CHAPTER-11

WIGGLER MAGNETIC FIELD ASSISTED ELECTRON ACCELERATION DURING LASER-CLUSTER INTERACTION

11.1 INTRODUCTION

Laser clusters interactions has been an interesting area of research as it exhibits a different coupling of laser field with clusters which presents many features which are not observed with gas atoms or other solid targets [18, 23, 42, 92]. Springate *et al.* [42] analysed the emission of fast electrons with the excitation of core electrons from the clusters during interaction with a strong-field laser. An intense laser pulse induces a large amplitude collective electron motion [92]. Donnelly *et al*. [30] was the first to find that the electron temperature from micro-scale targets is significantly higher than those from the solid targets during laser cluster interaction. Breizman *et al*. [43] called this effect the stochastic heating of the early extracted electrons through the ion Coulomb potential. The small plasma balls are formed during interaction of an intense short pulse laser with atomic clusters. The hydrodynamic expansions of such plasma balls is called Coulomb explosion [25, 44]. Another model of Coulomb explosion was suggested by Liu and Tripathi [44] in terms of a collision-less propagation of Gaussian laser beams through cluster. The electron density falls rapidly during such expansion in cluster and reaches three times the critical density. Thus, enhances the response of electron to the laser which give rise to strong absorption of laser energy [31]. This happens because under the action of intense laser pulse, the effective permittivity of the medium changes abruptly and thus gives rise to nonlinearity. Thus, the Coulomb explosion of the cluster produces energetic ions. Ultra-short laser pulse was employed to study this effect [51]. They presented theoretically the interaction between moderate Xe cluster with $10^4 - 10^6$ atoms with Ti:sapphire ($800nm$) laser pulses of intensity $I \approx 10^{18} W/cm^2$, and $I \approx 10^{19} W/cm^2$ with pulse duration of $30 fs$ and concluded that the electrons at rest can be accelerated to several hundreds of KeV energy with $I \approx 10^{18} W/cm^2$ and multi MeV of energy with $I \approx 10^{19} W/cm^2$ of laser intensity. An externally applied magnetic field influences the dynamics of electron while laser-electron interactions [122]. In recent experiments based on laser-cluster interactions, a TW laser pulse was employed to generate the electron acceleration in MeV of energy [85, 104, 123].

In this chapter we have studied the effect of LP and CP laser pulse on electron acceleration during laser-cluster interaction. Additionally, we have applied a wiggler magnetic field to improve the acceleration process by laser field in cluster. In section 11.2, the equation for laser, cluster, and external magnetic field has been defined. In section 11.3, results obtained have been discussed and in section 11.4, we have concluded the outcome of the presented work.

11.2 FIELD DISTRIBUTION AND ELECTRON DYNAMICS FOR LASER-CLUSTER INTERACTION

A single electron outside the cluster experiences the electromagnetic fields due to laser pulse, electrostatic field of clusters, and externally applied wiggler magnetic field. The electron dynamics due to laser-cluster interaction is expressed in terms of Lorentz equation as:

$$\frac{d\vec{p}}{dt} = -e\left(\vec{E}_L + \vec{E}_C + \vec{B}_W + \vec{v} \times \vec{B}_L\right), \tag{11.1}$$

where $\vec{p} = \gamma m_0 \vec{v}$ is the electron momentum, $\gamma = \sqrt{1 + p^2 / m_0^2 c^2}$ is the relativistic factor, $\vec{v}$ is the electron velocity, $-e$ is the electron's charge, m_0 is the rest mass of electron, $\vec{E}_L$ and $\vec{B}_L$ are the electric and magnetic fields of the laser, $\vec{E}_C$ is the electrostatic field of charged clusters, and $\vec{B}_W$ is the wiggler magnetic field.

The CP laser beam is propagating along the z-direction with transverse (x, y) electric field components expressed as [51]:

$$E_{Lx} = \frac{E_{L0}}{f}\sin(\phi)\exp\left(-\frac{(t-\frac{z-z_L}{c})^2}{\tau^2} - \frac{r^2}{r_0^2 f^2}\right), \tag{11.2}$$

$$E_{Ly} = \varepsilon\frac{E_{L0}}{f}\cos(\phi)\exp\left(-\frac{(t-\frac{z-z_L}{c})^2}{\tau^2} - \frac{r^2}{r_0^2 f^2}\right), \tag{11.3}$$

