DIELECTRIC LASER ACCELERATION FOR DARK SECTOR STUDIES

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Abstract

We have designed a 6-mm-long dielectric structure with 1.2 MeV/m energy gain and high particle survival rates of approximately 98%. To verify the dynamics and survival of the particles, we track them along the structure using DLAtrack6D, a code explicitly developed for dielectric laser accelerators. The structure parameters, including the transverse periodicity lengths, the electric field magnitude at the center of the structure, and the number of micro-cells per macro-cell, have been optimized using the genetic algorithm optimization function 'ga' provided by MATLAB.

INTRODUCTION

Dielectric Laser Acceleration (DLA) has gained considerable attention over the last decade due to its potential for designing compact accelerators, which offer novel opportunities in accelerator science and its applications. In this technique, a periodic dielectric structure is exposed to the laser electric field, and the electrons injected through the structure aperture gain energy as a result of near-field acceleration [1]. Additionally, it provides the highest gradients among non-plasma accelerators; studies have shown that GeV/m acceleration gradients are within reach based on DLAs [2].

The idea of particle acceleration using inverse Smith-Purcell or Cherenkov effects was suggested shortly after the invention of the laser [3]. However, due to the difficulties in manufacturing the structure, it was not applicable for experiments. Nowadays, thanks to the efforts of scientists in the semiconducting industry, nano-fabrication technologies are powerful enough for manufacturing DLA structures [4].

The compactness of DLAs is advantageous, but the small sub-400 nm wide accelerator channel and field non-uniformity in dielectric laser accelerators impose strict emittance requirements [5]. This limitation makes DLAs a suitable choice for applications with a low number of electrons, e.g., indirect search for dark matter, which is the focus of this study.

One of the approaches for dark matter detection is searching for missing energy or indirect search. In this method, an accelerated electron with a well-defined initial state hits a fixed target at a high repetition rate. Considering all the processes and measuring all the outputs, one can calculate the missing energy, which could potentially result from direct dark matter and dark mediator particle production. Two planned experiments, LDMX (Light Dark Matter eXperiment) [6] and eSPS [7], have been designed to provide high-luminosity measurements of missing momentum in fixed target collisions using conventional accelerators. The LDMX experiment has two phases. During phase 1, a 4 GeV electron beam will be utilized to acquire a total of 10^{14} electrons on target (EOT) over the course of one year. Phase 2 will use an 8 GeV beam to acquire a further 10^{16} EOT by increasing the runtime [8].

Designing such an experiment based on DLAs, several challenges need to be considered, including: 1. design and optimization of the single cell and the whole structure to achieve GeV energies, 2. high-repetition (GHz) source of single electrons, 3. a high-repetition (GHz) laser, 4. manufacturing the micron-sized structure, 5. longitudinal and transverse alignment of the structures, and 6. the detection process of GHz events (for more information on detection process, see [9]). This paper focuses solely on optimizing the structure with the aim of minimizing particle loss.

To design and optimize a DLA structure, we track particles through the structure and optimize its parameters based on survival rate. Our design is based on the work of Uwe Niedermayer et al. [5], who designed the structure for relativistic electrons with an initial energy of 6 MeV. To perform numerical tracking, we use DLAtrack6D [10], a tracking code specifically developed for dielectric laser accelerators. DLAtrack6D runs efficiently on an ordinary PC using MATLAB, without requiring a large amount of computing power. CST Studio Suite [11] will be used for the single cell design and simulation of the electric field distribution inside the structure.

SIMULATION RESULTS

If the DLA structure is periodic along the z-axis, the laser field can be expanded in spatial Fourier series given by

$$e_m(x,y) = \frac{1}{\lambda_{g,z}} \int_{-\frac{\lambda_{g,z}}{2}}^{\frac{\lambda_{g,z}}{2}} E_z(x,y,z)\, e^{im\frac{2\pi}{\lambda_{g,z}}z}\, dz \qquad (1)$$

In which the $\lambda_{g,z}$ is the periodicity length of the structure. It can be shown that $m = 1$ is the strongest spatial harmonic [10], such that the transverse distribution of the synchronous harmonic can be simplified as follows:

$$e_1(x,y) = e_1(0,0)\cosh(ik_y y)e^{ik_x x} \qquad (2)$$

The parameters e_1, ik_y, and k_x are determined by the geometry of the single cell, corresponding to the transverse periodicity lengths and electric field magnitude at the structure's center. Optimizing these parameters will reduce particle loss since they contribute to transverse kicks or, in other words,

