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# Undulator Induced Transparency in Magnetoactive Plasma

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## 1. Introduction

The effect of electromagnetically induced transparency (EIT), firstly discovered in quantum systems [1] is actively investigated in magnetized plasma now [2-6]. The basic features of EIT are the suppression of resonant absorption of low-power probe wave and group velocity deceleration within this "transparency window" with the presence of a strong pump wave. Plasma oscillations are exited in EIT regime by the beating between probe and pump waves.

In [3,5] it was proposed to use the magnetic undulator as the pump to increase the energy compression in the plasma. One of the possible applications of this effect can be ion acceleration, which is accomplished by the electrostatic field of the plasma wave.

In this work we continue the investigation of undulator induced transparency (UIT). Besides the resonant right-hand polarized probe wave at electron-cyclotron frequency, we consider the left-hand polarized wave, which is exited by the beating between probe and pump waves.

## 2. Basic equations

We will consider the propagation of two electromagnetic waves in plasma along the constant magnetic field $\mathbf{H}=H\mathbf{z_0}$ with the presence of the undulator field $\mathbf{B_w}=b_w\mathrm{Re}[\mathbf{e}_+\exp(\mathrm{i}k_w z)]$:

$$\mathbf{A}_\perp = \mathrm{Re}\{[\mathbf{e}_+ A_+(z) + \mathbf{e}_- A_-(z)]\exp(-i\omega t)\}. \qquad (1)$$

Here, $A_-$ and $A_+$ are the vector potentials of left-hand and right-hand polarized (probe) waves respectively, $\mathbf{A}_\perp$ is the total vector potential, $\mathbf{e}_\pm=2^{-1/2}(\mathbf{x_0}\pm \mathrm{i}\mathbf{y_0})$. As it was shown before [2,3], in these conditions the longitudinal plasma oscillations are excited at the frequency $\omega$. We will describe them by the potential $\varphi_\|=\mathrm{Re}[\varphi_p(z)\exp(-i\omega t)]$.

We will use the hydrodynamic theory. The full set of equations has the following form:

$$\begin{aligned}
&\partial\mathbf{V}_\perp/\partial t + \omega_H[\mathbf{V}_\perp,\mathbf{z_0}] = (e/mc)\partial\mathbf{A}_\perp/\partial t - (e/mc)V_\|[\mathbf{z_0},\mathbf{B_w}],\\
&\partial V_\|/\partial t = (e/m)\partial\varphi_\|/\partial z - (e/mc)(\mathbf{V}_\perp,\mathbf{B_w}),\\
&\{-(1/c^2)\partial^2/\partial t^2 + \partial^2/\partial z^2\}\mathbf{A}_\perp = -(4\pi e/c)N_0\mathbf{V}_\perp,\\
&\partial/\partial t\,(\partial\varphi_\|/\partial z) + 4\pi e N_0 V_\| = 0.
\end{aligned} \qquad (3)$$

Here, $\omega_H=eH/mc$ is the electron gyrofrequency, $N_0$ is the unperturbed plasma density.

We introduce the complex amplitudes of corresponding variables and only the terms with resonant frequencies are retained. This leads to the following system of coupled equations:

$$\left\{-\left(c^2/\omega^2\right)d^2/dz^2-n_{0+}^2\right\}A_+=gA_-\exp\left(i2k_wz\right),$$
$$\left\{-\left(c^2/\omega^2\right)d^2/dz^2-n_{0-}^2\right\}A_-=gA_+\exp\left(-i2k_wz\right), \tag{8}$$

Other variables are expressed via $A_\pm$. In particular, for longitudinal oscillations velocity:

$$V_p=\left(2igc/v\sqrt{u_w}\right)\left\{A_-\left(1-\sqrt{u}\right)\exp\left(ik_wz\right)-A_+\left(1+\sqrt{u}\right)\exp\left(-ik_wz\right)\right\}. \tag{9}$$

In (8) $n_{0+}$ is the refractive index of right-hand polarized wave if it propagates without the left-hand polarized one (i.e. $A_-$=0). $n_{0-}$ has analogous meaning for left-hand polarized wave:

$$n_{0\pm}^2=1-v\frac{(1-v)\left(1\pm\sqrt{u}\right)-u_w/2}{(1-v)(1-u)-u_w}, \tag{10}$$

and $g$ is the coupling parameter:

$$g=\frac{1}{2}\frac{vu_w}{(1-v)(1-u)-u_w}. \tag{11}$$

Also, $v=\omega_p^2/\omega^2$, $u=\omega_H^2/\omega^2$, $u_w=\omega_{Hw}^2/\omega^2$, where $\omega_p=(4\pi e^2N_0/m)^{1/2}$ is the electron plasma frequency, $\omega_{Hw}=eb_w/2^{1/2}mc$ is the electron gyrofrequency, corresponding to the undulator.

