Parameter study of a laser-driven dielectric accelerator for radiobiology research

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Abstract

A parameter study for a transmission grating type laser-driven dielectric accelerator (TG-LDA) 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 such as the self-phase modulation and self-focus. An irradiation intensity of $10^{11}$ W cm$^{-2}$ ($2$ GV m$^{-1}$) was suitable for a silica TG-LDA 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 $v/c = 1/2$, $1/3$, or $1/4$. The electrons at the initial energy of 20 kV are accelerated by an acceleration field strength of 20 MV m$^{-1}$, and the electrons were accelerated by higher fields as the speed increased. For relativistic energy electrons, the acceleration gradient was 600 MV m$^{-1}$.

Keywords: laser driven dielectric accelerator, radiobiology, microbeam, attosecond, optical nonlinear effects

(Some figures may appear in colour only in the online journal)

1. Introduction

High doses of ionizing radiation are known to produce immeasurable diseases in humans. However, at very low radiation doses, the extent of damage is much less clear, but the risks of low-dose radiation ($\leq 50$ mSv) are of societal importance with respect to a wide variety of issues such as medical screening tests, radiation treatments for cancer, nuclear power plant disasters, occupational radiation exposure, and radiological terrorism. Unfortunately, epidemiological studies require a large number of samples [1]. Recently, radiobiologists have applied a new approach to evaluate cancer risks of low-dose radiation, which is based on understanding the damage and repairing processes of DNA in an individual cell. Although micro-beams of ions, x-rays, and electrons are powerful tools for studying basic processes in the living cell [2–4], these devices are too big for most researchers. The recent experiments on radiobiological research using a micro-beam are concentrated on studying the basic process around the proton track in the cell. However, it is impossible to know which part of the cell interacts with the proton in advance of the irradiation, because protons are randomly distributed in the beam. A compact micro-beam device, which delivers spatially and temporally defined particle bunches or electromagnetic pulses, is desirable for studies of the radiation effects in the cell. A suitable beam size is on the order of the resolving power of an optical microscope or on the order of microns. Moreover, the beam direction should be controllable using an optical microscope. A laser-
driven dielectric accelerator is capable of delivering nanometer-sized beams with an atto-second pulse width because the characteristic length and frequency of the accelerator is on the order of those of laser light. A phase-modulation-masked-type, i.e., transmission grating type, laser-driven dielectric accelerator (TG-LDA) has a simpler structure [5] than other dielectric accelerators [6, 7]. Moreover, electron acceleration by TG-LDA was successfully demonstrated at two institutes [8, 9].

We have previously presented a variation of TG-LDA for application to radiobiology research [10, 11]. However, the nonlinear effects such as the limitations in the laser intensity and the effects of higher order electric field components on the acceleration were not well understood. In order to develop a miniature accelerator as a tool for radiobiology research, we discuss the required beam energy and bunch charge, accelerator parameters, and laser parameters in consideration of the optical nonlinear effects in this study.

2. Accelerator parameters

2.1. Electron bunch

The electron energy of the output beam is determined by the energy absorption and the electron beam blur via multiple Coulomb scattering in a living biological cell and thin vacuum window. For a typical human cell size of 10 μm, the electron blur must be restricted to 1 μm or less, which is nearly the serving resolution of the optical microscope, and consequently a radius of an electron spread by the multiple scattering in the 10 μm thick biological cell must be smaller than 0.5 μm and the width of the angular distribution must be less than 0.05 rad. The width of the angular distribution due to the multiple scattering can be approximated by

$$\theta_0 = \frac{13.6 (\text{MeV})}{\beta c p} \sqrt{\frac{x}{X_0}} \left(1 + 0.038 \ln \left(\frac{x}{X_0}\right)\right),$$

