DLA Flat Vs Periodic Structure for Low Energy Electron Beam Acceleration

Andrii Vasyliev, Gennadiy Sotnikov, Anatoliy Povrozin and Oleg Svistunov

January 19, 2023

DLA FLAT VS PERIODIC STRUCTURE FOR LOW ENERGY ELECTRON BEAM ACCELERATION

Andrii V.Vasyliev
National Science Center "Kharkov Institute of Physics and Technology"
Kharkiv, Ukraine
vasilyev.andrey90@gmail.com

Gennadiy V. Sotnikov
National Science Center "Kharkov Institute of Physics and Technology"
Kharkiv, Ukraine
gennadiy.sotnikov@gmail.com

Anatolij I. Povrozin
National Science Center "Kharkov Institute of Physics and Technology"
Kharkiv, Ukraine
anatoliypo@gmail.com

Oleh O. Svistunov
National Science Center "Kharkov Institute of Physics and Technology"
V.N. Karazin Kharkiv National University
Kharkiv, Ukraine
oleg.svistunov.98@gmail.com

***Abstract*—The dependence of the acceleration rate of charged particle bunches with the energy of 300 keV by a surface wave excited by a laser pulse is analyzed using flat and periodic chip structures. It is shown that when using periodic structures with the 2nd operating spatial mode, there is a decrease in the acceleration rate in comparison with the use of periodic structures with the 1st operation mode. It is also demonstrated that the acceleration rate when using a flat dielectric structure is significantly higher in comparison with a periodic chip structure.**

Keywords—dielectric laser accelerator, periodic chip structure, Gaussian laser pulse, electron beam.

I. INTRODUCTION

Nowadays dielectric laser accelerators (DLA) occupy one of the leading niches in the field of research of new acceleration methods . Currently, several types of dielectric laser accelerators are being developed, using a woodpile type structure [1], a periodic dielectric chip structure [2,3], and using a flat structure where acceleration is carried out by a surface wave [4,5]. All of them are united by high rates of acceleration and miniature size. However, they have slightly different acceleration principles and shortcomings associated with these principles.

In this paper, we consider two types of dielectric laser accelerators. The first is a widely studied accelerator based on a periodic dielectric chip structure, which is currently being studied at SLAC [2,3] within framework the A-chip program.. And the second type of acceleration with using a flat dielectric structure, theoretically studied at NSC KIPT, based on which published a patent [6], and in the works of other authors [4]. We compare these types for accelerating electrons with the electron energy of 300 keV, the electron velocity is near the lower limit of phase velocity of a surface wave excited by a laser pulse on the boundary of a quartz flat dielectric structure.

We had already considered the acceleration with using a periodic chip structure y [7,8], as well as the surface wave acceleration with using a flat structure [5], the last method showed its high efficiency acceleration of low-energy electrons. These methods are compared with each other at the same parameters of laser pumping and electron bunch energy in order to highlight their positive and negative aspects in this article.

This paper considers cases of electron acceleration in a single structure with one-sided laser pumping.

In order to approach the simulation results to the real experiment, the field amplitude created by the laser was equal to 6 GV/m, this is the maximum field amplitude that a periodic quartz chip structure can withstand without damage, as shown in [9].

All simulations were carried out at the same parameters of laser radiation. The Gaussian beam makes it possible to obtain simulation results that are close to real experiments. Its electric field can be represented as follows:

$$\begin{aligned} &\mathrm{E}(\mathrm{r},\mathrm{x},\mathrm{t}) \\ &= \mathrm{E_p}\frac{\omega_0}{\omega(\mathrm{x})}\exp\left[\frac{\mathrm{r}^2}{\omega(\mathrm{x})^2}\right]\exp\left[-2\ln(2)\frac{(\mathrm{x}-\mathrm{ct})^2}{\mathrm{c}^2\mathrm{t}_0^2}\right] \\ &\times \Re\left\{\exp\left[\mathrm{i}\omega_0\mathrm{t}-\mathrm{ik}_0\mathrm{x}-\mathrm{ik}_0\frac{\mathrm{r}^2}{2\mathrm{R}(\mathrm{x})}+\mathrm{i}\psi_\mathrm{g}(\mathrm{x})\right]\right\} \end{aligned} \quad (1)$$
,

