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Frequency Shifts Induced in Laser Pulses by Plasma Density Variations

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<p>An analytical theory is developed which describes how a radiation pulse becomes modified as it propagates through a plasma with arbitrary temporal and spatial density variations. Expressions are derived for the shifts induced in both the frequency and the wavenumber of the radiation pulse. It is shown that temporal variations in the plasma density result in frequency shifts of the radiation. The possibility of upshifting the frequency of the laser pulse using plasma waves is analyzed, and it is found that maximum shifts occur when the phase velocity of the plasma wave is equal to the group velocity of the laser pulse.</p>					
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FREQUENCY SHIFTS INDUCED IN LASER PULSES BY PLASMA DENSITY VARIATIONS

The propagation of electromagnetic radiation through plasmas is a problem of general interest with a wide variety of applications ranging from communications¹ to laser driven particle accelerators.^{2,3} For example, the results of plasma simulation studies have recently been reported^{4,5} which suggest two possible methods by which the frequency of an electromagnetic wave may be upshifted. In the first method, the plasma density through which the EM wave is propagating is suddenly increased in time,⁴ while the second method utilizes the interaction of a plasma wave (having a phase velocity near the speed of light)^{2,3,6,7} with a short EM pulse.⁵ Phenomena such as these, which result from variations in the plasma density, may offer a way of tuning the radiation from a laser or, alternatively, they may describe the distortion of radio signals in the ionosphere.

In the following, a general analytic theory is developed from first principles which describes how a EM radiation pulse is affected by variations in the plasma density. Specifically, the 1D wave equation is used to derive expressions for the shifts induced in the frequency and in the wavenumber by arbitrary plasma density variations (both in space and in time). In particular, for variations in the plasma density as a function of time, it is shown that the wavenumber of the EM wave remains constant while shifts are induced in the frequency. (This is to be contrasted to the case of spatial plasma density variations, for which the frequency remains constant and the wavenumber shifts.) For the case of a short radiation pulse interacting with a plasma wave with finite phase velocity, it is shown that shifts are induced in both the wavenumber and in the frequency. Maximum frequency shifts may be obtained when the phase velocity of the plasma wave is equal to the group velocity of the radiation pulse evaluated at the ambient plasma density. Furthermore, it is shown that for small frequency shifts, the amplitude of the vector potential maintains its initial profile while propagating forward at the ambient group velocity.

The 1D wave equation for the normalized vector potential $a = eA/(mc^2)$ of the radiation field is given by

$$\left(\frac{\partial^2}{\partial z^2} - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) a(z, t) = k_p^2(z, t) a(z, t), \quad (1)$$

where $k_p^2 \equiv k_{p0}^2 n(z, t)/(\gamma(z, t)n_0)$. Here $\gamma(z, t)$ is the relativistic factor associated with the motion of the plasma electrons, $n(z, t)$ is the plasma electron density and $k_{p0}^2 = \omega_{p0}^2/c^2$, where ω_{p0} is the electron plasma frequency in the ambient density n_0 . In deriving the above equation, conservation of canonical momentum was used, $p_{\perp} = eA_{\perp}/c$, which gives a transverse plasma current (in the fluid limit) of $J_{\perp} \equiv -enp_{\perp}/(m\gamma)$. Throughout the

following it will be assumed that $a^2 \ll 1$ such that $k_p^2(z, t)$ is independent of $a(z, t)$, i.e., the effects of the radiation field on the plasma wave will be ignored.

To solve the above wave equation, it is helpful to write $a(z, t) = b(z, t) \exp(ik_0 z - i\omega_0 t)$, where $b(z, t)$ is the radiation envelope and where ω_0 and k_0 are the frequency and wavenumber of the radiation in the ambient plasma (in the absence of a plasma wave) which satisfy the dispersion relation $\omega_0^2 = c^2 k_0^2 + c^2 k_{p0}^2$. Furthermore, it is convenient to introduce a change of variables $\zeta = z - v_g t$ and $\tau = t$, where $v_g = c^2 k_0 / \omega_0$ is the group velocity of the radiation in the ambient plasma. The wave equation is then given by