(1)

where \(c\), \(\beta\), \(p\), \(x\) and \(X_0\) are the speed of light, the electron velocity divided by \(c\), the momentum of the electron, the thickness of the scatterer in g cm\(^{-2}\), and the radiation length in g cm\(^{-2}\), respectively [12]. The radiation length \(X_0\) characterizes the length to reduce the energy of the electron in the scatterer by the factor \(1/e\). An approximated form of \(X_0\) is given by the Dahl’s formula [13]

$$X_0 = \frac{716.4 (g \text{ cm}^{-2}) A}{Z (Z + 1) \ln(287/\sqrt{Z})},$$

(2)

where \(Z\) and \(A\) are the atomic number and the mass number of the scatterer, respectively. We suppose that the vacuum window is made of 100 nm thick silicon nitride (SiN). Therefore, to restrict the width of the angular distribution to 0.05 rad, we estimate the lower limit of the electron energy using the above equations to be 0.5 MeV. Moreover, based on radiation safety regulations, the upper limit of the electron energy is set to 1 MeV. Here, the penetration of secondary electrons into the area surrounding the beam is neglected.

The required number of electrons in the bunch was estimated by comparing the energy deposition by the electron with the ion along beam axes in the cell. The collision stopping power of protons and electrons in the 0.5–1 MeV energy range in the water is \((4-2.6) \times 10^3\) MeV cm\(^2\) g\(^{-1}\) and \((1.7-1.6)\) MeV cm\(^2\) g\(^{-1}\), respectively [14]. Therefore, for making the same energy deposition in the cell by the electron beam with the energy deposition by the 1 MeV proton, required number of electrons in the bunch is 160–180, which corresponds to an electronic charge of 0.03 fC/bunch.

2.2. Laser intensity

Previous works supposed that the irradiation intensity of the laser pulse is limited by the optical damage threshold intensity [5–9]. 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. To save the laser pulse energy, the electric field of the laser should be localized around the electron bunch in the accelerator. These details will be discussed in section 3.

The condition for avoiding the SF is satisfied by maintaining the B-integral below \(\pi\) [15]

$$B = \frac{2\pi}{\lambda_0} \int n_2 I(z) dz < \pi,$$

(3)

where \(n_2\), \(\lambda_0\), and \(I(z)\) are the nonlinear refractive index, the laser wavelength, and the laser intensity along the optical path \(z\), respectively. Using the value of \(n_2 = 3.18 \times 10^{-20} m^2 W^{-1}\) for silica (SiO\(_2\)) [16], the highest intensity for avoiding SF is derived to be

$$I_0 (W \text{ cm}^{-2}) < 1.5 \times 10^{10} \lambda_0 (\mu m) / L (mm).$$

(4)

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

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

(5)

where \(\tau\) 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

$$I_0 (W \text{ cm}^{-2}) < 2.5 \times 10^{11} \tau^2 (ps) / L^2 (mm).$$

(6)

The laser intensities restricted by SF and SPM are shown in figure 1 with the optical damage threshold intensities of the smooth surface and of the grooved surface of the silica [17, 18].

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 \(10^{12} W \text{ cm}^{-2}\) can be utilized provided that the path length of the laser is shorter than 1 mm and the
The normalized pillar height is \( H_0/\lambda_0 \approx 1.1 \) at the refractive index of \( n_0 = 1.44 \) (\( \text{SiO}_2 \) at \( \lambda_0 = 1.03 \mu m \)).

The interval between opposite pillars \( D \) is determined by

\[
\frac{D}{\lambda_0} \leq \left( \frac{L_G}{\lambda_0} \right)^2 = \left( \frac{L_G}{2\lambda_0} \right)^2 \approx \frac{1}{4},
\]

which is derived by considering the blurring of the phase jump due to diffraction originating at the corner of the pillar. This interval is equivalent to the extent of the evanescent field from the top of pillars.