where E_p is an amplitude of the electric field; ω_0 is a waist or the smallest transverse size of the laser in the focal plane (x=0); c is the speed of light; t_0 is full width at half maximum of the pulse duration; $k_0 = 2\pi/\lambda_0$ and $\omega_0 = ck_0$ represent the wave number and angular frequency of the laser beam with the wavelength λ_0 respectively.

The propagation of a Gaussian laser pulse is completely characterized by the beam waist $\omega(x)$, the radius of curvature of the wave front R(z), and the Guy phase shift $\psi_g(x)$ as the function of x,

$$\omega(\mathrm{x}) = \omega_0\sqrt{1+\left(\frac{\mathrm{x}}{\mathrm{x_R}}\right)^2};\ \mathrm{R}(\mathrm{x}) = \mathrm{x}\left[1+\left(\frac{\mathrm{x}}{\mathrm{x_R}}\right)^2\right]; \quad (2)$$
$$\psi_\mathrm{g}(\mathrm{x}) = \arctan\left(\frac{\mathrm{x}}{\mathrm{x_R}}\right)$$
,

where $x_R = \pi\omega_0^2/\lambda_0$ is the Rayleigh length, which represents the position at which the transverse area of the laser beam is doubled compared to the area in the focal plane due to difraction.

The laser beam with $\omega_0 = 20$ µm (at half level), with a central wavelength of 800 nm. The initial energy of the accelerated electrons was 300 keV. The distance of electron flight over the surface of the structure was 200 nm in all cases.

II. Acceleration on flat structure

The scheme of acceleration in the flat structure by a surface wave is shown in Figure 1.

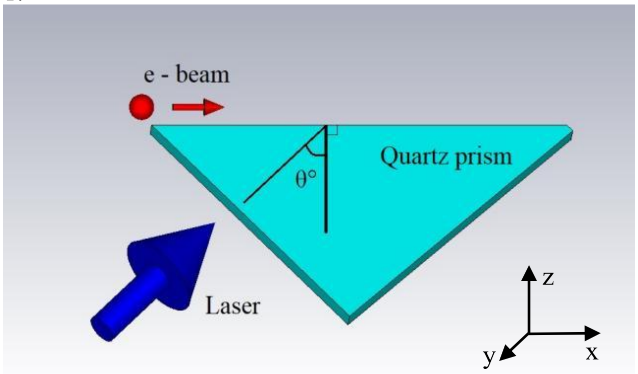

Fig. 1. Schematic diagram of surface wave acceleration in a flat dielectric structure with one-sided laser pumping.

The electron beam propagates at a distance of 200 nm above the plane of the quartz prism. The laser beam is directed at the side surface of the prism at a right angle and falls on the inner surface of the prism at an angle θ.

When accelerating by a surface wave in a flat structure, it is necessary to satisfy the condition of Cherenkov synchronism between the accelerated beam and the surface wave. The change in the phase velocity of the surface wave is made by changing the angle of incidence θ, which can be calculated by the formula:

$$\sin\theta = \frac{1}{n\cdot\beta} \tag{3}$$

where *n* - is the refractive index of the prism material at the pump laser wavelength, *β* - is the electron beam velocity, is calculated by the formula:

$$\beta = \frac{v}{c} = \sqrt[2]{1-\left(\frac{E_0}{E_k+E_0}\right)^2} \tag{4}$$

where *v* is an electron velocity, *c* - is the speed of light, E_0 - rest energy of an electron, E_k -electron kinetic energy.

For an electron energy of 300 keV, using formula (3) for n= 1.45 (quartz), we obtain the angle θ= 62.39 degrees.

