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INFLUENCE OF THE PROFILE OF THE DIELECTRIC STRUCTURE ON THE ELECTRIC FIELDS EXCITED BY A LASER IN DIELECTRIC ACCELERATORS BASED ON CHIP*

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Abstract

To provide experimental researches at the NSC KIPT theoretical studies and computations of the electron acceleration in a dielectric laser accelerator have been carried out. Laser accelerator consists of two periodic quartz structures on diffraction gratings or CHIPs, symmetrically located along both sides of the vacuum accelerating channel. Using PIC numerical simulations, electromagnetic fields excited by laser radiation with a wavelength of 800 nm in dielectric laser accelerators were investigated. The influence of the shape and depth of the profile of diffraction gratings or CHIP structures on the distribution of the electric field in the interaction space has been studied. For modeling, different types of profiles were taken, both in serial and a unique structure. In consequence of the analysis of the obtained results, estimated efficiency of acceleration was defined for each type of profile. The rectangular profile of the diffraction grating with the maximum accelerating gradient was selected as optimal for the next experiments.

MANUSCRIPTS

Today, accelerators excited by laser pulses are given an increasing place in research practice with a view to their promising application in such fields as medicine, materials science, biochemistry, and in physics - the production of ultrashort electron bunches of the order of 3-10 fs. Along with the development of laser-plasma accelerators [1], the development of accelerators based on CHIP structures has recently occupied a special niche. [2, 3].

For accelerators based on CHIP structures, two directions are relevant. This - with the maximum miniaturization of devices - obtaining the maximum efficiency of acceleration and on this basis - their optimization for the production of this type of accelerators for consumer and research purposes.

One of the important issues, which affects the degree of acceleration of charged particles, is associated with a change in the geometric parameters of CHIP structures. This work is devoted to this problem.

Below is a series of experiments performed by us to simulate the acceleration of electrons on periodic structures of various profiles when they are excited by plane and Gaussian waves. A comparative analysis was carried out, which determined the choice of the best structure. The acceleration principle is widely known and described in [4] for a rectangular CHIP structure.

Under the condition of the incidence of radiation perpendicular to the plane of the grating and its lines, the acceleration of particles will occur along the surface of the grating also perpendicular to its lines [4, 5]. Let us denote x as the coordinate along the lattice lines and perpendicular to the motion of the particles; y is the coordinate perpendicular to the lattice surface, and z is along the direction of particle motion. For the condition of synchronization of the electron velocity with the phase velocity of the exciting wave, one can use the formula [2]:

$$\lambda_p = n\beta\lambda \, , \tag{1}$$

where n - mode of the electromagnetic field excited by the incident wave on the grating; $\beta = v/c$ dimensionless speed, v - electron speed, c - speed of light; λ - wavelength of the exciting laser radiation.

Using the PIC numerical simulation method taking into account the exciting fields taken from [6, 7], we investigated the effect of the height of the electron beam above the surface of the CHIP structure, as well as the shape of the structure profile on the acceleration rate. The simulation was carried out for electron energies of 50 MeV and 2.1 MeV. Dimensionless velocity was defined as:

$$\beta = \sqrt{1 - \frac{1}{\left(1 + \frac{E_{kin}}{mc^2}\right)^2}} \, . \tag{2}$$

where E_{kin} - electron energy.

For electrons with an energy of 50 MeV at n = 1 and $\beta = 0.9995$, the period of the CHIP structures was determined by the Eq. (1). The result showed that $\lambda_p \approx \lambda = 800nm$ with an accuracy of 0.05%. To demonstrate the desynchronization, which is 2%, at an electron energy of 2.1 MeV ($\beta = 0.981$), the simulation was carried out with the same value λ_p. The results will be shown below

At all stages of modeling, structures with a length of L = 16 μm were used. For a comparative analysis of the acceleration efficiency on various types of structures, the structures shown in Fig. 1 were used in the experiments.

