# PLASMA CONTROL WITH INFRARED LASERS

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## I. INTRODUCTION

The central problem in feedback stabilization of fusion reactor plasmas is the introduction of the feedback signal into the interior of a dense plasma. The only scheme proposed so far[1] requires the generation of intense beams of high-energy neutral atoms, a rather cumbersome affair. In this paper, we suggest the use of $CO_2$ lasers, which are becoming powerful enough to be considered for plasma production ahd heating and are therefore surely powerful enough for plasma control.

We take advantage of a nonlinear interaction between an extraordinary electromagnetic wave ($\underset{\sim}{E}$, $\underset{\sim}{k} \perp \underset{\sim}{B}_o$) and a plasma to produce a dc drift of electrons relative to ions. This second-order drift, computed by Chen and Etievant[2] for a cold plasma, is given by

$$\underset{\sim}{v}_e^{(2)} = -4\pi \frac{\underset{\sim}{P}}{B_o^2} \frac{\omega_c^4}{\omega_p^4} \frac{1}{\delta^2}, \qquad \delta \equiv \frac{\omega_h^2 - \omega^2}{\omega_p^2}, \tag{1}$$

where $\omega_h$ is the upper hybrid frequency, $B_o$ is in gauss, and $\underset{\sim}{P} = (c/8\pi)(c\underset{\sim}{k}/\omega)E_t^2$ is the Poynting vector in ergs per cm$^2$ per sec, $E_t$ being the transverse component if the elliptically polarized X-wave E-vector. Since k varies as $\delta^{-1/2}$ near hybrid resonance, $\underset{\sim}{v}_e^{(2)}$ varies as $\delta^{-5/2}$; and the effect is localized to the density layer where $\omega \approx \omega_h$.

If $\underset{\sim}{v}_e^{(2)}$ is directed along $\nabla n_o$, it will cause a charge separation and an $E_\perp$. By feedback-modulating $\underset{\sim}{v}_e^{(2)}$, it is possible to suppress low-frequency waves. Results for resistive drift waves are given in Sec. II. That a nonlinear effect of this type actually occurs has been demonstrated by Wong et al.,[3] whose experimental results inspired this work.

Two major difficulties arise in applying this method to a fusion plasma. First, the free-space wavelength $\lambda$ corresponding to hybrid resonance in a plasma with $n = 10^{15}\ cm^{-3}$ and $B_o = 10^5 G$ is $750\mu$, much longer than the $10.6\mu$ wavelength of $CO_2$ lasers. Second, a wave launched outside the plasma will be reflected at the right-hand cutoff $\omega_R = \frac{1}{2}[\omega_c + (\omega_c^2 + 4\omega_p^2)^{1/2}]$ and will never reach hybrid resonance. Tunneling through the cutoff was possible in a microwave experiment[3] where $\lambda >> r_o \equiv n_o/n_o'$. The opposite is true in a fusion reactor, and computations by Kuehl[4] show that tunneling is then negligible. Both difficulties can be overcome by the optical mixing of two $CO_2$ or $N_2O$ laser beams to produce a difference frequency near $\omega_h$. This process is treated in Sec. III.

## II. STABILIZATION OF DRIFT AND FLUTE MODES

Following the procedure and notation of Ref. 1, we consider $\underset{\sim}{v}_e^{(2)}$ to have the same $\exp i(k_y y + k_z z - \omega t)$ dependence as the drift-wave variables and add it to the usual solution of the electron equation of motion. The usual resistive drift wave analysis is then carried out for $\underset{\sim}{B}_o = B\hat{\underset{\sim}{z}}$ and $\nabla n_o/n_o = \hat{\underset{\sim}{x}}/r_o$. Gravitational instabilities are included via a term $Mn_o g\hat{x}$ in the ion equation of motion. We define

$$\omega_f \equiv [v_{ex}^{(2)}/r_o + i\, v_{ey}^{(2)} k_y](n_o/n_1) \quad . \tag{2}$$

For g=0, there results the local dispersion relation

$$\omega(\omega - \omega_i) - i\omega_f(b^{-1}\omega^* - \omega + \omega_i) + i\omega_s[\omega - \omega^* + b(\omega - \omega_i)] = 0 \, . \tag{3}$$

This has been solved numerically to obtain curves, similar to those in Ref. 1, showing the optimum phase of $v_e^{(2)}$ relative to $n_1$. For $\omega \approx \omega^*$, sufficient conditions for marginal stability are

$$v_{ex}^{(2)} = 2ib\omega^* r_o(n_1/n_o) \quad \text{and} \quad v_{ey}^{(2)} = 2b(\omega^*/k_y)(n_1/n_o) \tag{4}$$

for "radial" and "tangential" beams, respectively. These values are independent of $\omega_s$ (resistivity) because $v_e^{(2)}$ cancels directly the charge separations caused by ion inertia and FLR, and parallel electron currents need not flow. We believe, therefore, that Eq. (4) has rather general applicability.