where E_{L0} is the peak amplitude of the laser, $\phi = \omega_0 t - k_0 z + \tan^{-1}(z/Z_R) - zr^2/(Z_R r_0^2 f^2) + \phi_0$, is the phase of laser pulse, $f^2 = 1 + (z/Z_R)^2$, $k_0 = \omega_0/c$ is the wave number, ω_0 is the laser's angular frequency, $Z_R = k_0 r_0^2/2$ is the Rayleigh length, ϕ_0 is the initial phase, τ is the laser pulse duration, $r^2 = x^2 + y^2$, r_0 is minimum laser spot size, z_L is the initial position of the pulse peak, and c is the velocity of light in vacuum. The factor ε represents the ellipticity and is equal to zero for a LP laser pulse. For a CP laser pulse $\varepsilon = \pm 1$ represents the positive and negative helicity. The intensity of CP laser pulse can be expressed in terms of intensity of LP laser pulse as: $I_{CP} = I_{LP}(1 + |\varepsilon|)$.

The longitudinal (z) electric field component is deduced by using expressions:

$$E_{Lz} = -\left(\frac{i}{k}\right)\left(\frac{\partial E_{Lx}}{\partial x} + \frac{\partial E_{Ly}}{\partial y}\right). \tag{11.4}$$

The transverse (x, y) and longitudinal (z) components of magnetic field representing the laser pulse can be derived from Maxwell's equation $\vec{\nabla} \times \vec{E}_L = -\partial \vec{B}_L / \partial t$.

We consider a single Xe cluster with $10^4 - 10^6$ atoms. During interaction with a short pulse laser of high intensity in the range of $10^{17} - 10^{19} W/cm^2$, there is a significant removal of electrons out of the cluster. Thus the inner free electrons get accelerated out of the cluster due to laser field. The electrostatic field due to cluster charge distribution is expressed as [51]:

$$E_C = \begin{cases} \dfrac{en\vec{r}}{\tilde{R}^3} & (r \le \tilde{R}) \\ \dfrac{en\vec{r}}{r^3} & (r \ge \tilde{R}), \end{cases} \tag{11.5}$$

where $n \propto I^{1/2} N^{2/3}$ is the total number of the ionized electrons from the cluster, N is the initial total number of atoms in cluster, $\tilde{R} \approx \sigma R_0$ is the average cluster radius, $R_0 \approx \sqrt[3]{9N}\ A^o$ is the initial cluster radius, σ is the expansion factor.

The externally applied wiggler magnetic field [84, 120] is given by:

$$\vec{B}_W = \hat{y} B_{W0} \exp(ik_W z), \tag{11.6}$$

where k_w is the wiggler wave number and B_{w0} is the amplitude of the wiggler magnetic field. The fields defined in equations (11.2)-(11.6) are substituted in equation (11.1) to draw a set of coupled ordinary differential equations representing electron momentum and energy. These equations have been solved numerically with a computer simulation code for electron momentum and energy. For calculations the factors of time, length, velocity, momentum, and energy are normalized by $1/\omega_0$, c/ω_0, c, $m_0 c$, and $m_0 c^2$ respectively. The normalized intensity parameter of laser pulse and the normalized magnetic field parameter are expressed as, $a_0 = eE_{L0}/m_0\omega_0 c$ and $b_{W0} = eB_{W0}/m_0\omega_0 c$ respectively.

11.3 RESULTS AND DISCUSSION

In simulation we have set the numerical values of used parameters as, $a_0 = 2.5$ for a LP and $a_0 = 1.76$ for a CP laser pulse (both the values of a_0 corresponds to laser intensity $I \sim 8.5 \times 10^{18} W/cm^2$), $a_0 = 5$ for a LP and $a_0 = 3.5$ for a CP laser pulse (both the values of a_0 corresponds to laser intensity $I \sim 3.46 \times 10^{19}\ W/cm^2$) with wave length $\lambda_0 \sim 1\mu m$; $r_0' = 300$ (corresponds to laser spot size $r_0 \sim 75\mu m$); and $p_0' = 1$; $\tau' = 70$ (corresponds to laser pulse duration of $200 fs$); $\phi_0 = 0$; $b_{W0} = 0.000032$ (corresponds to a magnetic field of $3.4kG$); and $z_L' = -300$.