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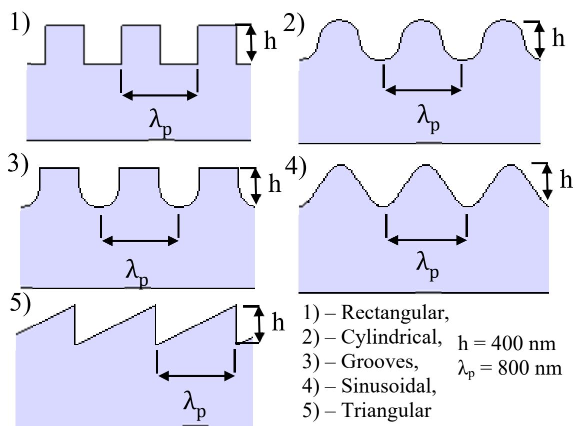

Figure 1: The different profiles of the investigated periodic CHIP structures.

The height of the pillar in all cases was h = 400 nm. The width of the pillar for all cases was also 400 nm, except for the triangular profile.

Plane Wave Modeling

When the structure was excited by a plane wave with an electric field strength $E_p = 10^9$ В/м, the wave fell perpendicularly from the side of the structure substrate.

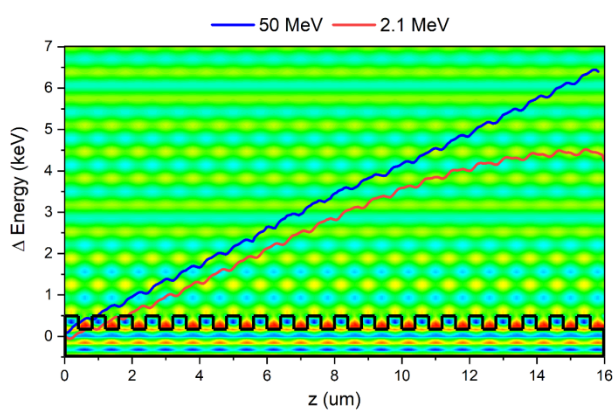

Figure 2: Distribution of the field excited by a plane wave over a rectangular structure.

Figure 2 shows the distribution of the field excited by a plane wave over a rectangular structure and the dependence of the increment in the average electron energy at a beam height of 200 nm. It can be seen how the effect of desynchronization affects the increase in the average energy of electrons with an initial energy of 2.1 MeV.

The results of the effect on the rate of acceleration of the change in the height of the electron beam above the surface of a CHIP structure with a rectangular profile are shown in Fig. 3.

Figure 3 shows a decrease in the energy gain depending on the height of the electron beam for the case of a plane wave. Similar experiments with modeling were also carried out for CHIP structures with profiles 2, 3, 4, 5 in Fig. 2. Based on the results obtained, the acceleration gradients were calculated for each case, which are summarized in Table 1.

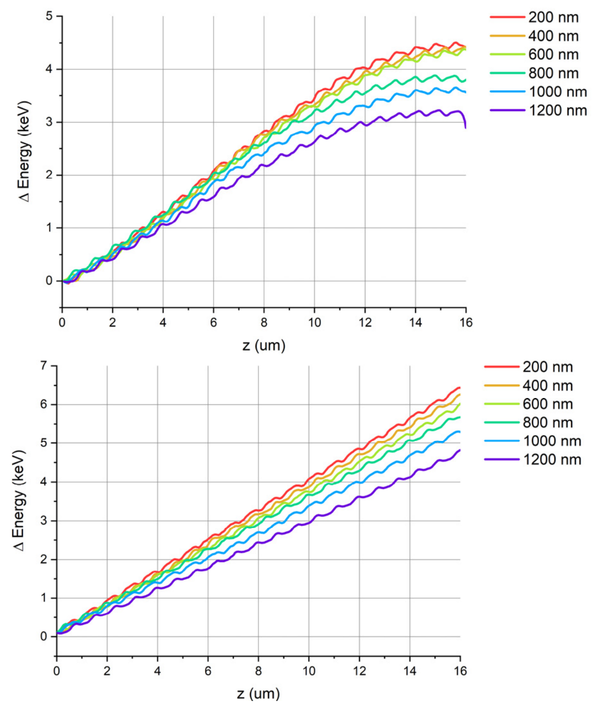

Figure 3: Increasing the average electron energy for different heights of the beam over a rectangular structure excited by a plane wave.

