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Impact of the chirping effect on charged particle acceleration in laser radiation

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Analysis and modelling

ABSTRACT

Purpose: The aim of this paper is to find in a numerical way the trajectories and kinetic energies gained by electrons, protons and deuterons accelerated in the laser or maser chirped radiation propagating in a vacuum, with an additionally applied external static axial magnetic field. The accelerated particles to the well defined energies are of interest in many applications, among others in medicine or in processing of different materials.

Design/methodology/approach: The acceleration processes of electrons, protons and deuterons were found to be strongly depending on the way the frequency of the laser or maser radiation changes in time. In order to design the realistic acceleration processes the appropriate parameters of a laser or maser and a static magnetic field were used.

Findings: The quantitative illustrations of the calculation results in a graphical form enable to discuss the impacts of the chirping effect on the acceleration process of electrons, protons and deuterons. It was found that the rate at which a particle gains the energy depends not only on the particle's mass but also on the laser radiation frequency variation rate. Due to the different rate at which a relativistic mass of an electron, proton or deuteron increases during the acceleration process the rate at which chirped frequency decreases in time should be different.

Research limitations/implications: Limits in the gained energy by the accelerated particles are a consequence of the limits in the available at present the laser or maser beam energy and the static magnetic field intensity.

Originality/value: The authors have found, in an exact numerical way, the values of the acceleration equipment parameters which should be applied to obtain the desired energy of the accelerated particles. It is explained why the rate at which a particle gains the energy depends on the way the radiation frequency varies in time.

Keywords: Acceleration of charged particles; Laser; Maser; Relativistic dynamics; Chirping

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1. Introduction

Laser based acceleration are capable of producing high energy charged particles in much shorter distances than conventional accelerators due to the large electric fields associated with a laser. Many experiments and theoretical works have been shown the possibility of particles acceleration as a result of their interaction with the laser or maser beams of different parameters [1-4]. The accelerated particles to the high energies are of interest in many applications, among others in fast ignition in inertial confinement fusion [5], proton cancer therapy, proton imaging and ion beam radiography [6], laser nuclear physics [7], or materials processing [8] etc. Recent years have seen important achievements in the development of laser particle accelerators [9]. Now there are accessible lasers showing radiation power density of the level 10^{22} W/cm^2, which corresponds to the electric field intensity amplitude 10^{14} V/m [10].

It was shown [11] that quasi monoenergetic collimated GeV electrons can be produced using a right choice of laser spot size, frequency chirp, intensity and pulse duration. The chirping effect (CE) of a laser pulse is usually understood as the time dependence of its instantaneous frequency. Now are available high power lasers with a frequency chirp of a few percent. The lasers with frequency chirping of a few tens percent should be possible in the near future. Generation of high intensity laser pulses with a considerable chirp is possible using solid state laser system, self-chirped optical pulse in a free electron laser oscillator, propagation of high intensity laser pulse through a plasma channel, and the reflecting of electromagnetic pulses from relativistic ionization fronts. The maximum electron energy gain during acceleration by linearly or circularly polarized chirped laser pulse is higher than that of the case of unchirped laser pulse. The retained energy, duration of interaction with laser radiation and energy gain increases with initial particle energy [12, 13]. The increasing wavelength allows the electron to stay within the laser pulse longer and the energy gain increase [14]. The frequency variation plays an important role to enhance the particle energy in the presence of a static magnetic field in vacuum.

Laser frequency chirp helps to maintain the resonance condition longer, which increases the particle energy [14]. The frequency chirping and tight focusing can enhance the electron energy gain significantly because an electron can be accelerated for a longer time in vacuum [15]. For an optimum value of magnetic field the electron attains the maximum energy because of resonance. For example in this case the electron with initial kinetic energy of 50 MeV can gain energy about 100 GeV [14]. An electron of initial energy 2.5 MeV can gain about 12 GeV if a chirped laser beam is used and tight focusing is included [15]. Kumar and Yoon [16] have demonstrated ultrahigh-gradient acceleration by a linear chirped circularly polarized laser pulse in presence magnetic field.. In mostly papers authors performed the numerical investigation of a single electron acceleration using a negative and linear chirped laser radiation. In [17] a scheme for electron acceleration by two crossing chirped lasers was proposed.

The main purpose of this paper is to find in a numerical way the basic advantages in the acceleration of electrons, protons and deuterons due to application of the CE in the laser or maser radiation propagating in a vacuum**,** with an additionally applied external static axial magnetic field [18, 19]. On the basis of the equation of motion of the charged particles in the laser beam and additionally applied magnetic field [20, 21], the further evolution of the acceleration process is shown. The benefits of the CE in the acceleration process is indicated. The results of numerical calculation have been presented in a graphical form illustrating the course of the electron, proton and deuteron trajectories and kinetic energies behavior under various parameters of a chirped laser beam and magnetic fields.

2. Some general features of the chirping effect during acceleration process

On the basis of the studies concerned with the acceleration of charged particles by the laser beam and an additionally applied magnetic field, the further evolution of the acceleration process connected with the changing in the acceleration apparatus will be shown. One of the possibilities is connected with a gradual variation of the laser or maser radiation frequency during the course of the acceleration process. This kind of the frequency variation is called the chirping [22] and shows a growing interest. If the special chirping apparatus is employed in the acceleration system, then the significant variation in the laser frequency can be obtained. Due to this, a modification in our results presented in the earlier papers should be expected [4, 18, 20, 21].