In figure 11.1, we have plotted the variation of electron energy gain with normalized propagation distance z' for LP and CP laser pulses with and without magnetic wiggler. The electron energy gain first increases and then saturates. The energy gain is higher with a CP laser pulse than that with a LP laser pulse. It is due to the wider interaction of CP laser pulse with electron during laser-cluster interaction than that with a LP laser pulse. The spiral motion of electrons with CP laser pulse enforces electrons for larger impact of cluster fields than the zigzag trajectory with LP laser pulse [51]. With a wiggler magnetic field, the electron energy gain is slightly higher with LP laser pulse whereas it is significantly higher with CP laser pulse than without wiggler magnetic field. We consider the optimized value of wiggler magnetic field $b_{W0} = 0.000032$ and wiggler wave number $k_w = k_0 / 2000$ for the maximum energy gain by electron. Chang *et al.* [51] reported that the intensity parameter $a_0 = 1/\sqrt{2}$ for a CP laser pulse corresponds to same intensity value as with $a_0 = 1$ for LP laser pulse. Since $a_0 = 1.76$ is $1/\sqrt{2}$ times the value of $a_0 = 2.5$. Thus, we have chosen $a_0 = 1.76$ for a CP laser pulse and $a_0 = 2.5$ for a LP laser pulse to analyze the impact of same intensity for the different polarization states of a short pulse laser.

In figure 11.2, we have plotted the variation of electrostatic cluster field experienced by accelerating electron with respect to normalized propagation distance z' for LP and CP laser pulses. The cluster field enforces electron to be in phase or out of phase with laser field, such that the electron can absorb energy from the laser pulse. One can clearly see from figures 11.1 and 11.2 that after a certain distance the impact of cluster field decreases, the electron energy gain increases. The electron energy gain saturates after attaining maximum value where cluster field is very small. Thus, cluster field play a vital role in effecting the dynamics of an accelerated electron. We observe the higher value of cluster field with a CP laser pulse than that with LP laser pulse for the same set of parameters. Xu *et al.* [68] stated that the CP laser field provides a relatively larger phase space for electron acceleration than that by LP laser field. We observe that the comparative impact of cluster field is higher with CP than that with LP laser field. This results in greater acceleration efficiency with CP laser field.

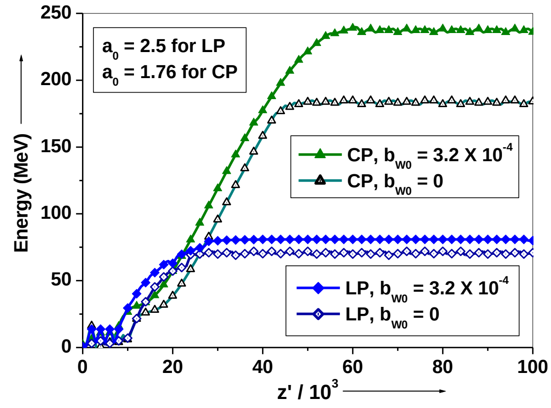


Figure 11.1. Variation plot for electron energy gain with normalized propagation distance with laser intensity $a_0 = 2.5$ for LP and, $a_0 = 1.76$ for CP laser pulse with and without magnetic wiggler in cluster. The other parameters are $r_0' = 300$, $\tau' = 70$, $z_L' = -300$, $N = 10^5$, $\sigma = 10$, and $\phi_0 = 0$.

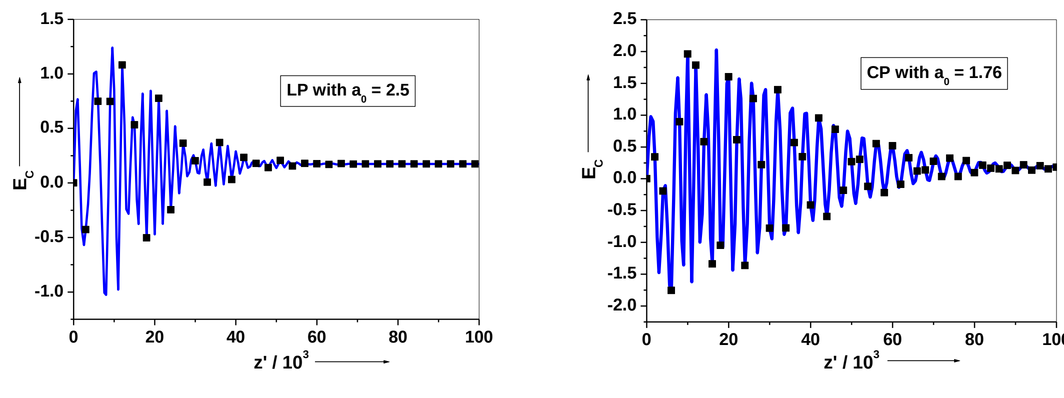
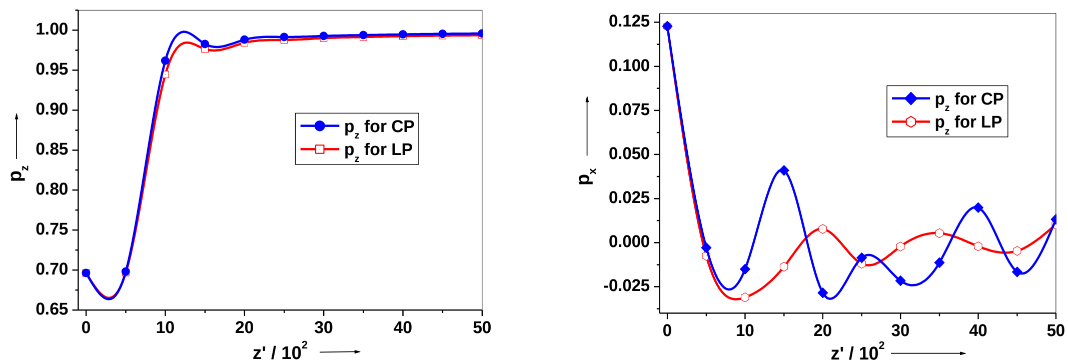