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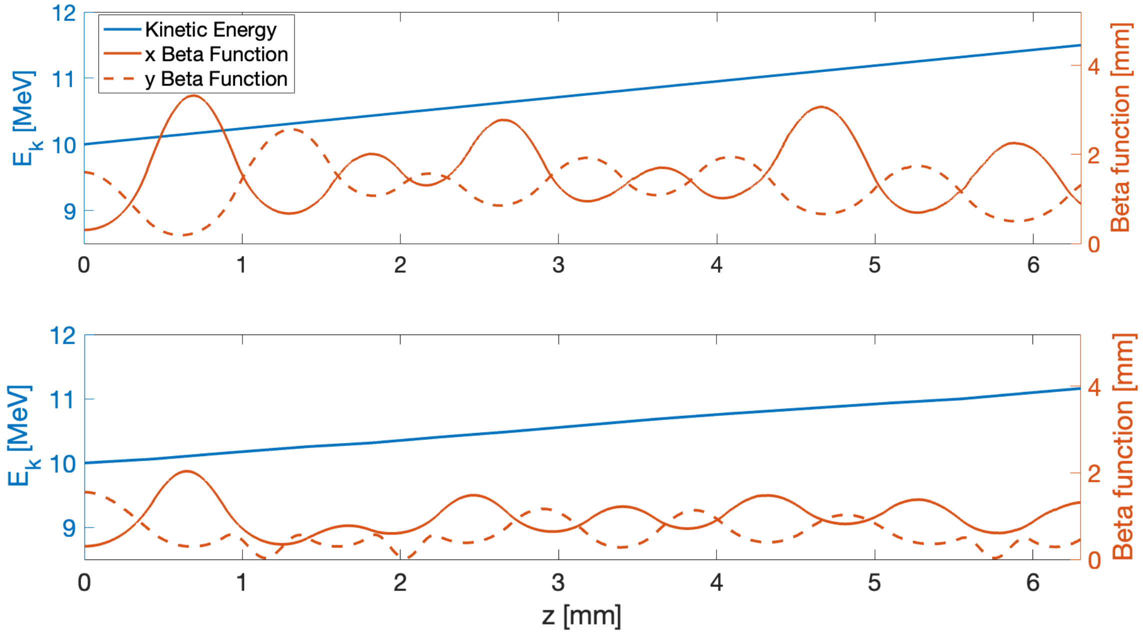

Figure 1: Beam dynamics and energy gain of electrons accelerating across a homogeneous (top) and a non-homogeneous structure (bottom).

transverse focusing. DLA structures consist of macro-cells separated by an APF drift section between each pair (for more information on Alternating-Phase Focusing, see [12]). The number of micro-cells per macro-cell is another parameter that can be considered when maximizing the survival rate.

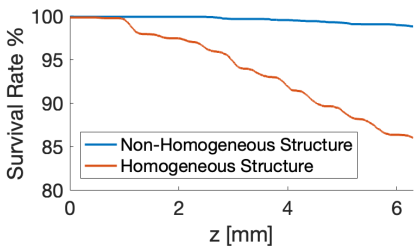

Figure 2: Survival rate of a 6 mm non-homogeneous (blue) and homogeneous structure (red).

The top of Fig. 1 shows the beam dynamics of particles with an initial energy of 10 MeV. The structure parameters are optimized using the MATLAB genetic algorithm optimization function 'ga' [13] to minimize particle loss. Particle tracking results indicate a 1.5 MeV energy gain for a 6 mm structure length, which contains approximately 3000 cells. The simulation is performed using a 2µm laser with an incident electric field of 750 MV/m. The gaussian beam consists of 10^4 non-interacting particles with an initial emittance of 1 pm in both transverse planes. As shown in Fig. 2 (red), the survival rate of the particles at the end of the structure is approximately 85%. This parameter is crucial since particles need to survive a hundred-meter-long structure and reach GeV energy ranges.

