BEAM DYNAMICS STUDIES INTO GRATING-BASED DIELECTRIC LASER-DRIVEN ACCELERATORS*

Y. Wei†, C.P. Welsch, Cockcroft Institute and University of Liverpool, UK
Steven Jamison, Accelerator Science and Technology Centre, STFC Daresbury National Laboratory, UK
G. Xia, K. Hanahoe, Y. Li, Cockcroft Institute and University of Manchester, UK
J.D.A. Smith, Tech-X UK Ltd, Sci-Tech Daresbury, Warrington, UK

Abstract

Dielectric laser-driven accelerators (DLAs) based on gratings confine an electromagnetic field induced by a drive laser into a narrow vacuum channel where electrons travel and are accelerated. This can provide an alternative acceleration scheme compared to conventional RF cavity accelerators. Due to the achievable high accelerating gradient of up to several GV/m this could pave the way for future ultra-short and low cost 'micro' accelerators.

This paper presents detailed beam dynamics simulations for a 100-period dual-grating structure. Using the computer code VSIM the achievable accelerating gradient and final beam quality in terms of emittance and energy spread are discussed.

INTRODUCTION

Dielectric laser-driven accelerators (DLAs) are promising candidates to shrink the size of particle accelerators. They provide access to accelerating gradients of up to several GV/m due to the higher damage threshold in dielectrics as compared to metals. So far two experiments have successfully demonstrated accelerating gradients of up to 300 MV/m [1] and 690 MV/m [2] for relativistic electrons in fused silica dual-grating structures while accelerating gradients of 25 MV/m [3], 220 MV/m [4] and 370 MV/m [5] were observed in fused silica and silicon structures for the case of non-relativistic electrons.

Optimization studies into dual-grating structures have already been performed with the aim to increase the maximum accelerating gradient and optimize the distribution of the electric field inside the structure [6-9]. However, only few studies have been done into the particle beam quality that can be obtained in a DLA, although this is one of the most essential parameters of any accelerator. Investigations into the beam quality of a small electron bunch travelling through a 100-period dual-grating structure have been carried out focusing on the final beam emittance, beam energy spread and maximum accelerating gradient. Simulation were divided into two parts: the first part focused on an electron bunch travelling in the vacuum channel of a grating structure without a laser driving the electric field, while in the second part a laser plane wave was introduced to interact with the electron bunch, as shown in Fig.1.

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† yelong.wei@cockcroft.ac.uk

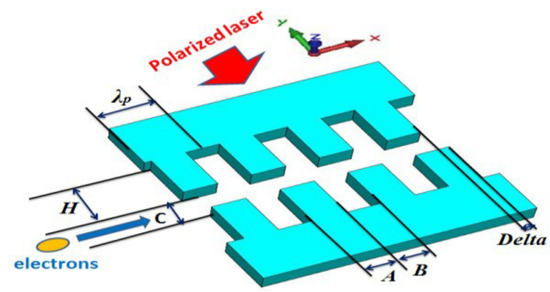


Figure 1 : Schematic of a dual-grating structure.

ELECTRON BUNCH IN A DLA WITHOUT A LASER

Using the VSIM code [10] for simulation studies, a 100-period dual-grating structure was modelled as shown in Fig.2. The geometry parameters are based on earlier optimization studies [9] and are summarized in the following Table 1.

Table 1: Geometry Details of a 100-Period Dual-Grating Structure

Geometry	
Number of periods	100
Grating period λ_p	2 µm
Vacuum channel gap C	$0.5\lambda_p$
Pillar height H	$0.9\lambda_p$
Pillar width A	$0.5\lambda_p$
Misalignment delta	0.0
D1	21 µm
D2	55 µm
D3	15 µm

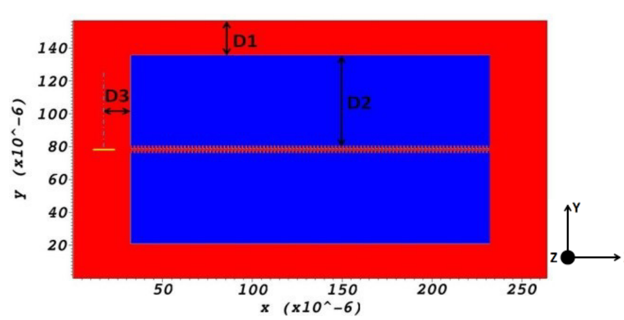


Figure 2 : Model of a 100-period dual-grating structure in the VSIM code. The red area represents vacuum, the blue area dielectric material with a refractive index n=1.5, and the injected electron bunch is represented in yellow.

