LASER WAKEFIELD ACCELERATION OF ELECTRONS IN THE CAVITATION REGIME

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Abstract

Plasmas are an attractive medium for the next generation of particle accelerators because they can support electric fields greater than several hundred gigavolts per meter, thus allowing acceleration to high energy in a very short distance [1]. These accelerating fields are generated by relativistic plasma waves – space-charge oscillations – that can be excited when a short, high-intensity laser pulse (with duration of the order of the plasma wavelength) propagates through a plasma [2]. If the intensity of the laser pulse is high enough then plasma electrons are radially expelled by the transverse ponderomotive force of the laser pulse leaving a cavity free from electron [3]. Thus in this high intensity regime, instead of a running plasma wave a cavity (bubble) free of plasma electrons is formed behind the laser pulse, moving at nearly the group velocity of the laser pulse. Strong longitudinal and transverse electric fields inside the cavity are responsible for acceleration and focusing of relativistic electrons which can, under the right circumstances, be injected into the bubble from the ambient plasma. In the present paper an analytical approach has been presented to understand the field inside the cavity and compare it with the earlier standard laser wakefield regime. The laser and plasma parameters have been explored using simulations with a three-dimensional PIC code VORPAL [4] to accelerate the electron beam up to GeV energy.

FIELD INSIDE THE CAVITATED REGION

Consider a linearly polarized laser pulse ($\vec{E}=\hat{e}_y(E(x,y,z)/2)\exp(\mathrm{ikx}-\mathrm{i}\omega t)+\mathrm{c.c}$), propagating inside a homogeneous plasma of density n_0. As the laser pulse propagates, its radiation pressure pushes the plasma electrons. The pushed plasma electrons flow backwards with respect to forward group velocity of laser pulse. However due to their large mass the ions are considered to immobile. If the intensity of the laser pulse is large enough, a cavity free of electrons is formed behind the laser pulse, as observed in 3D PIC simulations, moving with nearly the group velocity of the laser pulse. Starting with Maxwell's equations in terms of the potentials, and using the quasi-static approximation which assumes that all quantities depend on *y*, *z*, $\zeta = x - v_0 t$ instead of *y*, *z*, *x* and *t* gives,

$$\nabla_\perp^2 A_\perp + (1-\beta_0^2)\frac{\partial^2 A_\perp}{\partial \zeta^2} = \nabla_\perp[(\nabla_\perp . A_\perp) - \frac{\partial \varphi}{\partial \zeta}] - \frac{n}{n_0}\beta_\perp , \quad (1)$$

$$\nabla_\perp^2 \varphi + (1-\beta_0^2)\frac{\partial^2 \varphi}{\partial \zeta^2} + 1 = \frac{n}{n_0}(1-\beta_x\beta_0) , \quad (2)$$

$$\frac{\partial}{\partial \zeta}[(\nabla_\perp . A_\perp) - \frac{\partial \varphi}{\partial \zeta}] - \frac{1}{1+\beta_0} + \frac{n}{n_0}(1-\beta_x\beta_0+\beta_x) \ . \quad (3)$$

Here $A_\perp$ and $\varphi = \phi - \beta_0 A_x$ are the normalized vector and pseudo-scalar potential, $k_{p0} = (4\pi n_0 e^2/mc^2)^{1/2}$ and $\beta = v/c$. In deriving these equations a convenient gauge ($\phi = -A_x = \varphi/1+\beta_0$) has been used. Since inside the cavity nearly all the plasma electrons are expelled, *i.e.* *n*=0, the above equations reduce to,

$$\nabla_\perp^2 A_\perp + (1-\beta_0^2)\frac{\partial^2 A_\perp}{\partial \zeta^2} = \nabla_\perp[(\nabla_\perp . A_\perp) - \frac{\partial \varphi}{\partial \zeta}] , \quad (4)$$

$$\nabla_\perp^2 \varphi + (1-\beta_0^2)\frac{\partial^2 \varphi}{\partial \zeta^2} + 1 = 0 , \quad (5)$$

$$[(\nabla_\perp . A_\perp) - \frac{\partial \varphi}{\partial \zeta}] = \frac{\zeta}{1+\beta_0} + d , \quad (6)$$

