PARTICLE ACCELERATION WITH HELICALLY POLARIZED ULTRA-INTENSE LASER BEAMS

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Abstract – High power laser systems are usedin the study of particle accelerations. It has been shown that electrons can reach up to ~GeV energies and protons can gain energies up to 100 MeV. Laser driven accelerated particles can be used for medical applications such as hadron therapy and radionuclide productions. However, one of the problems that needs to be studied is the focusing of ions. Ions can be employed in hadron therapy if they can be focused after being accelerated. Previously, linear and circular polarized laser beams were studied on particles' angular distribution. It is known that laser pulses can be polarized helically by applying Laguerre-Gaussian distribution to the laser profile. In this study, we have shown the Laguerre-Gaussian mode effect onaccelerated particles and their angular distribution as well as their energies.

Keywords - Helical Polarization, PIC Simulations, Laser Plasma Interactions, Particle Accelerations

I. INTRODUCTION

With the development of laser technology, laser irradiances can reach up to 10^{22} - 10^{23} W cm^{-2}. Thus, multi petawatt laser systems can be employed for particle acceleration inside plasma. Ions are accelerated with high-power laser systems via several acceleration mechanisms such as target normal sheath acceleration(TNSA)[1-4], radiation pressure acceleration(RPA)[5-7], breakout afterburner (BOA) [8,9] and relativistic induced transparency acceleration (RITA)[10-12] which has a dependence on target and laser parameters. These mechanismsare mostly accelerating ionsin the laser propagation direction.However, although circular polarized (CP) laser beams carry angular momentum, it is difficult to distinguish the optical angular momentum of the CP laser light.

A laser beam with aLaguerre–Gaussian (LG) phase profile,occupies an orbital angularmomentum [13] as well. A linearly polarized (LP) LG laser with a helical wave-front structure has a central phase singularity [14].The generated angular momentum by a helical wave-front structure isreferred to as an orbital angular momentum. The mode of the LG laser pulse (LG_p^m) is described by integer indices m and p, where mdenotes the number of2π phase cycles around the circumference and (p +1) denotes the number of radial nodes in the mode profile.An LG_0^1 laser carries an orbital angular momentum m$\hbar$per photon. Therefore, in this study, we discuss the angular momentum variations on accelerated protons by changing the (LG_p^m)mode, where mis varied from 1 to 1000 and indicates the presence of an azimuthal phase term $e^{-im\phi}$ in thelaser mode. In this study, we employed 3D EPOCH particle-in-cell (PIC) code [15] to simulate them mode value on accelerated particle energies and angular distributions which is especially important for the hadron therapy and radionuclide productions. We have seen that increasing the m mode value up to 10 collimates the accelerated ions, while for higher values of m, collimation of ion beams is deformed.

II. EPOCH 3D PIC Simulations

We used 3D EPOCH PIC code to simulate thelaser-solid interactions with pre-formedplasma and QED effects on particle acceleration. The system size was 50x25x20 μm with a mesh resolution of 2500x250x200 cells with each cell containing 10 electrons and10 protons. The simulated laser irradiance was varied from $1x10^{21}$ $Wcm^{-2}$to $5x10^{23}$ Wcm^{-2}in a LG laser profile with a 5 μm FWHM focal spot and a laser incident angle of 0^o. The laser wavelength andpulse duration were 0.8 μm and 30 fs, respectively. The hydrogen gas was chosen asa target material and the peak electron density was limited to $2n_c$ initially, wheren_c is the plasma critical density. In the case of pre-plasma, an exponential density profile wasassumed with a maximum scale length of L = 0.5μm and a cutoff to zero density at $0.01n_c$ in front of a 1 μm target. Plasma scale length L can be defined as $\left[-\frac{\frac{\partial n_e}{\partial x}}{n_e}\right]^{-1}$ where n_e is the electron number density.

We have performed simulations with QED and without QED depending on the laser irradiances for several m mode values ranging between 1and 1000. Our simulations suggest theaccelerated particles' energy and angular distribution change whenm is greater than 10.

Laguerre-Gauss (LG) beams, which are the general type of the spiral beam, have a spiral phase $e^{-im\phi}$through the wave surface. Here m=1,2,…N is the mode index (helix) and φ represents the azimuth angle. Phase diversity is m=0 for the classical Gaussian beam, and for valuesgreater than m=0 the helicalstructure occurs. In Equation 1, the Laguerre-

Gaussian function is applied to 3D EPOCH PIC simulations and changes to the polarization of the laser are given as:

$$U_n^m(r,\varphi,z) = C_{m,n}\frac{\omega_o}{\omega(z)}\left(\frac{r\sqrt{2}}{\omega(z)}\right)^m L_n^m\left(\frac{2r^2}{\omega^2(z)}\right)\exp\left(\frac{-r^2}{\omega^2(z)}\right)\exp\left(-i\left(kz + k\frac{r^2}{2R(z)} - (2n+m+1)\arctan\left(\frac{z}{z_o}\right)\right)\right)\exp(-im\varphi) \quad (1)$$

The helical laser profile has a dependence on the m mode value which is shown in figure 1.The following figures are extracted for the laser irradiance I = $5x10^{22}$ $Wcm^{-2}$to show the laser and electron density profile.