Table 2: Parameters of the Gaussian Electron Bunch Used in the Simulations

Parameters	
Longitudinal direction	+x
Electron energy	5 MeV
Bunch charge	0.1 fC
Bunch longitudinal RMS length	3 µm
Bunch transverse RMS size(y direction)	0.05 µm
Transverse RMS normalized emittance (y direction)	0.2 nm
Energy spread	0.001
Peak density n_b	5.28×10^{21} m^{-3}

A Gaussian electron bunch as summarized in Table 2 with a longitudinal RMS size of 3 µm and a transverse RMS size of 0.05 µm was injected into the dual-grating structure. The transverse size of the beam was chosen smaller than the vacuum channel gap to ensure that most electrons are preserved when they travel through the vacuum channel.

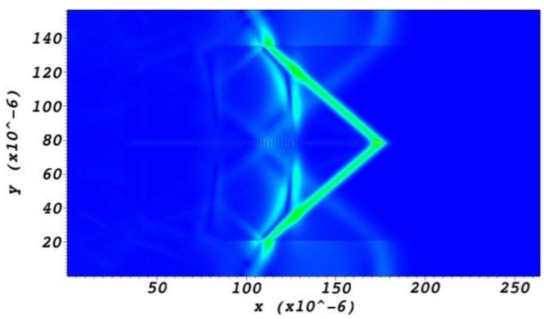
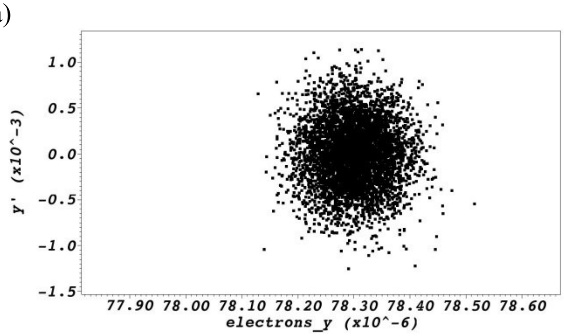


Figure 3 : The electric field of the electron bunch travelling along the vacuum channel of the structure.

(a)



(b)

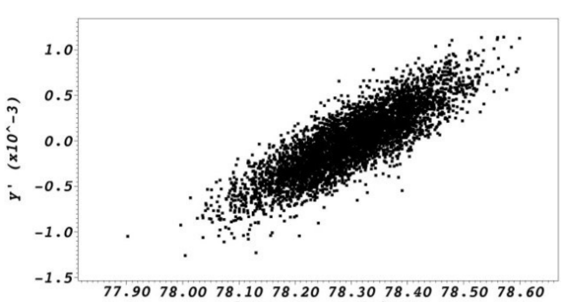


Figure 4 : Transverse (y direction) phase space for the electron bunch at time t=0 (a), and t= structure exit (b) without a laser, where y' is v_y/v_x, v_y is the transverse velocity, and v_x is the longitudinal velocity.

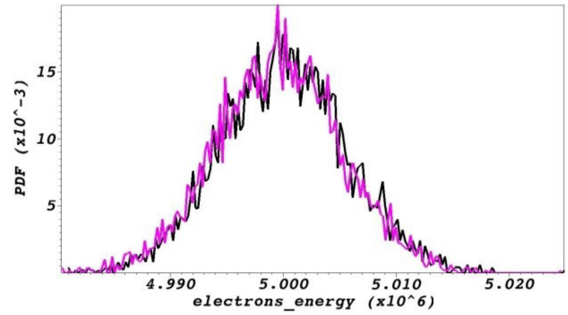


Figure 5 : Bunch energy distribution at time t=0 (black line), and t= structure exit (pink line) without a laser, where PDF stands for probability density function.

In the first simulation, where the electron bunch travels along the vacuum channel of the structure as shown in Fig.3, it excites an electric field with an amplitude of 9.0-10.5 MV/m. This field interacts with the bunch itself and has an effect on the bunch phase space in terms of its final emittance and energy. Particle tracking simulations show that the transverse normalized emittance is 0.1993 nm at time t=0, and grows to 0.1994 nm when the bunch travels out of the structure, see Fig.4. This indicates that the excited field inside the structure has only very little effect on the final beam emittance. The initial and final bunch energy distribution is shown in Fig.5 and there is hardly any change visible.

