NONLINEAR INTERACTION OF INTENSE ELECTROMAGNETIC BEAMS WITH PLASMAS

BY

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SUMMARY

In this thesis, we have studied some of the nonlinear phenomena associated with the propagation of a Gaussian electromagnetic (EM) beam in a collisionless plasma. Because of the nonuniform intensity distribution of the EM beam, in a plane transverse to the direction of propagation, the time independent component of the ponderomotive force becomes finite and leads to the redistribution of carriers in the plasma. This leads to the self-focusing of the EM beam if its power is above a certain threshold value. Because of the redistribution of the carriers the electrostatic modes of the plasma get nonlinearly coupled with the EM beam. This may lead to the enhancement in the amplitude of the electrostatic mode. The nonresonantly excited electrostatic mode may again interact with the EM beam and lead to (i) the generation of another electrostatic mode or (ii) the enhanced scattering of the EM beam. We have studied the nonlinear interaction of a Gaussian EM beam with an electron plasma wave in both unmagnetised as well as magnetoplasma. On account of the interaction between the two waves, the ponderomotive force at the difference frequency of the two waves becomes finite and leads to the generation of an ion-acoustic wave. We have also studied the nonlinear interaction of a Gaussian EM beam with an electrostatic upper hybrid wave in a collisionless magnetoplasma. The interaction between the two waves may

result in the generation of an electrostatic lower hybrid wave or an electrostatic ion cyclotron wave. We have also studied the generation of an electrostatic lower hybrid pulse at the difference frequency of two EM pulses in a collisionless magnetoplasma. When the pulse duration is comparable to the characteristic time of diffusion of the carriers across the pulse, the ponderomotive nonlinearity depends not only on the instantaneous intensity of the pulse but also on its previous history. Consequently the plasma wave generation becomes a transient phenomenon. Besides the generation of electrostatic waves, the scattering of a Gaussian EM beam off the electrostatic modes viz. the electron plasma wave, the ion-acoustic wave and the ion-cyclotron wave, in a magnetoplasma has also been studied in this thesis. We have also studied the effect of a radially symmetric ripple superimposed on a Gaussian EM beam on excitation and scattering in a magnetoplasma. It has been found that these phenomena depend on the position of the ripple on the EM beam and the phase angle between the ripple and the main beam. We have studied the nonresonant interactions for which the initial pump power may be well below the threshold for the parametric instabilities and thus the interactions studied may occur before the threshold for the parametric instabilities in the plasma.

PREFACE

The interaction of intense electromagnetic (EM) waves with plasmas has been the subject of intensive research during recent years on account of its relevance to controlled thermonuclear fusion, ionospheric and space studies and solid state plasma devices (Ginzburg, 1964; Tsytovich, 1970; Hughes, 1975). Intense EM waves are used in a number of schemes to heat the plasma upto thermonuclear temperatures. For example, in laser-pellet-fusion the idea is to achieve thermonuclear fusion by heating and confining a small pellet of suitable fuel, such as DT mixture, by intense laser beams (Nuckolls et al., 1972). Irradiation by a laser beam has been proposed as a promising method to heat a magnetically confined fusion plasma (Dawson et al.,1971). There is a great deal of interest in the use of radio frequency and microwaves for the supplementary heating of magnetically confined fusion plasmas (Morales, 1977; Chan and Chiu, 1979; Perkins, 1977; Porkolab and Chang, 1978; Maekawa et al., 1978). The success of these schemes depends on the efficient coupling of the EM wave energy with the plasma. Because of the rapid decrease of the electron-ion collision frequency with temperature ($\nu_{e,i} \sim T_e^{-3/2}$), the classical absorption (inverse bremsstrahlung) becomes inefficient at high temperatures (Brueckner and Jorna, 1974; Kristiansen and Hagler, 1976). In a collisionless plasma absorption of the EM waves, takes place through linear processes, such as mode conversion(Stix, 1965; Golant and Piliya, 1972), as well as through nonlinear processes (Tsytovich, 1970), such as parametric instabilities (Simon and Thompson, 1976). At high intensities the force exerted by the EM radiation on the plasma, called the ponderomotive force (Landau and Lifshitz, 1960; Hora, 1977) plays an important role in coupling the EM wave energy to the plasma (Boreham and Hora, 1979). This nonlinear force acts primarily on the electrons due to their small mass, and is transmitted to the ions by the condition of charge neutrality. The ponderomotive force gives rise to a number of nonlinear phenomena such as self-focusing and filamentation (Kaw et al., 1973; Sodha et al., 1976a), harmonic generation (Bobin, 1974), plasma density profile modification (Willi et al., 1980), parametric instabilities (Simon and Thompson, 1976; Porkolab and Chang, 1978), dc magnetic field generation (Woo and De Groot, 1978) etc., which play an important role in coupling the EM wave energy to the plasma. A number of other phenomena such as the nonlinear optical mixing of two EM waves in a plasma (Kristiansen and Hagler, 1976) have also been studied extensively in connection with the heating of a plasma to high temperatures. A clear understanding of these phenomena is necessary for the success of various heating schemes.

