6-D Phase Space Optimization of relativistic DLA at high Energy Gain

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Dielectric laser accelerator (DLA) has emerged as a miniaturised and cost-effective tool for particle acceleration. DLAs have proved to be a promising candidate for GeV/m acceleration gradient within the damage threshold of the materials used. However, the emittance growth and energy spread increase at higher particle energies and limit the realistic applications. Here we present the numerical simulations of a mm scale DLA, operated by a THz laser, with various injection schemes for an electron bunch created externally. We introduce a time dependent emission model and a focusing scheme for the electron bunch and show significant reduction in the numerical Cherenkov instability in CST simulation. We show that when the electron bunch is focused at the entrance of the grating structure, the emittance growth is preserved. The electron bunch achieved 0.5 MeV energy gain with the energy spread less than 5 % of the mean energy gain.

Introduction

- DLAs use the near field generated from the interaction of laser and dielectric structures and accelerate the electrons in a vacuum channel.

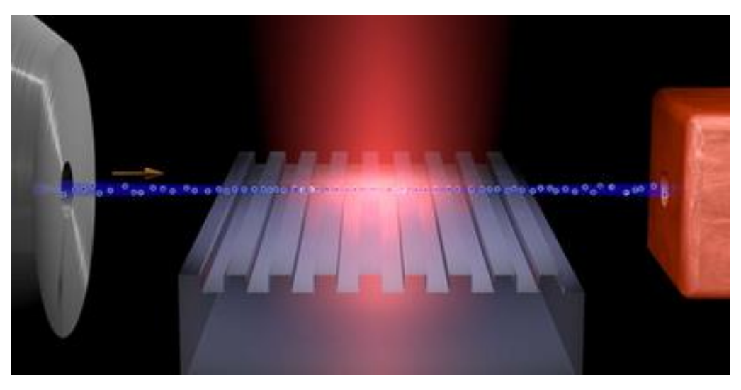

Figure 1: A DLA demonstrating the inverse smith Purcell concept. Laser is shined perpendicular to the grating periodicity. [1]

Inverse Smith-Purcell effect and grating optimization

- Smith-Purcell radiation is observed when a charged particle travels in the vicinity of periodic metallic/dielectric grating structures.
- Inverse concept of this effect is used for acceleration of electrons [2].
- Periodic grating structures are optimized using synchronicity condition

$$mk_g + k/(\beta \cos \alpha) = 0$$

where m = order of harmonic, k_g = grating period wave vector, β = relativistic velocity factor, α = grating tilt angle.

Motivation

- Most present DLAs are operated by solid state laser and near IR laser (800 nm to 2 μm), posing restrictions over the geometry tolerance and the amount of charge to be accelerated.
- Longer wavelength laser eases these restrictions, easier to focus electron bunch into the vacuum channel [3,4]

Minimizing emittance growth with high energy gain is a challenge. We present numerical simulation study, investigating various injection schemes for electron bunch and laser pulse to address this issue.

CST simulations

Full 3- D Time domain simulations in CST [5].

Input parameters	Value
Electron bunch energy	49.4 MeV
Energy spread	570 eV
Bunch charge	4 pC
Bunch longitudinal width	30 μm rms
Bunch transverse width	2.5 μm rms
Emittance	1.239e-8 m-rad
Laser wavelength	1 mm
Laser peak field	1 GV/m