ELECTRON BUNCH IN A DLA WITH A LASER

In a second simulation scenario, a Gaussian laser plane wave is introduced:

$$E = E_p * e^{-(\frac{x-LX*0.5}{w_x})^2-2*log2*\left(\frac{t-T_d}{\tau}\right)^2} * \cos(2\pi f t)$$

All relevant parameters are summarized in Table 3. The peak laser field E_p was set to 4.0 GV/m so that E_m remains under the damage threshold for silica dual-grating structures using a half wavelength channel gap [5]. T_d is chosen as 122.3 fs so that the electron bunch witnesses the peak field at the centre of the structure and LX is the total length of the structure along the x direction. The electric field envelope as shown in Fig.6 has a FWHM duration of 141.4 fs, and integration along this envelope with a peak accelerating gradient of 1 GV/m results in a maximum energy gain of ΔE=44.22 keV. This can be used to calculate the accelerating gradient for subsequent simulations.

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Table 3: Parameters of the Gaussian Laser Plane Wave Used in the Simulation

Parameters	
Propagation direction	+ y
Wavelength λ	2 μm
Peak laser field E_p	4 GV/m
FWHM duration τ	100 fs
waist radius w_x	70 μm
T_d	122.3 fs
f	150 THz

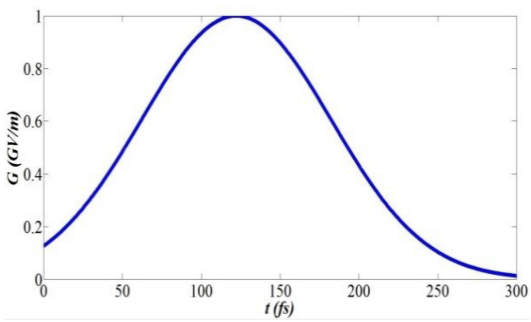

Figure 6 : The electric field envelope of the laser plane wave.

Figure 7 shows resulting final phase space distribution and yields an emittance of 0.2077 nm. The emittance increases by 4.20% inside the structure, probably caused by the deflective force caused by the laser field. With an RMS bunch length of 3 μm the electrons are able to sample all phases of the laser field, causing some electrons to gain energy while others are decelerated. This generates an energy spread of 0.00576 in the bunch.

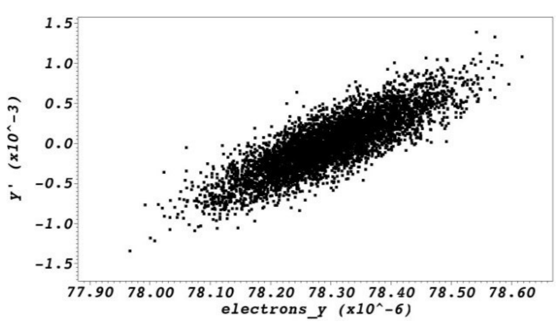

Figure 7 : Transverse phase space distribution at the structure exit after interaction with the laser.

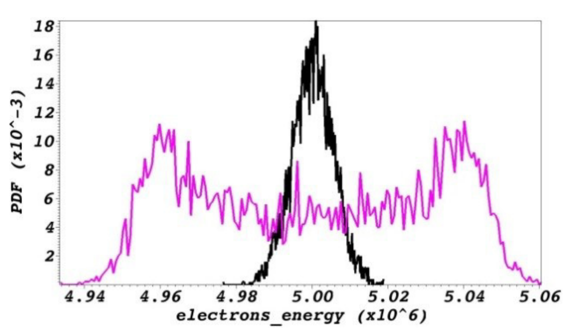

Figure 8 : The bunch energy distribution at time t=0 (black line), and t=structure exit (pink line) after interaction with the laser.

The longitudinal energy distribution is shown in Fig.8 and yields a maximum energy gain of 40±2 keV, corresponding to an accelerating gradient of G=905±45 MV/m.

CONCLUSION

Beam dynamics studies for a 100-period dual-grating structure have been carried out with a focus on the achievable emittance, energy spread and accelerating gradient. Using VSIM simulations, a Gaussian electron bunch with a transverse RMS size of 0.05 μm has been tracked through a realistic structure geometry. It was found that after the electron bunch interacts with a laser plane wave in the grating structure, its emittance increases by 4.20% from 0.1993 nm to 0.2077 nm and its energy spread changes from 0.001 to 0.00576. In this case a loaded accelerating gradient up to 905±45 MV/m can be expected. In a next step studies into multi-period grating structures, loaded with an electron bunch with the properties from the VELA/CLARA facility will be carried out. These will be the basis for experimental studies.

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