The propagation of the laser pulse in a direction orthogonal to the electron beam is a marked feature of the TG-LDA. The matching condition between the electron speed \( v \) and the grating period \( L_G \) is expressed by

\[ L_G/\lambda_0 = v/c, \]

where \( c \) is the speed of light in vacuum. This matching condition indicates the possibility of accelerating slow electrons by adopting a short grating period. However, the acceleration efficiency is poor because the standing wave-like structure of the electric field disappears if the grating period is shorter than the cutoff wavelength of the grating, described by \( \lambda_c = L_G (1 + \sin \theta_i) \), where \( \theta_i = 0 \) is the incident angle [19]. In spite of the undesirable cutoff wavelength condition, it is possible to accelerate nonrelativistic electrons at \( L_G/\lambda_0 = 1 \) using higher-order components of the spatial distribution of the electric field along the accelerator axis, which are a result of the wavefront distortion and Fresnel diffraction.

2.4. Simulation study of the acceleration field

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 simulation software, Meep [20]. 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. This procedure is mathematically expressed by

\[
E_a = \frac{1}{L_G} \int_0^{L_G} E(x, t(x))\,dx.
\]

The integral path and the instantaneous field strength along the path are shown in figures 3(a) and (b), respectively. 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 \( I_0 = 5 \times 10^{14} \text{ W cm}^{-2} (2 \text{ GV m}^{-1}) \), respectively. The laser pulse intensity corresponds to an electric field strength of \( E_0 = 2 \text{ GV m}^{-1} \) on the surface of silica. The refractive index of \( n_0 = 1.44 \) was used for silica.

The acceleration gradient reached the highest value at a pillar height of approximately \( H_0/\lambda_0 \approx 1 \), as shown in figure 4. This value slightly differed from the analytical result of 1.1. The difference might be caused by the deformation of
the wavefront in the pillar. To obtain the highest acceleration field, the filling factor of the grating \( \frac{L_P}{L_G} \) was approximately 0.5. The acceleration gradient attained a maximum value of \( E_0 = 600 \text{ MV m}^{-1} \) in the relativistic energy region and rapidly decreased with a reduction in the initial electron energy \( E_i \), as shown in figure 5. The periodic increase and decrease of the acceleration gradient at low electron energies (below 0.1 MeV) corresponded to the electron speed of \( v/c = 1/2, 1/3 \) and \( 1/4 \). They were due to the higher-order components of the spatial distribution of the electric field.

As shown in figure 6, the acceleration field gradient rapidly decreased when the grating constant became smaller than the laser wavelength \( (L_G/\lambda_0) \), which corresponds to the laser light cutoff. Electron at the initial energy of 20 kV are accelerated in the acceleration field gradient of \( 20 \text{ MV m}^{-1} \), and the electrons are accelerated by higher field gradients as the electron speed was increased. The field strength is \( 600 \text{ MV m}^{-1} \) in the relativistic energy region.

Figure 7 shows the energy evolution of the electrons along the beam axis at various initial electron energies, \( E_i \), by using the relation between the acceleration field strength and the electron energy shown in figure 5. 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. As shown in figure 8, 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.

3. Pump laser

The laser light intensity \( I_0 \) on the surface of the dielectric material must be kept below the values of the threshold \( I_{th} \) to avoid the nonlinear effects and the optical damage discussed in section 2.2. The required pulse energy of the pump laser for one side, \( E_{pump} \), is determined by multiplying the illumination area \( A = L_\alpha \times \frac{W}{\lambda} \) and the pulse width \( \tau \) as \( E_{pump} = I_0 A \tau = I_0 L_\alpha \frac{W}{\lambda} \tau \), where \( L_\alpha \) and \( \tau \) are the accelerator length and the average speed of the electron during the acceleration, 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 \( W = \frac{\lambda}{2N A} \), where \( N A \) is the numerical aperture of the lens. If the value of \( N A \approx 0.1 \) is chosen to avoid spherical aberration of the simple lens, the focal width is about 5 \( \mu \)m for 1 \( \mu \)m laser light. Because the Rayleigh length of 76 \( \mu \)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 peak power and energy of the laser pulse were estimated to be 200 MW and 10 mJ, as listed in table 1. According to figure 1, the irradiation intensity must be lower than \( 10^{13} \) W cm\(^{-2}\) for the laser pulse to be approximately 50–100 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 peak power, pulse width, and pulse energy are reduced to \( 1/N \), \( 1/N \) and \( 1/N^2 \), respectively. The laser parameters and dimensions