The significance of the chirping in the acceleration process is indicated. Now the method of obtaining the results for quantitative presentation of the acceleration process is subjected to change in some aspects. As it has been shown the acceleration processes without the chirping may be carried out using the both the analytical expressions or numerical methods [18, 20, 21]. With including the chirping however, the exact analytical expressions seem to be impossible to obtain and in order to get the proper result, this problem forced the authors of this paper to solve the original differential equations in a numerical way. The results of the numerical calculations using the Runge-Kutta method have been presented in a graphical form illustrating the course of the electron, proton and deuteron trajectories, and the kinetic energy behavior under various parameters of the laser beam and the magnetic field.

The differences in the calculation results which arises because of the chirping are shown below. As it is also shown, the stationary projections of the trajectories on the (x, y) plain [18] no longer exist. Due to the chirping the projections of the trajectories were found to be different from the stationary epi- and hypocycloids. A difference in the constant magnetic field interaction with the various particles is also shown. Finally, as it seems to be most important in the acceleration process, the rate of gaining the energy by the particle was found to be also different compared to the case without the chirping. It was shown how to maintain the conditions at which the particles can be accelerated to the high energies under the interaction with the chirped laser radiation and a static magnetic field.

3. The basic equations of a charged particle in a laser beam and co-axial static magnetic field with chirping applied

We assume that the laser produces continuous, monochromatic, coherent, circularly polarized, plane wave propagating in the vacuum and in an additional static co-axial magnetic field. The aim is to find the impact of this combined electromagnetic field on the trajectory and on the kinetic energy of a charged particle in the lossless conditions with the chirping applied. The dynamical relativistic equation and the continuous equation for charged particle in the electromagnetic and the static magnetic fields defining the trajectory and normalized energy γ in the lossless condition [23,24] has the following form

$$\frac{d\vec{p}}{dt} = q\vec{E} + q\left[\vec{V} \times \left(\vec{B} + \vec{B}_z\right)\right], \qquad \frac{d\gamma}{dt} = \frac{q}{m_0 c^2}\vec{V}\cdot\vec{E} \tag{1}$$

where p, V, q and m_0 are the momentum, velocity, electric charge and the rest mass of the particle, E is the electric field intensity and B is the magnetic field induction of the electromagnetic wave, c is the velocity of the electromagnetic wave and B_z is the external static magnetic induction in the direction along the z coordinate (the laser beam axis) and

$$\gamma = \left(1-\beta^2\right)^{-\frac{1}{2}}, \quad \vec{\beta} = \frac{\vec{V}}{c}, \quad \vec{p} = \gamma\cdot m_0 c\vec{\beta},$$

$$\beta^2 = \beta_x^2 + \beta_y^2 + \beta_z^2, \quad \beta_{x,y,z} = \frac{V_{x,y,z}}{c}$$

As it will be shown below, the result of solving are expressions for trajectory coordinates for a charged particle initially at rest. Assuming the electromagnetic wave is propagating in the direction z, coordinates of electric and magnetic field vectors at (x,y) plane, in the case of circularly polarized wave of circulation to the left side are without the CE as follows

$$\vec{E} = \vec{i}E_x + \vec{j}E_y = \vec{i}E_0\sin\phi + \vec{j}E_0\cos\phi, \qquad \vec{B} = \vec{j}B_y + \vec{i}B_x = \vec{j}\frac{E_0}{c}\sin\phi - \vec{i}\frac{E_0}{c}\cos\phi \tag{2}$$

where

$$\phi = \omega\left[t - \frac{z(t)}{c}\right], \quad B_0 = \frac{E_0}{c} \tag{3}$$

and ω is the electromagnetic wave angular frequency. In a complex system consisting of an electromagnetic field and a static axial magnetic field the following vectors are essential

$$\vec{E} = \left[E_x, E_y, 0\right], \quad \vec{B} = \left[-B_x, B_y, B_z\right]$$

$$\vec{p} = m_0\gamma V_x\vec{i} + m_0\gamma V_y\vec{j} + m_0\gamma V_z\vec{k}$$

$$\frac{d\vec{p}}{dt} = \vec{i}m_0 c\frac{d(\gamma\beta_x)}{dt} + \vec{j}m_0 c\frac{d(\gamma\beta_y)}{dt} + \vec{k}m_0 c\frac{d(\gamma\beta_z)}{dt}$$

and

$$E_x = E_0\sin\phi, \quad E_y = E_0\cos\phi$$

$$B_x = \frac{E_0}{c}\cos\phi, \quad B_y = \frac{E_0}{c}\sin\phi, \quad B_z = \pm aB_0$$

where ϕ is the phase, E_0 is the amplitude of electric field. The impact of the static magnetic field on the particle is included through the parameter $a = B_z/B_0$ for the field B_z directed along the z coordinate.