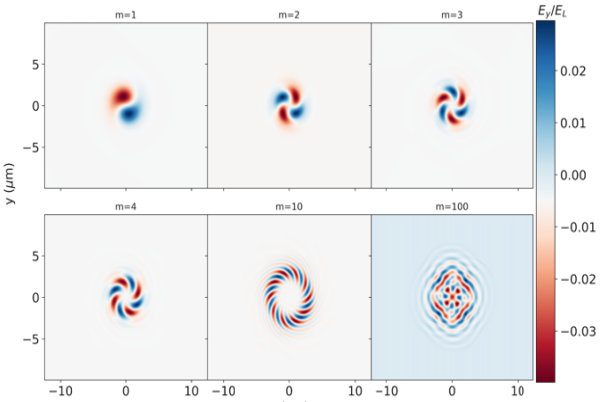


Fig.1. Laser E_y electric profile for different m mode values.

In figure 1, we show the $E_y$laser electric field on the x laser propagation axes for different m mode values at the beginning of the simulation time. It is seen that after m = 100, helical polarization is getting disturbed which reduces the accelerated particle energy and angular distribution.

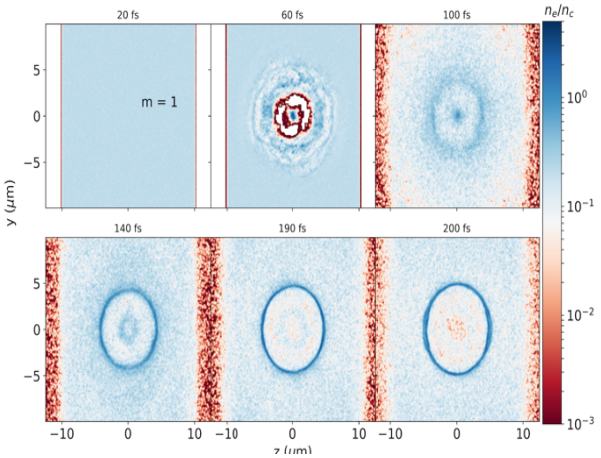


Fig.2. Electron density profilealong the x (laser propagation) axes for m= 1 mode and different time steps.

In figure 2,the electron number density on the x-axes is extracted for different time steps, when the m mode value is 1. A cross-section on the y-axes is taken from exactly the same pointin order to show the variation on electron density over time.

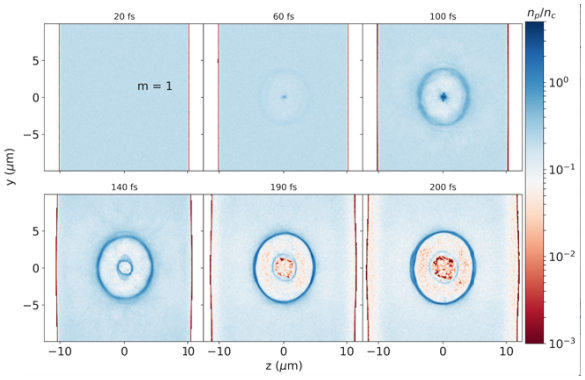


Fig.3. Proton density profile along the x (laser propagation) axes for m = 1 mode and different time steps.

In figure 3, theproton number density on the x-axes is extracted for different time steps, when the m mode value is 1. A cAross section on the y-axes is taken from exactly the same point in order to show the variation on proton density profile and collimation inside the target as a function of time.

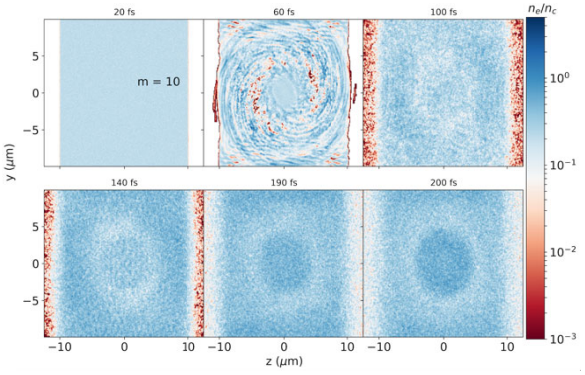


Fig.4. Electron density profile along the x (laser propagation) axes for m = 10 mode and different time steps.

In figure 4, electron number density on the x axes is extracted for different time steps, when m mode value is 10. A cross-section on the y-axes is taken from the same area in order to show the variation on electron density over time.