In a majority of theoretical investigations carried out so far, the waves in the plasma have been taken as infinite plane waves. Although the plane waves cannot be realised in practice, the analysis yields substantial information about the physics of various phenomena. In plasma heating experiments nonuniform EM beams of finite width are commonly used. Therefore it is necessary to take proper account of the nonuniformity and the finite width of the EM beam, in these investigations. Moreover, the scope of these investigations is usually limited to obtaining the condition for the growth of the instability and the dynamics of the growth has not received attention. In the present thesis we have studied some of the nonlinear phenomena associated with the propagation of a Gaussian EM beam in a collisionless plasma, taking proper account of the nonuniformity and the finite width of the EM beam.

When an EM beam, having nonuniform intensity distribution along its wavefront, propagates in an unmagnetised plasma, the time independent component of the ponderomotive force

$$\underline{F}_e = \left\{ - m_e (\underline{V}_e \cdot \underline{\nabla}) \underline{V}_e - \frac{e}{c} (\underline{V}_e \times \underline{B}) \right\}_{dc}$$

$$\equiv - \frac{e^2}{4 m_e \omega_c^2} \underline{\nabla} (\underline{E} \cdot \underline{E}^*)$$

(where $\underline{V}_e$ is the electron drift velocity in the electric field $\underline{E}$ of the EM beam, $\underline{B}$ is the magnetic field associated with the EM beam, ω_o is the frequency of the EM beam and m_e, e and c are respectively the mass of an electron, the charge of an electron and the speed of light in vacuum), becomes finite because of the nonuniform intensity distribution of the EM beam (Hora, 1969 and 1972; Sodha et al., 1976a). The existance of the ponderomotive force (socalled nonlinear force) has been verified experimentally (Boreham and Hora, 1979; Luther-Davies et al., 1979). The ponderomotive force leads to the redistribution of the carriers in the plasma such that the electron/ion density is minimum on the axis and increases away from the axis i.e. the edge of the beam and beyond. Consequently the dielectric constant of the plasma $\epsilon = 1 - \omega_{pe}^2/\omega_0^2$ (where $\omega_{pe} = (4\pi N_0 e^2/m_e)^{1/2}$ is the electron plasma frequency), becomes maximum on the axis and decreases away from it. Thus the phase velocity of the EM beam; $v_\varphi = c/\epsilon^{1/2}$ becomes minimum on the axis and increases away from it. Consequently, the EM beam with initially plane wave front focuses as it propagates in the plasma, provided its initial power is above a certain threshold value (Sodha et al., 1976a). This leads to the modification in the intensity of the EM beam in the plasma, hence the intensity dependent phenomena in the plasma are also modified because of the modification in the intensity of the EM beam. The self-focusing of an EM beam in a plasma has been observed experimentally (Johnson and Chu, 1974; Cohn et al., 1974; Haas et al., 1976; Del Pizzo and Luther-Davies, 1979; Bäkös et al., 1981; Lin et al., 1981; Joshi et al., 1982). Many theoretical investigations of self-focusing (Shearer and Eddleman, 1973; Max, 1976; Sodha et al., 1976a; Felber, 1980) are based on the paraxial ray approximation (Akhmanov et al., 1968) and thus they are valid for the regions close to the axis of the EM beam. In spite of this limitation these theories give qualitatively correct behaviour of the beam self-focusing. Recently, the theories of self-focusing based on the moment theory approach (Lam et al., 1977) and the variational approach (Anderson and Bonnedal, 1979) have also been developed. In the present thesis we have used the approach developed by Akhmanov et al. (1968) and Sodha et al. (1976a), based on WKB and the paraxial ray approximation, because of its mathematical simplicity. The self-focusing has the lowest threshold of all the nonlinear phenomena (Kristiansen and Hagler, 1976), hence it is expected to influence (initiate or enhance) the other nonlinear phenomena.

