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Charged particle acceleration by electron Bernstein wave in a plasma channel

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Abstract

A model of electron acceleration by an electron Bernstein mode in a parabolic density profile is developed. The mode has a Gaussian profile. It could be excited via the mode conversion of an electromagnetic wave or by an electron beam. As it attains a large amplitude, it axially traps electrons moving close to its parallel phase velocity, where parallel refers to the direction of static magnetic field. As the electrons are accelerated and tend to get out of phase with the wave, the transverse field of the mode enhances its energy and relativistic mass, increasing the dephasing length. The scheme can produce electron energies up to a few MeV.

Keywords: Bernstein wave; Dephasing length; Electron acceleration; Phase velocity

1. INTRODUCTION

Plasma based charged-particle acceleration is an active field of research (Bingham *et al.*, 2004; Ruhl, 1996; Ting *et al.*, 1997; Chien *et al.*, 2005; Sheng *et al.*, 2002*a*, 2002*b*; Wu & Chao, 2003; Kitagawa *et al.*, 2004; Muggli *et al.*, 2004; Shevts & Fisch, 1997; Reitsma *et al.*, 2005; Suk, 2002; Esarey *et al.*, 1996; Balakirev *et al.*, 2001; Faure *et al.*, 2004; Geddes *et al.*, 2004; Joshi, 2007; Mangles *et al.*, 2004; Reitsma & Jaroszynski, 2004; Singh *et al.*, 2003; Yugami *et al.*, 1996). It relies on the excitation of a large amplitude large phase velocity plasma wave by a relativistic electron beam or a short pulse laser (Meyer-Ter-Vehn & Sheng, 1999; Leemans *et al.*, 2002; Kong *et al.*, 2003; Cao *et al.*, 2004; Balakirev *et al.*, 2004; Kulagin *et al.*, 2008; Li *et al.*, 2004; Niu *et al.*, 2008; Xie *et al.*, 2009) of pulse length comparable to plasma period or by beating two long laser pulses with frequency separation equal to plasma frequency. The plasma wave accelerates the trapped electrons to high energies up to half GeV. Some experiments have even reported generation of mono-energetic electrons up to hundreds of energy with only ~3% energy spread (Ebrahim, 1994; Rosenbluth & Liu, 1972; Salamin & Keitel, 2002; Sauerbrey, 1996; Shvets *et al.*, 2000; Pukhov *et al.*, 1999; Amiranoff *et al.*, 1996; Lindberg *et al.*, 2004; Kimura *et al.*, 2004; Tochitsky *et al.*, 2004; Clayton *et al.*, 1994).

Magnetized plasma offers a richer variety of electrostatic modes that may be employed for charged particle acceleration. Katsouleas and Dawson (1983) developed the surfatron concept of unlimited electron acceleration by plasma when a transverse magnetic field is present. Prasad *et al.* (2009) studied the effect of an axial magnetic field and ion space charge on laser beat wave acceleration and surfatron acceleration of electrons. Sugaya (2004) studied the acceleration of electrons along and across a magnetic field *via* nonlinear electron Landau damping and cyclotron damping of almost perpendicularly propagating extraordinary waves, and the generation of an electric field transverse to the magnetic field. Oieroset *et al.* (2002) observed energetic particles inside a magnetic reconnection diffusion. Istomin and Leyser (2003) presented a model of electron acceleration by trapped upper hybrid waves inside density cavities that are pumped by an ordinary mode electromagnetic wave transmitted into the ionospheric F-region plasma. Akimoto (2002, 2003) studied the acceleration and heating of charged particles by a dispersive electrostatic pulse.

In this paper, we study the acceleration of electrons by an electron Bernstein wave in magnetized plasma.

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Bernstein waves possess large phase velocity along the direction of ambient magnetic field and small phase velocity across it, and can be driven by electron beams or electromagnetic waves (Kumar & Tripathi, 2004). A large amplitude Bernstein wave can trap electrons moving close to its parallel phase velocity and accelerate them to large parallel and perpendicular energies, where parallel and perpendicular refer to the ambient magnetic field. Dephasing of electrons along the magnetic field can be avoided for a longer distance by the transverse energy gain and mass increase due to the transverse electric field of the Bernstein wave.

In Section 2, we deduce the mode structure of an electron Bernstein wave in a plasma slab with parabolic density profile. In Section 3, we formulate the relevant equations governing the motion of electrons and solve them numerically to obtain energy gain. In Section 4, we discuss our results.

