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Inverse resonance absorption in an inhomogeneous magnetized plasma

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served nondependencies of the PLP's on various machine parameters, in particular on gas density, field gradients and dB_θ/dt are exactly as expected for such resonances. (The important field gradients seen by the fast electrons are dominated by the large internal gradients.) (3) Obviously both the observed enhancement of the dumps by an increased misalignment and the disappearance of the dumps when the copper wall is replaced by the resistive wall also agree with this explanation. [In the latter case, the toroidal ($m = 4$) modulation of B_θ will dominate the other perturbations and most likely lead to a variety of overlapping resonances.] (4) The observed dependence of the dumps on the ring length also can easily be explained by this hypothesis through the influence of a varying ring length on the poloidal orbital frequencies of the fast electrons. (5) Finally, first theoretical analyses also indicate the existence of ($m = 1$) resonances in the relevant parameter space. Additional studies are in progress to further investigate the situation.

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Inverse resonance absorption in an inhomogeneous magnetized plasma

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The linear mode conversion of a plasma wave to a light wave in a magnetized plasma has been examined theoretically and by computer simulation. This conversion is the inverse of resonance absorption exhibiting an identical dependence on magnetic field and density scale length with an optimum conversion efficiency of approximately 60%. Radiation from this source may contribute to the harmonic spectra observed from laser-irradiated plasmas.

The linear mode conversion of p-polarized radiation to plasma waves has been studied extensively in connection with wave propagation in the ionosphere and on account of its role in the absorption of light by laser-generated target plasmas.[1] The inverse process, by which plasma waves may generate radiation, has also been considered in a variety of contexts in both astrophysical and laboratory plasmas. For example, features in the dynamic spectrum of type II solar radio noise such as the structure and splitting of the fundamental, mirrored in the second harmonic, led to interpretations in terms of the coupling of a spectrum of plasma oscillations to the radiation field. In the laboratory, Ben-Yosef and Kaufman[2] detected radiation at the plasma frequency and its second harmonic from the positive column of an arc discharge. More recently, Means *et al.*[3] have examined the radiation spectrum and its dependence on the density gradient in experiments with a large unmagnetized dc discharge plasma. The nonthermal emission from tokamaks at the plasma frequency has also been attributed to radiation from plasma oscillations.[4]

In whatever context this particular mechanism is considered, two factors essential for significant emission are a strong nonequilibrium source of plasma waves and effective coupling of these waves to the radiation field. The neighborhood of the quarter-critical density in laser-generated plasmas is one in which plasma waves are localized on account of the role of stimulated Raman scattering and the two plasmon decay instability while propagation of plasmons oblique to a density gradient provides a coupling mechanism. Under conditions of nonuniform irradiation large self-generated magnetic fields will be present in target plasmas and fields of several megagauss have been recorded.[5,6] These

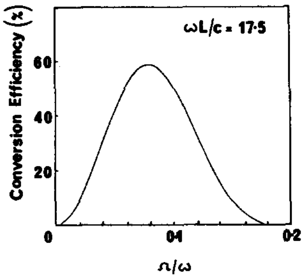

FIG. 1. Percentage energy conversion versus Ω/ω from the fluid model; $V_e/c = 0.05$, $\omega L/c = 17.5$.

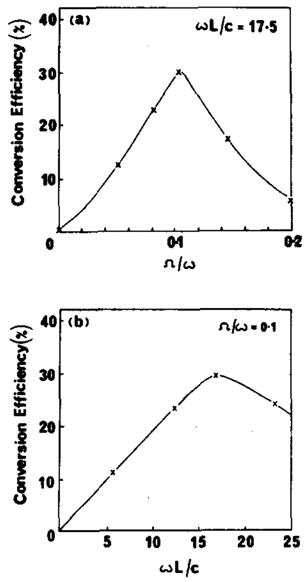

FIG. 3. Percentage energy conversion from particle simulations; $V_e/c = 0.05$, fixed ions. (a) plotted versus Ω/ω for $\omega L/c = 17.5$, (b) plotted versus $\omega L/c$ for $\Omega/\omega = 0.1$.