The numerical simulation of acceleration was carried out by using the Particle In Cell algorithm, the length of interaction of electrons with a surface wave was 16 µm.

The electron beam is injected parallel to the hypotenuse of the prism (x-coordinate, see Fig. 1), electron injection is carried out in such a way that the beam would reach the maximum intensity of the laser field. Figure 2 shows a graph of the distribution of the amplitude of the longitudinal component of the accelerating field (x - component) formed by the laser over a flat structure, along the direction of electron injection.

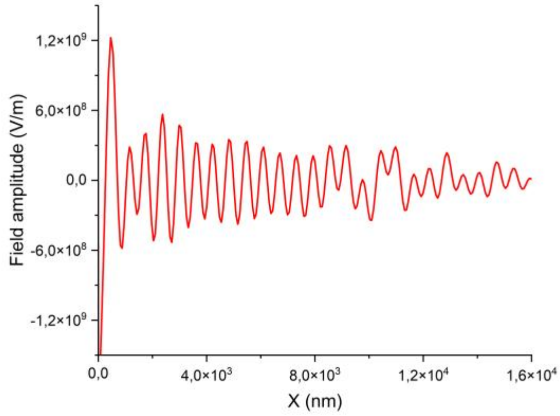

Fig. 2. Distribution of the longitudinal components of the accelerating field above the surface of a flat structure at a height of 200 nm.

The first peak with high intensity is caused by light diffraction at the edge of the prism, the field inhomogeneity at the end is due to reflections on the second face.

Figure 3 shows the results of simulation of the excited field by the laser pulse at the entrance to the prism, in the prism itself, and the accelerating field above its surface.

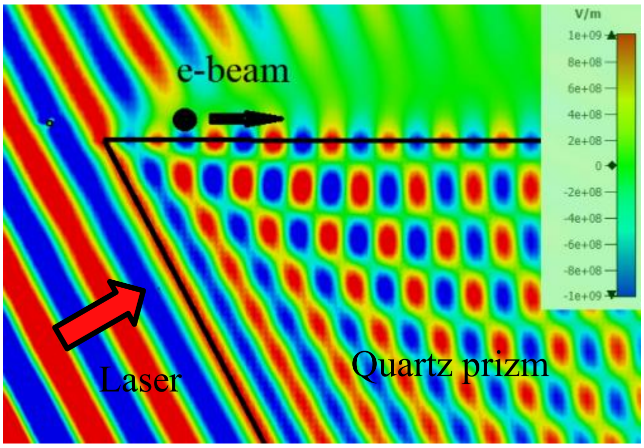

Fig. 3. Electric field generated by the laser and a prism in the space of interaction (blue - accelerating field, red – decelerating one).

A significant advantage of the acceleration method with using a flat dielectric structure, in comparison with periodic ones, is the possibility of using ultrashort laser pulses due to the input of radiation at the phase-matching angle. As can be seen from Figure 3, if an accelerated electron "lands" at the maximum of the wave front, then throughout the entire acceleration it is at the maximum of this wave that accompanies it, the acceleration process is limited only by the diameter of the laser beam and the design of the prism. In contrast to the case of acceleration on a periodic chip structure, where the limitation is introduced by the pulse duration, as well as the acceleration length is affected by the time envelope of the pulse intensity, after which it is necessary to install a new acceleration section. In simulation, the beam length was 1650 nm. Due to the fact that acceleration occurs at a distance of 16 μm, which is significantly lower than the dephasing distance, we can assume that the electron beam is locked to the phase of the wave throughout the entire interaction space.