2. ELECTRON BERNSTEIN EIGEN MODE

Consider a slab model of plasma channel with static magnetic field $B_s\hat{z}$ and plasma density (hence plasma frequency) profile $\omega_p^2 = \omega_{p0}^2\ (1 - x^2/a^2)$. A large amplitude electron Bernstein wave exists in the plasma with potential

$$\phi = A(x)\exp\left[-i(\omega t - k_y y - k_z z)\right]. \tag{1}$$

The local dispersion relation for the Bernstein wave is

$$\varepsilon = 0, \tag{2}$$

where $\varepsilon = 1 + \chi_e$ and χ_e is the electron susceptibility. In the limit of $\omega \approx \omega_c$, $\omega - \omega_c \gg k_z v_{th}$, one may write (Liu & Tripathi, 1986)

$$\chi_e = \frac{2\omega_p^2}{k^2 v_{th}^2}\left[1 - \frac{\omega I_1(b)\exp(-b)}{\omega - \omega_c}\right], \tag{3}$$

where $b = k_\perp^2 v_{th}^2/2\omega_c^2$ and $v_{th} = (2T_e/m)^{1/2}$ are the thermal speed of plasma electrons at electron temperature T_e, ω_c is the electron cyclotron frequency, ω_p is the electron plasma frequency, $I_1(b)$ is the modified Bessel function, and $k_\perp^2 = k_y^2 + k_x^2$. We presume $k_y^2 \gg k_x^2$. The mode structure equation for the Bernstein wave in the inhomogeneous plasma can be deduced from $\varepsilon\phi = 0$ by replacing k_x^2 by $-\partial^2/\partial x^2$ in ε (Kumar & Tripathi, 2004),

$$\frac{\partial^2\phi}{\partial x^2} - \left[\frac{(1+\chi_e)}{\partial\chi_e/\partial k_\perp^2}\right]_{k_\perp^2 = k_y^2}\phi = 0, \tag{4}$$

or for $k_y^2\ v_{th}^2/2\omega_{p0}^2 \ll 1$, this equation takes the form

$$\frac{\partial^2\phi}{\partial x^2} + \left(\alpha_1 - \alpha_2 x^2\right)\phi = 0, \tag{5}$$

where

$$\alpha_1 = k_y^2\left(1 + \frac{k_y^2 v_{th}^2}{2\omega_{p0}^2} - \frac{\omega I_1(b)e^{-b}}{\omega - \omega_c}\right)\frac{I_1(b)e^{-b}}{b\dfrac{d}{db}\left[I_1(b)e^{-b}\right]},$$

$$\alpha_2 = -k_y^2\frac{(\omega - \omega_c)}{\omega_c b\dfrac{d}{db}\left[I_1(b)e^{-b}\right]}\frac{k_y^2 v_{th}^2}{2\omega_{p0}^2 a^2}$$

$$\approx -\frac{k_y^2}{a^2}\frac{I_1(b)e^{-b}}{b\dfrac{d}{db}\left[I_1(b)e^{-b}\right]}\frac{k_y^2 v_{th}^2}{2\omega_{p0}^2}.$$

For $b \geq 1$, $\dfrac{d}{db}\left[I_1(b)e^{-b}\right] < 0$, that is, α_2 is positive and the mode structure equation reduces to harmonic oscillator equation. The Eigen value for the fundamental mode is

$$\alpha_1/\alpha_2^{1/2} = 1, \tag{6}$$

and the Eigen function is

$$\phi = A_0 e^{-x^2/2x_0^2}\cos\left(\omega t - k_y y - k_z z\right), \tag{7}$$

where $x_0 = \alpha_2^{-1/4}$. Eq. (6) gives the dispersion relation for the Bernstein mode

$$\omega = \omega_c\left[1 + \frac{I_1(b)e^{-b}}{1 + k_y^2 v_{th}^2/2\omega_{p0}^2 - \Delta}\right],$$

$$\Delta = -\left(v_{th}/a\omega_{p0}\right)\left[-\frac{b\dfrac{d}{db}\left[I_1(b)e^{-b}\right]}{2I_1(b)e^{-b}}\right]^{1/2}. \tag{8}$$

3. ELECTRON ACCELERATION

The response of an energetic electron to the electron Bernstein wave is governed by the equation of motion

$$\frac{d\mathbf{p}}{dt} = e\nabla\phi - \frac{\omega_c}{\gamma}\mathbf{p}\times\hat{z}, \tag{9}$$

where $\gamma = [1 + p^2/m^2c^2]^{1/2}$, $\omega_c = eB_s/mc$, and n_0, $-e$, m, are the electron density, charge and mass, respectively.

