ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB143

# SIMULATIONS FOR MeV ENERGY GAIN IN MULTI-MICRON VACUUM CHANNEL DIELECTRIC STRUCTURES DRIVEN BY A $CO_2$ LASER

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*Abstract*

Dielectric Laser Accelerators (DLAs) have been demonstrated as a novel scheme for producing high acceleration gradients (~1 GV/m) within the damage threshold of the dielectrics. The compactness of the DLAs and the low emittance of the output electron beam make it an attractive candidate for future endoscopic devices to be used in tumour irradiation. However, due to the small accelerating distances (sub-mm), the total energy gain is limited to sub-MeV which remains an obstacle for its realistic applications. Also, these DLAs operate under solid-state lasers with wavelengths near IR (800 nm to 2 µm), where required sub-micron vacuum channel at such wavelengths imposes major aperture restrictions for the amount of charge to be accelerated. Here, we present numerical simulation results for dielectric structures excited by a $CO_2$ laser with a wavelength of 10.6 µm. Upon injecting a 50 MeV electron bunch through a 5.3 µm diameter of vacuum channel width, our simulation suggests an energy gain beyond 1 MeV. These results are the initial steps for the realization of a mm-scale DLA capable of producing MeV energy electron beams.

## INTRODUCTION

DLAs have been proven to possess the capability to drive electrons with an acceleration gradient above 1 GV/m, without being damaged, which ranks them amongst the top performers in non-plasma accelerators [1, 2]. Most DLAs are operated under the illumination of solid state lasers, i.e. wavelength less than 2 µm. Recently there has been an idea presented to utilize a $CO_2$ laser as a pumping source for electron acceleration in a DLA [3]. Since the synchronicity condition [4] is fundamental in defining geometry dimensions and bunch length, this $CO_2$ laser can provide a few advantages due to its longer wavelength compared to near IR lasers. First, charge carrying capacity would be increased through the wider channel dimensions and second, due to the enhancement in tolerance values, the geometry manufacturing would be much easier. The shift of vacuum channel dimension from submicron scale to micron scale would also make electron beam transportation easier in longer DLA structures and minimize the divergence arising due to strong focusing at the entrance [3].

We performed the simulation study incorporating the key parameters from the BNL-ATF facility [5]. The VSim code [6] was used to optimize a rectangular dual period grating structure with 100 pillars. The code was executed on Shaheen-II supercomputing cluster from Saudi Arabia. In our finite difference time domain (FDTD) simulation, the grating structures are illuminated by a $CO_2$ laser with a 10.6 µm laser wavelength, a pulse duration of 1.6 ps and the intensity of the order of $10^{16}$ W/m$^2$. The electron beam travelling through the channel between the dual pillars of grating gains 2 MeV in energy from an initial energy of 50 MeV.

## PARTICLE IN CELL (PIC) SIMULATION STUDIES

We used the high-resolution advanced particle in cell simulation code VSim for our studies. For simplicity, we chose rectangular axisymmetric dual grating dielectric structures in our simulation. The periodicity of the structure was fixed at 10.6 µm to satisfy the synchronicity condition for relativistic beams. This condition must be met to acquire the necessary phase difference [4], ensuring the electron bunch gets acceleration. A 4-layer Bragg reflector (BR) is used along with the hundred dual pillar structure to mimic the double-sided laser illumination [7, 8]. The thickness of the dual pillars is 6 µm and the vacuum channel gap is kept 3.1 µm. The thickness of each BR was 2.5 µm and the vacuum gap between them was 5 µm. The total length of the accelerating structures is 1.06 mm. These parameters were optimized for maximum energy gain after a vast parameter space scan. Silicon, with a dielectric permittivity of 11.59 at a 10.6 µm laser wavelength, is chosen as the material for the structures. Recent developments in the micro/nanolithography techniques make it the most suitable material for this application. The relativistic electron bunch used for the design has an initial energy of 50 MeV, longitudinal rms bunch length of 30 µm, transverse rms radius equals to 2.5 µm, initial energy spread of 0.005% and normalized emittance of 1 mm-mrad. An input laser pulse with 10.6 µm wavelength, ~$10^{16}$ W/m$^2$ pulse intensity, 1.6 ps pulse duration, and 500 µm waist radius would generate a peak input field of ~4 GV/m.

Figure 1 (a) shows the longitudinal electric field $E_x$ generated after shining a linearly polarized $CO_2$ laser along the y-direction, perpendicular to the grating periodicity direction. The electron bunch is travelling through the vacuum channel between the dual pillars in the x (grating periodicity/longitudinal) direction (denoted by a dotted black line). The red region represents higher field while blue represents lower. The maximum field which is generated inside the geometric domain including the dielectric structures is of the order of few GV/m which is within the laser induced damage threshold limit of chosen material. Figure 1 (b) is the image of all hundred rectangular dual grating pillars along with the layer of BR. BR has high reflectivity (>90%) and its addition

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has been proven to increase the energy gaining efficiency of the electrons [7,8].