Figure 11.2. Variation plot for cluster field felt by electron with normalized propagation distance with laser intensity $a_0 = 2.5$ for LP and, $a_0 = 1.76$ for CP laser pulse. The other parameters are same as referred in fig. 11.1.



(a) **(b)**

Figure 11.3. Variation plot for normalized longitudinal (p_z') and transverse (p_x') components of accelerated electron momentum with normalized propagation distance for $a_0 = 2.5$ for LP and, $a_0 = 1.76$ for CP laser pulses. The other parameters are same as referred in fig. 11.1.

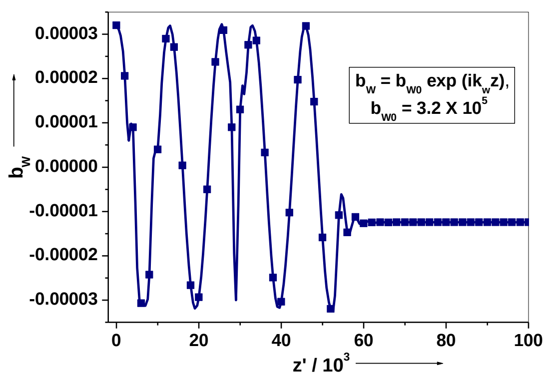


Figure 11.4. Variation plot for normalized wiggler magnetic field b_W experienced by accelerated electron with normalized propagation distance with normalized initial value of wiggler magnetic field is $b_{W0} = 3.2 \times 10^5$. The other parameters are same as referred in fig. 11.1.

In figure 11.3, we have plotted the variation of normalized longitudinal (p_z') and transverse (p_x') components of electron momentum with respect to normalized propagation distance z' for LP and CP laser pulse. The initial value of transverse momentum decreasing with normalized distance z' whereas the longitudinal momentum increases quickly which responsible for the electron acceleration in the direction parallel to the propagation of laser field. The initial values of momentum are slightly higher with CP than that with LP laser pulse. Thus higher acceleration appears with a CP laser pulse than that with LP laser pulse.

In figure 11.4, we have plotted the variation of normalized wiggler magnetic field b_W experienced by an accelerated electron with respect to normalized propagation distance z'. The betatron resonance can be maintained for a longer duration with an externally applied axial magnetic field during laser-electron interaction. Such field enhances the strength of $\vec{v}\times\vec{B}$ force which further enhances the electron acceleration [126]. As per eq. (1), the field component due to wiggler magnetic field contributes significantly in electron energy gain. We have employed a small magnetic field in the range of few kG. These days the magnetic field of the order of MG is feasible to generate experimentally [113].

In figure 11.5, we have plotted the variation of angle of electron emittance θ of an accelerated electron with respect to normalized propagation distance z'. Using relation $\tan\theta = (p_x^2 + p_y^2)^{1/2} / p_z$ with Lorentz force factor, the emittance of electron with respect to z axis is expressed as $\theta = \tan^{-1}(\sqrt{(\gamma^2 - 1)/(\gamma^2\beta_z^2) - 1})$, where β_z is the normalized longitudinal velocity [121]. We observed low scattering of electron with LP as well as CP laser pulses even for large energy gain by accelerated electron. For energy gain of about $240MeV$ with a CP laser pulse of $a_0 = 1.76$, the angle of emittance is less than 1° as depict from fig. 11.5.