On changing d/dt to $(p_z/m\gamma)d/dz$, one can write different components of Eq. (9) as

$$\frac{dp_x}{dz} = -e\frac{\gamma m x}{p_z x_0^2}A_0 e^{-x^2/2x_0^2}\cos\psi - \frac{m\omega_c}{p_z}p_y, \tag{10}$$

$$\frac{dp_y}{dz} = e\frac{mk_y\gamma}{p_z}A_0 e^{-x^2/2x_0^2}\sin\psi + \frac{m\omega_c}{p_z}p_x, \tag{11}$$

$$\frac{dp_z}{dz} = e\frac{mk_z\gamma}{p_z}A_0 e^{-x^2/2x_0^2}\sin\psi, \tag{12}$$

$$\psi = \omega t - k_y y - k_z z.$$

These equations are supplemented with

$$\frac{dx}{dz} = \frac{p_x}{p_z}, \tag{13}$$

$$\frac{dy}{dz} = \frac{p_y}{p_z}, \tag{14}$$

$$\frac{dt}{dz} = \frac{\gamma m}{p_z}. \tag{15}$$

In terms of dimensionless quantities $A_0' \rightarrow eA_0/mc^2$, $Z \rightarrow \omega_c z/c$, $X \rightarrow \omega_c x/c$, $Y \rightarrow \omega_c y/c$, $P_X \rightarrow p_x/(mc)$, $P_Y \rightarrow p_y/(mc)$, $P_Z \rightarrow p_z/(mc)$, $T \rightarrow \omega_c t$, $X_0 \rightarrow \omega_c x_0/c$, Eq. (10)–(15) can be written as

$$\frac{dP_X}{dZ} = -\frac{\gamma X}{X_0^2 P_Z}A_0'\cos\psi - \frac{P_Y}{P_Z}, \tag{16}$$

$$\frac{dP_Y}{dZ} = \frac{k_y c\gamma}{\omega_c P_Z}A_0' e^{-X^2/2X_0^2}\sin\psi + \frac{P_X}{P_Z}, \tag{17}$$

$$\frac{dP_Z}{dZ} = \frac{k_z c\gamma}{\omega_c P_Z}A_0' e^{-X^2/2X_0^2}\sin\psi, \tag{18}$$

$$\frac{dX}{dZ} = \frac{P_X}{P_Z}, \tag{19}$$

$$\frac{dY}{dZ} = \frac{P_Y}{P_Z}, \tag{20}$$

$$\frac{dT}{dZ} = \frac{\gamma}{P_Z}. \tag{21}$$

We solve Eqs. (16)–(21) numerically for following parameters $x_0 = 40c/\omega_c$, $\omega_c/\omega \sim 0.9$, $\omega/(k_y c) \sim 0.1$, $\omega/(k_z c) \sim 0.99$. The electron is injected initially with small energy. It follows a helical path. As the electron moves in plasma it interacts with the pre-existed electron Bernstein wave and gains energy from it. Electrons gyrate about the axial direct current magnetic field and are pushed forward by the wave electric field. As the electron advances along z it moves away from the region where Bernstein mode amplitude is maximum. In Figure 1, we display the trajectory in two dimension between normalized variable X and Z. For $\omega_c/\omega \sim 0.9$, $\omega/(k_y c) \sim 0.1$, $\omega/(k_z c) \sim 0.99$, with the initial values of the parameters $\Phi \approx 0.3$, $P_X = 0.0001$, $P_Y = 0.0001$, $P_Z = 0.001$, $X = 0$, $Y = 0$, $T = 0$, the electron moves away from $x = 0$ plane up to $x \sim -30c/\omega_c$ over a distance of $30c/\omega_c$. In Figure 2, we display the electron trajectory in two-dimension between normalized variable Y and Z for $x_0 = 40c/\omega_c$, $\omega_c/\omega \sim 0.9$, $\omega/(k_y c) \sim 0.1$, $\omega/(k_z c) \sim 0.99$ where we have considered the initial values of the parameters $\Phi \approx 0.3$, $P_X = 0.0001$, $P_Y = 0.0001$, $P_Z = 0.001$, $X = 0$, $Y = 0$, $T = 0$. In Figures 3, 4, and 5, we displayed the momentum evolution. p_x attains negative values up to $p_x/mc \sim -30$. p_y shows much rapid oscillations, although of smaller amplitude due to gyromotion. p_z goes almost linearly with z. Figure 6 shows the energy evolution of electron by varying Z for the parameters $x_0 = 40c/\omega_c$, $\omega_c/\omega \sim 0.9$, $\omega/(k_y c) \sim 0.1$, $\omega/(k_z c) \sim 0.99$ where we have considered the initial values of the parameters $\Phi \approx 0.3$, $P_X = 0.0001$, $P_Y = 0.0001$, $P_Z = 0.001$, $X = 0$, $Y = 0$, $T = 0$. The energy rises almost monotonically to ~2.1 MeV. The acceleration decreases with the increase of the value of parallel component of the Bernstein wave vector along the axial magnetic field. There are two possible resonance conditions $\omega - k_y v_y - k_z v_z \approx 0$ and $\omega - k_y v_y - k_z v_z \mp \omega_c \approx 0$. The first condition corresponds to Landau damping of the Bernstein wave in relativistic acceleration of electrons. In Figure 7, we

