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Review Article

Laser Beat Wave Acceleration

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Abstract

Laser based accelerators are splendid tools for future. Due to its uses in medical, industrial, and surgery. Its best advantage is compact and low maintenance cost. Laser's applications are no longer exorbitant. It is used by majorly in surgeries and industrial components. In this chapter we are going to discuss one of the laser-based accelerators phenomenon laser beat wave acceleration. And understand about the chirping of the laser and its effect upon the acceleration of electrons.

Keywords: Accelerators; Laser Acceleration; Beat; Vacuum

Introduction

In the present chapter, we proposed a scheme of laser beat wave acceleration in a vacuum for different laser chirps and the effect of the chirping of the laser on acceleration.

Conventional particle accelerators are very large and have high maintenance charges, whereas laser accelerators are compact. In particle acceleration using lasers, the mechanism is based upon the pondermotive force applied by the laser to the particle. Which is the Lorentz force. The electric field term of the Lorentz force is responsible for the increment of the velocity of the particle and the magnetic field term is used for the circular motion of the particle.

In 1960, the first laser was invented by Maiman after the first idea of a laser was given by Sir Albert Einstein in his paper "On the Quantum Theory of Radiation" in 1917. Present-time lasers are used in many industries, including clinical and communication. It has launched a multibillion-dollar industry. After the invention of the Ruby laser in 1960, Shimoda [1] was the first to propose the idea of the use of a laser for particle acceleration in a vacuum. after that several new ideas came in theoretically and experimentally for acceleration for different scenarios like; laser-plasma acceleration, beat wave acceleration, and Wakefield acceleration.

Mechanism of acceleration

A laser is a set of particles of high energies with high relativistic speed. The phase velocity of the laser is normally faster than the speed of light c, due to this electron and laser phase slippage will be fast and this results no net energy gain of an electron.

There is a theorem that states the conditions and the assumptions to accelerate an electron by any method which must be followed by the acceleration scheme which results no net acceleration of the electron. This theorem is named the L-W theorem.

Hence for the acceleration of electrons, some L-W theorem assumptions must be violated. It can be violated if the electron velocity is not relativistic, or the phase velocity of the laser would be less than c, etc. [2].

In laser acceleration in a vacuum electron interact with the high-speed laser, these interactions of the electron and laser, the electron oscillates between acceleration and deacceleration phase. So, no net energy is achieved by the electron. This is the major disadvantage of vacuum laser acceleration. In other mediums like plasma laser, phase velocity becomes slow compared to the speed of light c, due to this net energy gain can be achievable. So, we need some other schemes to accelerate electrons in a vacuum.

The beat wave acceleration scheme is one of them. It works on the concept of interference of two lasers such that the resultant laser field has phase velocity less than the speed of light c.

In broad terms there are two types of accelerations one is by pondermotive acceleration [3] and the other is CAS (capture acceleration scenario). Whereas in pondermotive acceleration electron velocity is low compared to CAS in which electron velocity is relativistic. In this chapter, we have discussed chirp beat wave acceleration where two chirped cosh gaussian laser pulses were used for acceleration. In chirp lasers, we have advantages for acceleration because in chirp lasers we have the same initial conditions as pondermotive acceleration, but energy and time variation are like CAS acceleration. In chirped lasers, the electron can be trapped for a longer time and transfer higher energy to the electron in the accelerating phase, and loss in the deceleration phase is insignificant compared to the acceleration phase. This is a great advantage of chirped laser pulses.

Beat wave acceleration

As we all know that when two slightly different frequency waves interact with each other then, they form a resultant beat wave. This resultant wave has its crest, trough, and different amplitude. The advantage of the beat wave is its phase velocity less than the parent waves.

By using this phenomenon, we can slow the phase velocity of a laser wave. So, we have used two same amplitude, same frequencies, and same polarization two lasers which are crossing at a small angle with z-axis and . Due to constructive interference between two lasers resultant laser wave generated which phase velocity is less than the speed of light. And the electron has been injected at a small angle with the z-axis. And we have shown the electron energy variation with injecting angles.

Figure 1

As we show in figure 1 two waves are crossing at the origin at some angle due to this both lasers have their z and x components of electric field and magnetic field. Here we are going to solve their mathematical terms to achieve resultant energy and momentum equations so that we can know about the factors and values of variables at which maximum energy can be achieved.

