My advice to ITER-Driven Plasma Physics

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Abstract

Comparing the device of ITER with ICF, I strongly notice that I have an advice to ITER Driven Plasma Physics. I used to study laser-plasma interaction which relates to a strong spontaneous magnetic field (in axial or in azimuthal direction) and found a new particle acceleration named laser-magnetic resonance acceleration (LMRA). The electron acceleration depends not only on the electromagnetic wave intensity, but also on the ratio between electron Larmor frequency and electromagnetic wave frequency. As the ratio approaches to unity, a clear resonance peak is observed. We point out that strong quasistatic magnetic fields affect electron acceleration dramatically in relativity. We derive an approximate analytical solution of the relativistic electron energy in adiabatic limit, which provides a full understanding of this phenomenon. ITER Driven has strong magnetic fields but no laser beam. If we add a laser beam inside plasma, it will give a quick and efficient ignition process.

Keywords: Acceleration of particles, Laser-magnetic resonance acceleration

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I. INTRODUCTION

I have the idea about "My advice to ITER-Driven Plasma Physics" because of my research in laser-plasma interaction. My work relates to a strong spontaneous magnetic field both in axial and in azimuthal direction. In the past two decades strong magnetic field caused much interesting both in astrophysics[1] and in laser-matter interaction[2], e.g. many novel and complex physics involved in ultraintense laser-plasma interaction studies especially in inertial confinement fusion (ICF), including relativistic self-focusing[3], explosive channel formation[4] and self-generated huge magnetic field[5]. A typical problem is to investigate the response of electron in the presence of strong quasistatic magnetic fields. Experiments[6, 7] and three-dimensional (3D) particle-in-cell (PIC) simulations[8] clearly demonstrate that the fact of strong currents of energetic $10-100\ MeV$ electrons manifest themselves in a giant quasistatic magnetic field with up to 100 MG amplitude. Recently the laboratory astrophysics has a long development with the high intensity ($> 10^{20} W/cm^{-2}$), high density ($\sim 1kg/cc$), high electric field ($\sim 300GV/m$) and high pressure ($\sim 10Gbar$) available in intense laser facilities.

From above, we restrict our attention to a typical problem which is to investigate the response of electron in ultraintense electromagnetic wave plasma system in the presence of strong magnetic field. Using test particle model, we solve relativistic Lorentz force equations theoretically and numerically. In our simulation, the electromagnetic wave is a circular polarized (CP) Gaussian profile. The magnetic field is considered as an axial constant field. A fully relativistic single particle code is developed to investigate the dynamical properties of the energetic electrons. We find that a rest electron can be accelerated to relativistic energy within a few electromagnetic wave cycle through a mechanism which is named laser-magnetic field resonance acceleration (LMRA)[9]. The electron acceleration depends not only on the electromagnetic wave intensity, but also on the ratio between electron Larmor frequency and electromagnetic wave frequency. As the ratio approaches to unity, a clear resonance peak is observed, corresponding to the LMRA. Near the resonance regime, the strong magnetic field affect the electron acceleration dramatically. We derive an approximate analytical solution of the relativistic electron energy in adiabatic limit, which provides a full understanding of this phenomenon. Our paper is organized as follows. In Sec.II we derive the dynamical equation describing relativistic electron in combined strong axial magnetic field and the CP laser field. The equation will be solved both numerically and analytically. We describe LMRA in a Gaussian CP beam with static axial magnetic field. An approximately analytical solution of relativistic electron energy is obtained, which gives a good explanation for our numerical simulation. In Sec. III we consider the acceleration mechanism of energetic electrons in a combined strong azimuthal magnetic field and a linearly polarized(LP) laser field[10]. We find that two different source of fast electrons are distinguished.

II. ELECTROMAGNETIC WAVE AND STATIC-MAGNETIC FIELDS RESONANCE ACCELERATION

The approach to the analysis the response of electron in ultraintense electromagnetic wave plasma system in the presence of strong magnetic field is in a single test model described in the relativistic Lorentz force equations

$$\frac{d\mathbf{p}}{dt} = \frac{\partial \mathbf{a}}{\partial t} - \mathbf{v} \times (\nabla \times \mathbf{a} + \mathbf{b_z}), \qquad (1)$$

$$\frac{d\gamma}{dt} = \mathbf{v}\cdot\frac{\partial \mathbf{a}}{\partial t}, \qquad (2)$$

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where $\mathbf{a}$ is the normalized vector potential, $\mathbf{b}_z$ is the normalized static magnetic field which is parallel to the electromagnetic wave propagation direction, $\mathbf{v}$ is the normalized velocity of electron, $\mathbf{p}$ is the normalized relativistic momentum, $\gamma = (1 - v^2)^{-1/2}$ is the relativistic factor or normalized energy. Their dimensionless forms are $\mathbf{a} = \frac{e\mathbf{A}}{m_e c^2}$, $\mathbf{b} = \frac{e\mathbf{B}}{m_e c\omega}$, $\mathbf{v} = \frac{\mathbf{u}}{c}$, $\mathbf{p} = \frac{\mathbf{p}}{m_e c} = \gamma\mathbf{v}$, $t = \omega t$, $r = kr$, m_e and e are the electric mass and charge, respectively, c is the light velocity. k is the wave number. We assume that the electromagnetic wave propagation is in positive $\hat{\mathbf{z}}$ direction and moving with nearly the speed of light.