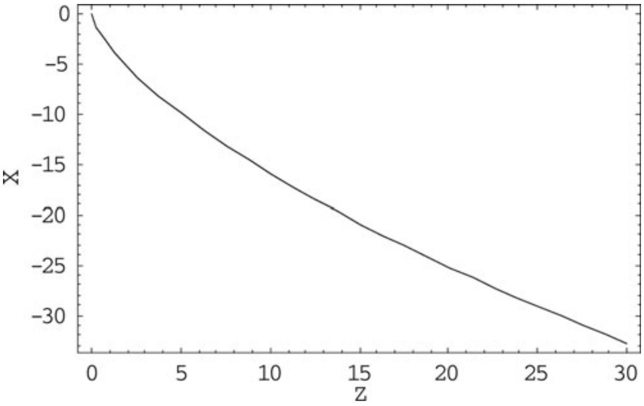

Fig. 1. Variation of normalized coordinate X as a function of Z the parameters $\Phi \approx 0.3$, $x_0 = 40c/\omega_c$, $\omega_c/\omega \sim 0.9$, $\omega/(k_y c) \sim 0.1$, $\omega/(k_z c) \sim 0.99$.

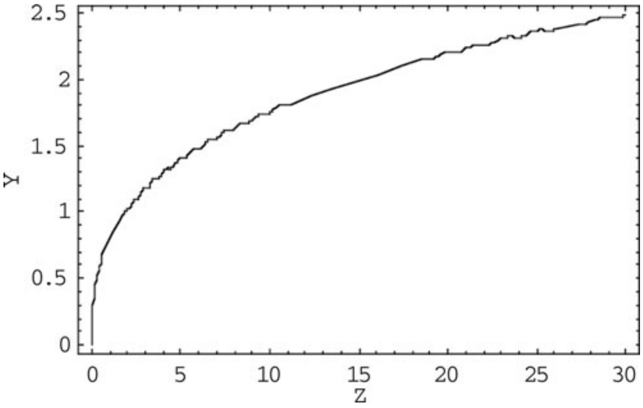

Fig. 2. Variation of normalized coordinate Y as a function of Z for the parameters $\Phi \approx 0.3$, $x_0 = 40c/\omega_c$, $\omega_c/\omega \sim 0.9$, $\omega/(k_y c) \sim 0.1$, $\omega/(k_z c) \sim 0.99$.

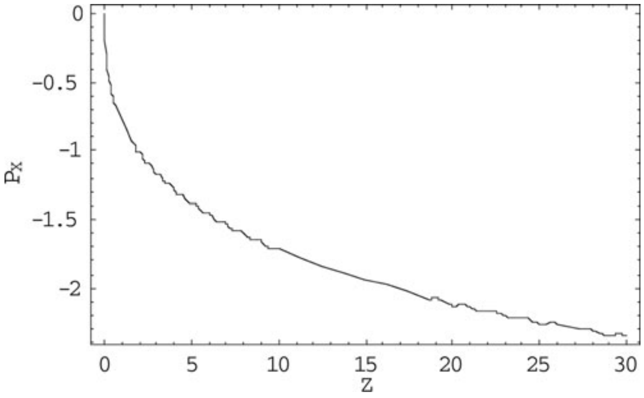

Fig. 3. Variation of normalized momentum P_X as a function of Z for the parameters $\Phi \approx 0.3$, $x_0 = 40c/\omega_c$, $\omega_c/\omega \sim 0.9$, $\omega/(k_yc) \sim 0.1$, $\omega/(k_zc) \sim 0.99$.

display $R_0 = \frac{\omega}{\omega_c} - \frac{ck_yP_y}{\gamma\omega_c} - \frac{ck_zP_z}{\gamma\omega_c}$ *versus* Z. Obviously, $R_0 > 0 (R_0 < 0)$ corresponds to the acceleration (deceleration). The second resonance condition $\omega - k_y\ v_y - k_z\ v_z \mp \omega_c \approx 0$ arises from the cyclotron damping of the Bernstein wave. The acceleration results from the resonance of the Bernstein wave with the gyromotion of electrons. In this case, $R_{\pm 1} = \frac{\omega}{\omega_c} - \frac{ck_yP_y}{\gamma\omega_c} - \frac{ck_zP_z}{\gamma\omega_c} \mp 1 \approx 0$ is satisfied.