where *d* is constant. The above three equations completely describe the field inside the cavity. From Eq. (5) it is clear that if $\beta_0 = 1$ then the solution of potential is $\varphi = \varphi_1(y,z) + \varphi_2(\zeta)$ where $\varphi_1 = (y^2/4 + z^2/4)$ and φ_2 is any kind of function of ζ, where we assume circular symmetry in y & z. Substituting this expression for the φ in Eq. 5, we can write, $\nabla_\perp^2\varphi_1 = p$, $\partial^2\varphi_2/\partial\zeta^2 = -(p+1)/(1-\beta_0^2)$, where *p* is constant. Then the solutions of the equations are, $\varphi_1 = p(y^2/4 + z^2/4) + g$, $\varphi_2 = -[\zeta^2/2(1-\beta_0^2)](p+1) + d'$, where g and d' are constant. The possible value of constant p is $-\beta_0$. So the total potential can be written as $\varphi = G - \beta_0(y^2/4 + z^2/4) - [\zeta^2/2(1+\beta_0)]$ where G is constant and the transverse component $A_\perp$=0. From this solution of the potential one can see that as β_0 deviates from unity, the shape of the cavity deviates from spherical. The field inside the cavity is given by $E_x = \zeta/(1+\beta_0)$, $E_y = y\beta_0/2(1+\beta_0)$, $E_z = z\beta_0/2(1+\beta_0)$, $B_x = 0$, $B_y = -z/2(1+\beta_0)$, $B_z = -y/2(1+\beta_0)$.

ACCELERATION OF ELECTRON BEAM INSIDE THE CAVITY

In order to study electron acceleration, we performed three-dimensional simulations with VORPAL. In the simulations a linearly polarized laser pulse having Gaussian temporal and radial profiles was launched in a homogeneous plasma. The simulation parameters were as follows: a grid size (dx, dy & dz) of 0.04 µm, 0.8 µm and 0.8 µm, two macro-particles per cell and a time-step of 0.13 fs. The laser wavelength (0.8 µm) was resolved over 20 cells in the propagation direction. We chose a low (though experimentally realised) plasma density of 1.1×10^{18} cm^{-3}, laser parameters a_0=2.2, r_0= 28 µm and τ_L= 15 fs. Figure 1 shows a plot of the charge density, after the laser has propagated a distance of 2.58 mm, in which a cavity nearly free from plasma electrons can be seen, along with an injected beam inside the cavity. Figure 2 shows the longitudinal field at the same distance; it can be seen that the field is nearly linear.

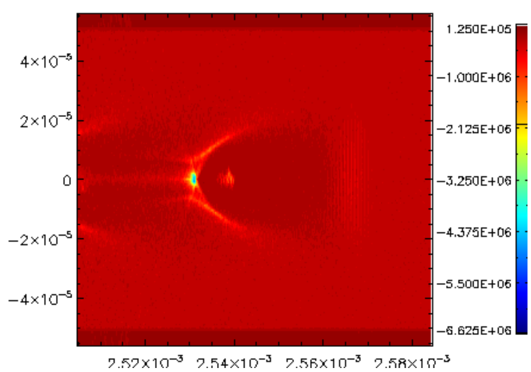

Figure 1: Contour plot of charge density, when the laser has propagated 2.58 mm, showing clearly the cavity and injected electrons in the cavity.

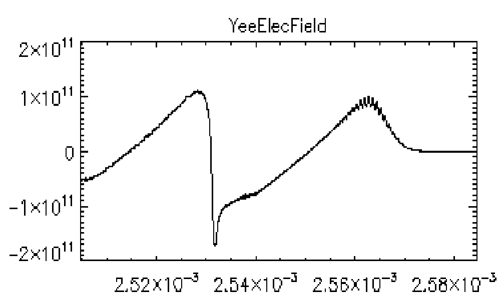

Figure 2: Axial electric field as a function of distance, corresponding to Fig.1, showing clearly that the field is linear within the cavity.

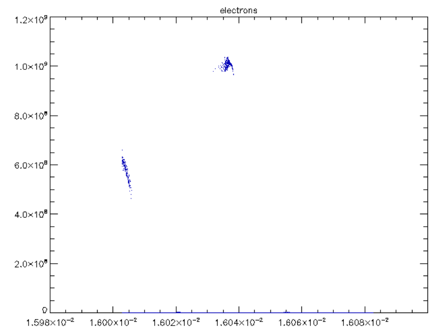

Figure 3: Kinetic energy as a function of distance.A bunched beam of around 1 GeV can be clearly seen.

The energy gained by the electron beam after propagating a distance of 1.6 cm is shown in Fig. 3. At this distance the electron beam has been accelerated to 1 GeV. After further propagation the beam comes into decelerating phase and starts decelerating. The quality of beam is as follows: a rms energy-spread of 1.4%, normalized emittance 20π mm-mrad, with a charge of 40 pC, and rms current of 11 kA with rms bunch length of 3.65 fs.

SUMMARY AND CONCLUSIONS

In summary, we have analytically shown the field inside the cavity generated due to high intensity short laser pulse with a homogeneous plasma. Inside the cavity the field is found to be linearly varying, which supports the quasimonoenergetic feature of the accelerated electrons. Using three-dimensional simulations, with a proper choice of laser and plasma parameters, we find that electron beam injected into the cavity is accelerated up to 1 GeV, in only 1.6 cm, with an energy-spread of 1.4% and a current of 11 kA. The normalized emittance of beam is quite high, and needs to be reduced in order to use this beam as a driver for a short wavelength free-electron laser.

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