As a solution of the three-dimensional wave equation, the vector potential of an Gaussian profile electromagnetic wave can be expressed as

$$\mathbf{a} = a_x + \delta a_y \tag{3}$$

$$a_x = a_0 e^{-\frac{x^2+y^2}{R_0^2}} \cdot e^{-\frac{(kz-\omega t)^2}{k^2L^2}} \cdot [\cos(\omega t - kz)] \tag{4}$$

$$a_y = a_0 e^{-\frac{x^2+y^2}{R_0^2}} \cdot e^{-\frac{(kz-\omega t)^2}{k^2L^2}} \cdot [\sin(\omega t - kz)] \tag{5}$$

where L and R_0 are the pulse width and minimum spot size, respectively. $\mathbf{a}$ is the electromagnetic wave amplitude. δ equals to 0, 1, and -1, corresponding to linear, right-hand and left-hand circular polarization, respectively. For simplicity, we assume $\delta = 1$ (right-hand circular polarization) in the following discussions.

$\mathbf{b}_z$ is the static magnetic-field aligned to the electromagnetic wave propagation direction. We assume that the trajectory of a test electron starts at $\mathbf{r}_0 = \mathbf{v}_0 = 0$. Eqs.(1) and (2) yield

$$\frac{dp_x}{dt} = (v_z - 1)\frac{\partial a_x}{\partial z} - v_y b_z, \tag{6}$$

$$\frac{dp_y}{dt} = (v_z - 1)\delta\frac{\partial a_y}{\partial y} + v_x b_z, \tag{7}$$

$$\frac{dp_z}{dt} = -v_x\frac{\partial a_x}{\partial z} - v_y\delta\frac{\partial a_y}{\partial z}, \tag{8}$$

$$\frac{d\gamma}{dt} = -v_x\frac{\partial a_x}{\partial z} - v_y\delta\frac{\partial a_y}{\partial z}. \tag{9}$$

Using Eqs.(4)-(7), we choose different initial position to investigate the electron dynamics for a Gaussian profile electromagnetic wave pulse. Because the initial velocity can be transformed to initial position in our single test electron case, we keep initial velocity at rest and change the initial positions of the test electrons. We assume that the trajectory of a test electron starts from $\mathbf{v}_0 = 0$ and $z_0 = 4L$ at $t = 0$, while the center of electromagnetic wave pulse locates at $z = 0$, then the classical trajectory is then fully determined by Eqs.(4)-(7). Now we choose following parameters that are available in present experiments, i.e. $L = 10\lambda$, $R_0 = 5\lambda$ ($\lambda = 1.06\mu m$), $\delta = 1$, $a_0 = 4$ (corresponding $I = 2 \times 10^{19} W/cm^2$), $\mathbf{b}_z = 0.9$ (corresponding static $B_z = 90MG$), $\mathbf{r}_0 = 0.1$. Then, we trace the temporal evolution of electron energy, i.e. $\gamma \sim t$.

Obtaining an exactly analytical solution of Eqs.(4)-(7) is impossible because of their nonlinearity. However, we notice that the second term on the left side of Eqs.(4)-(5) possesses symmetric form, which is found to be a small quantity negligibly after careful evaluation. Then, an approximately analytical solutions of Eqs.(4)-(7) in adiabatic limit can be obtained.

From the phase of the electromagnetic wave pulse, we have the equation

$$\frac{d\eta}{dt} = \omega(1 - v_z), \tag{10}$$

where $\eta = \omega t - kz$. Then, from Eq.(10) and Eq.(11), we can easily arrive at the second useful relation under the initial condition $\mathbf{v}_0 = 0$ at $t = 0$,

$$\gamma v_z = \gamma - 1. \tag{11}$$

Finally, the energy-momentum equation yields

$$\gamma^2 = 1 + (\gamma v_x)^2 + (\gamma v_y)^2 + (\gamma v_z)^2. \tag{12}$$

The solution of the electron momentum has symmetry. In adiabatic limit and under the initial condition of zero velocity electron, we find the solutions of Eq.(4) and Eq.(5) taking the form,

$$\omega p_x = -b_z \cos(\omega t - kz), \tag{13}$$

$$\omega p_y = b_z \sin(\omega t - kz). \tag{14}$$

Substituting Eq.(11) and Eq.(12) into Eq.(4), and using Eqs.(8)-(10), we obtain an equation having a resonance point (singularity) at a positive b_z $(= \omega)$

$$\gamma = 1 + \frac{1}{2}\frac{a^2}{\left(1 - \frac{b_z}{\omega}\right)^2}. \tag{15}$$

Eq.(13) is an approximately analytical energy solutions of Eqs.(4)-(7). The Eq.(13) can express the electron energy evolution very well.

