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Electron acceleration by surface plasma waves in double metal surface structure

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Two parallel metal sheets, separated by a vacuum region, support a surface plasma wave whose amplitude is maximum on the two parallel interfaces and minimum in the middle. This mode can be excited by a laser using a glass prism. An electron beam launched into the middle region experiences a longitudinal ponderomotive force due to the surface plasma wave and gets accelerated to velocities of the order of phase velocity of the surface wave. The scheme is viable to achieve beams of tens of keV energy. In the case of a surface plasma wave excited on a single metal-vacuum interface, the field gradient normal to the interface pushes the electrons away from the high field region, limiting the acceleration process. The acceleration energy thus achieved is in agreement with the experimental observations. © 2007 American Institute of Physics. [DOI: 10.1063/1.2817943]

I. INTRODUCTION

The acceleration of electrons by lasers has been a subject of considerable interest in recent years. The schemes of laser beat wave acceleration1–4 and laser wakefield acceleration5–7 have been pursued vigorously and electron acceleration approaching GeV energy is being achieved. However, the laser intensities involved in these acceleration schemes are large. For many applications one requires electron beams of moderately relativistic energies.

In last few years, significant work has been reported on electron acceleration by a surface plasma wave.8–13 Surface plasma waves are localized to metal-free space interface and can be excited using a p-polarized laser.14–19 Using the Kretschmann configuration20,21 for the surface plasma wave (SPW) coupling, Zawadzka et al.8–9 have observed energetic electrons of energies ~400 eV for laser intensity of 1013 W/cm2. Irvine et al.12,13 have also demonstrated similar acceleration in their experiments. The acceleration energies are comparable to ponderomotive energies due to the surface plasma wave and electrons move much slower than the phase velocity of the surface wave. Kalmykov et al.22 have studied SPW excitation on two parallel plane silicon carbide films separated by a vacuum region and discussed its potential for electron acceleration. Steinhauer et al.23 have developed an elegant analytical formalism for surface wave propagation over two parallel conducting planes and on the inner boundary of a hollow cylinder. They have discussed its potential for electron acceleration. However, detailed analytical treatments of electron acceleration have not been given.

In this paper, we propose a scheme of electron acceleration that employs resonant interaction of electrons with a surface plasma wave. This scheme can be useful in accelerating electrons to higher energies with the control in their trajectories. We employ a configuration of two parallel surfaces separated by a vacuum region. The configuration supports a surface plasma wave that propagates parallel to the metal surfaces with amplitude maxima on the two surfaces and a minimum in the middle. The surface waves have a finite axial electric field in the middle but the transverse ponderomotive force due to it vanishes, hence electrons placed in the middle can stay there for a long distance. When their axial velocities are comparable to the phase velocity of the surface wave, they can gain large energies from the wave. For the single metal surface configuration of Zawadzka et al.8, we obtain electron energies ~400 eV at laser intensity ~1013 W/cm2. In Sec. II, we derive the dispersion relation of a surface plasma wave in double metal surface configuration. In Sec. III, we discuss electron acceleration by a surface plasma wave. In Sec. IV, electron acceleration by a surface plasma wave over a single metal surface is studied. The results are discussed in Sec. V.

II. SURFACE PLASMA WAVE IN A DOUBLE METAL SURFACE CONFIGURATION

Consider two parallel metal half spaces x < −a/2 and x > a/2, separated by a thin vacuum region (−a/2 < x < a/2) (Fig. 1). The effective permittivity of metal at frequency \( \omega \) is

\[
\varepsilon = \left( \varepsilon_L - \frac{\omega_P^2}{\omega^2} \right),
\]

where \( \varepsilon_L \) is the lattice permittivity and \( \omega_P \) is the plasma frequency. A surface plasma wave propagates through the
configuration with $t$, $z$ variation as $\exp[-i(\omega t-kz)]$. The wave equation governing $E_z$ in the three media is

$$\frac{\partial^2 E_z}{\partial^2 z} - \left(k_x^2 - \frac{\omega^2}{c^2} \varepsilon' \right) E_z = 0,$$