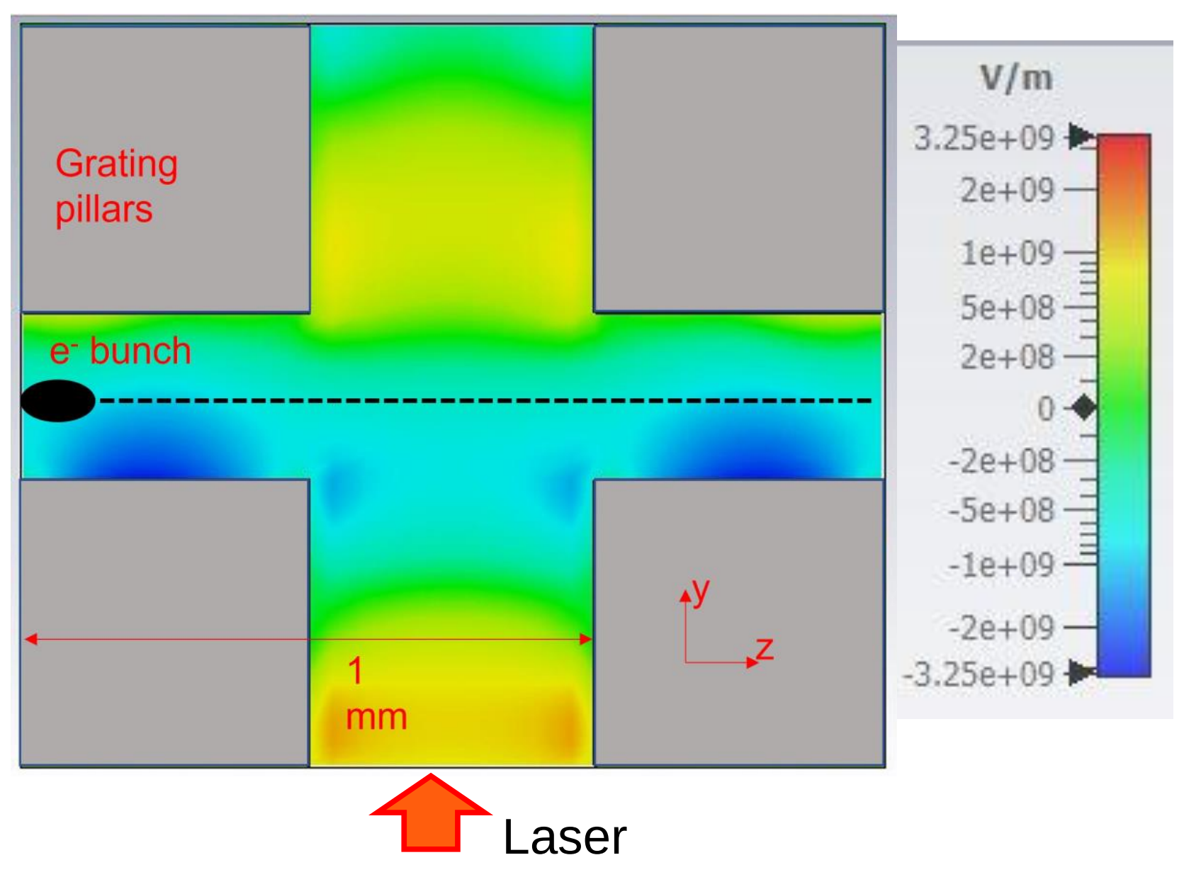

Figure 2: Electric field inside the grating structure.

A gaussian laser pulse with 1/e^2 diameter of 0.5 mm, maximum energy of 5 mJ and a pulse width of 5 ps can provide such a field amplitude.

- A 6-D gaussian electron bunch was defined in Matlab with the bunch parameters given in the table.