4. DISCUSSION

A large amplitude electron Bernstein wave has potential for electron acceleration up to a few MeV energy. The energy is primarily contained in the parallel motion (along the ambient magnetic field); however, transverse motion is also significant and helps in increasing the phase detuning length between the electron and the wave. The scheme may be relevant to current drive in tokamak, where electrons of hundreds of KeV energy carry the toroidal current. In a parabolic density profile (across the ambient magnetic field), Bernstein waves are localized around the density maximum, with Gaussian amplitude profile. The mode structure half width scale as square root of density scale length and is sensitive to transverse wave number. Bernstein waves with parallel phase velocity close to c are useful for

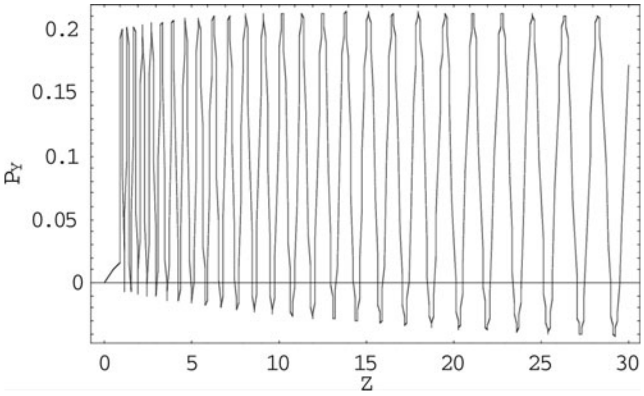

Fig. 4. Variation of normalized momentum P_Y as a function of Z for the parameters $\Phi \approx 0.3$, $x_0 = 40c/\omega_c$, $\omega_c/\omega \sim 0.9$, $\omega/(k_yc) \sim 0.1$, $\omega/(k_z\ c) \sim 0.99$.

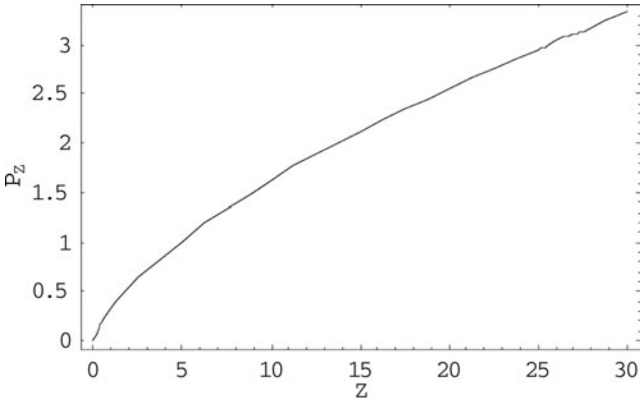

Fig. 5. Variation of normalized momentum P_Z as a function of Z for the parameters $\Phi \approx 0.3$, $x_0 = 40c/\omega_c$, $\omega_c/\omega \sim 0.9$, $\omega/(k_yc) \sim 0.1$, $\omega/(k_zc) \sim 0.99$.

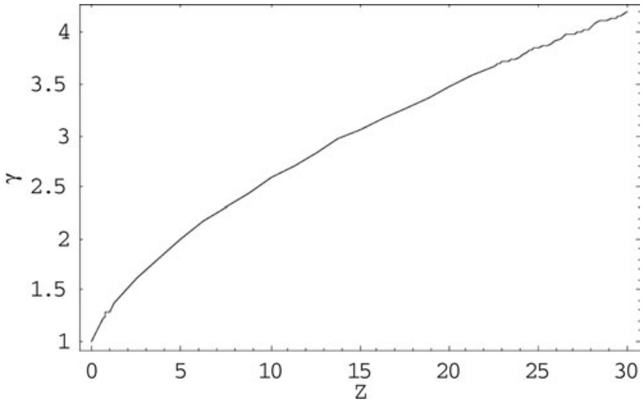

Fig. 6. Variation of γ factor as a function of Z for the parameters $\Phi \approx 0.3$, $x_0 = 40c/\omega_c$, $\omega_c/\omega \sim 0.9$, $\omega/(k_yc) \sim 0.1$, $\omega/(k_zc) \sim 0.99$.