(2)

where $\varepsilon' = 1$ for $-a/2 < x < a/2$ and $\varepsilon' = \varepsilon$ for $x > a/2$ and $x < -a/2$. The well-behaved solutions of Eq. (2), satisfying $\nabla \cdot E = 0$ in each region, are

$$E = A_1 \left( \hat{z} + \hat{x} \frac{ik_x}{\alpha_1} \right) e^{-\alpha_1 z}, \quad x > a/2,$$

$$E = A_2 \left( \hat{z} - \hat{x} \frac{ik_x}{\alpha_2} \right) e^{\alpha_2 z} + A_3 \left( \hat{z} + \hat{x} \frac{ik_x}{\alpha_2} \right) e^{-\alpha_2 z},$$

$$-a/2 < x < a/2,$$

$$E = A_3 \left( \hat{z} - \hat{x} \frac{ik_x}{\alpha_1} \right) e^{\alpha_1 z}, \quad x < -a/2,$$

where $\alpha_1 = (k_x^2 - \omega^2 \varepsilon/c^2)^{1/2}$, $\alpha_2 = (k_x^2 - \omega^2 \varepsilon/c^2)^{1/2}$. Applying conditions of continuity of $E_z$ and $\varepsilon' E_x$ at $x=a/2$ and $x=-a/2$, we get

$$A_1 e^{\alpha_1 a/2} + A_2 e^{-\alpha_1 a/2} = A e^{-\alpha_1 a/2},$$

(4)

$$A_1 e^{\alpha_1 a/2} - A_2 e^{-\alpha_1 a/2} = -A \left( \frac{\varepsilon \alpha_2}{\alpha_1} \right) e^{-\alpha_1 a/2},$$

(5)

$$A_1 e^{-\alpha_2 a/2} + A_2 e^{\alpha_2 a/2} = A_3 e^{-\alpha_2 a/2},$$

(6)

$$A_1 e^{-\alpha_2 a/2} - A_2 e^{\alpha_2 a/2} = A_3 e^{-\alpha_1 a/2},$$

(7)

Solving these equations, we obtain the dispersion relation

$$\frac{\alpha_2^2}{\alpha_1^2} = \left( \frac{1 - e^{\alpha_2 a}}{1 + e^{\alpha_2 a}} \right) \frac{1}{|E|^2},$$

(8)

Using dimensionless quantities $q = k_x c/\omega_p$, $\Omega = \omega/\omega_p$, and $a = a_0 \omega_p/c$, we normalize Eq. (8) and plot normalized frequency $\Omega$ versus normalized wavenumber $q$ in Fig. 2 for the mode that has $E_x$ symmetric about the $x=0$ ($A_3 = -A_2$). The parameters are $\varepsilon_1 = 1$ and $a \omega_p/c = 100$. One may note that as the wavenumber increases, frequency increases and then saturates at higher wavenumbers. For higher value of wavenumber $q$, the behavior of the curve is the same as that of single metal surface structure. However, in double metal surface, at lower value of wavenumber phase velocity is smaller and wave-electron synchronism is easy to achieve at low electron energies. The $E_z$ field of the SPW has minimum at $x=0$ but its amplitude is not very significantly different from the one at $x=\pm a/2, -a/2$ when $\alpha_2 a \ll 1$.

III. ELECTRON ACCELERATION IN DOUBLE SURFACE CONFIGURATION

Let an electron be injected into the center of the vacuum region bounded by two metal surfaces (Fig. 1), in the presence of large amplitude surface plasma wave. The electron response is governed by the equation of motion

$$\frac{dp}{dt} = -e(E + v \times B),$$

(9)

where $-e$ and $m$ are the electronic charge and mass and $B = (\nabla \times E)/\omega$. Expressing $d/dt = v \cdot d/dz$, the $x$ and $z$ components of Eq. (9) can be written as

$$\frac{dp_x}{dz} = \left[ \frac{e m \gamma (k_z/\alpha_2)}{\rho_z} + \frac{e}{\omega} \left( \frac{\alpha_2^2 - k_z^2}{\alpha_2^2} \right) \right] \times (e^{\alpha_2 z} + e^{-\alpha_2 z}) A_1^2 \sin(\omega t - k_z + \phi),$$

