*35th EPS Conference on Plasma Phys. Hersonissos, 9 - 13 June 2008 ECA Vol.**32D**, P-4.151 (2008)*

Electron trapping in moving void of laser-plasma interaction

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Laser-driven plasma-based accelerators was first proposed by Tajima and Dawson in 1979 [1], and later pioneer work on particle-in-cell simulation of plasma by John Dawson, who is regarded as the father of plasma-based accelerators [2]. Laser-plasma accelerators are of great interest and significance because of their ability to sustain extremely large acceleration gradients. The accelerating fields in conventional accelerators are currently limited to roughly 100 MV/m. Ionized plasmas, however, can sustain electron plasma waves with electric fields $E_0 \simeq 96\sqrt{\rho_0(\mathrm{cm}^{-3})}$(V/m), where ρ_0 is the ambient electron density. For example, a plasma density of $\rho_0 = 10^{18}$ cm^{-3} yields $E_0 \simeq 100$ GV/m, which is roughly three orders of magnitude greater than that of conventional accelerators. Among the various laser-plasma accelerator concepts, the high-gradient laser wakefield acceleration of charged particles in plasma is considered to be the most demanding research field [1, 3]. In addition to extremely large accelerating gradients, plasma-based accelerators have the capability to produce extremely short electron bunches. The length of the accelerating wave in a plasma-based accelerator is approximately the plasma wavelength $\lambda_p\ (\mu\mathrm{m}) \simeq 3.3\times 10^{10}/\sqrt{\rho_0(\mathrm{cm}^{-3})}$, e.g., $\lambda_p \simeq 30\,\mu$m for $\rho_0 = 10^{18}$ cm^{-3}.

During the interaction of ultra-relativistic intense laser pulse with an under-dense plasma, laser field pushes electrons aside through the action of the ponderomotive pressure. The laser pulse travels at a velocity close to the speed of light and excites a trailing plasma density wake. The generalized nonlinear ponderomotive force [4] can be derived by considering the electron momentum equation which is given by

$$\mathbf{F}_{\mathrm{pond}} = -m_e c^2 \nabla\gamma, \tag{1}$$

where γ is the relativistic factor. The pushed electrons have relatively large inertia and therefore will flow backwards with respect to the forward group velocity (v_g) of laser pulse along the x-direction. This process gives birth to a void region behind the moving laser pulse, which has been observed in three-dimensional (3D) particle-in-cell (PIC) simulations for relativistically intense laser pulses [5].

We focus on laser plasma interaction in the “void" or “bubble" regime [6]. We have undertaken 2D particle-in-Cell (PIC) simulations of laser plasma interaction using the OSIRIS code

[7, 8] . The incident laser pulse is circularly polarized, and has a Gaussian envelope with a peak intensity $a_0 = eA_0/mc^2 = 5$, where A_0 is the laser vector potential. The plasma density is given by $\rho_0 = \rho_c/\gamma_g^2$, where ρ_c is the critical plasma density and γ_g is the Lorentz factor for the laser pulse. In our simulation we have considered $\rho_0 \sim 6.2 \times 10^{-4}\rho_c$. Figure (1) shows a snapshot of the spatial distribution of the electron density. The void shape is determine by the ponderomotive potential of the laser pulse. From Fig.(1) we can trace a moving void which is roughly divided into three parts: (i) the void core region, i.e., the cavity with depleted electron density and a large positive space charge, (ii) the transverse boundary where the electrons are compressed and form the radial sheath around the cavity, and (iii) the front (tail of the laser pulse) and back (end of the void) cavity boundaries. As time goes on we find that electrons are trapped by the wakefield. At the back boundary selected electrons are trapped by the high fields and acquire high energy and accelerating as a bunch. A model for particle trapping in spherically symmetric space charge has been already discussed by Kostyukov et al. [6].

In this work we will discuss a simple model for predefined shapes of the space charge void to investigate the mechanism of electron trapping. We considered that the laser pulse is circularly polarized, and the azimuthal motion of plasma electron is neglected. The electron trajectories lie on the plane $z = 0$, and the laser pulse travels along the x-axis. For slowly varying electric fields of the void and $v_g \sim c$, the Hamiltonian is given by $\mathscr{H}_v = \{1 + (\mathbf{P} + \mathbf{A})^2 + a^2\}^{1/2} + \phi$, where $\mathbf{P}$ is the canonical momentum of electron, a is the vector potential of the laser field, and $\mathbf{A}$ and ϕ are the slowly varying vector and scalar potentials, respectively [6, 9]. Single electron trajectory can be described in the comoving coordinate $\zeta = x - v_g t$, where v_g is phase velocity of the wakefield, which is equal to the group velocity of the laser pulse along the x-axis. The Hamiltonian (2) in the comoving coordinate is