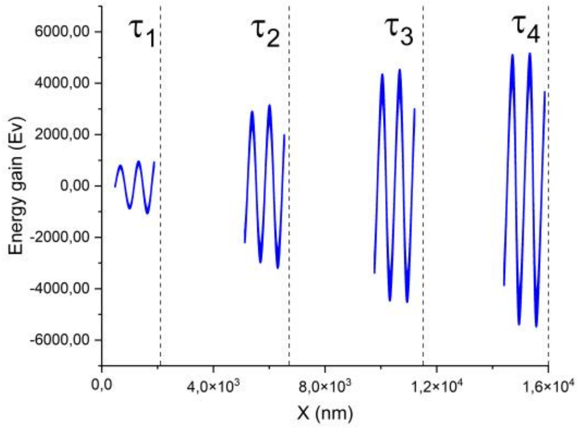

Fig. 4. Change in the energy of bunch electrons accelerated over a flat structure at specified time intervals.

Figure 4 shows the change in the energy of bunch electrons at different times τ with a step Δτ=20 fs. The length of the interaction is 16 μm. Since the electron beam spans two optical periods with its length, we can observe the full spectrum of electron energies, both accelerated and decelerating. We can determine the maximum possible increase in the energy of electrons that have fallen into the optimal phase and calculate the maximum of acceleration rate in a flat structure under given conditions. According to Fig. 4, the maximum of the acceleration rate is 318 MeV/m.

III. Acceleration on Periodic Structure

The exciting laser pulse falls vertically on the periodic chip structure (Fig. 5), exciting the diffraction pattern of the accelerating field. Figure 5 shows the fundamental spatial harmonic. As this traveling wave harmonic moves from left to right, the electrons whose velocity matches its phase velocity are synchronously accelerated as they move along the accelerating phase of the harmonic.

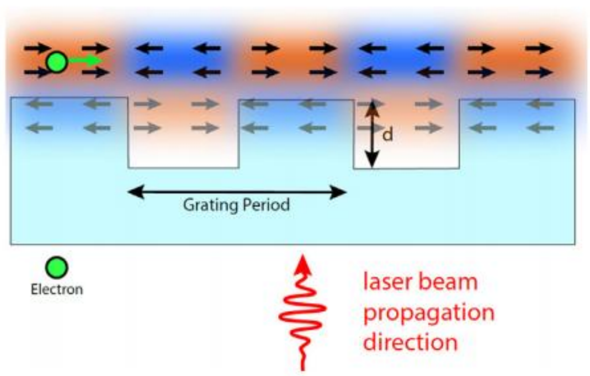

Fig. 5. Schematic diagram of acceleration by a surface wave on a periodic chip structure with one-sided laser pumping, d is the column height of the chip structure [10].

The conditions of synchronism of the accelerated beam with the wave diffracted on the grating gives the for a grating period λ_p

$$\lambda_p = k\beta\lambda \qquad (3),$$

where λ is the central wavelength of the laser radiation spectrum, k is the number of the spatial harmonic arising due to the diffraction of the incident wave by the grating, k = 0, 1, 2,…[11].

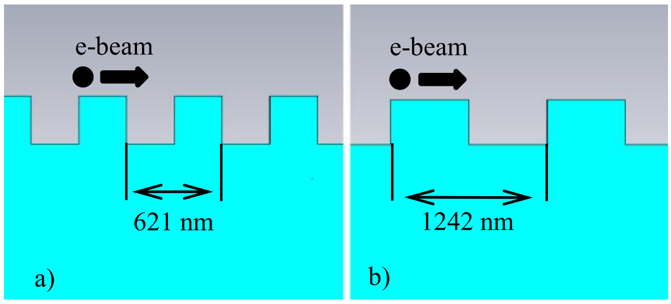

Fig. 6. Scheme of surface wave acceleration in a periodic chip structure for electrons with an energy of 300 keV, a) for the case of acceleration in the main mode k=1, b) for the case of acceleration in the second mode k=2.

Figure 6 shows the linear dimensions of the grating with period λ_p for simulation of electron acceleration by the first harmonic, Fig.6.a), and by the second harmonic, Fig.6.b). Chip structure column height d = 400 nm. Simulation of electron acceleration by different harmonics will make it possible to compare the efficiency of acceleration by different spatial harmonics.

