INVESTIGATIONS INTO DIELECTRIC LASER-DRIVEN ACCELERATORS USING THE CST AND VSIM SIMULATION CODES*

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Abstract

Dielectric laser-driven accelerators (DLAs) based on gratings structures have received a lot of interests due to its high acceleration gradient up to GV/m and mature lithographic techniques for fabrication. This paper presents detailed numerical studies into the acceleration of relativistic and non-relativistic electrons in double gratings silica structures. The optimization of these structures with regards to maximum acceleration efficiency for different spatial harmonics is discussed. Simulations were carried out using the commercial CST and VSim simulation codes and results from both codes are shown in comparison.

INTRODUCTION

Dielectric laser-driven accelerators (DLA) have good potential to become a strong candidate for future electron accelerators. Due to a higher damage threshold than metals, these dielectric microstructures can support accelerating fields higher than what can be achieved in conventional accelerators. This can increase the acceleration gradients up to GV/m. An experiment has successfully demonstrated acceleration of relativistic electrons with an accelerating gradient of 250 MV/m in a fused silica double grating structure [1] and the acceleration of non-relativistic 28 keV electrons with a gradient of 25 MeV/m in a single grating structure was also observed [2].

This paper investigates dielectric laser-driven acceleration of electrons in a double grating structure exploiting the different spatial harmonics excited by the diffraction of the incident laser. The double grating structure was originally proposed by Plettner [3] and is shown in Figure 1. Each grating pillar adds a phase shift with respect to the adjacent vacuum space, which produces a longitudinally periodic oscillating electric field in the centre of the vacuum channel. Optimization studies into these structures by parameter variation studies have already been performed with the aim to increase the acceleration efficiency for highly relativistic electrons [4,5]. Here, we consider also the non-relativistic case where electrons are injected at an energy of 25 keV, corresponding to β=0.3, where β=v/c, v the electron velocity and c the speed of light. Different spatial harmonics were considered using the CST [6] and VSim [7] simulation codes to identify the optimum acceleration efficiency and comparing simulation results.

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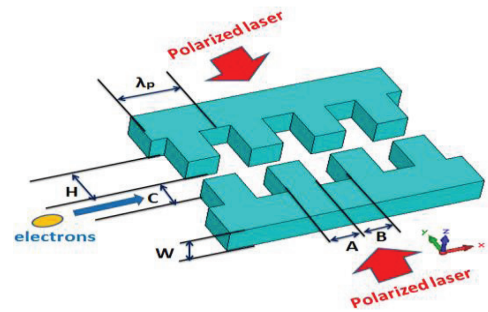

Figure 1. Schematics of a dielectric grating structure.

ACCELERATION OF HIGHLY RELATIVISTIC ELECTRONS

When a double grating structure is driven by two TM polarized laser beams from opposite sides, the diffraction of the incident laser at the grating excites different spatial harmonics which can all be used in principle to accelerate the electrons, see Figure 2.

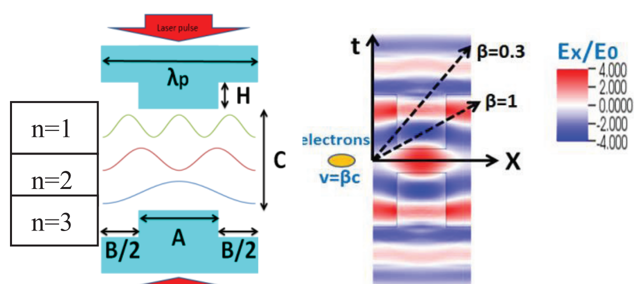

Figure 2. Illustration of the first, second and third spatial harmonics for the case that one grating period is illuminated by laser from two sides.

In the simulations an incoming plane wave with a wavelength of λ_0=1,550 nm was used to excite the grating structure from two sides. Silica (SiO_2, refractive index n=1.528) was chosen as grating material due to its good properties in terms of transparency and field damage threshold. Figure 3 shows the acceleration efficiency for different structure parameters for a grating period of λ_p = 1,550 nm. With an increase of the vacuum channel width C, the acceleration efficiency η gradually decreases, as can be seen in Figure 3(a). Figure 3(b) shows that the maximum acceleration efficiency can be achieved when the pillar height H=0.87λ_p. For further optimization the pillar ratio A/λ_p was varied and Figure 3(c) shows the resulting optimum acceleration efficiency of 0.25 and 0.26 as computed by VSim and CST, respectively.