| Table 1. Laser parameters required for accelerating electrons from 20 keV to 1 MeV. The laser is assumed to be a Yb-fiber laser and \( \lambda_0 = 1.03 \mu \)m. |
|----------------------------------------------------------|
| Grating period \( L_G/\lambda_0 \) | 1 |
| Initial electron energy \( E_i \) | 20 keV |
| Width of irradiation area \( W \) | 5 \( \mu \)m |
| Acceleration length \( L_\alpha \) | 4 mm |
| Area \( 2A \) | \( 4 \times 10^{-4} \) cm\(^2\) |
| Acceleration time \( \tau_\alpha \) | 50 ps |
| Laser intensity \( I_0 \) | \( 5 \times 10^{11} \) W cm\(^{-2}\) |
| Peak power for one side \( P_{pump} \) | 200 MW |
| Energy for one side \( E_{pump} \) | 5 mJ |
| Total energy \( E_{total} \) | 10 mJ |
| Number of pulse pairs \( N \) | 10 |
| Width of each pulse \( \tau_\alpha \) | 5 ps |
| Peak power of each pulse \( P_\alpha \) | 20 MW |
| Energy of each pulse \( E_{ch} \) | 50 \( \mu \)J |
| Total laser energy \( E_{L_{ch}} \) | 1 mJ |
of the accelerator are tabulated in Table 1. The required peak power of the laser pulse can be reduced to 20 MW when ten pairs of sequential laser pulses are irradiated. For producing such an illumination scheme, Plettner [5] proposed that the short laser pulse be divided into many segments by mirrors and that each pulse be introduced into the accelerator through a properly tuned optical delay. However, the use of many optical mounts is inconvenient for our intended mobile accelerator design. A fiber laser is capable of increasing the configuration freedom, as shown in Figure 9, because the fiber laser enables to control the phase and the polarization of each pulse by adopting the coherent beam combining technique [21]. A vacuum window at a bottom of dish is made of thin film of SiN. The 30 nm thick SiN film withstood the pressure difference of 3 atm for the window size of 0.3 mm × 0.3 mm [22].

4. Conclusions

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.

To investigate the basic process in biological cells, the energy and electronic charge of the electron bunch was estimated. The lower limit of the electron energy is 1 MeV. For simulating the energy deposition of a proton in biological cell, the required number of electrons in the bunch is 160–180, which corresponds to an electronic charge of 0.03 fC/bunch.

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} W 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} W cm^{-2} (2 GV m^{-1}) is suitable in the pulse width range from 1 ps to 10 ps.

It is unnecessary to consider the optical nonlinear effects for the TG-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 [23], because they use thick prisms or optical wedges.

Although our preliminary analysis concluded that the grating period and the electron speed must satisfy the matching condition of \( k_g / k_3 = v/c \), 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^{-1}, and the electrons are accelerated by higher fields as the electron speed increased. The field strength is 600 MV m^{-1} 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 \( 1/N, 1/N^2 \), and \( 1/N^3 \), respectively. The required peak power of the laser pulse is estimated to be 20 MW when ten pairs of sequential laser pulses are irradiated.

We are currently developing a sample transmission grating and a short pulse high-power fiber laser. These results will be published at a later time. This work was supported by KAKENHI, Grant-in-Aid for Scientific Research (C) 24510120.