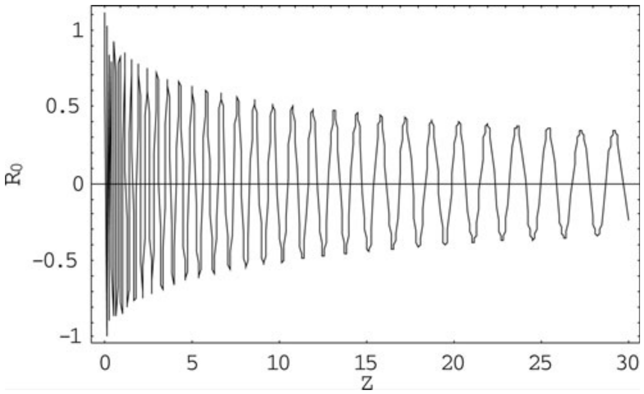

Fig. 7. Variation of R_0 as a function of Z for the parameters $\Phi \approx 0.3$, $x_0 = 40c/\omega_c$, $\omega_c/\omega \sim 0.9$, $\omega/(k_yc) \sim 0.1$, $\omega/(k_zc) \sim 0.99$.

electron acceleration. Such waves can be excited by nonlinear mixing of two nearly counter propagating intense electromagnetic waves across the magnetic field when the frequency difference in them is close to electron cyclotron frequency. The Bernstein wave amplitude is limited by relativistic detuning where the oscillation of plasma electrons in the combined fields of the laser and Bernstein wave results in a decrease in the plasma frequency taking the system off resonance. They may also be driven by relativistic electron beams via Cerenkov or slow cyclotron interaction.

REFERENCES

Akimoto, K. (2002). Acceleration and heating of charged particles by a dispersive electrostatic pulse. *Phys. Plasmas* **9**, 3721–3733.

Akimoto, K. (2003). Net accelerations of charged particles by a generalized electromagnetic wave. *Phys. Plasmas* **10**, 4224–4236.

Amiranoff, F., Antonetti, A., Audebert, P., Bernard, D., Cros, B., Dorchies, F., Gauthier, J.C., Geindre, J.P., Grillon, G., Jacquet, F., Mathieussent, G., Marques, J.R., Mine, P., Mora, P., Modena, A., Morillo, J., Moulin, F., Najmudin, Z., Specka, A.E. & Stenz, C. (1996). Laser particle acceleration: beat-wave and wakefield experiments. *Plasma Phys. Contr. Fusion* **38**, A295–A300.

Balakirev, V.A., Karas, I.V. & Levchenko, V.D. (2001). Plasma wakefield excitation relativistic electron bunches and charged particle acceleration in the presence of external magnetic field. *Laser Part. Beams* **19**, 597–604.

Balakirev, V.A., Karas, I.V., Levchenko, V.D. & Bornatici, M. (2004). Charged particle acceleration by an intense wake-field excited in plasmas by either laser pulse or relativistic electron bunch. *Laser Part. Beams* **22**, 383–392.

Bingham, R., Mendonca, J.T. & Shukla, P.K. (2004). Plasma based charged-particle accelerators. *Plasma Phys. control. Fusion* **46**, R1–R23.

Cao, L., Yu, W., Xu, H., Zheng, C., Liu, Z. & Li, B. (2004). Electron acceleration by the short pulse laser in inhomogeneous underdense plasmas. *J. Plasma Phys.* **70**, 625–634.

Chien, T.-Y., Chang, C.-L., Lee, C.-H., Lin, J.-Y., Wang, J. & Chen, S.-Y. (2005). Spatially localized self-injection of electrons in a self-modulated laser-wakefield accelerator by using a laser-induced transient density ramp. *Phys. Rev. Lett.* **94**, 115003.

Clayton, C.E., Everett, M.J., Lal, A., Gordon, D., Marsh, K.A. & Joshi, C. (1994). Acceleration and scattering of injected electrons in plasma beat wave accelerator experiments. *Phys. Plasmas* **1**, 1753–1760.

Ebrahim, N.A. (1994). Optical mixing of laser light in a plasma and electron acceleration by relativistic electron plasma waves. *J. Appl. Phys.* **76**, 7645–7647.

Esarey, E., Sprangle, P., Krall, J. & Ting, A. (1996). Overview of plasma-based accelerator concepts. *IEEE Trans. Plasma Sci.* **24**, 252–288.

Faure, J., Glinec, Y., Pukhov, A., Kieselev, S., Gordienko, S., Lefebvre, Rousseau, J.-P., Burgy, F. & Malka, V. (2004). A laser-plasma accelerator producing monoenergetic electron beams. *Nat.* **431**, 541–544.

Geddes, C.G.R., Toth, C.S., Van Tilborg, J., Esarey, E., Schroeder, C.B., Bruhwiler, D., Nieter, C., Cary, J. & Leemans, W.P. (2004). High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding, *Nat.* **431**, 538–541.