## 3. Propagation of the waves in UIT regime

After the substitution $A_\pm(z)=a_\pm(z)\exp(\pm ik_wz)$ the system (8) turns into the system of ordinary differential equations for $a_\pm(z)$. The *exact* solution of this system can be found:

$$A_\pm=A_{0\pm}\exp\left(ik_\pm z\right) \tag{14}$$

where, $k_\pm=k\pm k_w$ and the value of $k$ should be found from the following dispersive relation:

$$\left\{(n+n_w)^2-n_{0+}^2\right\}\left\{(n-n_w)^2-n_{0-}^2\right\}-g^2=0. \tag{15}$$

Here, $n=ck/\omega$ and $n_w=ck_w/\omega$. The solution of Eq. 15 corresponds to four separate modes. In general case ($n_w\neq 0$) the polarization ellipse of each normal wave rotates with period of $k_w/\pi$:

$$\mathbf{A}_\perp=\sum_{j=1}^4 C_j\exp\left(ik_jz-i\omega t\right)\left[\mathbf{e}_+\exp\left(ik_wz\right)+\mathbf{e}_-K_j\exp\left(-ik_wz\right)\right]. \tag{17a}$$

Here, $k_j=(\omega/c)n_j$ and $n_j$ is one of the four roots of Eq. 15, the value of $K_j$ determines, which of the waves prevails: $K_j=(n_j+n_w)^2-n_{0+}^2/g$. Obviously, the solution (17a) can also be represented as the superposition of 4 pairs of the waves, where each pair consists of right-hand polarized and left-hand polarized waves with different wavenumbers (below, $k_{j\pm}=k_j\pm k_w$):

$$\mathbf{A}_\perp=\sum_{j=1}^4 C_j\exp\left(-i\omega t\right)\left[\mathbf{e}_+\exp\left(ik_{j+}z\right)+\mathbf{e}_-K_j\exp\left(-ik_{j-}z\right)\right]. \tag{17b}$$

## 4. Mode conversion

Fig. 1 shows the behavior of the refractive index $n$ in inhomogeneous plasma for different fixed values of $u$. The regions, where $A_+$ or $A_-$ prevails are marked appropriately. If two certain roots $n_i$ and $n_{j\neq i}$ become close to each other, such that $|n_i-n_j|<<|g|$ (see also Fig. 1), then the right-hand polarized wave, corresponding to the solution $n_i$ and the left-hand polarized wave, corresponding to the solution $n_j$, became coupled via the expression $|k_{i+}-k_{j-}-2k_w|<<(\omega/c)|g|$. In this region there is the possibility of mode conversion in inhomogeneous plasma, i.e. the wave passes from one dispersive branch to another. It is important to note, that this is the conversion of one two-wave mode in (17b) to another.

The incident right-hand polarized wave should be converted into the left-had polarized with minimal efficiency, for the most effective excitation of electrostatic oscillations (see Eq. 9). The conversion efficiency is of the order of $\exp(-\delta)$ where $\delta$ can be found using the well-known technique [7]. Requiring the small efficiency: $\delta\geq 1$ (which corresponds to the conver-