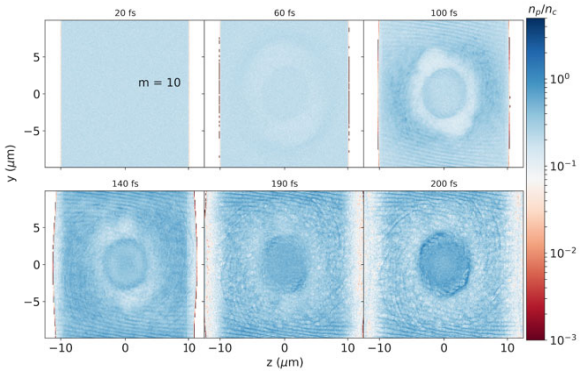


Fig.5.Proton density profile along the x (laser propagation) axes for m = 10 mode and different time steps.

In figure 5, the proton number density on the x-axes is extracted for different time steps, when m mode value is 10. A cross-section on the y-axes is taken

from exactly the same point in order to show the variation in the proton density profile and collimation inside the target as a function of time.

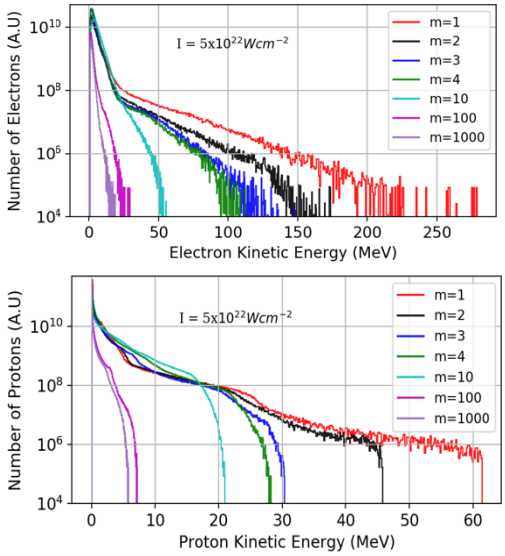


Fig.6. Electron and proton kinetic energy spectrum for different m mode values.

Figure 6 shows the extracted electron and proton kinetic energy spectrum for different m mode values. For laser irradiances ofI = $5x10^{22}$ Wcm^{-2}, electrons can reach up to 250 MeV energies and protons can reach up to 60 MeV energies when the m mode values is 1. When the m mode value is increased, we can see a drop in the energies of accelerated particles. However, from figure 7 it is seen that total angular momentum and ion angular momentum of the accelerated particles is reaching the maximum when m is 10 which suggests that the particles have a better collimation.

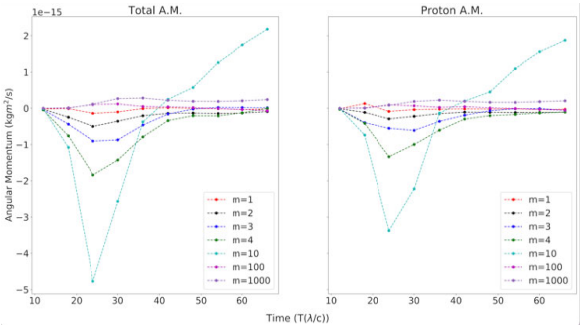


Fig.7.Total angular momentum and proton only angular momentumm_e $(yv_z - zv_y) + m_p(yv_z - zv_y)$ inthe x direction.

In figure 7, we show the total angular momentum of the particles (electronsand protons) and the angular momentum of protons only in 3D PIC simulations. To describe the rotationeffects of different LGmodes on the plasma, the angular momentum ofthe particles in the x direction (the longitudinal direction) is calculated by using the equation m_e $(yv_z - zv_y)$ + m_p $(yv_z - zv_y)$. It is seen that the m = 10 mode value has the highest rotational effect on particles.

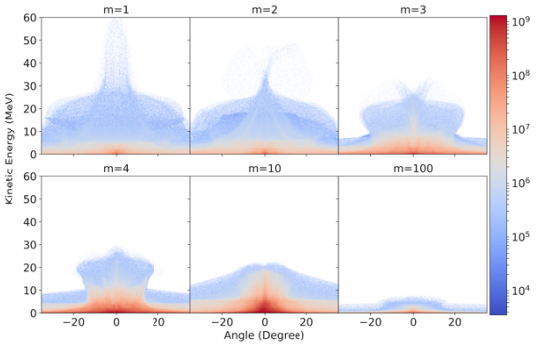


Fig.8. Proton angular distribution as a function of kinetic energy of protons for different m mode values.

Figure 8 shows the accelerated proton angular distribution as a function of the kinetic energy of protons for different m mode values. It is seen that most of the ions are focused tightly when m = 10.When m =1 we can still see the tight collimation however, the number of ions is low, which makes it insufficient to use them in some applications such as hadron therapy.

III. CONCLUSIONS

In conclusion, we have observed that the particles rotational alignment in the laser direction is possible with the use of an intense LG laser pulse with higher m mode values (up to 10). The enhancement of the proton angular momentum in the longitudinal direction is obtained when an intense LG laser pulse irradiates on a thin foil target with the maximum density of $2n_c$ for the mode value of 10.It is also found that electrons and protons are moving with the LG laser pulse in the laser direction. We also showed that the gained energy of the particles decreases with increasing m mode values up to 10.

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