(10)
\[
\frac{dp_z}{dz} = \left[ -\frac{em\gamma}{p_z} (e^{\alpha z} - e^{-\alpha z}) \cos(\omega t - k_z + \phi) + \frac{e}{\omega p_z} \left( -\alpha_z + \frac{k_z^2}{\alpha_z^2} \right) (e^{\alpha z} + e^{-\alpha z}) \sin(\omega t - k_z + \phi) \right] A'_1, 
\]
(11)
where \( A'_1 = A_1 e^{-(t-z/v_x)2^2} \), \( \gamma = (1 + p^2/m^2c^2)^{1/2} \), \( v_x \) is the group velocity of the surface plasma wave, \( \phi \) is the initial phase of the wave, and we have considered a Gaussian temporal profile of the SPW amplitude with \( \tau_L \) pulse width. These equations are supplemented with

\[
\begin{align*}
\frac{dx}{dz} &= \frac{p_x}{p_z}, \\
\frac{dt}{dz} &= \gamma m \end{align*}
\]
(12) (13)

We introduce dimensionless quantities \( \tilde{A}'_1 = eA'_1/m \omega_P c \), \( X = \omega_P x/c \), \( Z = \omega_P z/c \), \( P_x = p_x (mc) \), \( P_z = p_z (mc) \), \( T = \omega_P t \), \( \Omega = \omega/\omega_P \), \( q = k c/\omega_P \), and \( v_x = v_x/c \). In terms of these, Eqs. (10)–(13) can be written as follows:

\[
\begin{align*}
\frac{\partial P_x}{\partial Z} &= \left[ \frac{\gamma}{P_z} (\tilde{q} \tilde{A}'_1) + \frac{1}{\Omega} (\tilde{q}^2 - \tilde{\alpha}_z^2 \tilde{A}'_1) \right] \\
\times (e^{\alpha_z Z} + e^{-\alpha_z Z}) \sin(\Omega T - qZ + \phi), \\
\frac{\partial P_z}{\partial Z} &= \left[ -\frac{\gamma}{P_z} (e^{\alpha_z Z} - e^{-\alpha_z Z}) \cos(\Omega T - qZ + \phi) + \frac{1}{\Omega} P_x \right] \\
&\times \left( -\alpha_z^2 + \frac{q^2}{\alpha_z^2} \right) \sin(\Omega T - qZ + \phi) \tilde{A}'_1, \\
\frac{dX}{dZ} &= \frac{P_X}{P_Z}, \\
\frac{dT}{dZ} &= \frac{\gamma}{P_Z}.
\end{align*}
\]
(14) (15) (16) (17)

We solve Eqs. (14)–(17) numerically for electron energy and electron trajectory. In Figs. 3–5, we have plotted kinetic energy (in keV) gained by the electrons versus normalized distance \( z \omega_P / c \) for different values of laser frequency, for the parameters \( P_z(0)=0.0, P_z(0)=0.09, \chi(0)=0.0, \tau(0)=0.0, \tau_L \omega_P=200, e_L=1, \phi = \pi/2, E_{SP}=1.2 \times 10^{11} \text{ V/m}, \omega_P=1.3 \times 10^{16} \text{ rad/s}, \omega/\omega_P=0.06, \text{ and } a \omega_P/c=100. \)

![Figure 3](image3.png)

**FIG. 3.** Variation of kinetic energy of the accelerated electron (\( \gamma-1 \)mc\(^2\)) (in keV) vs normalized distance \( z \omega_P / c \) in double metal surface. The parameters are \( P_z(0)=0.0, P_z(0)=0.09, \chi(0)=0.0, \tau(0)=0.0, \tau_L \omega_P=200, e_L=1, \phi = \pi/2, E_{SP}=1.2 \times 10^{11} \text{ V/m}, \omega_P=1.3 \times 10^{16} \text{ rad/s}, \omega/\omega_P=0.06, \text{ and } a \omega_P/c=100. \)

![Figure 4](image4.png)