For $g \neq 0$ and $k_z = 0$, the dispersion relation is

$$(\omega + i\omega_f)(\omega - \omega_i + kv_g) - g/r_o - i\omega_f \omega^* b^{-1} = 0, \quad (5)$$

where $v_g = -g/\Omega_c$. For radial injection, gravitational flute modes are stabilized by $v_{ex}^{(2)} = (ibg/\omega^*)(n_1/n_o)$.

## III. NONLINEAR CONVERSION TO $\omega \approx \omega_h$.

We consider two ordinary waves ($E \| B_o$) $\omega_1 >> \omega_h$ and $\omega_2 >> \omega_h$ propagating at a relative angle $\theta_{12}$ in the plane perpendicular to $B_o$. If we make $\omega_1 - \omega_2 = \omega_3 \approx \omega_h$, nonlinear mixing will form an extraordinary wave propagating at an angle $\theta_{13}$ relative to $\omega_1$, also in the plane perpendicular to $B_o$. The wave $\omega_3$ can then produce the drift $v_e^{(2)}$. It is essential that the polarizations of $\omega_1, \omega_2$, and $\omega_3$ be as stated above. Since the result will depend on the fourth power of the incident wave amplitudes, the estimates given below, based on weakly nonlinear theories, are probably pessimistic.

The conversion of $\omega_1, \omega_2$ to $\omega_3$ has been computed by Etievant et al.[5] for a cold plasma. The result can be written

$$P_3 = 5.7 \times 10^{-18} \pi R_o^2 \, P_1 P_2 F(\omega_1, \omega_2, \omega_c, \omega_p) , \quad (6)$$

where $\pi R_o^2$ is the area of intersection of the incident beams. For $\omega_3 \approx \omega_h$, the linear dispersion relations give $k_3^2 \approx \omega_c^2/c^2\delta$ and $k_{1,2}^2 = \omega_{1,2}^2/c^2$, whence F takes the form

$$F \approx \frac{\omega_3 \omega_c^3}{\omega_1^2 \omega_2^2} \, \delta^{-5/2} \quad . \quad (7)$$

Computations of log F, $\cos\theta_{12}$, and $\cos\theta_{13}$ are shown in Fig. 1. Our computations differ from those of Ref. 5 in that the wave $\omega_3$ is not required to propagate out of the plasma; it may be trapped and converted to $v_e^{(2)}$ locally. The restriction $\omega_p \leqq \omega_c$ of Ref. 5 is then removed. F is sharply peaked near $\delta = (\omega_h^2 - \omega_3^2)/\omega_p^2 = 0$. In cold-plasma theory, F has a maximum value $F_{max}$ imposed by the condition $\underset{\sim}{k}_3 = \underset{\sim}{k}_1 - \underset{\sim}{k}_2$, which causes $\cos\theta_{12} < -1$

and $\cos\theta_{13} > 1$ for $\delta < \delta_{min}$. Thus, an upper limit to $P_3$ is given by Eq. (6) and

$$F = F_{max} \approx 32\,\omega_1\omega_h/\omega_c^2 \ . \qquad (8)$$

Note that setting $\theta_{12} = 180^o$ automatically ensures operation at $F_{max}$.

From Eqs. (1), (6), and (7), one finds that $v_e^{(2)}$ varies as $\delta^{-9/2}$. Clearly, a very accurate computation of the width of the hybrid resonance is required. In the absence of such a calculation, we shall give an estimate of the thermal corrections. First, we have extended the work of Refs. 2 and 5 to include a $\nabla p$ term; this procedure splits the singularity at $\delta=0$ but does not remove it. Second, we have used the condition $\omega/k \geqq v_{th}$, where $v_{th}^2 \equiv 3KT_e/m$. This yields a result intermediate between our optimistic estimate [Eq. (8)] and our pessimistic estimate. Finally, we have made a pessimistic estimate on the basis that finite electron Larmor radius (FLR) effects broaden the resonance. Hedrick[6] has shown that $\underset{\sim}{k}$ for X-waves with FLR becomes complex near $\omega=\omega_h$, where the X-wave couples to the Bernstein modes. If we require $\underset{\sim}{k}$ to be real, we obtain from Ref. 6 the condition $\delta \geqq v_{th}/c$. Using this in Eqs. (1) and (7), we obtain a pessimistic estimate because nonlinear FLR effects have been neglected.