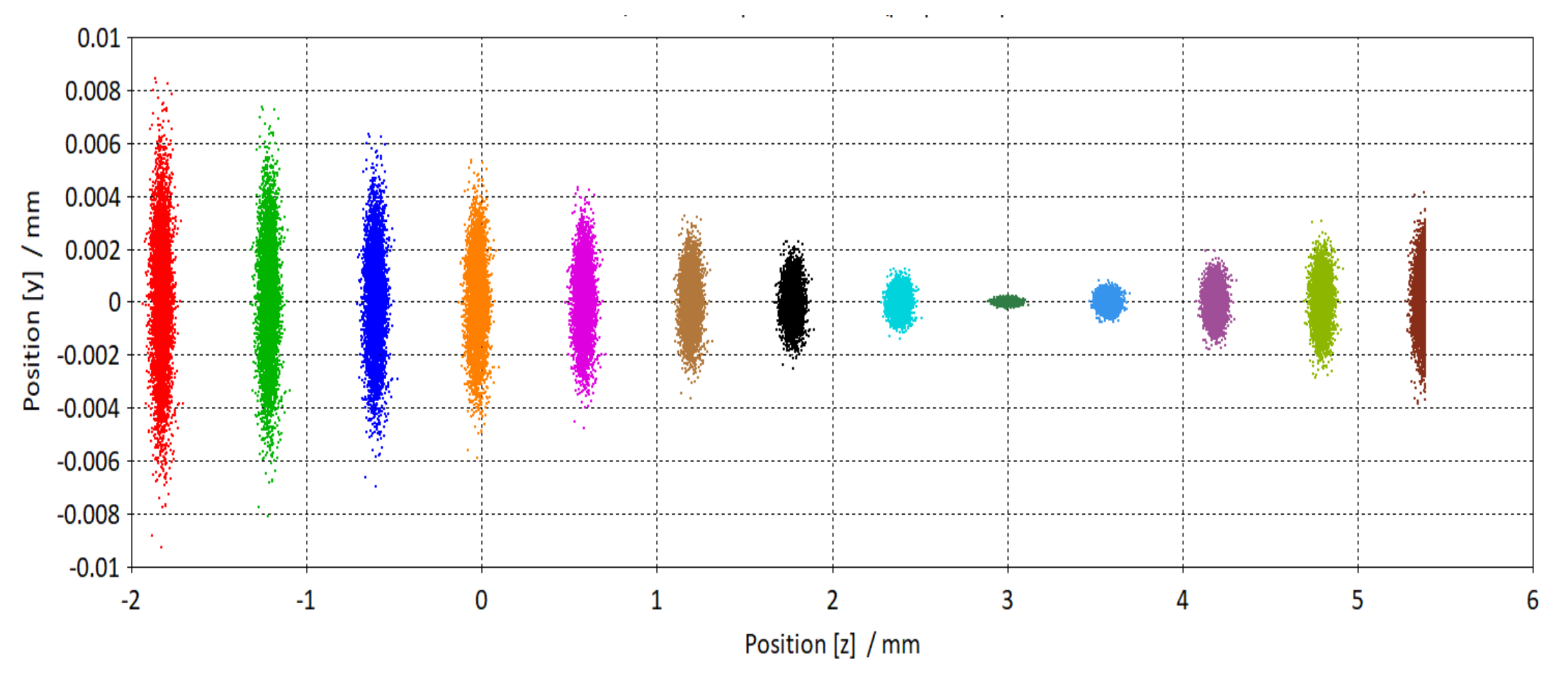

Figure 3: Electron bunch propagation in vacuum with an introduced focusing at the entrance of the grating structure. Each color represents the electron bunch position space, 1 ps apart.

We chose silicon with a dielectric constant of 11.59 for simulation studies. The structures with a grating period of 1 mm can be easily fabricated with commercial additive manufacturing technique.

Numerical Cherenkov radiation in CST simulation

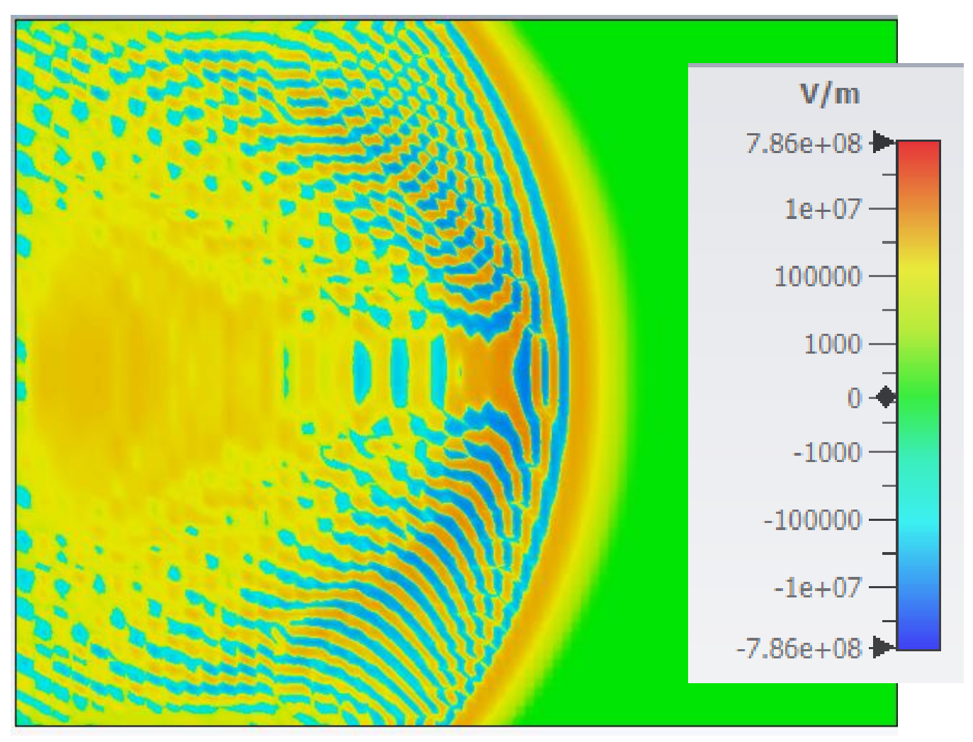

Figure 4: Electron bunch travelling in vacuum showing numerical Cherenkov instability.