We can use the differential equations derived from Eqn. (1) describing dynamics of a charged particle in the relativistic case which has the following form with the different frequency:

$$\begin{aligned}\frac{d(\gamma\beta_x)}{dt} &= -(1-\beta_z)f\sin\phi - fa\beta_y, \\ \frac{d(\gamma\beta_y)}{dt} &= -(1-\beta_z)f\cos\phi + fa\beta_x, \\ \frac{d(\gamma\beta_z)}{dt} &= -\beta_x f\sin\phi - f\beta_y\cos\phi, \\ \frac{d\gamma}{dt} &= -\beta_x f\sin\phi - f\beta_y\cos\phi\end{aligned} \tag{4}$$

this time the phase ϕ is assumed to be

$$\phi = \omega_C\left[t - \frac{z(t)}{c}\right], \quad \omega_C = \omega\left[1-(b\cdot\omega\cdot t)^n\right]$$

$$f = \frac{-qB_0}{m_0} \tag{5}$$

where ω_C is the chirped angular frequency of a laser wave acting on the particle in the laboratory frame of reference, n is the parameter which equals one for the linear chirping and can posses the other values (depending on the experimental set or the studied model), b is the arbitrary dimensionless constant.

4. The features of the acceleration process

Eqs (4) completely describe all the components of a position and velocity of the accelerated particle, as well as its total velocity under the interaction of the laser and the static magnetic field. An electromagnetic field of the electrical amplitude $E_0 = 10^{12}$ V/m and 10^{11} V/m have been used in the calculations. Generally speaking, the increase in the laser beam intensity results in the increase of the particle's energy and its trajectory dimension. However, the increase of the external magnetic field causes shrinking of the helical trajectories. It enables keeping the particle inside the laser beam if a sufficiently high magnetic field is applied.

The quantitative illustrations of the calculation results presented in a graphical form enable the discussion of the influence of many parameters on the acceleration process of these particles. Limits in the achievable energy of the accelerated particles arise from the limits in the available at present the laser beam power, the laser beam diameters, the pulse duration and the static magnetic field intensity.

The energy gained by the charged particle due to the interaction with the laser beam and the static magnetic field has been calculated using the relativistic formula (6). In order to maintain the acceleration, one should be sure that during the circulation of the particle in its helical motion it should not escape from the laser beam. This can be achieved by the application of the above mentioned co-axially directed static magnetic field. The larger the field intensity the smaller the circulation radius of the particle. Especially for protons and deuterons as well as for electrons at large velocities, the magnetic field intensity should be extremely high in order to keep the particle inside the laser beam, if the acceleration process is to be continued. If such a high field is not available, the particle will leave the beam with the energy which may be sufficient for some purposes. The amplitude of electric field E_0 has an impact on the duration at which the charged particle gains the expected energy. The larger the amplitude the less time is required to obtain the defined level of the kinetic energy.

The acceleration process of the charged particles is closely connected with the distance which the particle has to travel in order to get a desired level of the kinetic energy. Since the component V_Z of the electron velocity through almost the whole acceleration process is close to the light velocity c the distance $z(t)$ increases almost independently of the magnetic field or the laser beam intensity. The simple product ct is approximately equal to $z(t)$ for an electron. It is not the case for a proton or deuteron, since their velocities remain rather far away from the light velocity through the significant part of the acceleration time.

In this paper it is not examined the acceleration process with the use of the visible or ultraviolet lasers, since in this region lower energies of the accelerated particles are expected. In the numerical evaluation the initial conditions for the V_Z component of the velocity has been chosen to be zero, as well as the remaining velocity and the position components were chosen to be zero in all presented cases. From Eqns 4 and 5 it can be seen that the chirping is applied by using the radiation frequency ω_C which depends on the time. During the particles acceleration the frequency continuously changes in a linear or another manner. Due to this fact, in the calculation procedure some problems arise. The chirping was found to be of significant importance in the acceleration process, especially in the relativistic region of the particle velocities. Due to the frequency modification it is impossible to solve Eqns (4) analytically without the significant approximations, so they are solved numerically using the Runge-Kutta solving procedure.

5. Variation in time of the velocity and kinetic energy gained by a charged particle

In the acceleration process the most important item to discuss is the process of the kinetic energy gaining by the charged particles. We present some examples of the kinetic energy gained by the particles during the acceleration process. From numerical calculations of Eqn. 4, we can obtain the total reduced velocity β of the particle. This enables to calculate the relativistic kinetic energy using the following relativistic formula