**FIG. 4.** Variation of kinetic energy of the accelerated electron (\( \gamma-1 \)mc\(^2\)) (in keV) vs normalized distance \( z \omega_P / c \) in double metal surface. The parameters are \( P_z(0)=0.0, P_z(0)=0.09, \chi(0)=0.0, \tau(0)=0.0, \tau_L \omega_P=200, e_L=1, \phi = \pi/2, E_{SP}=1.2 \times 10^{11} \text{ V/m}, \omega_P=1.3 \times 10^{16} \text{ rad/s}, \omega/\omega_P=0.087, \text{ and } a \omega_P/c=100. \)

![Figure 5](image5.png)

**FIG. 5.** Variation of kinetic energy of the accelerated electron (\( \gamma-1 \)mc\(^2\)) (in keV) vs normalized distance \( z \omega_P / c \) in double metal surface. The parameters are \( P_z(0)=0.0, P_z(0)=0.09, \chi(0)=0.0, \tau(0)=0.0, \tau_L \omega_P=200, e_L=1, \phi = \pi/2, E_{SP}=1.2 \times 10^{11} \text{ V/m}, \omega_P=1.3 \times 10^{16} \text{ rad/s}, \omega/\omega_P=0.1, \text{ and } a \omega_P/c=100. \)
accelerated electron, launched in the center of vacuum region, has been shown by curve (b) in Fig. 7. It turns out to be a straight line for $x=0$, i.e., the electron moves in $z$ direction without deviation from its path. The upper curve, i.e., (a), is the trajectory for the accelerated electron in the case of single metal surface discussed in next section.

IV. ELECTRON ACCELERATION BY A SURFACE PLASMA WAVE OVER A SINGLE METAL SURFACE

Consider an interface separating free space ($x > 0$) and a metal ($x < 0$). The effective permittivity of the metal is given by Eq. (1). A surface plasma wave propagates over the surface with

$$E = \left( \hat{z} + \frac{i k_z}{\alpha_1} \right) A e^{-\alpha_1 x} e^{-i(\omega t - k_z z)} \quad \text{for } x > 0,$$

$$E = \left( \hat{z} - \frac{i k_z}{\alpha_1} \right) A e^{+\alpha_1 x} e^{-i(\omega t + k_z z)} \quad \text{for } x < 0,$$

$$k_z^2 = \frac{\omega^2}{c^2} \left( \frac{1}{\varepsilon} - \frac{1}{\varepsilon_0} \right),$$

where $\alpha_1 = (k_z^2 - \omega_0^2 / c^2)^{1/2}$ and $\alpha_2 = (k_z^2 - \omega_0^2 c^2 / c^2)^{1/2}$, so chosen that $\nabla \cdot E = 0$ for both $x < 0$ and $x > 0$. The magnetic field of the wave can be obtained as $B = (\nabla \times E) / i \omega$.

We launch an electron beam parallel to the surface with initial velocity $v_0$. Its response to the surface plasma wave is governed by Eqs. (9), (12), and (13). In dimensionless form, these equations are

$$\frac{\partial \nu}{\partial Z} = A'' \left[ - \frac{\gamma}{P_z} \alpha_1 \sin(\Omega T - qZ + \phi) 
+ \frac{1}{\Omega} \left( \frac{q^2}{\alpha_1^2} - \alpha_1 \right) \sin(\Omega T - qZ + \phi) \right],$$

$$\frac{\partial P_z}{\partial Z} = A'' \left[ - \frac{\gamma}{P_z} \cos(\Omega T - qZ + \phi) 
- \frac{1}{\Omega} \left( \frac{q^2}{\alpha_1^2} - \alpha_1 \right) \sin(\Omega T - qZ + \phi) \right],$$

$$\frac{dX}{dZ} = P_{XZ},$$

$$\frac{dT}{dZ} = \frac{P_z}{P_z},$$

where $A'' = A' e^{-\alpha_1 x} e^{-(T - Z/\nu_p)^{1/2} / \alpha_1^2}$.

