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Abstract

Laser acceleration of electrons is considered. A general formulation of the problem is developed which would allow the recently proposed NAIBEA accelerator to function with any state of polarization and shape of the laser pulse, and any kind of applied field. Analytical estimates as well as numerical analysis for the case of an applied magnetic field are made. It is found that electrons, injected with few tens of MeV's, can be accelerated to GeV energies using a NAIBEA accelerator of a length of few meters.

Laser acceleration of particles, has been the focus of significant attention in the last few years. Recently, two of us[1)] have proposed a method of linearly accelerating electrons with the aid of a powerful laser coupled to an optimally determined static electric field which is made to change sign at appropriate places along the accelerator. With initial electron energy of 35 MeV, a laser power of 10^{15} W/cm^2 for a wavelength of 10 μm and an applied field intensity of $\sim 10^{-5}$ that of the laser intensity, we predicted a final electron energy of, say, ~ 400 MeV if three inversions of the static field are made along an accelerator tube of a length of about 3 meters! The advantages of such a machine obviously calls for a more general discussion concerning how optimum the set up is and the dependence on the laser parameters as well as the nature of the applied field.

In the present paper we develop a very general formulation of the problem that allows both semi–analytical and numerical answers to the above questions. Before entering into details, we first give some general remarks concerning the new acceleration principle which we called non–linear amplification of inverse bremsstrahlung electron acceleration (NAIBEA) in ref. 1). First, the new machine is meant to be a very high energy booster; the initial particle energy should already be highly relativistic. The reason is very simple. What sets the macroscopic scale of the machine is basically the Doppler shift of the laser wavelength as seen in the particle rest frame. Calling the laser wavelength λ_0 and, the velocity of the particle v_0 then the shifted wavelength obtained with the appropriate Lorentz transformation is

$$\lambda = \lambda_0 \left[\frac{1+\beta_0}{1-\beta_0}\right]^{1/2} , \qquad \beta_0 = v_0/c \ . \tag{1a}$$

Whereas λ_0 is microscopic (μm's), λ becomes macroscopic (cm's) if β_0 is close to unity. The distance Δz travelled by the electron in the laboratory during a one cycle encounter with the laser is then

$$\Delta z = v_0(\lambda/c)\gamma = \lambda_0 \frac{\beta_0}{1-\beta_0} \ . \tag{1b}$$

Clearly Δz is one of the quantities that would decide the size of the accelerator.

Secondly, the rate of change of the particle energy is determined by $\vec{v}\cdot\vec{E}$ and thus to keep the particle gaining energy from the laser, $\vec{v}\cdot\vec{E}$ should be made always positive. This calls for another degree of freedom to couple to the system. A possible simple form for this extra degree of freedom, was found in Ref. 1) to be an array of applied static electric field with interchanging signs placed at appropriate positions along the accelerator. Clearly a more general form for this degree of freedom can be found that would make the machine more efficient. A combination of electric and magnetic fields, not necessarily static could be one of the choices. In Ref. 2 we derived the Free Wave Accelerator (FWA) equations and we refer the reader to this reference for details.

We have used the FWA equations of Refs. 1 and 2 in the following numerical example. The initial value of γ, $\gamma_0 = 70$, $P = \frac{3}{2}\nu_0^2 10^{+15}$ W/cm^2 for $\lambda_0 = 10^{-3}$ cm. The parameter $\nu_0 = 1$ refers to the maximum value of electric field of the pulse in our units. We also take nine cycles within the pulse. The shape of the pulse is taken to be a Gaussian, $\bar{A}_0^2 = \exp(-\varphi^2/\Delta^2)$, Fig. 1, with $\Delta = 3\pi$. The applied field intensity is taken to be 2.34 teslas which corresponds to $\sim 5 \times 10^{-5}$ that of the laser. The electrons are injected at an angle of 0.6° with respect to the z–axis $\left(p_y(0) \approx \frac{0.6}{180}\pi\gamma_0\right)$. We consider, as an example nine changes in the sign of the modulated applied magnetic field. In figure 1 we show the change of how the relativistic factor γ varies with z. The gain in energy is a factor of 35 over a distance (accelerator length) of seven meters!

To understand the average linear increase of γ with z it is convenient to consider the rate of change of the electron energy $\varepsilon = mc^2\gamma$

$$\frac{d\varepsilon}{dt} = e\, v_y\, E_y^{(0)} \quad , \tag{1}$$

The presence of the applied magnetic field is needed in order to make the product $v_y E_y^{(0)}$ positive. If we take for $E_y^{(0)} = E_{y_0}^{(0)} \sin\varphi$, then if v_y is made to vary as $v_y^{max}\sin\varphi$, the resulting equation is integrated straightforwardly and the result is

$$\gamma = \gamma_0 + \frac{e\left(v_y^{max}/c\right) E_{y_0}^{(0)}}{2mc^2}\, z \tag{2}$$

$$z = Z_0\varphi \;\; ; \;\; Z_0 = \frac{1}{\pi}\, \frac{1}{1 + \gamma_0^2\left[\frac{v_y^{max}}{c}\right]^2}\, \gamma_0^2 \lambda \tag{3}$$

and

$$y = \left[\frac{v_y^{max}}{c}\right] Z_0 \sin\left[\frac{z}{Z_0}\right] \tag{4}$$

Using the values of γ_0, λ, $v_y^{max} \sim v_0 \sin\theta_0$, cited earlier, we reproduce very well the average trend of γ shown in Fig. 1.

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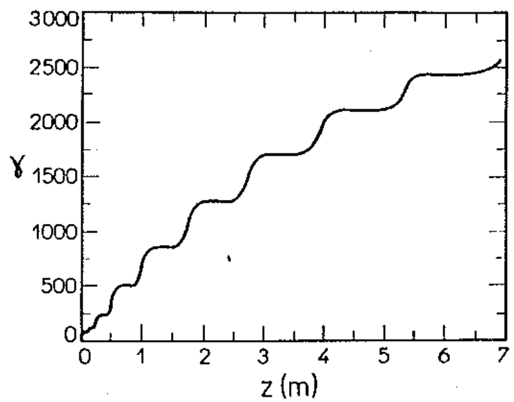

Figure 1 The energy of the particle in units of mc^2 vs. the traveled distance z.