Particle in cell simulation results

- To mitigate the numerical instability we used a time dependent emission model. We used a metal substrate to create image charge.

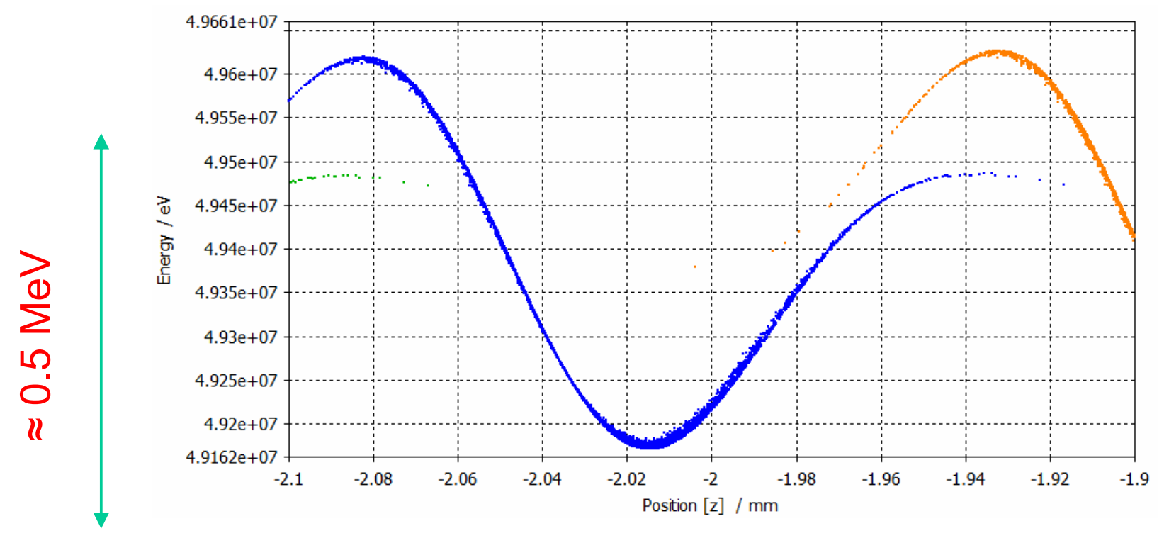

Figure 5: Electron bunch energy oscillations in vacuum, with an oscillation amplitude of 0.5 MeV

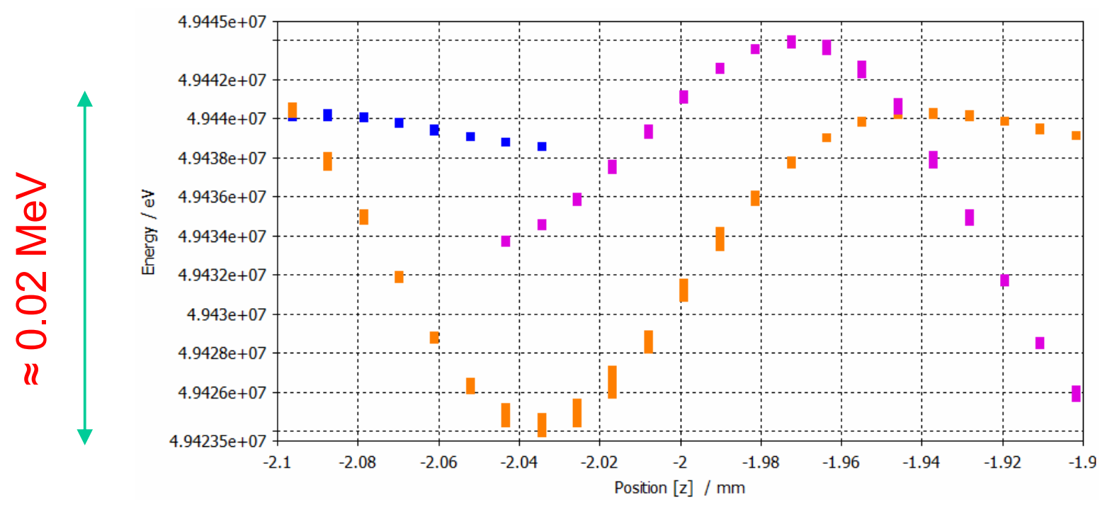

Figure 6: Bunch energy with a time dependent emission model. The oscillation amplitude is significantly decreased Different color represents bunch at different time instant.