fields provide an additional means of coupling longitudinal plasma waves to the radiation field (even for plasmons propagating parallel to the density gradient). Given these conditions—a strong source of plasma waves, a density gradient, and coupling either by oblique propagation or by magnetic field—it is natural to examine the role of so-called inverse resonance absorption in the physics of the quarter-critical density region. This region is well known as a source of harmonic emission from laser-target plasmas.[7] The details of the spectrum of light at $\omega_0/2$, where ω_0 is the frequency of the incident light, are not yet fully understood. The radiation is widely attributed to the Raman instability, but this, of itself, leaves some details of structure in recent measurements unexplained, in particular the doublet appearance with red and blue wings, which is a common feature of the spectra. If two-plasmon decay occurs as well as Raman scattering, then in view of the conditions for effective coupling at the quarter-critical density, it is possible that the conversion of plasmons to photons can contribute to the emission seen.

The purpose of this letter is to examine inverse resonance absorption under these conditions, both theoretically and by simulation. For convenience we have considered only magnetic field coupling since it allows inverse resonance absorption to be studied in a one-dimensional geometry. Within an inhomogeneous plasma of density $n = n(x)$, a uniform (self-generated) magnetic field $\mathbf{B}_c = B_c\mathbf{z}$ is assumed to exist. We consider waves propagating parallel to the density gradient with their electric field component polarized orthogonal to $\mathbf{B}_c$. In this case the normal modes are the extraordinary and upper-hybrid waves. It is the linear conversion of the latter to the former which we concentrate on here. (Note that the electrostatic and electromagnetic fields are uncoupled in the opposite polarization: no linear mode conversion occurs between an ordinary mode and an electron plasma wave.)

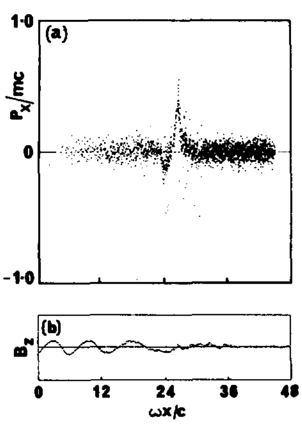

FIG. 2. Results from a typical simulation; $V_e/c = 0.05$, $\omega L/c = 23.3$, $\Omega/\omega = 0.1$. (a) electron phase space p_x/mc vs $x\omega/c$, (b) magnetic field component B_z vs $x\omega/c$.

From Maxwell's equations and the linearized warm plasma fluid equations, we readily obtain the coupled equations describing both resonance absorption and its inverse (distinguished only by the boundary conditions),

$$c^2E_y'' + (\omega^2 - \omega_p^2)E_y = i\omega\Omega E_x, \tag{1}$$

$$3V_e^2E_x'' - 3V_e^2L^{-1}E_x' + (\omega^2 - \omega_p^2 - \Omega^2)E_x = -i\Omega\omega_p^2E_y/\omega, \tag{2}$$

where a time dependence $\exp(-i\omega t)$ is assumed; ω_p is the local plasma frequency, $\Omega = eB_c/mc$, the cyclotron frequency, V_e, the electron thermal speed and $L = n/(dn/dx)$, the density gradient scale length. The primes indicate differentiation with respect to x.

The basic physics follows directly from (1) and (2) in the cold-plasma limit. The extraordinary wave may propagate up to its cutoff where $\omega_{p1}^2 = \omega^2 - \omega\Omega$, whereas the upper-hybrid wave is confined to a layer at higher densities between the upper-hybird resonant density for which $\omega_{p2}^2 = \omega^2 - \Omega^2$ and its cutoff where $\omega_{p3}^2 = \omega^2 + \omega\Omega$. A stop-band exists between the extraordinary wave cutoff (ω_{p1}) and the upper-hybrid wave resonance (ω_{p2}). However, when $\Omega/\omega \ll 1$, as is the case in most laser-plasma applications, these layers are in close proximity, thus making it possible for electric fields to tunnel from one region to the other.