$$\left(2i \frac{\omega_0}{c^2} \frac{\partial}{\partial \tau} + 2 \frac{v_g}{c^2} \frac{\partial^2}{\partial \zeta \partial \tau} + \frac{1}{\gamma_g^2} \frac{\partial^2}{\partial \zeta^2} - \frac{1}{c^2} \frac{\partial^2}{\partial \tau^2} \right) b = \delta k_p^2(\zeta, \tau) b(\zeta, \tau), \quad (2)$$

where $\delta k_p^2 \equiv k_p^2 - k_{p0}^2$ and $1/\gamma_g^2 = 1 - v_g^2/c^2$.

It will now be assumed that the radiation envelope $b(\zeta, \tau)$ is slowly varying compared to the radiation frequency ω_0 , that is $|\partial b / \partial \tau| \ll |\omega_0 b|$ and $|\partial b / \partial \zeta| \ll |\omega_0 b / c|$. Assuming this, the second order derivatives in Eq. (2) may be neglected. Equation (2) may then be solved giving

$$b(\zeta, \tau) = b_0(\zeta) \exp \left[-\frac{ic^2}{2\omega_0} \int_0^\tau d\tau' \delta k_p^2(\zeta, \tau') \right]. \quad (3)$$

The condition $|\partial b / \partial \tau| \ll |\omega_0 b|$ implies $|c^2 \delta k_p^2 / (2\omega_0^2)| \ll 1$. For a plasma density perturbation δn , this condition implies $|\omega_{p0}^2 \delta n / (2\omega_0^2 n_0)| \ll 1$. The condition $|\partial b / \partial \zeta| \ll |\omega_0 b / c|$ implies $|\int_0^\tau d\tau' (\partial \delta k_p^2 / \partial \zeta) c^3 / (2\omega_0^2)| \ll 1$ as well as $|(db_0 / d\zeta) c / (b_0 \omega_0)| \ll 1$. The first of these inequalities generally implies that the wavenumber shift must be small compared to ω_0 / c , while the second inequality indicates that the initial envelope $b_0(\zeta)$ must be slowly varying compared to ω_0 / c .

The total phase $\Phi(\zeta, \tau)$ of the radiation field may be identified by writing $a(\zeta, \tau) = |a(\zeta, \tau)| \exp i\Phi(\zeta, \tau)$. It is then possible to examine the evolution of the frequency as well as the wavenumber of the radiation through the definitions $\omega(\zeta, \tau) \equiv -\partial \Phi / \partial t = -(\partial / \partial \tau - v_g \partial / \partial \zeta) \Phi$ and $k(\zeta, \tau) \equiv \partial \Phi / \partial z = \partial \Phi / \partial \zeta$. Using the above solution for $b(\zeta, \tau)$ gives

$$\omega(\zeta, \tau) = \omega_0 + \frac{c^2}{2\omega_0} \delta k_p^2(\zeta, \tau) - \frac{v_g c^2}{2\omega_0} \int_0^\tau d\tau' \frac{\partial}{\partial \zeta} \delta k_p^2(\zeta, \tau'), \quad (4)$$

$$k(\zeta, \tau) = k_0 - \frac{c^2}{2\omega_0} \int_0^\tau d\tau' \frac{\partial}{\partial \zeta} \delta k_p^2(\zeta, \tau'). \quad (5)$$

The above equations are valid for arbitrary variations $\delta k_p^2(\zeta, \tau)$. (Recall, $k_p^2 = k_{p0}^2 n / (n_0 \gamma)$ and the effects of γ become important for nonlinear relativistic plasma waves.⁷) Provided

$b(\zeta, \tau)$ remains slowly varying compared to ω_0 , the amplitude of the normalized vector potential $|a|$ does not change. That is, Eq. (3) indicates that $|a| = |b_0(\zeta)|$ and, hence, the initial envelope of the vector potential is simply convected forward at the group velocity v_g .