Under the influence of the ponderomotive force an EM wave may decay parametrically into two electrostatic modes or one electrostatic wave and an EM wave in a plasma, if its initial power is above a certain threshold value (Simon and Thompson, 1976; Porkolab and Chang, 1978). In an unmagnetised plasma, the EM wave may decay into an electron plasma wave and an ion-acoustic wave near the critical density region or into two electron plasma waves near the quarter critical density region (Jackson, 1967). In a magnetised plasma a number of decay instabilities can occur (Porkolab and Chang, 1978). For instance an EM wave can decay into two upper hybrid waves (Grebogi and Liu, 1980a) or into upper hybrid and lower hybrid plasma waves (Kovalev and Romanov, 1979). The decay waves are electrostatic waves which are efficiently absorbed by the plasma particles because of their slow phase velocities and thus lead to the anomalous absorption of the EM wave. Thresholds and growth rates of these processes have been obtained theoretically (Brueckner and Jorna, 1974; Simon and Thompson, 1976; Porkolab and Chang, 1978). These processes have also been observed experimentally (Ebrahim et al., 1980; Porkolab and Chang, 1978).

In contrast to these processes there are other processes which lead to the scattering of the EM wave from the plasma. In an unmagnetised plasma the EM wave may decay into an electron plasma wave and an EM wave (Raman scattering) or an ion-acoustic wave and an EM wave (Brillouin scattering). The scattering processes occur in the underdense region of the plasma and prevent a large fraction of the EM energy from reaching the critical density region where the EM radiation is absorbed through the resonance absorption or parametric decay instability. A magnetised plasma can support a wide variety of natural modes e.g. the upper hybrid wave, the lower hybrid wave and the ion cyclotron wave etc. (Krall and Trivelpiece, 1973; Chen, 1974). The scattering in a magnetoplasma can take place from these modes. For example, the EM wave launched into the toroidal plasma for the purpose of supplementing the initial

Joule heating, may scatter from the electostatic upper hybrid wave or the electrostatic lower hybrid wave (Grebogi and Liu, 1980b). This may prevent the EM wave energy from reaching the upper hybrid and the electron cyclotron resonance layers where it is absorbed through cyclotron damping. In laser-pellet fusion, the magnetic field generated near the critical density region by the resonance absorption of the EM wave may spread to the underdense region of the plasma by convection and diffusion (Colombant and Winsor, 1977), and in this case the scattering may take place from the upper hybrid or the lower hybrid waves in place of the electron plasma or the ion-acoustic waves. The scattering of the EM waves from a plasma has been intensively studied theoretically (Drake et al., 1974; Liu et al., 1974; Forslund et al., 1975; Cohen and Max, 1979; Grebogi and Liu, 1980b) and experimentally (Lee et al., 1974; Lubin et al., 1974; Yamanaka et al., 1974; Offenberger et al., 1976; Ripin et al., 1977; Watt et al., 1978; Massey et al., 1978; Ng et al., 1979a; Turner and Goldman, 1980). Theoretical studies show that the EM radiation is scattered predominantly in the backward direction (Drake et al., 1974 and Forslund et al., 1975). This has been confirmed by experiments (Yamanaka et al., 1974 and Herbst et al., 1980). The plasma inhomogeneity affects the threshold of this process (Liu et al., 1974). The size of interaction region and nonlinear effects may be important in determining the amount of backscatter (Forslund et al., 1975). The magnetic field greatly reduces the threshold for Brillouin scattering by the lower hybrid wave. The Raman scattering by the upper hybrid wave has substantial growth rate because of the reduction of linear Landau damping due to the magnetic field (Grebogi and Liu, 1980b).