(a) (b) (c)

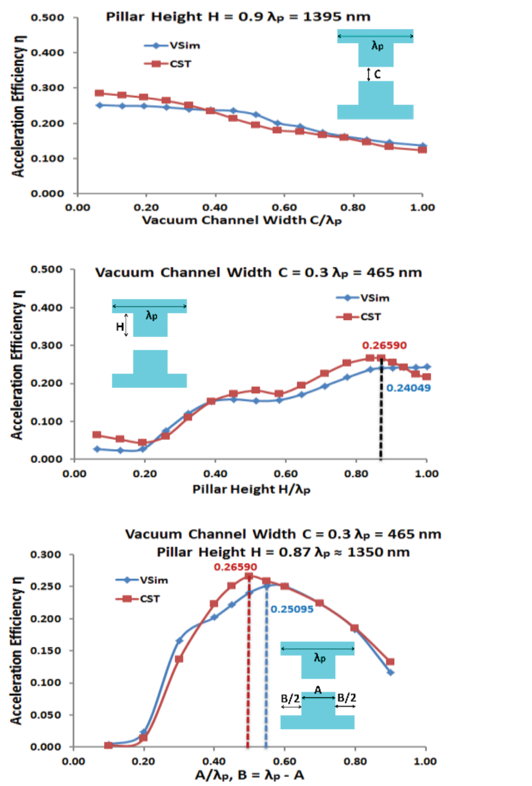

Figure 3. Acceleration efficiency $\eta = G/E_p$, where G is the average acceleration gradient and E_p the peak electric field in the grating structure as a function of vacuum channel width C (a), pillar height H (b) and pillar ratio A/λ_p (c).

Table 1. Optimum Parameters for Relativistic Electrons at a Fixed Channel Width $C=0.3\lambda_p=465$ nm

	VSim	CST
Pillar height H/λ_p	0.87	0.87
Pillar ratio A/λ_p	0.55	0.50
Acceleration efficiency η	0.25	0.26
Maximum gradient G (GV/m)	2.175	2.262

The damage threshold for silica is about 1 J/cm^2 for laser pulses of 100 fs [8]. This is equivalent to an electric field of E_{th}=8.7 GV/m and hence the maximum gradient is about 0.25·8.7=2.175 GV/m and 0.26·8.7=2.262 GV/m according to VSim and CST, respectively, see Table 1.

A laser system with 2 mJ pulse energy and 1 ps width would generate an input field E_0=2 GV/m and hence a gradient of about 2 GV/m for a 10 mm long and 0.04 mm high double grating structure. In this configuration even gradients as high as 2.0 GV/m would still not damage the silica structure.

ACCELERATION OF NON-RELATIVISTIC ELECTRONS

In the case of non-relativistic electrons the grating period λ_p, the laser wavelength λ_0 and the electron velocity β=v/c have to be matched, yielding the synchronicity condition $\lambda_p = n\ \beta\ \lambda_0$ [9]. Here, n is the numbers of laser cycles per electron passing one grating period, v is the speed of the electron and c is again the speed of light. Different spatial harmonics will be excited in the double grating structure, providing several principle options to accelerate the electrons. This will be studied in the following.

First Spatial Harmonics

First, a grating period of $\lambda_{p1}=0.3\lambda_0$ was chosen. In this case the first spatial harmonics is in synchronicity with the electrons along the double grating structure.

(a) (b) (c)

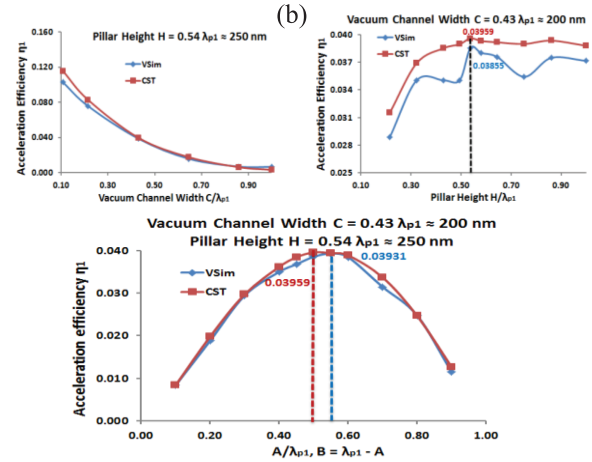

Figure 4. Acceleration efficiency as a function of vacuum channel width C (a), pillar height H (b) and pillar ratio A/λ_{p1} (c).

Figure 4(a) shows the effect from increasing the vacuum channel gap on the acceleration efficiency. Figure 4(b) shows that the maximum gradient appears if $H=0.54\lambda_{p1}$. Finally, an optimization of the pillar ratio A/λ_{p1} can be done to give the maximum acceleration efficiency, as shown in Figure 4(c). Optimum parameters are summarized in Table 2.

