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An Analytical model of plasma cavity for producing of quasi-monoenergetic electron in intense laser-plasma interaction

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ABSTRACT

During the recent experiments and PIC simulations, quasi-monoenergetic for electron is observed [1, 2]. Forming the free of cold plasma electrons cavity behind the laser pulse is possible instead of periodic plasma wave and plasma channel guided method [3] . In this bubble cavity a dense bunch of relativistic electrons with a monoenergetic spectrum is self-generated [3].The profiles [3] and PIC simulation [4] show the ellipsoid shape cavity behind the laser pulse. In this work we present an analytical ellipsoid model and discuss how quasi-monoenergetic electron is produced in the bubble field.

1-INTRODUCTION

Compact systems generating multi-terawatt are available now with CPA technics [5]. The petawatt laser pulses reach intensities up to I = 10^{21} W/cm^2 and the electric field strength is E = 10^{14} V/m [6].An ultrashort, intense laser pulse propagates through an underdense plasma can generate large amplitude plasma wave by the effect of ponderomotive force associated with the laser pulse envelope $F_p \approx \nabla a^2$. It expels electrons from the region of the laser pulse.One of the simplest ways to put energetic electrons into the acceleration phase of the wakefield is plasma-wave breaking [7, 8].This wave-breaking process is the randomization of regular oscillations of plasma electrons where the rate depends on plasma and laser pulse parameters [8,9].Due to the transverse wave breaking [10] only a few periods of plasma waves remain intact behind such a laser pulse. Ultra short MeV electron bunch has been generated by the wave breaking using a shock wave driven by the irradiation of laser prepulses [11,12]. The main features of the bubble regime are the following: (i) a cavity free from cold plasma electrons is formed behind the laser pulse instead of a periodic plasma wave; (ii) a dense bunch of relativistic electrons with a monoenergetic spectrum is self-generated; (iii) the laser pulse propagates many Rayleigh lengths in the homogeneous plasma without a significant diffraction [13].

2-CAVITY FORMATION AND ELECTRON INJECTION

Quasimonoenergetic beams have also been produced with homogenous or parabolic plasmas at higher density and even with longer laser pulse with $\tau_l > \tau_{plasma}$. Part of the laser pulse energy generated a bubble cavity which can sustain the self-injection and the production of quasimonoenergetic spectra.The optimal case corresponded to the plasma density $n_e = 6 \times 10^{18}$ cm^{-3} [14].As the effective radius of the laser pulse decreases, the laser intensity increases and finally becomes sufficient to generate the so-called ‘‘bubble’’ [15], which is the shape of the plasma wave when the peak vector potential greatly exceeds unity. Since the laser pulse also pushes electrons forward, it propagates in plasma with rising density. The laser group velocity will then be higher on the back of the pulse than on its front. This will compress temporally the laser pulse as was recently measured [16] and will also contribute to the generation of the bubble.When the beam charge becomes comparable with the ion charge in the cavity, the injection stops, which finally leads to a monoenergetic electron beam .Temporal information based on infrared emission measurements indicated that the electron bunch had temporal structures with durations shorter than 50 fs [17,18].

3-ELECTRONS WITH QUASI-MONOENERGETIC ENERGY SPECTRA

Plasma electrons are expelled off the axis by the front of the incident relativistic laser pulse and form a bubble-like structure with longitudinal and transverse dimensions close to the plasma wavelength λ_p. This bubble is void of electrons at the beginning of the interaction and moves through the background plasma ions with a speed close to c. However, in the frame of the moving bubble, the net positive potential of the bubble core attracts electrons that fall back to the laser axis behind the cavity. These electrons are captured and accumulated inside the bubble and are thus accelerated to high energies. The energy distribution of the bubble electron bunch is quasi-monoenergetic and its peak is calculated in [19] .

4-ELECTROSTATIC POTENTIAL IN A PLASMA ELLIPSOID CAVITY

Let us consider an electrically neutral bulk plasma ellipsoid cavity with axes 2a, 2b and 2c. The volume of the ellipsoid is $V = 4\pi abc/3$, the total charge of the ions is enV (here $e > 0$ is the value of the electron charge, n is the number of ions per unit volume of a sample). The electrostatic potential inside a uniformly charged ellipsoid (with total charge enV) was calculated in [20]:

$$\varphi(x,y,z) = (enV/C) + \{3enabcV/2\varepsilon[(ab)^2 + (ac)^2 + (bc)^2]\}[1 - (x/a)^2 - (y/b)^2 - (z/c)^2], \quad (3)$$

Where c is the electrical capacity of the plasma ellipsoid in vacuum.