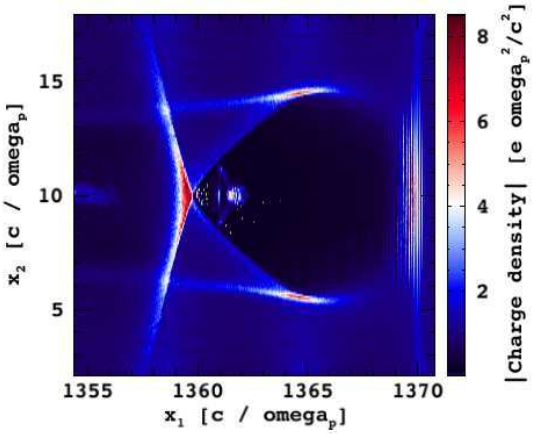

Figure 1: Snapshot of absolute value of electron density ($\rho_0 \sim 6.2 \times 10^{-4}\rho_c$, $\gamma_g = 40$, and $a_0 = 5$) in the x-y plane from the PIC simulation when the laser pulse has elapsed about t=2293.20/ω_p.

$$\mathscr{H} = \gamma - v_g p_x - \phi \,, \tag{2}$$

where p_x is the longitudinal momentum. We use $\Psi = \phi - v_g A_x$ as the static normalized wakefield

potential for our calculation. The equations of motion in the comoving frame are given by

$$\frac{dp_x}{dt} = -v_x\frac{\partial A_x}{\partial \zeta} - v_y\frac{\partial A_y}{\partial \zeta} + \frac{\partial \phi}{\partial \zeta}, \quad (3)$$

$$\frac{dp_y}{dt} = -v_x\frac{\partial A_x}{\partial y} - v_y\frac{\partial A_y}{\partial y} + \frac{\partial \phi}{\partial y}, \quad (4)$$

$$\frac{d\zeta}{dt} = \frac{p_x}{\gamma} - v_g; \frac{dy}{dt} = \frac{p_y}{\gamma}. \quad (5)$$

We approximate the void region by a sphere to obtain an analytical result. The electron sheath around the void screens the ion in the surrounding plasma. We modeled the wakefield potential which is given by

$$\Psi(h,R,r) = kr^2 - f_1(h,R,r) + \mathrm{erf}[h,R,r]\, f_2(h,R,r), \quad (6)$$

where k is constant, h is the width of electron sheath, R is the radius of the void, and f_i is a function. We can solve the above coupled Eqns.(3-5) numerically assuming $v_x \to c$ and $v_y \ll c$. Figure (2) shows electron trajectories for a plasma density ($\rho_0 \sim 6.2 \times 10^{-4}\rho_c$, $\gamma_g = 40$) in the x-y plane. The electron sheath $h = 0.4$ and the radius of void is $R = 6c/\omega_p$. Initially, electrons are placed at the front of the void, and after their traverse around it they arrive on the axis of the laser pulse with vanishing transverse momentum and trapping occurs at the rear of the void. This situation helps the strong wakefield of the void to pull them forward accompanied by betatron oscillation and emission of synchroton radiation.

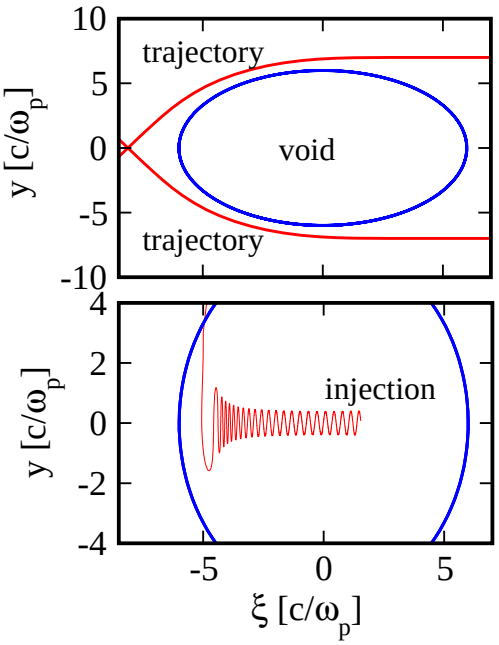

Figure 2: Trajectories of several selected electrons in the x-y plane by solving the coupled equations (3-5) using the wakefield potential (6) for a spherical void of radius $R = 6c/\omega_p$, and sheath width $h = 0.4$.

In this work we have discussed electron trapping in the spherical void regime using a predefined simple model for the wakefield potential in the laser plasma interaction. The nonlinear ponderomotive force has been neglected because trapping occurs behind the laser pulse where the field is very small. The simulation results show the basic findings and this model can be used for further investigations of beam properties. Although the void (cavity) shape is not exactly spherical our model gives us a phenomenological theory to understand the trapping mechanism. However, we should investigate this further to pin-point the underlying physics regarding

trapping and acceleration of electrons in the void regime.

We gratefully acknowledge the OSIRIS Consortium, consisting of UCLA, IST (Lisbon, Portugal), and USC, for the use of OSIRIS, and IST for providing access to the OSIRIS 2.0 framework. We also acknowledge financial support from the EPSRC and the EU Euroleap Nest contract 028514.

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