Most of the investigations on these processes consider infinite plane waves and are limited to obtaining the thresholds and the growth rates of these processes. The dynamics of the growth has not been paid attention. In contrast, in the present thesis, we have studied the nonlinear interaction of a Gaussian EM beam with the electrostatic modes of plasma, taking the proper account of the nonuniformity of the EM beam. The interaction between the two waves may result in the generation of another electrostatic wave or the scattering of the EM beam. We have considered the nonresonant interactions for which the initial pump power may be less than the threshold for the parametric instabilities, and thus the interactions studied may occur before the threshold for the parametric instabilities in the plasma.

The modification in the plasma density due to the nonuniform intensity distribution of the EM beam leads to the nonlinear coupling between the electrostatic modes of oscillation of the plasma and the EM beam, since the amplitude of the electrostatic modes depends on the background carrier density in the plasma. Consequently the dynamics of the electrostatic mode is modified and under appropriate conditions the focusing of the electrostatic mode may take place, leading to the enhancement in its amplitude (Sodha et al., 1976b). The nonresonantly excited electrostatic wave may again interact with the EM beam, leading to enhanced Raman or Brillouin scattering (Sodha et al., 1979a and b). In addition to enhanced scattering, the excited electrostatic wave may also interact with the EM beam and generate another electrostatic wave. In the present thesis we have studied the nonlinear interaction of a Gaussian EM beam with an electron plasma wave in both unmagnetised as well as magnetoplasma. On account of the interaction between the two waves the ponderomotive force at the difference frequency becomes finite and leads to the generation of an ion-acoustic wave. The nonlinear interaction of a Gaussian EM beam with an electrostatic upper hybrid wave in a collisionless magnetoplasma has also been studied. The interaction may result in the generation of electrostatic lower hybrid wave or electrostatic ion cyclotron wave. We have also studied the nonlinear interaction of a Gaussian EM beam with an electron plasma wave, an ion-acoustic wave and an electrostatic ion cyclotron wave in a magnetoplasma and the resultant scattering of the EM beam off these modes.

Excitation of plasma waves at the beat frequency of the two EM waves has attracted considerable attention during recent years (Rosenbluth and Liu, 1972; Kaufman and Cohen, 1973; Kristiansen and Hagler, 1976). This mechanism has been suggested as a possible method for heating the plasma upto thermonuclear temperatures. The $\underline{V} \times \underline{B}$ term in the equation of motion, leads to the resonant excitation of the electrostatic waves if the difference in the frequencies and the wave numbers of the EM waves satisfy the dispersion relation of the electrostatic wave. The excited electrostatic waves have small phase velocities and hence get Landau damped leading to the enhanced heating of the plasma. Most of the studies reported consider uniform and continuous EM waves, whereas in plasma heating experiments the EM pulses are commonly used. When the pulse duration is comparable to the characteristic time of diffusion of the carriers across the pulse, the ponderomotive nonlinearity depends not only on the instantaneous intensity of the pulse but also on its previous history (Sodha et al., 1976a). Consequently the focusing of the EM pulses and the plasma wave generation becomes a transient phenomenon. In the present thesis, we have studied the generation of a lower hybrid pulse at the difference frequency of two EM pulses propagating in ordinary mode in a hot, collisionless magnetoplasma.

The direct and indirect experimental evidences reveal that the smooth looking EM beams have strong intensity spikes which may lead to the formation of filaments in nonlinear media (Loy and Shen, 1969; Chilingaryan, 1969; Abbi and