$$E_k = m_0 c^2 \left(\frac{1}{\sqrt{1-\beta^2}} - 1 \right) \tag{6}$$

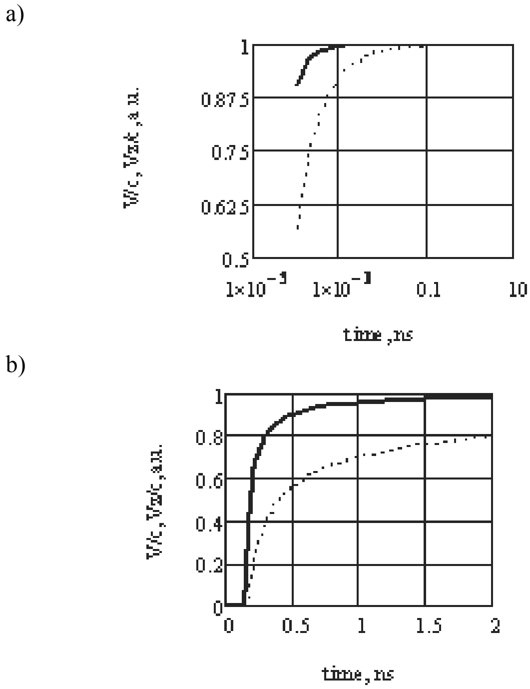

Fig. 1. Variation in time of velocity of (a) an electron and (b) a proton without chirping. Amplitude of an electric field of an electromagnetic wave $E_0 = 10^{11}$ V/m, the wavelength $\lambda = 10$ μm and the induction of the static magnetic field $B_z = -10$ T for an electron and 50 T for a proton (dashed curves for V_z/c)

Fig. 1 shows how the velocity of an electron and a proton evolves in time as a result of the interaction of the laser electromagnetic field and the constant magnetic field directed along the laser beam axis. As it is expected, due to the difference in the masses of the considered particles the velocities rise in a different manner and especially at a different rate. The electron velocity almost immediately approaches the limit of the light velocity in the vacuum, while the velocity of a proton advances much slower (Figs. 1a and 1b). Now the impact of the laser frequency on the acceleration process will be discussed. The method called 'chirping' is commonly used to obtain the radiation frequency variation during the acceleration process.

6. Frequency variation of the chirped laser wave

Due to the CE we get a downward change in frequency of the wave acting on the particle being accelerated when the particle moves in the laser beam direction. The frequency of the wave should decrease as the acceleration time increases. In order to illustrate this effect, we show some examples of the decrease of the angular frequency of the laser wave acting on an electron and other charged particles during the acceleration process. Firstly, the frequency has been calculated using Eqn. (5) and assuming the parameter $n = 1$ which means that the frequency changes with time in a linear way. Fig. 2 illustrates the case for two wavelengths.

The results of the computations for the laser of wavelength $10\ \mu m$ and $1\ \mu m$ presented in Fig. 2 indicate the linear change in time of the laser radiation angular frequency ω_C acting on the particle in the laboratory system of reference. In Fig. 2 the reduction of the frequencies were 1000 fold. As it will be shown later, the linear decrease in frequency is not efficient for improvement of the acceleration process.

In order to obtain the frequency decrease with time in the nonlinear way, while using the relation $\omega_c = \omega[1 - (b\omega t)^n]$ we have to assume the parameter $n > 1$ or $n < 1$. Various functions describing frequency vs time dependence have been studied and the results are shown in Fig. 3.

It can be seen that for the parameter n>1 the significant frequency drop occurs only in the final region of acceleration process (not shown in Fig. 3). However, for n<1 the drop occurs at the early regions of the process as well. As it will be shown below, this fact has been found to be of significant importance in acceleration process.

7. Acceleration of an electron, a proton and a deuteron with nonlinear chirping

The linear chirping do not lead to the satisfactory acceleration neither for an electron nor a proton (the examples not shown in Figures). When the acceleration conditions are selected to be outside the resonance the linear chirping rises the energy but only slightly. Moreover, the energy value remains rather low. This forced us to search for another chirping function which would result in a deeper variation of the frequency with time, especially at the early stage of acceleration process. This cannot be achieved through the linear mode. Variation in the parameter b was found to be insufficient in a proper frequency modulation. We propose not linear variation of the laser frequency during the process of acceleration. In order to find the frequency as a function of time which would show sufficiently large variation in time instead of linear equation $\omega_C/\omega = 1 - b\omega t$, we can try nonlinear relation $\omega_C/\omega = 1 - (b\omega t)^n$, and in order to enhance the ratio of absorbing the energy by a particle the value of the exponent n can be arbitrary adjusted to the acceleration parameters and to the accelerated particle.

a) b)

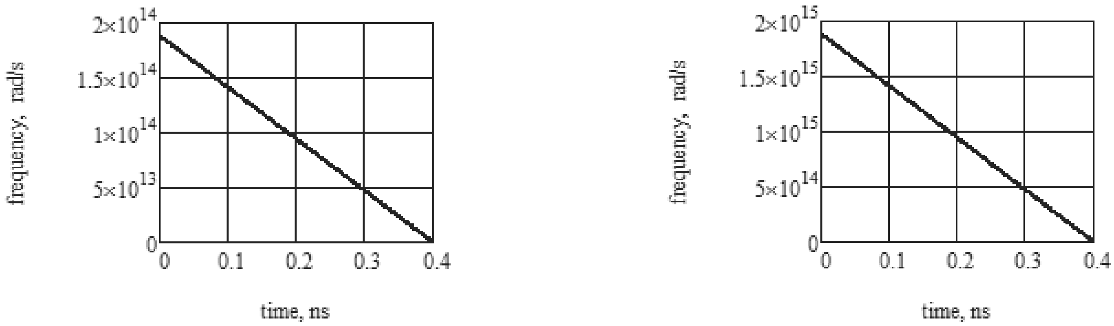

Fig. 2. Radiation frequency variation of the laser wave acting on an the charged particle as a result of application of the linear CE, $n = 1$, (a) the wavelength $\lambda = 10\ \mu m$, chirping parameter $b = 1.33\text{x}10^{-5}$ the final $\lambda = 10\ mm$, and (b) $\lambda = 1\ \mu m$, $b = 1.32\text{x}10^{-6}$ the final $\lambda = 1\ mm$

a) b) c)