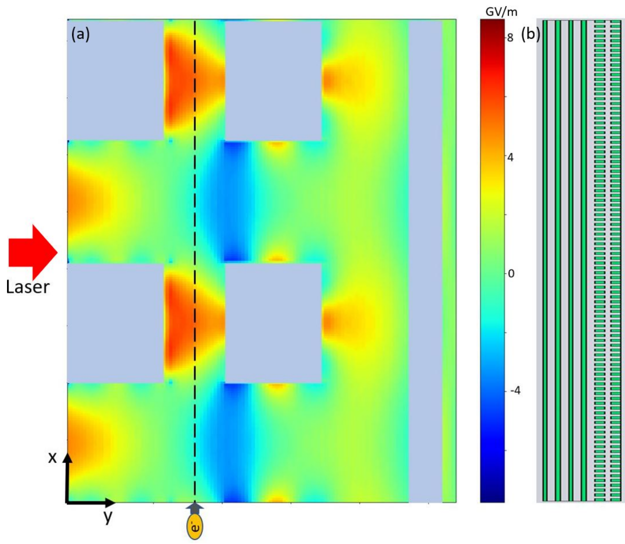


Figure 1: (a) 2-D simulation of longitudinal electric field inside the grating structures. The laser is incident from the y direction and electrons are injected from the x direction (black dotted line). (b) Hundred dual pillar grating structures with four Bragg reflectors.

Figure 2 depicts the energy gain of electrons versus their longitudinal position in the x-direction, after the electrons have reached at the end of the accelerating structures. From the initial energy of 50 MeV, above 52 MeV of final energy is recorded in the simulation for several particles, bringing the energy gain >2 MeV with an average acceleration gradient of 2 GeV/m.

The energy gain occurs in an oscillatory manner because of the constructive and destructive field patterns produced due to the time dependent nature of the fields induced in the vacuum channel. However, with the proper phase matching between the laser pulse and electron bunch, the peak of the gain curve keeps on increasing. Figure 3 shows the electric field experienced by the electrons for two time wise consecutive simulation dumps. During Figs. 3 (a) to 3 (b), the phase has been reversed, so in the perfect phase matching condition electrons will mostly go through positive field amplitude, thus gaining higher energy. However, due to a bunch length larger than the grating periodicity/laser wavelength, all electrons can't achieve the same maxima of electric field.

## *Time Delay Adjustment*

The synchronization of the time delay between the electron bunch and laser beam arrival is very crucial. The time delay is chosen such that the electron bunch and the laser pulse meet around the middle of the channel and have a longer interaction time. Figure 4 shows the plot between various values of time delay versus energy gain obtained. The energy gain achieved its maximum value of 2.65 MeV at about 1400 fs.

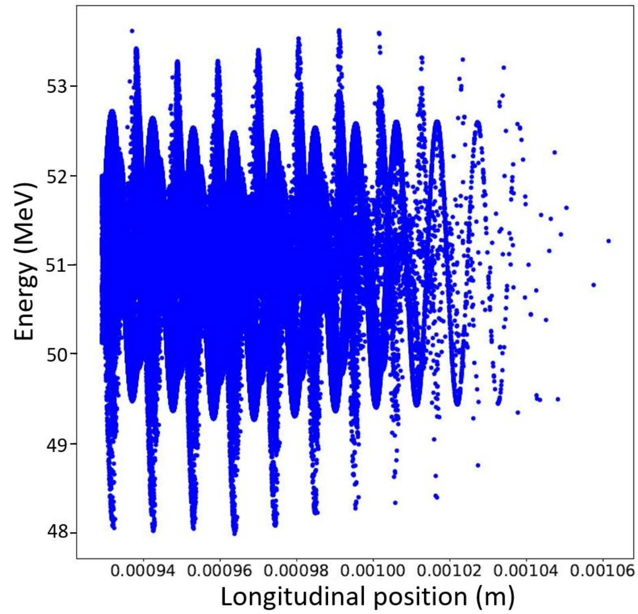


Figure 2: Energy gain of electrons with their longitudinal position close to the end of the grating structures.

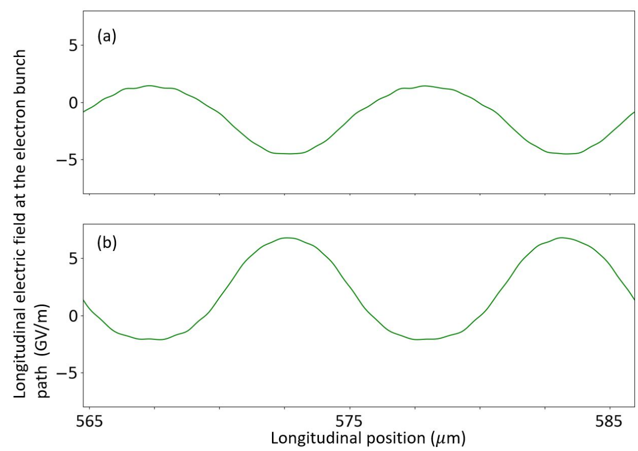


Figure 3: The longitudinal field at the path of the electron bunch for two consecutive time steps (a) and (b) (∼120 fs) apart versus longitudinal position.