Estimates have been made for a plasma with $n=10^{15}\text{cm}^{-3}$, $B=10^5$G, $T_e=10$ kev, $R=2r_o=50$ cm, $n_1/n_o = 10^{-3}$, and an azimuthal mode number m. A single 10.6$\mu$ beam operating off-resonance would require $P=2\times10^7 m^3$ W/cm$^2$, according to Eqs. (1) and (4a). A single beam with $\omega \approx \omega_h$, $\delta=v_{th}/c$, would require only $P=1.3\times10^{-2} m^3$ W/cm$^2$, but the beam would not penetrate. Two $CO_2$ laser beams with $\pi R_o^2=1$ cm$^2$ would require $P_1=P_2=2.4\times10^{-2} m^{3/2}$W/cm$^2$ optimistically and $P_1=P_2=2\times10^7\ m^{3/2}$W/cm$^2$ pessimistically. We conjecture that the latter is a gross overestimate.

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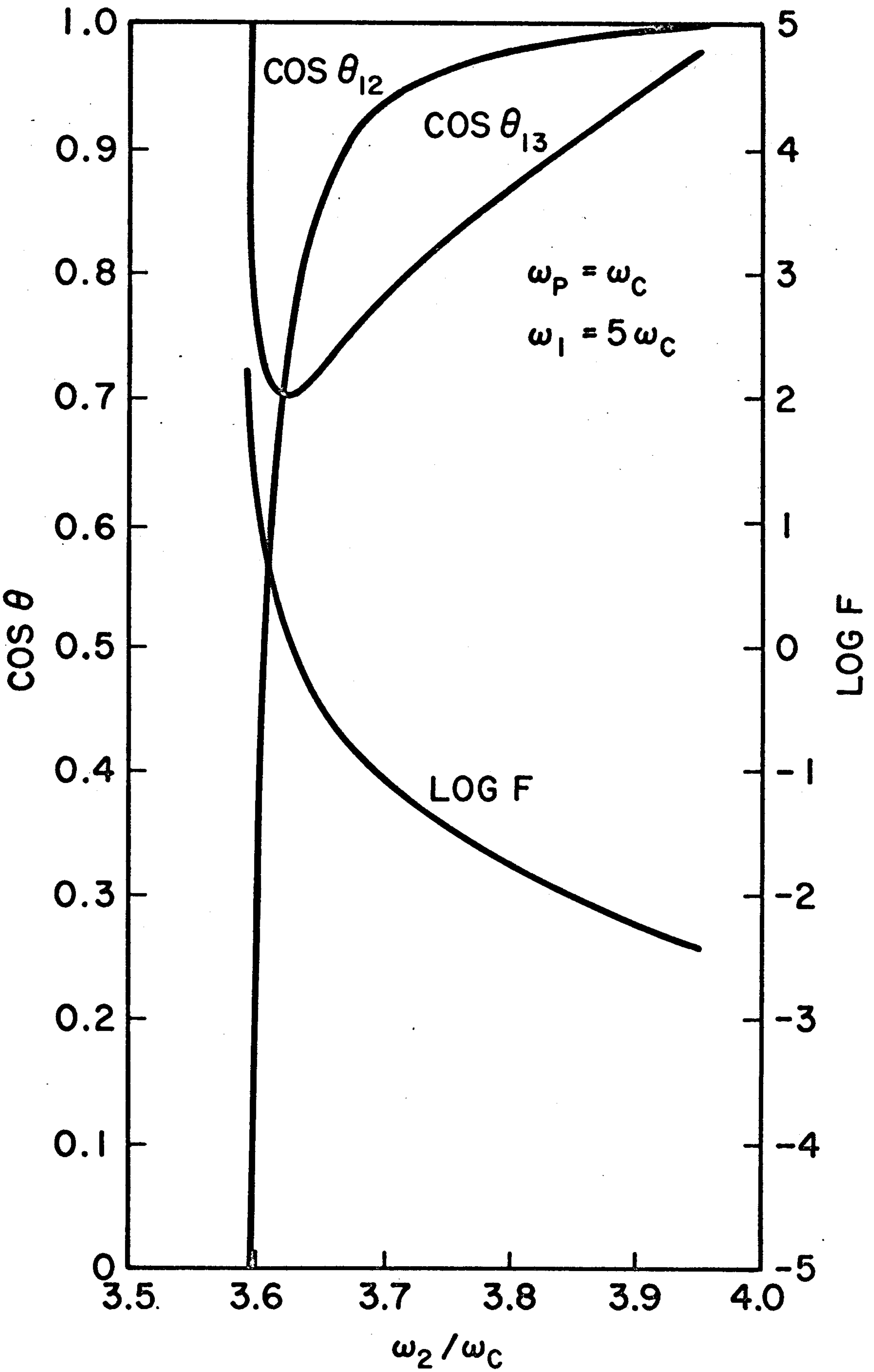


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Figure 1