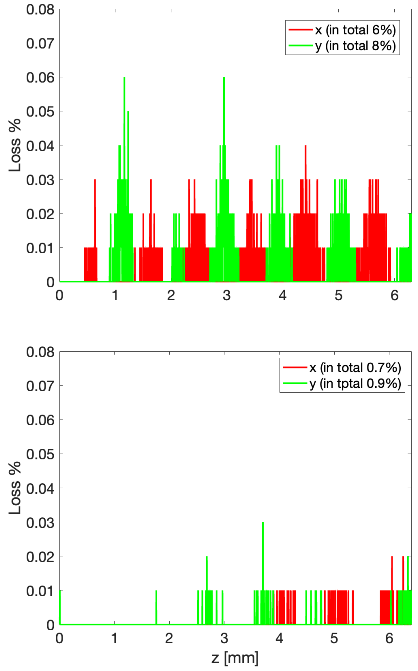

Figure 3: Particle loss along the homogeneous (top) and non-homogeneous structure (bottom).

To further reduce particle loss in the structure, different single cells for each macro-cell are used, creating a non-homogeneous structure. The bottom of Fig. 1 shows the beam dynamics of particles with the same laser and electron source properties, with energy gain decreasing to 1.2 MeV. According to Fig. 2 (blue), the new survival rate for the non-homogeneous structure is 98%, a significant enhancement.

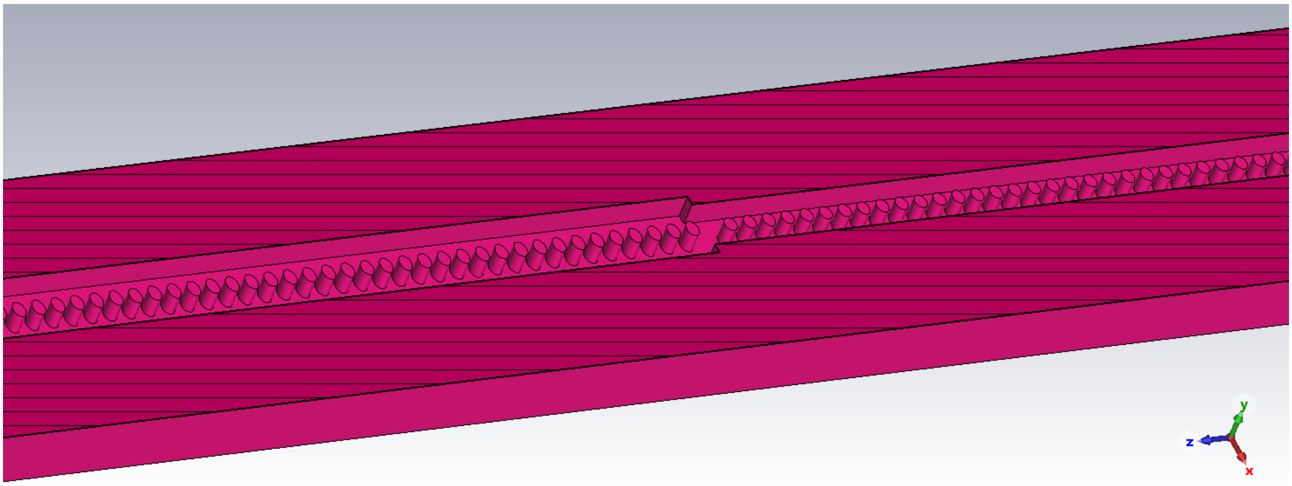

Figure 4: half of the non-homogeneous structure (Note: the electrons trajectory is along z-direction).

However, to accelerate particles along a 100 m-long structure with a total survival rate of 50%, the survival rate for a mm-long structure should be 99.93%.

Figure. 3 shows the particle loss in two transverse directions. The homogeneous structure experiences more particle loss in the y-direction. To reduce this loss, new structure parameters were chosen to decrease the beta function in the y-direction, as evident from the comparison of the two plots in Fig. 1.

After optimizing the structure parameters, the single cell and the whole structure are designed based on the optimized parameters. Fig. 4 shows the first two macro-cells of the non-homogeneous structure designed using CST Studio Suite. The APF drift section is visible in the middle of the figure.

CONCLUSION

For the purpose of indirect search of dark matter, we designed laterally driven DLA structure that achieves 1.2 MeV energy gain in 6 mm length together with 6D confinement. The design originated from [5] and was supplemented with non-homogenous shapes following the APF segments and optimized using a genetic algorithm together with the DLAtrack6D tracker. The achieved throughput could be increased to 98%. In the future, we plan to investigate the optimization using machine learning algorithms.

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