Mahr, 1971). Filamentation has recently been observed experimentally in a plasma (Ng et al., 1979b; Willi and Rumsby, 1981). Several theories have been proposed for the filamentation instability (Kaw et al., 1973; Drake et al., 1974; Bingham and Lashmore-Davies, 1976; Sodha et al.,1976a). The filamentation instability occurs at moderate threshold power and has a reasonably large growth rate. It may affect the other nonlinear phenomena which take place when an EM beam interacts with a plasma. Most of the above mentioned theoretical investigations of the filamentation instability are limited to obtaining the condition for growth and the actual dynamics of the growth has not been properly studied. Recently the dynamics of the growth of the filamentation instability has been studied by Sodha et al. (1981), in an unmagnetised plasma. It has been shown that a radially symmetric ripple superimposed on a Gaussian EM beam may focus as the beam propagates in the plasma and the excitation of the electron plasma wave significantly depends on the position of the ripple on the EM beam and the phase angle between the ripple and the main beam. In the present thesis in chapter VIII, we have extended the analysis of Sodha et al., to a magnetoplasma. The pump wave has been assumed to be propagating in the ordinary mode and the electrostatic wave has been taken to be a lower hybrid wave. In addition to studying the effect of the ripple on the excitation of the lower hybrid wave, we have also taken into account the ripple effects on the scattering of the EM wave off the excited lower hybrid wave by taking the interaction to be nonresonant. Thus the present analysis is valid for pump powers much below the parametric instability thresholds. A chapterwise summary of the thesis is as follows:

Chapter-I : Nonlinear interaction of an intense laser beam with an electron plasma wave: Generation of ion-acoustic wave.

In this chapter we have studied the nonlinear interaction of a high power Gaussian laser beam with an electron plasma wave in a hot, collisionless unmagnetised plasma. On account of the interaction between the two waves, the ponderomotive force at the difference frequency becomes finite and leads to the generation of another electrostatic wave in the plasma. It has been found that, when the frequency of the laser beam is in the vicinity of the electron plasma frequency, the generated wave is a low frequency ion wave.

Chapter-II: Nonlinear interaction of a right-handed circularly polarised Gaussian EM beam with an electron plasma wave: Generation of ion-acoustic wave.

In this chapter we have studied the nonlinear interaction of a right-handed circularly polarised Gaussian EM beam with an electron plasma wave in a hot, collisionless magnetoplasma. On account of the interaction between the two waves an ion-acoustic wave is generated at the difference frequency of the two waves. The power of the generated ion-acoustic wave increases as we approach the critical density region.

Chapter-III: Nonlinear interaction of a Gaussian EM beam with an electrostatic upper hybrid wave: Generation of electrostatic lower hybrid wave

In this chapter we have studied the nonlinear interaction of a Gaussian EM beam, propagating in ordinary mode, with an electrostatic upper hybrid wave in a hot, collisionless magnetoplasma. Because of the Gaussian intensity distribution of the EM beam, the time independent component of the ponderomotive force becomes finite. This leads to the nonlinear coupling between the EM beam and the electrostatic upper hybrid wave. Consequently the weak electrostatic upper hybrid wave gets excited. The excited electrostatic upper hybrid wave may again interact with the EM beam and lead to the generation of an electrostatic lower hybrid wave of significant power.

Chapter-IV: Nonlinear interaction of a Gaussian EM beam with an electrostatic upper hybrid wave: Generation of electrostatic ion cyclotron wave

In this chapter we have studied the nonlinear interaction of a Gaussian EM beam, propagating in ordinary mode, with an electrostatic upper hybrid wave in a hot collisionless magnetoplasma. The interaction between the two waves may lead to the generation of an electrostatic ion cyclotron wave of appreciable power.

Chapter-V: Generation of an electrostatic lower hybrid pulse by two EM pulses at difference frequency in a collisionless magnetoplasma.

In this chapter we have studied the generation of an electrostatic lower hybrid pulse at the difference frequency of two Gaussian (in space and time) pulses, propagating perpendicular to the static magnetic field in ordinary mode, in a collisionless magnetoplasma. On account of the interaction between the two EM pulses, the ponderomotive force at the difference frequency becomes finite and leads to the generation of the electrostatic lower hybrid pulse. The time independent component of the ponderomotive force, leads to the redistribution of the carriers in the plasma and the focusing of the two EM pulses. The focusing of the EM pulses modifies the power of the generated electrostatic lower hybrid pulse.

Chapter-VI: Raman and Brillouin scattering of a right-handed circularly polarised Gaussian EM beam from a plasma.