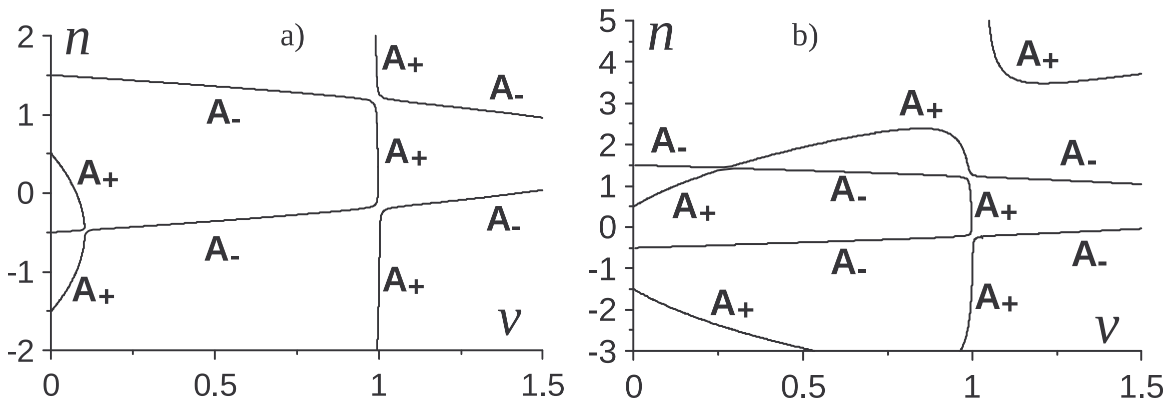


Fig. 1. Dependency $n(v)$ in UIT regime. $n_w$=0.5, $u_w$=6·10$^{-3}$, $u$=0.8 (a), $u$=1.2 (b).

sion less than 50%), one can find the inhomogeneity scale $L\sim\delta$ [7]. For example, $L$ should be greater than $5(c/\omega)$ for the following parameters: $n_w$=1.6, $u_w$=0.04, $u$=1.

**5. Proper profiles of plasma density and external magnetic field**

To put the real experiment into practice, it is necessary to consider the propagation of the waves through the finite plasma region. Let us assume, that plasma density never exceeds the critical one ($v$<1). As it can be seen from expression for $n_{0+}$, for propagation of probe wave ($n_{0+}^2>0$) the following condition should be satisfied: $(1-v)(1-u)-u_w<0$, which means, that the external magnetic field should increase near the bounds of plasma region (in other words it should have the magnetic trap configuration).

The propagation of incident right-hand polarized radiation through the plasma slab was investigated in details using the particle-in-cell simulations. The results of these calculations, demonstrating the effect of UIT are shown at Fig. 2. It can be seen, that the incident probe wave is transmitted through the plasma region at electron-cyclotron frequency and electrostatic oscillations are effectively excited. About 30% of incident energy is converted into the nonresonant component, which is in the agreement with estimations made above.

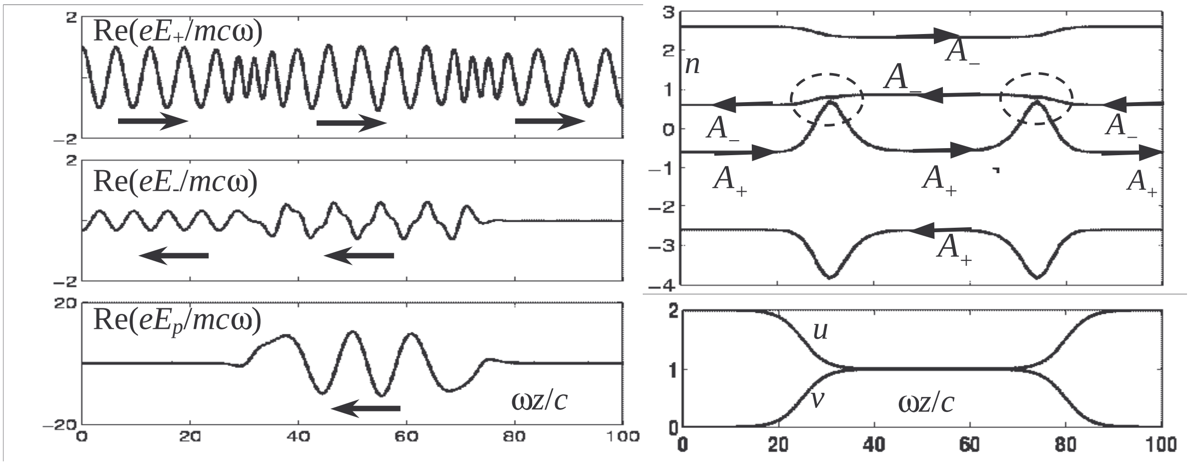


Fig. 2. Numerical calculations of UIT. $n_w$=1.6, $u_w$=0.04, $u$=1, $v$=0.99 (in plasma center). Arrows show the direction of wave propagation. Circles denote the regions of mode conversion.

## 6. Conclusion

We theoretically investigated the self-consistent structure of normal waves in the regime of UIT. The effect of mode conversion during the propagation of the waves in inhomogeneous plasma is demonstrated. The conversion efficiency is estimated.

Numerical simulations were used for modelling this effect and the comparison of the results with the theory is performed. Various profiles of the plasma density and external magnetic field are studied. The proper selection of undulator wavelength combined with judicious choice of axial magnetic field profile enables microwaves to penetrate plasma with realistic (smooth) density profiles at moderate level of the undulator field, suppressing the strong resonant absorption at the cyclotron frequency.

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