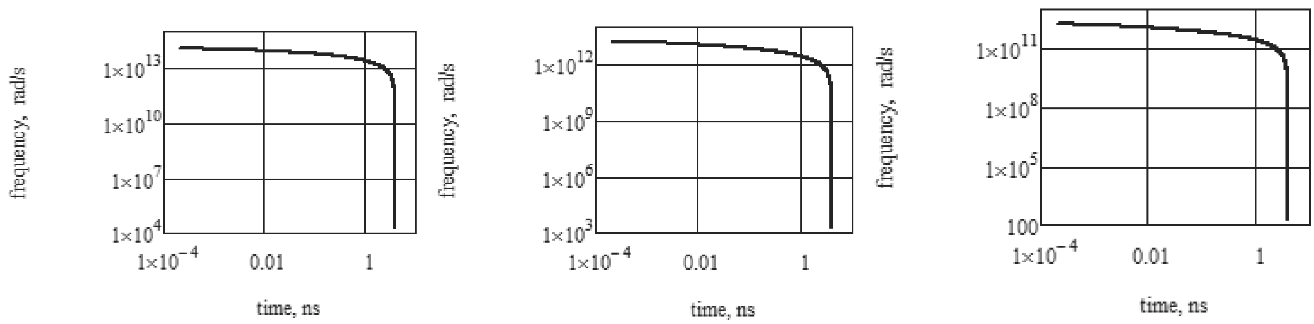

Fig. 3. Radiation frequency variation during the acceleration process lasting 4 ns, the both axis are log scaled. The initial wavelength $\lambda = 10\ \mu m$, (a) $(\alpha t)^{0.1}$, $(\alpha t)^{0.01}$, c) $(\alpha t)^{0.001}$, where $\alpha = \omega b$, $b = 1.33\text{x}10^{-6}$

7.1. Acceleration of an electron

Fig. 4 shows the results of an electron acceleration during 80 ps if parameters n = 0.1 and b = 3.3x10^{-5} were selected. It is clearly evident that acceleration process proceeds with the energy rising continuously. As can be seen from Fig. 4 due to the CE, in spite of relatively small intensity of the magnetic field the acceleration process enters into the resonance conditions at the moment the electron enters the laser radiation beam and continues to stay in this condition through the rest of the process. Now the electron energy rises continuously and its energy does not show any oscillations. The energy gained by the electron approaches the GeV range. In the example presented in Fig. 4 the variation in the radiation wavelength starts from 10 µm and terminates at λ = 144 µm. Variation in CE parameters results in the change of the final wavelength. In the example presented the electron was found to remain rather within the laser beam. This can be controlled by the intensity of B_z. In order to obtain the larger energy the electron should be accelerated for a longer time which is presented in Fig. 5. To prevent the electron from escaping the laser beam the larger B_z.is applied. Under parameters shown in Fig. 5 the acceleration conditions are close to the resonance. Fig. 6 shows the acceleration process if radiation has the wavelength λ = 72 μm. during the entire acceleration process. In this case, the selected parameters gave the acceleration conditions near the resonance. Due to no need to use a very long wavelengths as well as magnetic field of very high intensity, the CE has been proved to be advantageous in the electron acceleration process. The same resonance condition may be reached as well as without CE but with magnetic field intensity over 1000 T what is a very high value, hardly achievable today. Due to comparatively small mass of an electron the acceleration rate of this particle is high. Velocity of an electron reaches the light velocity in a much shorter time than a proton or deuteron.

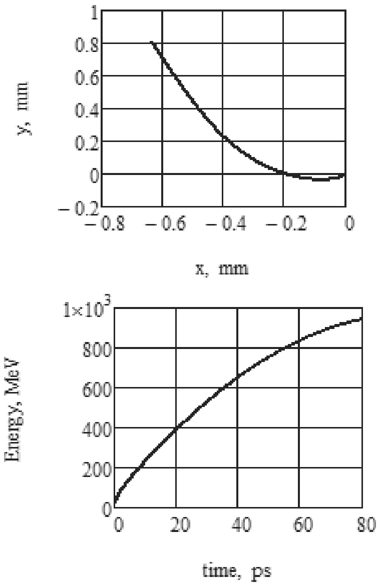

Fig. 4. Acceleration of electron during 80 ps, the starting wavelength λ = 10 μm, B_z = -50 T, E_0 = 10^{12} V/m. The chirping parameters are $(\alpha t)^{0.1}$, $\alpha = \omega b$, b = 3.3x10^{-5}, final λ is 144 μm