To illustrate the above theory, consider a plasma density variation which is a function only of space. For example, consider a radiation pulse entering a plasma ($\omega_p^2/\omega_0^2 \ll 1$) from vacuum with a plasma density profile $\delta k_p^2 = \delta k_p^2(z)$ for $z > 0$ and equal to zero for $z < 0$. Assume that at $t = 0$, the radiation pulse extends from $-L < z < 0$, where $\omega_0 L/c \gg 1$. Equations (3)-(5) indicate, that as the pulse propagates, the frequency and wavenumber evolve according to $\omega(z, t) = \omega_0$ and $k(z, t) = k_0 - c^2 \delta k_p^2(z)/(2v_g \omega_0)$. This is in agreement with the well-known result¹ that as radiation propagates into a plasma with spatial density variations, the frequency remains constant whereas the wavenumber changes such that the dispersion relation $\omega^2 = c^2(k^2 + k_p^2)$ remains satisfied.

On the other hand, consider a plasma density variation which is a function only of time. For example, consider a radiation pulse (of length $L \gg c/\omega_0$) propagating through a long, uniform plasma column (where $\omega_p^2/\omega_0^2 \ll 1$) in which the density is temporally changing, $\delta k_p^2 = \delta k_p^2(t)$. Equations (3)-(5) indicate, that as the pulse propagates, the frequency and wavenumber evolve according to $\omega(z, t) = \omega_0 + c^2 \delta k_p^2(z)/(2\omega_0)$ and $k(z, t) = k_0$. This is in agreement with the simulations of Ref. 4 which indicate that as radiation propagates through a plasma with temporal density variations, the wavenumber remains constant whereas the frequency changes such that the dispersion relation $\omega^2 = c^2(k^2 + k_p^2)$ remains satisfied.

Consider a plasma density variation which is a function both of time and of space. For example, consider the case in which a plasma wave (with phase velocity near c)^{2,3,6,7} is used to upshift the frequency of a laser pulse, as suggested by the simulations of Ref. 5. Assuming a plasma wave with a phase velocity v_p such that the plasma wave quantities are functions of only $z - v_p t$ implies $\delta k_p^2(\zeta, \tau) = \delta k_p^2(\zeta - \Delta v \tau)$, where $\delta k_p^2(\zeta - \Delta v \tau)$ has the form of a periodic oscillation and $\Delta v = v_p - v_g$. Defining the shift in frequency and in wavenumber as $\Delta \omega = \omega(\zeta, \tau) - \omega(\zeta, 0)$ and $\Delta k = k(\zeta, \tau) - k(\zeta, 0)$ gives

$$\Delta \omega = \frac{c^2 v_p}{2\omega_0 \Delta v} [\delta k_p^2(\zeta - \Delta v \tau) - \delta k_p^2(\zeta)], \quad (6)$$

$$\Delta k = \frac{c^2}{2\omega_0 \Delta v} [\delta k_p^2(\zeta - \Delta v \tau) - \delta k_p^2(\zeta)]. \quad (7)$$

The above equations indicate that the frequency shift will be maximum for the case



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$v_p = v_g$. For this case $\Delta\omega = -(v_g\tau c^2/2\omega_0)d\delta k_p^2/d\zeta$ and $\Delta k = -(c^2\tau/2\omega_0)d\delta k_p^2/d\zeta$. Hence, $\Delta\omega$ is a linear function of $v_g\tau$, the distance that the pulse has propagated through the plasma. In such a way $|\Delta\omega|$ will increase until it becomes sufficiently large so that the approximation that $b(\zeta, \tau)$ is slowly varying is no longer valid. For $b(\zeta, \tau)$ to be slowly varying requires $|c\Delta\omega/(v_g\omega_0)|^2 \ll 1$. Consider a plasma wave with $v_p = v_g$ such that $\delta k_p^2(\zeta) = k_{p0}^2 \delta n(\zeta)/n_0$, where $\delta n(\zeta)$ is the plasma wave density perturbation. For $\delta n(\zeta) = \delta n_0 \sin k_{p0}\zeta$, then

$$\frac{\Delta\omega}{\omega_0} = -\pi \frac{\omega_{p0}^2}{\omega_0^2} \frac{\delta n_0}{n_0} \frac{v_g\tau}{\lambda_{p0}} \cos k_{p0}\zeta. \quad (8)$$

Hence, a positive frequency shift $\Delta\omega > 0$ requires the laser pulse to be positioned properly in the phase of the plasma wave such that $d\delta n/d\zeta < 0$. This is illustrated in Fig. 1. A convenient method for producing such a plasma wave may be the laser wakefield accelerator,³ in which a driving laser pulse of frequency ω_0 is used to generate a plasma wave with $v_p = v_g$.