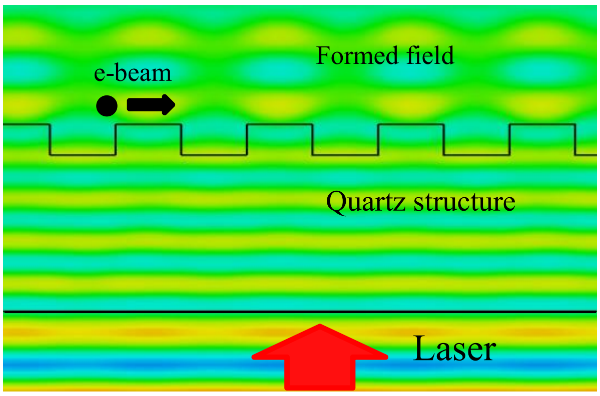

Fig. 7. Accelerating field formed by the quartz chip structure and the laser pulse.

Figure 7 shows the exciting laser field at the entrance of the chip structure and the accelerating field above the grating surface. The blue antinodes above the columns show the field minima through which the electron beam is accelerated. Field maxima are shown in yellow.

In Figure 8 shows the distributions of the longitudinal components of the fields for various harmonics along the direction of the initial electron injection.

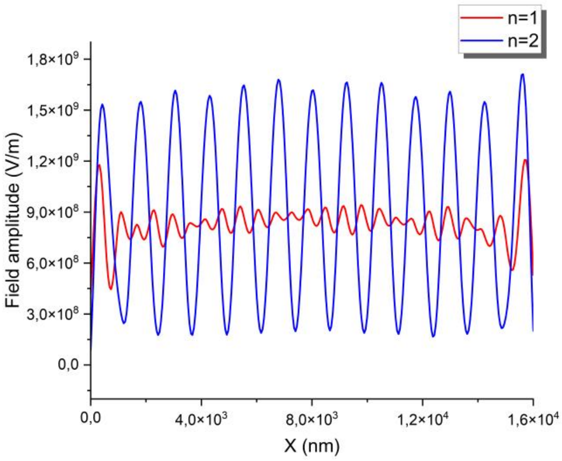

Fig. 8. Distribution of the longitudinal components of the accelerating field above the surface of the periodic chip structure at a height of 200 nm, red curve - acceleration with using the 1st mode, blue curve - acceleration with using the 2nd mode.

In Fig. 8 in red color shows the longitudinal distribution of the field for the case of acceleration in the main mode k=1, in blue - for the case of acceleration in the second mode k=2. The field characteristic was taken for the moment when the electron beam is above the tooth at the maximum of the accelerating field. We can observe a significant difference in the modulation and intensity of the field, which does not significantly affect the acceleration rate of the electron bunch, as evidenced by Fig. 9, which shows the change in the energy of electron bunches for electron acceleration using the 1st and 2nd mode.

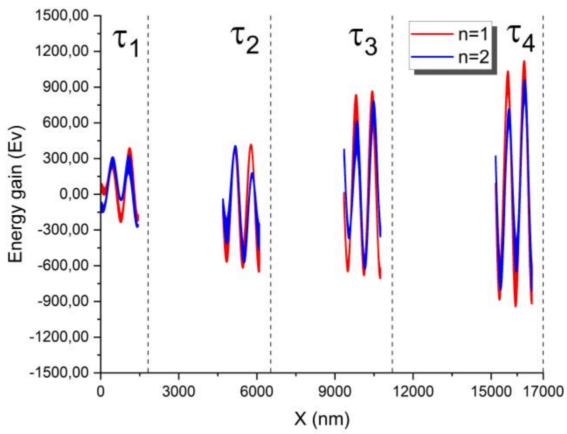

Fig. 9. Change in the energy of electron bunches accelerated over a periodic dielectric chip structure at specified time intervals, red curve corresponds to the - acceleration with using the 1st mode, blue curve - the acceleration with using the 2nd mode

Acceleration with using the 1st harmonics (red curve in Fig.9) gives a slightly larger increase in the acceleration rate (71.9 MeV/m) compared to the acceleration rate for the case of acceleration in the 2nd mode (60 MeV/m).