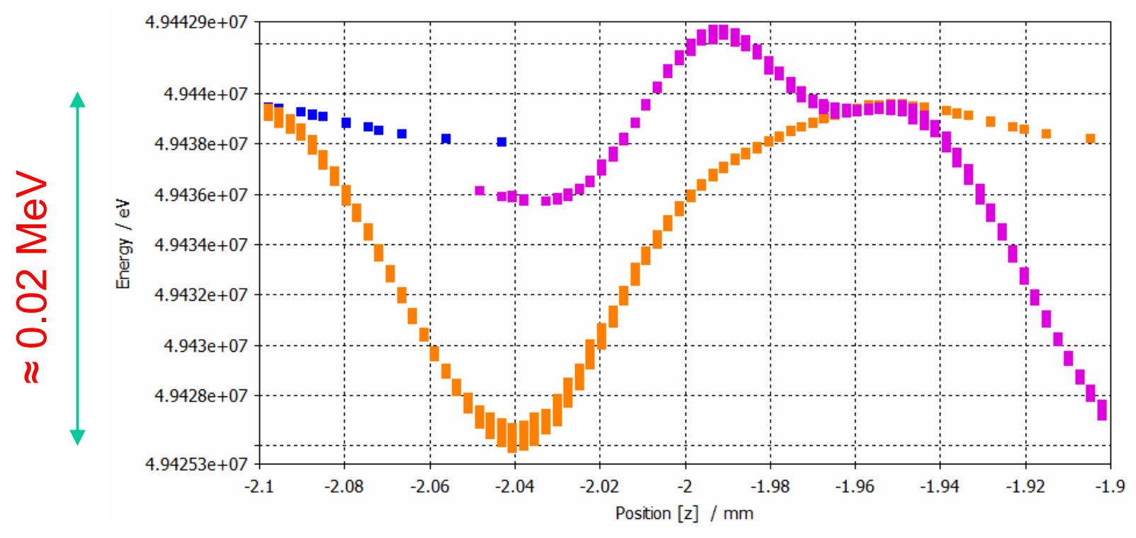

Figure 7: Bunch energy with a time dependent emission model from a metallic substrate. The oscillation amplitude is decreased further to 0.01 MeV. Different color represents bunch at different time instant.

- After incorporating the electron bunch focusing scheme and a time dependent emission model, the electron bunch was made to travel inside the grating channel and achieved a 0.5 MeV energy with an acceleration gradient of 350 MeV/m.

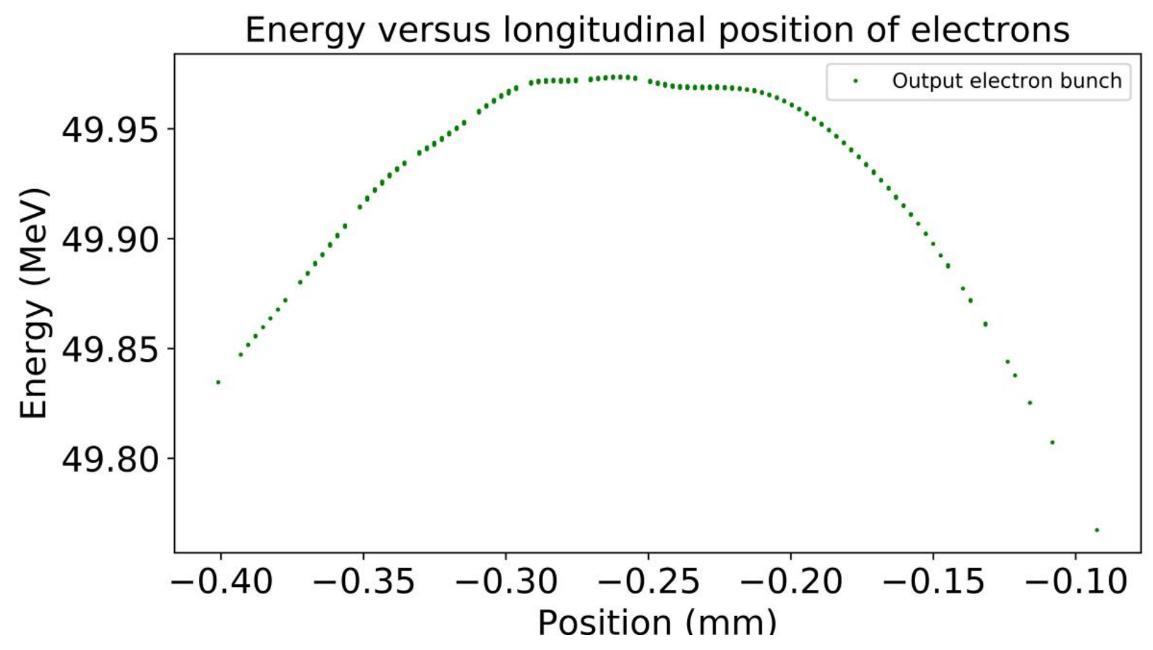

Figure 8: Energy versus the longitudinal position of all the electrons after acceleration.

