

DESIGN STUDY OF THE LASER DRIVEN DIELECTRIC ACCELERATOR*

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Abstract

A parameter study for a dielectric accelerator taking account of nonlinear optical effects and higher harmonics of the acceleration field distribution was performed. The optimum pulse laser width was concluded to be 2 ps from the restrictions on the optical damage threshold intensity and the nonlinear optical effects. An irradiation intensity of $5 \times 10^{11} \text{ W/cm}^2$ (2 GV/m) was suitable for the accelerator made of silica with a pulse width range from 1 ps to 10 ps. The higher order harmonics of the axial electric field distribution was capable of accelerating electrons provided that the electron speed approximately satisfies the conditions of $v/c = 1/2, 1/3, \text{ or } 1/4$. The electrons at the initial energy of 20 kV are accelerated by an acceleration field strength of 20 MV/m, and the electrons were accelerated by higher fields as the speed increased. For relativistic energy electrons, the acceleration gradient was 600 MV/m.

PARAMETERS OF ACCELERATOR

Threshold Intensity of Laser Irradiation

An acceleration field of a laser driven dielectric accelerator (LDA) is produced by modulating a wavefront of a laser by properly designed dielectric structure. Previous works supposed that the irradiation intensity of the laser pulse is limited by the optical damage threshold intensity [1–5]. However, the nonlinear refractive index due to the optical Kerr effect, causing phenomena such as self-focusing (SF) and self-phase modulation (SPM), can significantly affect the deformation of the wavefront in dielectric materials, especially for ultra-short laser pulses of sub-picoseconds.

The condition for avoiding the SF is satisfied by maintaining the B-integral below π [6]. Using the value of $n_2 = 3.18 \times 10^{-20} \text{ m}^2/\text{W}$ for silica (SiO_2), highest intensity for avoiding SF is derived to be

$$I_0 \left[\text{W/cm}^2 \right] < 1.5 \times 12^{10} \lambda_0 \left[\mu\text{m} \right] / L \left[\text{mm} \right]. \quad (1)$$

A shift in the instantaneous phase in the pulse due to SPM causes phase mismatch between the electron motion and the alternating acceleration field. Therefore, the condition for avoiding serious phase mismatch due to SPM is estimated by

$$\frac{\Delta\lambda}{\lambda_0} = \frac{4\pi n_2 I_0 t L}{\lambda_0 \tau^2} \frac{\lambda_0}{2\pi c} < \frac{1}{4}, \quad (2)$$

where τ is the $1/e$ -width of the Gaussian laser pulse and $t = L/cn_0$ is the transit time of the laser pulse across the optical path length L . The refractive index of the dielectric is n_0 . The highest intensity for avoiding SF is derived as

$$I_0 \left[\text{W/cm}^2 \right] < 2.5 \times 10^{11} \tau^2 \left[\text{ps} \right] / L^2 \left[\text{mm} \right]. \quad (3)$$

The laser intensities restricted by SF and SPM are shown in Fig. 1. The upper limit of the irradiation intensity is defined by the SPM effect at pulse lengths shorter than 1 ps and by the damage threshold value at pulse lengths longer than 100 ps. The high intensity of 10^{12} W/cm^2 can be utilized provided that the path length of the laser is shorter than 1 mm and the laser pulse width is approximately 2 ps. Moreover, the irradiation intensity of $5 \times 10^{11} \text{ W/cm}^2$ (2 GV/m) is suitable in the pulse width range from 1 ps to 10 ps. It is unnecessary to consider the optical nonlinear effects for the LDA because the thickness of the base plate is smaller than 1 mm in many cases. However, it must be noted that SPM plays a significant role in other types of laser-driven dielectric accelerators, such as polariton or plasmon accelerators and their variations

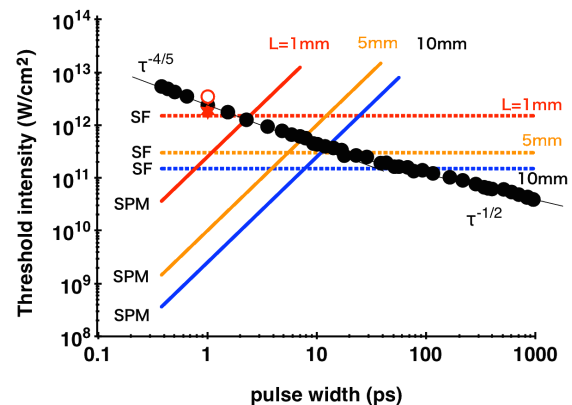


Figure 1: Threshold intensity of SPM (solid lines) and SF (dotted lines) as well as published damage threshold values for fused silica (circles and star) at different optical path lengths. Filled circles are deduced from the damage fluence data [7]. The red open circle and red star are published damage threshold values for the plane surface and the grating of silica, respectively [8]. The wavelength is assumed to be $1.03 \mu\text{m}$.