From the above analytic solution, we find that the strong magnetic field affect the electron acceleration dramatically through the electromagnetic and magnetic field resonance acceleration (EMRA). The electron acceleration depends not only on the electromagnetic wave intensity, but also on the ratio between electron Larmor frequency and electromagnetic wave frequency.

In order to get the analytical expression of electron energy γ near the exact resonance point ($b_z = \omega$), we plug following approximate solutions into the dynamical equations,

$$\omega p_x = c(t)\sin(\omega t - kz), \tag{16}$$

$$\omega p_y = c(t)\cos(\omega t - kz), \tag{17}$$

where $c(t)$ is a coefficient to be fitted. Careful analysis gives the solution at $t \to \infty$ in the following approximate expression

$$\gamma \approx (\frac{3}{\sqrt{2}} a\omega t)^{\frac{2}{3}}. \tag{18}$$

It indicates that the resonance between the electromagnetic wave and magnetic field will drive the energy of electrons to infinity with a 2/3 power law in time. In typical perimeter of pulsar magnetospheres, the mechanism provide chance to allow particles to increase their energies through the resonance of high magnetic field and high frequency electromagnetic wave in each electromagnetic wave period.

We now review the exact solutions of Eqs.(4)-(7) in plane-wave from previously work, where $\eta = \omega t - \mathbf{k}\cdot\mathbf{r}$. We first consider the right-hand CP wave. The resonance point is in the positive b_z

$$\gamma(\eta) = 1 + 2a_0^2 \frac{\sin^2[(1-\frac{b_z}{\omega})\eta/2]}{\left(1-\frac{b_z}{\omega}\right)^2}. \tag{19}$$

Then we consider the lift-hand CP wave. The resonance point is in the negative b_z

$$\gamma(\eta) = 1 + 2a_0^2 \frac{\sin^2[(1+\frac{b_z}{\omega})\eta/2]}{\left(1+\frac{b_z}{\omega}\right)^2}. \tag{20}$$

For LP wave, both positive and negative b_z are the resonance point. The exact solution has obtained by Yousef I. Salamin before[11]

$$\gamma(\eta) = 1 + \frac{a_0^2}{2} \frac{[\cos\eta - \cos[\frac{b_z}{\omega}\eta)]^2 + [\frac{b_z}{\omega}\sin\eta - \sin[\frac{b_z}{\omega}\eta)]^2}{[1-(\frac{b_z}{\omega})^2]^2}. \tag{21}$$

Equations (17)-(19) are also the basic exact static resonance equations which agree with general physical mechanism. The dimensionless form of $b_z (= \frac{e\mathbf{B}_z}{m_e c\omega})$ is equal to classical Larmor frequency Ω $(= \frac{eB_z}{m_e c})$. So the electron obtain energy efficiently from near or at resonance point which is the ratio of classical Larmor frequency $(\Omega = b_z)$ and electromagnetic wave frequency (ω).

III. GAUSSIAN LP LASER PULSE

When a short-pulse ultraintense laser into plasma, free electrons begin to quiver at velocity close to the speed of light c in the transverse oscillating direction of the laser field. Cicchitelli *et al.* and Brice *et al.*[12] have proved that when the neodymium glass laser intensity is above $10^{18} W/cm^2$, the electron momentum of two transverse directions are independent on the laser polarization. Because the ponderomotive potential in this two transverse directions are equal. Experiments, theories and particle-in-cell simulations (PIC) usually use linearly polarized (LP) laser pulse as a power source for simplicity, e.g.[13–20]. But there are polarization dependent phenomena clearly appearing in the relevant range. We consider the acceleration mechanism of energetic electrons in a combined strong azimuthal magnetic field and a linearly polarized(LP) laser field[10]. We find that two different source of fast electrons are distinguished. The first is that the electron acceleration depends on the laser intensity, known as the pondermotive acceleration[21–24]. The second is that, around the peak of azimuthal magnetic field, laser-magnetic resonance acceleration (LMRA) partly occurs which causes the electron to gain energy from the ratio between electron Larmor frequency and laser frequency within one laser period. If we consider a LP laser pulse, the LMRA results in a dependence of the laser accelerated electrons on the laser polarization. Because in the resonance regime, the strong magnetic field affects the electron acceleration dramatically though the LMRA mechanism. Only just from the second source, polarization dependence of electron is appeared. In our knowledge, this different sources of fast electrons are mentioned for the first time. This clears up many experiments and PIC simulations which are related with polarization dependence phenomena.

IV. DISCUSSIONS AND CONCLUSIONS

Using a single test electron model, we investigate the acceleration mechanism of energetic electrons in combined strong axial magnetic field and circular polarized electromagnetic wave field. An analytic solution of electron energy is obtained. We find that the electron acceleration depends not only on the electromagnetic wave intensity, known as the pondermotive acceleration, but also on the ratio between electron Larmor frequency and the electromagnetic wave frequency. As the ratio equals to unity, a clear resonance peak is observed. The strong magnetic field affects electron acceleration dramatically. ITER Driven plasma has strong magnetic fields but no laser beam. If we add a laser beam inside plasma, it will give a quick and efficient ignition process.

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