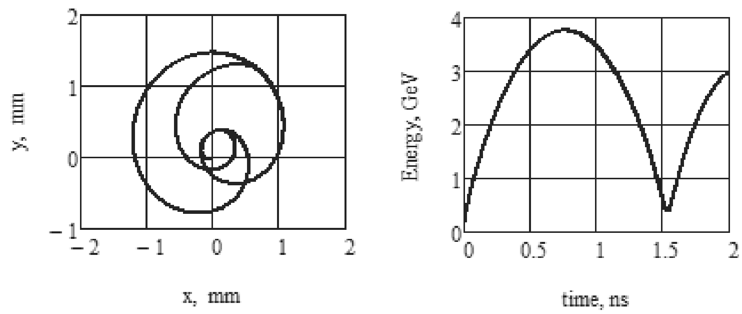

Fig. 5. Acceleration of electron during 2 ns, the starting wavelength λ = 10 μm, B_z = -200 T, E_0 = 10^{12} V/m. The chirping parameters are $(\alpha t)^{0.05}$, $\alpha = \omega b$, b = 1.33x10^{-7}, final λ is 72 μm

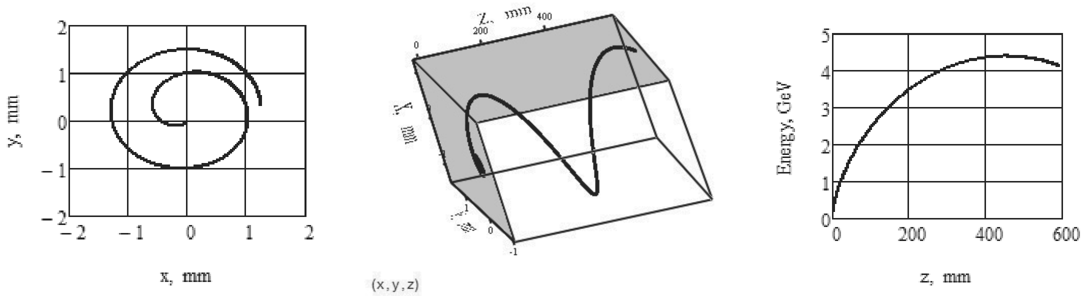

Fig. 6. Trajectory and energy of accelerated electron during 2 ns, E_0 = 10^{12} V/m, B_z = -200 T. ω is constant. The wavelength λ = 72 μm

7.2. Acceleration of a proton

Now let us see at the impact of the CE when a proton is subjected to the acceleration. In Fig. 7 is presented the case with the chirping parameters $n = 0.01$ and $b = 2.7\times10^{-4}$. It can be seen that in spite of relatively low as for a proton magnetic field being at resonance, the range of hundreds MeV can be achieved during only few picoseconds. Which may be reached also without CE but with magnetic field intensity of very high value, not achievable today.

If the acceleration process is continued the larger energies can be achieved. This is shown in Fig. 8 where the different chirping parameters are applied to ensure the conditions approaching the resonance effect. During 2 ns of acceleration tens of GeV may be expected. However, in spite of very high intensity of the magnetic field approaching the technological limits applied in this case, the proton seems to be moving to far away from the laser beam axis.

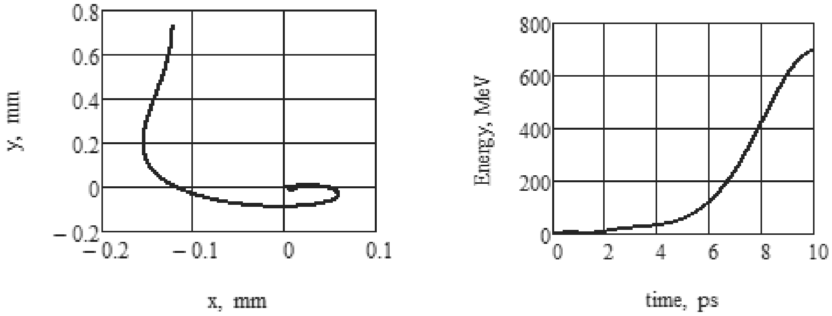

Fig. 7. Trajectory and energy of accelerated proton during 10 ps, the starting wavelength λ = 10 μm, $E_0 = 10^{12}$ V/m, B_z = 1000 T. The chirping parameters are $(\alpha t)^{0.01}$, $\alpha = \omega b$, $b = 2.7\text{x}10^{-4}$, final λ is 1.44 *mm*

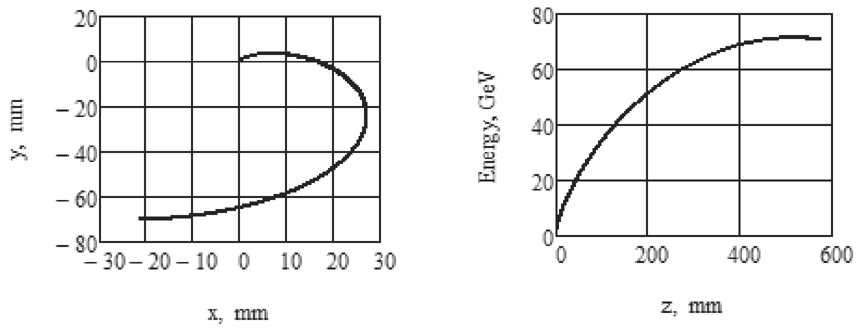

Fig. 8. Trajectory and energy of accelerated proton during 2 *ns*, the starting wavelength λ = 10 μm, $E_0 = 10^{12}$ V/m, B_z = 1000 T. The chirping parameters are $(\alpha t)^{0.0001}$, $\alpha = \omega b$, $b = 1.3\text{x}10^{-7}$, final λ is 33 *mm*