In this chapter we have investigated the Raman and Brillouin scattering of a high power right-handed circularly polarised Gaussian EM beam from a hot, collisionless magnetoplasma. Because of the Gaussian intensity distribution of the EM beam, the time independent component of the ponderomotive force becomes finite and leads to the modification in the background electron/ion density. This leads to the nonlinear coupling between the electron plasma wave or ion-acoustic wave with the EM beam. Consequently the electron plasma wave or ion-acoustic wave is excited. The excited electron plasma wave or the ion-acoustic wave may interact with the EM beam and lead to Raman or Brillouin scattering.

Chapter-VII: Nonlinear interaction of a Gaussian EM beam in extraordinary mode with an electrostatic ion cyclotron wave: Brillouin scattering.

In this chapter we have studied the nonlinear interaction of a high power Gaussian EM beam in extraordinary mode with an electrostatic ion cyclotron wave in a hot, collisionless magnetoplasma. Because of the Gaussian intensity distribution of the EM beam the ponderomotive force becomes finite and leads to the redistribution of carriers in the plasma. This leads to the nonlinear coupling between the electrostatic ion cyclotron wave and the EM beam. Consequently the focusing of the electrostatic ion cyclotron wave may take place and under appropriate conditions its interaction with the EM beam may lead to the scattering of the EM beam.

Chapter-VIII: Effect of a ripple superimposed on a Gaussian EM beam on the excitation and scattering in a magnetoplasma.

In this chapter we have studied the effect of a radially symmetric ripple superimposed on a Gaussian EM beam on excitation and scattering in a magnetoplasma. Because of the Gaussian intensity distribution of the EM beam, the ponderomotive force becomes finite and leads to the redistribution of carriers in the plasma. In the presence of the ripple the magnitude of the ponderomotive force and hence the background electron/ion density is further modified. This leads to the modification in the amplitude of the electrostatic lower hybrid wave since it depends on the background carrier density in the plasma. It has been found that the amplitude of the electrostatic lower hybrid wave depends on the position of the ripple on the EM beam and the phase angle between the ripple and the main beam. The scattering of the EM beam off the electrostatic lower hybrid wave has also been studied. It has been found that the scattered power also depends on the position of the ripple on the EM beam and the phase angle between the ripple and the main beam.

The above mentioned work has been reported in the following publications/communications:-

1. Nonlinear interaction of an intense laser beam with an electron plasma wave: Generation of ion-acoustic wave, M.S.Sodha, P.K.Malhotra and R.P. Sharma, Plasma Phys. 23, 163 (1981).
2. Nonlinear interaction of a right-handed circularly polarised Gaussian EM beam with an electron plasma wave: Generation of ion-acoustic wave, M.S.Sodha, P.K.Malhotra and R.P.Sharma, (Communicated)
3. Nonlinear interaction of a Gaussian EM Beam with an electrostatic upper hybrid wave: Generation of electrostatic lower hybrid wave, M.S.Sodha, P.K.Malhotra and R.P.Sharma, Phys.Rev.A. 25, 2359 (1982).

4. Nonlinear interaction of a Gaussian EM beam with an electrostatic upper hybrid wave: Generation of electrostatic ion cyclotron wave, M.S.Sodha, P.K. Malhotra and R.P.Sharma (Communicated)

5. Generation of an electrostatic lower hybrid pulse by two EM pulses at difference frequency in a collisionless magnetoplasma, M.S.Sodha, P.K. Malhotra and R.P.Sharma (Communicated)

6. Raman and Brillouin scattering of a right-handed circularly polarised Gaussian EM beam from a plasma, M.S.Sodha, P.K. Malhotra and R.P.Sharma (Communicated).

7. Nonlinear interaction of a Gaussian EM beam in extraordinary mode with an electrostatic ion cyclotron wave: Brillouin scattering, M.S.Sodha, P.K. Malhotra and R.P. Sharma (Communicated).

8. Effect of a ripple superimposed on a Gaussian EM beam on excitation and scattering in a magnetoplasma, M.S.Sodha, P.K. Malhotra and R.P.Sharma (Communicated).

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