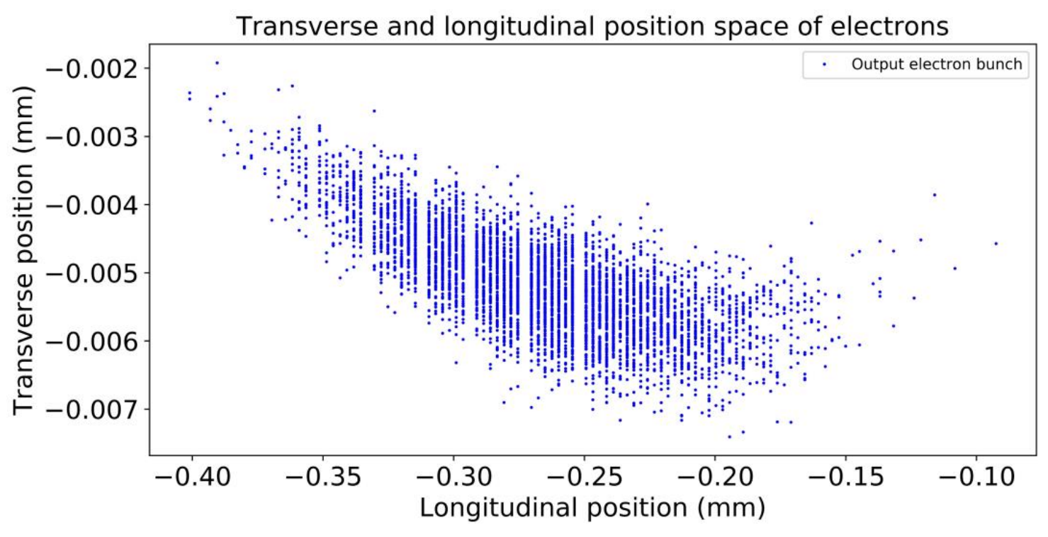

Figure 7: Position space of the electron bunch while exiting the grating structures after acceleration..

Output parameters	Value
Peak energy	49.97 MeV
Mean energy	49.96 MeV
Energy spread	0.017 MeV
emittance	1.235e-8 m-rad
Mean energy gain	0.5 MeV
Acceleration gradient	350 MeV/m

Hexahedral mesh were used for studies, with minimum resolution of 0.003 mm.

The time delay between the laser pulse and electron bunch was tuned for maximum energy gain.

Conclusion and future directions

- We mitigated the numerical Cherenkov instability in CST simulations by introducing a time dependent emission model for the electrons.
- We have shown the acceleration of relativistic electrons with a special injection scheme and driven by a THz pulse. A 4 pC electron bunch achieved an energy gain of 0.5 MeV inside 1.5 mm long grating structure with preserved emittance and less than 5% energy spread.
- To achieve higher energy gain and longer interaction of the laser fields with the electron bunch, pulse front tilt can be implemented. Multistage structures can be used with further optimization of electron bunch and laser pulse injection.

References

[1] Breuer J. *et al*, Laser-Based Acceleration of Nonrelativistic Electrons at a Dielectric Structure. Phys. Rev. Lett. 111, 134803 (2013).

[2] Peralta E A, *et al*, Demonstration of electron acceleration in a laser-driven dielectric microstructure, *Nature 503, 91–94 (2013).*

[3] Kimura W. D., *et al*, CO2-Laser-Driven Dielectric Laser Accelerator, *IEEE Advanced Accelerator Concepts Workshop (AAC)*, pp. 1-5 (2018).

[4] Yadav G. *et al,* Simulations for MeV Energy Gain in Multi-Micron Vacuum Channel Dielectric Structures Driven by a CO$_2$ Laser, JACoW IPAC2021 MOPAB143 (2021).

[5] https://www.3ds.com/products-services/simulia/products/cst-studio-suite/

Acknowledgement

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