For the case $v_p \neq v_g$, $|\Delta\omega|$ is no longer a linearly increasing function of $c\tau$. In fact, Eq. (6) indicates that $\Delta\omega$ will oscillate as a function of $c\tau$. Consider a plasma wave of the form $\delta k_p^2(\zeta, \tau) = k_{p0}^2 |\delta n/n_0| \cos k_{p0}(\zeta - \Delta v\tau)$. Assuming the laser pulse (with a pulse length $L \ll \lambda_{p0} = 2\pi/k_{p0}$) is initially centered about $\zeta_0 = 0$, Eq. (6) indicates that the maximum frequency shift is given by $|\Delta\omega_m| = |\omega_{p0}^2 v_p \delta n_0 / (\omega_0 n_0 \Delta v)|$ and occurs when $c\tau = |\lambda_{p0}/(2\Delta v)|$. Furthermore, notice that $\Delta\omega_m$ may either be positive or negative, depending on the sign of Δv (for the present example, $\Delta\omega_m > 0$ for $v_p < v_g$). Again, the assumption that $b(\zeta, \tau)$ is slowly varying implies $|c\Delta\omega_m/(2v_p\omega_0)|^2 \ll 1$.

Physically, the frequency shifts induced in a radiation pulse by a plasma wave may be understood as follows. A plasma wave gives rise to variations in the plasma parameter $k_p^2(\zeta, \tau)$. These variations lead to variations in the "local" phase velocity of the laser pulse. Heuristically, the "local" dispersion relation for the radiation field is given by $\omega^2(\zeta, \tau) = c^2 k^2(\zeta, \tau) + c^2 k_p^2(\zeta, \tau)$. For small $c\tau$, this gives $v_p^2(\zeta)/c^2 = 1 + k_{p0}^2 n(\zeta)/(k_0^2 n_0)$. For example, the local phase velocity near the front of the laser pulse ($\zeta = \zeta_0$) will be less than the local phase velocity near the back of the pulse ($\zeta = \zeta_L$) provided $n(\zeta_0) < n(\zeta_L)$. Hence, the individual phase peaks in the pulse $a(z, t) = |a| \exp(ikz - i\omega t)$ may move relative to one another (i.e., closer together for the present example). In such a way both the frequency and the wavenumber of the radiation pulse will change, as is given by Eqs. (4) and (5).

It should be pointed out that due to the local nature of the frequency shift (the dependence of $\Delta\omega$ on ζ), a laser pulse with a finite pulse length L will develop a spread

in frequency shifts. That is, the frequency shift at the front of the pulse may be different than the frequency shift at the back of the pulse. For example, consider a plasma wave with $v_p = v_g$ of the form $\delta k_p^2 = k_{p0}^2 (\delta n_0/n_0) \sin k_{p0} \zeta$ and a laser pulse centered about $\bar{\zeta} = \pi$ with $L < \lambda_{p0}/2$ (see Fig. 1). The difference in the frequency shift at the center of the pulse with a point $\Delta\zeta$ away is given by $|(\Delta\omega(\bar{\zeta}) - \Delta\omega(\bar{\zeta} + \Delta\zeta))/\Delta\omega(\bar{\zeta})| = 1 - \cos \Delta\zeta$. This spread in frequency shifts may be quite significant.