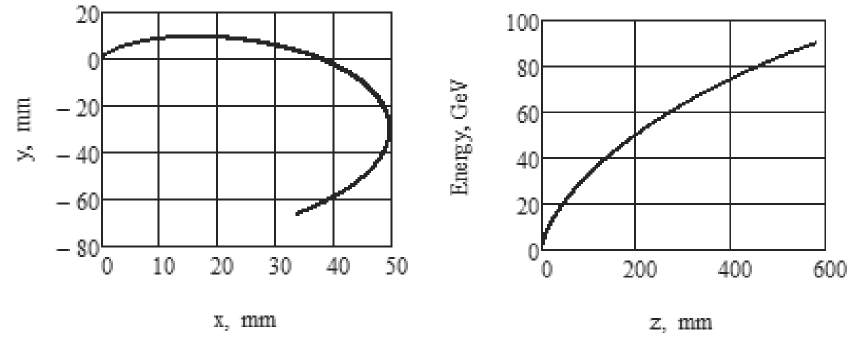

Fig. 9. Trajectory and energy of accelerated proton during 2 *ns*, $E_0 = 10^{12}$ V/m, B_z = 1000 T. ω is constant. The wavelength λ = 33 *mm*

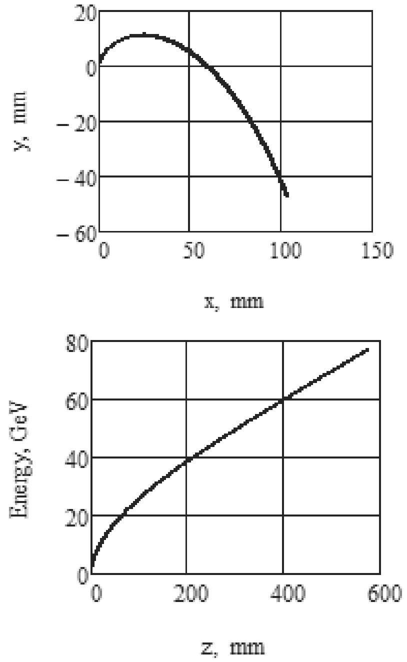

Fig. 10. Trajectory and energy of accelerated proton during 2 *ns,* the starting wavelength λ = 10 μm, E_0 = 10^{12} V/m, B_z = 0. The chirping parameters are $(\alpha t)^{0.0001}$, $\alpha = \omega b$, b = 1.3x10^{-7}, final λ is 33 *mm*

In order to compare acceleration processes with and without the CE in Fig. 9 the energy vs penetration distance curves are shown without the CE when radiation wavelength is chosen to be equal to the final wavelength in the process shown in Fig. 8 (with the CE). The results appear to be similar with and without CE but it requires application during the entire process of very long wavelength radiation if the CE is not applied. In the both cases the acceleration process seems to be at the resonance or close to the resonance conditions. Note that the proton after 2 ns of acceleration is subjected to about 7 cm displacement from the centre of the beam. Such wide laser beams show much lower E_0 than used in our calculations. In some applications much lower energy may be sufficient achievable as a result of acceleration during the reduced time (Fig. 7). The impasse may be also overcome by using much higher B_z (not achievable to day) causing the trajectory shrinking. However, it should be pointed out that the application of higher B_z leads to the acceleration process which was found to be no longer at the resonance conditions.

The impact of B_z on the acceleration process may be deeper understood if the additional simulation is performed with B_z = 0 (Fig. 10). Figs. 8 and 10 show similar energy vs time courses. However, may be seen that if B_z is large (Fig. 8) the acceleration process begins to escape from the resonance conditions as a result of which the oscillations of the energy gained by the proton starts to occur. Maximal value of the energy appears to be lowered. It is also evident that even for such high magnetic field the trajectory is rather far away from the beam axis (Fig. 8).

7.3. Acceleration of a deuteron

Now let us see at the impact of the CE when a deuteron is subjected to the acceleration. Since deuteron's mass is only two fold the mass of a proton we should not expect much difference in the acceleration process courses between the two particles. At least not so much as between an electron and a proton. This time the final results of acceleration appear to be similar for the both particles. In Fig. 11 is presented the case with the chirping parameters n = 0.0001 and b = 1.3x10^{-7}, the similar as for a proton (Fig. 8). Similarly the range of hundreds GeV may be achieved. This range may be reached also at the same wavelength without CE but with magnetic field intensity of very high value, not achievable today. In Fig. 12 the energy vs penetration distance curves are shown without the CE when radiation wavelength is chosen to be equal to the final wavelength in the process shown in Fig. 11. The results appear to be similar with and without CE but in this case during the entire acceleration process very long wavelength of radiation is applied (33 mm). The deuteron after 2 ns of acceleration is subjected to nearly 10 cm displacement from the centre of the beam. In order to keep a deuteron inside the laser beam a much higher B_z should be applied. However, similarly as for a proton, the application of higher B_z leads to the acceleration process of a deuteron being no longer at the resonance conditions.