Istomin, YA.N. & Leyser, T.B. (2003). Electron acceleration by cylindrical upper hybrid oscillations trapped in density irregularities in the ionosphere. *Phys. Plasmas* **10**, 2962–2970.

Joshi, C. (2007). The development of laser and beam-driven plasma accelerators as an experimental field. *Phys. Plasmas* **14**, 055501.

Katsouleas, T. & Dawson, J.M. (1983). Unlimited electron acceleration in laser-driven plasma waves. *Phys. Rev. Lett.* **51**, 392–395.

Kimura, W.D., Babzien, M., Ben-Zvi, I., Campbell, L.P., Cline, D.B., Dilley, C.E., Gallardo, J.C., Gottschalk, S.C., Kusche, K.P., Pantell, R.H., Pogorelsky, I.V., Quimby, D.C., Skaritka, J., Steinhauer, L.C., Yakimenko, V. & Zhou, F. (2004). Demonstration of high-trapping efficiency and narrow energy spread in a laser-driven accelerator. *Phys. Rev. Lett.* **92**, 054801.

Kitagawa, Y., Sentoku, Y., Akamatsu, S., Sakamoto, W., Kodama, R., Taneka, K.A., Azumi, K., Norimatsu, T., Matsuoka, T., Fujita, H. & Yoshida, H. (2004). Electron acceleration in an ultraintense-laser-illuminated capillary. *Phys. Rev. Lett.* **92**, 205002.

Kong, Q., Miyazaki, S., Miyanaga, N. & Ho, Y.K. (2003). Electron bunch acceleration and trapping by the ponderomotive force of an intense short-pulse laser. *Phys. Plasmas* **10**, 4605–4608.

Kulagin, V.V., Cherepenin, V.A., Hur, M.S., Lee, J. & Suk, H. (2008). Evolution of a high-density electron beam in the field of a super-intense laser pulse. *Laser Part. Beams* **26**, 397–409.

Kumar, A. & Tripathi, V.K. (2004). Excitation of electron Bernstein waves by a gyrating relativistic electron beam in a plasma slab. *Phys. Plasmas* **11**, 538–541.

Leemans, W.P., Catravas, P., Esarey, E., Geddes, C.G.R., Toth, C., Trines, R., Schroeder, C.B., Shadwick, B.A., Tilborg, J.V. & Faure, J. (2002). Electron-yield enhancement in a laser-wakefield accelerator driven by asymmetric laser pulses. *Phys. Rev. Lett.* **89**, 174802.

Li, B., Ishiguro, S.M., Skoric, M.M., Takamaru, H. & Sato, T. (2004). Acceleration of high-quality well-collimated return beam of relativistic electrons by intense laser pulse in a low-density plasma. *Laser Part. Beams* **22**, 307–314.

Lindberg, R.R., Charman, A.E. & Wurtele, J.S. (2004). Robust autoresonant excitation in the beat-wave accelerator. *Phys. Rev. Lett.* **93**, 055001.

Liu, C.S. & Tripathi, V.K. (1986). Parametric instabilities in a magnetized plasma. *Phys. Reports* **130**, 143–216.

Mangles, S.P.D., Murphy, C.D., Najmudin, Z., Thomas, A.G.R., Collier, J.L., Dangor, A.E., Divall, E.J., Foster, P.S., Gallacher, J.G., Hooker, C.J., Jaroszynski, D.A., Langley, A.J., Mori, W.B., Norreys, P.A., Tsung, F.S., Viskup, R., Walton, B.R. & Krushelnick, K. (2004). Monoenergetic beams of relativistic electrons from intense laser-plasma interactions. *Nat.* **431**, 535–538.

Meyer-Ter-Vehn, J. & Sheng, Z.M. (1999). On electron acceleration by intense laser pulses in the presence of a stochastic field. *Phys. Plasma* **6**, 641–644.

Muggli, P., Blue, B.E.,Clayton, C.E., Deng, S., Decker, F.-J., Hogan, M.J., Huang, C., Iverson, R., Joshi, C., Katsouleas, T.C., Lee, S., Lu, W., Mash, K.A., Mori, W.B., ÒConnell, C.L., Raimondi, P., Siemann, R. & Walz, D. (2004). Meter-scale plasma-wakefield accelerator driven by a matched electron beam. *Phys. Rev. Lett.* **93**, 014802.

Niu, H.Y., He, X.T., Qiao, B. & Zhou, C.T. (2008). Resonant acceleration of electrons by intense circularly polarized Gaussian laser pulses. *Laser Part. Beams* **22**, 407–413.