References

[1] Brenner D J et al 2003 Cancer risks attributable to low doses of ionizing radiation: assessing what we really know Proc. Natl. Acad. Sci. 100 13765
[2] Shao C et al 2003 Bystander effect induced by counted high-LET particles in confluent human fibroblasts: a mechanistic study Fed. Am. Soc. Exp. Biol. J. 17 1422

[3] Schettino G et al 2003 The ultrasoft x-ray microbeam: a subcellular probe of radiation response Radiat. Res. 160 505

[4] Sowa M B and Morgan W F 2004 Microbeam developments and applications: a low linear energy transfer perspective Cancer Metastasis Rev. 23 323

[5] Plettner T P, Lu P and Byer R L 2006 Proposed few-optical cycle laser-driven particle accelerator structure Phys. Rev. ST Accel. Beams 9 111301

[6] Lin X 2001 Photonic band gap fiber accelerator Phys. Rev. ST Accel. Beams 4 051301

[7] Cowan B et al 2008 Three-dimensional dielectric photonic crystal structures for laser-driven acceleration Phys. Rev. ST Accel. Beams 11 011301

[8] Peralta E A et al 2013 Demonstration of electron acceleration in a laser-driven dielectric microstructure Nature 503 91

[9] Breuer E A and Hommelhoff P 2013 Laser-based acceleration of nonrelativistic electrons at a dielectric structure Phys. Rev. Lett. 111 134803

[10] Aimidula A et al 2013 Numerical investigations into fiber laser based dielectric reverse dual-grating accelerator Nucl. Instrum. Methods Phys. Res. A 740 108

[11] Koyama K et al 2012 Designing of photonic crystal accelerator for radiation biology Proc. III Int. Particle Accelerator Conf. IPAC-2012 (New Orleans, LA; JACoW) WEPP091 (http://accelconf.web.cern.ch/AccelConf/IPAC2012/papers/weppp091.pdf)

[12] Lynch G R and Dahl O I 1991 Approximations to multiple Coulomb scattering Nucl. Instrum. Methods B 58 6

[13] Eidelman S et al (Particle Data Group) 2004 Review of particle physics Phys. Lett. B 592 1

[14] Berger M J et al 2005 Stopping-Power and Range Tables For Electrons, Protons, and Helium Ions NISTIR 4999 (http://www.nist.gov/pml/data/star/index.cfm)

[15] Perry M D, Ditmire T and Sturt B C 1994 Self-phase modulation in chirped-pulse amplification Opt. Lett. 19 2149

[16] Milam D 1998 Review and assessment of measured values of the nonlinear refractive-index coefficient of fused silica Appl. Opt. 37 546

[17] Stuart B C et al 1995 Laser-induced damage in dielectrics with nanosecond to subpicosecond pulses Phys. Rev. Lett. 74 2248

[18] Oskooi A F et al 2010 MEEP: a flexible free-software package for electromagnetic simulations by the FDTD method Comput. Phys. Commun. 181 687

[19] Breuer J et al 2014 Dielectric laser acceleration of nonrelativistic electrons at a single fused silica grating structure: experimental part Phys. Rev. ST Accel. Beams 17 021301

[20] Van Den Berg P M 1971 Rigorous diffraction theory of optical reflection and transmission gratings PhD Thesis Delft University of Technology, der Technische Hogeschool Delft, Netherlands

[21] Klenke A et al 2011 Basic considerations on coherent combining of ultrashort laser pulses Opt. Express 19 25379

[22] Nishiyama H et al 2010 Reprint of: atmospheric scanning electron microscope observes cells and tissues in open medium through silicon nitride film J. Struct. Biol. 172 191

[23] Irvine S, Dechant A and Elezzabi A 2004 Generation of 0.4-keV femtosecond electron pulses using impulsively excited surface plasmons Phys. Rev. Lett. 93 184801

[24] Lu P, Wu J, Qi H and Zeng H 2008 Ponderomotive electron acceleration by polarization-gated surface-enhanced optical fields Appl. Phys. Lett. 93 201108