings.

Table 1: Simulation Results for Different Cases

Cases	**Max Energy Gain [keV]**	**Max Gradient [GV/m]**
Normal	37	0.925
A Bragg reflector	63	1.575
PFT laser illumination	88	0.978
A Bragg reflector + PFT laser illumination	131	1.456

CONCLUSION

In conclusion, we have presented results from numerical studies into two schemes to improve the electron energy efficiency for dual-grating structures: adding a Bragg reflector and using PFT laser illumination. When a Bragg reflector is added, a loaded gradient of 1.575 GV/m can be achieved, which is 70% higher than that of bare dual-gratings. This indicates that the energy efficiency is improved by 70% when a Bragg reflector is used. When using PFT laser illumination on bare dual-gratings, the energy gain is increased by 138% as compared to normal illumination. When both schemes are combined together for dual-grating DLAs, the energy gain generated is increased by 254% compared to normal laser illumination on bare dual-gratings.

However, realistic fabrication and experimental studies are still required, to pave the way for implementing such a nano-structure driven by a PFT laser beam.

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