Oieroset, M., Lin, R.P., Phan, T.D., Larson, D.E. & Bale, S.D. (2002). Evidence for electron acceleration up to ~300 keV in the magnetic reconnection diffusion region of earth's magnetotail. *Phys. Rev. Lett.* **89**, 195001.

Prasad, R., Singh, R. & Tripathi, V.K. (2009). Effect of an axial magnetic field and ion space charge on laser beat wave acceleration and surfatron acceleration of electrons. *Laser Part. Beams* **27**, 459–464.

Pukhov, A., Sheng, Z.-M. & Meyer-Ter-Vehn, J. (1999). Particle acceleration in relativistic laser channels. *Phys. Plasmas* **6**, 2847–2854.

Reitsma, A.J.W. & Jaroszynski, D.A. (2004). Coupling of longitudinal and transverse motion of accelerated electrons in laser wakefield acceleration. *Laser Part. Beams* **22**, 407–413.

Reitsma, A.J.W., Cairns, R.A., Bingham, R. & Jaroszynski, D.A. (2005). Efficiency and energy spread in laser-wakefield acceleration. *Phys. Rev. Lett.* **94**, 085004.

Rosenbluth, M.N. & Liu, C.S. (1972). Excitation of plasma waves by two laser beams, *Phys. Rev. Lett.* **29**, 701.

Ruhl, H. (1996). Uphil acceleration of electrons and secular fields in laser produced plasmas. *Phys. Plasmas* **3**, 3129–3132.

Salamin, Y.I. & Keitel, C.H. (2002). Electron acceleration by a tightly focused laser beam. *Phys. Rev. Lett.* **88**, 095005.

Sauerbrey, R. (1996). Acceleration in femtosecond laser-produced plasmas. *Phys. Plasmas* **3**, 4712–4716.

Sheng, Z.-M., Mima, K., Sentoku, Y., Jovonovic, M.S., Taguchi, T., Zhang, J. & Meyer-Ter-Vehn, J. (2002*a*). Stochastic heating and acceleration of electrons in colliding laser fields in plasma. *Phys. Rev. Lett.* **88**, 055004.

Sheng, Z.-M., Mima, K., Sentoku, Y. Nishihara, K. & Zhang, J. (2002*b*). Generation of high-amplitude plasma waves for particle acceleration by cross-modulated laser wakefields. *Phys. Plasmas* **9**, 3147–3153.

Shevts, G. & Fisch, N.J. (1997). Beam-channeled laser-wakefield accelerator. *Phys. Rev. E* **55**, 6297–6300.

Shvets, G., Fisch, N.J. & Pukhov, A. (2000). Acceleration and compression of charged particle bunches using counterpropagating laser beams. *IEEE Trans. Plasma Sci.* **28**, 1185–1192.

Singh, K.P., Gupta, V.L., Bhasin, L. & Tripathi, V.K. (2003). Electron acceleration by a plasma wave in a sheared magnetic field. *Phys. Plasmas* **10**, 1493–1499.

Sugaya, R. (2004). Electron beam acceleration and potential formation induced by the Compton scattering of extraordinary waves. *J. Plasma Physics* **70**, 331–357.

Suk, H. (2002). Electron acceleration based on self-trapping by plasma wake fields. *J. Appl. Phys.* **91**, 487–491.

Ting, A., Moore, C.I., Krushelnick, K., Manka, C., Esarey, E., Sprangle, P., Hubbard, R., Burris, H.R., Fischer, R. & Baine, M. (1997). Plasma wakefield generation and electron acceleration in a self-modulated laser wakefield accelerator experiment. *Phys. Plasmas* **4**, 1889–1899.

Tochitsky, S.YA., Narang, R., Filip, C.V., Musumeci, P., Clayton, C.E., Yoder, R.B., Marsh, K.A., Rosenzweig, J.B., Pellegrini, C. & Joshi, C. (2004). Enhanced acceleration of injected electrons in a laser-beat-wave-induced plasma channel. *Phys. Rev. Lett.* **92**, 095004.

Wu, D.J. & Chao, J.K. (2003). Auroral electron acceleration by dissipative solitary kinetic Alfven waves. *Phys. Plasmas* **10**, 3787–3789.

Xie, B.-S., Aimidula, A., Niu, J.-S., Liu, J. & Yu, M.Y. (2009). Electron acceleration in the wakefield of asymmetric laser pulses. *Laser Part. Beams* **27**, 27–32.

Yugami, N., Kikuta, K. & Nishida, Y. (1996). Electron acceleration by a transverse electromagnetic wave supplemented with a crossed static magnetic field. *Phys. Rev. Lett.* **76**, 1635.