## *Electron Bunch Divergence*

Figure 5 shows the longitudinal and transverse positions of electrons at the end of the accelerating structures. More than half of the particles have remained inside of the vacuum channel. The longitudinal spread of the bunch in position space is 120 μm, three times more than the initial spread. The final normalized emittance of the bunch is calculated to be 105.3 mm-mrad, which is 100 times higher than the initial value. Emittance growth is thought to be due to transverse fields induced in the channel, and studies on different injection optics and multipole field analysis are ongoing to circumvent this.

12th Int. Particle Acc. Conf. IPAC2021, Campinas, SP, Brazil JACoW Publishing
ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB143

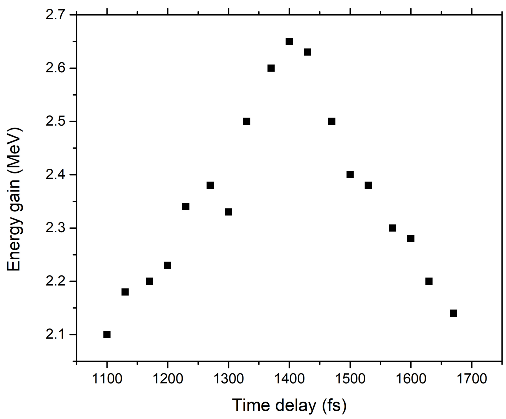


Figure 4: Maximum energy gain of electrons with respect to the time delay between the electrons and the incident laser.

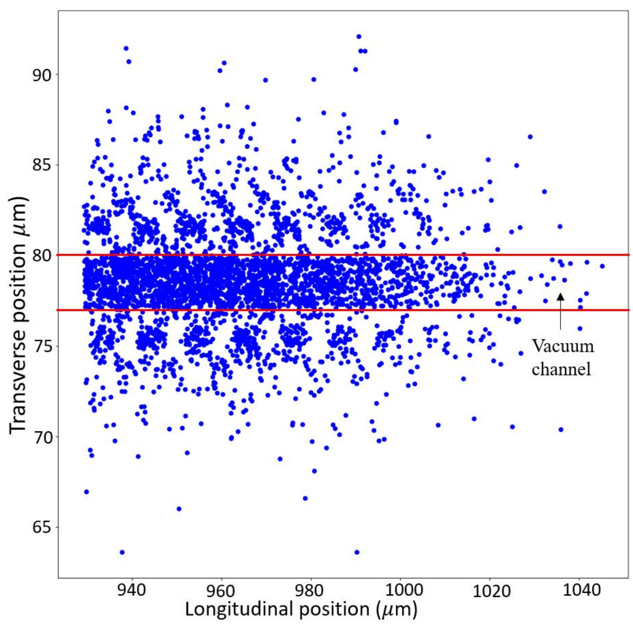


Figure 5: Positions of electrons in the 2-D space at the end of the structures.

## CONCLUSION

In conclusion, our numerical simulation presents a mm long DLA where particles have achieved energy gain higher than 2 MeV, utilizing the fields generated by a laser having a 10.6 µm wavelength. With the proper phase matching conditions, we have transported a relativistic electron bunch in a 3.1 µm wide vacuum channel with 50 MeV of initial energy and having longitudinal rms bunch length of 30 µm. Our scan for the time delay values emphasize the importance of precise adjustment of the meeting time of electron bunch and laser pulse in the channel. Experiments with larger wavelengths of the laser beam can enable the transportation of high amount of charge to MeV energy gain while keeping the average acceleration gradient above GeV/m. In combination with the pulse front tilt [9] and alternating phase focusing technique [10], the number of pillars can be increased and a very stable transportation of electron bunch to much higher energy can be attained. Our preliminary simulation results demonstrate an interesting first step towards this direction. However, the feasibility of DLAs rely on the quality of the beam produced. Currently, our studies are focused on improving the six-dimensional phase space preservation.

## ACKNOWLEDGEMENTS

This work is supported by STFC Liverpool Centre for Doctoral Training on Data Intensive Science (LIV.DAT) under grant agreement ST/P006752/1. The authors would like to acknowledge the support of the Supercomputing Laboratory at King Abdullah University of Science and Technology (KAUST) in Thuwal, Saudi Arabia for providing necessary computational resources. The authors would like to thank Ben Hounsell for his careful review of the paper.

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