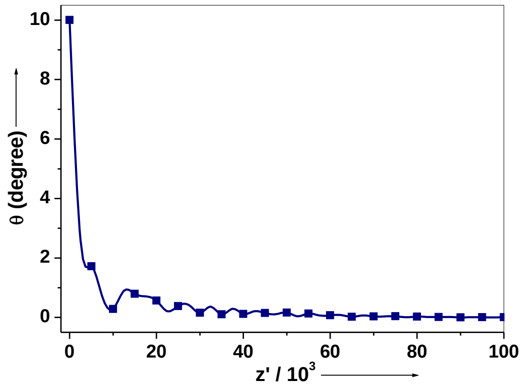


Figure 11.5. Variation plot for scattering of accelerated electron with normalized propagation distance. The other parameters are same as referred in fig. 11.1.

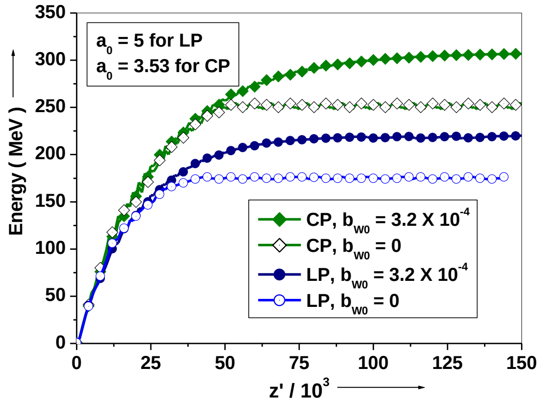


Figure 11.6. Variation plot for electron energy gain with normalized propagation distance at laser intensity $a_0 = 5$ for LP and, $a_0 = 3.53$ for CP laser pulse with and without magnetic wiggler. The other parameters are same as taken for fig. 11.1.

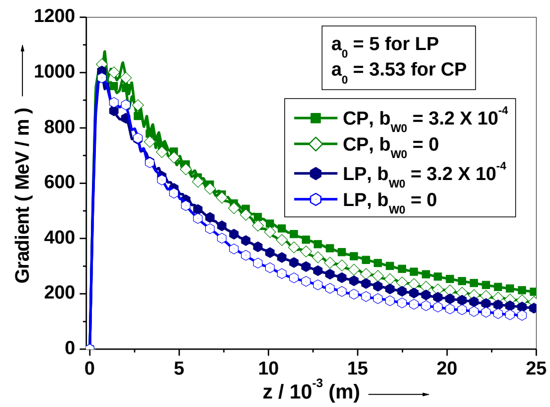


Figure 11.7. Acceleration gradient as a function of distance z with laser intensity $a_0 = 5$ for LP and, $a_0 = 3.53$ for CP laser pulse with and without magnetic wiggler. The other parameters are same as taken for fig. 11.1.

In figure 11.6, we have plotted the variation of electron energy gain with normalized propagation distance z' for intensity parameter $a_0 = 5$, and $a_0 = 3.53$ for LP and CP laser pulses respectively. The electron energy gain appears higher with magnetic wiggler than that without magnetic wiggler. We find that a rest electron gains energy of the order of $300 MeV$ with CP laser pulse of peak intensity about $10^{19} W/cm^2$ with a wiggler magnetic field of $3.4 kG$ during laser-cluster interactions.

Figure 11.7 shows the variation plot of acceleration gradient with distance z. The acceleration gradient [121] is calculated by using relation $d\gamma / dz = -e\vec{\beta}.\vec{E} / \beta_z$ and is plotted with distance z for intensity parameter $a_0 = 5$ for LP and $a_0 = 3.53$ for CP laser pulse with and without magnetic wiggler. We observe the acceleration gradient in the range of GeV per meter. High gradient is observed at a very small distance of propagation which goes on decreasing with propagation distance. This indicates an effective acceleration of electron with increasing distance of propagation.

11.6 CONCLUSION

We have investigated the roles of laser fields, polarization state, cluster field and external magnetic wiggler on electron acceleration during laser-cluster interactions. We have found that a short pulse laser can accelerate a rest electron in the direction parallel to the propagation of laser pulse with small scattering. We have observed the relativistic electron acceleration to MeV energies. The electron energy is further enhanced in the presence of wiggler magnetic field. The polarization characteristics of CP laser beams support better acceleration of the electron than LP laser beams in clusters. The wiggler magnetic field enforces better trapping during interaction of the electron with laser pulse. A significant enhancement in electron energy gain is observed with a wiggler magnetic field of small and optimum values.