Equations (4) and (5) provide convenient analytic expressions for the frequency and wavenumber shifts resulting from variations in the plasma parameter k_p^2 . However, these expressions are only valid for a slowly varying envelope $b(\zeta, \tau)$, which implies that the frequency shifts must be small, $|\Delta\omega/\omega_0|^2 \ll 1$. To calculate the behavior of the vector potential for large shifts, $|\Delta\omega/\omega_0| \geq 1$, it is necessary to retain the $\partial^2/(\partial\zeta\partial\tau)$ derivative in the wave equation for $b(\zeta, \tau)$. Keeping this derivative, the wave equation can formally be solved for the case $\delta k_p^2(\zeta, \tau) = \delta k_p^2(\zeta)$, giving

$$b(\zeta, \tau) = \int_0^\zeta d\zeta' F(\zeta') \exp[i\omega_0(\zeta' - \zeta)/v_g] J_0[\alpha(\zeta', \zeta, \tau)], \quad (9)$$

$$\alpha(\zeta', \zeta, \tau) = \left(2c^2\tau \int_\zeta^{\zeta'} d\zeta'' \delta k_p^2(\zeta'')/v_g \right)^{1/2},$$

where J_0 is the Bessel function of order zero and $F(\zeta) = (\partial/\partial\zeta + i\omega_0/v_g)b_0(\zeta)$. In solving for $b(\zeta, \tau)$, it has been assumed $b(\zeta = 0) = 0$, i.e., $\zeta = 0$ is chosen to be in front of the pulse. Analysis of the above equation indicates that now both the amplitude $|b(\zeta, \tau)|$ and the phase evolve as a function of τ . Determination of the precise behavior of $b(\zeta, \tau)$ requires further computation.

In the analysis of Ref. 5, heuristic arguments based on Lorentz transformations of the dispersion relation are used to determine an expression for $\partial\omega/\partial z$. The above analytic theory may be used to derive an equation for $\partial\omega/\partial z$ by operating on Eq. (4) with $\partial/\partial z = \partial/\partial\zeta$. For the case of a plasma wave with phase velocity v_p , Eq. (4) gives

$$\frac{\partial\omega}{\partial z} = \frac{c^2}{2\omega_0\Delta v} \left[v_p \frac{\partial}{\partial z} \delta k_p^2(z - v_p t) - v_g \frac{\partial}{\partial z} \delta k_p^2(z - v_g t) \right], \quad (10)$$

which for $v_p = v_g$ reduces to the expression given in Ref. 5 when $\delta k_p^2 = k_{p0}^2 \delta n/n_0$. Hence, the expression given in Ref. 5 has been shown to be valid provided i) $v_p = v_g$, ii) v_p is independent of z and t , iii) relativistic effects associated with $\gamma(z, t)$ are neglected and iv) the frequency shift remains small, $|\Delta\omega/\omega_0|^2 \ll 1$. Whether or not the arguments of Ref. 5 are valid for large shifts $|\Delta\omega/\omega_0| \geq 1$ remains uncertain.

The analytic theory presented above describes how a laser pulse becomes modified due to variations in the background plasma. Specifically, arbitrary variations in the plasma parameter $\kappa_p^2(\zeta, \tau)$ leads to shifts in both the frequency and wavenumbers indicated by Eqs. (4) and (5). Provided these shifts are sufficiently small, the amplitude of the vector potential remains unchanged and propagates forward at the group velocity v_g . The above theory indicates that changes in the plasma density as a function of time lead to shifts in the radiation frequency. In particular, the possibility of upshifting the frequency of the laser pulse using a plasma wave has been examined and it is found that maximum frequency shifts result when $v_p = v_g$. For this case, $\Delta\omega$ increases linearly with the propagation distance $v_g\tau$ and positive frequency shifts require phasing the laser pulse such that it is centered at a position of decreasing density or, more precisely, at a position where $d\delta k_p^2/d\zeta < 0$. The above theory is valid, in general, for small frequency shifts, $|\Delta\omega/\omega_0|^2 \ll 1$. However, Eq. (8) implies that large shifts of order $|\Delta\omega| \sim \omega_0$ require propagation distances of order $c\tau \sim |\delta n_0/n_0|^{-1} \omega_0^2/\omega_{p0}^2$. Since, typically (for a KrF laser), $\omega_0^2/\omega_{p0}^2 \gg 1$, this propagation distance can be quite large. The detailed examination of large shifts $|\Delta\omega| \sim \omega_0$ requires further evaluation of Eq. (9).