Table 1: Acceleration Gradients for Different Profiles Excited by a Plane Wave

Beam height y, nm	Gradient for plane wave, [MeV/m]									
	2.1 MeV					50 MeV				
	1	2	3	4	5	1	2	3	4	5
200	313	266	271	248	119	413	350	350	331	163
400	306	259	251	244	118	400	331	325	319	153
600	300	241	228	241	116	388	313	300	306	145
800	281	216	209	221	110	363	288	275	286	141
1000	256	199	191	196	91	338	256	238	264	129
1200	234	182	168	179	85	313	225	204	238	115

From the results obtained, we can conclude that the acceleration gradients for the case of desynchronization are on average 25% lower than for the case when synchronization takes place.

Gauss Beam Modeling

In order to approximate the simulation results to a real experiment, a simulation was performed for the excitation of CHIP structures with a Gaussian field:

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$$E(r,z,t) = E_p \frac{w_0}{w(z)} \exp\left[-\frac{r^2}{w^2(z)}\right] \exp\left[-2\ln(2)\frac{(z-ct)^2}{c^2\tau_0^2}\right] \quad (3)$$
$$\times \Re\left\{\exp\left[i\omega_0 t - ik_0 z - ik_0 \frac{r^2}{2R(z)} + i\psi_g(z)\right]\right\}.$$

where E_p - amplitude of the electric field, w_0 - waist or the smallest transverse size of the laser in the focal plane (z = 0), c - speed of light, τ_0 - full width at half maximum of the pulse duration, a $k_0 = 2\pi/\lambda_0$ and $\omega_0 = ck_0$ represent respectively the wavenumber and angular frequency of the laser beam with the wavelength λ_0. The propagation of a Gaussian laser pulse is completely characterized by the beam waist $w(z)$, the radius of curvature of the wavefront $R(z)$, and the Guy phase shift $\psi_g(z)$.

$$w(z) = w_0\sqrt{1+\left(\frac{z}{z_R}\right)^2}; \; R(z) = z\left[1+\left(\frac{z}{z_R}\right)^2\right]; \quad (4)$$
$$\psi_g(z) = \arctan\left(\frac{z}{z_R}\right).$$

where $z_R = \pi w_0^2 / \lambda_0$ - Rayleigh length that represents the position. The following parameters were used in the simulation: τ_0 = 150 fs, $E_p = 10^9$ V/m, $\lambda_0 = 800$ nm. A laser beam with $w_0 = 10$ µm was focused on the surface of the CHIP structure.

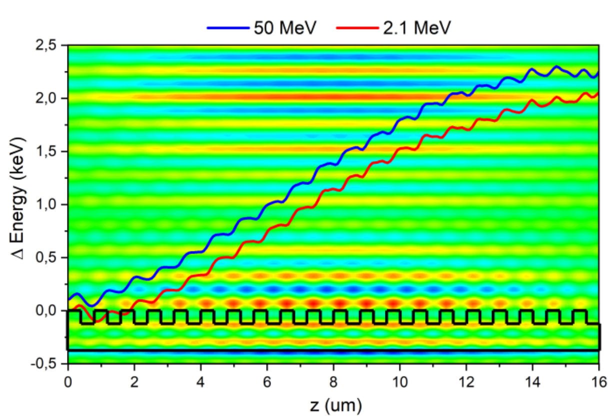

Figure 4: Distribution of the field excited by a Gaussian wave over a rectangular structure.

Figure 4 shows the distribution of the field excited by a 150-fs Gaussian pulse. Figure 4 also shows the change in the average values of electron beams at a height of 200 nm for 2.1 MeV and 50 MeV. The influence of the desynchronization effect on electrons with an energy of 2.1 MeV is no longer so significant when simulating with a Gaussian wave.