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Acceleration Field

Parameters of a transmission grating type LDA (TG-LDA) are illustrated in Fig. 2. Because the wavefronts were deformed during propagation in the pillar, the electric field distribution was deformed from the symmetry. To precisely study the acceleration field properties along a central line, we calculated the field distribution by using the finite-difference time-domain (FDTD) simulation software, Meep [9]. The acceleration field E_a was evaluated by integrating the electric field distribution along the electron trajectory in $x-t$ space, which is the so-called world line. Because E_a strongly depends on the start-phase (starting time) of the integral path, we calculated the complete phase set and selected the maximum value as the acceleration gradient. For the simulation studies, it was assumed that the grating period, the gap distance between gratings, and the intensity of the laser pulse were $L_G/\lambda_0 = 1$, $D/\lambda_0 = 0.25$, and $I_0 = 5 \times 10^{11} \text{ W/cm}^2$ (2GV/m), respectively. The laser pulse intensity corresponds to an electric field strength of $E_0 = 2\text{GV/m}$ on the surface of silica. The wavelength and the refractive index were $\lambda_0 = 1.03\mu\text{m}$ and $n_0 = 1.44$, respectively.

The acceleration gradient reached the highest value at a pillar height of approximately $H_p/\lambda_0 \approx 1$. The slight difference from the analytical result of 1.1 might be caused by the deformation of the wavefront in the pillar. To obtain the highest acceleration field, the filling factor of the grating L_p/L_G was approximately 0.5. These results are similar to previous results for another laser wavelength of $\lambda_0 = 1.55\mu\text{m}$ [10, 11]. The acceleration gradient attained

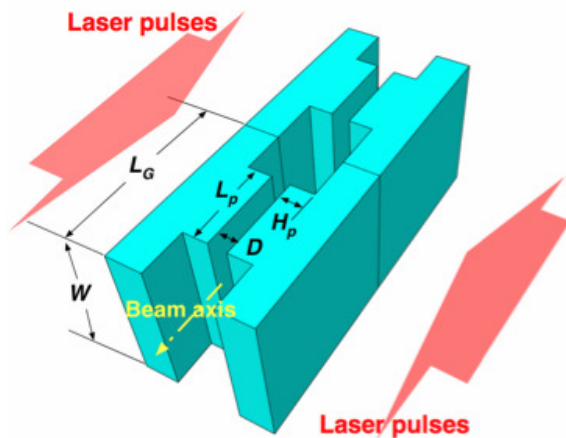


Figure 2: Schematic drawing of two periods of an accelerator unit.

a maximum value of 600MV/m ($E_a/E_0 = 0.3$) in the relativistic energy region and rapidly decreased with a reduction in the initial electron energy E_i , as shown in Fig. 3. The periodic increase and decrease of the acceleration gradient at low electron energies (below 100 keV) corresponded to the electron speed of $v/c = 1/2, 1/3$ and $1/4$. They were

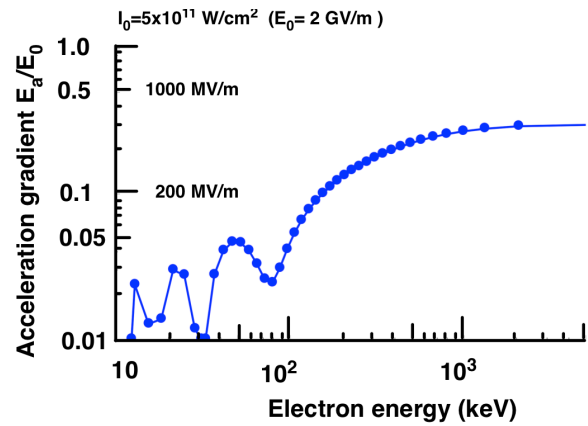


Figure 3: Dependencies of the acceleration field gradients on the electron energy.

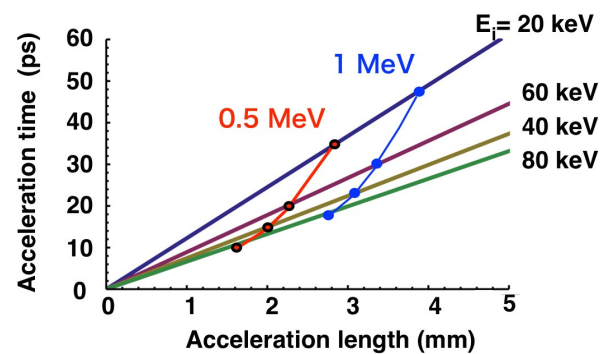


Figure 4: The electron acceleration time and energy along the beam axis for various initial electron energies.

due to the higher-order components of the spatial distribution of the longitudinal component of the electric field. The acceleration field gradient rapidly decreased when the grating constant became smaller than the laser wavelength, which corresponds to the laser light cutoff. Electron at the initial energy of 20 kV are accelerated in the acceleration field gradient of 20 MV/m, and the electrons are accelerated by higher field gradients as the electron speed was increased.