The critical parameter for resonance absorption in a magnetized plasma has been shown[8] to be $\tau = (\omega L/c)^{1/3}(\Omega/\omega)^{1/2}$. This emerges from Eqs. (1) and (2) on assuming a linear density profile $\omega_p^2 = \omega^2x/L$ and letting $\zeta = (\omega L/c)^{2/3}(1 - x/L)$. If τ is too small the coupling is weak; if τ is large the upper-hybrid resonance and the extraordinary wave mirror point are remote from one another. A value of $\tau \simeq 0.8$ was predicted by Kruer and Estabrook[8] for optimum conversion ($\sim 40\%$) of extraordinary to upper-hybrid waves. The same scaling must hold for the inverse process, and we have confirmed this using a particle simulation code and by solving the coupled-mode equations (1) and (2).

Equations (1) and (2) were solved numerically for E_x and E_y using a centered finite difference scheme on a staggered mesh. Transmitting boundary conditions were used at the low-density end of a linear plasma ramp. A finite electron temperature and neglect of damping enables upper-hybrid waves, launched from the low-density boundary, to propagate to their cutoff density. At the high-density end of the ramp, the electric fields of the waves were set equal to zero since the waves are evanescent in this region. Figure 1 plots the percentage of plasma wave energy converted into light wave energy as a function of cyclotron frequency for a density scale length $\omega L/c = 17.5$ and an electron thermal speed of $V_e = 0.05c$ (though in practice V_e is not a sensitive parameter). A maximum conversion of 60% occurs when the parameter $\tau = 0.73$. An identical curve is obtained for the inverse process. Previous studies of resonance absorption in magnetized plasmas[8–11] give optimum conversion in the range 40%–70%, each with $\tau \sim 0.8$. The reciprocal nature of the two processes has been studied in microwave experiments for the usual linear mode conversion of waves propagating oblique to a density gradient in an isotropic plasma by Means *et al.*[3] This reciprocity extends to the magnetized case as well.

The particle simulations were performed using a $1\frac{1}{2}$-D relativistic particle code with transmitting boundary conditions. A fixed neutralizing ion background was used. The upper-hybrid wave was excited at its resonance by locally applying a weak driver field E_d along the density gradient. A typical run showed the growth of the upper-hybrid wave, its saturation by wave breaking at an amplitude $E_{\max} \simeq 12E_d$, and the conversion to an extraordinary wave which propagated down the density gradient and out of the simulation region. Figure 2(a) represents the artificially excited upper-hybrid wave, while Fig. 2(b) shows clearly the extraordinary wave generation. Some emission at the second harmonic[8,12] of the driver frequency was also observed. The variation of time-averaged conversion efficiency with cyclotron frequency and density scale length are shown in Fig. 3. These show an optimum conversion efficiency of 30% when $\tau \simeq 0.8$. This conversion efficiency is a time-averaged value over the duration of the simulation. A time average taken over only that period of the run for which emission was steady and maximum gives a value of 50%–60%, in good agreement with the fluid model.

We see from these results that self-generated magnetic fields may play a significant role in contributing to emission spectra from laser-produced plasmas. For example, plasma wave energy generated at the quarter-critical density by parametric processes may be effectively coupled to the radiation field by this process provided τ is close to the optimum value of 0.8. The magnetic field required at the quarter-critical density for optimum conversion is

$$B\,(\mathrm{MG}) \simeq 25(\lambda_L/L)^{2/3}\lambda_L^{-1}(\mu\mathrm{m}).$$

In a typical experiment with green light ($\lambda_L = 0.53\,\mu$m) and a scale length of 150 μm, a magnetic field of about 1 MG would be required. In very long scale length experiments, efficient conversion requires only very modest magnetic field strengths. Mode conversion of plasma waves can also affect the parametric processes which are their source by effectively introducing an additional damping into the instability. It has been shown,[13] for example, that emission from SRS can be significantly reduced in a magnetized plasma. Because of the reciprocal nature of the processes, mode conversion of the plasma wave to the radiation field and vice versa occur simultaneously with equal efficiency.

In summary, particle simulations and theory show that plasma waves may radiate efficiently in an inhomogeneous magnetized plasma. This mechanism may contribute to emission spectra observed in recent laser-target experiments.

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