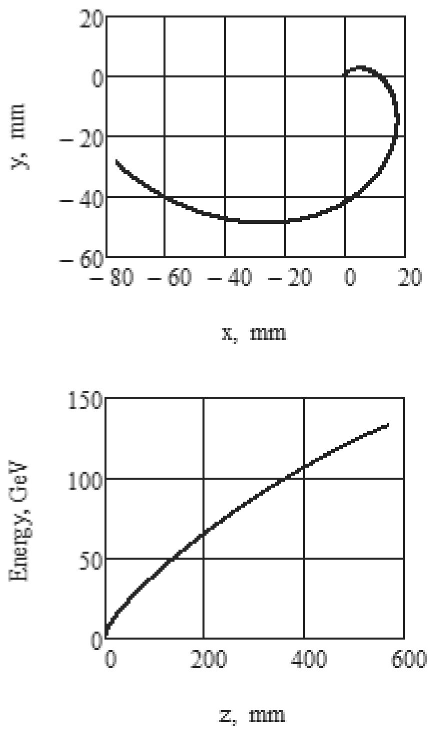

Fig. 11. Trajectory and energy of accelerated deuteron during 2 *ns,* the starting wavelength λ = 10 μm, E_0 = 10^{12} V/m, B_z = 1000 *T*. The chirping parameters are $(\alpha t)^{0.0001}$, $\alpha = \omega b$, b = 1.3x10^{-7}, final λ is 33 *mm*

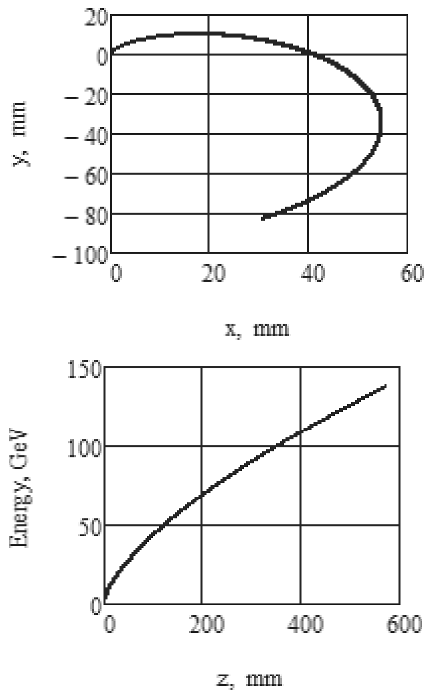

Fig. 12. Trajectory and energy of accelerated deuteron during 2 *ns*, $E_0 = 10^{12}$ *V/m*, $B_z = 1000$ *T*. ω is constant. The wavelength $\lambda = 33$ *mm*

8. Conclusions

The original equations (4) were used to perform the numerical study the particle's trajectory, velocity, and kinetic energy as a function of the acceleration time or the penetration distance by the particle. One of the possibilities to enhance the rate a particle gains an energy is connected with application of the CE – a gradual variation of the laser or maser radiation frequency during the course of the acceleration process. If the special chirping apparatus is included to the acceleration set, then the significant variation in the laser frequency can be obtained. The figures presented show the simulation results obtained with the CE applied. The linear chirping was found to be inefficient and do not lead to the satisfactory acceleration neither for an electron nor a proton or a deuteron.

It is proposed non linear chirping showing larger variation of the frequency with time than the linear one. Due to the non linear CE, in spite of relatively small intensity of the magnetic field the acceleration process enters into the resonance conditions at the moment the electron or other particle enters the radiation beam and continues to stay in this condition through the rest of the process. Now the particle's energy rises continuously and its energy does not show any oscillations. The energy gained by an electron enters in the GeV range and the energy of a proton or deuteron may enter even into hundreds of GeV range. The level of the gained energy depends on the duration of the particles acceleration process and the amplitude E_0.

From figures presenting the (x-y) projection of the trajectory it is evident that due to the rather moderate magnetic field the particles are subjected to travel along the trajectories deflected at a rather large distance from the laser beam axis. This is disadvantage in the laboratory circumstances but the presented results can be useful in a deeper understanding of some cosmological phenomena. The initial fragments of the presented acceleration processes may be useful in the designing of the laboratory experiments. It could be expected that in order to force the trajectory to be winding at a closer distance from the laser beam axis the larger magnetic field intensity should be applied. It is correct but it was found that in this case the oscillations of the energy appear with reduced its maximum value (Fig. 8). This is connected with the acceleration process which was found to be no longer at the resonance conditions.

It should be admitted that the energy in the range of GeV gained by the accelerated particles may be also achieved without the chirping. However, this is connected with some experimental disadvantages. The main of which is the necessary to apply rather very high static magnetic field in order to enter into the resonance conditions. This high magnetic field is already achievable for electron but for such particles as a proton or deuteron is not achievable today. This field may be reduced but in the case of high initial velocity of the accelerated particles.

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