Figure 4, shows the electron acceleration time and energy along the beam axis for various initial electron energies, obtained by using the relation between the acceleration gradient and the electron energy (Fig. 3) provided that the phases of each acceleration unit are properly tuned. For obtaining 1 MeV electrons, the acceleration lengths were 4 mm and 3 mm for initial electron energies of 20 keV and 80 keV, respectively. The acceleration time required for the electron to attain 1 MeV energy was 50 ps and 20 ps for initial electron energies of 20 keV and 80 keV, respectively.

Laser

The laser light intensity I_0 on the surface of the dielectric material must be kept below the values of the thresholds I_{th} to avoid the nonlinear effects and the optical dam-

age. The required pulse energy of the pump laser for one side, E_{pump} , is determined by multiplying the illumination area $A = L_a W$ and the pulse width τ_0 as $E_{pump} = I_0 A \tau_0$, where L_a is the accelerator length, respectively. Therefore, for reducing the laser energy, it is important to decrease the illumination area by adopting a small focus area width W , which is defined by the diffraction limit of the focusing optics $W = \lambda_0/2NA$, where NA is the numerical aperture of the focusing lens. If the value of $NA = 0.1$ is chosen to avoid spherical aberration of the simple lens, the focal width is about $5\mu\text{m}$ for $1\mu\text{m}$ -wavelength laser light. Because the Rayleigh length of $76\mu\text{m}$ is sufficiently large, the wavefront between the grating is considered to be the plane wave, as we assumed in the simulation.

The simplest way to pump the dielectric accelerator is to irradiate the whole area of the dielectric during the acceleration time. The required laser power and the laser energy were estimated to be 200 MW and 10 mJ. According to Fig. 1, the irradiation intensity must be lower than $10^{11}\text{W}/\text{cm}^2$ for the laser pulse to be approximately 50 ps to 100 ps. Therefore, the acceleration length and the pulse width become long at 9 mm and 112 ps, respectively. However, the required laser energy does not change.

In order to reduce the required laser energy, the laser illumination area and time must be limited around the electron bunch by synchronizing multiple laser pulses. If the accelerator is illuminated by N sequential pairs of pulses, the pulse power, pulse width, and pulse energy are reduced to $1/N$, $1/N$ and $1/N^2$, respectively. The laser parameters and dimensions of the accelerator are tabulated in the table. The required laser power per pulse can be reduced to 20 MW when ten pairs of sequential laser pulses are irradiated. For producing such an illumination scheme, a fiber laser is capable of increasing the configuration freedom.

CONCLUSION

Although the real intensity profile and pulse shape of the laser light must be included for a practical accelerator design, a simple parameter study is effective for understanding the basic TG-LDA behavior.

The optimum pulse width of the laser is selected by considering the acceleration time, irradiation scheme, optical damage threshold intensity, and optical nonlinear effects on the pulse propagation. A short laser pulse is preferable from the optical damage threshold intensity perspective. However, SPM produces undesirable phase distortion in pulse widths shorter than 1 ps, provided that the path length of the laser in the silica is longer than several millimeters. The high intensity of $10^{12}\text{W}/\text{cm}^2$ is usable, provided that the

path length of the laser is shorter than 1 mm and the pulse width of the laser is around 2 ps. The irradiation intensity of $5 \times 10^{11}\text{W}/\text{cm}^2$ (2 GV/m) is suitable in the pulse width range from 1 ps to 10 ps.

Although the preliminary analysis concluded that the grating period and the electron speed must satisfy the matching condition of $L_G/\lambda_0 = v/c$, the higher-order harmonics of the axial electric field are capable of accelerating the electrons provided that the speed approximately satisfy the conditions of $v/c = 1/2, 1/3$, and $1/4$. Furthermore, there is a possibility of making atto-second bunching using the higher order components of the field.

Electrons at the initial energy of 20 keV are accelerated at the acceleration field strength of 20 MV/m, and the electrons are accelerated by higher fields as the electron speed increased. The field strength is 600 MV/m in the relativistic energy region. To obtain 1 MeV electrons, the acceleration lengths were 4 mm and 3 mm for initial electron energies of 20 keV and 80 keV, respectively. Electron transit times to attain 1 MeV energy were 50 ps and 20 ps for initial electron energies of 20 keV and 80 keV, respectively. If the accelerator is illuminated by N sequential pulses, the pulse power, pulse width, and pulse energy are reduced to $1/N$, $1/N$ and $1/N^2$, respectively. The required laser power per pulse is estimated to be 20 MW when ten pairs of sequential laser pulses are irradiated.

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