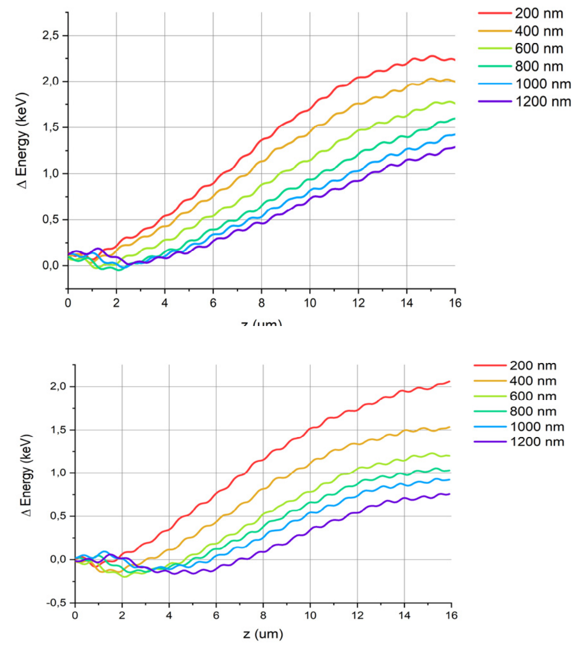

Figure 5: Increasing the average electron energy for different heights of the beam over a rectangular structure excited by a Gaussian beam wave.

In Figure 5 shows graphs of changes in the average energy of electron beams for different heights. Data from simulation experiments are summarized in Table 2.

You can see a qualitative agreement between the plane and Gaussian waves. As expected, a Gaussian momentum gives less acceleration than a plane wave.

Table 2: Acceleration Gradients for Different Profiles Excited by a Gaussian Beam Wave

Beam height y, nm	Gradient for gauss beam, [MeV/m]									
	2.1 MeV					50 MeV				
	1	2	3	4	5	1	2	3	4	5
200	150	158	142	150	70	151	130	111	116	62
400	112	111	104	103	48	134	110	104	100	52
600	84	81	75	75	36	117	94	97	84	41
800	76	69	64	62	33	104	83	86	76	36
1000	68	60	57	53	26	97	78	79	70	33
1200	56	47	48	42	20	86	68	74	59	29

CONCLUSION

Based on the results obtained, it can be concluded that it is possible to use structures with groove and sinusoidal profiles to create miniature accelerators, which, when approaching real experiments, are not much inferior to a rectangular profile.

To conduct experiments, in some cases, structures with incomplete matching can be used.

The practical value of the performed model experiments lies in the fact that industrial diffraction gratings can be used in real experiments.

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REFERENCES

[1] C. Joshi and V. Malka, "Focus on Laser- and Beam-Driven Plasma Accelerators", *New J. Phys.*, vol. 12, p. 045003, Apr. 2010. doi:10.1088/1367-2630/12/4/045003

[2] J. Breuer and P. Hommelhoff, "Laser-Based Acceleration of Nonrelativistic Electrons at a Dielectric Structure", *Phys. Rev. Lett.,* vol. 111, p. 134803, Sep. 2013. doi:10.1103/PhysRevLett.111.134803

[3] U. Niedermayer, O. Boine-Frankenheim, and T. Egenolf, "Designing a Dielectric Laser Accelerator on a Chip", *J. Phys.: Conf. Ser.,* vol. 874, p. 012041, Jul. 2017. doi:10.1088/1742-6596/874/1/012041

[4] R. J. England and Z. Huang, "Dielectric Accelerators and Other Non-Plasma Accelerator Based Compact Light Sources", in *Proc. 60th ICFA Advanced Beam Dynamics Workshop on Future Light Sources (FLS'18)*, Shanghai, China, Mar. 2018, pp. 74-78. doi:10.18429/JACoW-FLS2018-WEA1PL02

[5] I. Z. Borovskiy, S. V. Vilkov, N. A. Khizhnyakh, and V. G. Papkovich, "On the theory of laser acceleration over a dielectric comb", *PAST. Series: Tech. of Phys. Exp.,* vol. 3, no. 34, pp. 69-70, 1987.

[6] R. B. Palmer, "A Laser Driven Grating Linac", in *Proc. 11th International Conference on High-Energy Accelerators (HEACC'80),* W. S. Newman, Ed. Birkhäuser, Basel, 1980, pp. 375-384.

[7] J. Breuer, "Dielectric laser acceleration of nonrelativistic electrons at a photonic structure", Dissertation, LMU München: Faculty of Physics, Munich, Germany, Aug 2013. doi:10.5282/edoc.16147