Let the electric field of both lasers is

$$E_{xi} = \frac{E_{0i}}{f_i}\cos(\phi_i)\exp\left[-\frac{(t-z_i/c)^2}{\tau_0^2} - \frac{r_i^2}{r_0^2 f_i^2}\right] \quad --- (1)$$

$$E_{zi} = -\frac{2E_{0i}x_i}{k_0 r_0^2 f_i^2}\left[\sin(\phi_i) - \frac{z_i}{R_d}\cos(\phi_i)\right] \times \exp\left[-\frac{(t-z_i/c)^2}{\tau_0^2} - \frac{r_i^2}{r_0^2 f_i^2}\right] \quad --- (2)$$

Electric field components for both lasers are attributed for and in the above equations. where $\phi_i = k_0 z_i - \omega_0(t)t + (z_i r_i^2/R_d r_0^2 f_i^2) - \tan^{-1}(z_i/R_d) + \phi_0$, Here $k_0 = \omega_0(z)/c$,, $R_d = k_0 r_0^2/2$, ω_0 is the incident laser frequency at

$z = 0$. R_d is rayleigh length, τ_o is initial pulse duration, r_o is minimum laser spot size,

ϕ_o is a constant and is the speed of light in vacuum. Magnetic field components of the laser can be calculated by Maxwell equation

$$\nabla \times \overrightarrow{E_1} = -\delta\overrightarrow{B_1}/\delta t.$$

Both lasers have the same amplitude so, their electric field components have the same magnitude and in x-direction have opposite directions. So, the resultant electric field in the x-direction is zero and, in the z-direction resultant electric field is:

$$E_z = -\frac{2E_0}{\xi^{3/2}}\exp\left[-\frac{(t - z\cos\theta/c)^2}{\tau_0^2} - \frac{z}{r_0\xi}\sin^2\theta\right] \times \left(\cos\phi + \frac{z}{R_d}\cos\theta\sin\phi\right) \quad ---- (3)$$

Where $\phi = k_0 z\cos\theta - \omega_0(t)t + z\cos^3\theta\tan^2\theta/r_0\xi - \tan^{-1}(z\cos\theta/R_d) + \phi_0$, $\xi = 1 + (z/R_d)^2\cos^2\theta$ and $E_{o1} = E_{o2} = E_o$.

Electron momentum and energy governing equations are deduced as:

$$\frac{dp_z}{dt} = -eE_z \quad ------ (4)$$

$$\frac{d\gamma}{dt} = -\frac{e}{m_o c^2}E_z v_z \quad ------- (5)$$

Here $\gamma = (1 + p_z^2/m_o^2c^2)^{1/2}$ is the relativistic factor. e and m_0 are the electron's charge and rest mass respectively.

As we know single laser in vacuum cannot accelerate electron. For single laser acceleration we can choose chirp wave acceleration. Chirp frequency helps to increase the interaction time between electron and laser. So, chirp is one of reliable mechanisms for acceleration. Further we will see comparison between the beat wave acceleration and chirp beat wave acceleration.

Chirped acceleration

Chirp is a modification in which wave frequency increases and decreases with respect to time. By chirping we achieve higher energy from wave with short pulses. To achieve this modification firstly short pulse is being stretched and after that this stretched pulse being amplified for higher amplitude. After this it compressed again to short pulse. Doing this mechanism, we achieve amplified short pulse which is called chirp pulse. It is very useful short pulses which can deliver higher energies to the electron. (As shown in figure 2).

Figure 2: Source: https://cuos.engin.umich.edu/researchgroups/hfs/facilities/chirped-pulse-amplification

Comparison between the beat wave acceleration and the chirp beat wave acceleration

To understand the phenomenon of beat wave acceleration and advantages of chirp in beat wave acceleration we borrow some energies vs normalised distance variation figures from ref. [4].

In figure 3 authors accelerate an electron with initial energy of 0.9 MeV. As we see they use beat wave acceleration and achieve energy approx. 60 MeV. On the other hand, red curve in fig. 03 shows the effect of Linear chirp laser in acceleration and energies can be increased. And they achieve energy around 833 MeV.

Figure 3

In this figure 4 quadratic chirp is applied to laser and achieve considerable higher energy approx. 525 MeV with less decimal chirp parameter compared to linear chirp.

Figure 4

Conclusion

From these figures we can understand that by using beat wave acceleration electron can be accelerated in vacuum. And by applying chirp we can achieve higher energies compared to without chirp. These accelerated electrons have many advantages in clinical, surgical and industrial.

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