Table 2. Optimum Parameters for the 1st Spatial Harmonic as Calculated by VSim and CST for $C=0.43\lambda_{p1}\approx 200$ nm

	VSim	CST
Pillar height H/λ_{p1}	0.54	0.54
Pillar Ratio A/λ_{p1}	0.55	0.50
Acceleration efficiency η_1	0.04	0.04
Maximum gradient G (GV/m)	0.348	0.348

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Second Spatial Harmonics

Second, a grating period $\lambda_{p2}=0.6\lambda_0$, was considered, allowing electron acceleration by the second spatial harmonics.

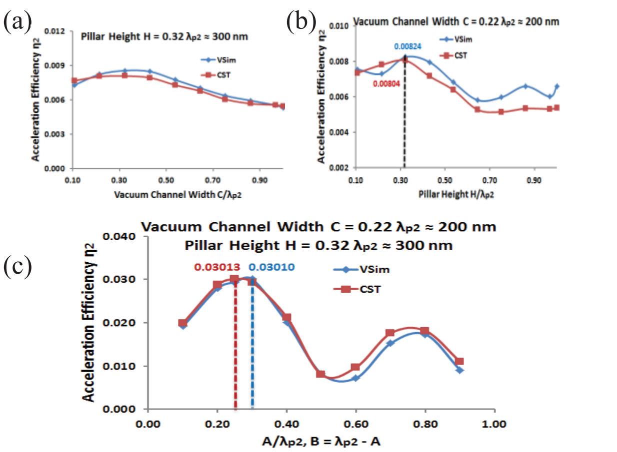

Figure 5. Acceleration efficiency as function of vacuum channel width C (a), pillar height H (b) and pillar ratio A/λ_{p2} (c).

Table 3. Optimum Parameters for the 2nd Spatial Harmonic Using $C=0.22\lambda_{p2}\approx 200$ nm

	VSim	CST
Pillar height H/λ_{p2}	0.32	0.32
Pillar Ratio A/λ_{p2}	0.30	0.25
Acceleration efficiency η_2	0.03	0.03
Maximum gradient G (GV/m)	0.261	0.261

Third Spatial Harmonics

Third, a grating period $\lambda_{p3}=0.9\lambda_0$ was analysed, allowing to use the third spatial harmonic for acceleration .

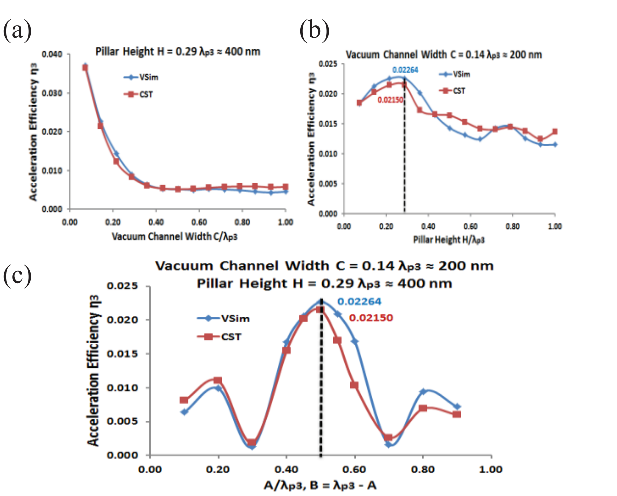

Figure 6. Acceleration efficiency as function of vacuum channel width C (a), pillar height H (b) and pillar ratio A/λ_{p3} (c).

Table 4. Optimum Parameters for the 3rd Spatial Harmonic at a Fixed $C= 0.14\lambda_{p3}\approx 200$ nm

	VSim	CST
Pillar height H/λ_{p3}	0.29	0.29
Pillar Ratio A/λ_{p3}	0.50	0.50
Acceleration efficiency η_3	0.02	0.02
Maximum gradient G (GV/m)	0.174	0.174

CONCLUSION

The results from optimization studies to maximize the acceleration efficiency of highly relativistic and non-relativistic ($\beta=0.3$) electrons in a double grating structure were presented in this paper. Simulations were performed with the VSim and CST codes and very good agreements between the simulation results were found, giving confidence in the validity of the results. For highly relativistic electrons where $\lambda_p=\lambda_0$ the maximum gradient was found to be 2.175 GV/m and 2.262 GV/m, according to VSim and CST, respectively. As for non-relativistic electrons, an optimum compromise between acceleration efficiency and fabrication limitations, was identified in acceleration using the second spatial harmonics ($\lambda_{p2}=0.6\lambda_0$) to accelerate 25 keV ($\beta=0.3$) electrons. In this case accelerating gradients of up to 261 MV/m can be expected.

In a next step multistage DLA from the non-relativistic to highly relativistic regime will be investigated. It is also planned to carry out experimental studies into these structures using the available electron beam at Daresbury laboratory in the near future.

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