We have solved these equations numerically for the following parameters $P_{X}(0) = 0.0$, $P_{Z}(0) = 0.007$, $X(0) = 1.0$, $T(0) = 0.0$, and $\phi = \pi$. We express the surface wave amplitude as $|E_0| = \eta |E_0|$, where $|E_0|$ is the amplitude of the laser used to excite it in the attenuated total reflection (ATR) configuration and $\eta$ is the enhancement factor. Presuming laser energy conversion to the SPW as 50%, enhancement factor comes out to be $\eta \approx 3.2$, corresponding to the laser intensity of $10^{13}$ W/cm². We choose $E_L = 2.9 \times 10^5$ V/cm. The results are displayed in Figs. 6 and 7. The maximum kinetic energy gained by the electrons comes out to be $\approx 0.39$ keV (Fig. 6), which is close to the experimentally observed value of 0.4 keV by Zawadzka et al. In Fig. 7, curve (a) represents the electron trajectory for the above parameters. One may note that the electron moves away from the metal surface as it gains energy.

V. DISCUSSION

Double metal surface configuration appears to have significant promise for accelerating electrons by a surface plasma wave up to tens of keV energy. Close to the surface wave cutoff frequency $\omega_0 = \omega_{SPW}/(1 + \varepsilon_0)^{1/2}$, the phase velocity of surface plasma wave is small, hence energy gain is small.

![Diagram](image_url)

**FIG. 6.** Variation of kinetic energy of the accelerated electron ($\gamma - 1)m^2$ vs normalized distance $\omega \nu_P / c$ over the single metal surface. The parameters are $P_{X}(0) = 0.0$, $P_{Z}(0) = 0.007$, $X(0) = 0.1$, $T(0) = 0.0$, $\tau_L = 27$ fs, $E_{SPW} = 3 \times 10^{10}$ V/m, $\omega_0 = 5$, $\omega = 375$ THz, and $\phi = \pi$. Curve (b) is the trajectory of the accelerated electrons in double metal surface configuration. The corresponding parameters are $P_{X}(0) = 0.0$, $P_{Z}(0) = 0.09$, $X(0) = 0.0$, $T(0) = 0.0$, $\tau_L = 200$, $E_{SPW} = 1.2 \times 10^{11}$ V/m, $\omega_0 = 1.3 \times 10^{10}$ rad/s, $\omega / \omega_0 = 0.1$, and $\alpha \omega_0 / c = 100$.

![Diagram](image_url)

**FIG. 7.** The trajectory of the accelerated electron along the $x$ direction vs normalized distance $\omega \nu_P / c$.
However, at $\omega \approx 0.8 \omega_c - 0.9 \omega_c$, one can achieve electron energies in the 10 keV range with moderately relativistic laser intensities. For $P_x(0)=0.0$, $P_y(0)=0.09$, $x(0)=0.0$, $t(0)=0.0$, $\tau_L \omega_p = 200$, $\epsilon_L = 1$, $\phi = 90^\circ$, $E_{SP} = 1.2 \times 10^{11}$ V/m, $\omega_p = 1.3 \times 10^{16}$ rad/s, and $\omega / \omega_p = 0.06$, we obtain the electron acceleration of $\sim 12.7$ keV.

In the case of a single metal surface, electron acceleration is limited by the transverse ponderomotive force induced displacement of electrons. Our model of ponderomotive acceleration of electrons explains the experimental results by Zawadzka et al.\cite{9} at laser intensity of $10^{13}$ W/cm$^2$. We obtain the electron acceleration of 0.39 keV by surface plasmons excited by a laser of intensity $10^{13}$ W/cm$^2$ over the single metal surface. However, in this case as the electron gains energy it moves away from the interface. When a vacuum region is bounded by two metal surfaces with surface plasma waves propagating at both metal-vacuum interfaces then a symmetric SPW field is generated in the vacuum region. The electrons injected in the center of vacuum region can be accelerated to higher energies with the control in their trajectory. The present paper is limited to single particle dynamics, hence does not address two core issues, viz., the efficiency of the SPW conversion into electron energy and the number of electrons that can be accelerated. Subsequent studies shall focus on these issues.

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