Thus, a comparison of the electron acceleration rates for flat and periodic chip structures shows that flat chip structures provide an acceleration rate 4–5 times higher than for periodic chip structures.

CONCLUSIONS

The carried out simulation experiments show that for the same laser parameters and relatively low energies of the electron beam, the acceleration by a laser pulse using a flat dielectric structure gives a significantly higher acceleration rate than using a periodic chip structure. What makes this method preferable for use to accelerate electrons with initially low energy.

Comparison simulation experiments for high electron energies were also carried out, the results will be presented in further publications.

ACKNOWLEDGMENT

The study is supported by the National Research Foundation of Ukraine under the program "Leading and Young Scientists Research Support" (project # 2020.02/0299), by NAS of Ukraine program "Perspective investigations on plasma physics, controlled thermonuclear fusion and plasma technologies", project P-1/63-2020.

REFERENCES

[1] C. McGuinness, E. Colby, R.J. England, "Fabrication and Characterization of Woodpile Structures for Direct Laser Acceleration", SLAC-PUB-14228, 2010, DOI: 10.1063/1.3520360.

[2] J. Breuer, P. Hommelhoff "Laser-Based Acceleration of Nonrelativistic Electrons at a Dielectric Structure" PRL 111, 134803, 2013, pp. DOI: 10.1103/PhysRevLett.111.134803

[3] R.J.England, Z.Huang "Dielectricandothernon-plasmaacceleratorbased compact lightsources", 60th ICFA Advanced Beam Dynamics Workshopon Future Light Source, FLS2018, Shanghai, China, JACoW pp.75-78, 2018, doi:10.18429/JACoW-FLS2018-WEA1PL02.

[4] Weihao Liu , Zijia Yu, Li Sun, et al. "Microscale Laser-Driven Particle Accelerator Using the Inverse Cherenkov Effect", PHYSICAL REVIEW APPLIED 14, 014018, 2020.

[5] O.O. Bolshov, A.V.Vasiliev, A.I. Povrozin, G.V. Sotnikov, "About the acceleration rate of relativistic beams by a surface wave in a dielectric laser accelerator", Problems of Atomic Science and Technology, 136(6), 2021, pp. 57–60.

[6] A.I. Povrozin, A.V.Vasiliev, G.V. Sotnikov "The method of electron acceleration by surface electromagnetic waves excited by a laser beam", Application for an invention №u201909665 from 05.09.2019.

[7] A.V. Vasyliev, O. Bolshov, K. Galaydych, A. Povrozin, G.V. Sotnikov, "Influence of the profile of the dielectric structure on the electric fields excited by a laser in dielectric accelerators based on-chip", Proc. 13th Int. Conf. on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'11), Grenoble, France, 2021, paper ID TUPAB247.

[8] J. Breuer, "Dielectric laser acceleration of non-relativistic electrons at a photonic structure", dissertation, Munchen , 2013.

[9] O.O. Bolshov, A.V.Vasiliev, A.I. Povrozin, G.V. Sotnikov, K.V. Galaydych / Acceleration of electron bunches using periodic dielectric structures with and without coating, Problems of Atomic Science and Technology, 134(4), 2021, p. 60–64.

[10] J. McNeur, et al., / Laser-driven acceleration of subrelativistic electrons near a nanostructured dielectric grating: From acceleration via higher spatial harmonics to necessary elements of a dielectric accelerator, Nuclear Instruments & Methods in Physics Research A 2016, DOI:10.1016/j.nima.2016.01.009i.

[11] R. Palmer, "A laser-driven grating linac", Part. Accel. 11, 1980, pp. 81–90.