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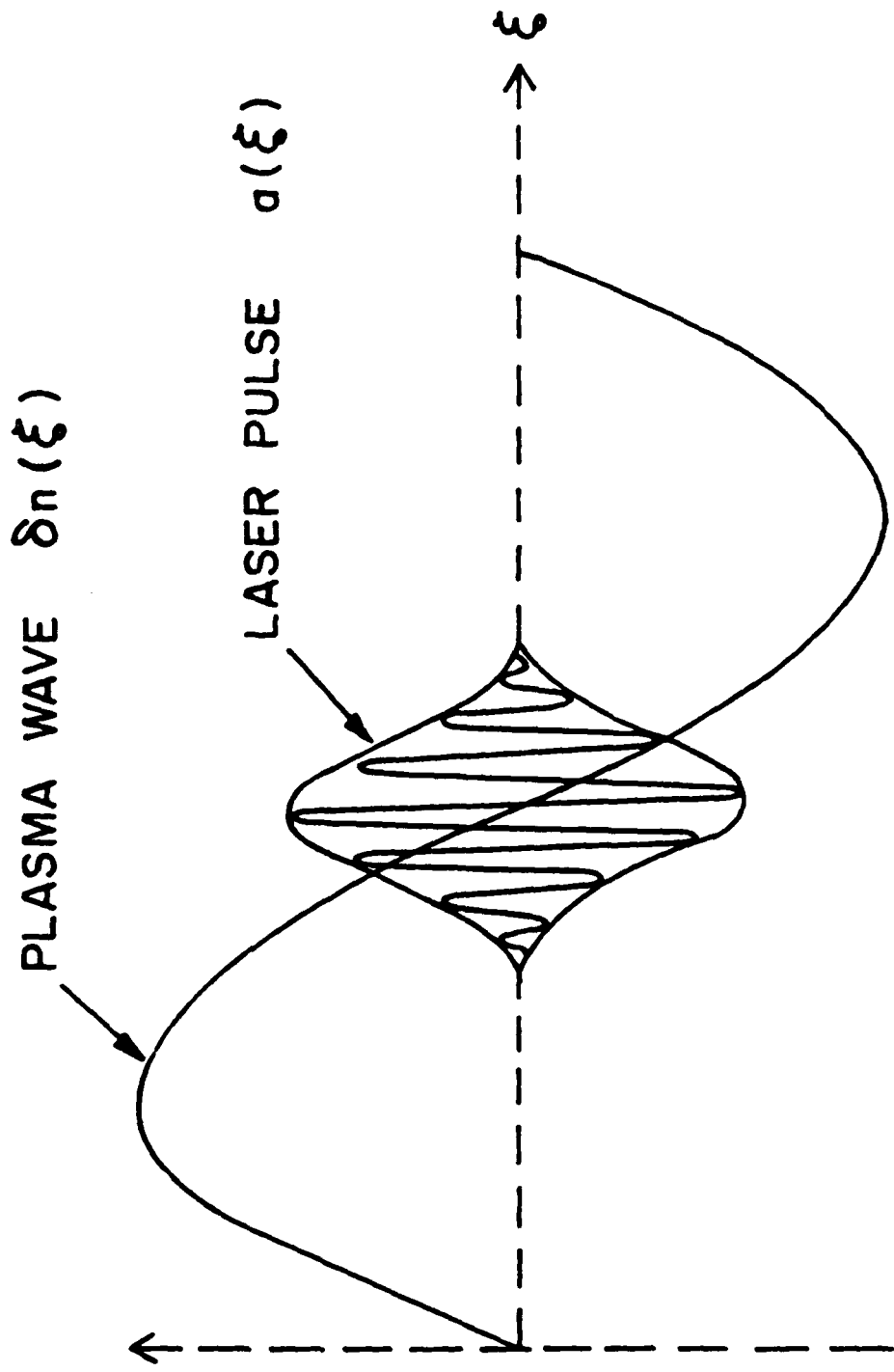


FIG. 1. Schematic of the upshifting of a laser pulse by a plasma wave with $v_p = v_g$. Positive frequency shifts require the laser pulse to be centered about regions of the wave with a decreasing density slope.

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