One can see that Eq. (3) satisfies the Poisson equation,

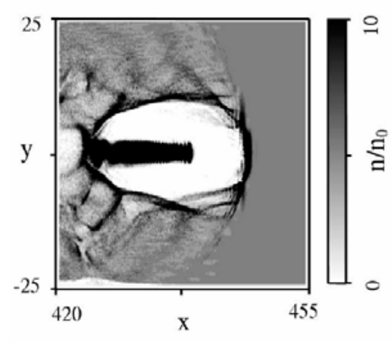
$$\Delta\varphi = -4\pi en/\varepsilon , \quad (4)$$

And all necessary boundary conditions .Where we choose that the potential is equal to unity at the ellipsoid boundary.

$$\Phi\ (x,y,z) = 1 + \varphi_0\ [1 - (x/a)^2 - (y/b)^2 - (z/c)^2]\ ,\ (5)$$

Fig.1 Uniform plasma cavity as a whole relative to the lattice of ions in the ellipsoid of plasma.

The black color shows shell's electrons and trapped electrons. On-axis cuts of the electron density n in the x − y plane from the PIC simulation at the times when the laser pulse passed about L2 = 442c/ $\omega_p \approx 900\lambda$.[21].



Now we are interested in the question what are the fields inside a ellipsoid electron cavity moving in plasma. This cavity is similar to the hole in semiconductor physics [22]. Contrary to the case discussed above, the ions are now immobile in the cavity while the cavity runs with the relativistic velocity $\upsilon_0 \approx 1$ along x-axis. The ion dynamics is neglected because the cavity radius is assumed to be smaller than the ion response length ≈ c/ω_{pi}, where ω_{pi} = $(4\pi e^2 n_0/M)$ is the ion plasma frequency and M is the ion mass.Now let us calculate the electrostatic field in a sample when the ellipsoid of plasma ions is shifted along the x-axis by a shift $\upsilon_0 t$ relative to the ellipsoid of ions. The electrostatic potential produced by the shifted ellipsoid of ions according to Eq. (3) is:

$$\varphi(x,y,z) = 1 + \varphi_0\ \{1 - [(x - \upsilon_0 t)/a)\ ]^2 - (y/b)^2 - (z/c)^2\}\ ,\ (6)$$

We use all quantities depend on $\zeta = x - \upsilon_0 t$ instead of x and t, so:

$$\varphi(x,y,z) = 1 + \varphi_0\{1 - (\zeta/a)^2 - (y/b)^2 - (z/c)^2\},\ (7)$$

The electrostatic field is equal to minus gradient of φ.

$$E\ \zeta_i = -2\ \varphi_0\ /a^2\ \zeta\ \ (8)\ ,\ E_{yi} = = -2\ \varphi_0\ /b^2\ y\ \ (9)\ ,\ E_{zi} = = -2\ \varphi_0\ /c^2\ z\ \ (10)$$

This field acts on each of the trapped electrons with restoring force $-eE_i$.

$$dp/dt = -eE + [-e\ /\ c(v \times B)]\ ,\ (11)$$

The electromagnetic fields inside the relativistic cavity are

$$E_x = -2\ \varphi_0\ /a^2\ \zeta\ \ (12),\quad E_y = -B_z = -2\ \varphi_0\ /b^2\ y\ \ (13),\quad B_x = 0, E_z = B_y = -2\ \varphi_0\ /c^2\ z\ \ (14)$$

The calculated distribution of electromagnetic fields in ellipsoid cavity is closer than spherical cavity [21] to the one observed in the 3D PIC simulation .The Lorentz force acting on a relativistic electron inside the cavity is

$$F_x = f_x / e = -E_X = 2\,\varphi_0 / a^2\,\zeta \quad (15),\quad F_y = f_y / e = -E_y + B_z = 4\,\varphi_0 / b^2\,y \quad (16),\quad F_z = f_z / e = -E_z - B_y = 4\,\varphi_0 / c^2\,z \quad (17)$$

The Lorentz force for the electron is zero when it's velocity reach to υ_0 **,** so the cavity can hold the equal energy electrons bunch.

5-CONCLUSIONS

Instead of periodic plasma wave, forming the free cold electron cavity behind the laser plasma is possible when laser pulse intense is enough to break the plasma wave already after than the first oscillation. In this work, it is observed without the prepulse and channel forming how the laser pulse propagates many Rayleigth lengths in the homogeneous plasma without a significant diffraction. A dense bunch of relativistic electrons with a monoenergetic spectrum is self-generated. It showed the fields linearly depend on the coordinates .So relativistic trapped electrons are holed inside the ellipsoid cavity with equal energy.

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